Hinode7@Takayama, Gifu, 11-15 Nov, Session 4 ``Flares and Coronal Mass Ejections'' 14 Nov 2013 (Thu) S4-I-02, 10:45h-11:15h

Nonlinear Fragmentation of Flare Current Sheets

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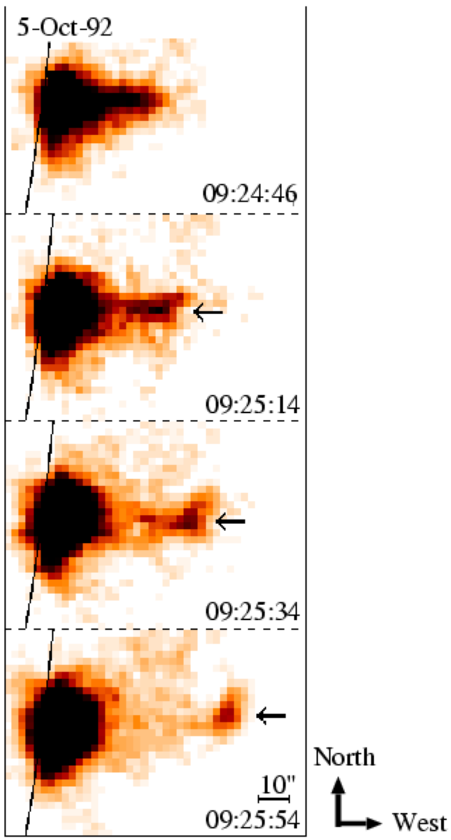
[3]Kyoto University

N. Nishizuka & K. Shibata 2013, **Phys. Rev. Lett.** `` Fermi Acceleration in Plasmoids Interacting with Fast Shocks of Reconnection via Fractal Reconnection''

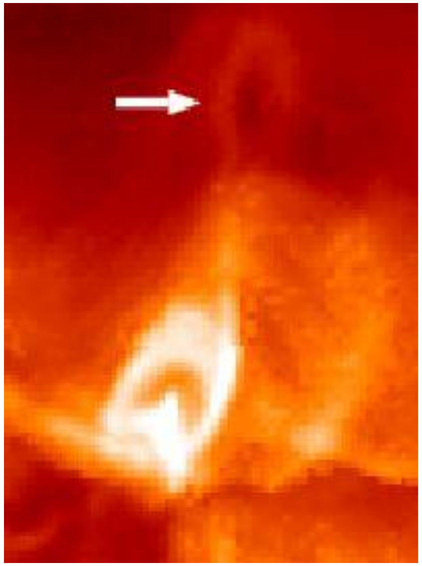
K. Nishida, N. Nishizuka & K. Shibata **2013**, **ApJ Lett**.

Various sizes of Plasmoid (flux rope) ejections in solar flares

Yohkoh/SXT

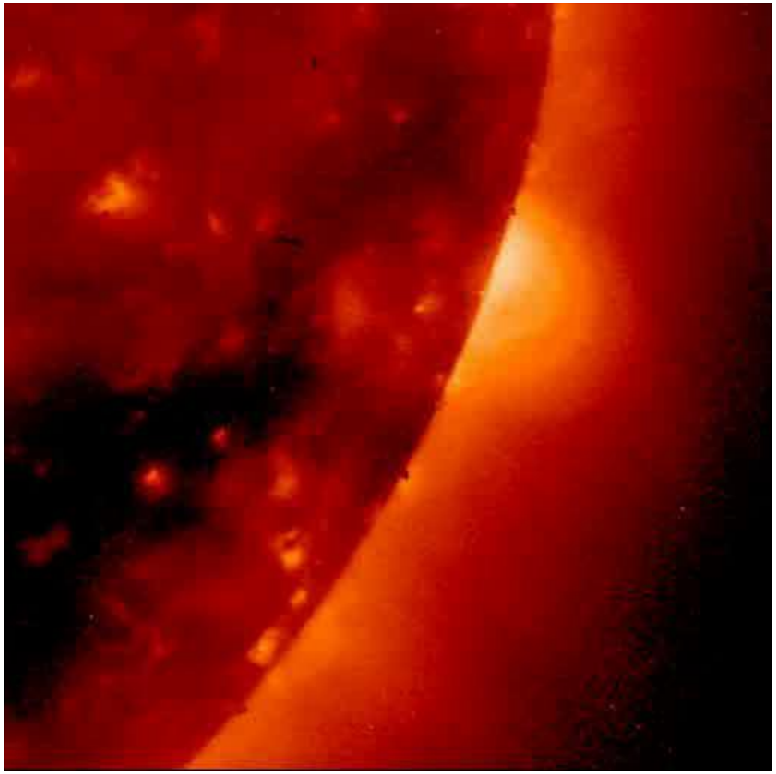


impulsive flares
~ 10^9 cm



LDE(Long Duration Event) flares
~ 10^10 cm

Hinode/XRT

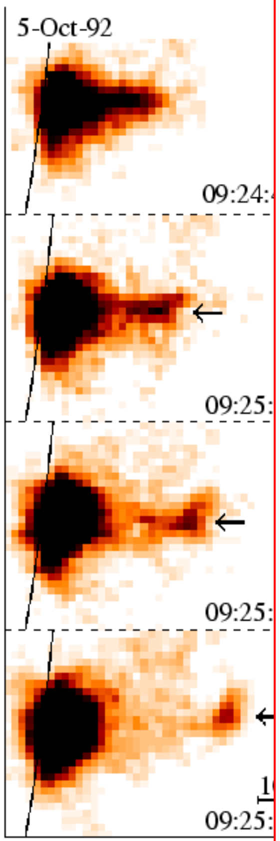


2008 Apr 9 Hinode / XRT

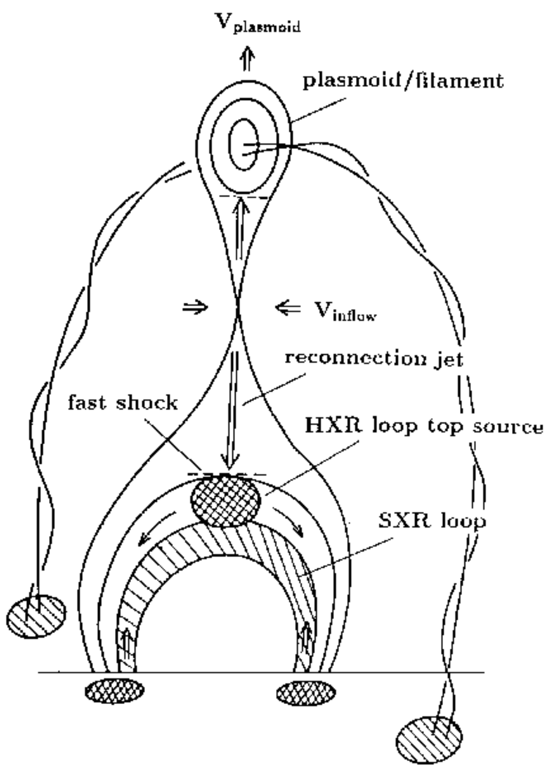
Solar atmosphere is MHD scale-free.

Various sizes of Plasmoid (flux rope) ejections in solar flares

Yohkoh/SXT

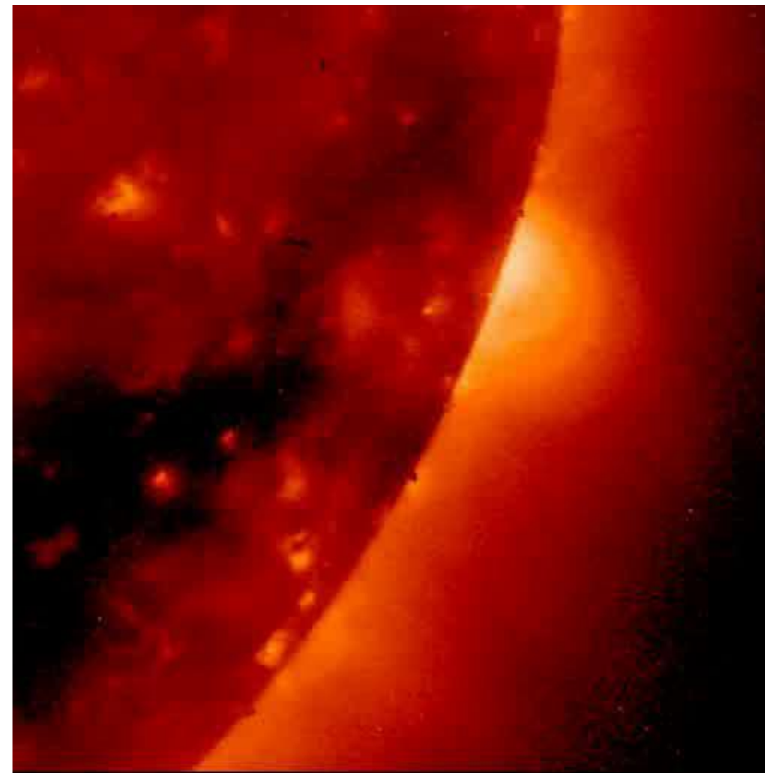


impuls
~ 10^



Plasmoid-Induced
-Reconnection model
(Shibata 1999)

Hinode/XRT

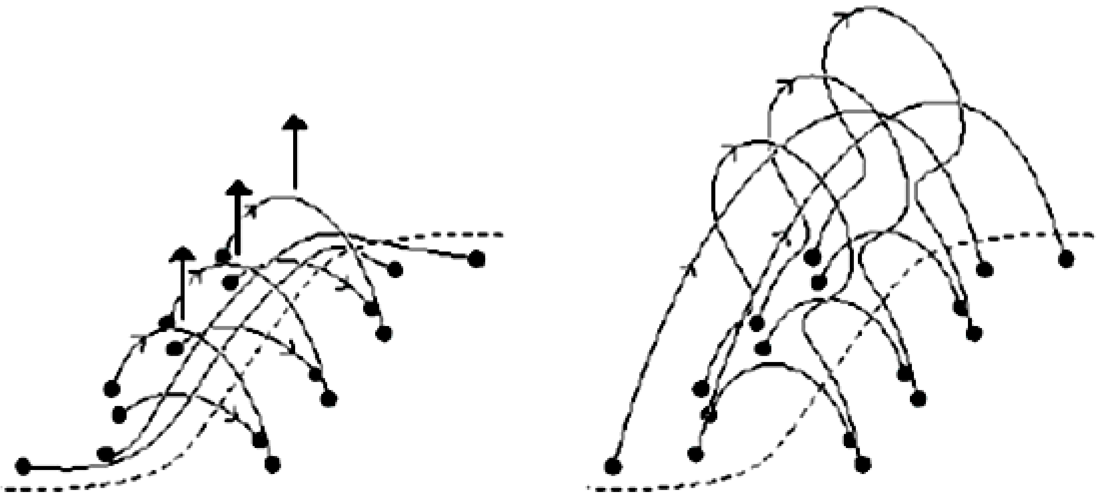


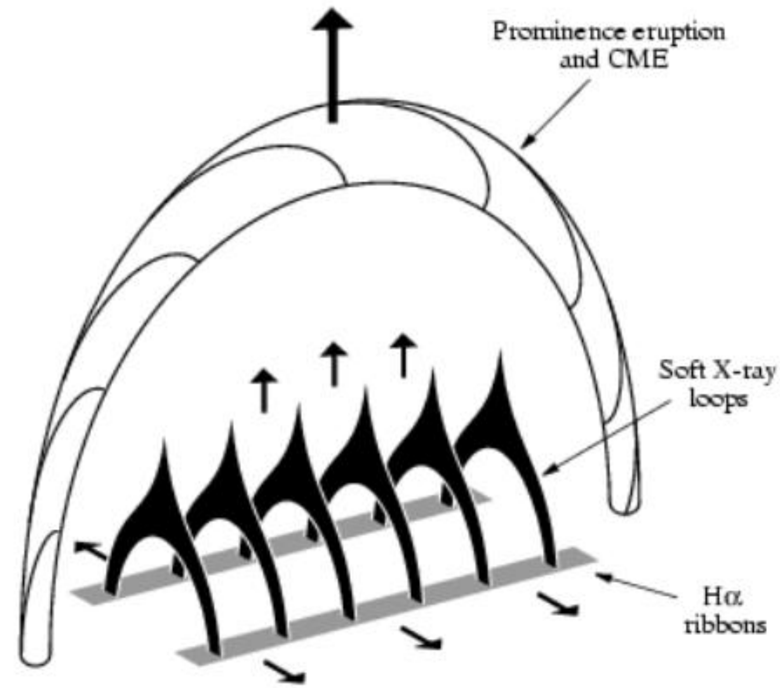
2008 Apr 9 Hinode / XRT

Solar atmosphere is MHD scale-free.

Overall Picture of Eruption
~ Reconnection creates loops/ribbons ~

[from E. Priest's Lecture slides]





[Qu et al.]

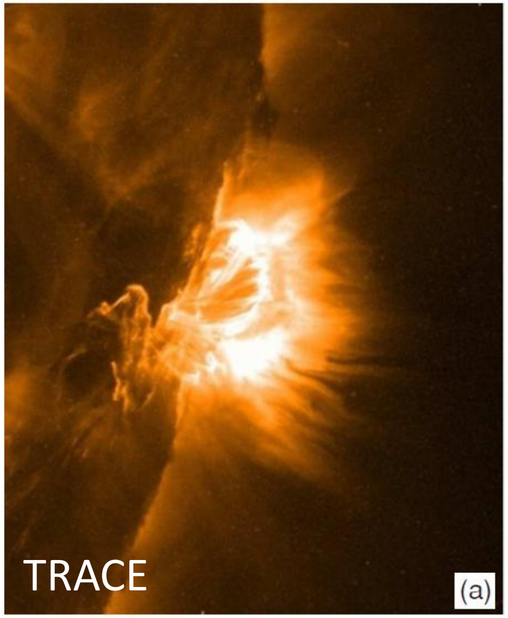
In core - twisted magnetic tube

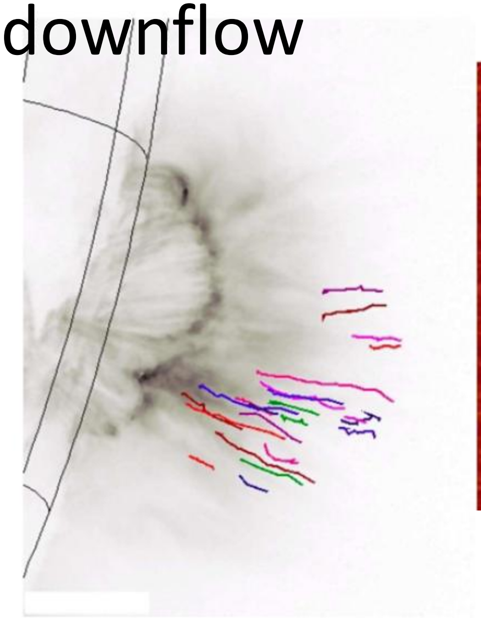
(energy stored in Force-Free Field)

