Generation, transportation and dissipation of magnetic field in the Sun

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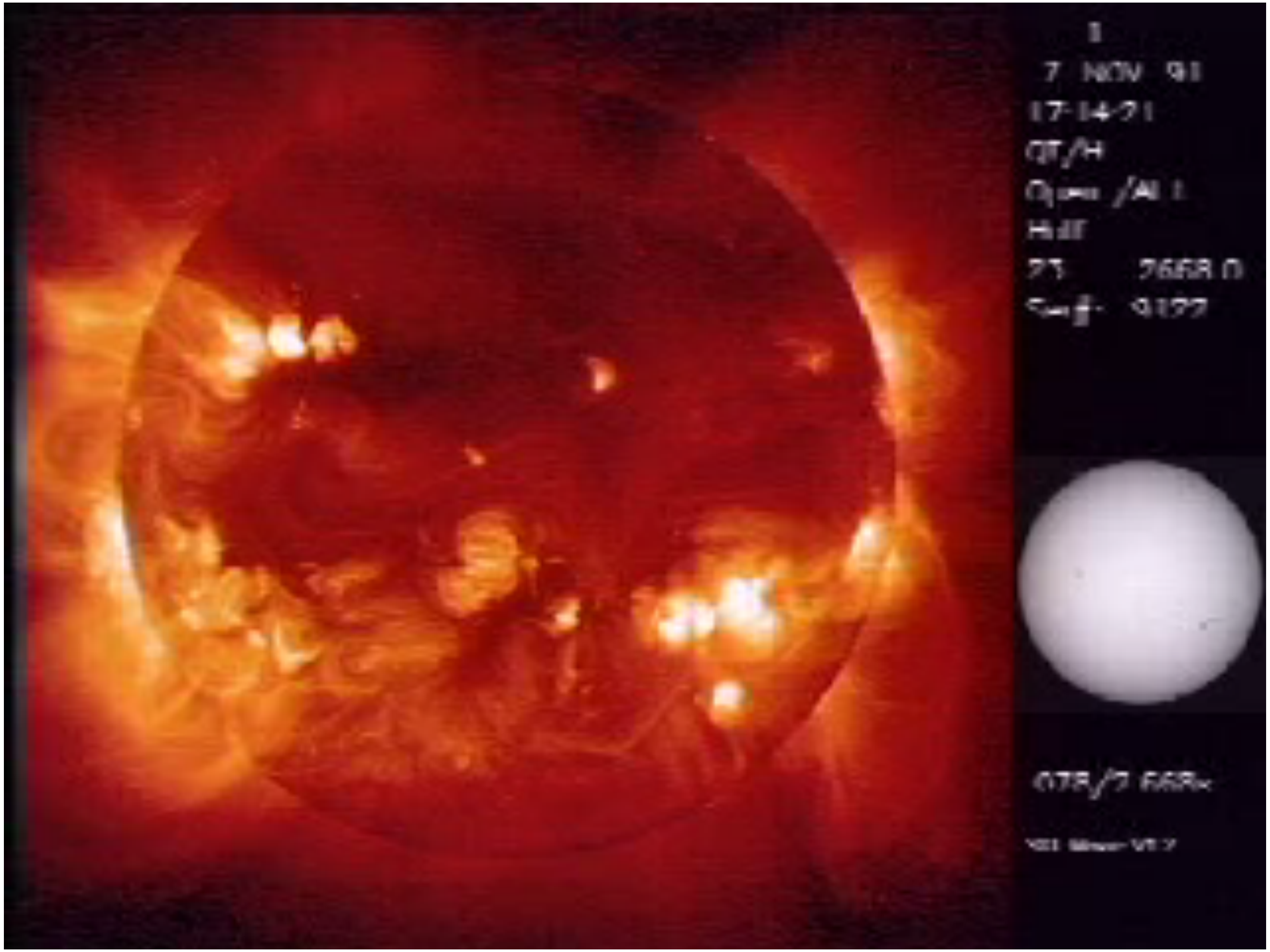
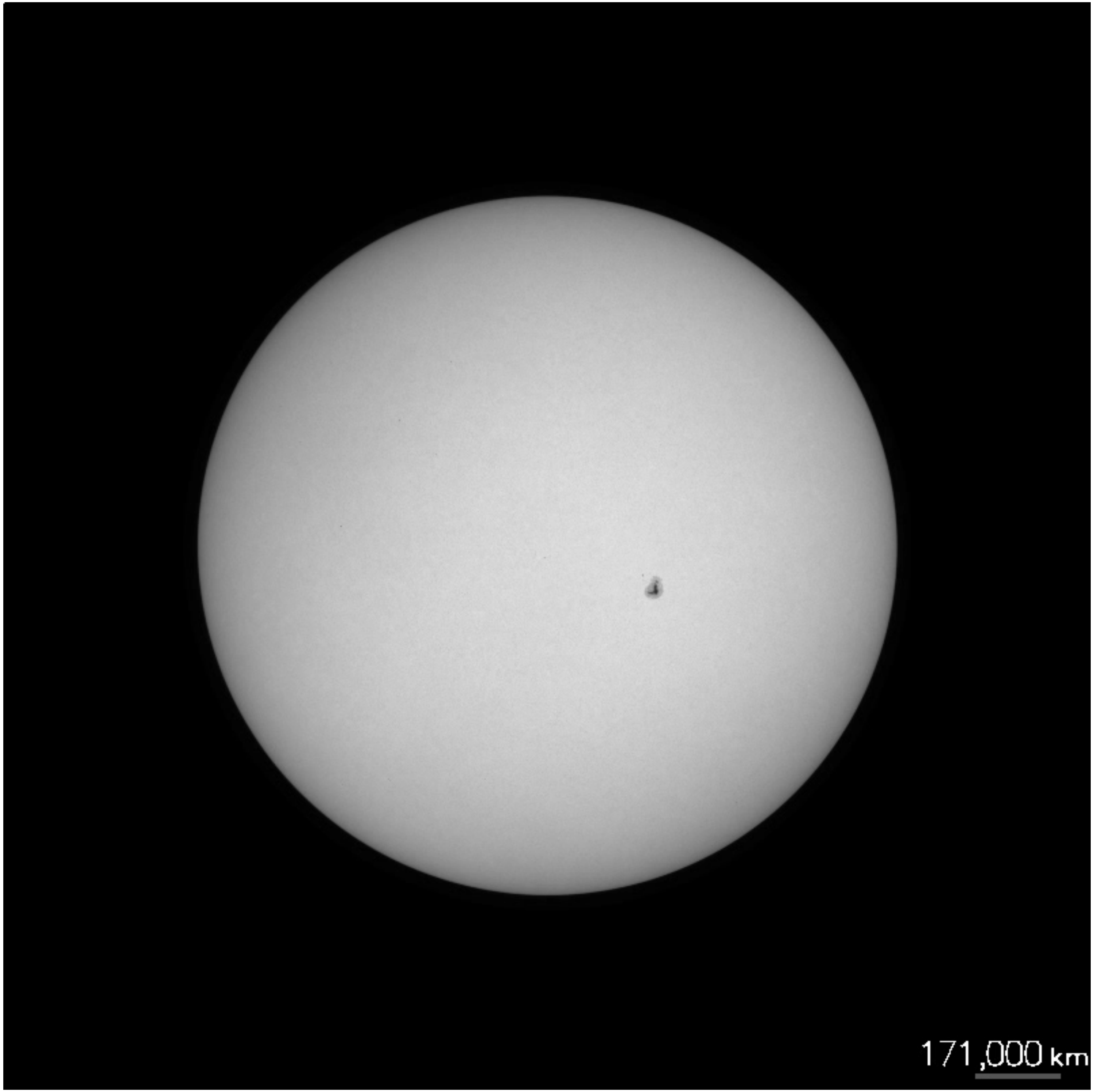
2012 Nov 19, Pohang

The sun as a MHD laboratory

- 1MK corona
- Solar wind
- Flares and coronal mass ejections

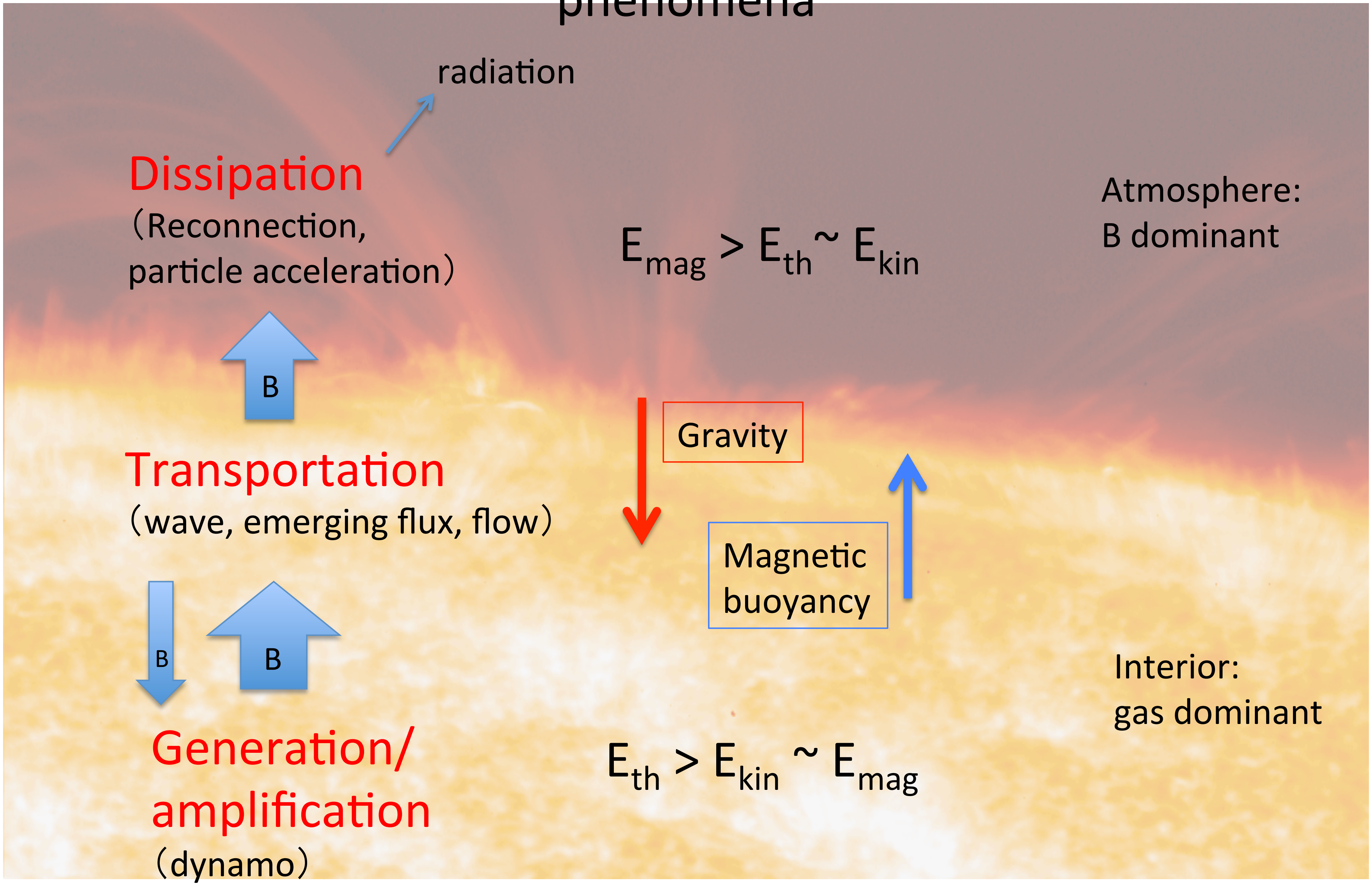
Yohkoh soft X-ray (2-20MK, thermal)

