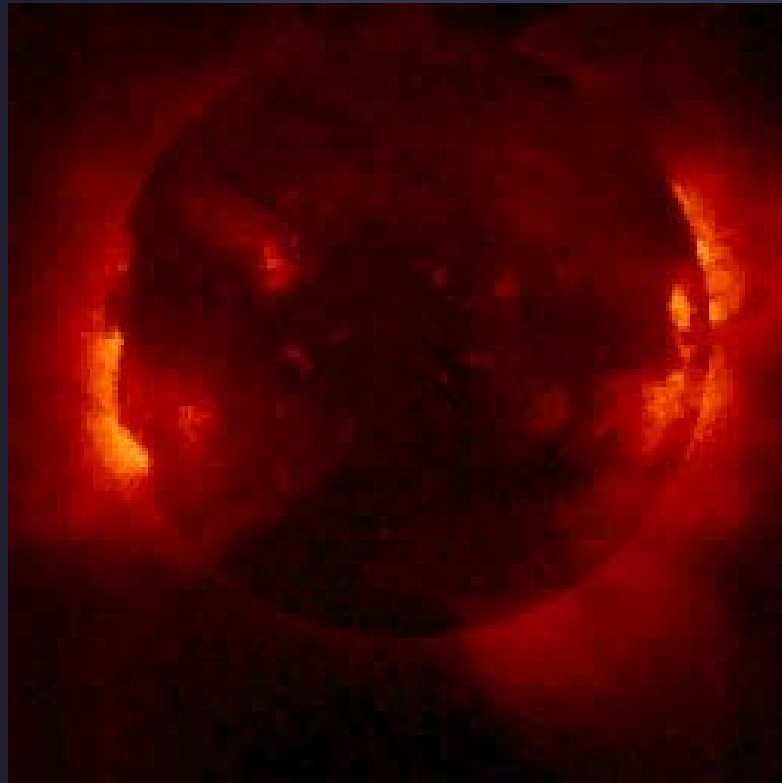


Why is the Sun's corona so hot and violent?

Lecture 6: Coronal heating and flares

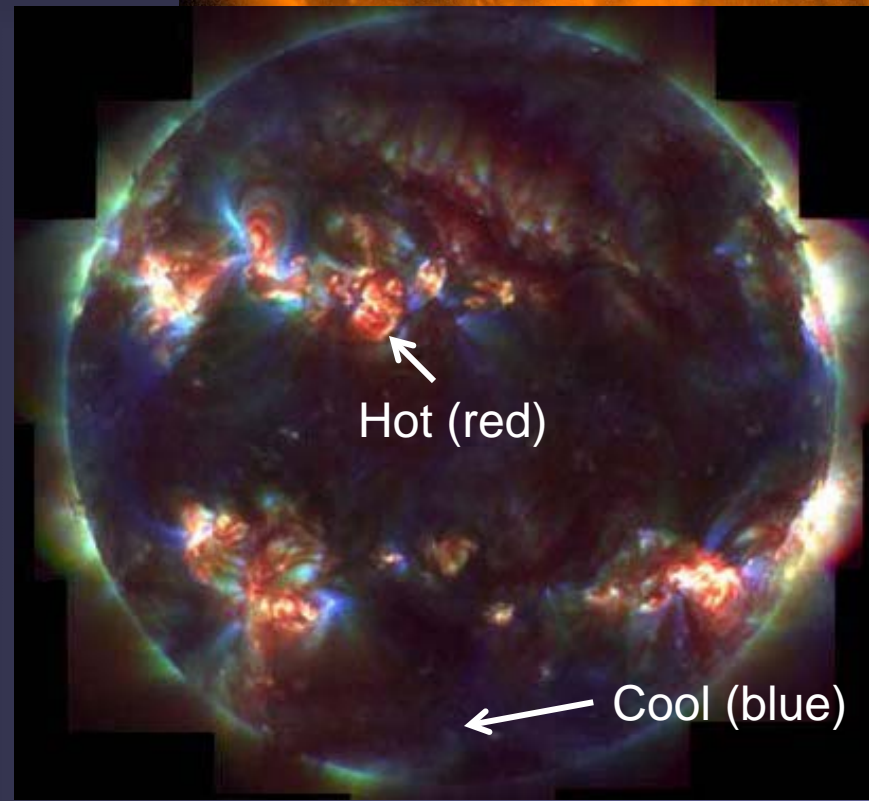
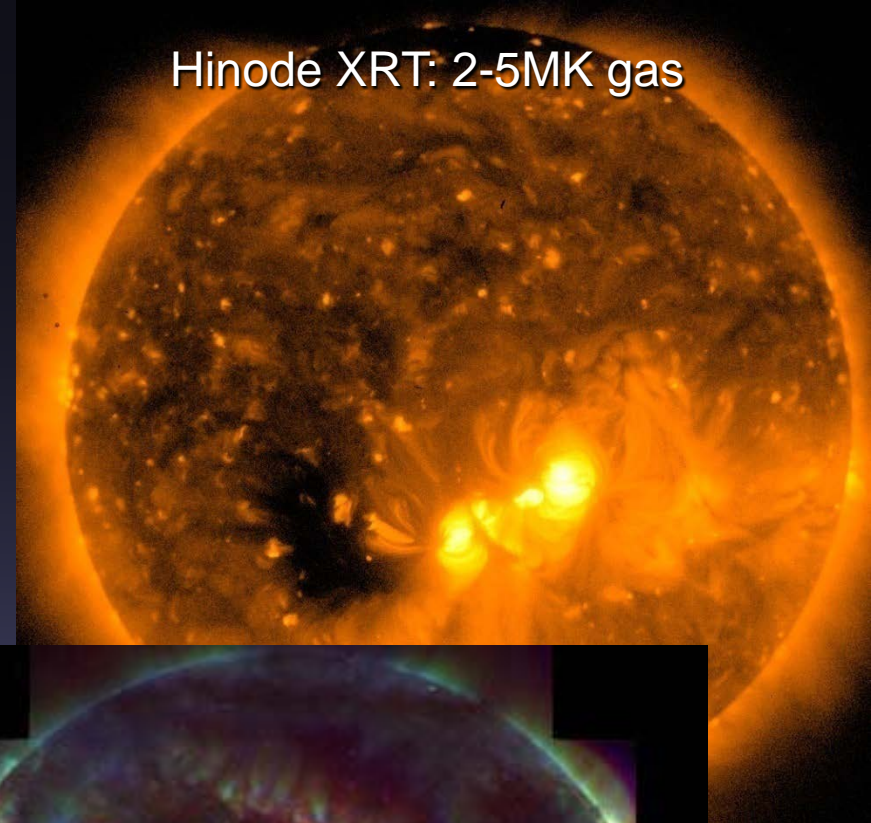


The hot corona: a brief history

- Eclipse of 1868: spectral line not seen in lab. found in solar spectrum. Norman Lockyer → belongs to a new element, Helium (after Helios, greek sun god)
- Eclipse of 7 Aug. 1869: discovery of a line at 530.3 nm in corona (green line) also never seen in the lab. Must be another unknown element → Coronium
- 1930s: Walter Grotrian and Bengt Edlén recognized that the green line belongs to Fe XIV (Fe^{+13})
- No element coronium, but corona must be extremely hot $\approx 10^6$ K!

Coronal temperature

- Repetition (from lecture 4)
- Different temperatures & densities co-exist in the corona
- Temperature range: <1 MK (Coronal hole) to 10 MK (act. region)
- Range of e^- densities (inner corona):
 - Loop: 10^{10} [cm $^{-3}$]
 - coronal hole: 10^7 [cm $^{-3}$]



Coronal heating: required energy fluxes

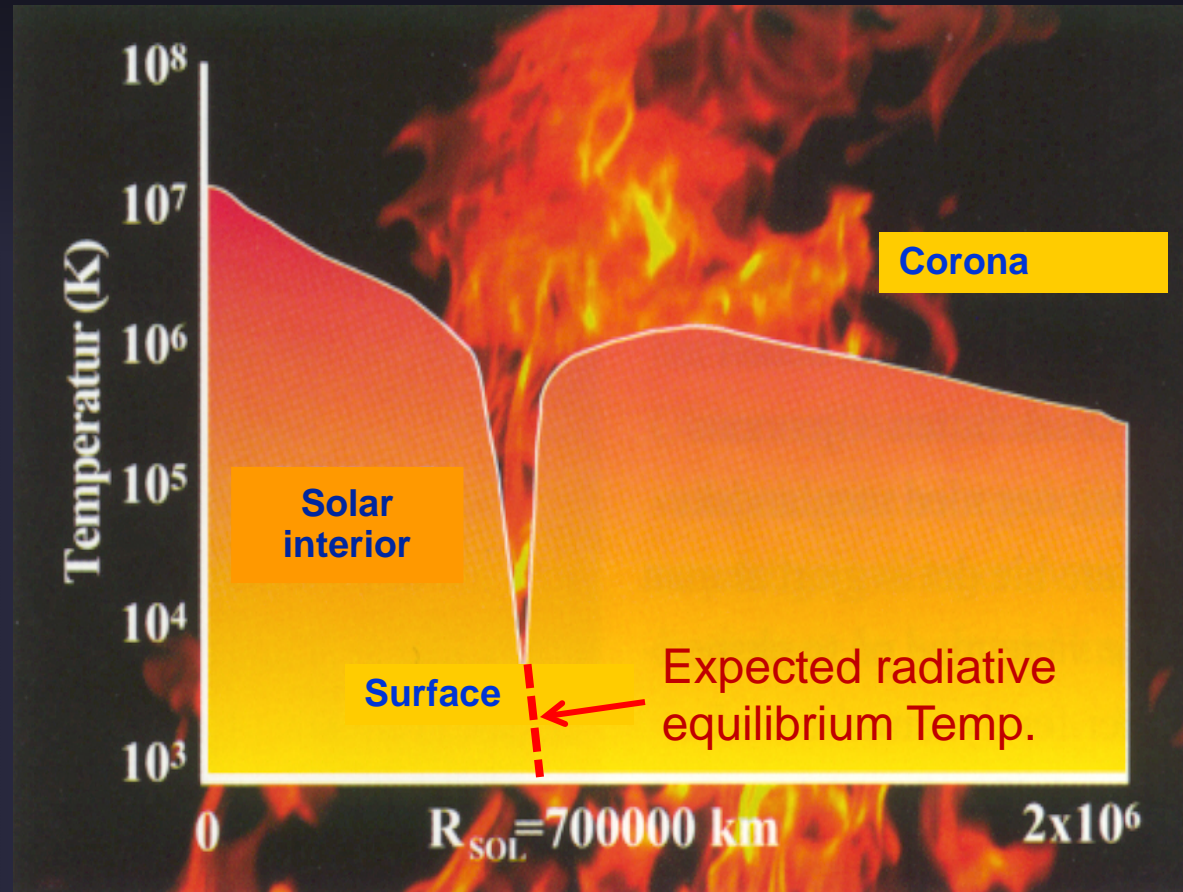
- Energy flux required to heat corona depends on type of region
 - Quiet Sun: $3 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$
 - Active region: $1\text{-}2 \times 10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$
 - Coronal hole: $8 \times 10^5 \text{ erg cm}^{-2} \text{ s}^{-1}$
 - Average corona: $10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$
- Energy flux to heat **chromosphere**: $10^7 \text{ erg cm}^{-2} \text{ s}^{-1}$
 $\approx 10 \times$ average energy flux for corona ($10^5 \times$ higher density in chromosphere)
- **Photosphere radiates $6.3 \times 10^{10} \text{ erg cm}^{-2} \text{ s}^{-1}$**
- Units: $10^5 \text{ erg cm}^{-2} \text{ s}^{-1} = 100 \text{ W m}^{-2}$

Solar corona: not heated by radiation

While surface is $\approx 6,000$ K, temp. in corona reaches $\approx 2 \cdot 10^6$ K

Corona cannot be heated to 10^6 K by Sun's radiation (violates 2nd law of thermodyn.)

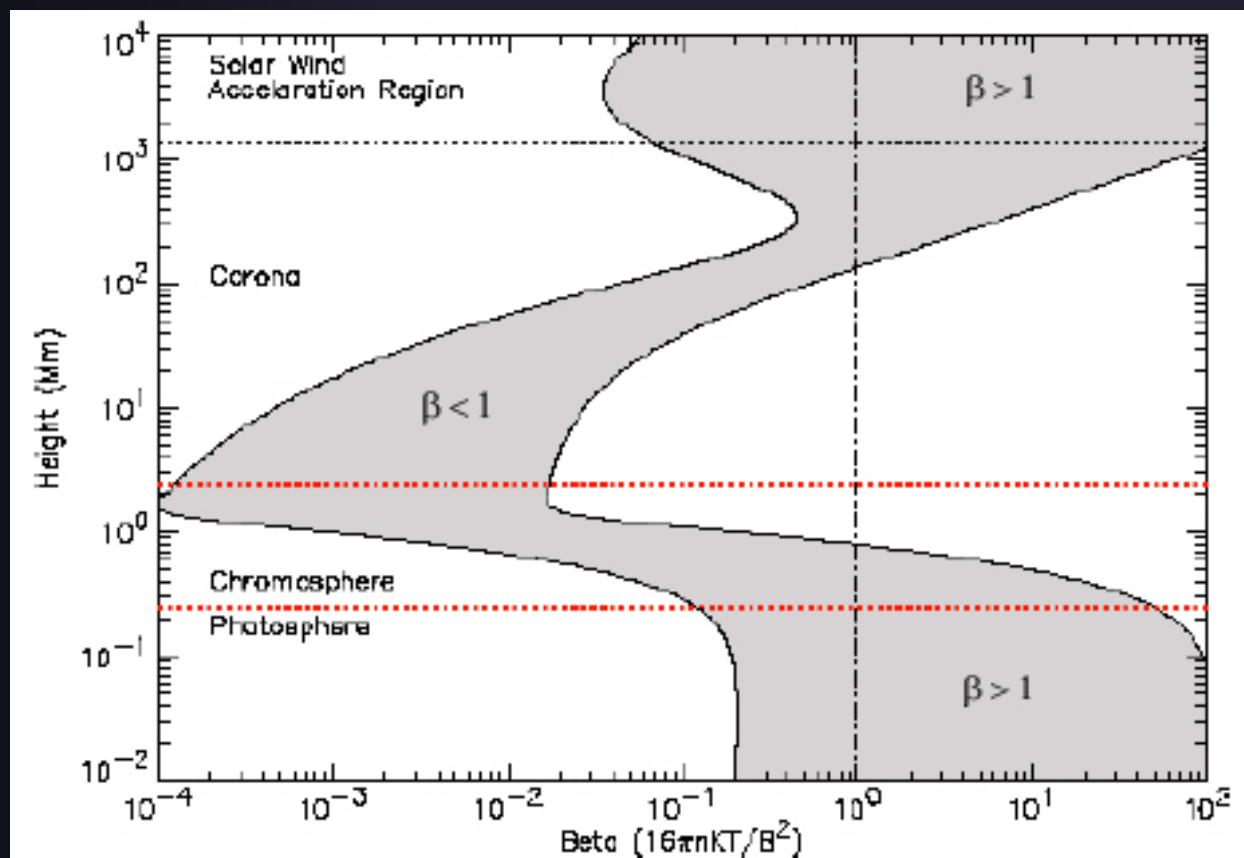
Another mechanism is needed to heat it



Convection produces acoustic waves: do they heat the corona?

Plasma β : solar corona is a magnetosphere

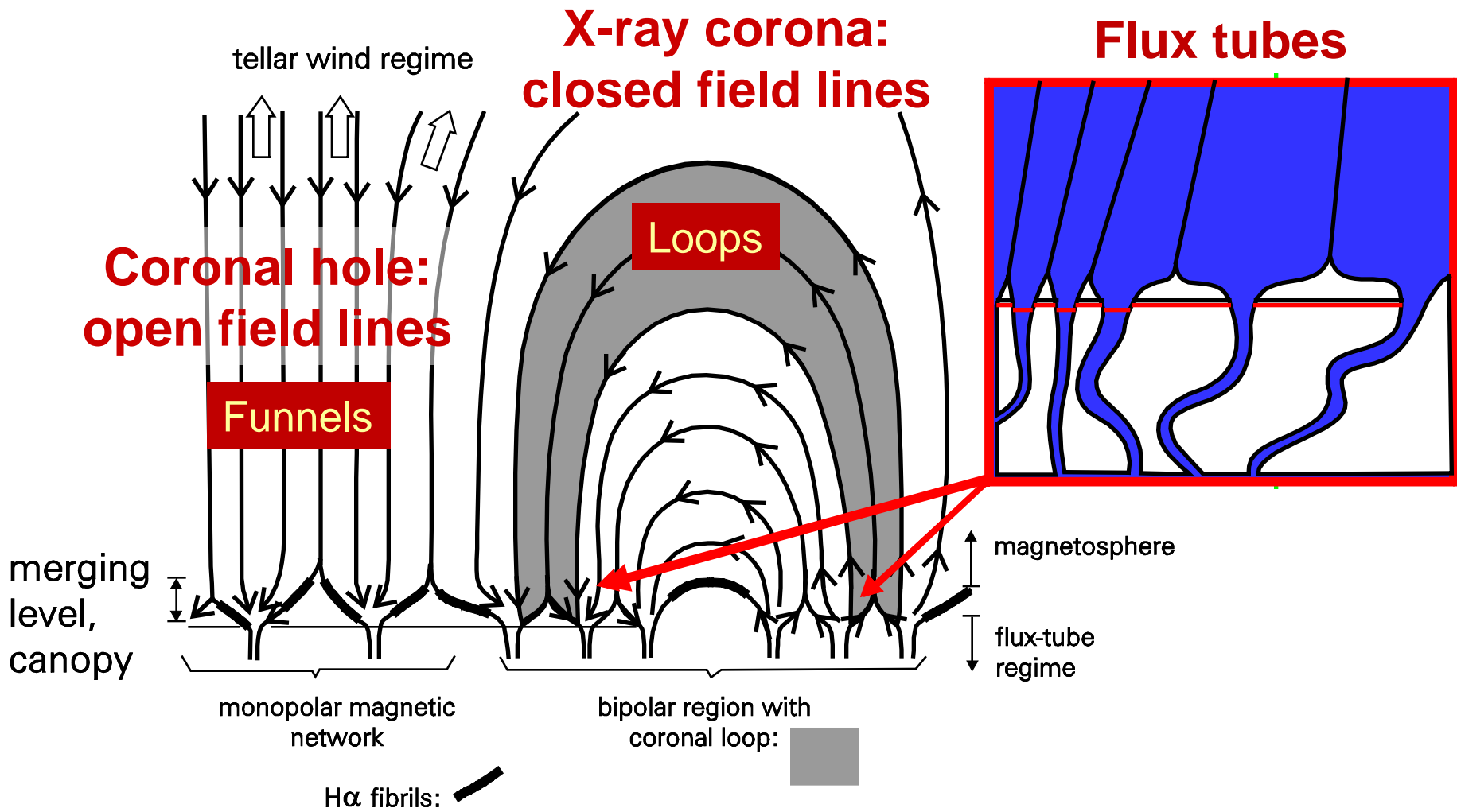
Field dominates ← → Gas dominates



Magneto-
sphere

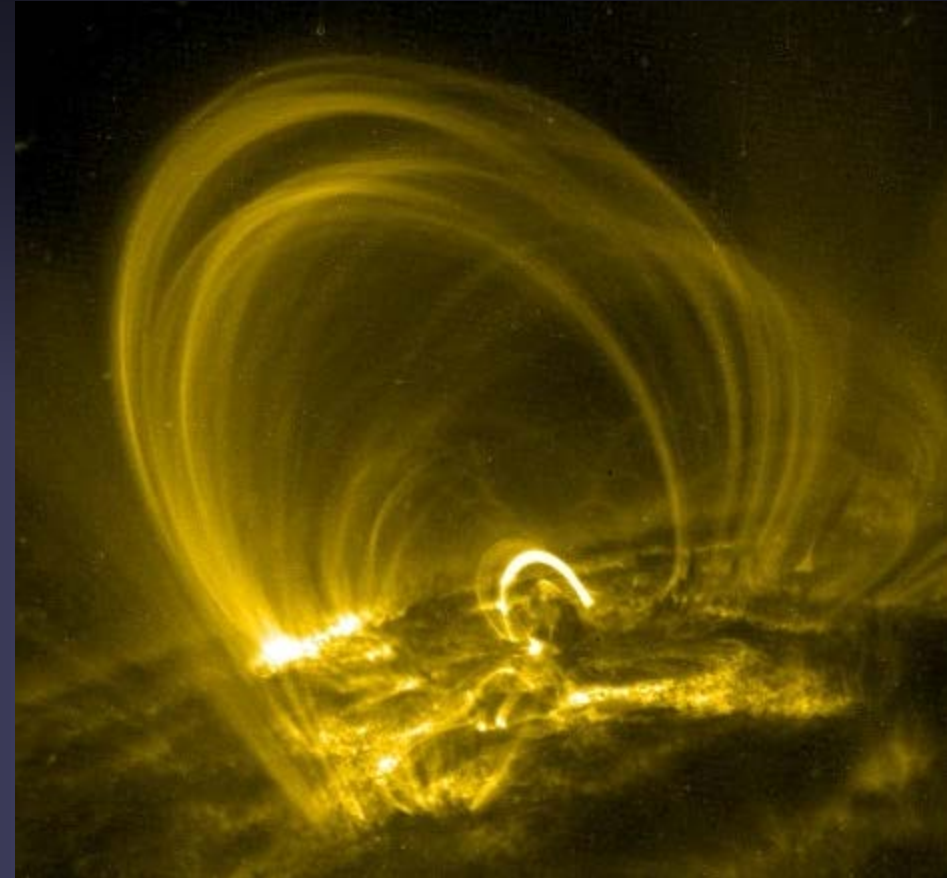
Figure 1. Ratio of gas pressure to magnetic pressure (β) as a function of height¹.
(Gary 2000)

