AST5770
Solar and stellar physics

University of Oslo, 2022

Sven Wedemeyer

Assignment #3

General feedback

Some "editorial" tips:

- Refer to figures as: *See Fig. 2 and Figs. 3-4. Figure 5 is another example.*
  (Different at the beginning of a sentence.)

- Abbreviations and acronyms should be introduced with their complete name on their <u>first appearance</u> in the main text.

- Be <u>precise</u> with usage of terms. For the final version: Read again critically word by word.

- Layout: Try to get the tables and figures to be placed at the top or bottom of a page with the [b] or [t] option.

- How to refer to information / code / data for which there is no reference?
  - Web address if available. Otherwise, refer to the person who provided that part as *"Name (priv. comm.)"*

- **Level of detail** in the descriptions depends on the overall focus of the analysis/study.
  - You may want to review and update your Data & Methods section after you are done with the results section (and maybe again after the conclusion section).

Assignment #3

General feedback

- **CO^{5}BOLD**

  - Equation of state and opacities are provided as pre-calculated look-up tables. Calculations of needed quantities for every grid cell and time step are replaced by simple interpolations in the provided tables. Saves computation time!

  - Radiative transfer only to get F_{rad} for the energy equation:

    - Frequency-dependence reduced to a few opacity bins (to save computation time)

    - Does produce Rosseland mean intensities but not more.

- **Spectrum synthesis**

  - Detailed intensities for continua /spectral lines are calculated in <u>separate second</u> step!

  - Used: Linfor3D: Steffen et al. Linfor3D User Manual. http://www.aip.de/mst/Linfor3D/linfor_3D_manual.pdf, 2010.

  - You do not need to read the manual or go into much detail!

  - Summary: CO^{5}BOLD model cubes as input for Linfor3D

    - Linfor3D calculates all quantities needed for radiative transfer (opacities, source function, …)

    - Formal solution of the radiative transfer equation in LTE along rays through the 3D box at wanted inclination angle (here from top only) —> intensities

- **Optical depth** depends on wavelength (or using Rosseland mean opacities?) — Please specify.

Assignement #4

- **Group class** on Wednesday with Aditi!

  - Work on your analysis - ask and discuss as a group

  - Share tips & tricks

  - Use this opportunity!

- **During your analysis until April 20:**

  - Do you gather enough material for your results section?

  - If not:

    - Do you go sufficiently into depth?

    - Any directions in which you could extend your analysis in a meaningful way relevant for your science question? (Remember: You can update all parts incl. the science question.)

      - Ask for inspiration in the group session!

Energetic phenomena
in
Active Regions

Sunspots / Active Regions — Recap

- Strong magnetic fields have important impact on the occurrence of surface convection, related energy transport, and atmospheric structure/stratification

 - Consequences notable in oscillatory and dynamic behaviour
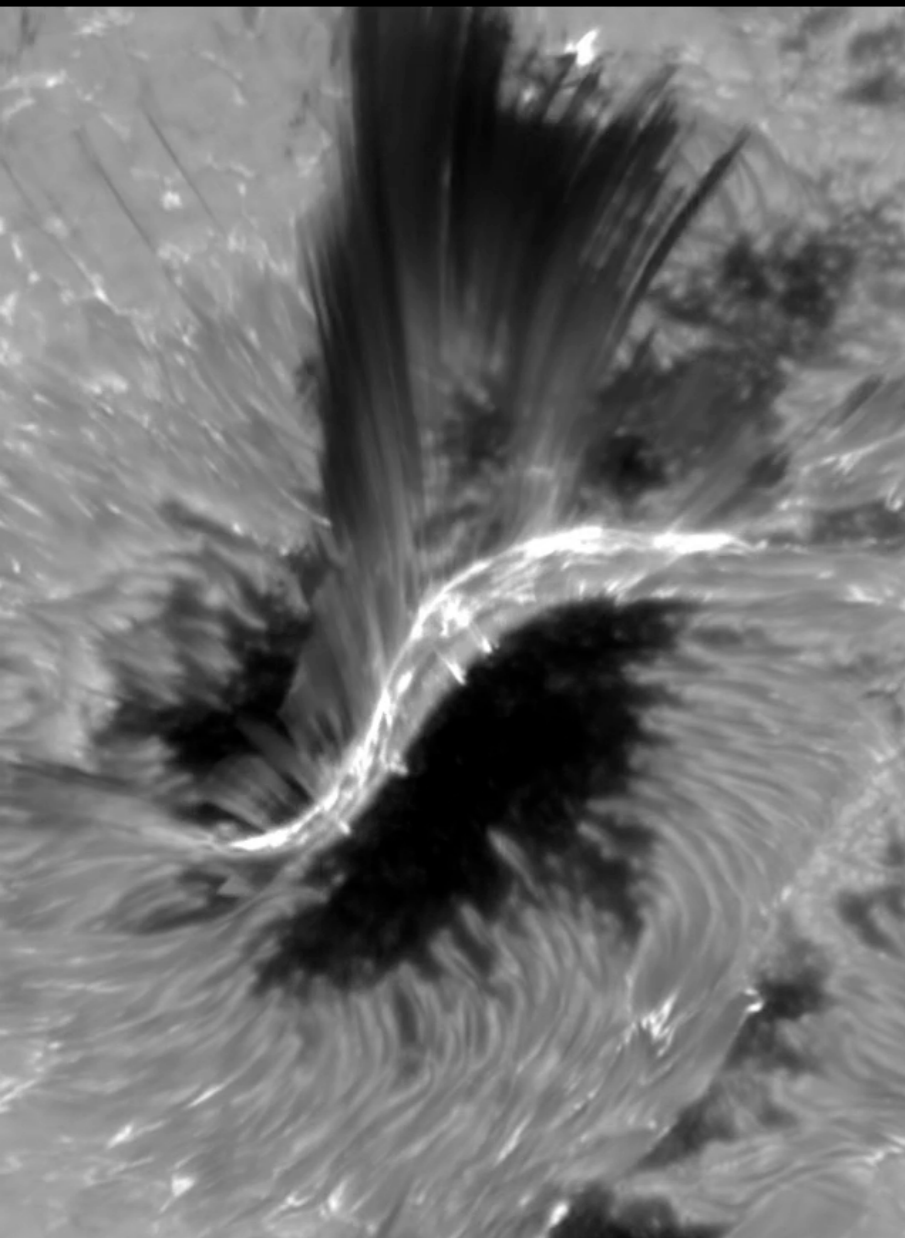
- Magnetic reconnection can occur in different situations

  - Sets free large amounts of energy

  - Source for a range of dynamic phenomena (Ellerman bombs, surges, flares, …)

  - Acceleration of plasma to high velocities (> 100 km/s)

Scharmer & Rouppe van der Voort
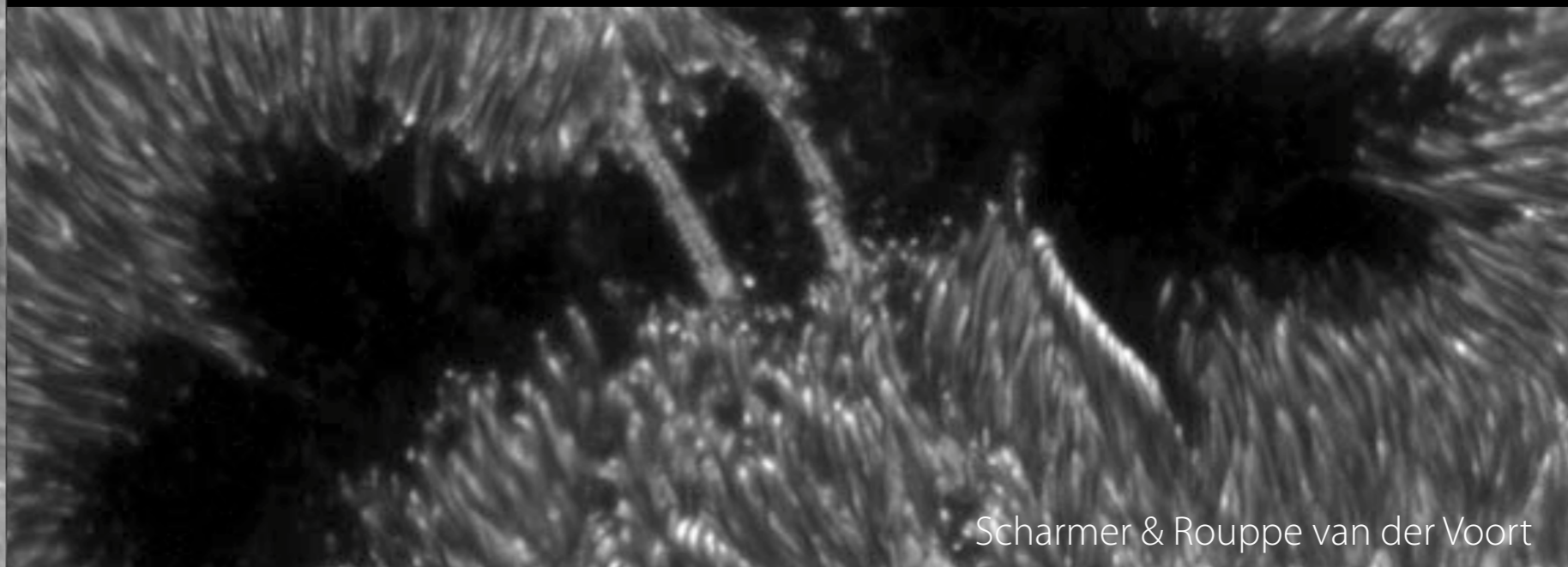
Sunspots / Active Regions — Jets

Small-scale surface motions and the twist in the solar jet

Example of jet observed with SDO/AIA and IRIS
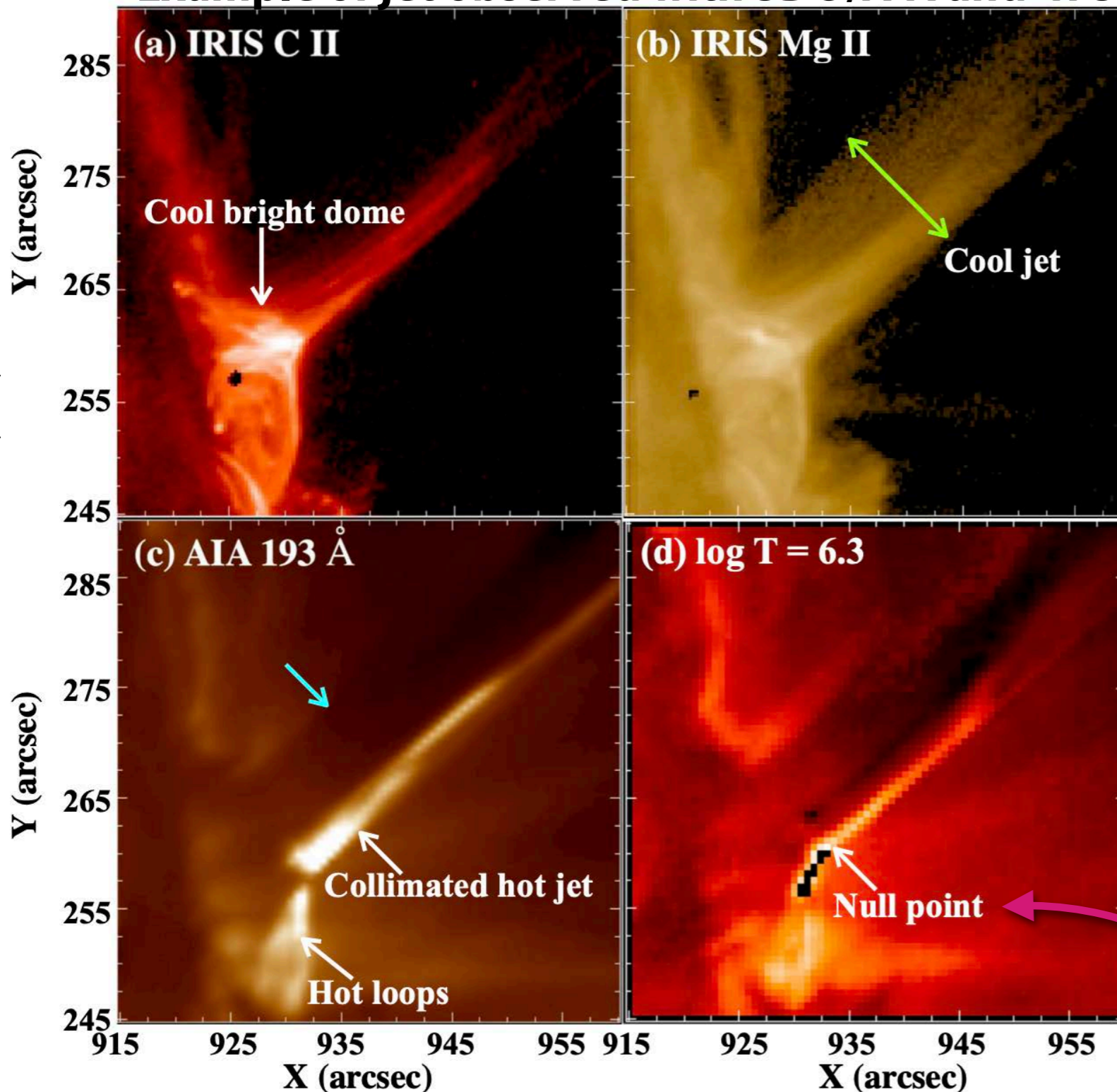
Joshi et al. (2020)

- Energy released by **magnetic reconnection**
  - Local Joule **heating** at reconnection site
    - ➡ Raises internal energy of plasma
  - Bulk **acceleration** of plasma away from reconnection site by magnetic tension force of newly formed field lines
    - ➡ Large kinetic energies
  - Strong electric fields at reconnection site **accelerate particles** to high velocities.
- Magnetic reconnection in **3D** different from 2D, complex!
  - *More later*

Sunspots / Active Regions — Jets

Small-scale surface motions and the twist in the solar jet

Joshi et al. (2020)
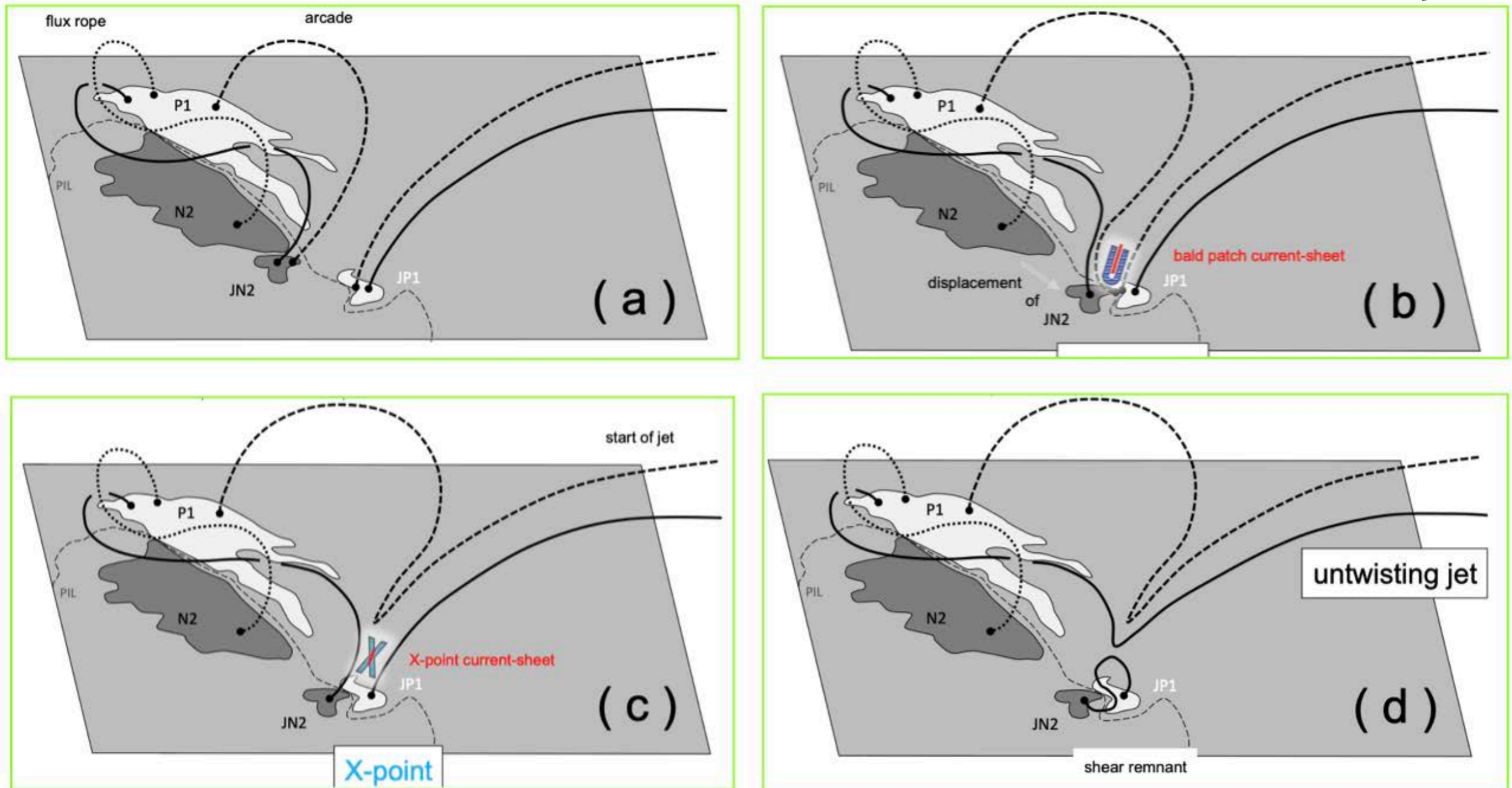
- Panel a: Magnetic configuration before the reconnection.
- Panel b: Formation of the bald patch current sheet.
- Panel c: X-point current sheet.
- Panel d: Untwisting jet after the reconnection and the remnant twist in the bipole.

