AST5770

Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Assignment #4

Results

- The part of a paper, in which the **new results are presented in detail**.
- **Describe** the results and leave the detailed interpretation (and comparison to literature) for the discussion section!
- It should not be a (random) collection of all facts and things you found out.

  ➡ **Select** the results that serve a purpose in exploring and addressing the scientific question/topic of your paper!
- Be **concise and focused but yet consistent and complete**.

Results	Discussion	Conclusion
• Detailed but yet focused **description** of the **new results** found in this study • Thorough analysis of the introduced data, using the introduced methods • Results presented with good figures (and tables if applicable)	• **Interpretation** of the new results (described in the previous section), setting them into **context** / comparing them to results in the literature (and possibly complementary data)	• The **essence** and take-away message • **Brief** summary of the most important results and conclusions!

Avoid details and repetitions!

Assignment #4

How to start?!

1. Get familiar with the data.

- Start with the data analysis by plotting different aspect of your data — use standard tools like profiles, maps, histograms etc.
- Do you see any trends/properties of the data that might be relevant with regard to your science question?

2. Initial detailed data analysis.

- Try to split the scientific question into small steps/aspects and investigate in detail.
- How can you check these sub-questions by plotting the data in different ways?
- Find good ways to visualise your findings. Make preliminary plots/tables (simple, do not yet use much time on making them "pretty").

3. Collect, sort, and filter your findings and plots so far.

- Pre-select material (your "puzzle pieces") and start with the most important ones (as far as you can tell at this point)
- Now put your findings and material into order (in your tentative manuscript)
- Describe the figures/tables in detail in your text.

4. Connect the dots.

- Put the results into a logical order and create a "story" with a "red thread".

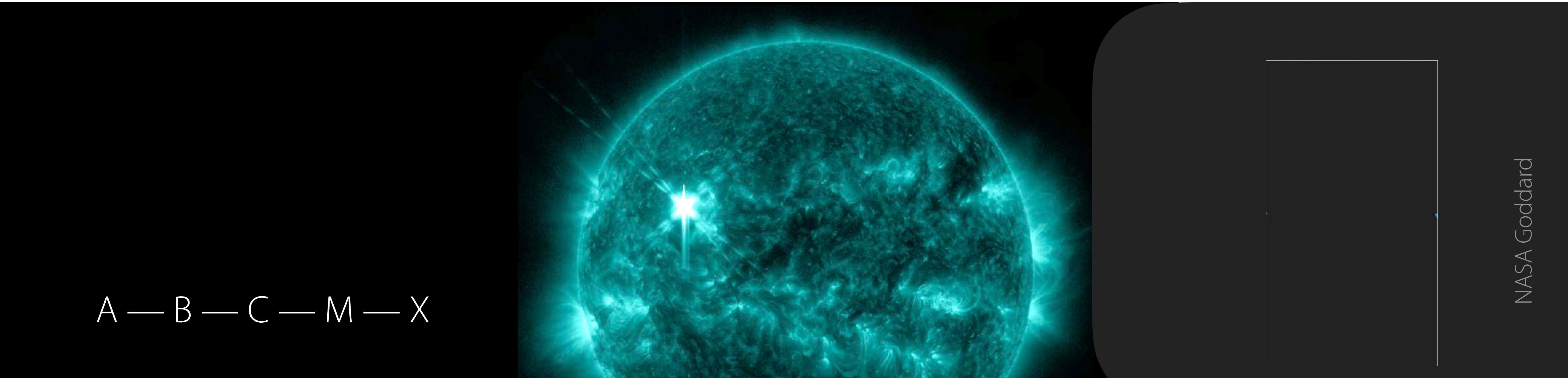
5. Polish — Make the text, figures, table nice and consistent

- Go through the text again and again and make sure it connects well and that all figures and tables are referred to and made good use of. You may want to update your figures to emphasise your findings.

Solar flares

Solar flares — recap

1. Flares release large amounts of energy. Where is this energy stored prior to its release?
2. With which process is this amount of energy (gradually) built up?
3. Where goes the energy that is released during flares?
4. What is the name of the largest flare ever observed? And what is the name of the first flare ever observed?
5. How much stronger is a X1 flare compared to a C1 flare (in terms of irradiance as measured in soft X-rays by the GOES satellites)?
6. Why are loops lightening up and emitting in soft X-rays?

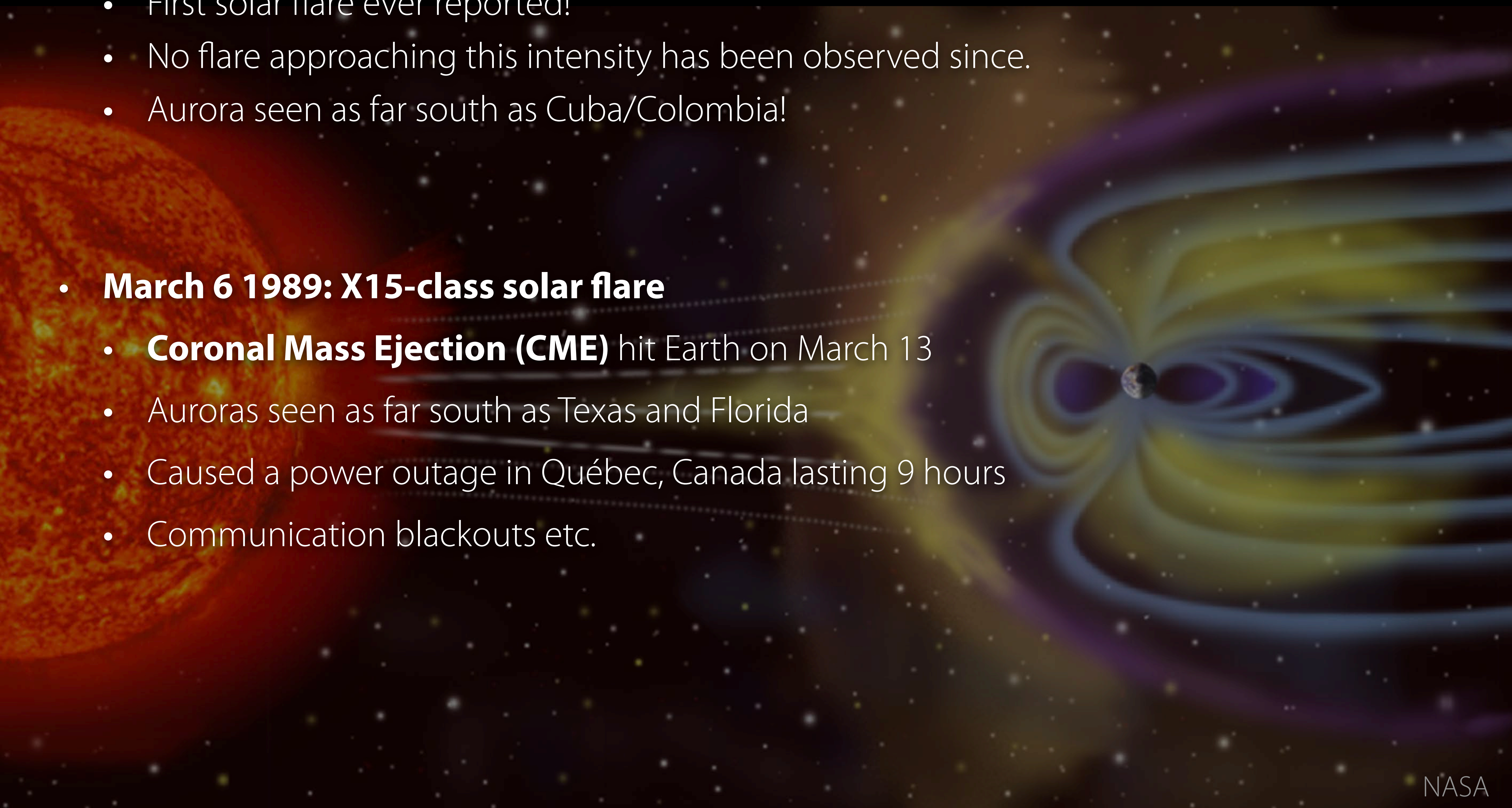


Flares

Extreme examples

- **Carrington Event** — The Great Flare of 1859
  - First solar flare ever reported!
  - No flare approaching this intensity has been observed since.
  - Aurora seen as far south as Cuba/Colombia!

- **March 6 1989: X15-class solar flare**
  - **Coronal Mass Ejection (CME)** hit Earth on March 13
  - Auroras seen as far south as Texas and Florida
  - Caused a power outage in Québec, Canada lasting 9 hours
  - Communication blackouts etc.

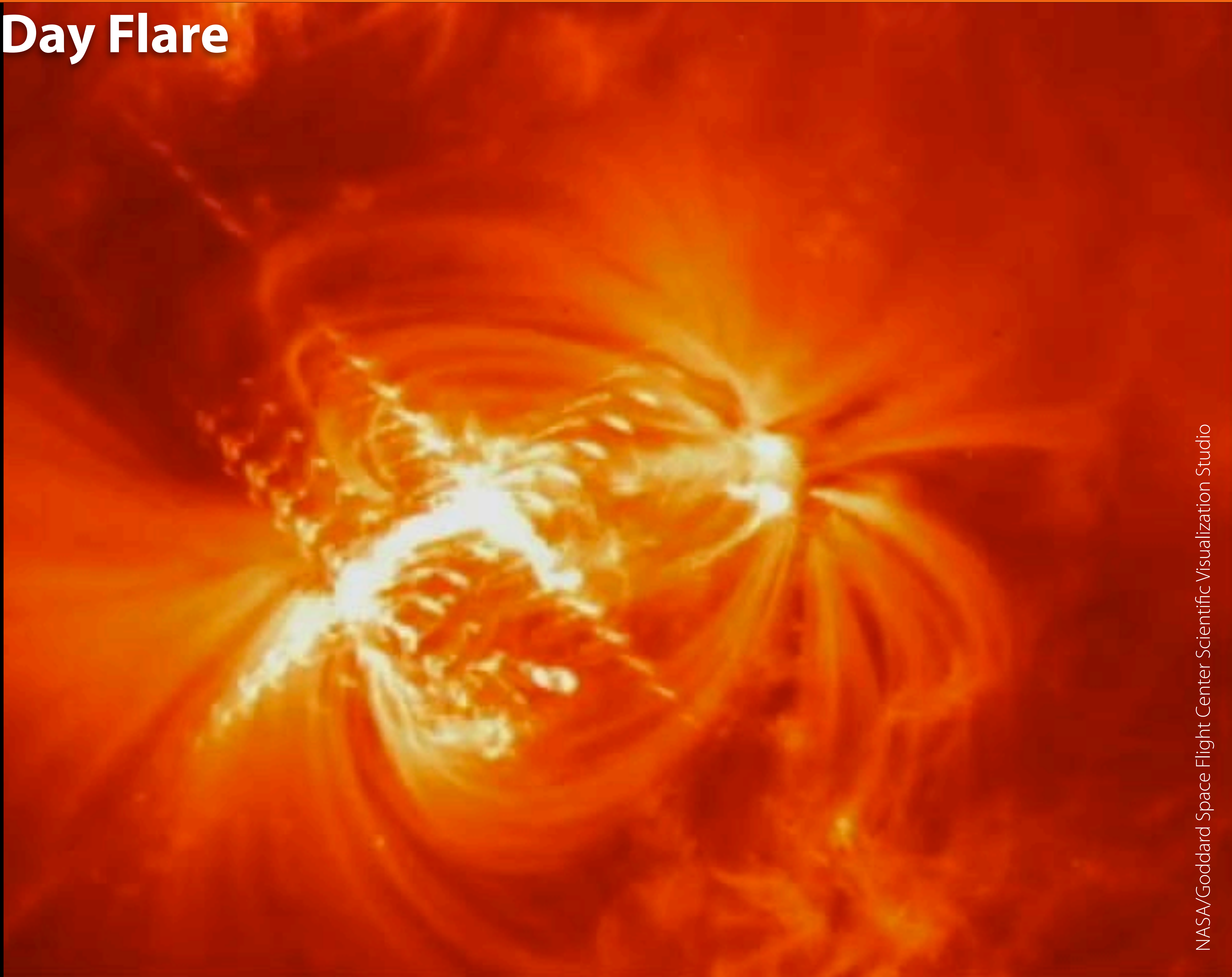


NASA

Flares

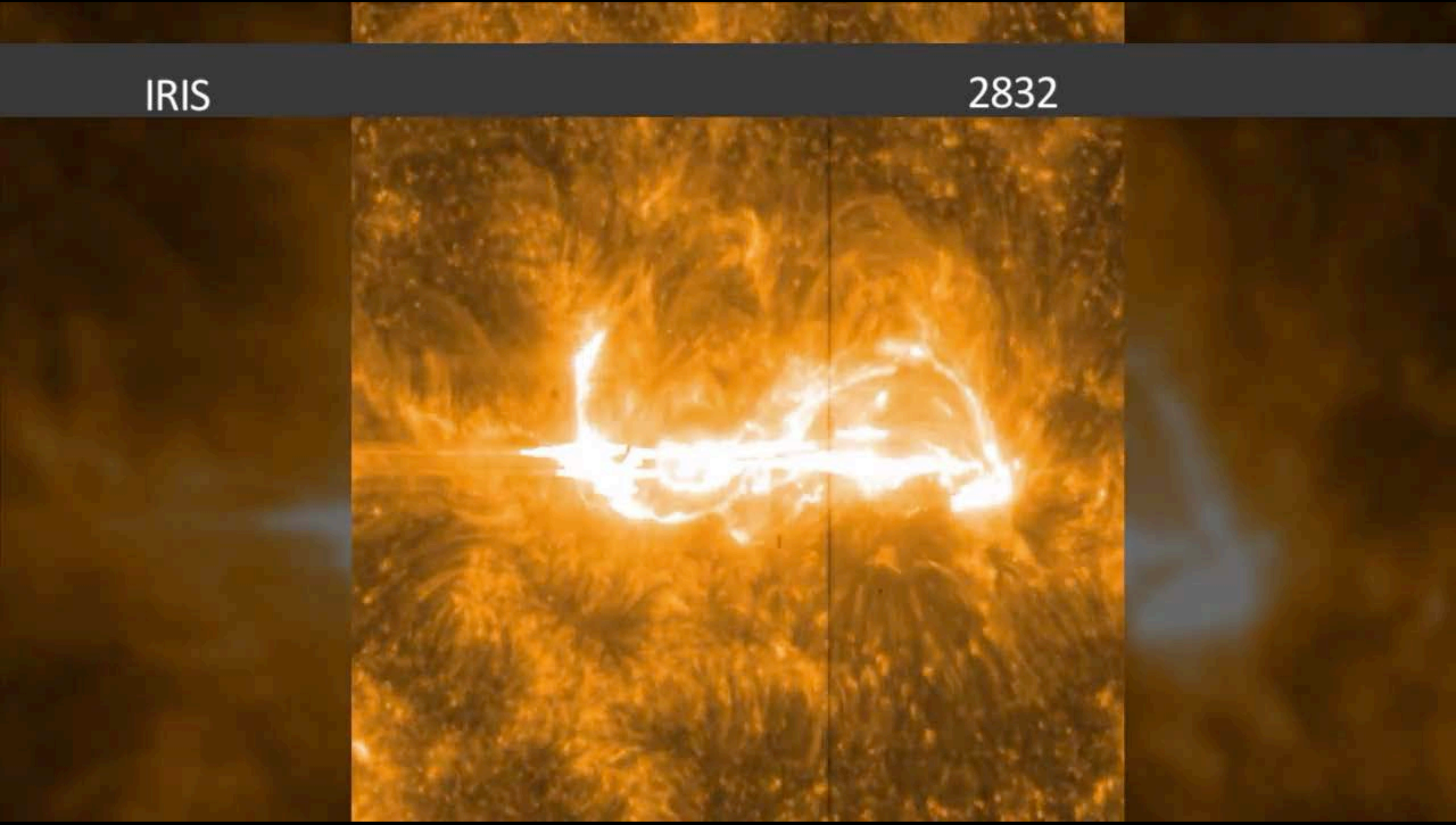
Bastille Day Flare

- July 2000
- X5.7-class !
- Observations with NASA's TRACE satellite
- Caused a Coronal Mass Ejection and then a geomagnetic storm with minor damage to satellite and power grid infrastructure

