16-20 Sep 2013 ISSI team meating@Bern
``Turbulence and Self-Organized Criticality''
17 Sep 2013 (Tue), 09:30h-10:30h

Fractal Structure (**Turbulence**) and **SOC** of a Current Sheet in a Solar Flare via Dynamic **Magnetic Reconnection**

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In cooperation with
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THE ROLE OF A FLUX ROPE EJECTION IN A THREE-DIMENSIONAL MAGNETOHYDRODYNAMIC SIMULATION OF A SOLAR FLARE

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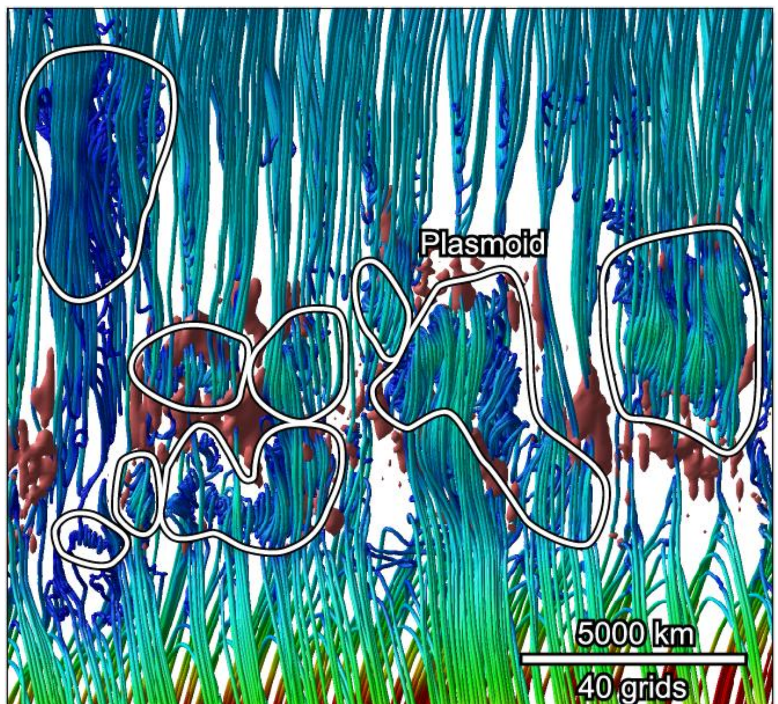

PRL 110, 051101 (2013) PHYSICAL REVIEW LETTERS week ending 1 FEBRUARY 2013

Fermi Acceleration in Plasmoids Interacting with Fast Shocks of Reconnection via Fractal Reconnection

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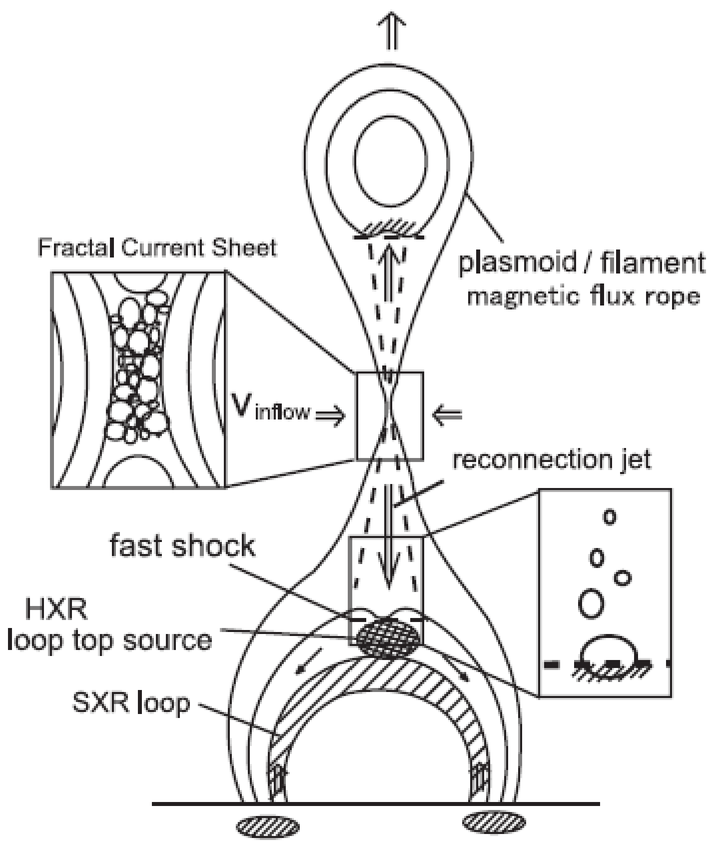
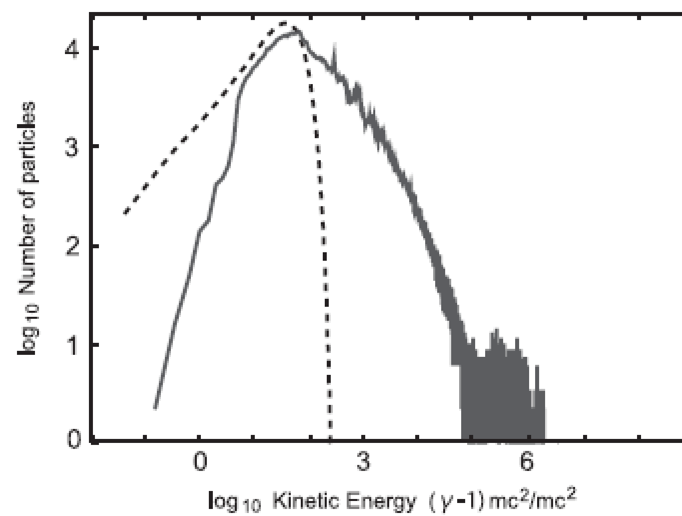




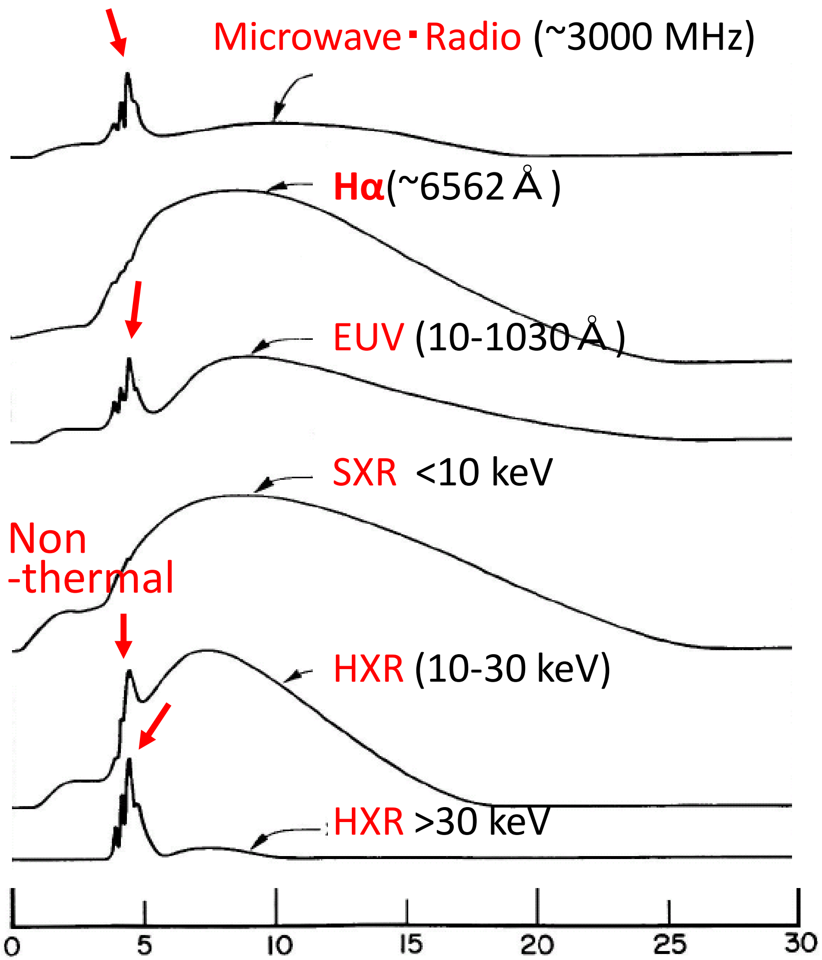
Motivation of my study

- Magnetic Reconnection is SOC?
  (current automaton model is ok?)

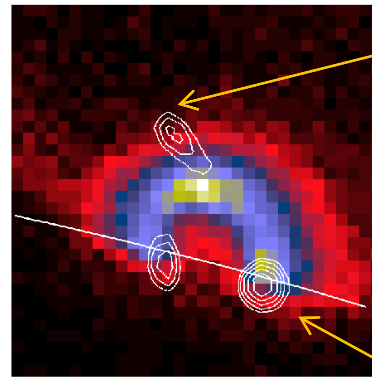
- What is the origin of Turbulence in solar flares?

- How turbulence/SOC state affects Reconnection mechanism (dynamics, reconnection rate)?

Multiwavelength emissions from a Solar Flare



Time (minutes) (Kane 1974)



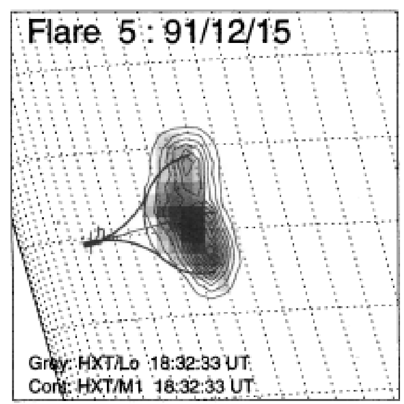
Energy Release

Magnetic Reconnection

Particle Acceleration

Emission from loop-footpoint

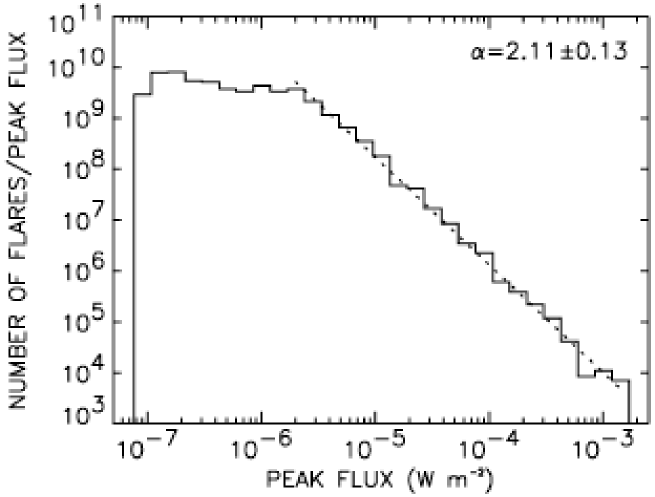
Loop-top HXR source
(Masuda 1994)

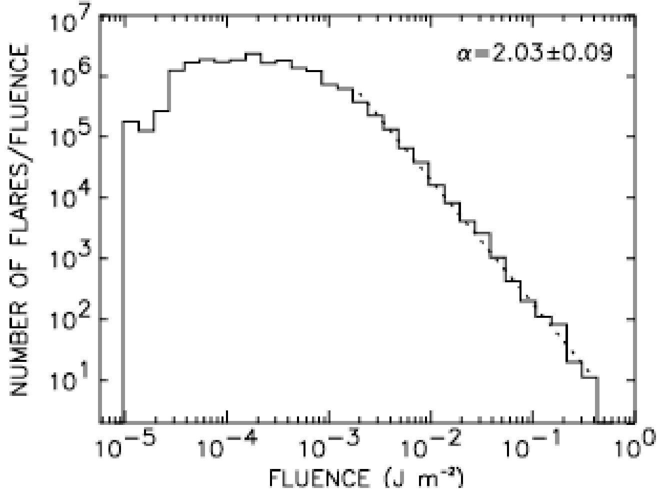


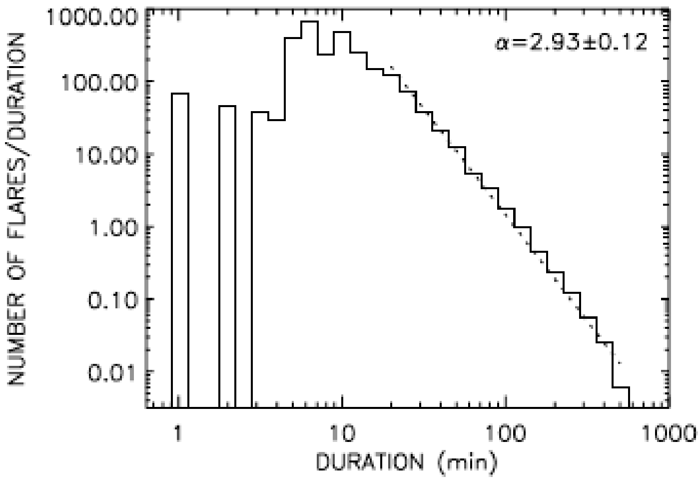
Time-of-flight method
[Aschwanden 1996]

Various scales of Solar Flares

Soft X-rays (~ total released energy)







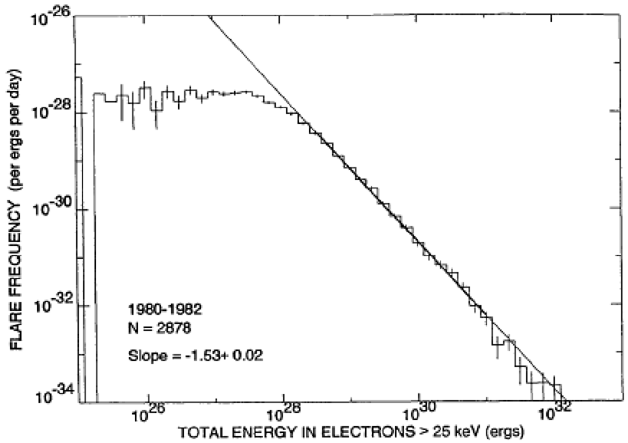
[Veronig et al. 2002]

Solar Flares show power-law distributions of peak flux, duration and time interval.

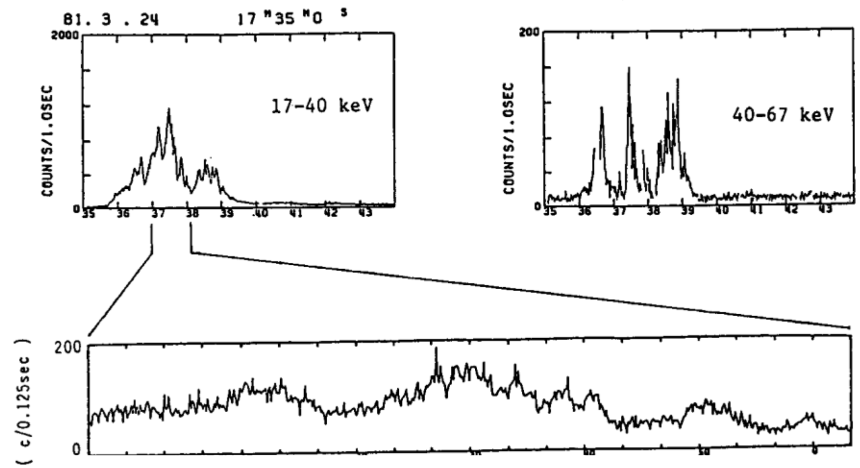
MHD scale free & SOC

Observations of hard X-rays and Microwave emissions show fractal-like time variability.

Hard X-rays (~ released particle energy)

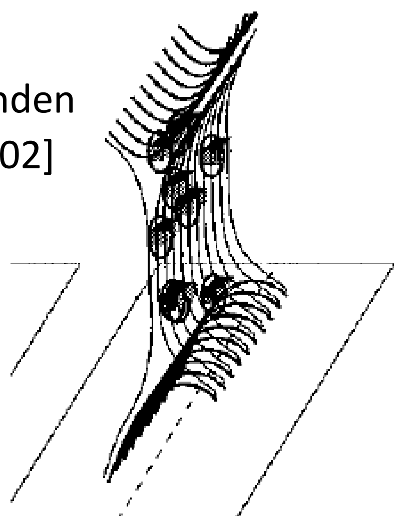


[Crosby et al. 1993]



[Ohki et al. 1992]

[Aschwanden et al. 2002]

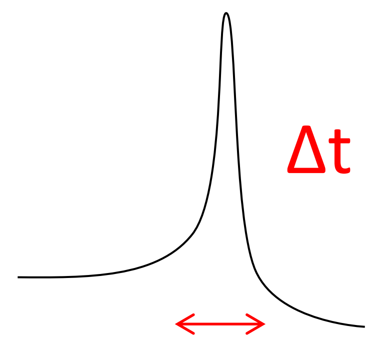


Multiple X-points

- Fractal Reconnection
  (= ensemble of elemental reconnection?)

v.s.