- erupts (catastrophe / breakout / instability)
- drives reconnection below tube

3D Energy Release in a Solar Flare

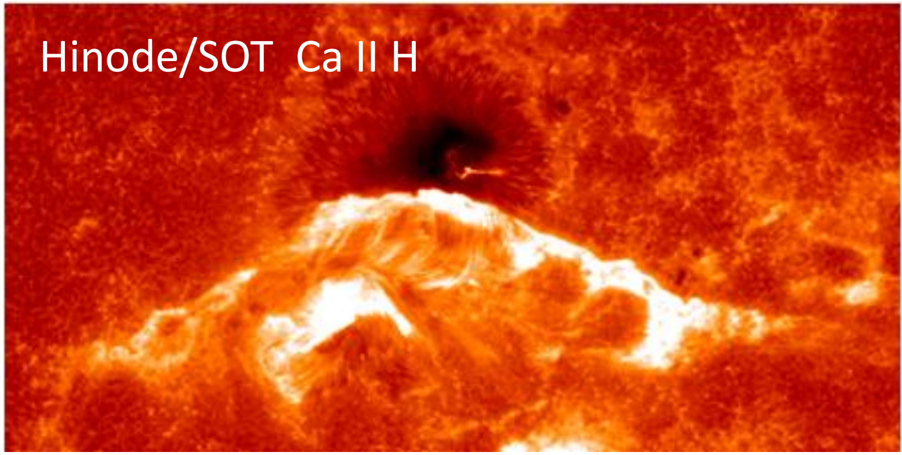
Multi supra-arcade downflow



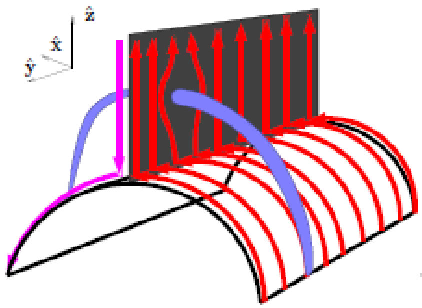


2002 April 21 flare [McKenzie & Savage 2009]

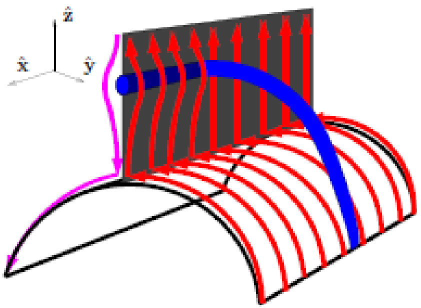
Flare BPs（two-ribbon）



2011 February 15 flare



Savage et al. 2012

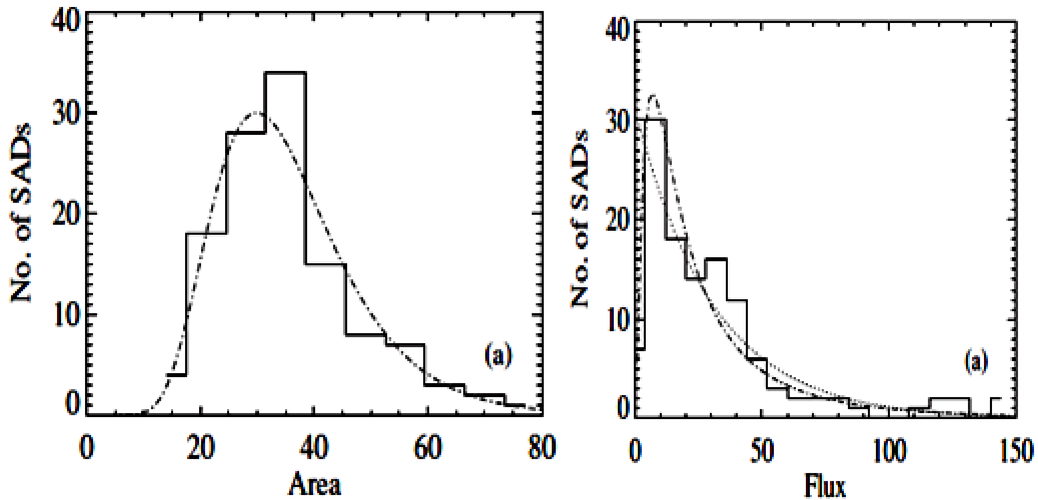


Linton & Longcope 2006

- Energy release in 3D, along neutral line.
- Intermittent (unsteady, time-depend.)
- Small-scale energy release regions, at several heights.

[From Scott et al. 2013]

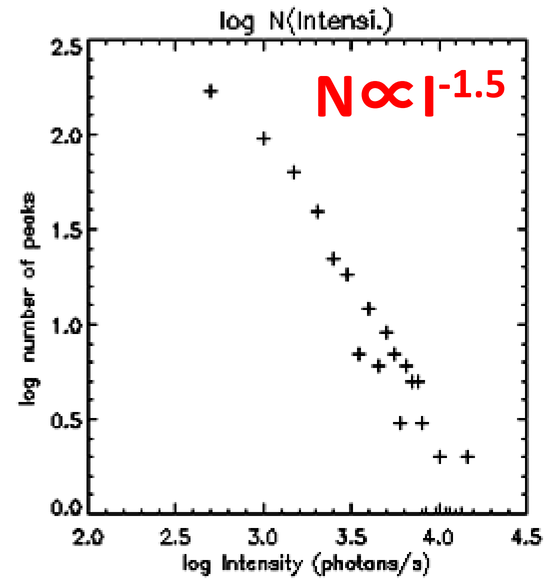
Multi supra-arcade downflow



[McKenzie & Savage 2011]

- **Area /Flux** of SADs show
log-normal (Gaussian) dist.

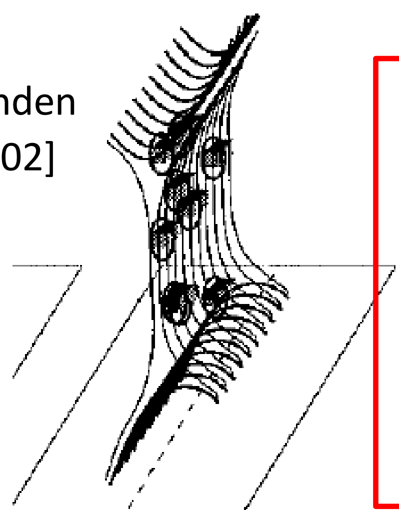
Flare BPs（kernels）



[Nishizuka et al. 2009]

- **Intensity / Duration/Time interval** of Flare BPs show **power-law** dist.

[Aschwanden et al. 2002]



Multiple X-points

- **Patchy Reconnection**
(same size of reconnection region)

[McKenzie, Longcope, etc]

v.s.

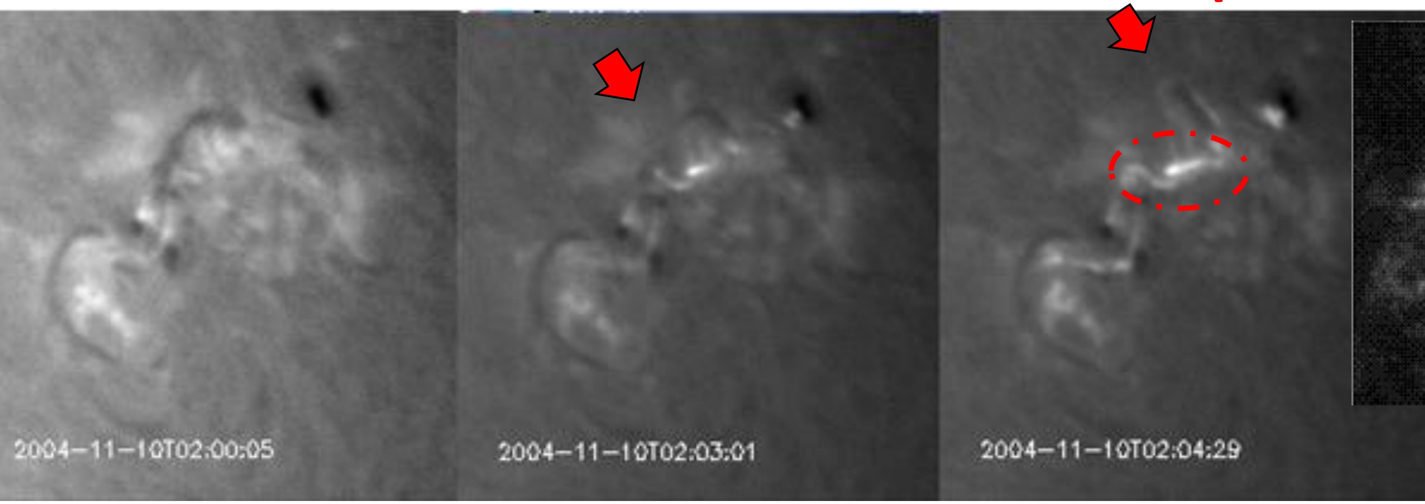
- **Fractal Reconnection**
(= ensemble of elemental reconnection?)

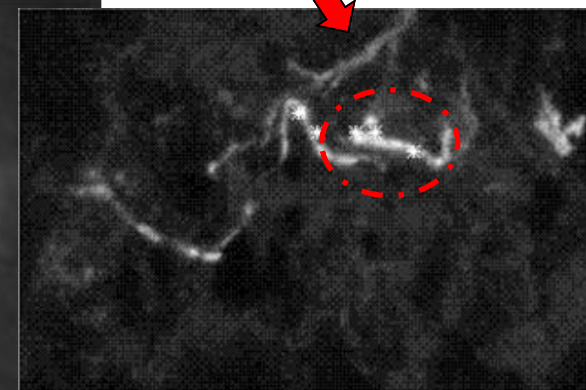
(multi-scale Fragmentation)

Onset of Filament eruption & Reconnection

Hα Filament eruption

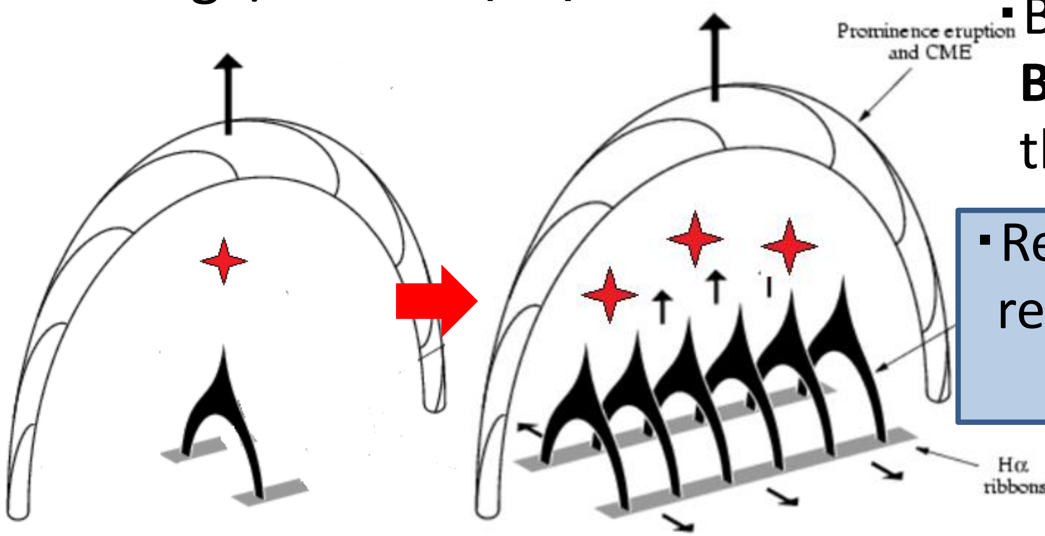
UV filament erupt.





C IV (UV) image

Hα image/Satorius/ Kyoto Uni.



- Before/at the **Hα filament eruption, Bright point** appears just below the erupting position.

- Reconnection starts from a **small** region, leading to **global catastrophe**.
  → **two-ribbon structure**

- analogy with earthquake

Remaining Fundamental Puzzles of Solar Flares

- Motivation of this talk -

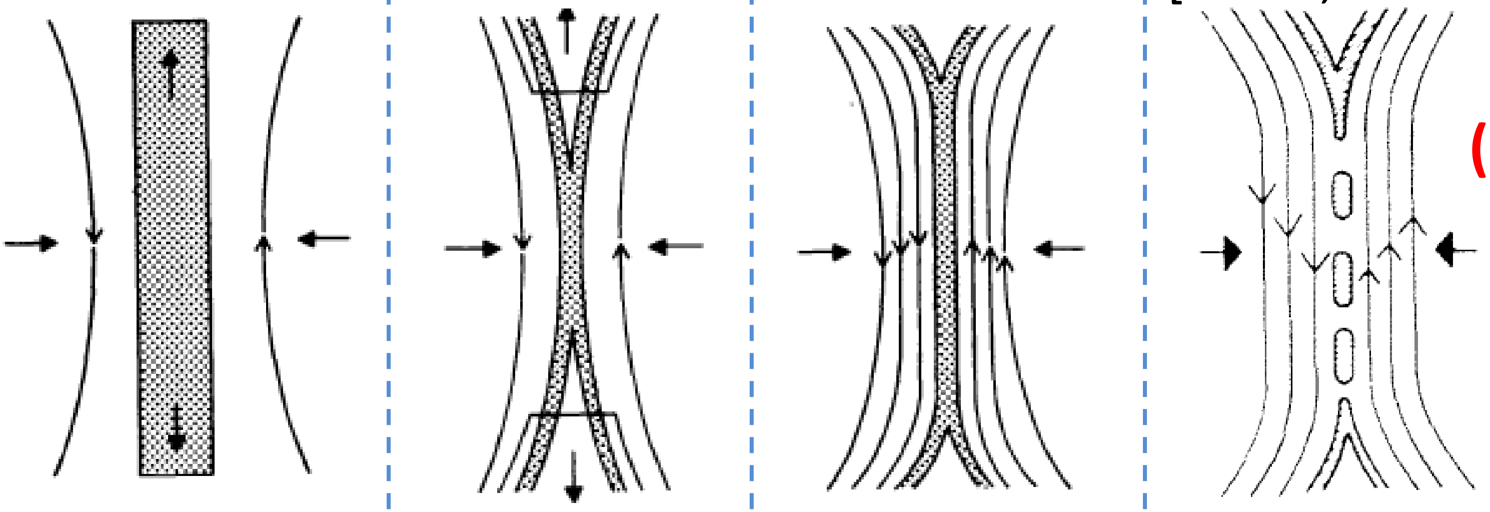
- What is energy storage mechanism?
- What is the trigger mechanism?
- What is the energy release mechanism?
  How energy release occurs in a solar flare?
- What controls the energy release rate or reconnection rate?

- 3D structure/dynamics, Intermittency

⇒We consider Nonlinear Fragmentation of current sheet in a solar flare.

Regime of Fast Reconnection: Steady or Impulsive Bursty (unsteady)

[Priest, in Proc '85,'86]



(Unsteady)

Slow | **Fast** | **Super -critical** | **Impulsive Bursty**

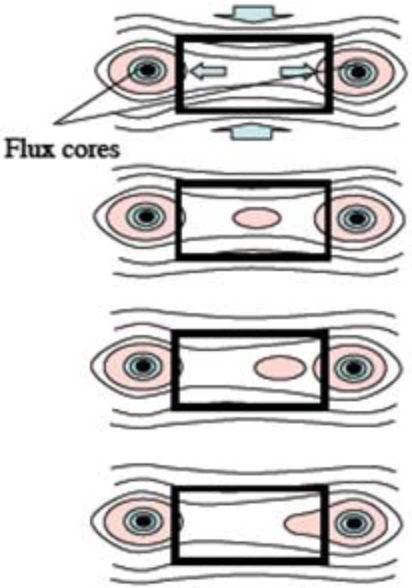
(Steady)

$$M_A = \frac{v_i}{v_A} = \frac{1}{\sqrt{R_m}} \cong 10^{-7} v_A$$

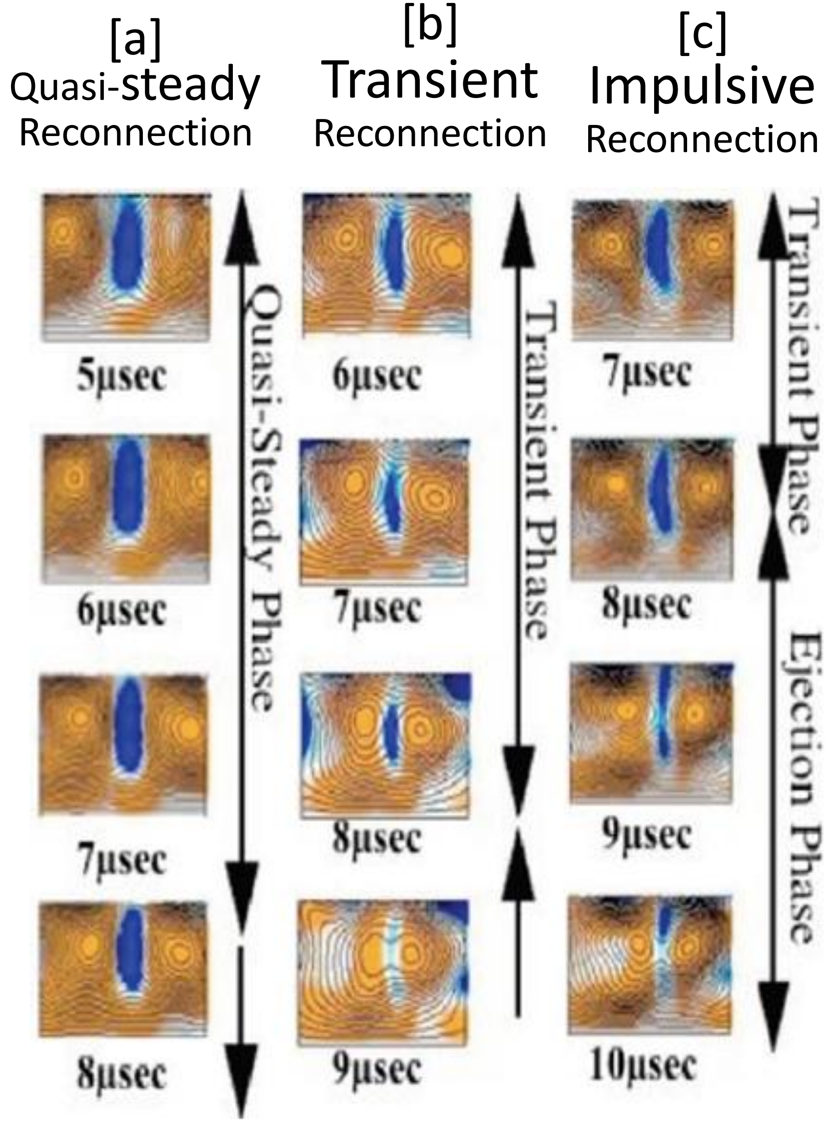
$$M_A \cong \frac{\pi}{8 \log R_m} \cong 0.01 - 0.1$$

