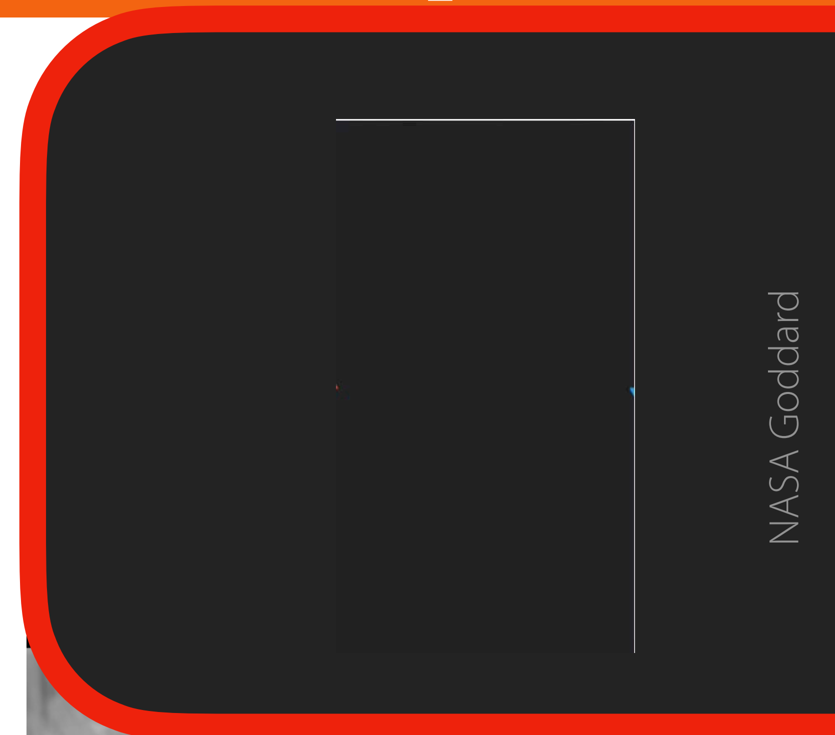
AST5770

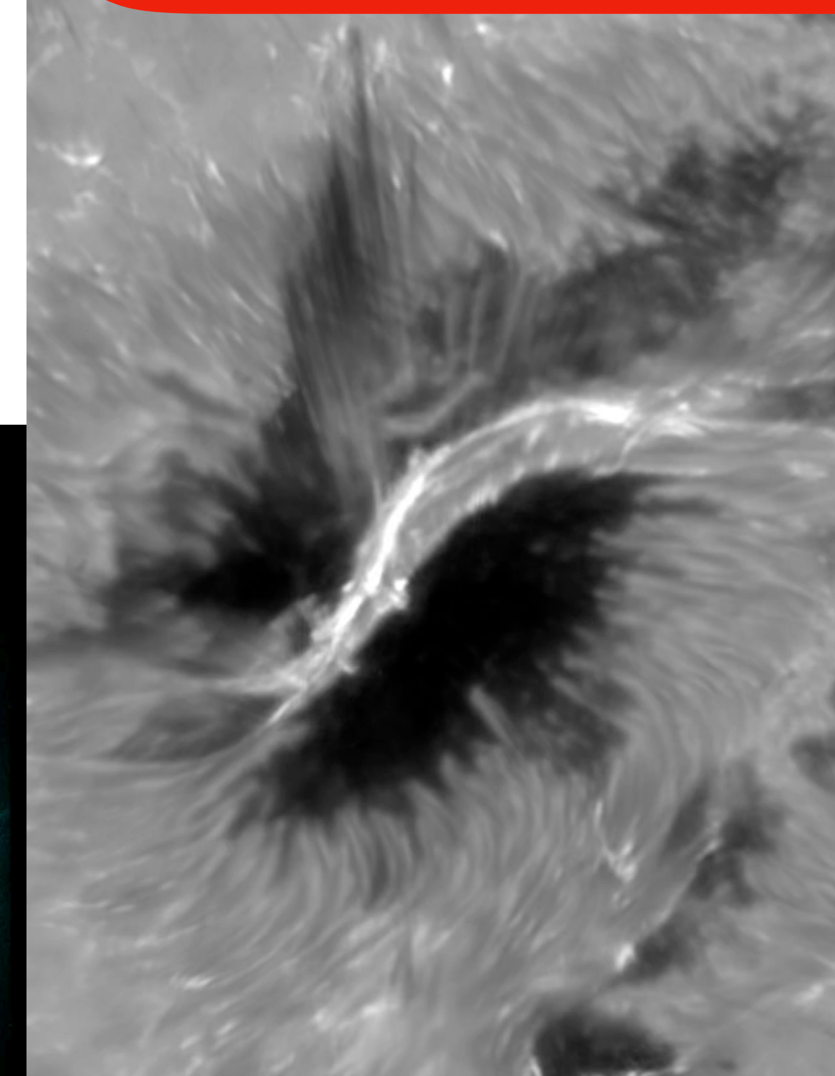
Solar and stellar physics

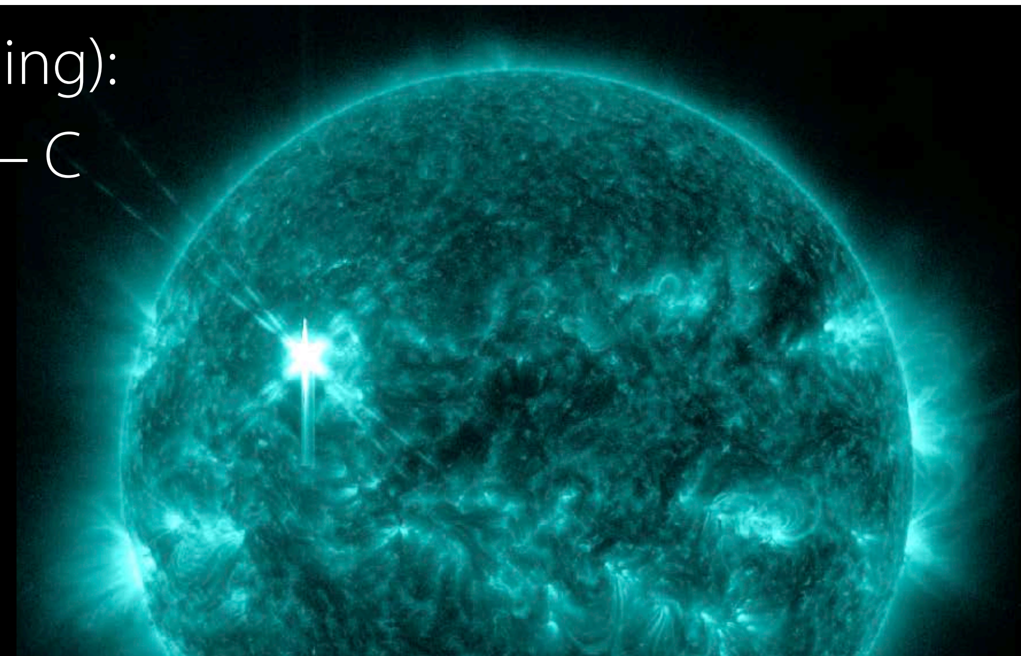
Sven Wedemeyer, University of Oslo, 2023

Active Regions and flares — recap



1. What have “peacock jets” and “Ellerman bombs in common?
2. What is “powering” phenomena like jets, surges, flares?
3. Why does the magnetic field “want to” reconfigure?
4. Where goes the energy that is released during flares?
5. How are flares commonly classified?
6. What is the impulsive phase?
7. How much energy is released in solar flares and over which time span does (most of) it happen?
8. Order by strength (increasing):
   - M — A — D — X — B — C



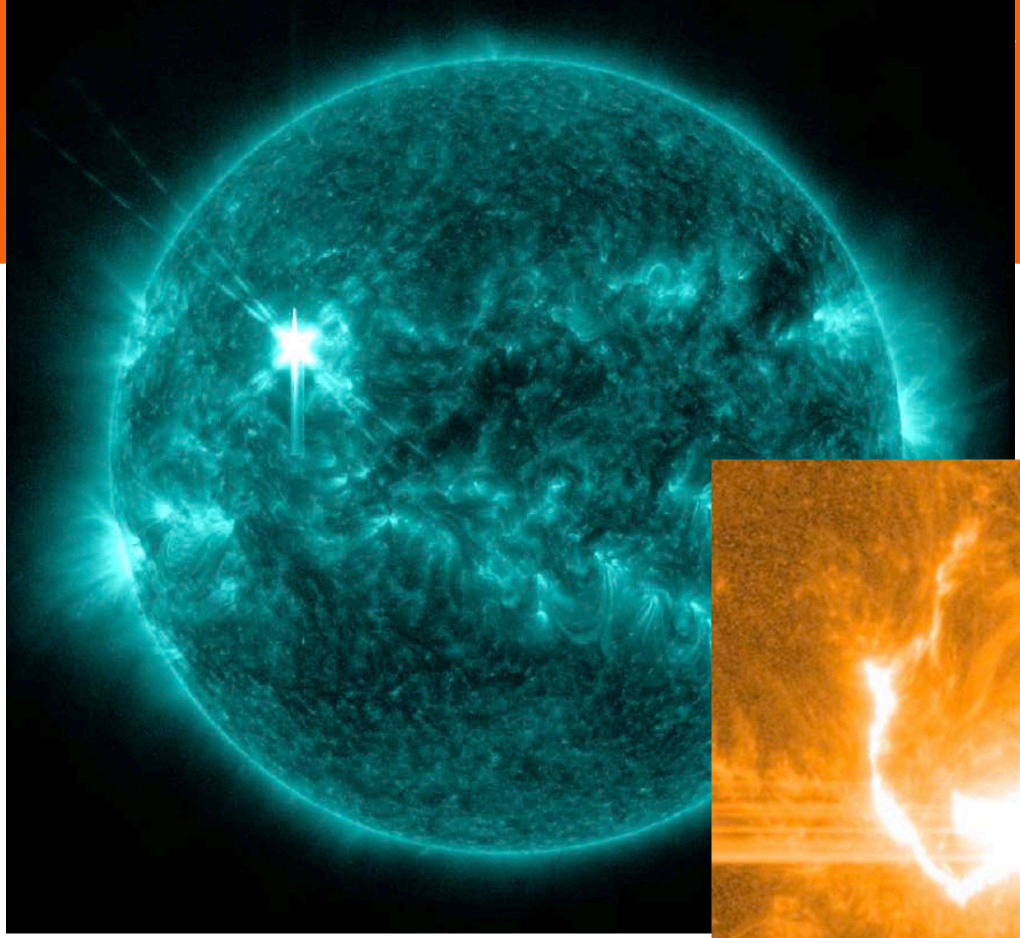


Solar flares

Flares

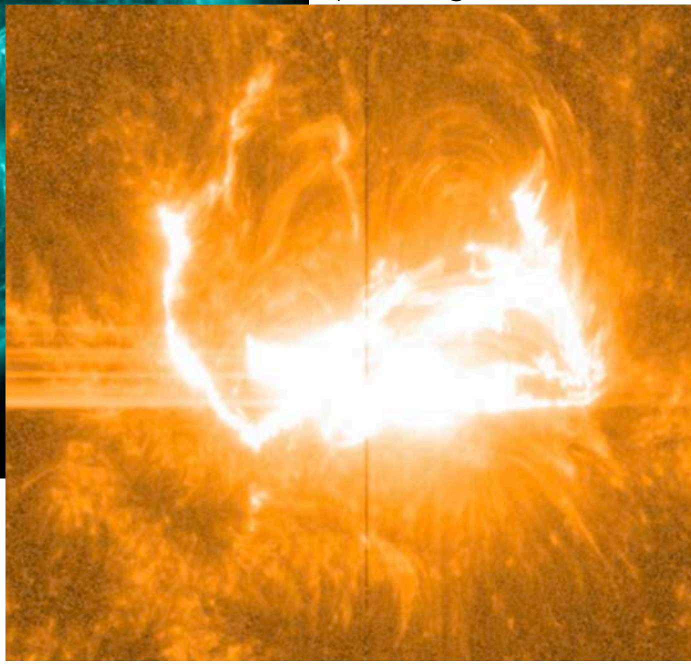
Summary so far

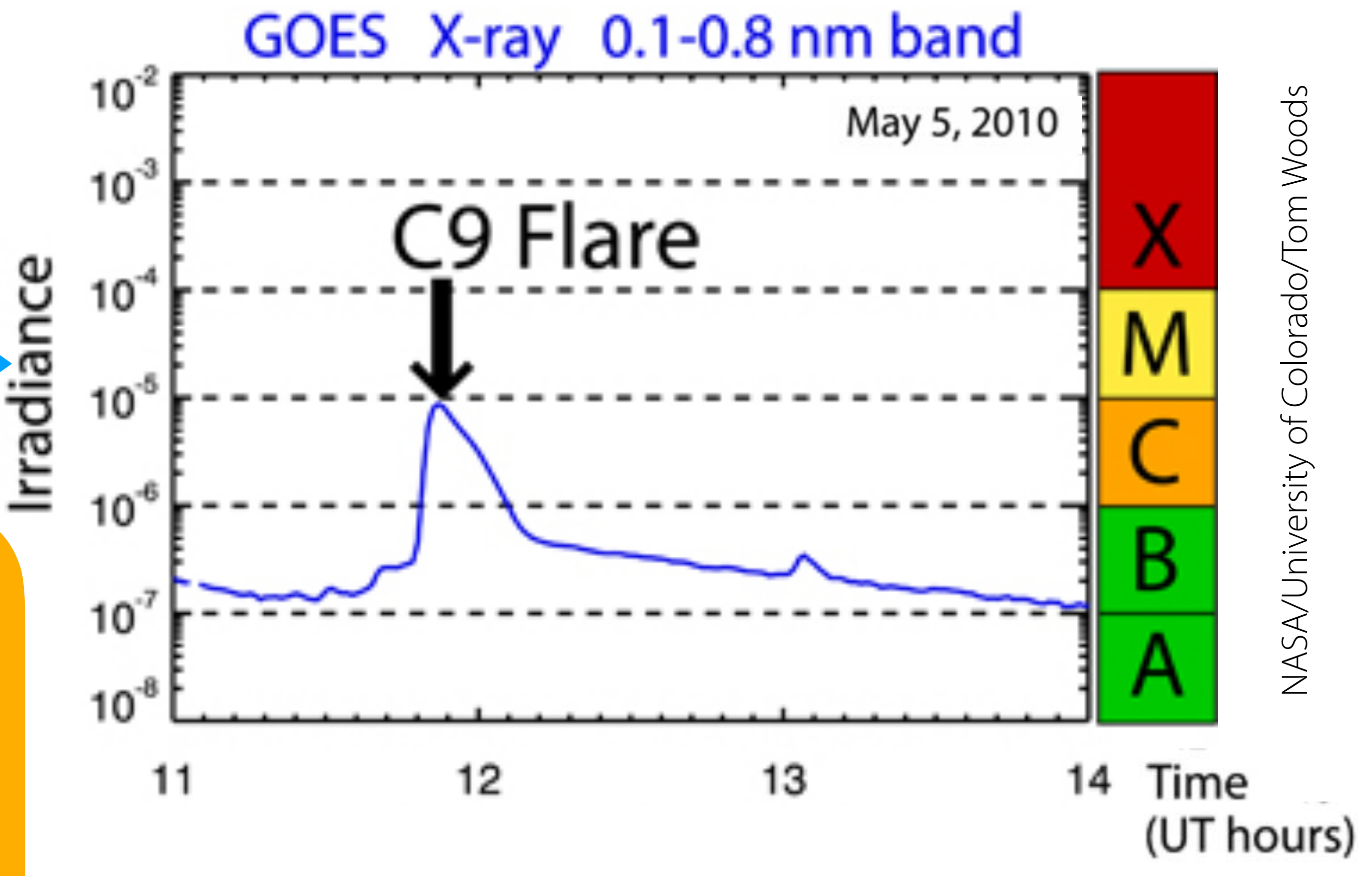
- Sudden brightening with emission across the whole electromagnetic spectrum (e.g. in Hα)
- Huge amount of energy released (10^{27} - 10^{32} ergs), most of it emitted within a few min/10min
- Three major phases:
  - Pre-flare phase
  - Impulsive phase (incl. peak, main)
  - Gradual phase (post-flare)
- Classification according to peak flux in soft X-ray band (GOES)
  - X (strongest)
- **Event size**: height of a flaring loop from < 10Mm to 100 Mm
- Size correlates with flare duration (10^3-10^4s) and amount of released energy



NASA/SDO/AIA

NASA/IRIS/Goddard Space Flight Center



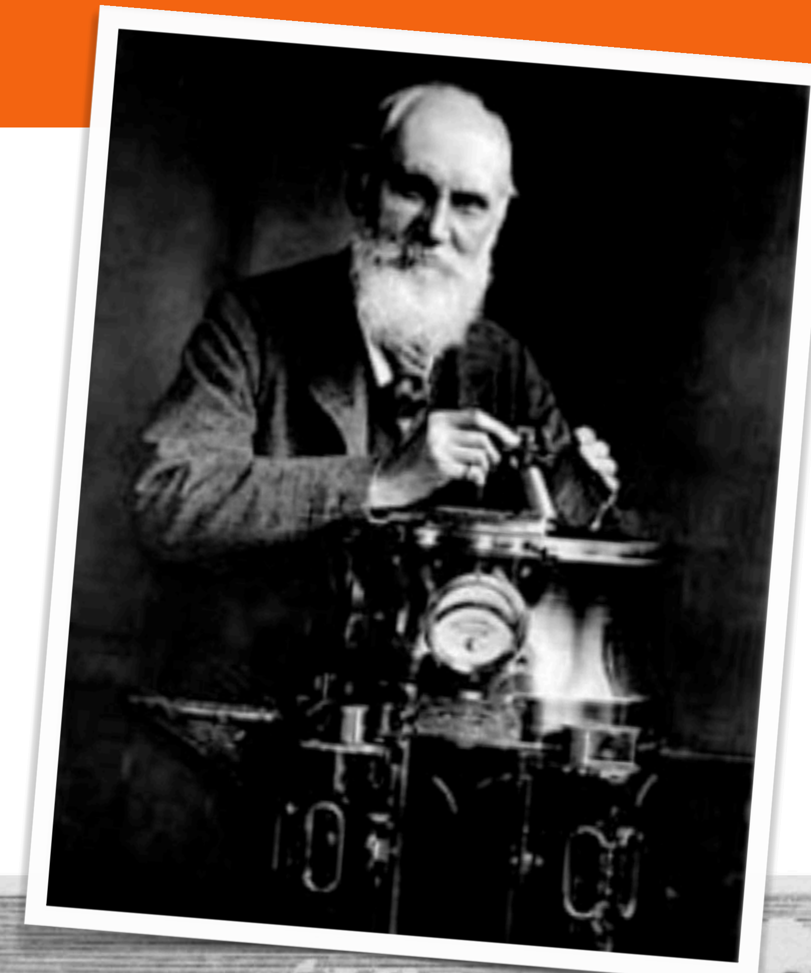


NASA/University of Colorado/Tom Woods

Flares

Carrington

- Richard Carrington (1826-1875)   English astronomer
- Particularly famous for the first continuous detailed observation of sunspots.
- Established that the sun rotates differentially (so must be a fluid not a solid body!)
- Began the series of solar rotations now known as Carrington Rotations.