Flux tubes, canopies, loops & funnels



Coronal loops

- Coronal loops are closed field lines in the corona. Closed magnetic flux must be *filled with hot plasma* to be called a *coronal loop*
- Loops are the basic building blocks of closed-field corona
- Loop temps range from below 0.1MK to 10MK
- Observations in a given spectral band sample radiation in a narrow range of temperatures. A typical image show only a small fraction of all loops



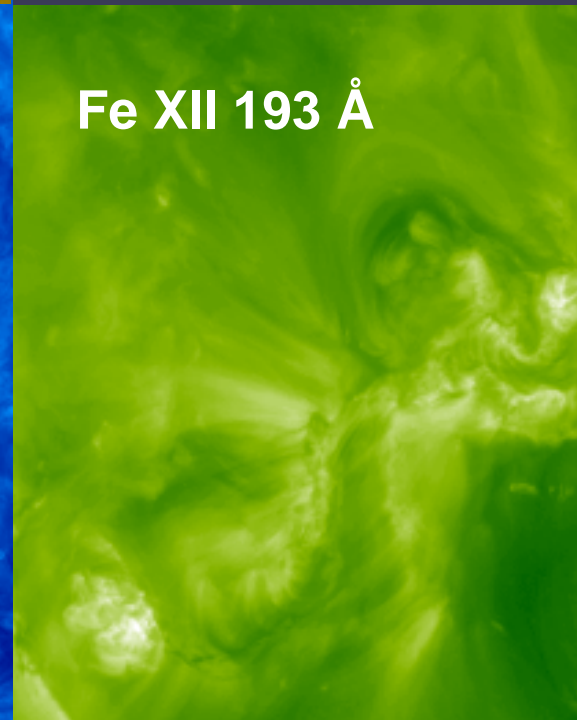
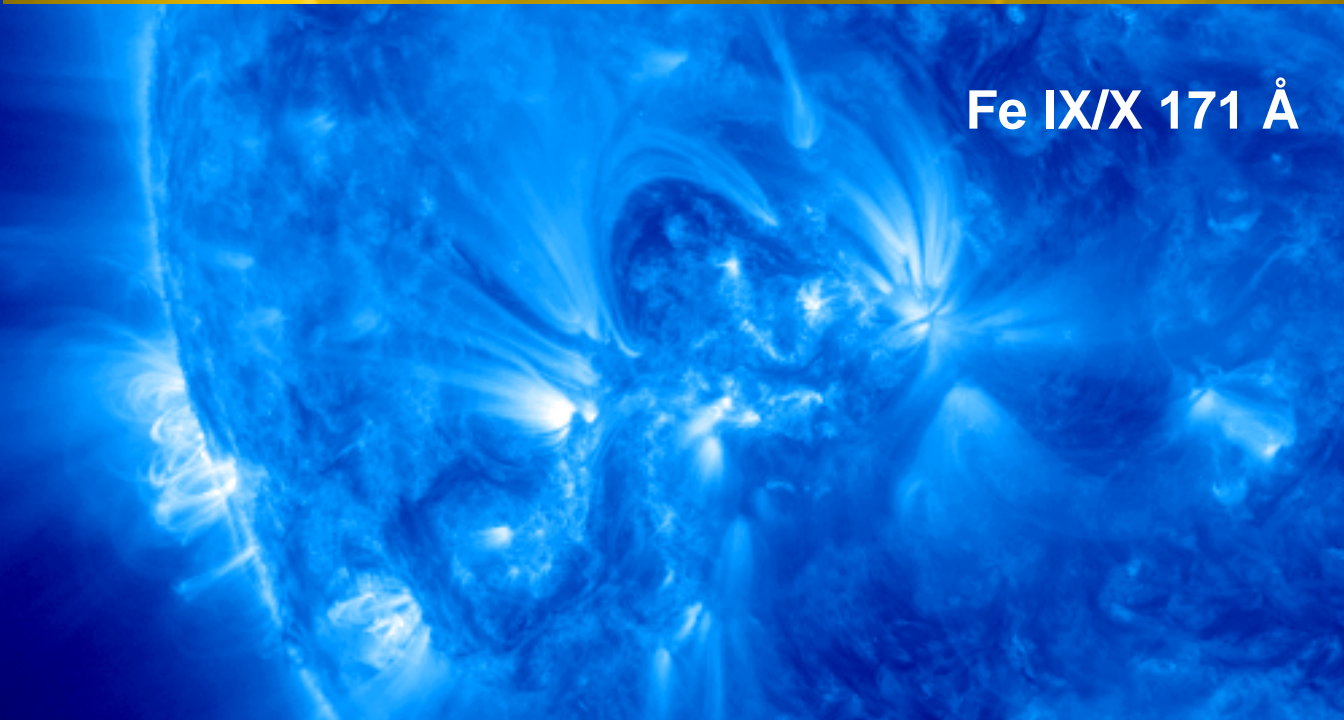
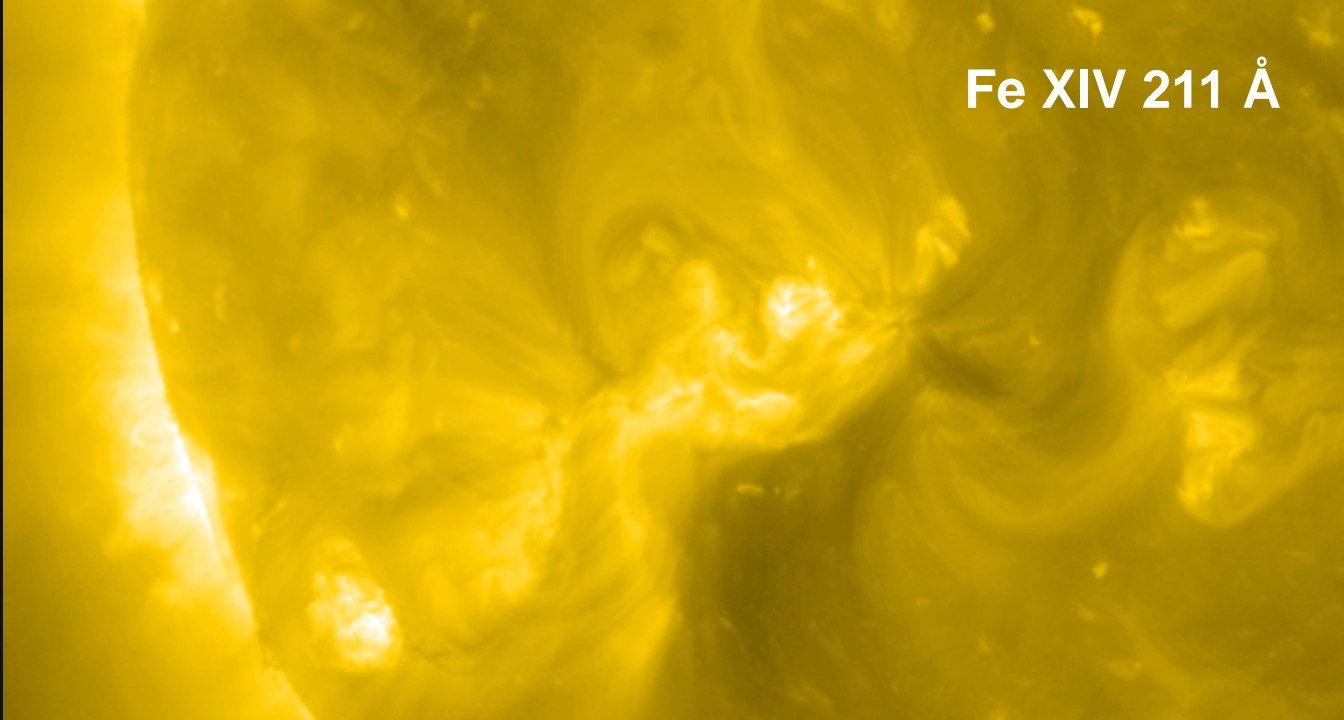
Loops at 0.9MK (TRACE
Fe IX 171Å)

Fe XIV 211 Å

**Loops at 3
temperatures**

Fe IX/X 171 Å

Fe XII 193 Å

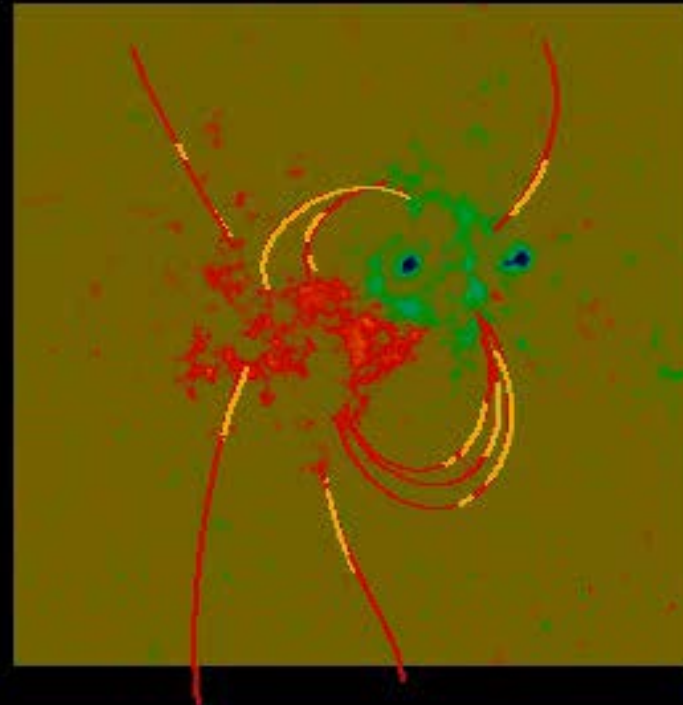


Coronal loops in 3-D

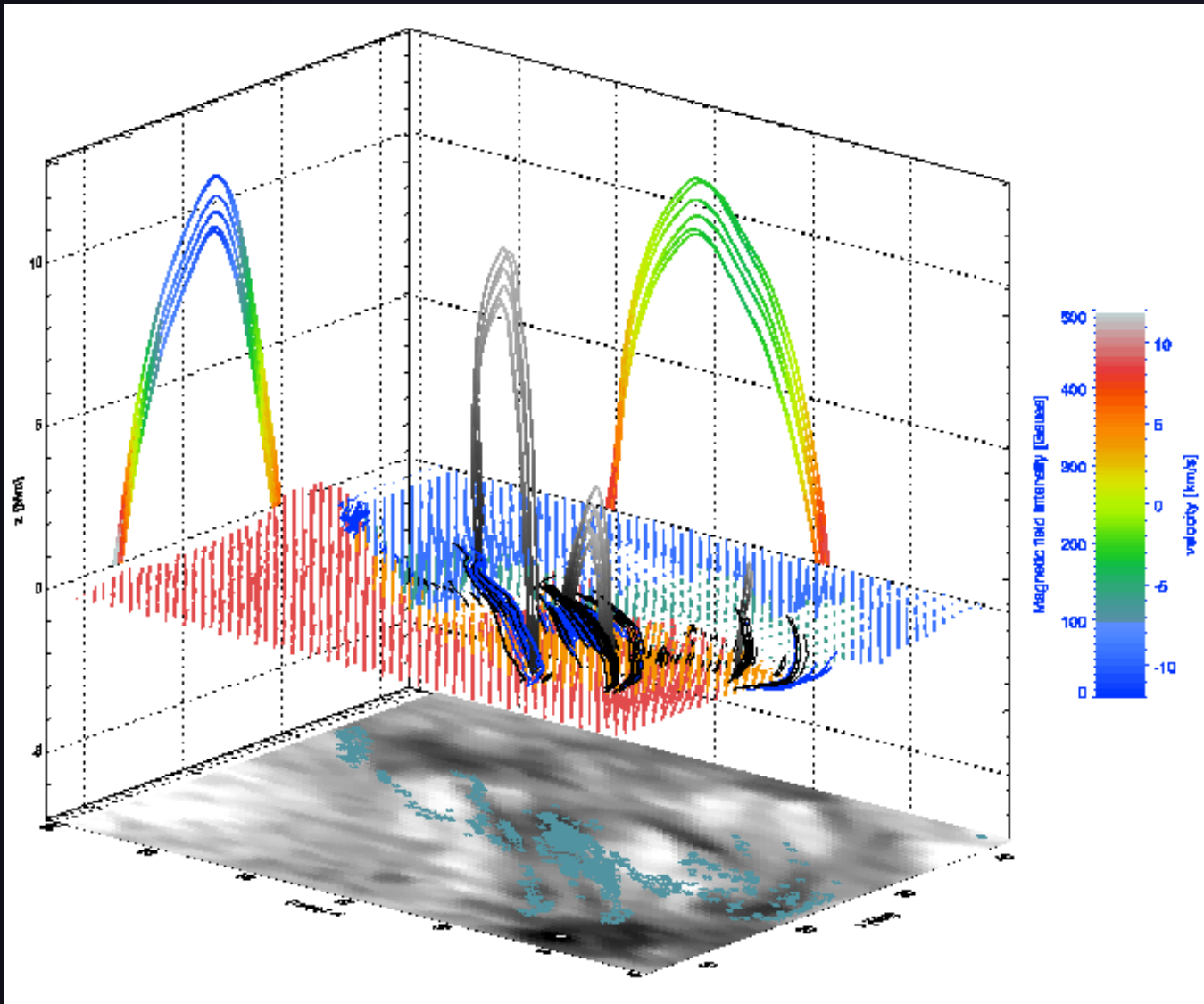
Yellow lines: First stereoscopic reconstruction of coronal loops observed by the two STEREO spacecraft looking at the Sun from different directions.

Red lines: magnetic field extrapolations starting from magnetogram on solar surface

Feng et al. 2007



Structure of Cool Magnetic Loops



Magnetic loops deduced from measurements of He I 10830 Å

Stokes profiles in an emerging flux region.

Left projection: Field strength

Right projection: Vertical velocity

Andreas Lagg

Stages involved in coronal heating

- Three stages of coronal heating:
 - **Generation** or storage of mechanical and magnetic energy: photosphere
 - **Transport** of mechanical and magnetic energy: from photosphere via chromosphere and TR to corona
 - **Release** of mechanical and magnetic energy: corona
- A fourth stage is:
 - The **reaction of the atmosphere** to the heating

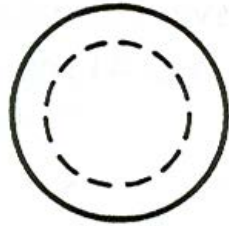
Coronal heating mechanisms

- Heating mechanisms associated with magnetic field are divided into 3 classes
 - **AC mechanisms:** wave heating (energy transported by waves, dissipated in shocks or by ohmic heating)
 - **DC mechanisms:** ohmic dissipation at current sheets due to finite resistivity
 - **Impulsive heating or nanoflare heating:** heating by magnetic reconnection: acceleration of particles to supersonic speeds. Heating at shocks, etc.

