Solar Magnetohydrodynamics

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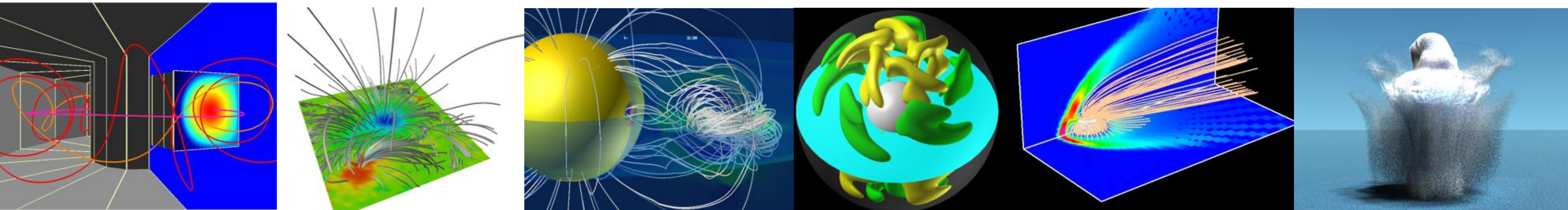
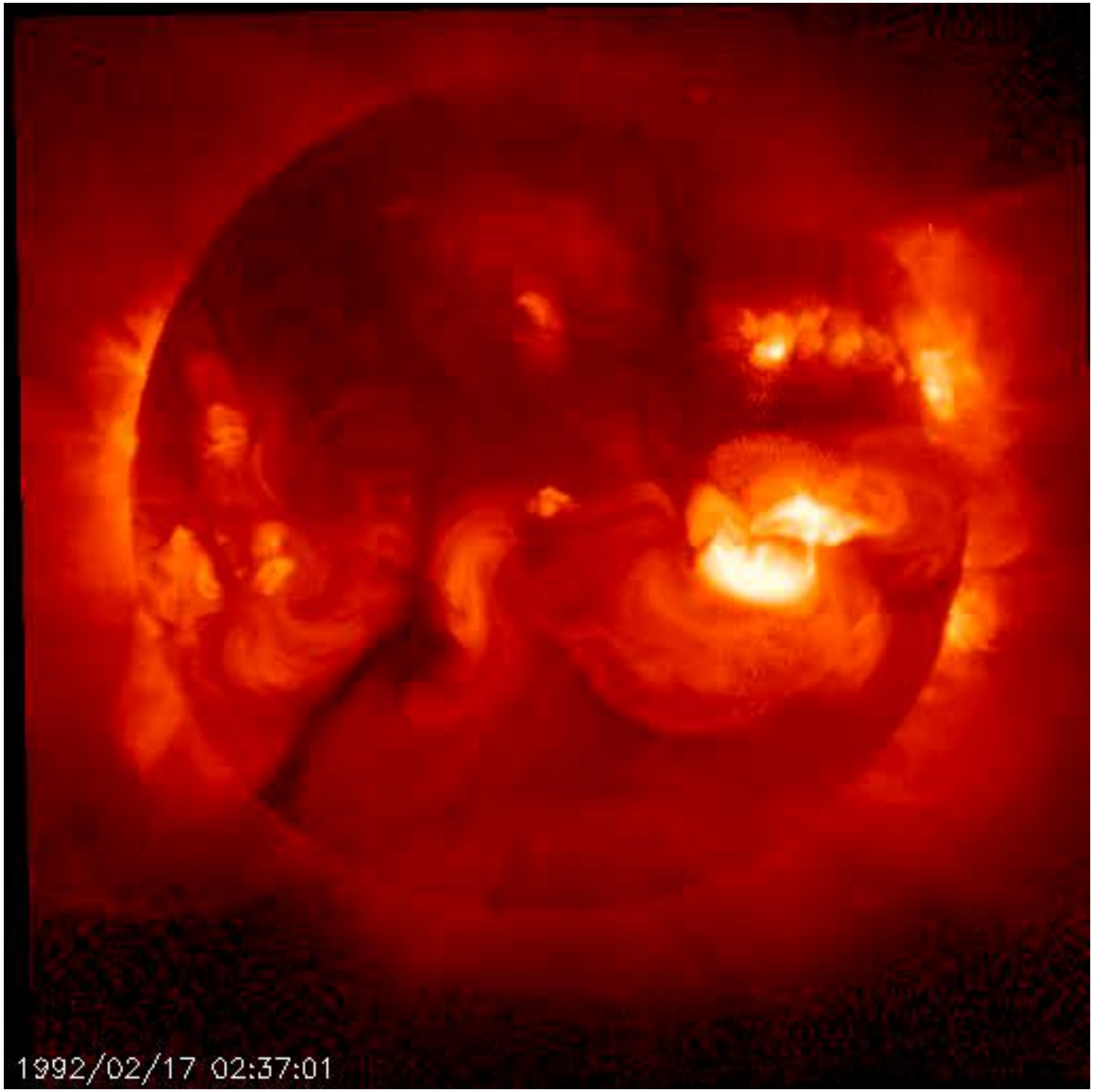


Dynamic Sun



Outlook

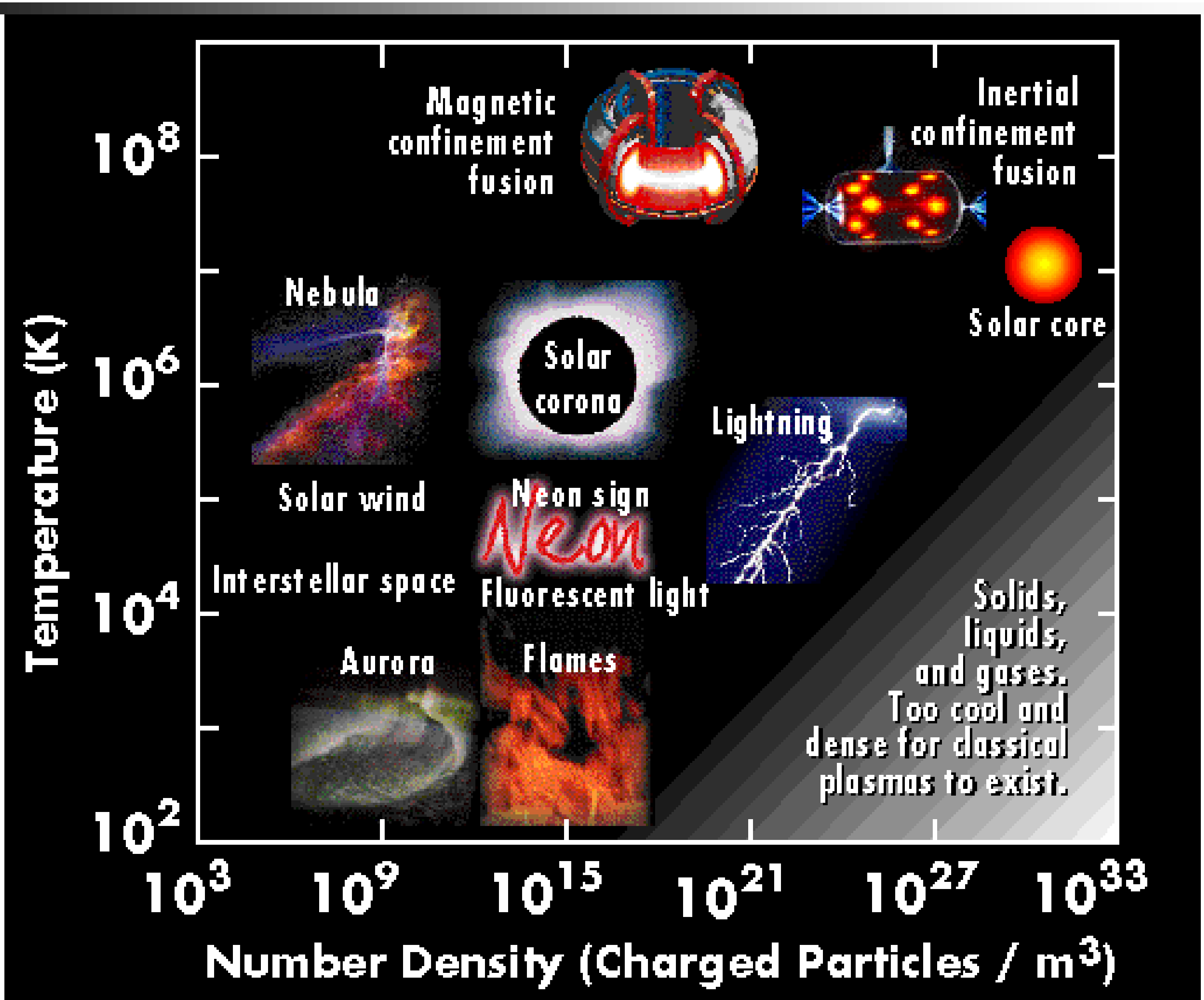
- Introduction to Magnetohydrodynamics
  - Alfven's theorem (frozen-in)
- Magnetic Structure in Solar Active Region
  - Solar magnetic field
  - MHD equilibrium
  - Magnetic helicity and free energy
  - Force-free field model

- Dynamics in solar coronal magnetic field
  - Solar eruptions (flare and CME)
  - Magnetic reconnection
- What triggers the onset of solar eruptions? [NEW]
  - Ensemble 3D MHD simulation study
  - Hinode Observations
  - Discussion: Predictability of solar eruptions

Introduction to MHD

Hannes Alfvén

Plasmas

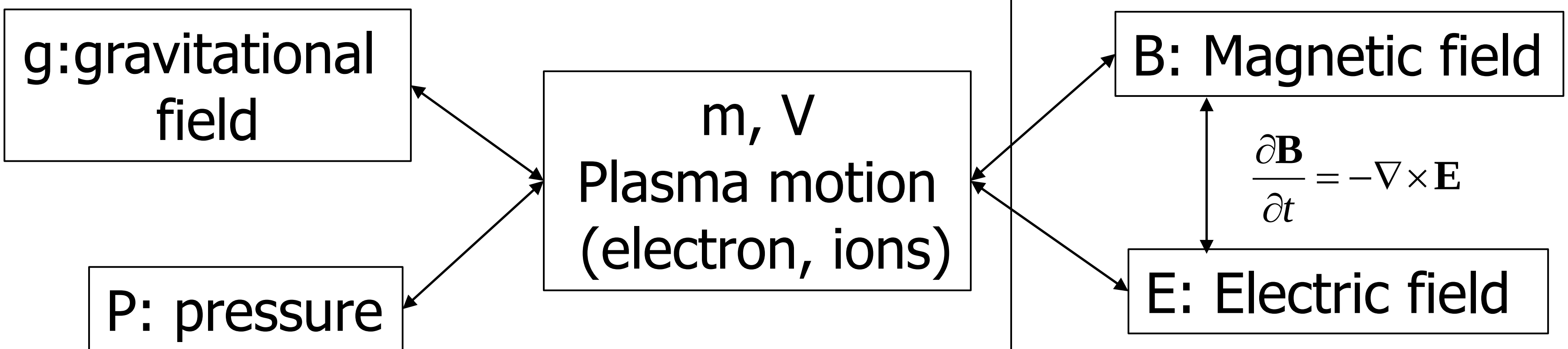


Temperature (K)
10^8
10^6
10^4
10^2
Magnetic confinement fusion
Inertial confinement fusion
Solar core
Nebula
Solar corona
Lightning
Solar wind
Neon sign
Neon
Interstellar space
Fluorescent light
Aurora
Flames
Solids, liquids, and gases. Too cool and dense for classical plasmas to exist.
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

Plasma Dynamics

mechanics

electromagnetism



$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

macroscopic view point
&
microscopic view point

Equations of motion

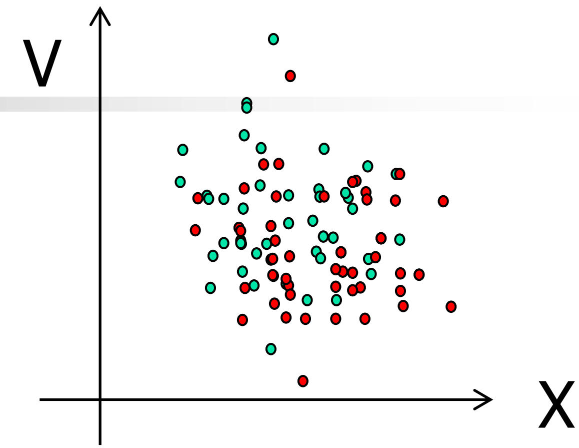
$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Maxwell equations

Klimontvich equation



$$\frac{\partial \hat{F}_s}{\partial t} + \mathbf{v}\cdot\frac{\partial \hat{F}_s}{\partial \mathbf{r}} + \hat{K}_s\cdot\frac{\partial \hat{F}_s}{\partial \mathbf{v}} = 0$$

$$\hat{F}_s(\mathbf{r},\mathbf{v},t) = \sum_{j=1}^{N_s}\delta[\mathbf{r}-\mathbf{r}_j(t)]\delta[\mathbf{v}-\mathbf{v}_j(t)],\ \ \hat{K}_s(\mathbf{r},\mathbf{v},t) = \frac{q_s}{m_s}[\hat{\mathbf{E}}(\mathbf{r},t)+\mathbf{v}\times\hat{\mathbf{B}}(\mathbf{r},t)]$$

$$\textit{where}\ \ \delta[\mathbf{a}] = \delta(a_x)\delta(a_y)\delta(a_z)$$

$$\hat{\mathbf{J}}_s(\mathbf{r},t) = \sum_s q_s\int \mathbf{v}\hat{F}_s(\mathbf{r},\mathbf{v},t)d\mathbf{v}$$

$$\hat{\sigma}_s(\mathbf{r},t) = \sum_s q_s\int \hat{F}_s(\mathbf{r},\mathbf{v},t)d\mathbf{v}$$

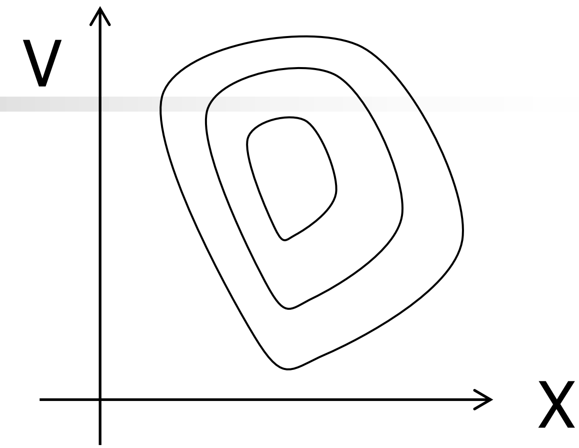
$$\nabla\times\hat{\mathbf{E}}(\mathbf{r},t) = -\frac{\partial\hat{\mathbf{B}}(\mathbf{r},t)}{\partial t}$$

$$\nabla\times\hat{\mathbf{B}}(\mathbf{r},t) = \frac{1}{c^2}\frac{\partial\hat{\mathbf{E}}(\mathbf{r},t)}{\partial t} + \mu_0\hat{\mathbf{J}}(\mathbf{r},t)$$

$$\nabla\cdot\hat{\mathbf{B}}(\mathbf{r},t) = 0$$

$$\nabla\cdot\hat{\mathbf{E}}(\mathbf{r},t) = \frac{1}{\varepsilon_0}\hat{\sigma}_e(\mathbf{r},t)$$

Vlasov equation



$$\frac{\partial F_s}{\partial t} + \mathbf{v} \cdot \frac{\partial F_s}{\partial \mathbf{r}} + K_s \cdot \frac{\partial F_s}{\partial \mathbf{v}} = 0$$

$$F_s(\mathbf{r}, \mathbf{v}, t) = < \hat{F}_s(\mathbf{r}, \mathbf{v}, t) > = \int d\{\mathbf{r}_i, \mathbf{v}_i\} D(\{\mathbf{r}_i, \mathbf{v}_i\}; t) F_s(\mathbf{r}, \mathbf{v}, \{\mathbf{r}_i, \mathbf{v}_i\})$$

ensemble average

$$\mathbf{J}_s(\mathbf{r}, t) = \sum_s q_s \int \mathbf{v} F_s(\mathbf{r}, \mathbf{v}, t) d\mathbf{v}$$

$$\sigma_s(\mathbf{r}, t) = \sum_s q_s \int F_s(\mathbf{r}, \mathbf{v}, t) d\mathbf{v}$$

$$\nabla \times \mathbf{E}(\mathbf{r}, t) = -\frac{\partial \mathbf{B}(\mathbf{r}, t)}{\partial t}$$

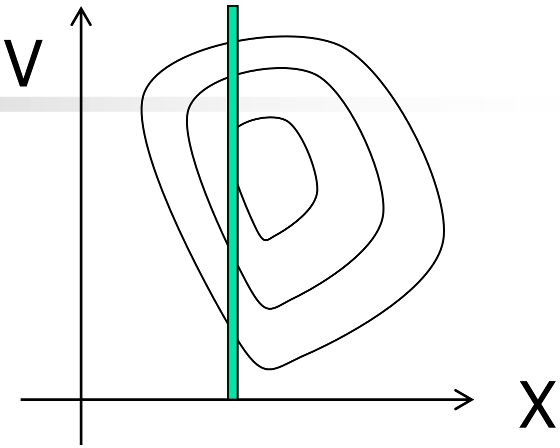
$$\nabla \times \mathbf{B}(\mathbf{r}, t) = \frac{1}{c^2} \frac{\partial \mathbf{E}(\mathbf{r}, t)}{\partial t} + \mu_0 \mathbf{J}(\mathbf{r}, t)$$

$$\nabla \cdot \mathbf{B}(\mathbf{r}, t) = 0$$

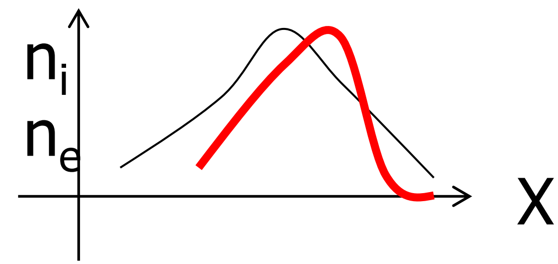
$$\nabla \cdot \mathbf{E}(\mathbf{r}, t) = \frac{1}{\varepsilon_0} \sigma_e(\mathbf{r}, t)$$

Macroscopic Variables

- the n-th moment in velocity space



$$\mathrm{M}^n = \int \mathbf{v}^n F_s(\mathbf{r},\mathbf{v},t)d\mathbf{v}$$



$$\mathrm{n}_s(\mathbf{r},\mathrm{t}) = \mathrm{M}^0 = \int F_s(\mathbf{r},\mathbf{v},t)d\mathbf{v}$$

$$\Gamma_s(\mathbf{r},t) = \mathrm{M}^1 = \int \mathbf{v}F_s(\mathbf{r},\mathbf{v},t)d\mathbf{v}$$

$$\mathbf{u}_s(\mathbf{r},t) = \bar{\mathbf{v}}_s(\mathbf{r},t) = \Gamma_s(\mathbf{r},t)/\mathrm{n}_s(\mathbf{r},\mathrm{t})$$

$\mathbf{c} = \mathbf{v}_s - \mathbf{u}_s$ *velocity fluctuation* (速度揺らぎ)

$$\tilde{\mathrm{P}}_s(\mathbf{r},t) = m_s M^2 = m_s \int \mathbf{c}\mathbf{c}F_s d\mathbf{v}$$

$$Q_s(\mathbf{r},t) = \frac{1}{2} m_s \int \mathbf{c}c^2 F_s d\mathbf{v}$$

Macroscopic Equations

$$\int \mathbf{v}^n [\frac{\partial F_s}{\partial t} + \mathbf{v} \cdot \frac{\partial F_s}{\partial \mathbf{r}} + K_s \cdot \frac{\partial F_s}{\partial \mathbf{v}} = (\frac{\delta F}{\delta t})_{collision}] dv$$

moment in velocity space

$n=1$ $$\frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{u}) = 0$$

$n=2$ $$\frac{\partial}{\partial t}(\rho_s \mathbf{u}_s) + \nabla \cdot (\rho_s \mathbf{u}_s \mathbf{u}_s) + \nabla \cdot \tilde{\mathrm{P}}_s - \rho_{cs} \mathbf{a}_s = (\frac{\delta M_s}{\delta t})_{collision}$$

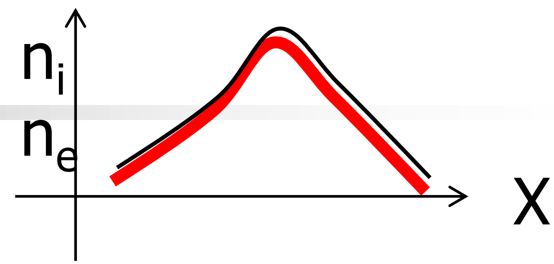
$n=3$ $$\frac{\partial}{\partial t}(\frac{3}{2}\tilde{\mathrm{P}}_s + \frac{1}{2}\rho_s u_s{}^2) + \nabla \cdot \{(\frac{1}{2}\rho u_s^2 + \frac{5}{2}\tilde{\mathrm{P}}_s)\mathbf{u}_s + Q_s\} - \rho \mathbf{J} \cdot \mathbf{E}$$

$$= \int \frac{m}{2} c^2 (\frac{\delta F_s}{\delta t})_{collision} d\mathbf{v}$$

s=ion or electron

"closure"

Single-fluid variables



For the macro-scale variables

$$L >> \lambda_D \qquad \omega << \omega_p \quad \longrightarrow \quad n_e \approx n_i$$ quasi-neutrality 準中性

- Total mass density

$$\rho(\mathbf{r},t) = n_e m_e + n_i m_i = n(m_e + m_i) \sim n m_i = \rho_i$$

- Center of mass velocity

$$\mathbf{u}(\mathbf{r},t) = \frac{1}{\rho}(n_e m_e \mathbf{u}_e + n_i m_i \mathbf{u}_i) \sim \mathbf{u}_i$$

- Electric current density

$$\mathbf{J}(\mathbf{r},t) = e(n_i \mathbf{u}_i - n_e \mathbf{u}_e) \sim -n e u_e$$

Magnetohydrodynamics (MHD) eq.

- Cont. eq.

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

- Eq. Motion

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) + \nabla \cdot \tilde{\mathrm{P}} - \mathbf{J} \times \mathbf{B} = \left(\frac{\delta M}{\delta t}\right)_{collision}$$

- Energy eq.

$$\frac{\partial}{\partial t}\left(\frac{1}{\gamma - 1}\tilde{\mathrm{P}} + \frac{1}{2}\rho u^2 + \rho U_{grav} + \frac{\varepsilon_0}{2}E^2 + \frac{B^2}{2\mu_0}\right)$$

$$+ \nabla \cdot \left\{\rho \mathbf{u}\left(\frac{\gamma}{\gamma - 1}\frac{P}{\rho} + \frac{1}{2}u^2 + U_{grav}\right) + \frac{\mathbf{E} \times \mathbf{B}}{\mu_0} + \mathbf{Q}\right\} = -\mathbf{J} \cdot \mathbf{E} + \int \frac{m}{2}c^2 \left(\frac{\delta F_s}{\delta t}\right)_{collision} d\mathbf{v}$$

- Generalized Ohm's law

$$\mathbf{E} = -\mathbf{u} \times \mathbf{B} + \eta \mathbf{J}$$

Faraday's law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

Ampere's law

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$$

Hierarchy of Plasma equations

long
large

↕

short
small

- Macro-scale
  - Magneto-hydrodynamic (MHD) eq. f(r)
    - Single fluid model

      ⇧ quasi-neutral

    - Two-fluid model

      ⇧ velocity space moment

- Micro-scale
  - Kinetic model
    - F(r,v)

      ⇧ ensemble average

    - $\hat{F}(r_i,v_i)$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$\nabla \cdot \mathbf{B} = 0$$

$$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t}$$

Maxwell eq.

