Lin-Forbes Model for the Solar Eruption and Large-Scale Magnetic Reconnection

Lin, Jun

林隽

Chief-Scientist of Solar Physics

中国科学院云南天文台
YUNNAN ASTRONOMICAL OBSERVATORY CHINESE ACADEMY OF SCIENCES

Yunnan Astronomical Observatories

Keys Words

- Solar Eruptions
- Catastrophe model, Lin-Forbes model
- Magnetic reconnection
- Large-scale current sheet
- Turbulence, multiple structures and processes

Content

- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

Content

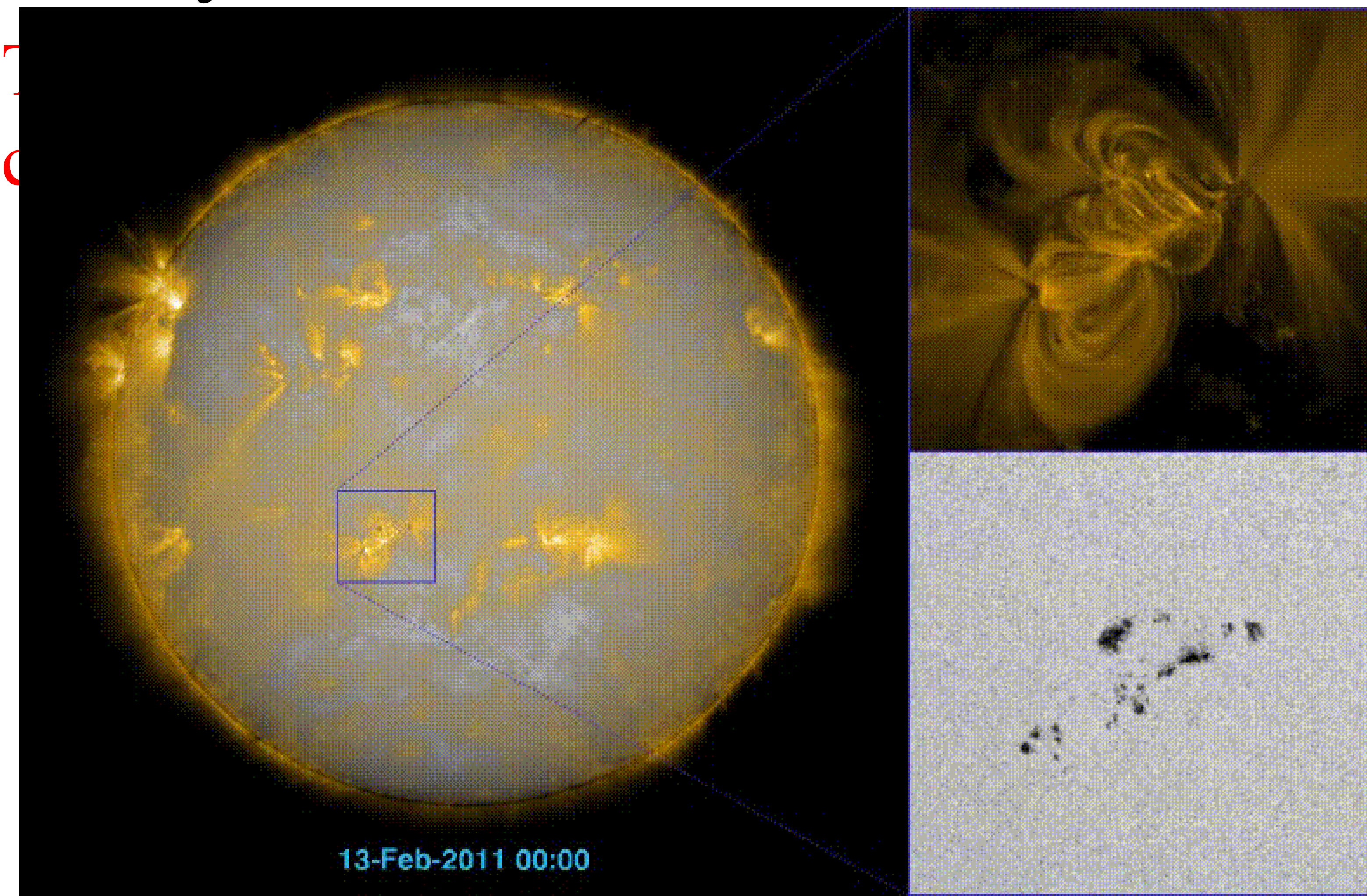
- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

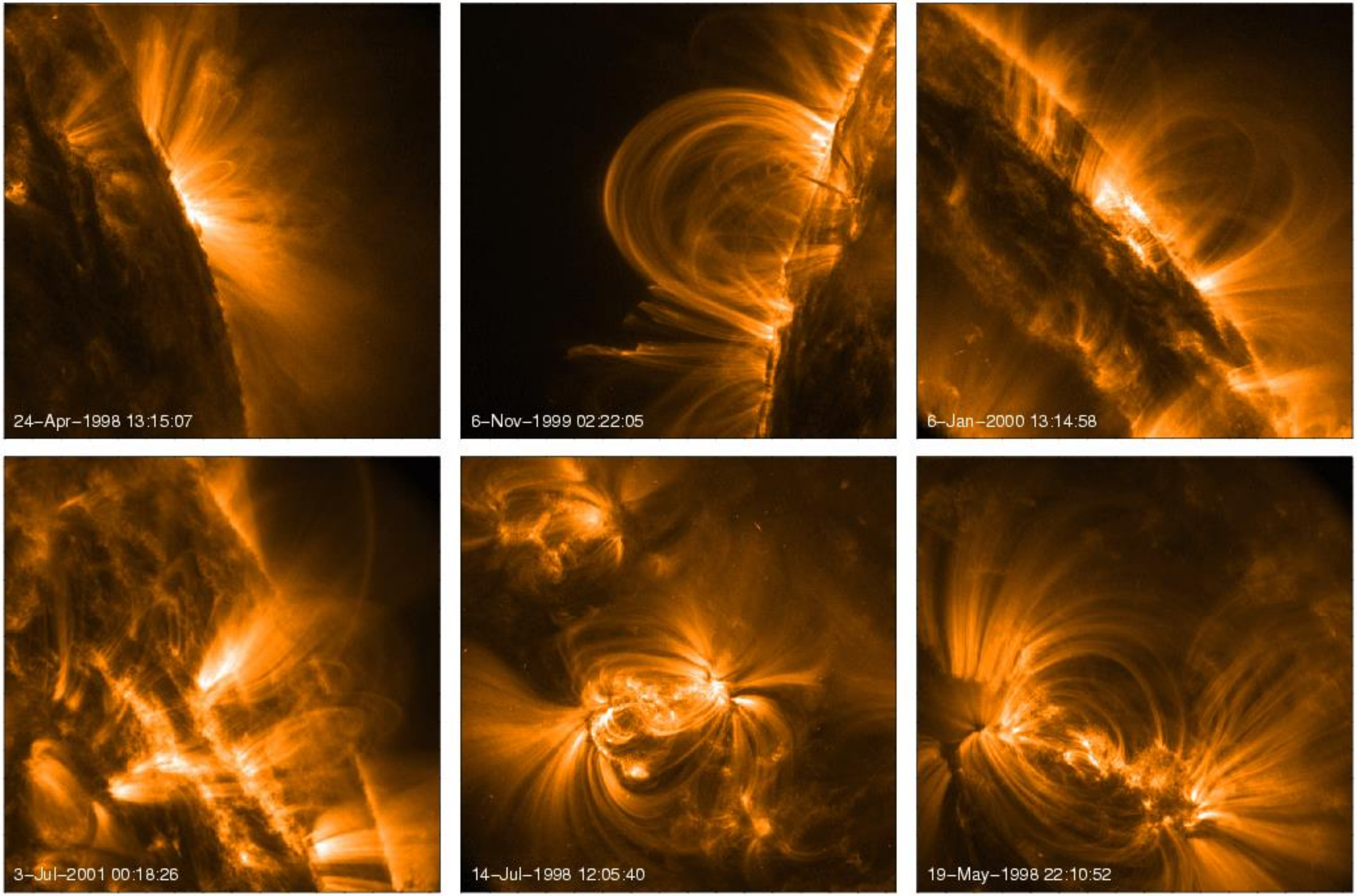
Solar Eruptions

- Solar flares, eruptive prominences, and coronal mass ejections;

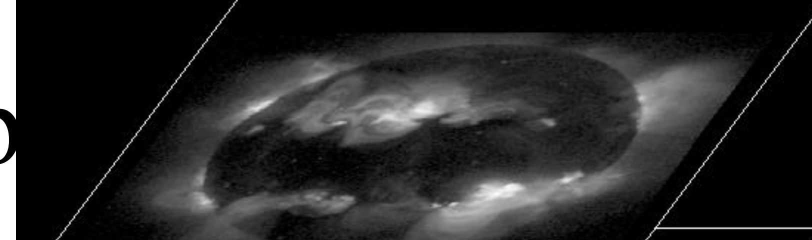
Solar Eruptions

- Solar flares, eruptive prominences, and coronal mass ejections;
- T e
  c

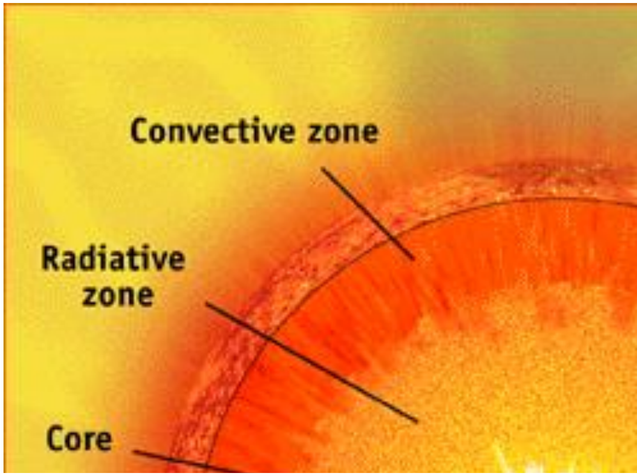


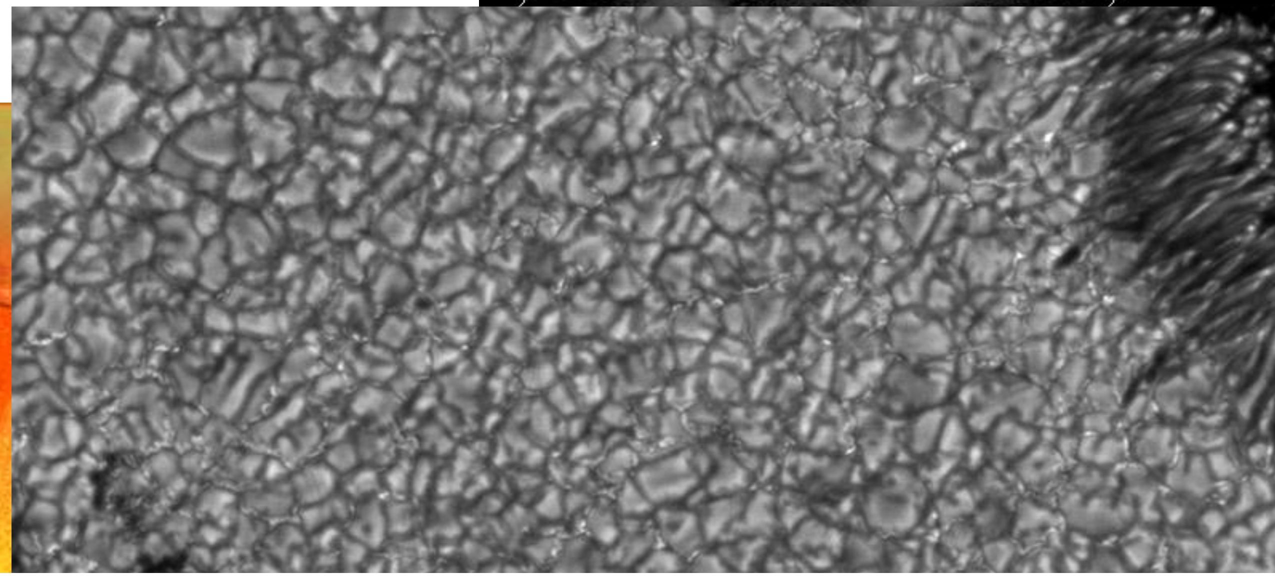

24–Apr–1998 13:15:07
6–Nov–1999 02:22:05
6–Jan–2000 13:14:58
3–Jul–2001 00:18:26
14–Jul–1998 12:05:40
19–May–1998 22:10:52