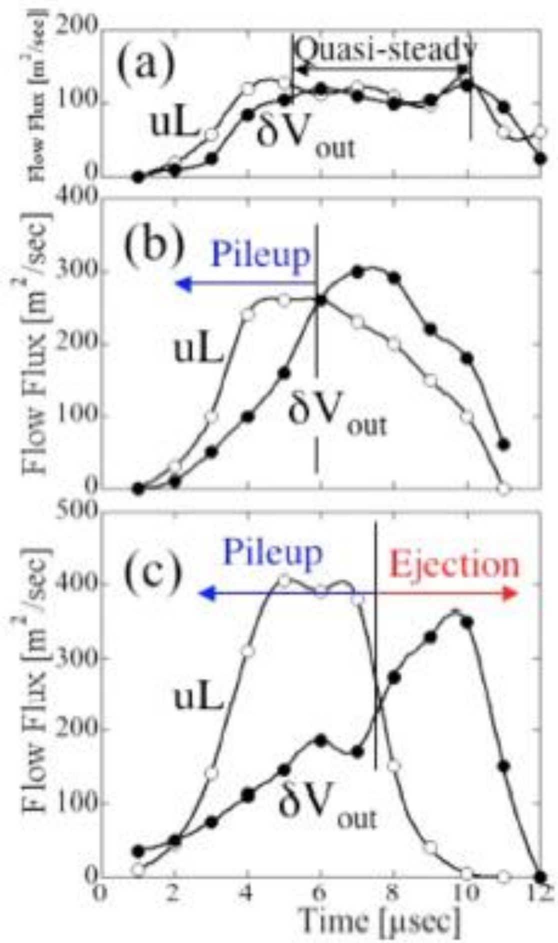
Biskamp's criteria [1986] $R_m \geq 10^4$

Plasmoid ejection in Lab. Experiments



[Ono et al. 2011]



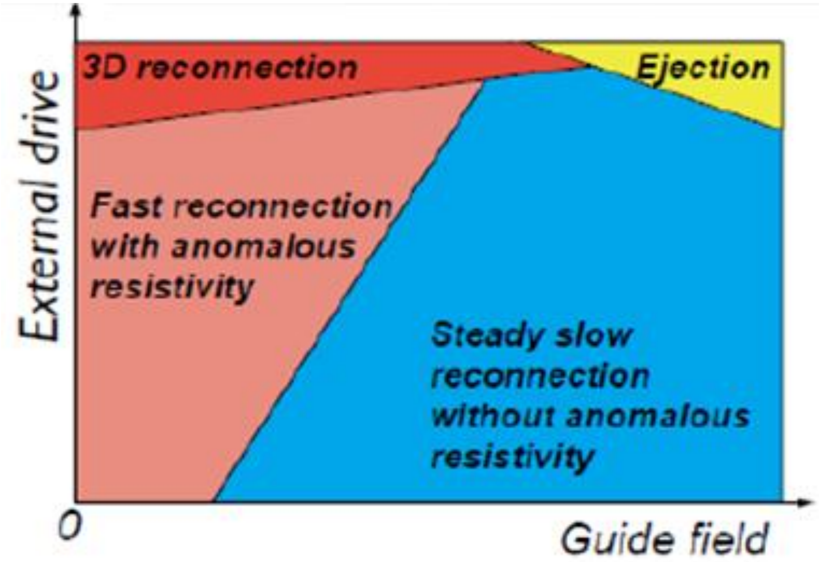


Micro-scale measurements are possible.

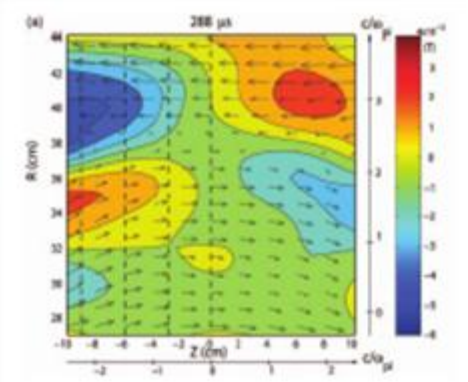
Pile-up drives ejection.

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

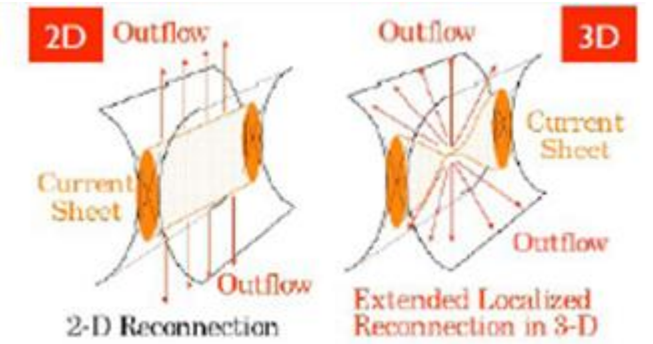


[Inomoto et al. 2012
NINS-UT reconnection Workshop]



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

[Yamada et al. 2006]

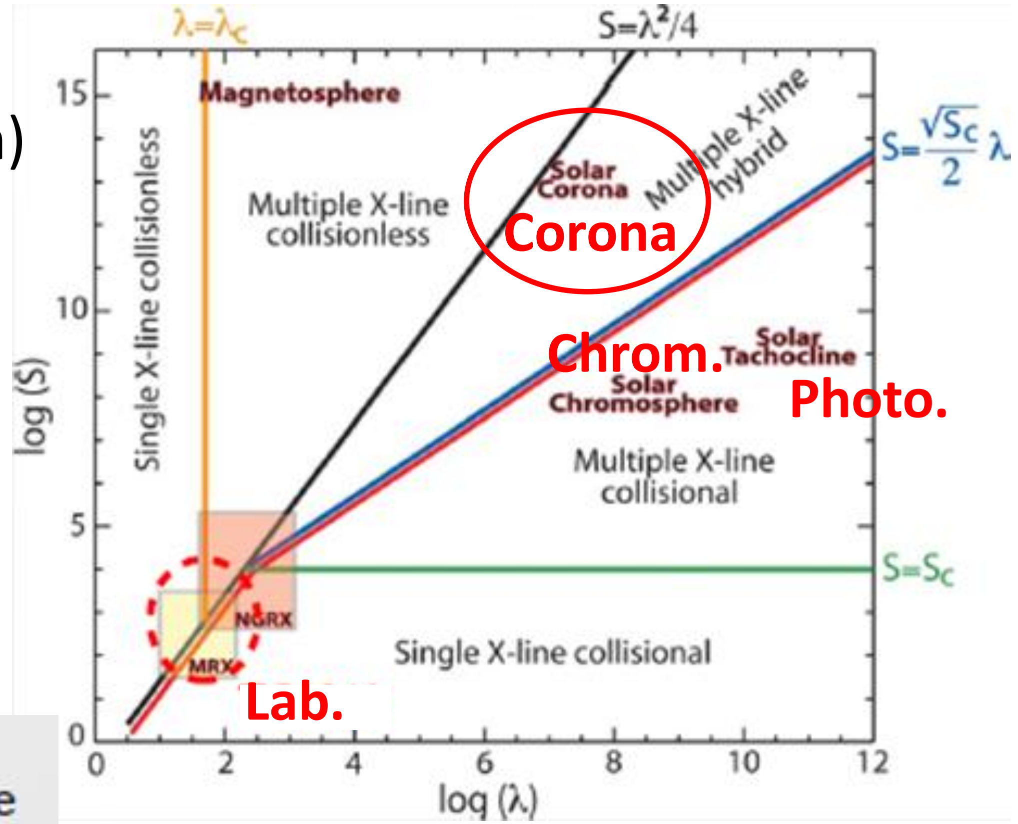


Faster reconnection by 3D structure change of a current sheet.

Classification of Reconnection in Parm. Regime

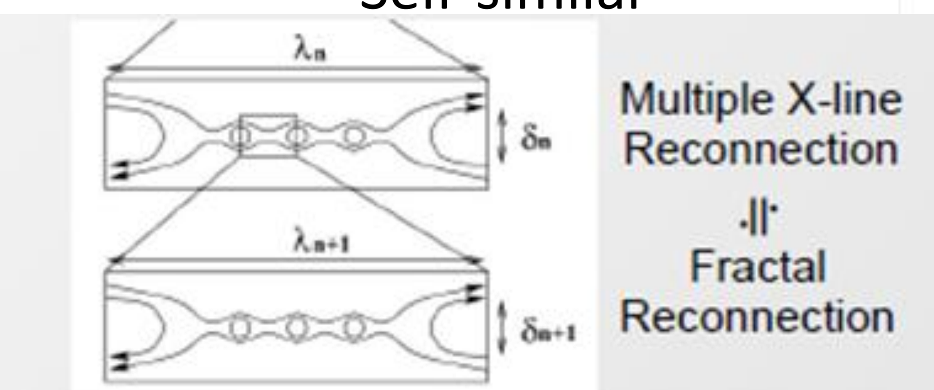
- Phase diagram
  - vertical: Lundquist num (Rm)
  - horizontal: size parameter

- Solar corona:
  - **multiple X-line** hybrid
- Solar chromosphere:
  - **multiple X-line** collisional



[Ji & Daughton 2011]

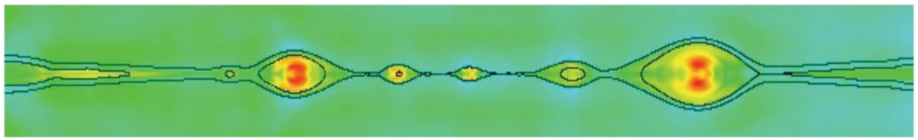
Self-similar



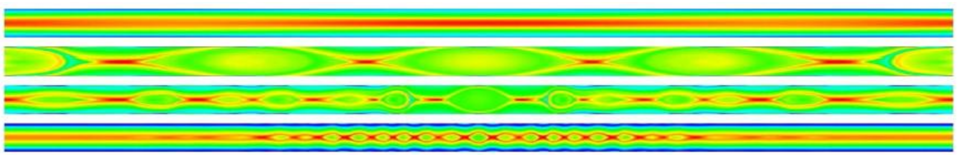
K.Shibata and S.Tanuma, EPS, 53, 473 (2001)

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

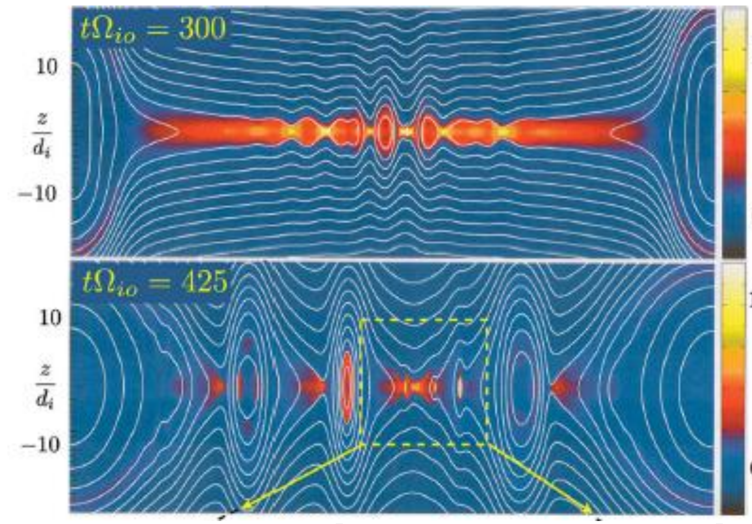
Multiple plasmoids in a Current Sheet



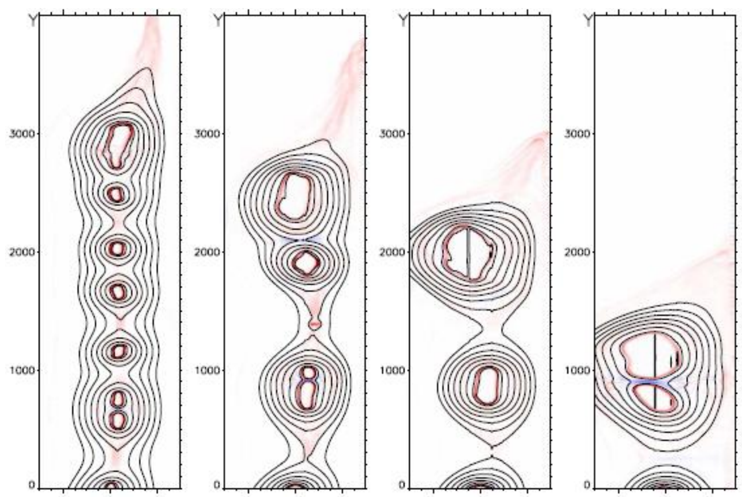
[Loureiro et al. 2009]



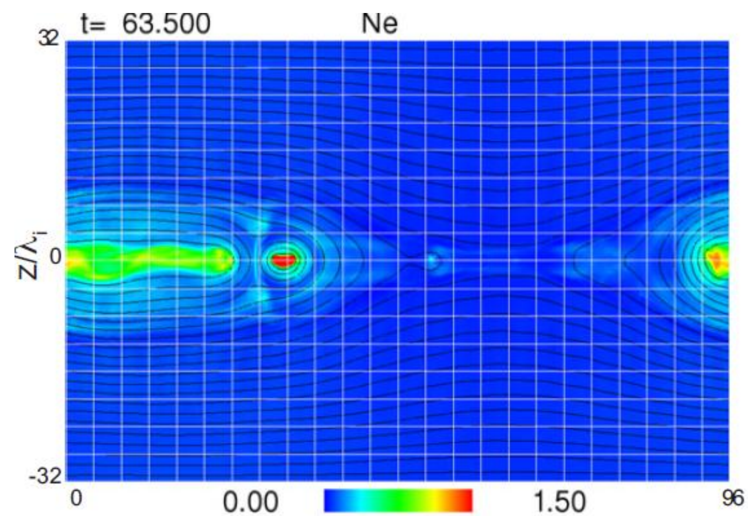
[Samtaney et al. 2009]



[Daughton et al. 2009]