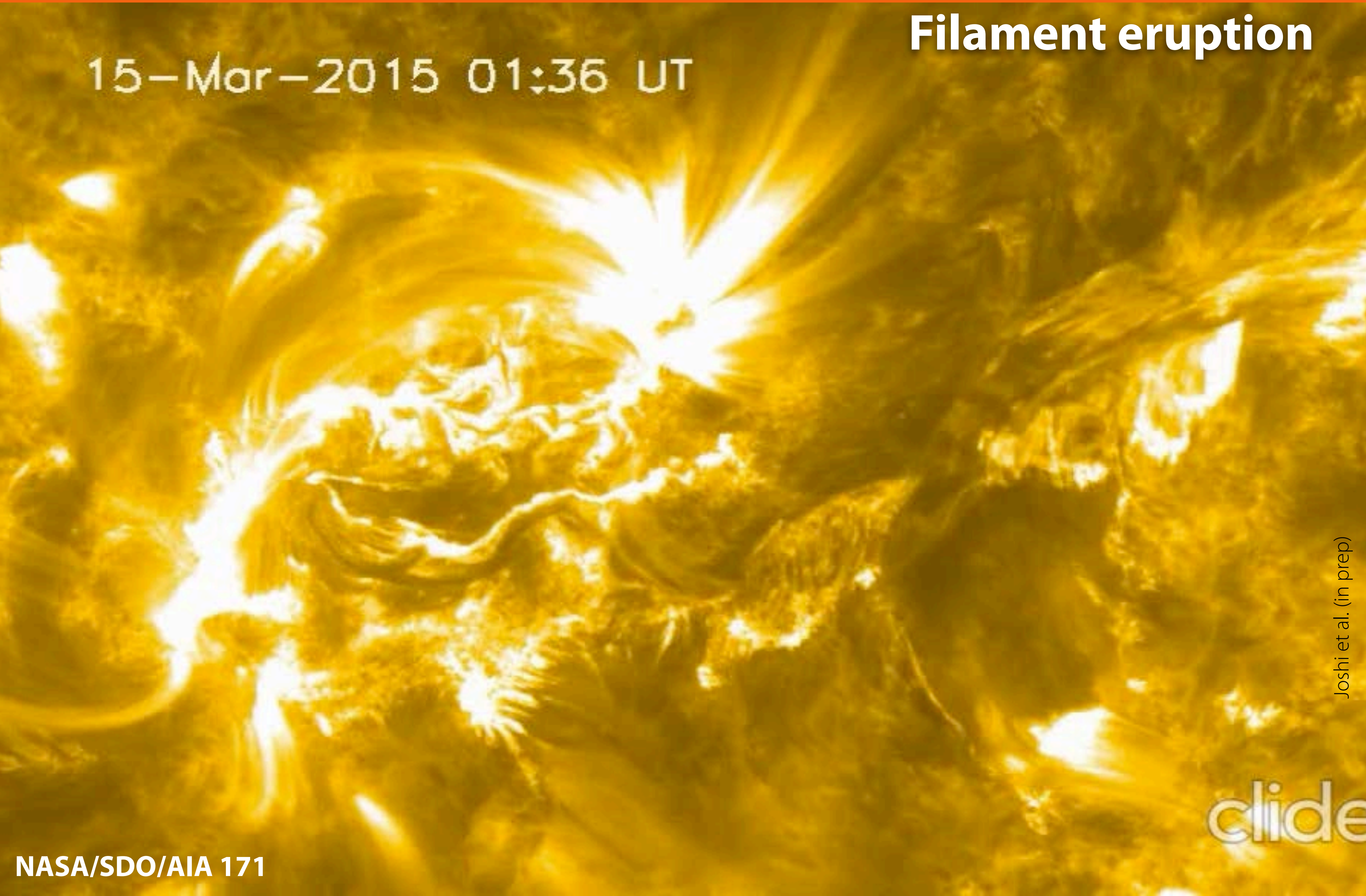


Flares

"Best observed flare ever" — X-class — March 29, 2014

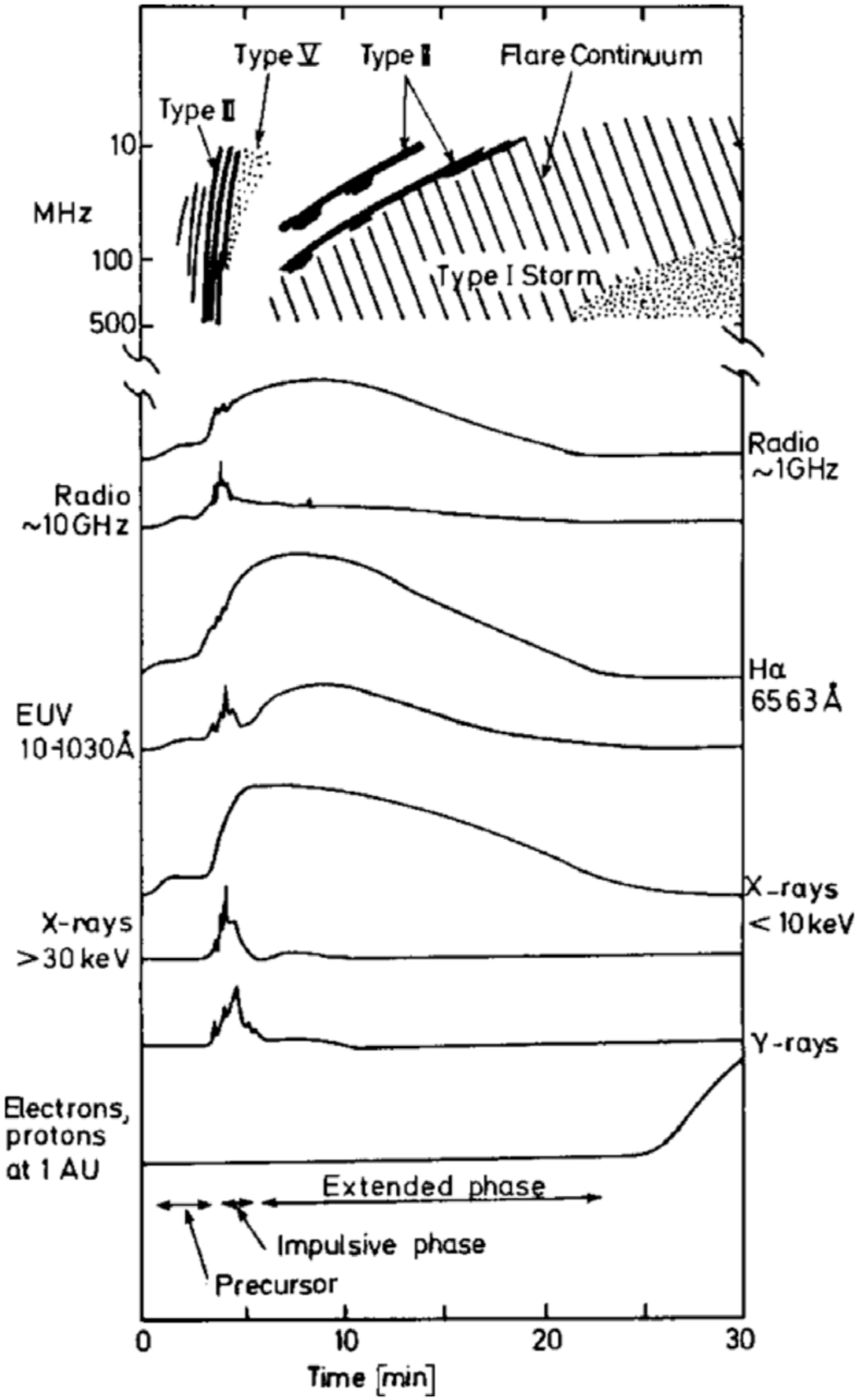


Flares


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

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
- X-ray spectrum can be fitted with two components, following power laws each
  - Lower-energy component
  - Higher-energy component

➡ Constraints for the physical mechanism behind flares

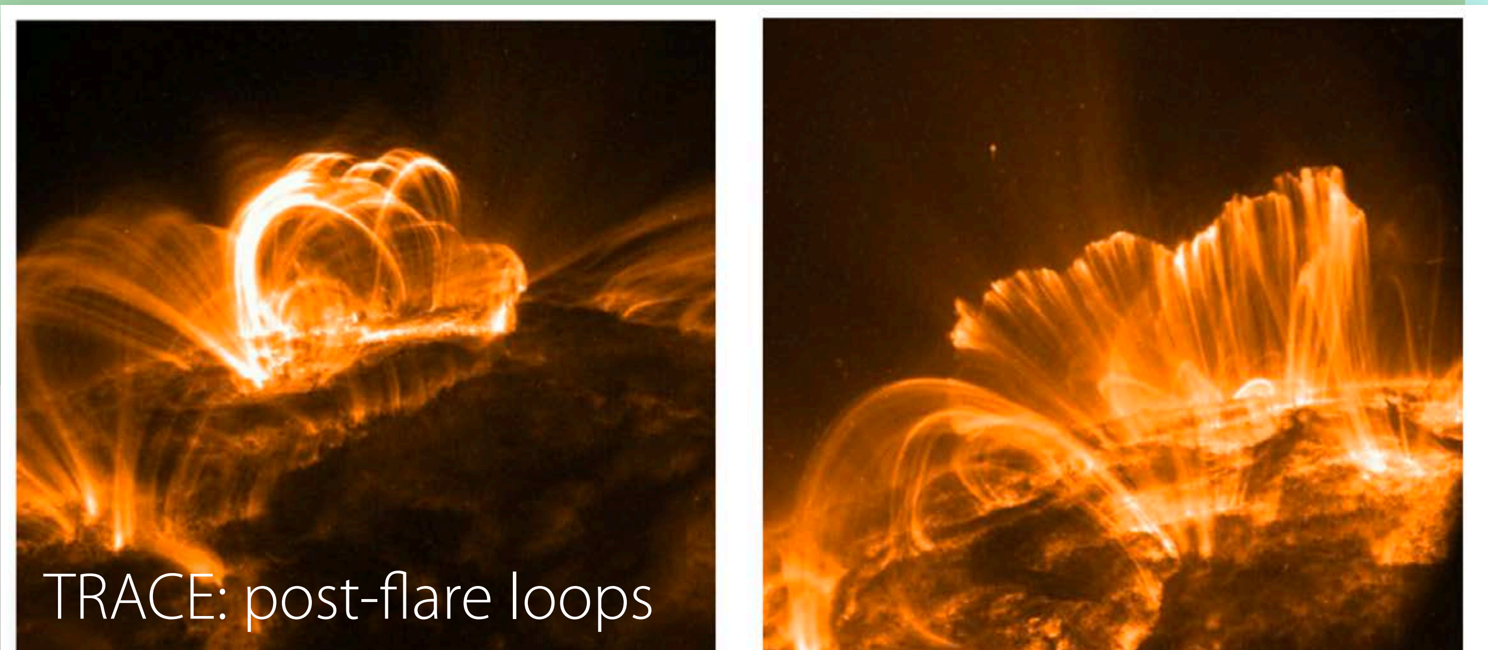
  - Thermal radiation (bremsstrahlung)
  - Non-thermal radiation due to highly energetic particles (radio, hard X- ray, γ-rays)

Flares

Towards a physical model

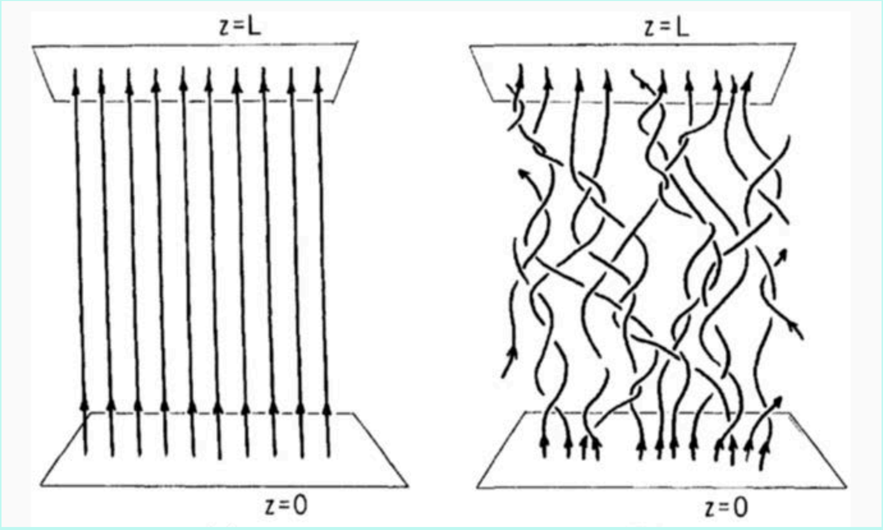
Observations so far:

- 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



Physical mechanism

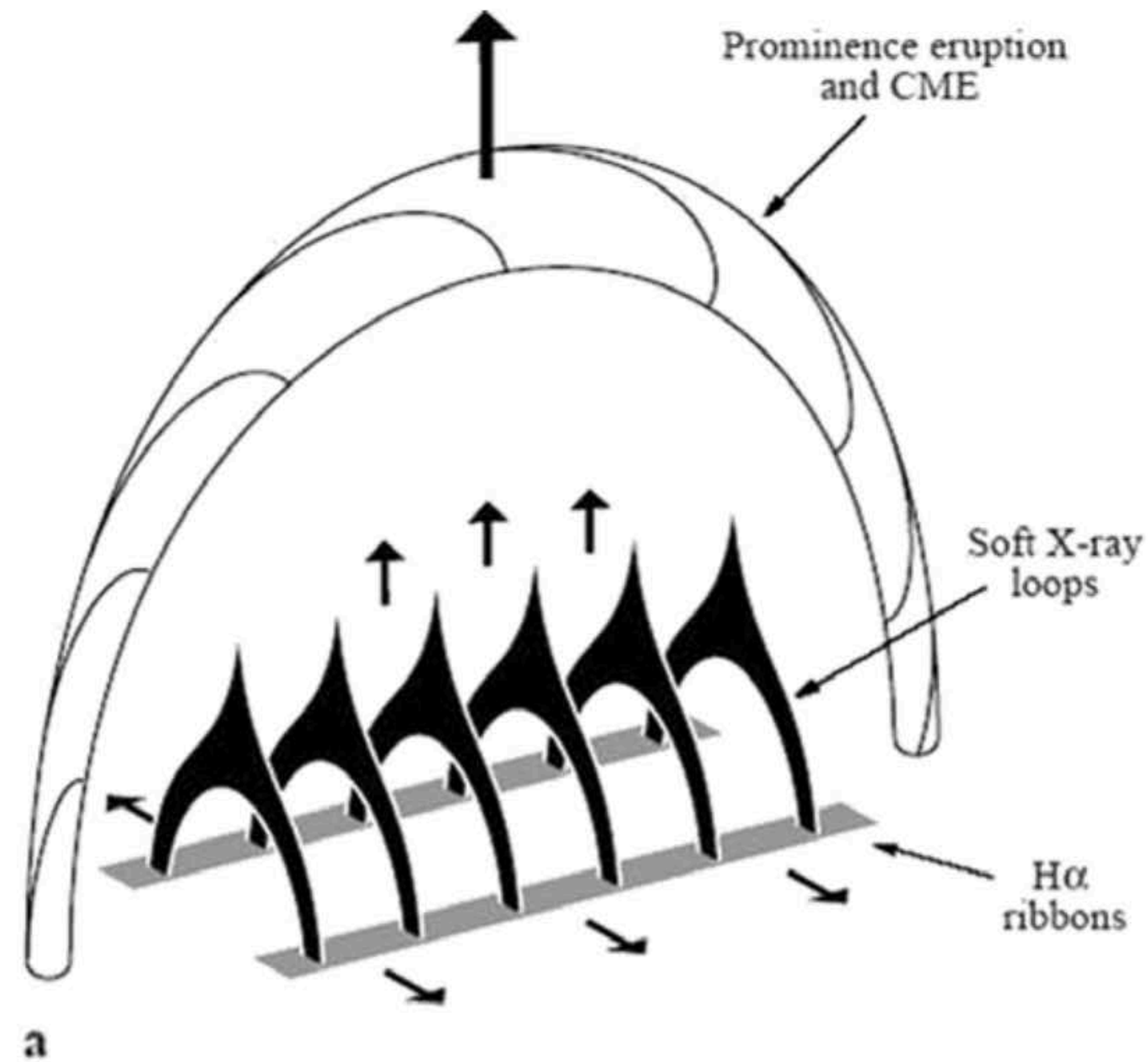
- Large amount of energy stored in a small volume that can be quickly transformed and released as energetic electrons and photons
- Only sufficient energy source is energy stored in strong magnetic fields, built up braiding of field lines
- Only mechanism capable of such a sudden energy release in the solar atmosphere:
Magnetic reconnection.

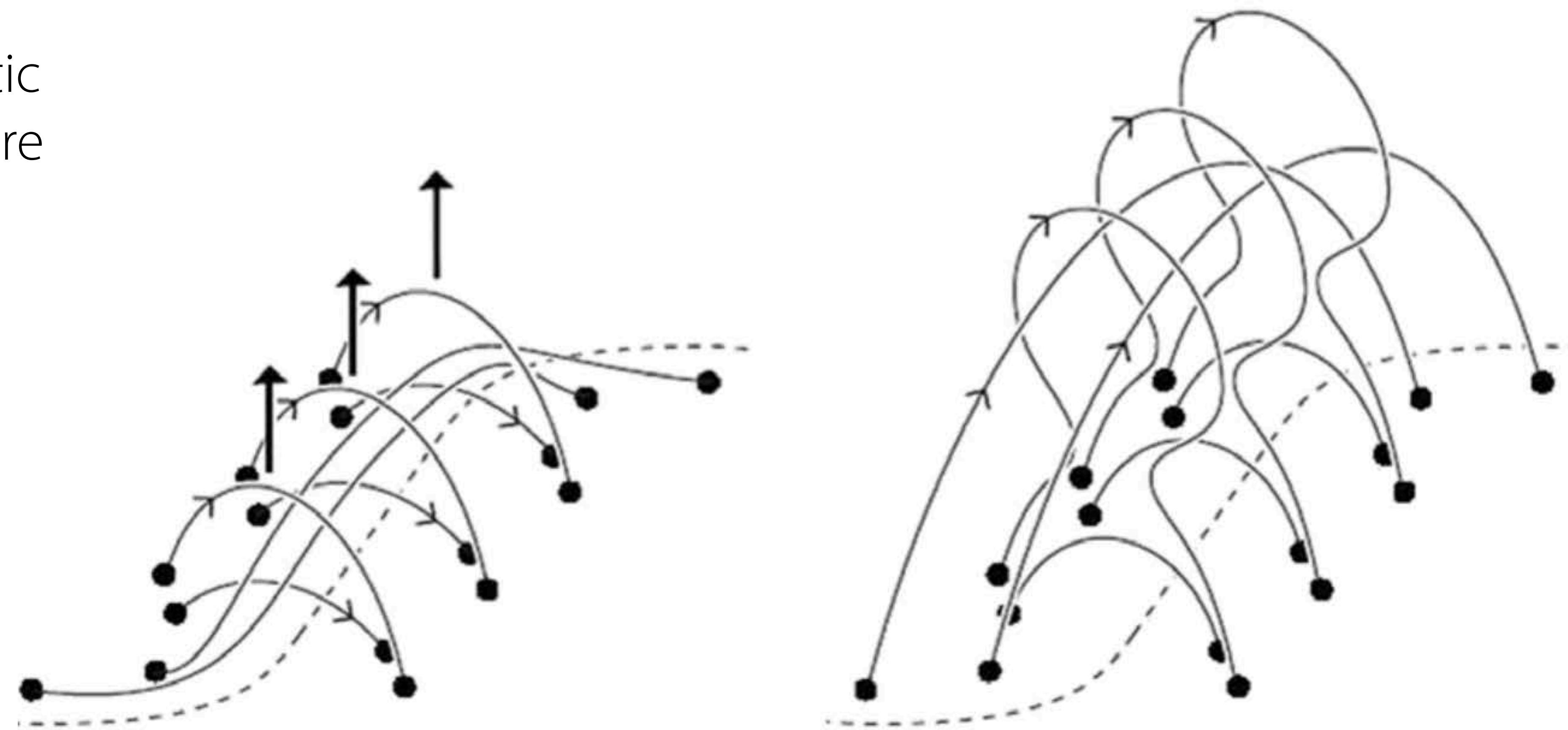


Flares

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





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

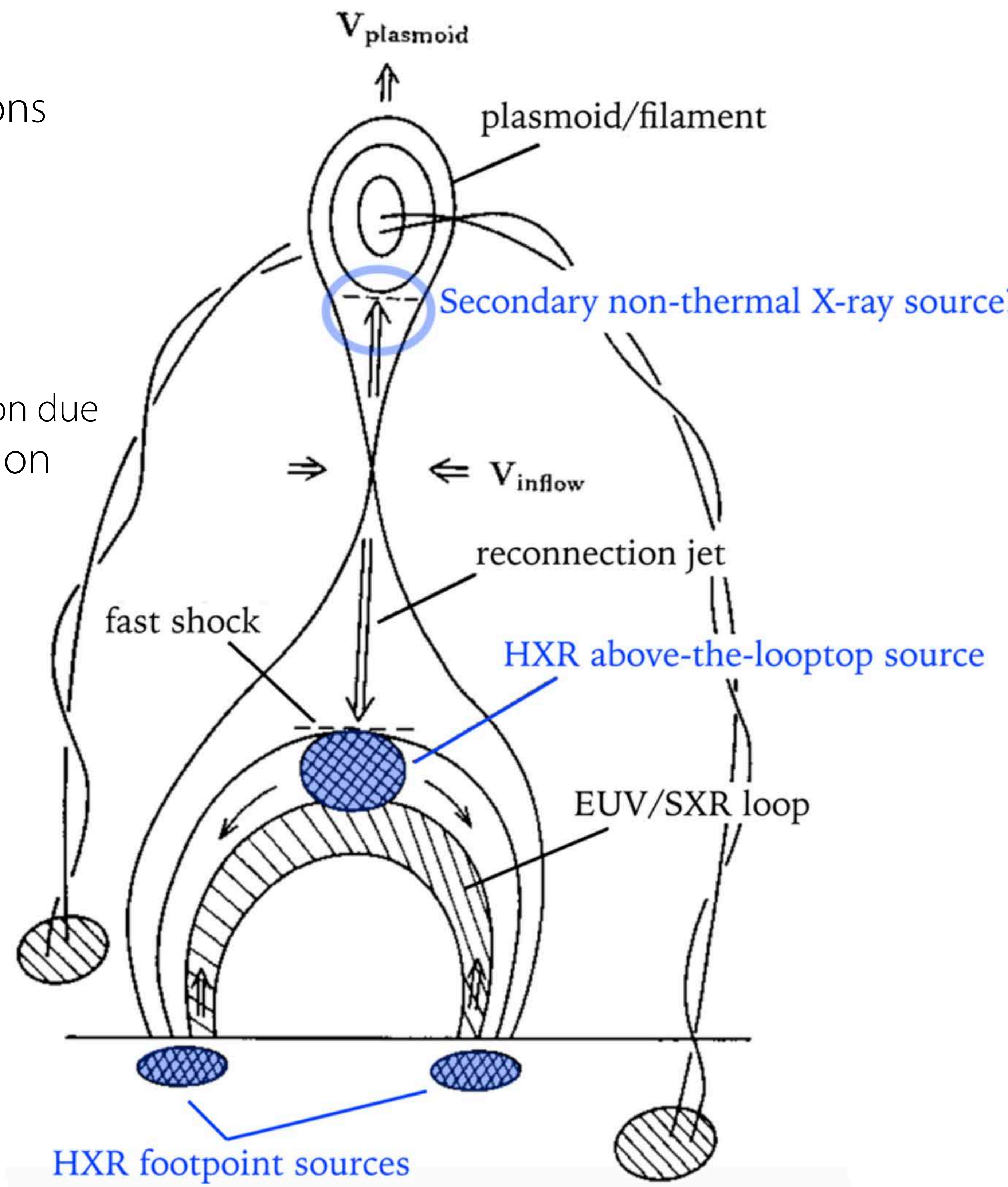
➡ Magnetic reconnection occurs.