Scales

- Gyro-radius

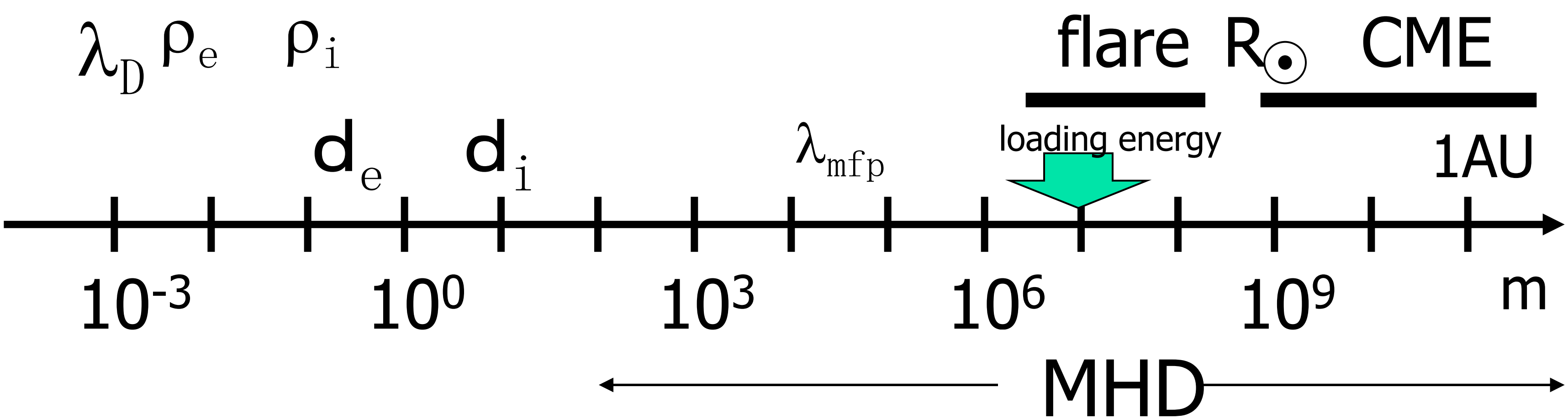
$$\rho_s = \frac{v_{th}}{\omega_{s,gyro}} \qquad \omega_{s,gyro} = \frac{eB}{m_s}$$

- Skin length

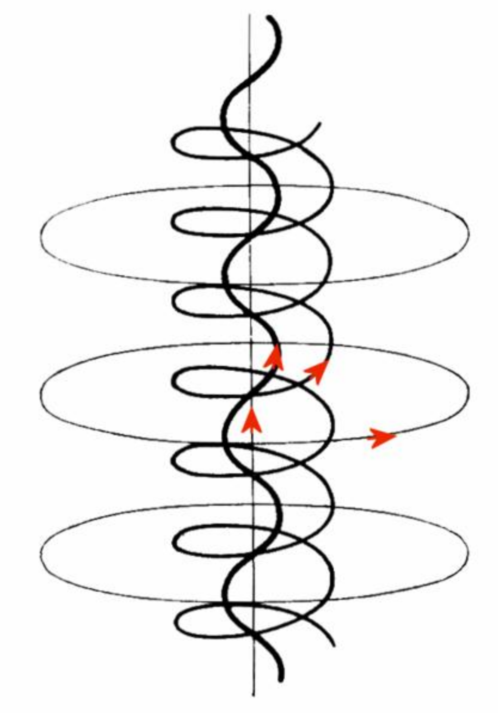
$$d_s = \frac{c}{\omega_{ps}} \qquad \omega_{ps} = \sqrt{\frac{ne^2}{m_s \varepsilon_0}}$$

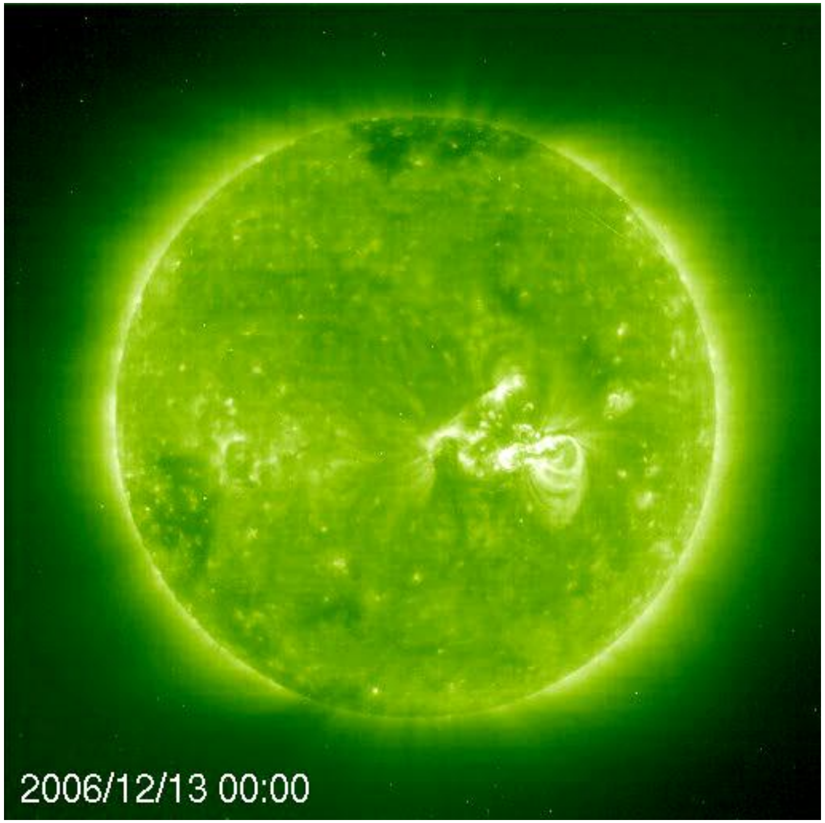
- Debye length

$$\lambda_D = \sqrt{\frac{\varepsilon_0 kT}{2ne^2}}$$



Scales in the solar coronal plasma

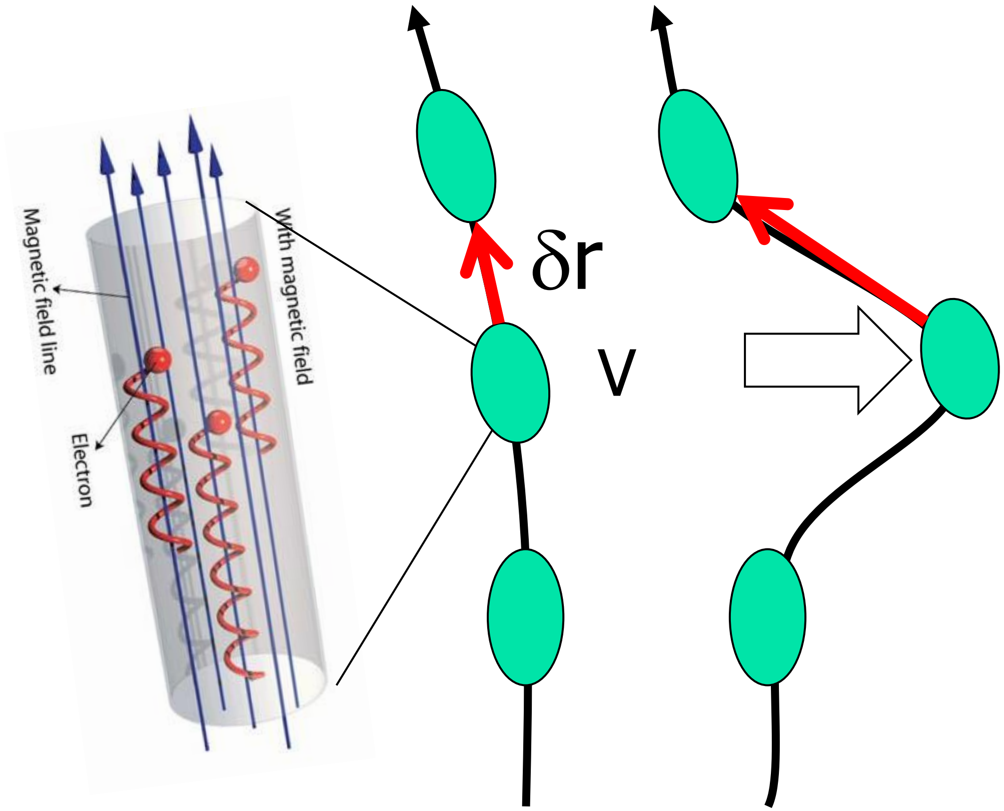




$r_i \sim 1$ m, $\omega_{gi} \sim 10^6$
$r_e \sim 2 \times 10^{-2}$ m, $\omega_{ge} \sim 10^9$

$R_{sun} \sim 7.0 \times 10^8$m

“凍結 (frozen-in)”



Ideal MHD eq.

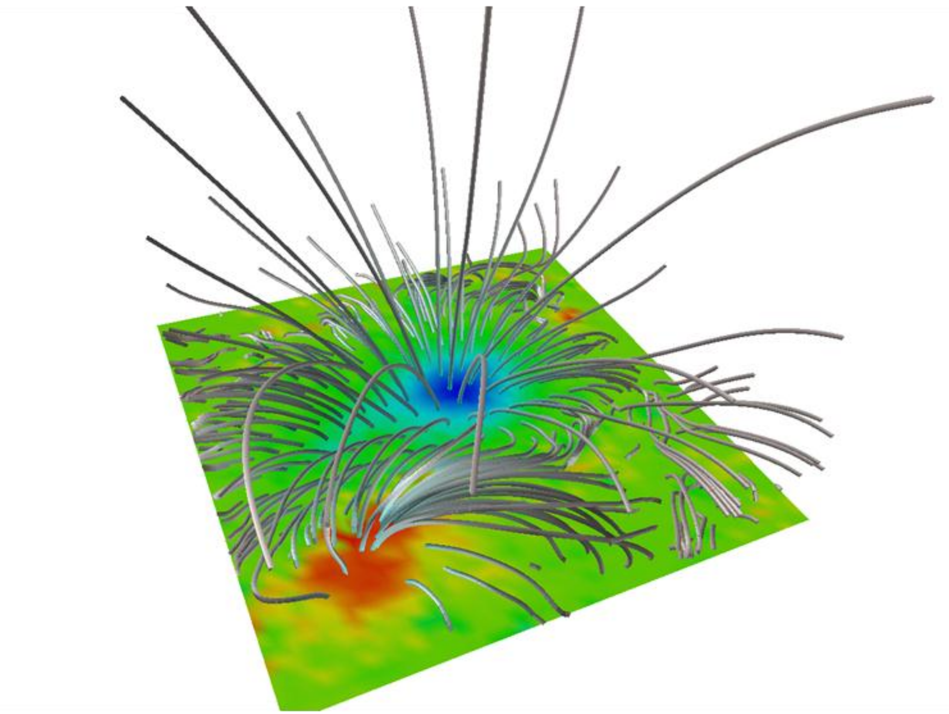
$$\frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B} - \cancel{\eta\mathbf{J}})$$

$$\frac{d}{dt}\left(\frac{\mathbf{B}}{\rho}\right) = \left(\frac{\mathbf{B}}{\rho}\cdot\nabla\right)\mathbf{V}$$

Same eq.

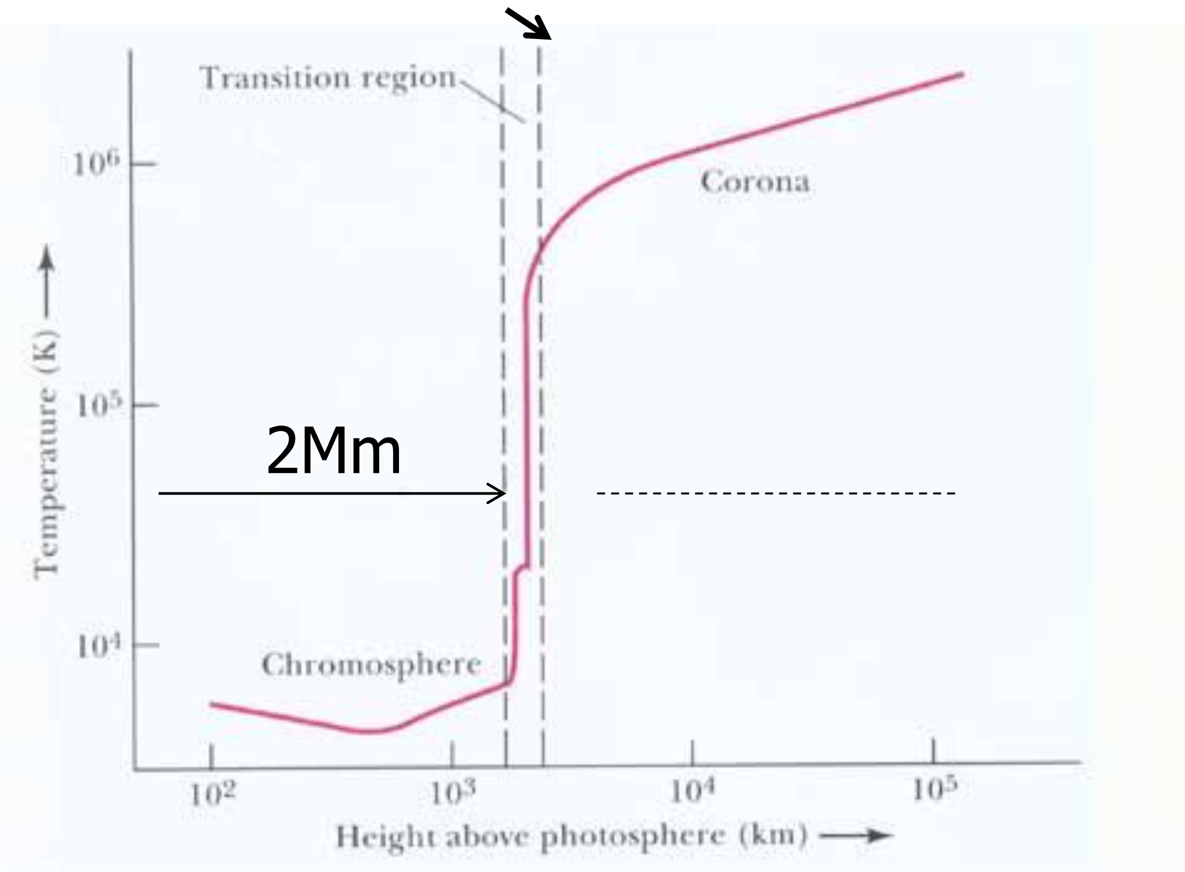
$$\frac{d}{dt}(\delta\mathbf{r}) = (\delta\mathbf{r}\cdot\nabla)\mathbf{V}$$

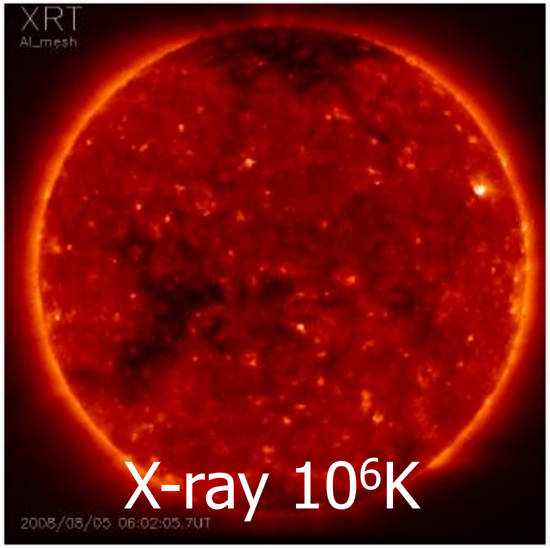
Magnetic Structure in Solar Active Regions



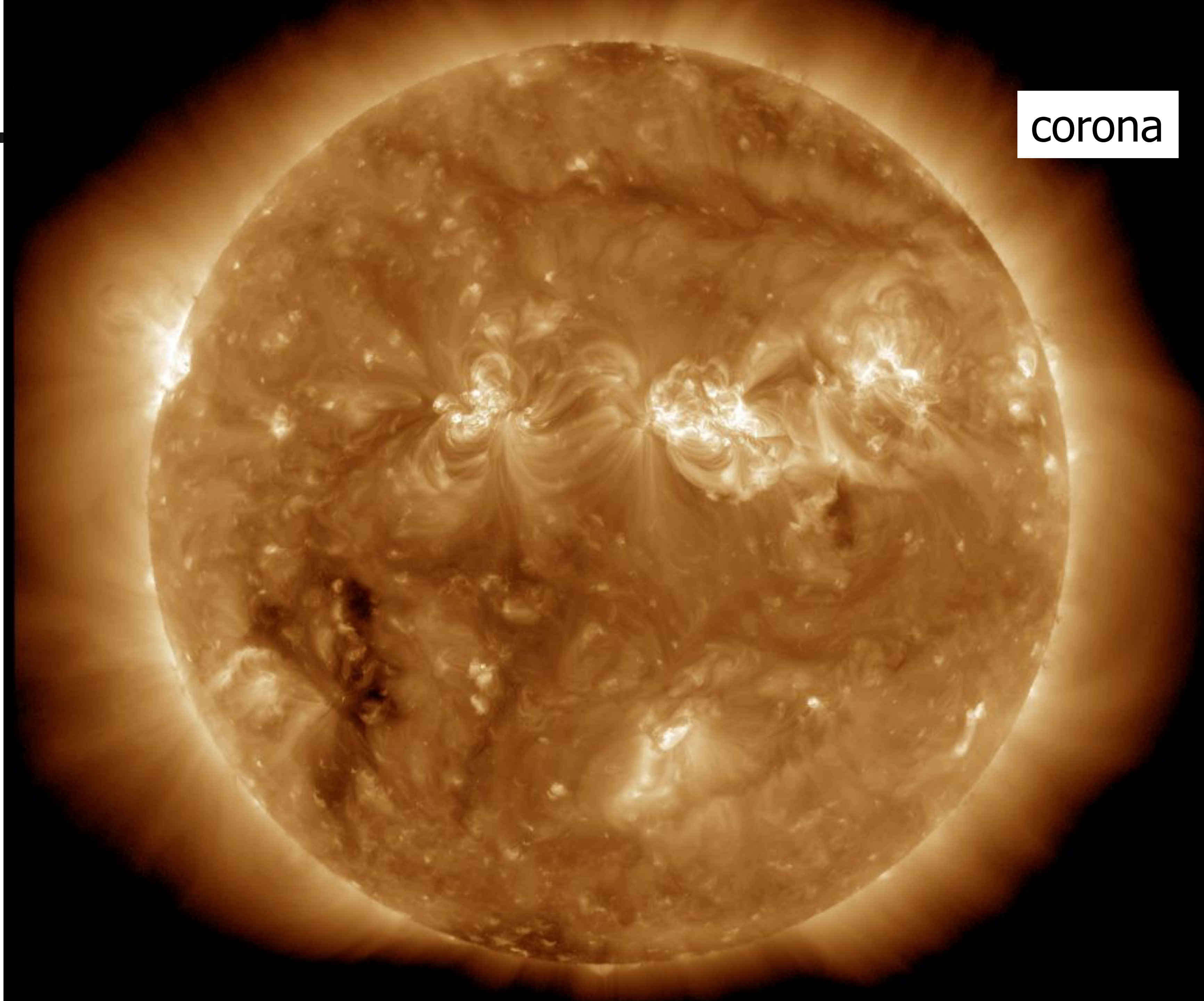
Solar Atmosphere

- Multi-layer Structure

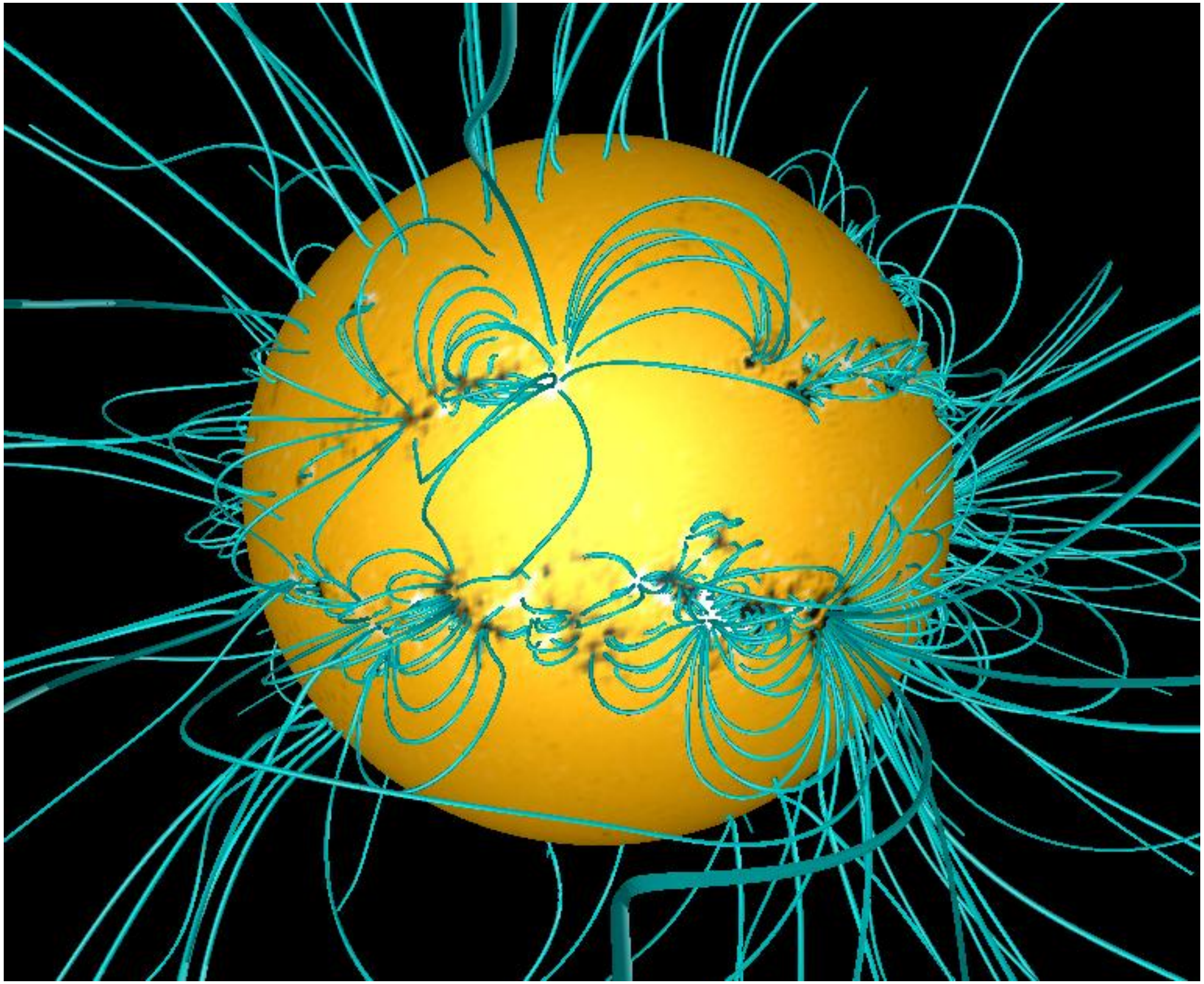




white light $6x10^3$K


corona

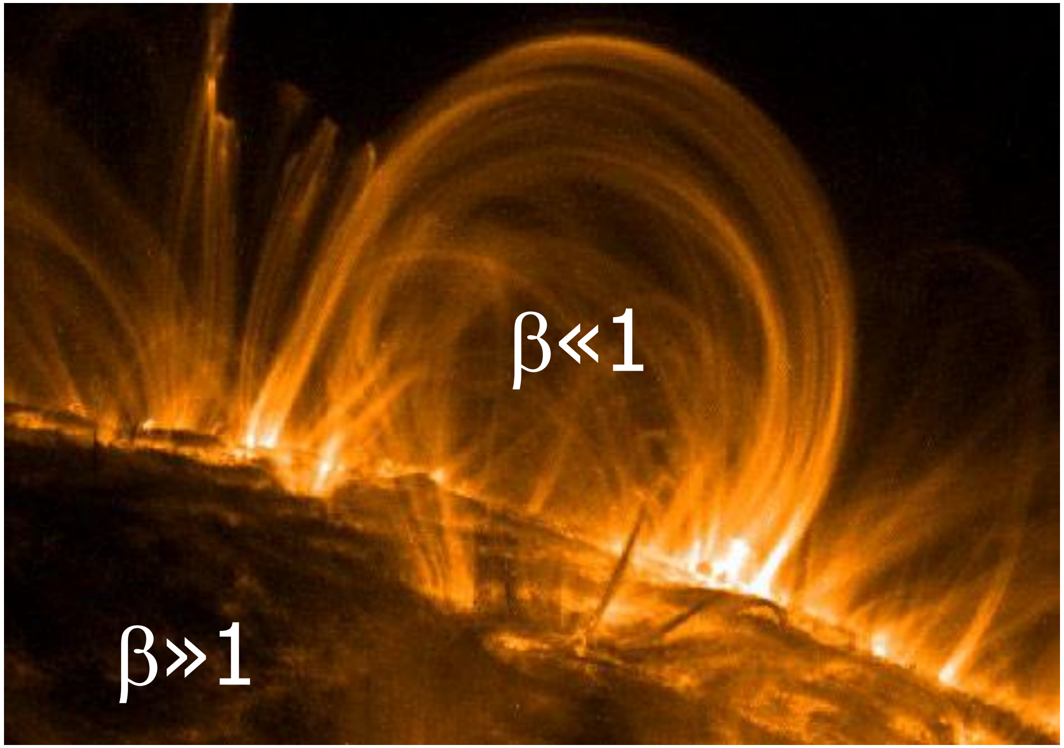
Magnetic Structure



open field

closed field

Plasma β ratio



$$\beta = \frac{plasma\ pressure}{magnetic\ pressure}$$

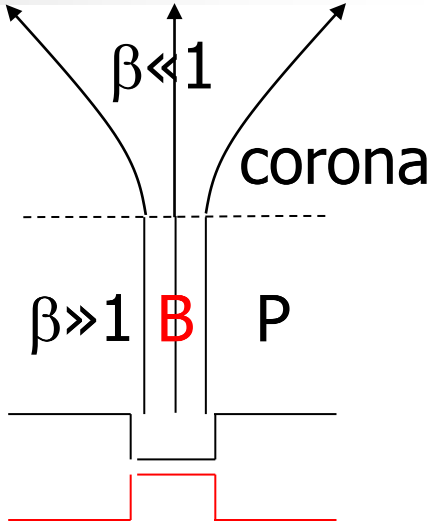
$$= \frac{p}{\dfrac{B^2}{2\mu_0}}$$

MHD Equilibrium

$$\frac{\partial}{\partial t}(\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = \mathbf{J} \times \mathbf{B} - \nabla \cdot \tilde{\mathrm{P}}$$

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} - \nabla P = (B \cdot \nabla) B - \nabla(\frac{B^2}{2\mu_0} + p) = 0$$

$$\mathbf{J} = \mathbf{J}_{\parallel} + \frac{\mathbf{B} \times \nabla P}{B^2}$$



- Force-Free Field (β<<1)

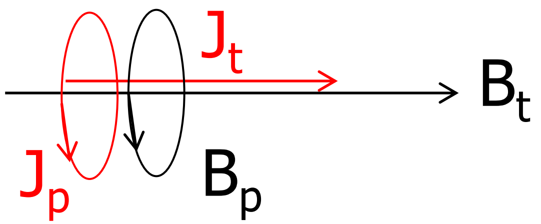
$$\mathbf{J} \times \mathbf{B} = 0, \quad \nabla P = 0$$

$$\mathbf{J} = \mathbf{J}_{\parallel} \Rightarrow \nabla \times \mathbf{B} = \alpha \mathbf{B}$$

- Nonlinear Force-Free Field $\quad \mathbf{B} \cdot \nabla \alpha = 0$
- Linear Force-Free Field $\quad \nabla \alpha = 0$
- Potential Field $\quad \alpha = 0 \quad (B = -\nabla \varphi)$