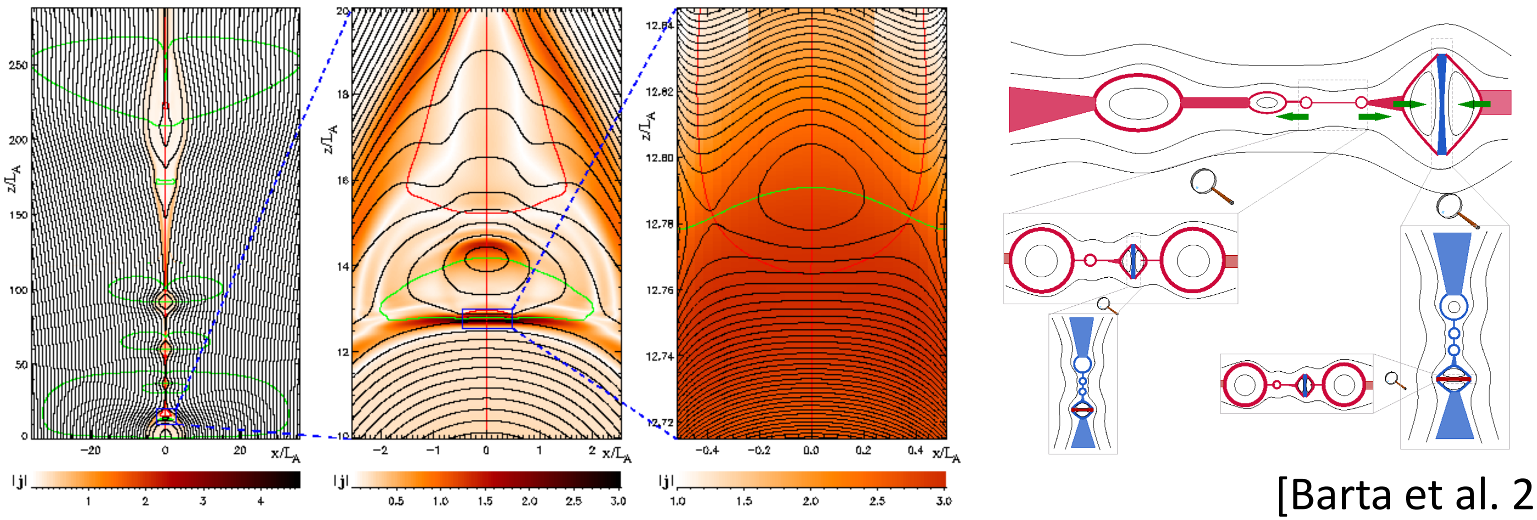


[Karlicky and Barta. 2011]



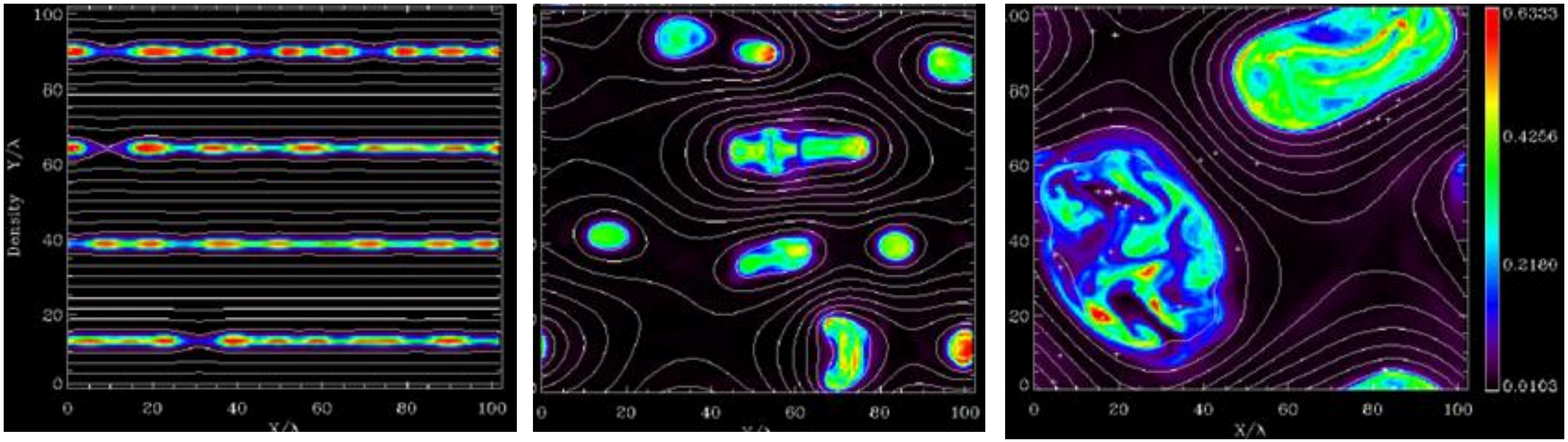
[Tanaka et al. 2010]

Multiple plasmoids in 2D direction



[Barta et al. 2010]

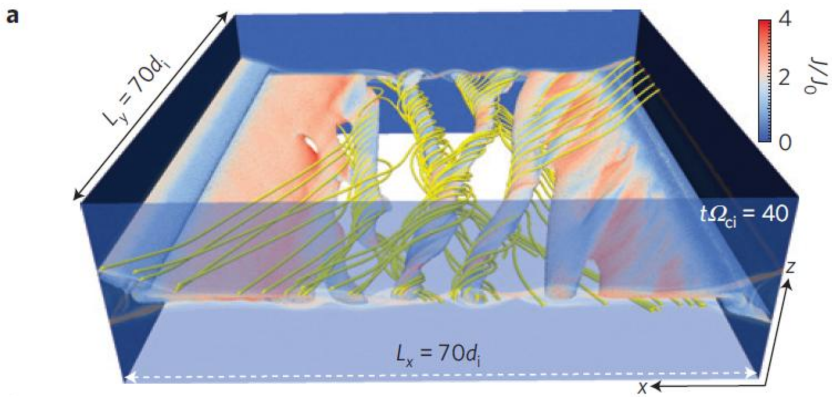
Plasma density



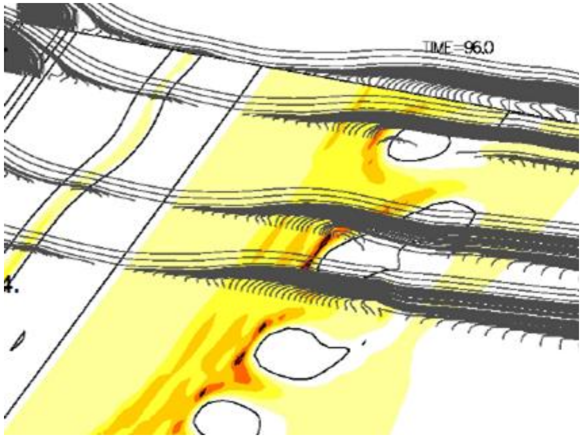
Reconnection in acretion disk (magneto-rotational Instability)

[Hoshino 2012]

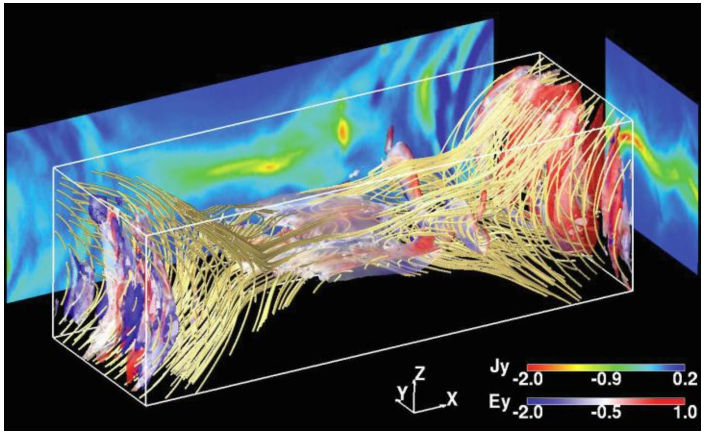
Plasmoid and Turbulent current sheet in 3D simulation



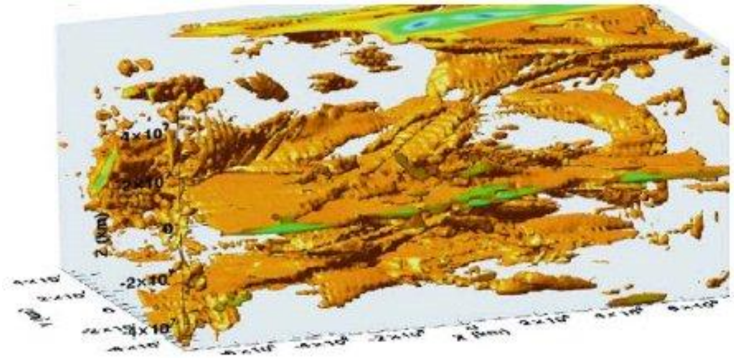
[Daughton et al. 2011] **PIC** simulation
Guide field is very strong.
→multi fractal analysis [S. Chapman et al. 2012]



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

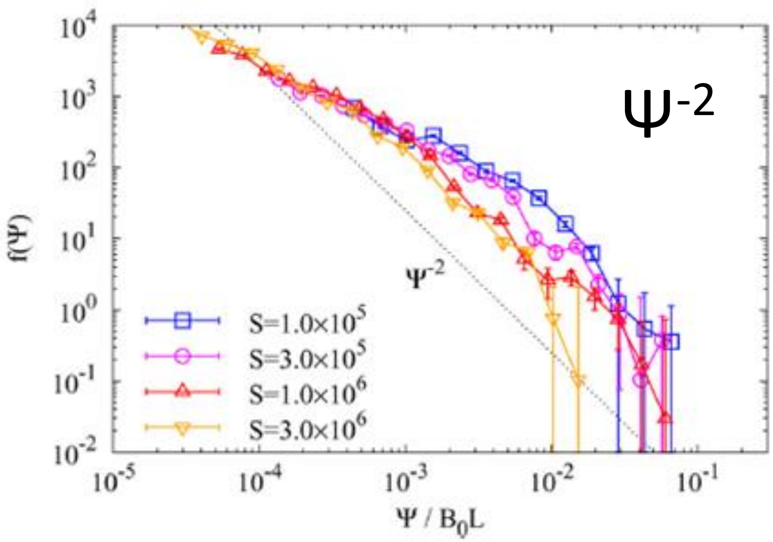


[Fujimoto & Sydora 2012] **PIC** simulation
Reconnection generates kinetic turbulence.

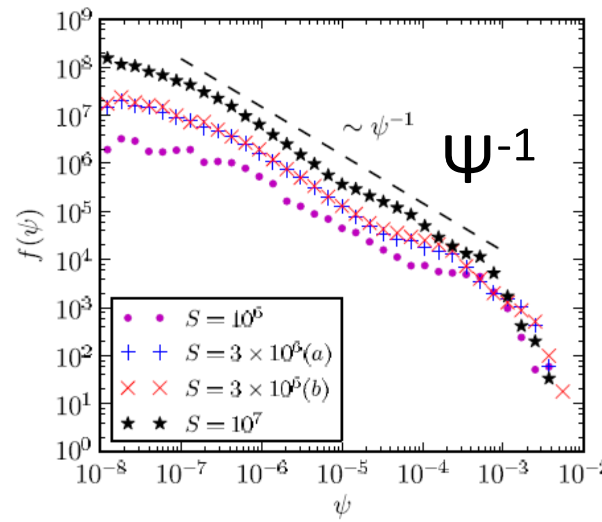


[Galsgaard & Nordlund 1996, Vlahos 2004]
Idea of SOC-formed current sheet.
Simulation is **very diffusive** (**small R_m**)

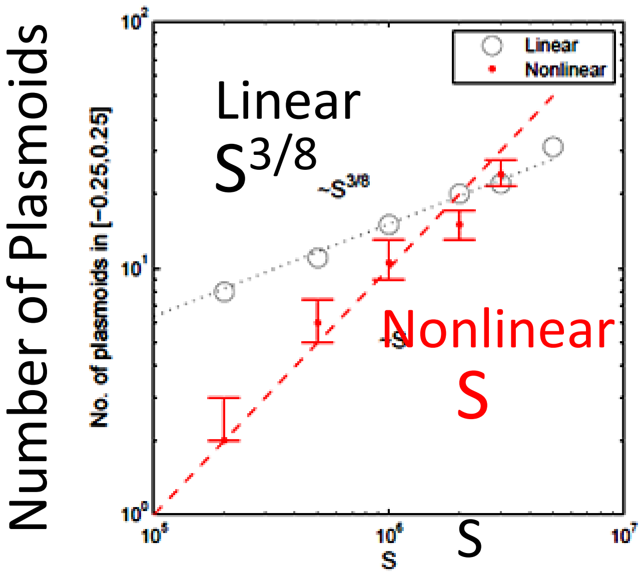
Multi-scale fragmentation & Power-law



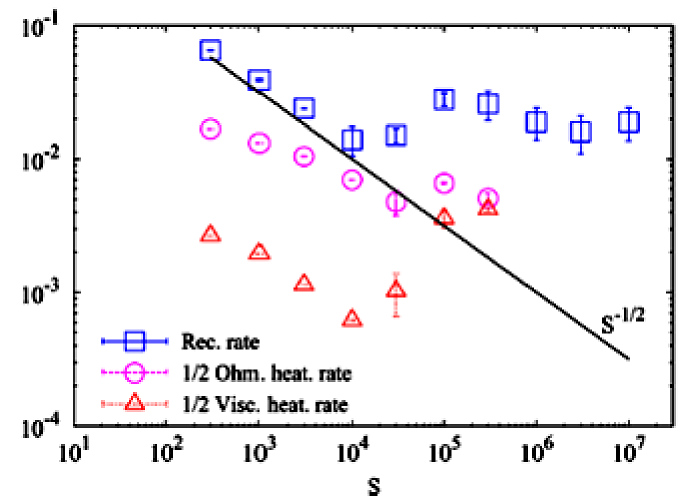
[Loureiro et al. 2012] cf) Barta et al. 2012



[Huang et al. 2012]



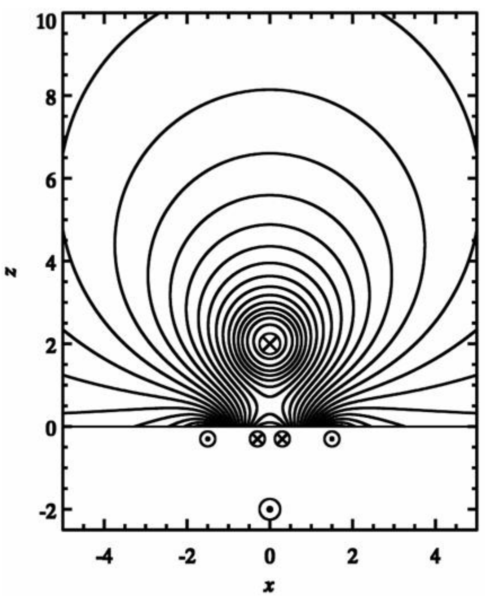
[Huang et al. 2010] cf) Samtaney et al. 2006,Ni et al.2010



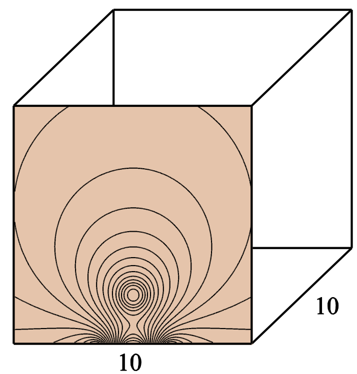
[Loureiro et al. 2012]