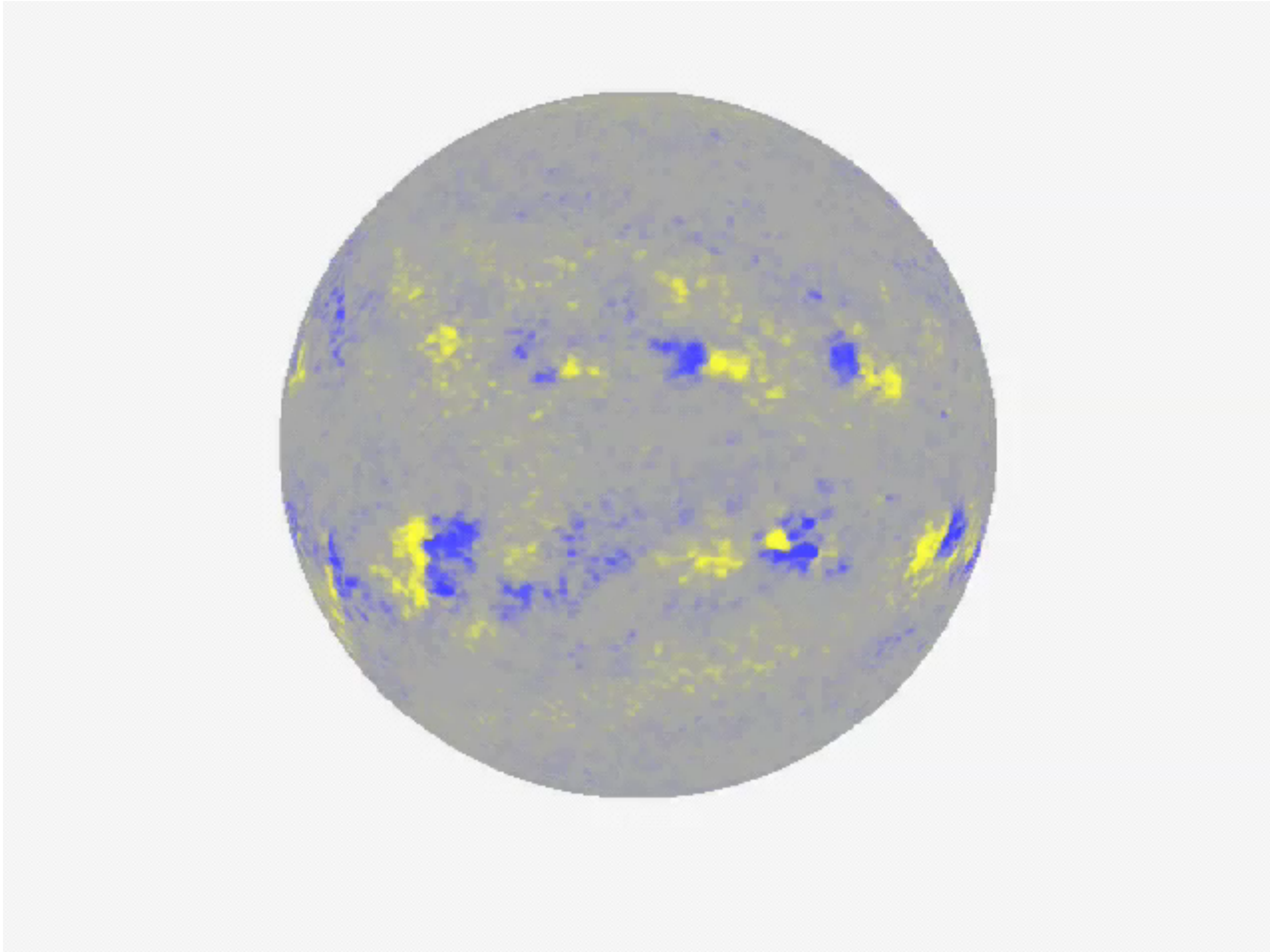


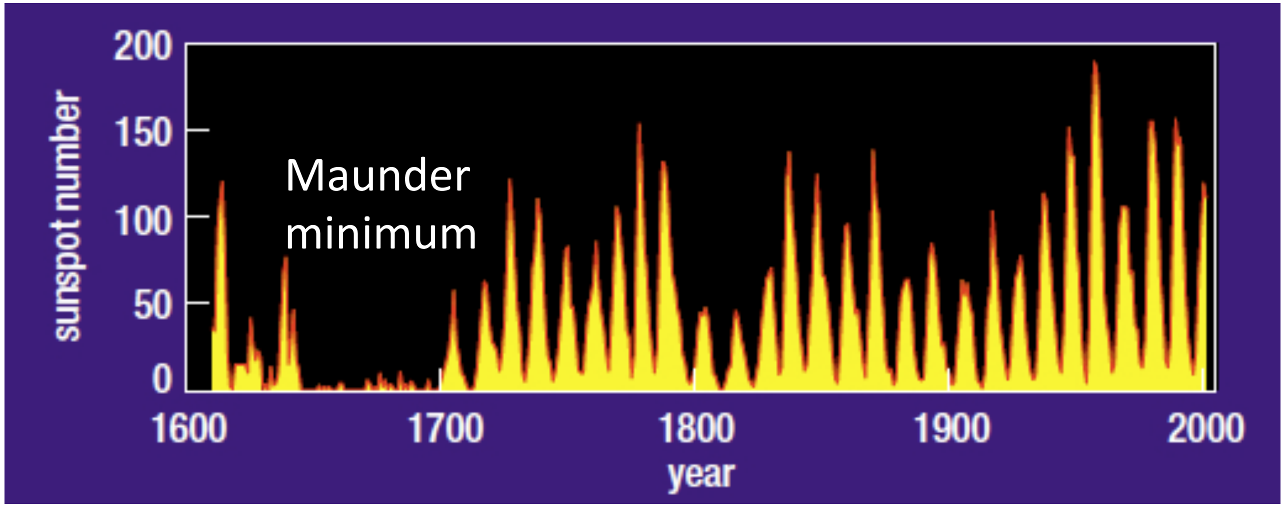


Hinode SOT
Movie by T.J.
Okamoto

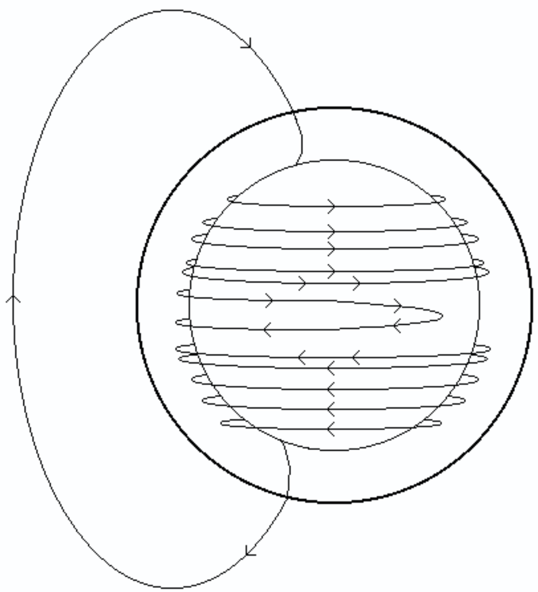
Why magnetic field can accommodate high energy phenomena





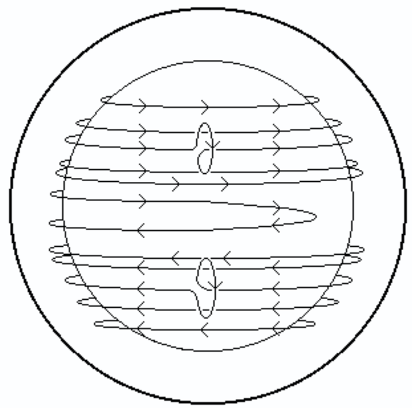

200
150
100
50
0
sunspot number
Maunder
minimum
1600
1700
1800
1900
2000
year

Paradigm of dynamo theory: αΩ dynamo



The ω-effect

Ω-EFFECT generates toroidal field from poloidal field by differential rotation

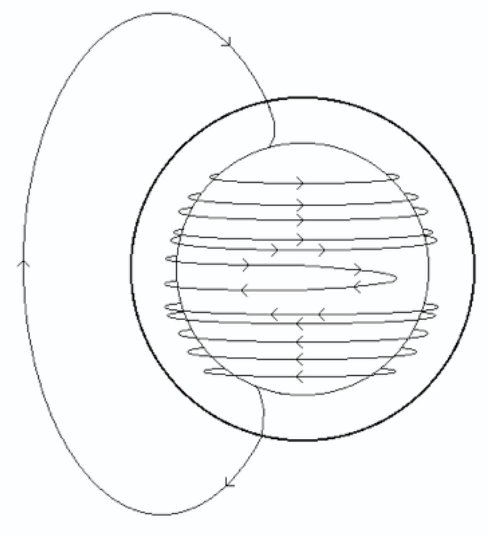


The α-effect

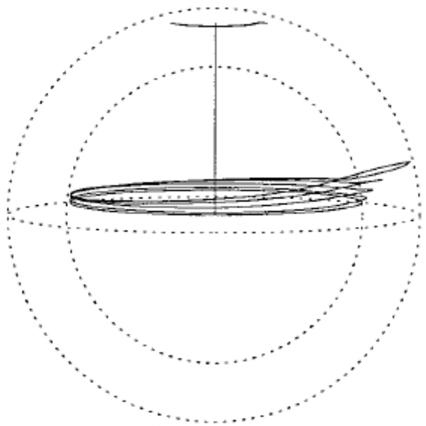
α-EFFECT generates poloidal field from toroidal field by something (coriolis force, helical turbulence etc...)

Flux Transport Dynamo

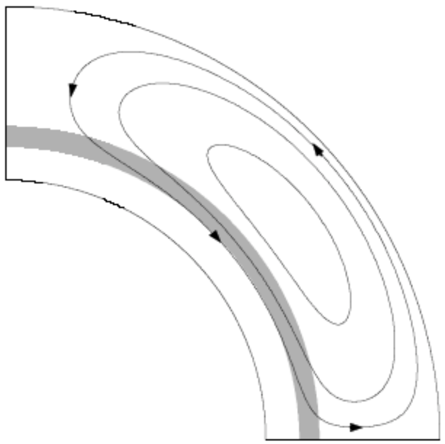
- Linear theory (V given)
- Successfully reproduce several observed features
- Many free parameter
  - α effect
  - turbulent diffusion
  - velocity field



Ω-effect just below the convection zone (for stabilization against magnetic buoyancy)



Amplified fields emerge to surface by magnetic buoyancy => sunspots

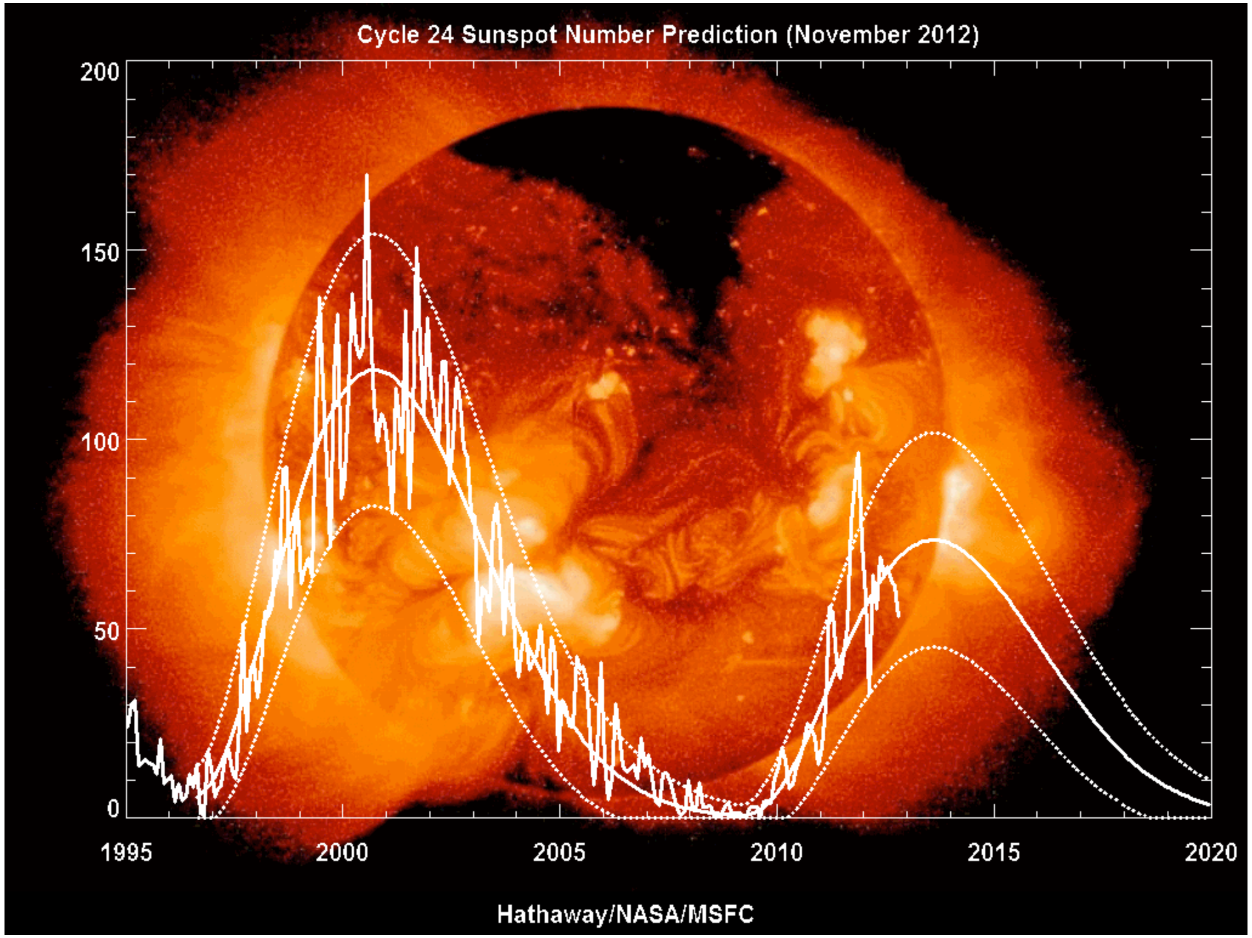


Magnetic flux of decayed sunspots transported to the pole and then base of CZ by meridional circulation and/or turbulent diffusion