Linear Force Free Field

$$\nabla \times \mathbf{B} = \alpha \mathbf{B} \quad where\ \alpha = \alpha_0\ (const.)$$

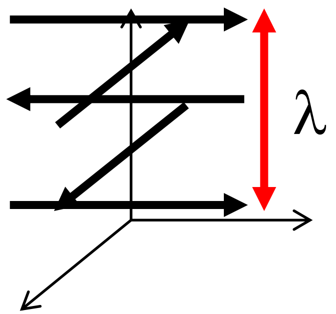


$$\alpha = 2\pi / \lambda$$

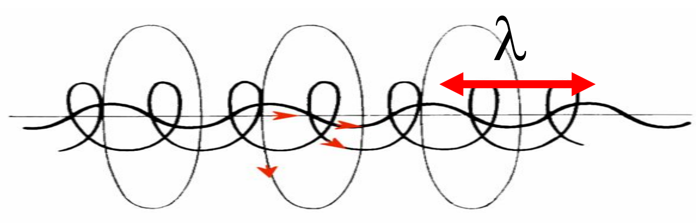
- Rectangle system

$$\mathbf{B} = B_0(\cos\alpha z, -\sin\alpha z, 0)$$

$$\nabla \times \mathbf{B} = \alpha B_0(\cos\alpha z, -\sin\alpha z, 0) = \alpha \mathbf{B}$$

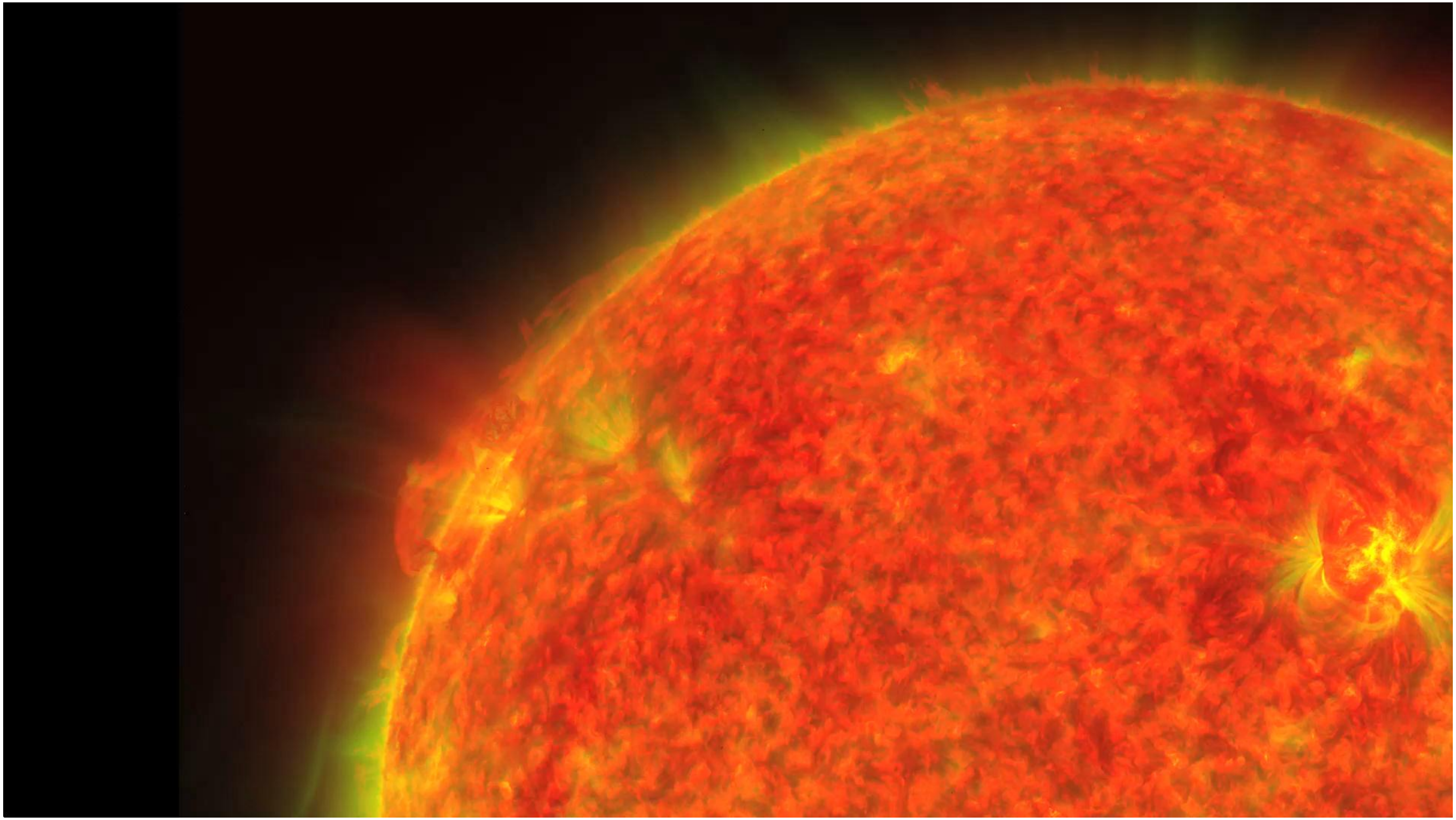


- Cylindrical system

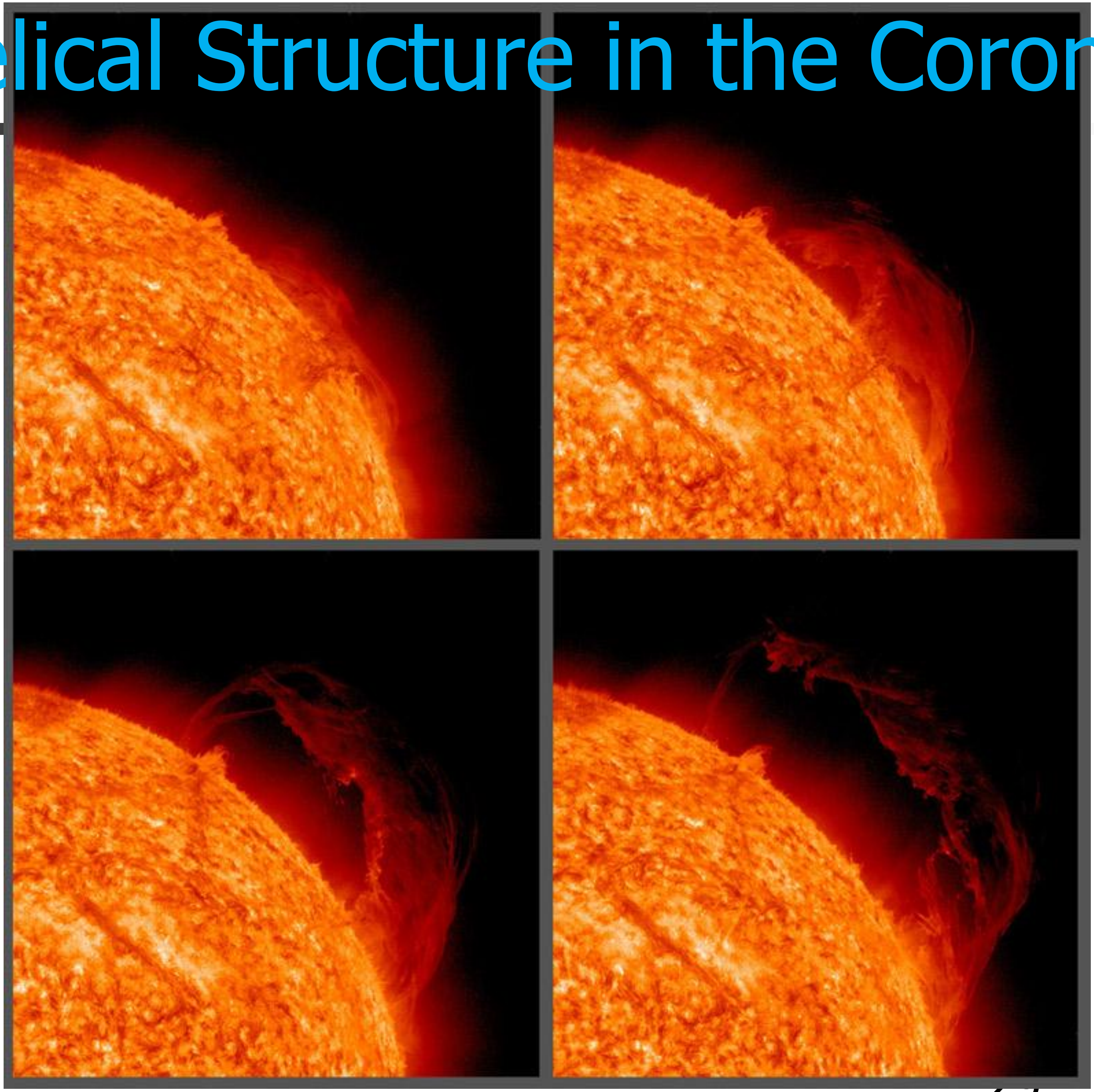


$$\mathbf{B} = B_0(0, J_1(\alpha r), J_0(\alpha r))$$

$$\nabla \times B = (0, -\frac{\partial B_z}{\partial r}, \frac{1}{r}\frac{\partial}{\partial r}(rB_\phi)) = \alpha B_0(0, J_1(\alpha r), J_0(\alpha r))$$

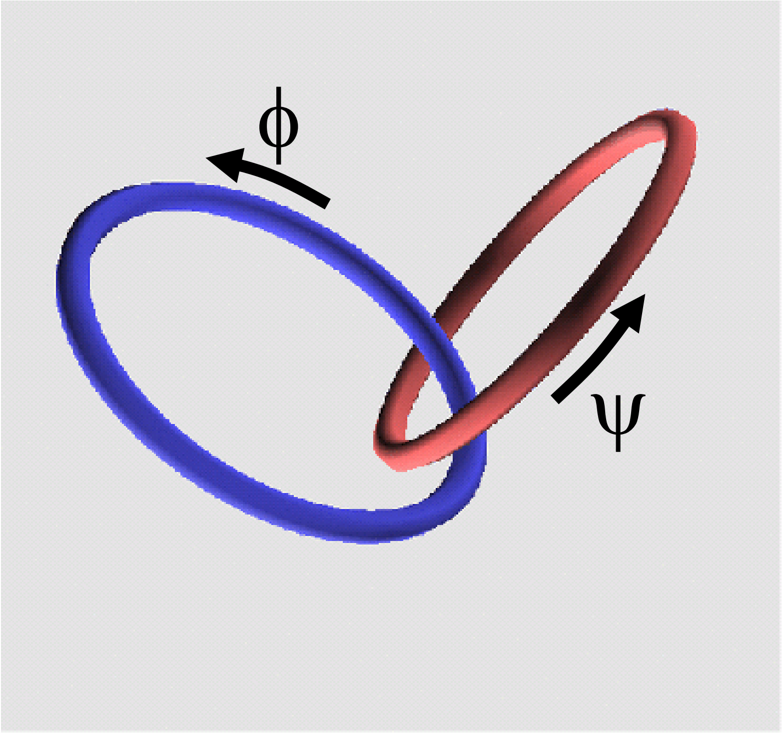


Helical Structure in the Corona

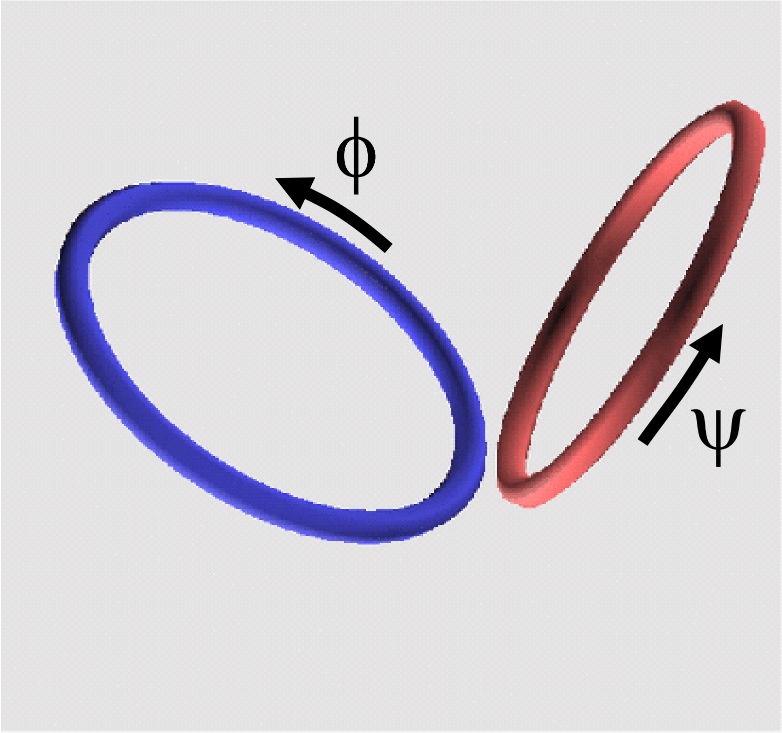


Magnetic Helicity (field linkage)

$$H = \int \mathbf{A} \cdot \mathbf{B} \, dV$$



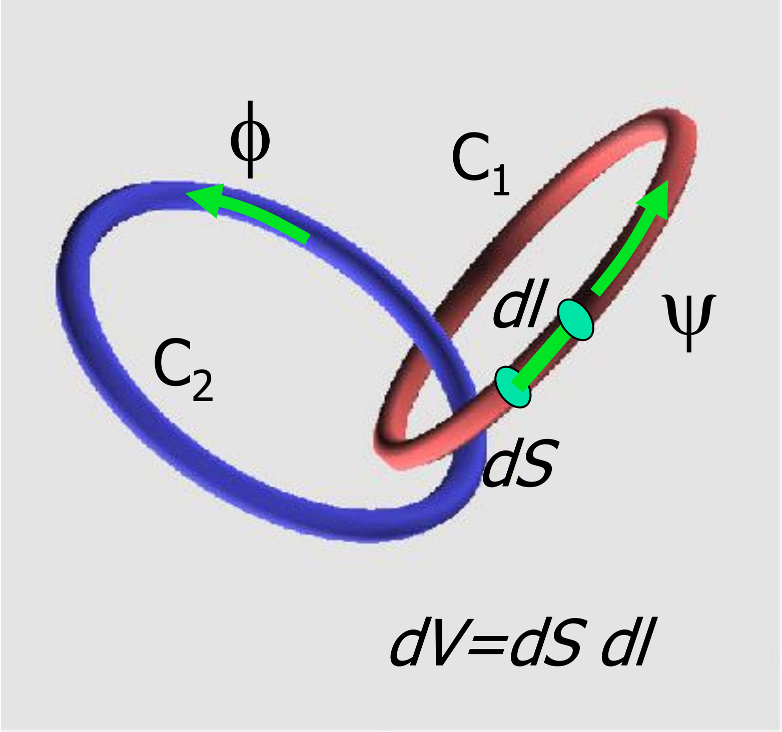
H=2ϕψ



H=0

Helicity is a topological invariant.

- Linking Fluxes



$$H = \int \mathbf{A}\cdot\mathbf{B}\, dV$$

$$= \oint_{C_1} \mathbf{A}\cdot d\mathbf{l} \int \mathbf{B}\cdot d\mathbf{S}$$

$$+ \oint_{C_2} \mathbf{A}\cdot d\mathbf{l} \int \mathbf{B}\cdot d\mathbf{S}$$

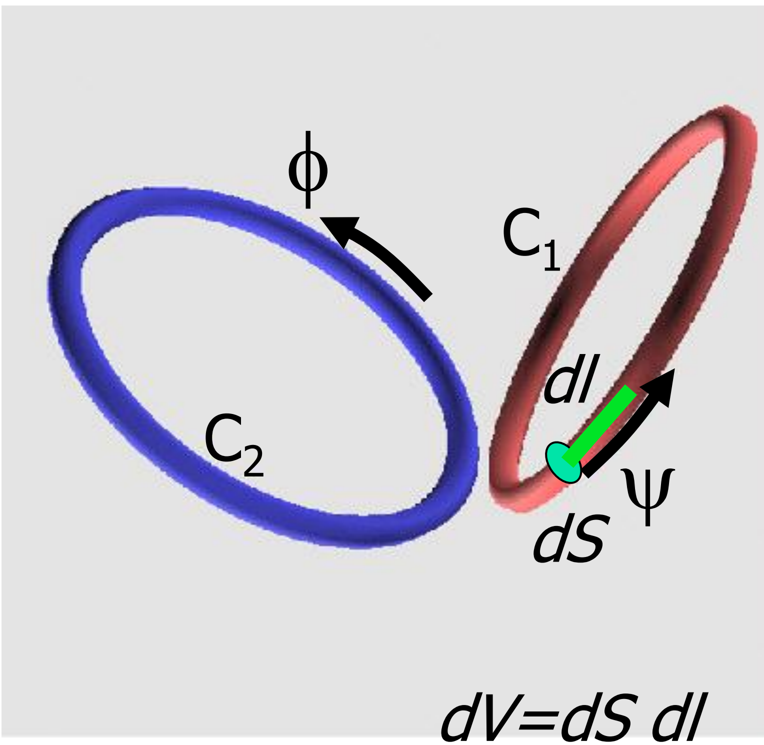
$$= \quad \phi \quad \psi$$

$$+ \quad \psi \quad \phi$$

$$= 2\psi\phi$$

Helicity is a topological invariant.

- Not Linking Fluxes



$$H = \int \mathbf{A} \cdot \mathbf{B} \, dV$$

$$= \oint_{C_1} \mathbf{A} \cdot d\mathbf{l} \int \mathbf{B} \cdot d\mathbf{S}$$

$$+ \oint_{C_2} \mathbf{A} \cdot d\mathbf{l} \int \mathbf{B} \cdot d\mathbf{S}$$

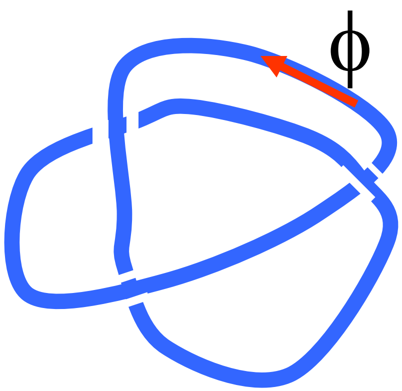
$$= \quad 0 \quad \psi$$

$$+ \quad 0 \quad \phi$$

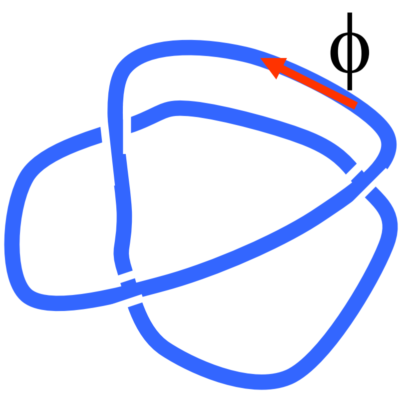
$$= 0$$

Questions

Calculate the magnetic helicity of these flux tubes.



$H=2\phi^2$



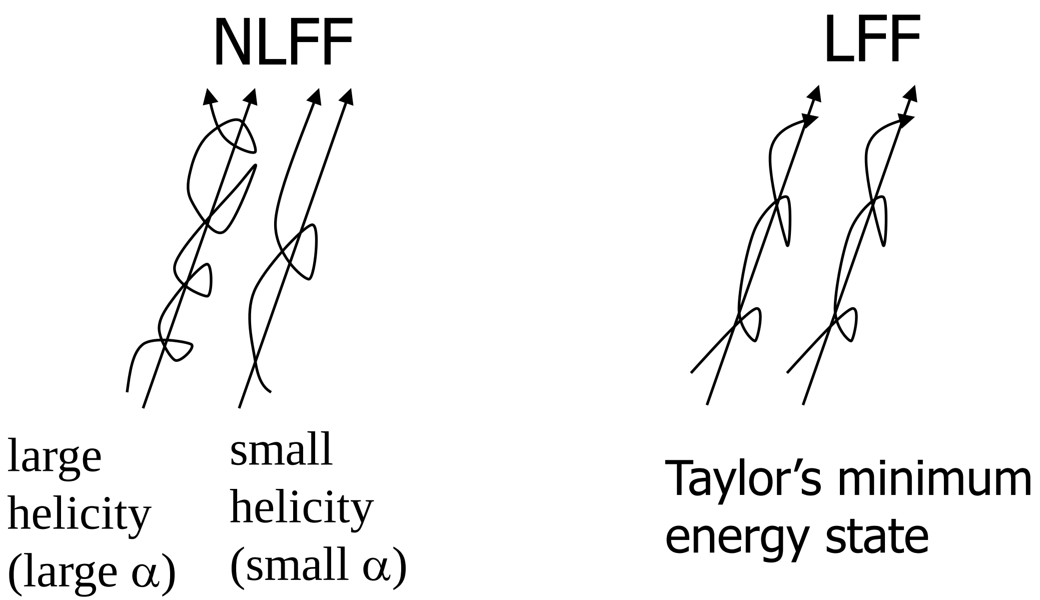
$H=0$

- Magnetic helicity is a topological invariant.
- Magnetic helicity is conserved in the ideal MHD systems.

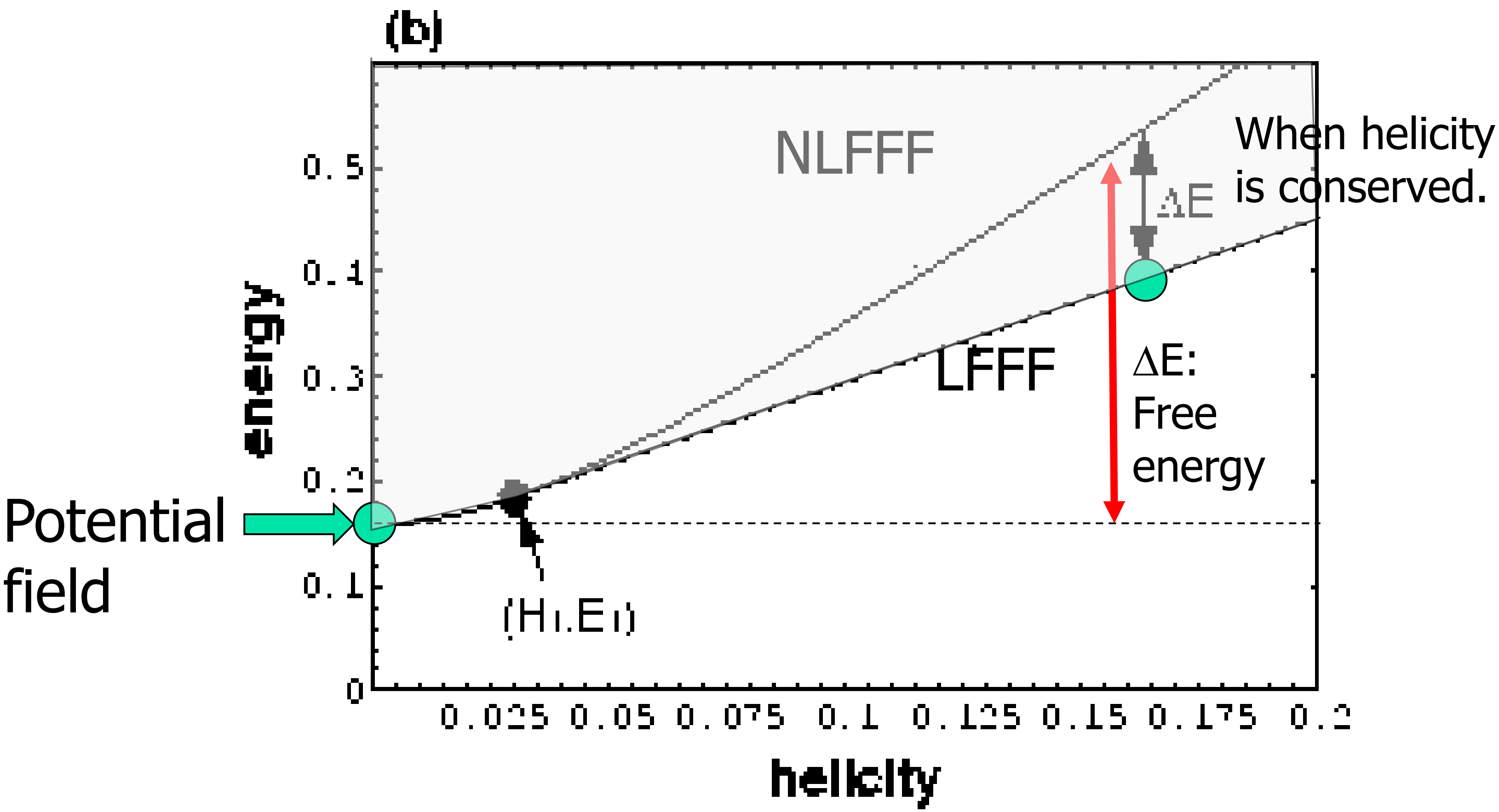
Taylor’s minimum energy state

- When mag. helicity is approximately conserved in the resistive MHD system, the minimum energy state is given by a linear force-free field.

$$\left.\begin{aligned}\text{minimize}: E &= \int \mathbf{B}\cdot\mathbf{B}\,dV \\ \text{invariance}: H &= \int \mathbf{A}\cdot\mathbf{B}\,dV\end{aligned}\right\}\nabla\times\mathbf{B}=\alpha\mathbf{B}$$