Numerical simulation

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

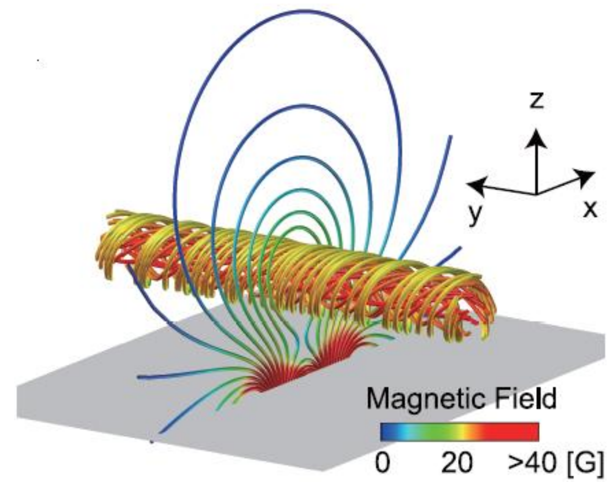


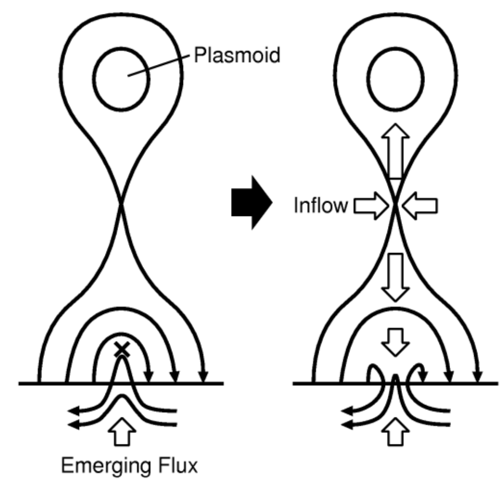
3D



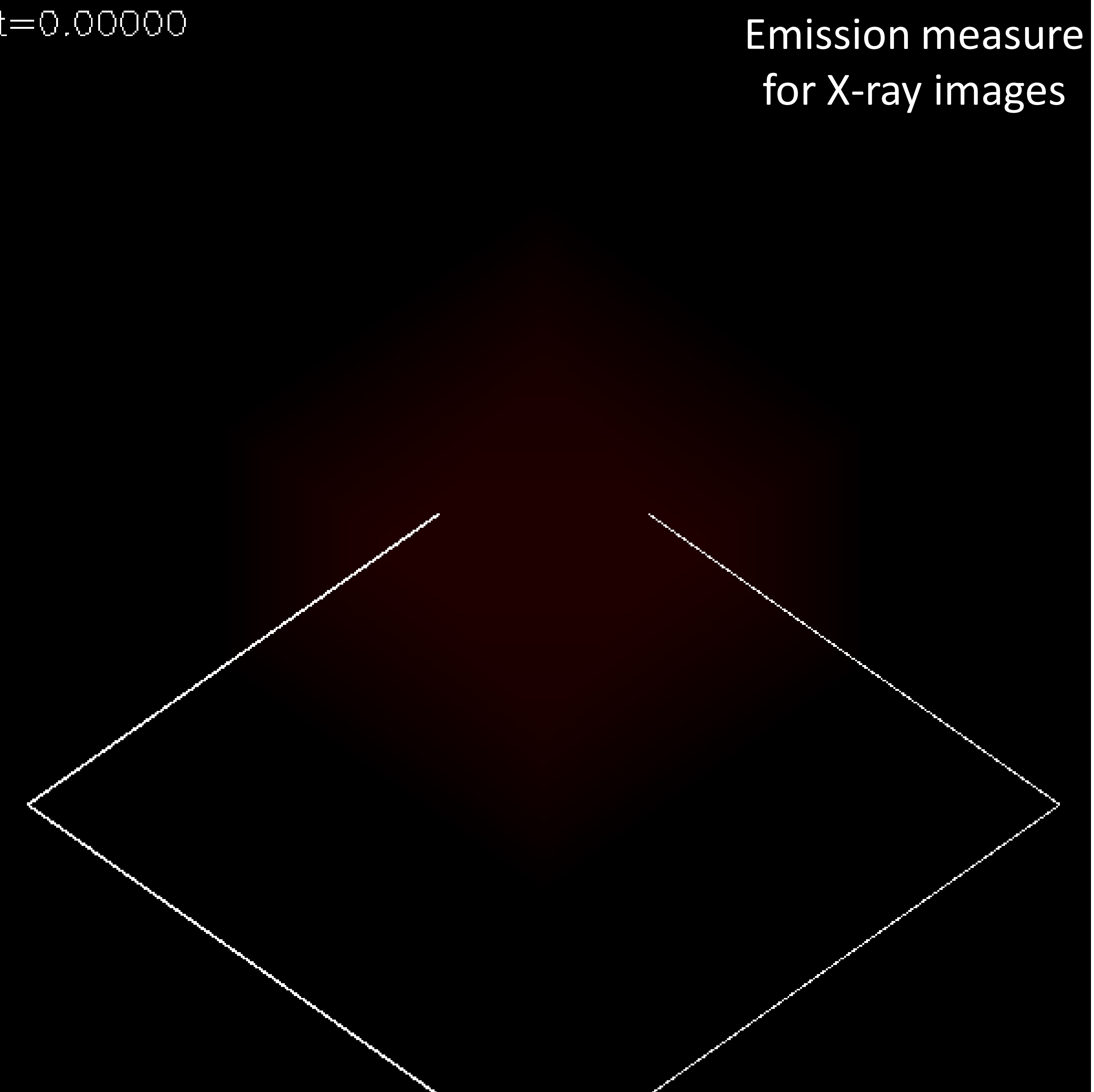
Unit : L0=10^9cm

Grid : [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 (→)



Nishida, Nishizuka, Shibata, 2013, ApJL

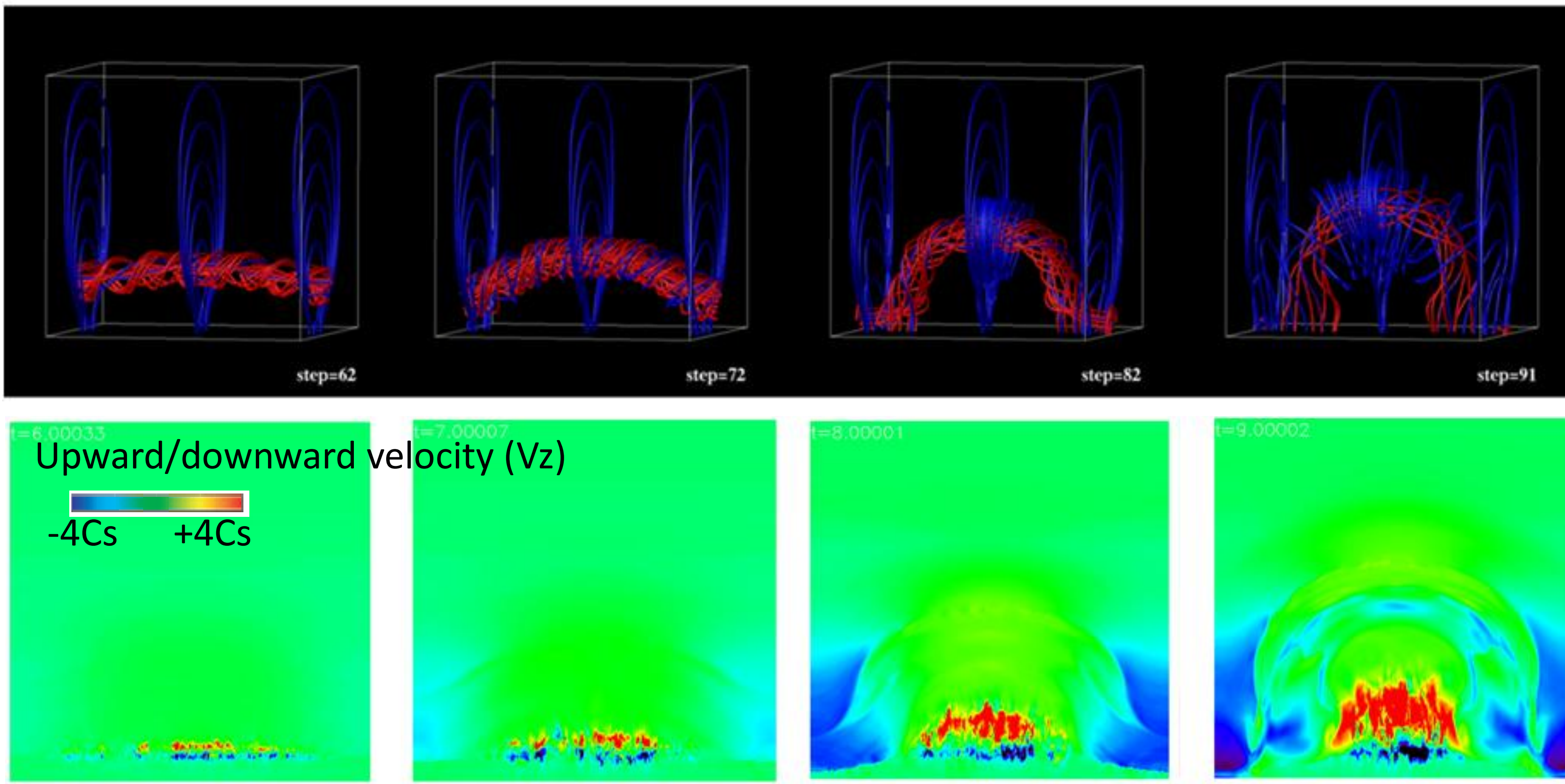
density

temperature

Snapshot images of a weakly twisted flux rope

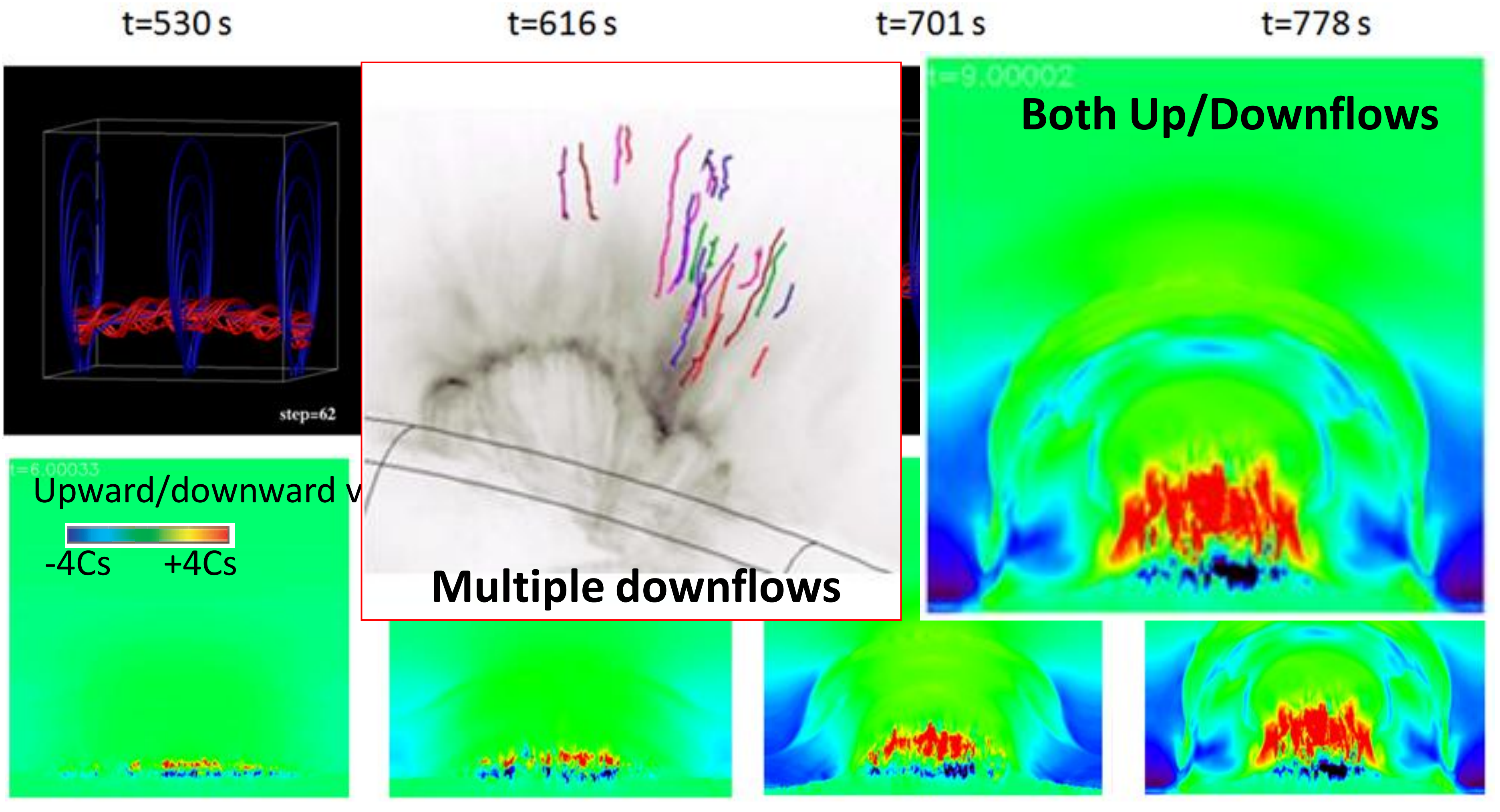
$$\Phi(r=0)\approx 1.5 \quad \Phi(r)=\frac{LB_{\varphi}(r)}{2\pi r B_z(r)}$$