➡ 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

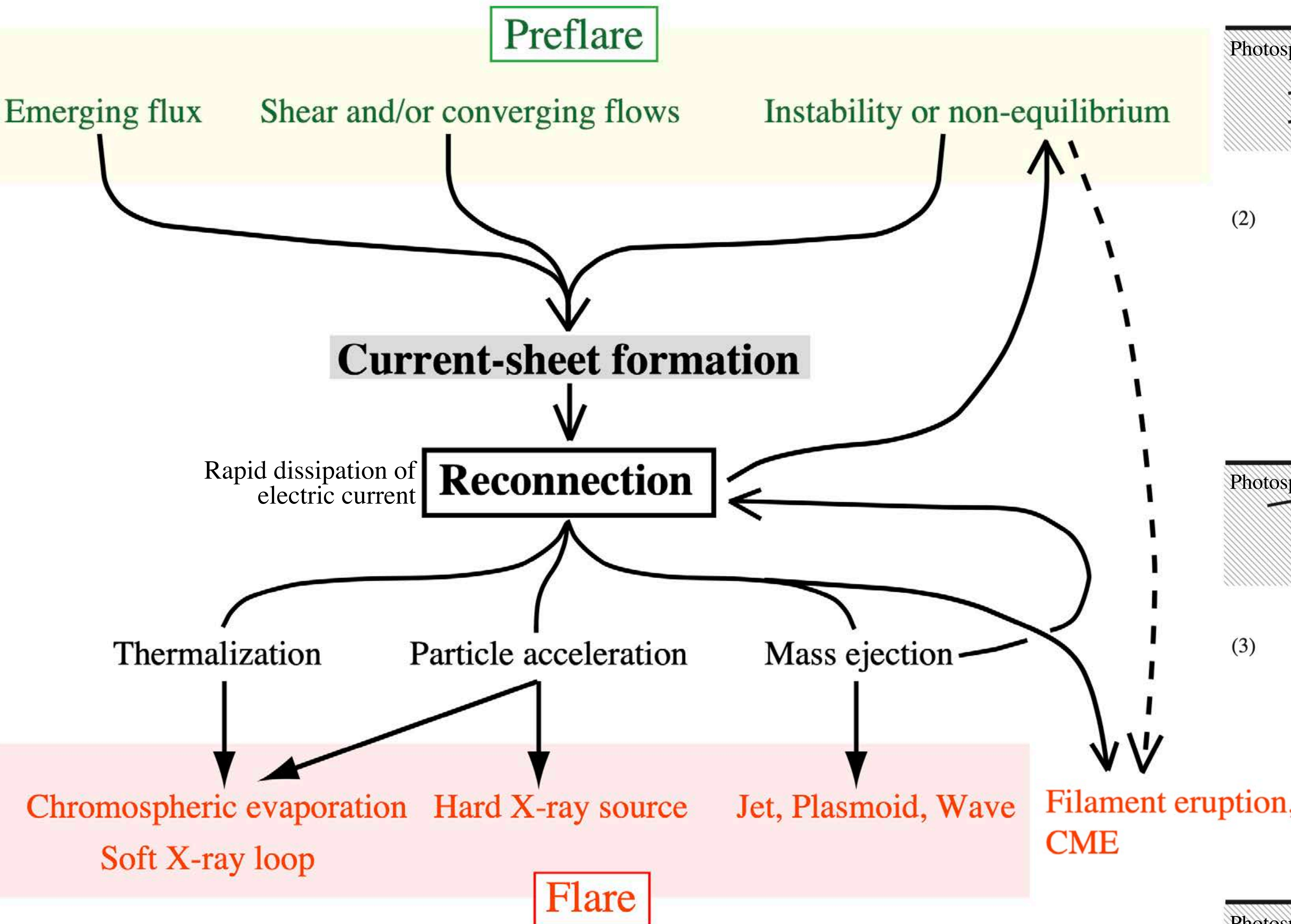
➡ Electrons accelerated at magnetic reconnection site propagate downwards and emit hard X-rays via bremsstrahlung (Brown 1971).

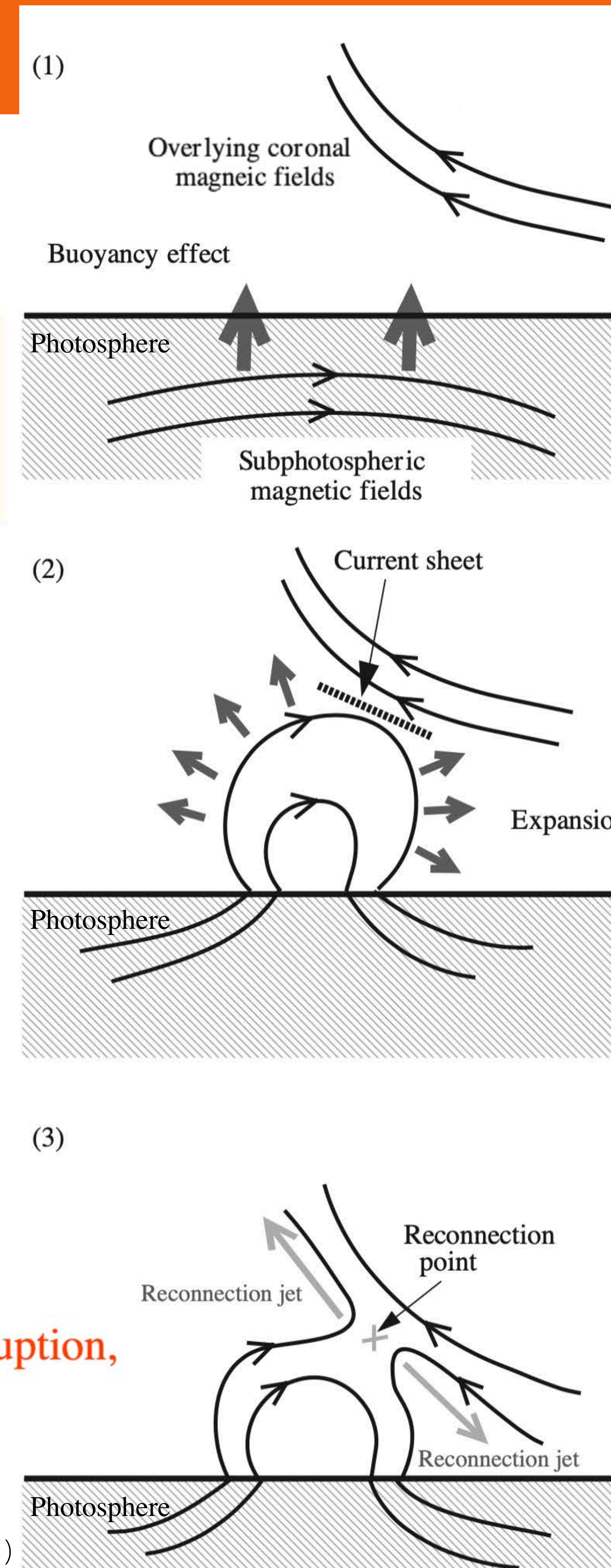


Shibata et al. (1995), Oka et al. (2018)

Flares

Physical mechanism — overview

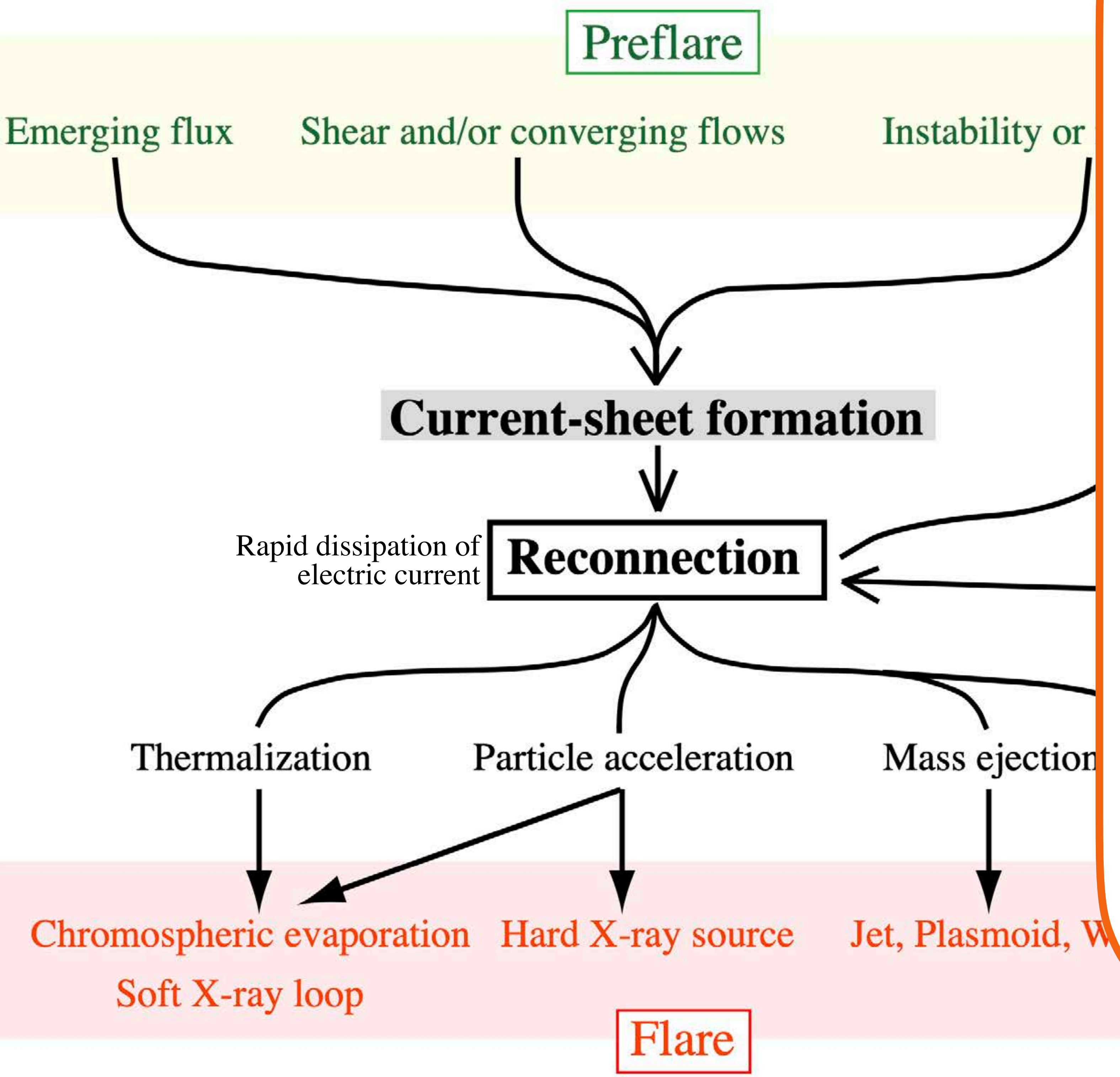




Shibata & Magara (2011)

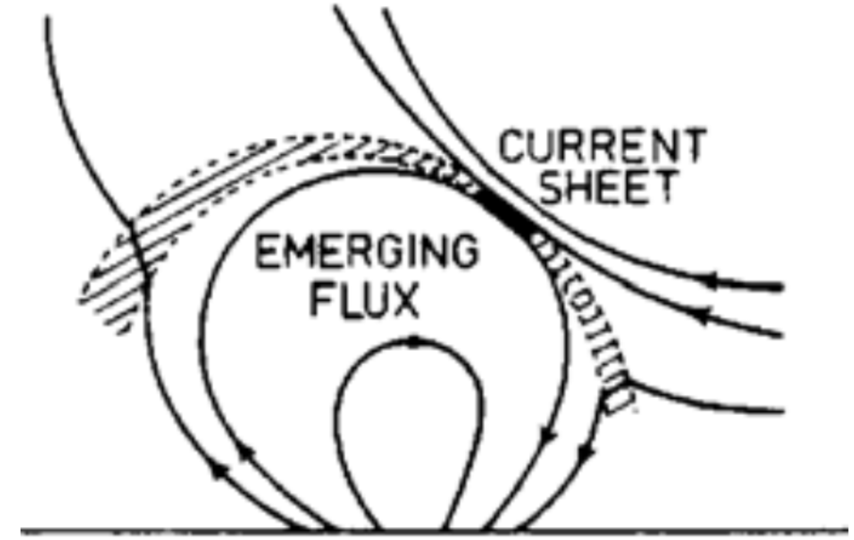
Flares

Physical mechanism — overview

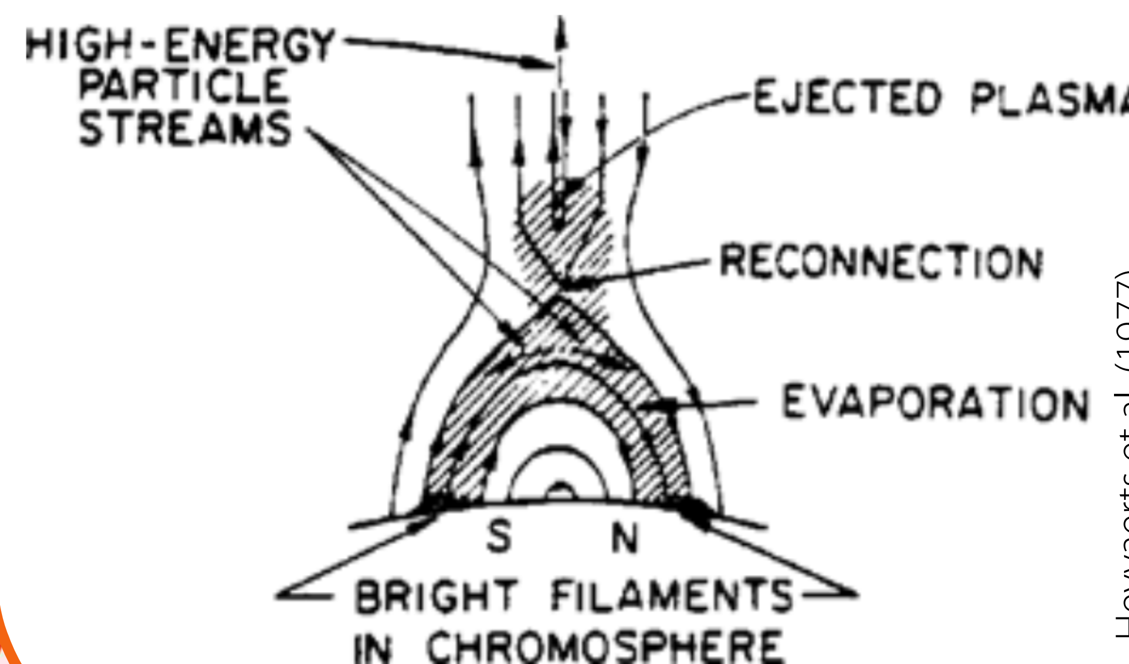


Shibata & Magara (2011)

Different possible configurations



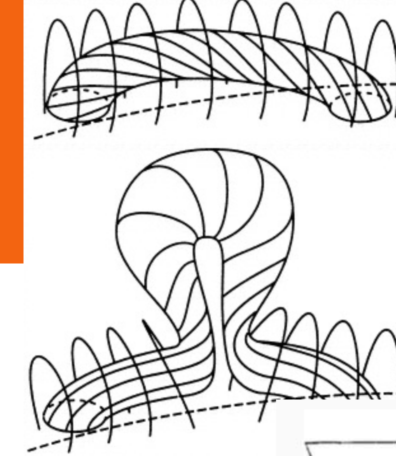
Sturrock (1980)

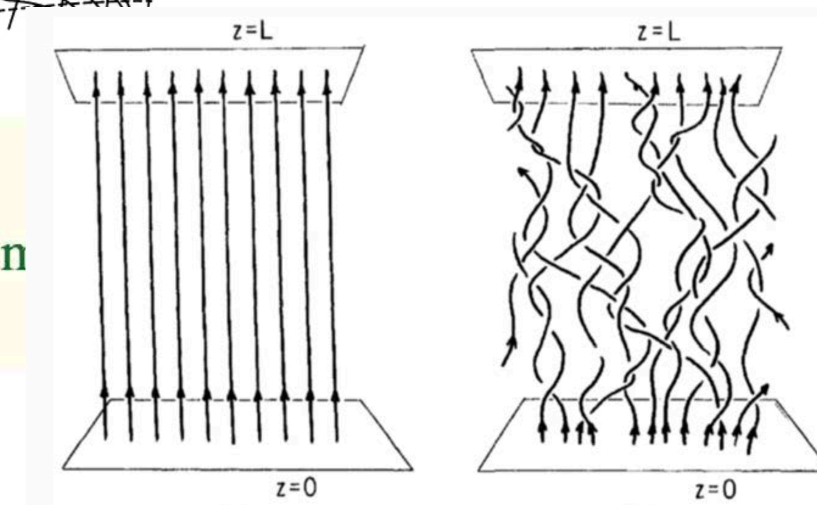


Heyvaerts et al. (1977)