Richard Carrington built this manor house with an adjoining observatory Redhill, Surrey. It was from here that he witnessed the solar flare. (Imag Royal Astronomical Society)

Flares

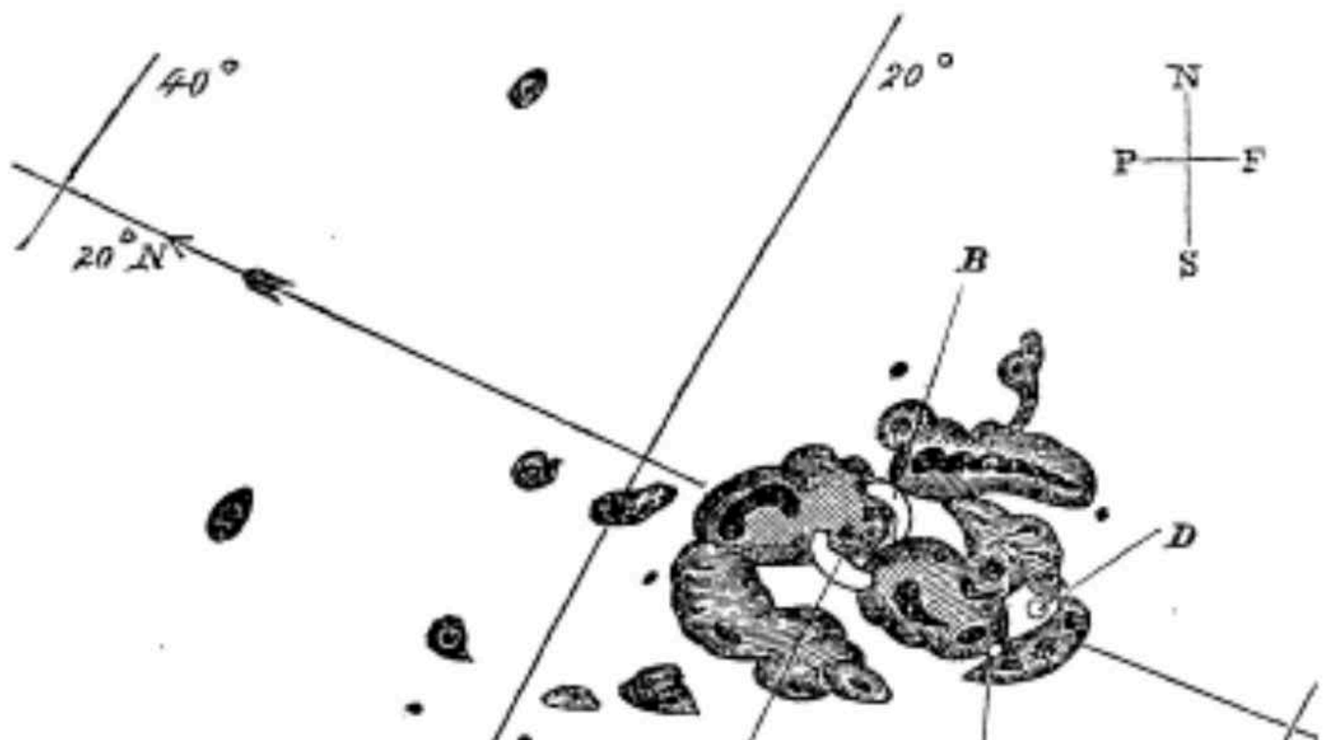
Carrington event — 1859

- The Great Flare of 1859 — observed by Richard Carrington
- First solar flare ever reported!
- White Light Flare – only the strongest flares notable in white light.
- No flare approaching this intensity has been observed since.
- Caused geomagnetic storm (Aug. 27-Sep.7)
- Aurora seen as far south as Cuba/ Colombia!
- Telegraph systems / wires in Europe and the US affected / failed, sparks caused fires at telegraph stations
- Night sky lit brighter than full moon

Historic geomagnetic data at:
http://www.geomag.bgs.ac.uk/education/carrington.html

Description of a Singular Appearance seen in the Sun on September 1, 1859. By R. C. Carrington, Esq.

While engaged in the forenoon of Thursday, Sept. 1, in taking my customary observation of the forms and positions of the solar spots, an appearance was witnessed which I believe to be exceedingly rare. The image of the sun's disk was, as usual with me, projected on to a plate of glass coated with distemper of a pale straw colour, and at a distance and under a power which presented a picture of about 11 inches diameter. I had secured diagrams of all the groups and detached spots, and was engaged at the time in counting from a chronometer and recording the contacts of the spots with the cross-wires used in the observation, when within the area of the great north group (the size of which had previously excited general remark), two patches of intensely bright and white light broke out, in the positions indicated in the appended diagram by the letters A and B, and of the forms of the spaces left white. My



Monthly Notices of the Royal Astronomical Society, Volume 20, November 11, 1859

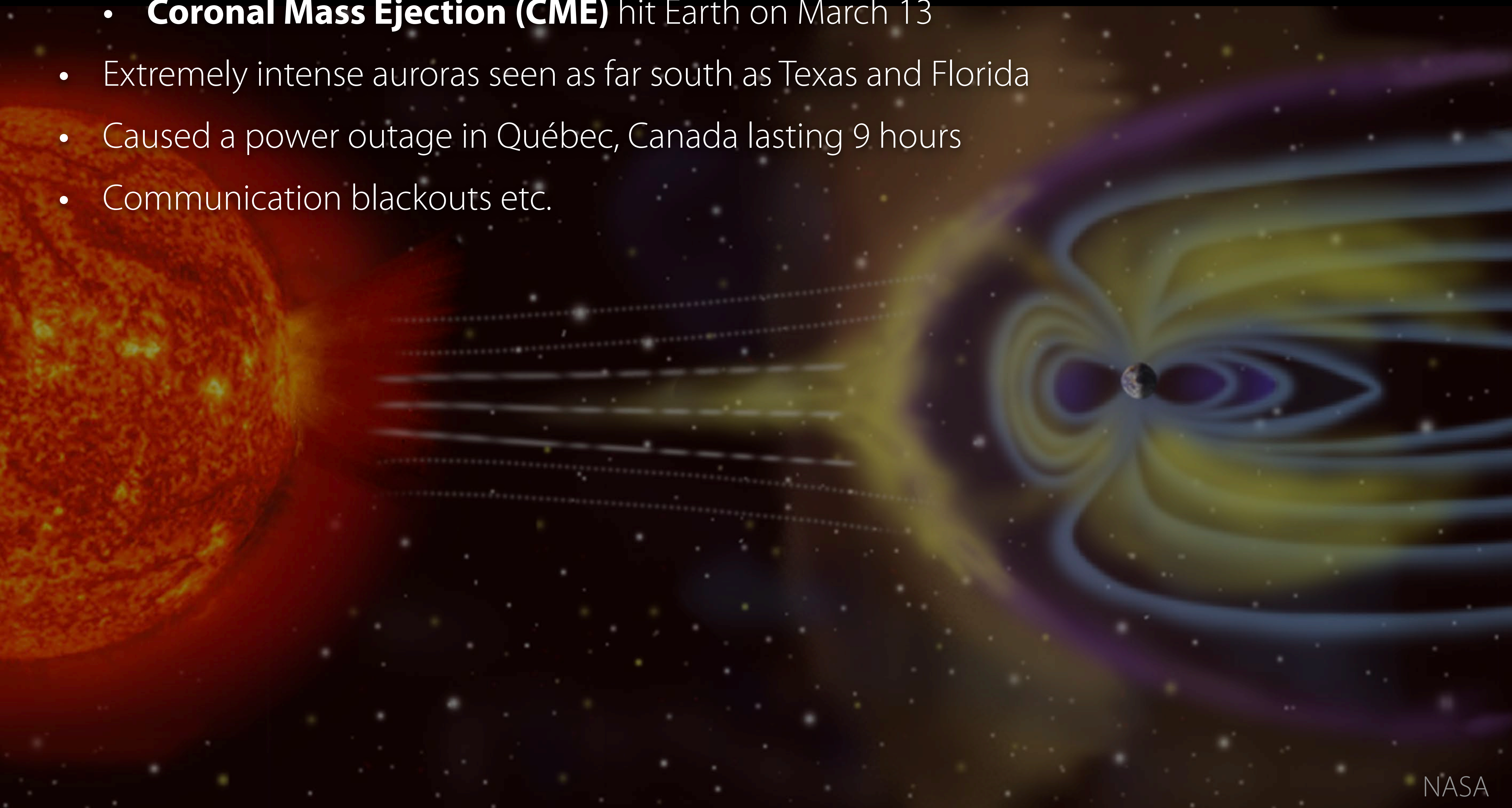
A one-time event?

➡ Arctic/Antarctic ice cores indicate that ***flares of similar strength on avg. occur once in a century.***

Flares

March 1989 geomagnetic storm

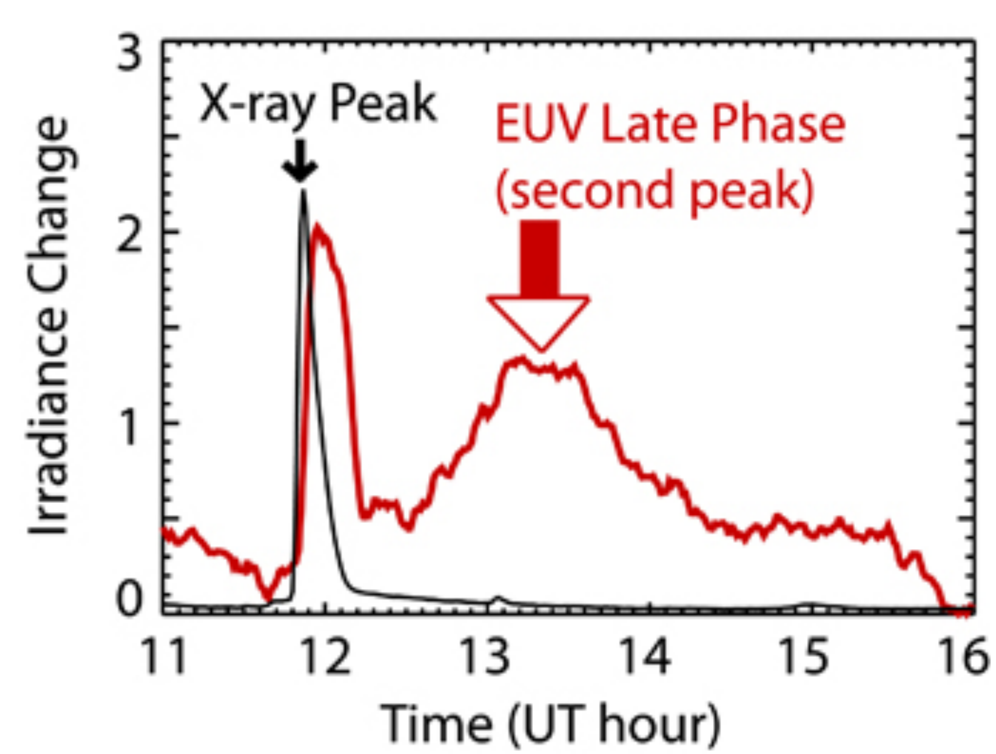
- March 6 : **X15-class solar flare**
  - **Coronal Mass Ejection (CME)** hit Earth on March 13
- Extremely intense auroras seen as far south as Texas and Florida
- Caused a power outage in Québec, Canada lasting 9 hours
- Communication blackouts etc.



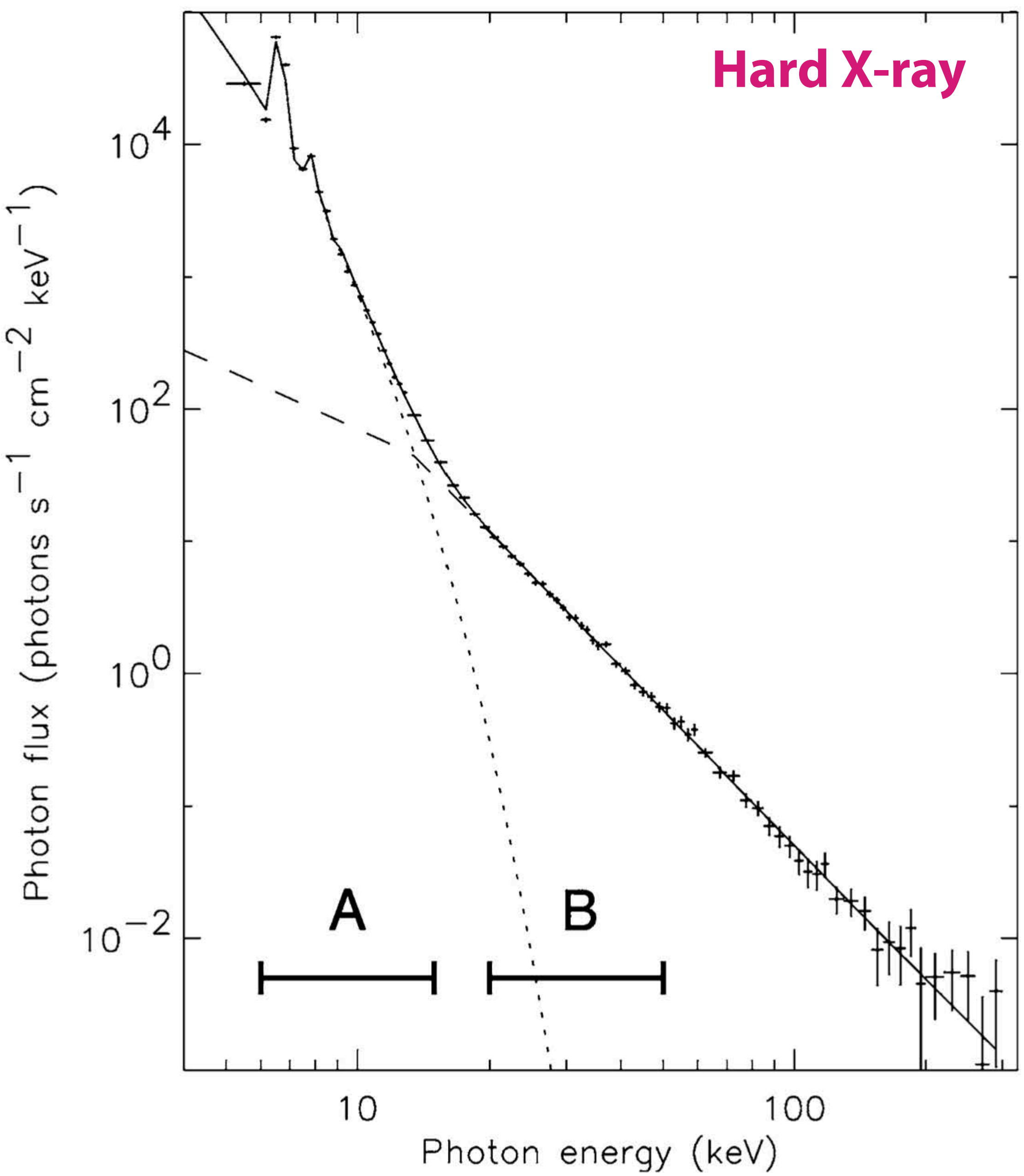
Flares

A complex and varied phenomenon

- Observed for some powerful flares: Secondary peak in EUV about 90 min later than the X-ray peak with substantial energy release