Solar cycle prediction

The current prediction for Sunspot Cycle 24 gives a smoothed sunspot number maximum of about 73 in the Fall of 2013. Cycle 24 will be the smallest cycle since Cycle 14 (maximum 64.2, 1906)

Prediction based on "precursor" methods that use polar fields and geomagnetic activity etc.

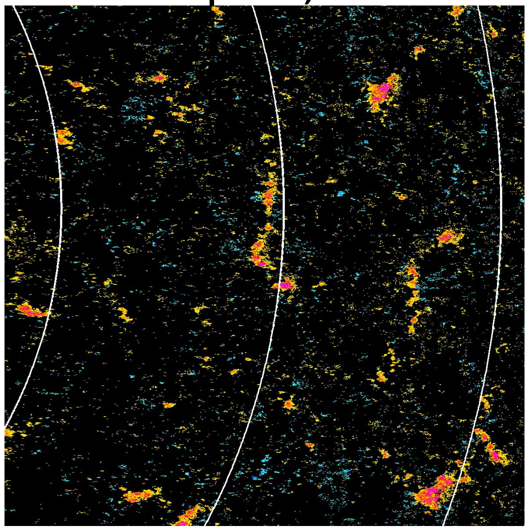


http://solarscience.msfc.nasa.gov/predict.shtml

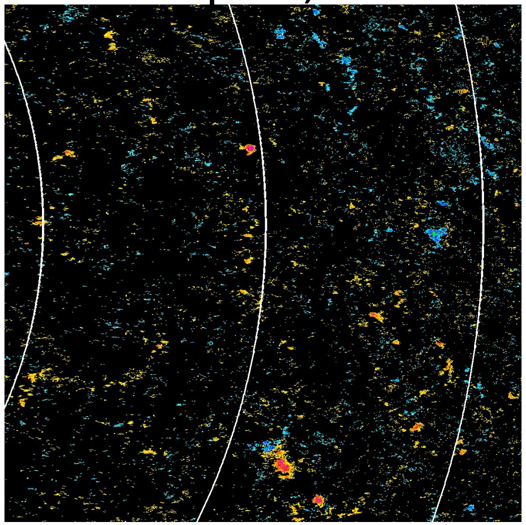
Polarity inversion of large-scale dipolar field

Shiota et al. 2012

North pole, 2008

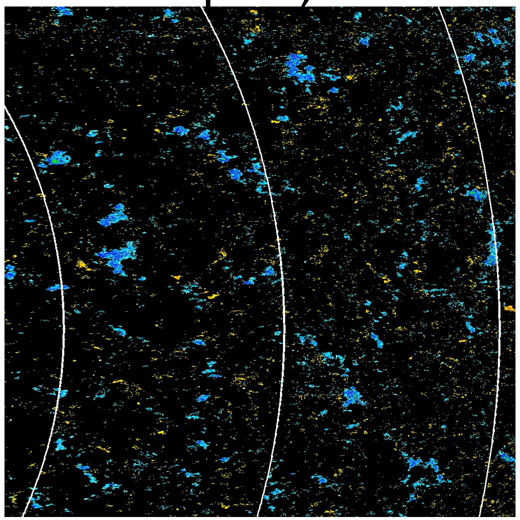


North pole, 2011

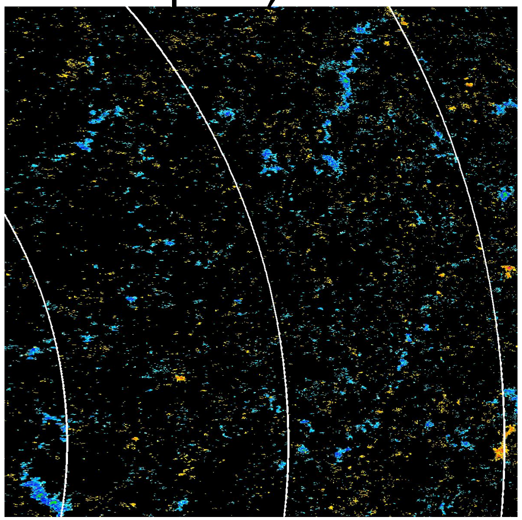


Polarity Inversion in N. pole had started, but polarity in South pole remains unchanged.

South pole, 2009



South pole, 2012



Magnetic buoyancy

(Parker 1955)

- Consider pressure balance between an isolated magnetic structure (e.g., a flux tube) and the ambient field-free plasma:

$$\rho_{in} R T_{in} + \frac{B^2}{8\pi} = \rho_{out} R T_{out}$$

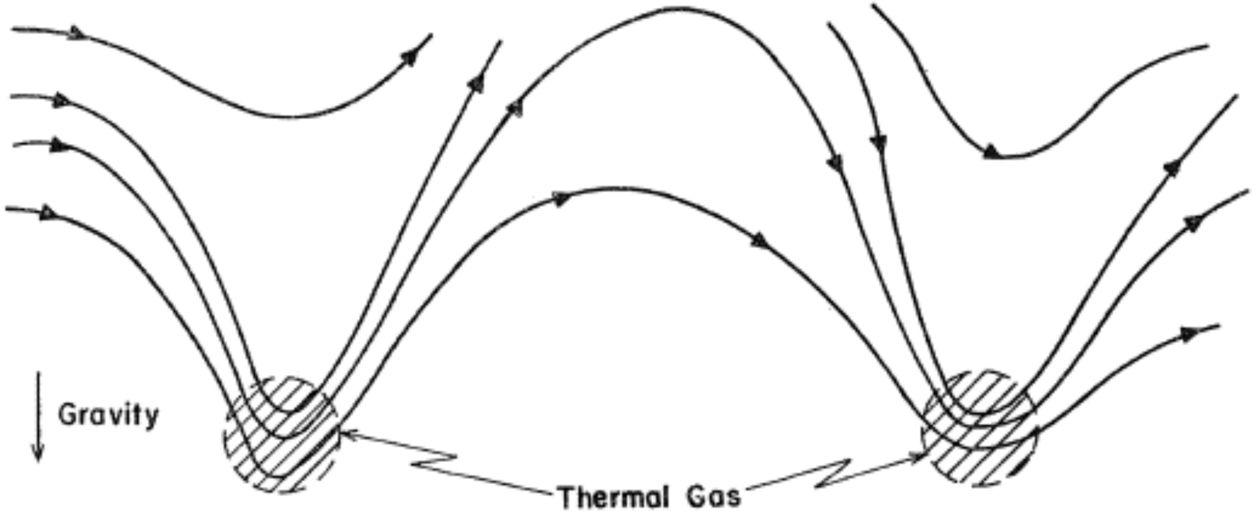
- If they are in thermal equilibrium, i.e., $T_{in} = T_{out}$, then

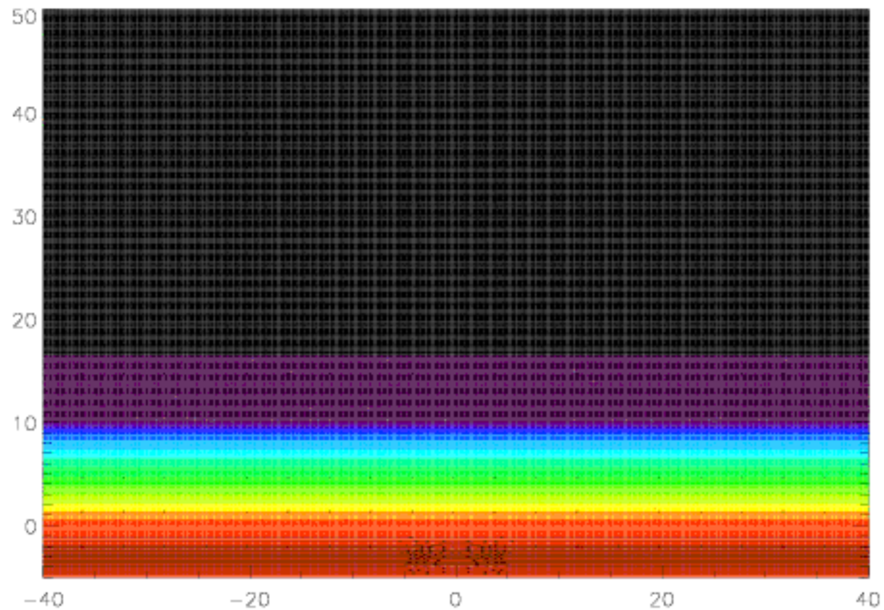
$$\frac{\rho_{out} - \rho_{in}}{\rho_{out}} = \frac{B^2 / 8\pi}{\rho_{out} R T_{out}} = \frac{1}{\beta} > 0$$

- Magnetic field in thermal equilibrium with ambient plasma is always buoyant

Magnetic buoyancy instability

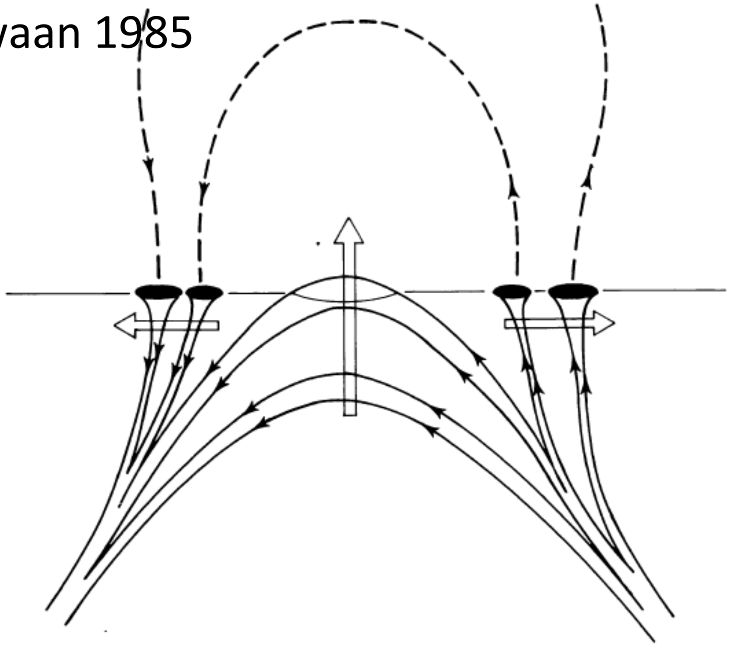
Parker 1966 as mechanism of molecular cloud formation