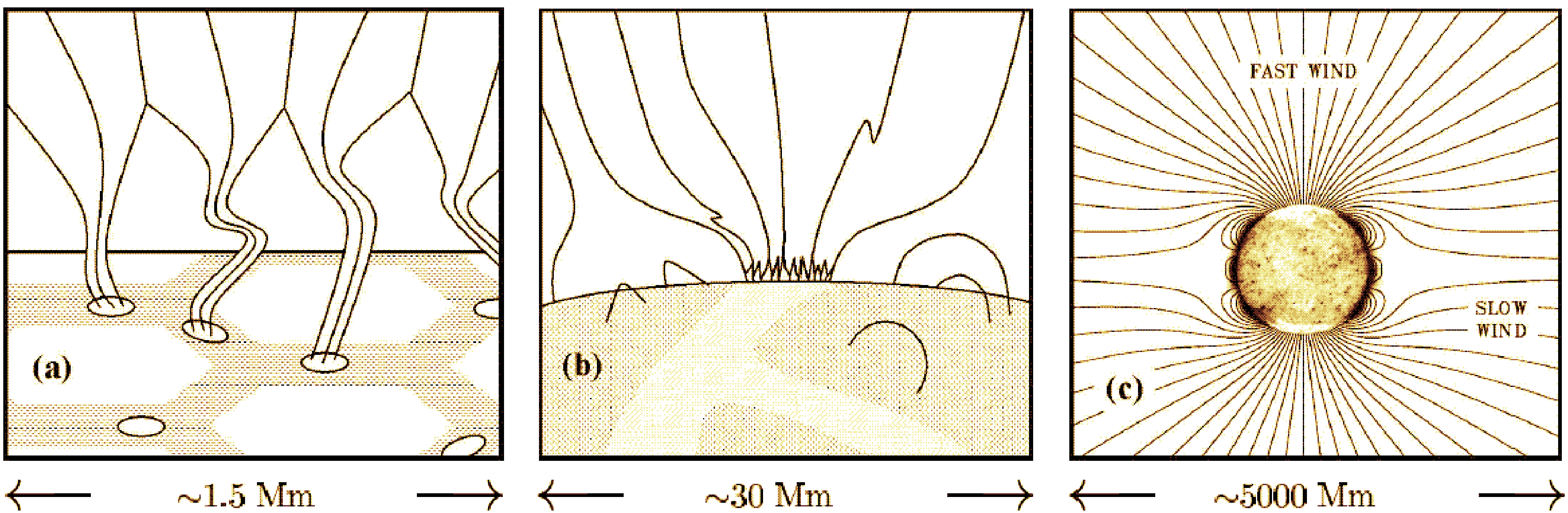
Solar Erup



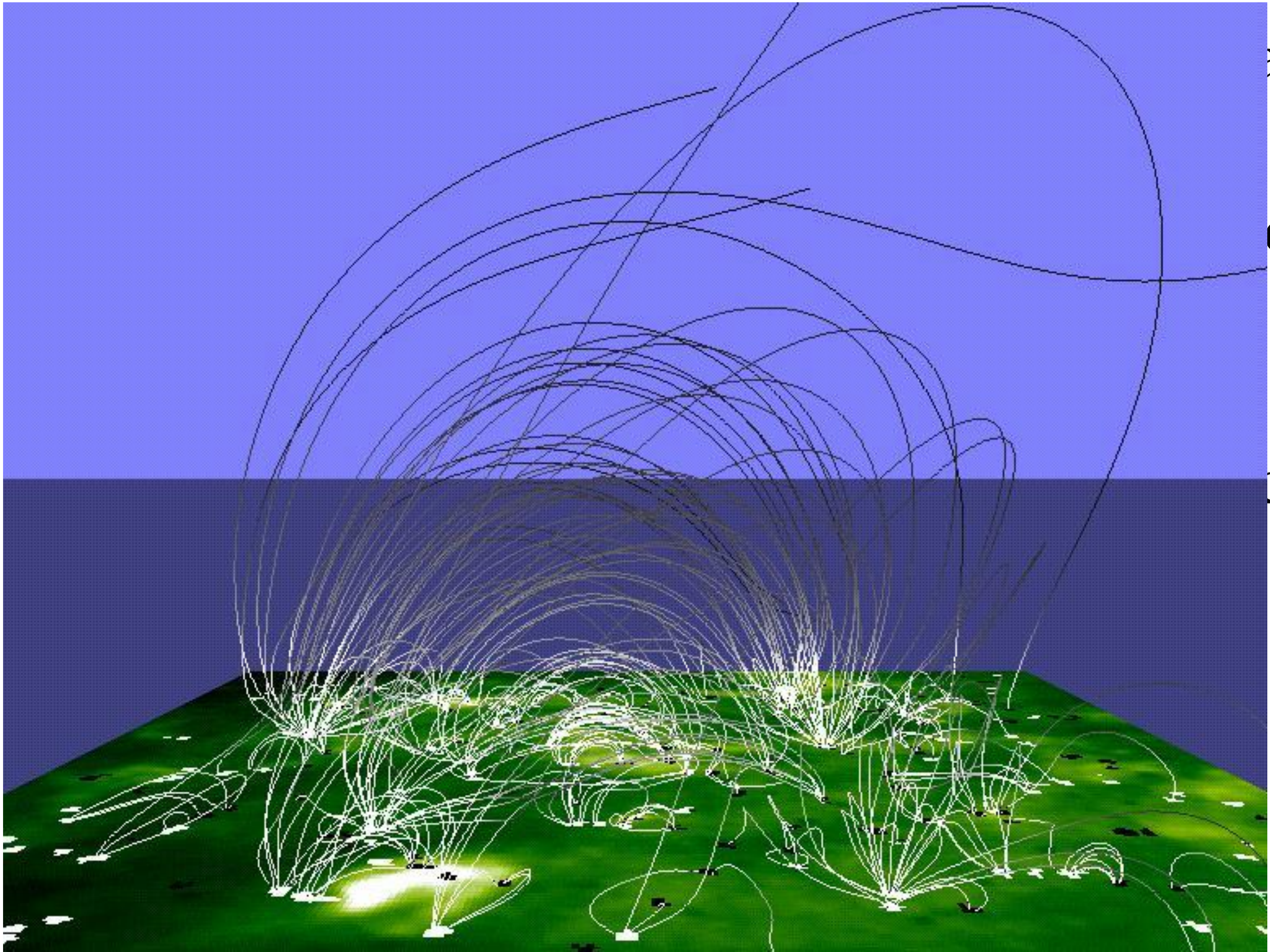
- Solar flares,







Solar Eruptions

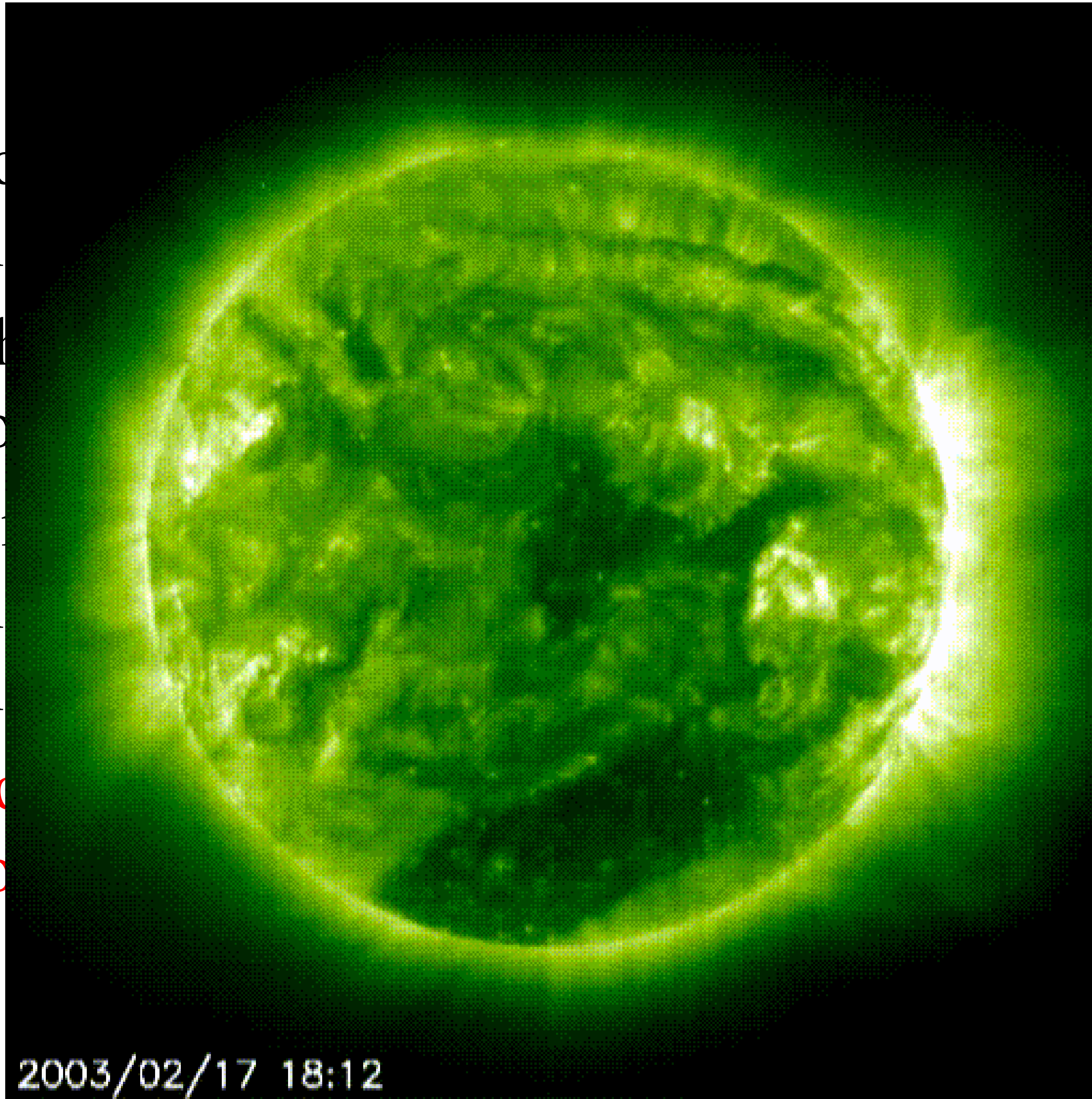


al

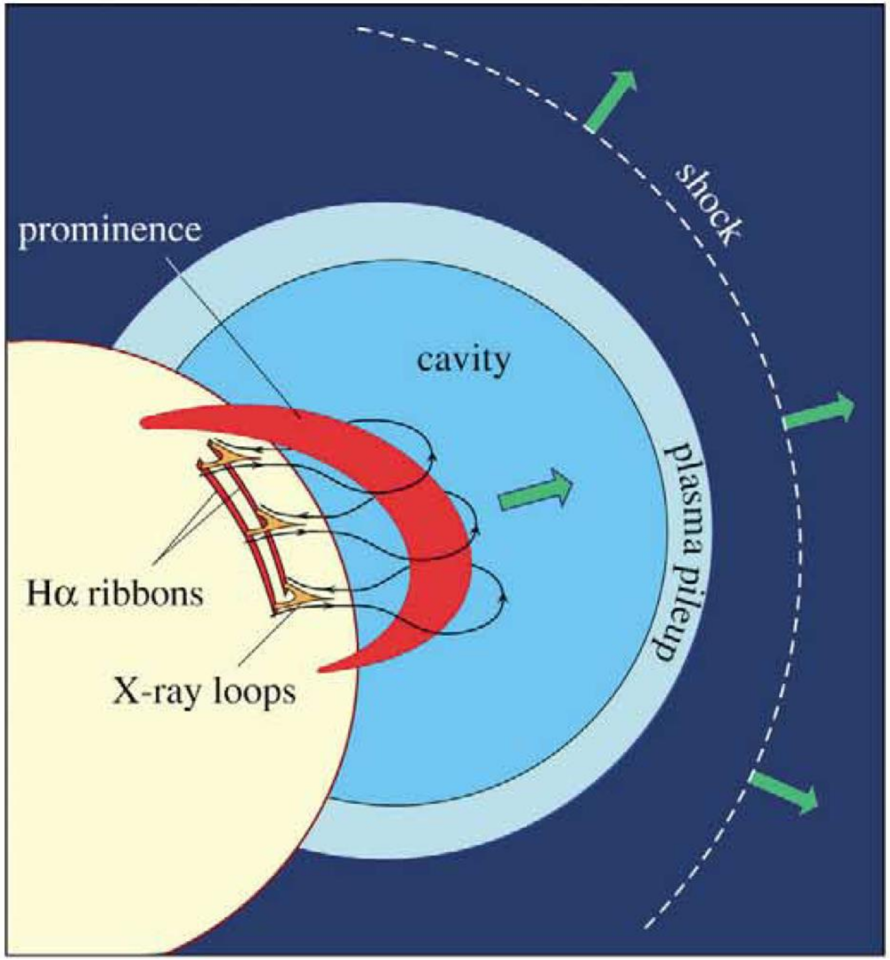
e

d

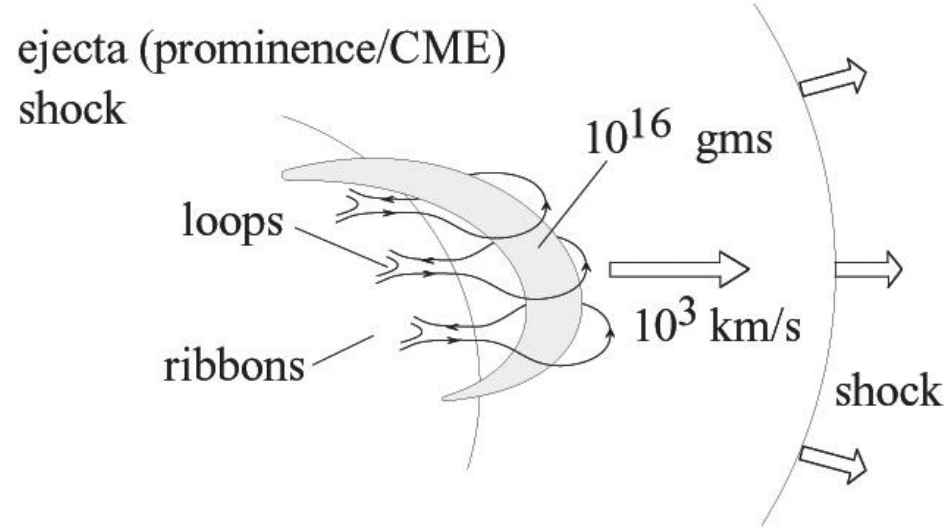
- Sc … oronal
  m
- Th … n the
  co
- H
  m … tored
  in
- Lo … tic
  co



Energy Involved in a Typical Eruption



kinetic energy of mass motions: $\approx 10^{32}$ ergs



heating / radiation: $\approx 10^{32}$ ergs

work done against gravity $\approx 10^{31}$ ergs

volume involved: $\gtrsim (10^5 \text{ km})^3$

energy density: $\lesssim 100$ ergs/cm^3

Magnetic field is the only source that can provide enough energy for eruption

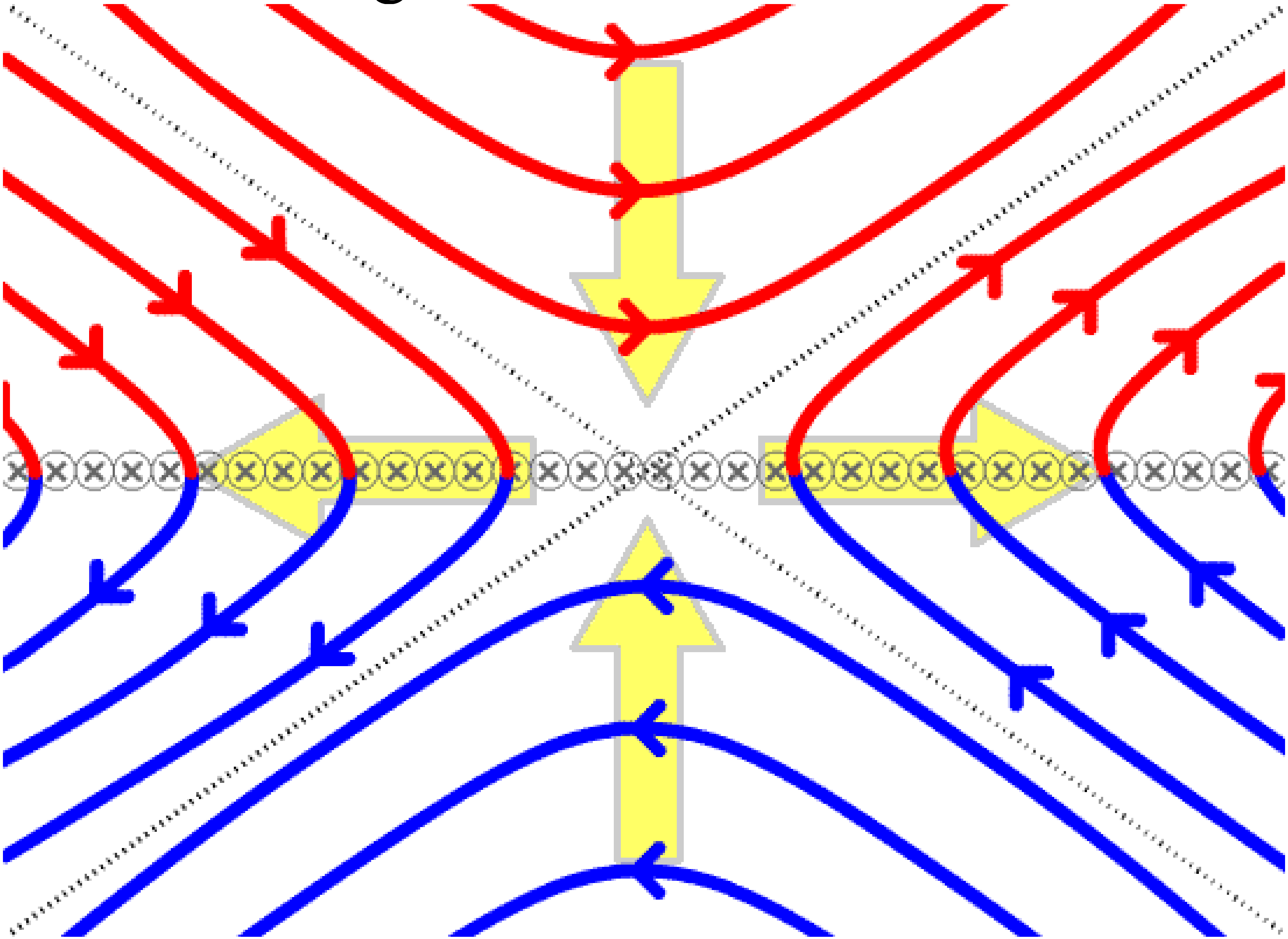
Solar Eruptions

- Solar flares, eruptive prominences, and coronal mass ejections;
- The energy driving the eruption is stored in the coronal magnetic field beforehand;
- Highly complex structures of the coronal magnetic field allows extra energy to be stored in the corona;
- Loss of equilibrium in the coronal magnetic configuration triggers the eruption;
- Magnetic reconnection allows the consequent evolution to continue.