Magnetic Free Energy

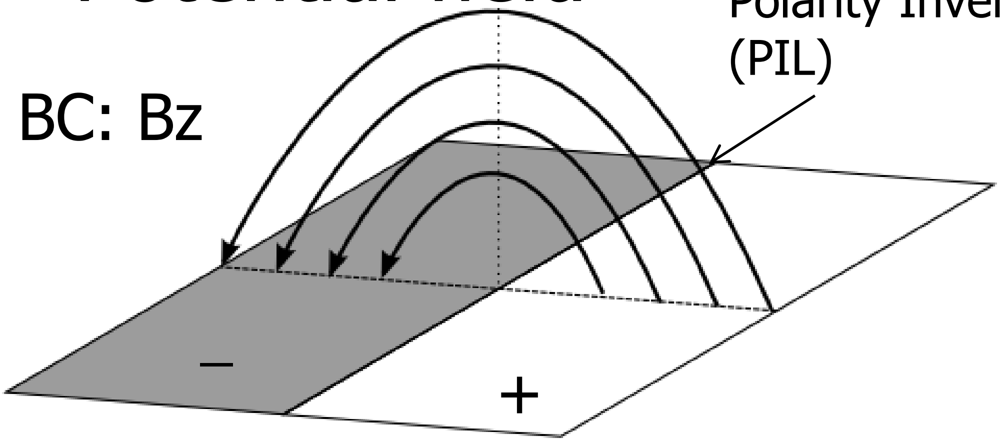


Force-Free Field in the Corona

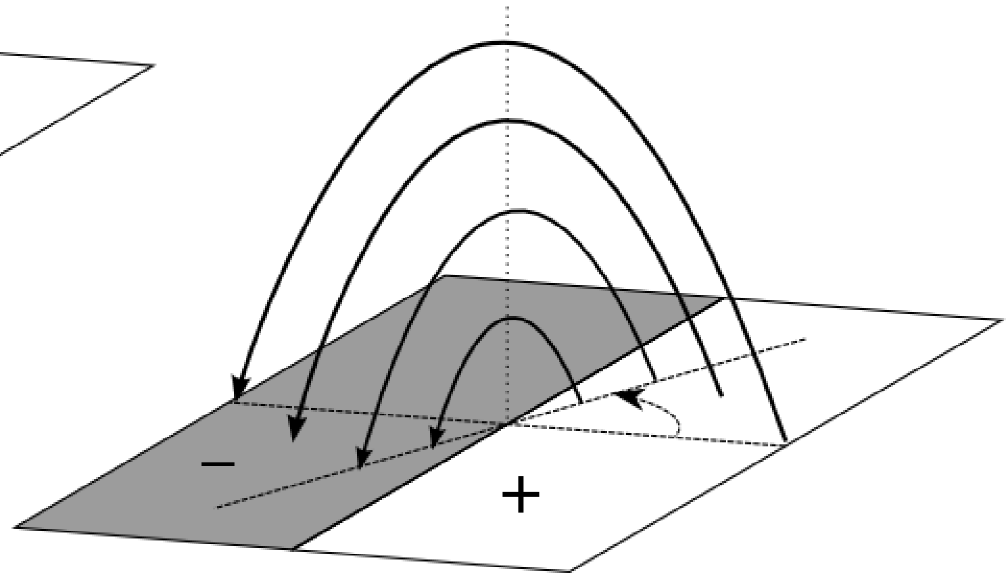
- Potential field

BC: Bz

Polarity Inversion Line (PIL)



NLFFF

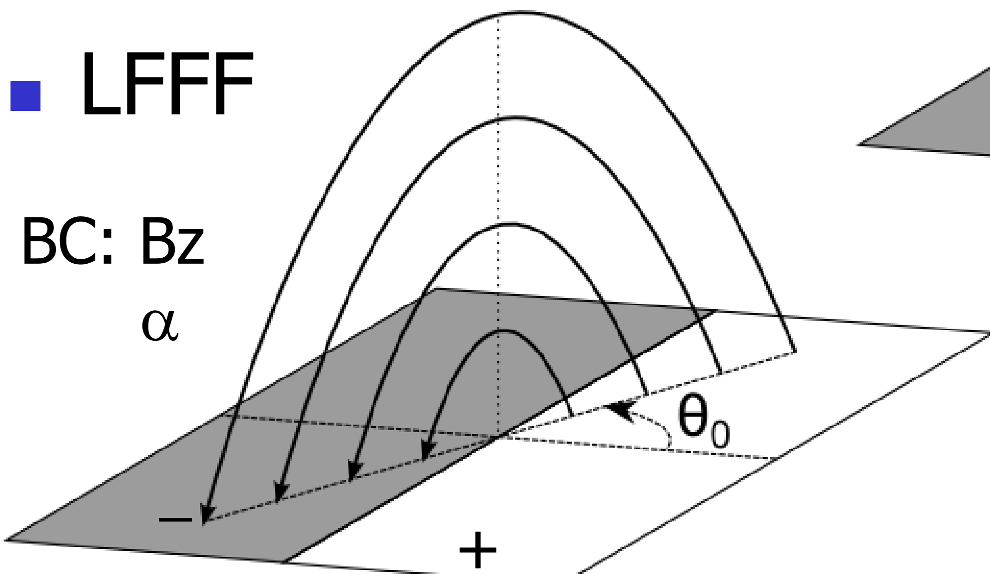


BC: Bx, By, Bz

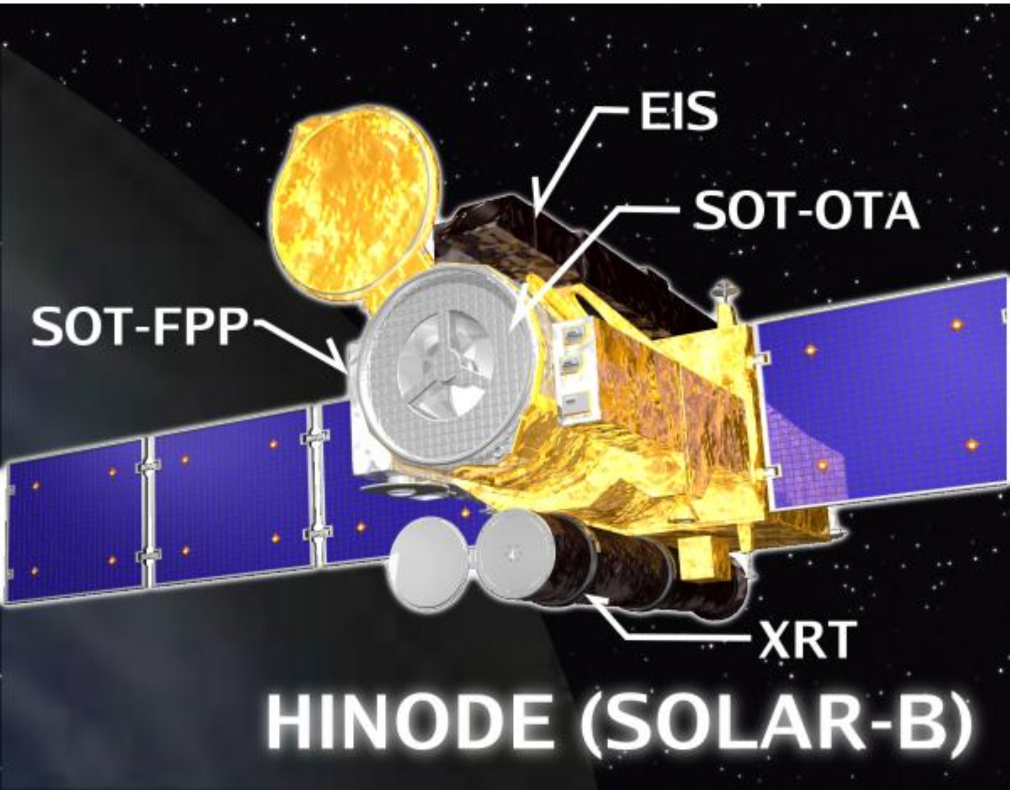
- LFFF

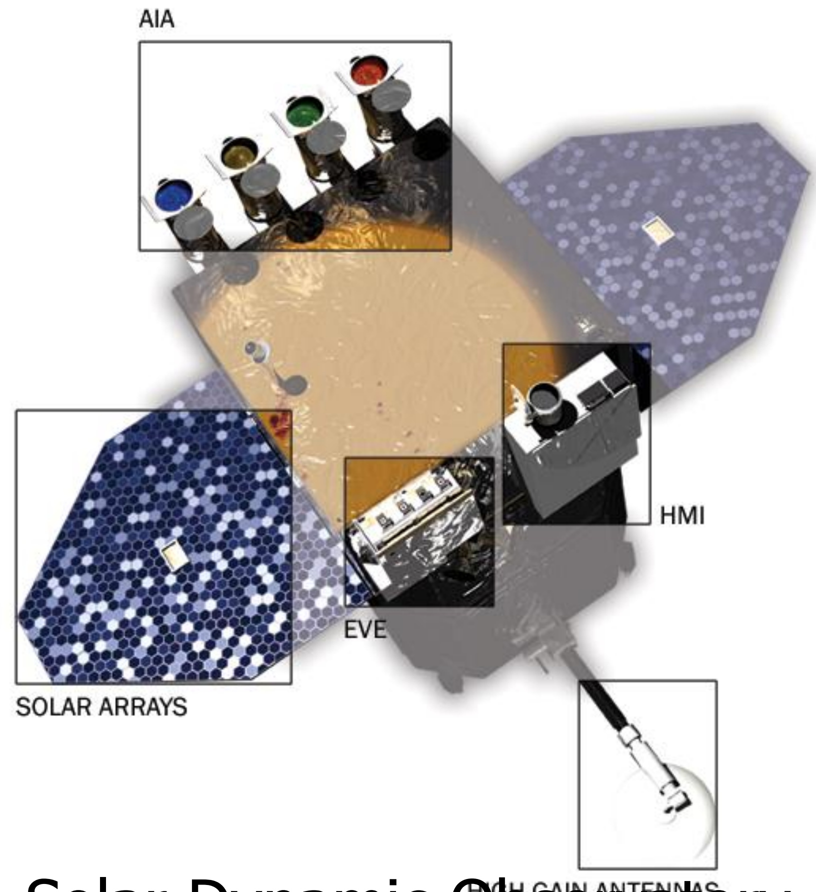
BC: Bz

α



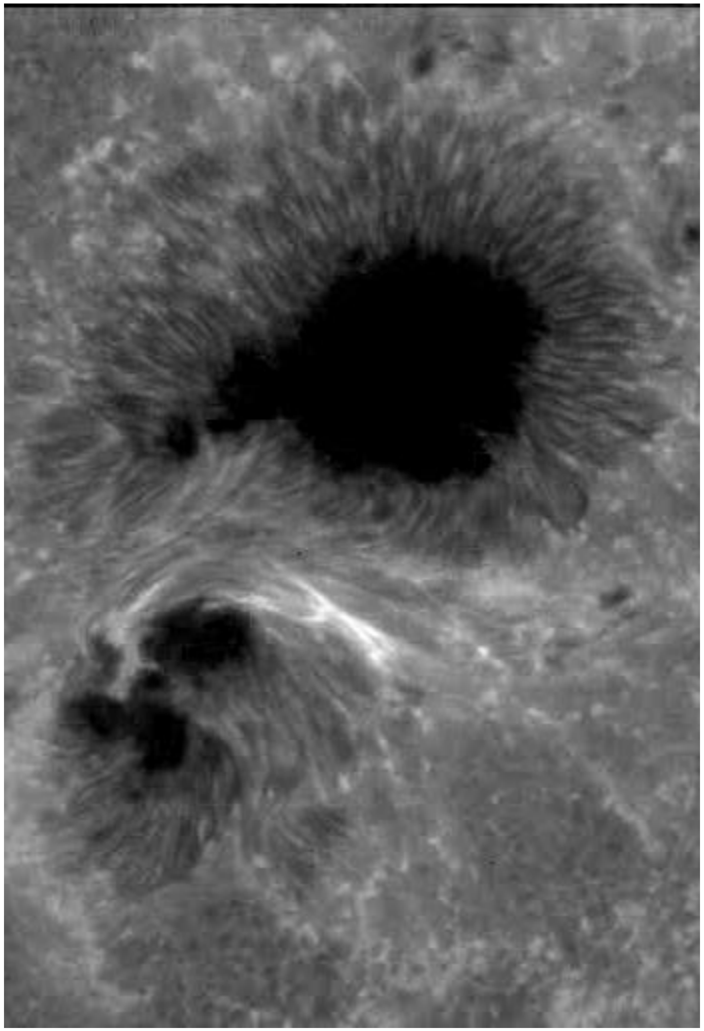
Solar Observatories in Space

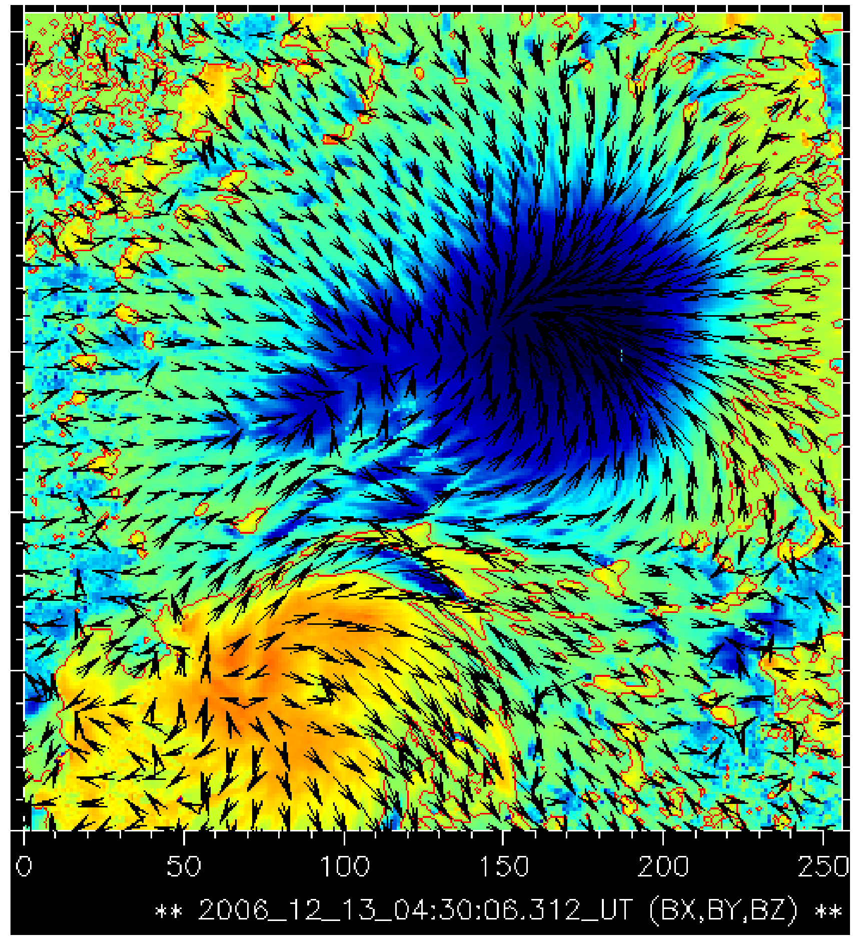




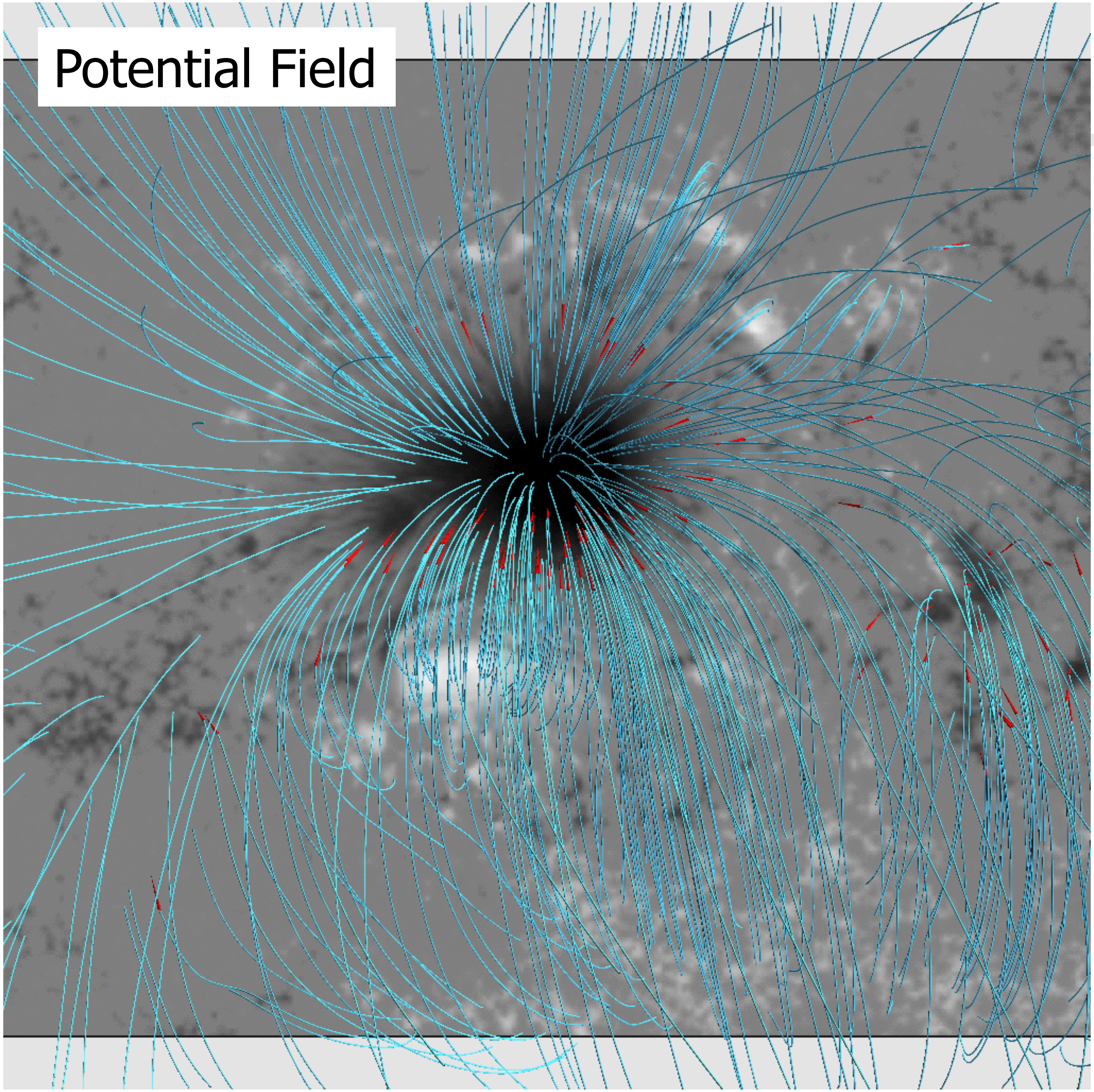
Solar Dynamic Observatory (SDO)