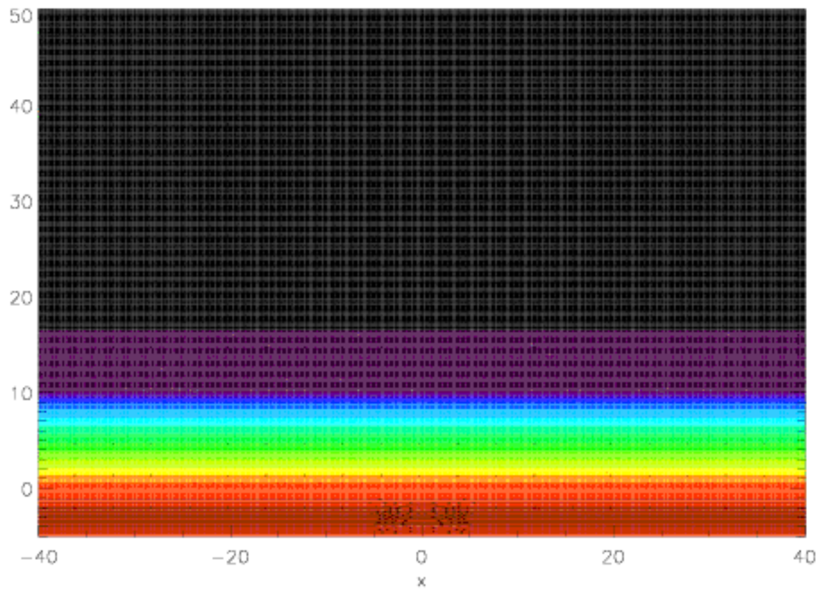


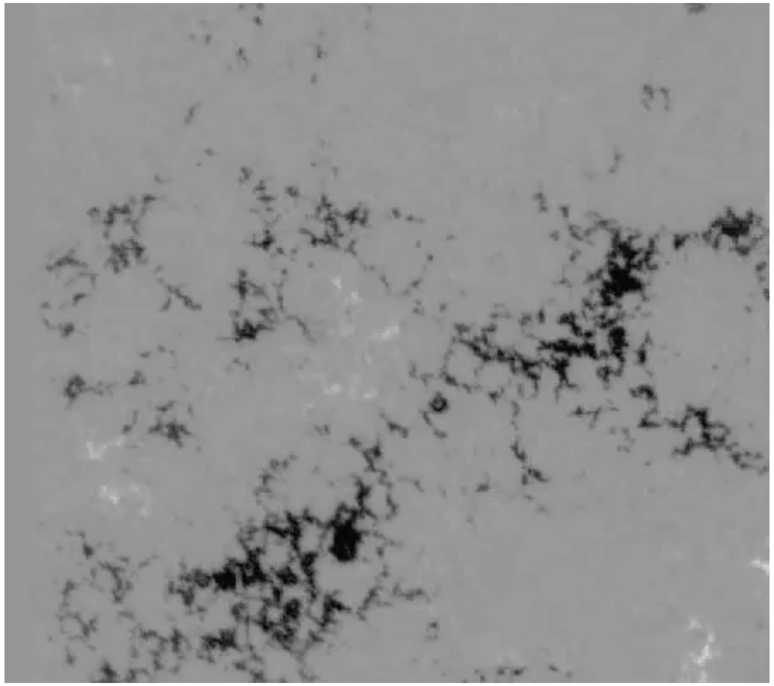


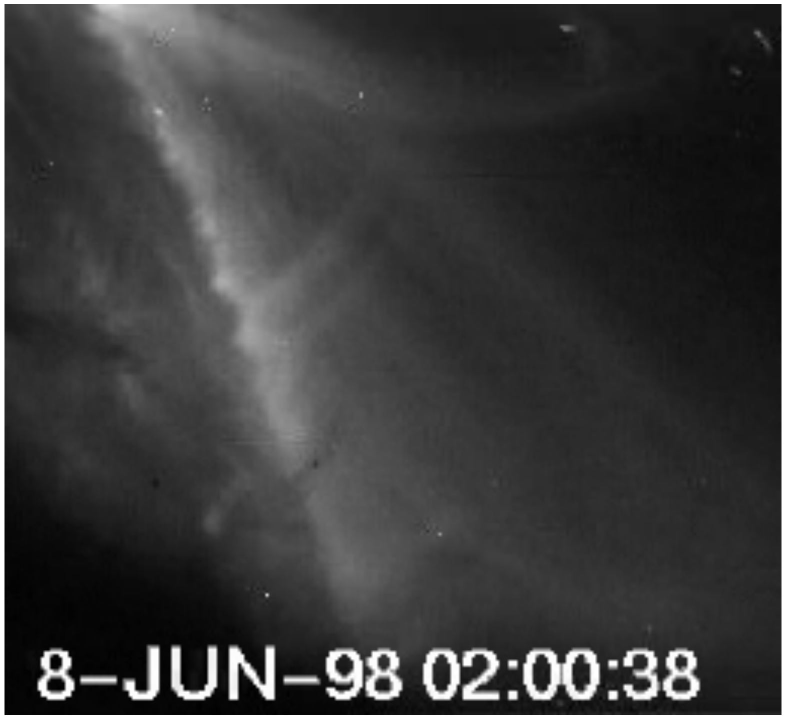
Application to solar emerging flux by Shibata et al. 1989