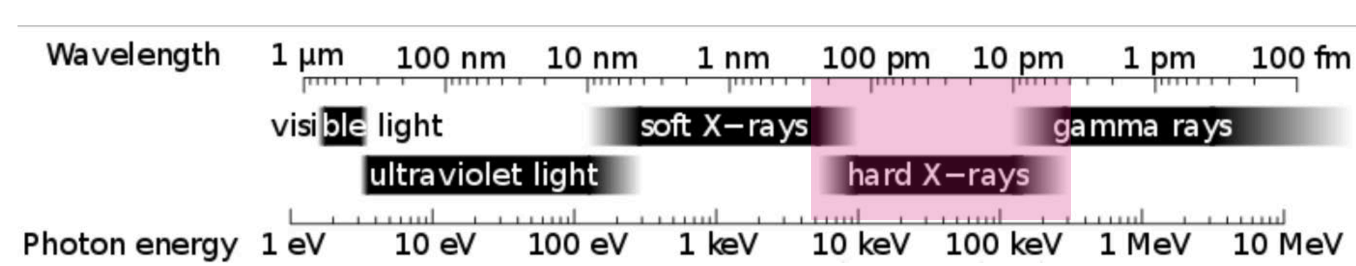


NASA/University of Colorado/Tom Woods



Gigris & Benz (2004)/ ESO / Oka et al. (2018)

- **Spectrum** can be fitted with two components, following power laws each
  - Lower-energy component
  - Higher-energy component



Flares

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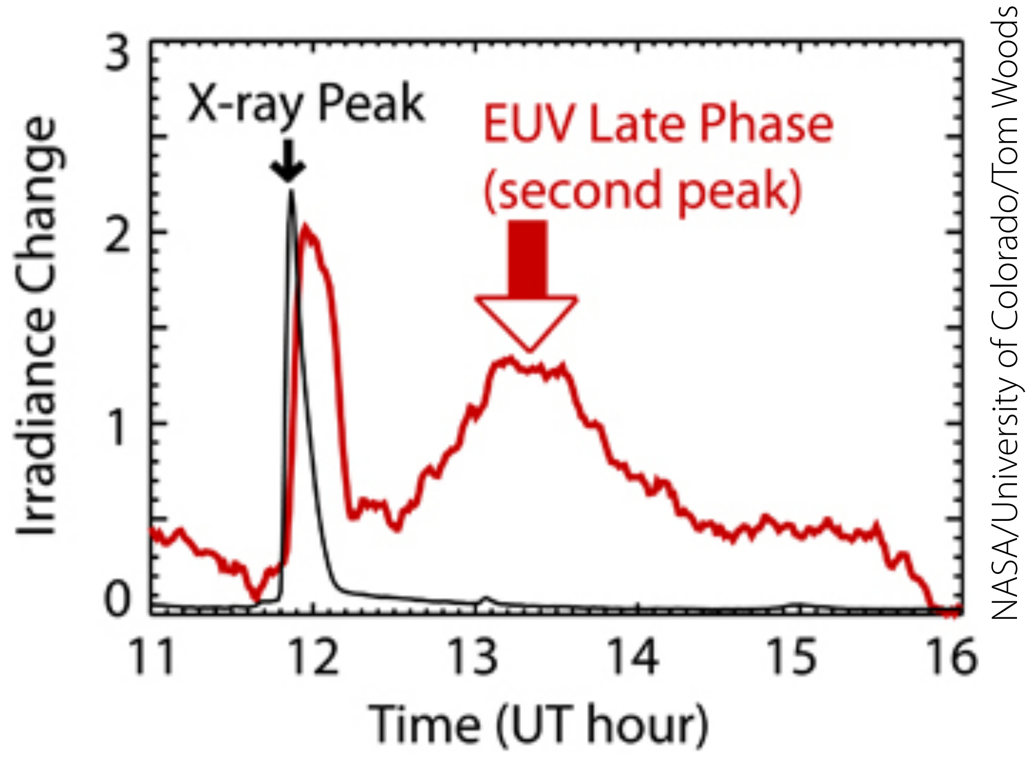
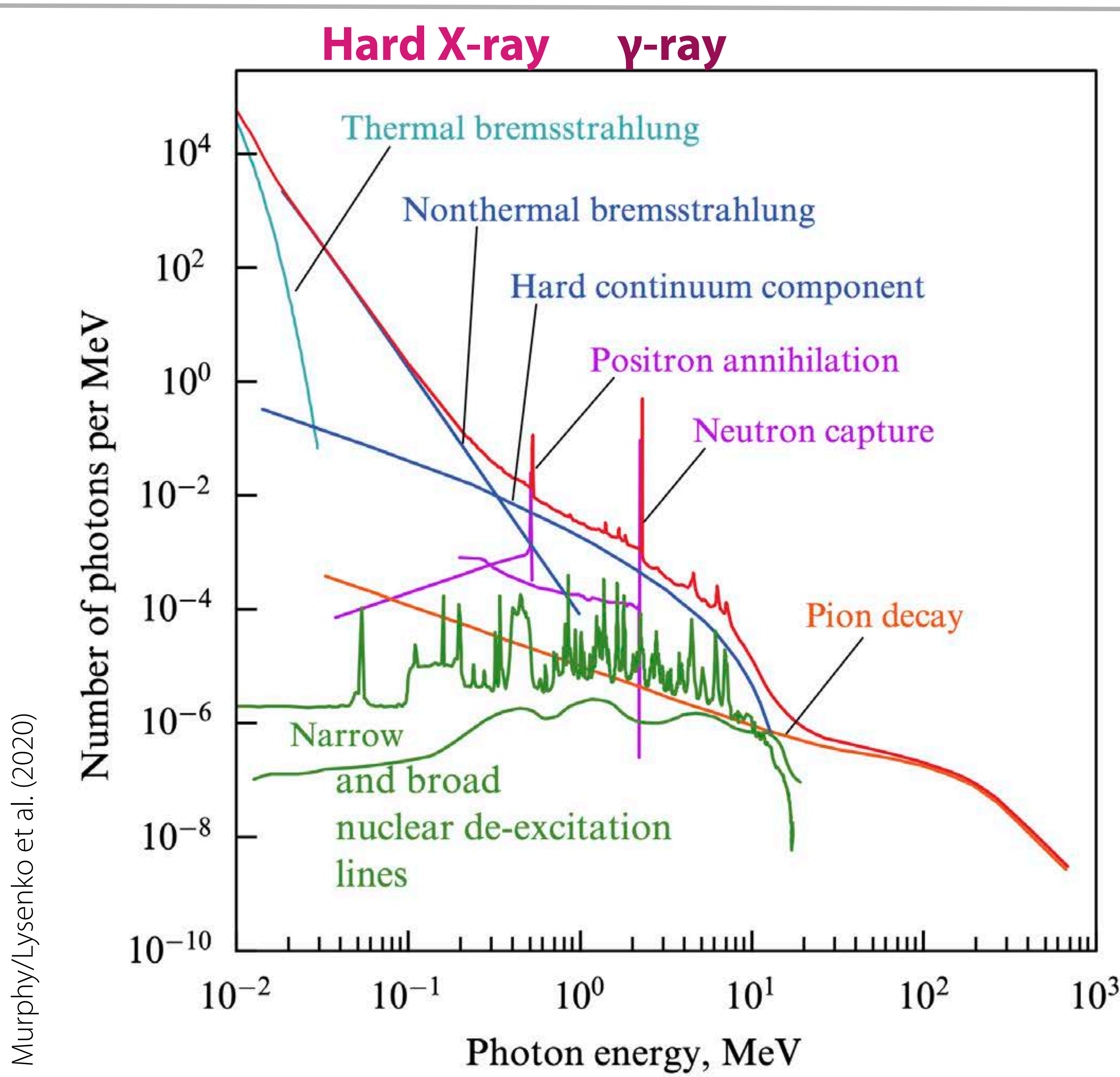
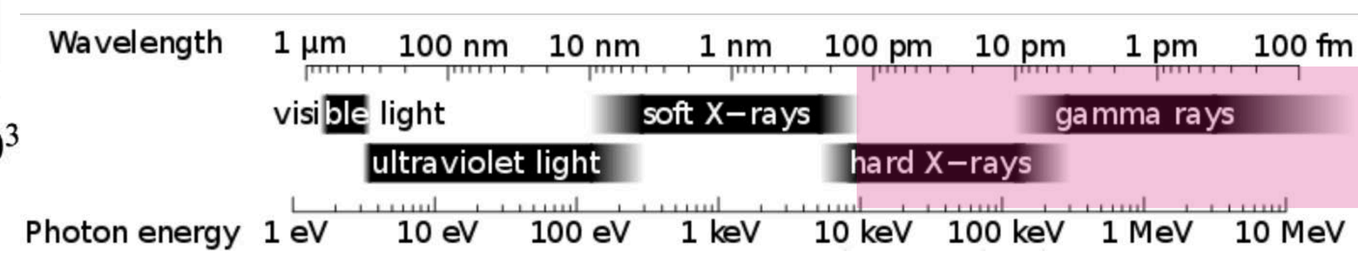


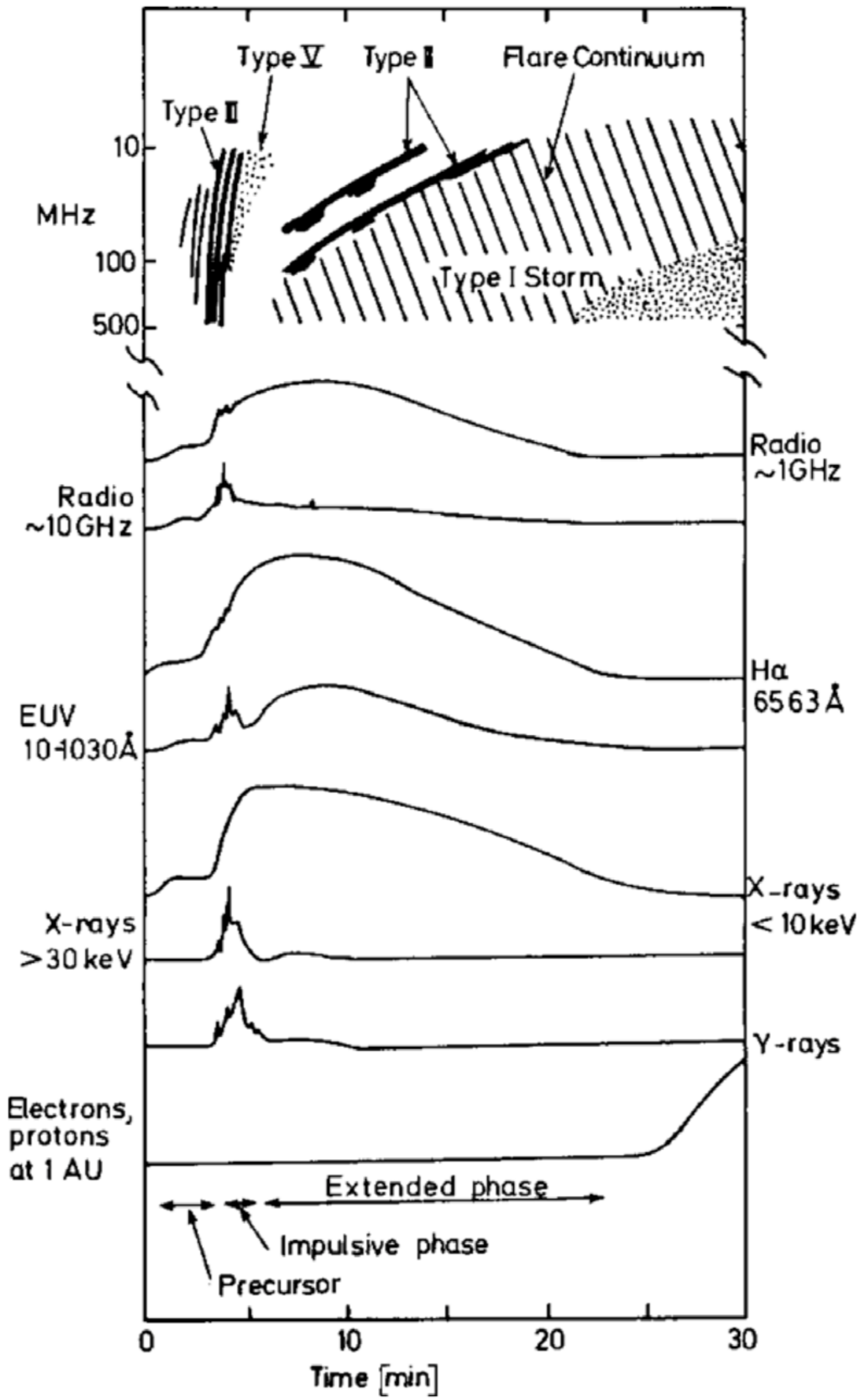


- Spectrum implies contributions due to many different physical mechanisms
- Thermal radiation (bremsstrahlung)
- Non-thermal radiation due to highly energetic particles (radio, hard X- ray, γ-rays)



Flares

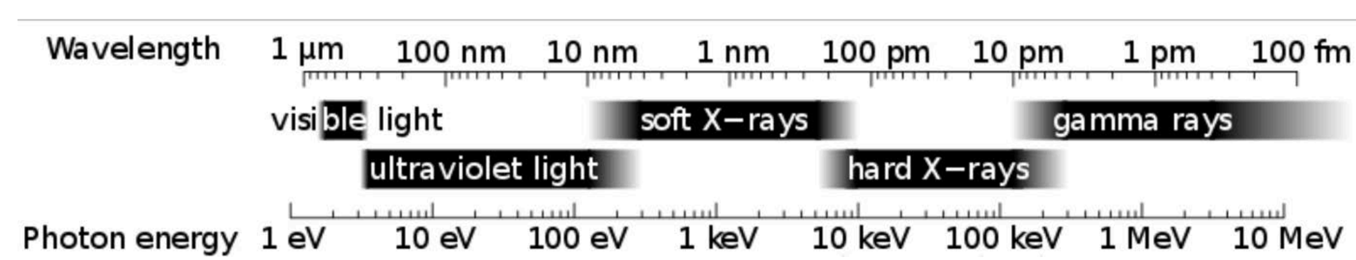
A complex and varied phenomenon



Dulk (1985)

- Different parts of the spectrum show different behaviour
- Hα and soft X-rays: Smoother variations
- Hard X-rays, γ-rays: Spiky emission
- EUV a bit of both

➡ Constraints for the physical mechanism behind flares

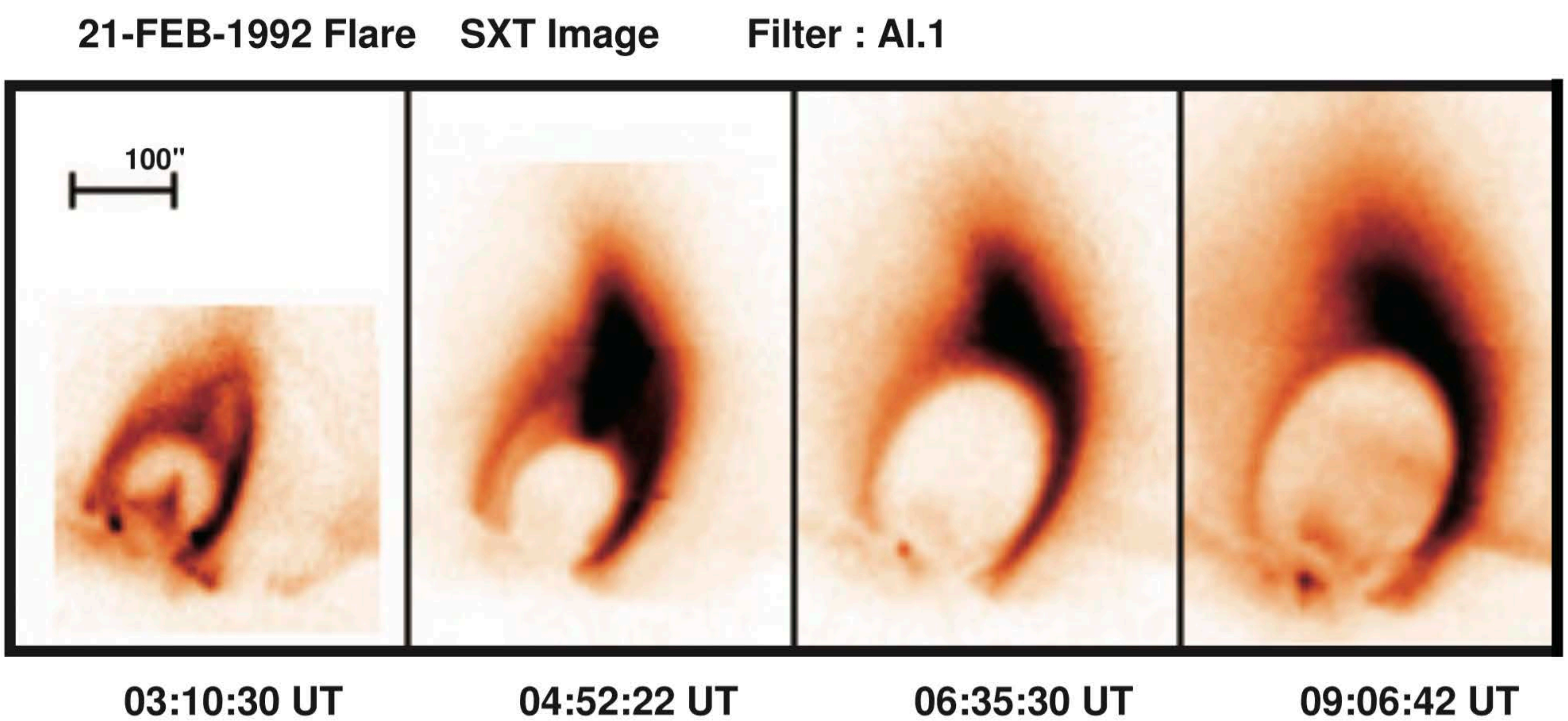


Flares

Different stages and scales

- **Impulsive (phase) flares** (compact or confined flares)
  - Simple loop structure in soft X-ray and no cusp-shaped structure