Content

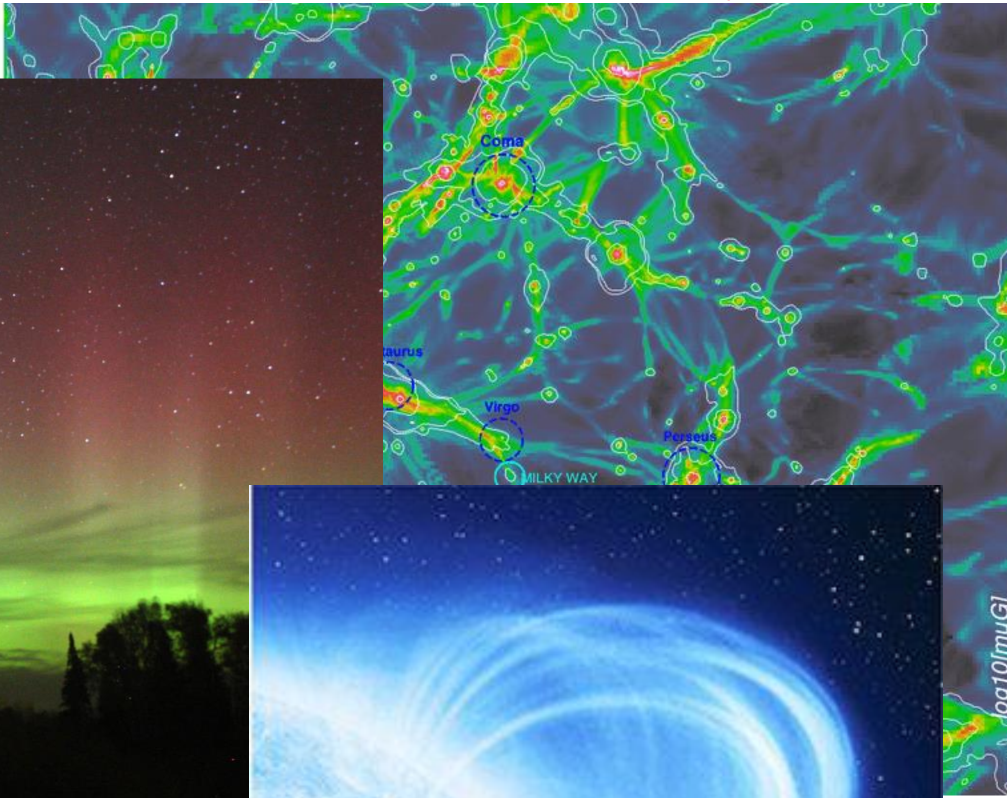
- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

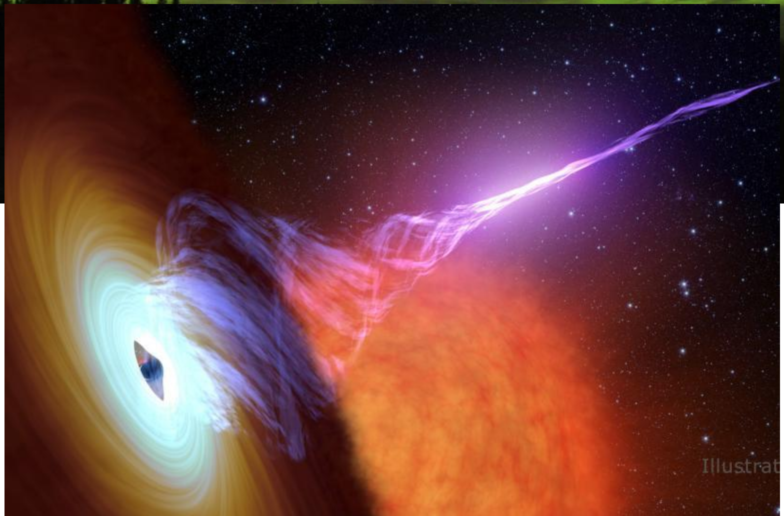
Magnetic Reconnection



Magnetic Reconnection

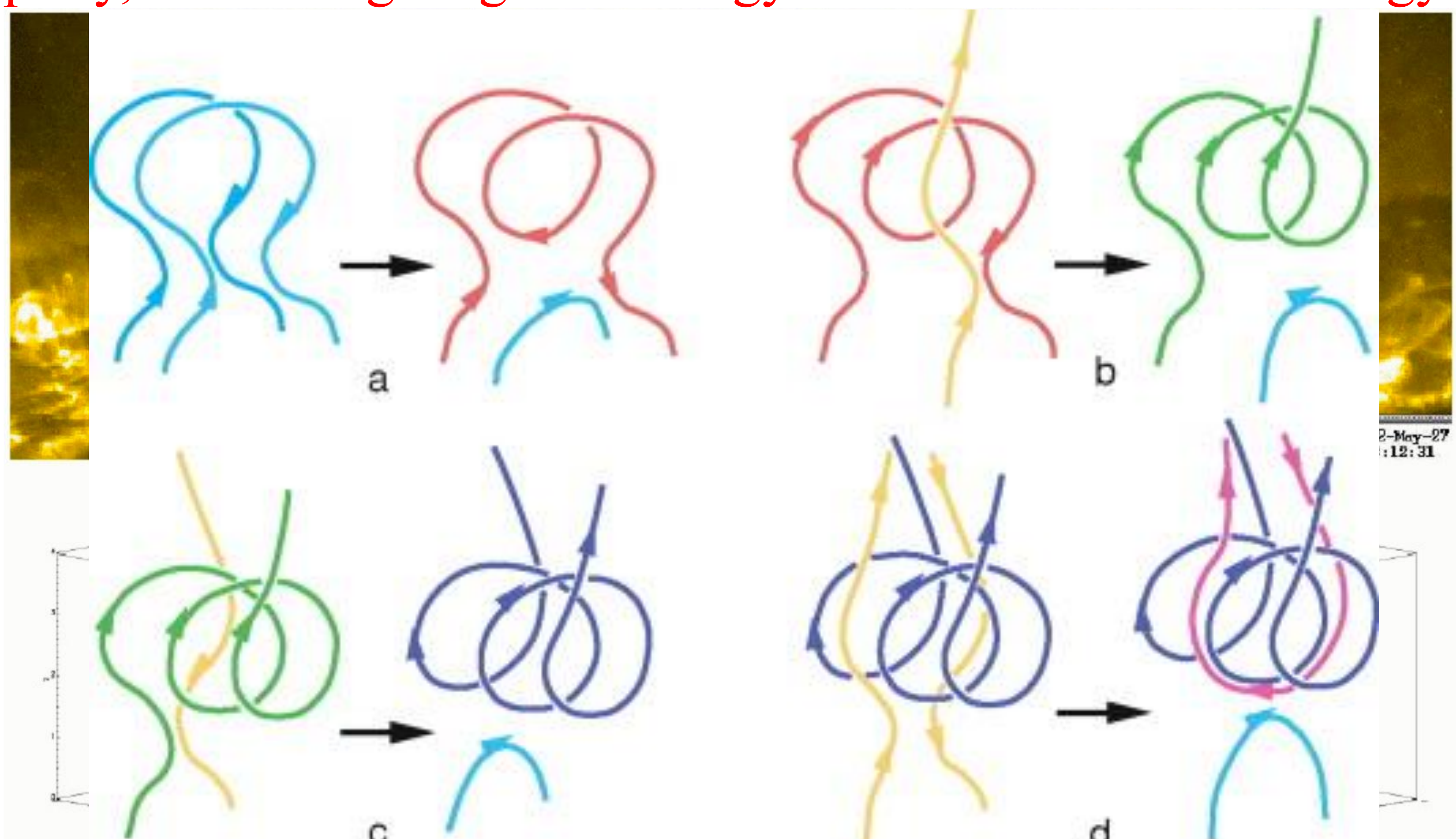
- Most of the universe is in the form of a plasma threaded by a magnetic field.



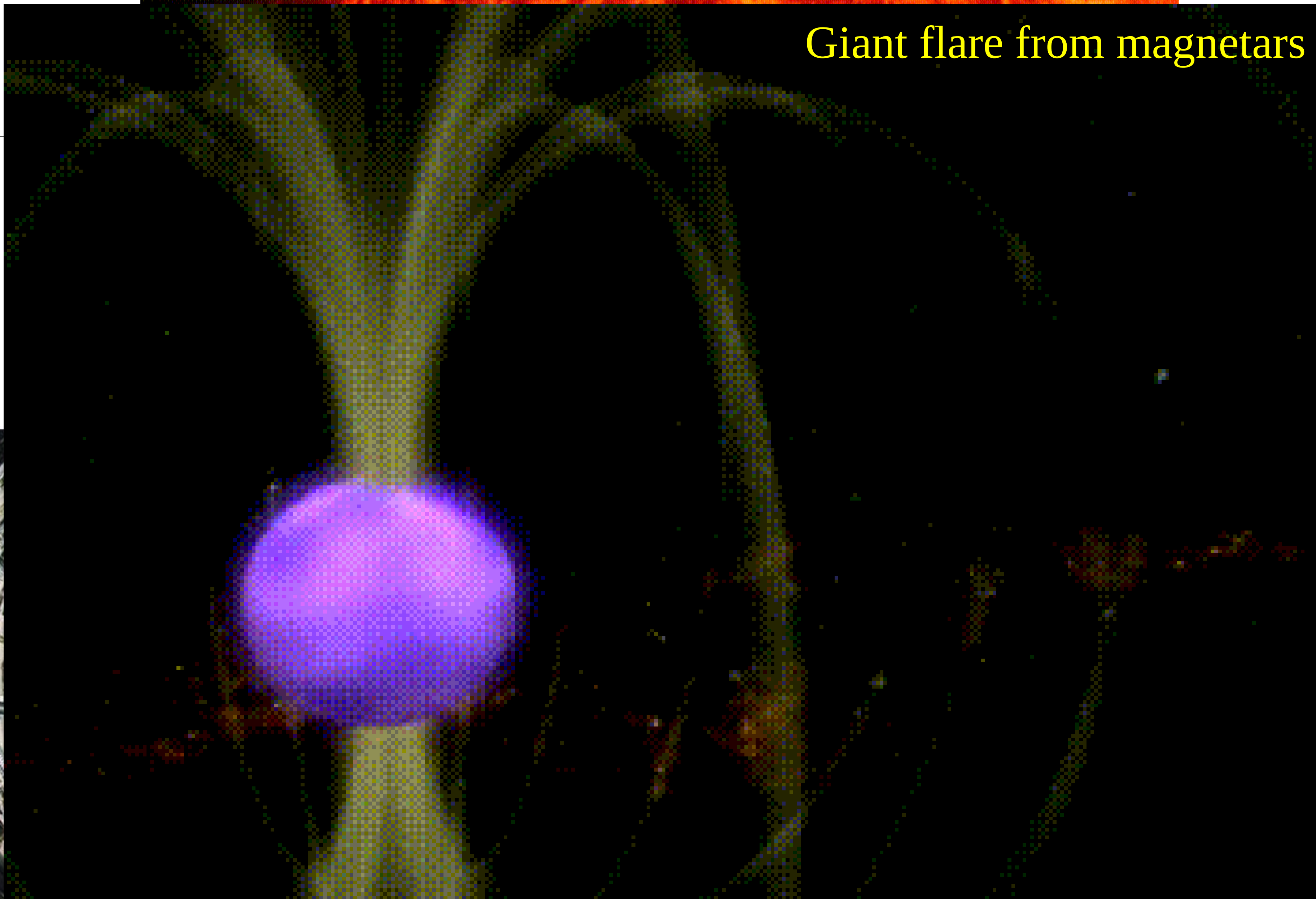


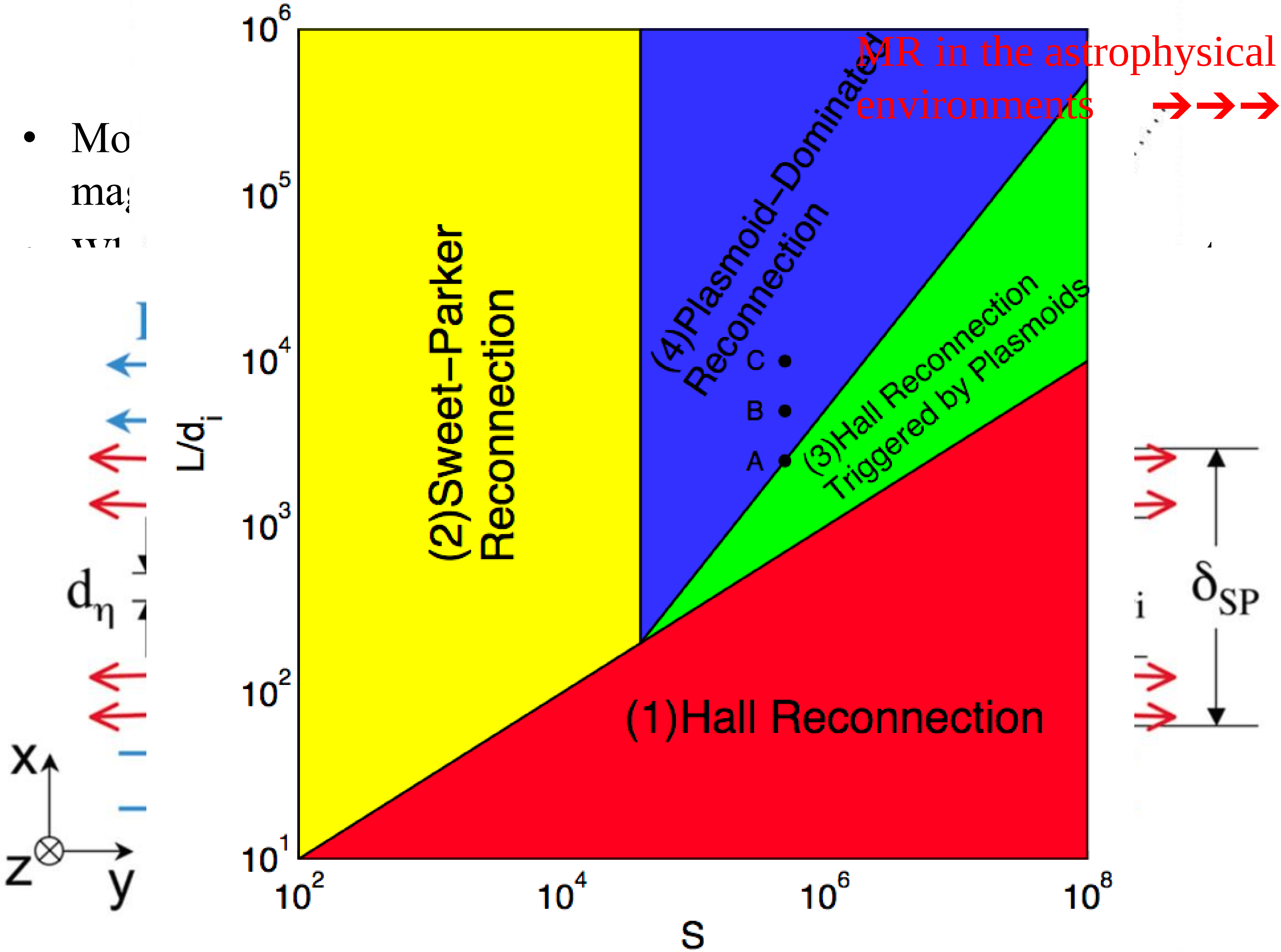
Magnetic Reconnection

- Most of the universe is in the form of a plasma threaded by a magnetic field.
- When twisted or sheared, the field lines may break and reconnect rapidly, converting magnetic energy into heat and kinetic energy.