Zwaan 1985



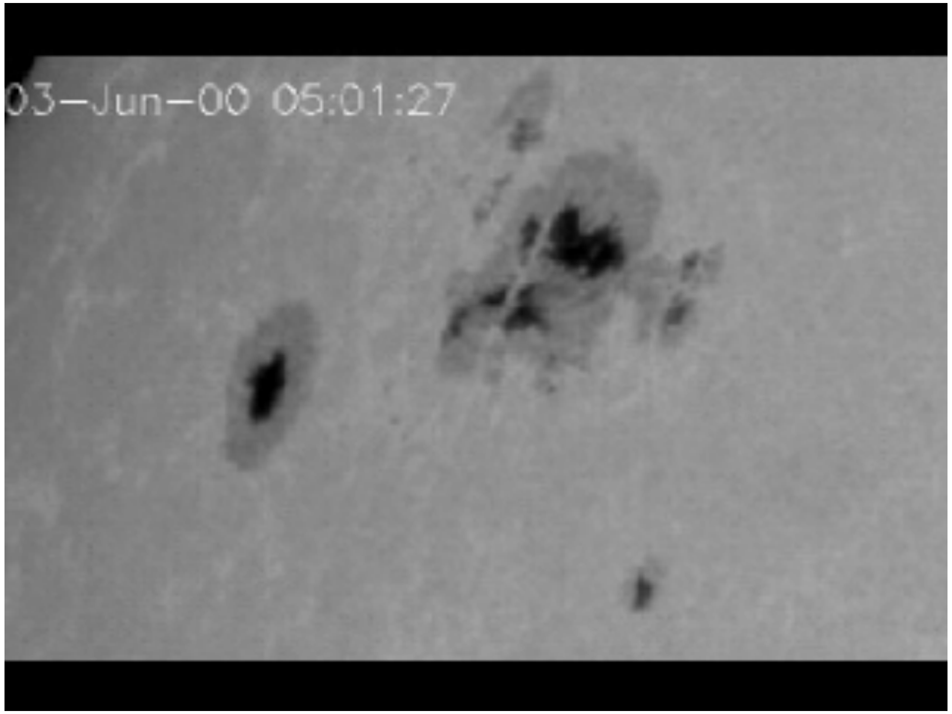




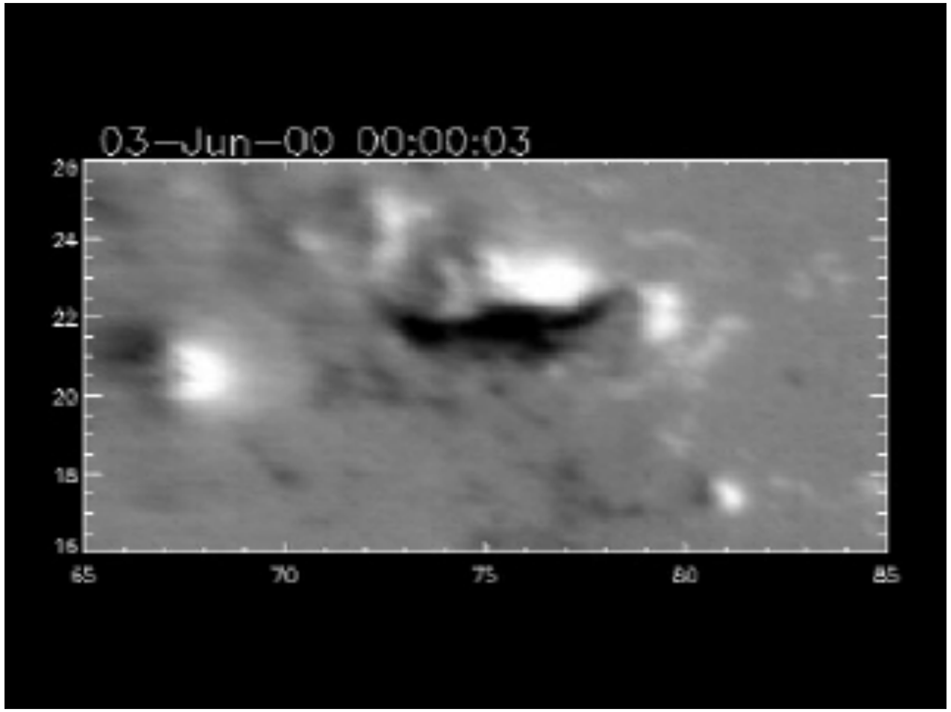


Simple spots last longer

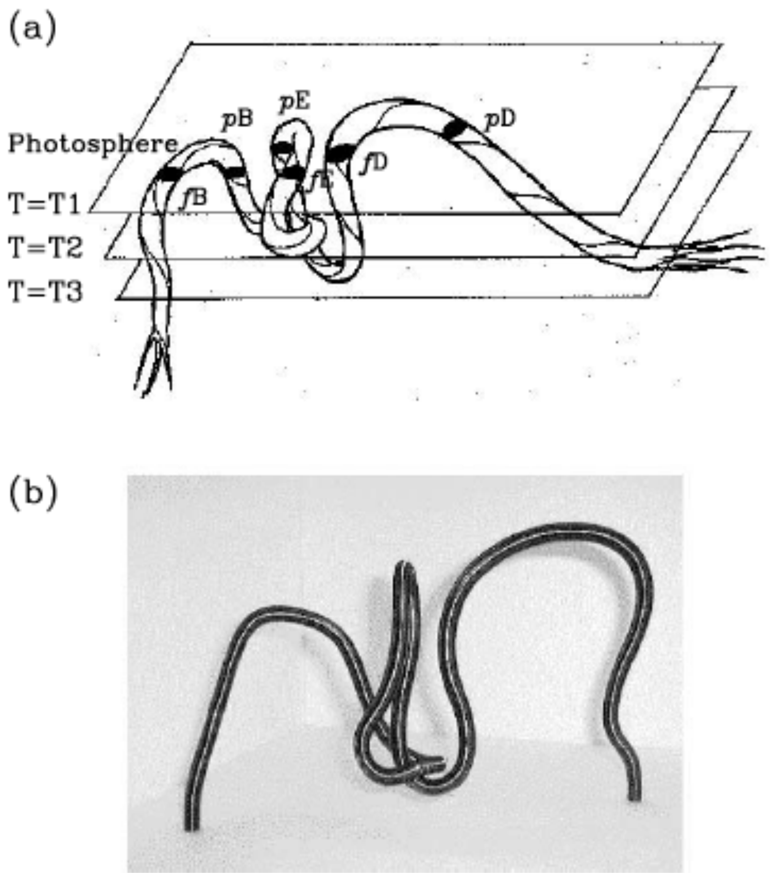
White light



Magnetic field

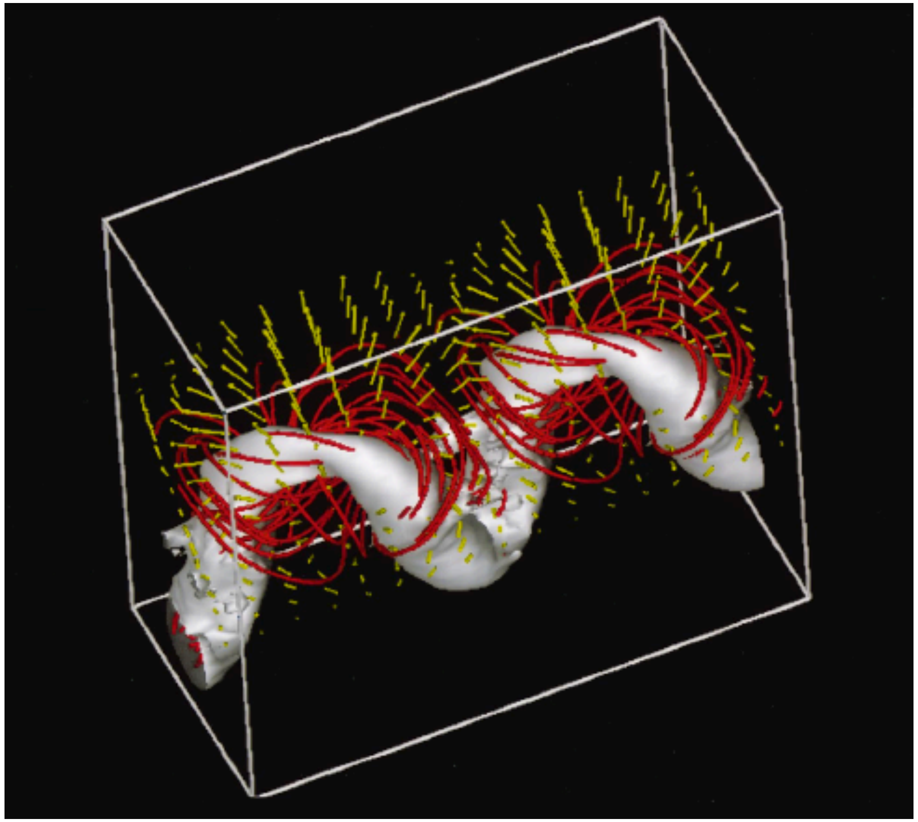


Emergence of twisted tube?

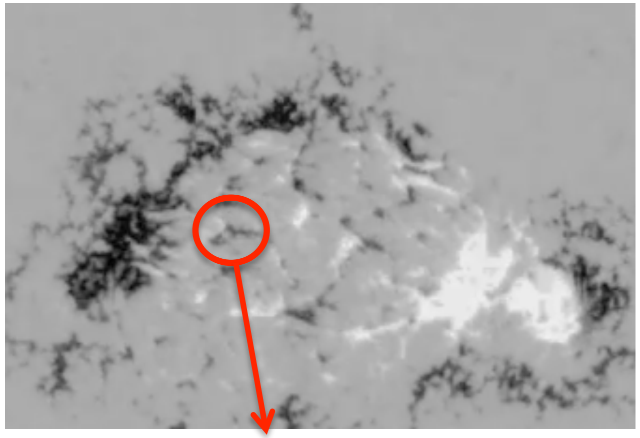


Reconstruction of sub-surface magnetic structure by tracking proper motion of sunspots (Kurokawa et al. 2002)

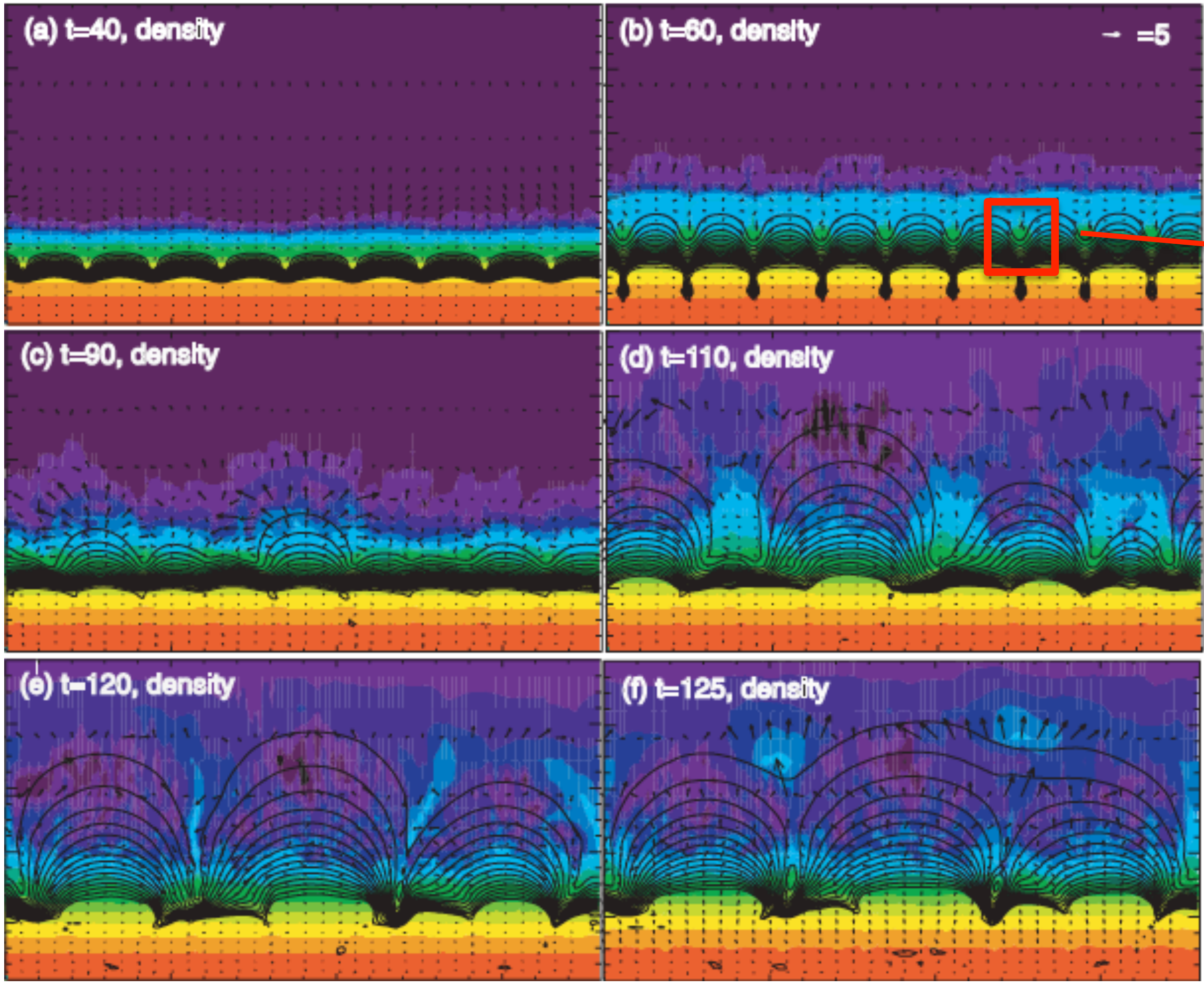
3D MHD simulation of the emergence of Kink-unstable flux tube (Matsumoto et al. 1998)

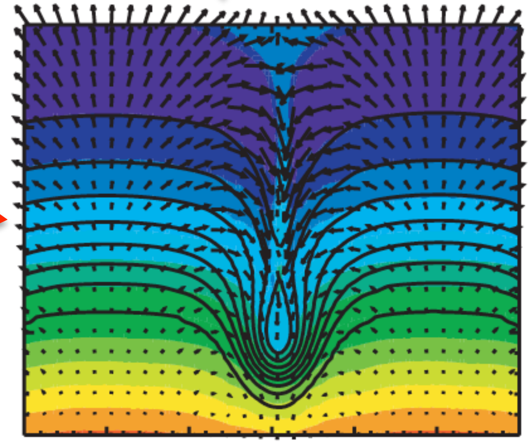


Ellerman bombs



Isobe, Tripathi, Archontis 2007

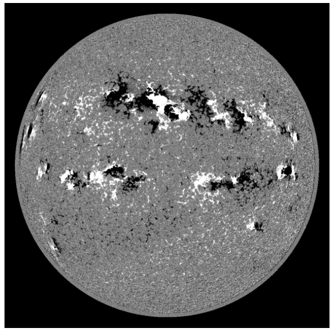




Reconnection of neighboring loops in lower atmosphere

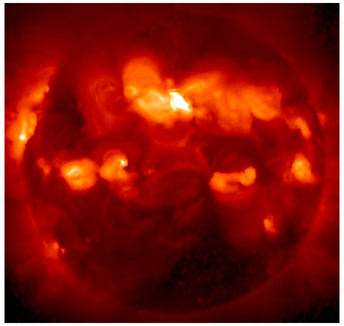
Allows removal of heavy plasma from magnetic field

How long can an active region last?



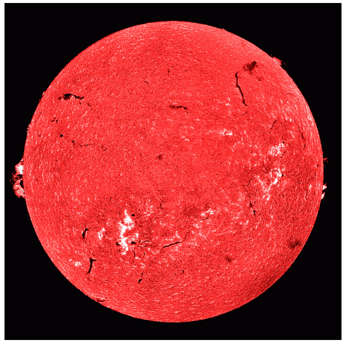
Magnetic energy of an active region

$$E_{mag} \approx 4\times10^{32}\left(\frac{B}{100\mathrm{G}}\right)^2\left(\frac{L}{10^5\mathrm{km}}\right)^3 \mathrm{erg}$$



Radiative loss from corona

$$R_{corona} \approx 10^{27}\left(\frac{n}{3\times10^9\mathrm{cm}^{-3}}\right)^2\left(\frac{L}{10^5\mathrm{km}}\right)^3 \mathrm{erg/s}$$



Radiative loss from chromosphere

$$R_{chromo} \approx 10R_{corona}$$

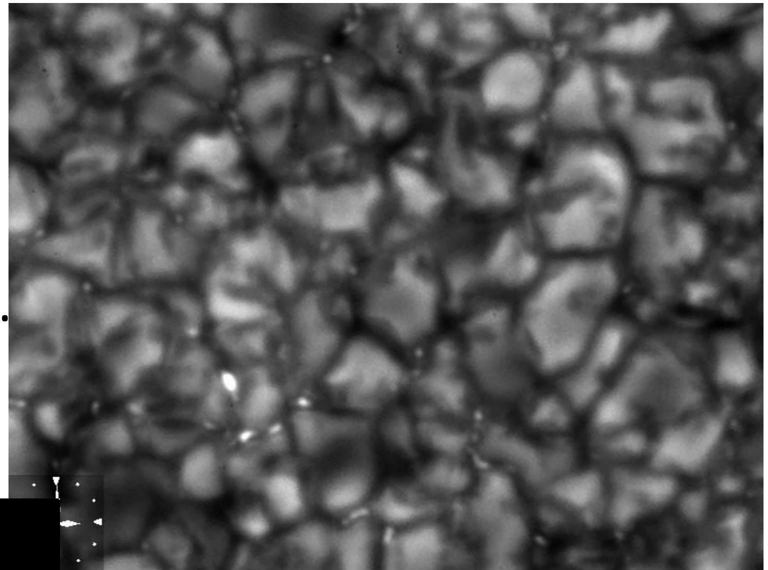
(though no simple calculation, chromospheric heating is more problematic!)