Magnetograph of NOAA10930

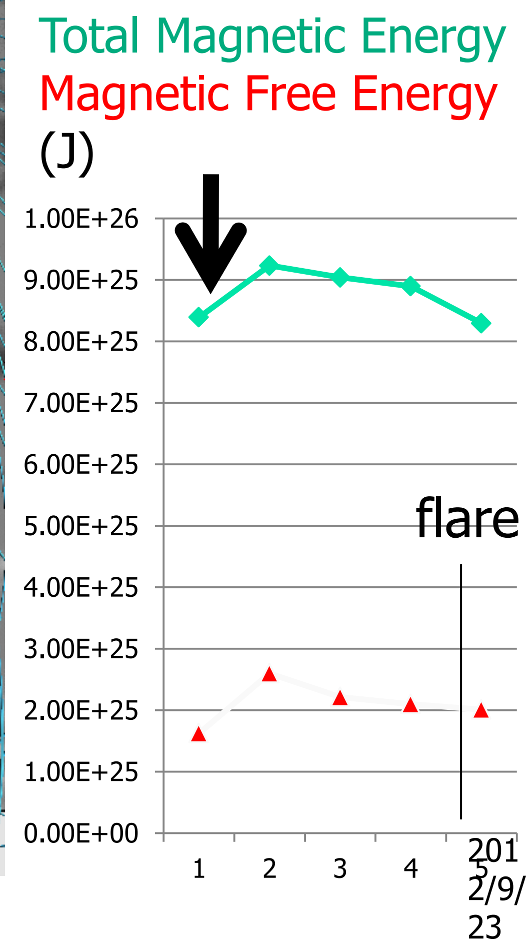




2006.12.13 01:42:37

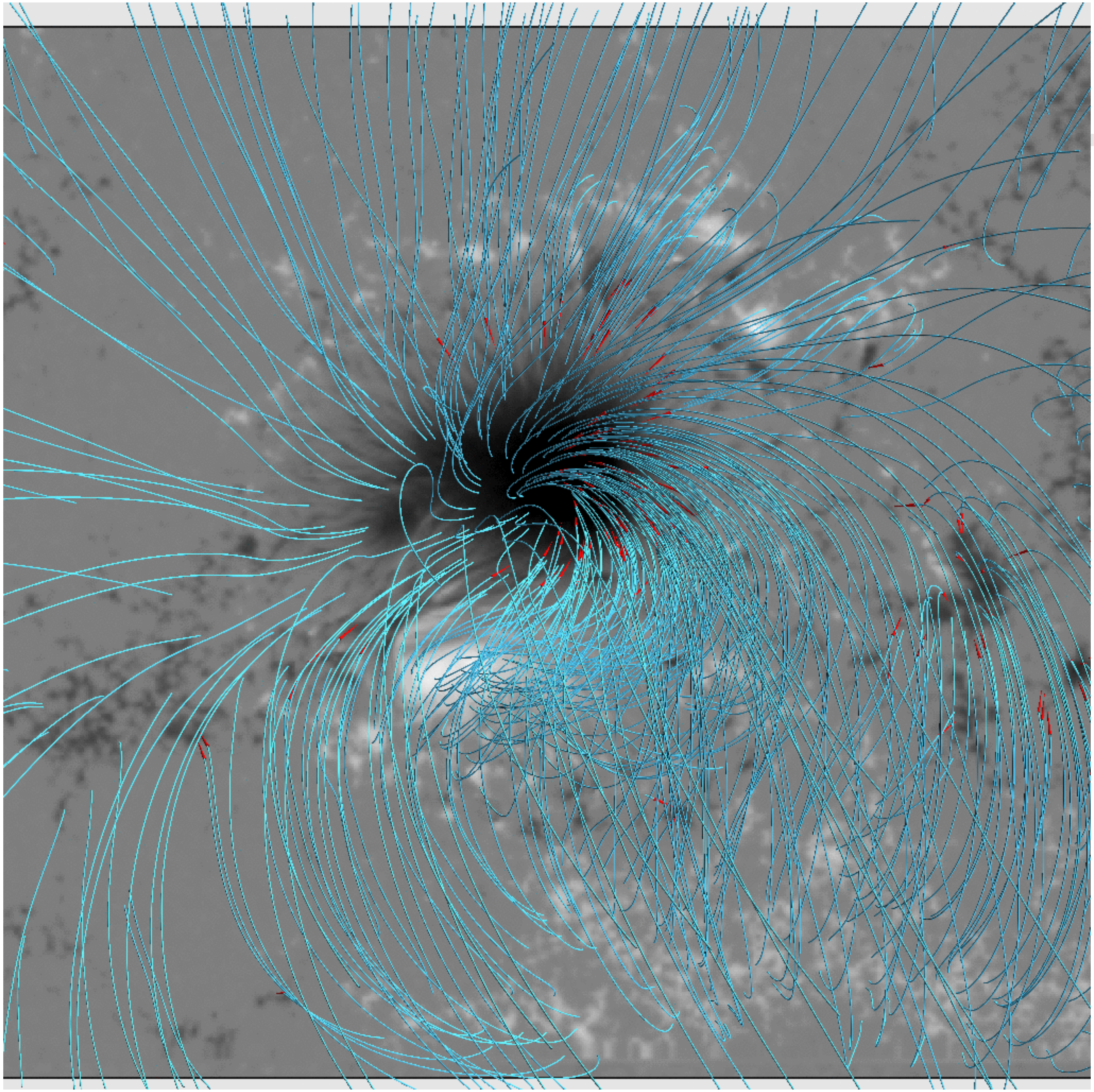


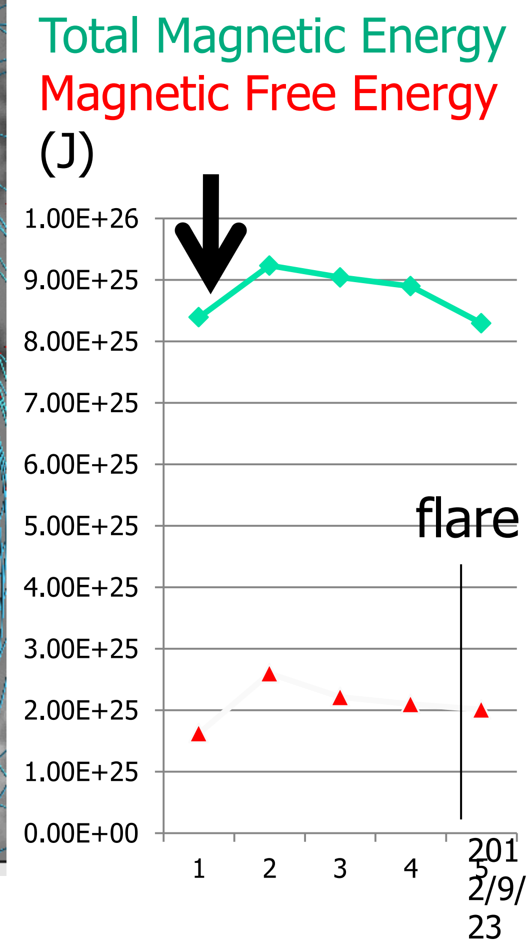
2006_12_11
17:00 UT

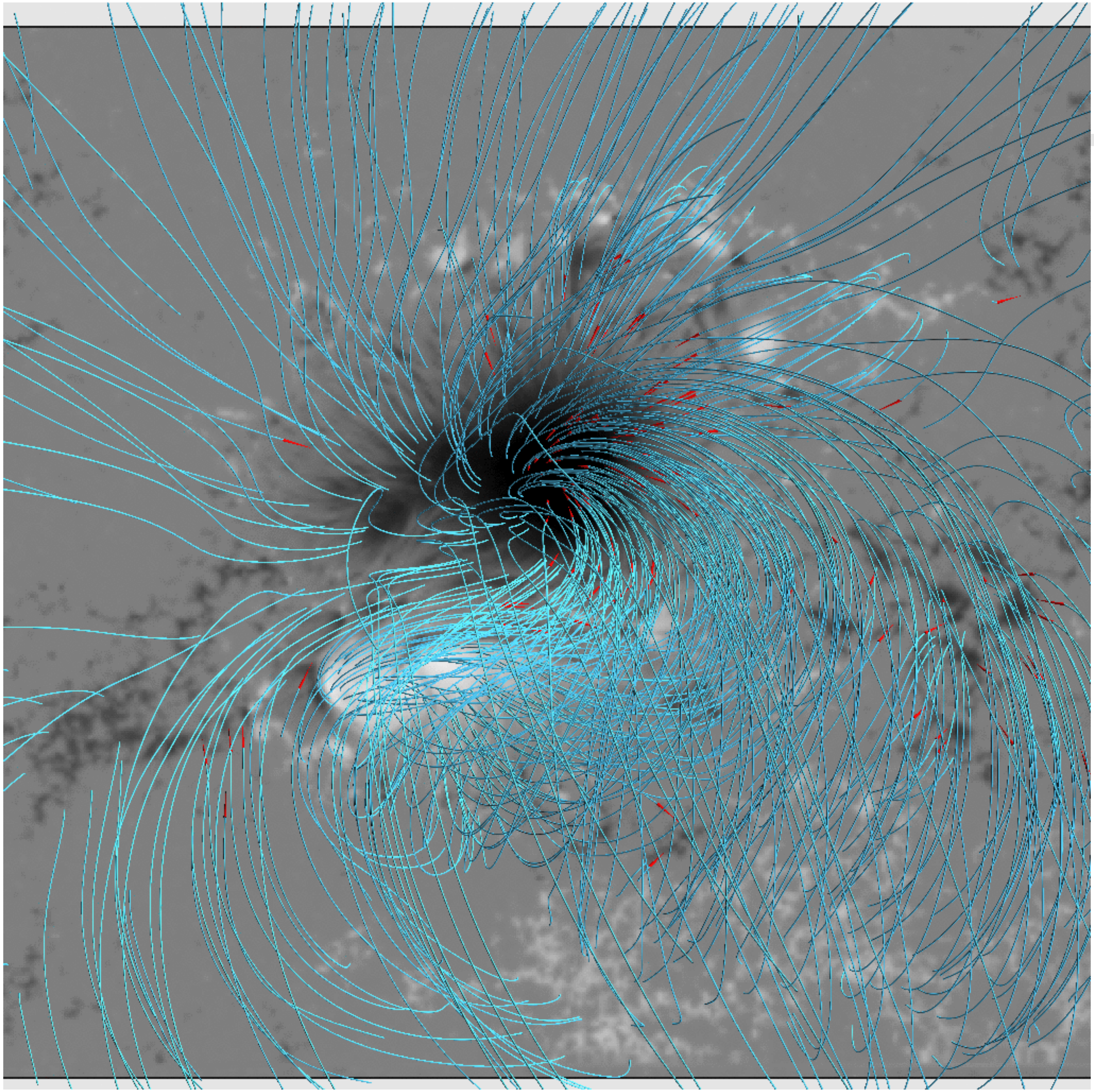


33h prior to flare

2006_12_11 17:00 UT

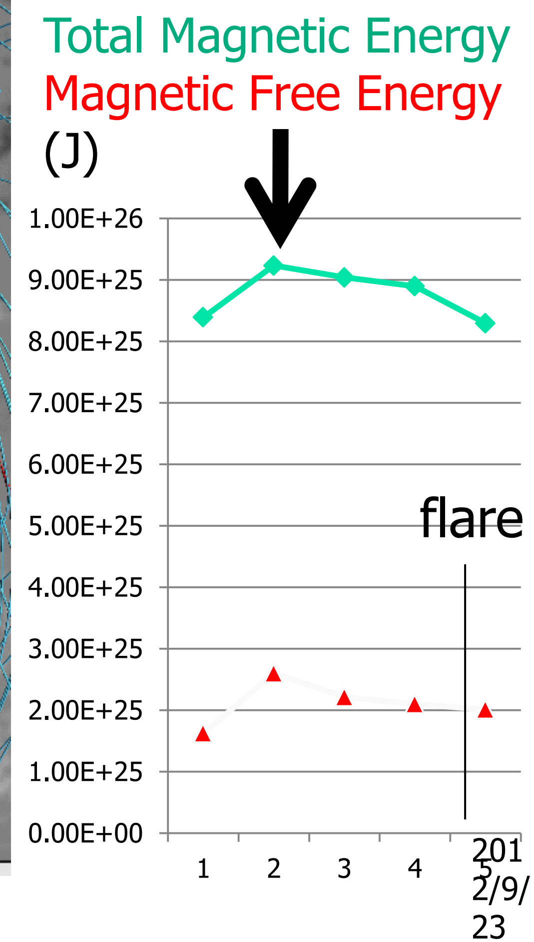






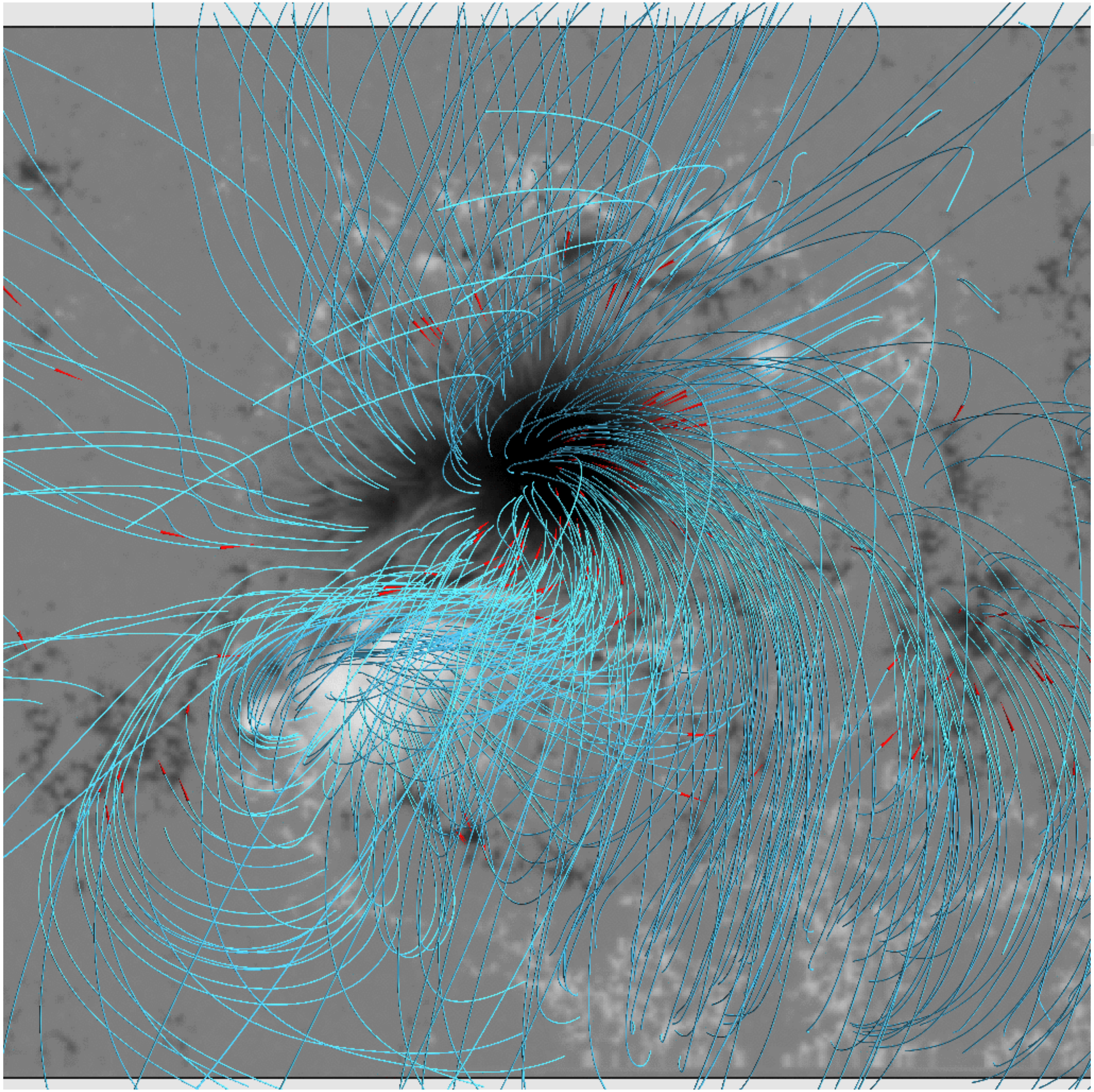
21h prior to flare

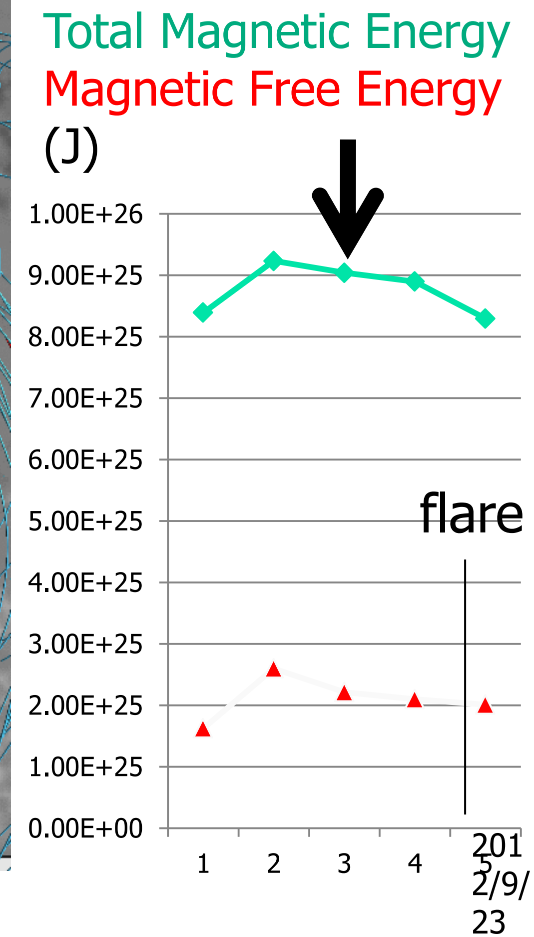
2006_12_12
03:50 UT

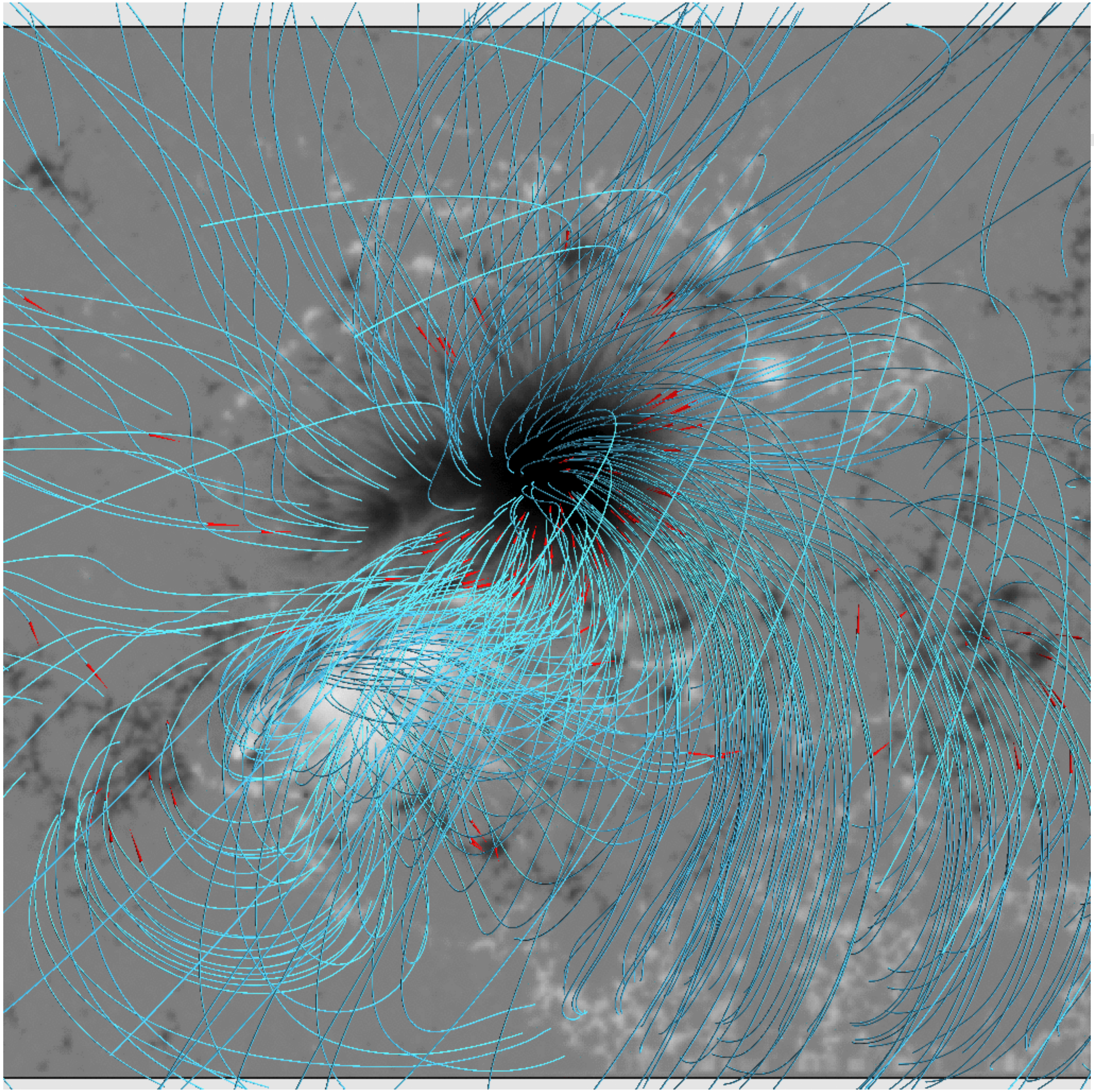


8h prior to flare

2006_12_12
17:40 UT



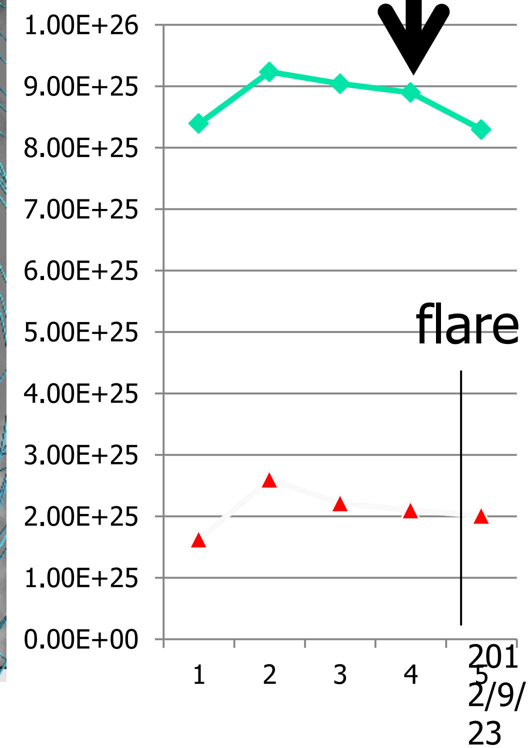




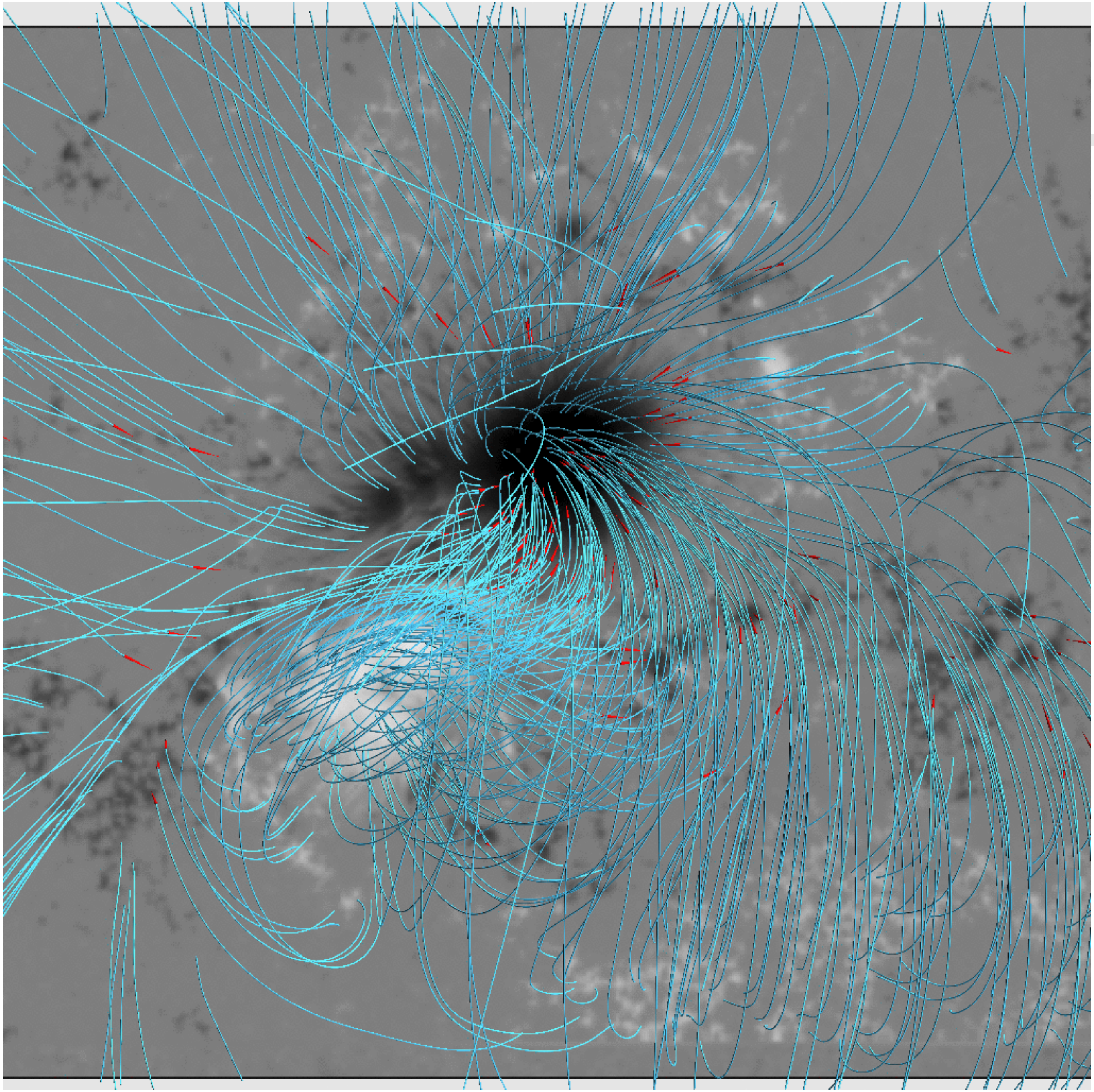
5h after flare

2006_12_12
20:30 UT

Total Magnetic Energy
Magnetic Free Energy
(J)

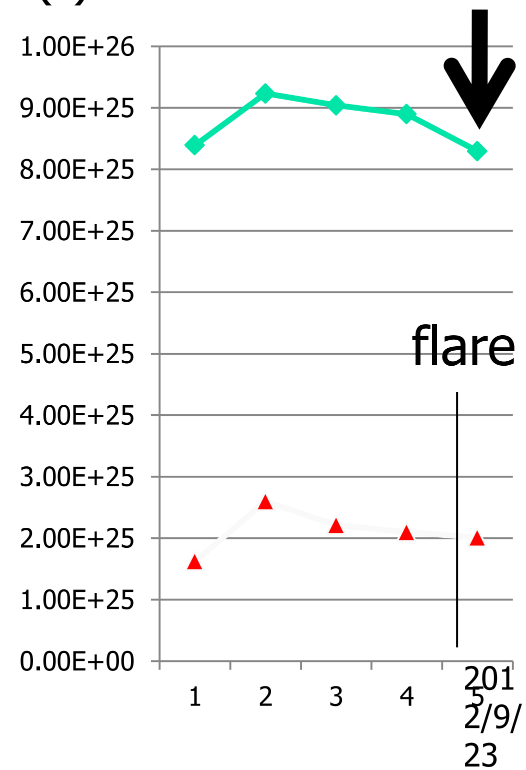


フレア発生
5時間後

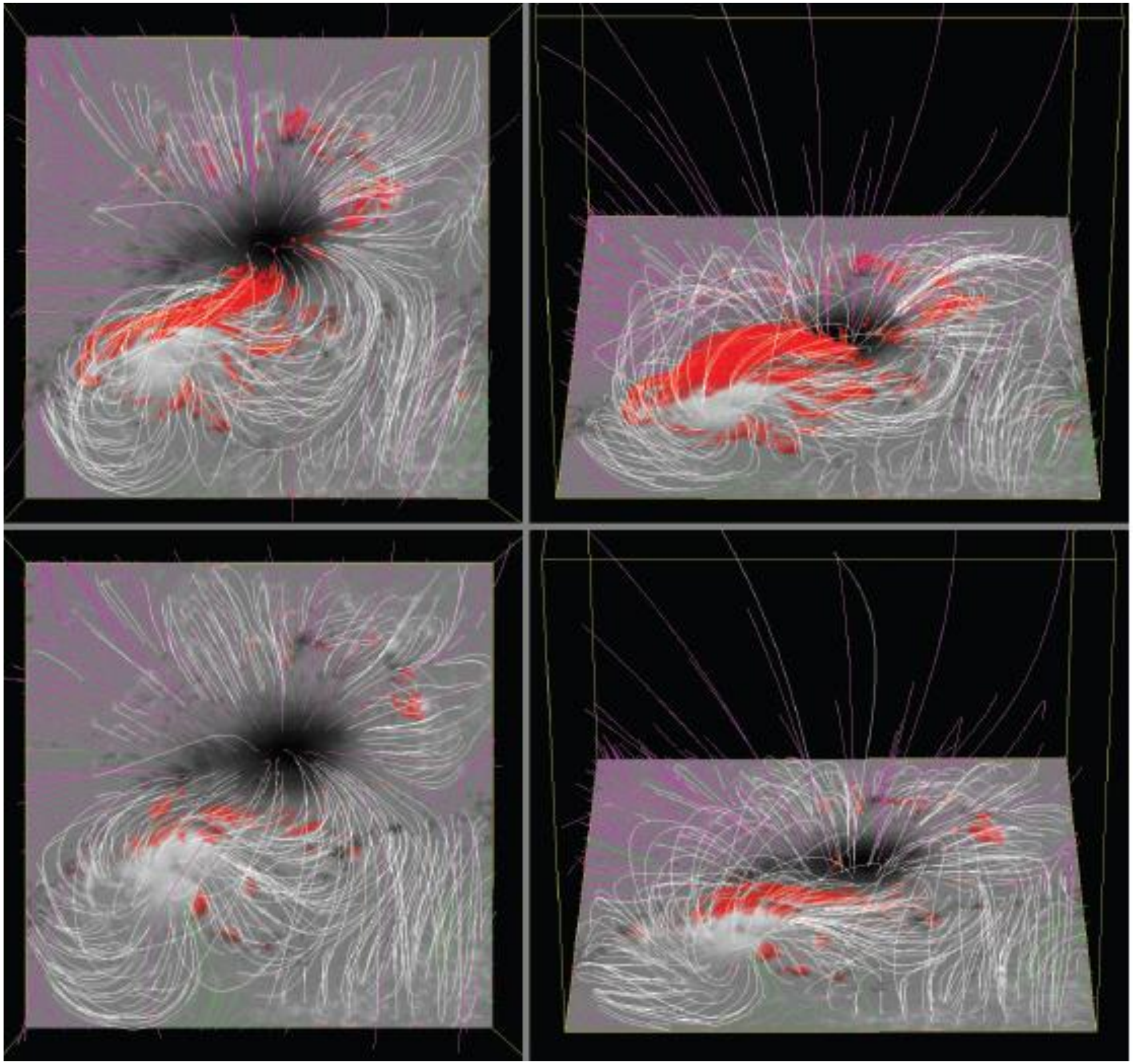


2006_12_13
07:00 UT

Total Magnetic Energy
Magnetic Free Energy
(J)