Sunspots / Active Regions — Jets

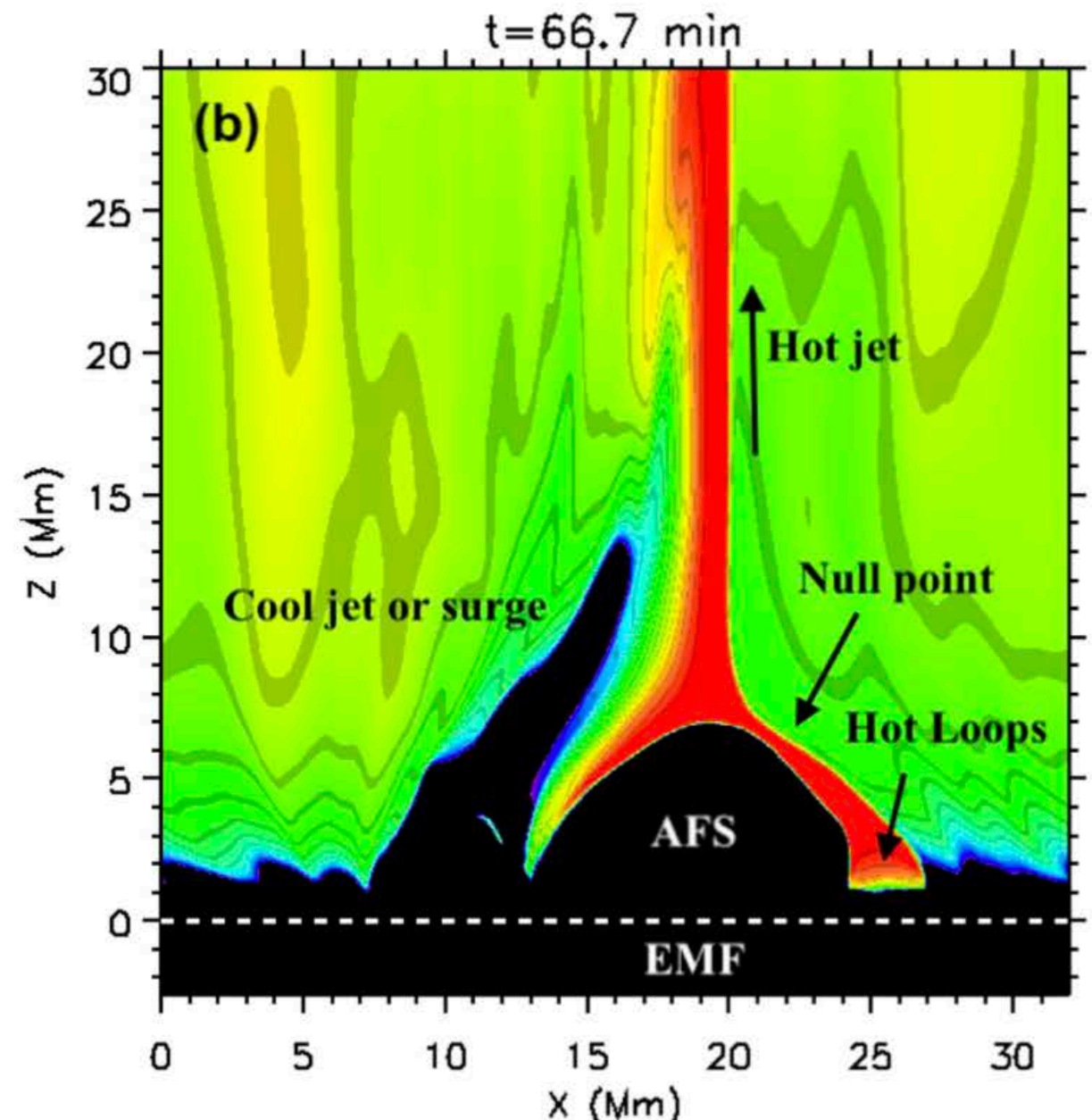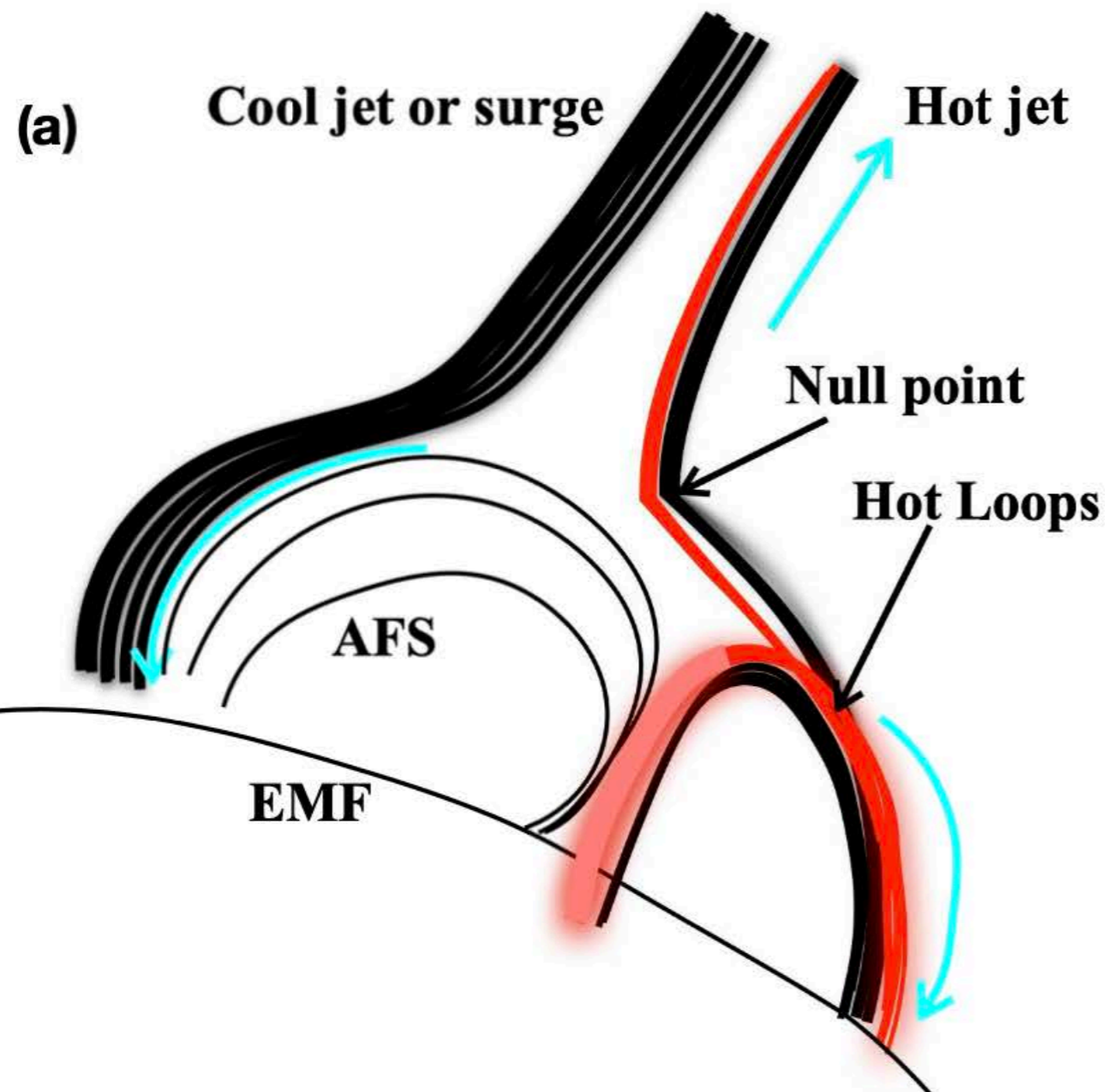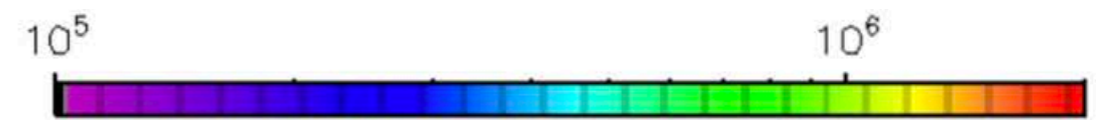## Small-scale surface motions and the twist in the solar jet

Joshi et al. (2020)

Schematic view of the 3D jet
derived from Moreno-Insertis et al. (2008)

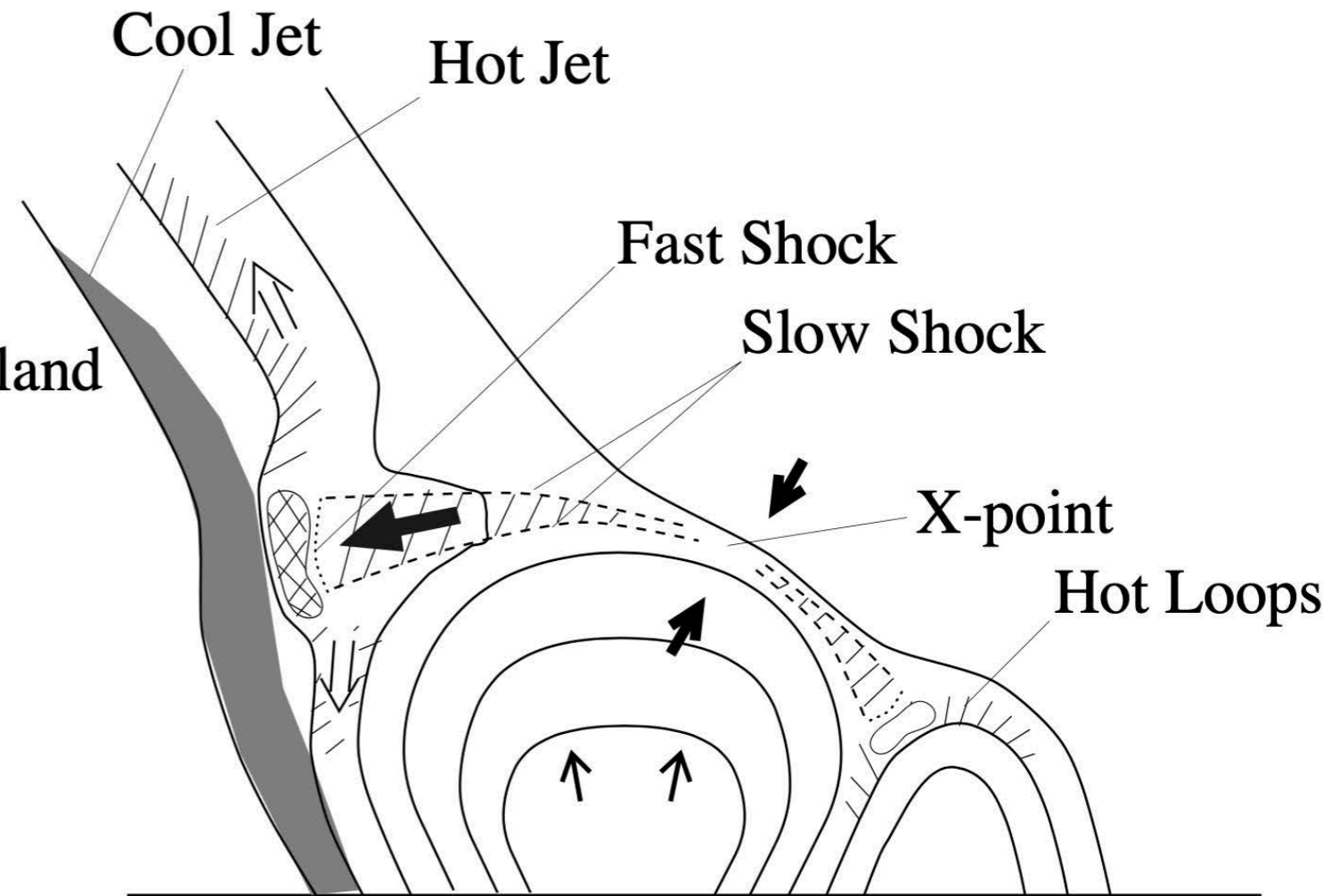**Numerical simulation (temperature)**
(Nóbrega-Siverio et al. 2017, 2018)

Sunspots / Active Regions — Jets
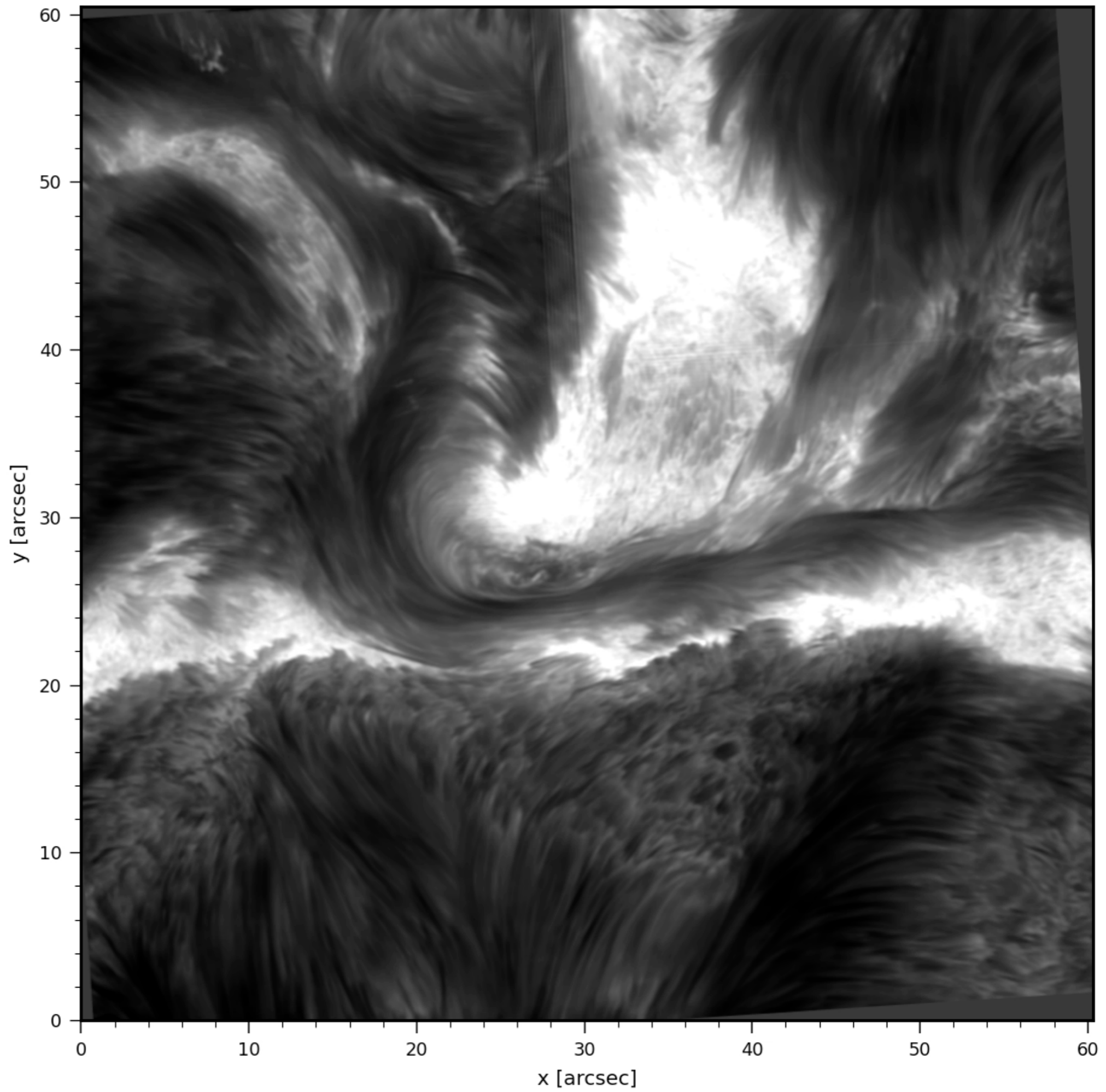
X-ray jets

Two sided-loop jet

Anemone-type jet

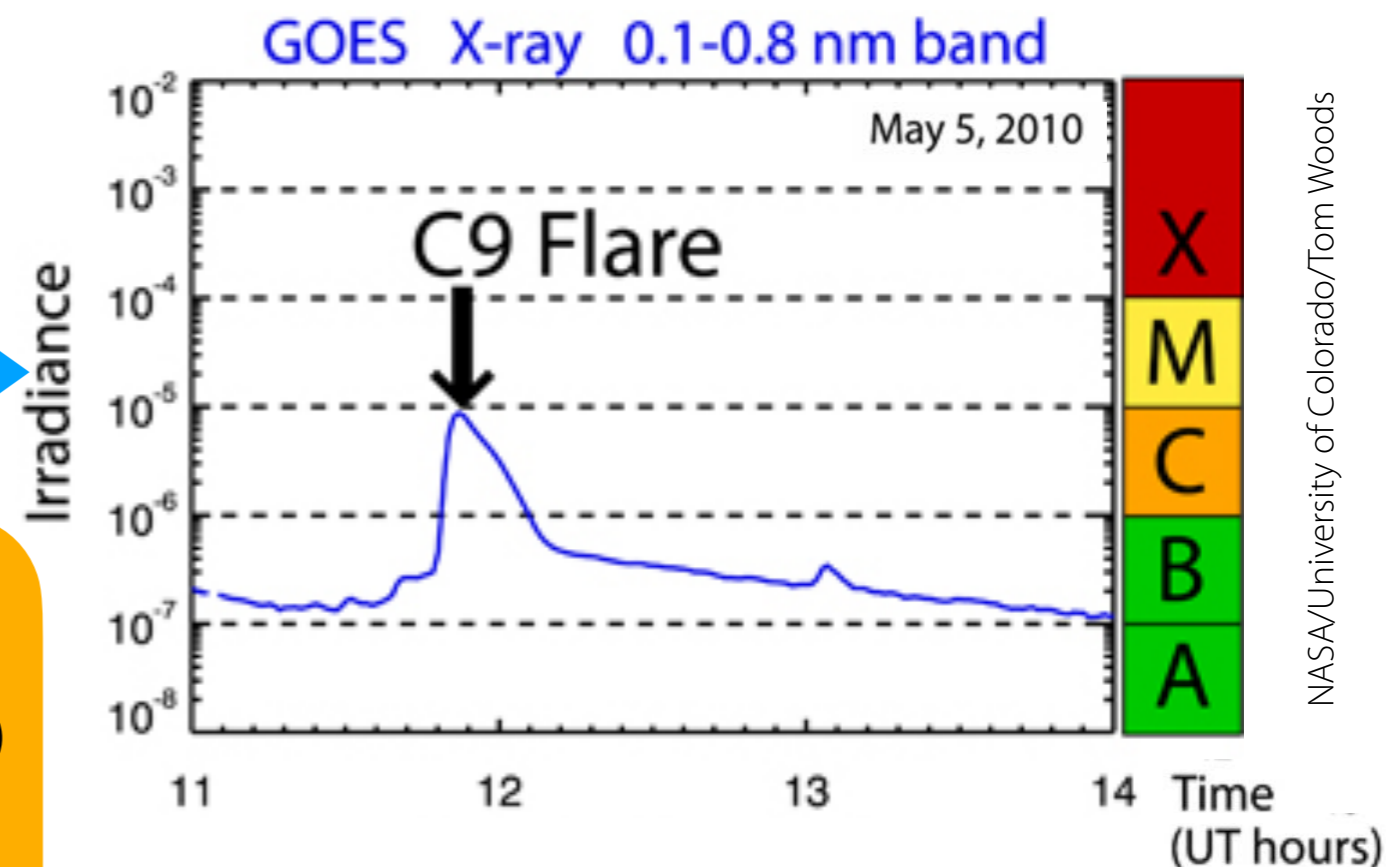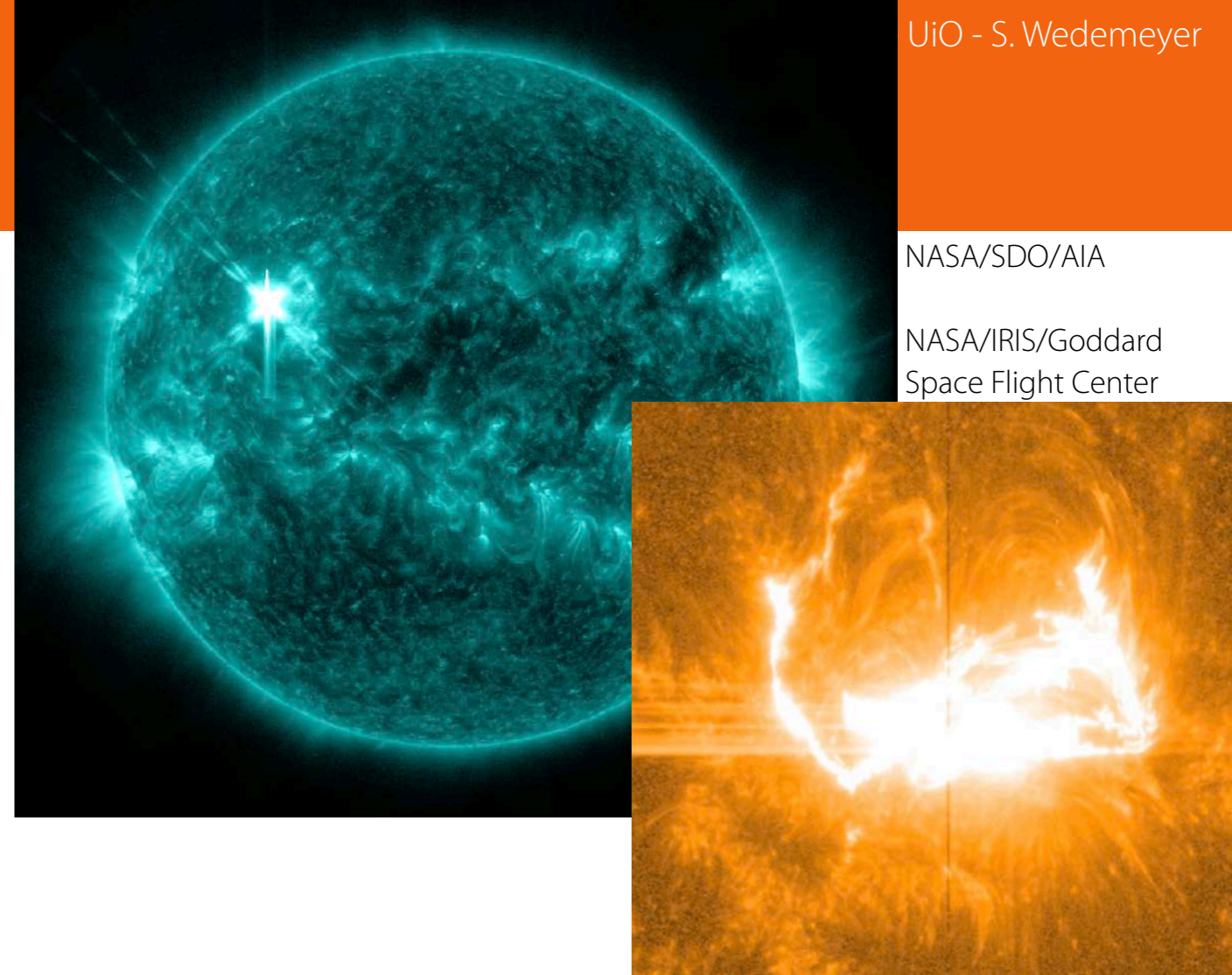Yokoyama and Shibata (1996)
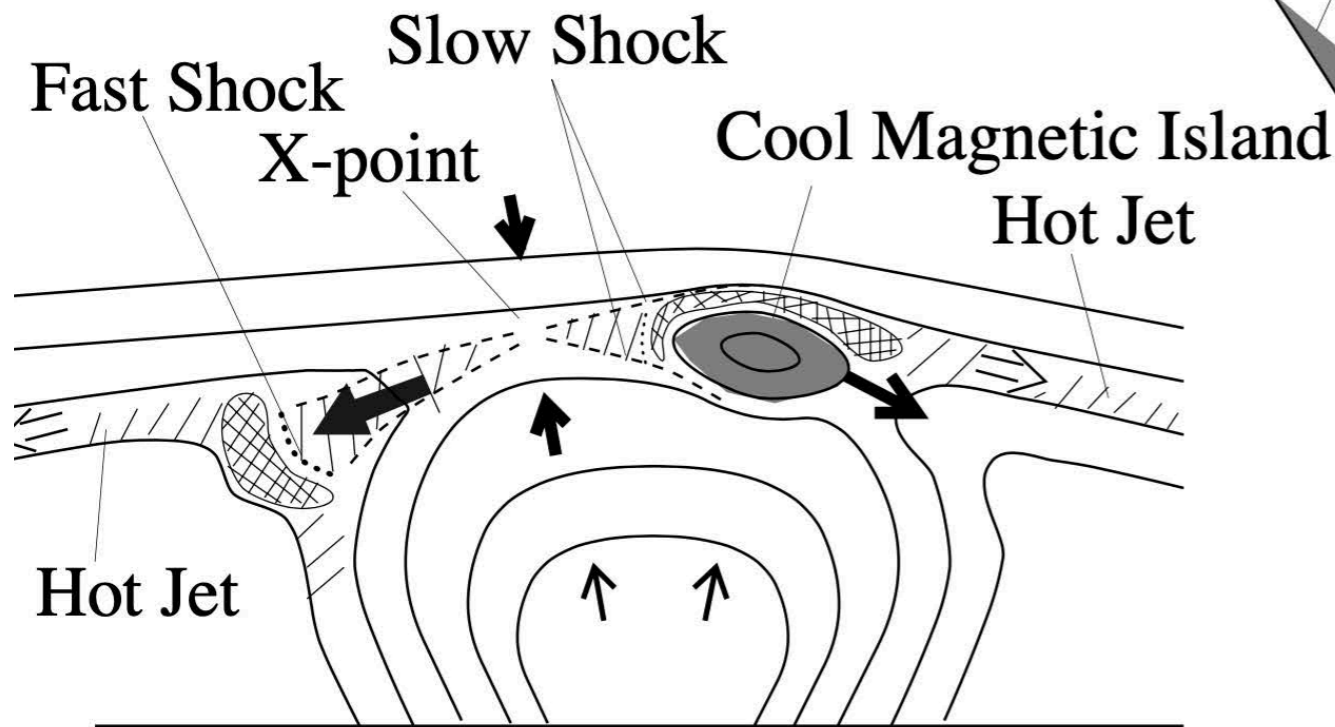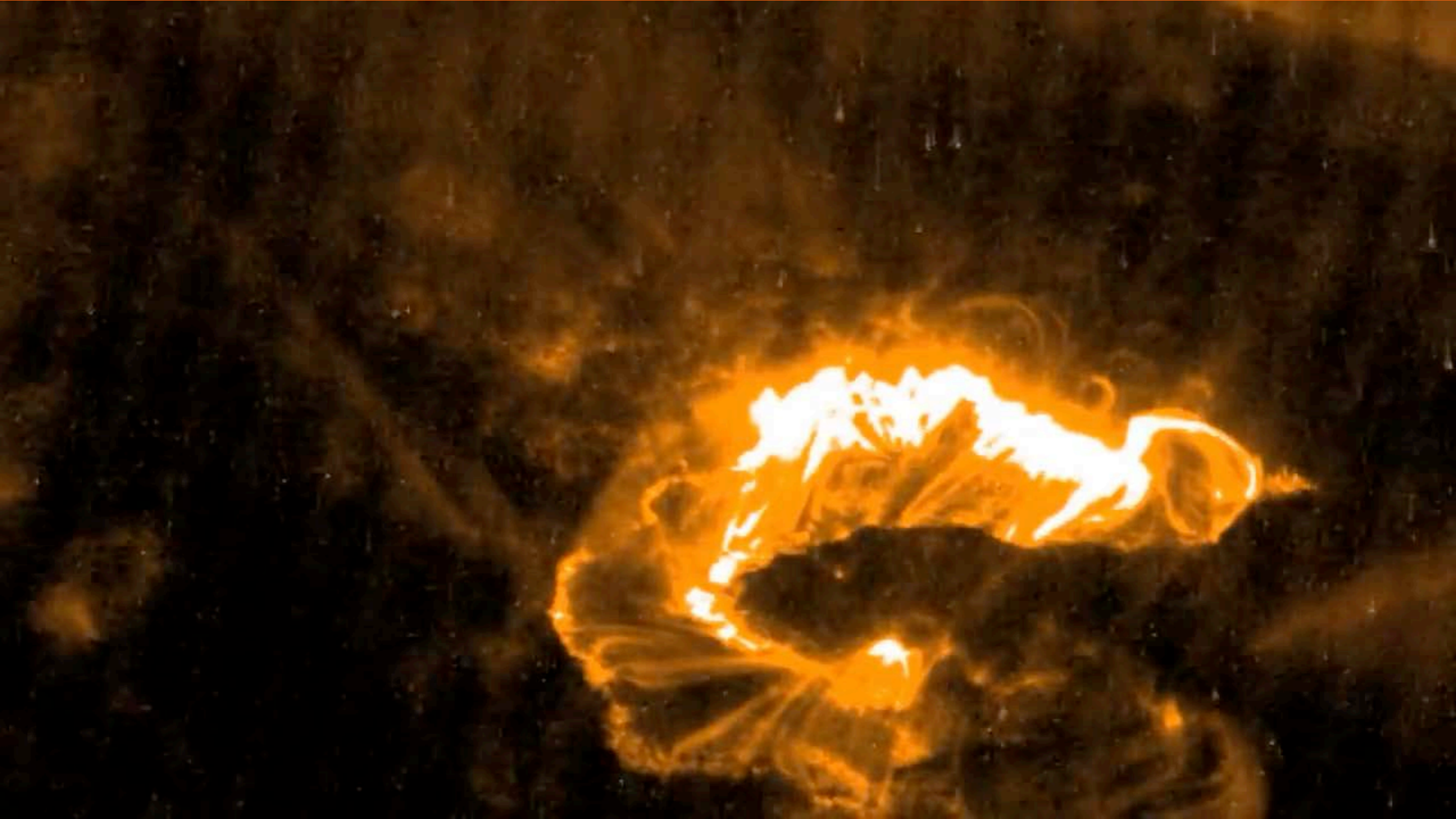
Solar flares