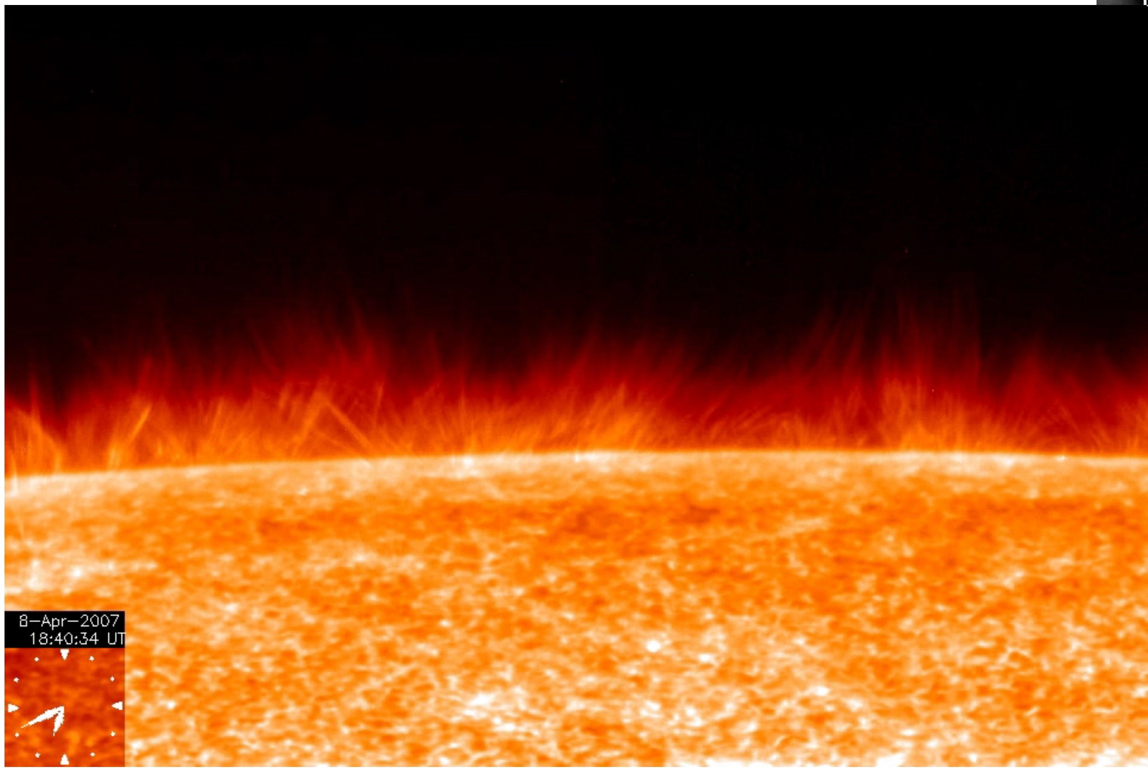
$E_{mag}/(R_{corona}+R_{chromo})$ ~ 11 hours << Observed Life time of active region (weeks)???

The energy source = convective motion

The kinetic energy of convection is transported upward as Poynting flux:

$$P \approx 10^{8}\left(\frac{B}{100G}\right)^{2}\left(\frac{V}{1km/s}\right) \quad \text{(erg cm}^{-2}\text{ s}^{-1}\text{)} \ldots$$

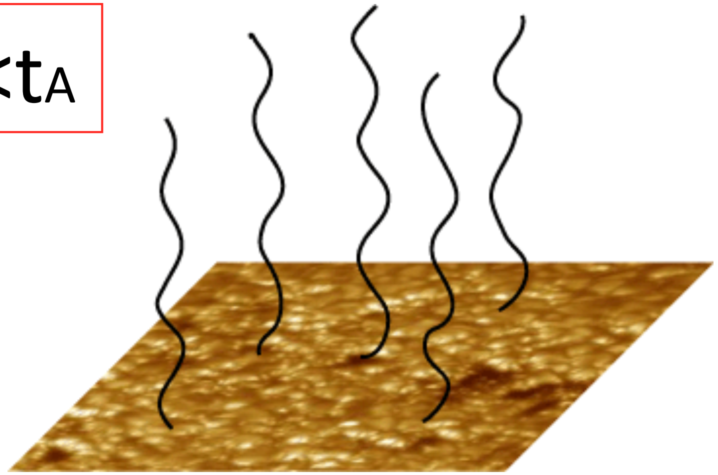




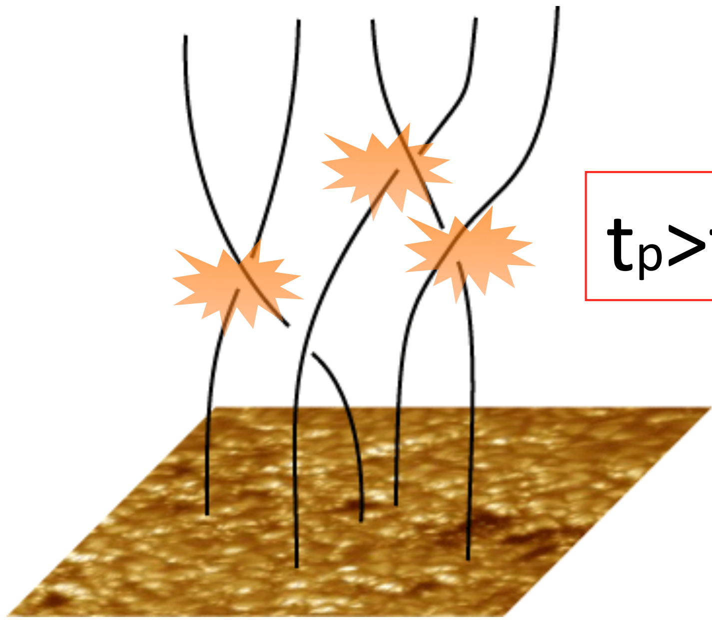
Vertical energy transport via magnetic field

t_p: Time scale of perturbation at photosphere
t_A: Alfven time of coronal structure

$t_p<t_A$



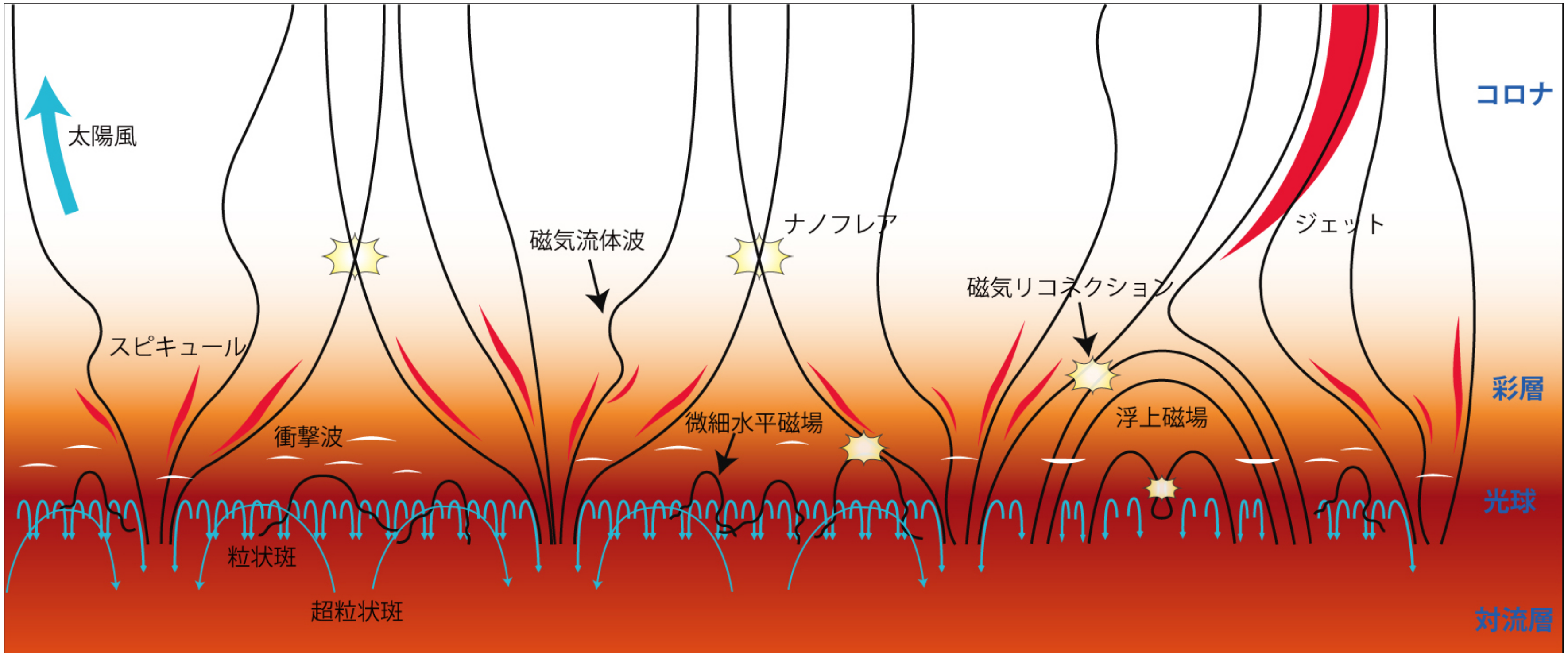
Energy transported as MHD waves (Alfven ,fast, slow).
Relative contribution? Dissipation mechanism?



$t_p>t_A$

Slow shearing motion generates electric currents in the corona => reconnection

Summary of transportation



- Flux emergence transports large-scale magnetic energy => free energy accumulation in the corona => flares
- Waves and shearing motions transports the kinetic energy in convection zone as a small-scale perturbation => coronal heating and solar wind

Dissipation

- What's the problem?
  - Resistivity too small! Dissipation too slow!

- What's the answer?
  - Magnetic reconnection!

So, how it works?

Uzdensky (2006, astro-ph/0607656)

… the most important reconnection mechanism in Astrophysics invokes waves, a certain type of waves, in fact. Called <u>*handwaves*</u> (See Fig 1).

Fig. 1.— Main Reconnection Mechanism in Astrophysics.

The mechanism works like this: *Well, we know that fast reconnection happens in the Solar corona, and in the Earth magnetosphere. So it should also happen in OUR astrophysical system.*

What's the real problem?

- Fast reconnection required for flares

Reconnection rate $M_A = V_{\inf low} / V_A \approx 0.01 - 0.1$

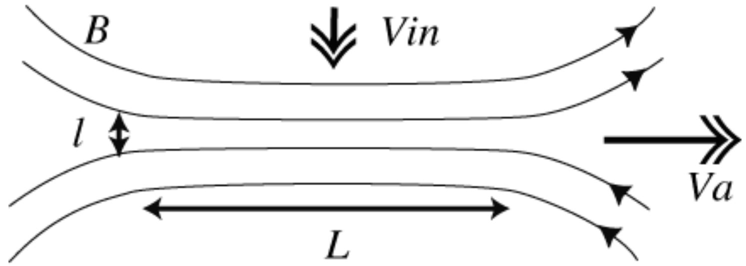
- Extremely small resistivity in corona

Lundquist number $S = \tau_{resistive} / \tau_A = V_A L / \eta \approx 10^{14}$

How to realize fast (independent to S) reconnection?

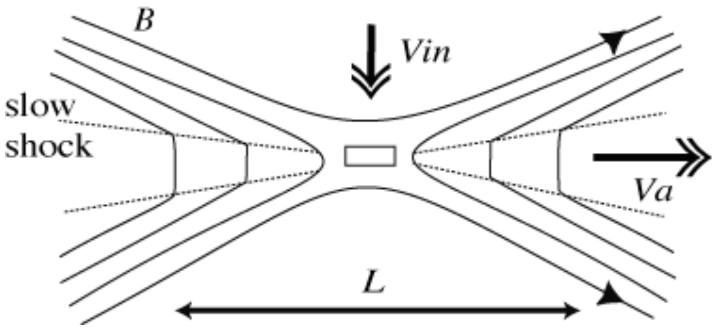
Classical MHD reconnection models

Sweet-Parker reconnection



$M_A = S^{-1/2} \approx 10^{-7}$ ... too slow

Petschek reconnection



Localized diffusion region

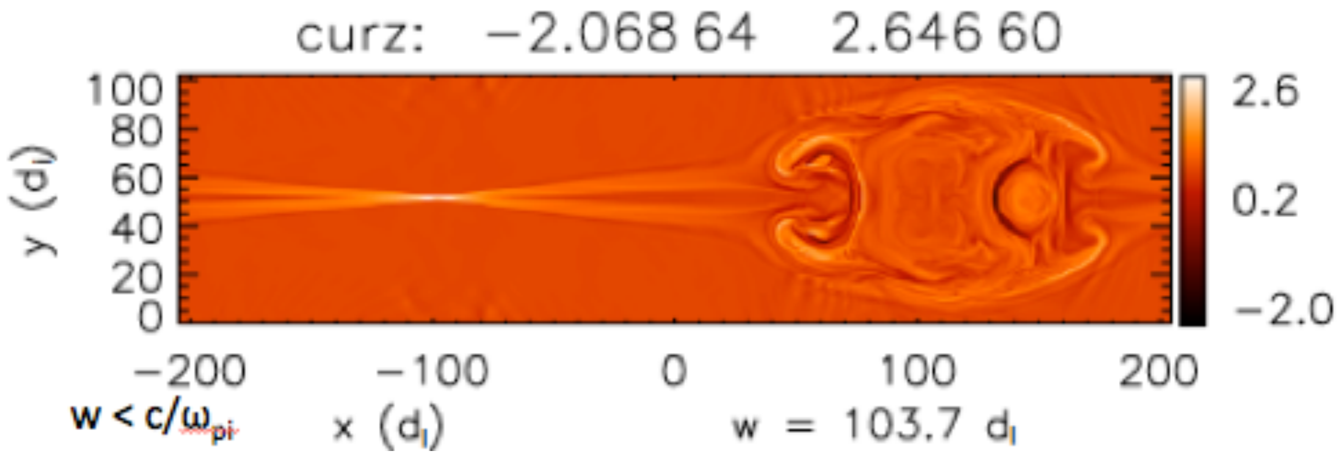
Energy conversion via slow shocks

$M_A = \pi/8\ln S \approx 0.01\text{-}0.1$ ... OK?