- Patchy Reconnection
  (same size of reconnection region)



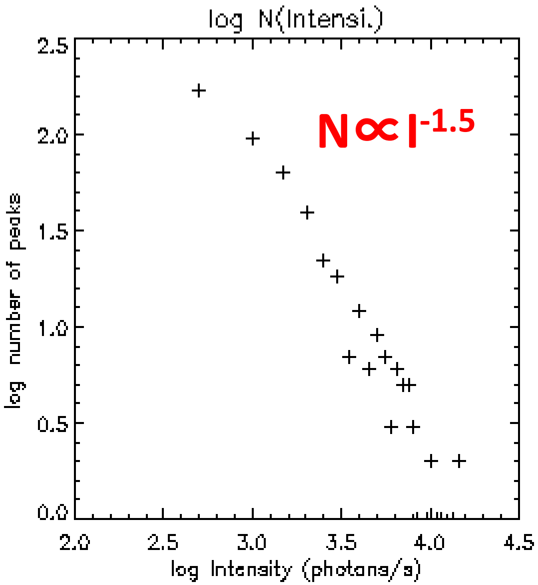
$\Delta t = L_{acc}/c$

If Δt is power-law,
L_{acc} may be also power-law.

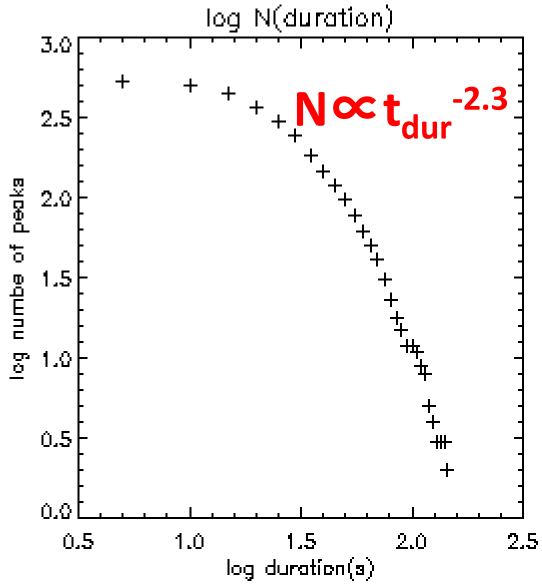
Power-laws of UV Footpoint Brightenings

TRACE1600A (C IV 1550A) UV emission

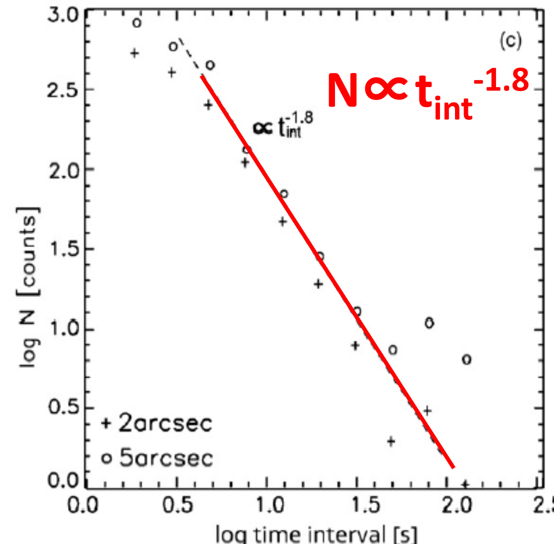
[Nishizuka et al. 2009]



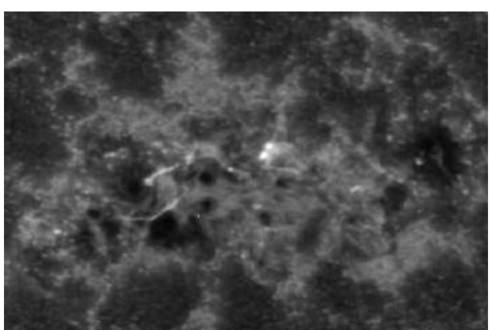
↑distribution of peak intensity of kernels



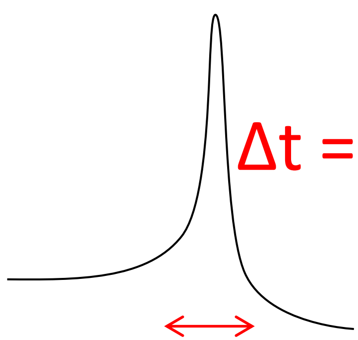
↑distribution of peak duration of kernels



↑distribution of time Intervals of kernels



2004 Nov 10 TRACE1600A

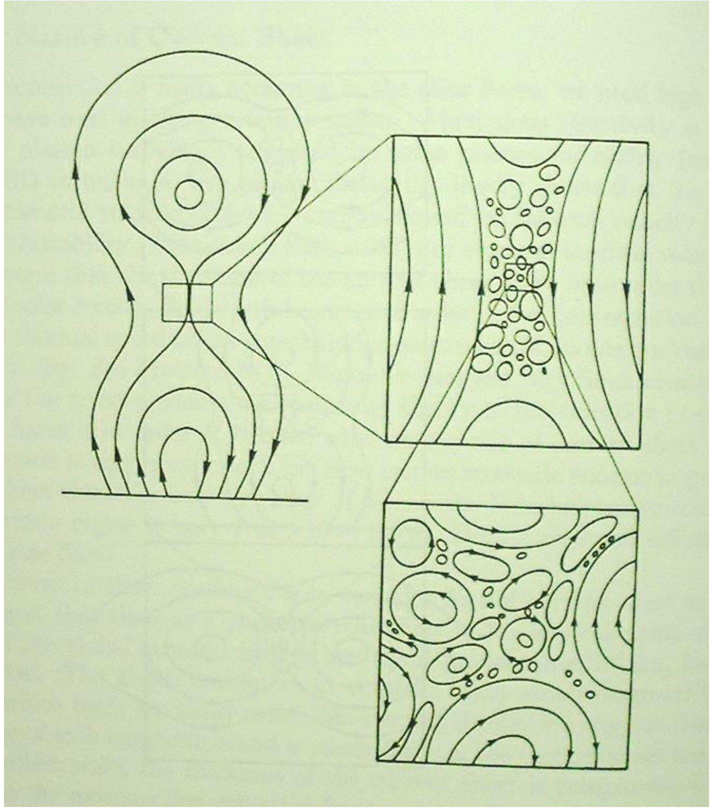


$\Delta t = L_{rec}/V_A$

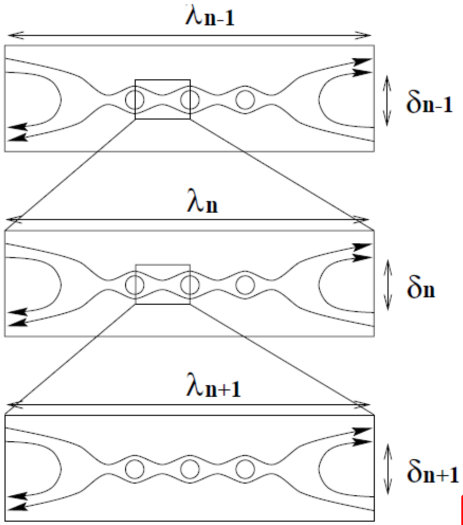
If Δt is power-law,
L_{rec} may also be power-law.

→ Evidence of Fractal Reconnection?

Fractal Current Sheet



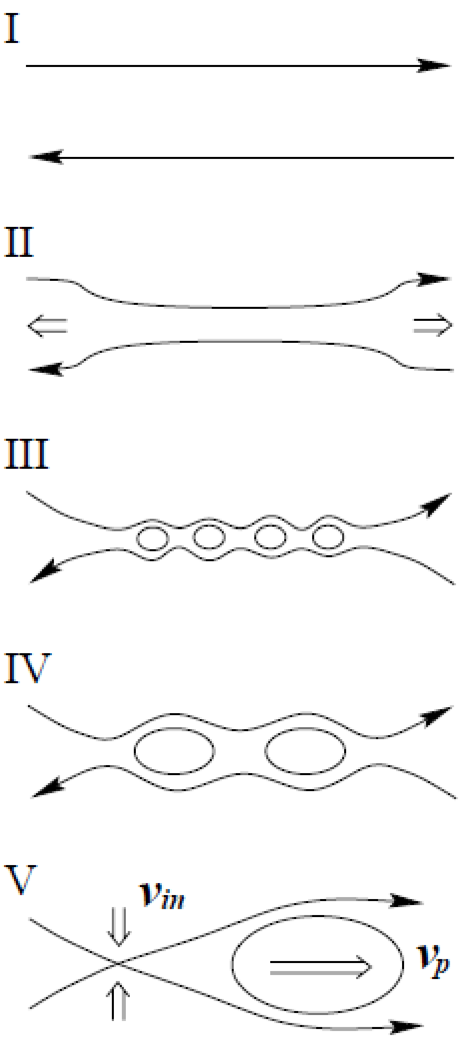
[Tajima & Shibata 1997]



[Shibata & Tanuma 2001]

Self-similar

■Scenario of fast reconnection



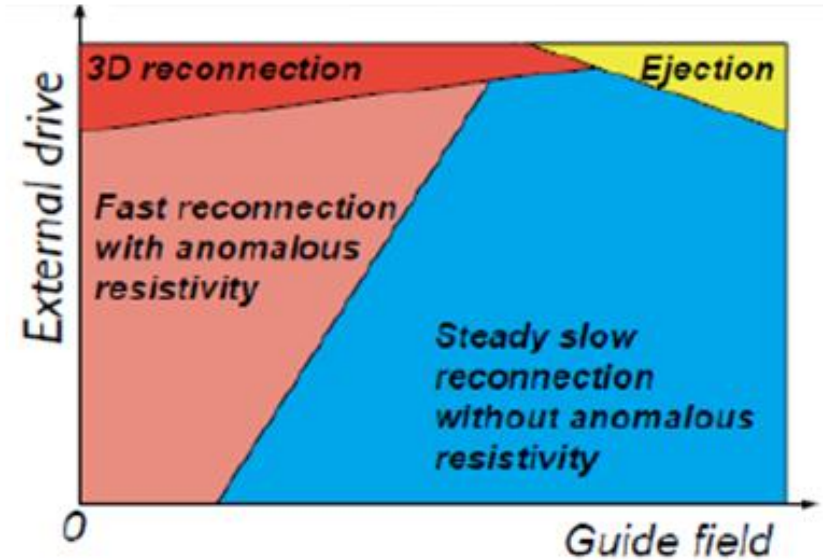
During this merging process, avalanching system works?
No avalanche model.

Classification of Fast Reconnection in Lab Plasma

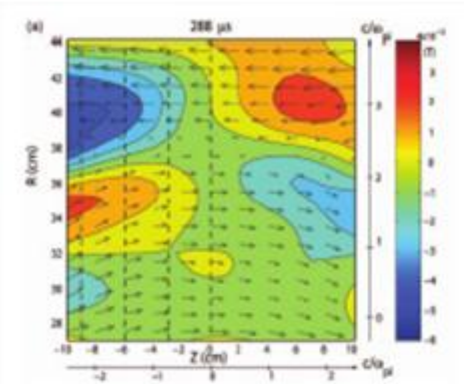
●Driver of Fast reconnection

- Anomalous resistivity

  (Hall effect, Disturbance?, Instability?)
- 3D effect
- Non-steady effect
  - Density pile up
  - Current sheet ejection
  - Plasmoid ejection

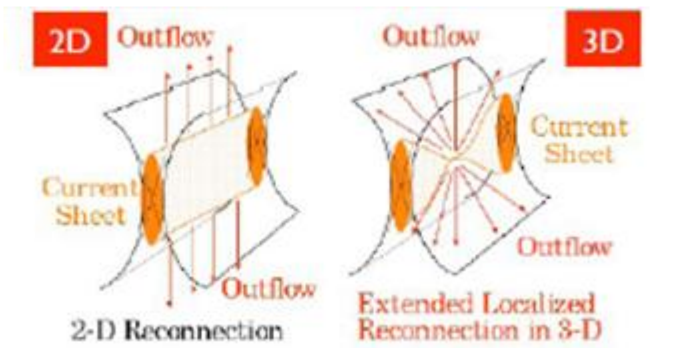


[Inomoto et al. 2012
NINS-UT reconnection Workshop]



MRX at PPPL
Null-helicity Pull mode
Hall reconnection
Quadrapole
measurement

[Yamada et al. 2006]

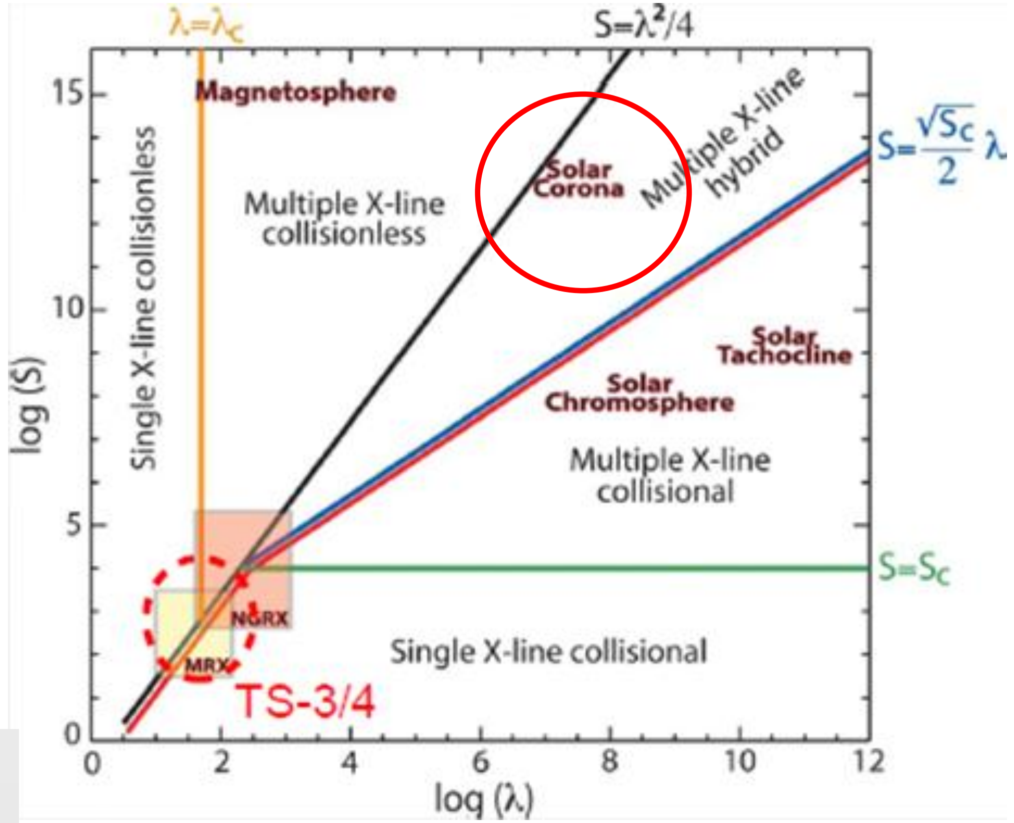


Faster reconnection by 3D structure change of a current sheet.