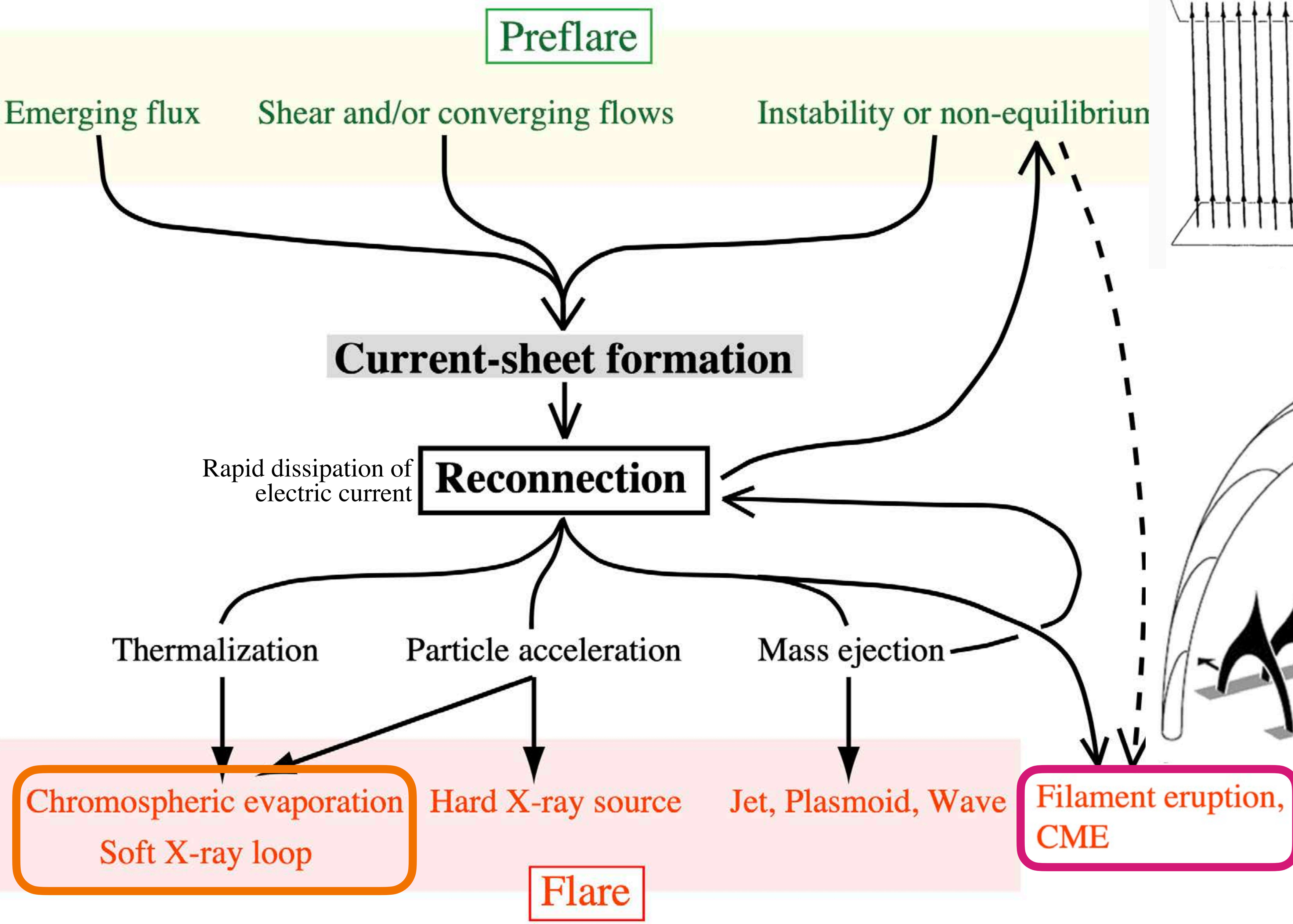
Flares

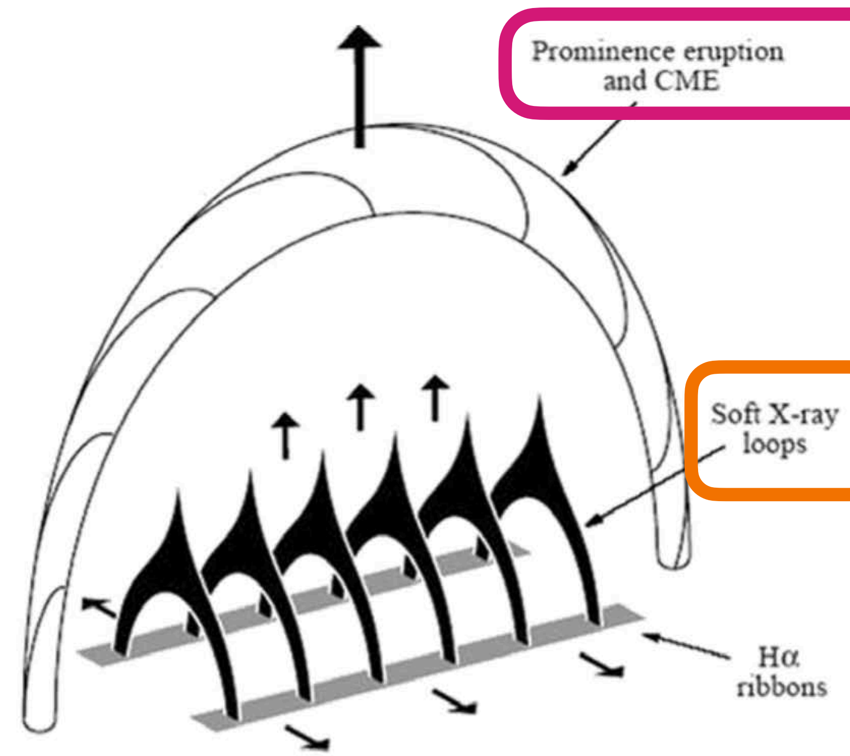
Physical mechanism — overview





Parker (1994)



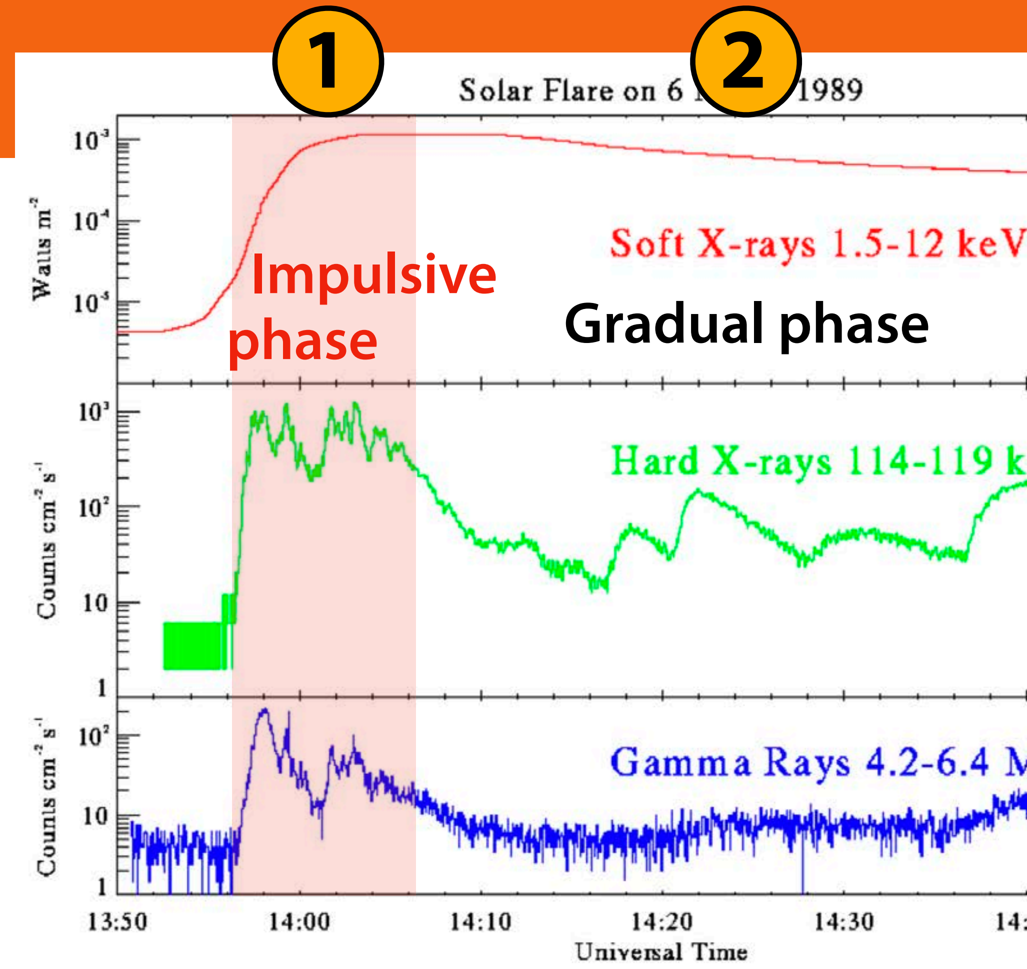


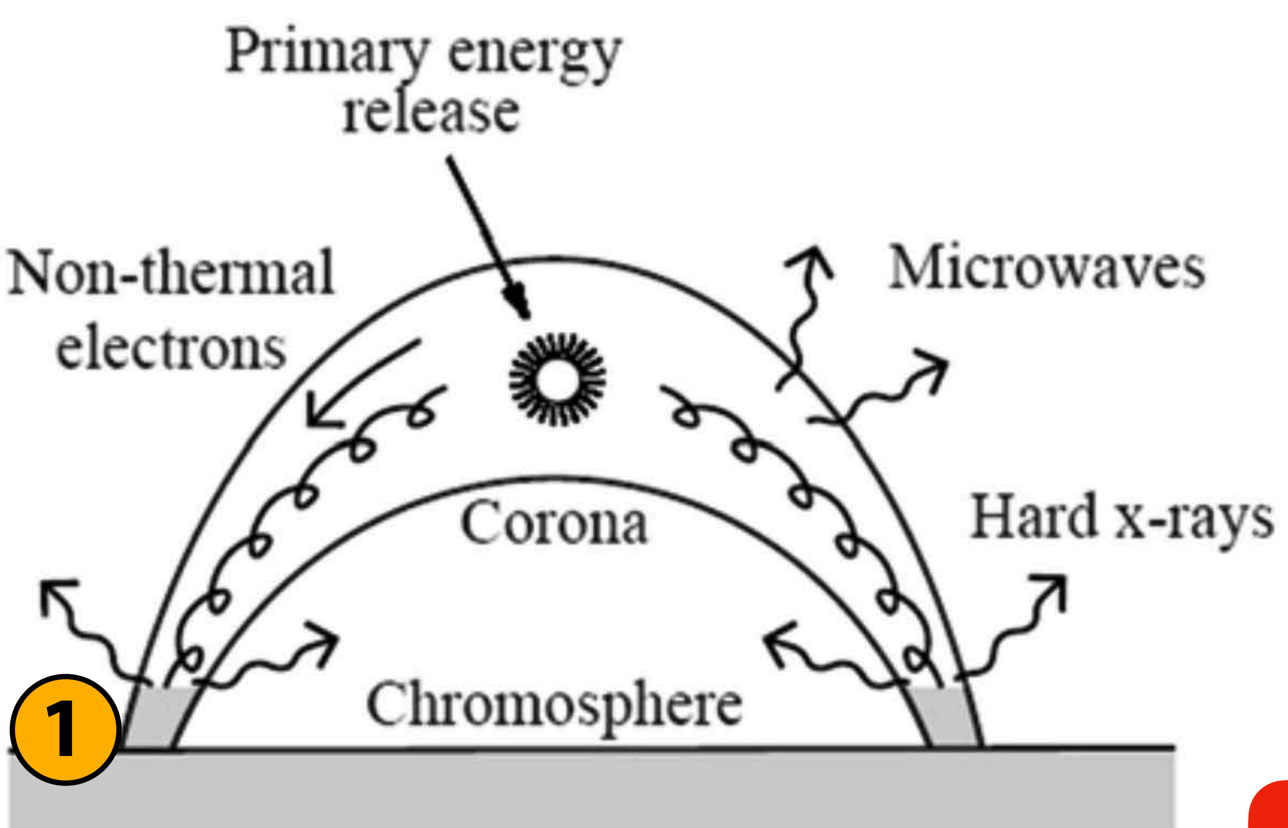
Shibata & Magara (2011)

Flares

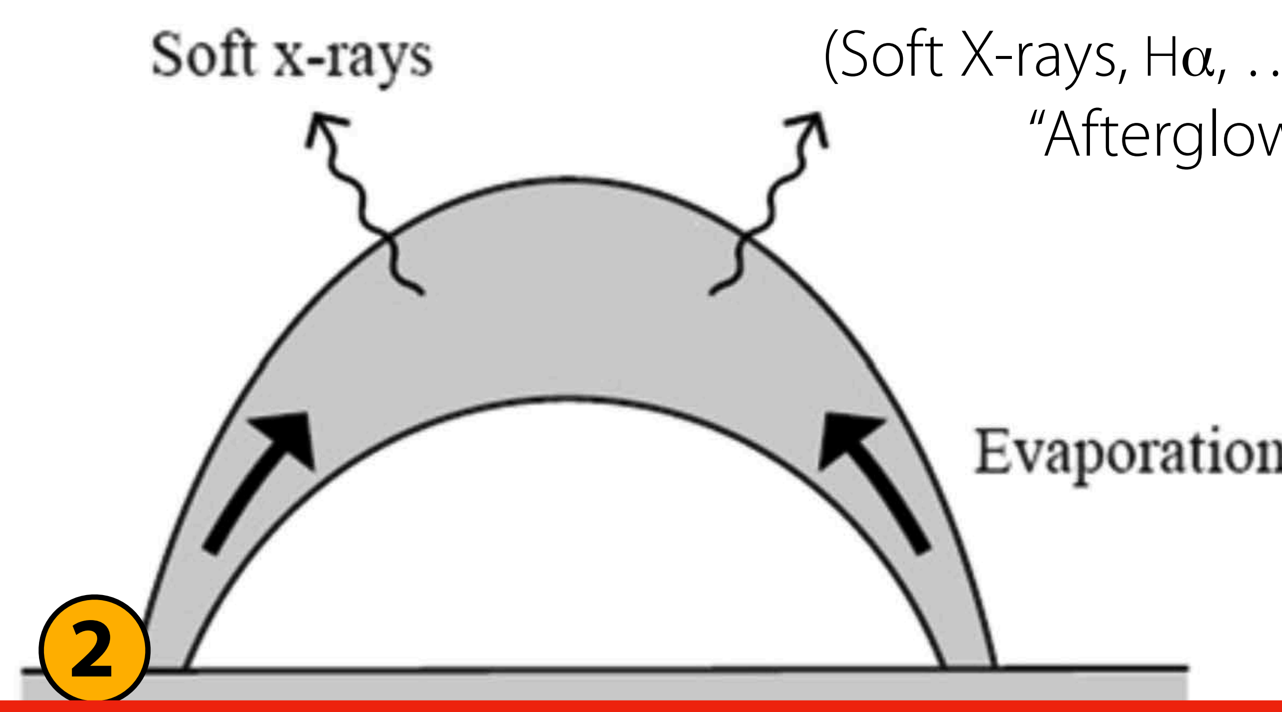
Thick target model (Brown 1971)

- Magnetic reconnection
- ➡ Plasma (electrons) accelerated away from reconnection site as oppositely directed hot jets.
- 1 ➡ Downward streaming of fast particles
- ➡ Hit denser plasma in chromosphere below, emission of hard X-rays via bremsstrahlung
- 2 ➡ Consequence: Heating ("evaporation") and upward streaming of plasma from lower atmosphere





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

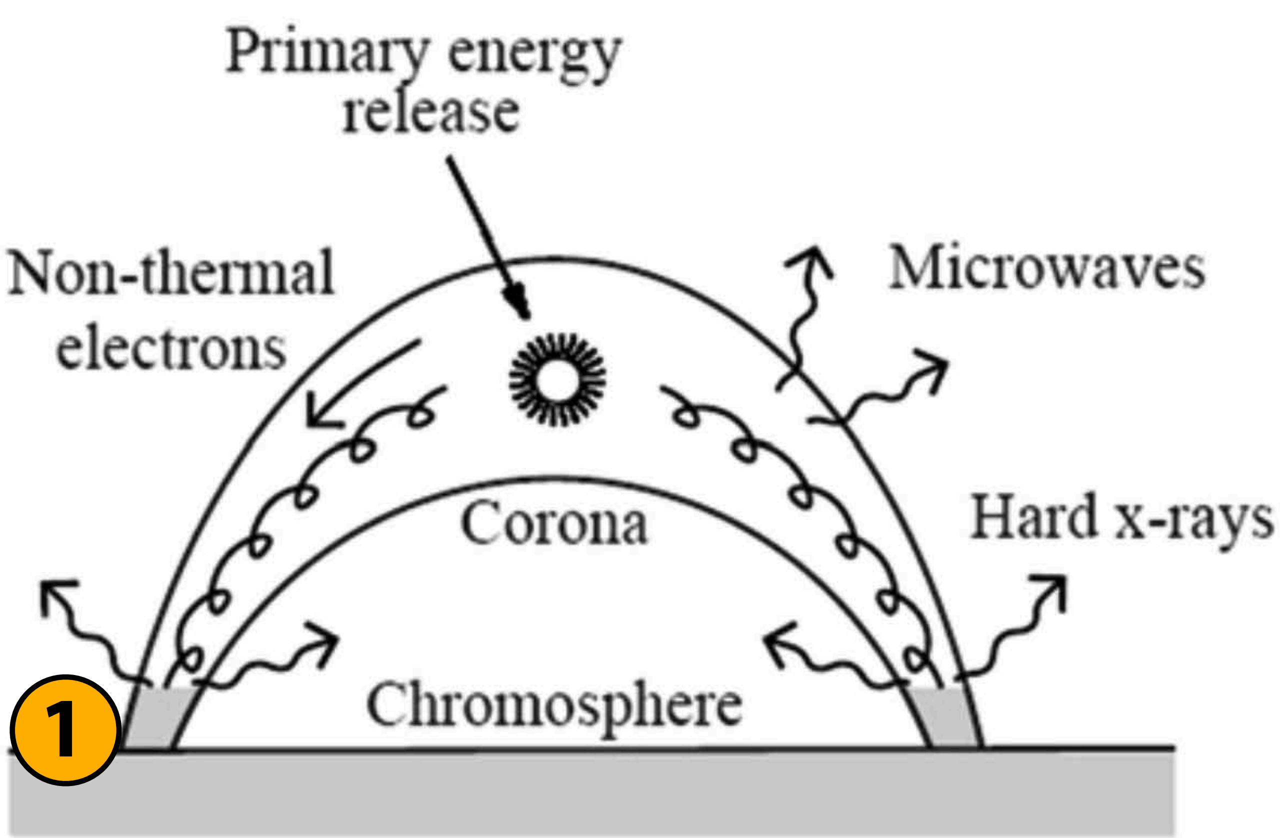


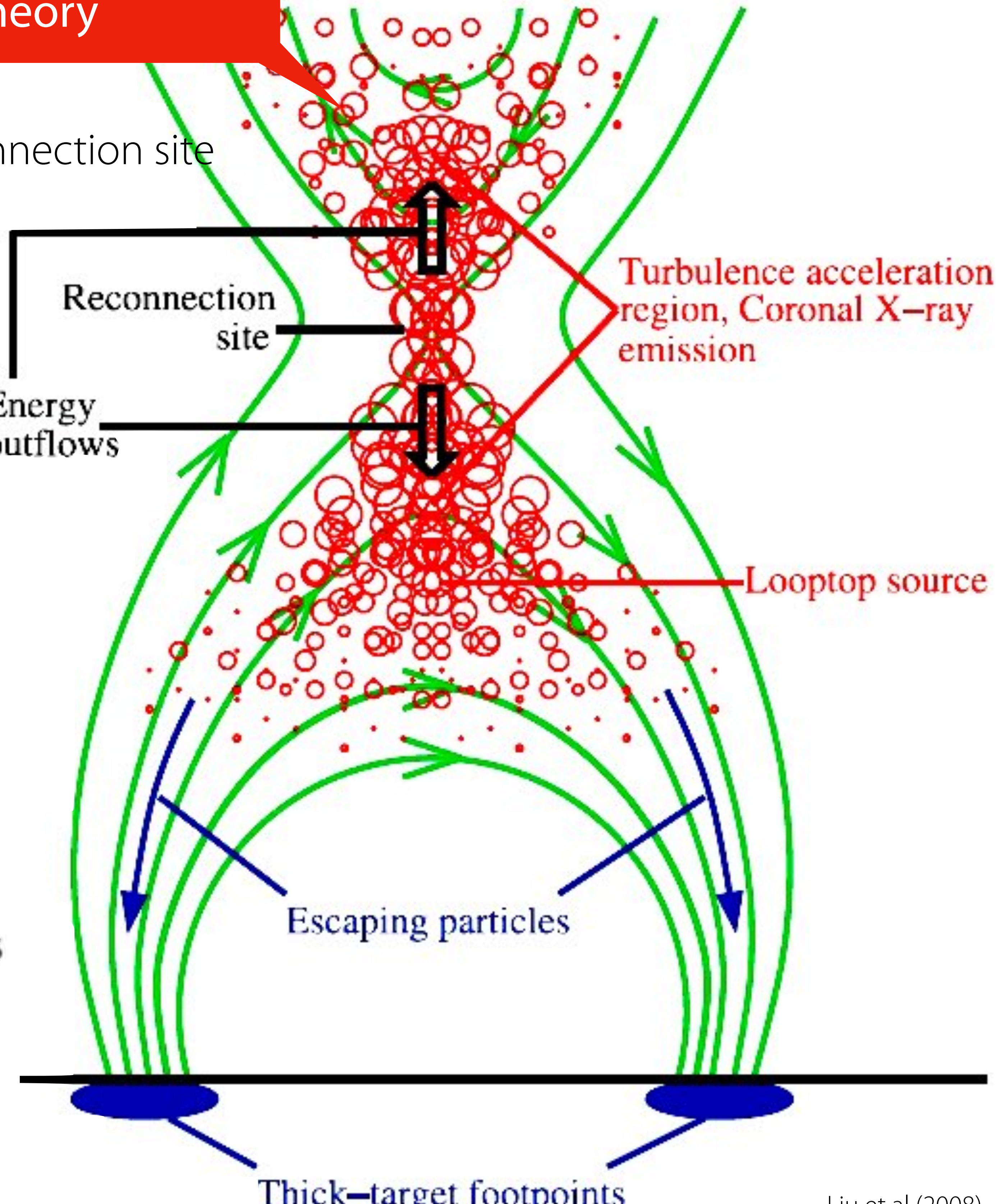
Correct model? Thin target model? Still debated.