How to localize diffusion region? Kinetic effects?

Hall reconnection? but...

- When current sheet becomes thinner than ion inertia length $d_i = c/\omega_{pi}$, Hall effect becomes significant, and fast reconnection (with Petschek-like configuration) is realized.

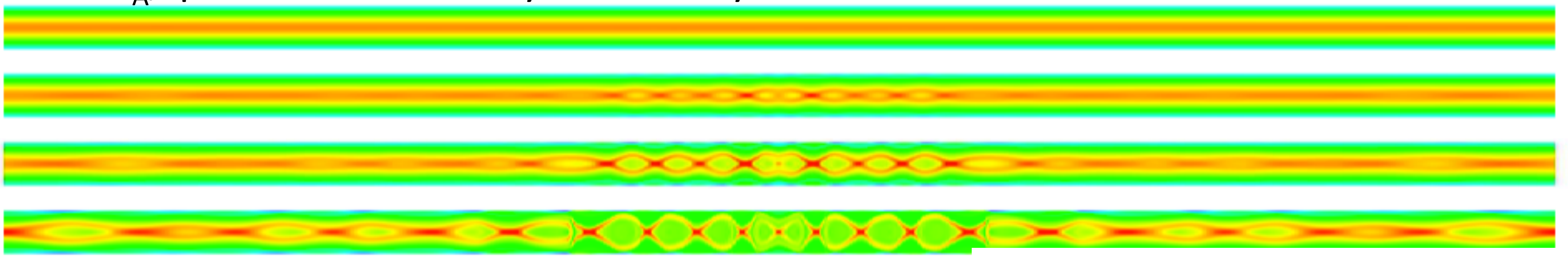


Cassak+05

- Ion scale in corona $d_i \sim 10^2$ cm
- Spatial size of flare $L \sim 10^9$ cm
- How to fill the scale gap?

Reconnection with multiple plasmoids/X-lines in High S reconnection

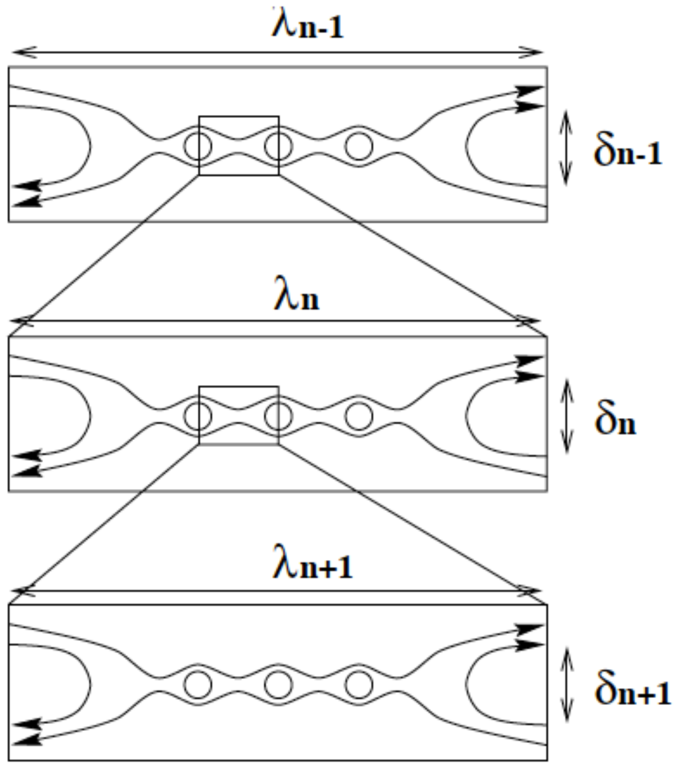
$S = LV_A/\eta = 10^7$ simulation by Samataney+09



- Multiple islands (plasmoids) by tearing
  => effectively reducing L
  => reconnection faster

- Tearing in reconnecting current sheet
  => further thinning
  => connection to kinetic scales?

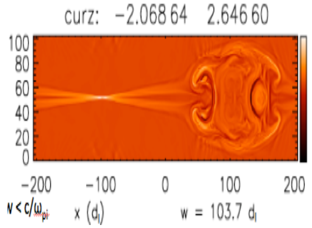
- Enhanced reconnection rate with ejection => inherently intermittent

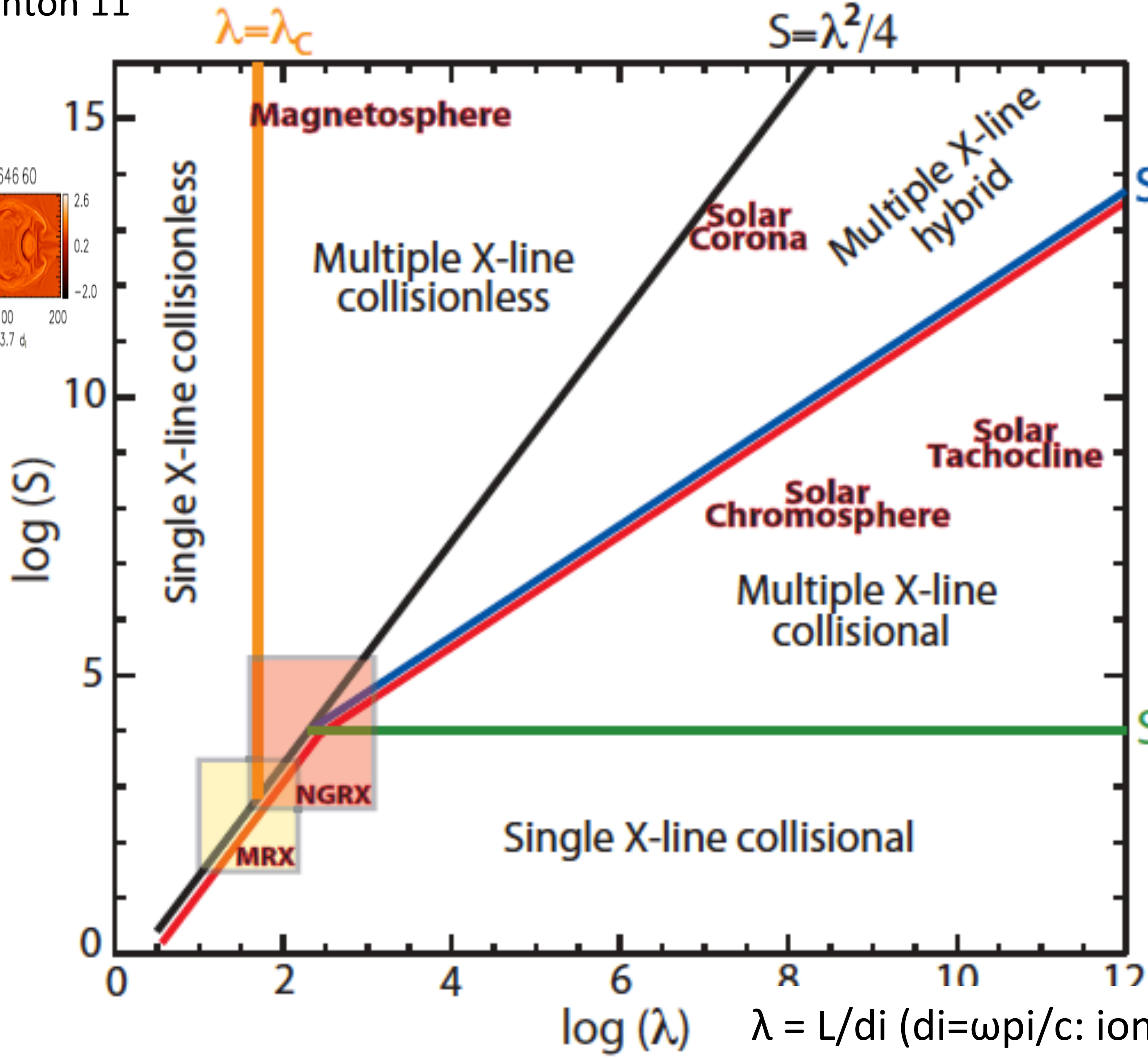


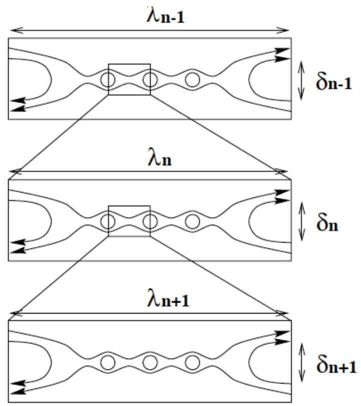
Shibata & Tanuma 01

Reconnection type depends on S and system size?

Ji & Daughton 11





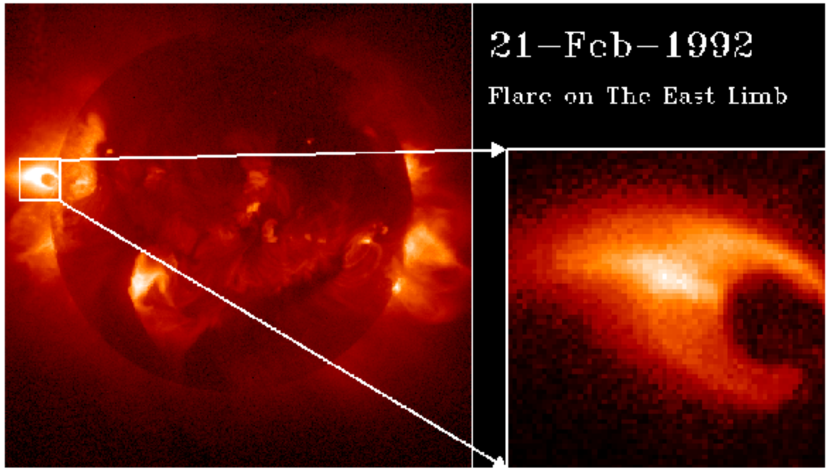


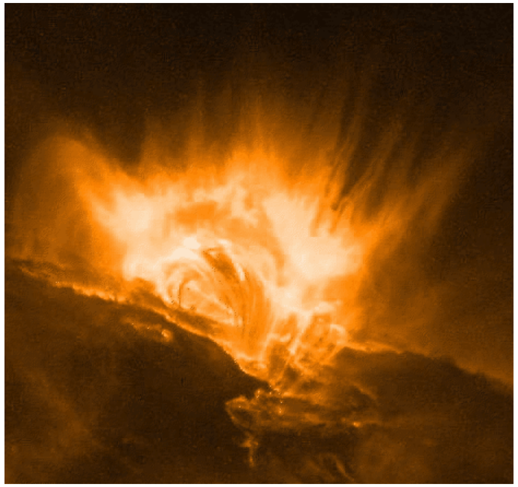
$S=LV_A/\eta$: Lundquist number

$\lambda = L/di$ (di=ωpi/c: ion inertia length)

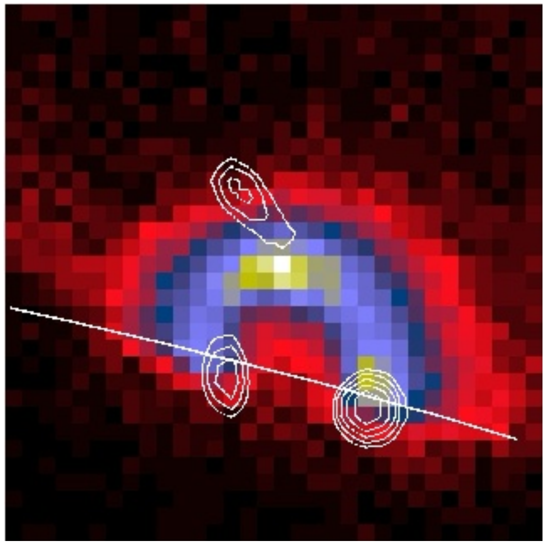
Observations of magnetic reconnection in the corona