Ca II 8542 - 2021-10-28T15:30

Flares

Flares

Recap

- 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 < 10 Mm to 100 Mm
- Size correlates with flare duration (10^3-10^4 s) and amount of released energy

GOES X-ray 0.1-0.8 nm band

May 5, 2010

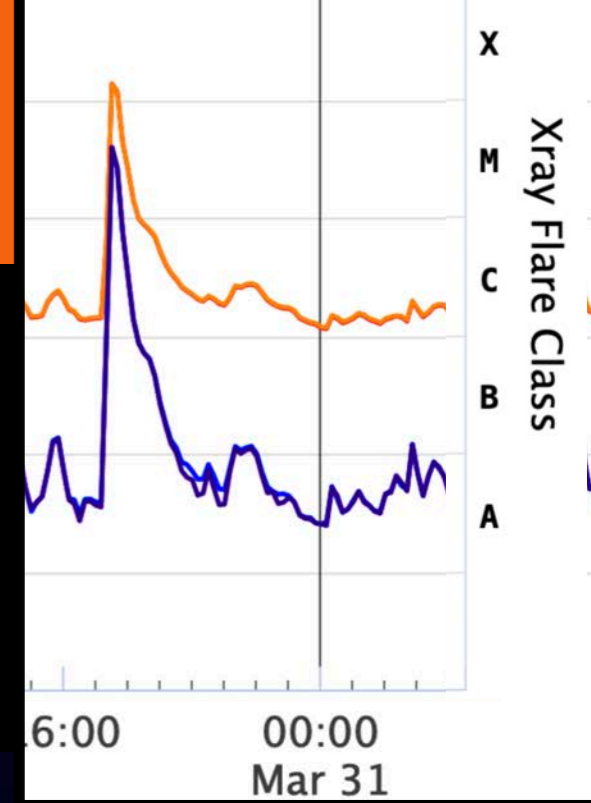Irradiance

C9 Flare

X M C B A

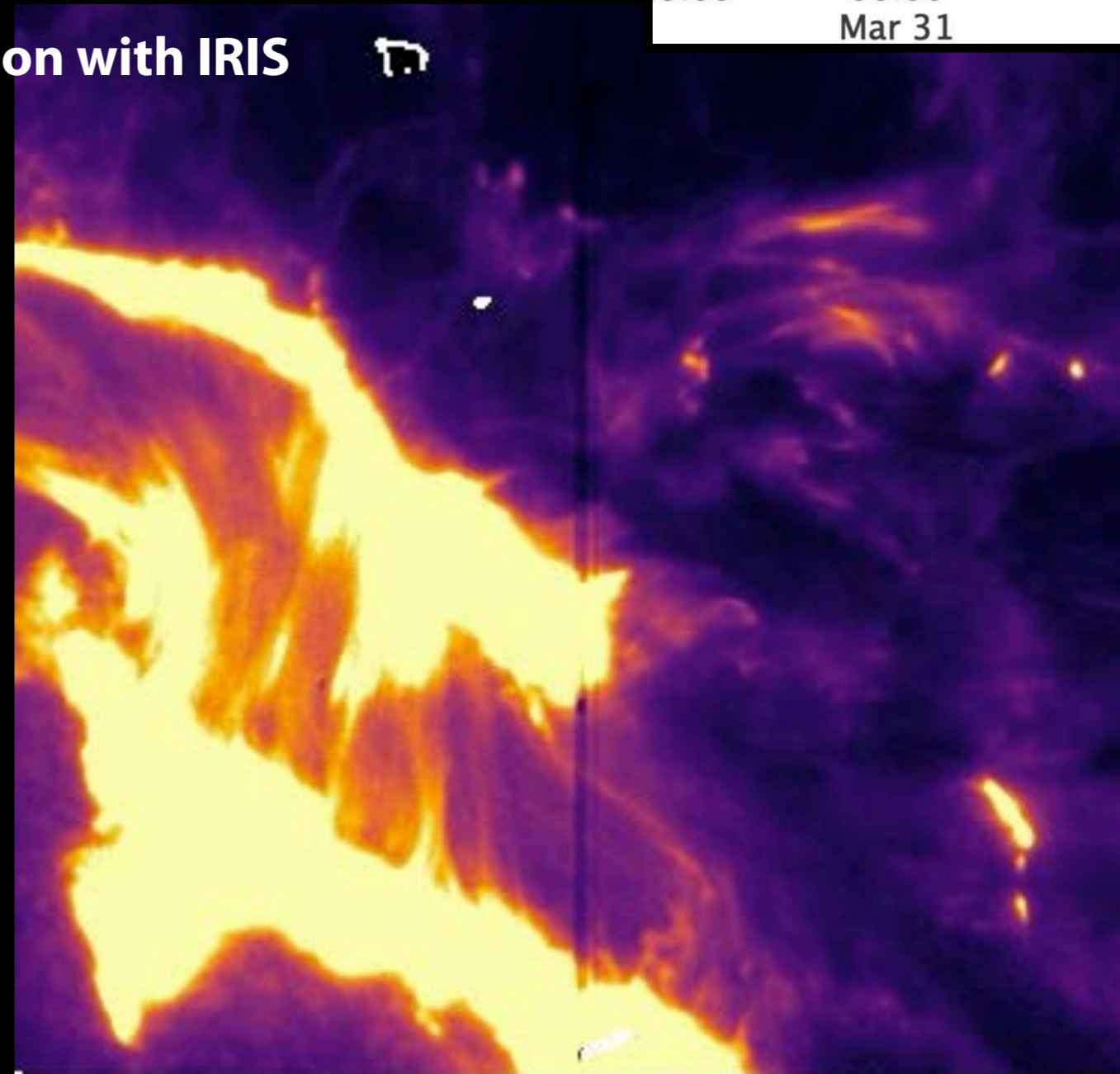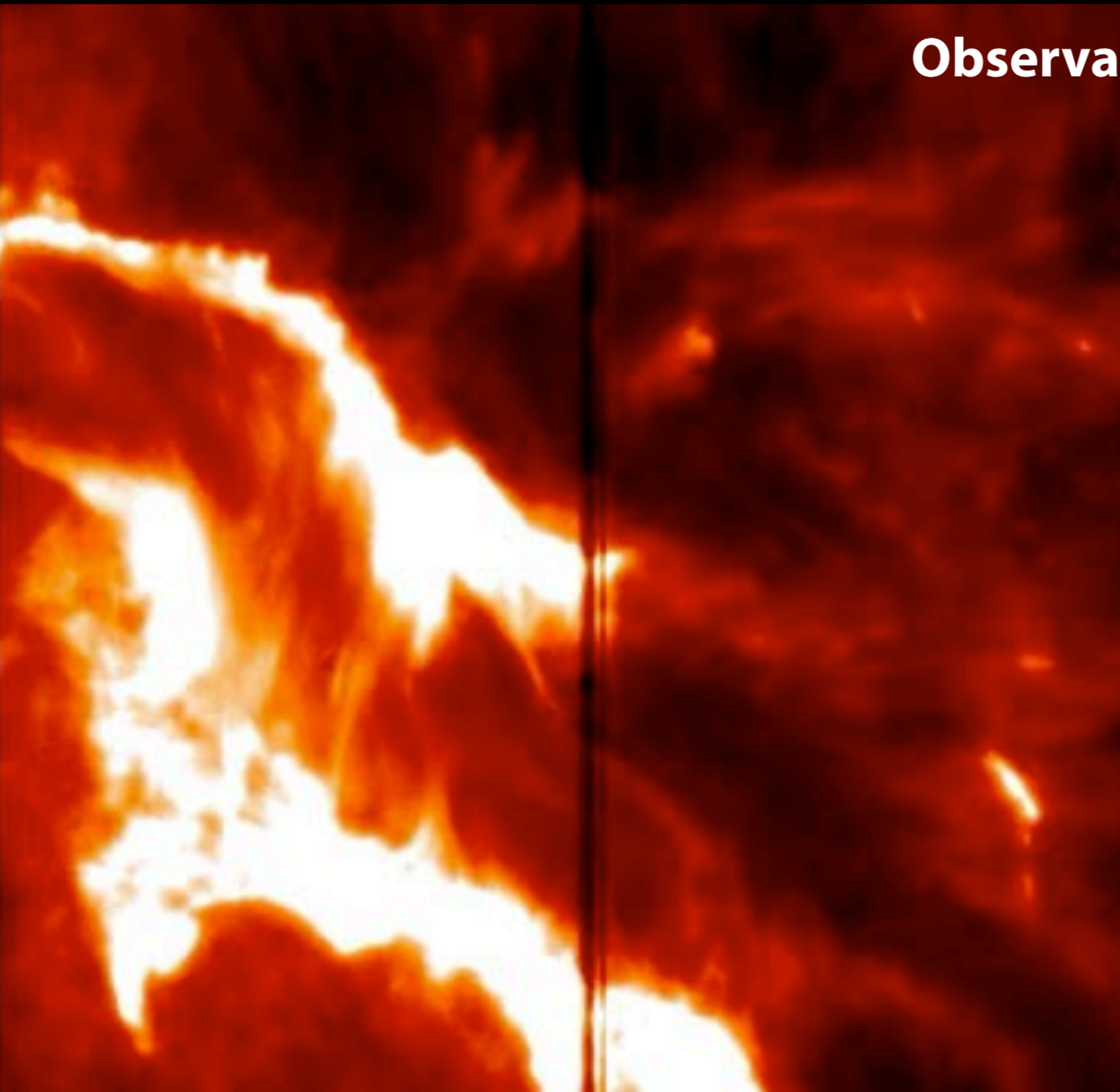11 12 13 14 Time (UT hours)

Flares

Flares

Breaking News!

- Flare on March 30, 2022, 17:40UT — AR12975
- X1 class flare
- Check it out in jhelioviewer!

Observation with IRIS

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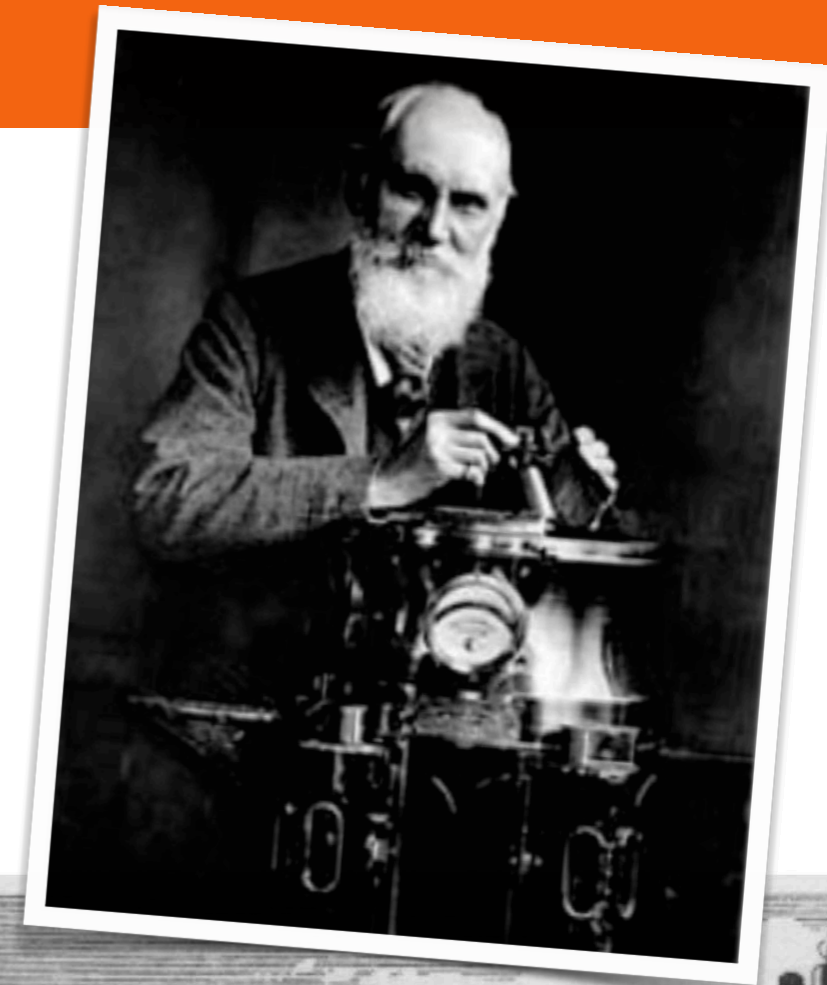
Richard Carrington built this manor house with an adjoining observatory Redhill, Surrey. It was from here that he witnessed the solar flare. (Ima Royal Astronomical Society)