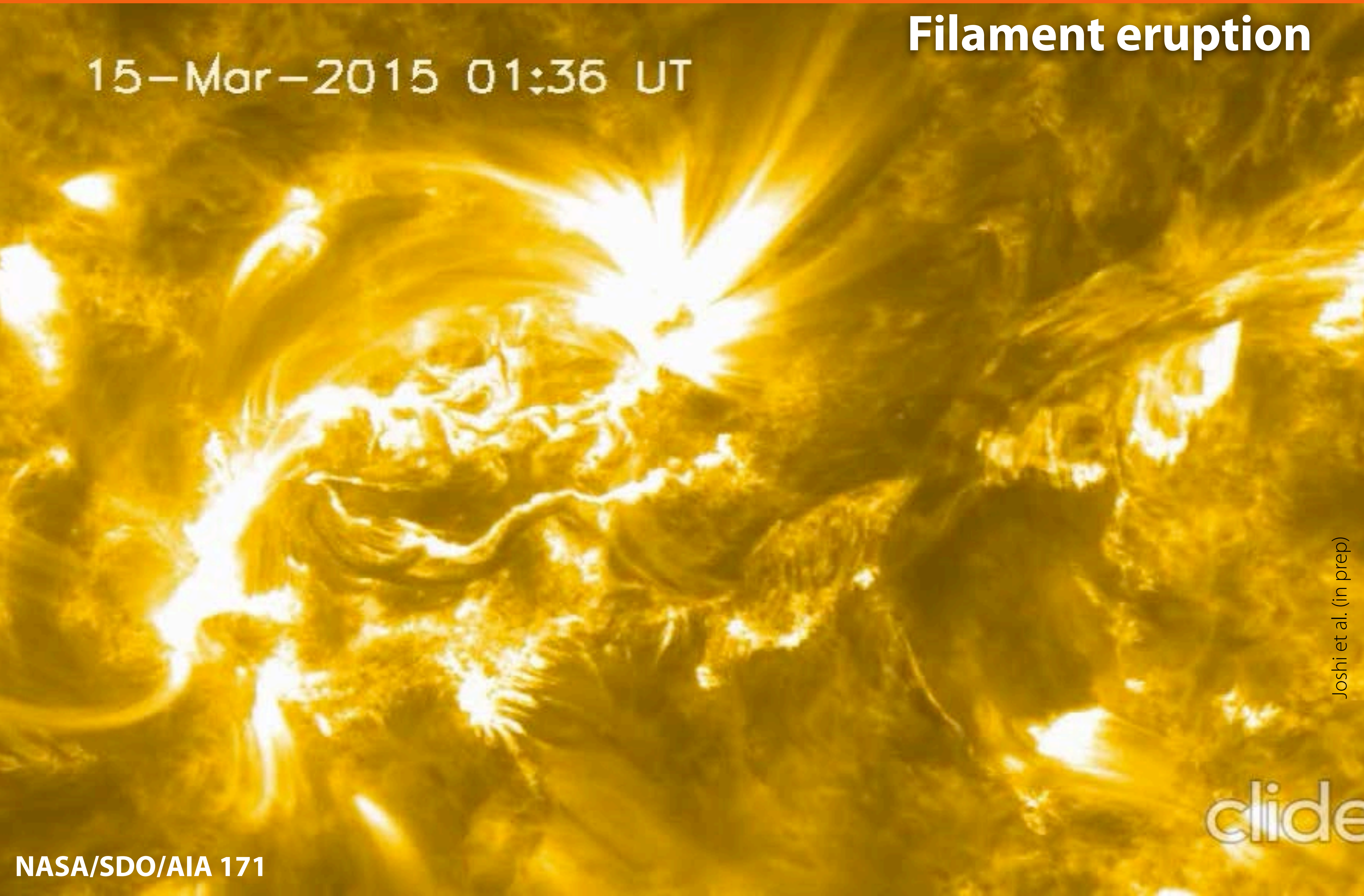
- **Long-durational-event (LDE) flares (gradual phase)**



Feb. 21, 1992 (Tsuneta et al., 1992a; Tsuneta, 1996). Shown in reversed contrast.

- **Giant-arcade formation associated with filament eruption**
  - much larger than LDE flares
  - usually associated with the disappearance of a dark filament.

Flares

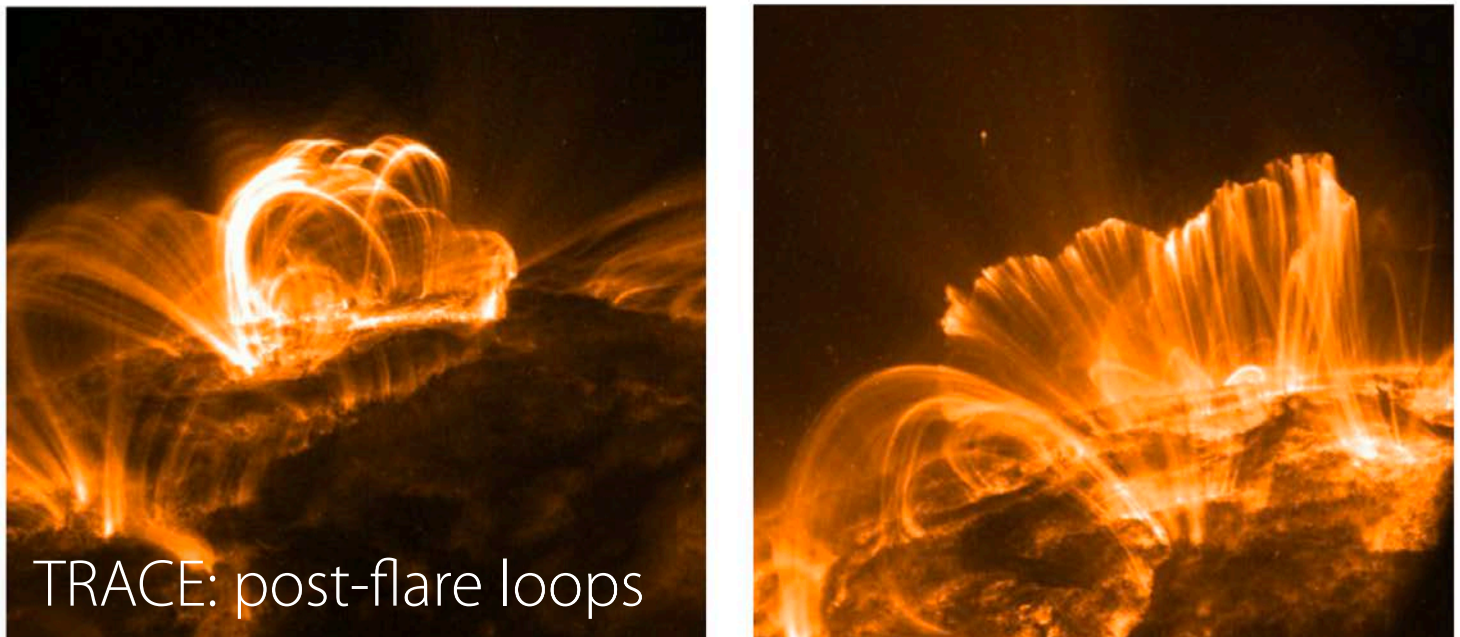

Filament eruption
15-Mar-2015 01:36 UT
Joshi et al. (in prep)
NASA/SDO/AIA 171

Flares

Towards a physical model

Observations so far:

- Substantial intermittent brightening across the spectrum
- Temporal change in emission slightly different across the spectrum
- Large amount of energy released from a small volume in a short period of time.
- Structure of the Active Regions changes during a flare
- Hot loops visible afterwards



TRACE: post-flare loops

Physical mechanism — Requirements

- **Conversion of stored energy** into particle energy and heat
- Either large amount of energy stored in small volume that can be quickly transformed and released as energetic electrons and photons
  or very efficient transport of energy into that volume where it is then converted into the observed forms.
- Available energy:

Pre-flare conditions ($T = 10^6$K)

$E_{th} \approx 3nkTV = 10^{28}$ erg

$E_{mag} \approx (B^2/2\mu)V \approx$ **10^{32} erg**

Flares

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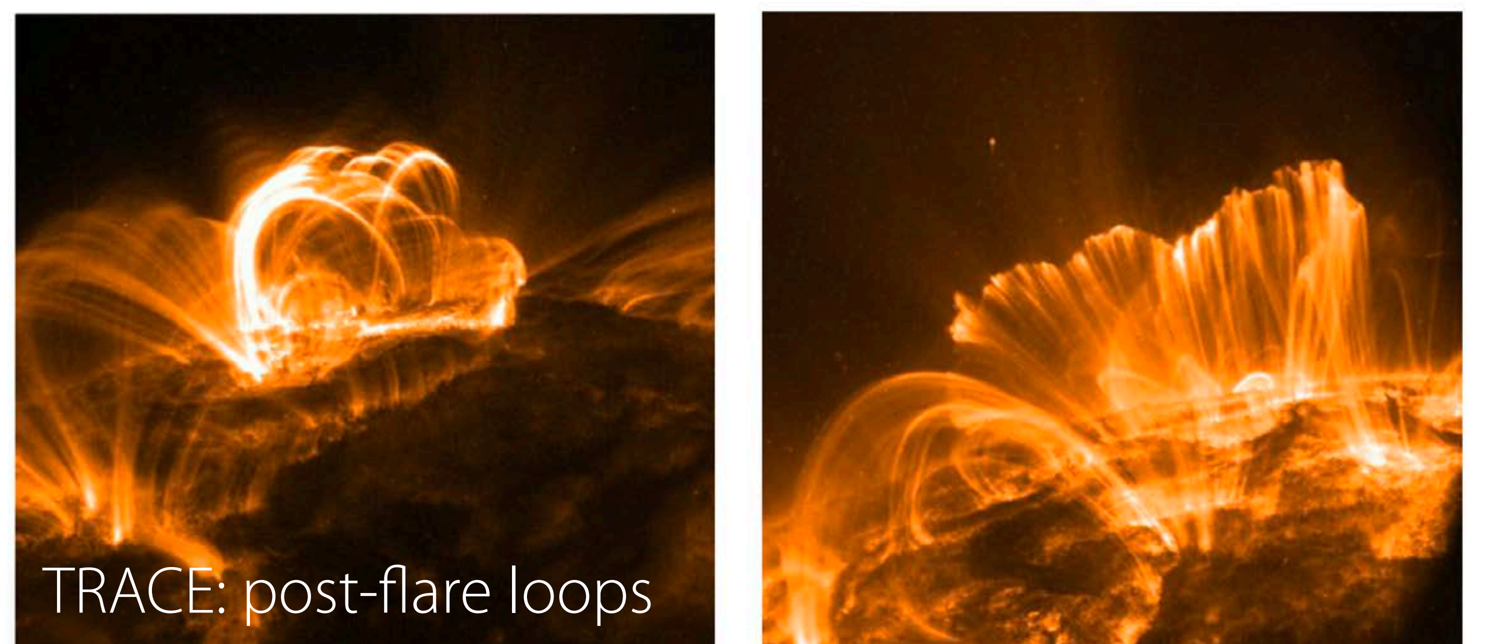


Physical mechanism

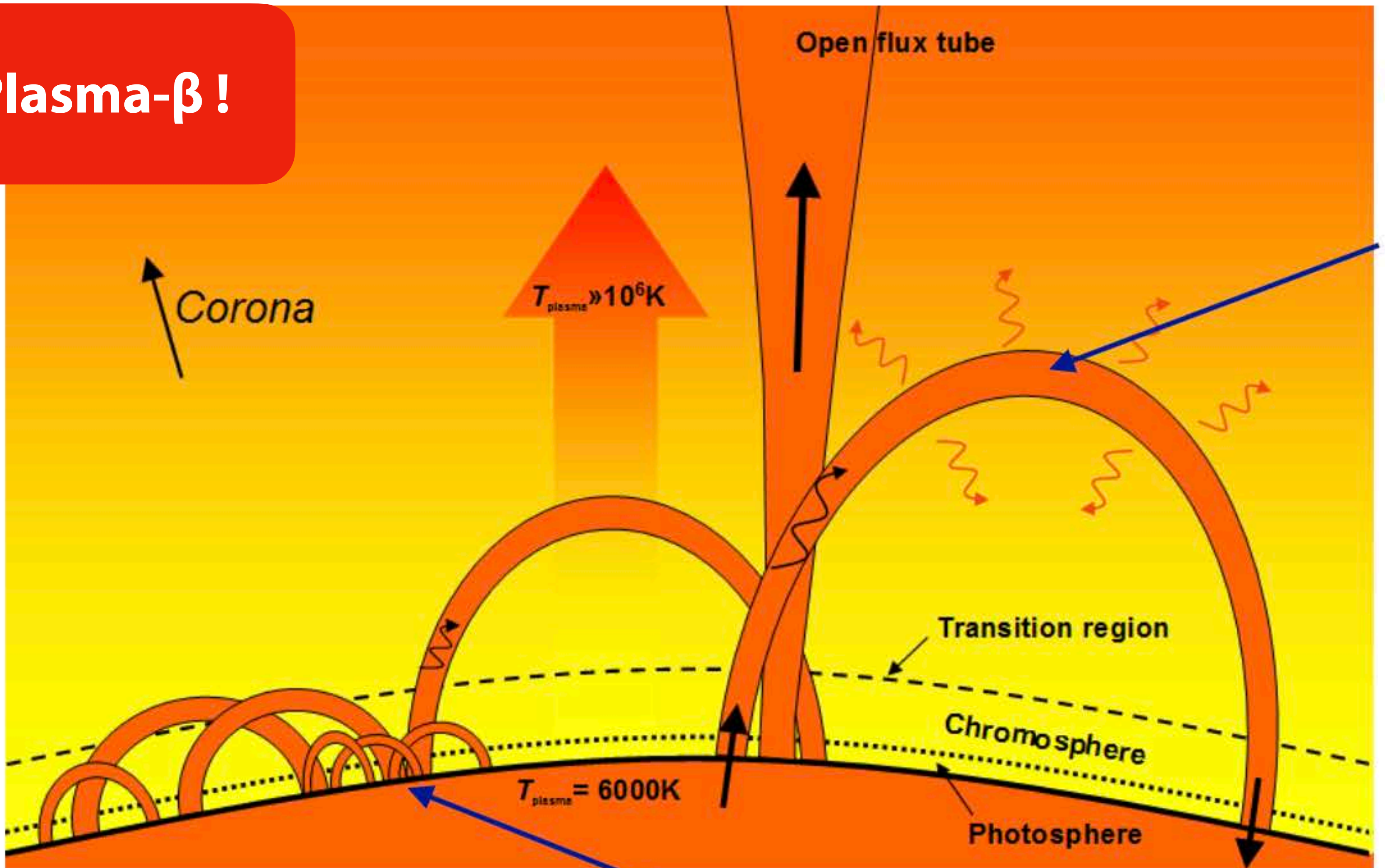
- Requires either large amount of energy stored in a small volume that can be quickly transformed and released as energetic electrons and photons **or** very efficient transport of energy into that volume where it is then converted into the observed forms.
- Needed: converting stored magnetic energy into particle energy and heat
- Available energy:
  - Thermal energy many orders of magnitude too small
  - Only sufficient energy source is energy stored in strong magnetic fields.

➡ **Magnetic reconnection.**

Flares

Towards a physical model — Storing energy in the magnetic field

Plasma-β !



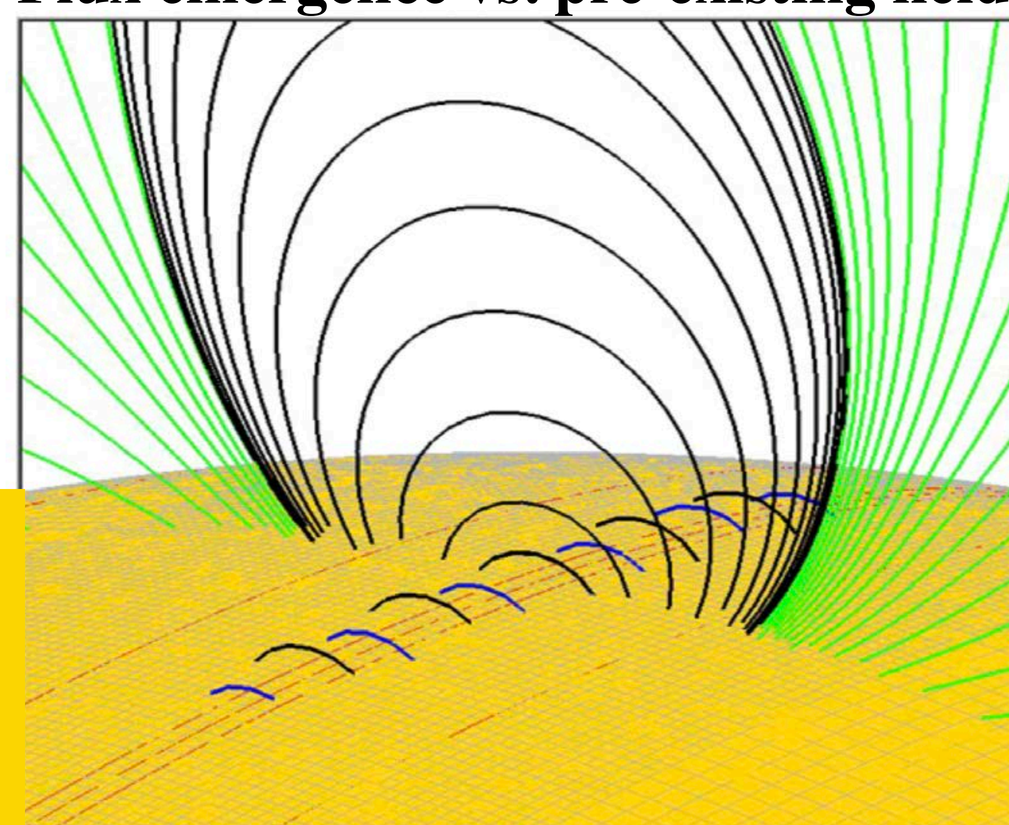
Corona:

Plasma-β << 1: Magnetic force control field shape, gas flow constrained by field.