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

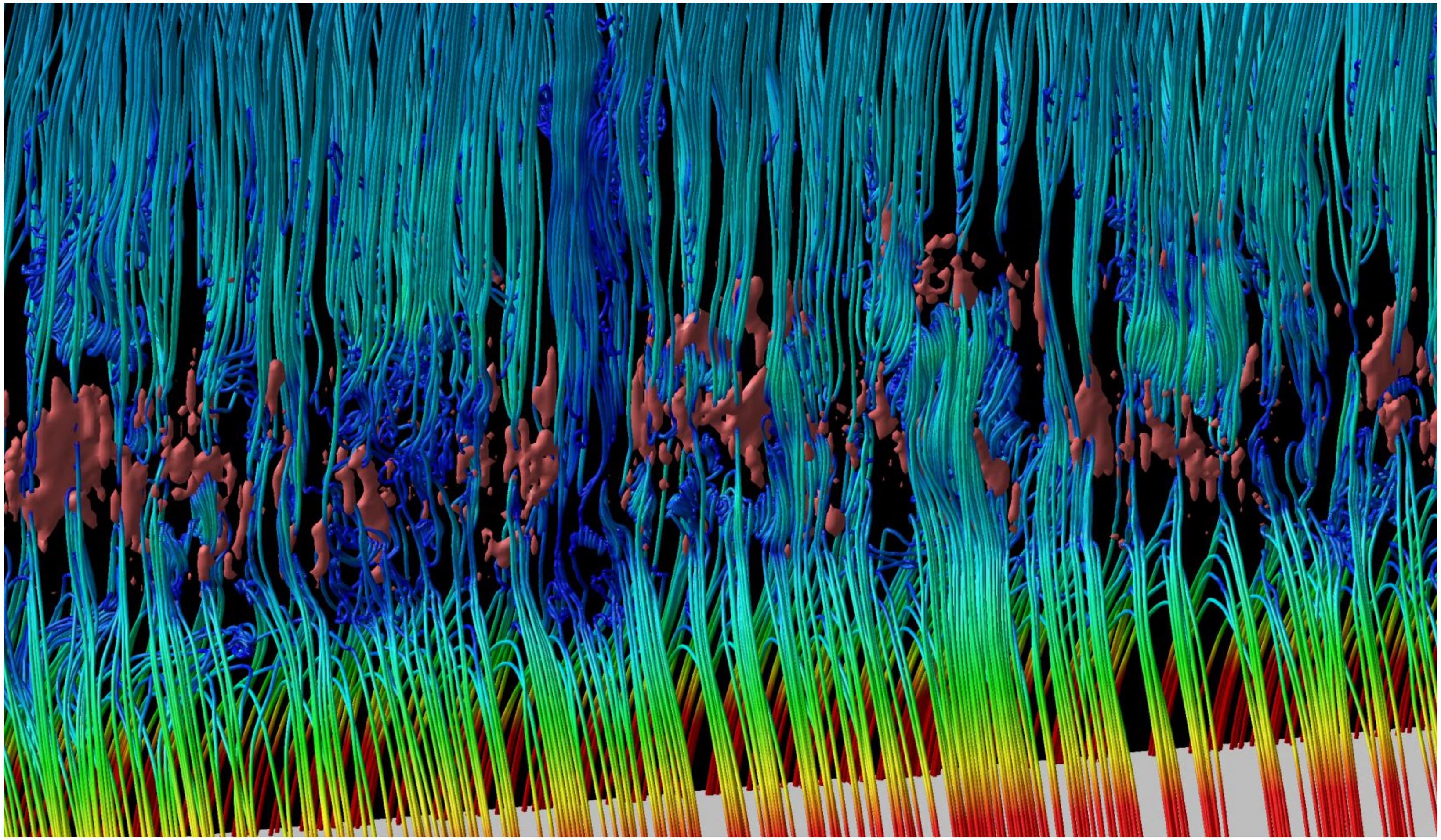


Snapshot images of a weakly twisted flux rope

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



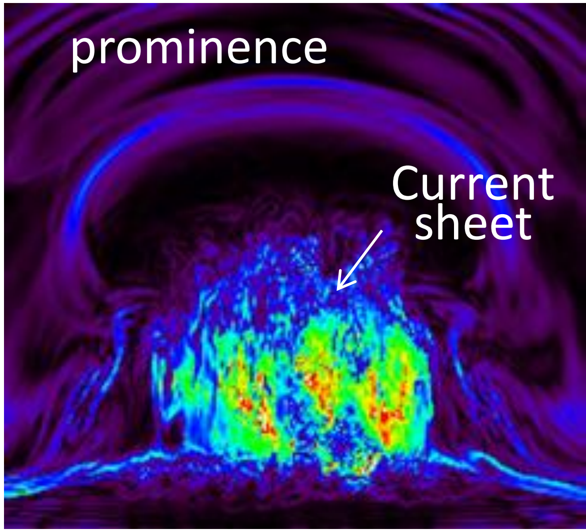
Current sheet in 3D



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

Fragmented Current sheet

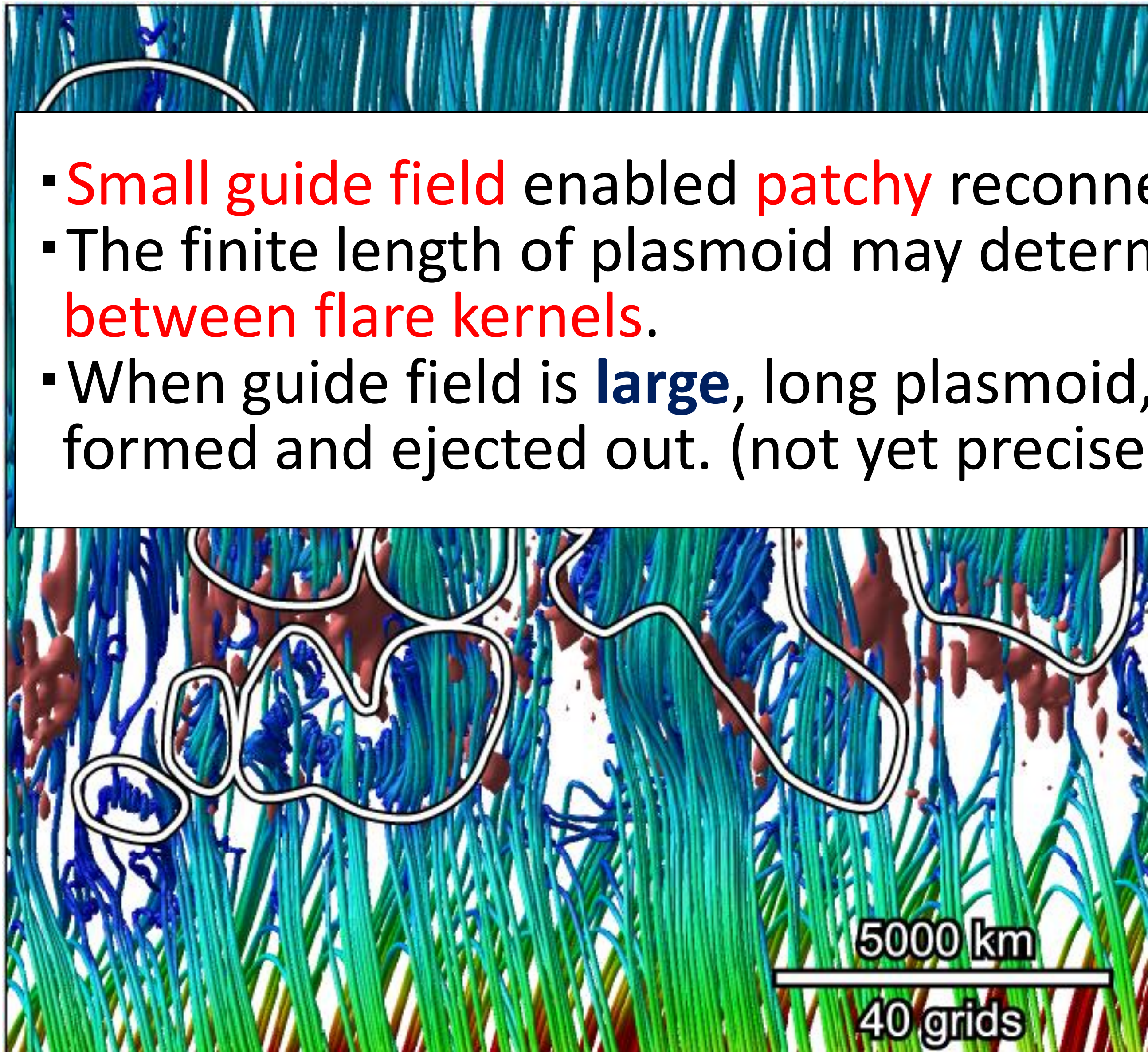
Current density



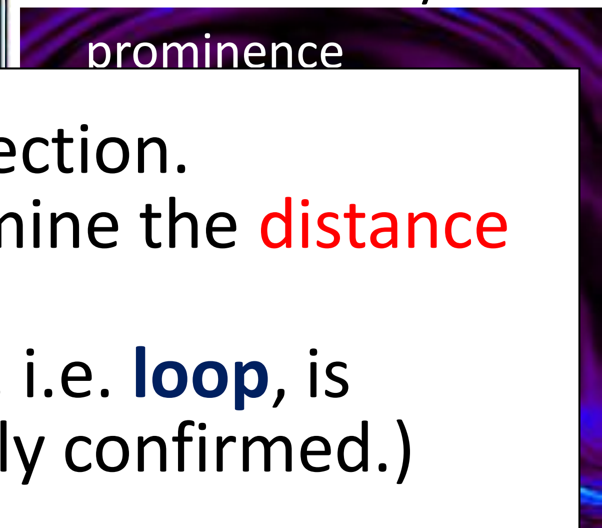
- Multiple plasmoids are formed in a current sheet.
- 3D plasmoid with a **finite** length.
- Strong E-field ■ is enhanced between plasmoids.

Fragmented Current sheet

- Small guide field enabled patchy reconnection.
- The finite length of plasmoid may determine the distance between flare kernels.
- When guide field is **large**, long plasmoid, i.e. **loop**, is formed and ejected out. (not yet precisely confirmed.)



Current density



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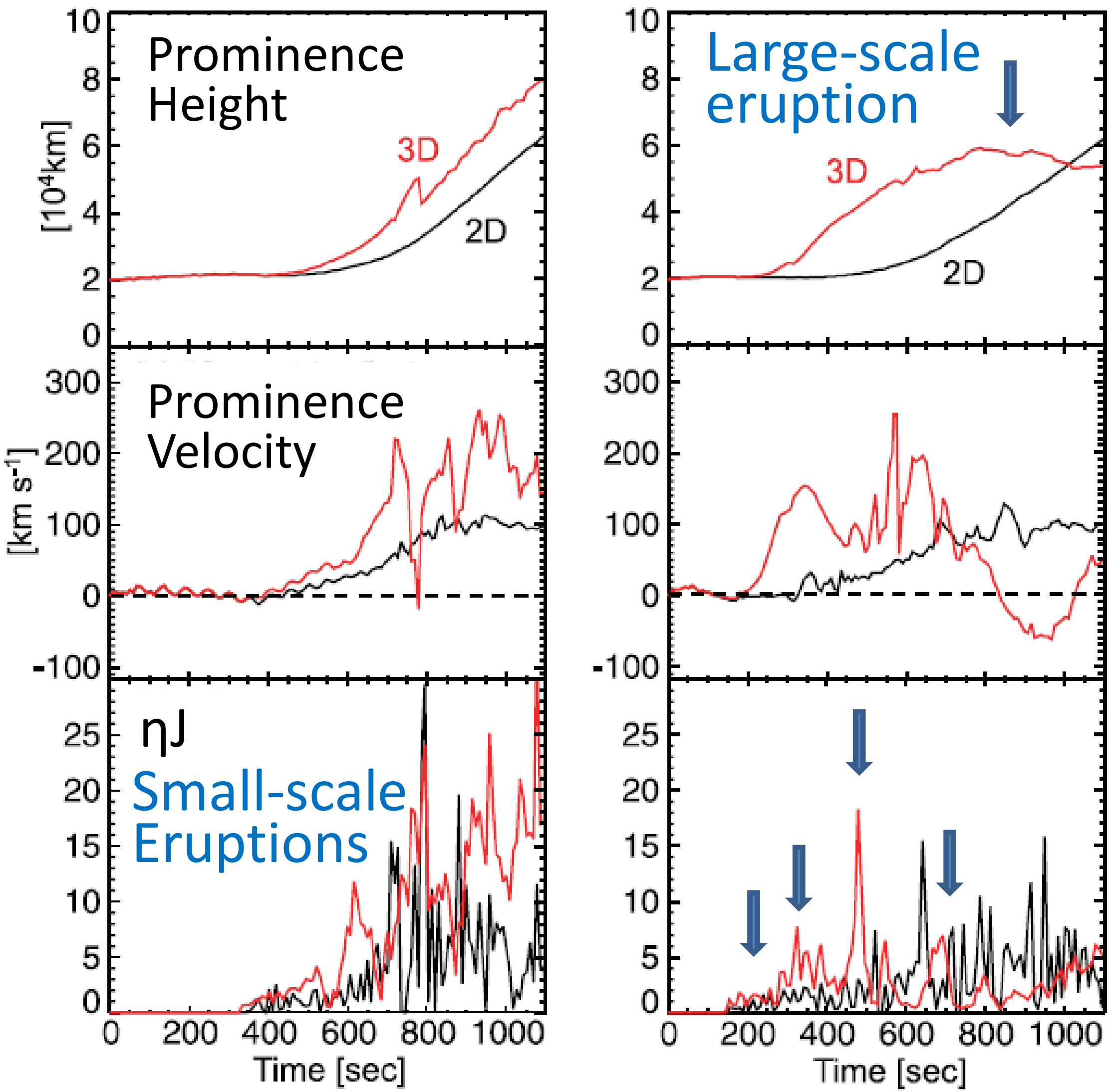
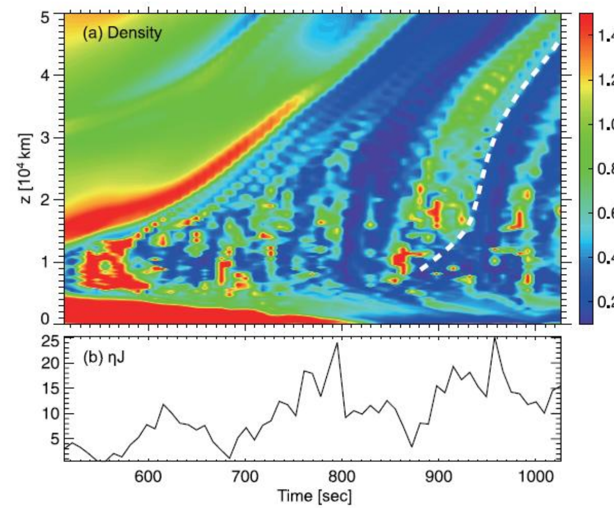
Turbulent structure & Intermittency

Weakly twisted case — Strongly twisted case



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

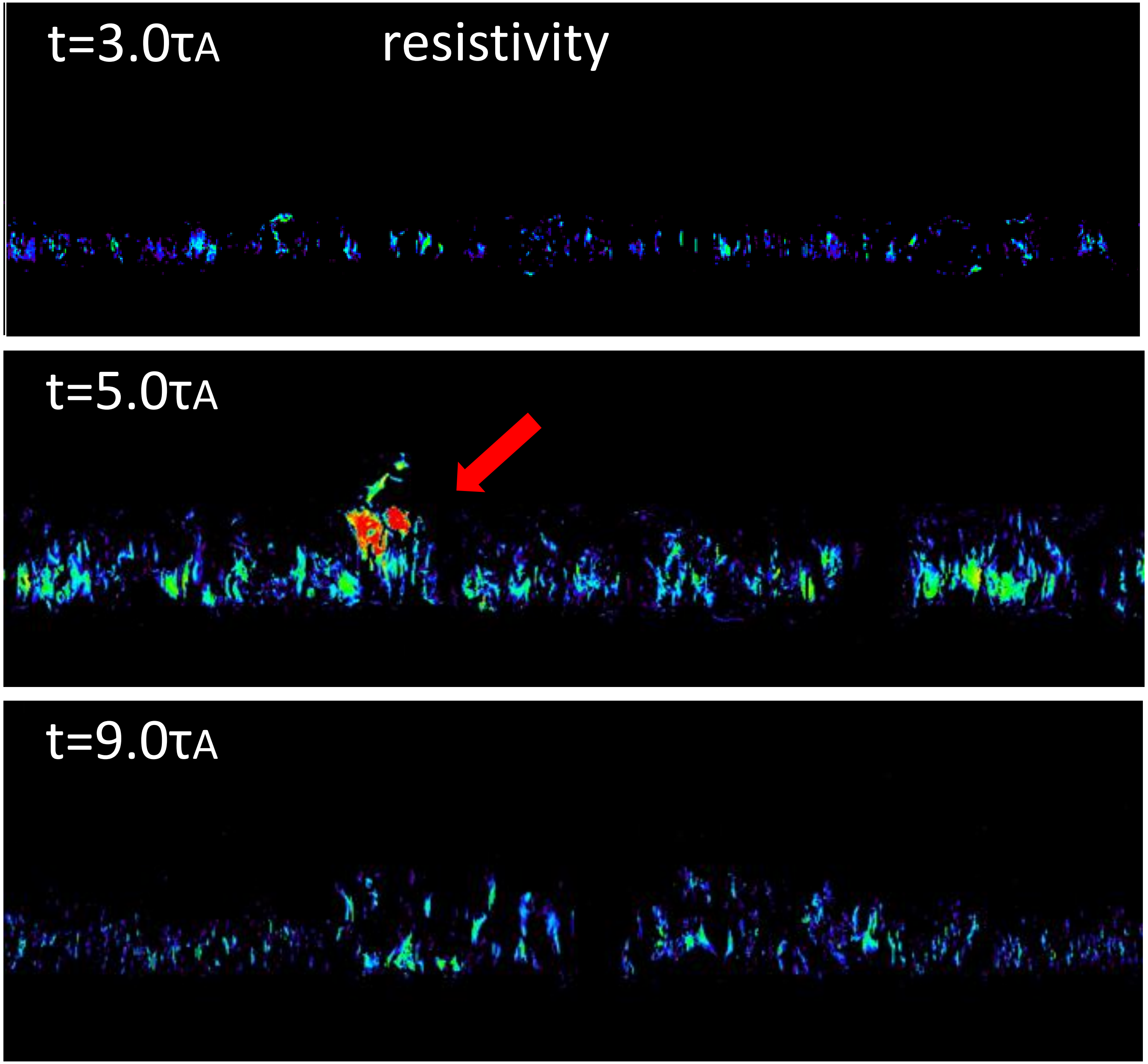


Turbulent structure

correlated

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

Critical state of a current sheet



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

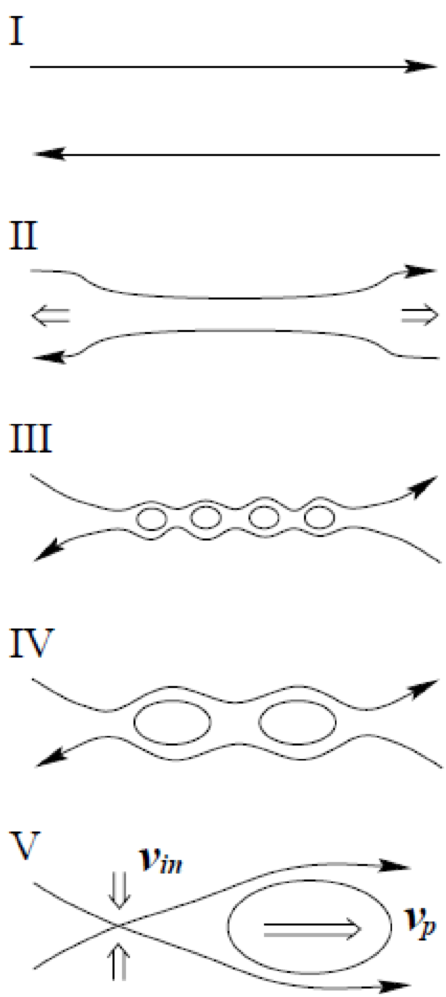
Once anomalous resistivity is triggered, it affects the surroundings (=avalanching).