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

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
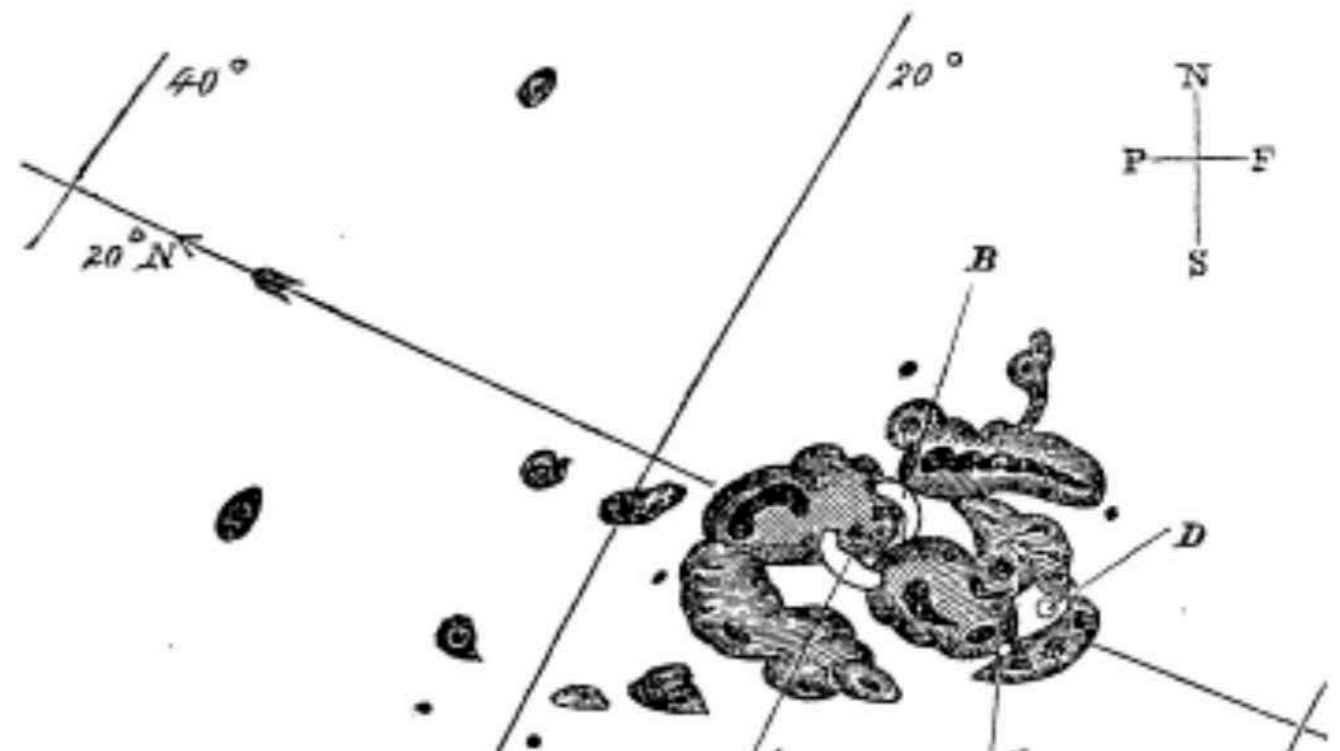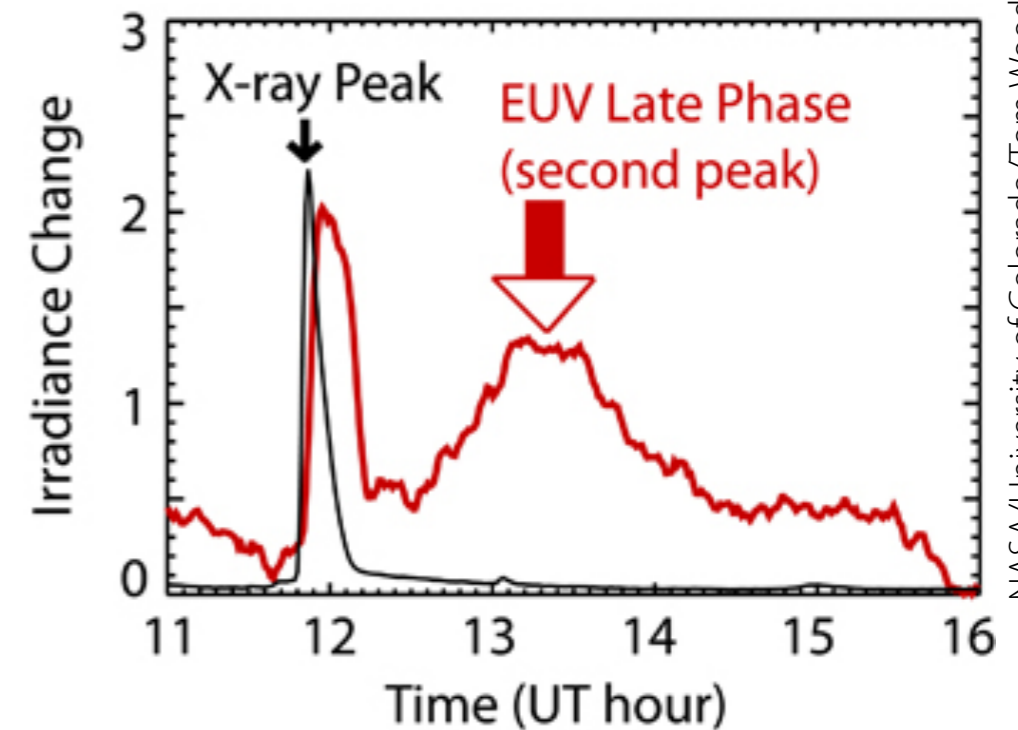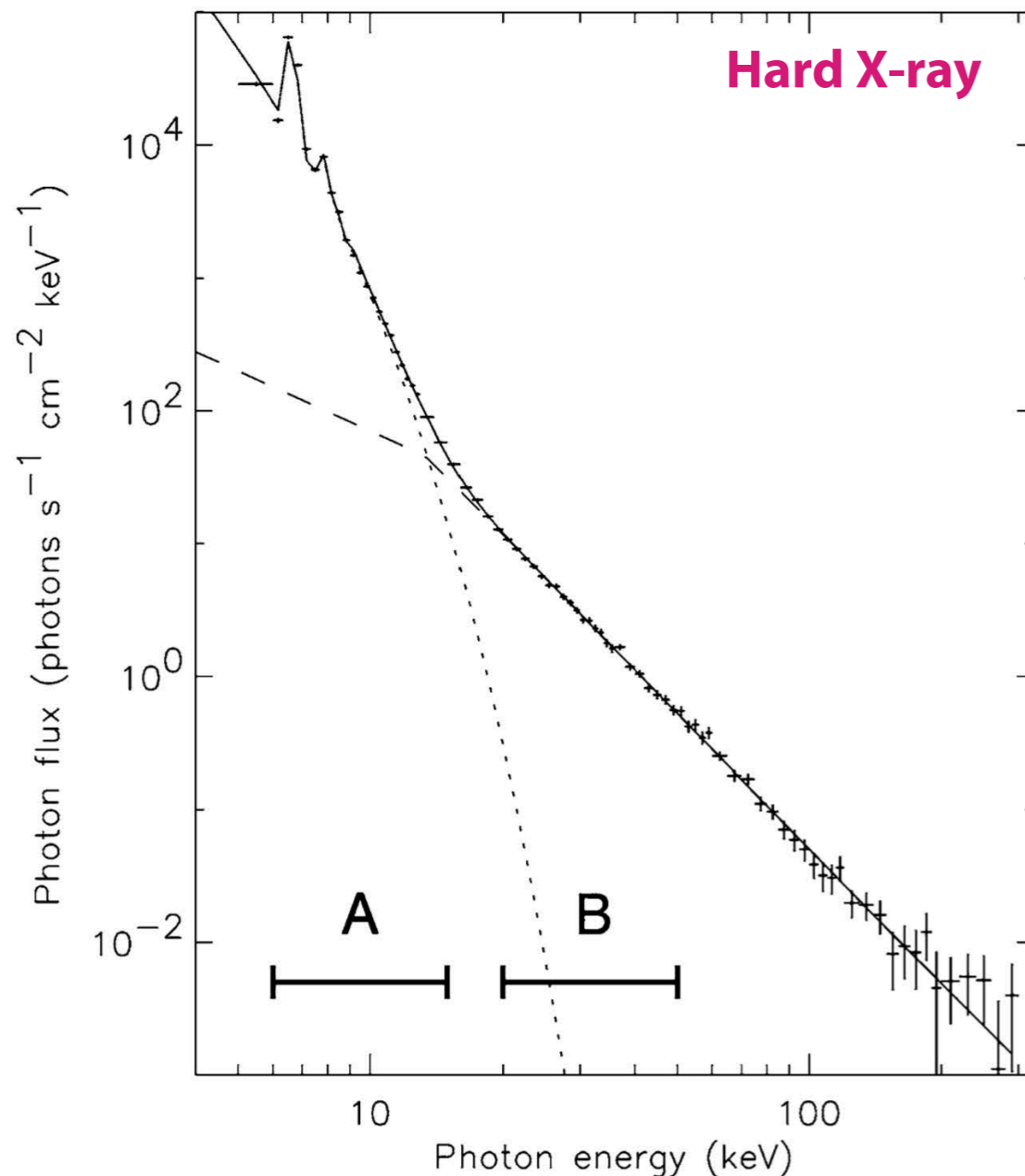

A one-time event?
➡ *Arctic/Antarctic ice cores indicate that **flares of similar strength on avg. occur once in a century.***
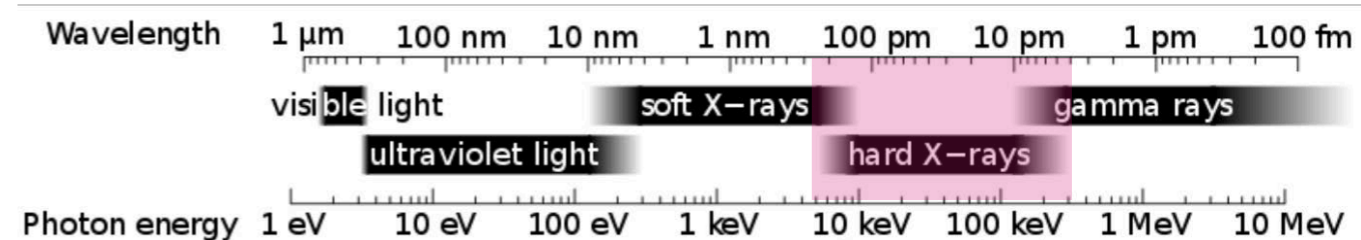
Flares

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

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
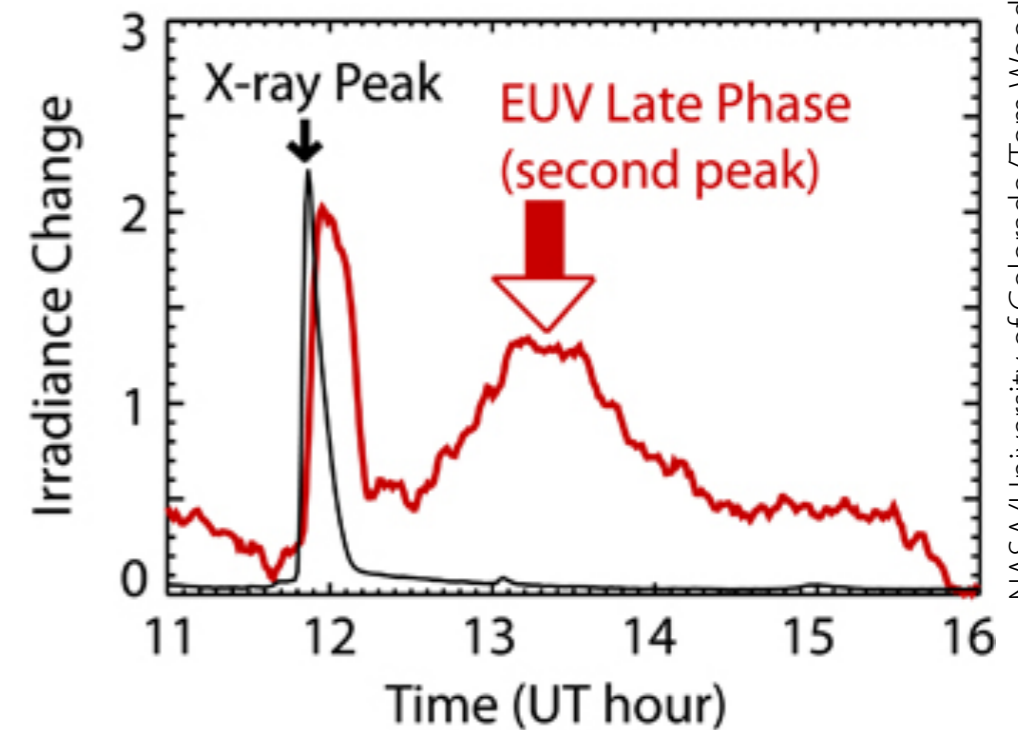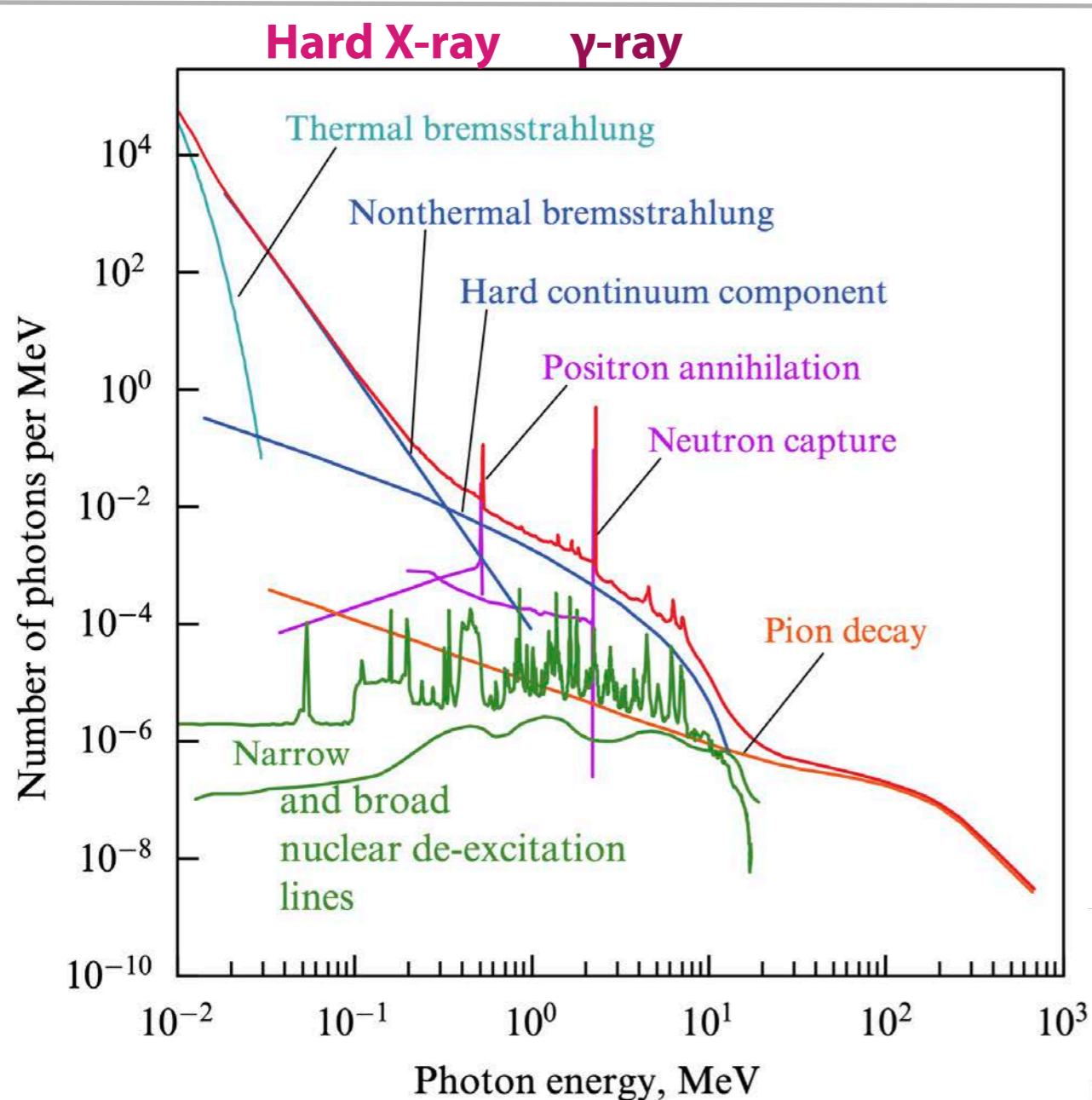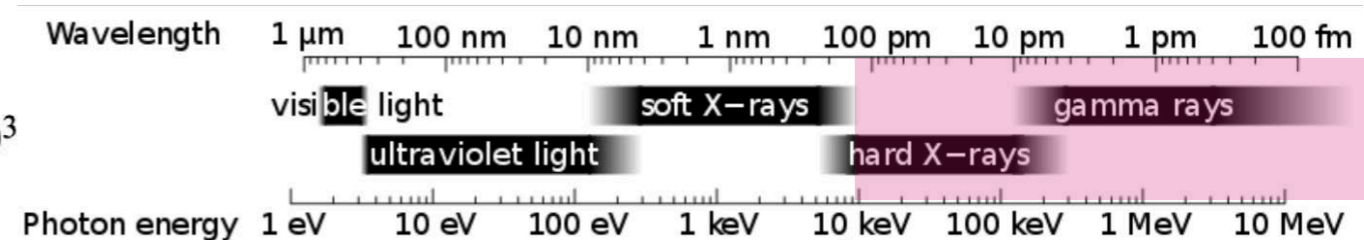

NASA/University of Colorado/Tom Woods

Hard X-ray   γ-ray
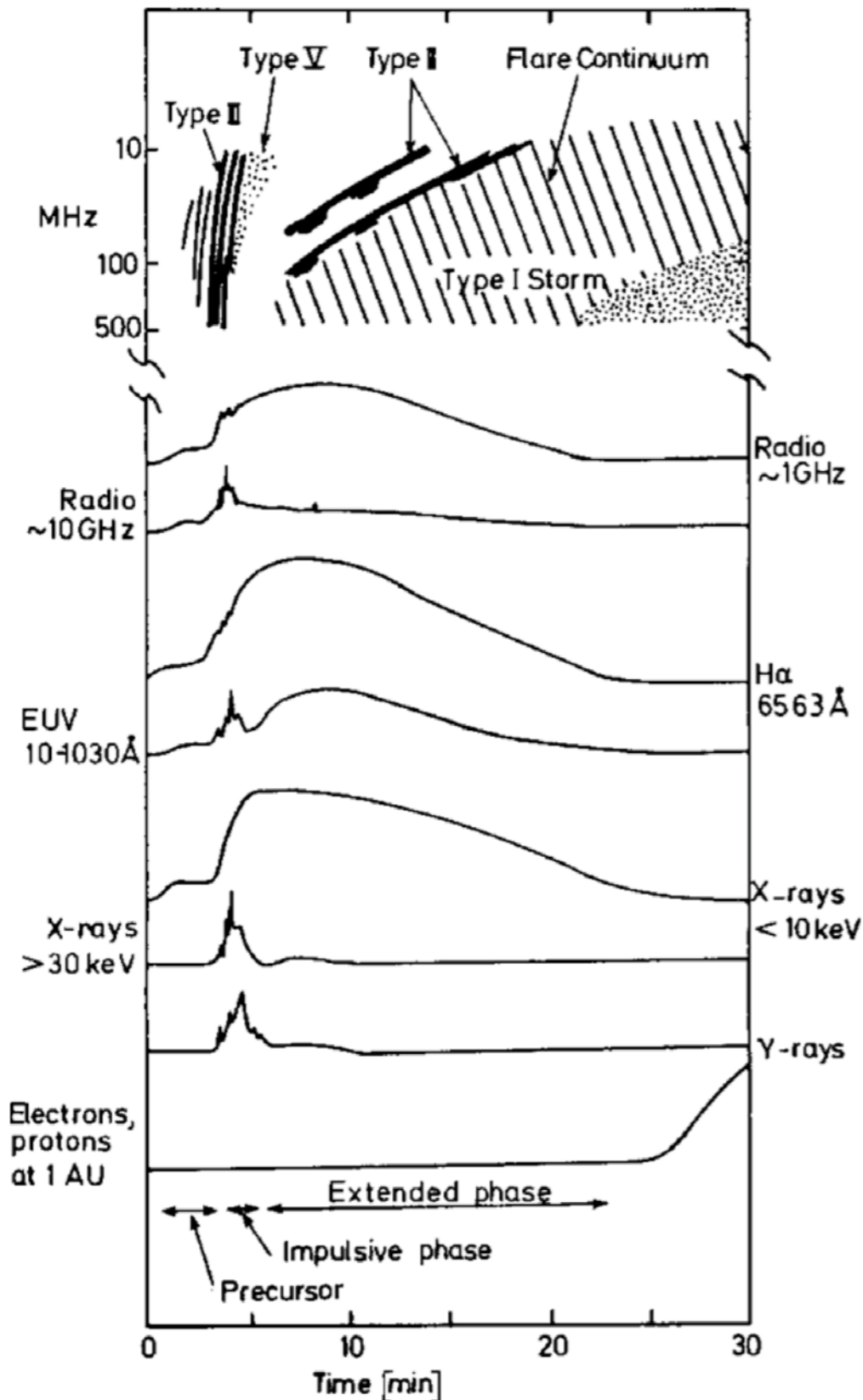

Murphy/Lysenko et al. (2020)

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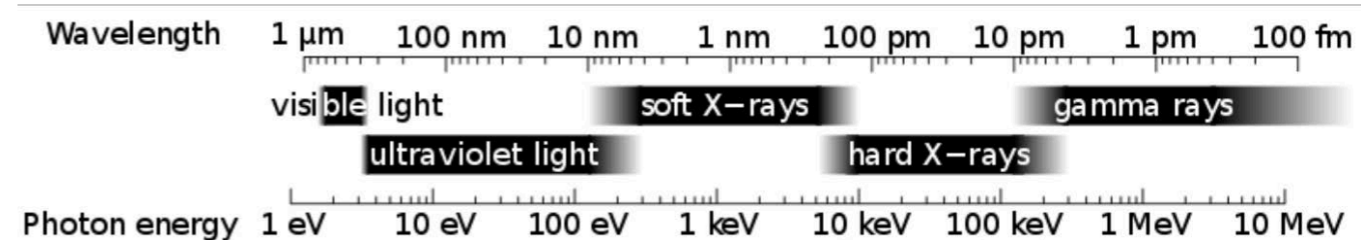- Non-thermal radiation due to highly energetic particles (radio, hard X- ray, γ-rays)