Giant flare from magnetars





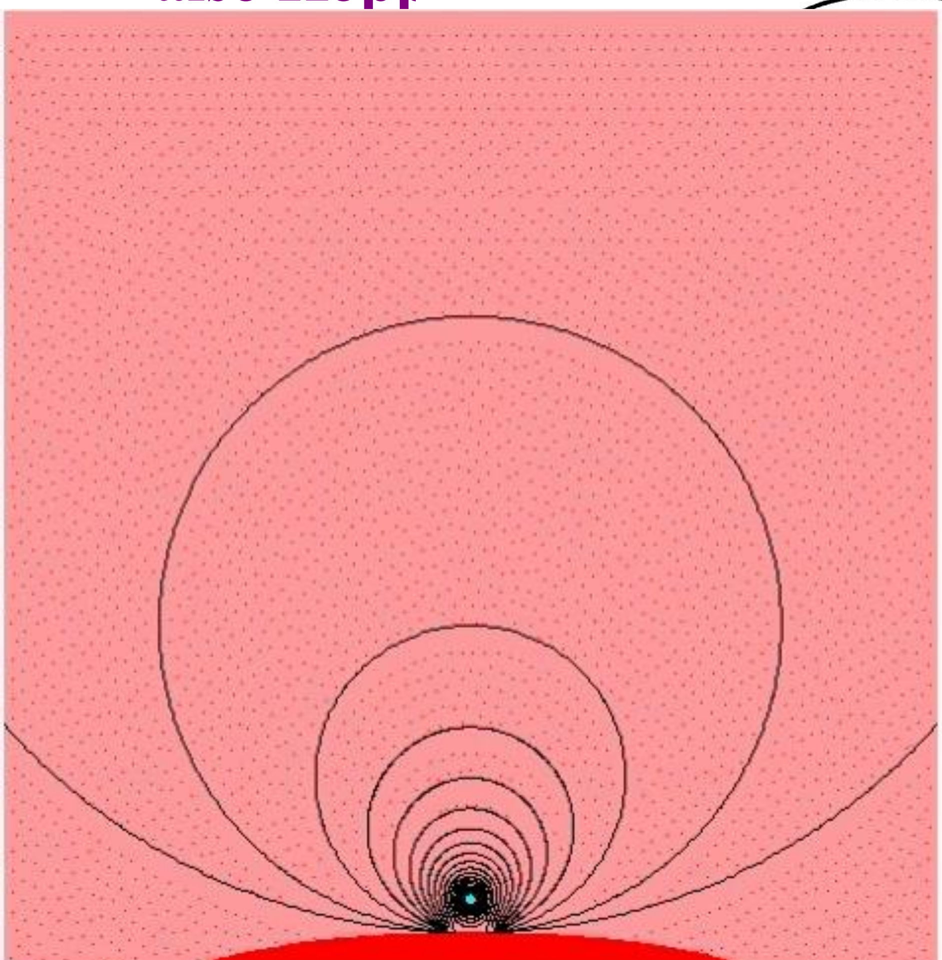
MR in the astrophysical environments
(1)Hall Reconnection
(2)Sweet–Parker Reconnection
(3)Hall Reconnection Triggered by Plasmoids
(4)Plasmoid–Dominated Reconnection
A
B
C
L/d_i
S
10^1
10^2
10^3
10^4
10^5
10^6
10^2
10^4
10^6
10^8
d_η
δ_SP
x
y
z
Mo
ma

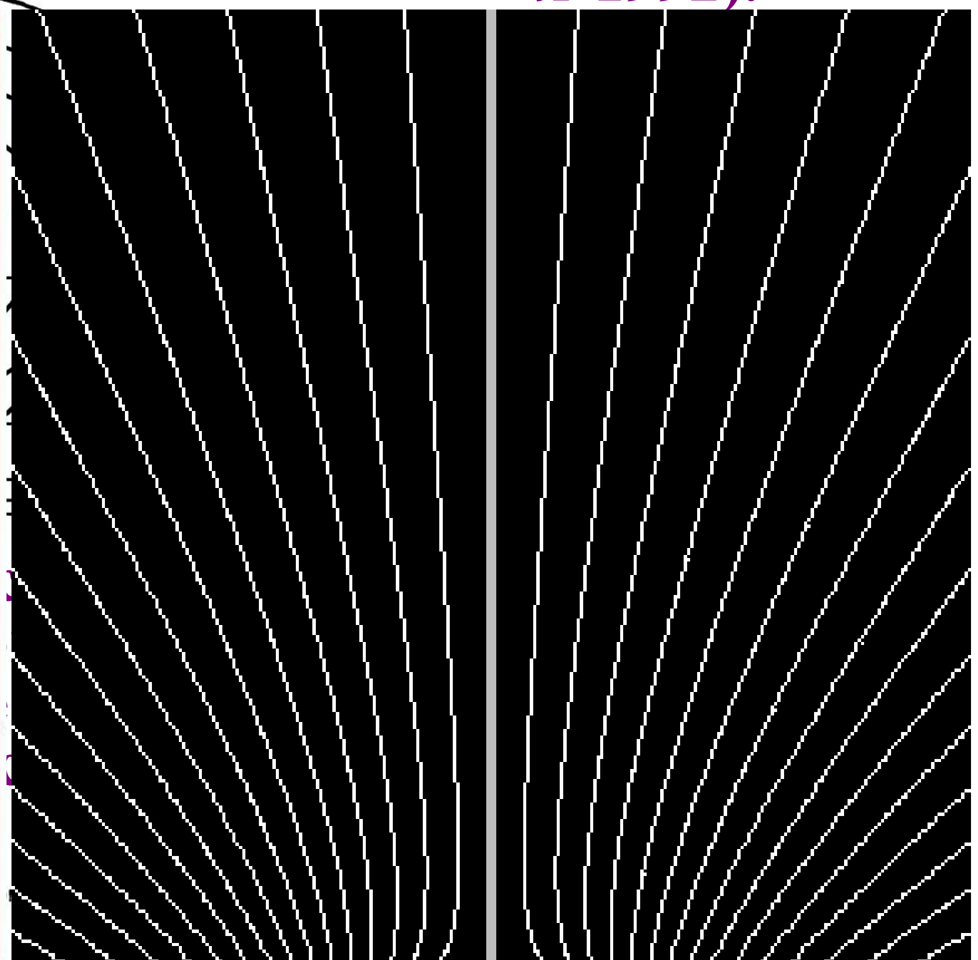
Content

- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

Theories/Models of CME/Flare Current Sheets

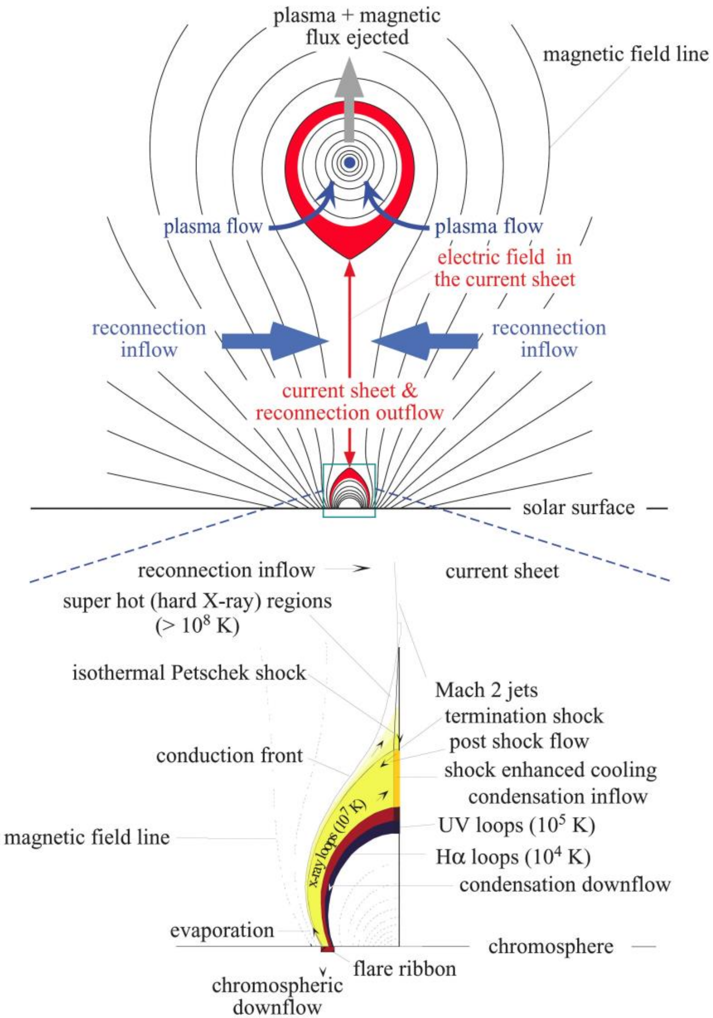
- **Since Carmichael (1964), it has been suggested that the two-ribbon flare took place as magnetic reconnection occurred in the currer … nodel, see also Kopp … er 1992).**

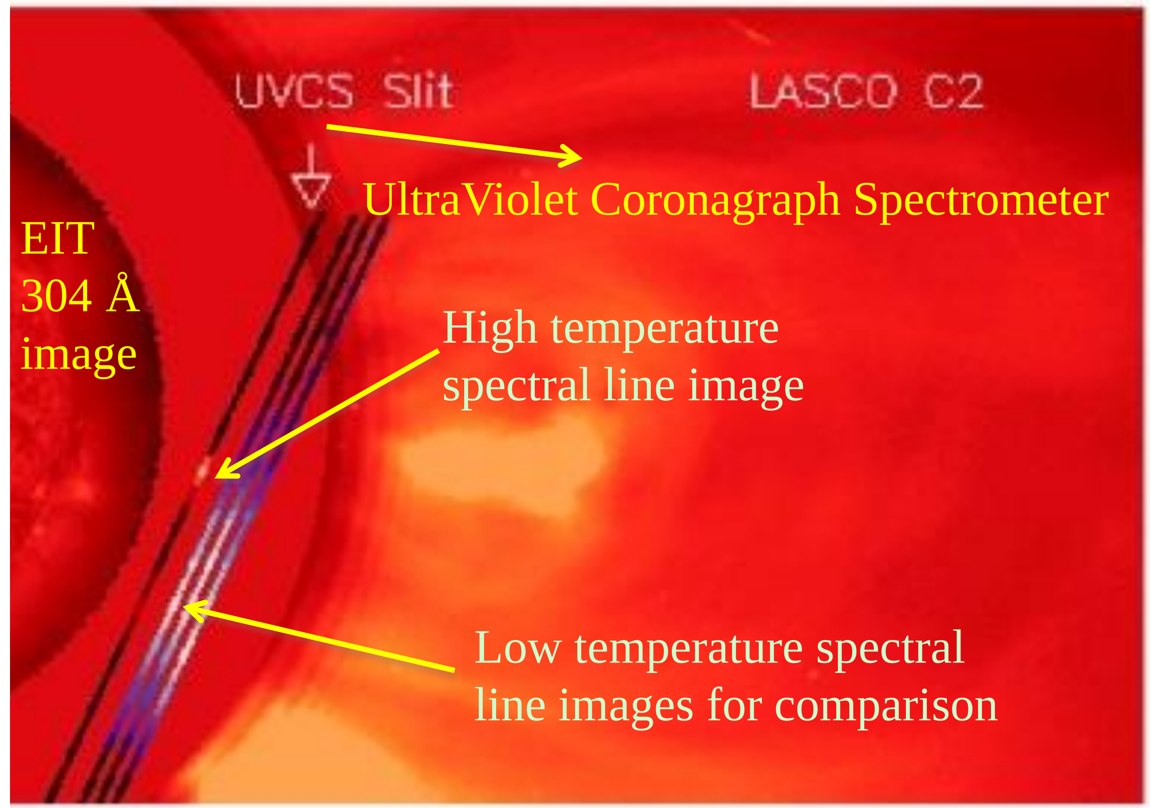




The First Observational Evidence of the CME/Flare CS

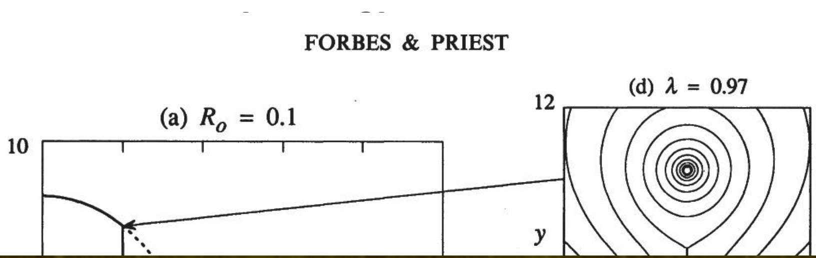
(Ciaravella *et al*. 2002;Webb *et al*. 2003)

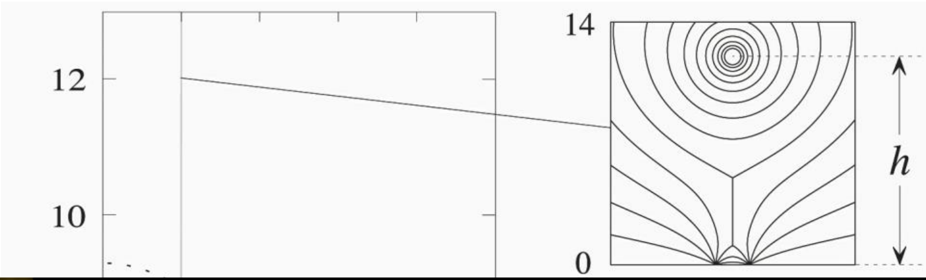


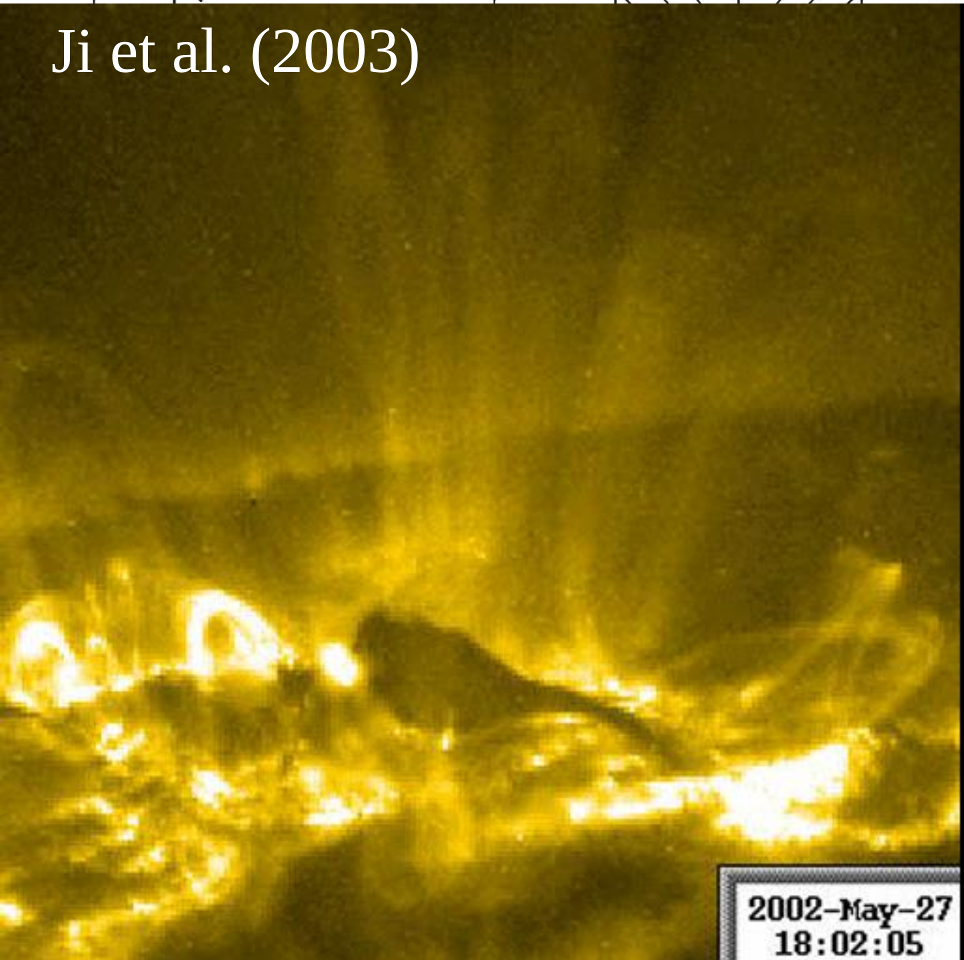


Composite image of EIT 304 Å (22:24 UT), LASCO C2 (12:33 UT), and line intensity distribution along the UVCS (16:56 UT) slit taken on 1998 March 23. The arrow indicates the true position of the UVCS entrance slit.