Ohmic heating

- Ohmic dissipation of magnetic energy acts where resistivity is finite and electric current is large
- Heating rate: $H \sim \eta j^2$
- $\eta \sim \sigma^{-1}$ = resistivity (magnetic diffusivity)
- $j = (c/4\pi) \nabla \times B$ = electric current density
- Heating is large where currents are large, i.e. where the field changes on **small length scales**, so-called tangential discontinuities, or electric current sheets
- Ohmic heating: important for AC & DC mechanisms

AC mechanism: Flux tube waves



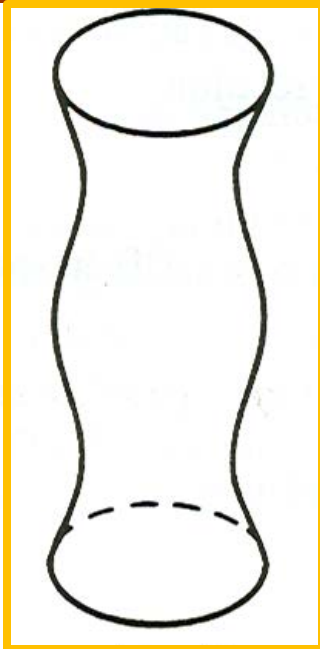
$$c_T^2 = c_S^2 c_A^2 / (c_S^2 + c_A^2)$$

$$c_K^2 = \rho_i c_A^2 / (\rho_i + \rho_e)$$

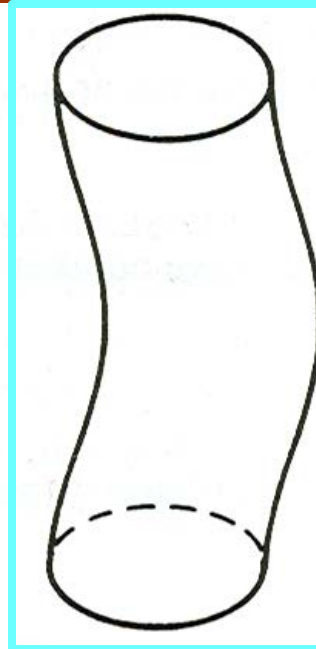
$$c_A = B / \sqrt{4\pi\rho}$$

Compressible

Restoring force:
Magnetic and thermal pressure (magneto-acoustic)



Longitudinal (Sausage)



Transverse (Kink)



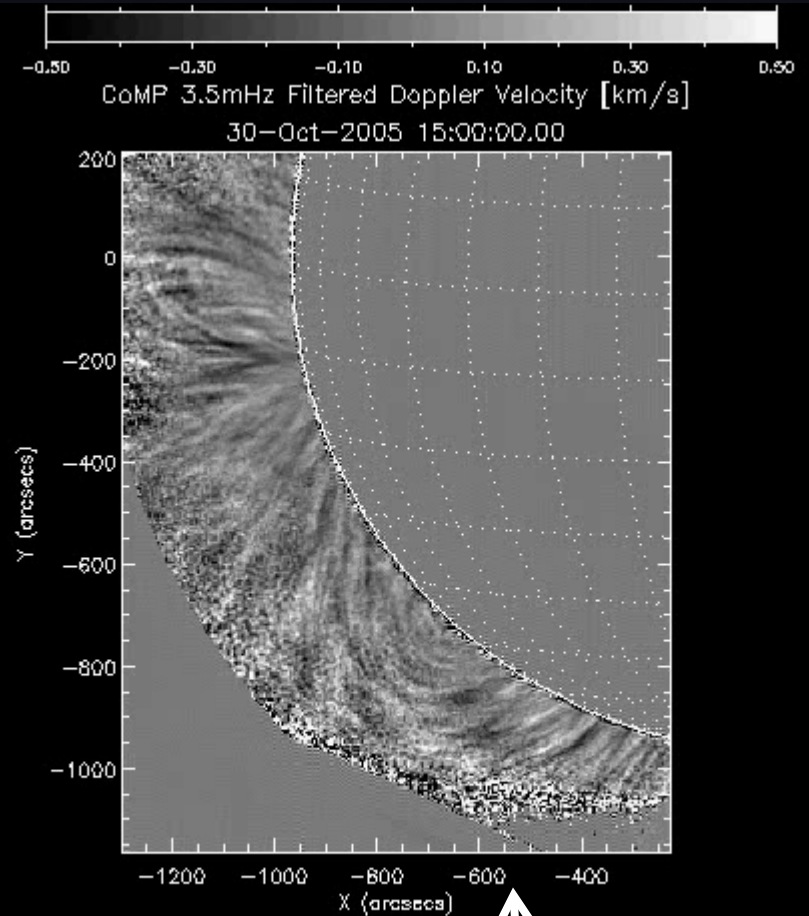
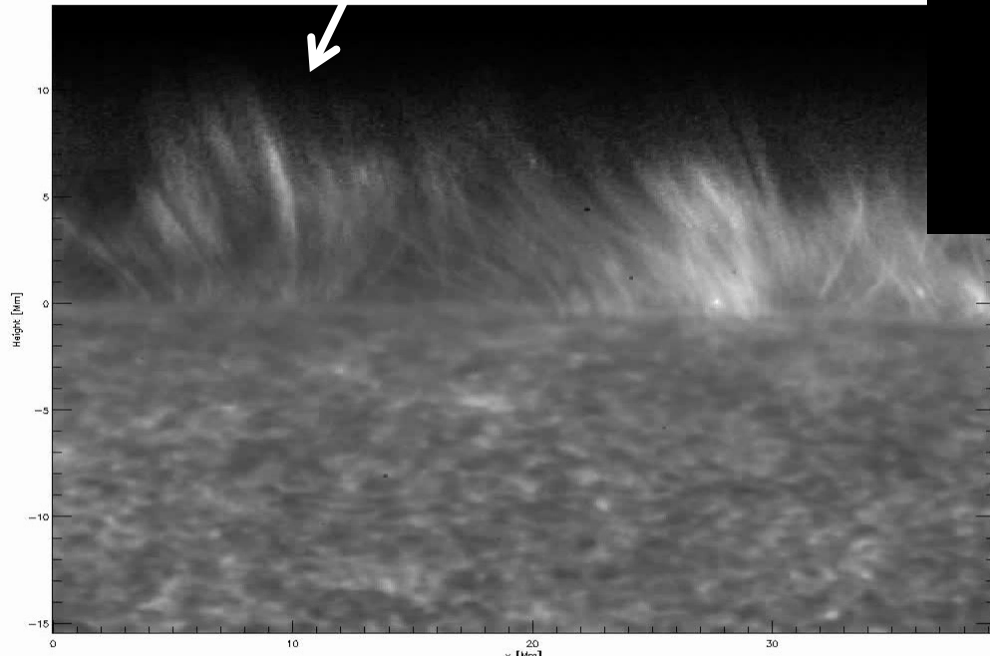
Torsional (Alfvén)

(Mainly) Incompressible

Restoring force:
Magnetic curvature force (tension)

Evidence of waves in solar atmosphere

Kink-mode wave in spicules



Propagating Alfvén
(or possibly kink)
waves in Corona

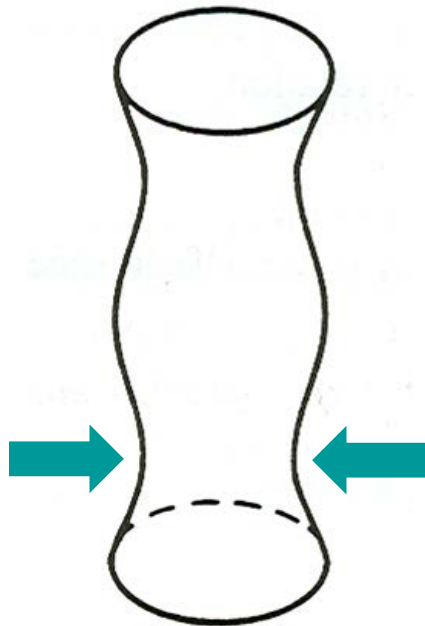
How are flux tube waves excited?

Interaction of convective flow with magnetic field

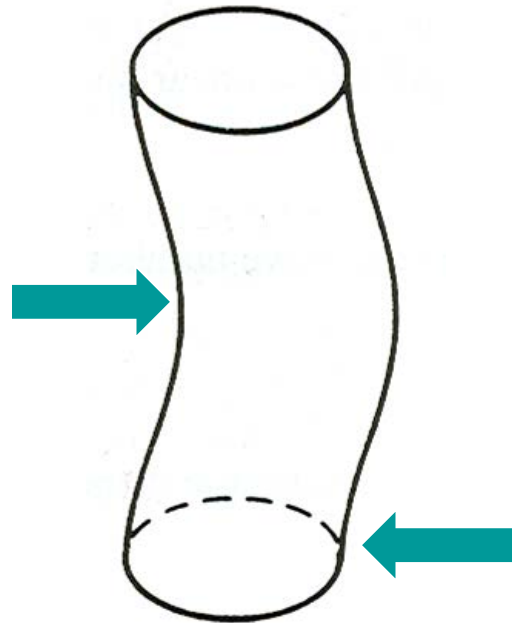
compression

shear

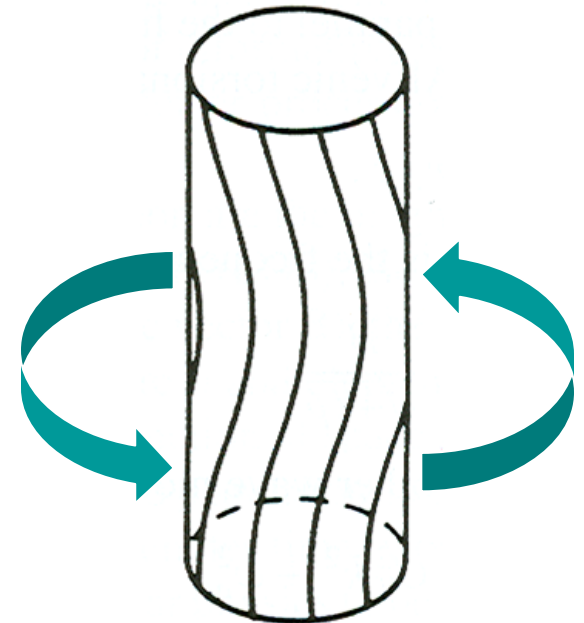
vortex flow



Longitudinal



Transverse



Torsional

Wave dissipation mechanisms

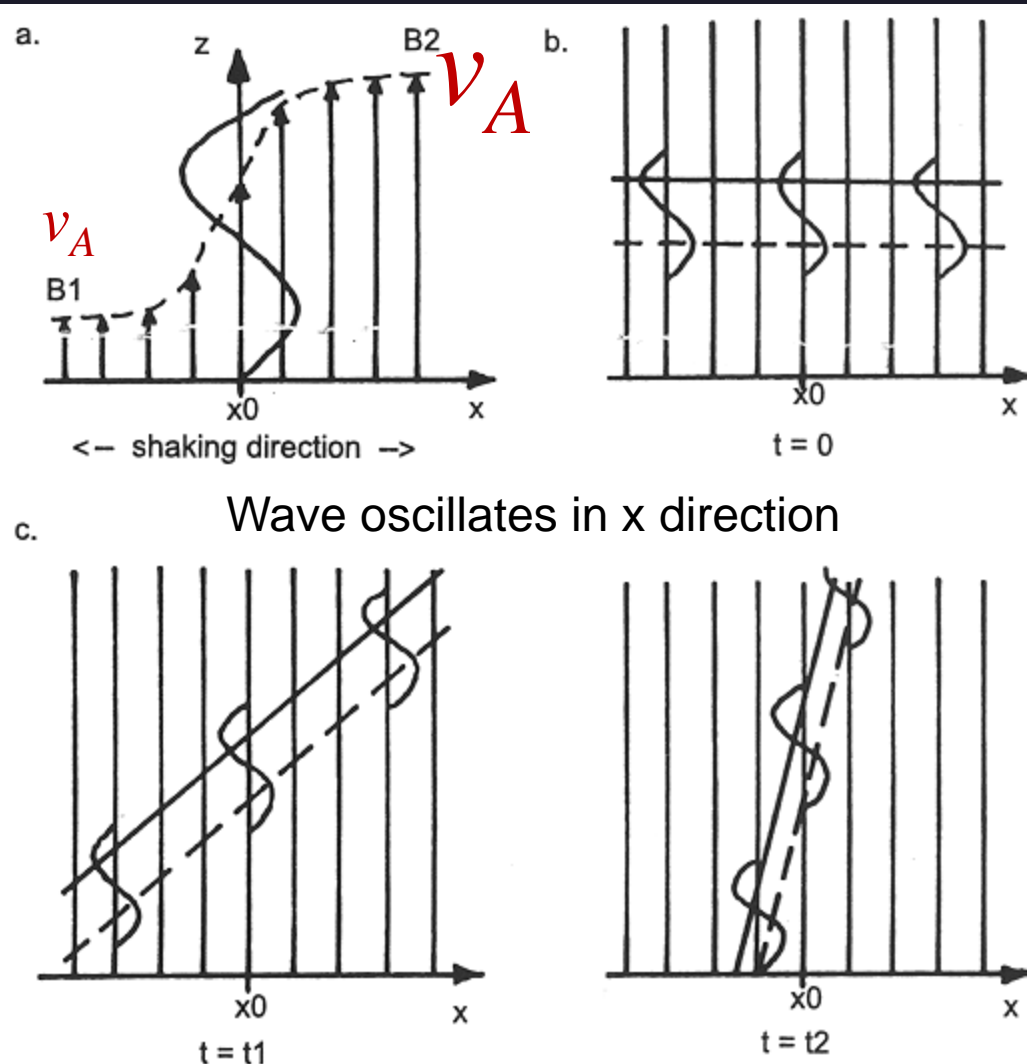
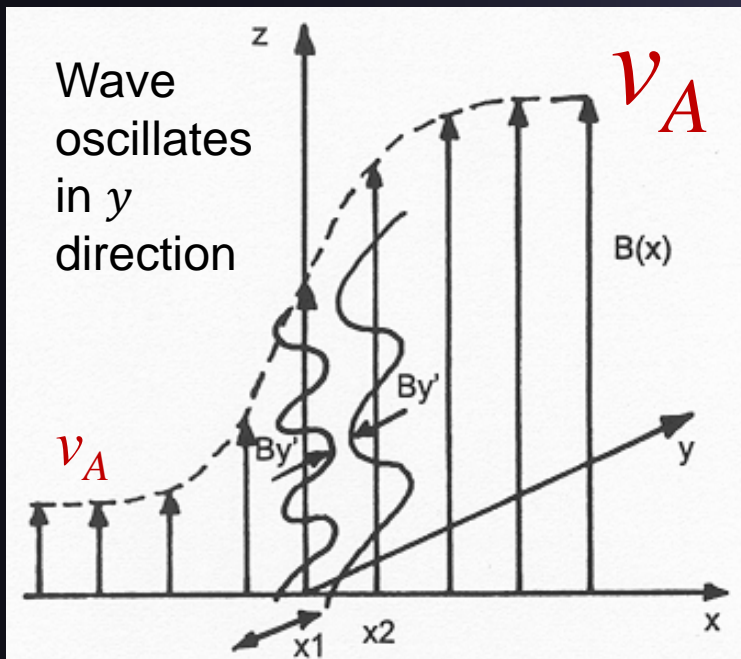
- Dissipation means that the ordered motions of waves are converted into disordered motions of particles (heat). It occurs at small scales!
- **Longitudinal** (magnetoacoustic): Dissipation in **shocks** (very high densities, very large gradients)
- **Alfvenic** (incompressible) waves: Dissipation in presence of **magnetic field gradient**. Leads to current sheets → ohmic dissipation
 - **Phase mixing**: wave oscillates perpendicular to v_A gradient
 - **Resonant absorption**: wave oscillates parallel to v_A gradient

Wave dissipation mechanisms

Ulmschneider 1998

Resonant absorption: Formation of small scales due to wave front tilting

Phase mixing:
formation of small
scales as waves in
neighbouring pixels get
out of phase ($v_A \sim B$)

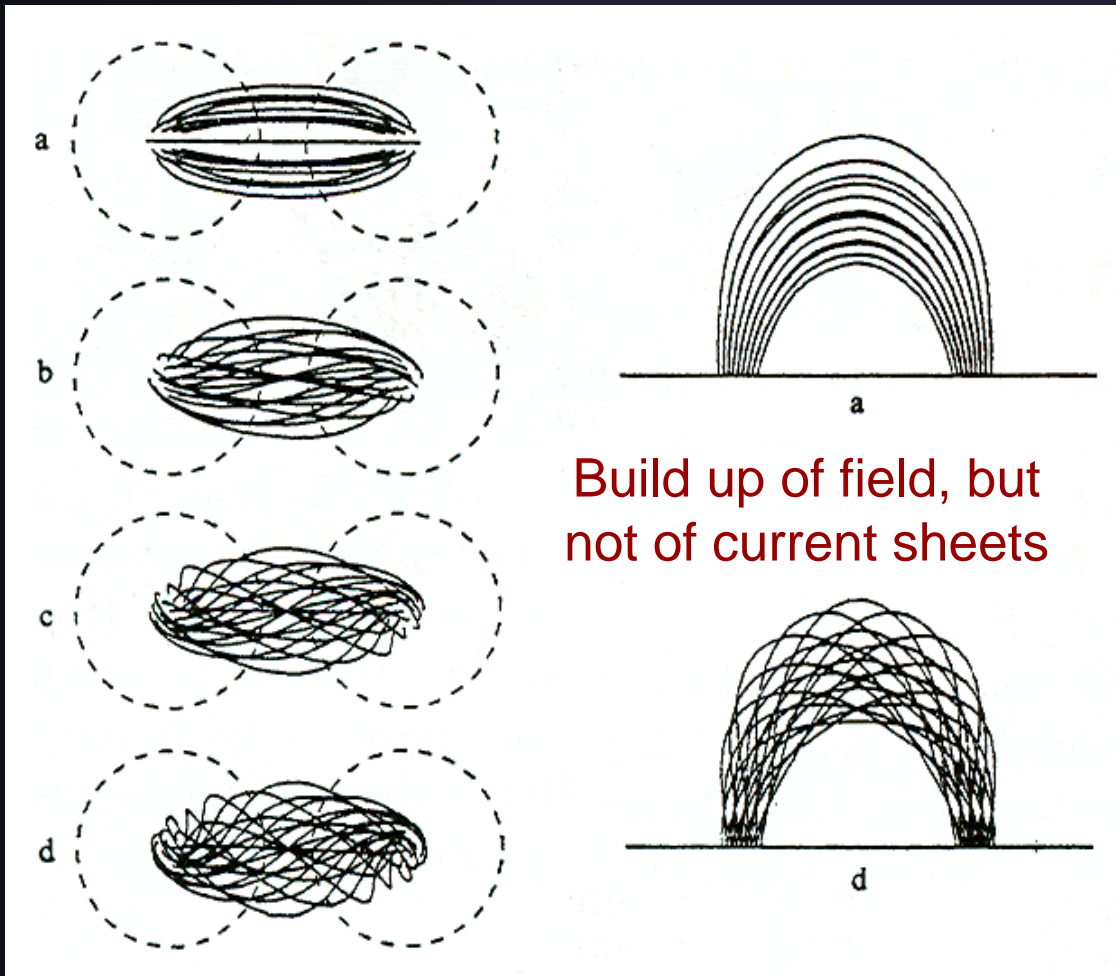


Coronal heating: DC mechanisms

- Slow build up of magnetic energy and its non-catastrophic release
- Energy release (dissipation) possible at current sheets = tangential discontinuities of magnetic field = sharp boundaries between magnetic field lines pointing in different directions
 - Ohmic dissipation: gradual energy release; efficient at very small scales

Example of magnetic energy build-up

Example of braiding for predefined footpoint motions of a loop: oppositely directed twists at the two footpoints