Photosphere:

Plasma-β >> 1: field lines are advected with the motion of the convecting photospheric gas.

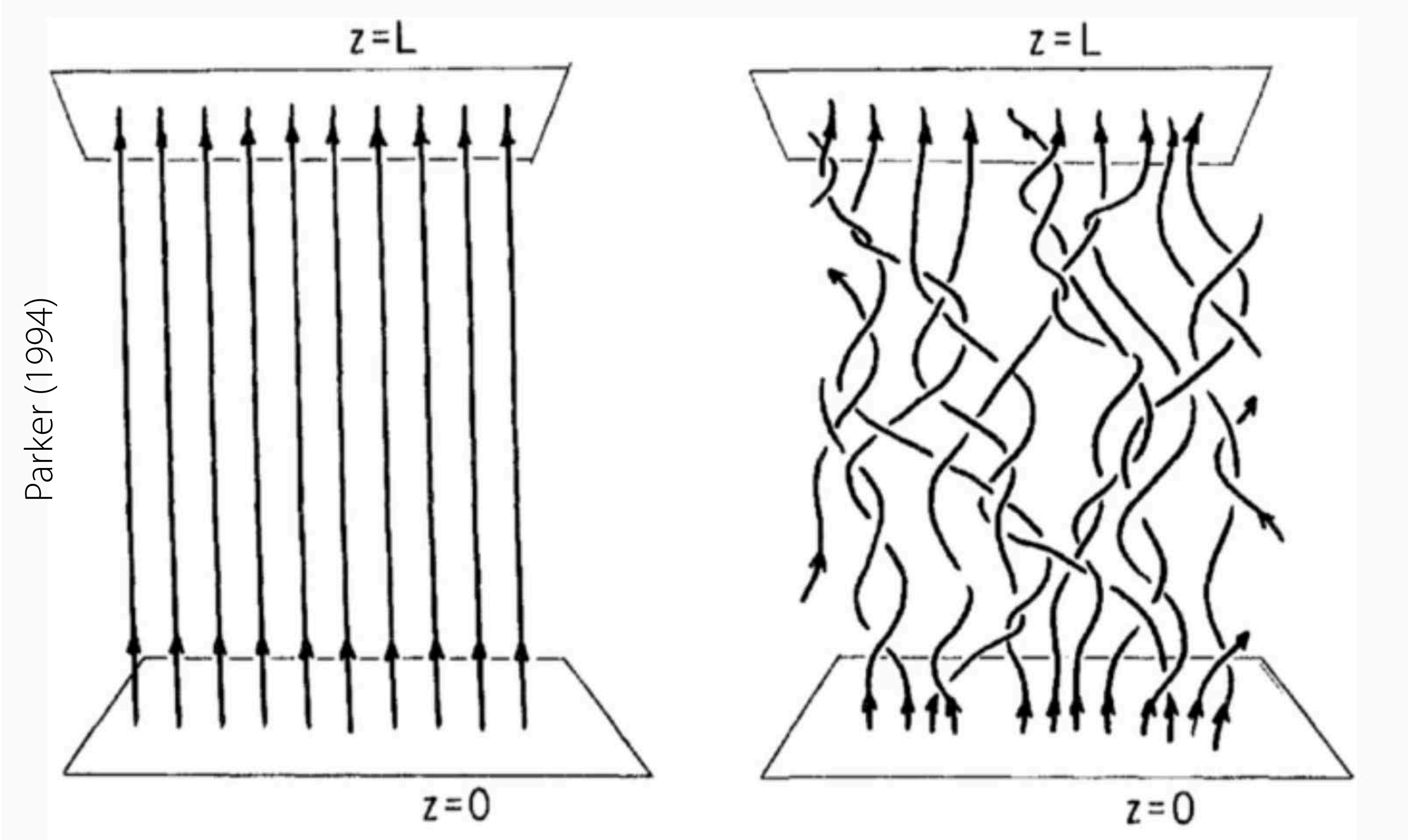
Flux emergence vs. pre-existing field



- Emerging and pre-existing field
- Motion of photospheric foot points
- **Twisting and stressing of magnetic field**

Flares

Towards a physical model — Storing energy in the magnetic field



Initially unipolar, homogeneous vertical field configuration

Mixed and entangled field as a result of braiding

- Building up energy "excess" occurs on timescales of days to weeks
- Energy release on much shorter timescales (as observed in flares)

- Motion of photospheric foot points
- ➡ "Braiding" of magnetic field lines
- ➡ Energy stored in the entangled magnetic field (magnetic tension!)
- Idea goes back to Parker (1994)

Amount of energy to be released during flare = difference between magnetic energy of actual (stressed) field configuration and energy of a potential (linear force-free) configuration

$$\nabla \times \boldsymbol{B} \propto \mu \boldsymbol{B}$$

Flares

Towards a physical model

- **How to release the energy stored in coronal magnetic field as rapidly as observed?**

- **Idea:** Release of magnetic energy triggered by fast magnetic reconnection in a current sheet

- **Problem:**
  - Time scale of diffusion is much longer than typical time scale of a flare
  - Region where electric current is dissipated must be of order ~10m!

- **Solution:**
  - Advanced models of magnetic reconnection

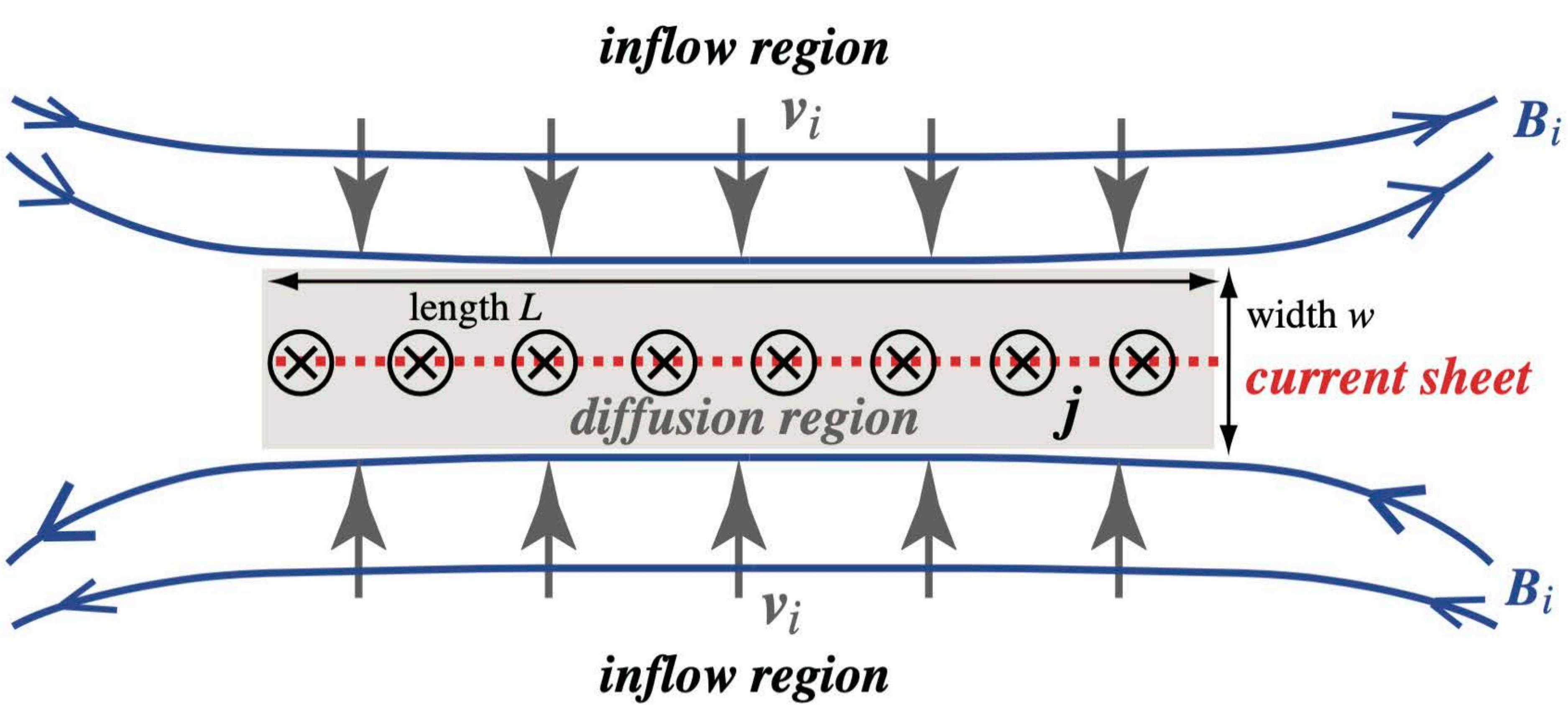
- **Development and current state**
  - Many models proposed over the years
  - Still many open questions and thus an active field of research
  - Implications of magnetic reconnection beyond the Sun & stars

Flares

Magnetic reconnection

- **Sweet–Parker** model for magnetic reconnection (Sweet, 1958; Parker, 1957)
  - Several orders of magnitude too slow to explain rapid energy release in a flare

- **Petschek model** for magnetic reconnection
  - Enables much faster energy release



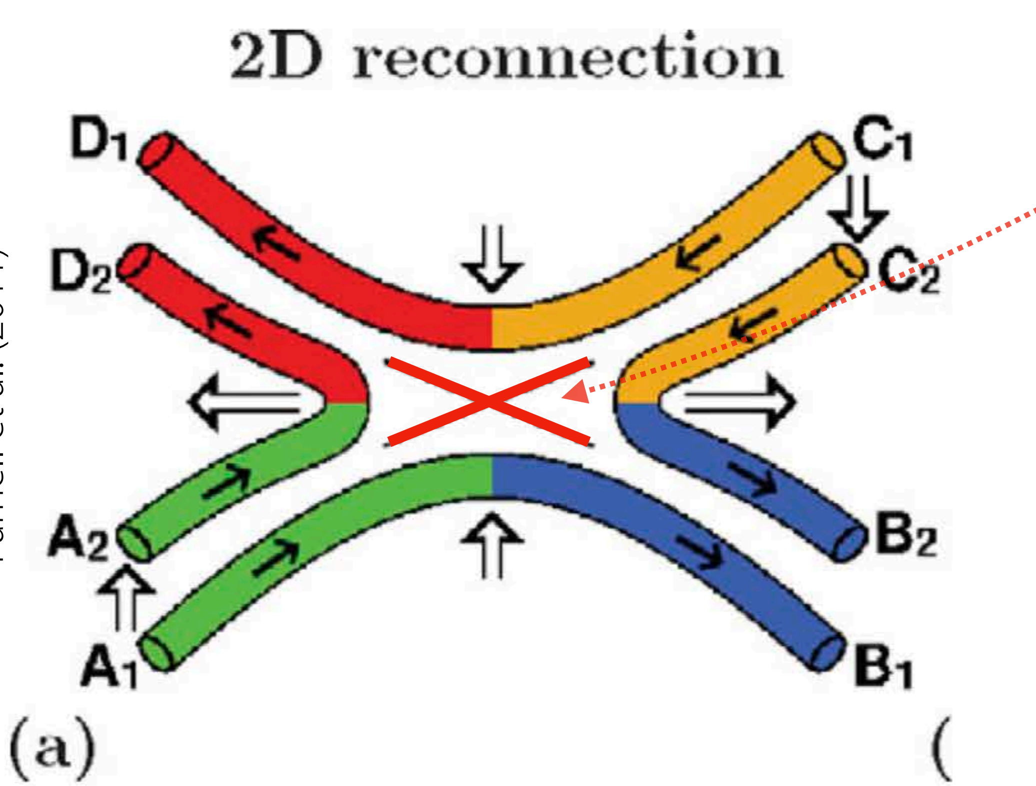
Shibata & Magara (2011)

Flares

Magnetic reconnection in 2D

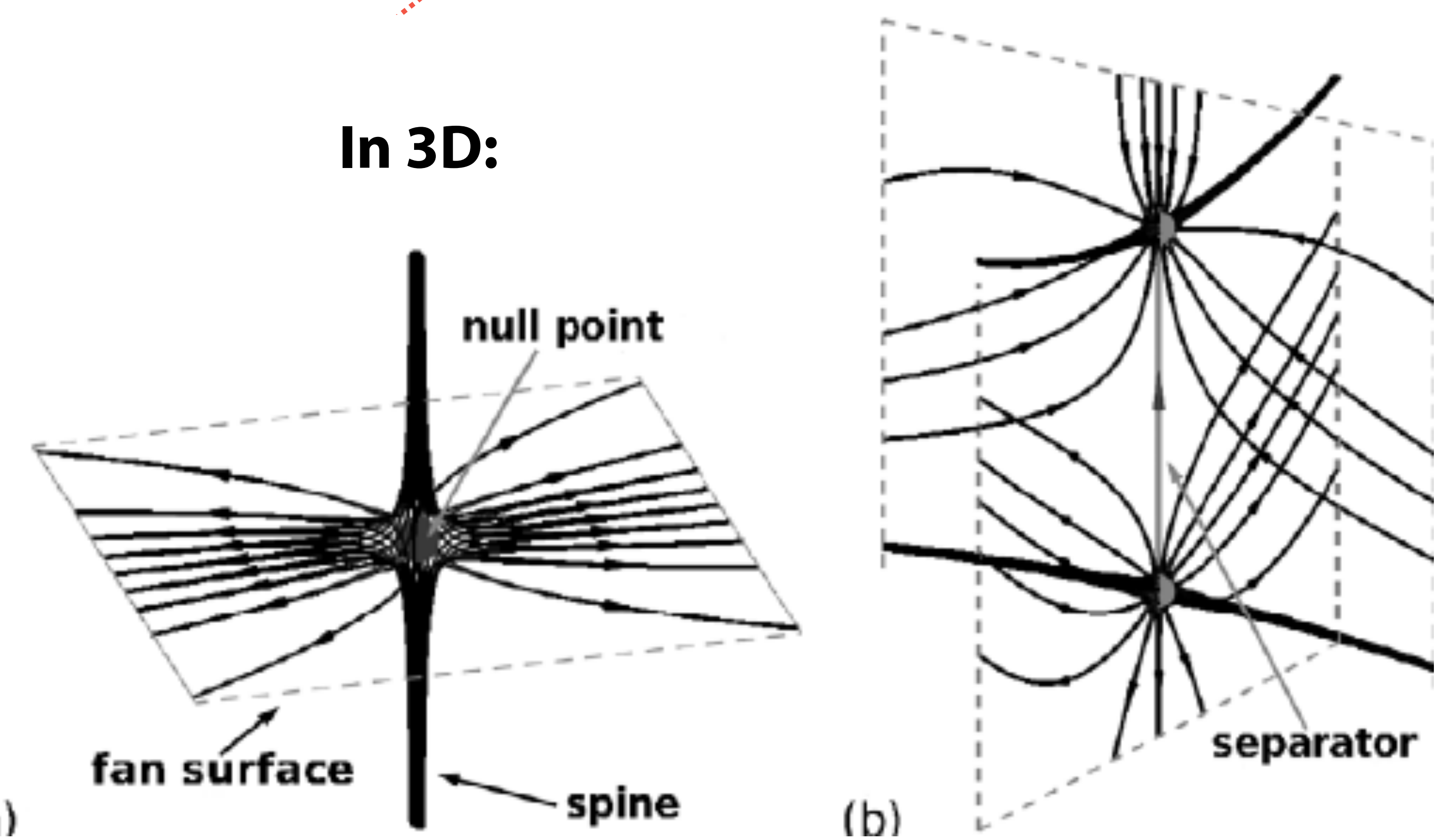
- Magnetic reconnection can <u>only occur</u> at **X-type null points**.
- Important: Magnetic field lines are <u>theoretical</u> construct!
  In reality: (Large number of) charged particles interacting via electromagnetic force

Null point = point in a field where the field quantity is zero (because opposing forces cancel out)



Parnell et al. (2011)

In 3D:



Flares

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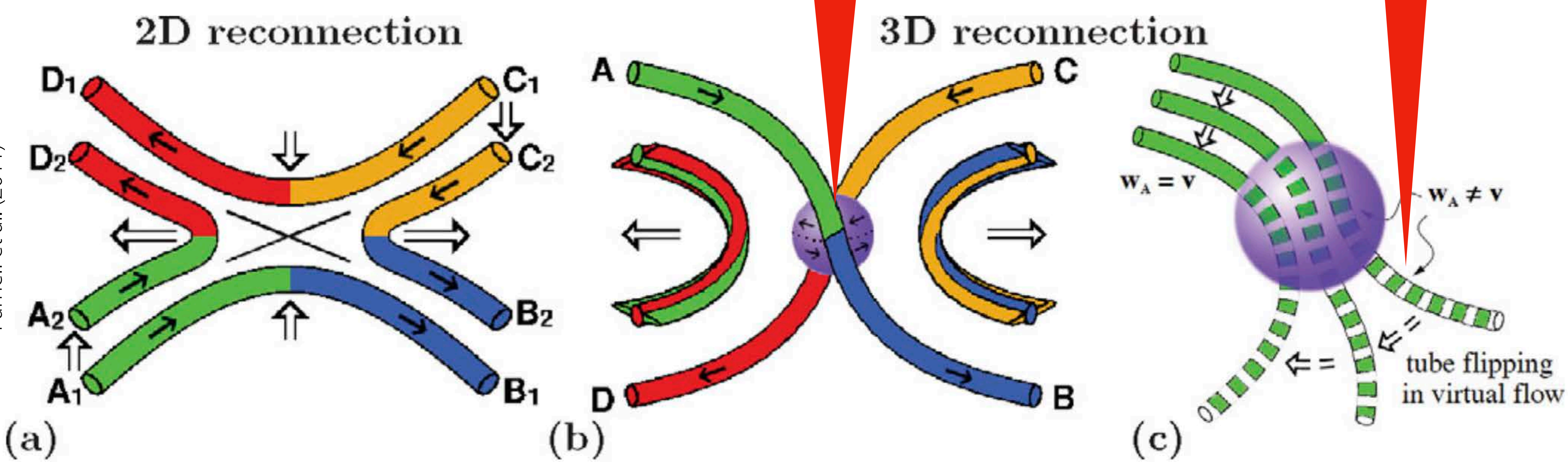
Diffusion region

Reconfiguration: Change of field line **connectivity**



Parnell et al. (2011)

Flares

Magnetic reconnection in 3D

- Necessary condition for 3D reconnection in a considered region:
  Assumption of ideal magnetohydrodynamic (MHD) breaks down, diffusion instead:

$$\int_{fl} \mathbf{E}_{||} \mathrm{d}l \neq 0$$

fl: Field line path and
$\boldsymbol{E}_{||}$: Electric field component parallel to the field line

- Ohm's law in MHD:

$$\mathbf{E} \cdot \mathbf{B} + (\mathbf{v} \times \mathbf{B}) \cdot \mathbf{B} = \mathbf{j} \cdot \mathbf{B}/\sigma$$

$$\Longrightarrow \quad \mathbf{E}_{||} = \mathbf{j}_{||}/\sigma$$

B: Magnetic field
v: Plasma velocity
j: Electric current
σ: Electrical conductivity

➡ Presence of **electric currents essential for magnetic reconnection**.