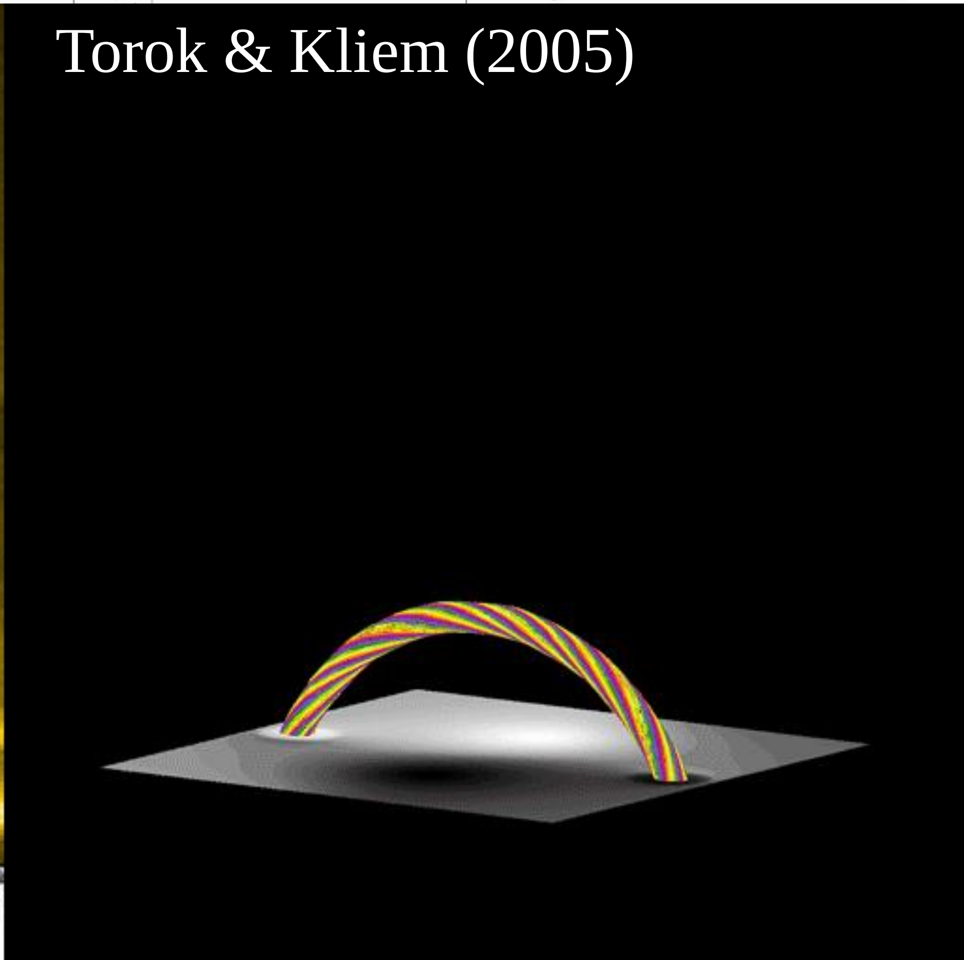
Role of Reconnection in Eruptions







Ji et al. (2003)

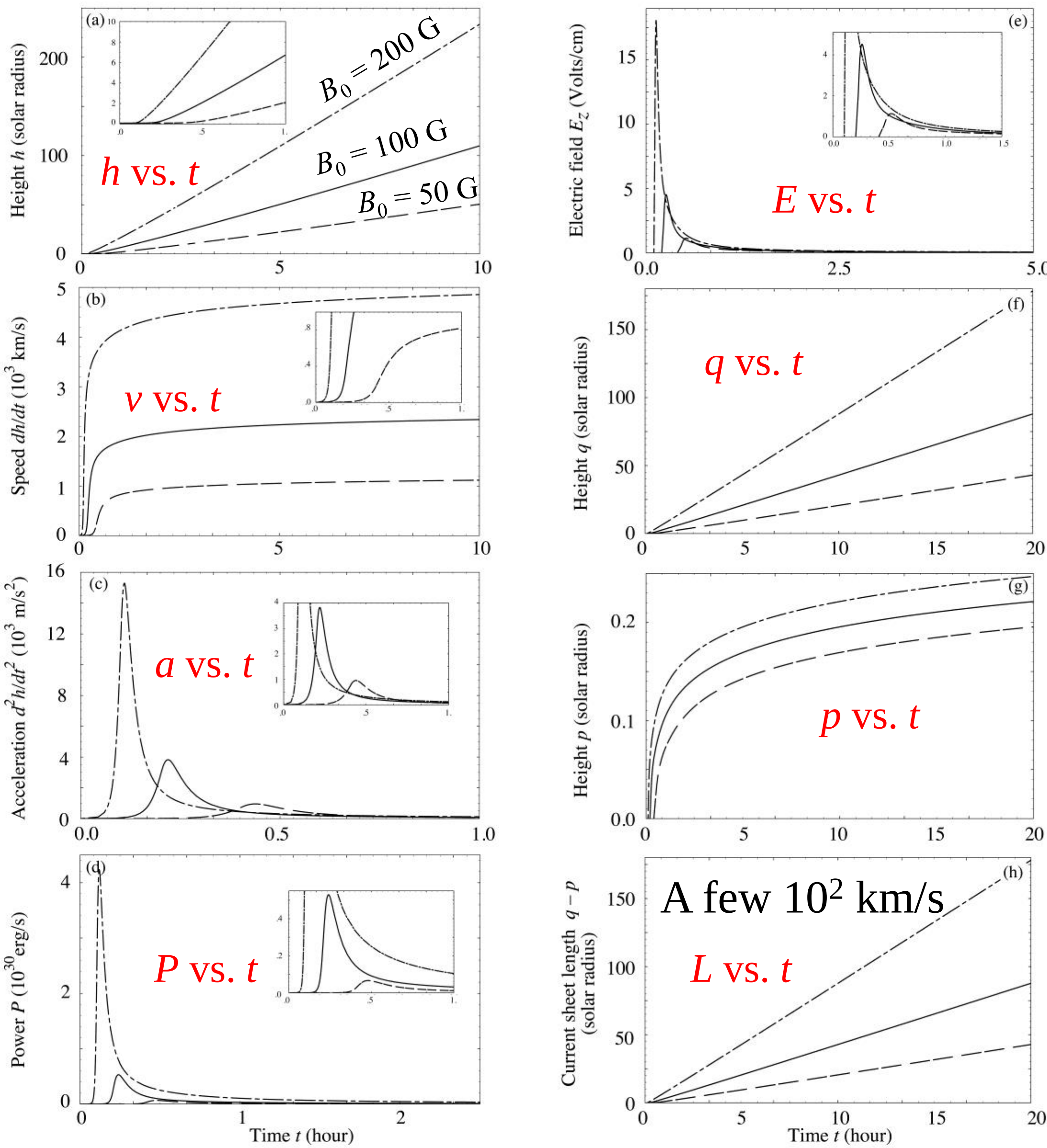


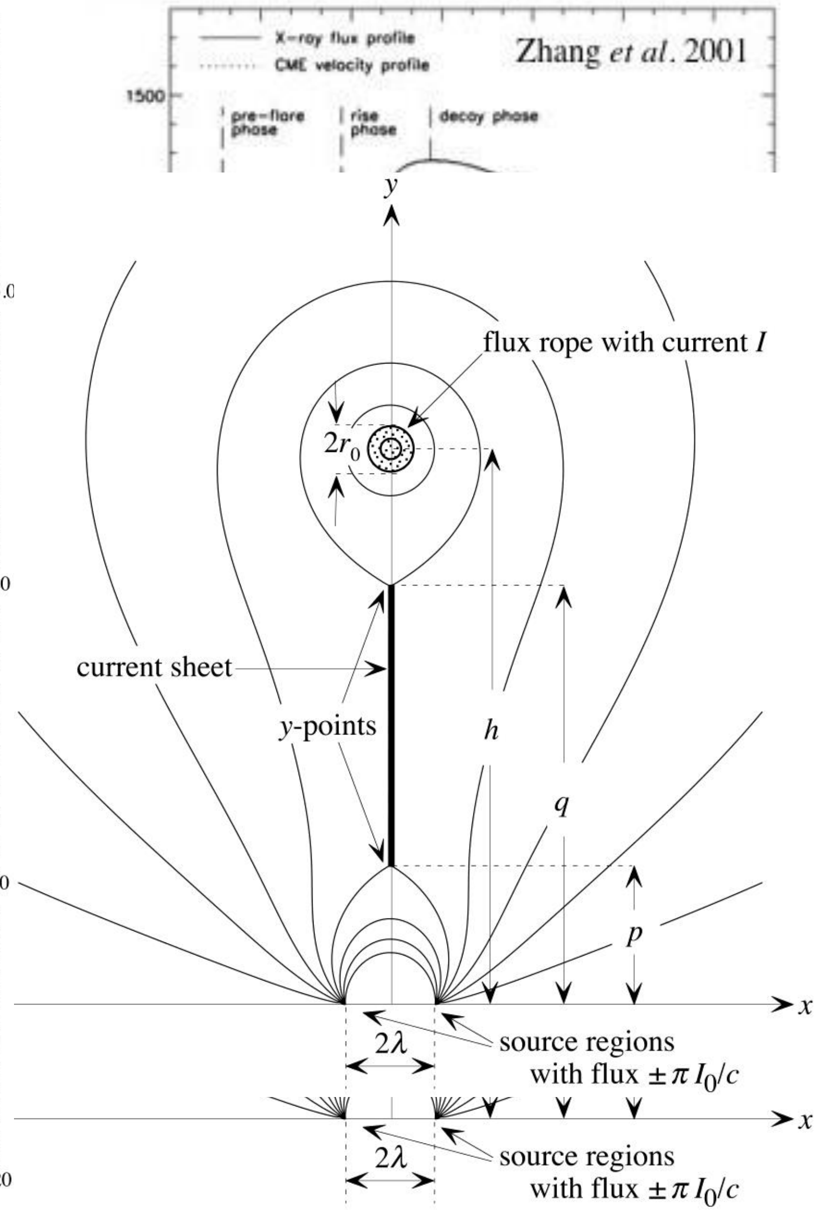
Torok & Kliem (2005)

Dynamical Properties of CMEs: Theory and Observations

$(M_A = 0.1)$

Lin (2002)