Potential field: lowest energy density

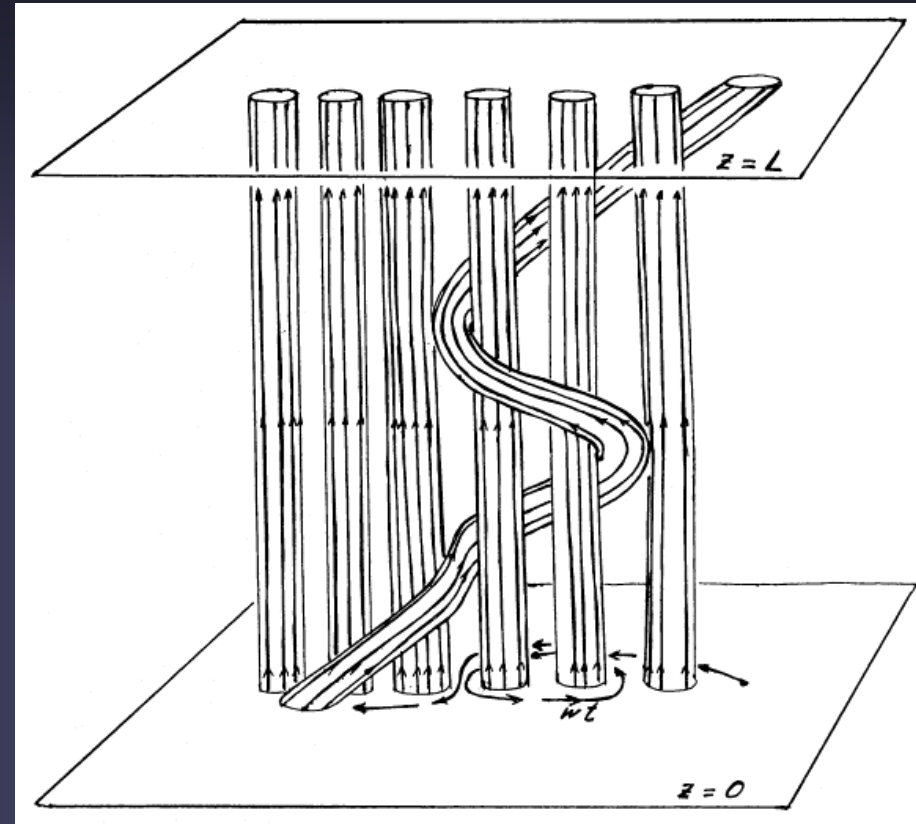
Increasing twist

Force-free field: high energy density

Sakurai 1979

Braided fields

- Parker (1972): Flows in photosphere move footpoints of coronal field lines around
- Random flows \rightarrow small-scale braiding of field
- The braided fields carry large currents: $j \sim \nabla \times B$
- Ohmic dissipation is effective at locations of large j :
 $H \sim \eta j^2$



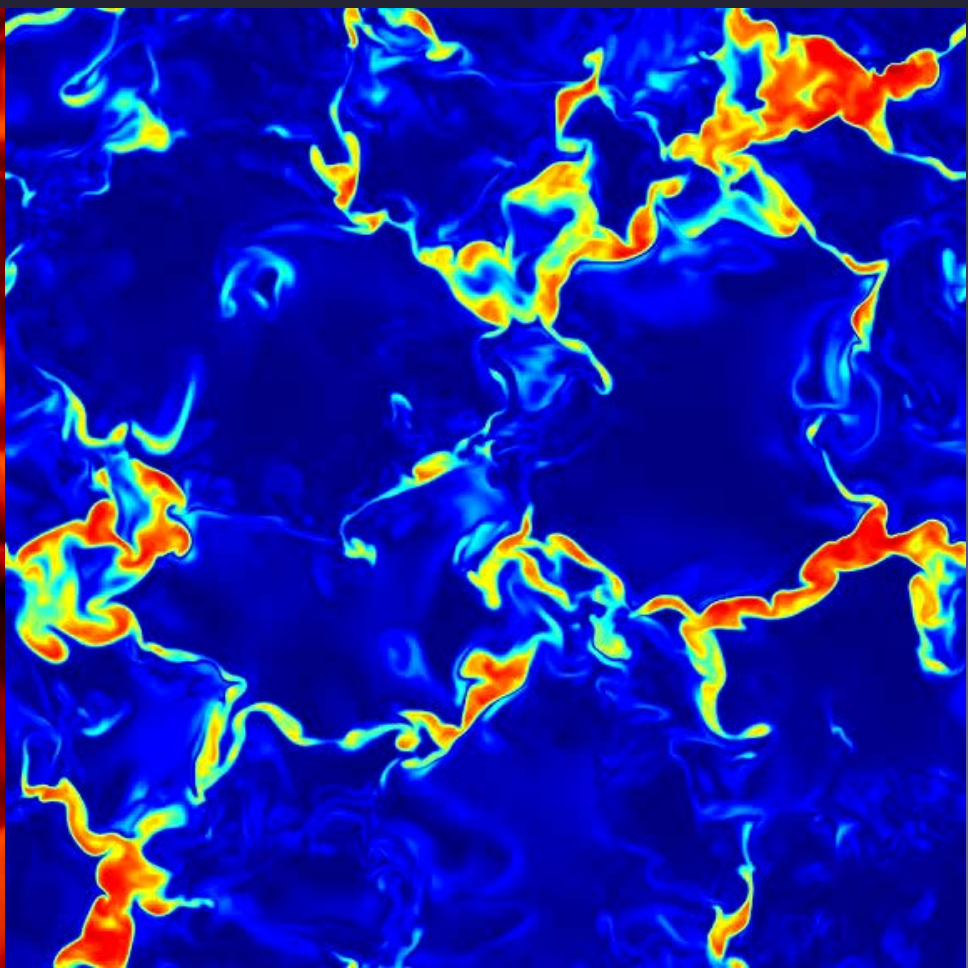
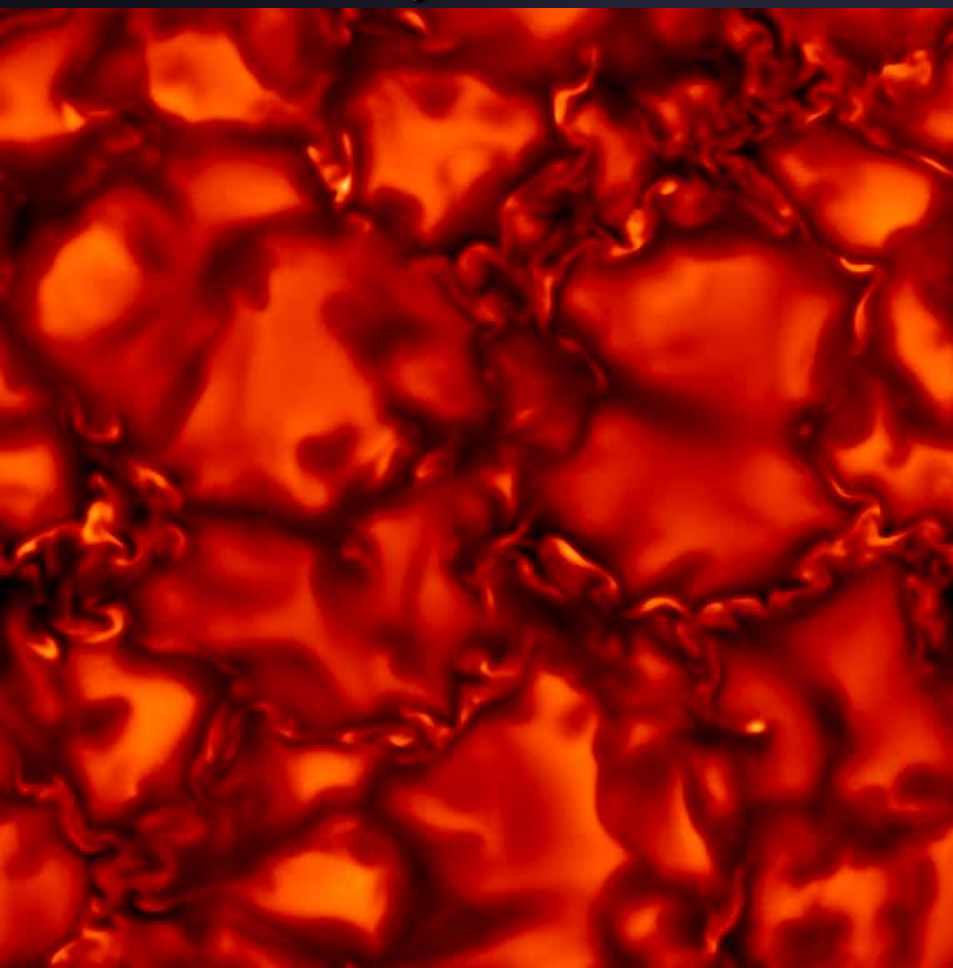
MHD simulations of footpoint motions

Evolution of granulation moves magnetic field: random walk

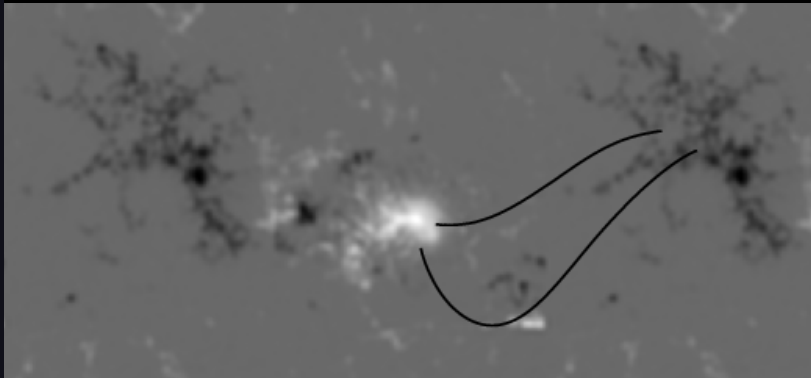
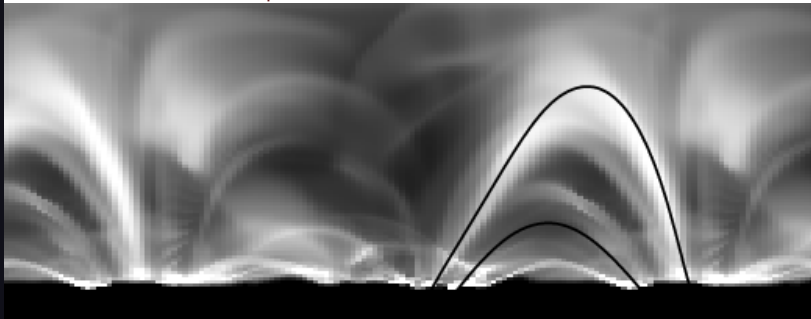
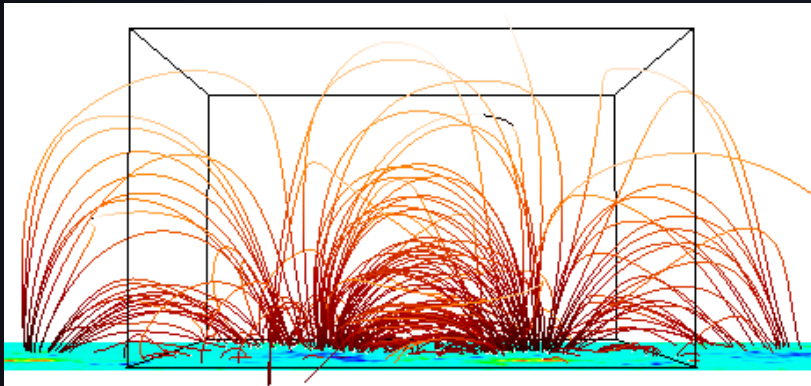
Intensity

$\langle B \rangle = 200\text{G}$

B



Simulation of DC coronal heating



Gudiksen & Nordlund (2002)

Coronal loops maintained at MK temperatures by current dissipation at current sheets



Braiding of coronal magnetic field lines \rightarrow current sheets

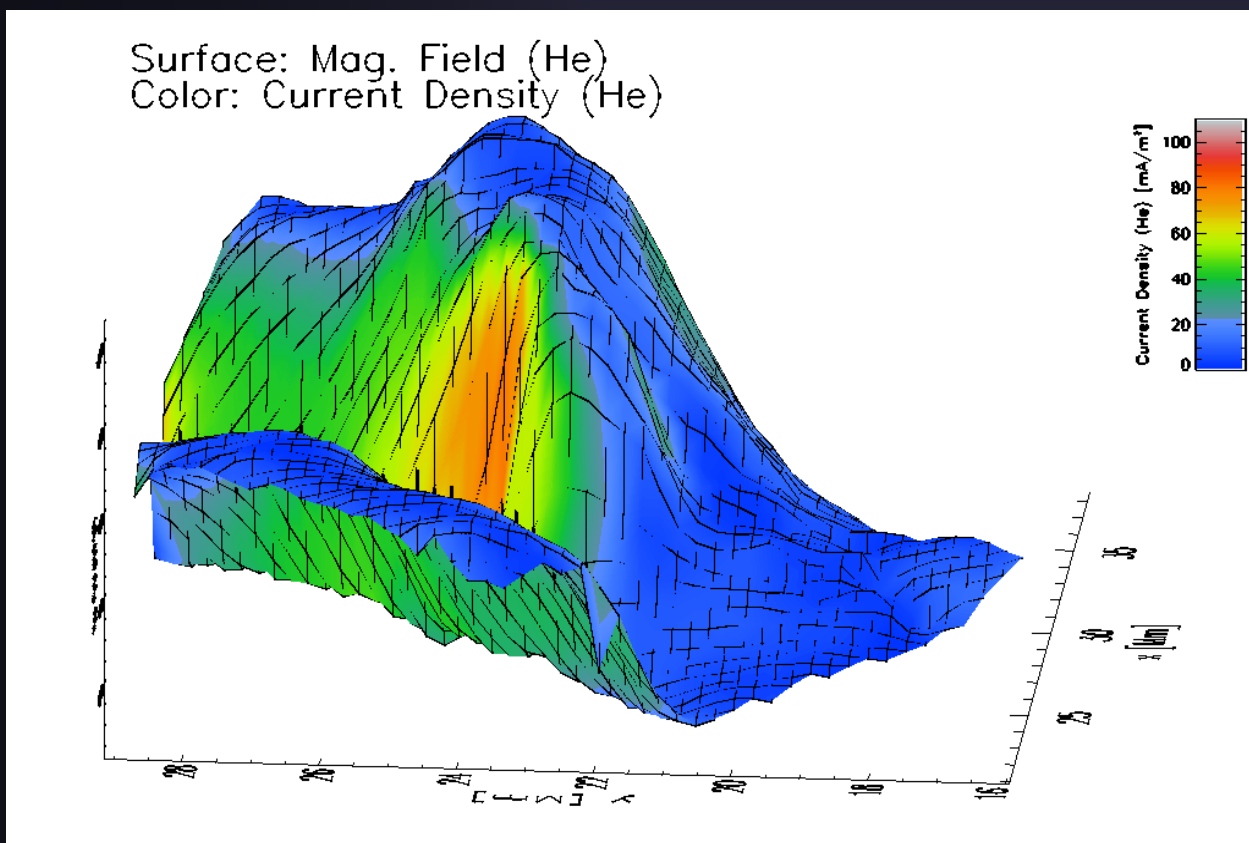


Interaction of magnetic flux with convection: Magnetic footpoint motions

Parker (1972)

Electric current sheet near base of corona

First observed electric current sheet (tangential discontinuity of magnetic vector) at base of corona in emerging flux region



Solanki et al. 2003, Nature

Figure:

Surface: magnetic field strength (note the valley)

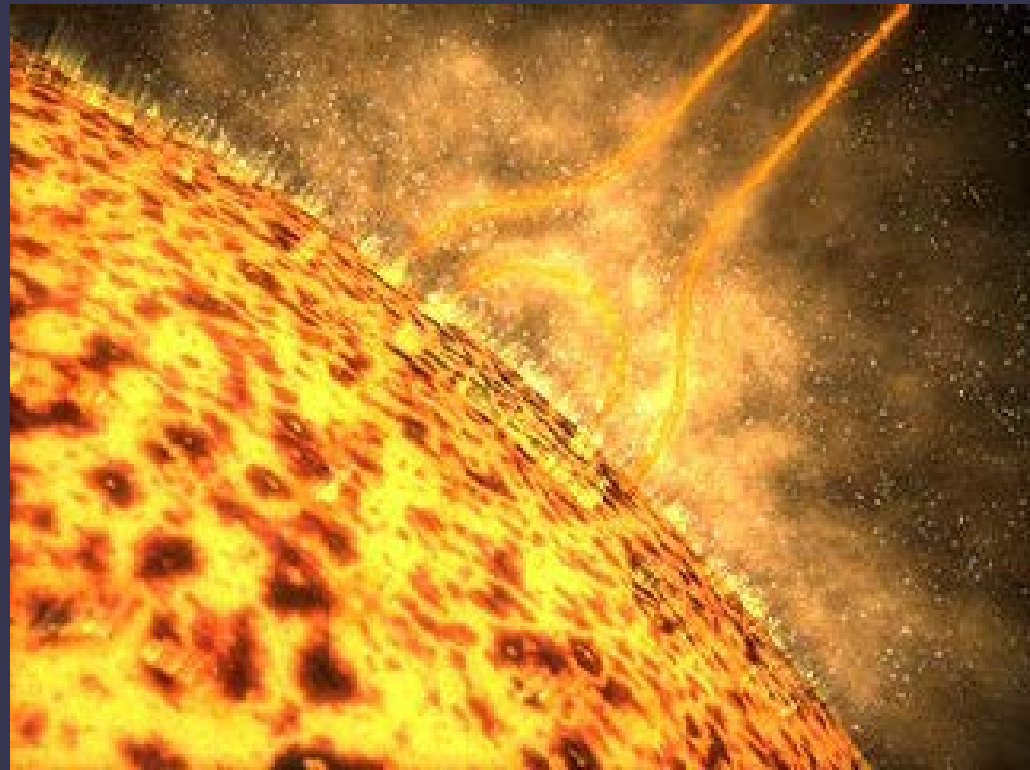
Colour: current density

Observed using He I 10830 Å polarimetry

Coronal heating: nanoflare heating

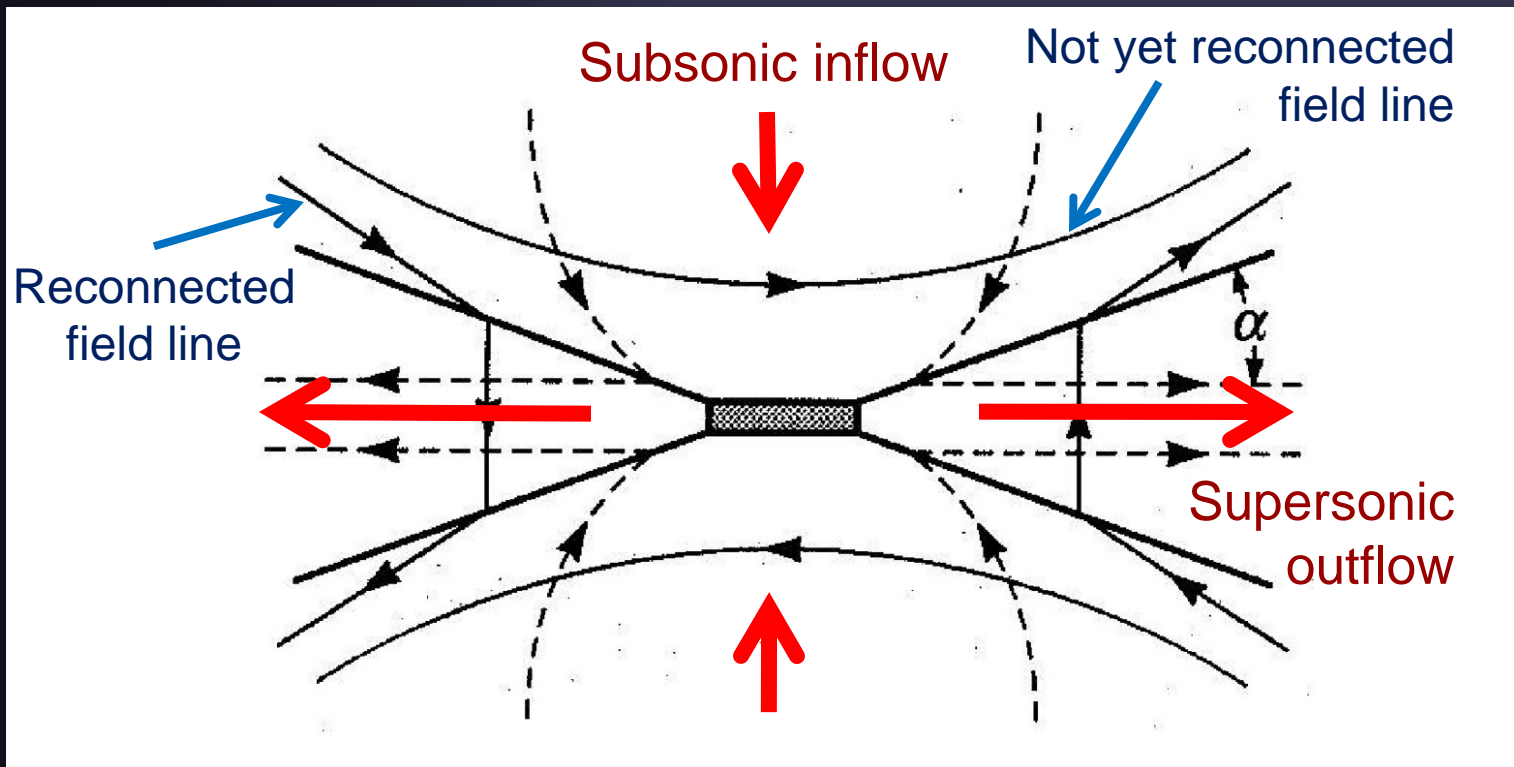
- Build-up of magnetic energy through
 - footpoint motions (random or ordered, e.g. shearing)
 - emergence of fresh magnetic flux
- Catastrophic release of excess magnetic energy through magnetic reconnection
- Energy release is visible as brightening: flare or microflare