Cusp (Tsuneta+92)



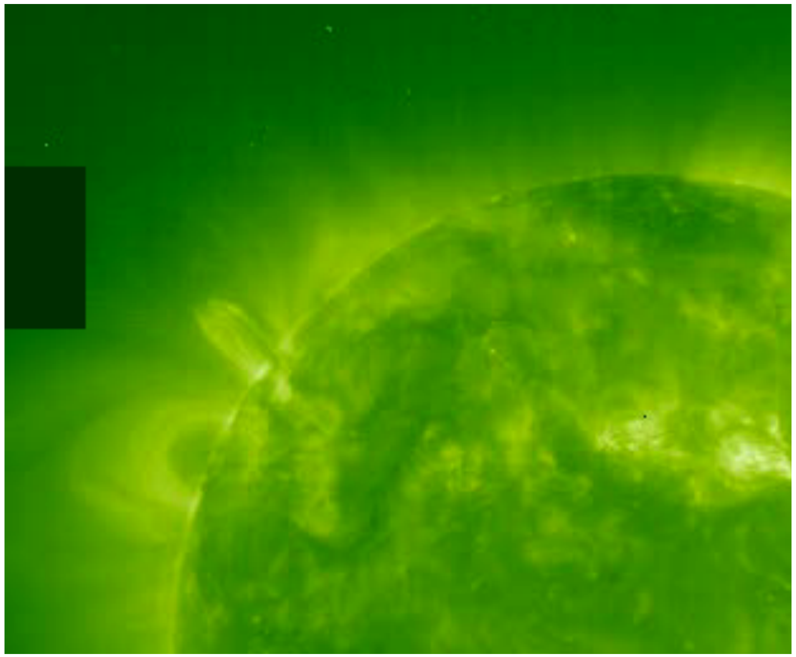


Supra-arcade downflow
(McKenzie Hudson 99)



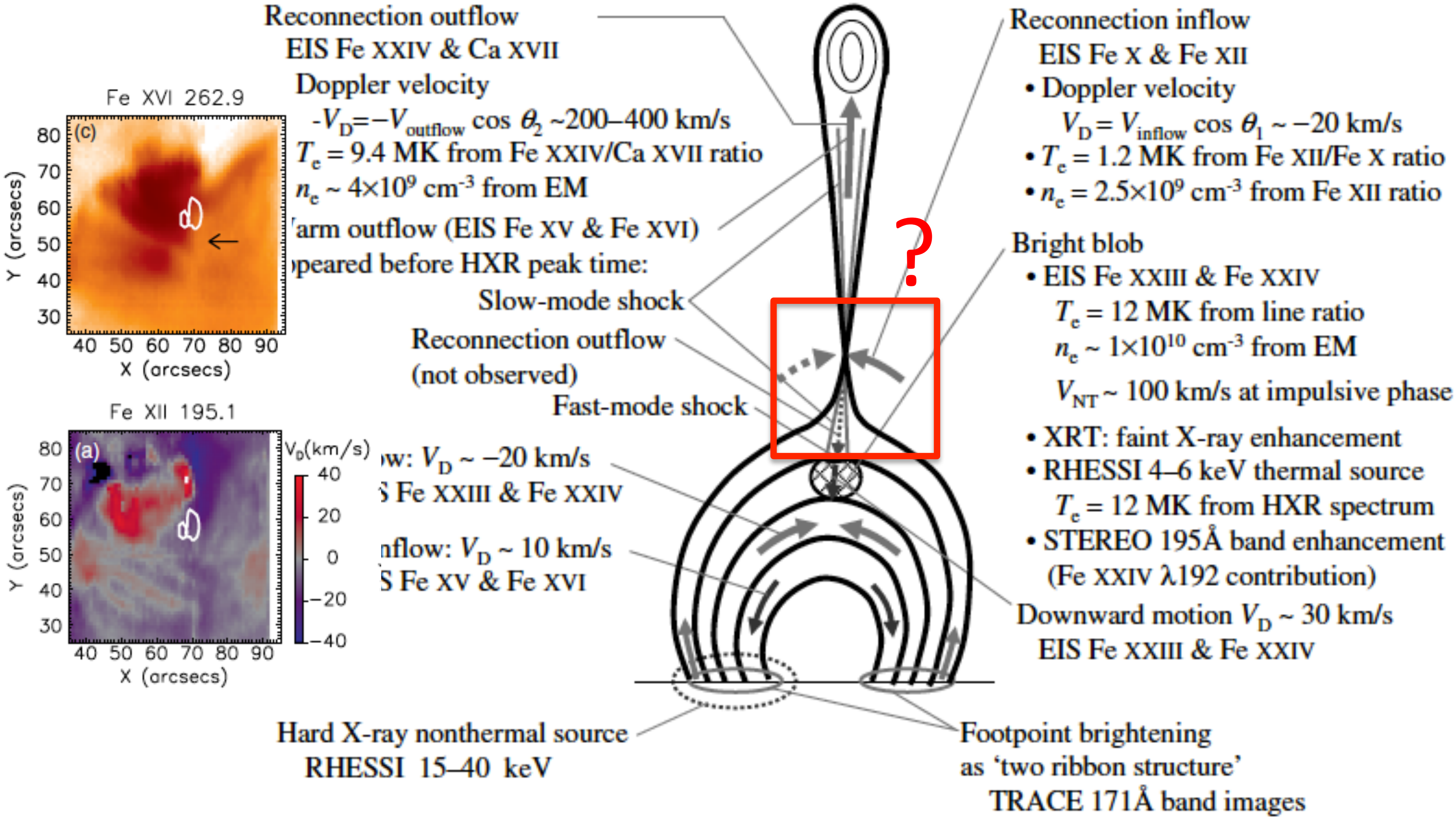
Loop-top HXR source
(Masuda+94)

Inflow
(Yokoyama+01)



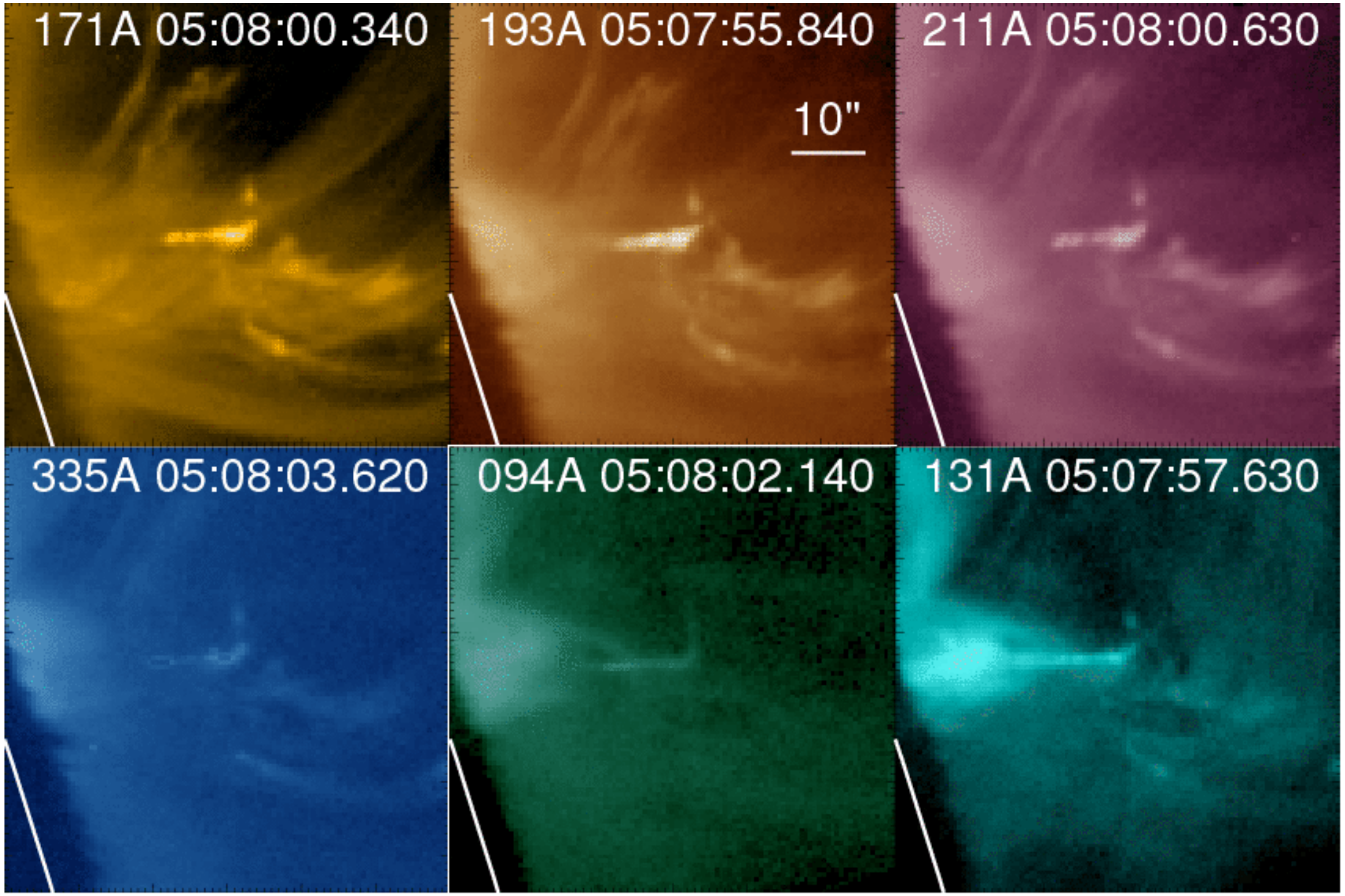
Quantification by Hinode

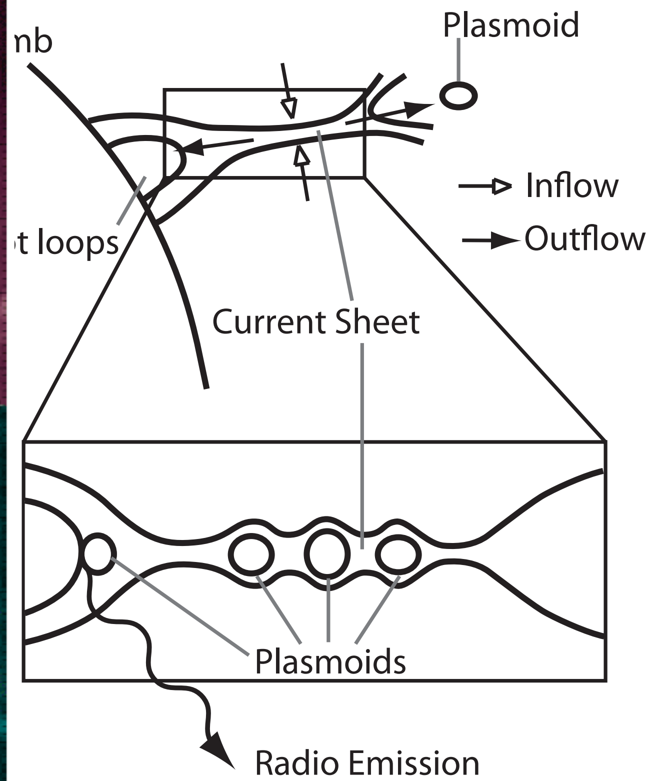
(Hara et al. 2011)



Formation, coalescence and ejection of multiple blobs

(Takasao, Asai, HI, Shibata 2012)





- Time scale < 10s
- High-throughput of LEMUR will allow spectroscopy of events like this

Summary

- Dynamo theory is still “fragile”
  - direct numerical simulation still far from reality
  - little observational information
- Transportation is being observed
  - quantification underway
- Dissipation is still problematic
  - reconnection is not a magic word
  - collaboration of solar, space, lab and astro plasmas essential
  - inter-plasma collaboration is often more difficult than inter-national collaboration, though. Let us talk!