Flares

Thick target model + Turbulent acceleration theory

- Magnetic reconnection
- ➡ Plasma (electrons) accelerated away from reconnection site as oppositely directed hot jets.
- 1 ➡ Downward streaming of fast particles
- ➡ Hit denser plasma in chromosphere below, emission of hard X-rays via bremsstrahlung

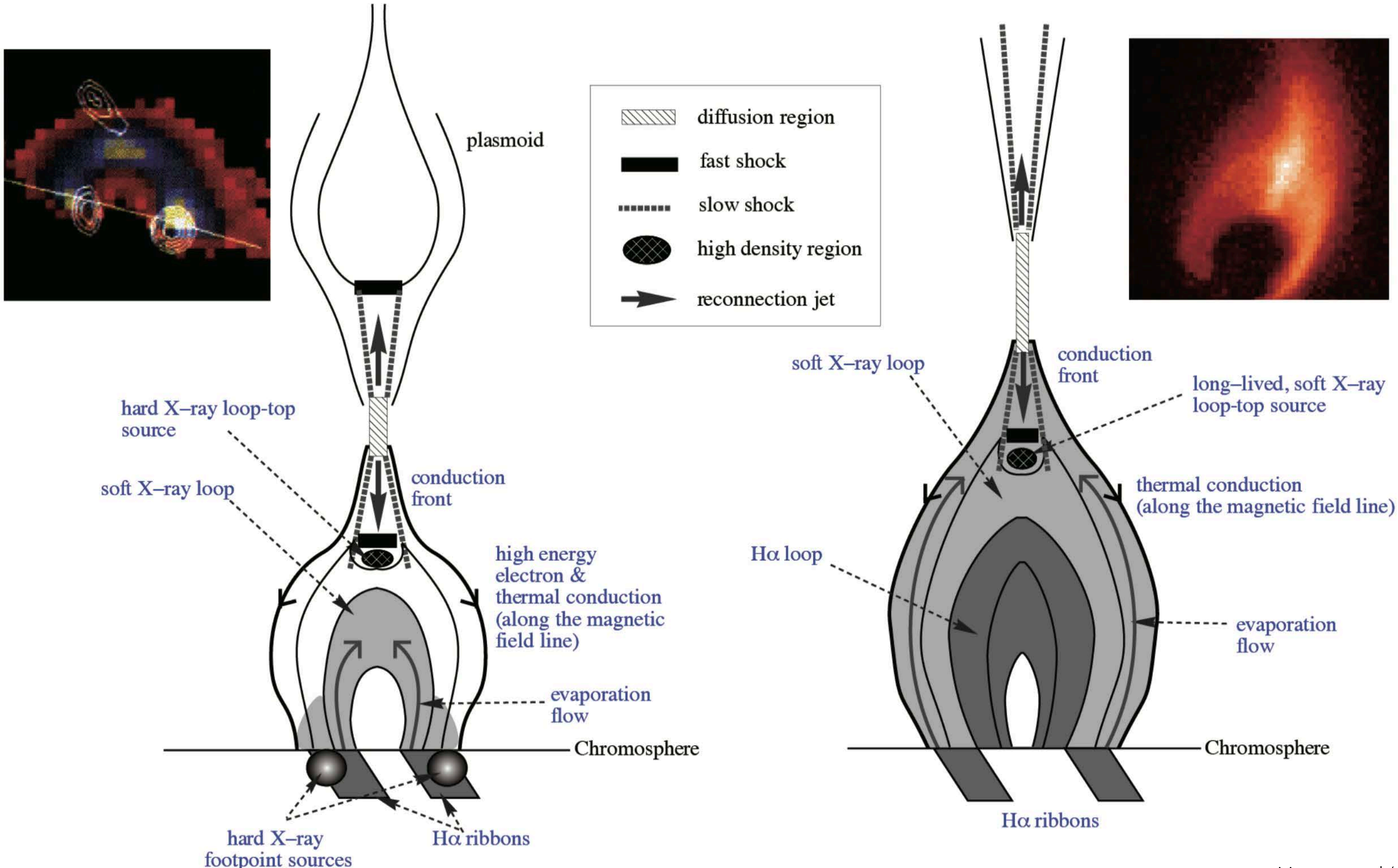




Liu et al (2008)

Flares

Impulsive and gradual phase



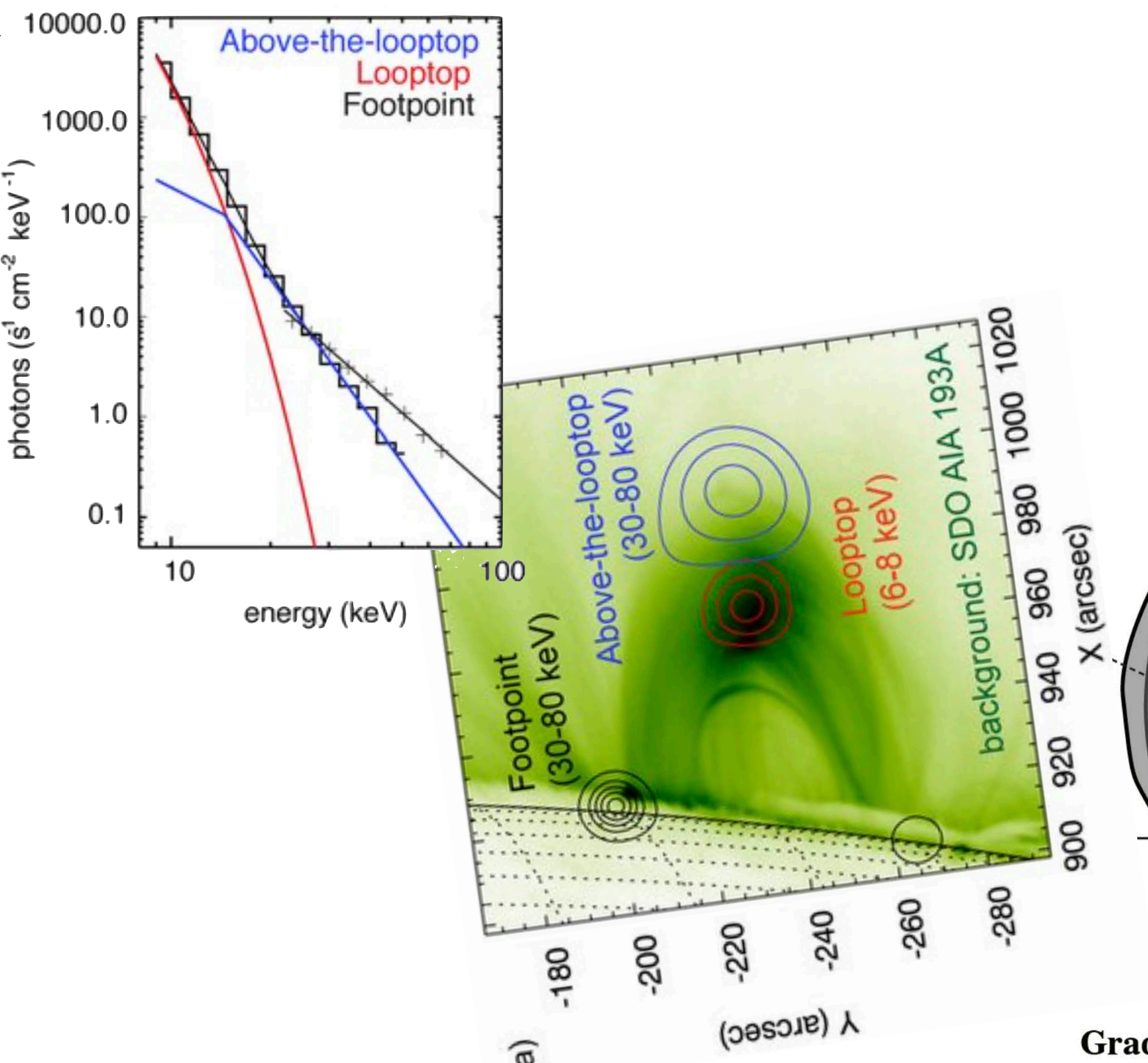
Impulsive phase (or impulsive flare) **Gradual phase (or LDE flare)**

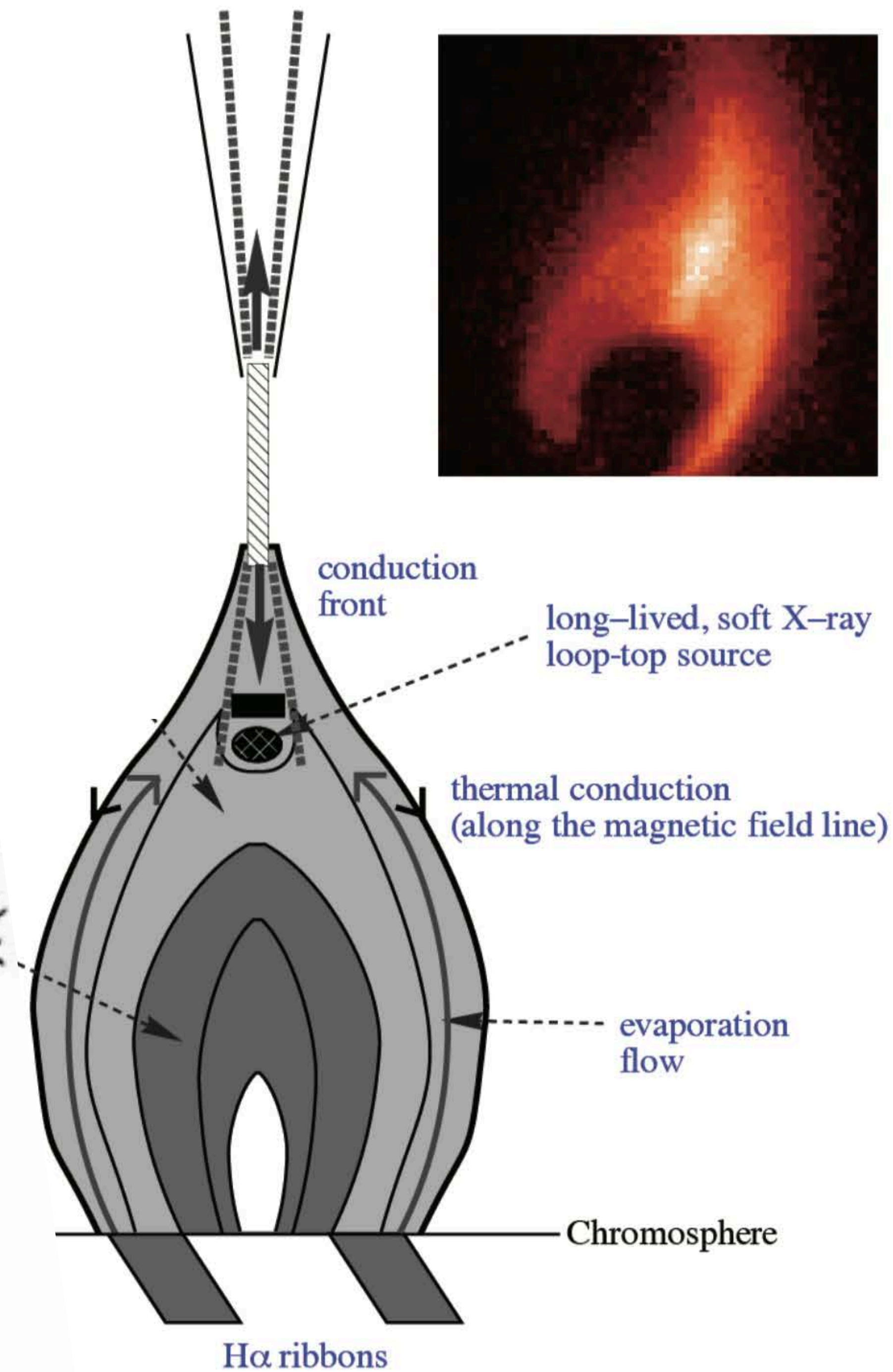
Magara et al (1996)
Masuda (1994)
Tsuneta et al (1992)

Flares

Impulsive and gradual phase

Oka et al. (2018)

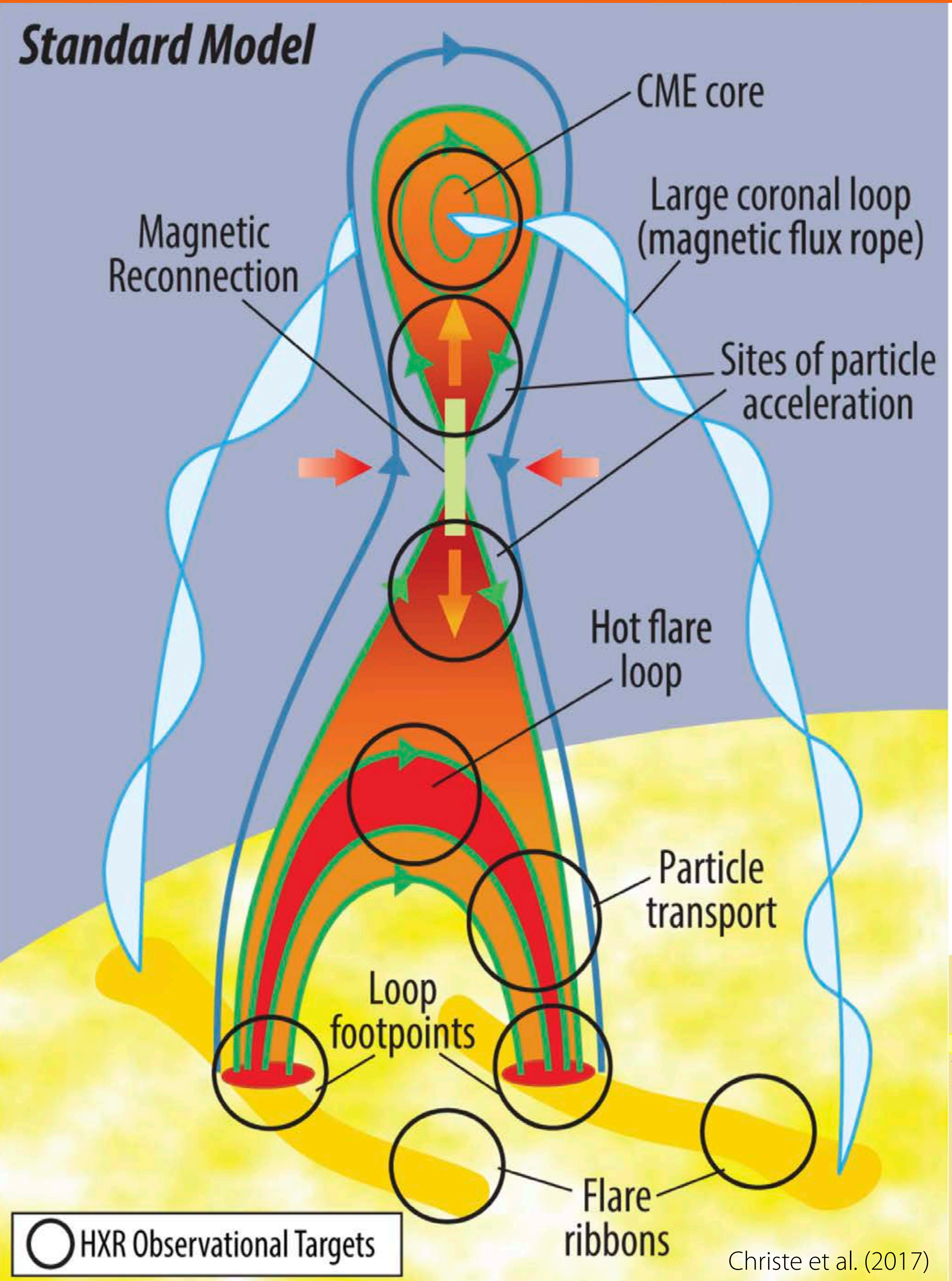




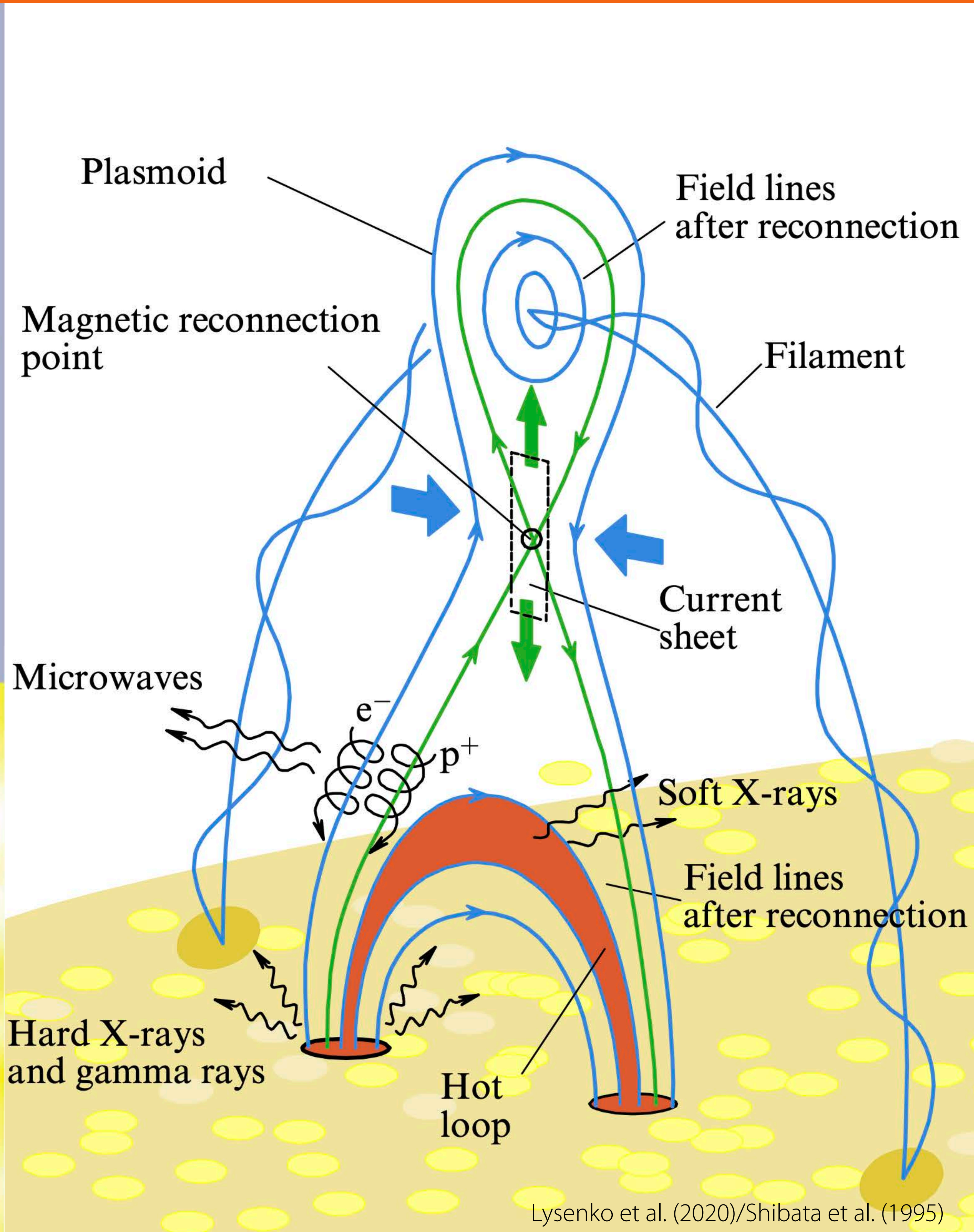
Gradual phase (or LDE flare)