Flare: artist's impression

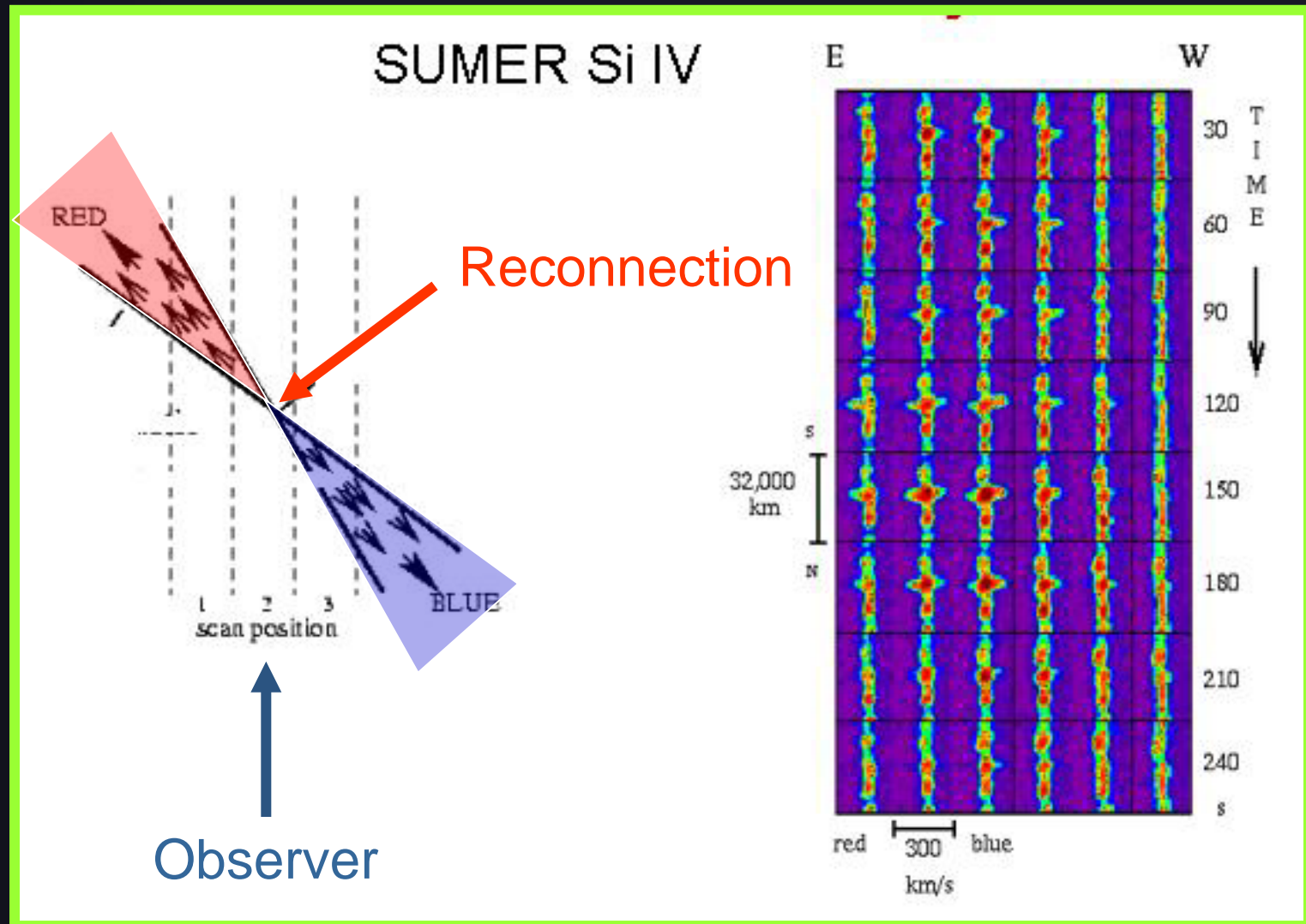


Conditions for magnetic reconnection

- Magnetic tangential discontinuities (e.g. X-type configuration)
 - Opposite polarity field lines are pushed towards each other
 - Magnetic energy: after reconnection < before reconnection.
- Magnetic energy converted mainly to kinetic energy of gas

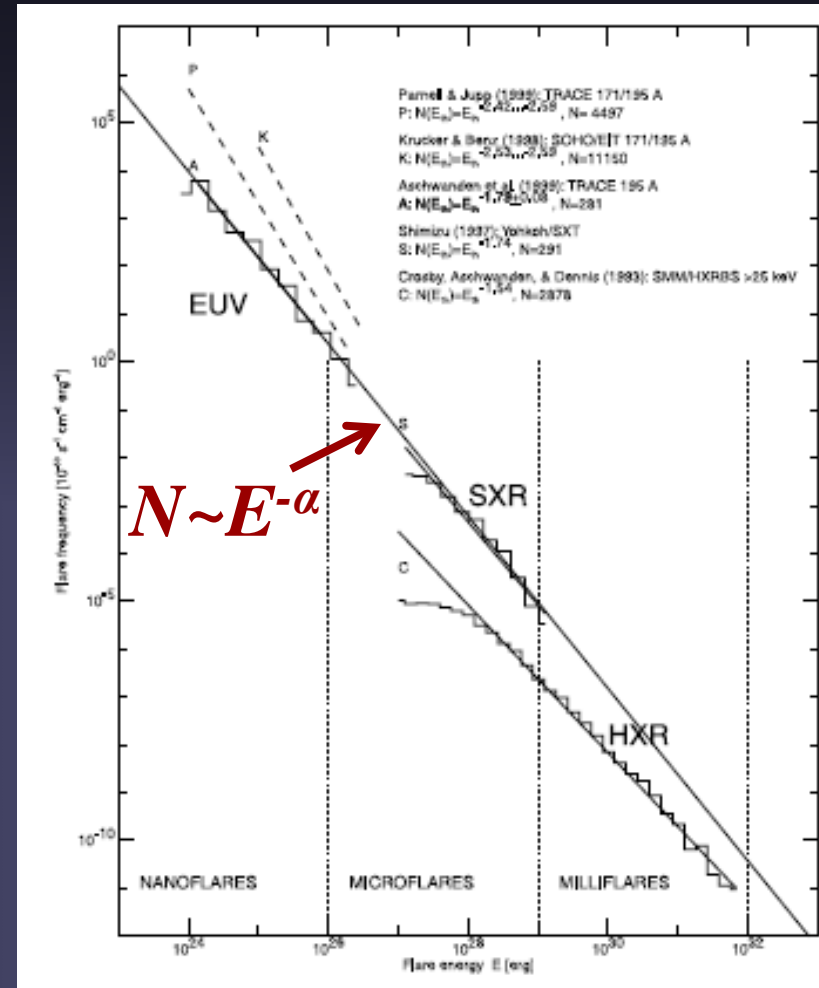


Evidence for reconnection: Explosive events



The missing energy problem

- There is an insufficient number of flares or even microflares to heat the corona
- ➔ Hypothetical nanoflares needed in large numbers
- Extrapolate to lower energies:
 - Sufficient energy to heat if power law exponent $\alpha > 2$
 - Most obs. give $\alpha < 2$

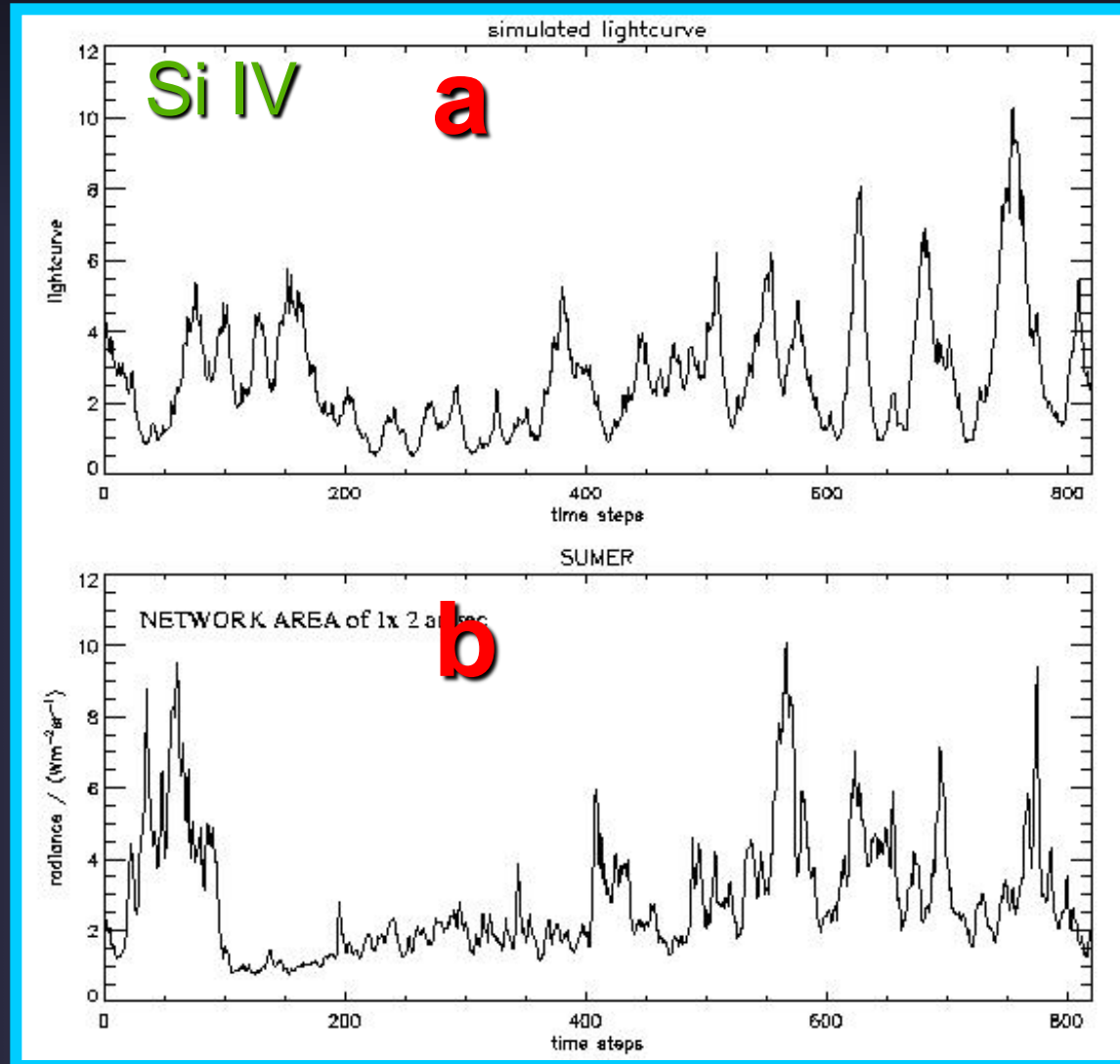


Aschwanden et al. 2000

Coronal brightness fluctuations: microflares

a SUMER time series of quiet Sun. All variations interpreted as nanoflares (proposed by Parker 1983 to heat the corona)

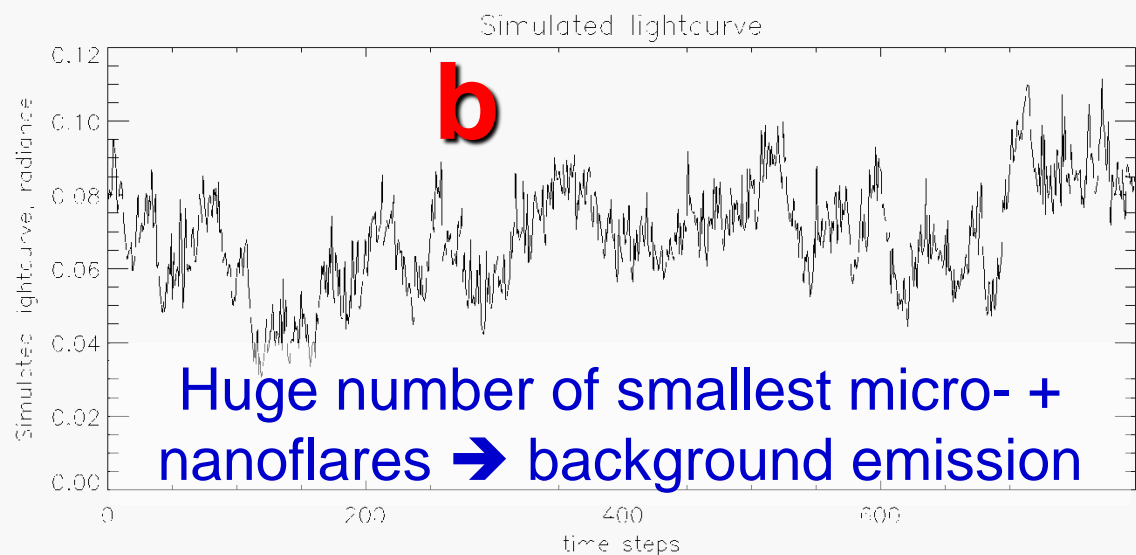
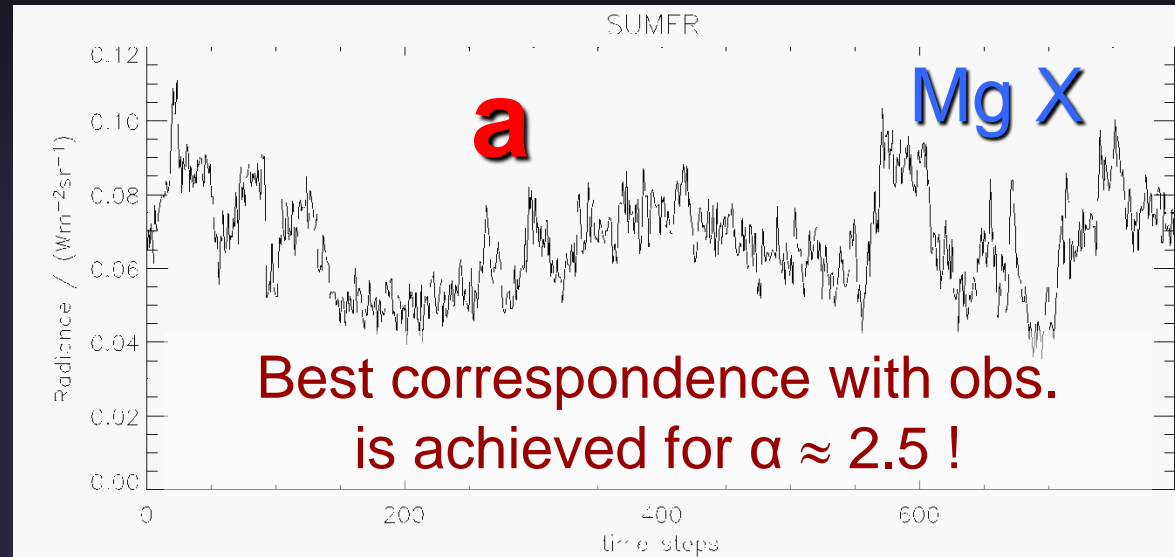
b synthetic light curve produced under the assumption that all emission is due to nanoflares (very simple model)



Coronal brightness fluctuations: microflares

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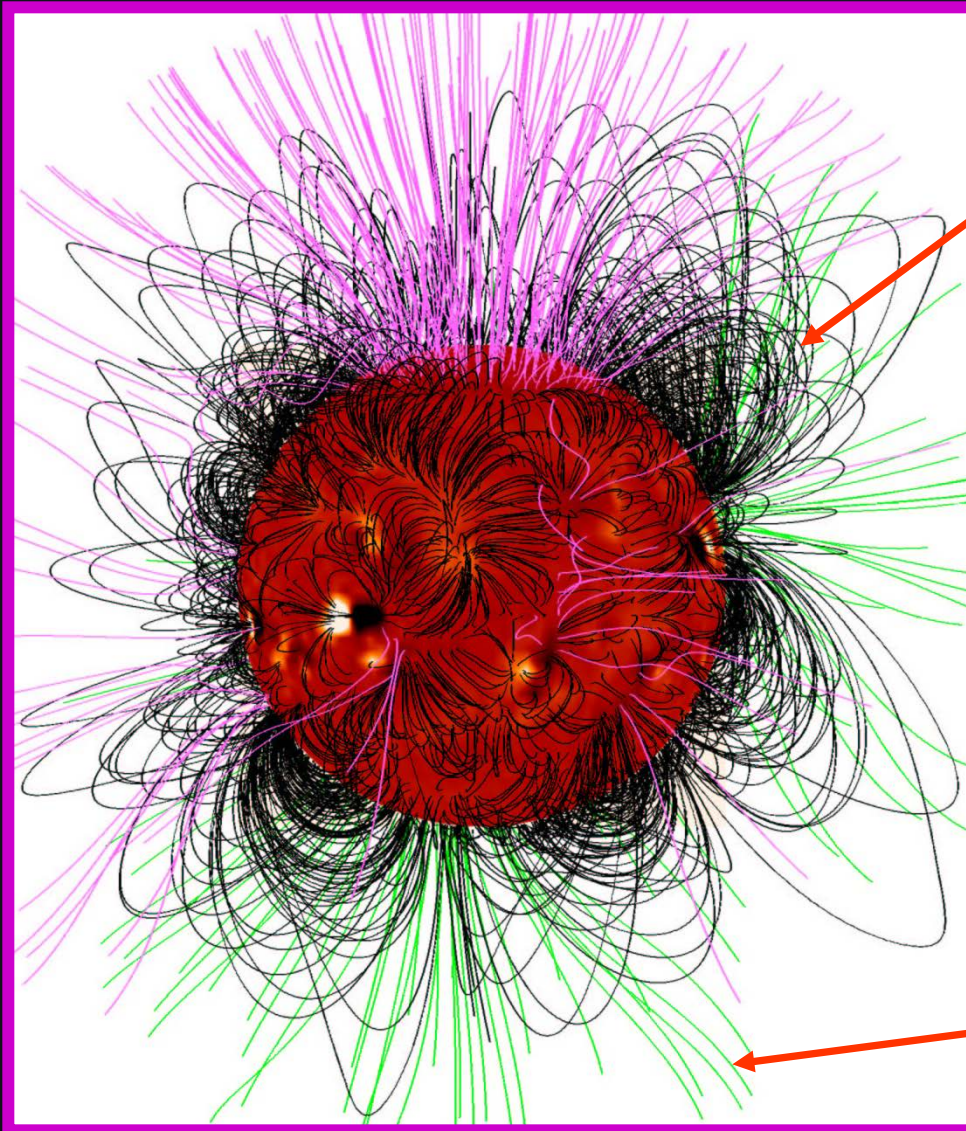
b synthetic light curve produced under the assumption that all emission is due to nanoflares (very simple model)