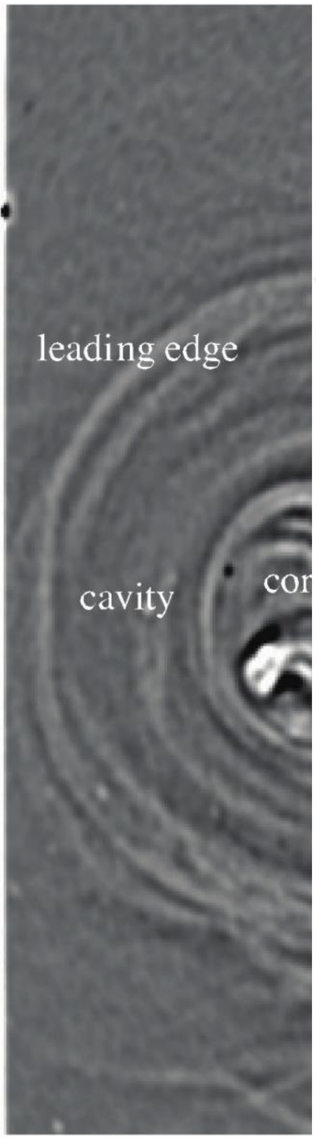


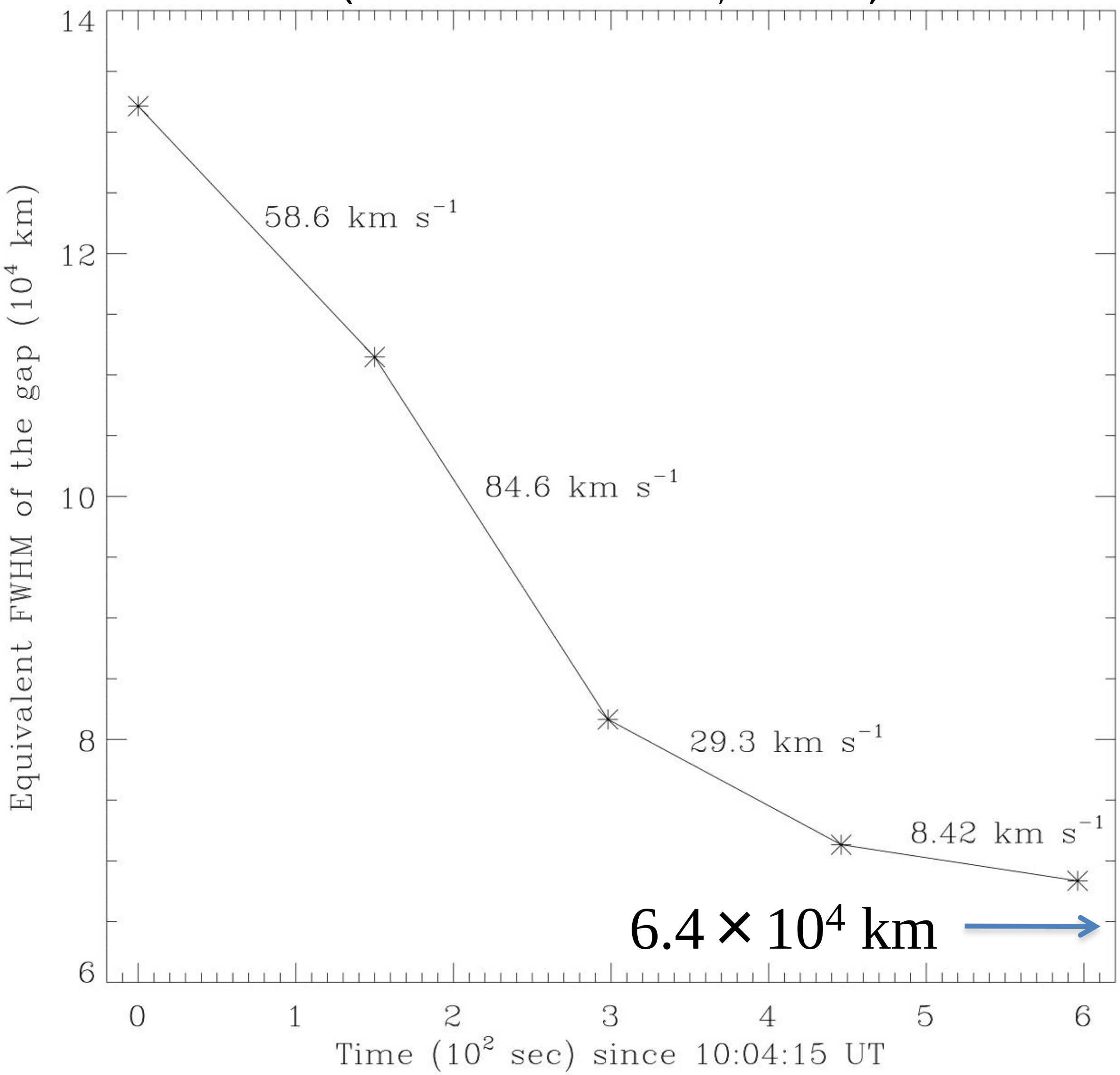
Content

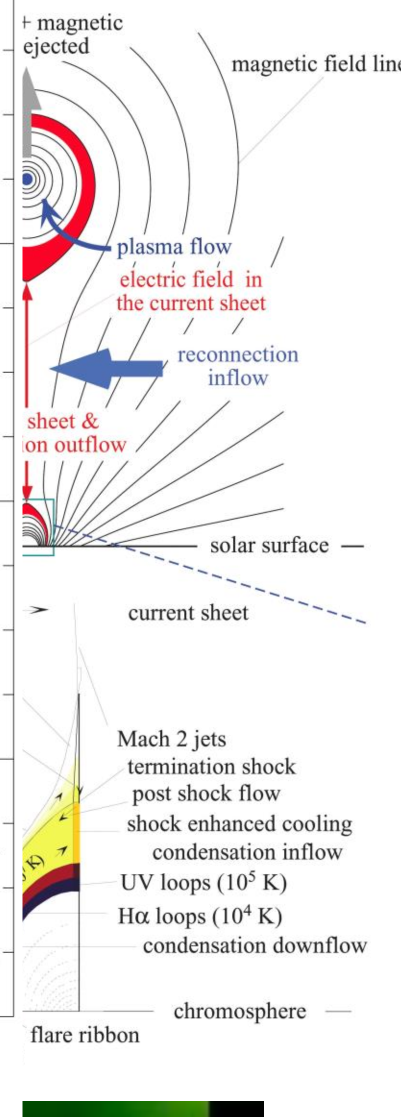
- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

The First Direct Measurement of the Reconnection Inflow Speed and the CS Thickness

(Lin et al. 2005, 2007)







Thickness of the CME/Flare Current Sheet Observed

- Results deduced from the UVCS data in Lyα:

1. 6.4×10^4 km (Lin *et al*. 2007).

- Results deduced from the UVCS data in [Fe XVIII]:

1. $4.0 \times 10^4 - 3.5 \times 10^5$ km (Ciaravella & Raymond 2008; Cairavella et al. 2013),
2. 10^5 km (Lin *et al*. 2009),
3. 2.1×10^5 km (Schettino *et al*. 2009).

- Results deduced from LASCO data:

1. 5.0×10^5 km (Lin *et al*. 2009),
2. 3.0×10^5 km (Vrsnak *et al*. 2009).

- Results deduced from Hinode/XRT data:

1. A few times 10^3 km (Savage *et al*. 2010),
2. 1.3×10^5 km (Landi *et al*. 2012).

Thickness of the CME/Flare Current Sheet Observed

- Results deduced MK4 MLSO (the only result deduced from the ground-based observations alone so far):

1. 3.7×10^4 km (Ling et al. 2014).

- Results deduced from STEREO and LASCO:

1. 2.38×10^5 — 3.50×10^5 km (Kwon et al. 2016).

- Results deduced from SDO/AIA:

1. 1.72×10^3 — 3.83×10^4 km (Seaton et al. 2017),
2. $\sim 3.3 \times 10^3$ km (Yan et al. 2018).

- Results deduced from SDO/AIA and HINODE/EIS:

1. 6.9×10^3 — 9.6×10^3 km from EMs, and 9.6×10^3 — 1.1×10^4 km from plasma non-thermal velocity distributions (Cheng et al. 2018; Li et al. 2018).

The CS thickness d ranges from a few 10^3 to a few 10^5 km.

Origin of the Problem

- Traditionally, it is believed that the thickness of the reconnection current sheet is governed by the proton gyroradius, r_g, which is tens of meters in the coronal environment, and even much smaller in the lab environment;

- Huge difference exists between the theoretical expectation and observational results!

10^2 m vs. 10^4 km!

Stable vs. unstable!

Content

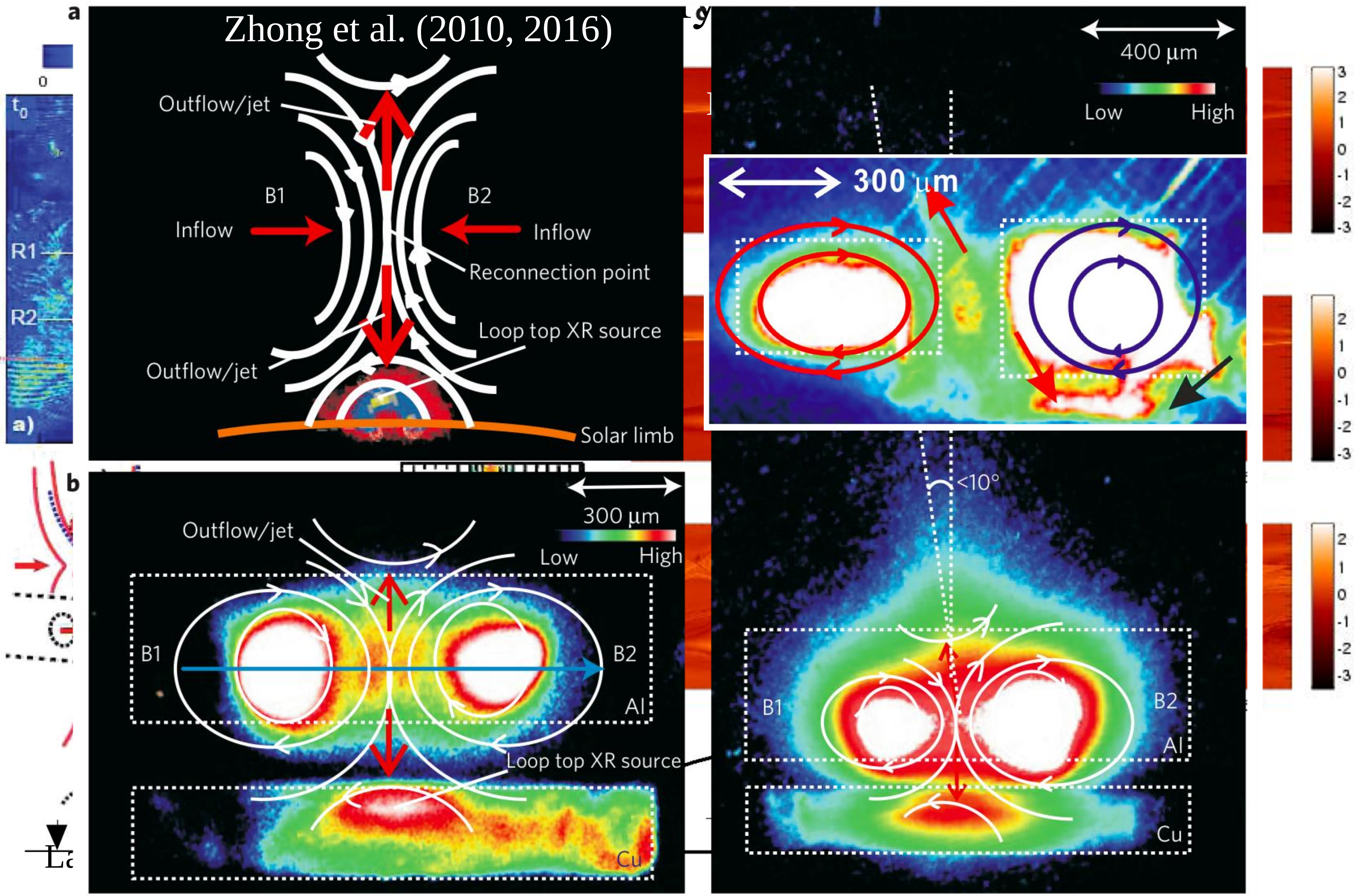
- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

Manifestations of Large-Scale Magnetic Reconnection Process

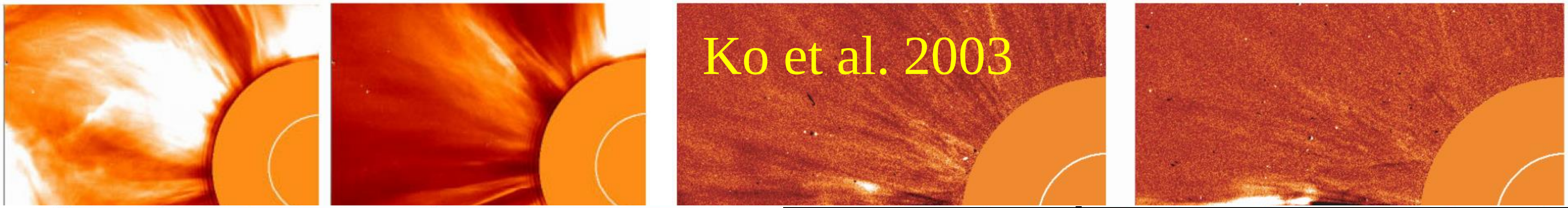
- Large-scale current sheet is unstable to several plasma instabilities, especially the tearing mode instability;

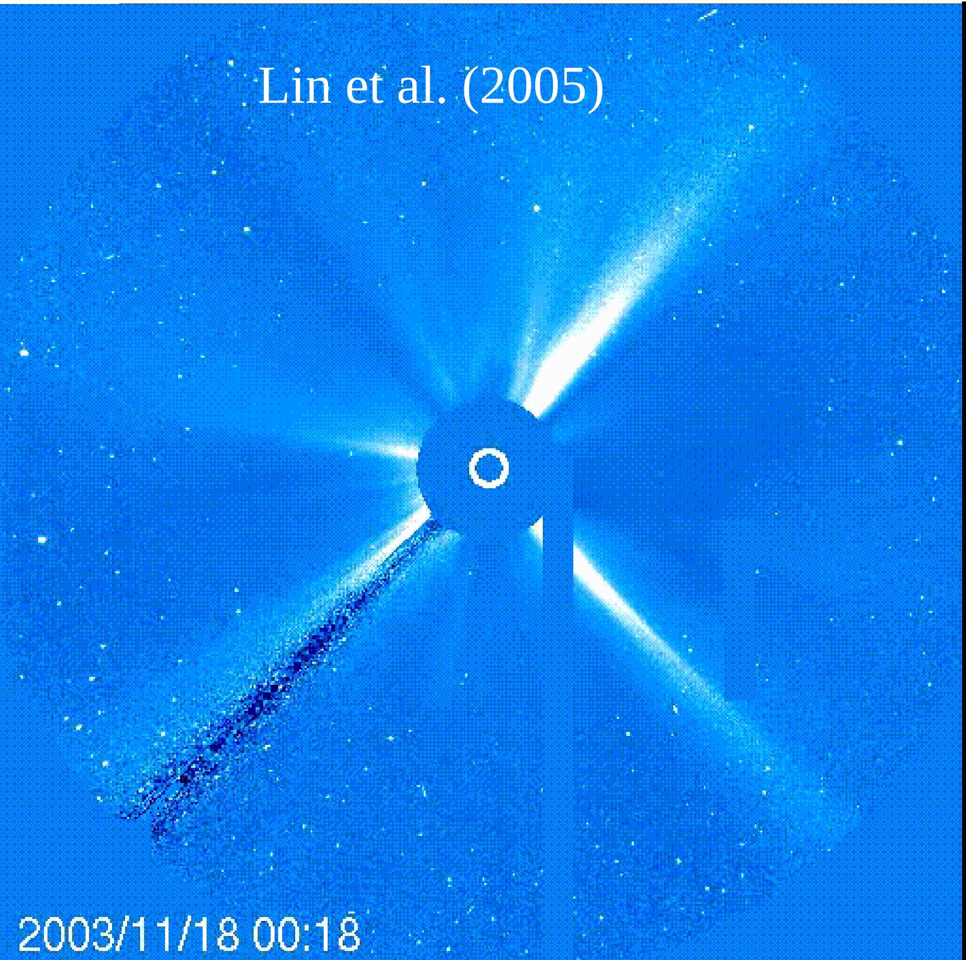
- Many structures of various scales and the associated processes are allowed to occur simultaneously in a large-scale current sheet.

What Causes Fast Reconnection in a Thick Current Sheet?

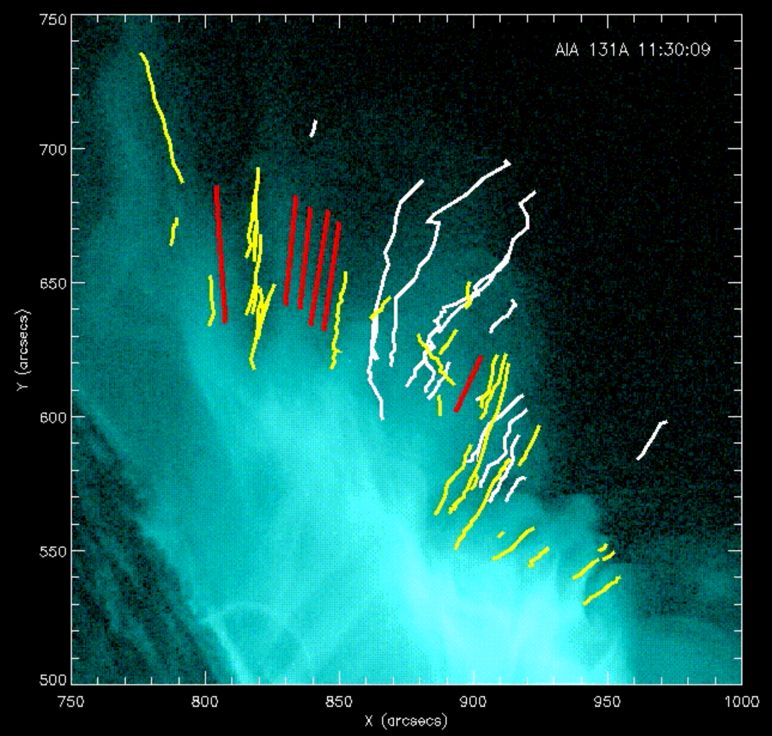


Plasmoids Observed to Flow inside CS in Eruptions





Reeves et al. (2017)