Magara et al (1996)
Masuda (1994)
Tsuneta et al (1992)

Flares



Christe et al. (2017)

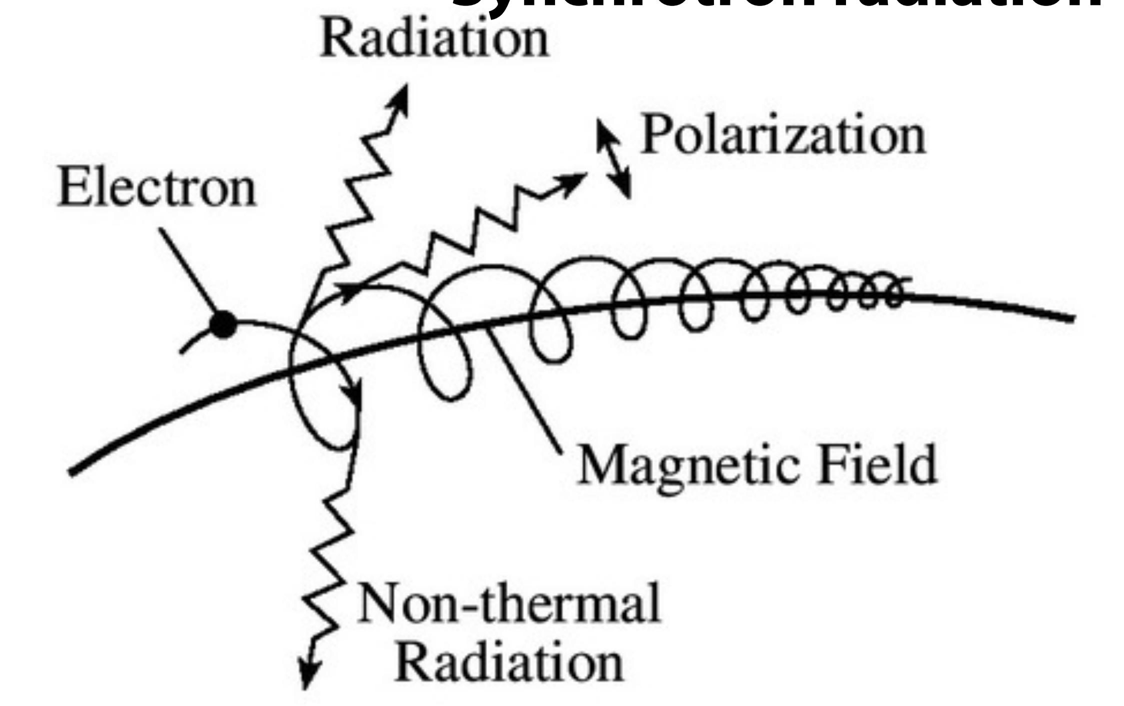


Lysenko et al. (2020)/Shibata et al. (1995)

Flares

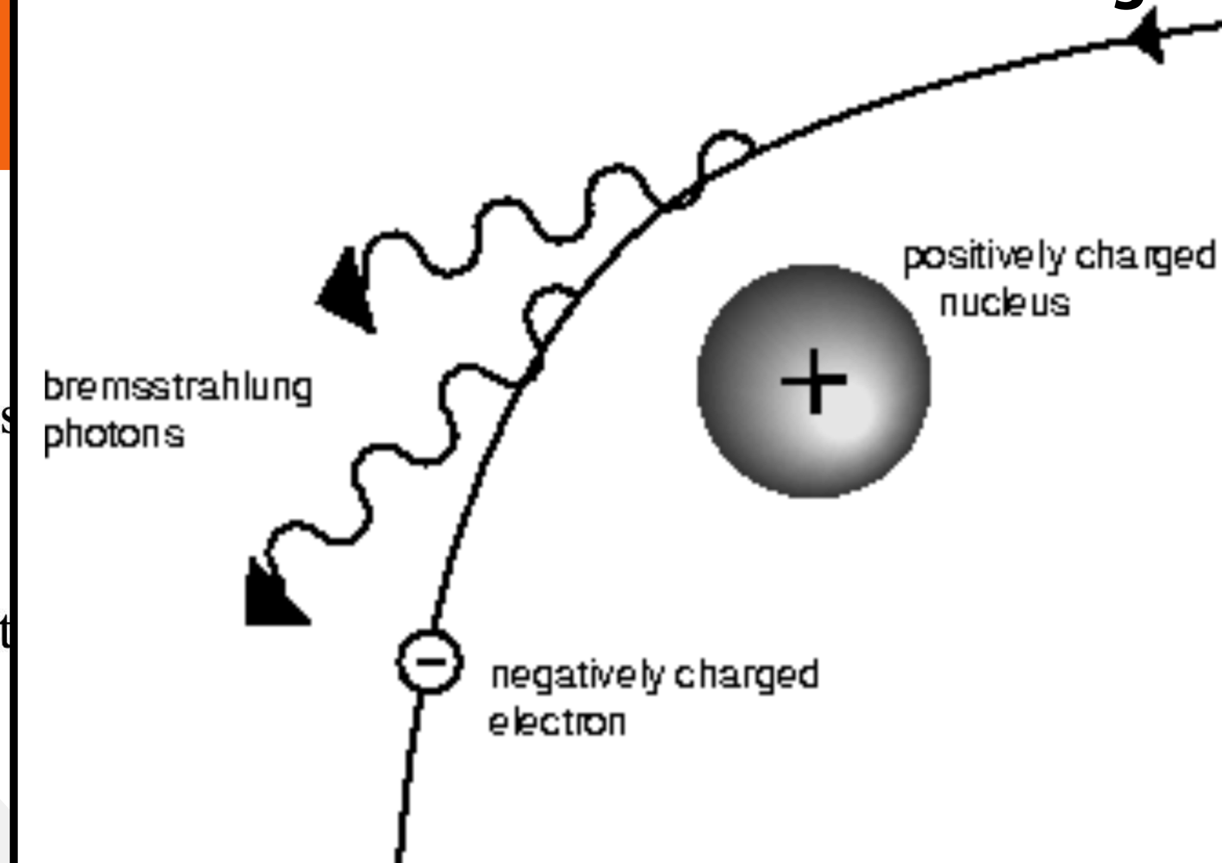
Emission mechanisms

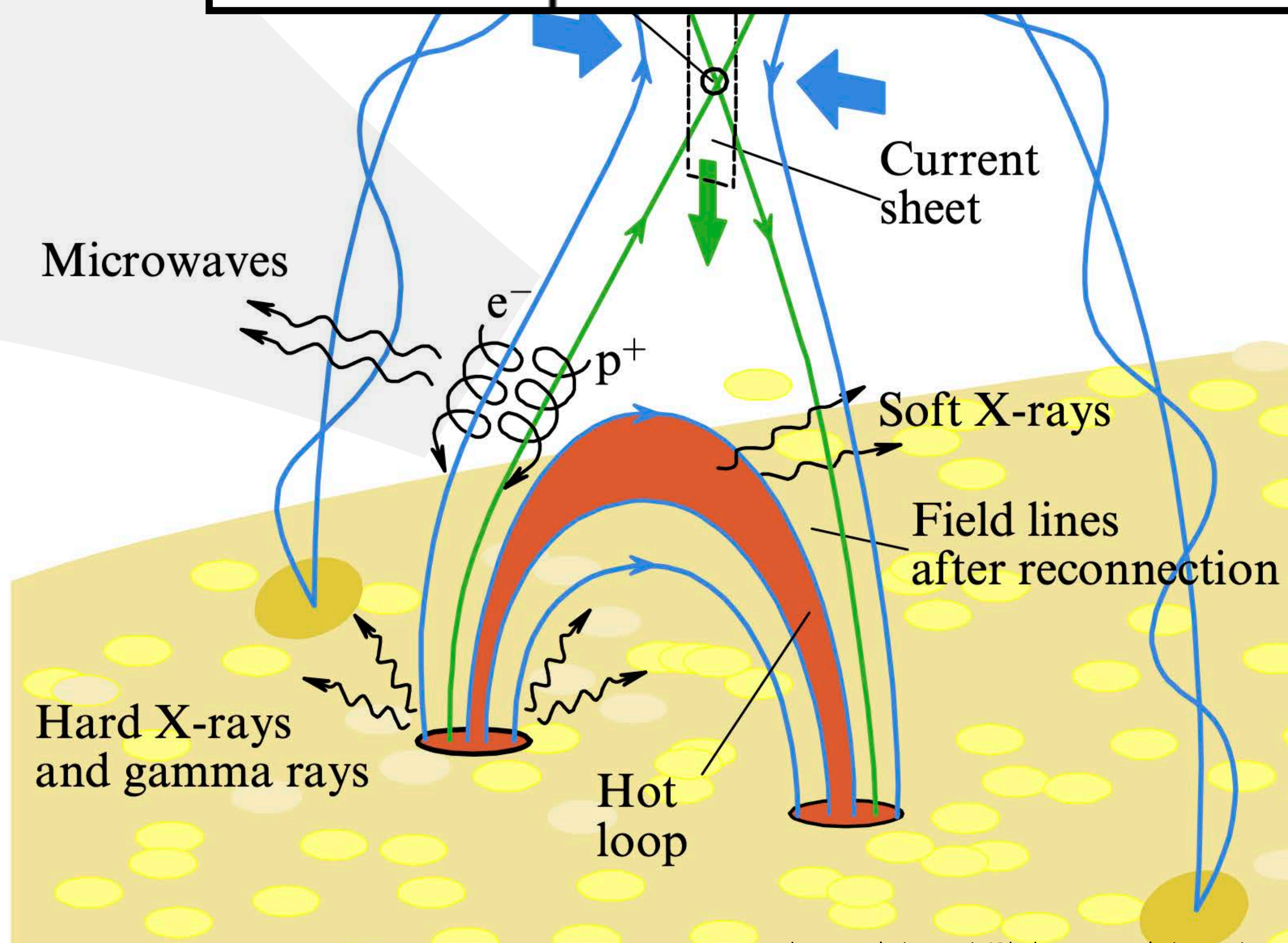
Non-thermal radiation — Synchrotron radiation



K. R. Lang, Tufts University

Thermal radiation — Bremsstrahlung





Lysenko et al. (2020)/Shibata et al. (1995)

- Electrons accelerated to relativistic speeds

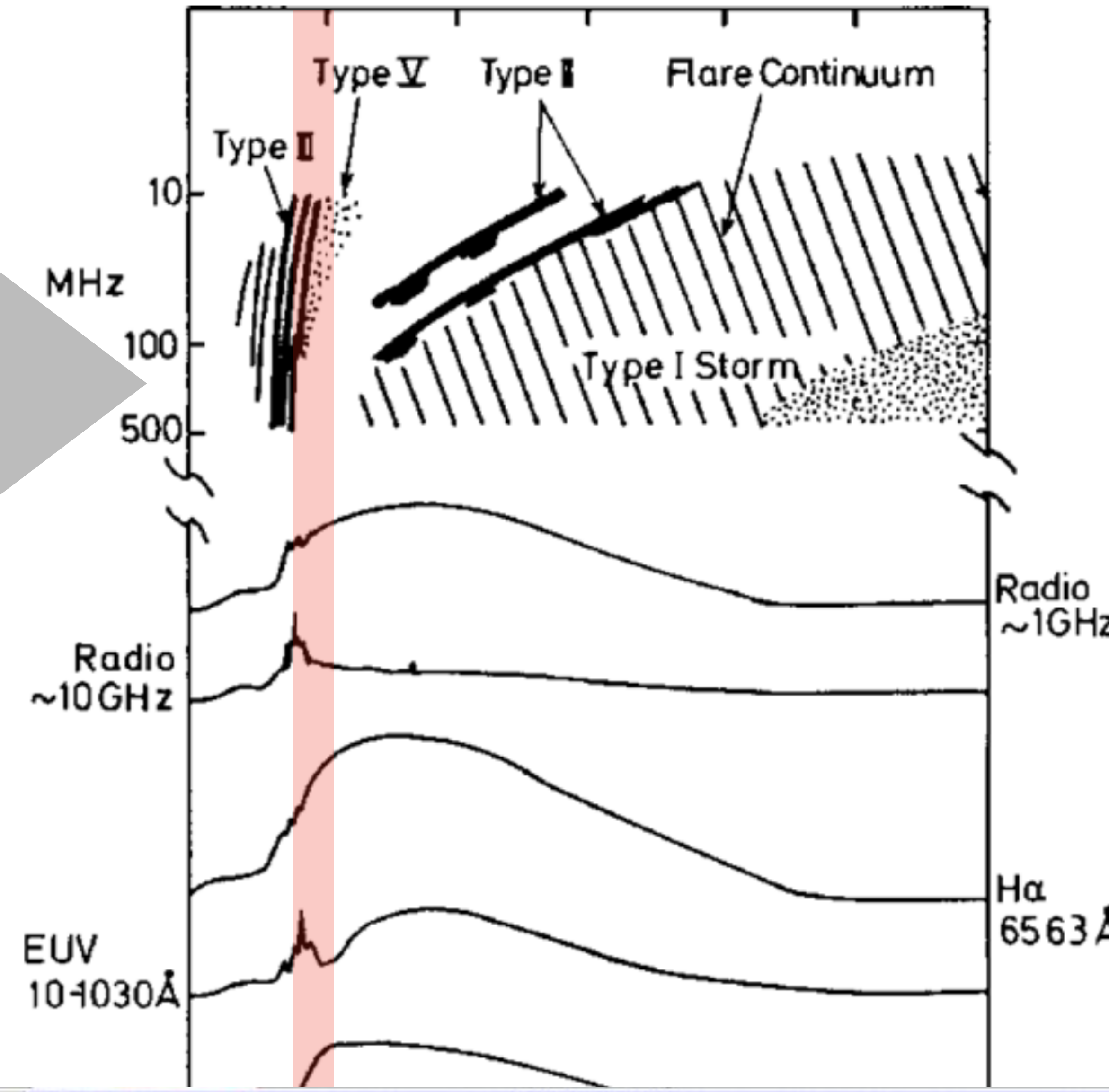
➡ Synchrotron radiation becomes beamed for electrons moving at relativistic speeds

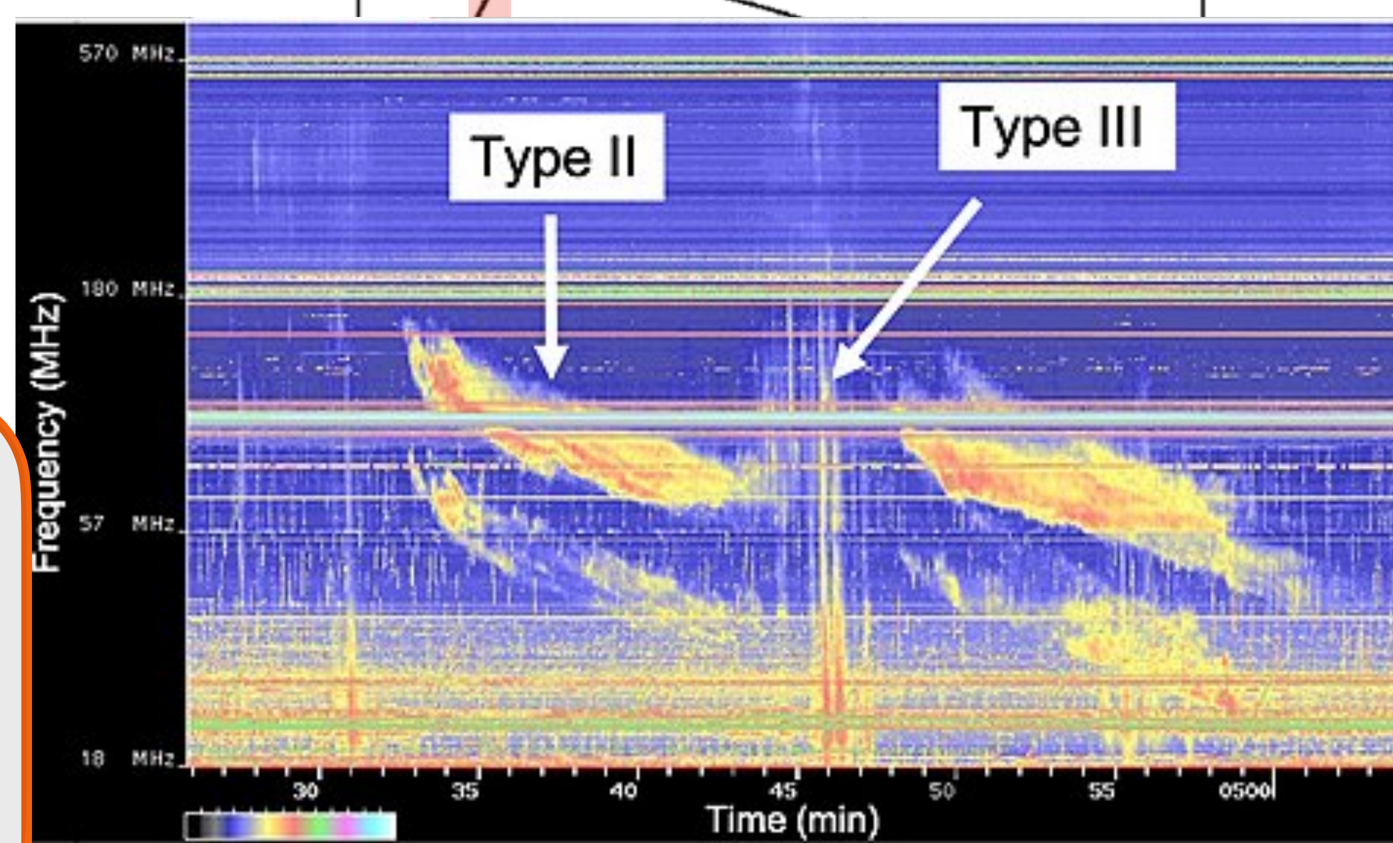
- Bremsstrahlung when particles are decelerated when hitting denser plasma and/or in hot plasma due to thermal particle motions (spectrum related to plasma temperature)