Reaction of atmosphere to heating

- **So far:** briefly considered energy transport (from photosphere to corona) and release (in corona)
- **Now:** how does solar atmosphere react to heating?
- Reaction depends strongly on magnetic structure, in particular open or closed field regions
- In general: atmosphere must remove the energy from the place where it is deposited
- ➔ Energy transport in corona: thermal conduction, radiation, particle acceleration (reconnection)

Open and closed magnetic flux



Closed flux: slow solar wind

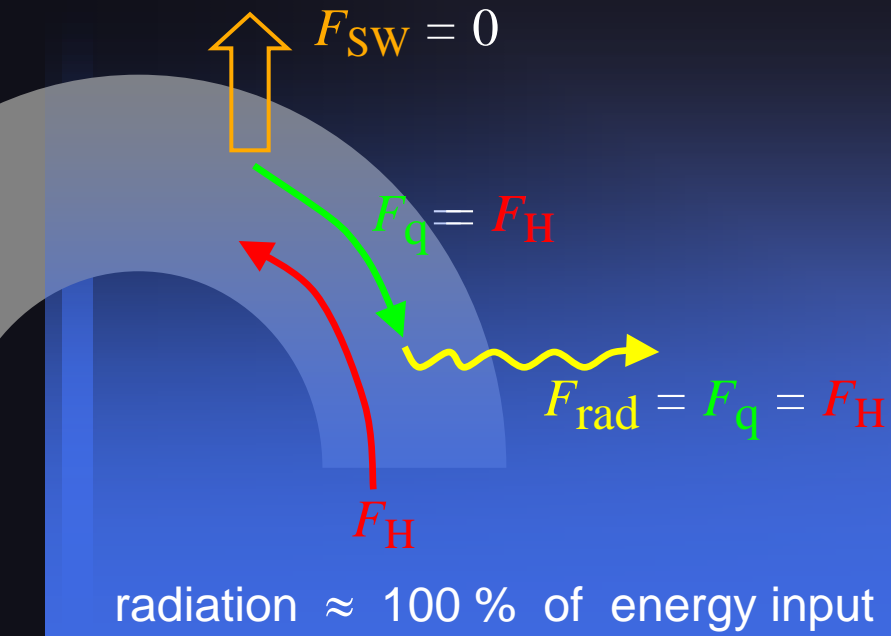
Most of the solar flux returns to the solar surface within a few R_{\odot} (closed flux)

A small part ($\approx 5\%$) of the total flux through the solar surface connects as "open flux" to interplanetary space

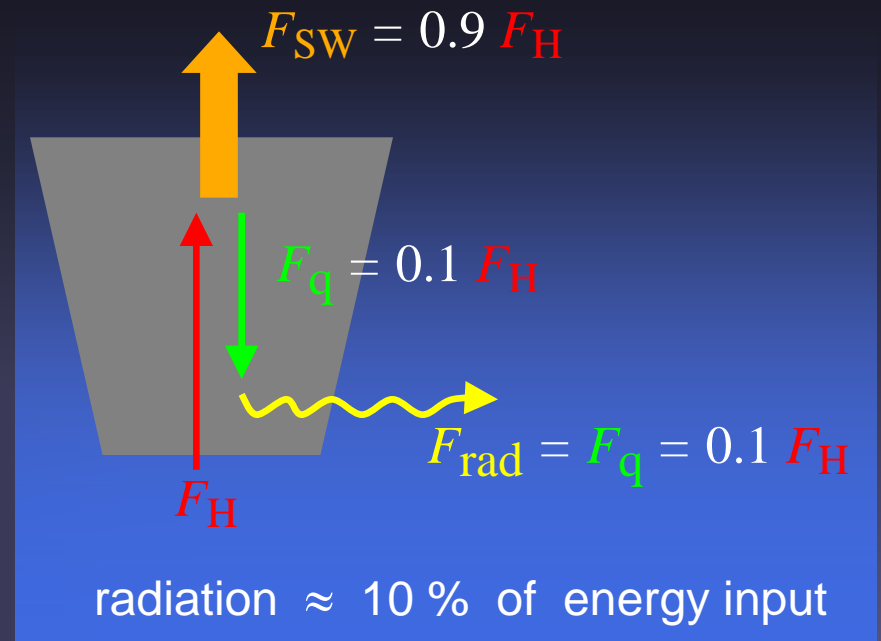
Open flux: fast solar wind

Energy budget: Open & closed coronal field

magnetically closed



magnetically open



F_H = Energy flux heating the gas; F_q = Conductive energy flux; F_{SW} = Solar wind flux

Assume the same energy input into open and closed regions:

➔ almost ALL emission we see on the disk outside coronal holes originates from magnetically closed structures (loops) !

kindly provided by Hardi Peter

Heat conduction

- In the corona and transition region main method of heat transport is thermal conduction by electrons. Conducted heat flux F_c for fully ionized gas (Spitzer & Härms 1953):

$$F_c = \kappa_e T_e^{5/2} \nabla T_e$$

where κ_e is heat conduction coefficient and T_e is e^- - temp.

- Clearly, F_c increases with temperature *and* with temperature gradient
- In magnetized atmosphere: conduction is far more effective along magnetic field, since e^- can flow freely, than across it (motion of e^- is limited to gyro-radius).

Radiation in the corona

- Corona is \approx **optically thin**: emitted photons are generally not reabsorbed in corona
- No radiative transfer needed. Atomic processes are sufficient
- Main atomic processes in corona (many collisions, weak radiation):

- **Collisional excitation of atom or ion, X , followed by radiative decay:**



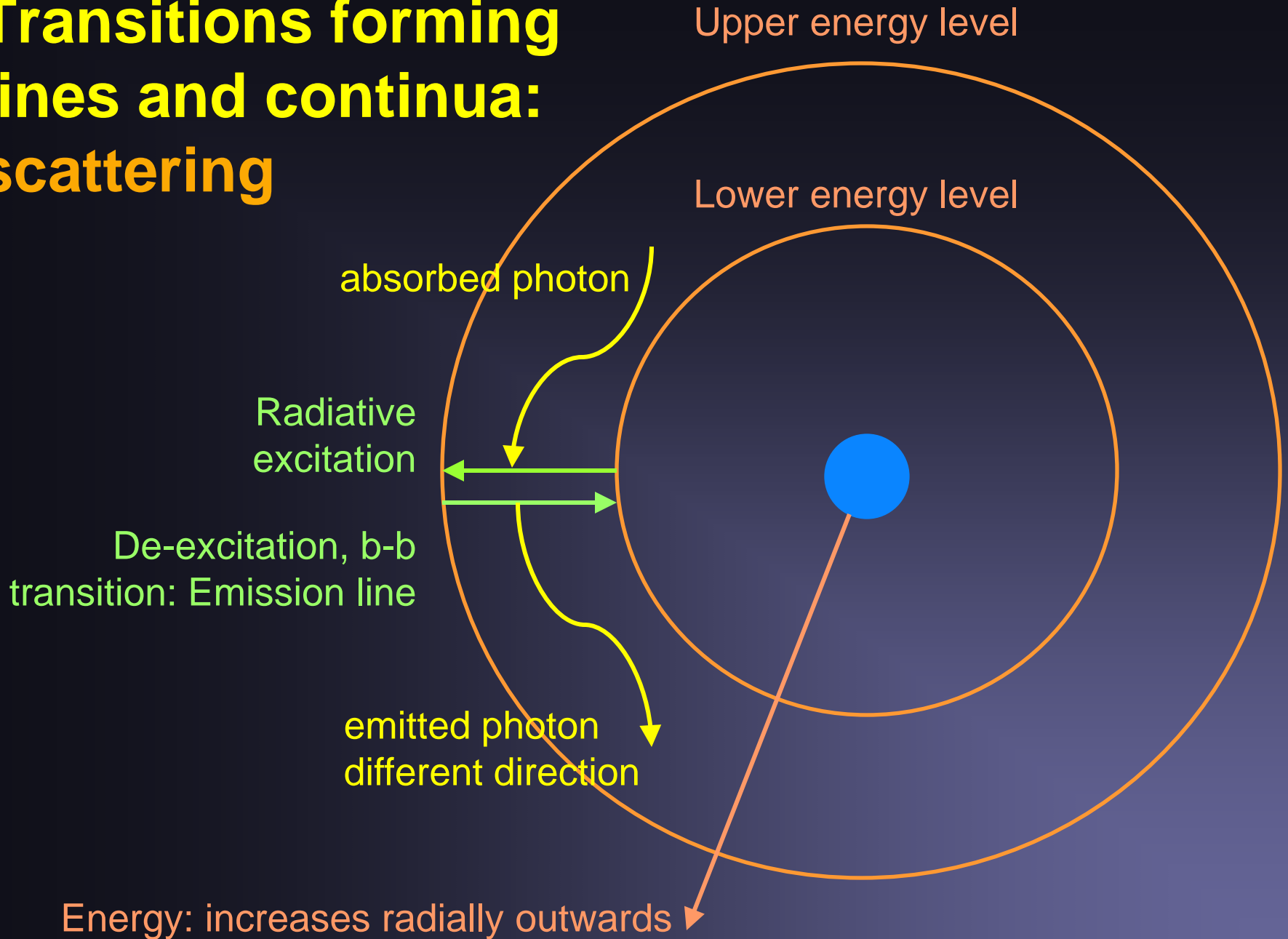
- **Resonant scattering (fluorescence):**



- **Collisional ionisation followed by radiative recombination:**



Transitions forming lines and continua: scattering



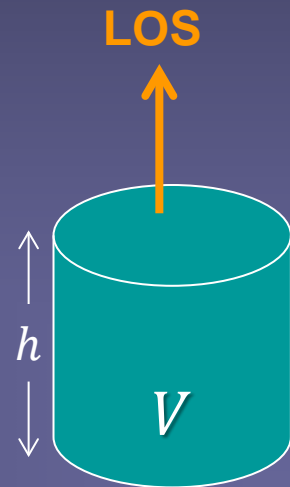
Radiation in the corona II

- Intensity of typical coronal spectral lines depends on
 - **temperature**, since $+m$ ionization state of atom only exists in a given temperature range
 - **gas density** $\sim e^-$ **density**: more atoms/vol \rightarrow more emission
 - **e^- density**: more e^- /volume \rightarrow more collisions with atoms \rightarrow more atoms get excited to higher level \rightarrow more emission
 - **volume**: larger the emitting volume \rightarrow more atoms \rightarrow more emission

- Intensity \sim Emission Measure (\times atomic factors):

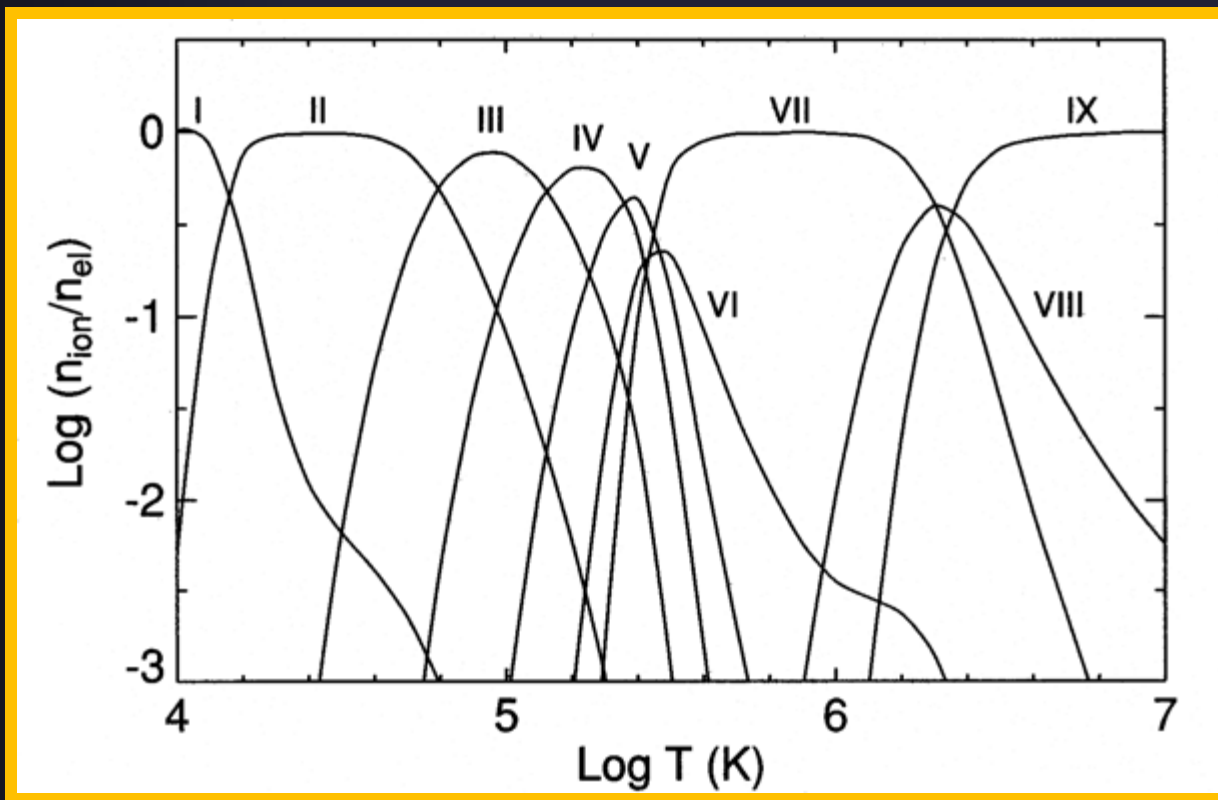
$$EM = \int_V n_e^2 dV \sim \int_h n_e^2 dh = \int_h n_e^2 (dT/dh)^{-1} dT$$

- \rightarrow Radiative cooling most effective in active regions & in chromosphere (high n_e)



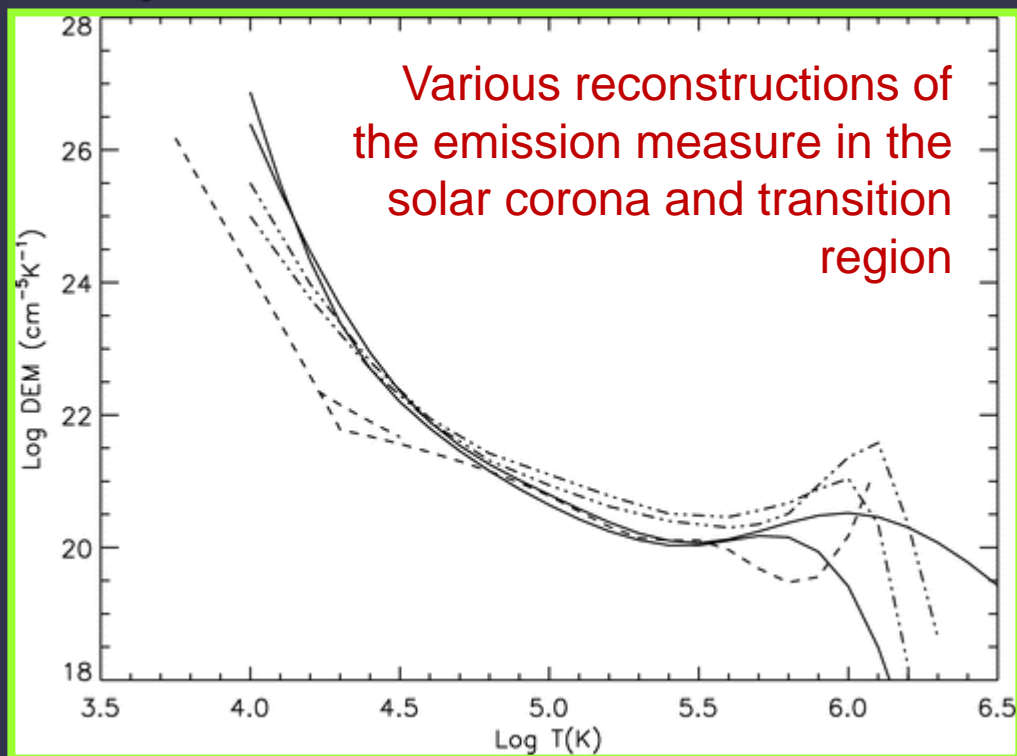
Dependence of ionization states on temperature

Example: ionization balance of Oxygen

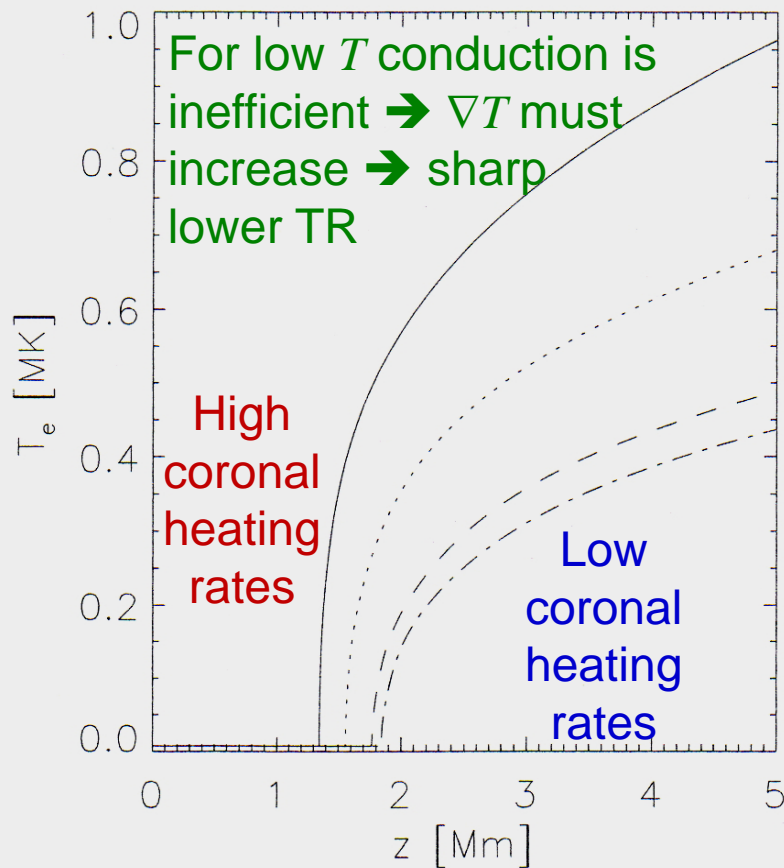


Emission measure & formation of transition region

- Emission measure is low in corona!
- Emission measure is high in lower TR and chromosphere
- Consequently, energy deposited in corona is transported down till it can be radiated away in lower TR and chromosphere
- Downward transport if via thermal conduction