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

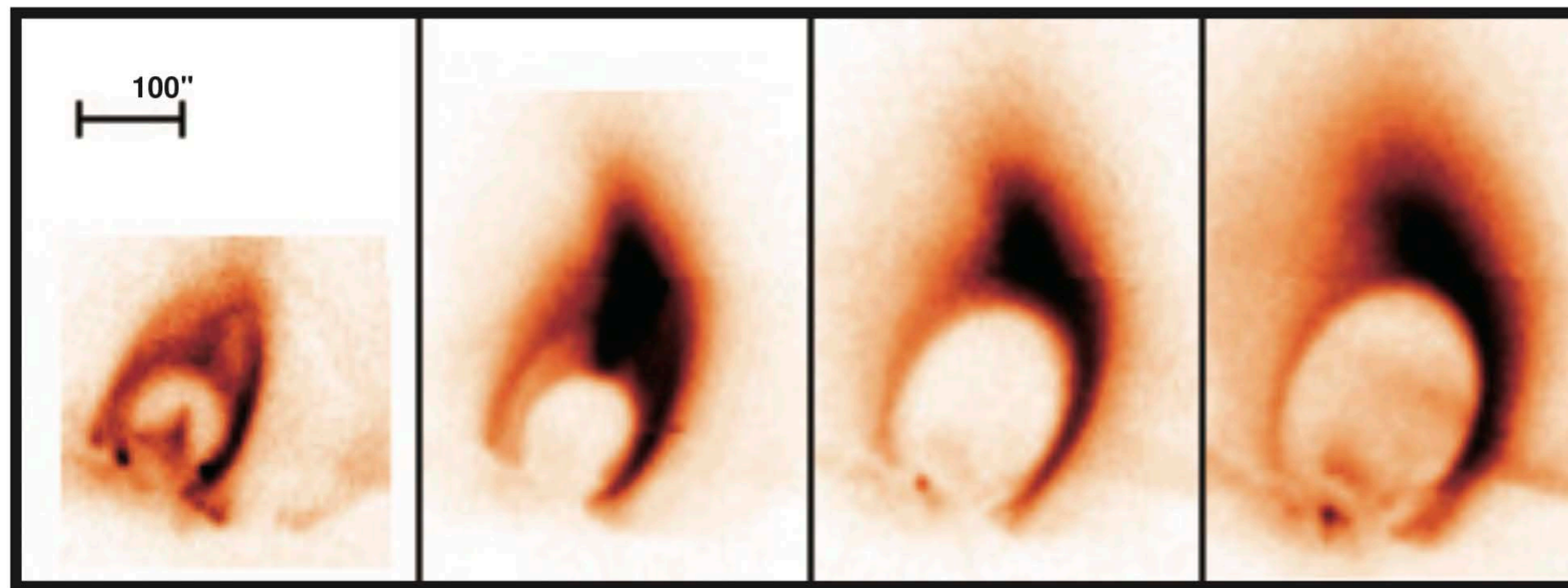➡ Constraints for the physical mechanism behind flares

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)**

21-FEB-1992 Flare   SXT Image   Filter : Al.1

100"

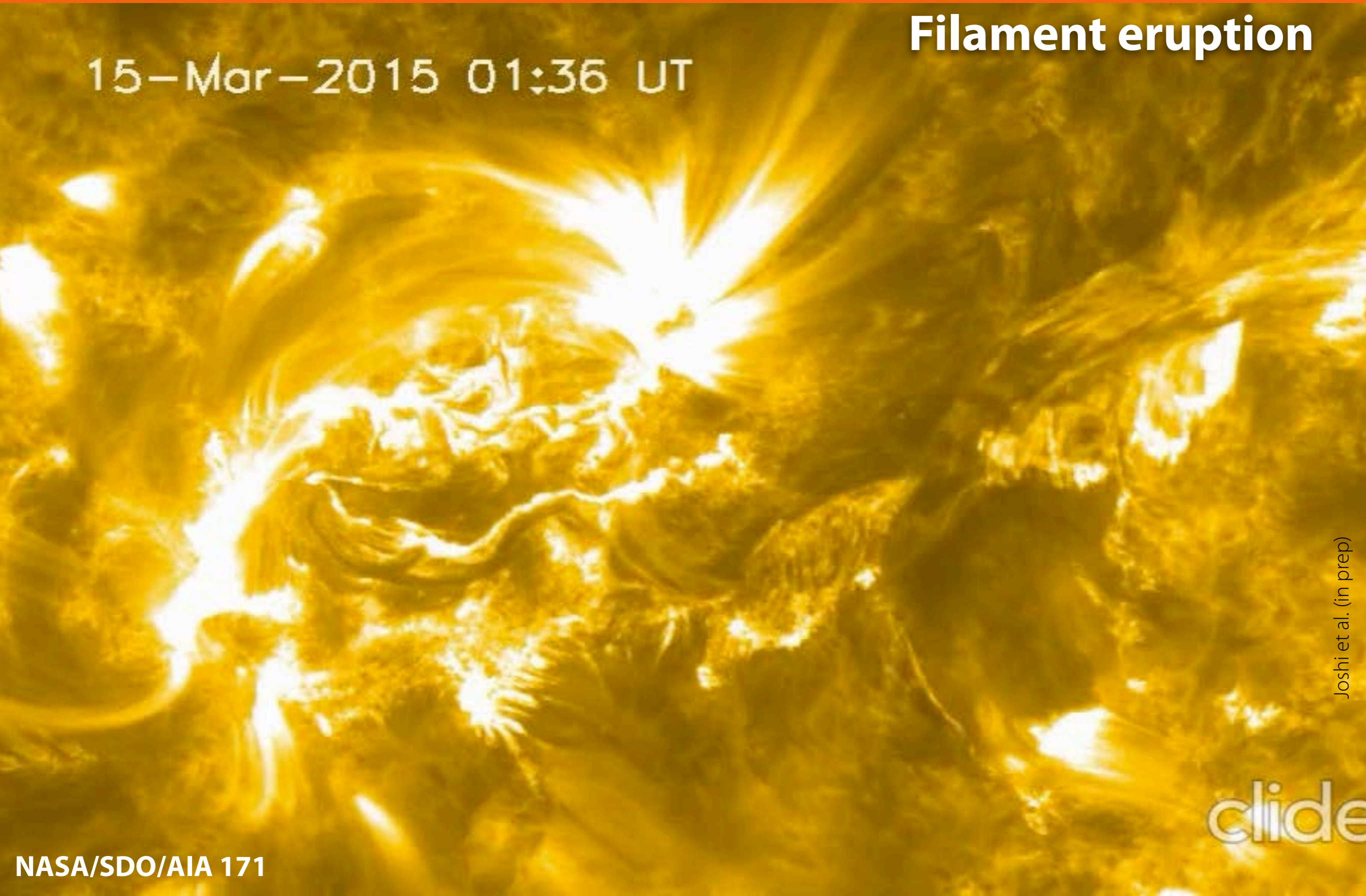03:10:30 UT   04:52:22 UT   06:35:30 UT   09:06:42 UT

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
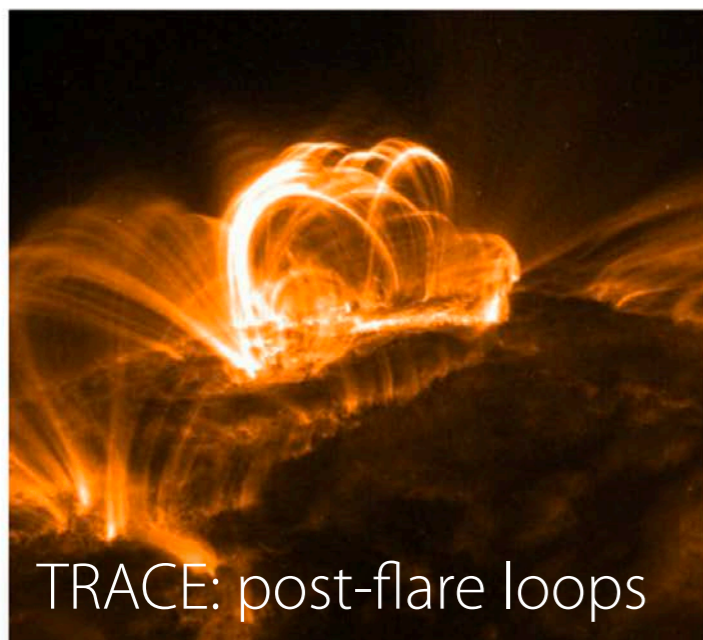

TRACE: post-flare loops

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 $(T = 10^6 \text{K})$

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

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

Flares

Towards a physical model

Observations so far:

- Substantial brightening 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

- 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

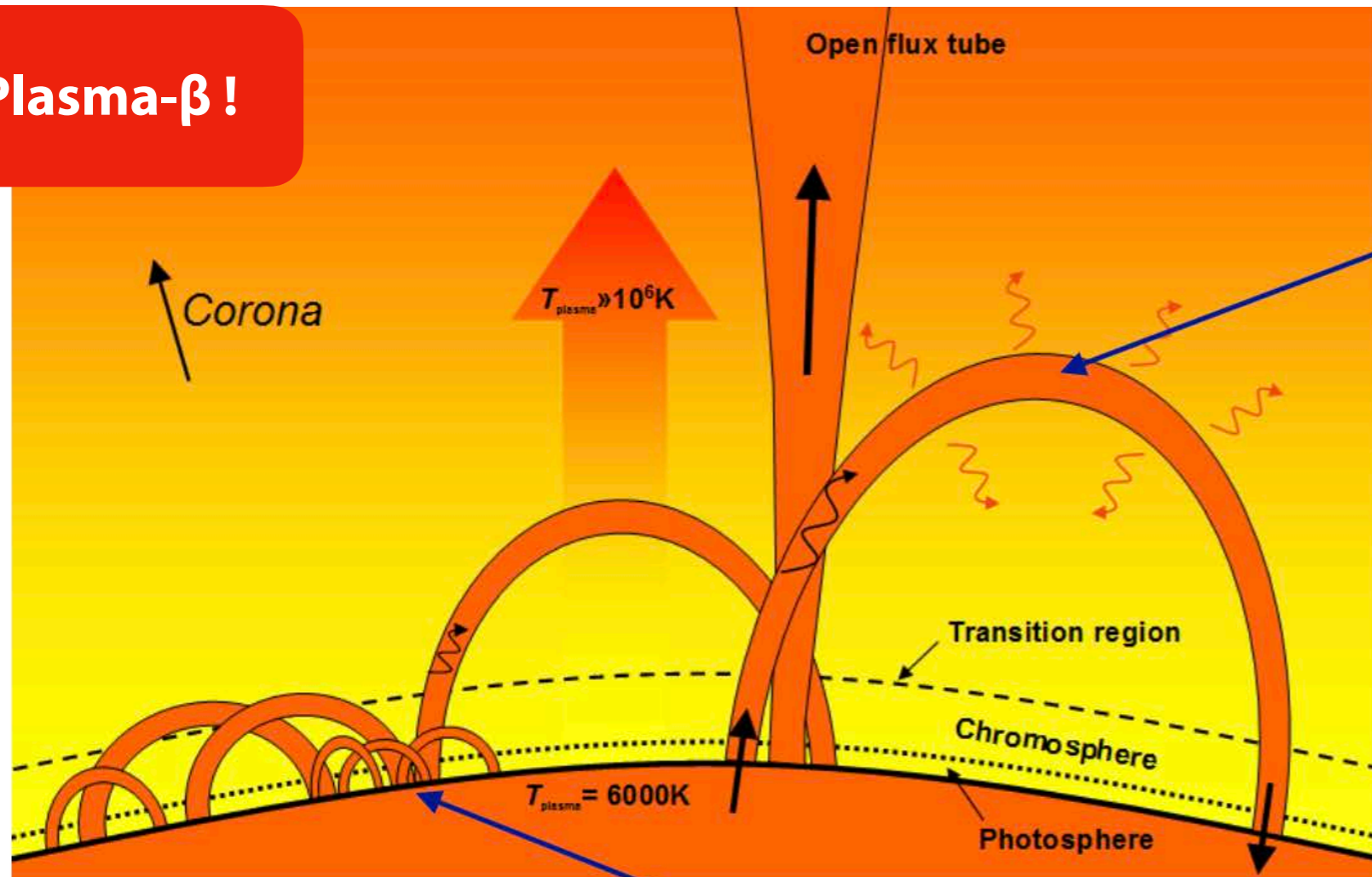 - Only sufficient energy source is energy stored in strong magnetic fields.
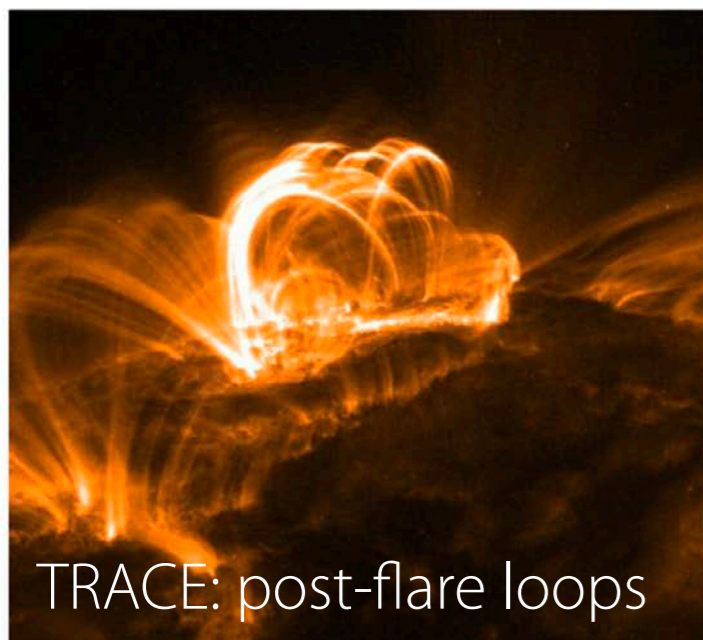
➡ **Magnetic reconnection.**

Flares

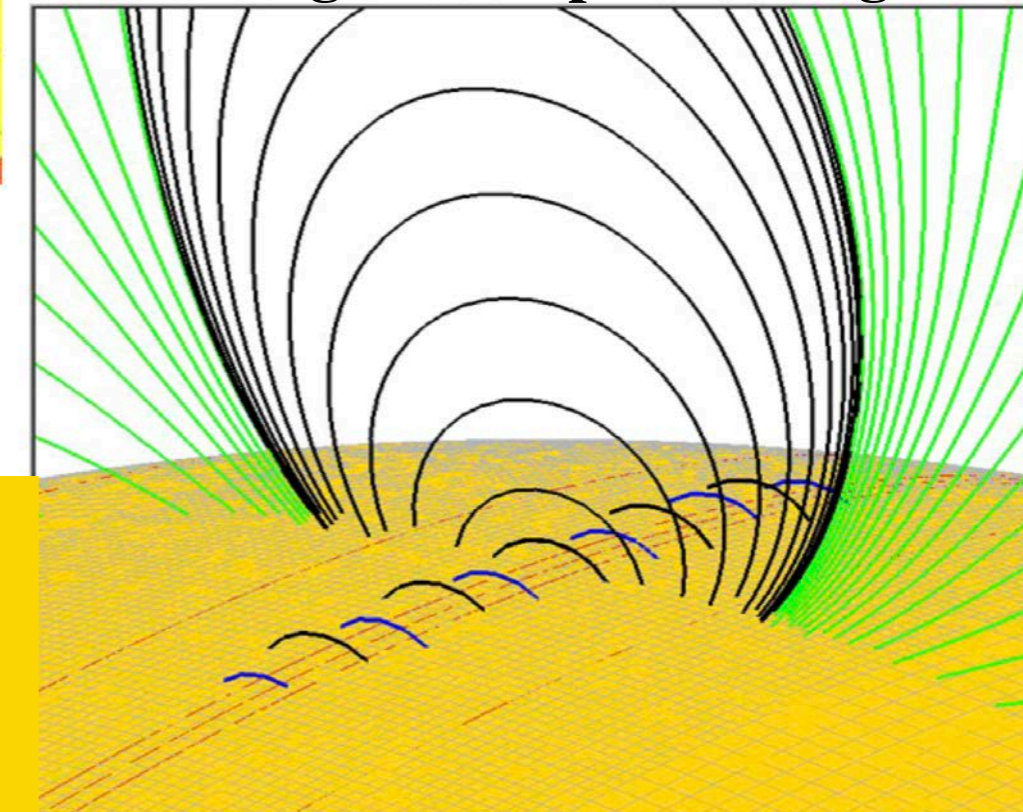## Towards a physical model — Storing energy in the magnetic field

Plasma-β !

Open flux tube

Corona

$T_{plasma} \gg 10^6$K

$T_{plasma} = 6000$K

Transition region

Chromosphere

Photosphere

Corona:

Plasma-β << 1: Magnetic force control field shape, gas flow constrained by field.
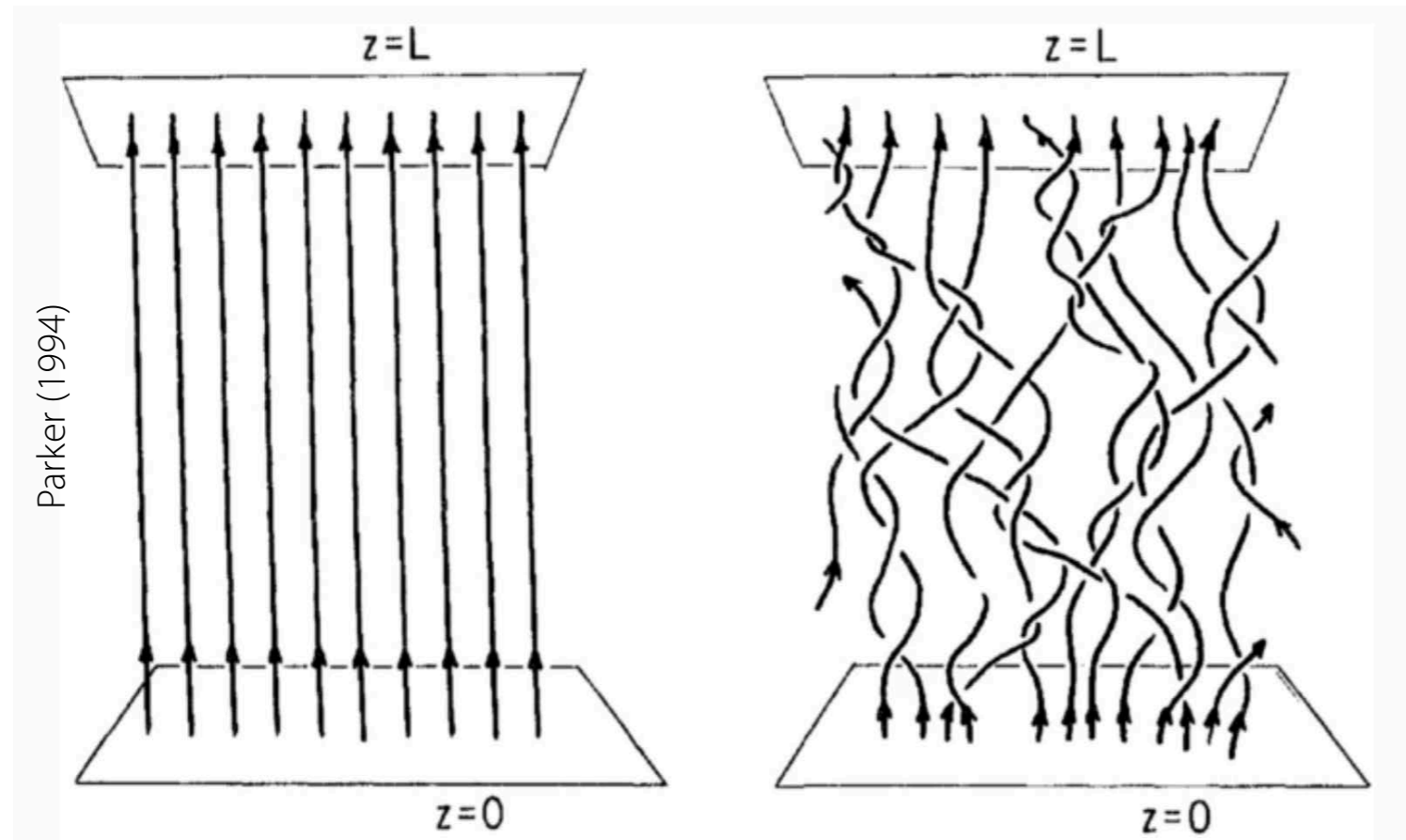
Flux emergence vs. pre-existing field

Photosphere:

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

- 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

Parker (1994)