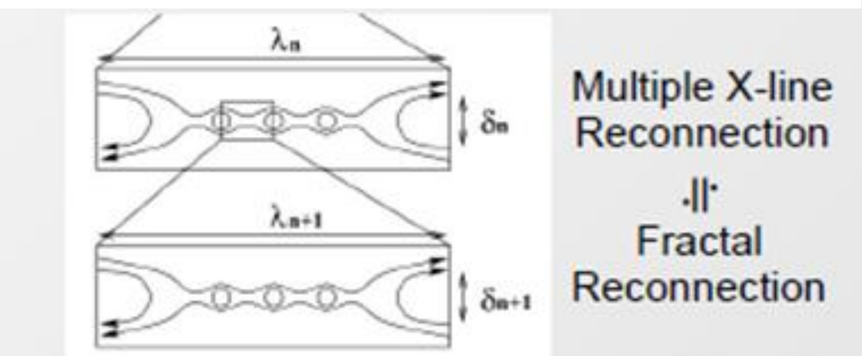
Classification of Reconnection in Parm. Regime

- Phase diagram
  - vertical: Lundquist #num
  - horizontal: size parameter

- Solar corona
  - multiple X-line hybrid



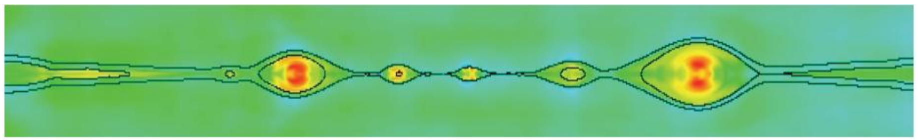
[Ji & Daughton 2011]



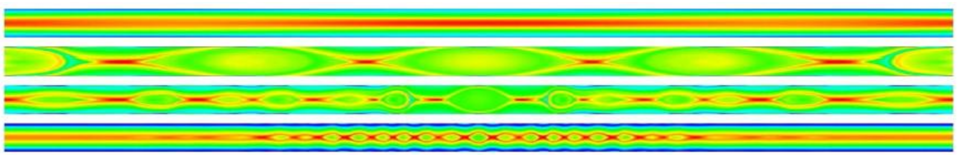
K.Shibata and S.Tanuma, EPS, 53, 473 (2001)

$$\left(S \equiv \frac{\mu_0 L_{CS} V_A}{\eta} \quad , \quad \lambda \equiv \frac{L}{\rho_s} = \frac{L}{\frac{\sqrt{(T_i + T_e) m_i}}{q_i B_{total}}} \right)$$

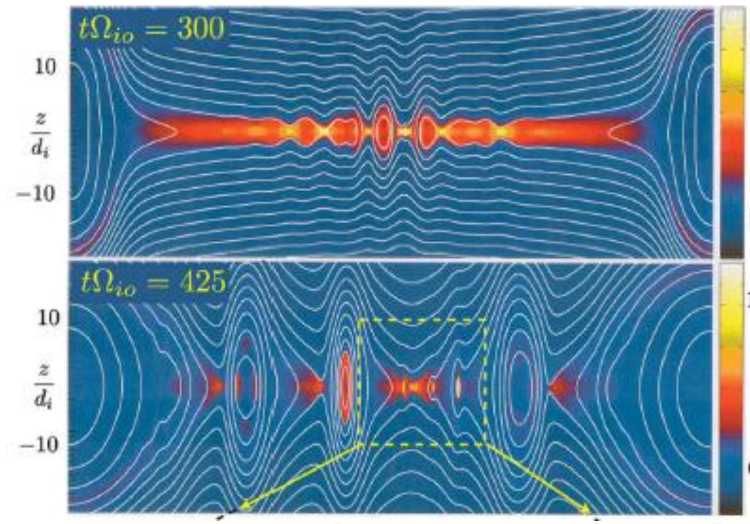
Multiple plasmoids in a Current Sheet



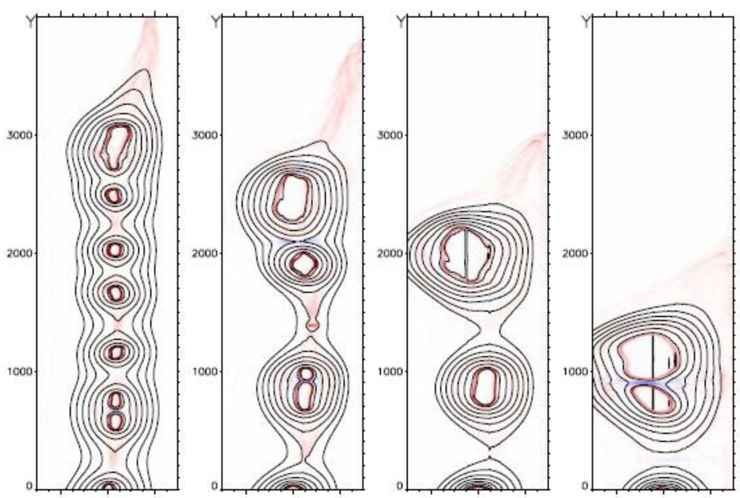
[Loureiro et al. 2009]



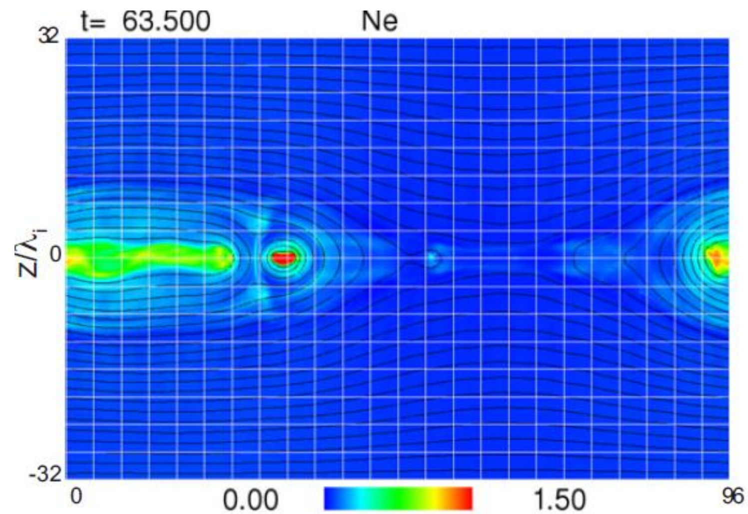
[Samtaney et al. 2009]



[Daughton et al. 2009]

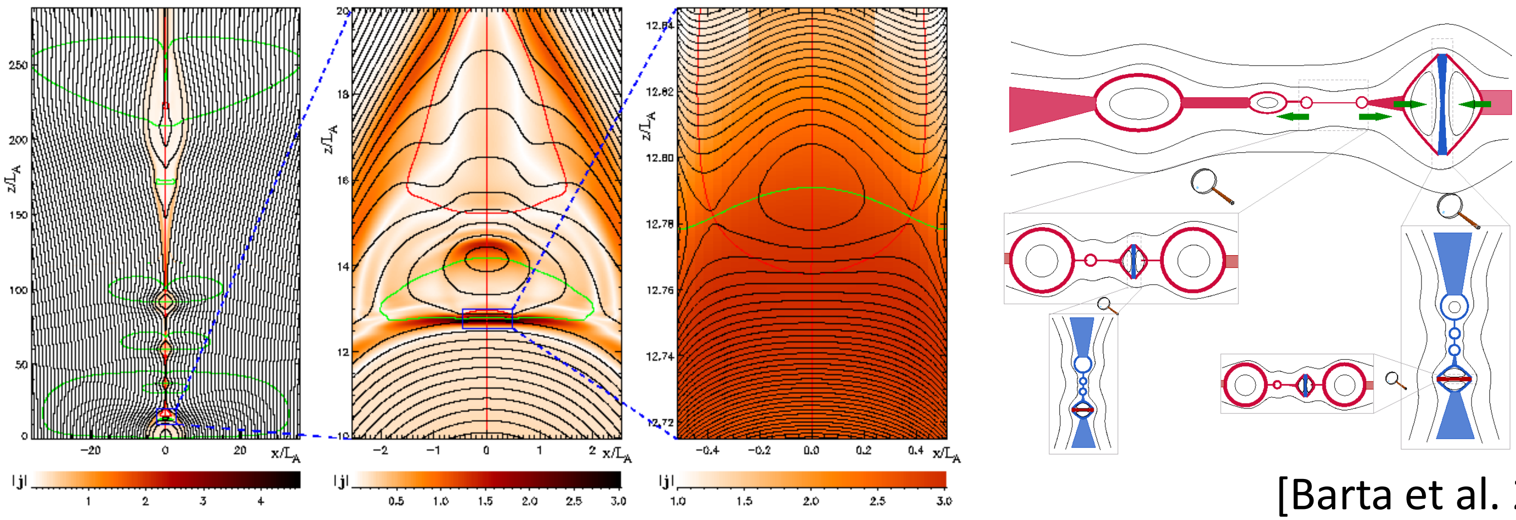


[Karlicky and Barta. 2011]



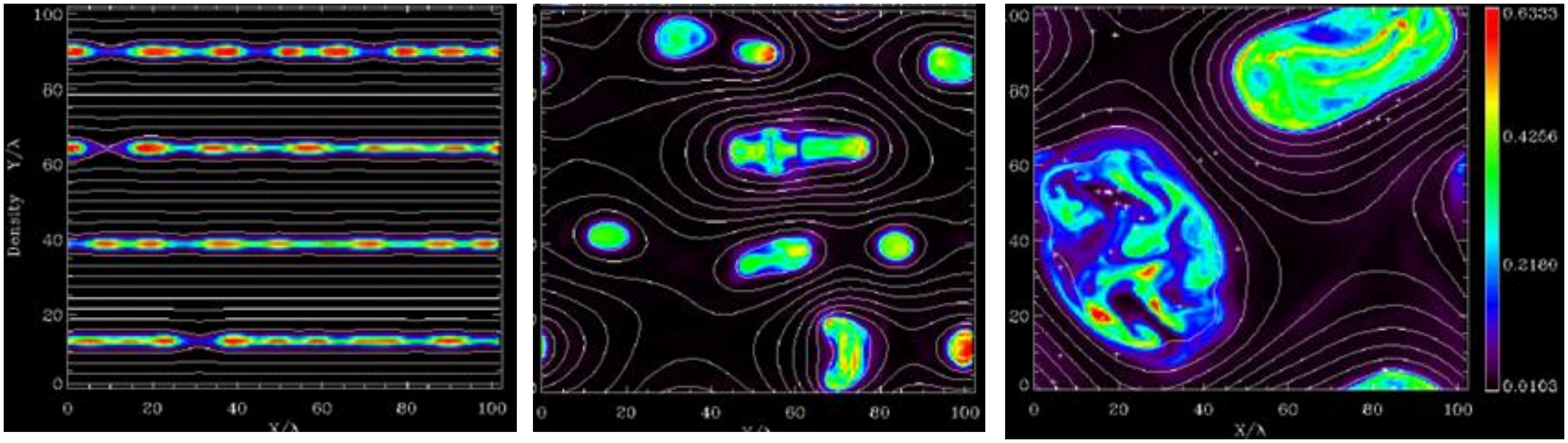
[Tanaka et al. 2010]

Multiple plasmoids in 2D direction



[Barta et al. 2010]

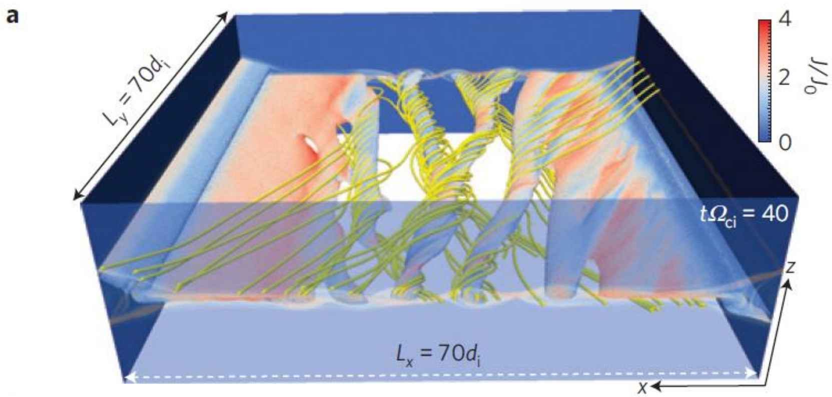
Plasma density



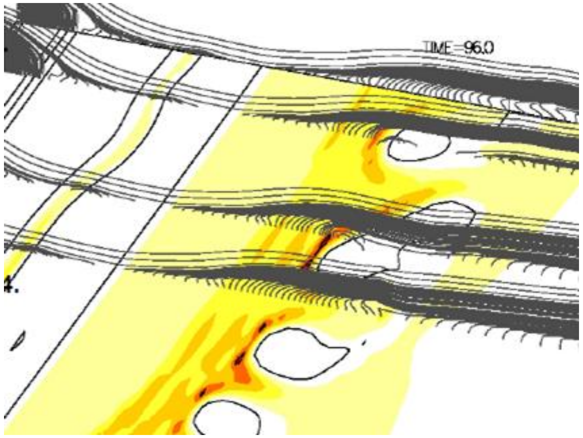
Reconnection in acretion disk (magneto-rotational Instability)

[Hoshino 2012]

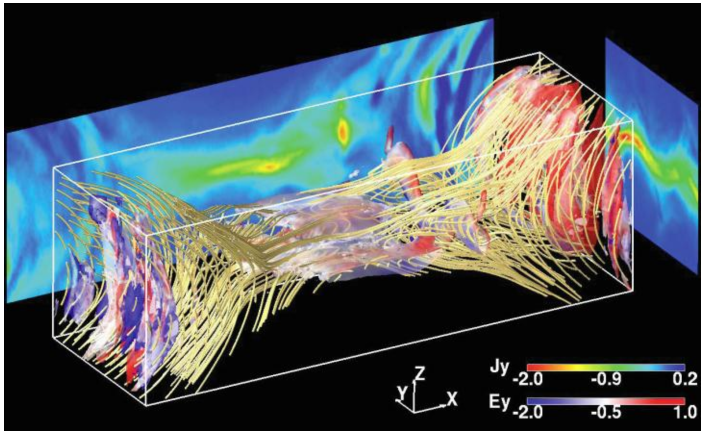
Plasmoid and Turbulent current sheet in 3D simulation



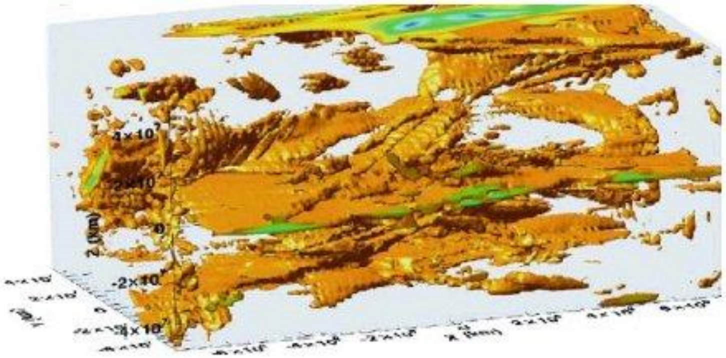
[Daughton et al. 2011] **PIC** simulation
Guide field is very strong.
→multi fractal analysis [S. Chapman et al. 2012]



[Shimizu et al. 2011] **MHD** simulation
Guide field is small, patchy reconnection



[Fujimoto & Sydora 2012] **PIC** simulation
Reconnection generates kinetic turbulence.



[Galsgaard & Nordlund 1996, Vlahos 2004]
Idea of SOC-formed current sheet.
Simulation is **very diffusive** (**small R_m**)

3D simulation of a Solar Flare and Reconnection current sheet with high resolution

with **small guide field** (patchy reconnection), low beta plasma (β=0.01), R_m~10000

Numerical Method

- We solved 3D MHD equations and calculated time evolution with multistep implicit scheme (Hu 1989).
- Localized Anomalous resistivity
- Emerging flux as a trigger mechanism (Chen & Shibata 2000)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \mathbf{v}}{\partial t} + (\mathbf{v} \cdot \nabla)\mathbf{v} + \frac{1}{\rho}\nabla p - \frac{1}{\rho}\mathbf{j} \times \mathbf{B} = 0$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{v} \times \mathbf{B}) + \nabla \times (\eta \nabla \times \mathbf{B}) = 0$$

$$\frac{\partial \mathrm{T}}{\partial t} + \mathbf{v} \cdot \nabla \mathrm{T} + (\gamma - 1)\mathrm{T} \cdot \nabla \mathbf{v} - \frac{2(\gamma - 1)\eta}{\beta_0}\frac{\mathbf{j} \cdot \mathbf{j}}{\rho} = 0$$

$$\text{Plasma beta} : \beta_0 = 0.01$$

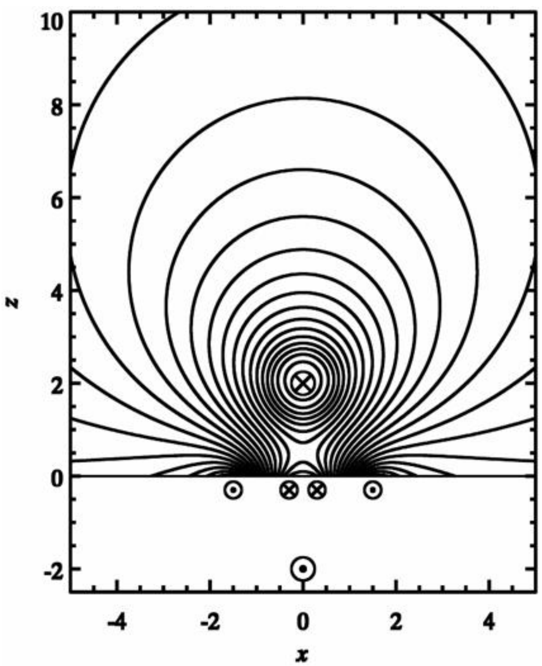
$$\eta = \begin{cases} \eta_0 & |v_d| > 2v_c \\ \eta_0\left(\left|\frac{v_d}{v_c}\right| - 1\right) & v_c < |v_d| < 2v_c \\ 0 & |v_d| < v_c \end{cases}$$

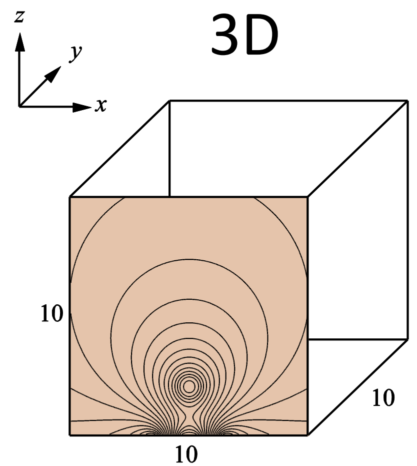
$$v_d = \frac{j_z}{\rho}$$

* When current density in a current sheet (= relative velocity of ions and electrons) becomes strong, plasma instability in micro-scale generate localized anomalous resistivity.