Transition region structure due to coronal heating

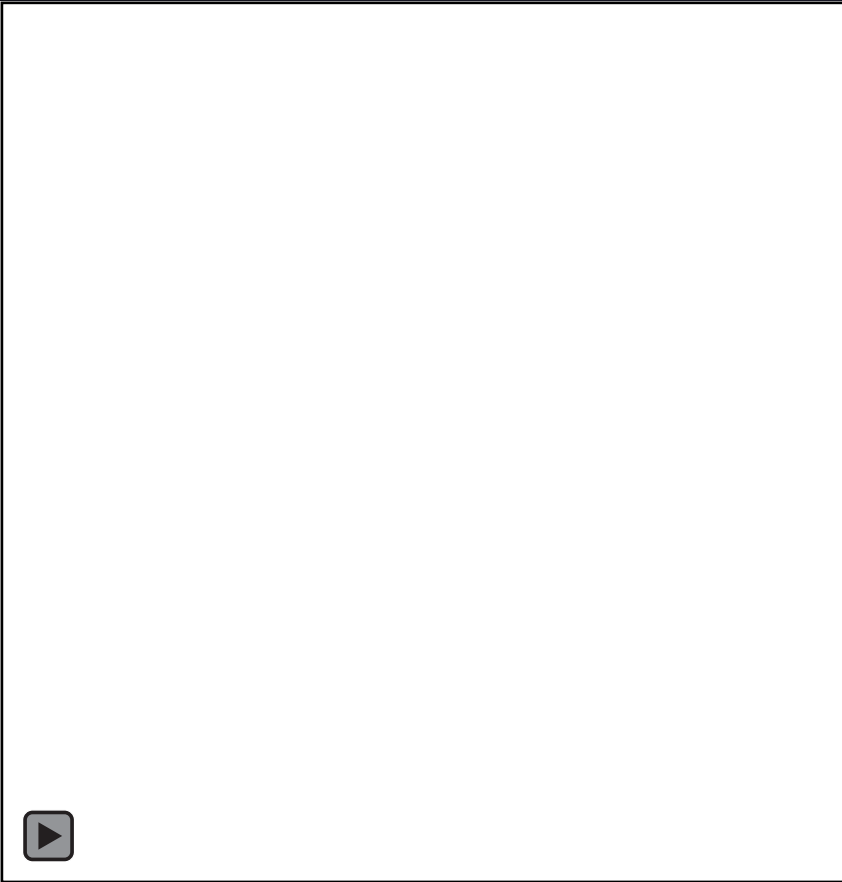


$F_{m0} = 100 \text{ W m}^{-2}$ (chain curve), $F_{m0} = 500 \text{ W m}^{-2}$ (broken curve), $F_{m0} = 1000 \text{ W m}^{-2}$ (dotted curve), $F_{m0} = 3000 \text{ W m}^{-2}$ (full curve).

Hansteen 2000

- Figure: temperature structure of TR assuming all heat deposited in corona is conducted down to chromosphere (which has sufficiently strong spectral lines to radiate it away it)
- Different curves correspond to different coronal heating rates
- Higher heating rate \rightarrow hotter corona \rightarrow transition region moves down \rightarrow higher density \rightarrow stronger TR spectral lines
- Curves become flat at 20 kK \rightarrow Ly α radiates all energy away

Solar Flares

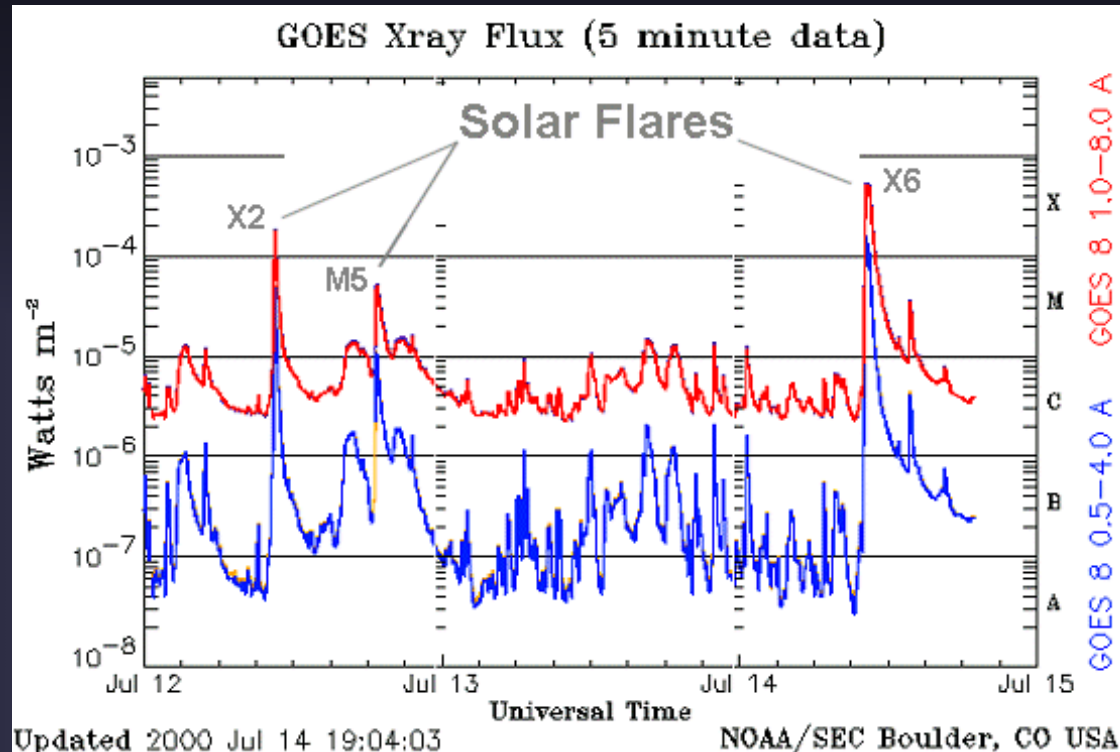


SDO/AIA 195 Å

- Sudden localized and transient release of energy
- maximum energy of 10^{32} to 10^{33} erg released in 10–1000 s
- Only a fraction of the released energy is radiated directly away:
 - 50%: acceleration of CMEs
 - 30 – 50%: acceleration of energetic ions ($> 1\text{MeV}$), electrons (20-100keV) . These particles eventually radiate away their energy as well
 - 1-10%: radiant energy from radio to γ -rays + unknown amount in UV and visible

Flare classification

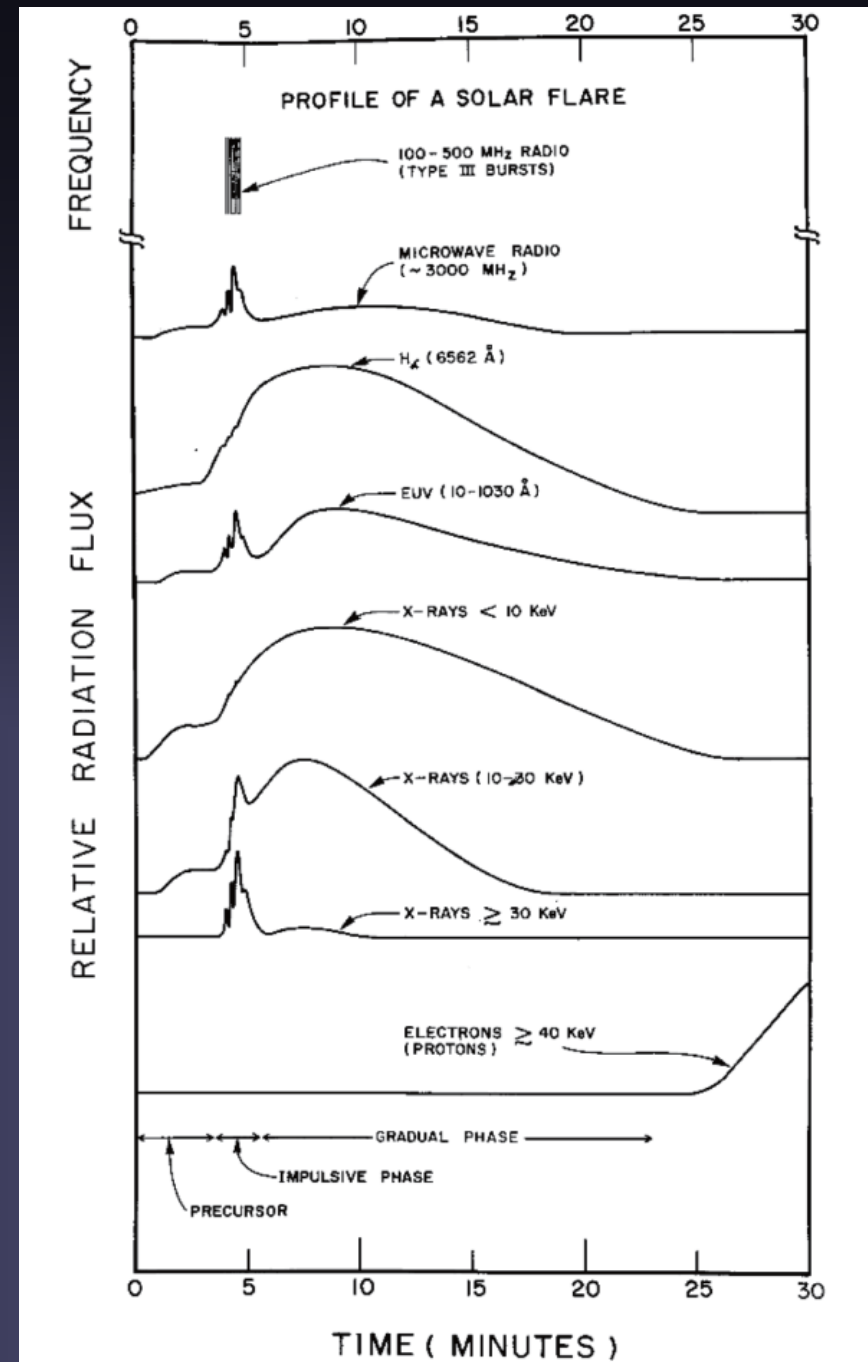
- Flares are classified according to their strength:
 - X-class: strong
 - M-class: medium
 - C-class: weak
 - B-class: very weak
- Factor of 10 difference in strength between classes
- Subdivision into:
 - X1 → X9 : incr. strength
 - similarly M1 - M9, C1 - C9



Weaker, but more common than flares are the microflares. Even weaker are nanoflares: below today's obs. sensitivity

Flare light curves

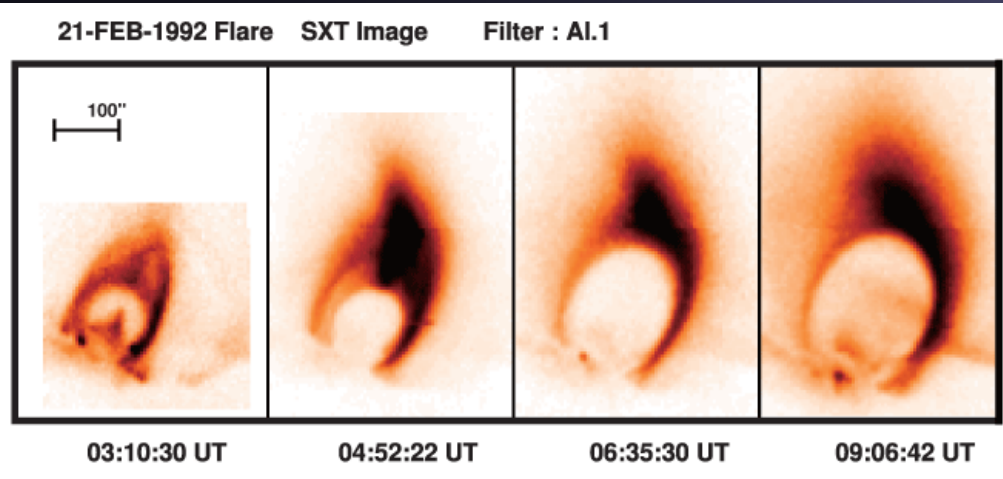
- Flares radiate over the full solar spectrum, from γ -rays to radio wavelengths
- The light curve displays different shapes in the different spectral parts
- In general one distinguishes between an impulsive and a gradual phase
- At many wavelengths also a precursor is often observed



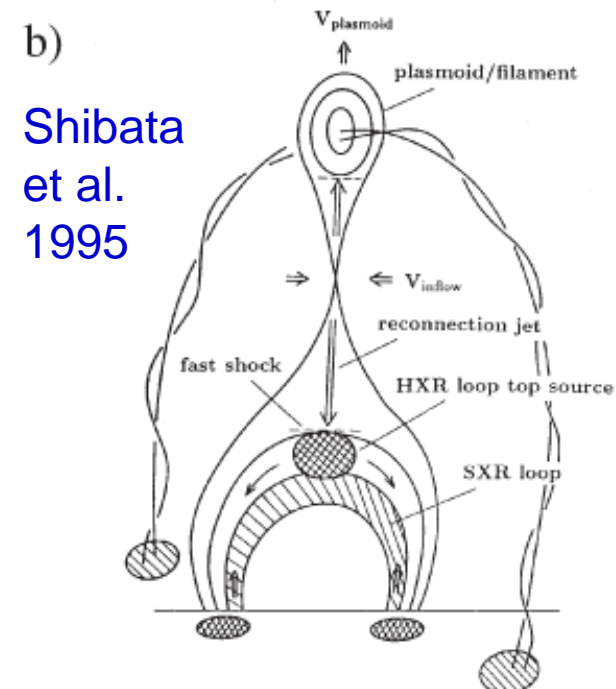
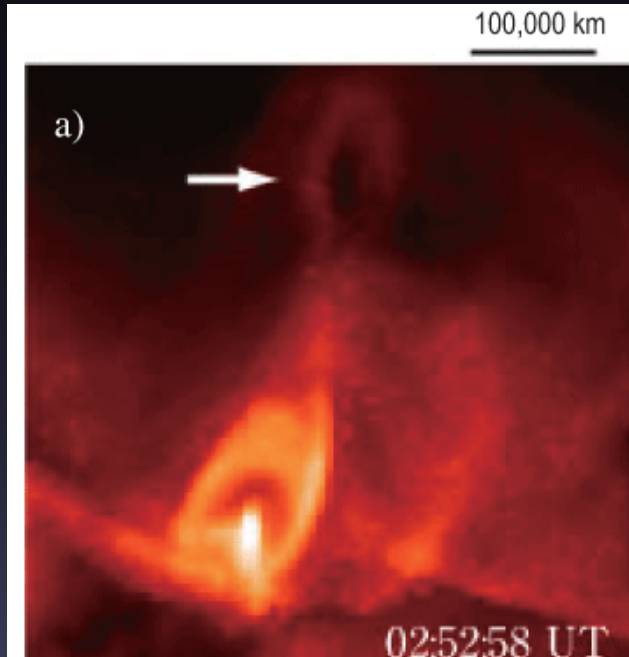
Kane 1974

Evidence of reconnection in flares

- Soft x-rays show typical cusp-shaped loop-tops during flares
- Such cusps: interpreted as the lower parts of X-points where magnetic reconnection occurs
- Presence of hard X-rays at loop tops also supports this interpretation



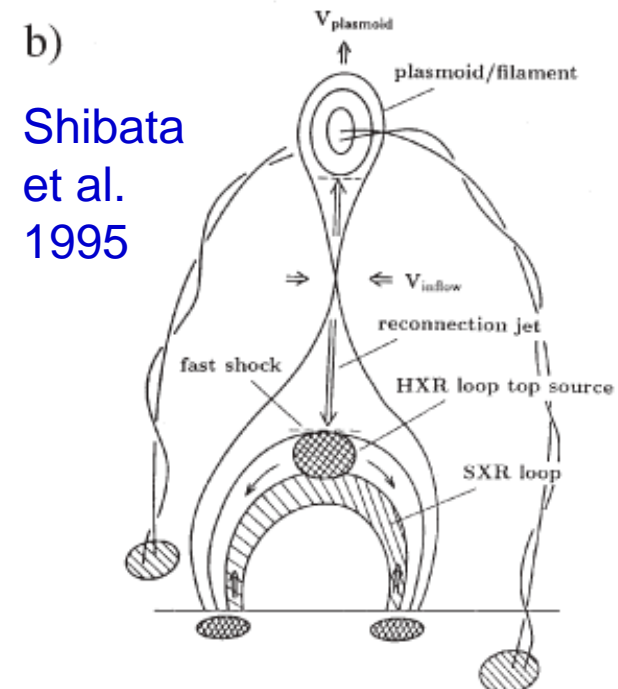
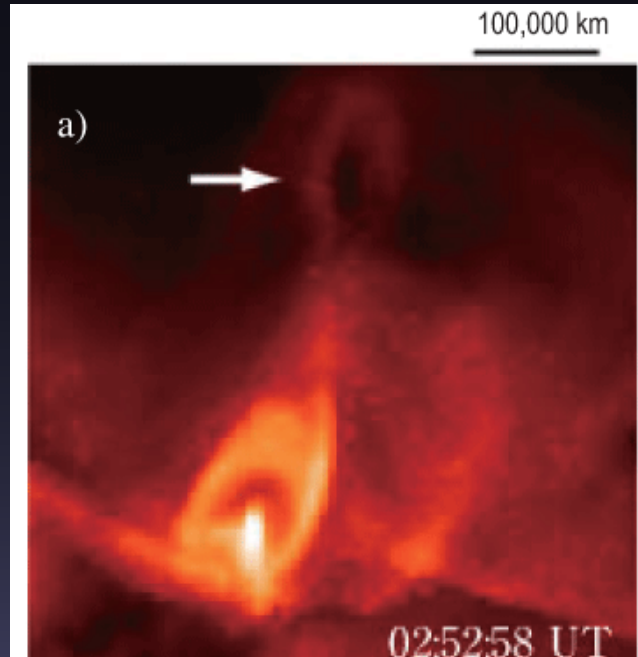
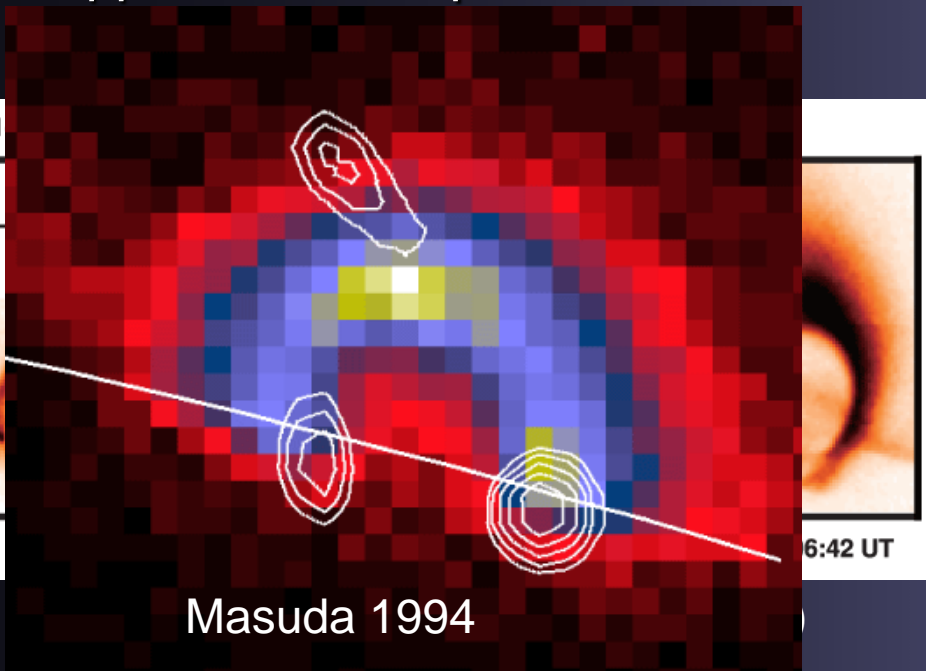
Tsuneta (1992), Tsuneta et al. (1996)