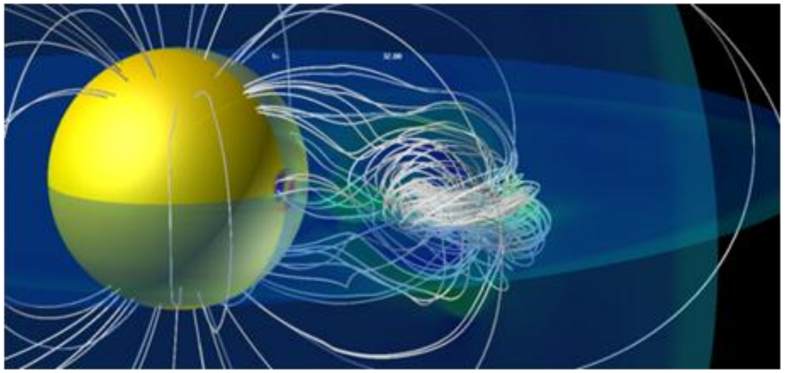


NLFF before & after flare

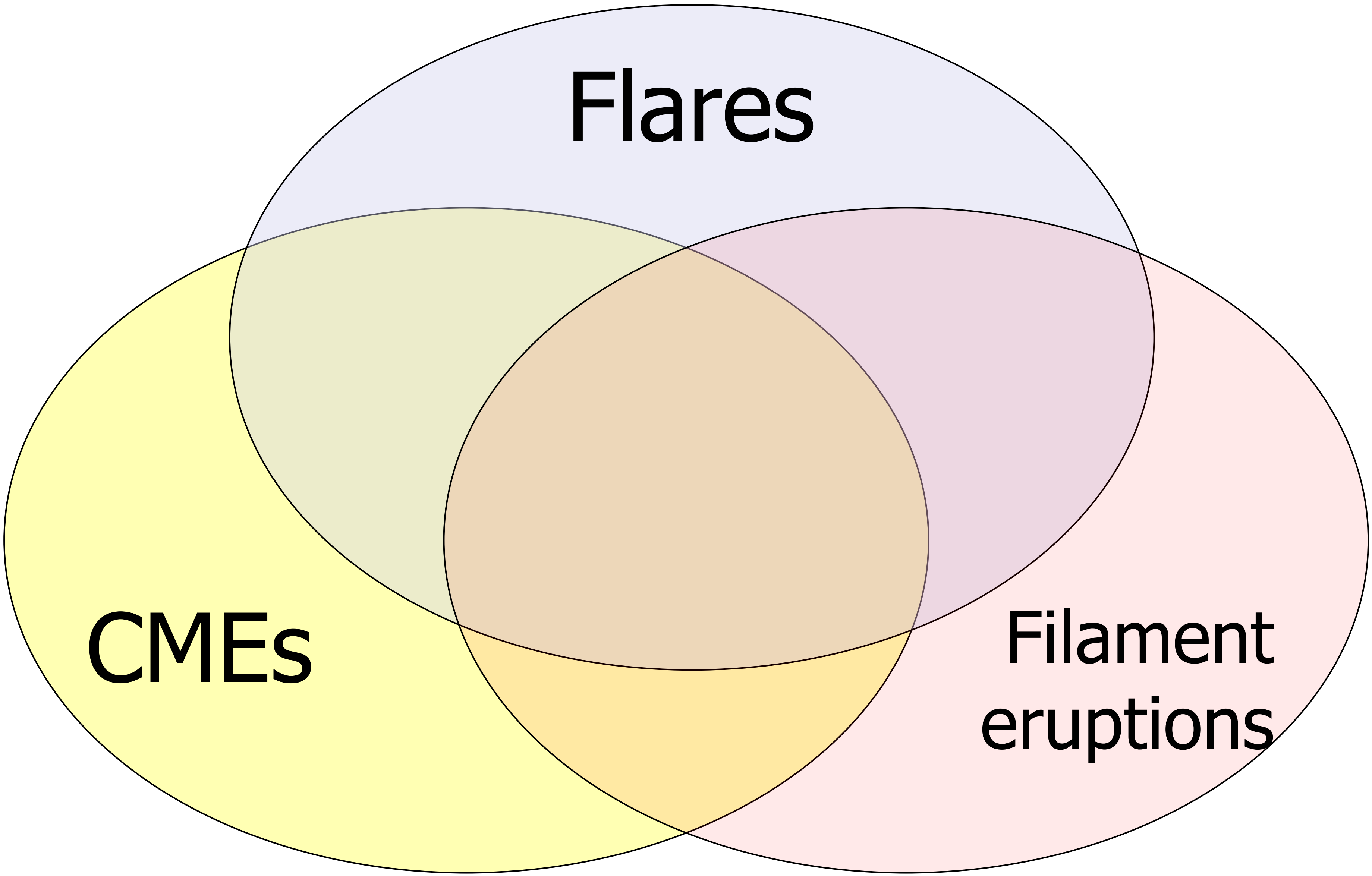


Schrijver et al. 2008

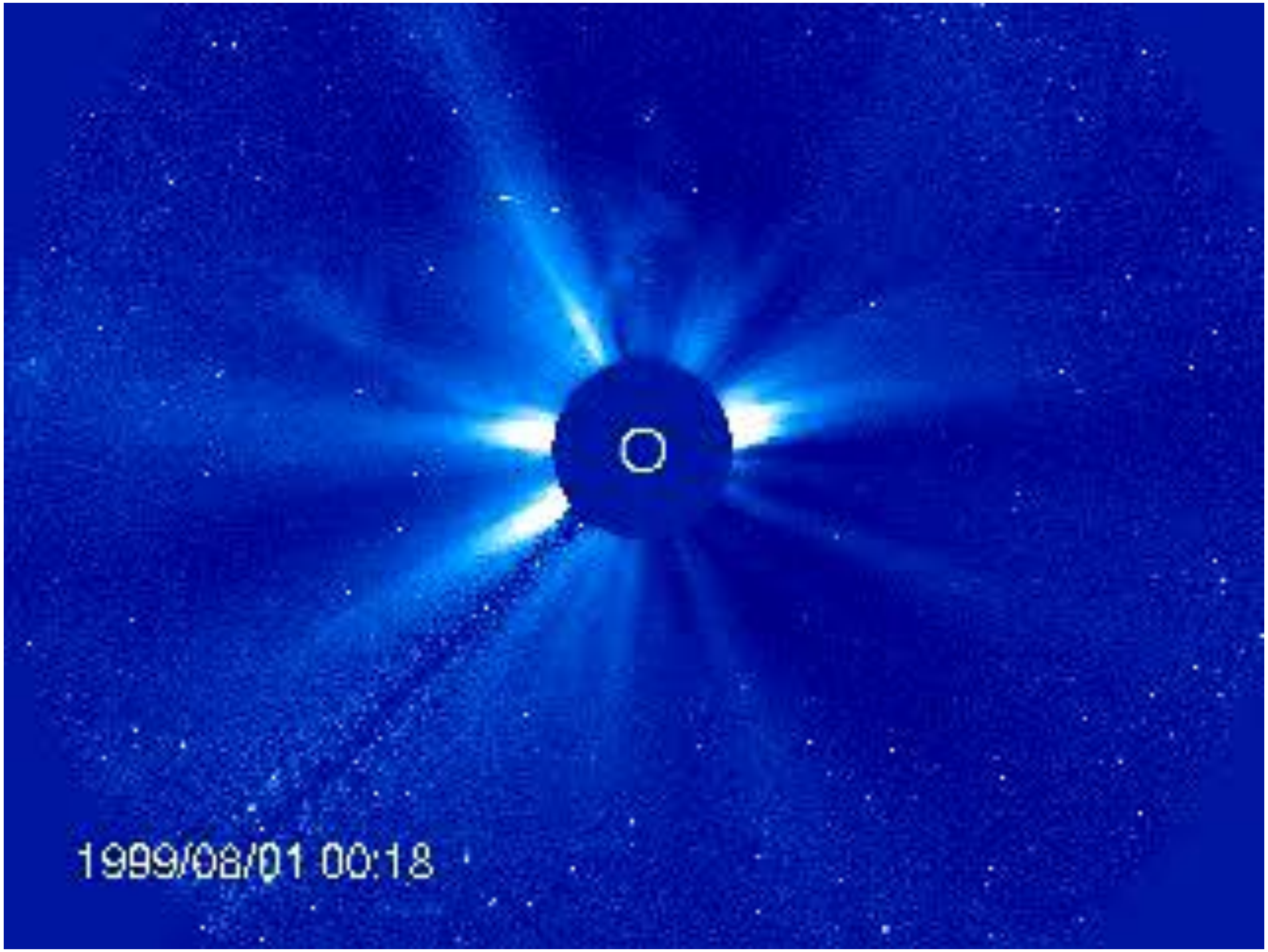
Dynamics in solar coronal magnetic field



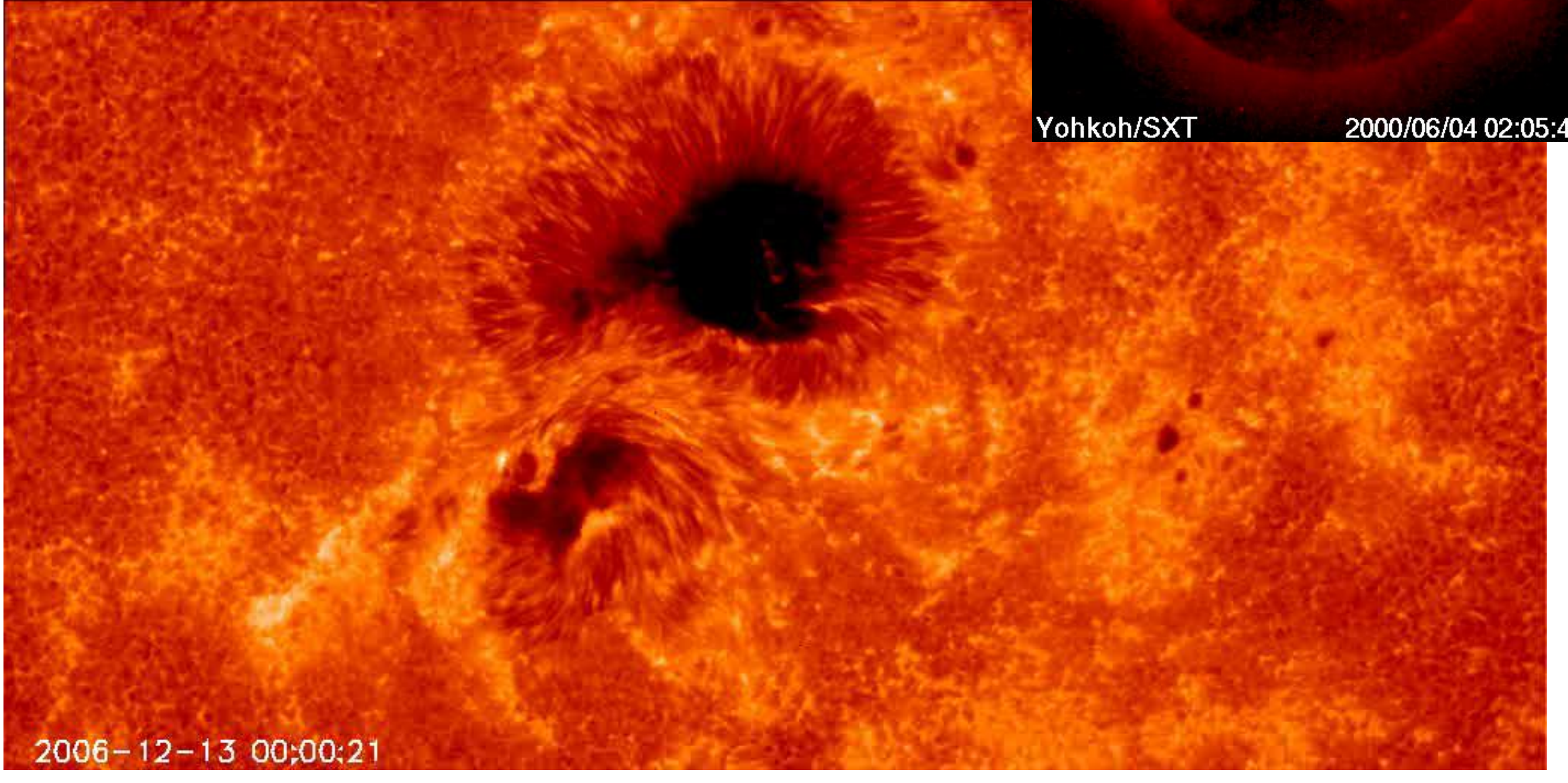
Solar Eruptions

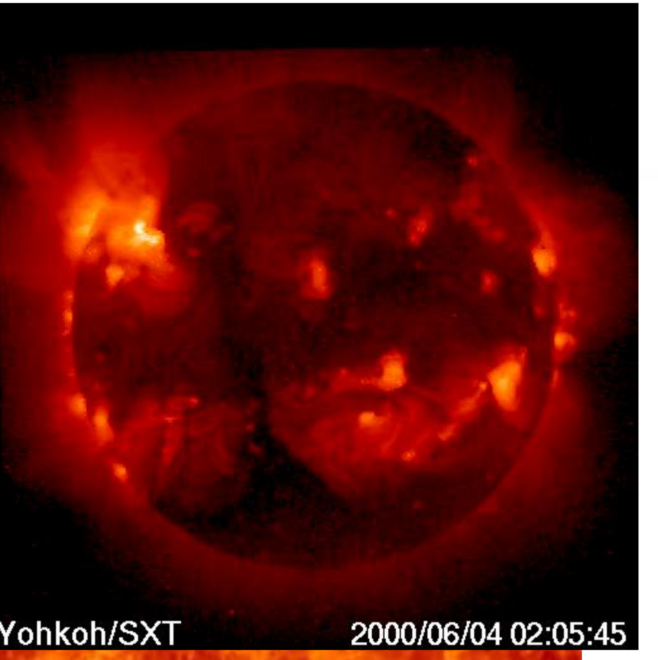


CMEs



Solar Flares





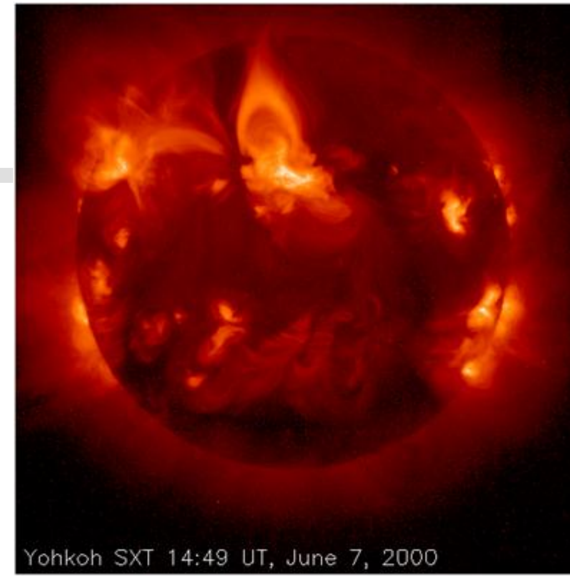
Properties of Flares

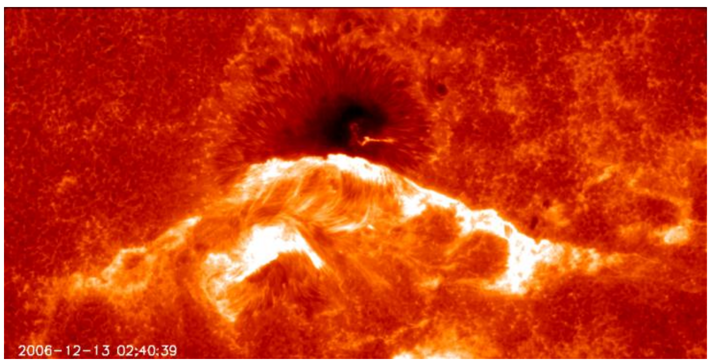
near sunspots

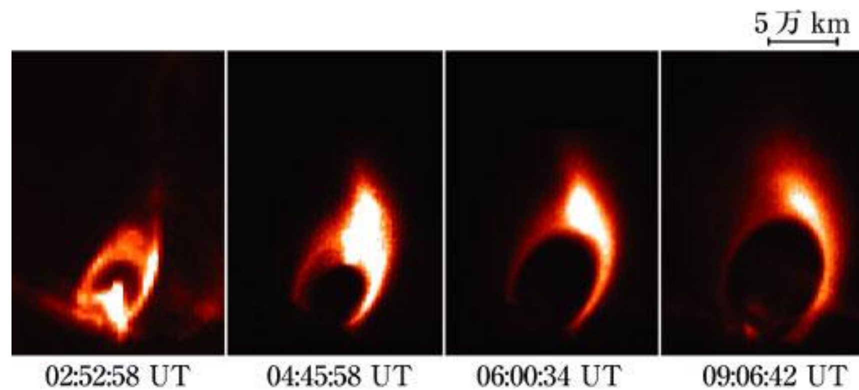
cusp loop

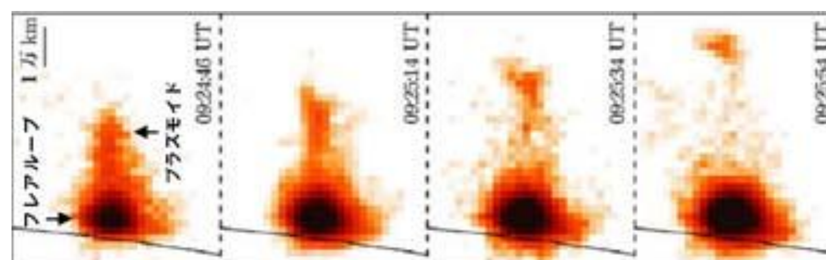
two-ribbon

plasmoid ejection

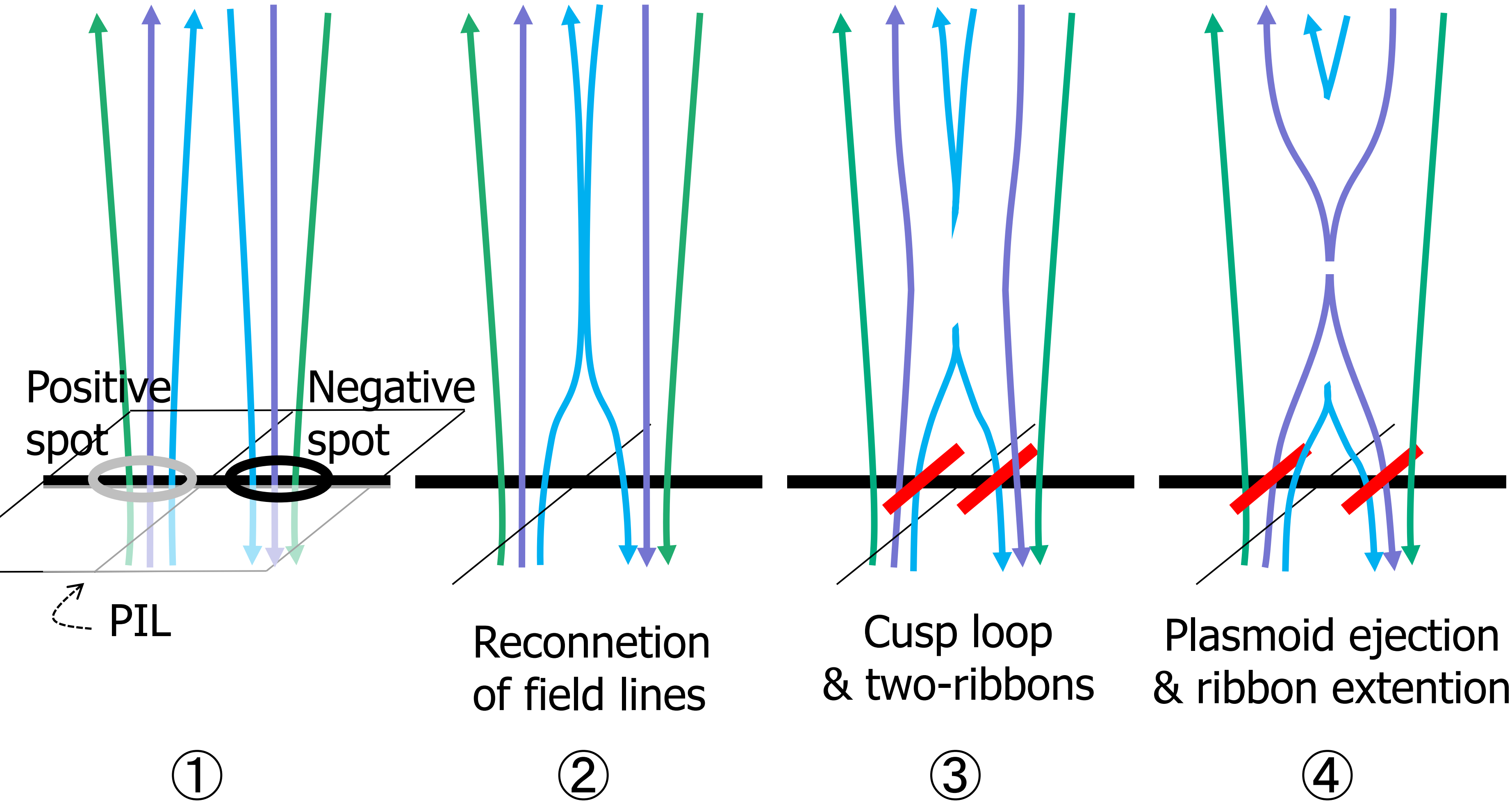




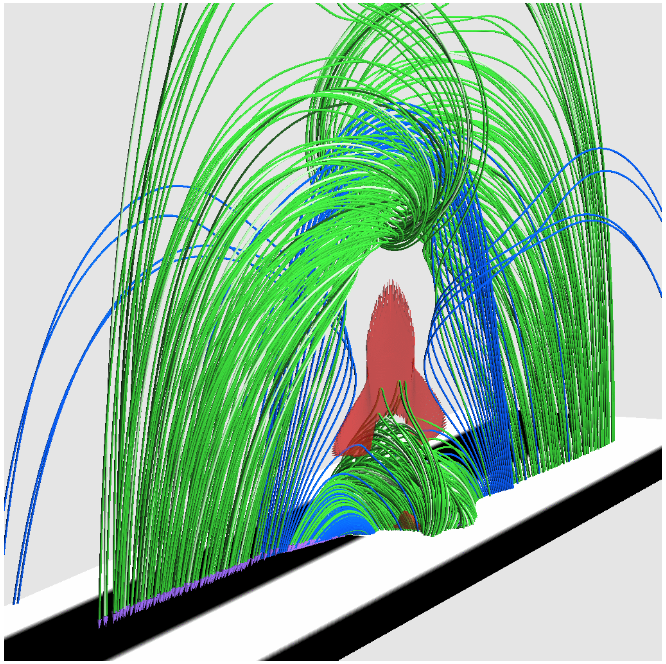




Magnetic Reconnection Model



What triggers the onset of solar eruptions?



Prediction is important.

- For the space weather forecasting
  - When will giant flares and CMEs occur?
  - How is the geo-effectiveness?

- For the promotion of scientific understandings
  - New theories have been established through the efforts for prediction.
    e.g. Halley's prediction (1682, 1758)

1656-1742

Papers for Flare Prediction

- Poisson statistics (Gallagher et al. 2002, Bloomfield1 et al 2012)
- Bayesian statistics (Wheatland 2005)
- wavelet predictors (Yu et al. 2010a)
- Bayesian networks (Yu et al. 2010b)
- vector machines (Li et al. 2007)
- discriminant analysis (Barnes et al. 2007)
- ordinal logistic regression (Song et al. 2009; Yuan et al. 2010)
- neural networks (Colak & Qahwaji 2009; Yu et al. 2009; Ahmed et al. 2012)
- predictor teams (Huang et al. 2010)
- superposed epoch analysis (Mason & Hoeksema 2010)
- empirical projections (Falconer et al. 2011).