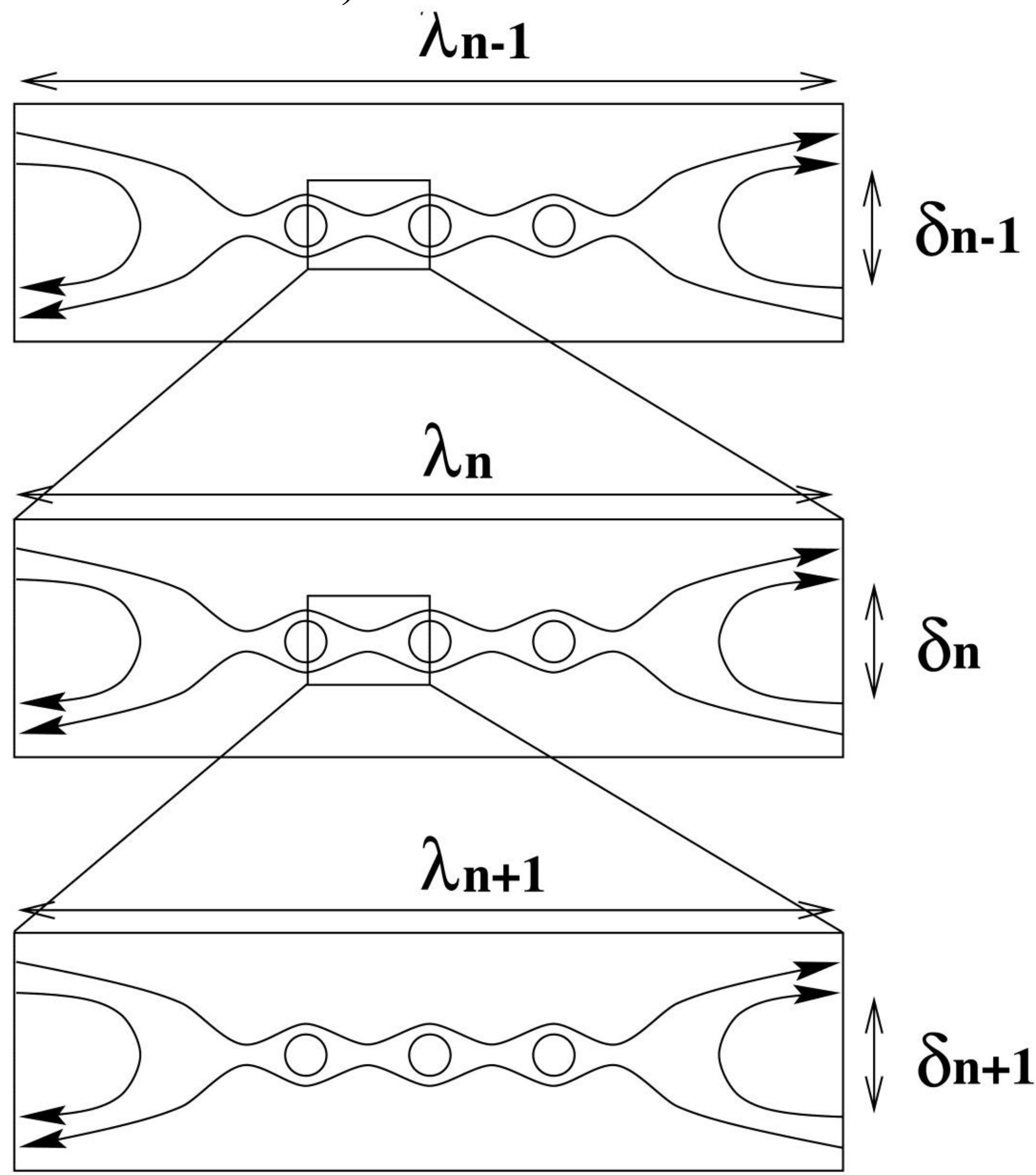


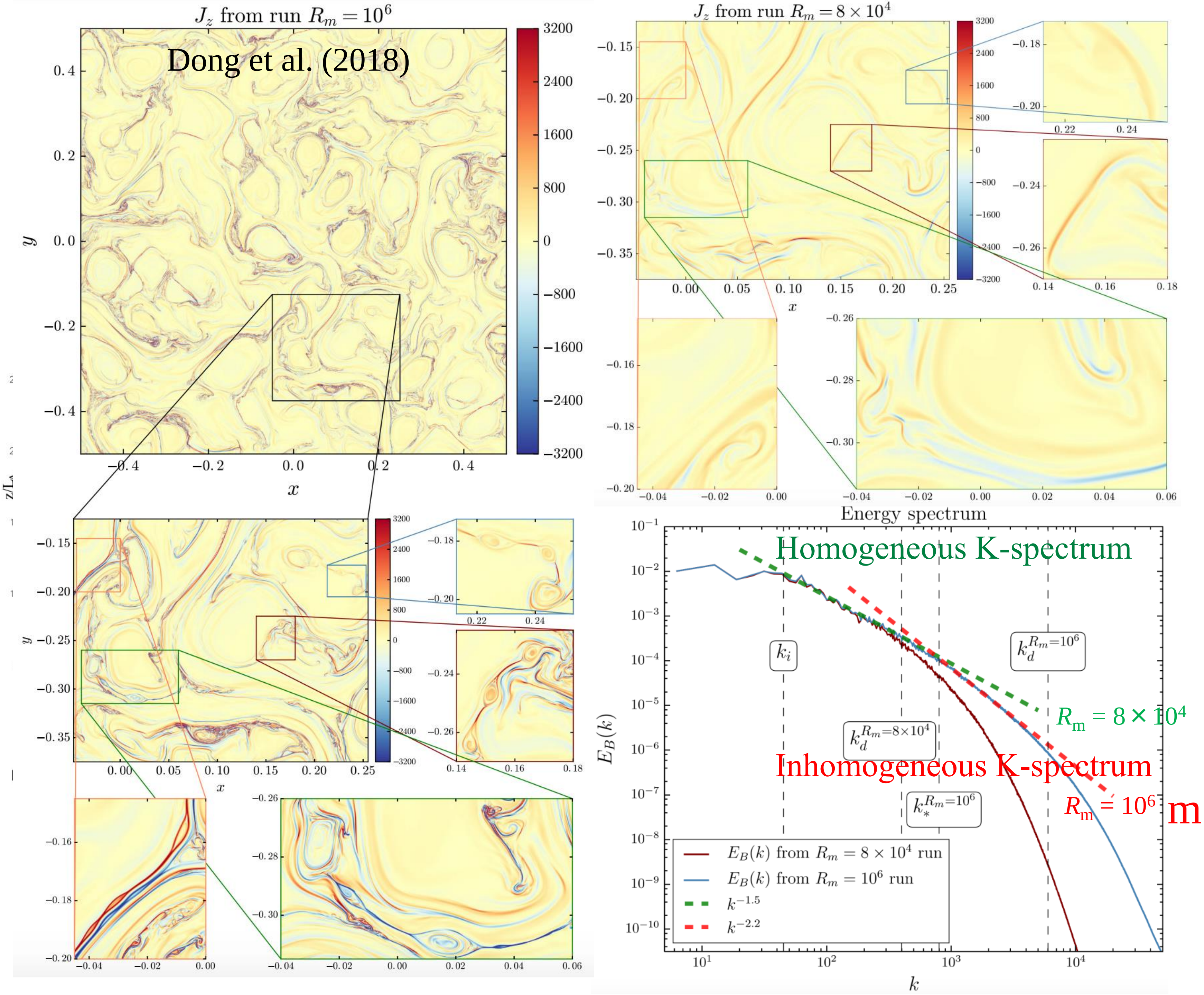
Fractal Reconnection Process

(Shibata & Tanuma 2001)

- Resistivity invokes tearing mode, kinetic processes, and the current sheet then shows the fractal features;
- The time, t_0, of the formation of the first magnetic island is governed by the initial property of the CS:

$$t_0 = (\delta/L)^{1/2} R_m^{1/2} \delta/v_A$$

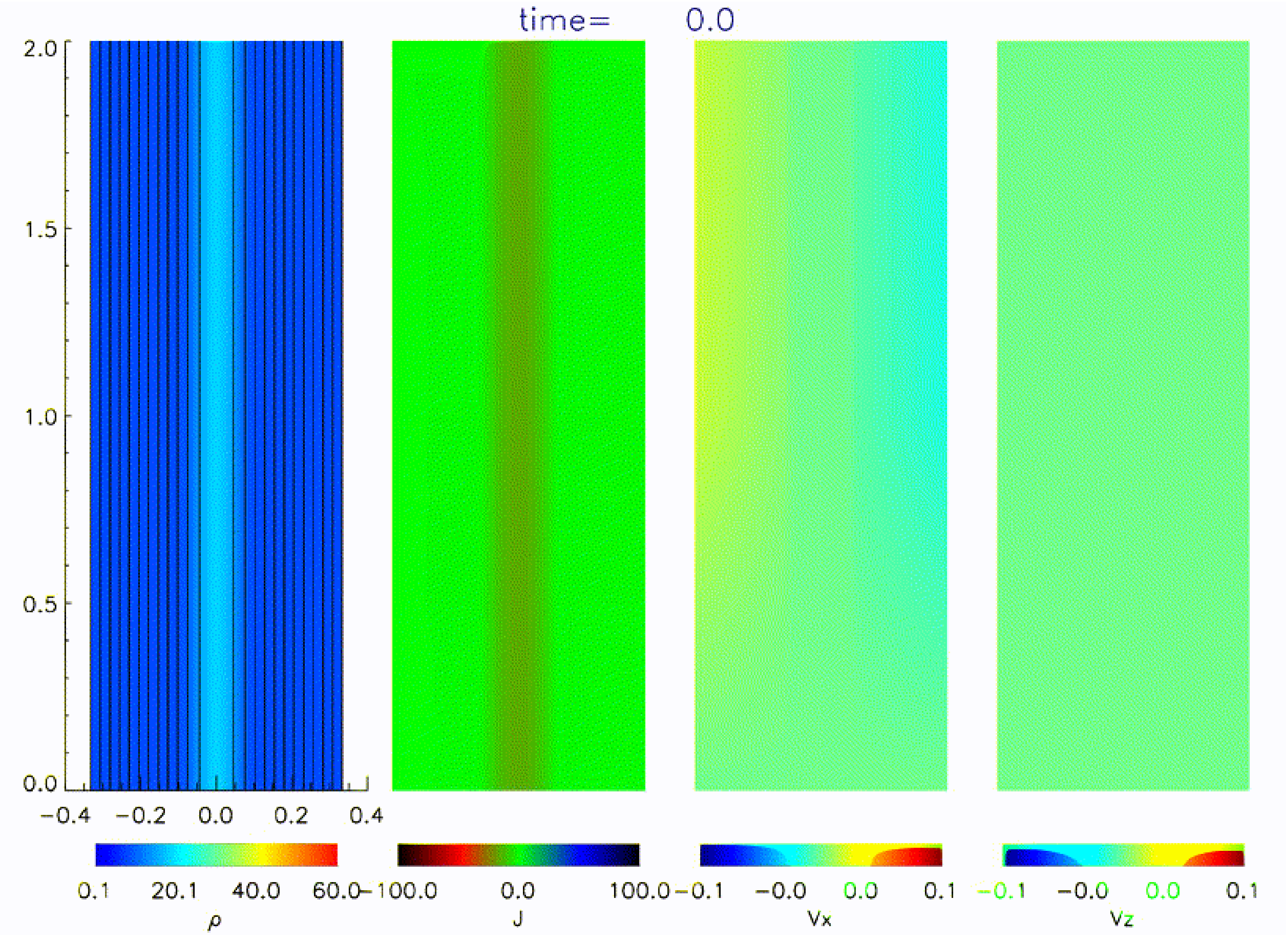




J_z from run $R_m = 10^6$
Dong et al. (2018)
J_z from run $R_m = 8 \times 10^4$
Energy spectrum
Homogeneous K-spectrum
Inhomogeneous K-spectrum
$R_m = 8 \times 10^4$
$R_m = 10^6$
m
k_i
$k_d^{R_m=10^6}$
$k_d^{R_m=8\times10^4}$
$k_*^{R_m=10^6}$
$E_B(k)$ from $R_m = 8 \times 10^4$ run
$E_B(k)$ from $R_m = 10^6$ run
$k^{-1.5}$
$k^{-2.2}$
$E_B(k)$
k
x
y

Fast Reconnection Begins with Turbulence

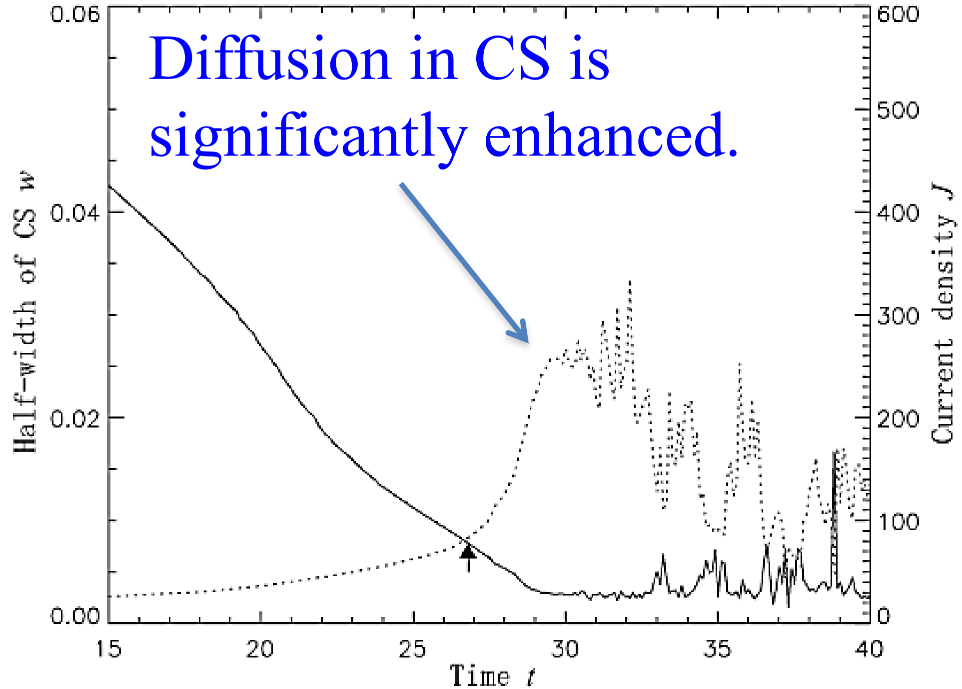
(Shen et al. 2011)



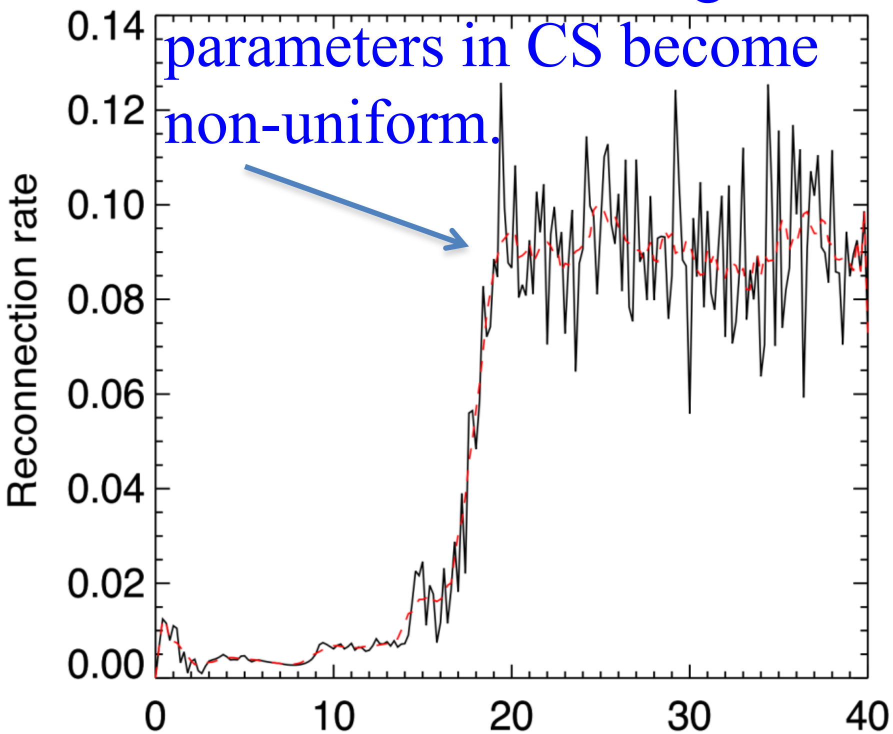
- **Current density and Half-width of Current sheet**

The half-width w (solid line) near the PX-point, decrease to about 7.5×10^{-3} at time t=26.8τ_A when the first island appearing.