Application to Self-Organized Criticality (SOC)

Avalanche model with Scenario of fast reconnection

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

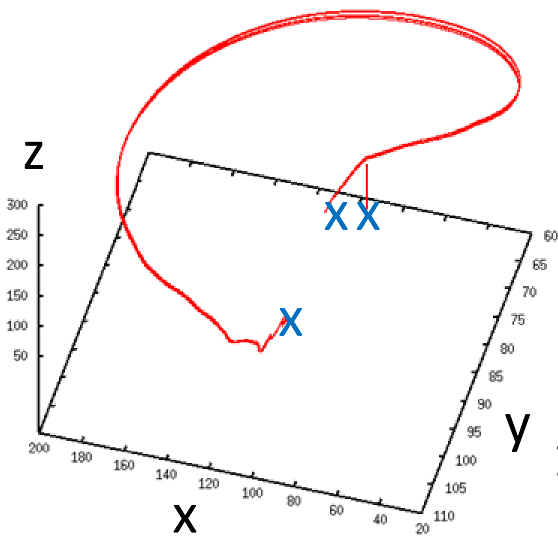
(ii) Instability saturates, and whole system is unstable. J is close to J_{thres} in smallest current sheets almost everywhere. (=critical state)



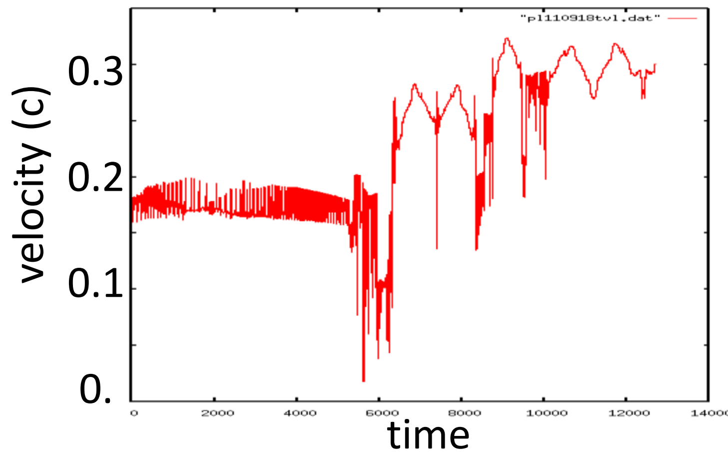
(iii) Once anomalous resistivity occur somewhere, surrounding plasmoids start merging each other, and finally ejected outward. (inverse cascade)

Particle orbit (protons) in **3D** configuration
[stochastic acc. & propagation]

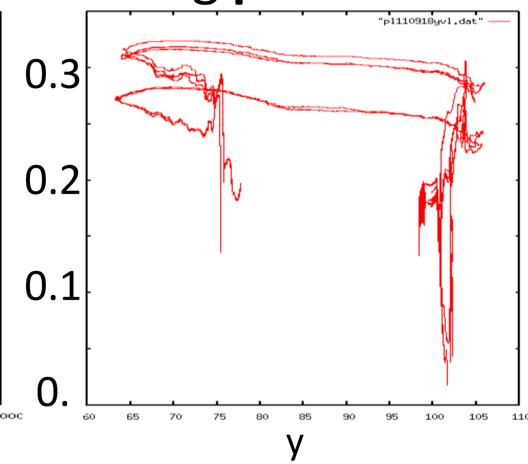
3D orbit

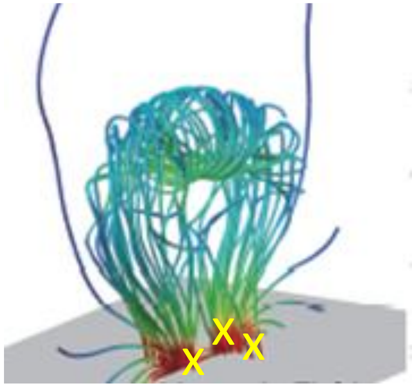


Acceleration **in current sheet**



along **prominence**



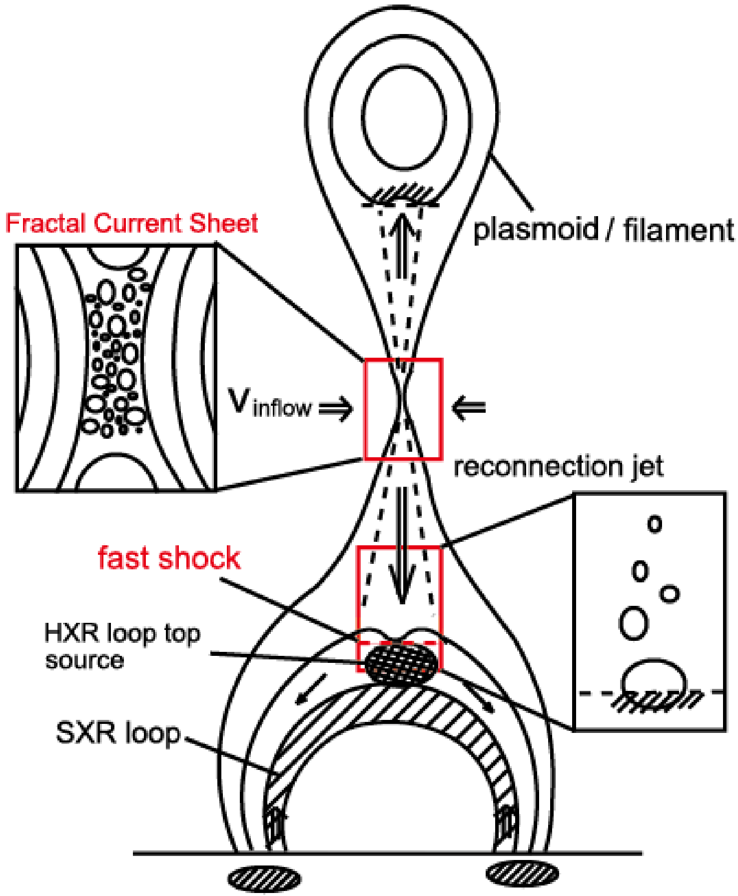


1. Particles are stochastically accelerated in **multiple X-points in a current sheet**, with **finite** length in depth.

Turbulence structure is effective for **trapping** particles.

2. Particles released upward from a current sheet can propagate along a prominence, with slight acceleration by curvature drift. This makes **another pair of footpoint bright points**, apart from the original one.

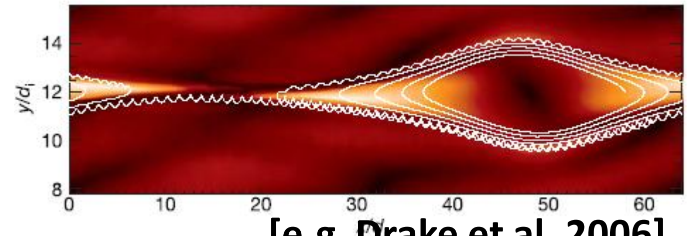
3 Steps of **Heating/Acceleration** by Plasmoids



[**Nishizuka & Shibata 2013**]

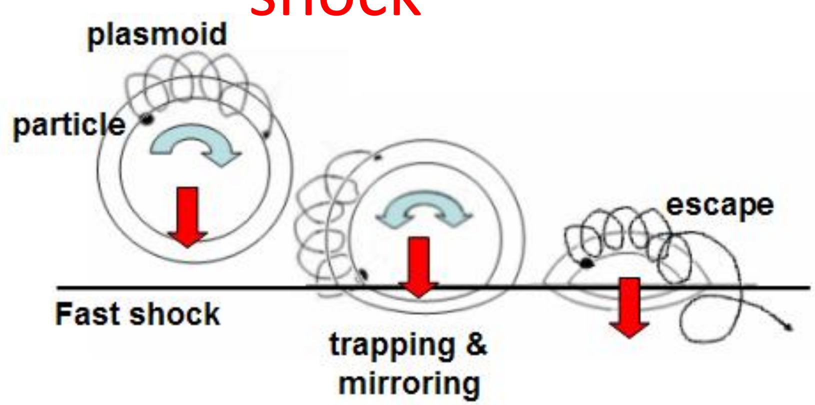
(1) Current sheet between two colliding plasmoids (reversed X-point)

(2) Constraction of a plasmoid upon coalescence



[e.g. Drake et al. 2006]

(3) Interaction with loop-top fast shock

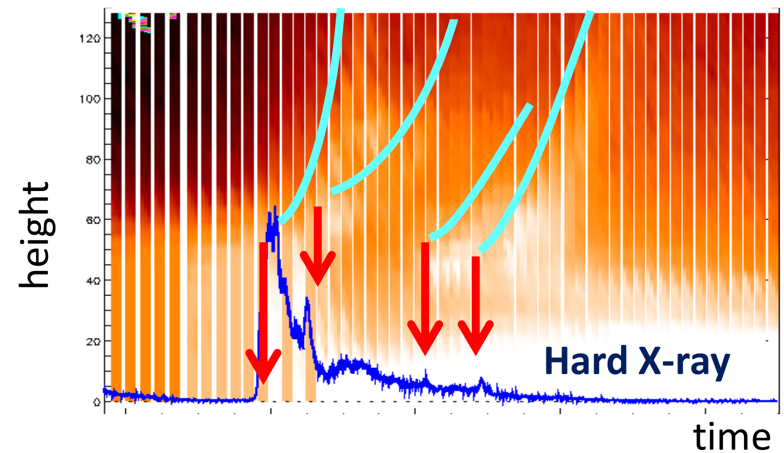


Observations of Multiple Plasmoid Ejections

(1) Correlation with **Hard X-ray** emission (Particle acceleration)

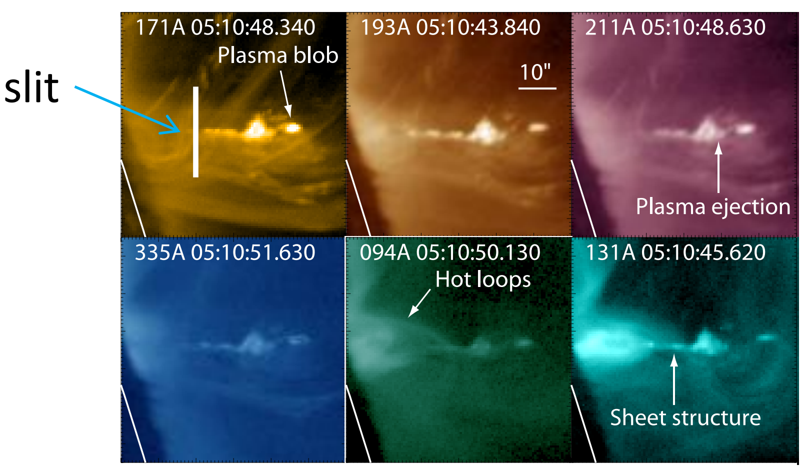
Yohkoh/SXT [Nishizuka et al. 2010]

Time slice image (**plasmoid ejection**)

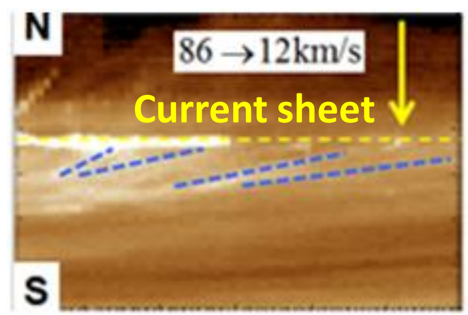


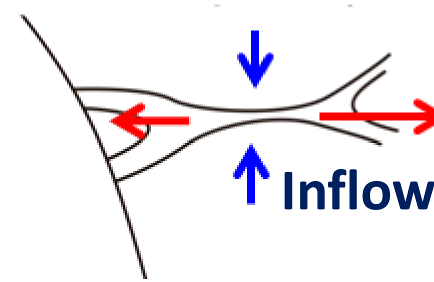
$I_{HXR} \propto M_A$

(2) Increasing **Inflow** speed (i.e. Reconnection rate: V_{in}/V_A)



AIA/SDO [Takasao et al. 2012]

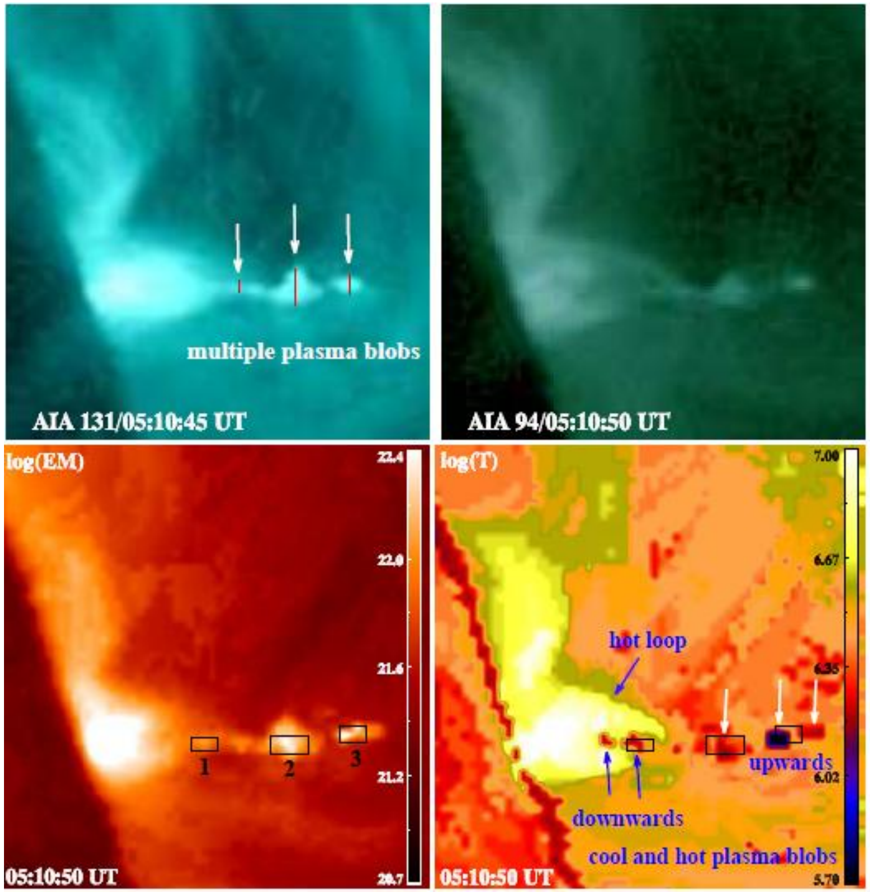


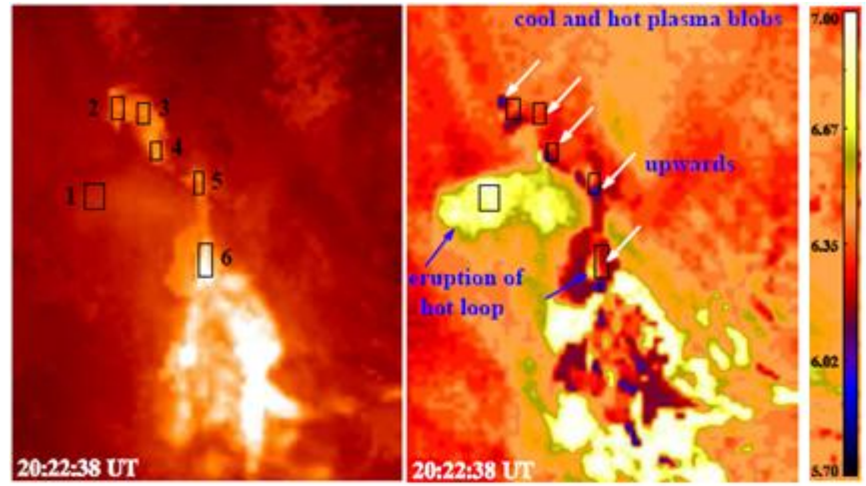


$$M_A \equiv V_{\mathrm{inflow}} / V_{\mathrm{A}} \approx 0.20 \rightarrow 0.026$$

(during 5 min.)

How to Heat up plasmoids/turbulent current sheet?





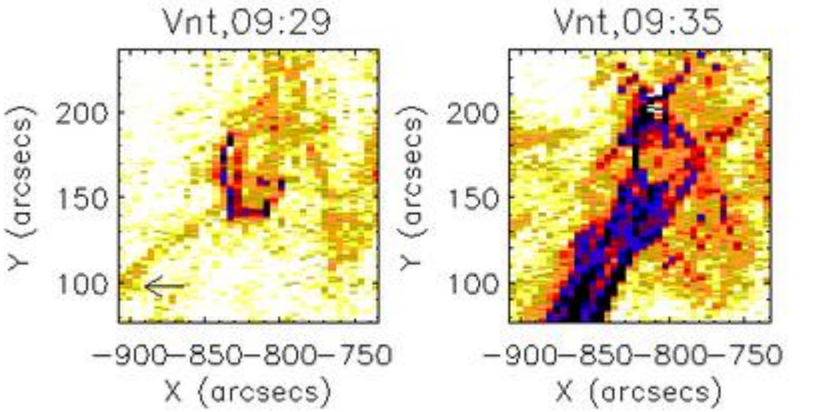
Small scale plasmoids are **cooler** than the coronal temperature.