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

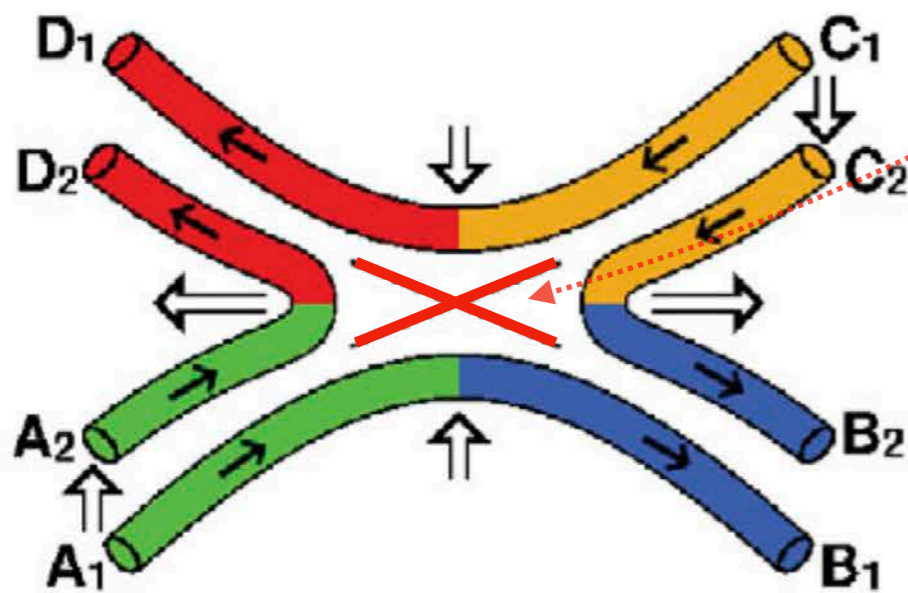   - Enables much faster energy release
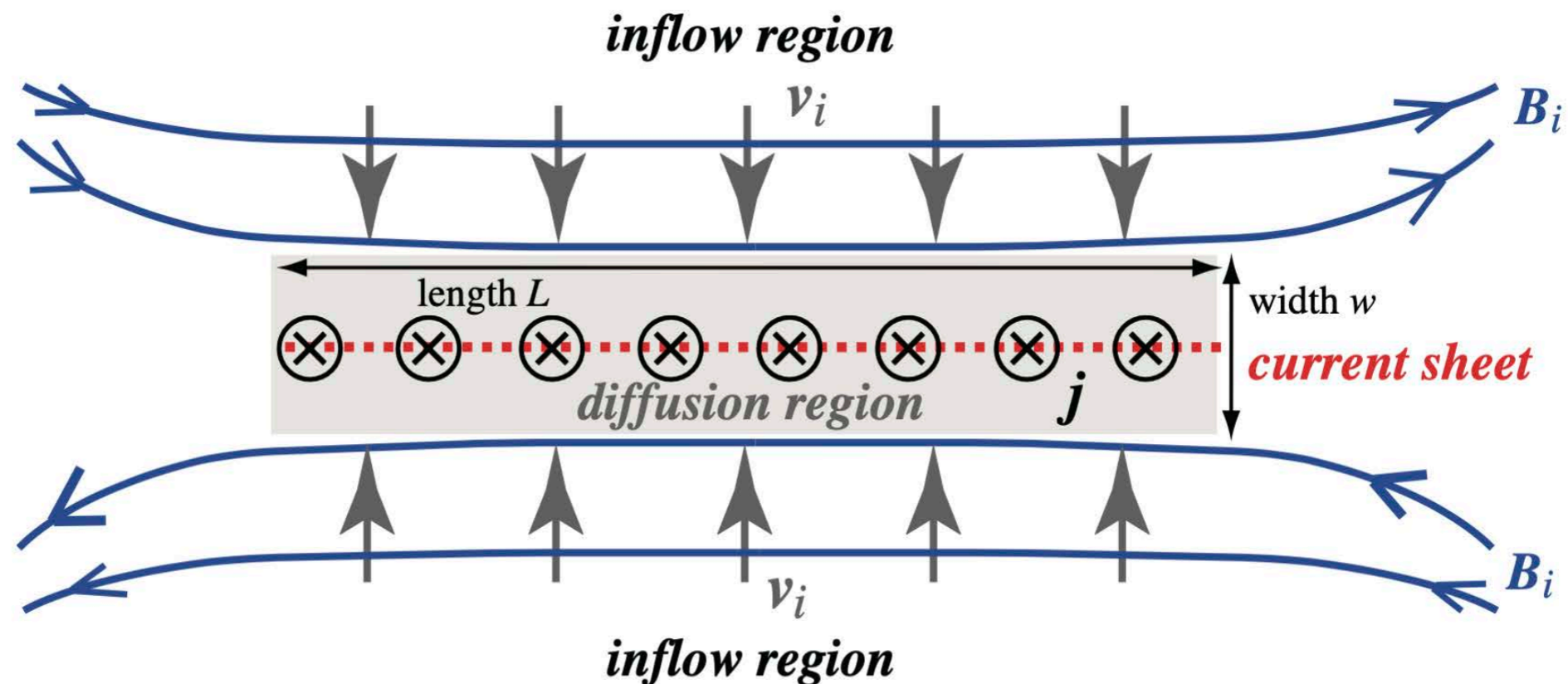
Shibata & Magara (2011)

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
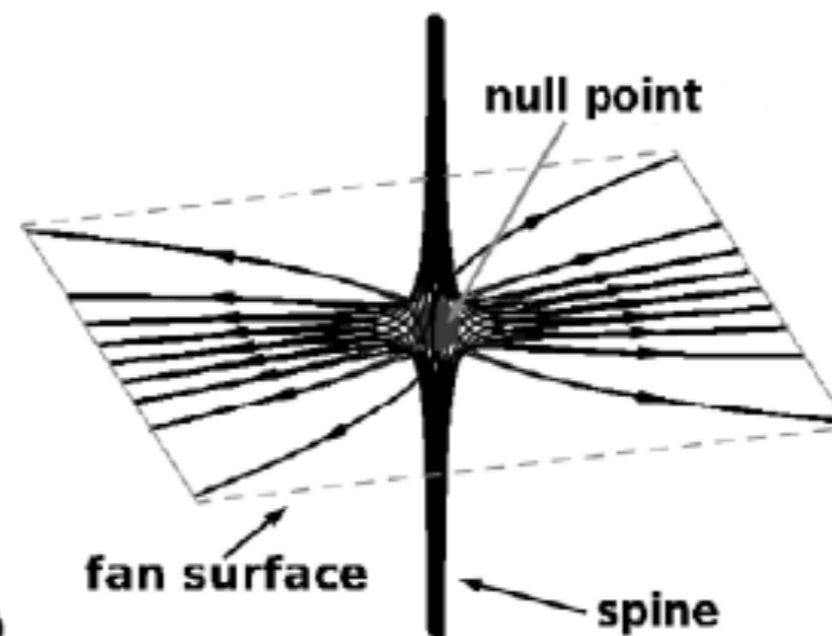 electromagnetic force

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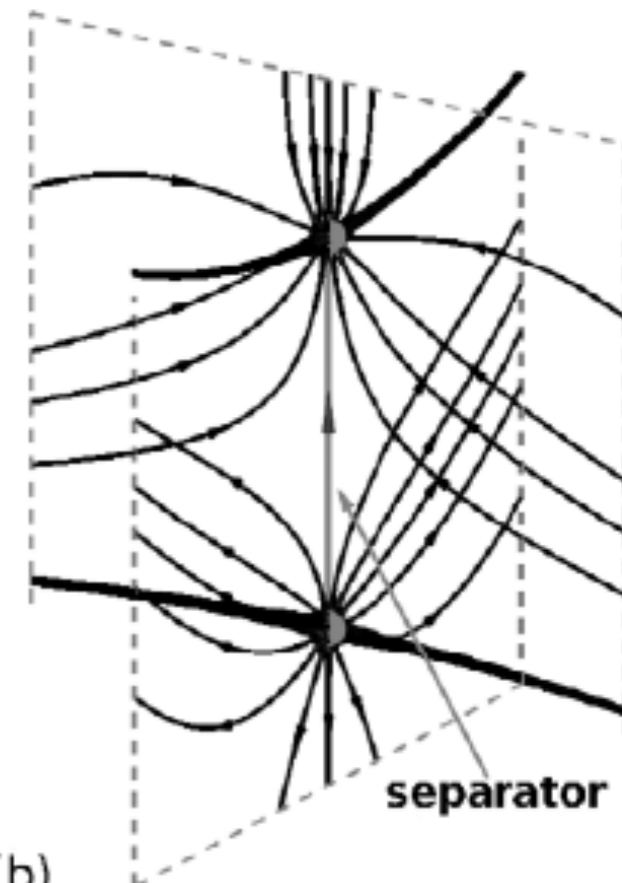quantity is zero (because opposing forces
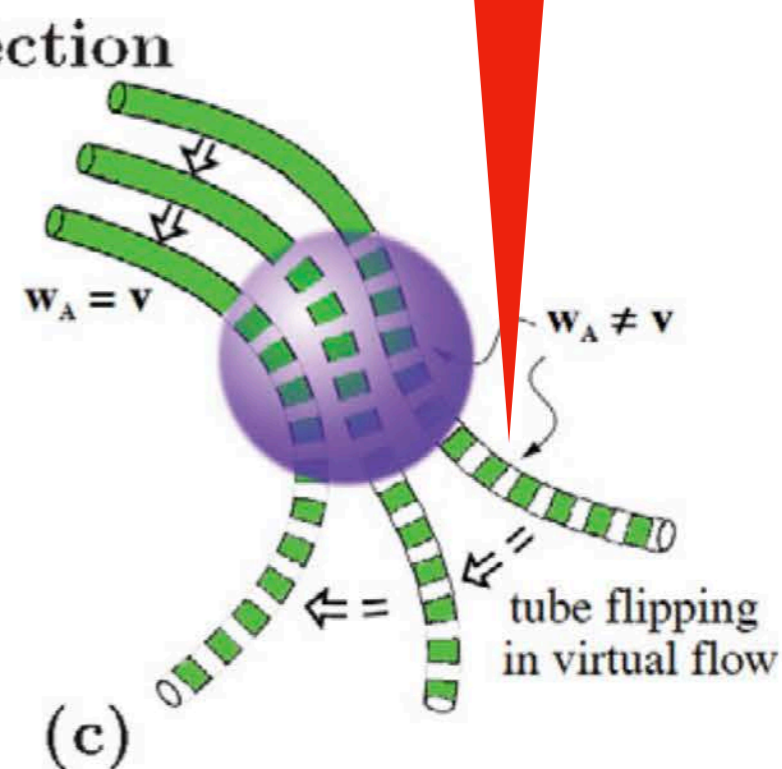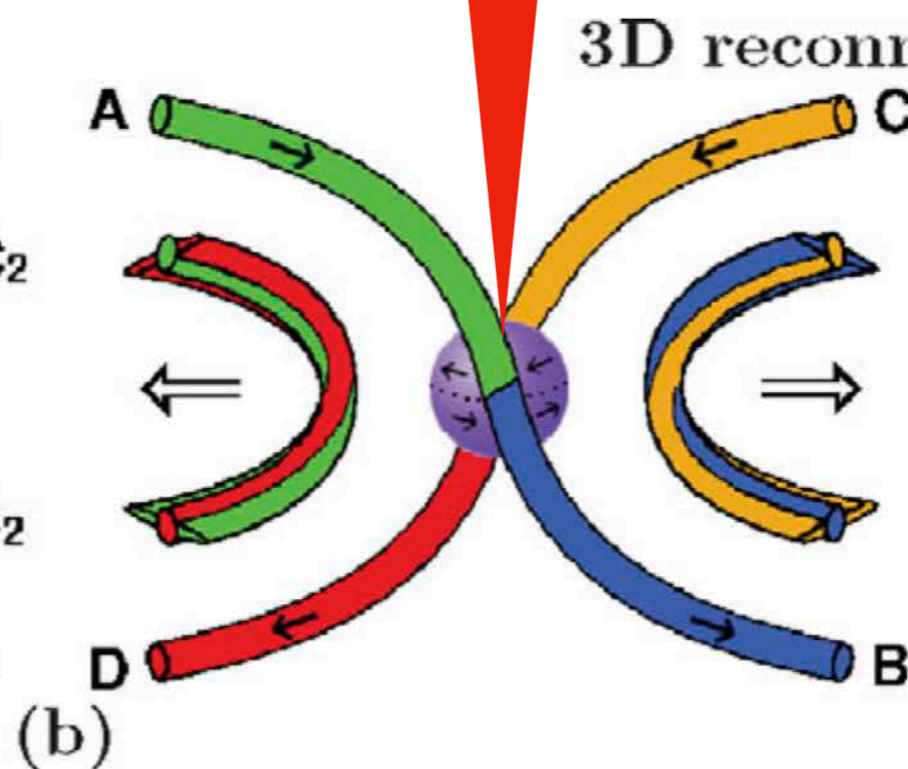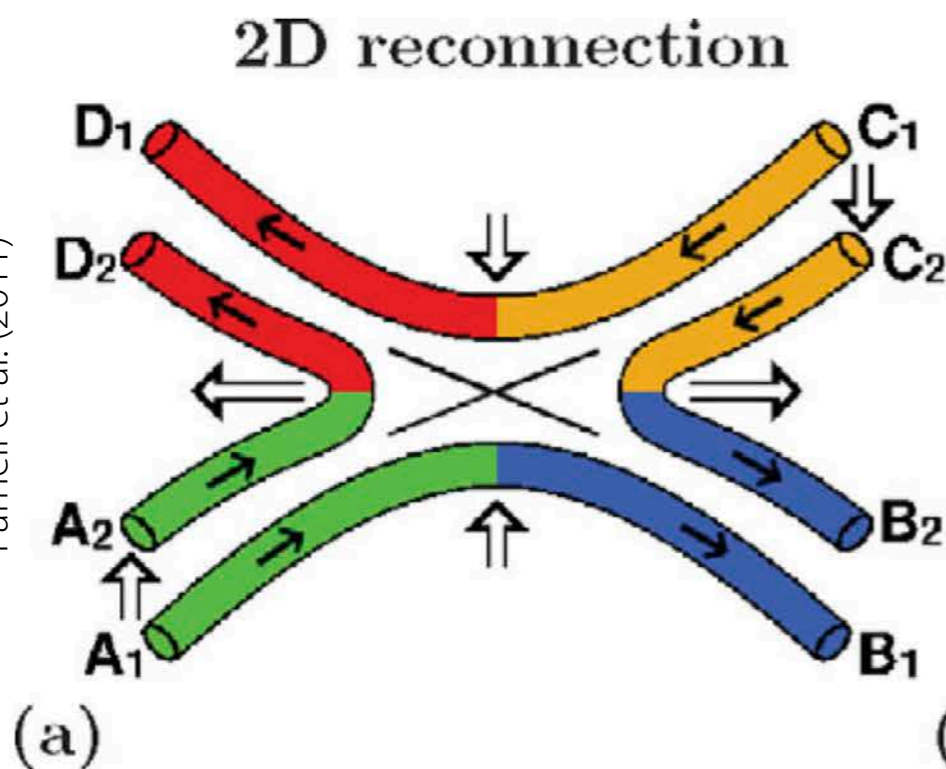cancel out)

Parnell et al. (2011)

In 3D:

Flares

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

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)
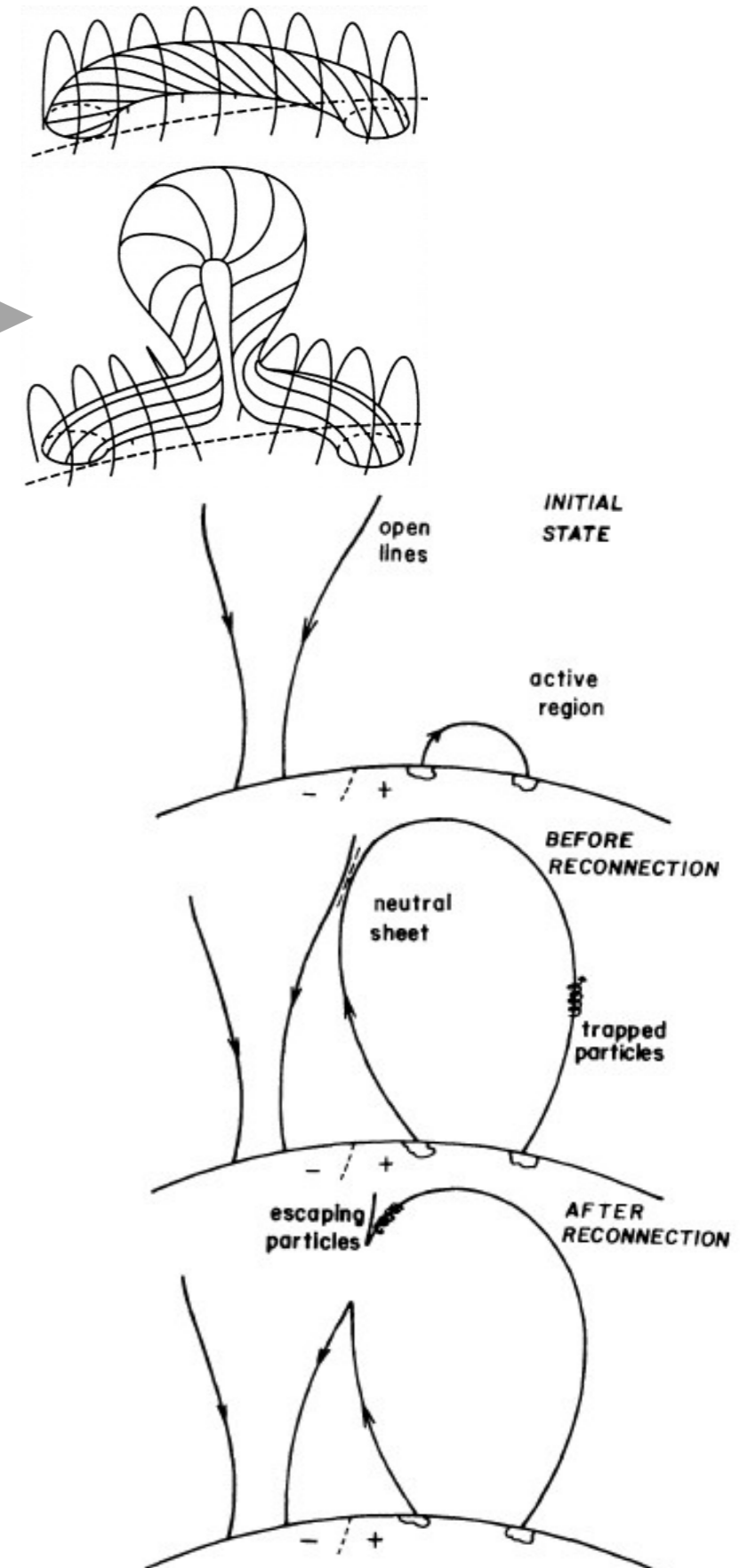

Shibata & Magara (2011)
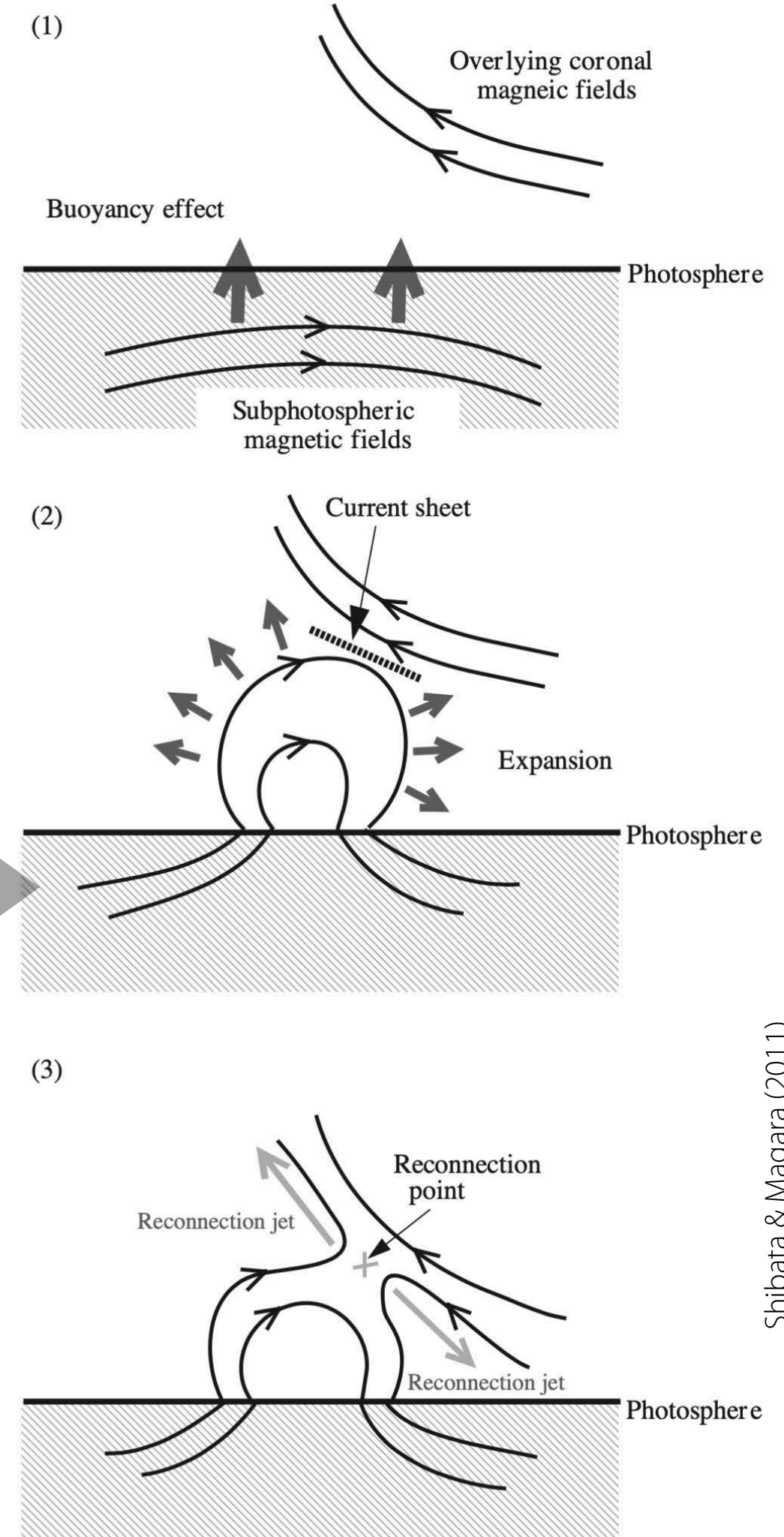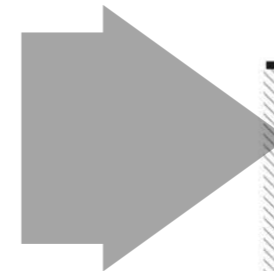
Flares