Extended 3D Model

Initial condition & Perturbation

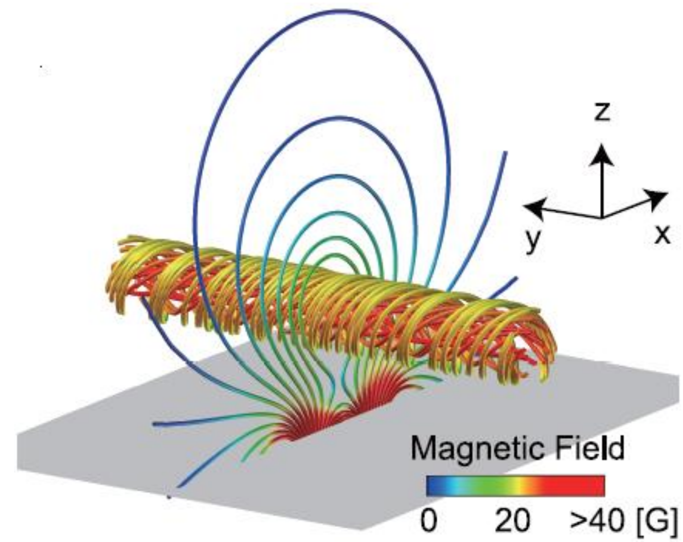




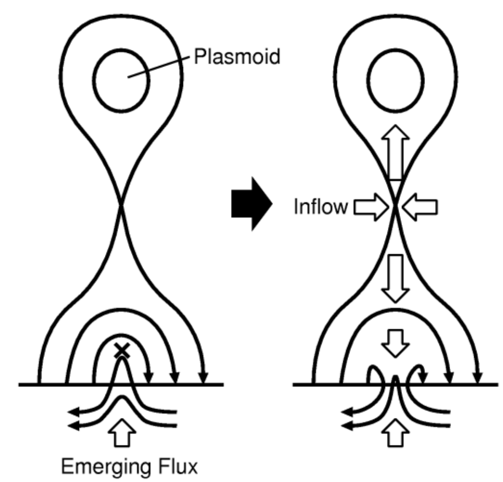
Unit : L0=10^9cm

Grid : [400x400x400]

or [800x800x800]

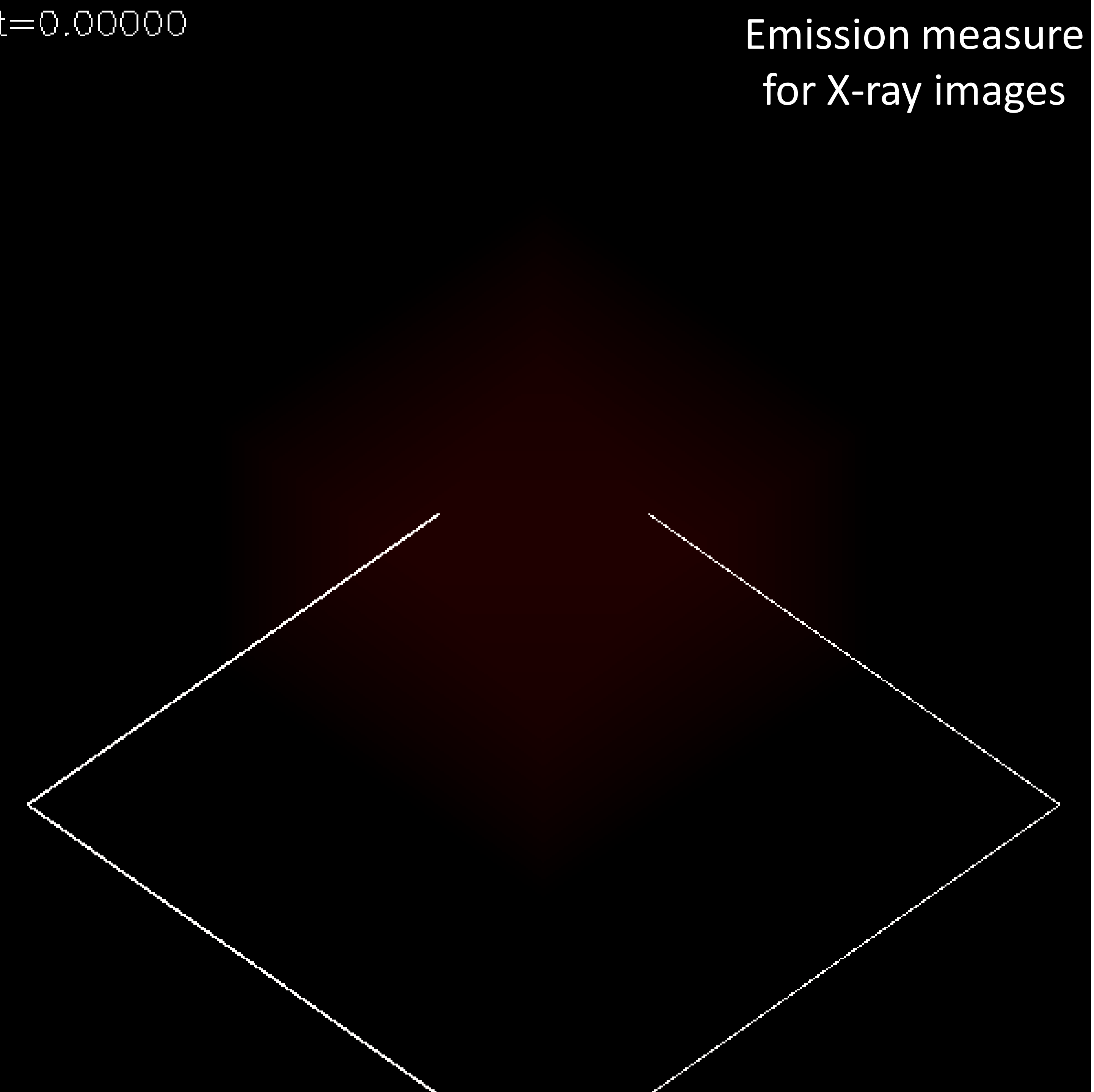


- Boundary condition: Periodic in y-direction, fixed at z=0, open at others
- Initially P, T, ρ=const, and β~0.01.
- Trigger mechanism by emerging flux (→)



Emission measure for X-ray images

Nishida, Nishizuka, Shibata, 2013, ApJL

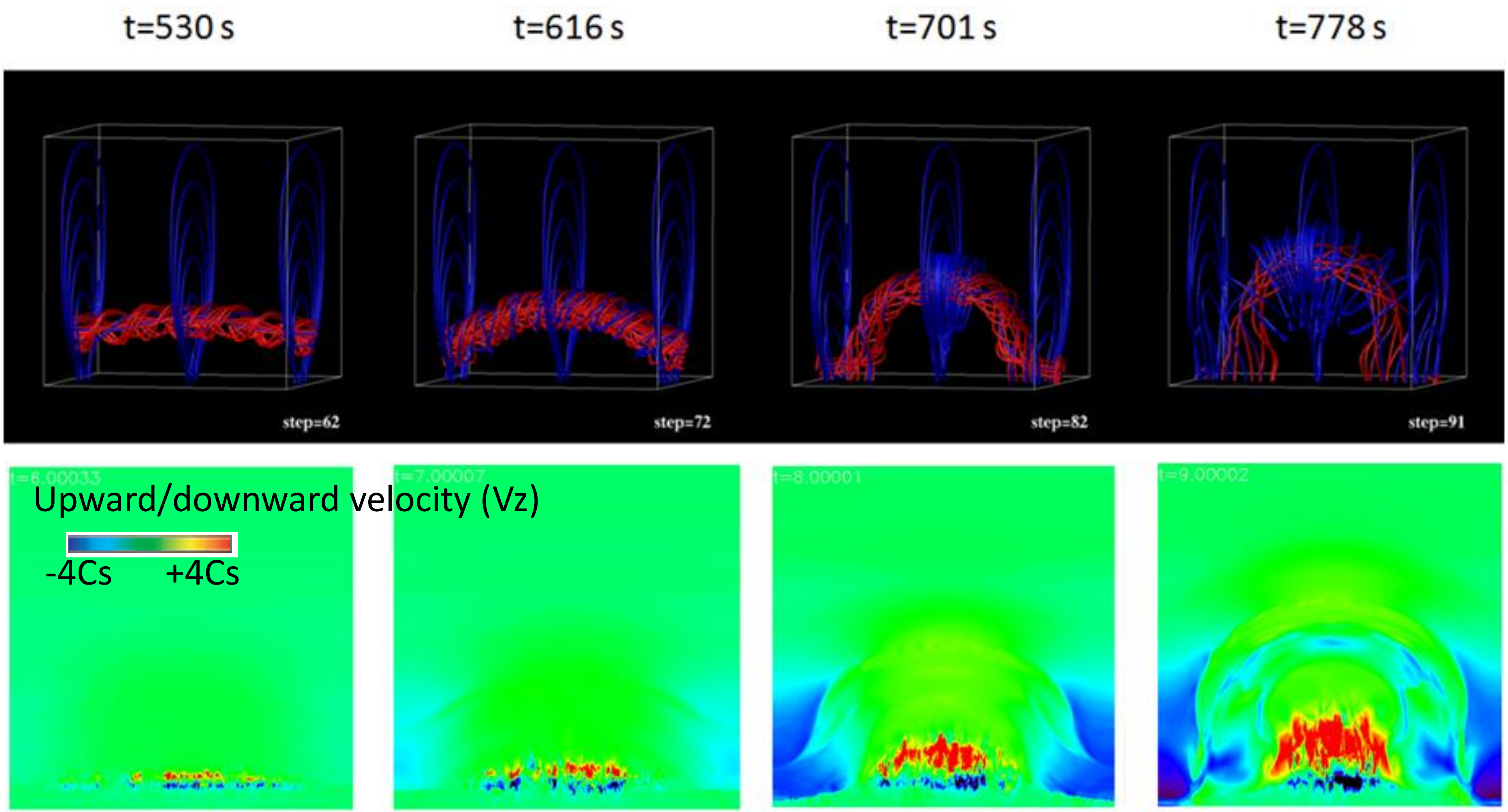


density

temperature

Snapshot images of a weakly twisted flux rope

$$\Phi(r=0)\approx 1.5 \quad \Phi(r)=\frac{LB_{\varphi}(r)}{2\pi r B_z(r)}$$

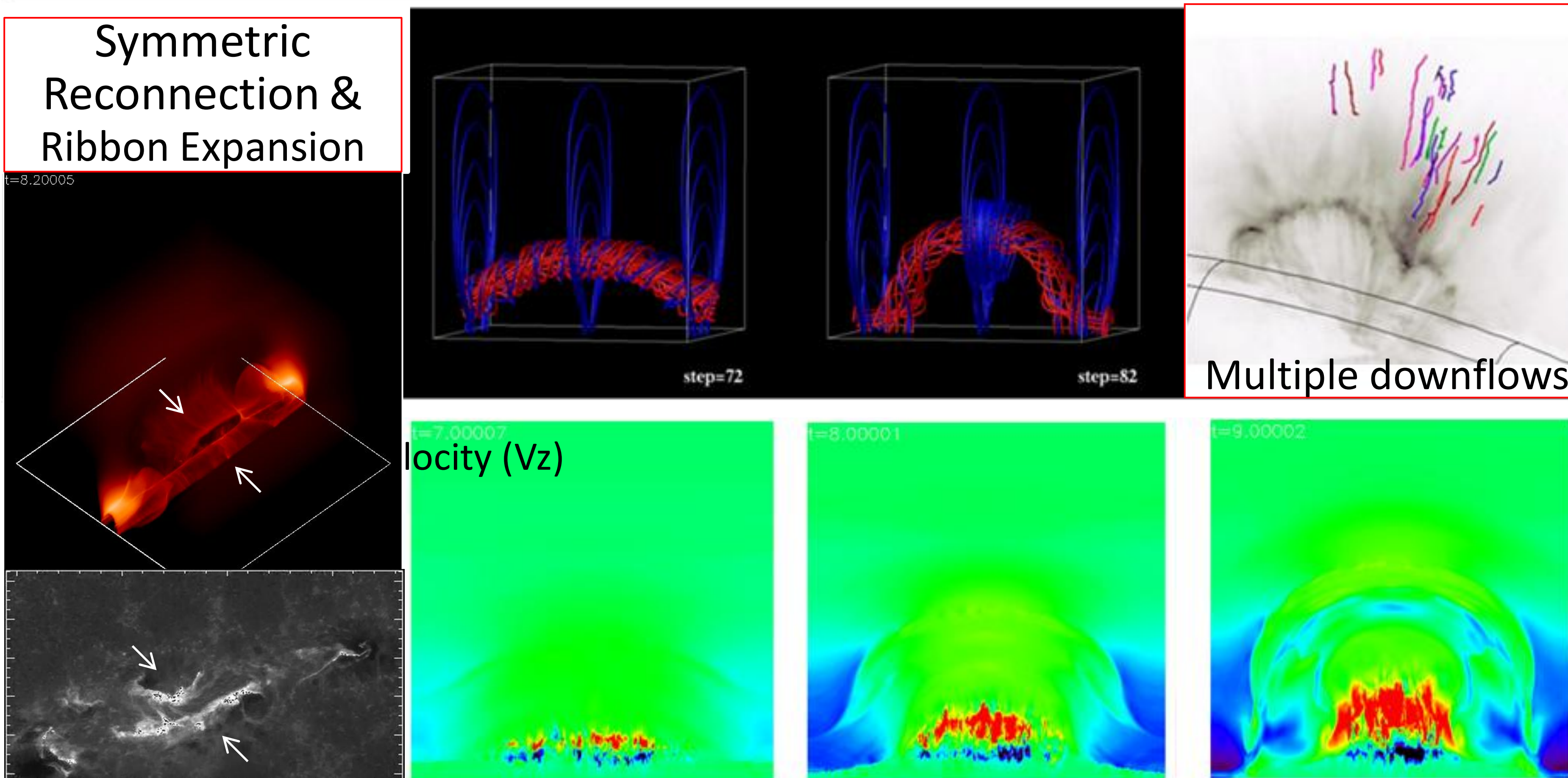


Snapshot images of a weakly twisted flux rope

$$\Phi(r=0)\approx 1.5 \quad \Phi(r)=\frac{LB_{\varphi}(r)}{2\pi r B_z(r)}$$

t=530 s   t=616 s   t=701 s   t=778 s

Symmetric Reconnection & Ribbon Expansion



Multiple downflows

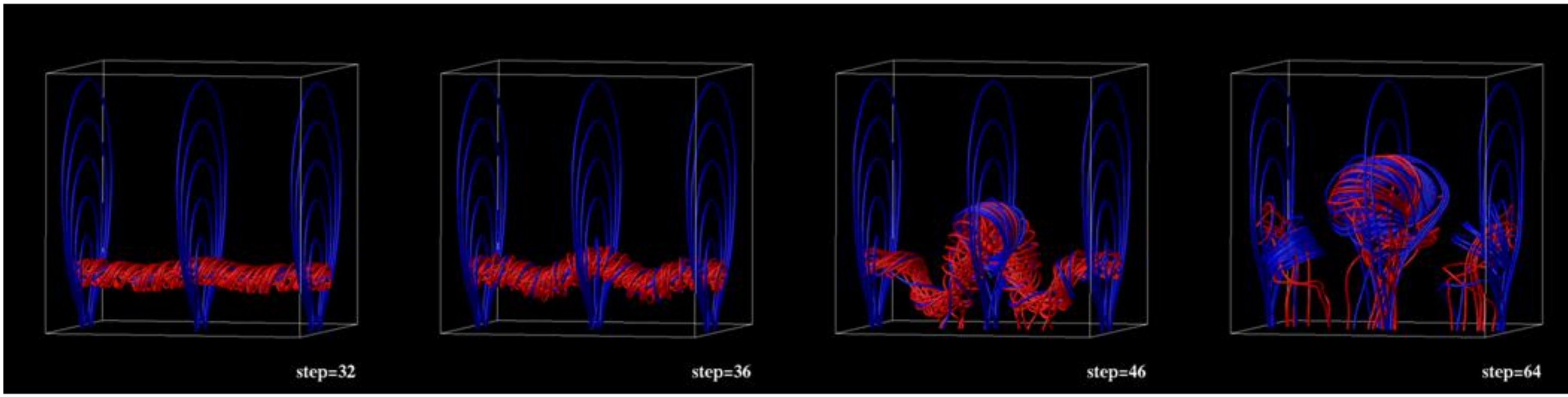
locity (Vz)