→ Difference from X-ray plasmoid (10MK)

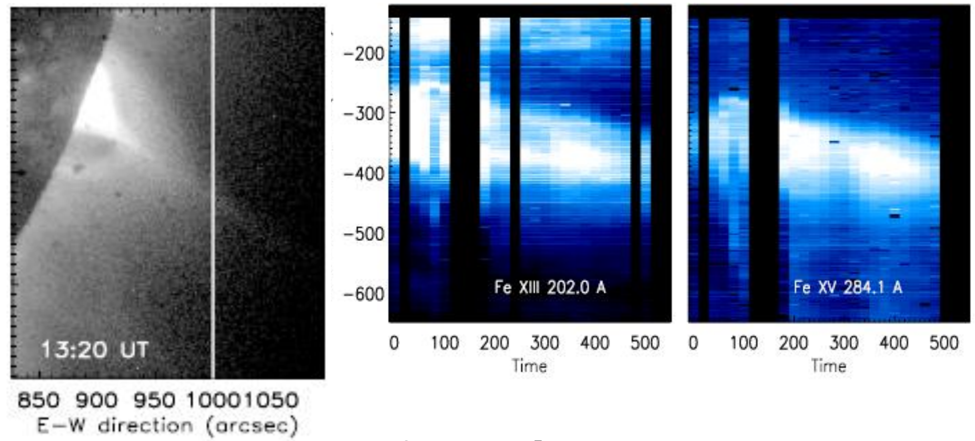
- What is the heating process?
- How about the time evolution?
- Small scale plasmoids finally become X-ray plasmoids?

Observation of turbulent current sheet by Hinode/SDO

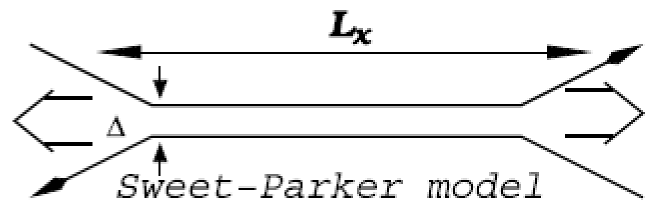
Nonthermal velocity in early phase



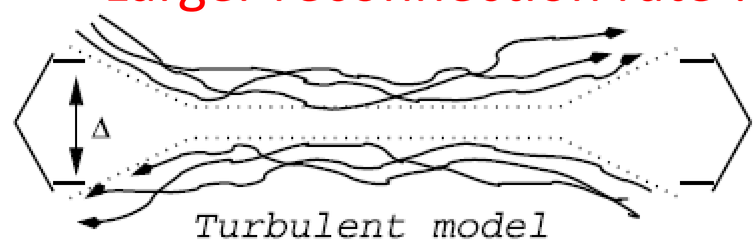
[Hara et al. 2013]



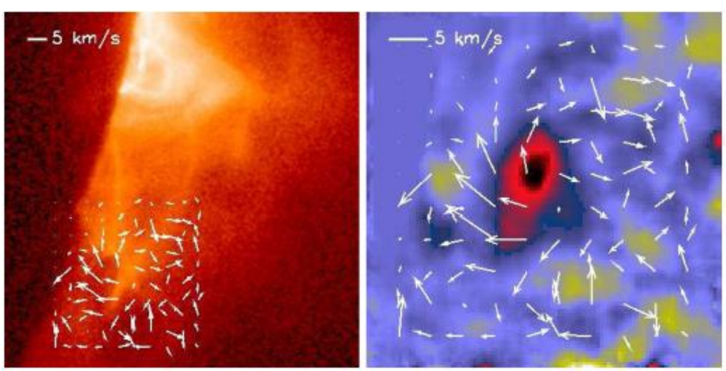
[Landi et al. 2012] EIS+XRT, DEM, ne



Larger reconnection rate !?

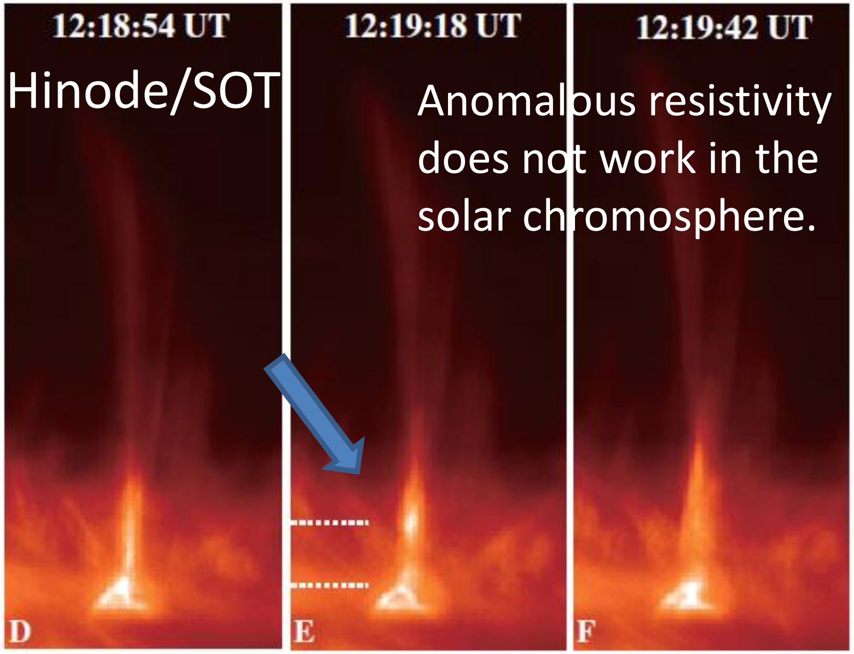


[Lazarian et al. 2004, 2013]



[McKenzie 2013] XRT correlation Tracker

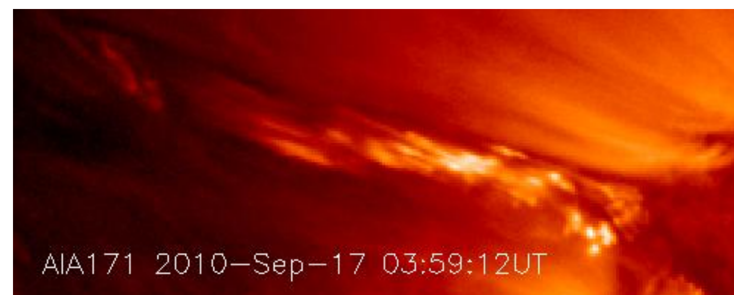
Current sheet fragmentation in Jets



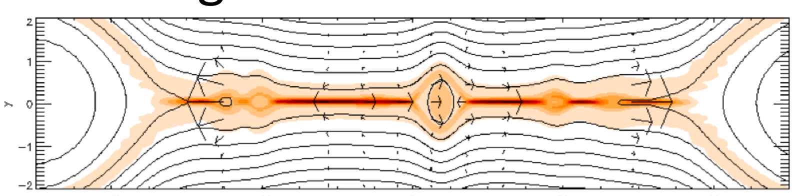
[Singh et al .2012]

SDO/AIA 193A(FeXII) T=1.2x10^{6}K

ISSI-Jet team [Schmieder etal. 2013]



Ambipolar Diffusion & Current Sheet Thinning



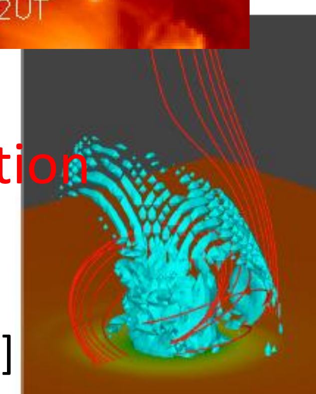
[Isobe et al., 2010, in prep]

Small Bright Points in a Jet

⇒ Local heating or condensation

Plasmoids/ Wave ?

Evaporation/ LOS effect ?



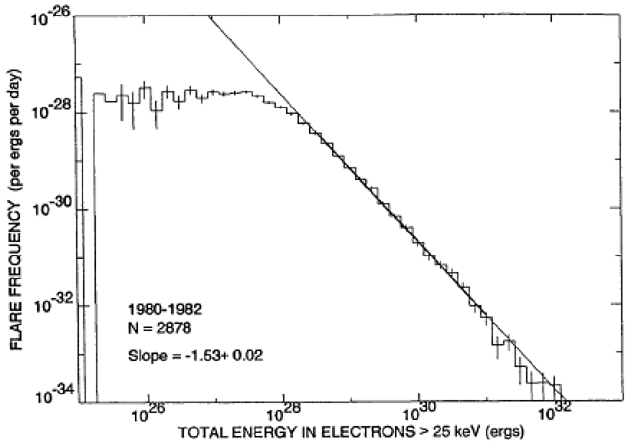
[Pariat et al. 2010]

Summary

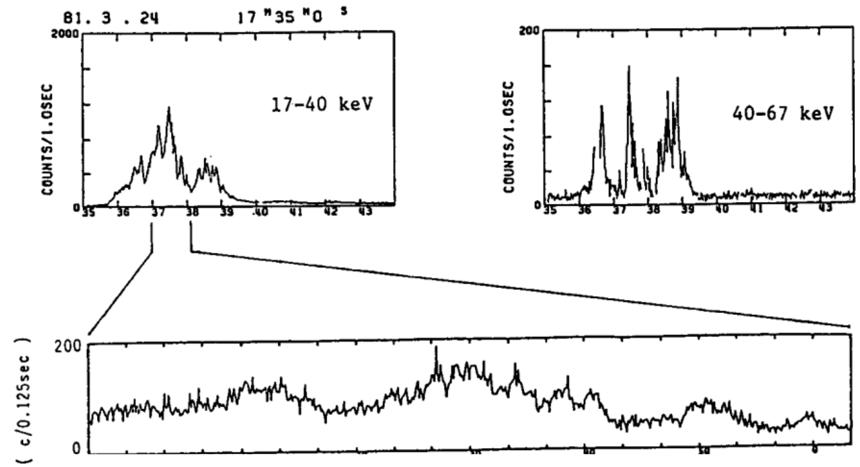
- Magnetic reconnection in a solar flare is **unsteady** and **impulsive bursty**. Current sheet is unstable ($R_m > 10^4$) and fragmented to small ones, which lead to **intermittent** energy release.
- Energy release occurs at the one **small** region, spreading to global energy release (**avalanching, Self-organized criticality**).
- We performed 3D MHD simulation and showed turbulent current sheet, in which multi-plasmoids are formed. We assumed **weak guide field** in the current sheet (but Bz is large in the prominence), so that **patchy** reconnection occur. This may determine the distances between flare bright points (& supra-arcade downflow).
- Fragmented current sheet may also have a role in **heating and accelerating plasma**. We introduced some observations of multi-plasmoids and turbulent current sheet by Hinode and SDO.

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

Hard X-rays (~ released particle energy)

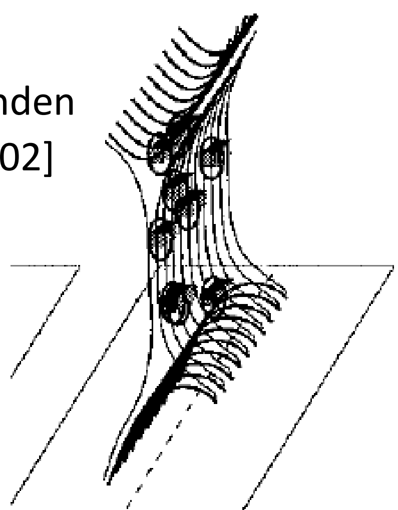


[Crosby et al. 1993]



[Ohki et al. 1992]

[Aschwanden et al. 2002]

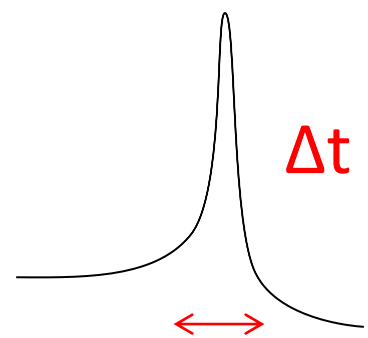


Multiple X-points

- Fractal Reconnection
  (= ensemble of elemental reconnection?)

v.s.

- Patchy Reconnection
  (same size of reconnection region)



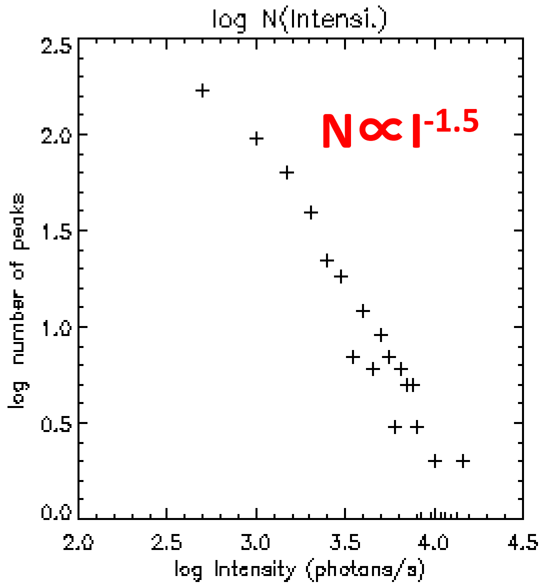
$\Delta t = L_{acc}/c$

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

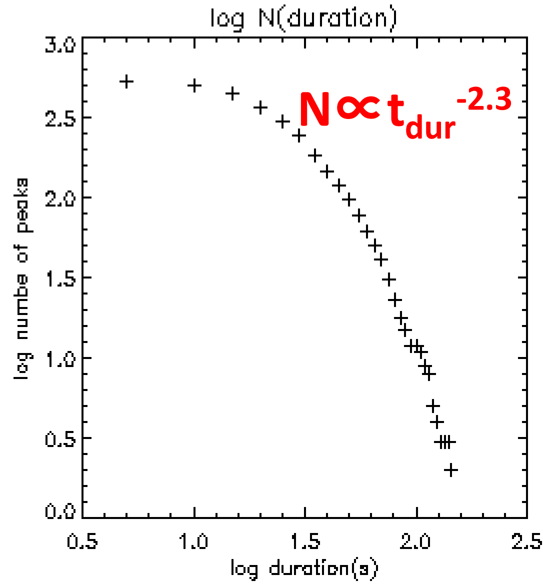
Power-laws of UV Footpoint Brightenings

TRACE1600A (C IV 1550A) UV emission

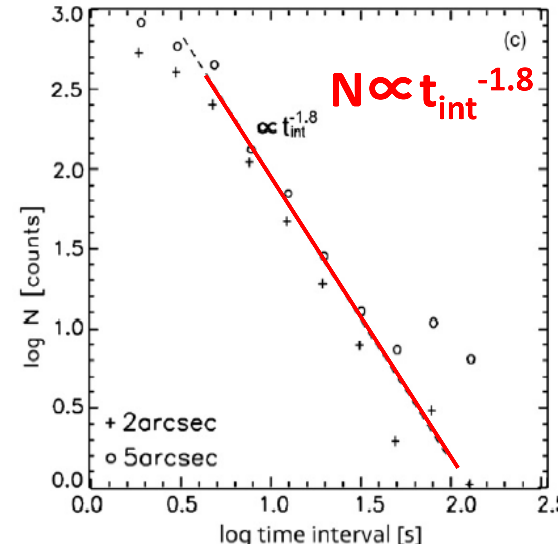
[Nishizuka et al. 2009]



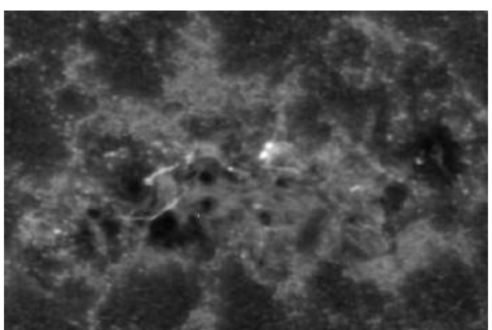
↑distribution of peak intensity of kernels



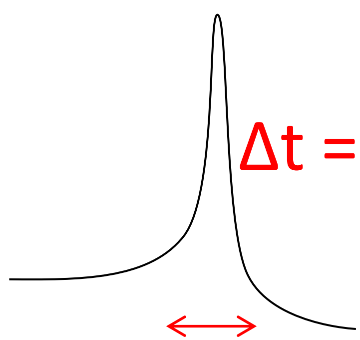
↑distribution of peak duration of kernels



↑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?