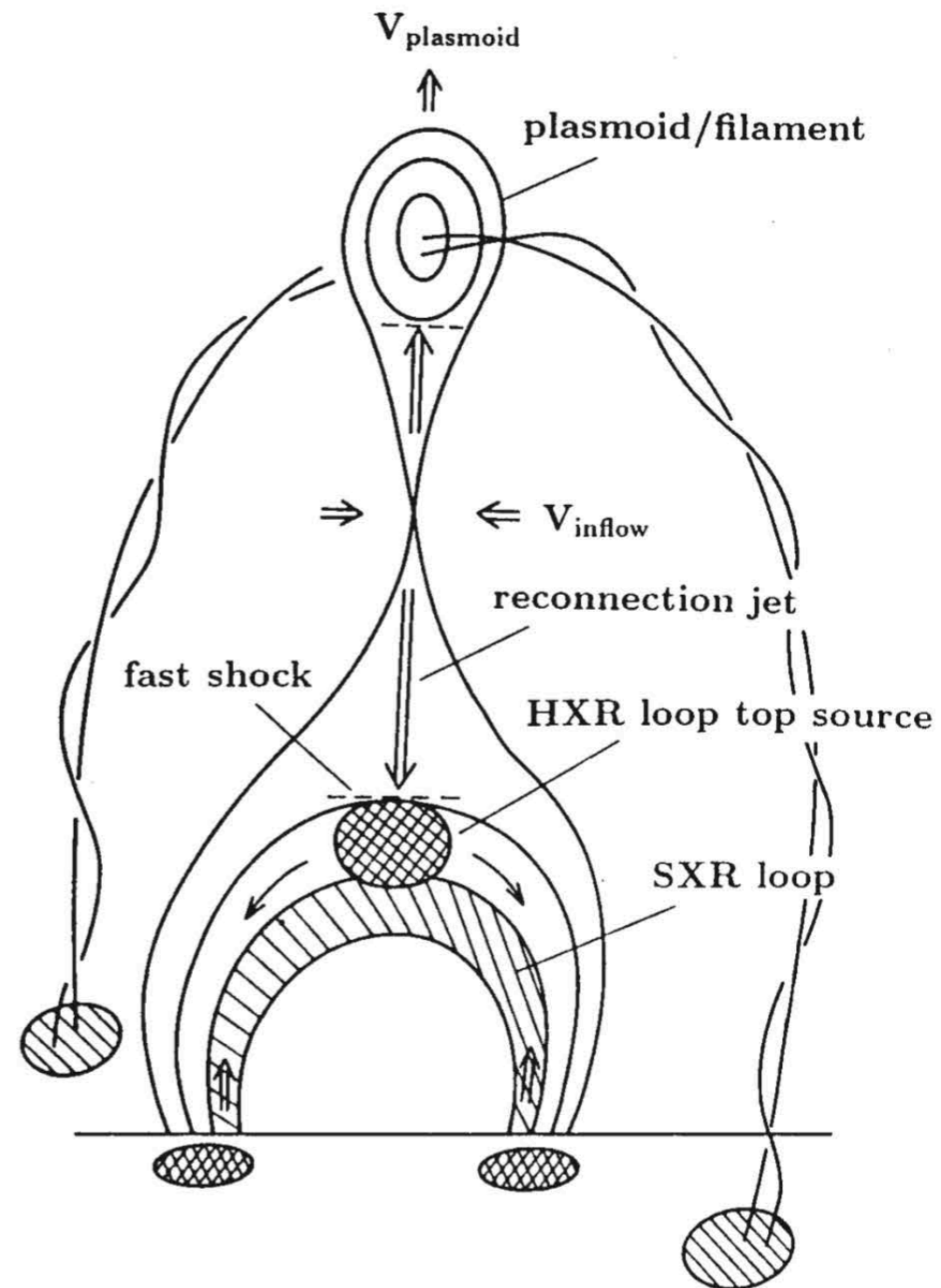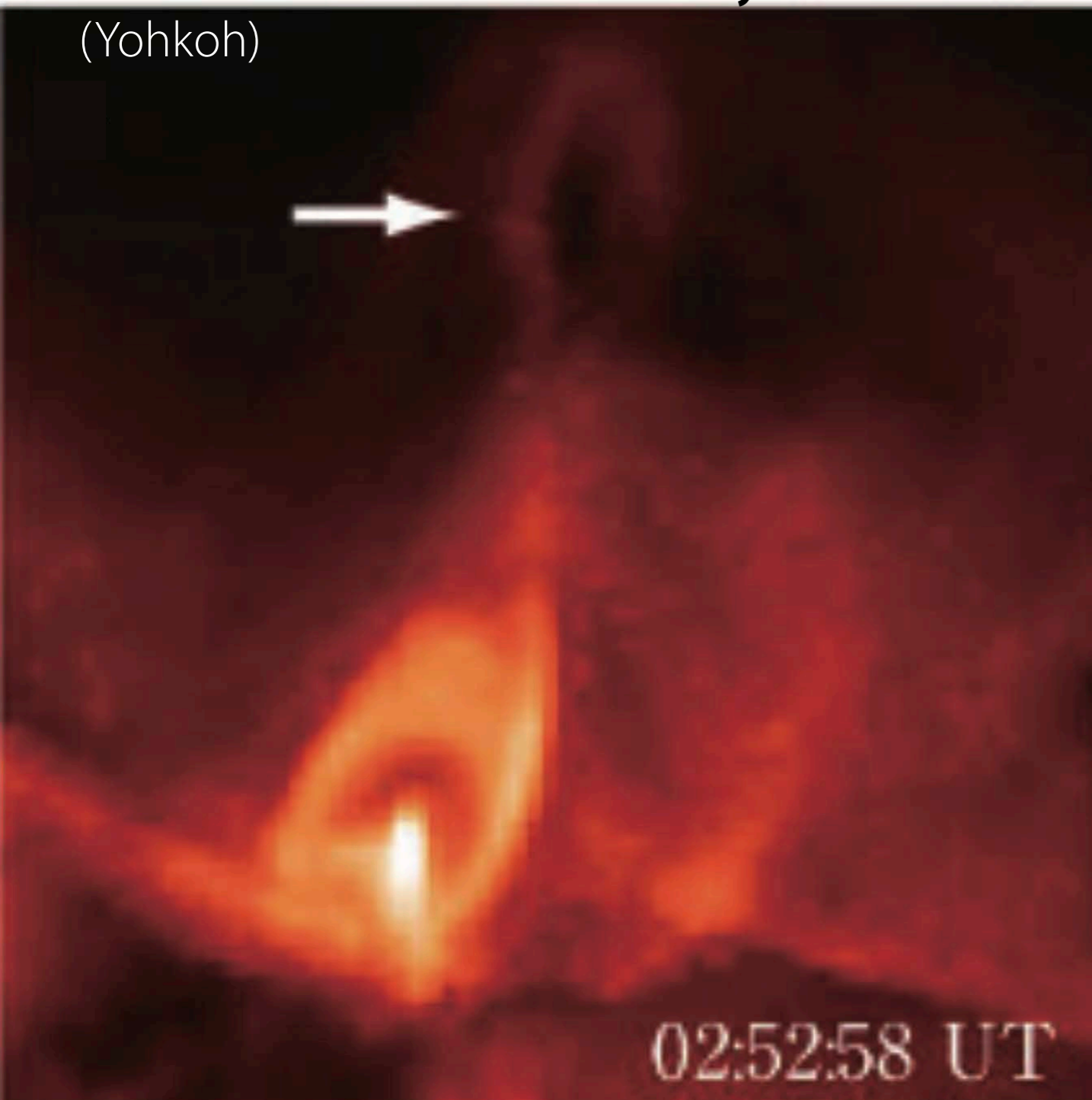## Towards a physical model

- **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.
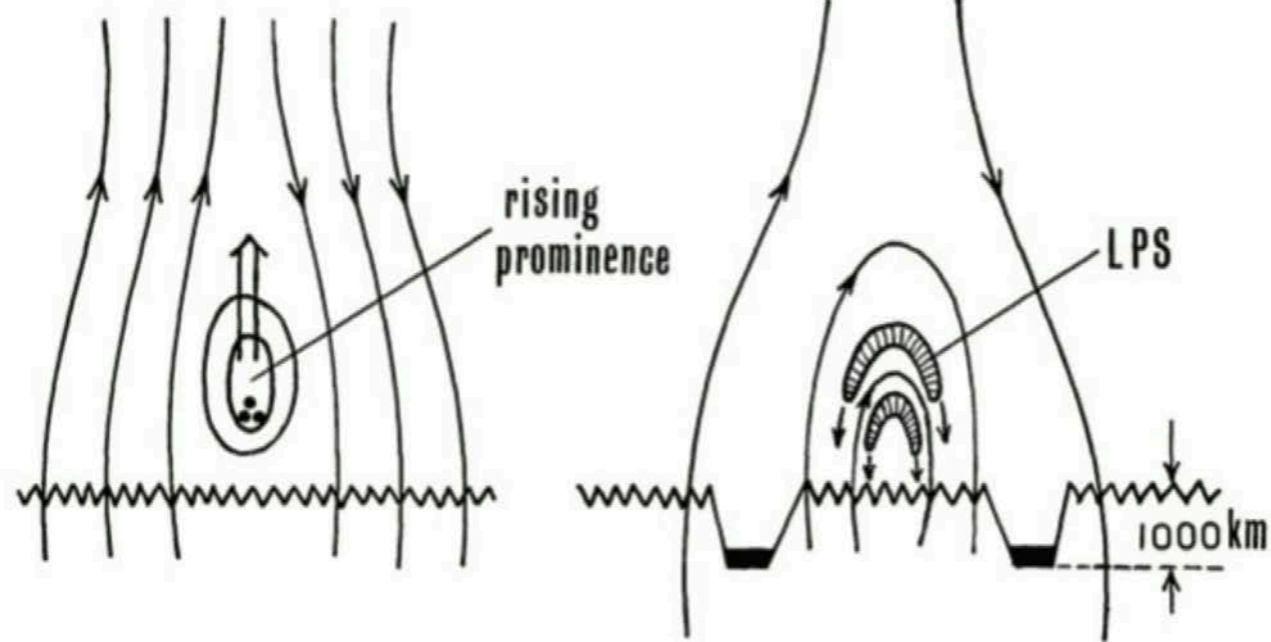
Flares

Standard flare model
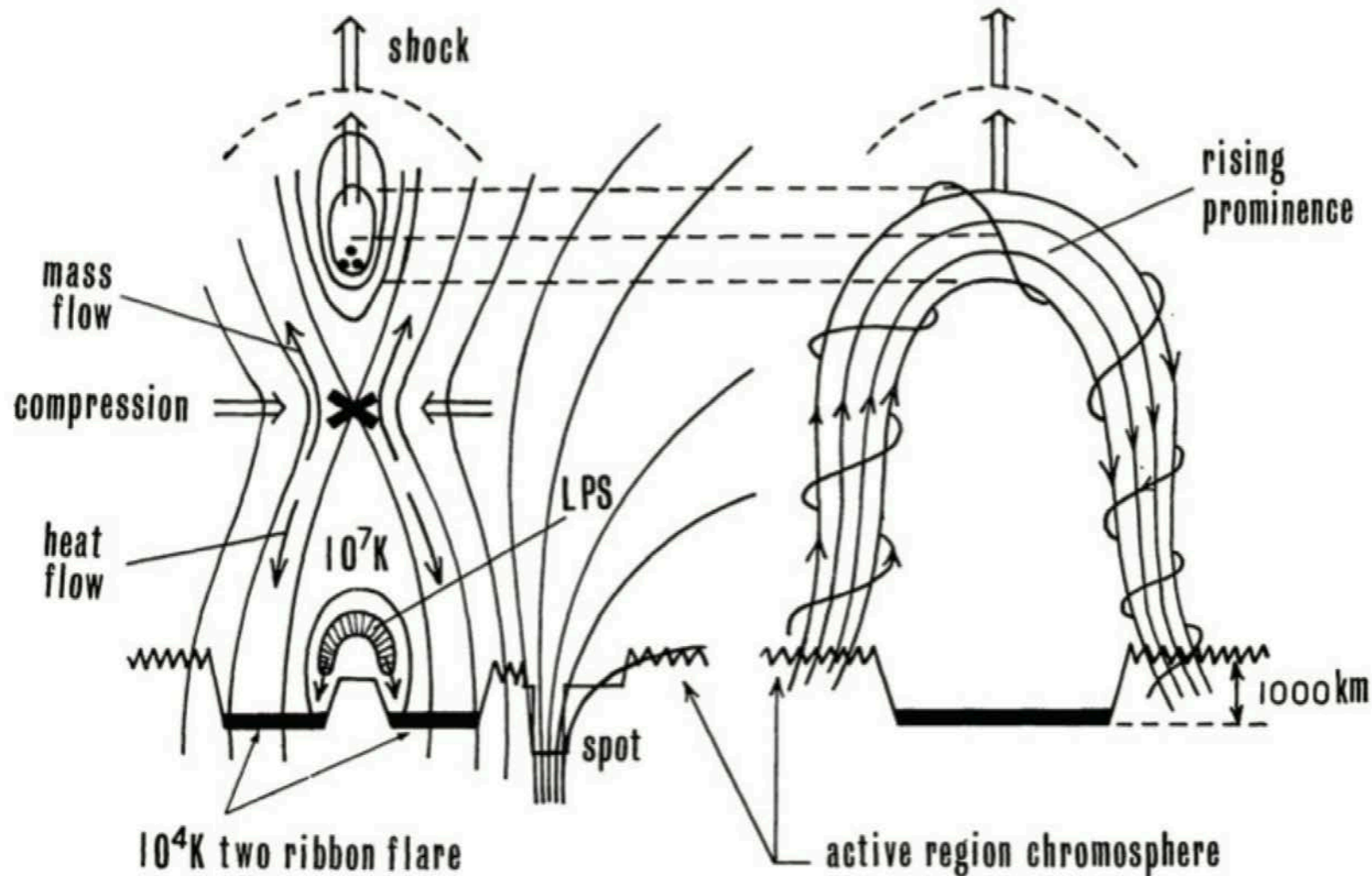
LDE flare observed in soft X-rays
(Yohkoh)

100,000 km

02:52:58 UT

$V_{plasmoid}$

plasmoid/filament

V_{inflow}

reconnection jet

fast shock

HXR loop top source

SXR loop

Shibata et al. (1995)