- In 3D: Parallel component of current is essential
  - Strong accumulations of current and current layers can arise in variety of locations, not just associated with magnetic nulls as in 2D

Further reading: Priest, Solar Magnetohydrodynamics; Parnell et al. (2011)

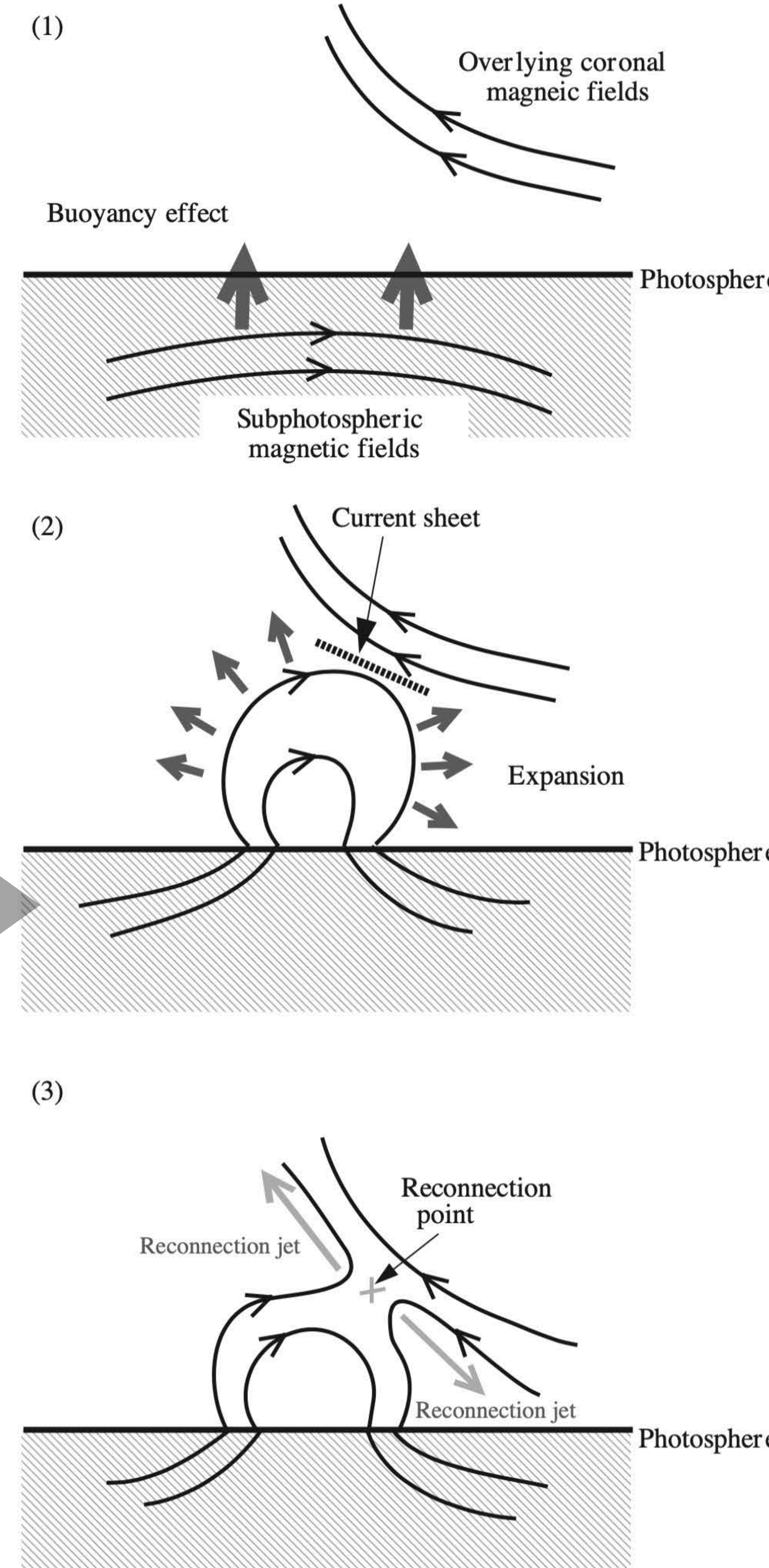
Flares

Current sheet formation

How is a current sheet is formed in the corona?

- Possible scenarios:

1. At interface between different flux domains interacting each other. Multiple flux domains might be formed via emergence of a partially split flux tube.
2. Inside a single flux domain where sheared magnetic field develops (development of magnetic shear)

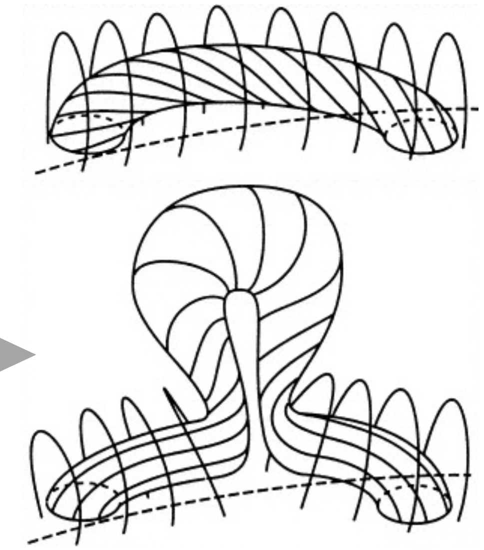


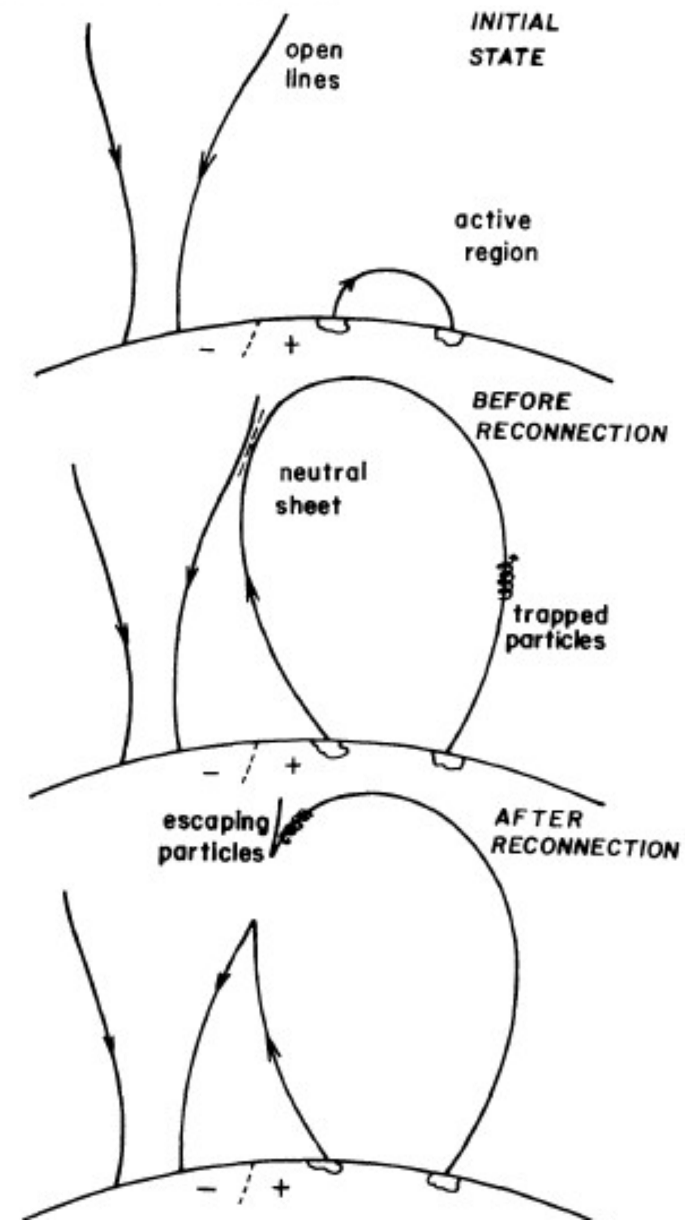
Shibata & Magara (2011)

Flares

Towards a physical model

- **Key physical processes for producing a flare**
  - Emergence of magnetic field from the solar interior to the solar atmosphere (flux emergence)
  - Local enhancement of electric current in the corona (formation of a current sheet)
  - Rapid dissipation of electric current (magnetic reconnection)
  - Causes shock heating, mass ejection, and particle acceleration.