Shibata
et al.
1995

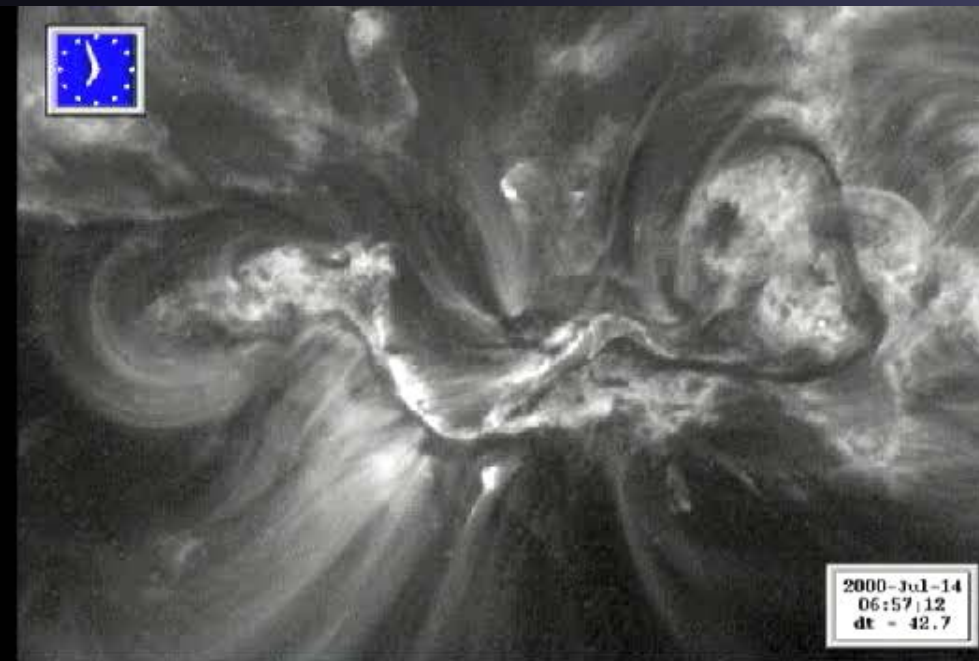
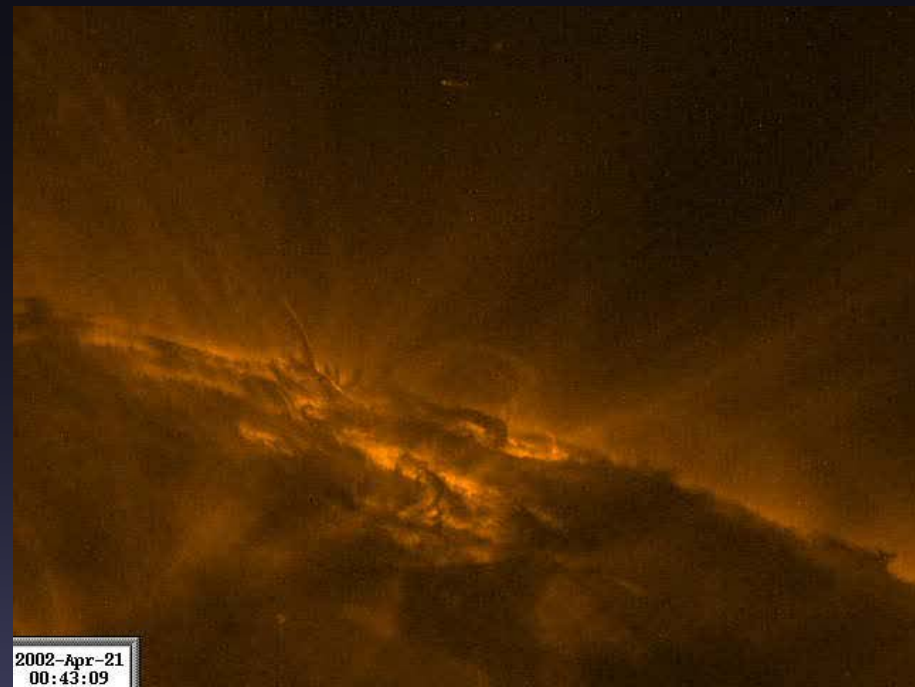
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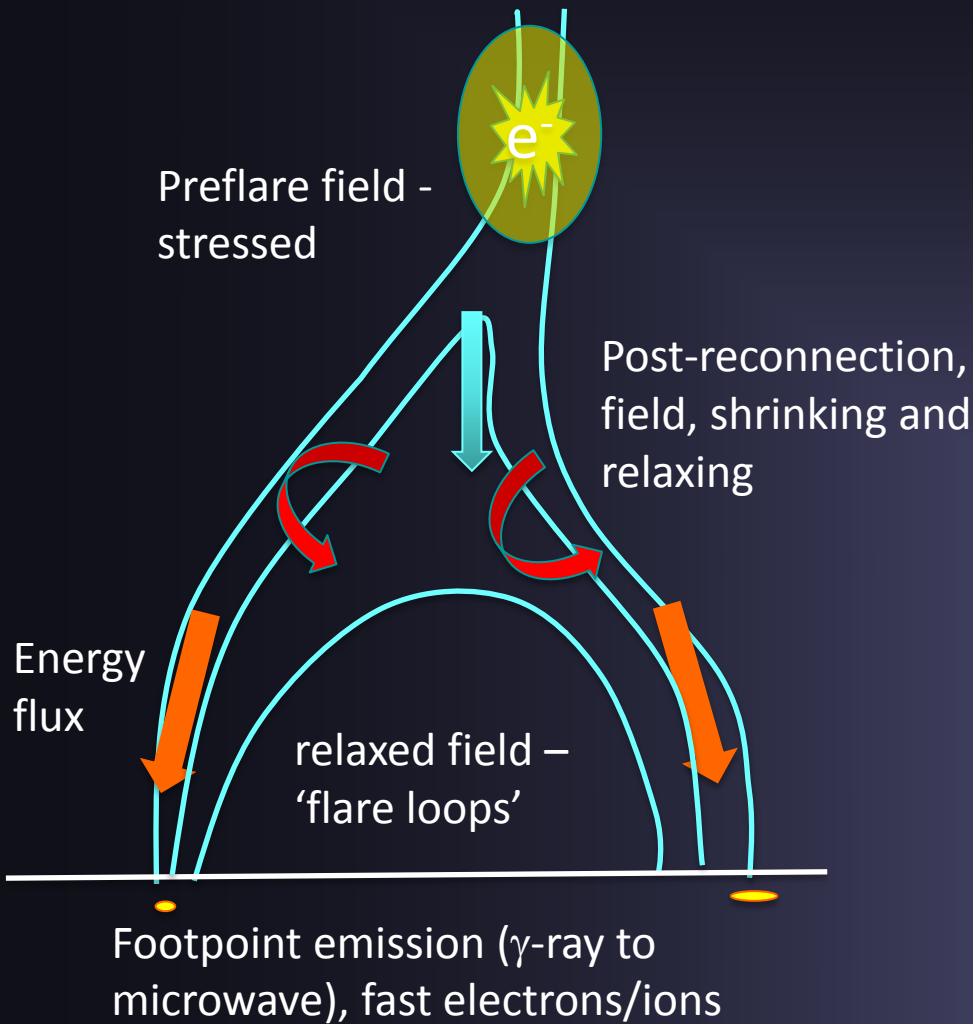
Post-flare loops

- Production of dense hot post flare loops is a typical signature of strong flares
- This occurs during the gradual phase, after the impulsive phase is over



- According to theory, the gas in these loops is originally chromospheric material heated and evaporated by the high energy particles accelerated by the flare

Cartoon of a flare



1) Magnetic energy stored in corona is released via magnetic reconnection

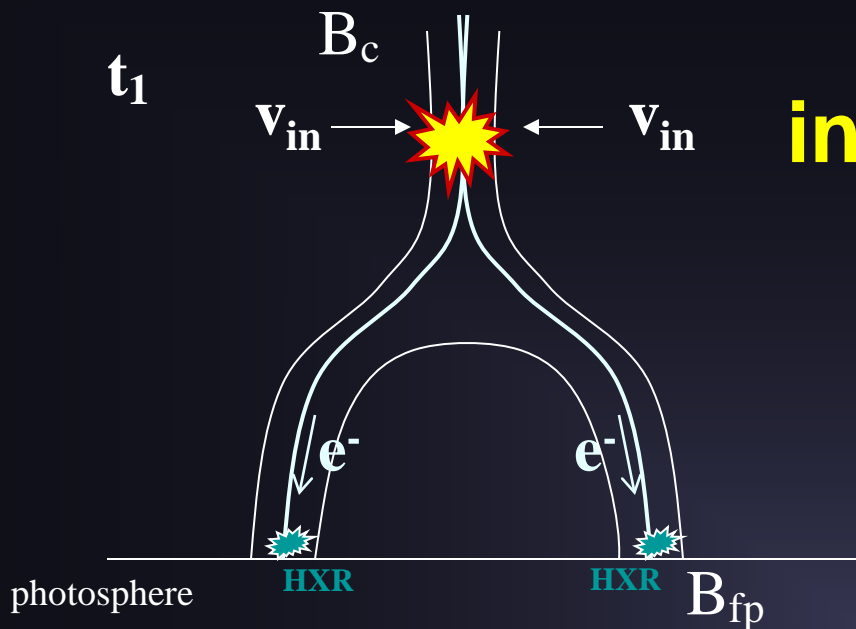
2) Energy transported from corona to chromosphere by energetic particles

3) Most of energy is radiated by chromosphere (opt-UV)

4) HXR, γ -ray emission is evidence of non-thermal electrons/ions

5) Chromosphere is heated and expands into corona \rightarrow dense, hot flare loops

HXR source motions in magnetic reconnection



v_{in} = coronal inflow velocity

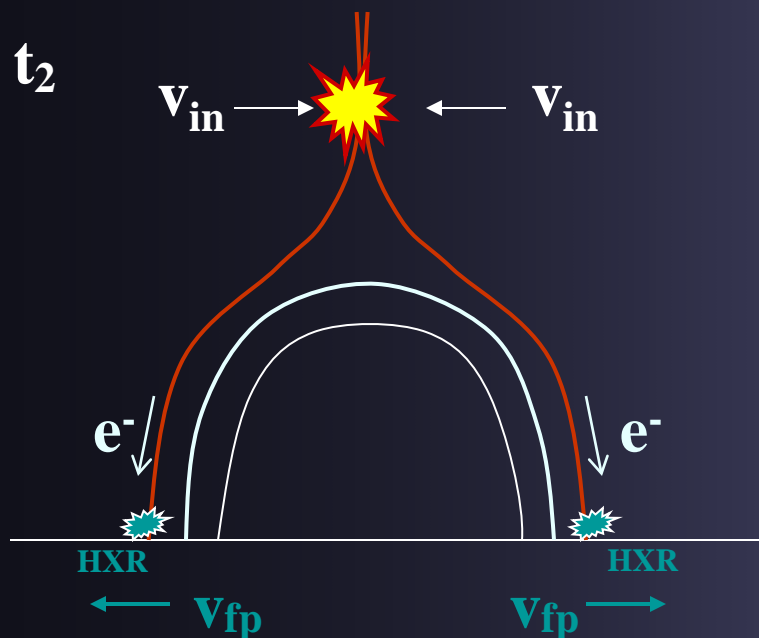
B_c = coronal magnetic field

a_c = coronal width

v_{fp} = HXR footpoint velocity

B_{fp} = HXR footpoint magnetic field (photospheric)

a_{fp} = HXR footpoint width

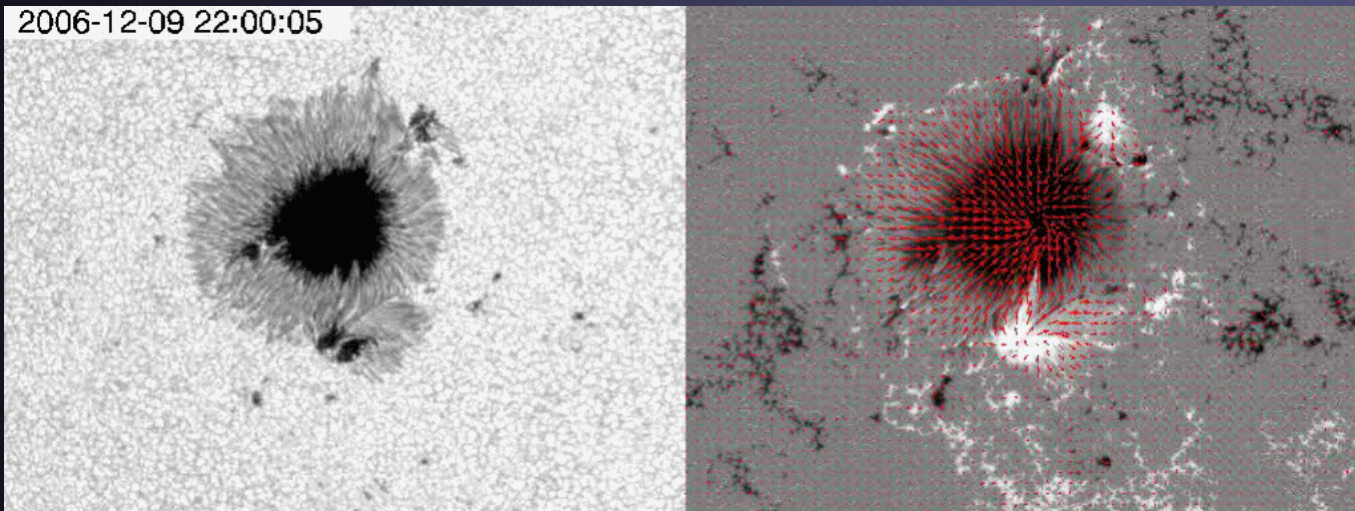


Magnetic reconnection rate

$$d\Phi/dt = v_{in} B_c a_c = v_{fp} B_{fp} a_{fp}$$

Causes

- Flares are produced when energy built up in a magnetic field is released via magnetic reconnection
- Energy build-up occurs via shear-flows and/or the emergence of fresh magnetic flux at a location of already existing flux
- Flares occur preferentially in young active regions with still emerging magnetic flux



Flares, electric currents and changes in the magnetic field

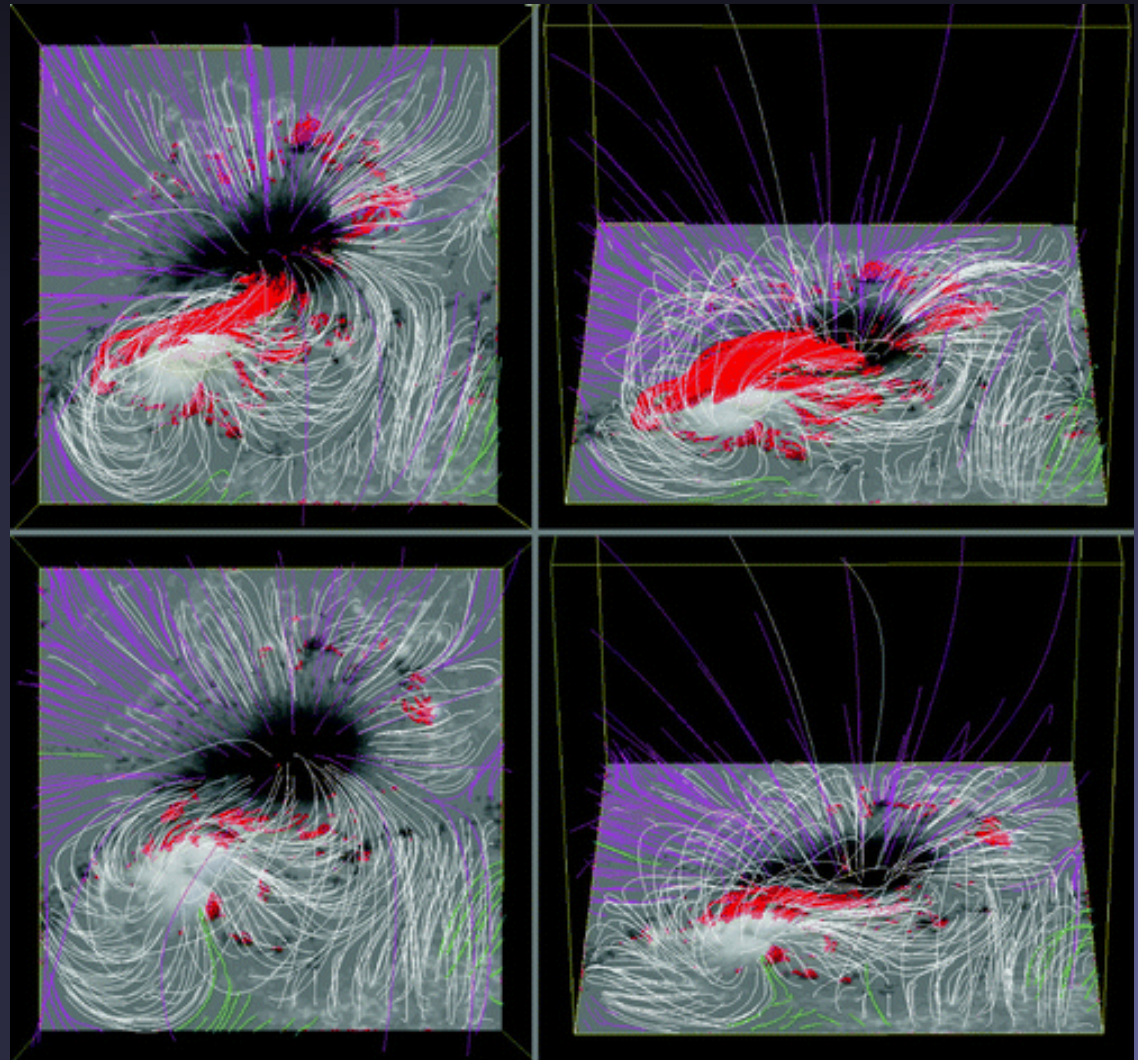
Before flare

White field lines:
closed field lines
(from force-free
extrapolations)

Coloured lines: field
lines open within box

Red area: currents

After flare



Schrijver et al. 2008