Hirayama 1974
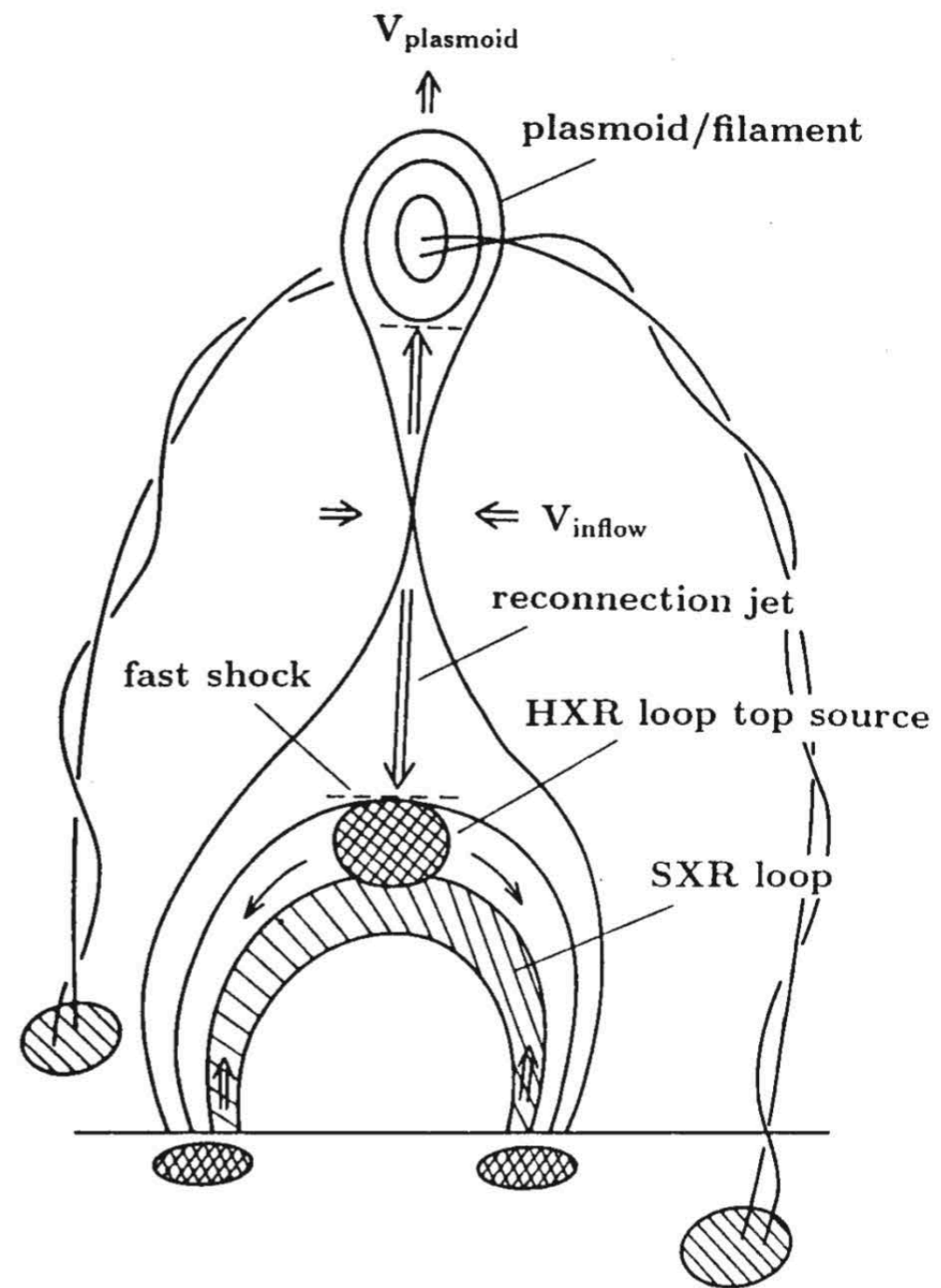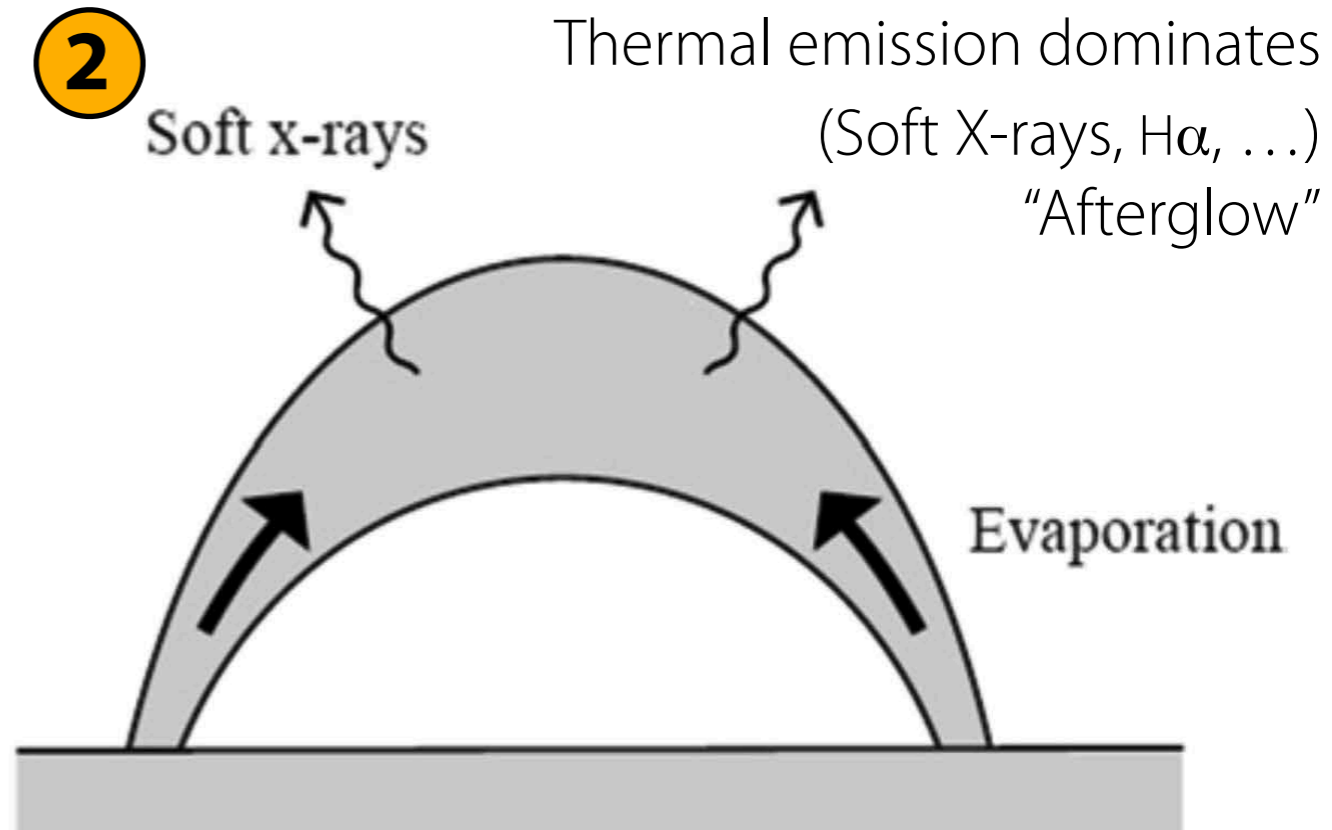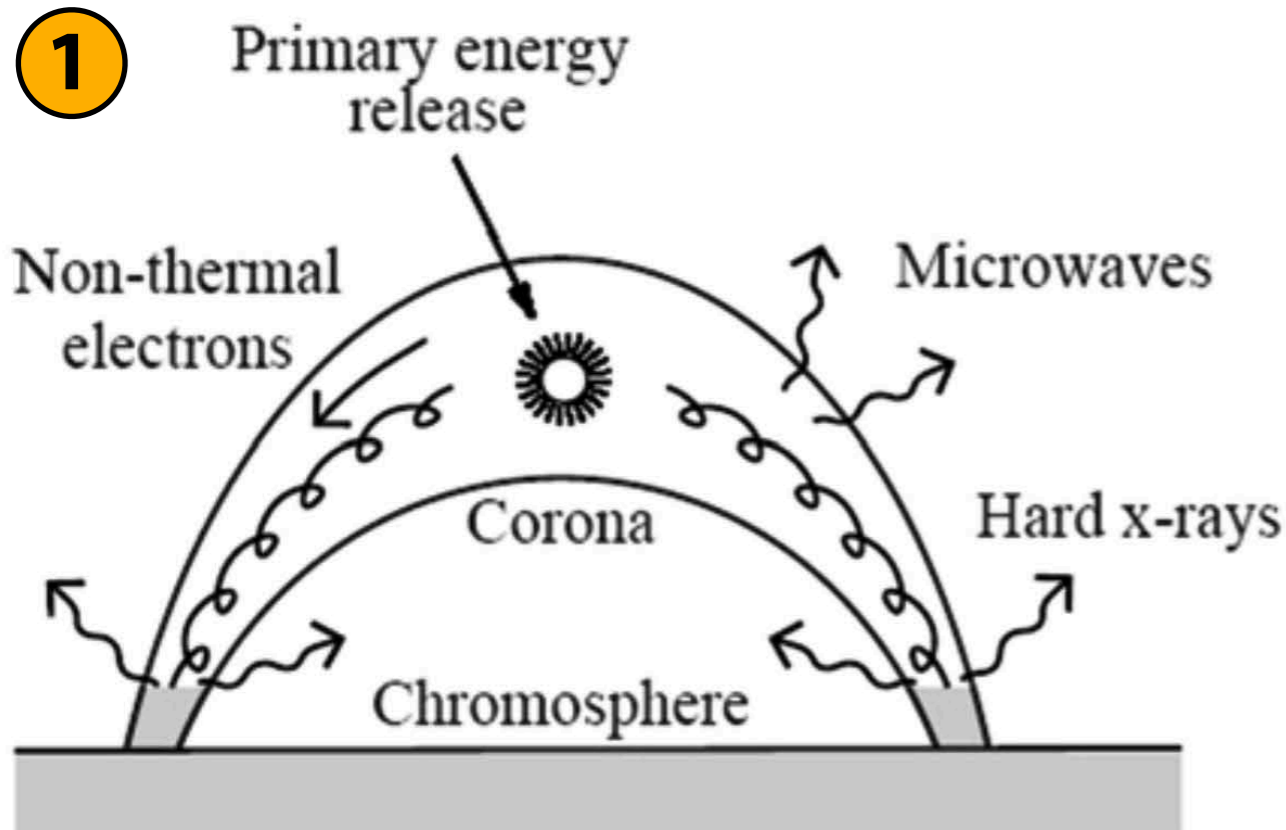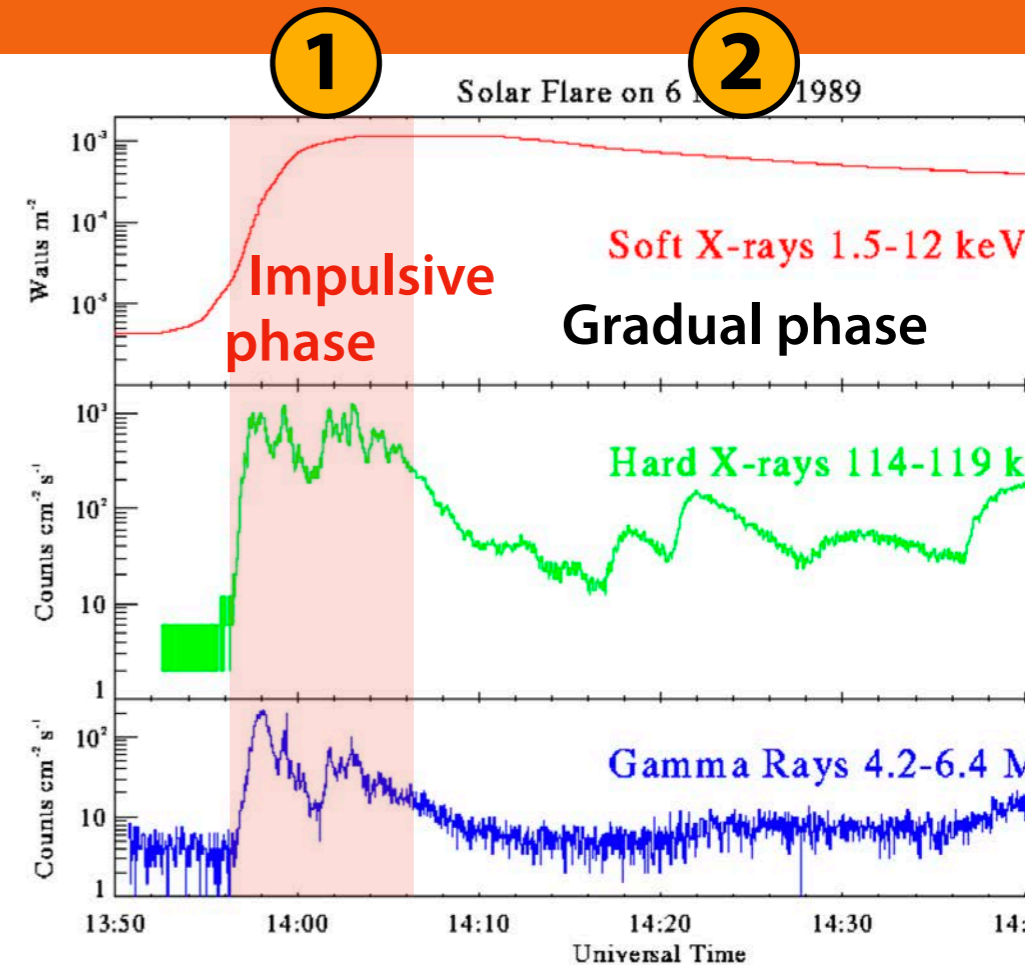
Shibata et al. (1995)

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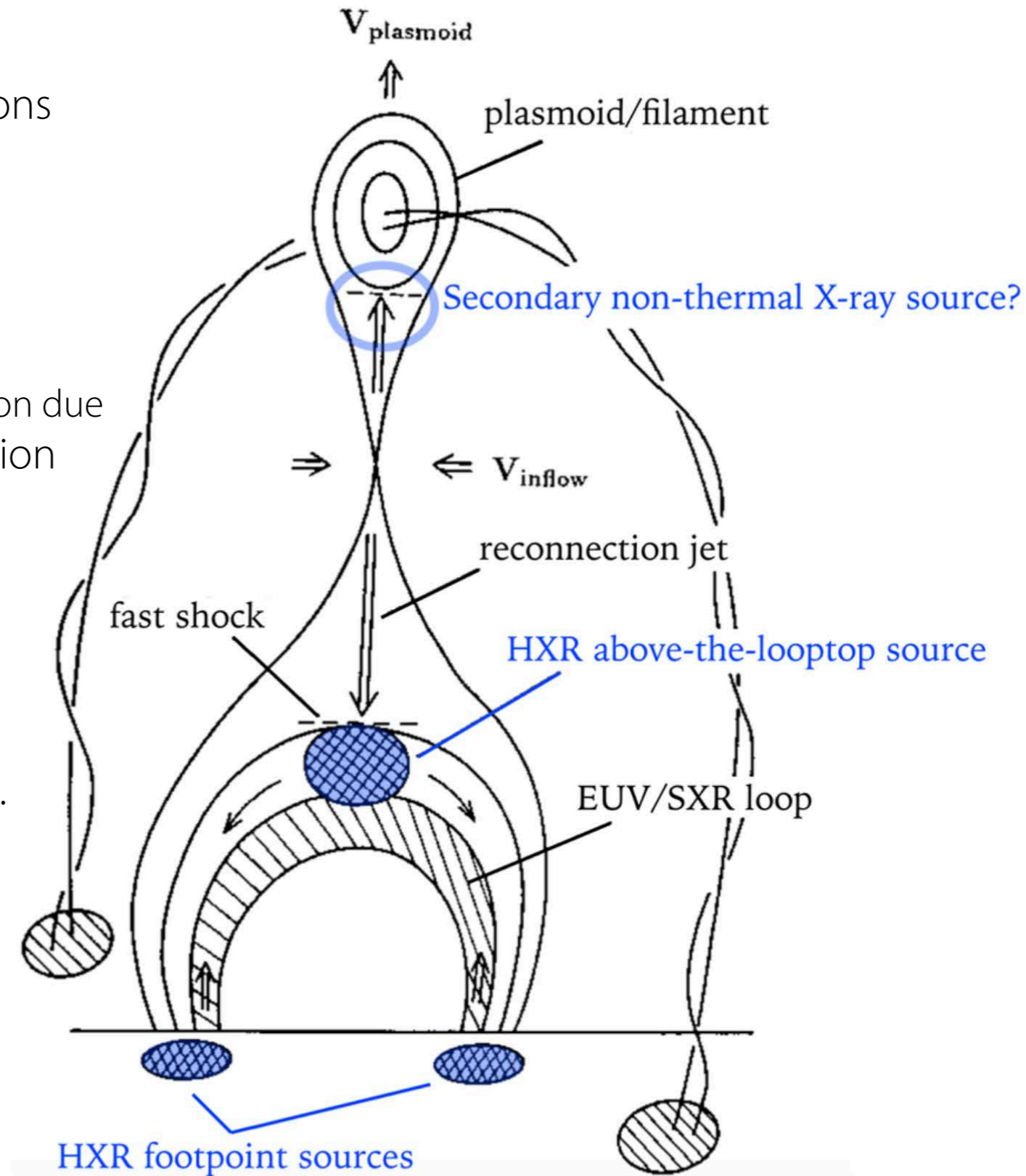
Shibata et al. (1995), Oka et al. (2018)

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, …)
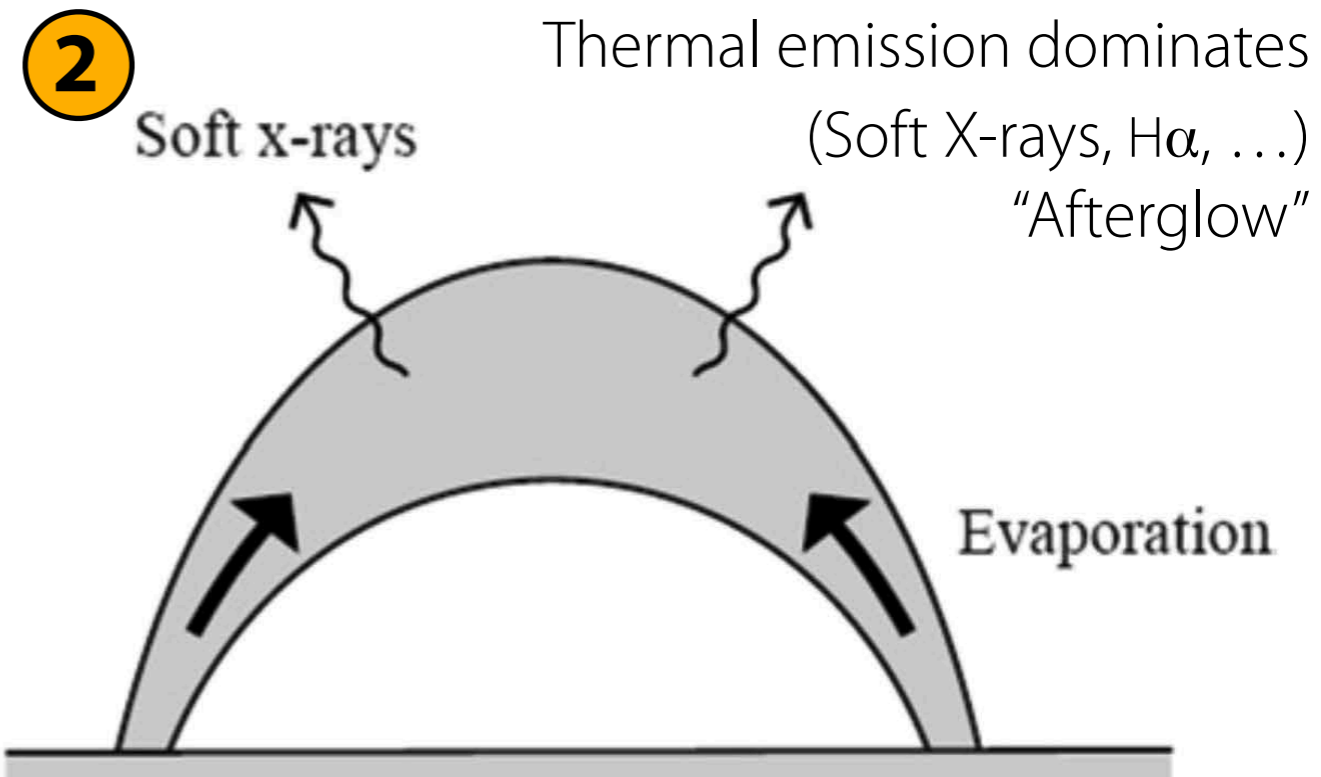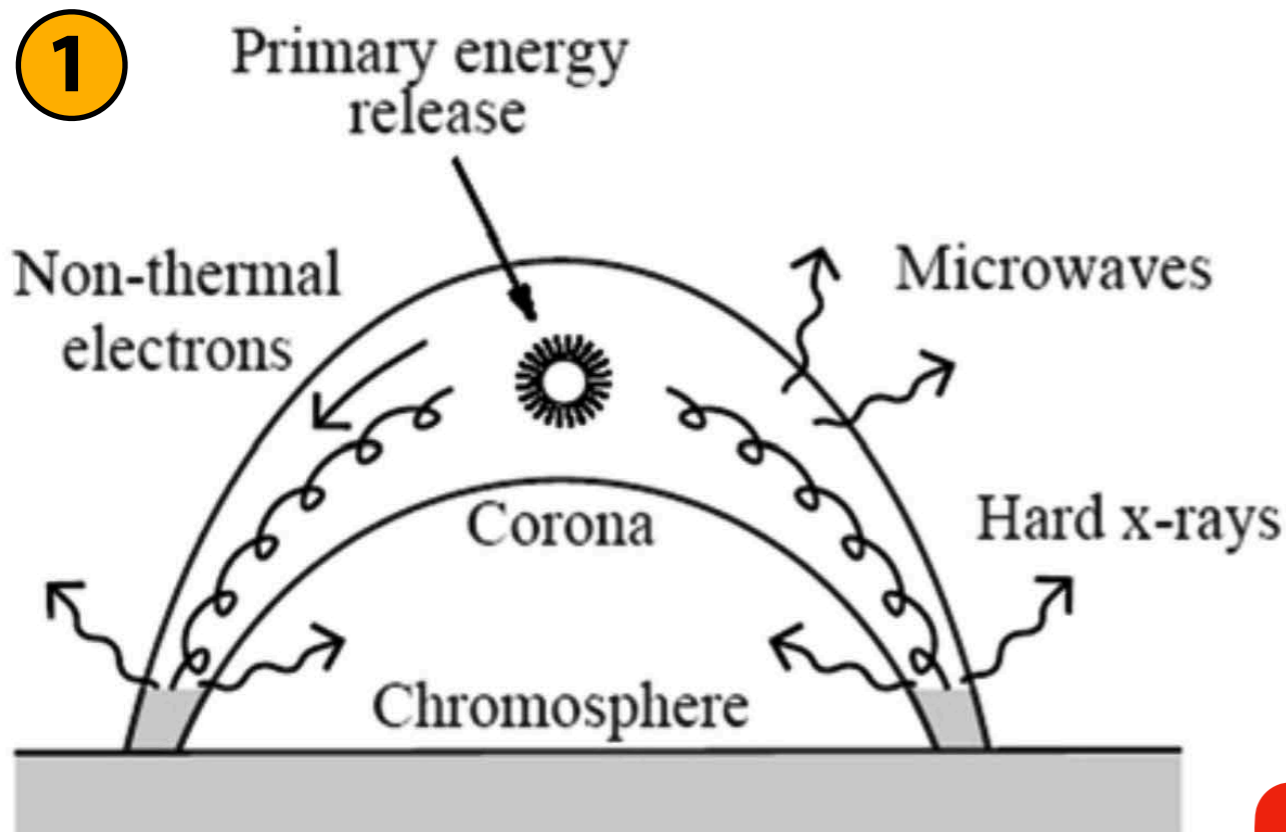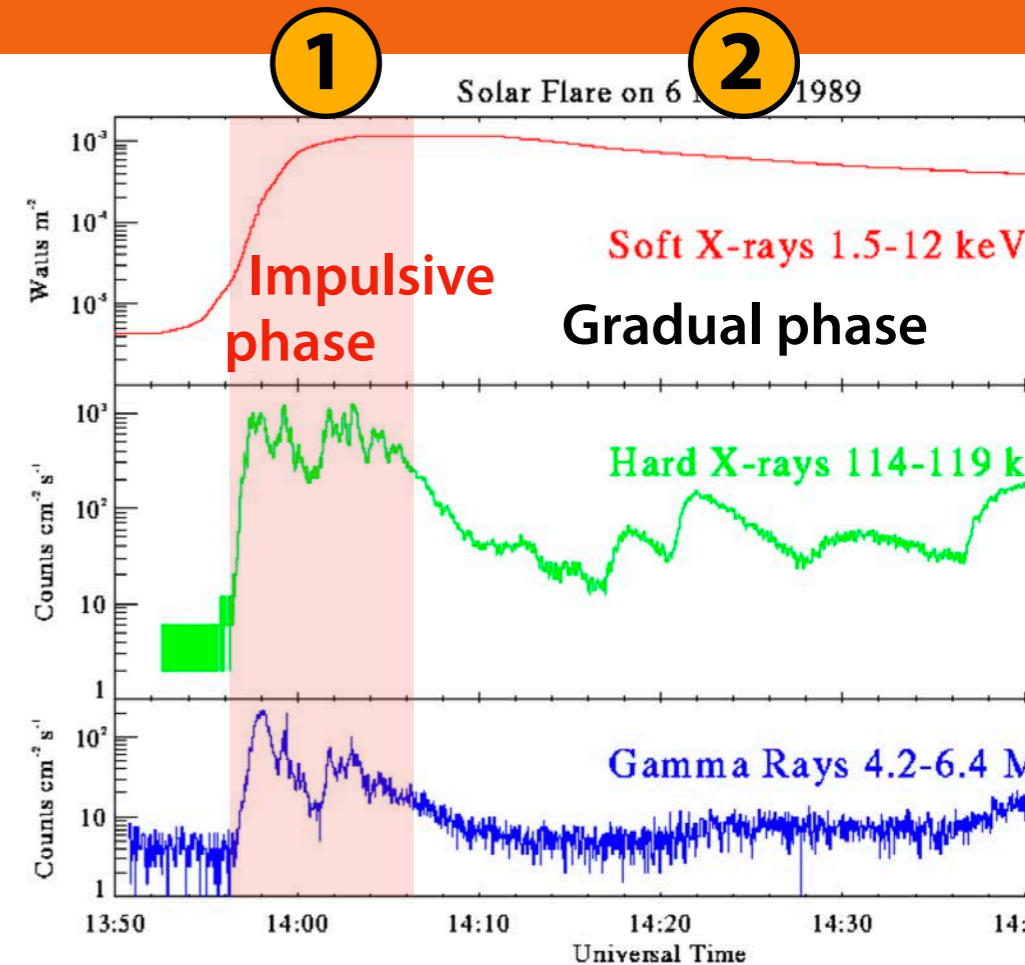"Afterglow"

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

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     upward streaming of plasma from lower atmosphere

Impulsive phase

Gradual phase

Solar Flare on 6 … 1989

Soft X-rays 1.5-12 keV

Hard X-rays 114-119 k…

Gamma Rays 4.2-6.4 M…

Primary energy release

Non-thermal electrons

Microwaves

Corona

Hard x-rays

Chromosphere

Soft x-rays

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

Evaporation

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

Prominence eruption and CME

Soft X-ray loops

Hα ribbons

a