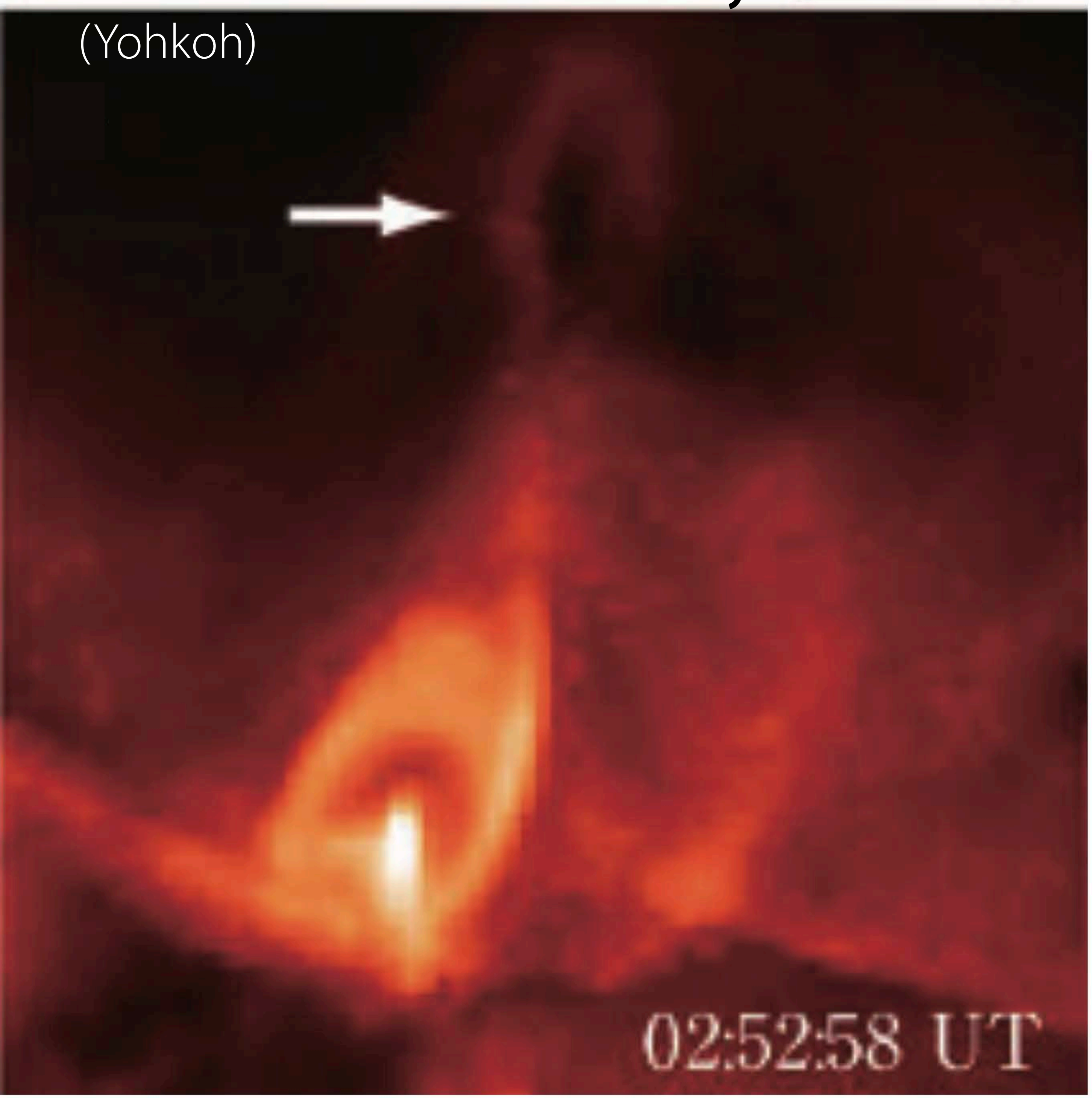


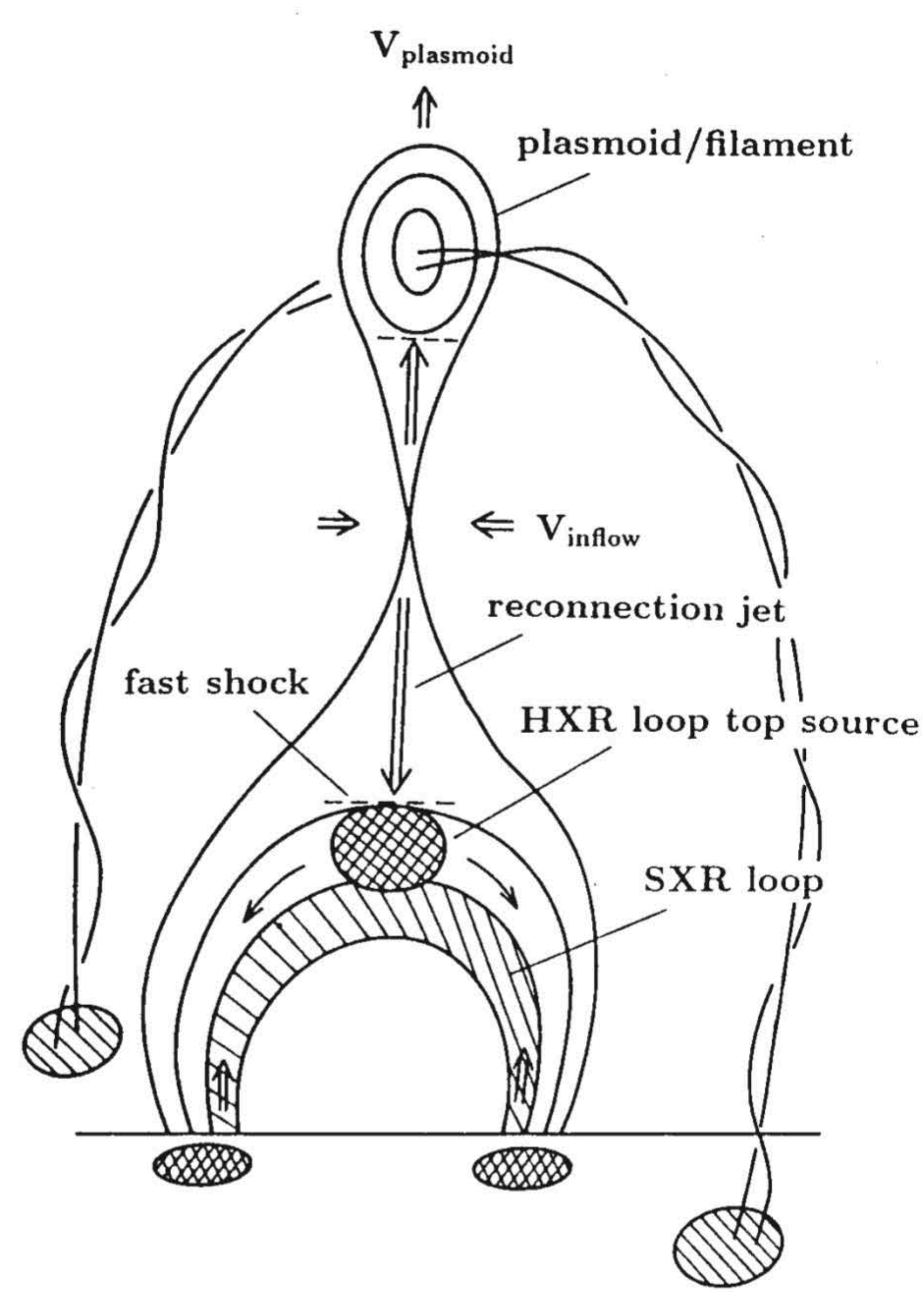


Flares

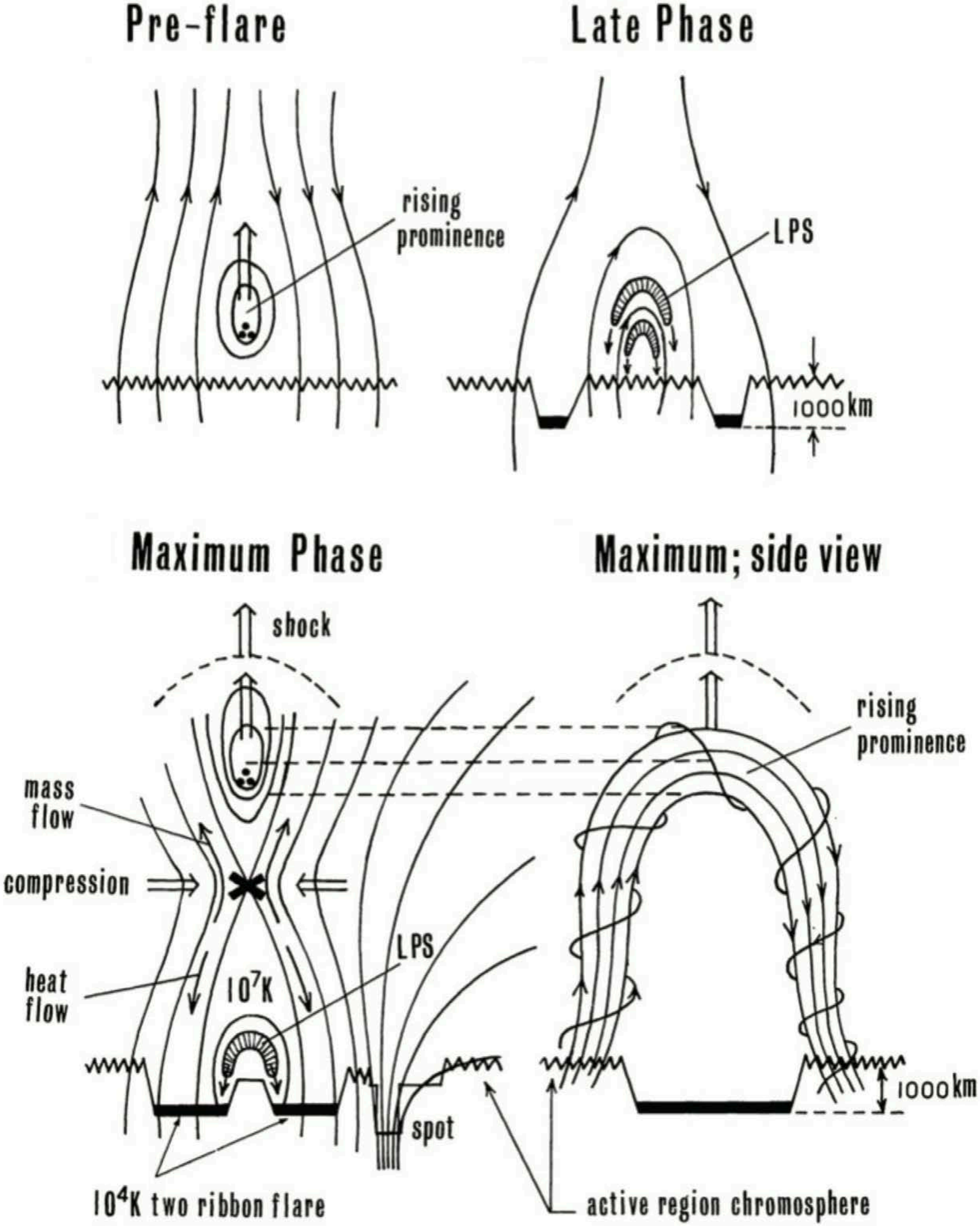
Standard flare model

LDE flare observed in soft X-rays
(Yohkoh)

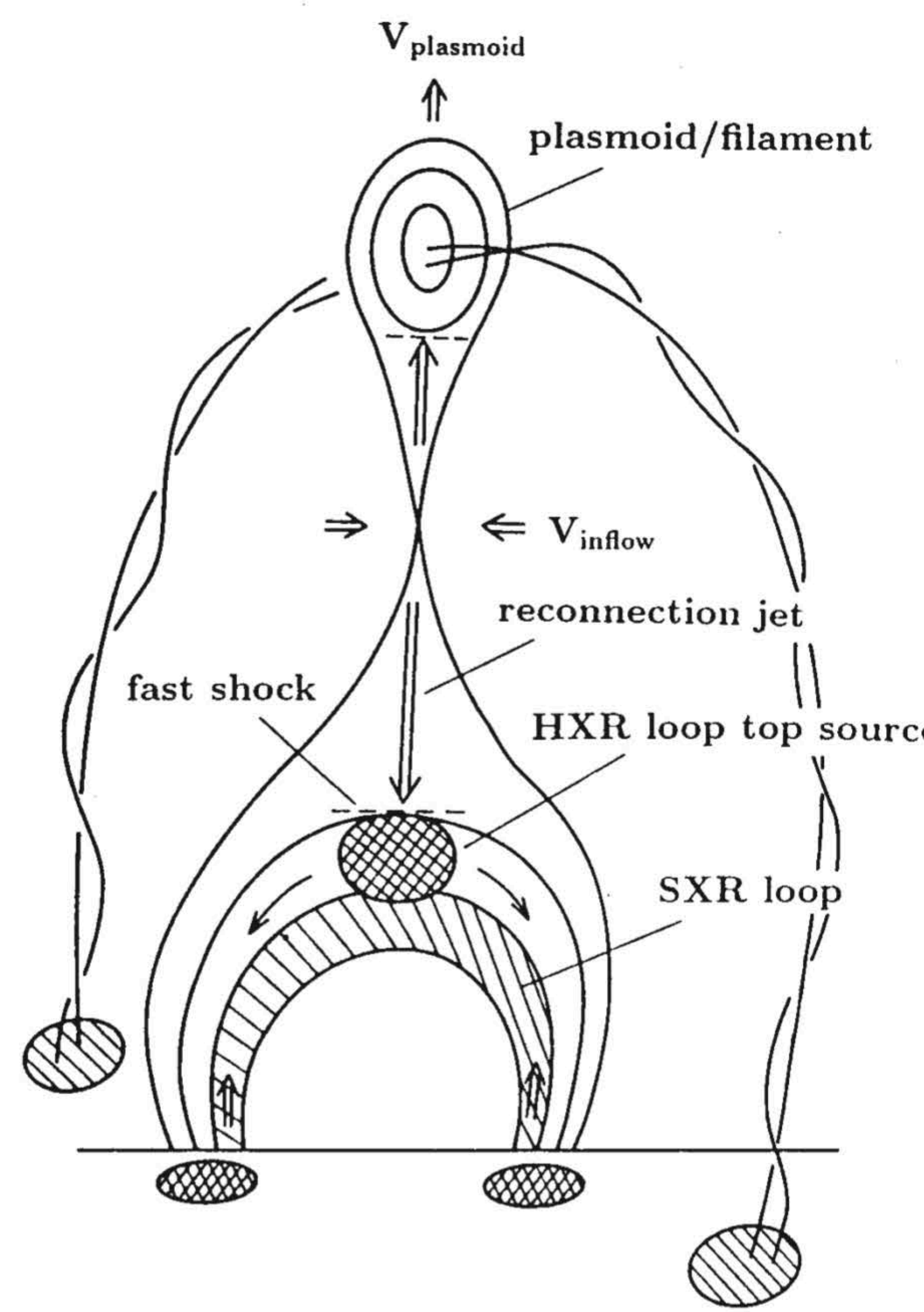




Shibata et al. (1995)



Hirayama 1974



Shibata et al. (1995)

Flares

Standard flare model

- Prominence (closed magnetic field structure) destablized due photospheric footpoint motions

➡ Field structure rises upwards.

➡ Underlying magnetic field lines are stretched.

➡ Formation of a current sheet.

➡ Resistivity suddenly increased (plasma wave excitation due to various instabilities) — produces diffusion region

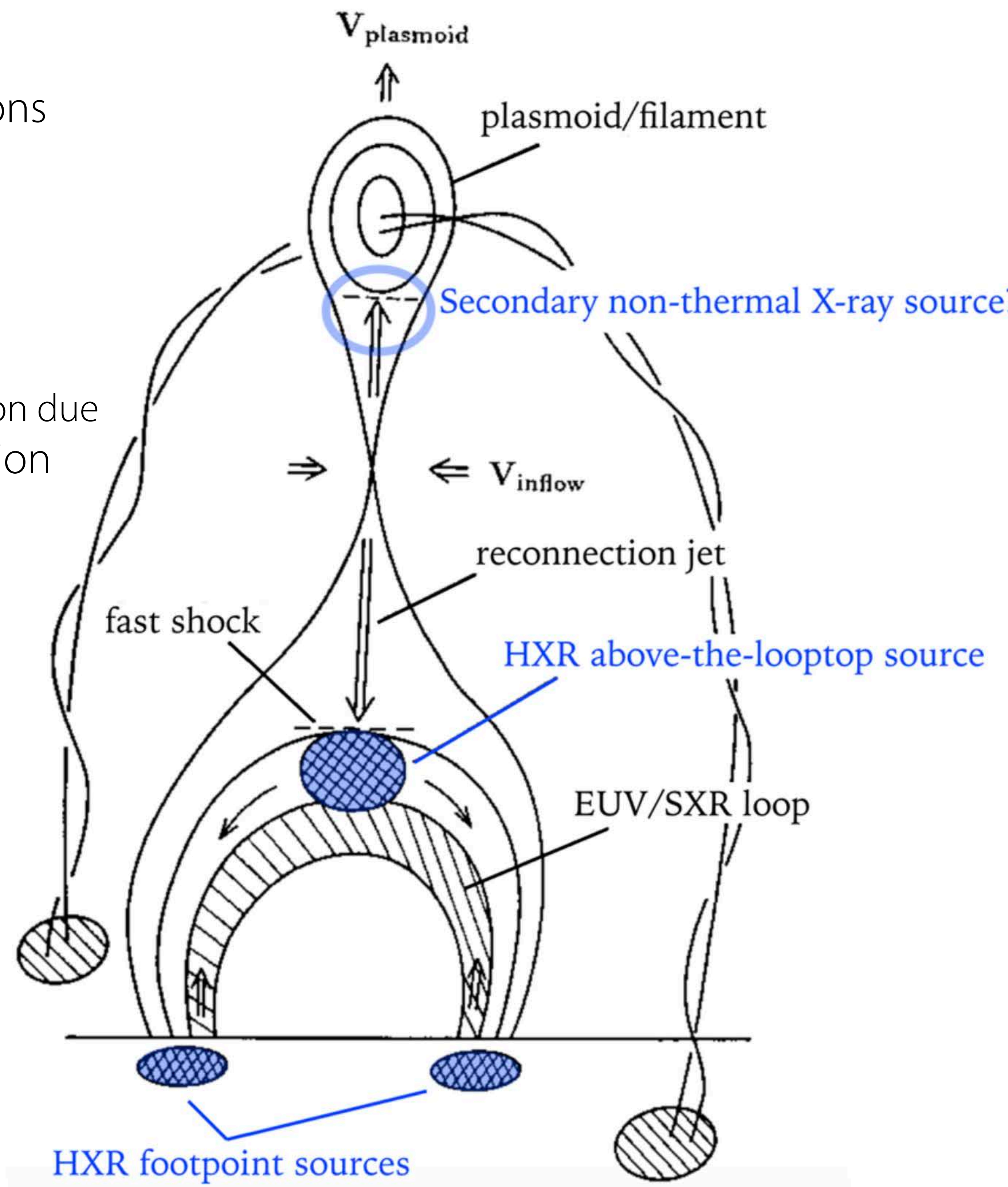
➡ Magnetic reconnection occurs.

➡ Plasma shoots away from reconnection site as oppositely directed hot jets.

➡ Inflow region gets separated from outflow region by pairs of slow-mode standing shocks.

➡ If speed of outflow jet > Alfvén speed: termination shock produced

➡ Electrons accelerated at magnetic reconnection site propagate downwards and emit hard X-rays via bremsstrahlung (Brown 1971).

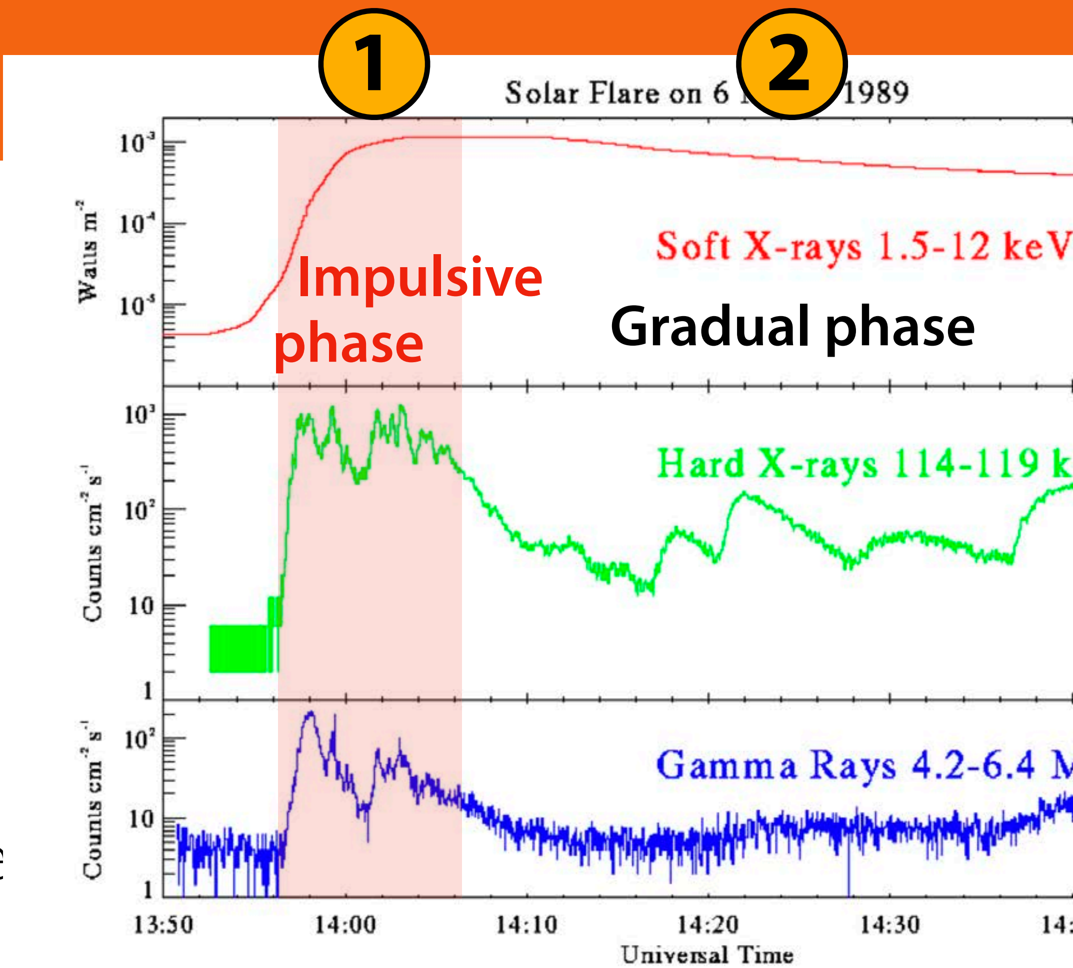


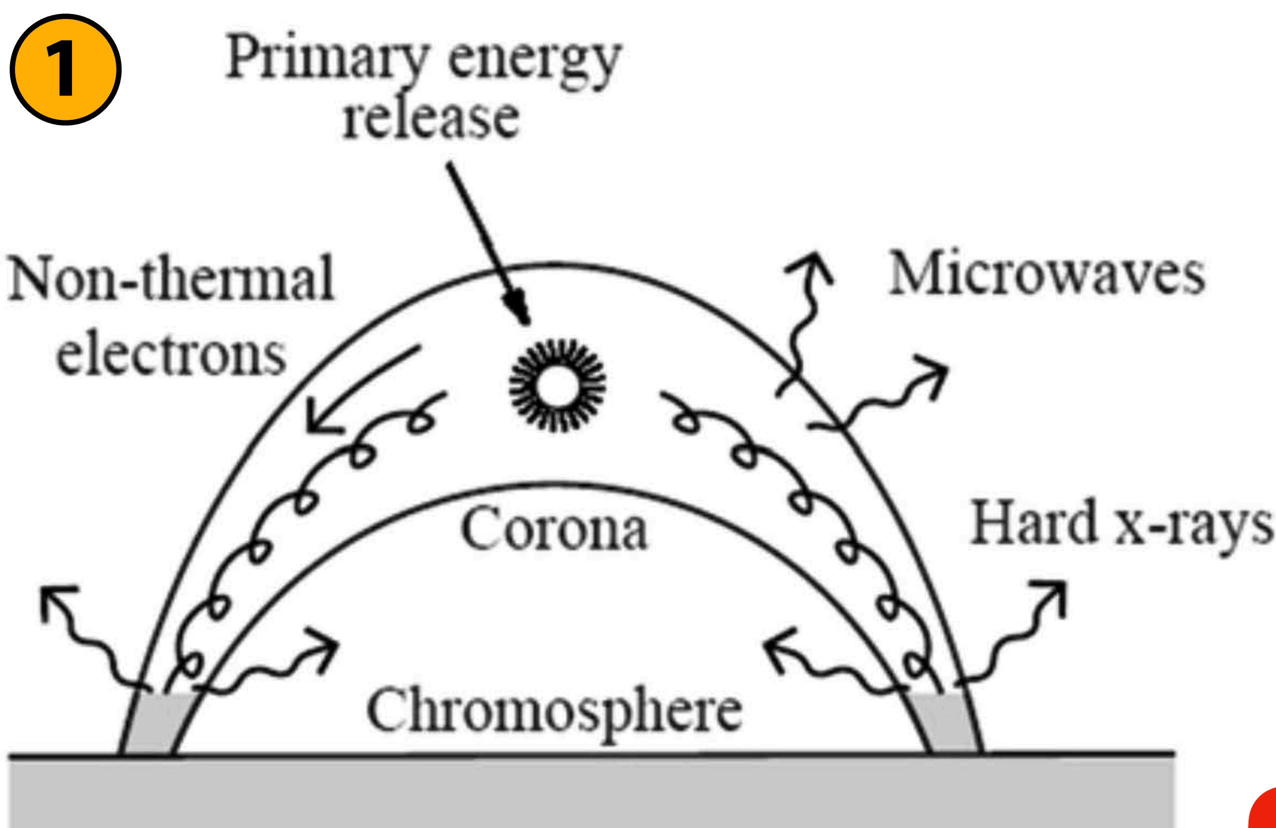
Shibata et al. (1995), Oka et al. (2018)