Then w gradually decreases to the minimum value 2.5×10^{-3} and it subsequently fluctuates around this minimum value.



Fast reconnection begins as parameters in CS become non-uniform.

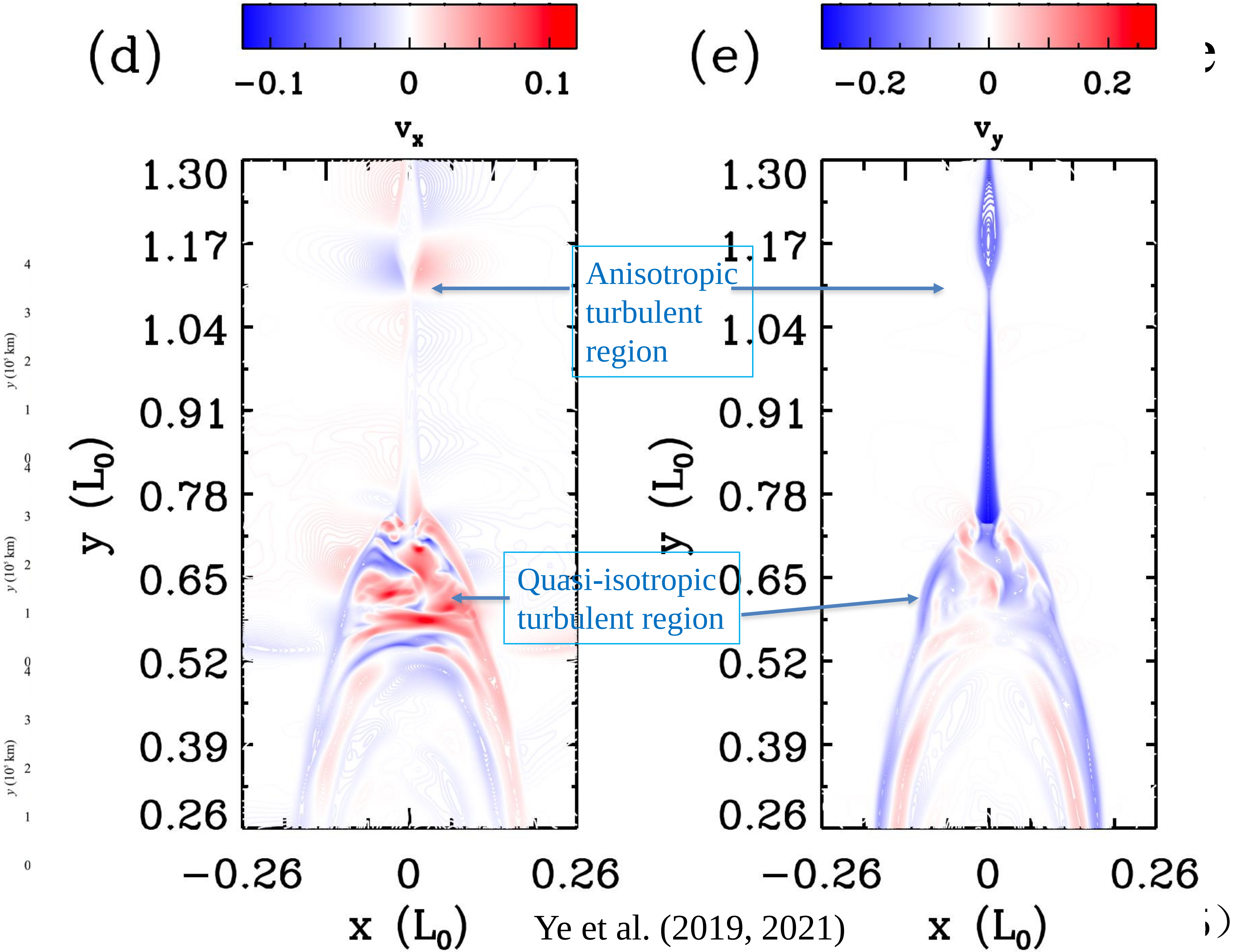


- **The Rate of magnetic reconnection M_A.**

$$M_A = \frac{v_i}{v_A}$$

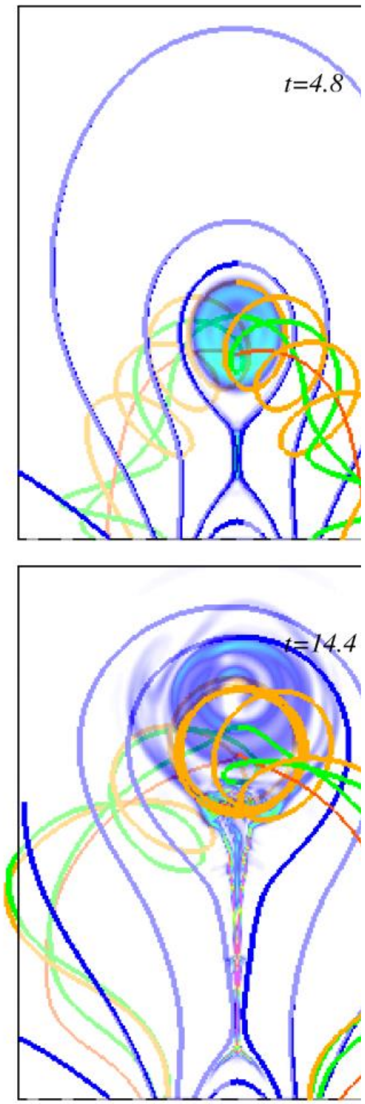
The solid line shows the instant value and the dotted line is for the corresponding average value. The arrow indicates time t = 26.8 τ_A when the first magnetic island forms

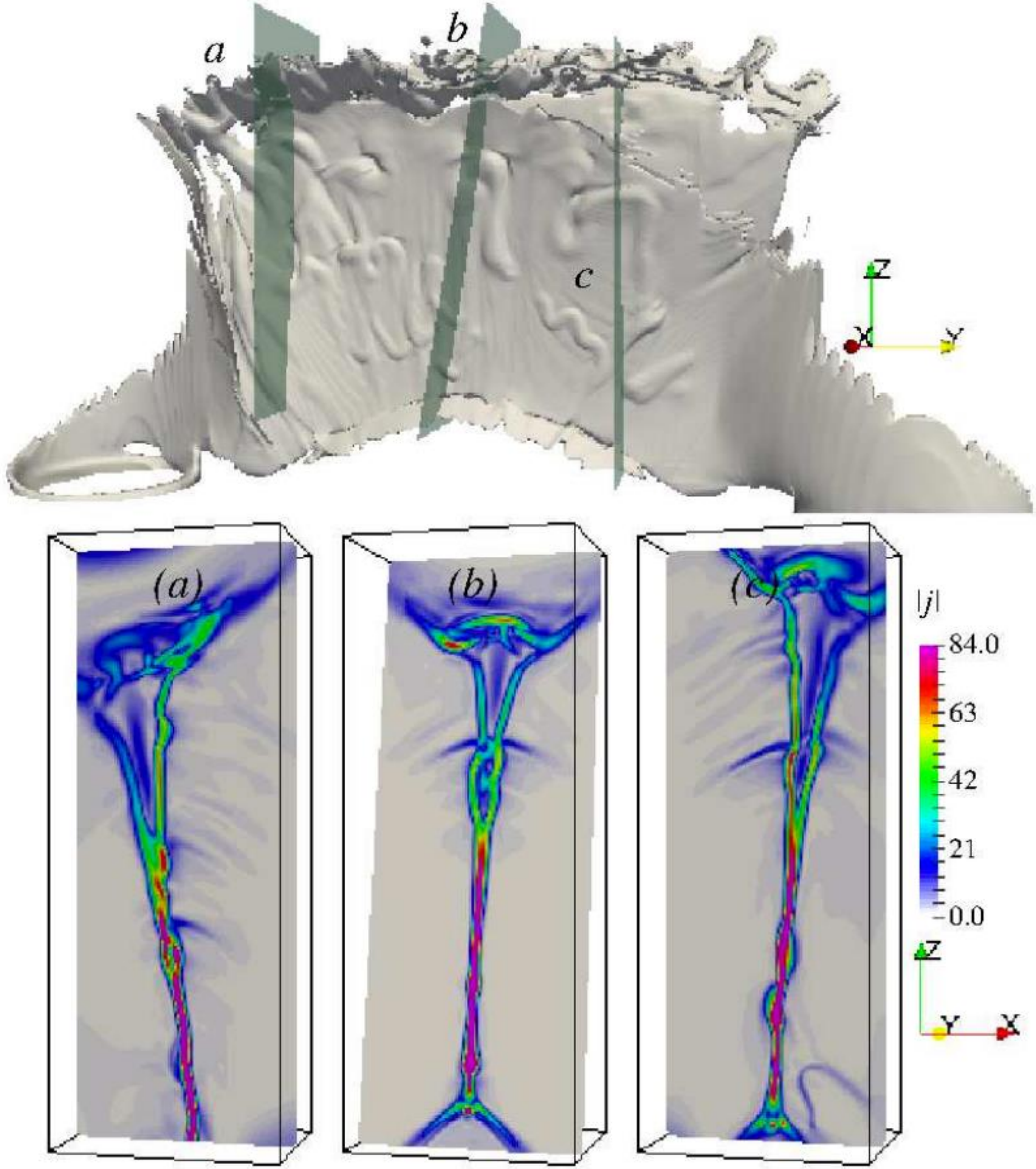
Shen et al. (2011), Ye et al. (2020)



Ye et al. (2019, 2021)

Multipl ures





Content

- Brief discussions of solar eruptions
- Magnetic reconnection
- Catastrophe model and observational results
- Large-scale CME/flare current sheet
- Turbulence and Small scale structures in the current sheet
- Summary

Summary

- The solar eruption results from the conversion of magnetic energy into heating, bulk motion of the flaring plasma, and energetic particles;
- Magnetic reconnection occurs in a long and thick, as well as highly dynamic CS connecting CME to flare;
- A long CS is unstable to various plasma instabilities, turbulence is the direct consequence;
- A CME/flare CS is an assembly of many structures of various scales and the associated diffusive processes, reconnection could occur fast in a thick CS;
- Large-scale CS only appears in the astrophysical environment, lots of new physics might be included;
- Large-scale and turbulent reconnection is a new and open question.

Summary

- The solar eruption results from the conversion of magnetic energy into heating, bulk motion of the flaring plasma, and energetic particles;
- Magnetic reconnection occurs in a long and thick, as well as highly dynamic CS connecting CME to flare;
- A long CS is unstable to various plasma instabilities, turbulence is the direct consequence;
- A CME/flare CS is an assembly of many structures of various scales and the associated diffusive processes, reconnection could occur fast in a thick CS;
- Large-scale CS only appears in the astrophysical environment, lots of new physics might be included;
- Large-scale and turbulent reconnection is a new and open question.

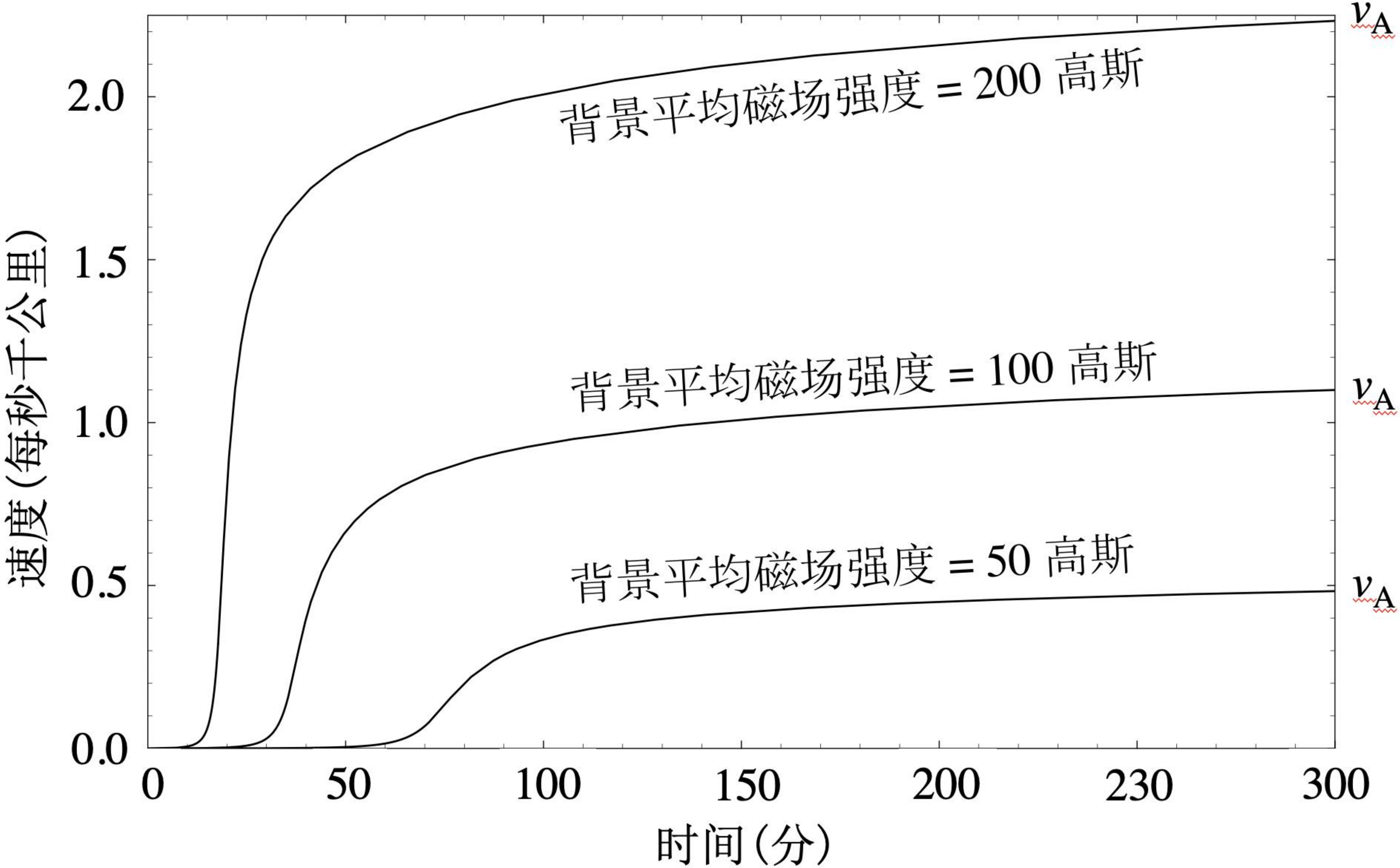
- Thanks very much for your attention!

Key Points

- Difference is huge between the solar eruption and its counterpart in laboratory on the Earth:
- Length scale: $10^5 \sim 10^6$ km vs. tens of meters
- Plasma density: $10^8 \sim 10^{10}$ cm^{-3} vs. $10^{19} \sim 10^{20}$ cm^{-3}
- Period of process: several hours vs. tens of minutes
- Total energy involved: $10^{30} \sim 10^{32}$ ergs vs. $\sim 10^{10}$ ergs
- Boundary conditions: line-tied + open vs. others

- Scaling law may help relate two to one another on some specific aspects, help understand some, but not all, physics behind solar eruptions through looking into the results from experiments in lab;
- Changes in scale may somehow cause changes in physics as well;
- Size does matter.

Key Points



速度(每秒千公里)
时间(分)
背景平均磁场强度 = 200 高斯
背景平均磁场强度 = 100 高斯
背景平均磁场强度 = 50 高斯
v_A
v_A
v_A
2.0
1.5
1.0
0.5
0.0
0
50
100
150
200
230
300