Skill Score of X-flare prediction

1day	2day	3day	year (events)
-0.068	-0.096	-0.141	2011 (8)
0.112	-0.147	-0.171	2006 (4)
0.242	0.147	0.127	2005 (13)
0.052	-0.001	-0.044	2004 (9)
0.200	0.093	0.076	2003 (17)
-0.037	-0.050	-0.033	2002 (12)
-0.061	-0.034	-0.006	2001 (18)

Space Weather Prediction Center

http://www.swpc.noaa.gov/forecast_verification/

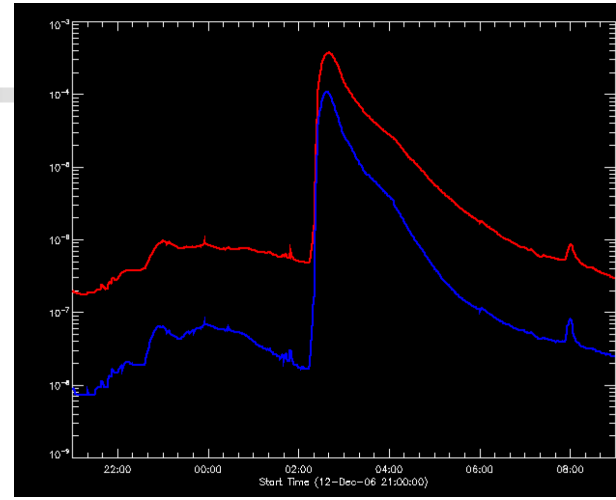
$$SS = \frac{n_{ff} - (n_q - n_{qq})}{n_f}$$

Storage & Release Process

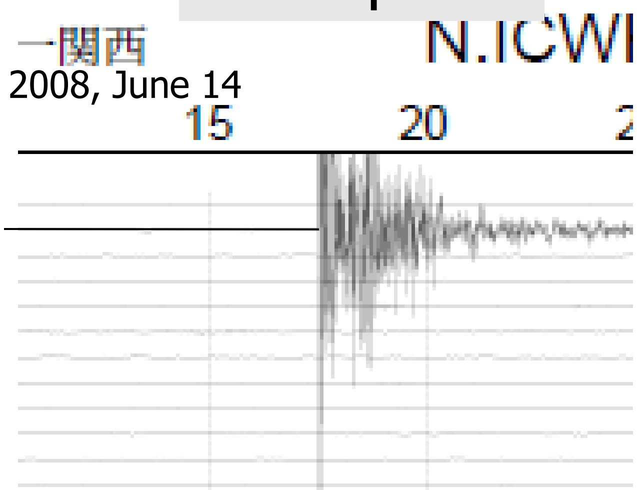
High State → Transition → Low State

Storage of free energy | trigger | Release of Free Energy

solar flare (GOES X-ray flux)



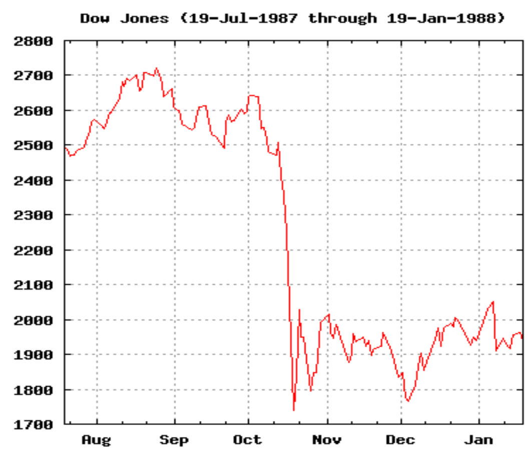
earthquake



防災科学研究所

stock market

(Dou Jones in Black Monday)



low price → fear of investor → sell order → low price

segative spiral

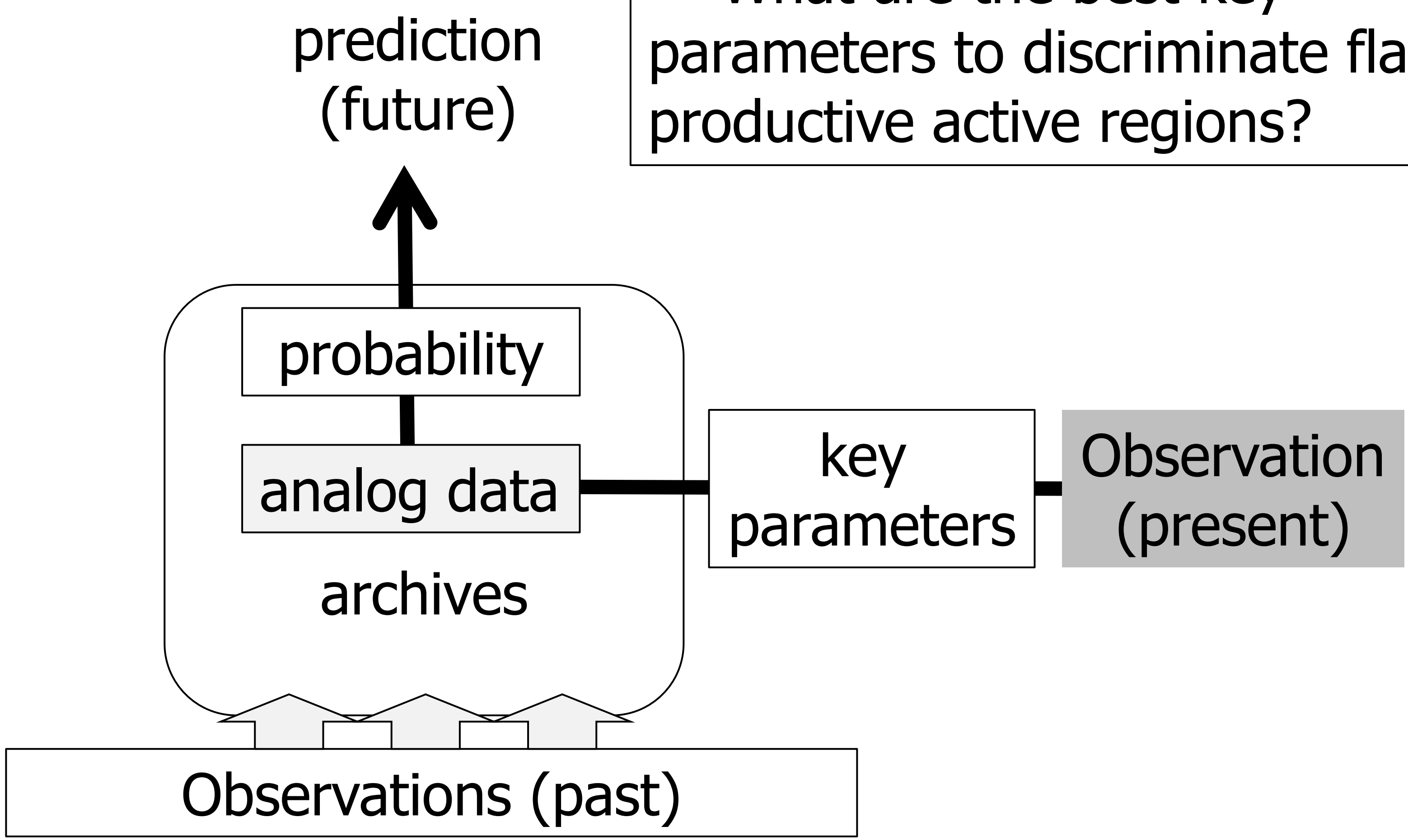
http://en.wikipedia.org/wiki/Black_Monday_%281987%29

Empirical Prediction

Analog Method

Problem

What are the best key parameters to discriminate flare productive active regions?



McIntosh classification

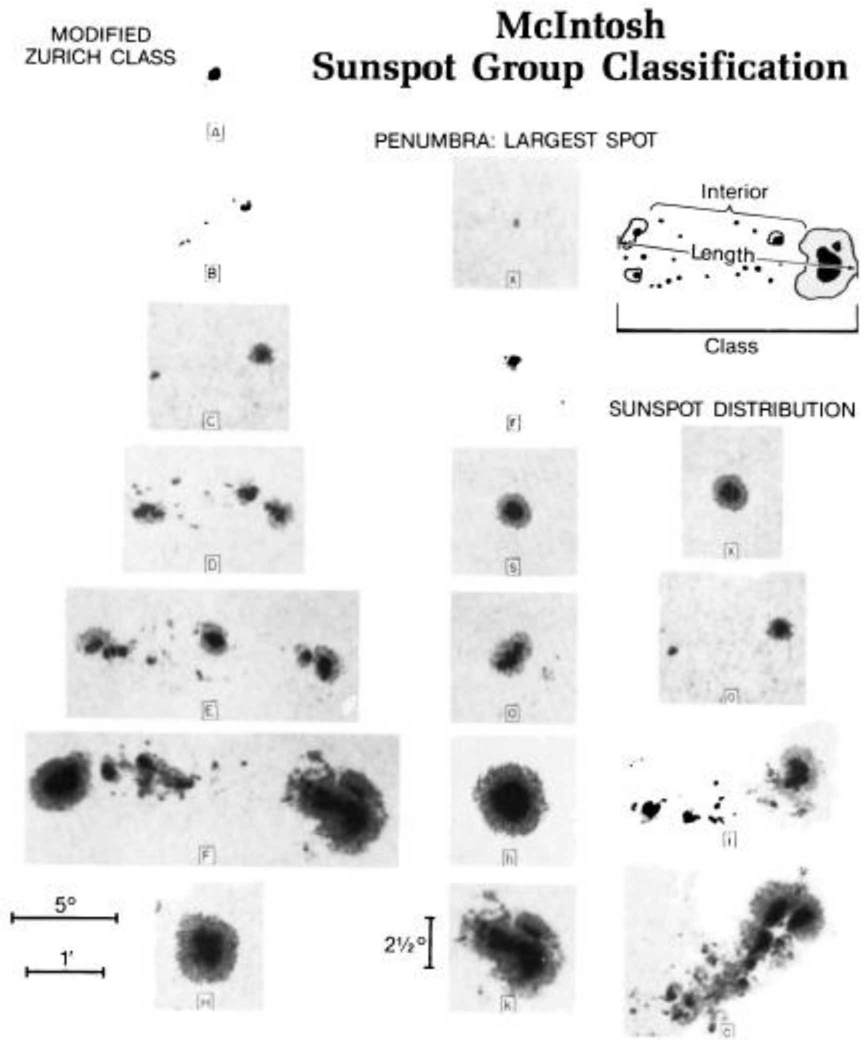


Fig. 1. The 3-component McIntosh classification, with examples of each category.

McIntosh 1990

Flare Prob. for each McIntosh class

- Gallacher, Moon, Wang 2002 Sol. Phys.

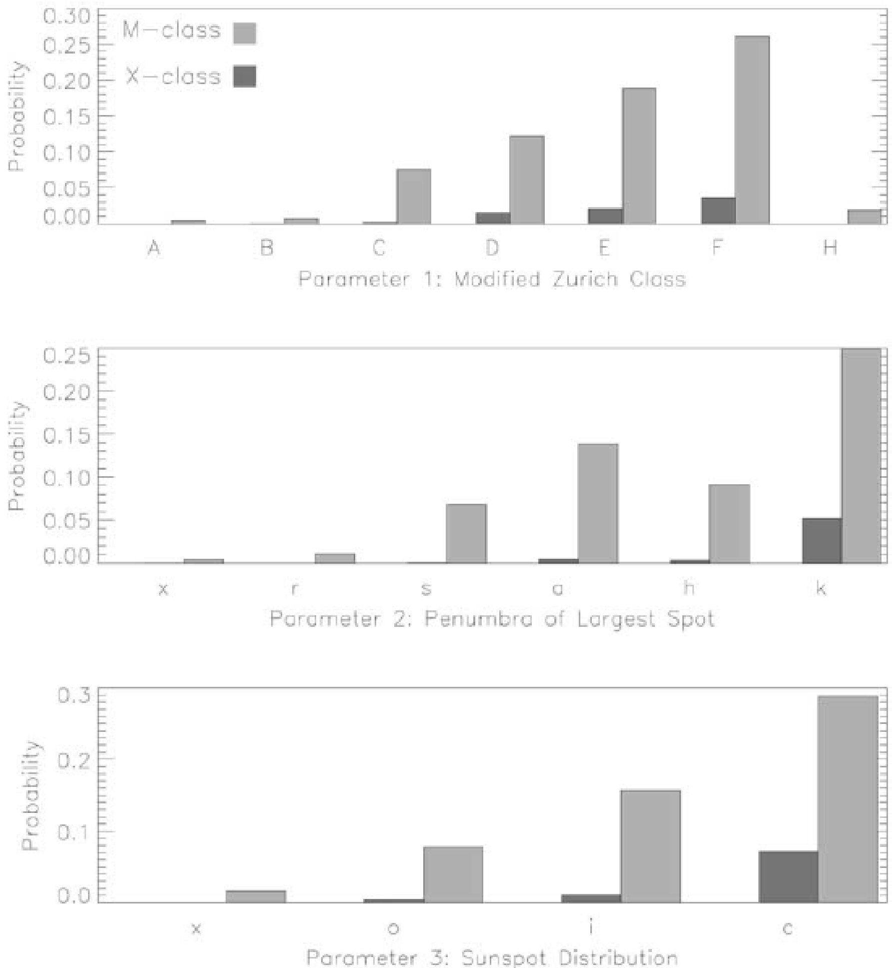
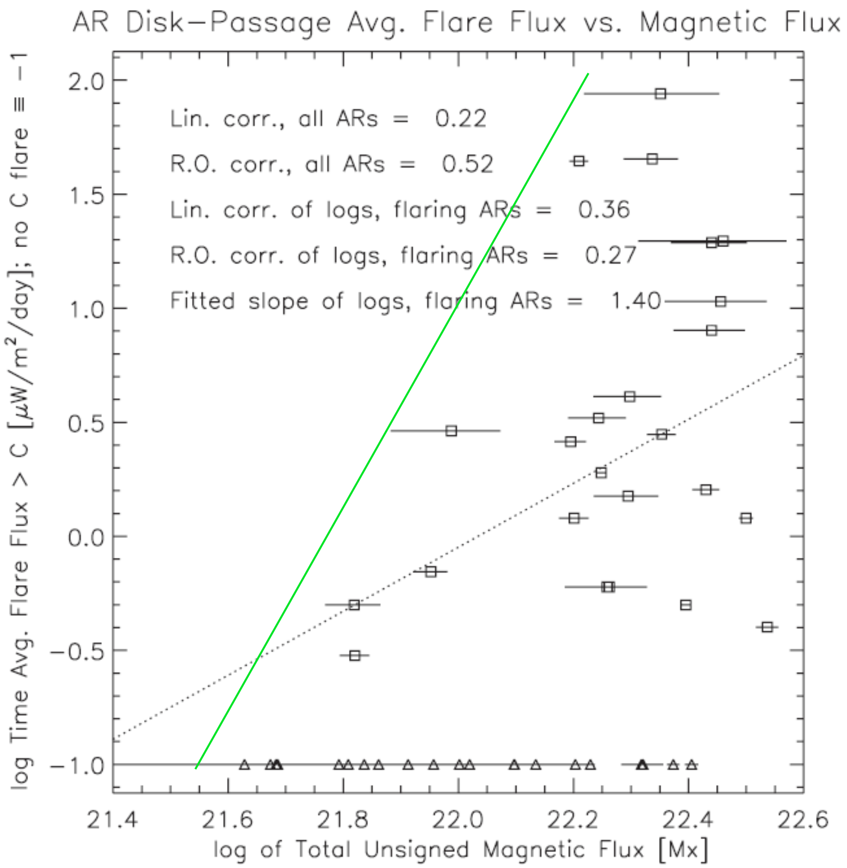


Figure 4. Derived 24-hour active-region flare probabilities for each of the three McIntosh classification parameters using Poisson statistics.

Welsch et al. 2009 ApJ

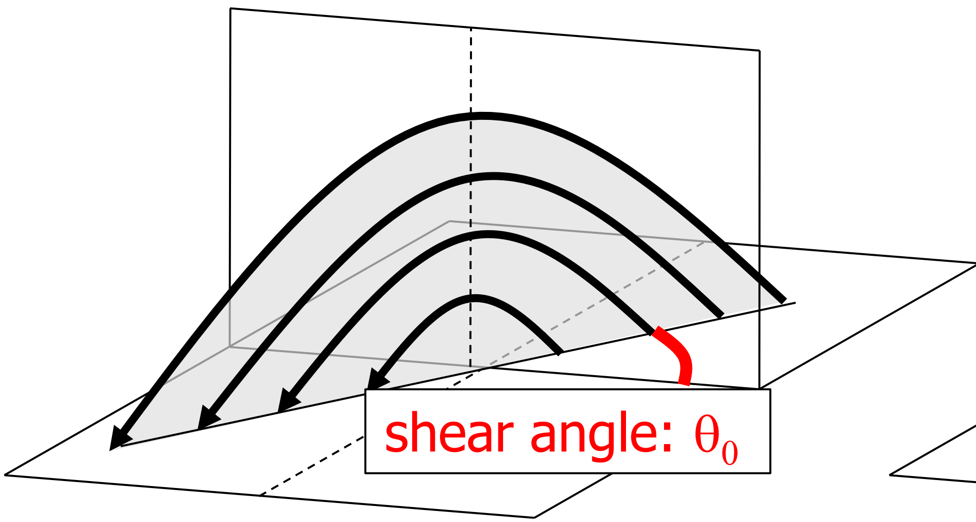
- The total magnetic flux decides the maximum flare size.

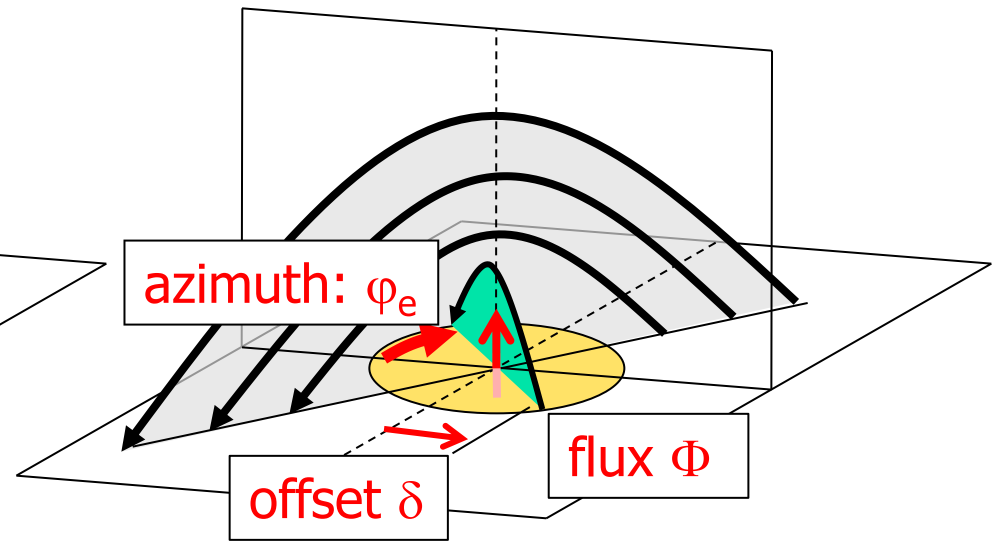


Kusano et al. 2012 submitted to ApJ

Ensemble Simulation Study

Large field (free energy) & Small field (trigger)





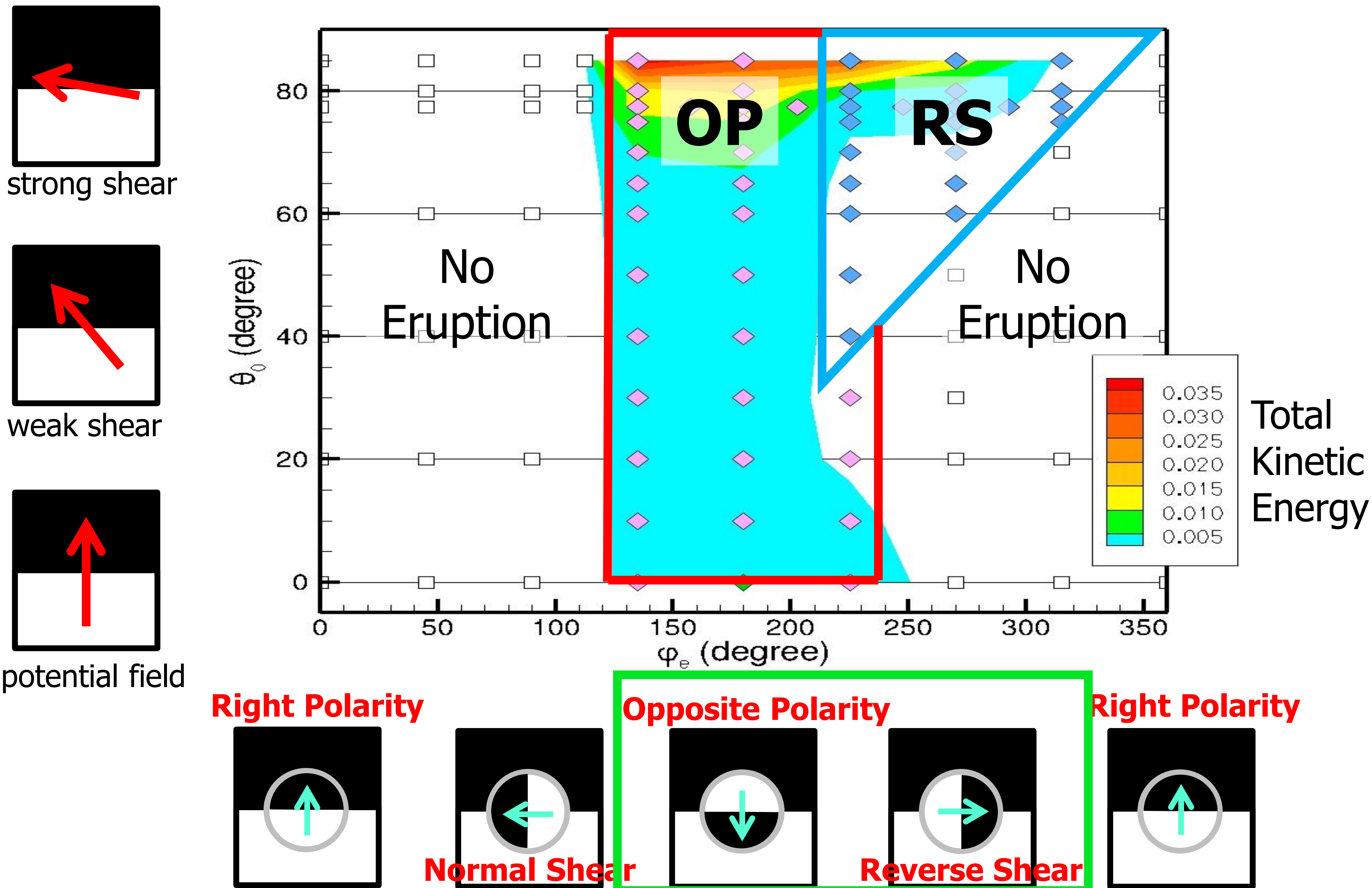
Box : Rectangle including PIL
Initial condition : LFFF

BC : imposing the electric field to simulate flux emerging

161 simulations

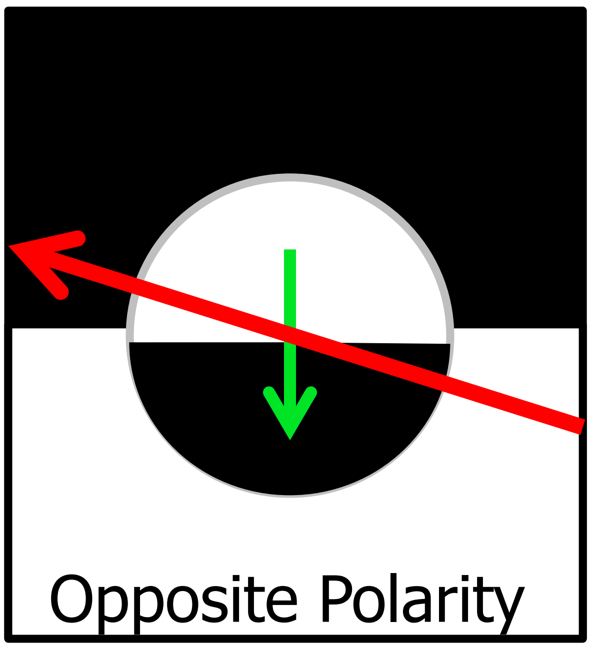
- 3D MHD (zero-beta model)
- 256x1024x512 grids (finite difference scheme)
- output: 800 GB／run

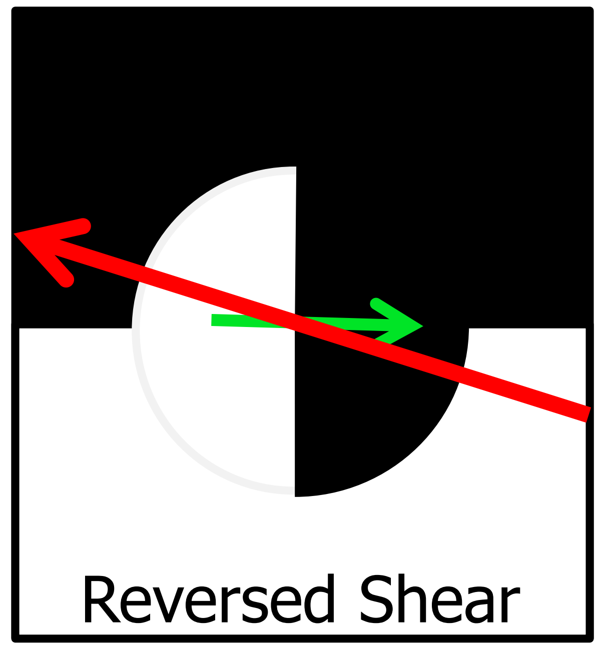
Simulation Results



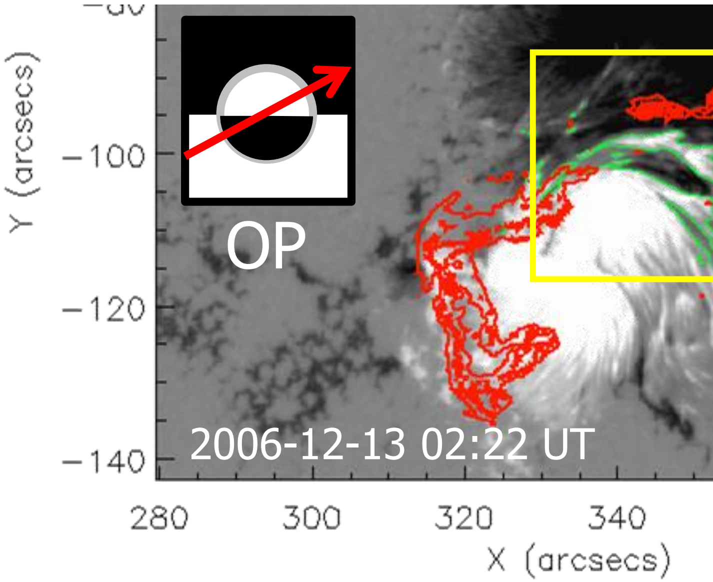
Two Structures Triggering Eruption

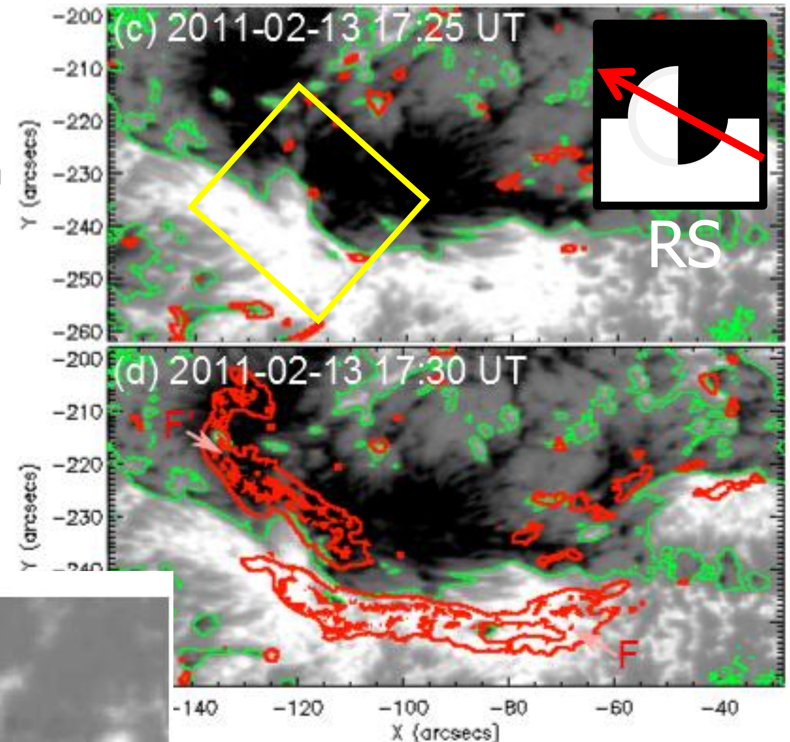
- There are the two different structures (OP and RS) favorable to the onset of solar flares.