Ribbon expansion

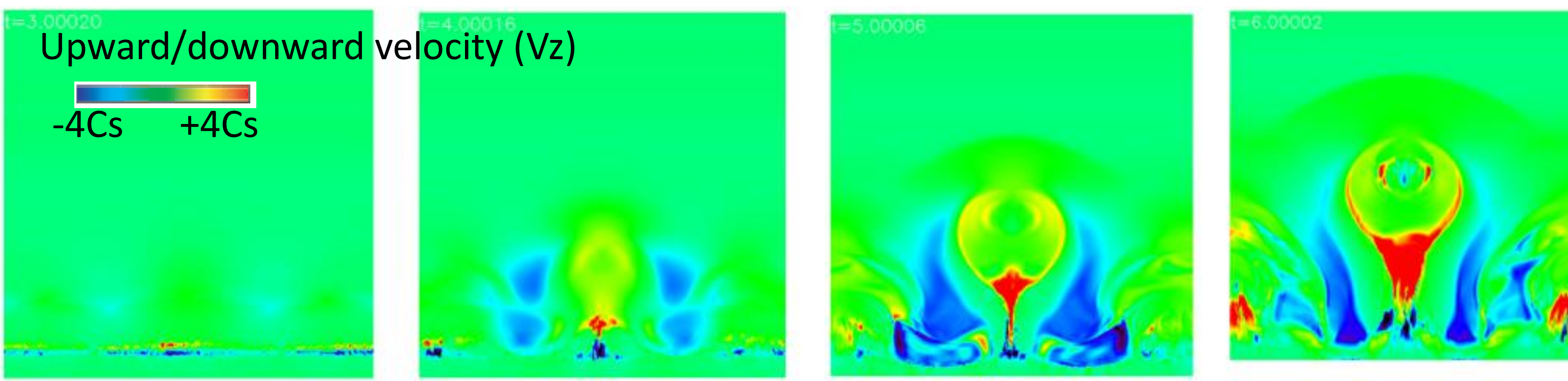
Snapshot images of a strongly twisted flux rope

$$\Phi(r=0) \approx 2.2 \quad \Phi(r) = \frac{LB_{\varphi}(r)}{2\pi r B_z(r)}$$

t=274 s　t=308 s　t=393 s　t=547 s

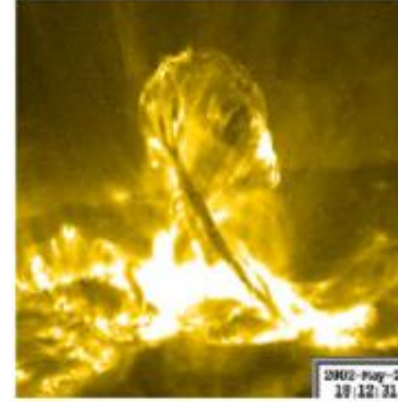


Kink-instability

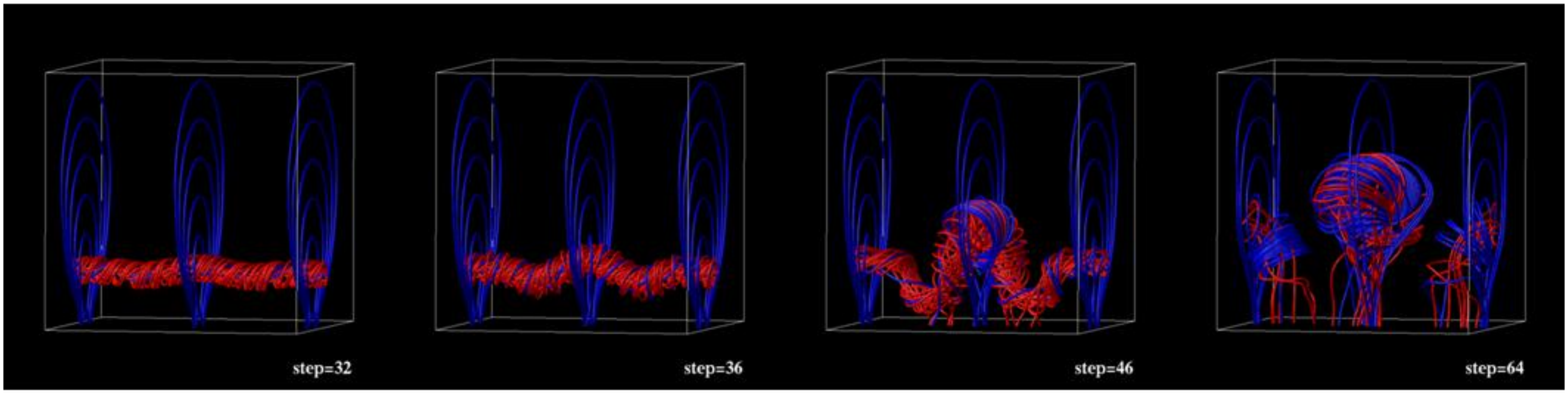


Snapshot images of a strongly twisted flux rope

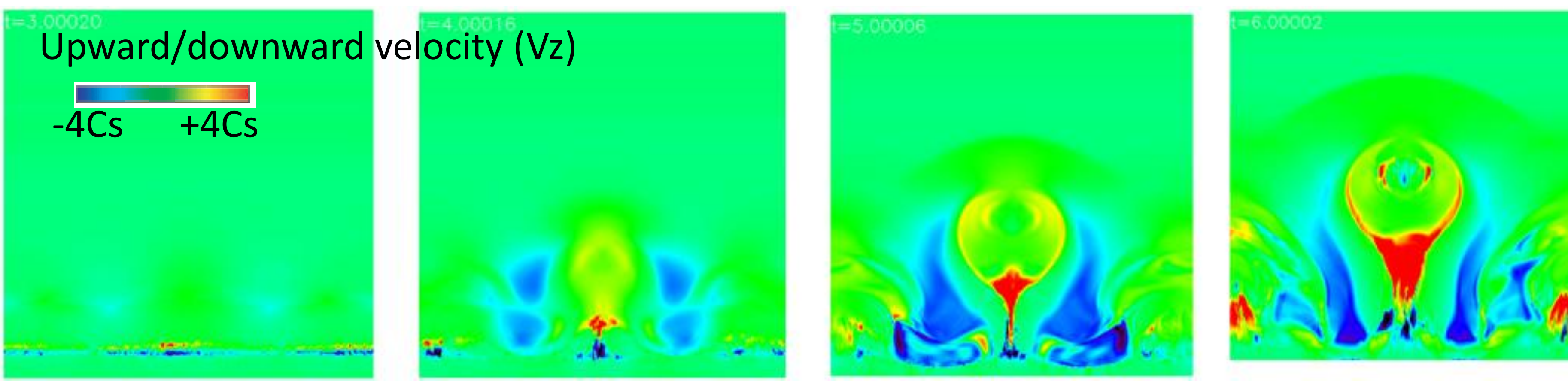
$$\Phi(r=0) \approx 2.2$$



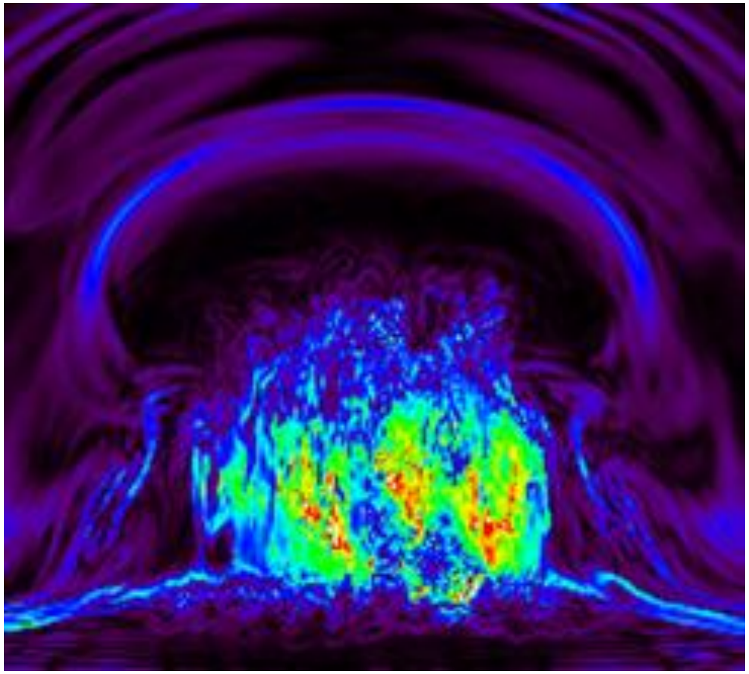
t=274 s t=308 s t=393 s



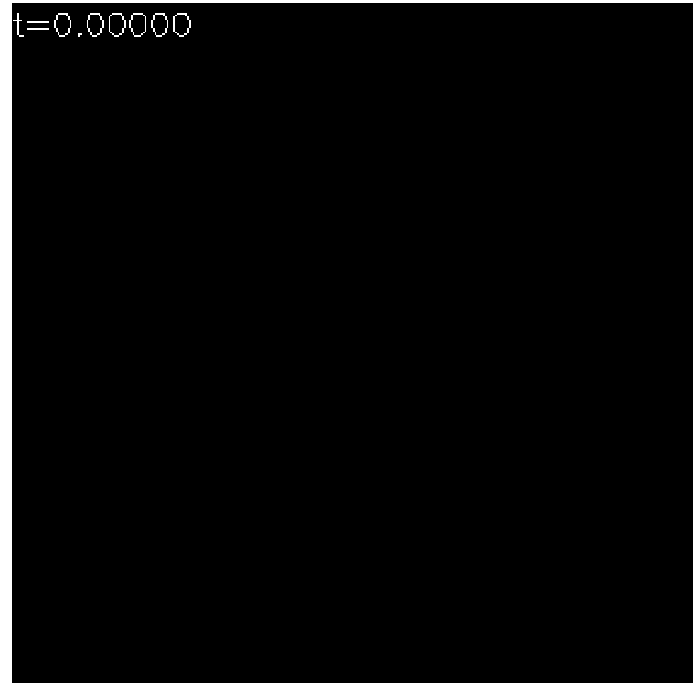
Kink-instability



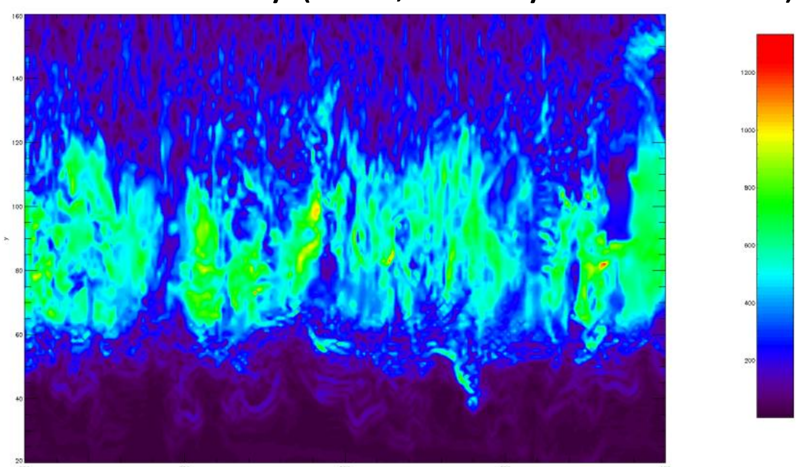
Turbulent structure in 3D current sheet



Current density (t=90, weakly twisted case)

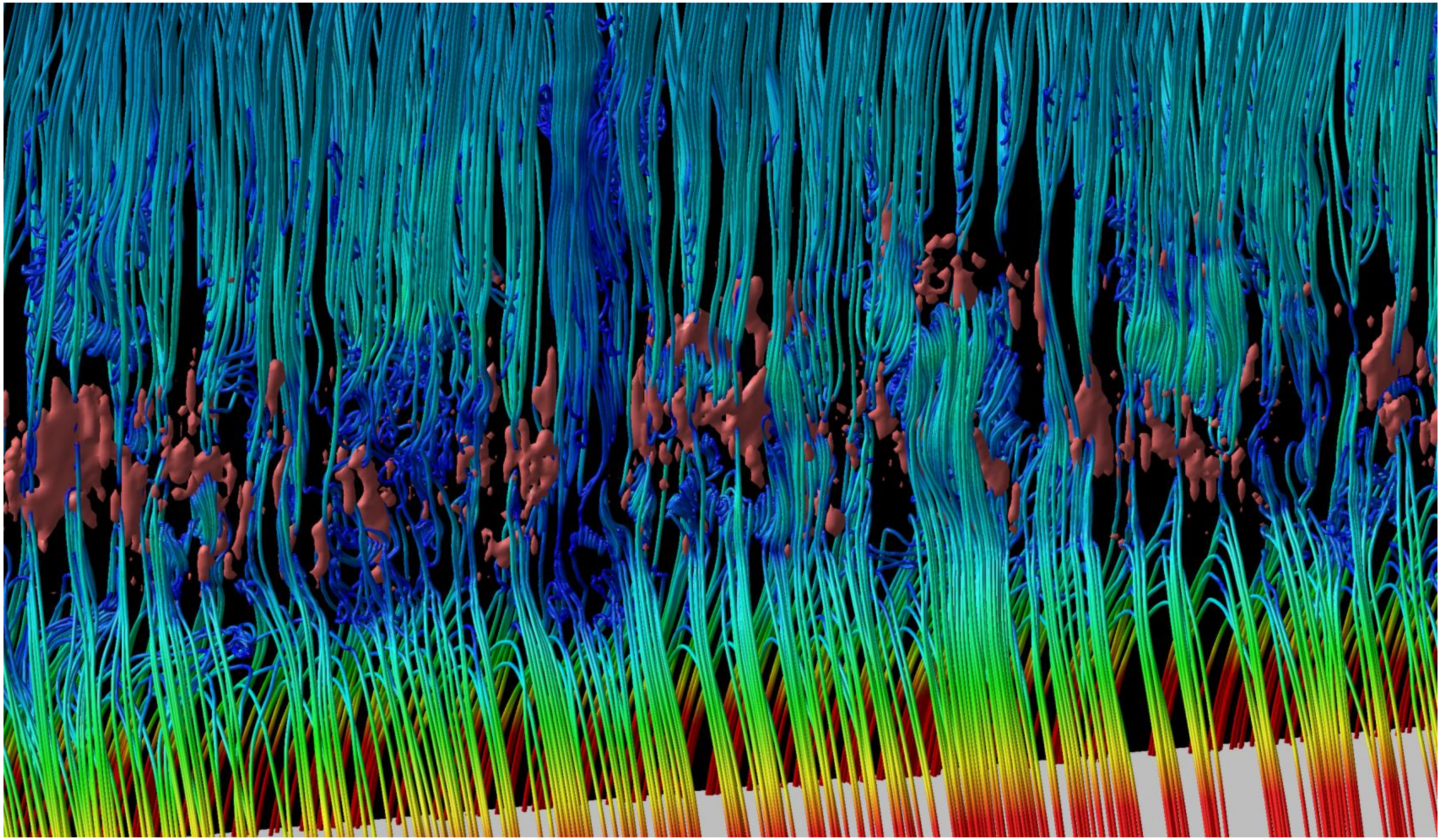


Electric field : E=ηJ (+ vxB)



- 3D reconnection forms turbulent fractal structure in a current sheet.
- Multiple plasmoid ejections enhance E-field, which is favorable for particle acceleration.