Flares

Radio Bursts

- **Radio wavelengths > 0.1 m** : eruptive events recorded since first discovery of solar radio signals (~1942)
- Many radio bursts associated with flares
- **Classification: Types I to V** (Wild 1959).
- Types II and III most characteristic due to banded structure in a frequency-time diagram.
- Lowest (fundamental) band is interpreted in terms of the local plasma frequency ν_P, higher bands are harmonics to ν_P
- Due to motion of emitting sources across the corona (change in density)





Plasma frequency

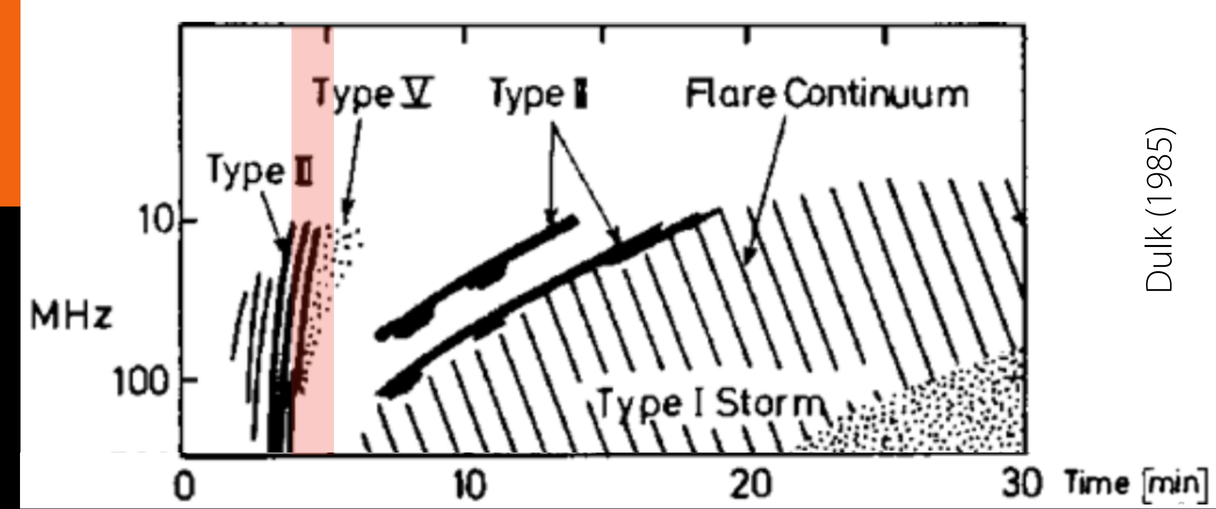
$$\nu_P = \frac{e}{2\pi}\left(\frac{n_e}{\varepsilon_0 m_e}\right)^{1/2}$$

Electromagnetic waves with frequency < ν_P cannot propagate, will be absorbed or reflected

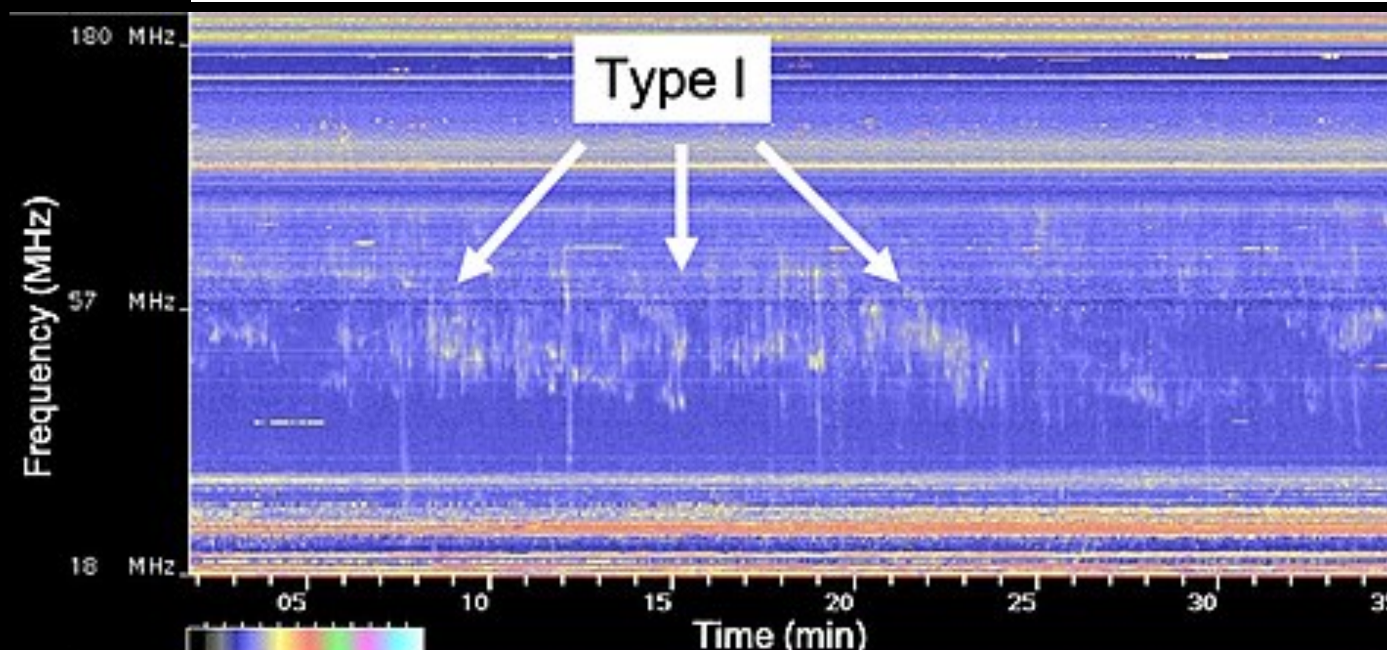
Flares

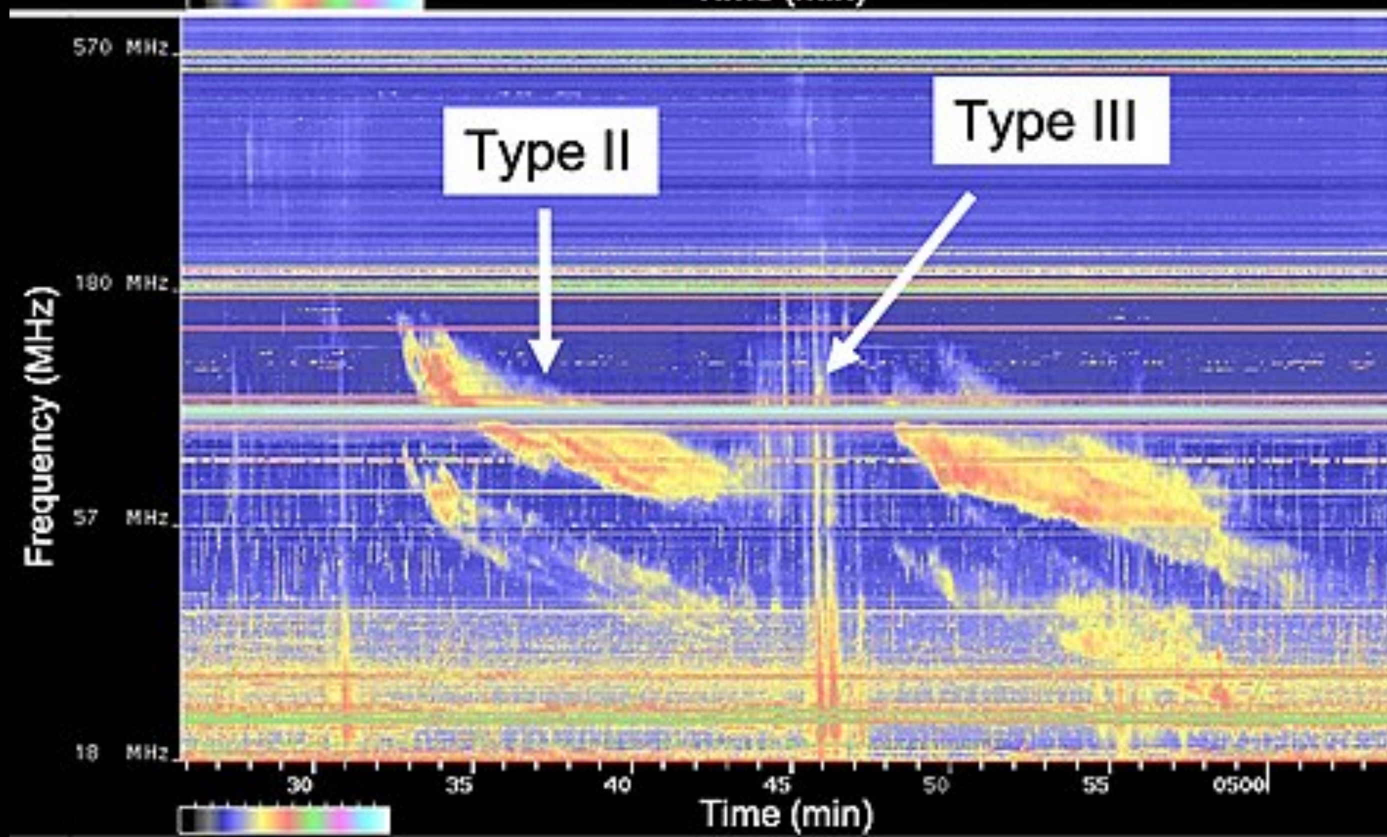
Radio Bursts

- **Type III:** during impulsive flare phase, simultaneously with hard x-ray emission
  - Fast frequency drift corresponding to velocities of 10^4 - 10^5 km/s (consistent with 10–100 keV electrons)
- **Type II:** occur after type III
  - Move more slowly ($v \sim 10^3$ km/s), consistent with velocity measured for the coronal mass ejections
  - Explanation: Source propagates outwards through corona (shock wave generated by a flare or eruptive prominence)
- **Type I:** Noise storms due to plasma emission in Active Regions
- **Type IV-V** and additional types: associated, less common



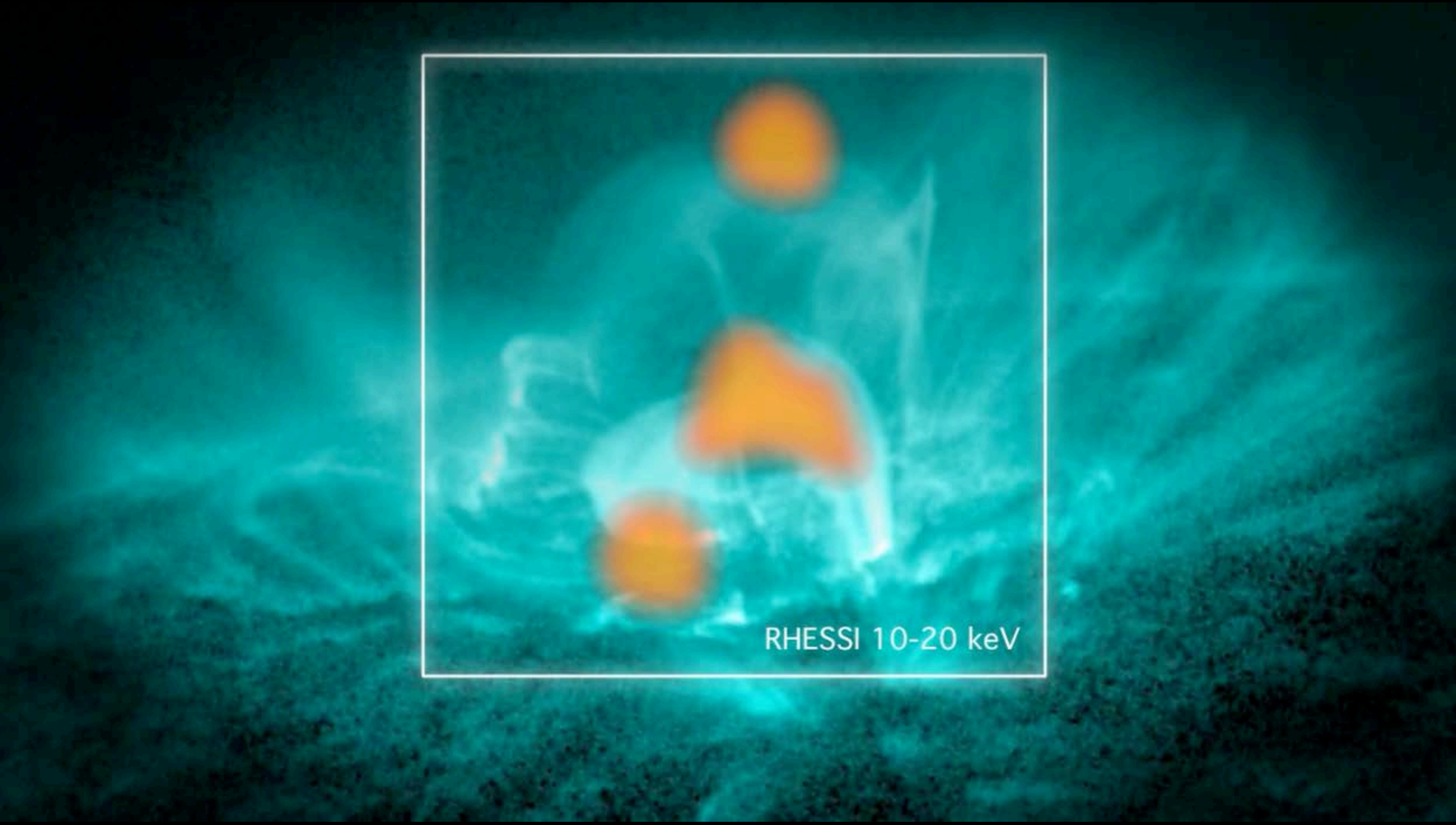
Dulk (1985)





Flares

Observational evidence for reconnection



Flares

Numerical simulations

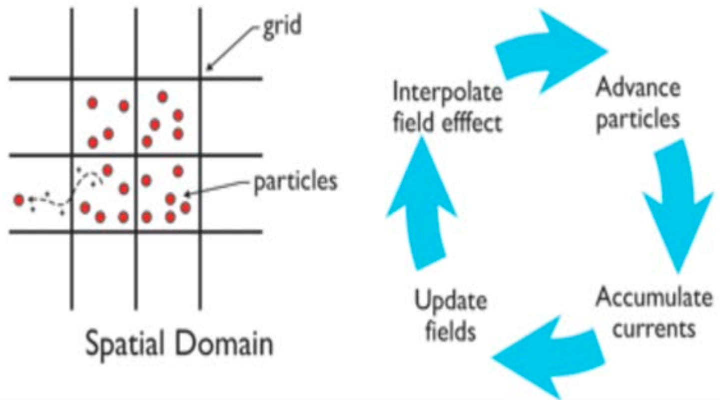
Flares

Flares — Challenges for understanding and modelling

- **Spatial scales:**
  - Particle trajectories on scales: ~1cm (electron Larmor radii)
  - Typical thickness of a current sheet: ~100 – 1000 m
  - Coronal loops, filaments — height, length: several Mm to 10-100Mm
- **Time scales:**
  - Kinetic processes: as small as 10^{-9} s
  - Global flare evolution: minutes to hours
- **Plasma conditions** (especially in the current sheet) cannot be described adequately using fluid approach (i.e. (ideal) MHD)

  ➡ Requires kinetic description (i.e. on particle level)

- **Current numerical approach**:
  - Simplifying assumptions and approximations needed to render problem computationally feasible
  - Particle-in-cell (PIC) method
    - Iterative method for solving the evolution of a system of particles (here: charged particles in a magnetic field)
    - Uses macro-particles to represent many real-particles