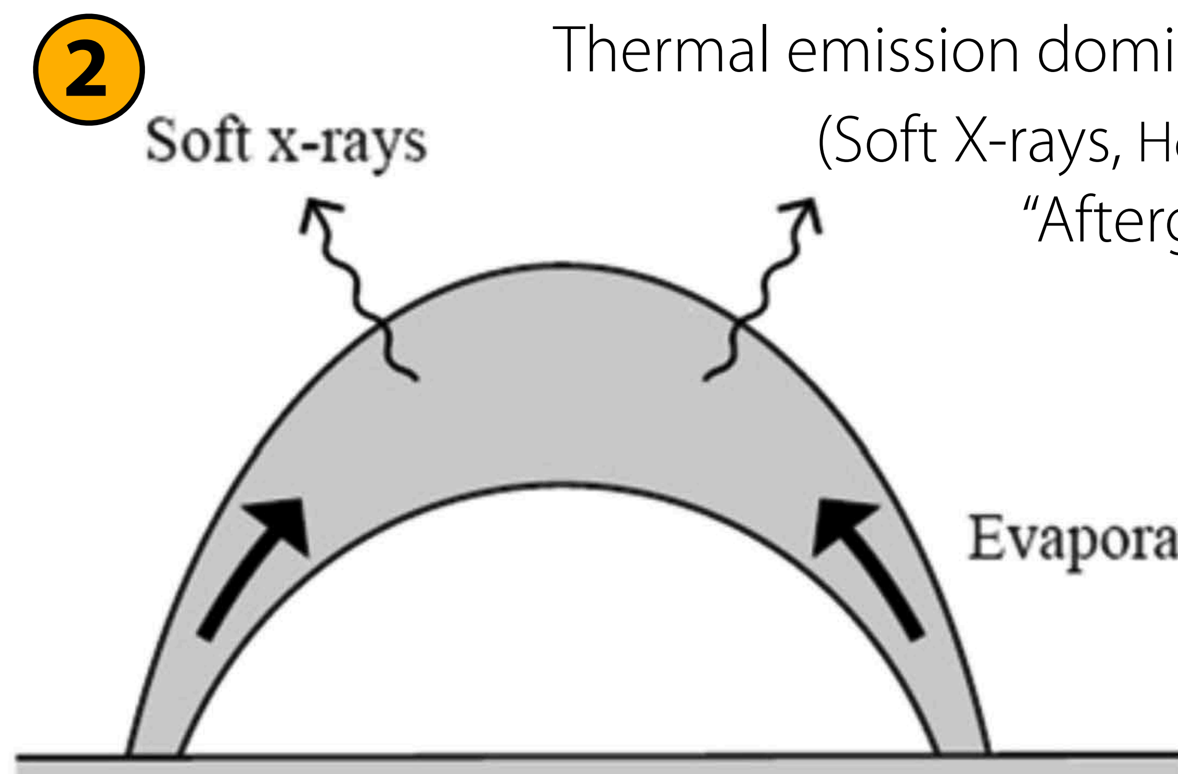
Flares

Standard flare model

- (non-thermal) **thick target model** — Major stages:
  1. Magnetic reconnection
  2. Downward streaming of fast particles
     — hit denser plasma in chromosphere below
  3. Consequence: Heating ("evaporation") and
     upward streaming of plasma from lower atmosphere







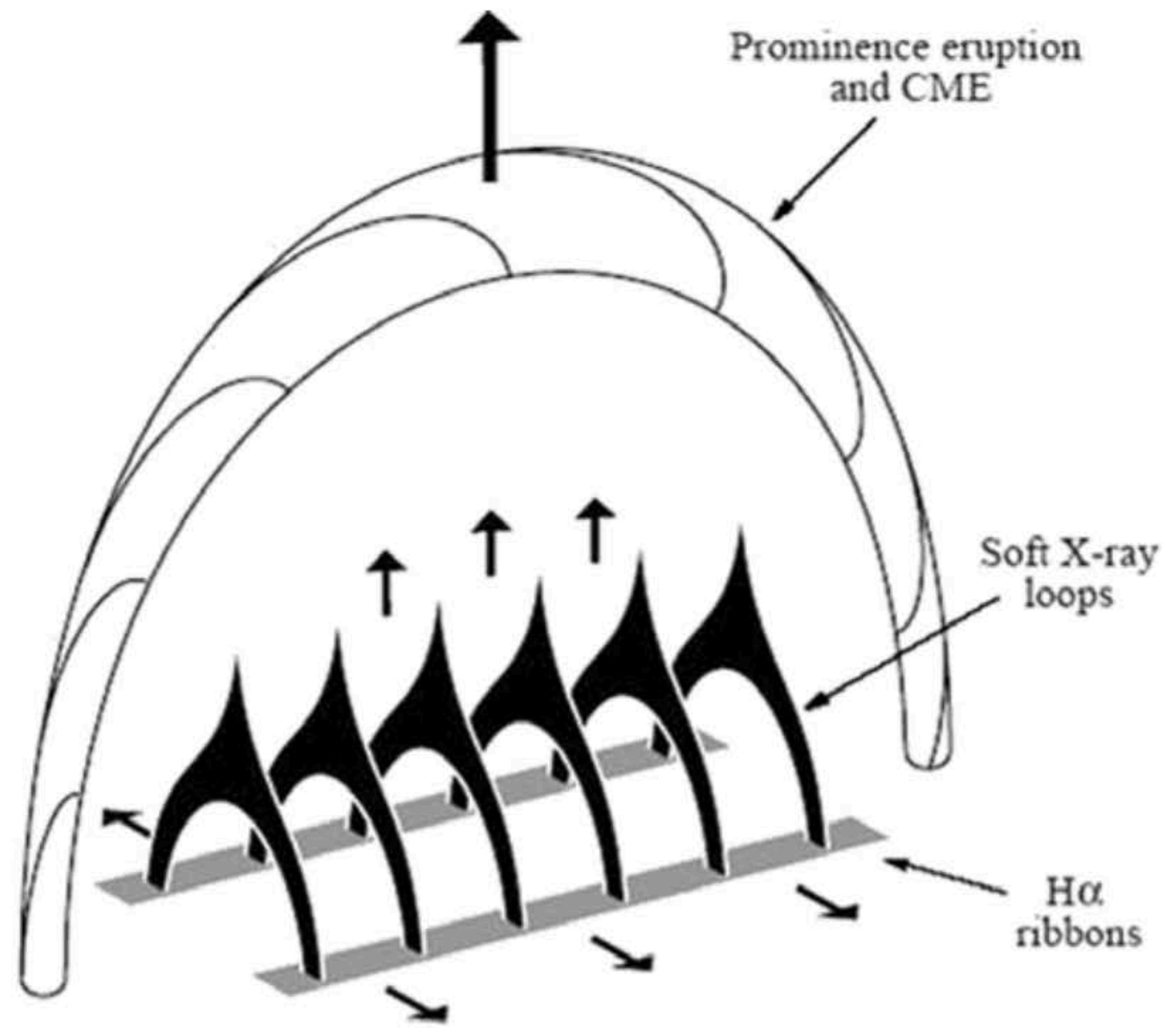
Thermal emission dominates
(Soft X-rays, Hα, …)
"Afterglow"

Correct model? Thin target model? Still debated.

Flares

Standard flare model

- **Two-ribbon flare**
- Ribbons move apart in (gradual) decay phase (typical speeds 10km/s)
- Space between ribbons usually spanned by post-flare loops (transverse filamentary pattern seen in Hα)
- Outlines the new magnetic configuration after the flare



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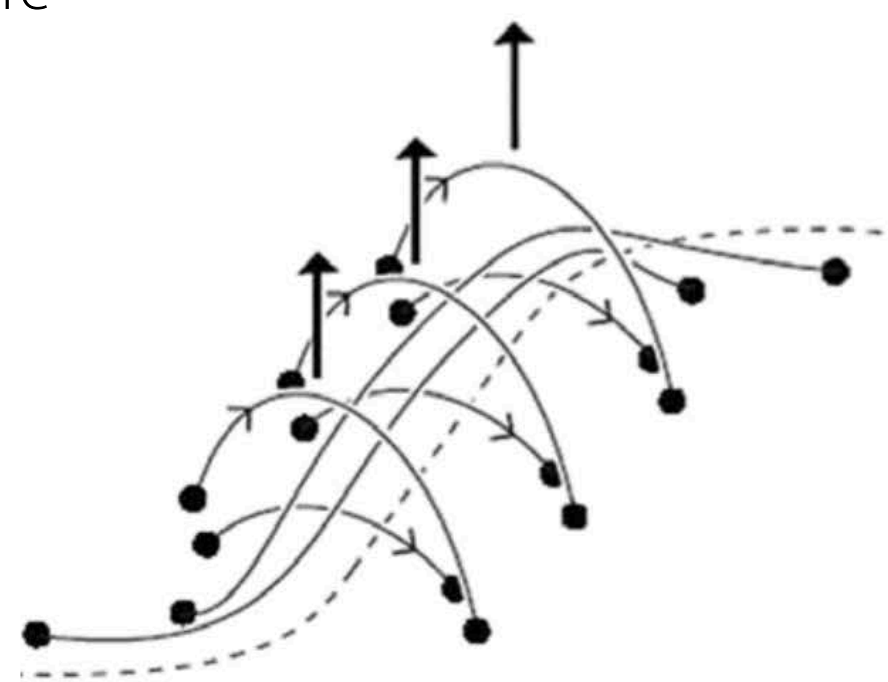

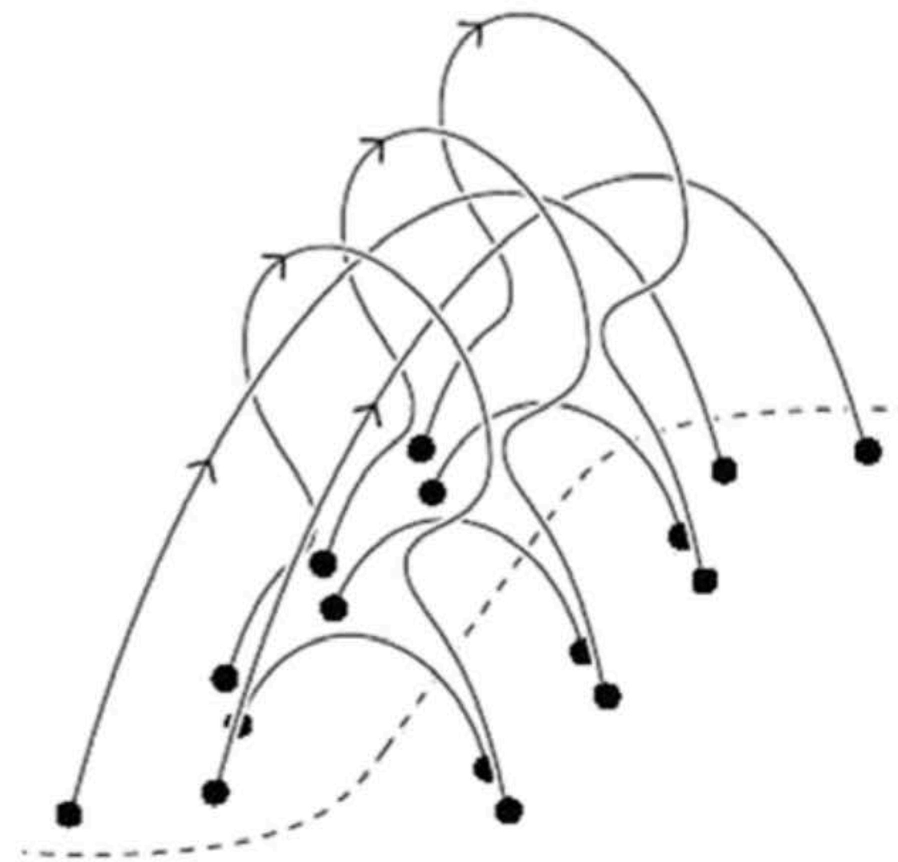

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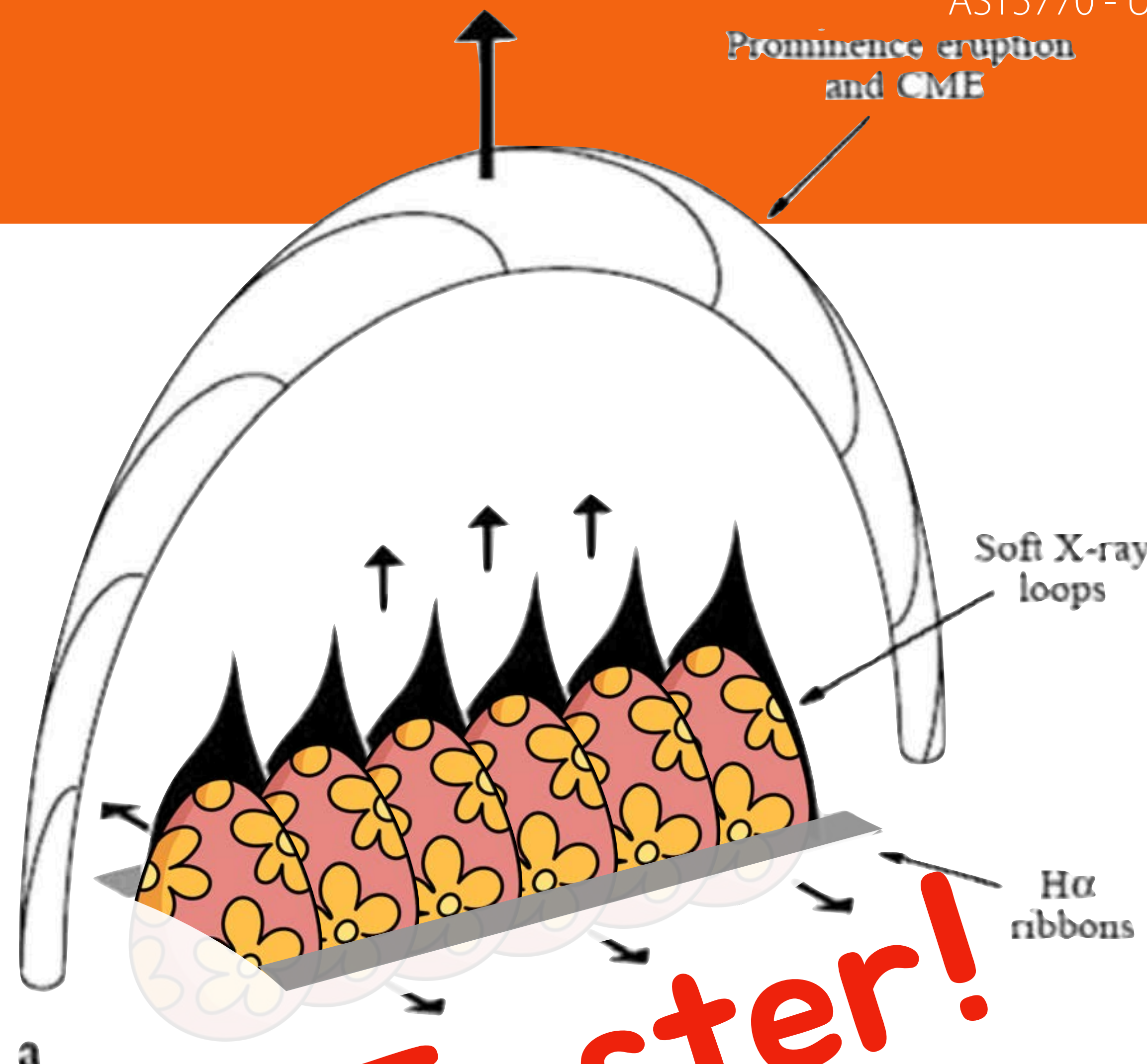

Happy Easter!