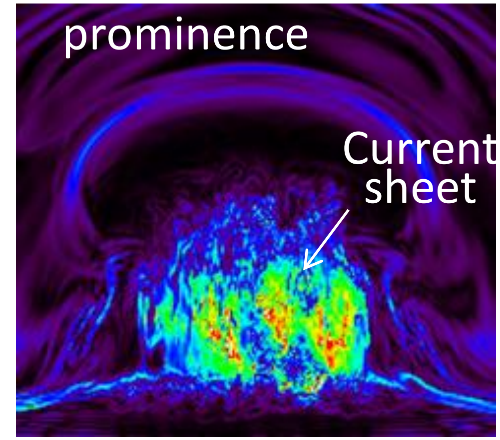
Current sheet in 3D



B-field lines (color: B-strength) and current sheet with strong J (pink surface)

Fragmented Current sheet

Current density

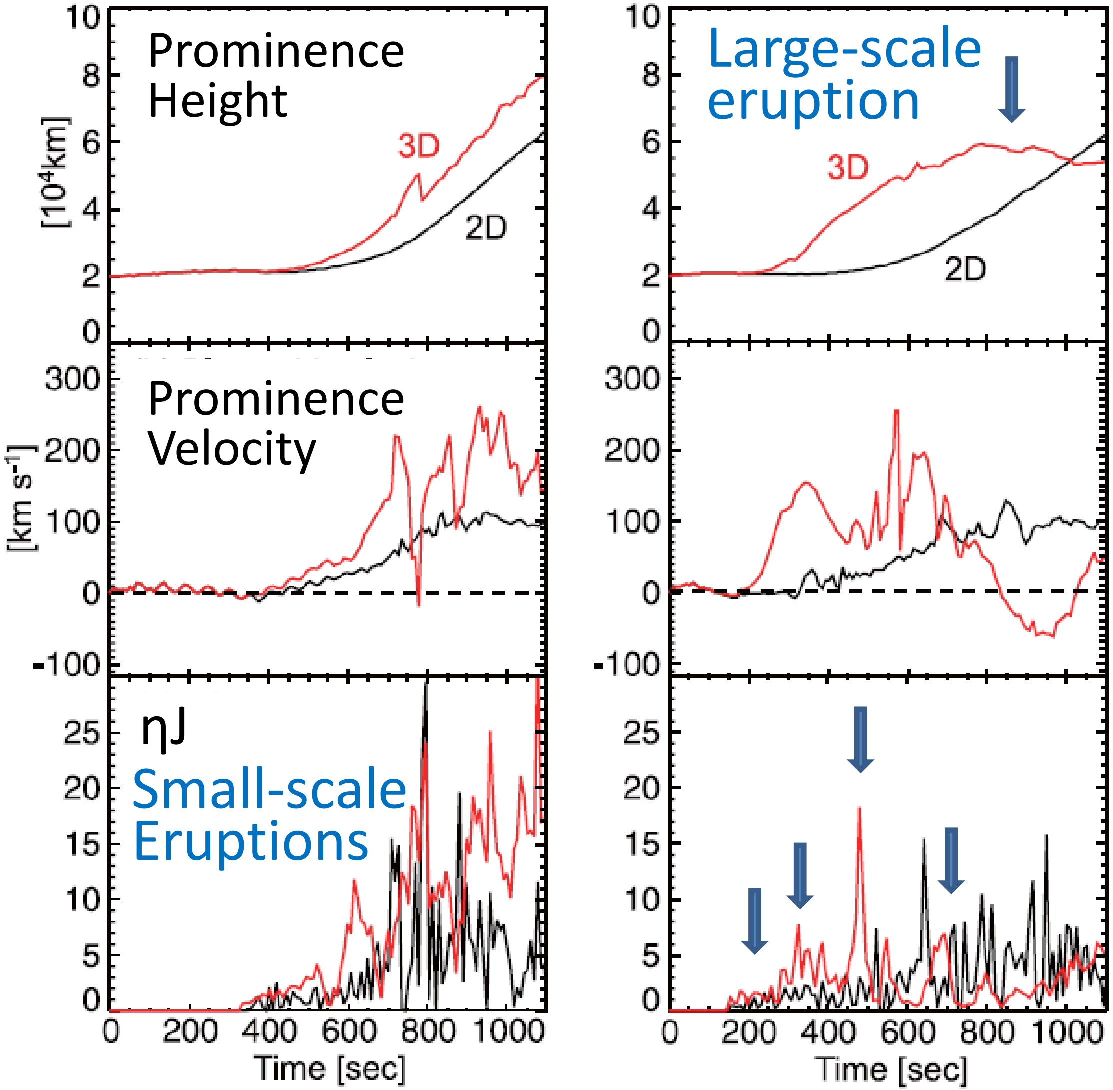


- Multiple plasmoids are formed in a current sheet.
- 3D plasmoid with a **finite** length.
- Strong E-field is enhanced between plasmoids.

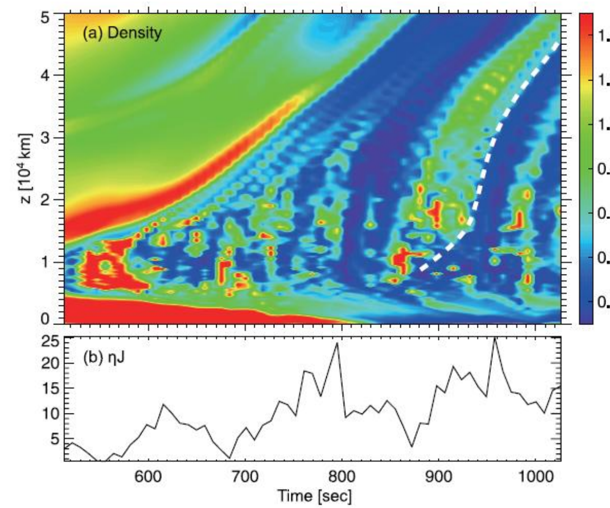
Turbulent structure & Intermittency

Weakly twisted case

Strongly twisted case



Large scale **prominence** eruption & **small** scale **plasmoid** ejections increase **Reconnection rate** (E=ηJ) and **E-field.**

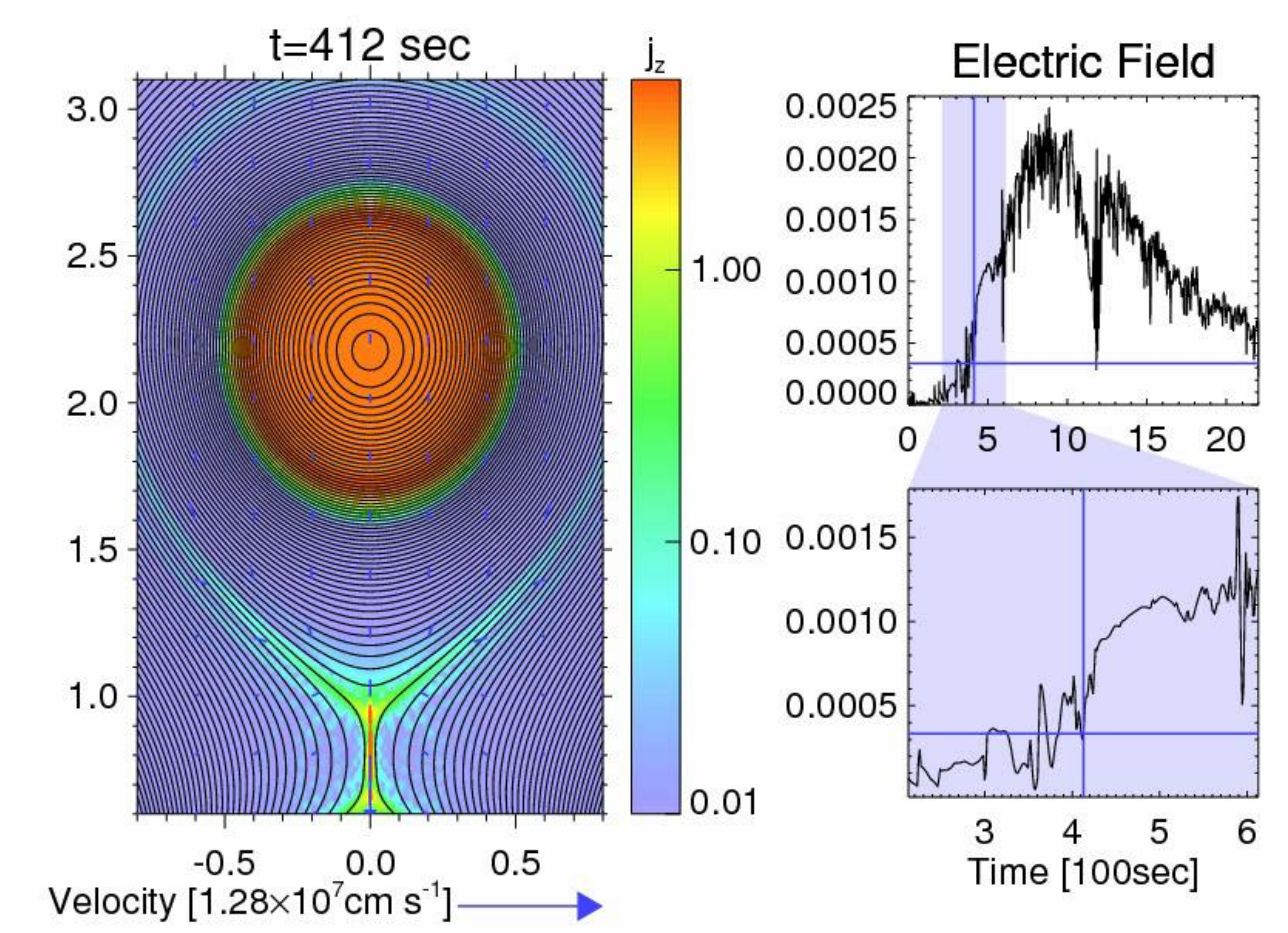


Turbulent structure

correlated

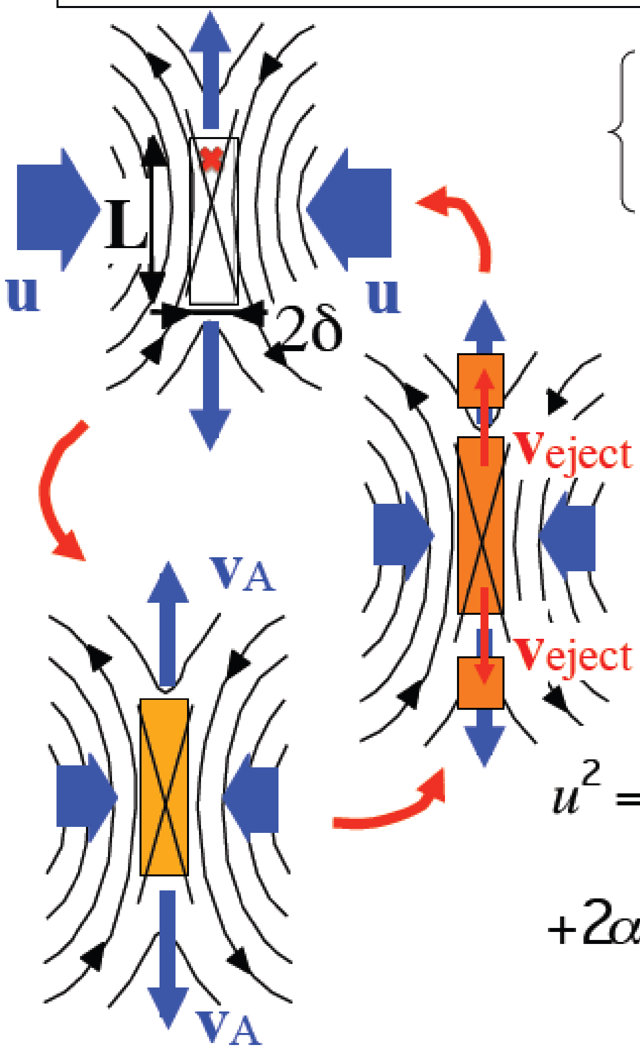
Intermittency of energy release, E-field (∝HXR emission)

Intermittent Reconnection in 2D



[Ono et al. 2011 PoPs]

The combination of mass pileup and ejection increases effective mass ejection and rec. speed.



$$\begin{cases} uL = 2\delta V_A + \underbrace{L\delta(d\alpha/dt)}_{\text{Pile-up}} + \underbrace{2\delta\alpha V_{eject}}_{\text{Ejection}} \\ u = \dfrac{\eta}{\mu_0 \delta'} \end{cases}$$

where pileup factor $\alpha = \dfrac{n_{sheet}}{n_0}$

$$u = \sqrt{\frac{\eta}{\mu_0}\left(\frac{2V_A}{L} + \underbrace{d\alpha/dt}_{\text{Pile-up}} + \underbrace{\frac{2\alpha V_{eject}}{L}}_{\text{Ejection}}\right)}$$

For simplicity,

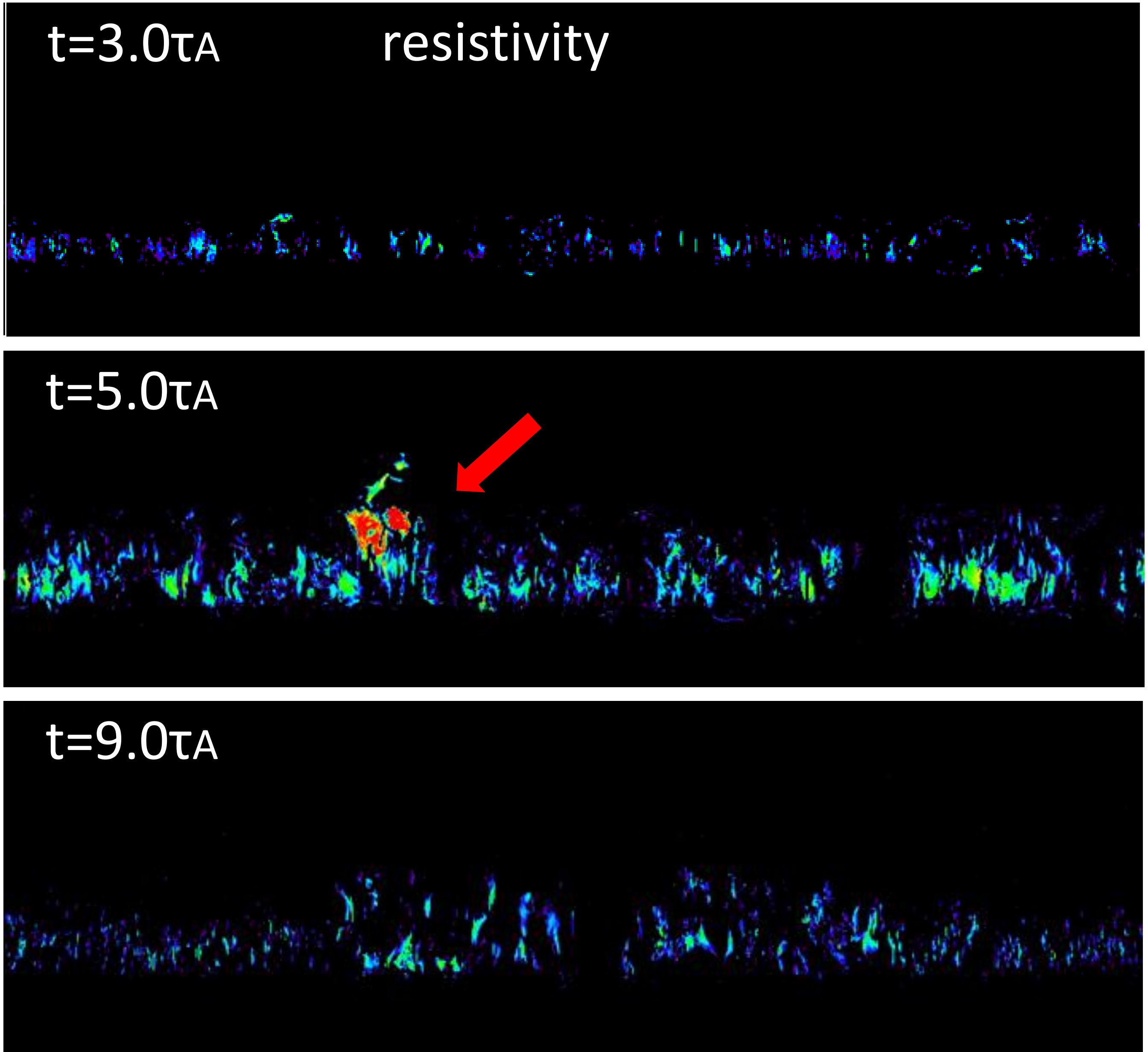
$$\alpha = n/n_0 = n_1(1 + \sin\omega t)$$

$$v_{eject} = v_1\{1 + \sin(\omega t + \theta)\}$$

$$u^2 = \frac{\eta}{\mu_0 L}[2V_A + \underline{2\alpha_1 V_1} + 2L\alpha_1\omega\cos\omega t + 2V_1\sin\omega t$$

$$+ 2\alpha_1\sin(\omega t + \theta) + \underbrace{2\alpha_1 V_1 \sin\omega t \cdot \sin(\omega t + \theta)}_{\text{Ejection}}$$

Critical state of a current sheet

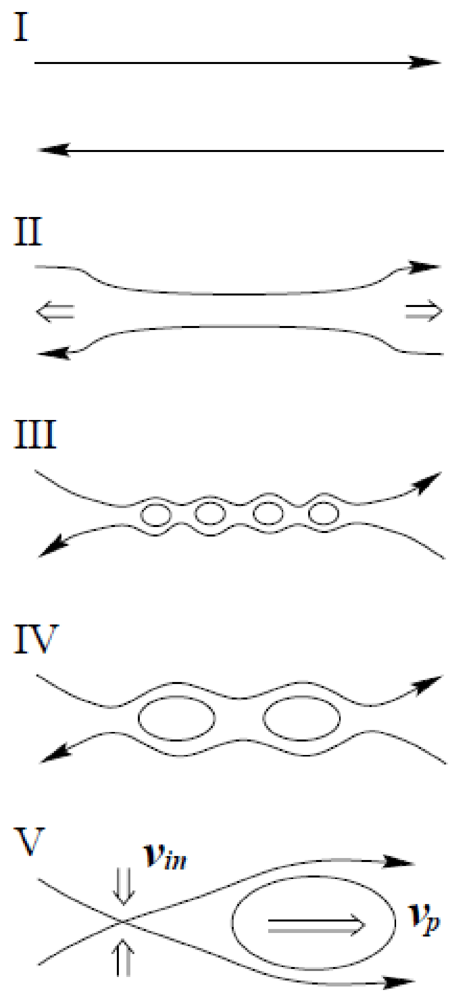


J is close to threshold value J_{thresh} almost everywhere.
(=critical state)

Once anomalous resistivity is triggered, it affects the surroundings (=avalanching).