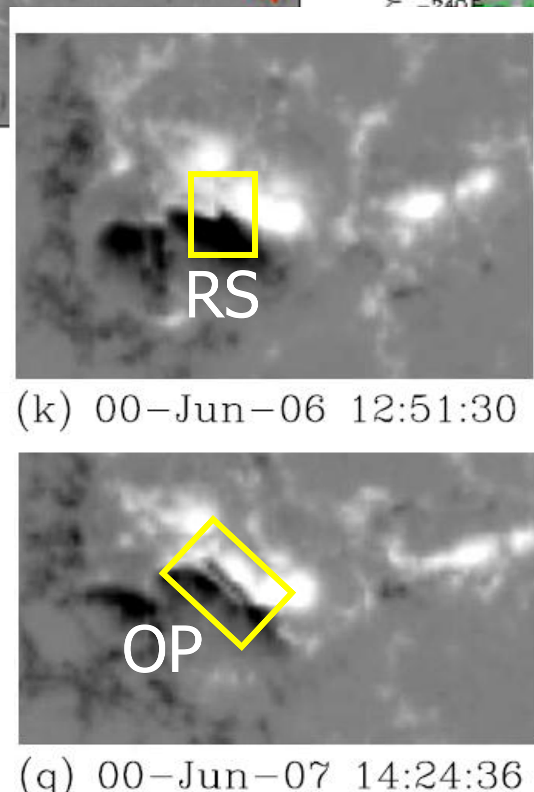


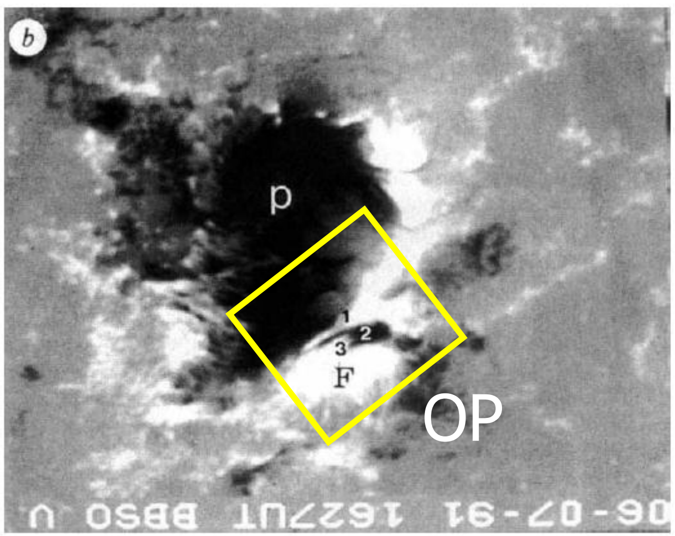


Observations



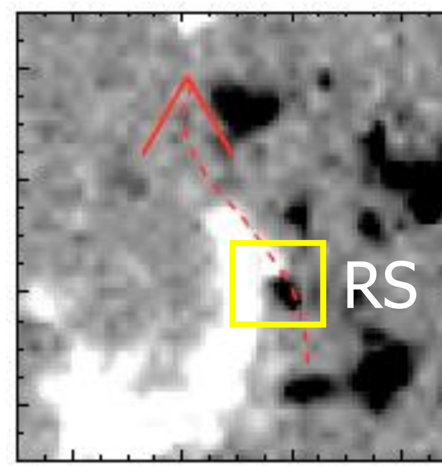






Zirin and Wang 1993

Kurokawa, Wang & Ishii 2002



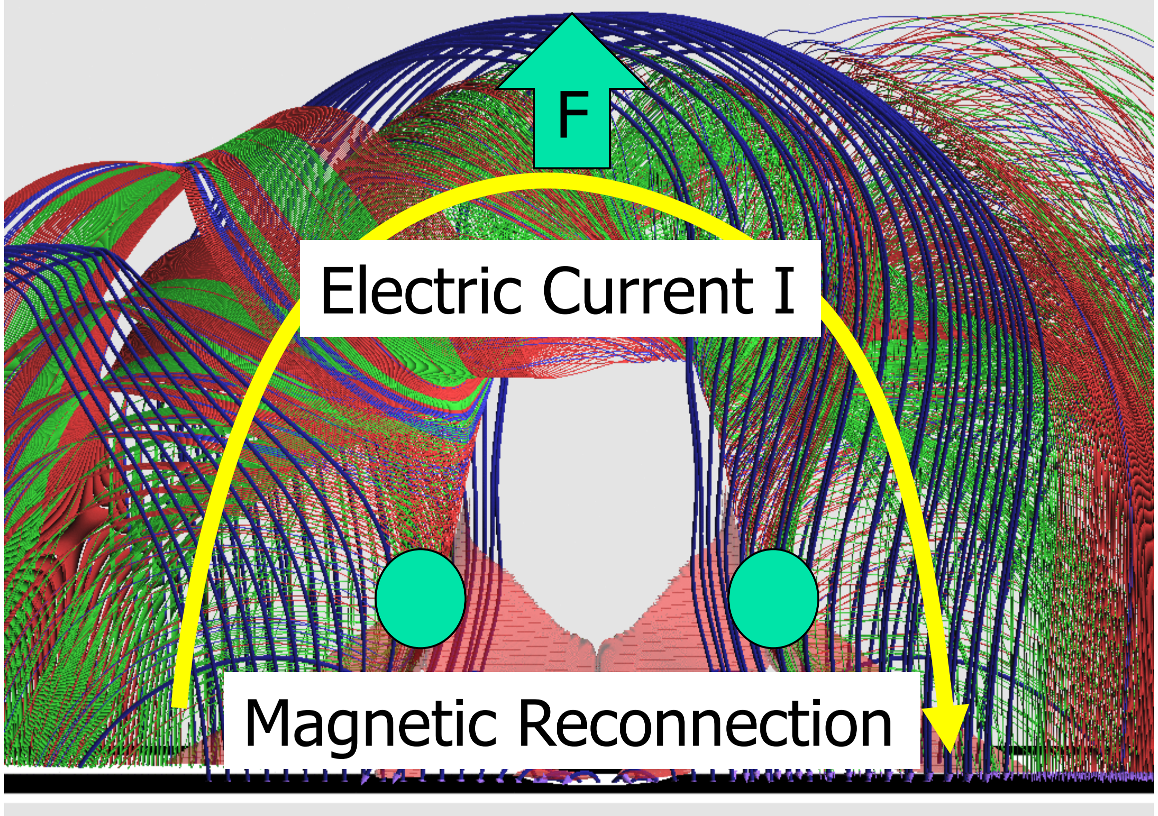
Green, Kliem & Wallace 2011

Eruption & Reconnection (OP)

Tether cutting model
Moore & Roumeliotis
1992

$$F = r_c I^2 - B_p I$$

Loss of equirlibrium
Forbes & Priest 1995
Torus Instability
Kliem & Torok 2006



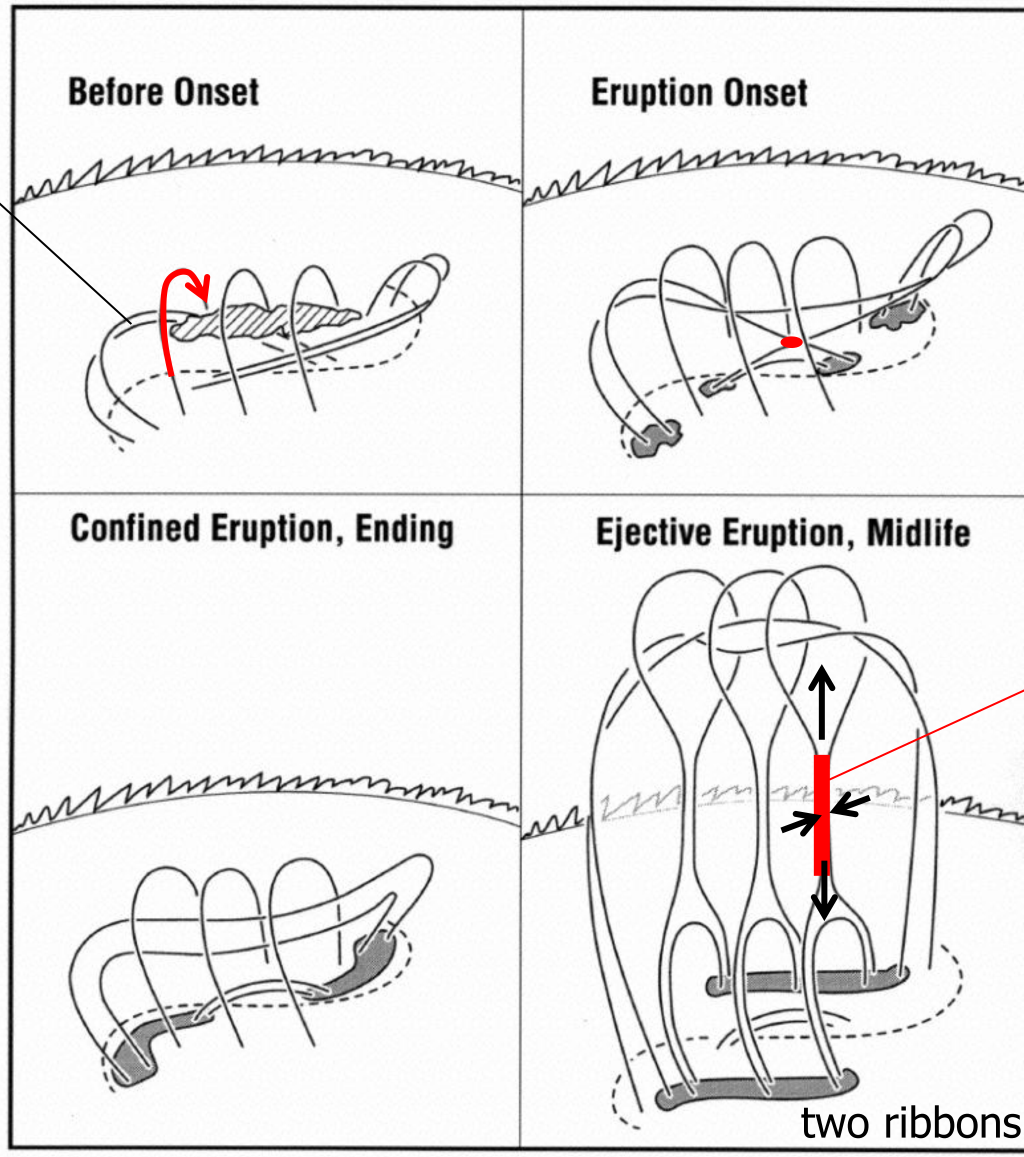
Tether Cutting Scenario

magnetic shear (field-aligned current)

magnetic free energy (magnetic helicity)

force-free field

$$\nabla \times \mathbf{B} = \alpha \mathbf{B}$$

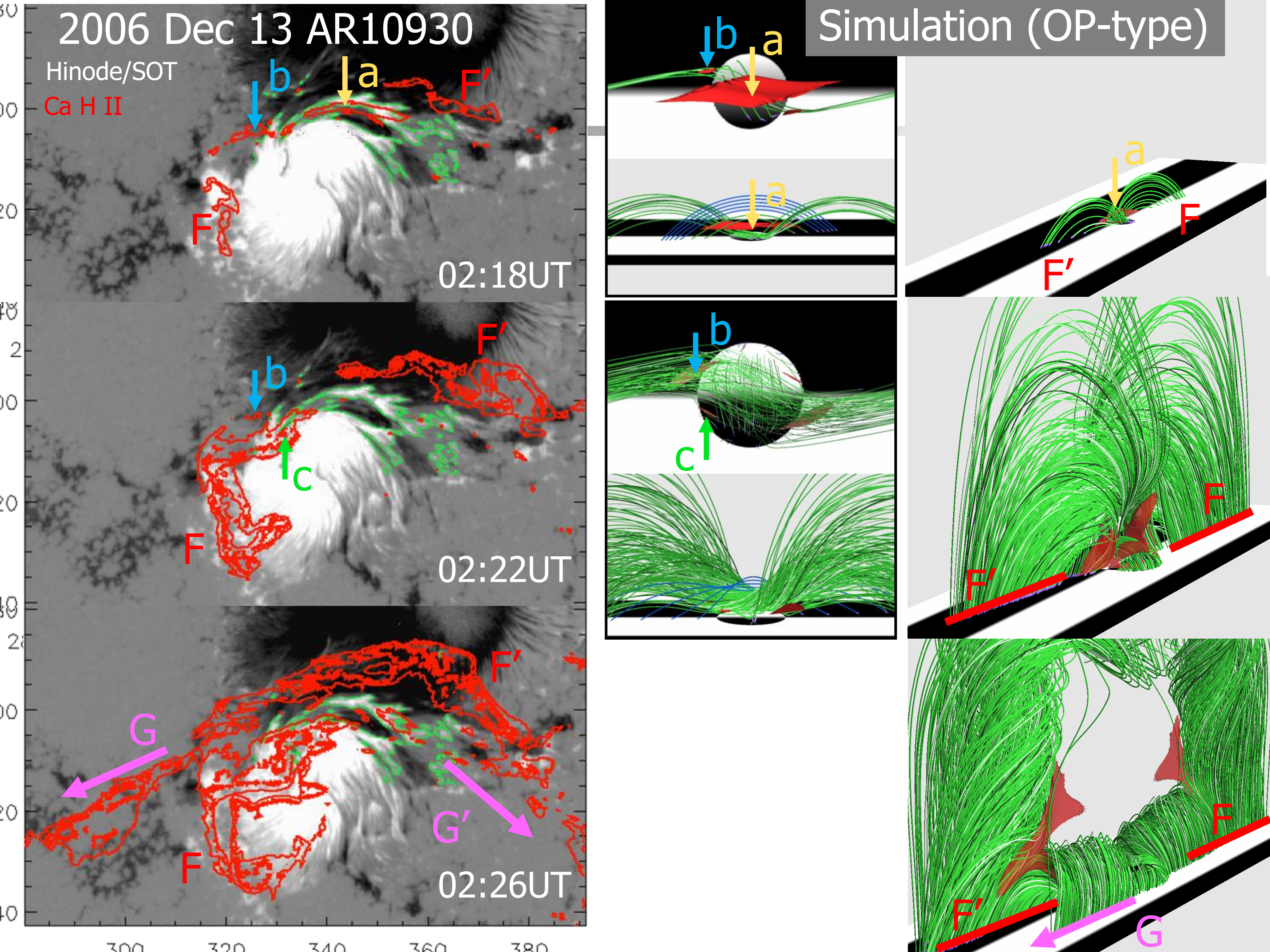


Moor et al. 2001

Reconnection as trigger

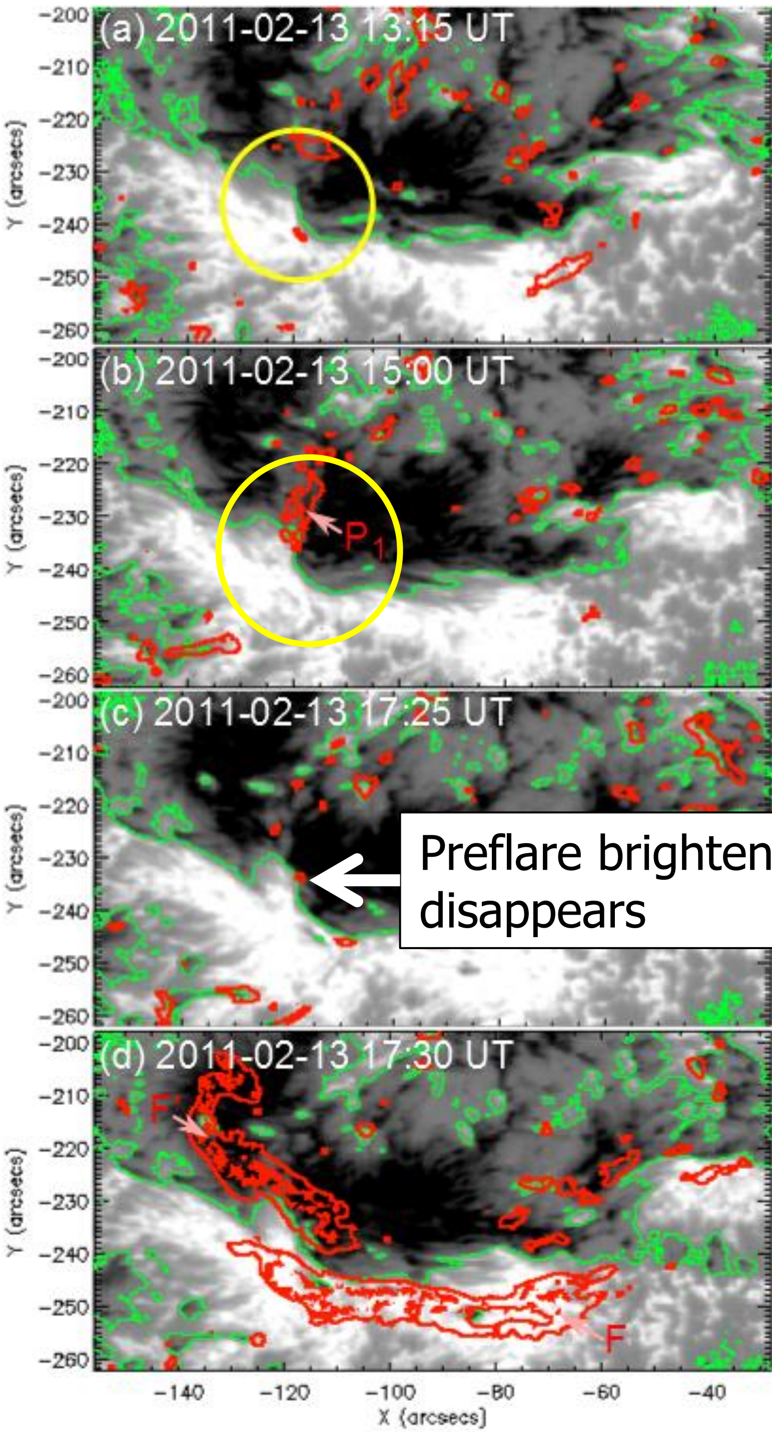
vertical current sheet (diffusion region)

flare reconnection

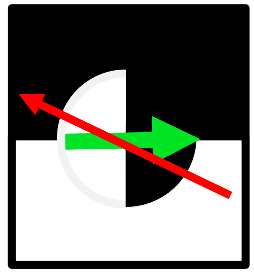


2006 Dec 13 AR10930
Hinode/SOT
Ca H II
02:18UT
02:22UT
02:26UT
Simulation (OP-type)
a
b
c
F
F′
G
G′
300
320
340
360
380

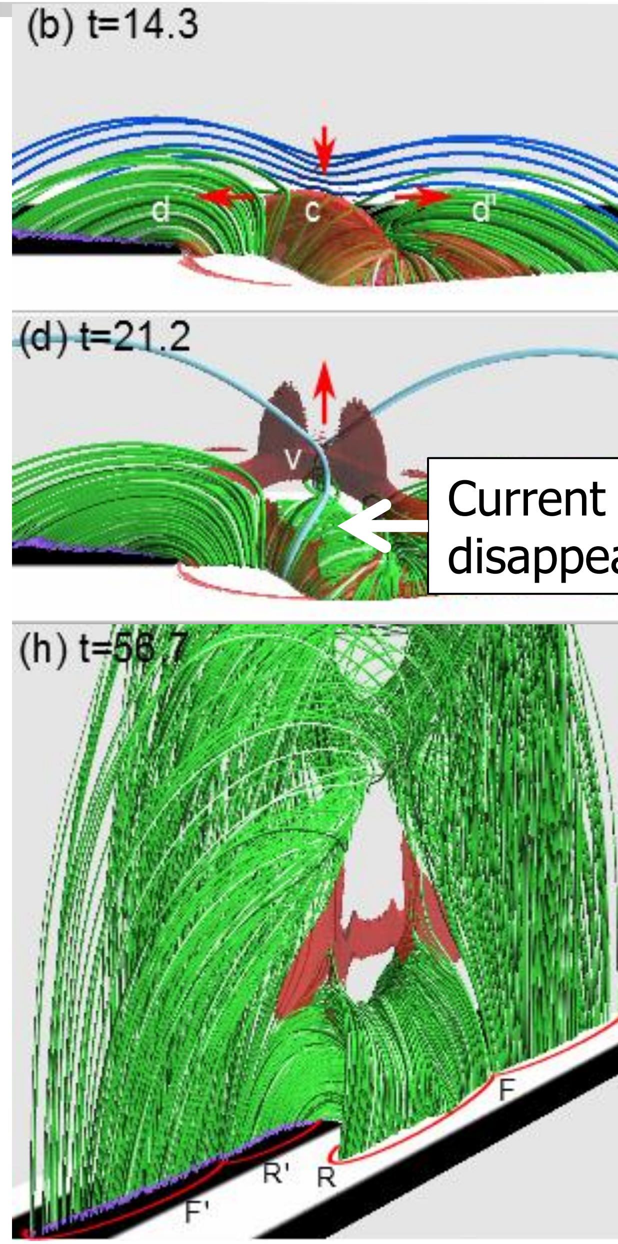
Simulation (RS-type)



Preflare brightening disappears

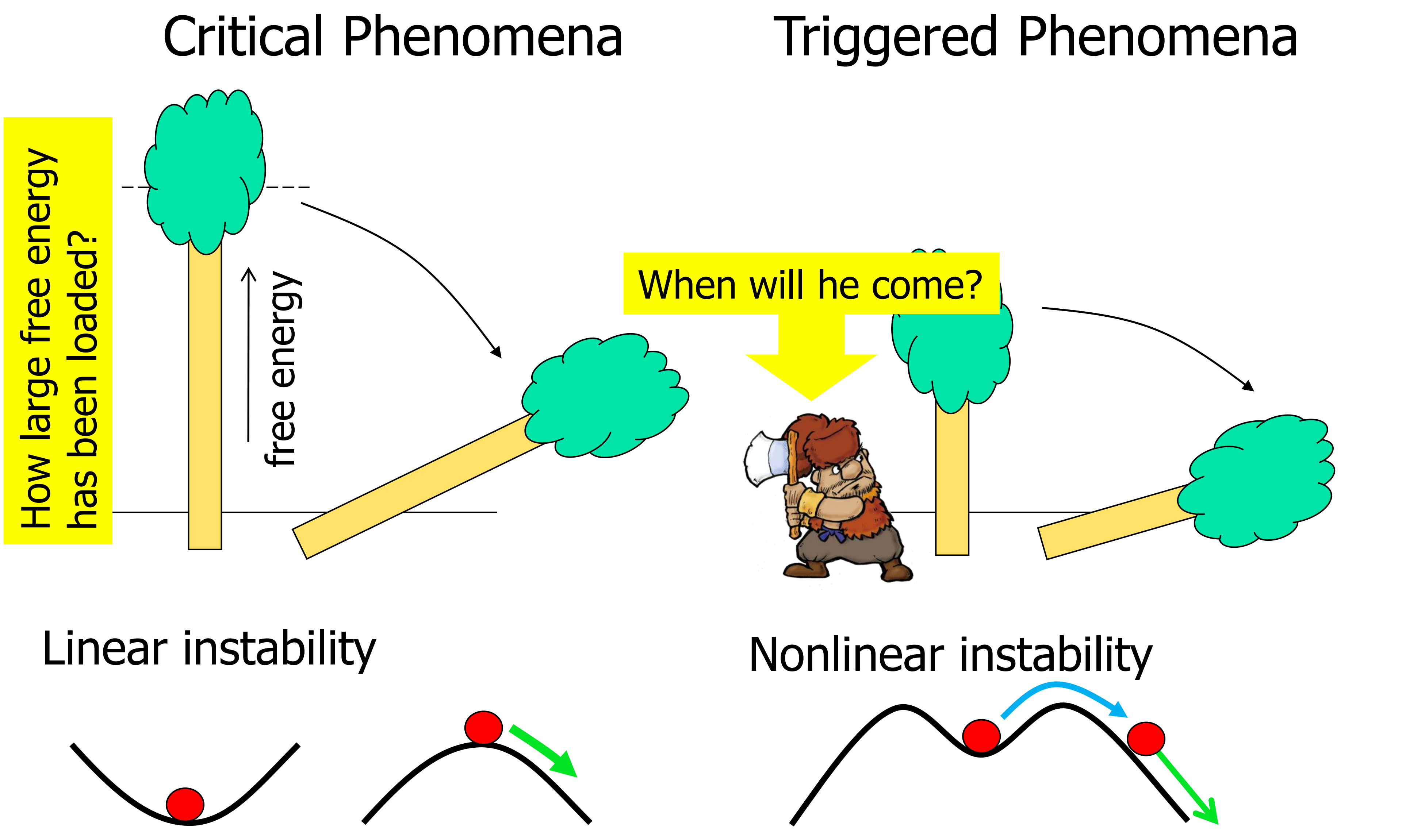


RS configuration



Current sheet disappears

The Onset of Storage-and-Release



Summary

- We find that the two different structures (OP and RS) favorable to the onset of solar flares in terms of the ensemble simulations for different magnetic configurations.
- The detail comparison with Hinode and other observations demonstrates that events indeed occurred, which are well consistent with the two scenarios.
- It means that the solar forecast is possible in terms of the sophisticate magnetic observation. However, the lead time of deterministic forecast of flares must be limited by the time-scale of small magnetic structures and flow driver, which is about several hours, presumably.
- The longer term forecast could be performed in a probabilistic manner.