Avalanche model with Scenario of fast reconnection

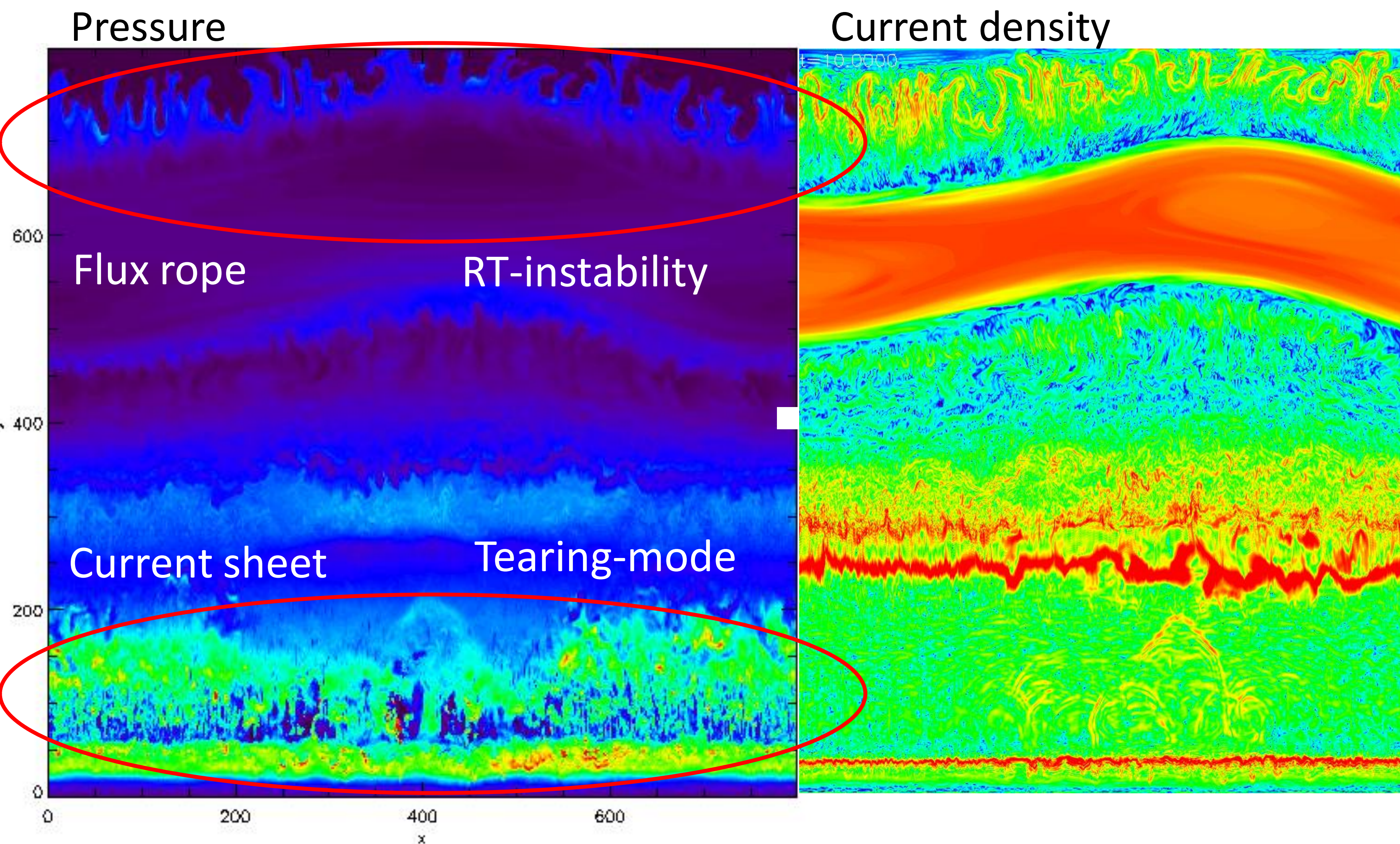
(ii) Instability saturates, and whole system is unstable. J is close to Jthres in smallest current sheets almost everywhere. (=critical state)



(i) Current sheet thinning and/or pile up lead to Tearing mode instability. (-> cascading and Fractal formation)

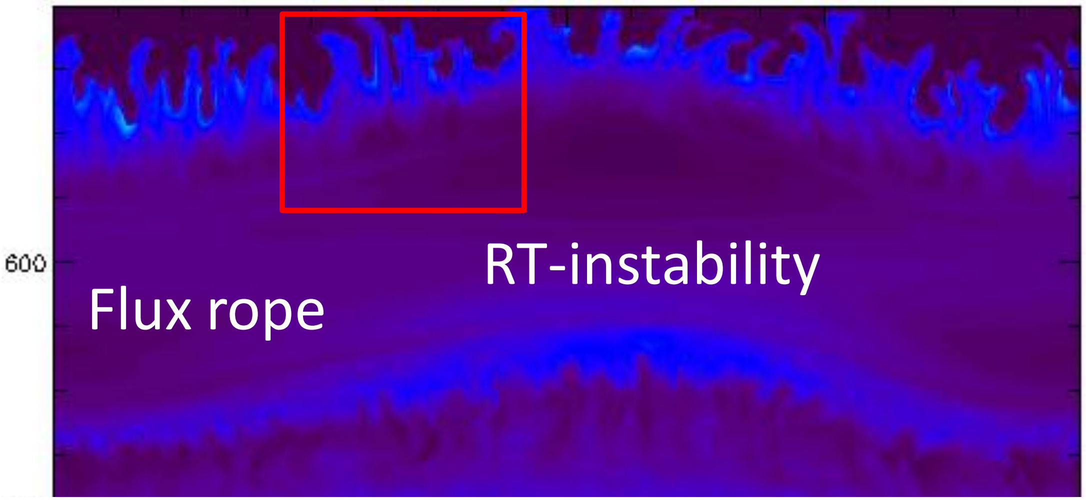
(iii) Once anomalous resistivity occur somewhere, surrounding plasmoids start merging each other, and finally ejected outward. (inverse cascade)

Turbulence by Rayleigh-Taylor instability (or interchange/flute instability)



Turbulence by Rayleigh-Taylor instability (or interchange/flute instability)

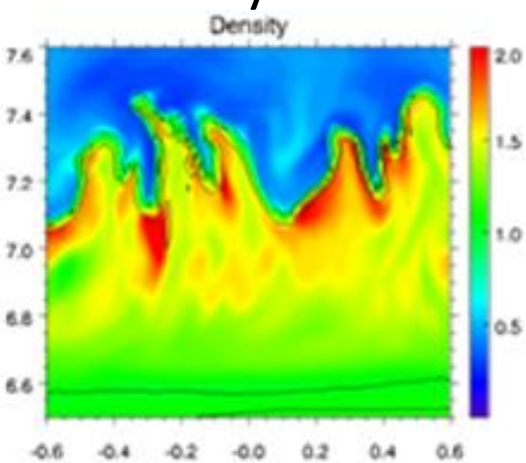
Pressure



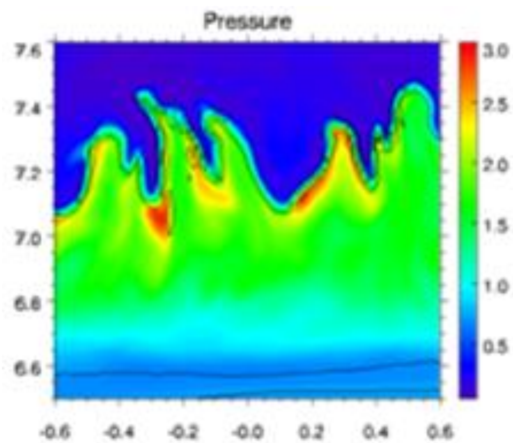
Density distribution and outward Effective gravity generate RT-instability at the surface of a flux rope.

Structure: 1000-2000 km

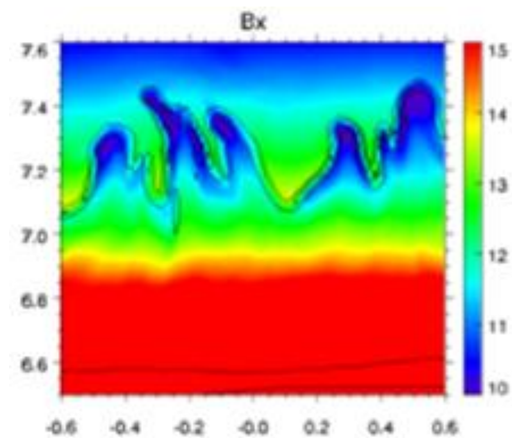
Density



Pressure

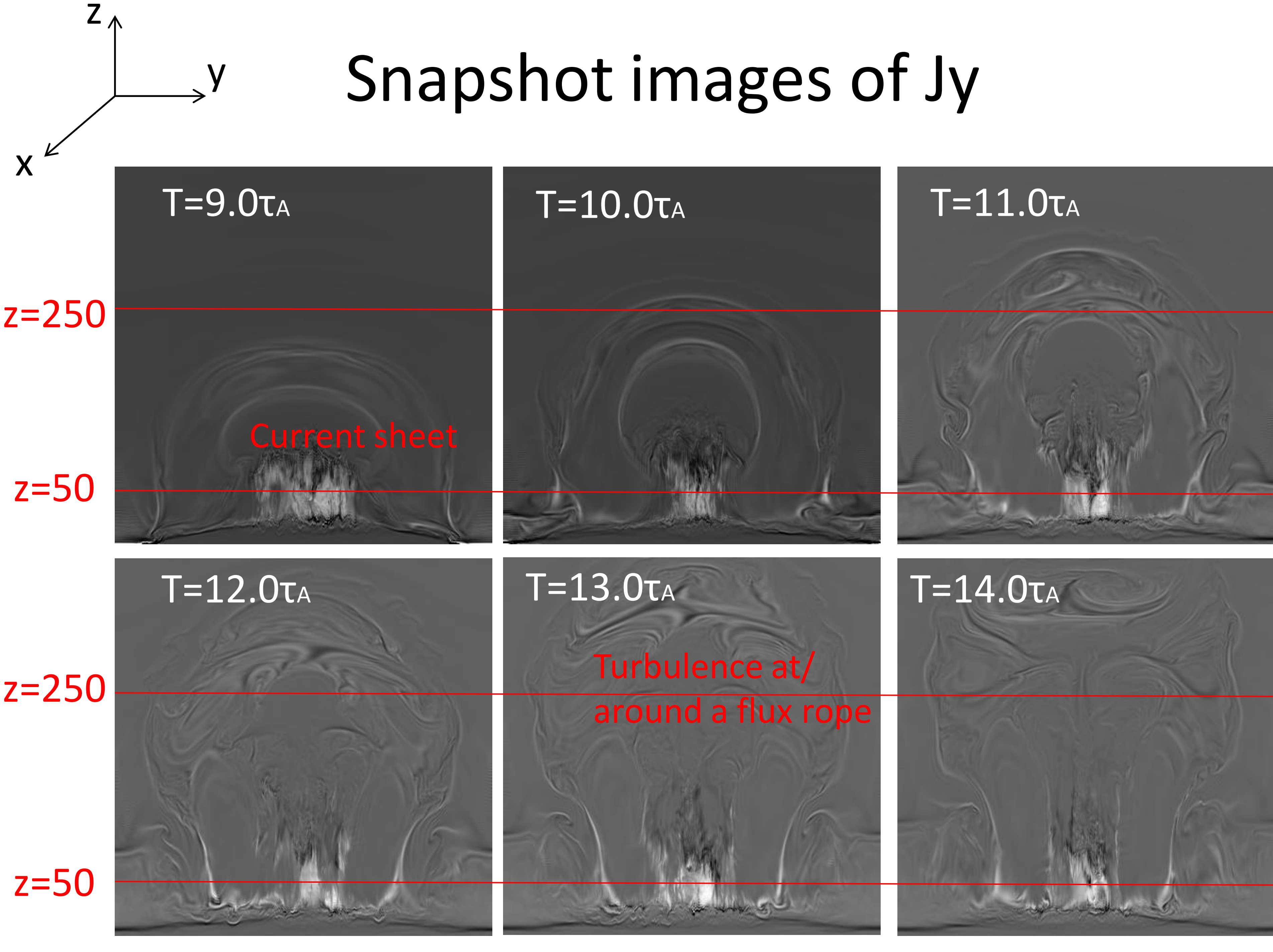


Bx -field

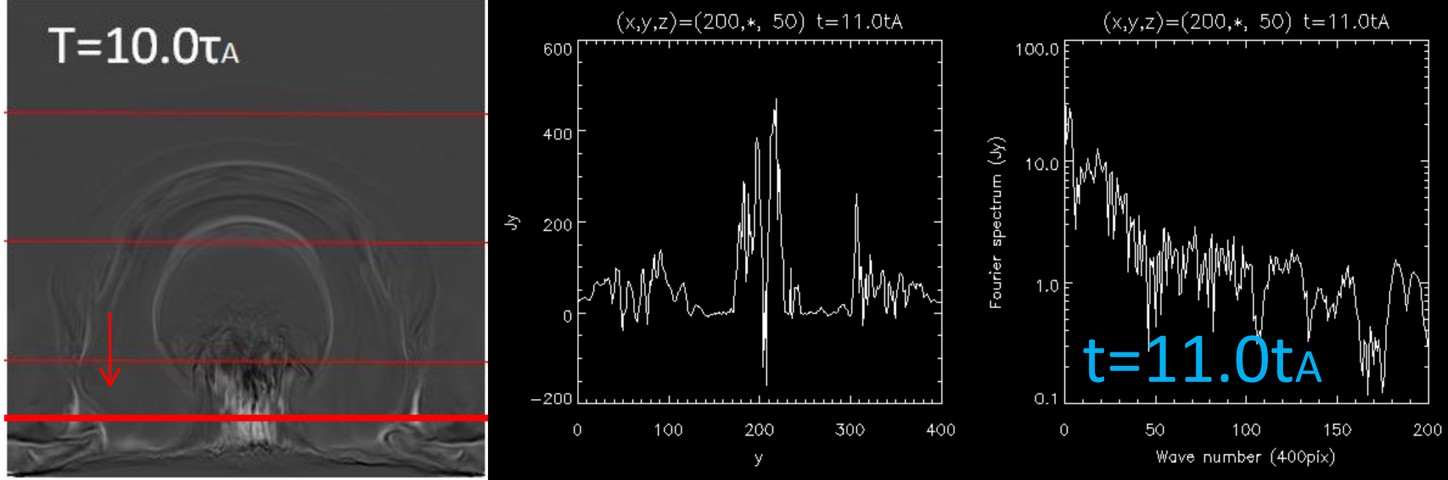


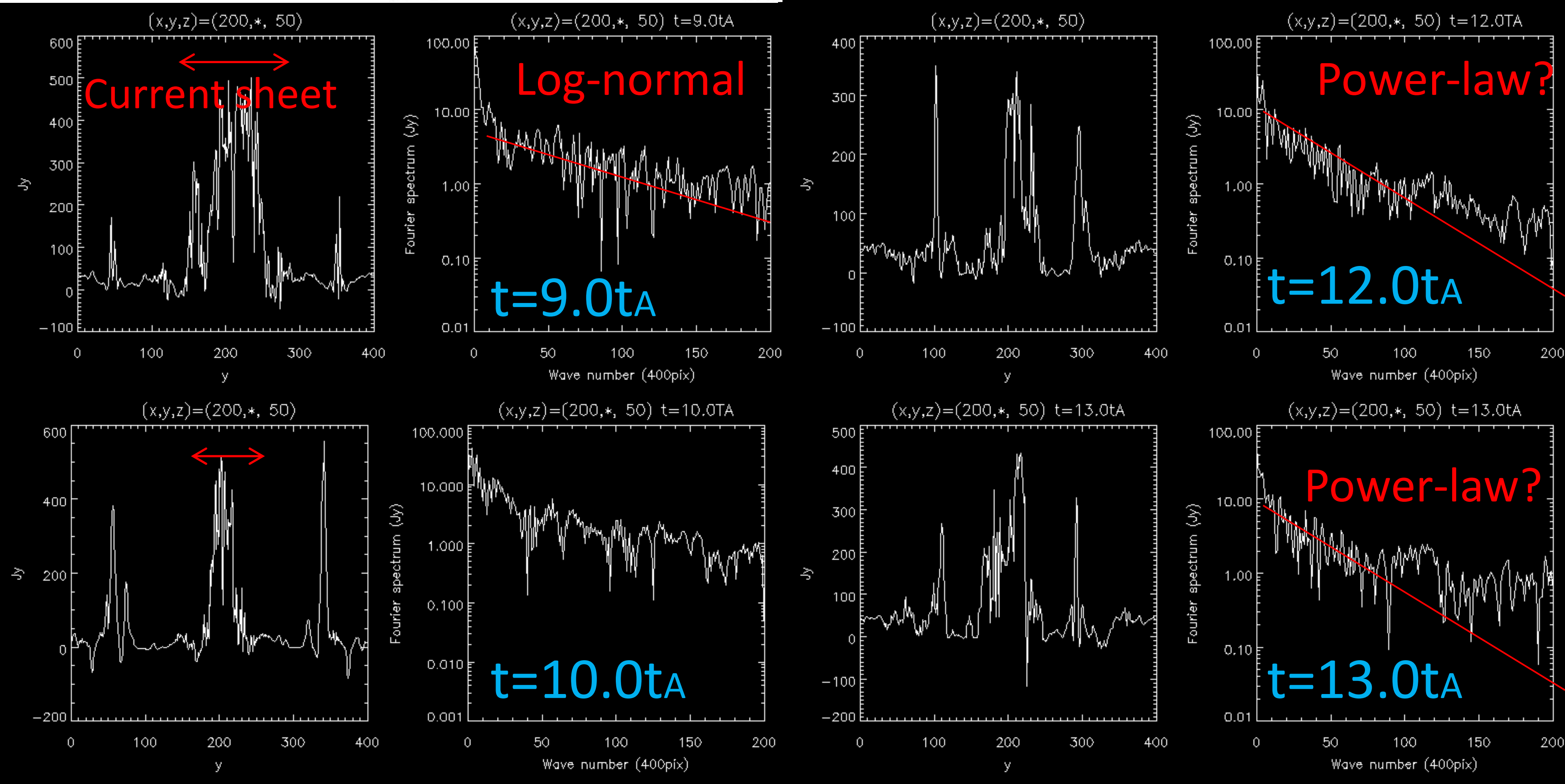
12000 km

Snapshot images of Jy

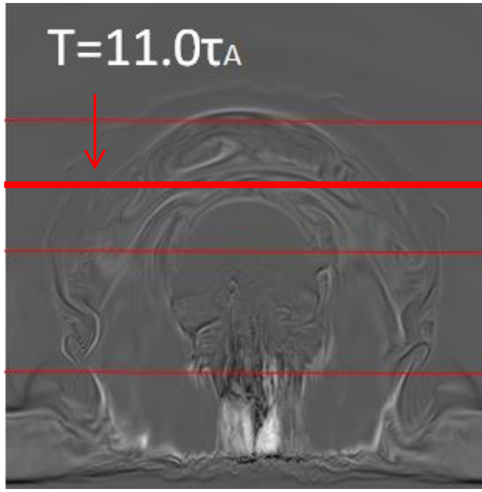


Fourier spec trum (Jy) in a current sheet (z=50) tearing-mode



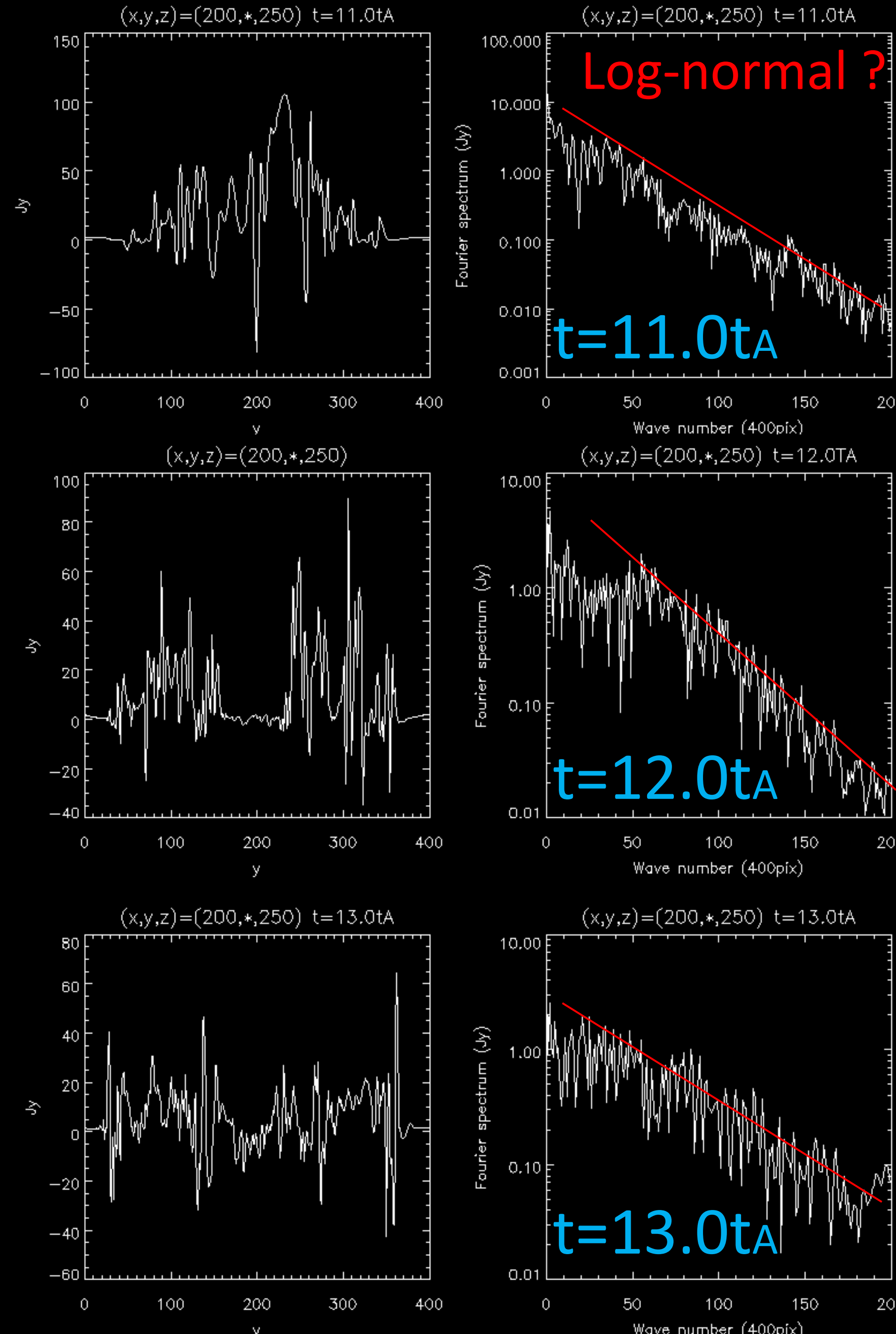


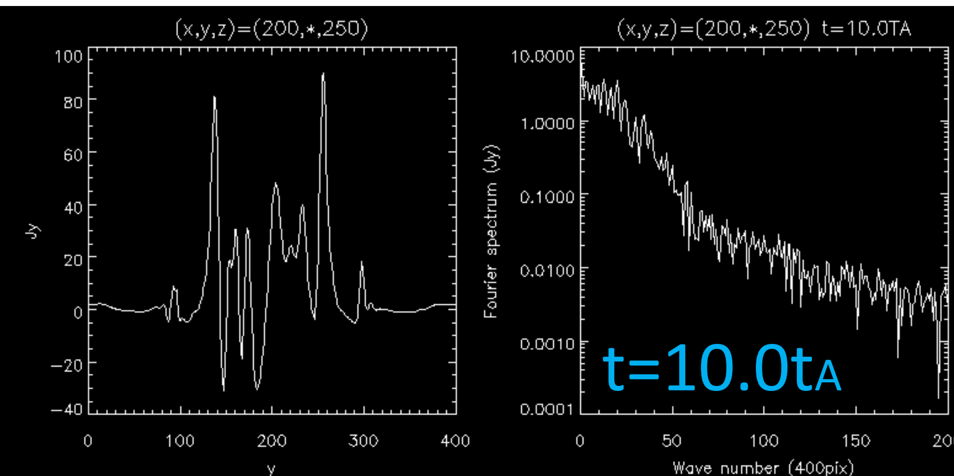
Fourier spec trum (Jy) in a flux rope (z=20)



Rayleigh-Taylor instability

- Power-law index varies in time and locations.
- Different source of turbulence makes power-law index different.





Summary and Conclusion

- Magnetic Reconnection is SOC?
  (current automaton model is ok?)

  ⟶ It looks like SOC. Fractal/turbulence structure and intermittency are correlated. Further analysis needed.

- What is the origin of Turbulence?

  ⟶ Tearing instability (plasmoids) & RT-instability.

- How turbulence/SOC state affects Reconnection mechanism (dynamics, reconnection rate)?

  ⟶ Positive feedback by plasmoid ejections (and/or turbulent flows) increase energy release rate.

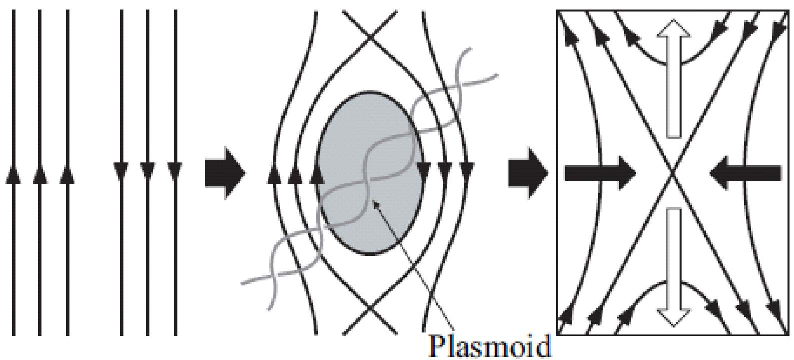
Time scales related to Solar flares

- Solar Flare $$t_{flare} = 10^2 - 10^4 \text{ sec}$$
- Magnetic diffusion $$t_D \cong \frac{L^2}{\eta} \cong 10^{14} \left(\frac{L}{10^9 \text{cm}}\right)^2 \left(\frac{T}{10^6 \text{K}}\right)^{\frac{3}{2}} \text{sec}$$
  Spitzer resistivity: $\eta = \eta_{Spitzer} \cong 10^4 \left(\frac{T}{10^6 \text{K}}\right)^{-\frac{3}{2}} \text{ cm}^2 \text{ sec}^{-1}$
- Alfven time $$t_A = \frac{L}{V_A} \cong 10 \left(\frac{L}{10^9 \text{cm}}\right) \left(\frac{n}{10^9 \text{cm}^{-3}}\right)^{\frac{1}{2}} \left(\frac{B}{10\text{G}}\right)^{-1} \text{ sec}$$
- Mag. Reynolds num. $$R_m = \frac{t_D}{t_A} = \frac{LV_A}{\eta} \cong 10^{13} \left(\frac{L}{10^9 \text{cm}}\right) \left(\frac{T}{10^6 \text{K}}\right)^{\frac{3}{2}} \left(\frac{B}{10\text{G}}\right) \left(\frac{n}{10^9 \text{cm}^{-3}}\right)^{-\frac{1}{2}}$$
- Thermal conduction $$t_{cond} = \frac{3nkL^2}{\kappa_0 T^{5/2}} \cong 1.4 \left(\frac{n}{10^9 \text{cm}^{-3}}\right) \left(\frac{L}{10^9 \text{cm}}\right)^2 \left(\frac{T}{10^7 \text{K}}\right)^{-\frac{5}{2}} \text{ sec}$$
- Radiation cooling $$t_{rad} = \frac{3kT}{nQ(T)} \cong 4 \times 10^4 \left(\frac{n}{10^9 \text{cm}^{-3}}\right)^{-1} \left(\frac{T}{10^7 \text{K}}\right)^{\frac{3}{2}} \text{ sec}$$

Plasmoid-induced reconnection model

(Shibata & Tanuma 2001)

(1) To store energy by inhibiting reconnection

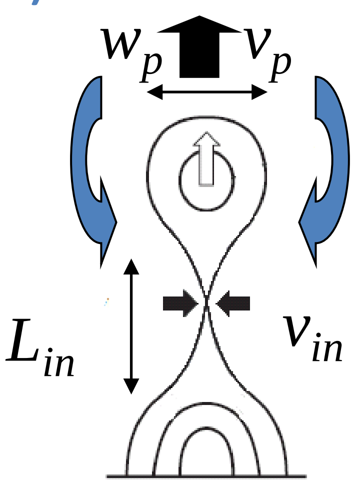


Plasmoid inhibits reconnection

Energy is stored

When plasmoid is ejected,
energy is released suddenly

(2) To induce strong inflow into reconnection region

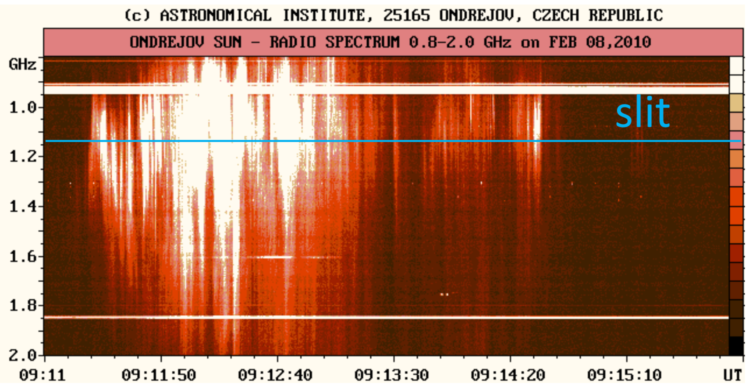


$$v_{in} = \frac{w_p}{L_{in}} v_p$$

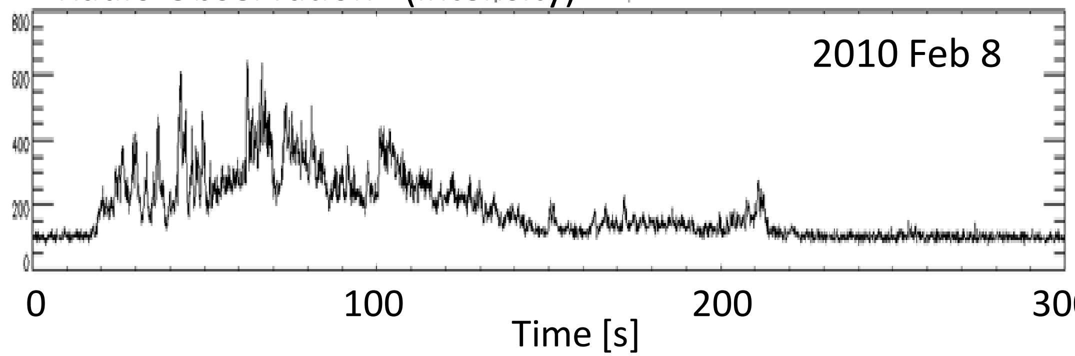
reconnection → plasmoid ejection → strong inflow → reconnection

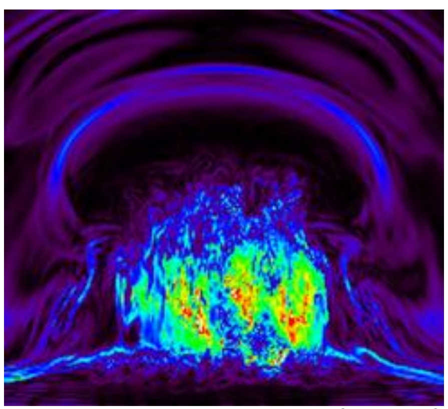
Nonlinear instability

Comparison between Type III burst (electron beam) and E-field enhancement in the simulation



Radio Observation (intensity)

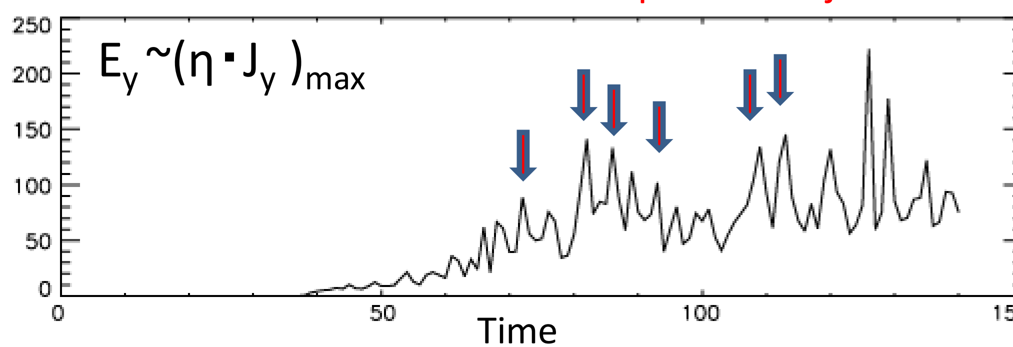




Current density (t=90)

Simulation result

Small plasmoid ejections



- Simulation show intermittent time variability of E-field enhancement in the turbulent current sheet, as observed in Type III burst. Each of them corresponds to a small plasmoid ejection.