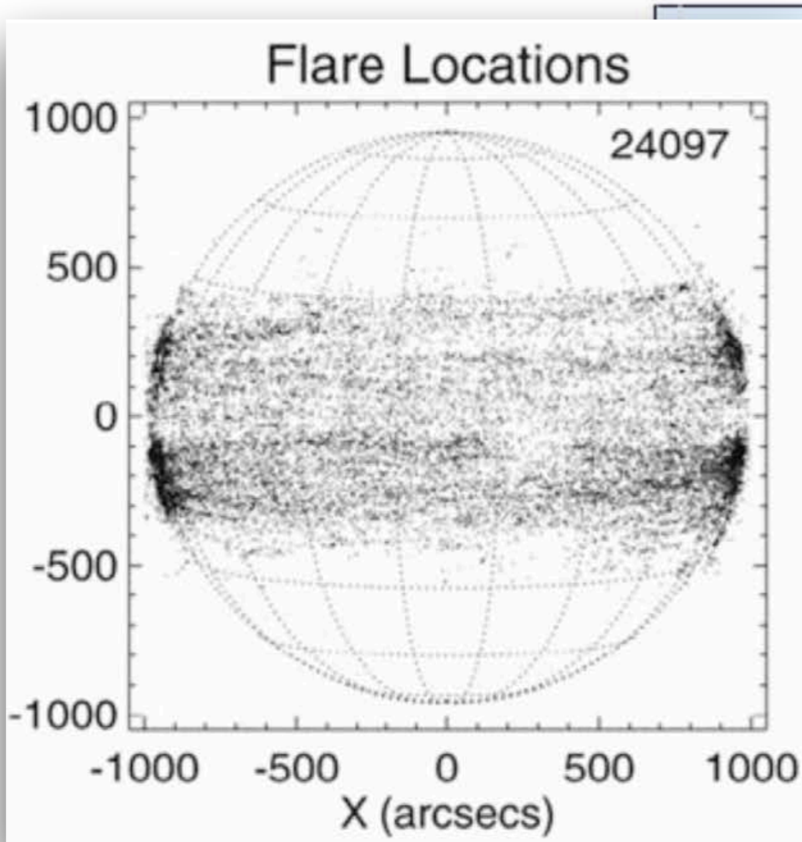


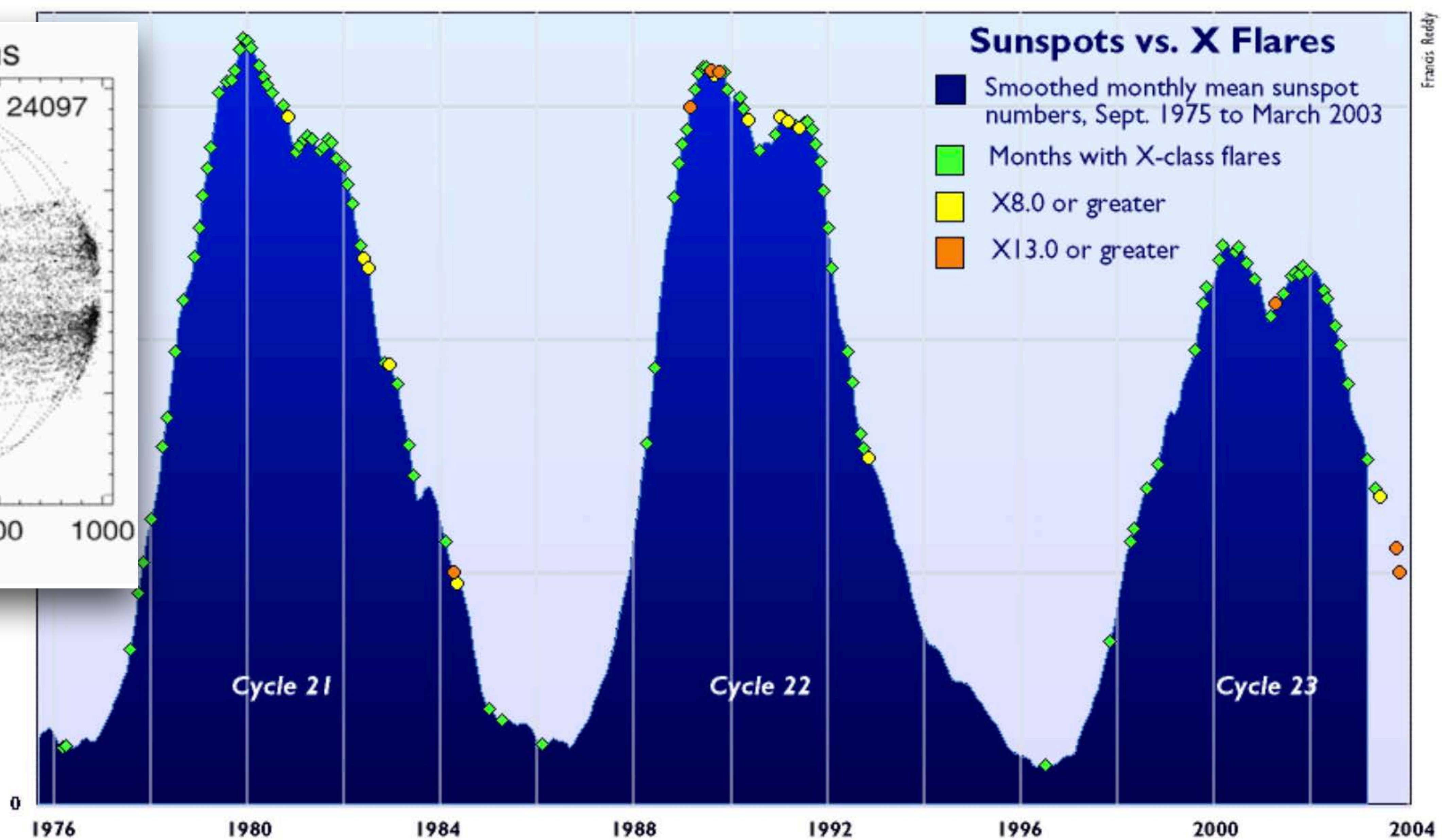
Flares

Occurrence of major (X-class) flares over the solar cycle

- Flares occur in Active Regions

➡ Number of flares (and X-class flares) thus varies with the number of present sunspots and thus with the solar cycle

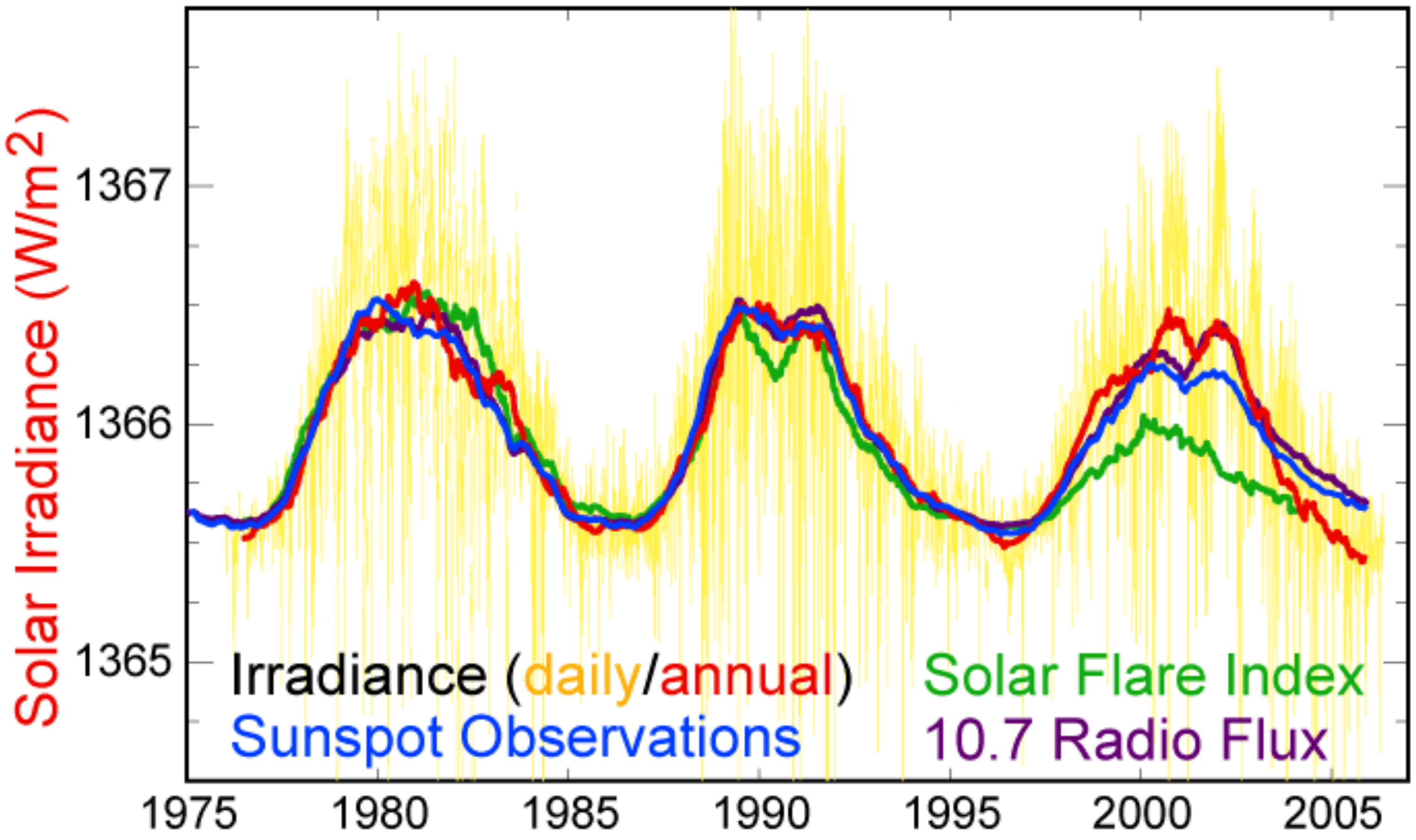




Flares

Occurrence

- Total number per day depends on flare intensity!
- Solar minimum: on average one per day
- Solar maximum: on average as high as 20 per day
- Flare rate is very **irregular**!
  - There can be long periods of time at solar minimum with no detectable flare!
  - A large active region can produce many flares in just a few days.

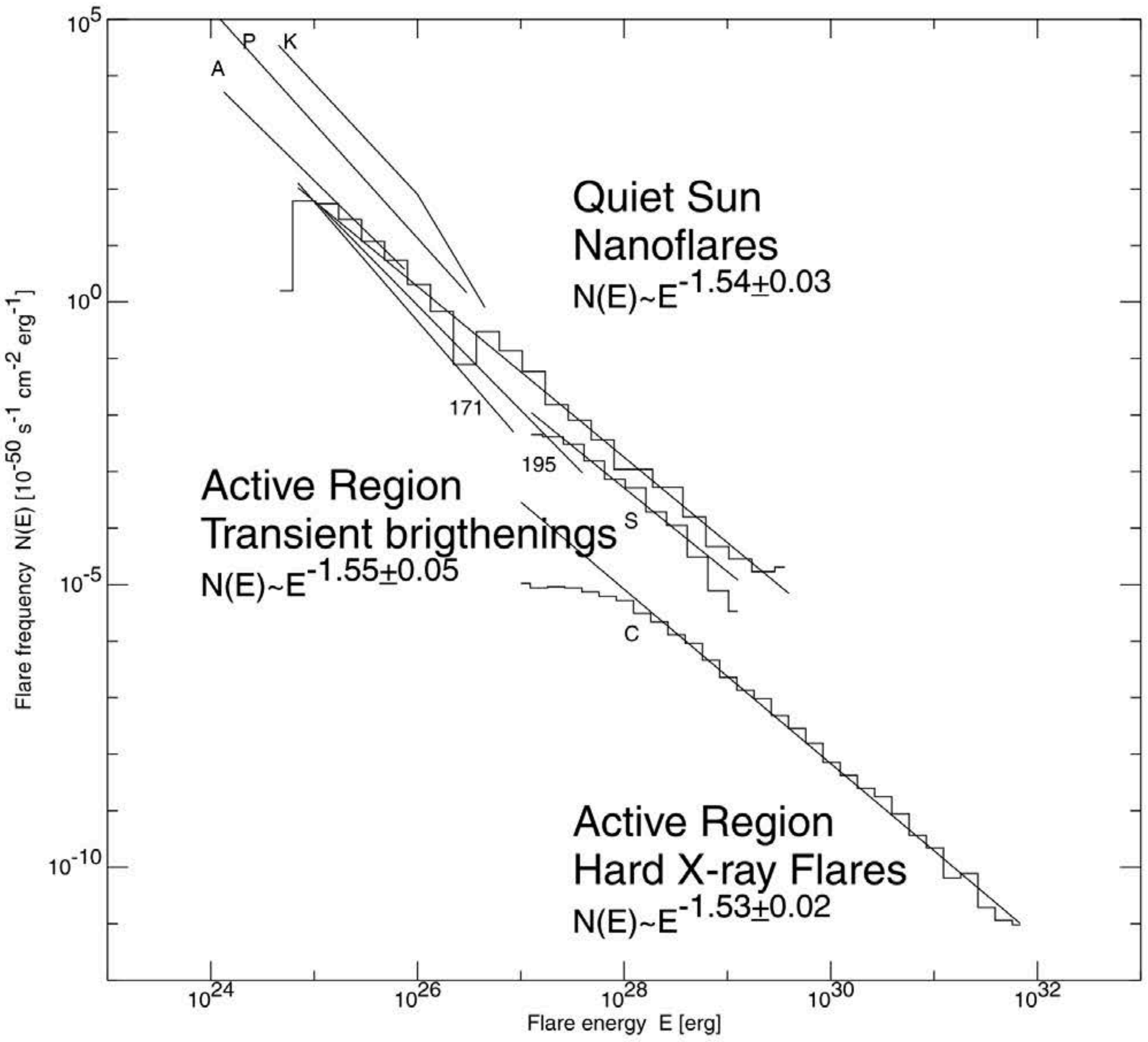


Solar flare index:
based on flare's brightness
and importance.

Flares

Flares as a scalable phenomenon

- Magnetic field on the Sun is structured on a larger range of scales
- “Stored” magnetic energy in stressed magnetic field scales correspondingly
- Magnetic reconnection can trigger energy release in structure over a large range of spatial scales.
- From small to large:
  - Nanoflares
  - Microflares
  - (normal) flares



Aschwanden & Parnell (2002)

Recap — Flares

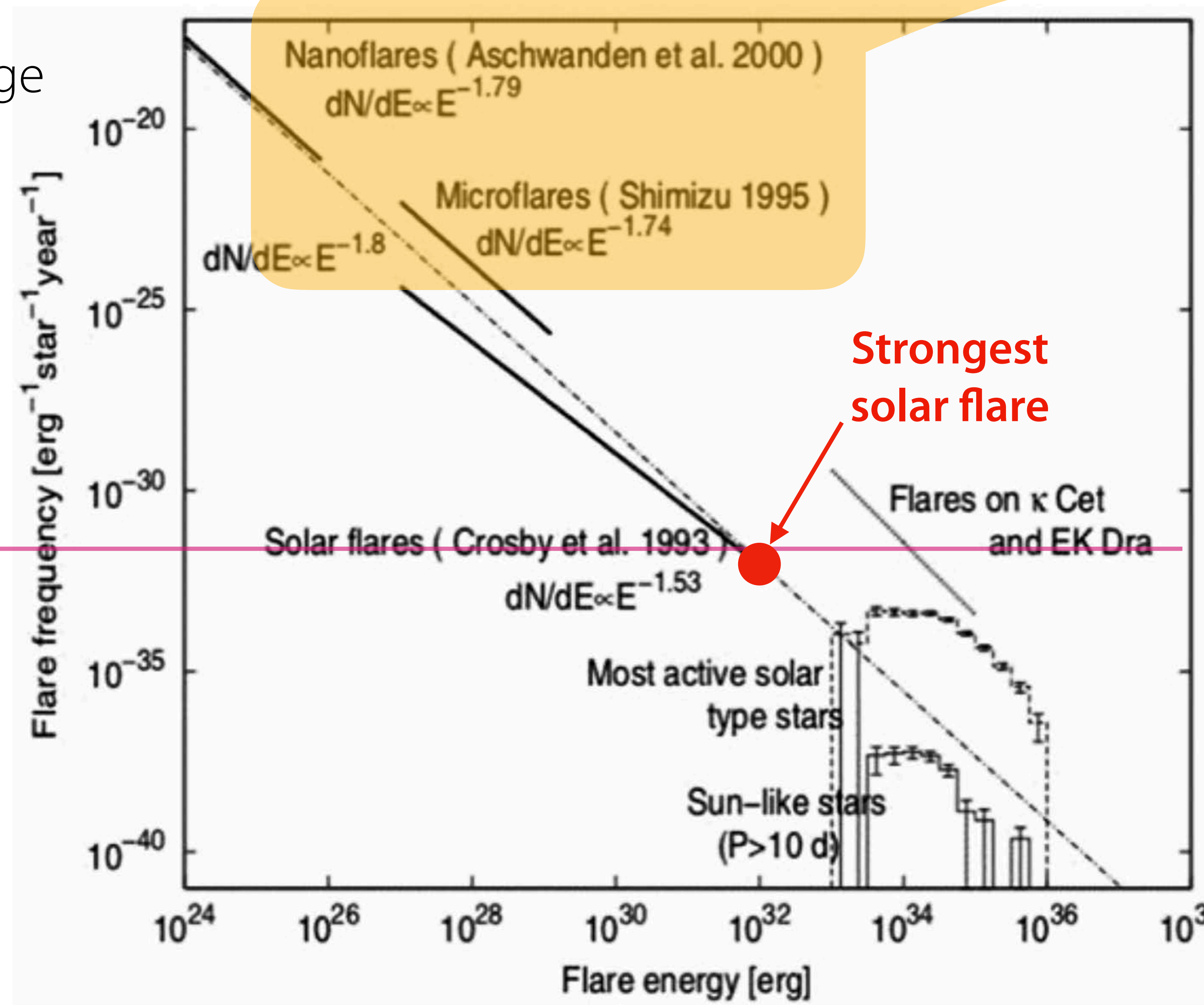
Flares as a scalable phenomenon

Can occur outside Active Regions!

- Magnetic field on the Sun is structured on a larger range of scales
- "Stored" magnetic energy in stressed magnetic field scales correspondingly
- Magnetic reconnection can trigger energy release in structure over a large range of spatial scales.
- From small to large:
  - Nanoflares
  - Microflares
  - (normal) flares

  Observed on the Sun

  - **Superflares**
  - **Megaflares**
    - Observed on other stars
    - M-dwarfs know for strong flares (e.g., AD Leo, Proxima Cen)
    - Can outshine whole star for minutes



Aschwanden & Parnell (2002)

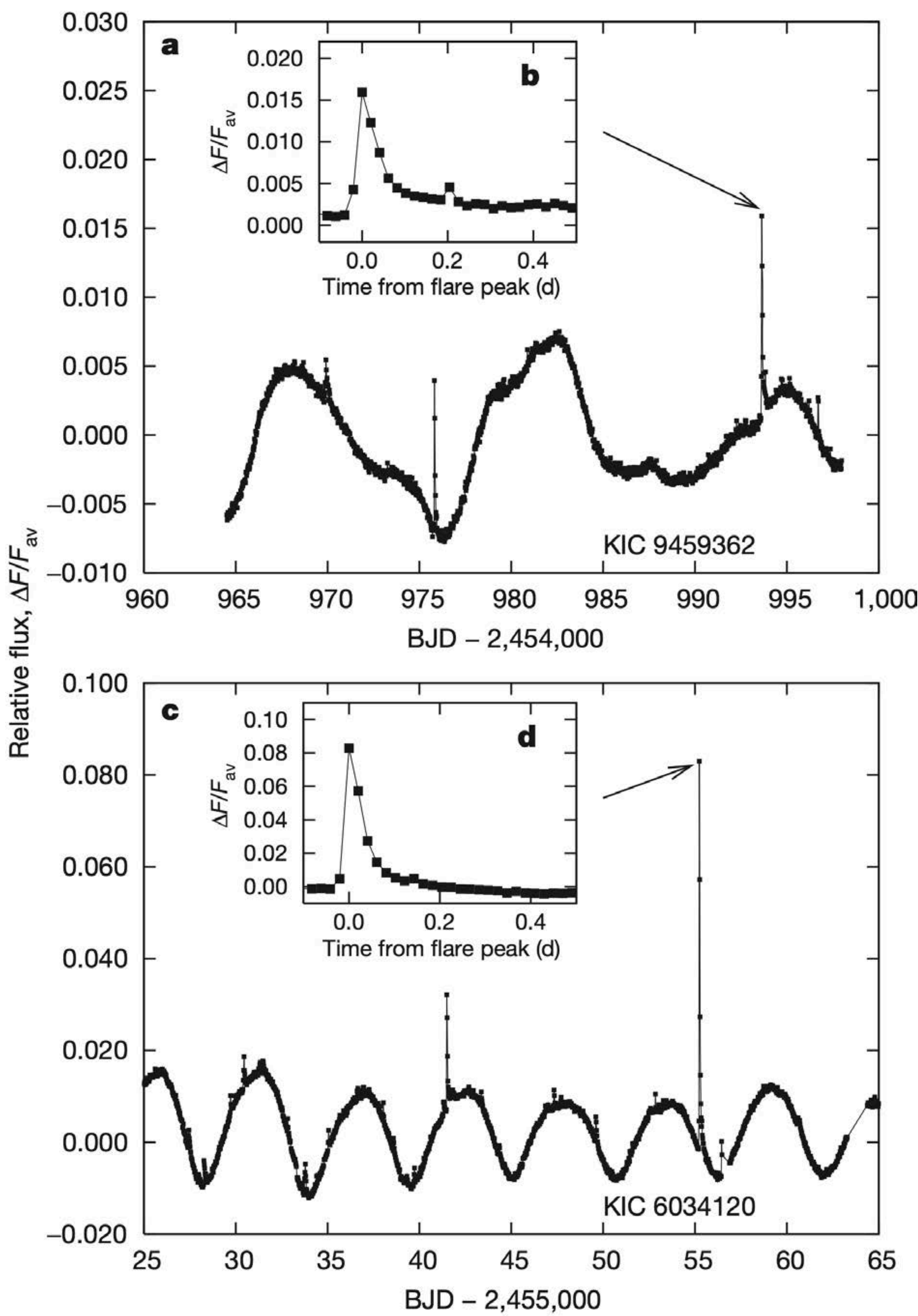
Stellar flares

Superflares

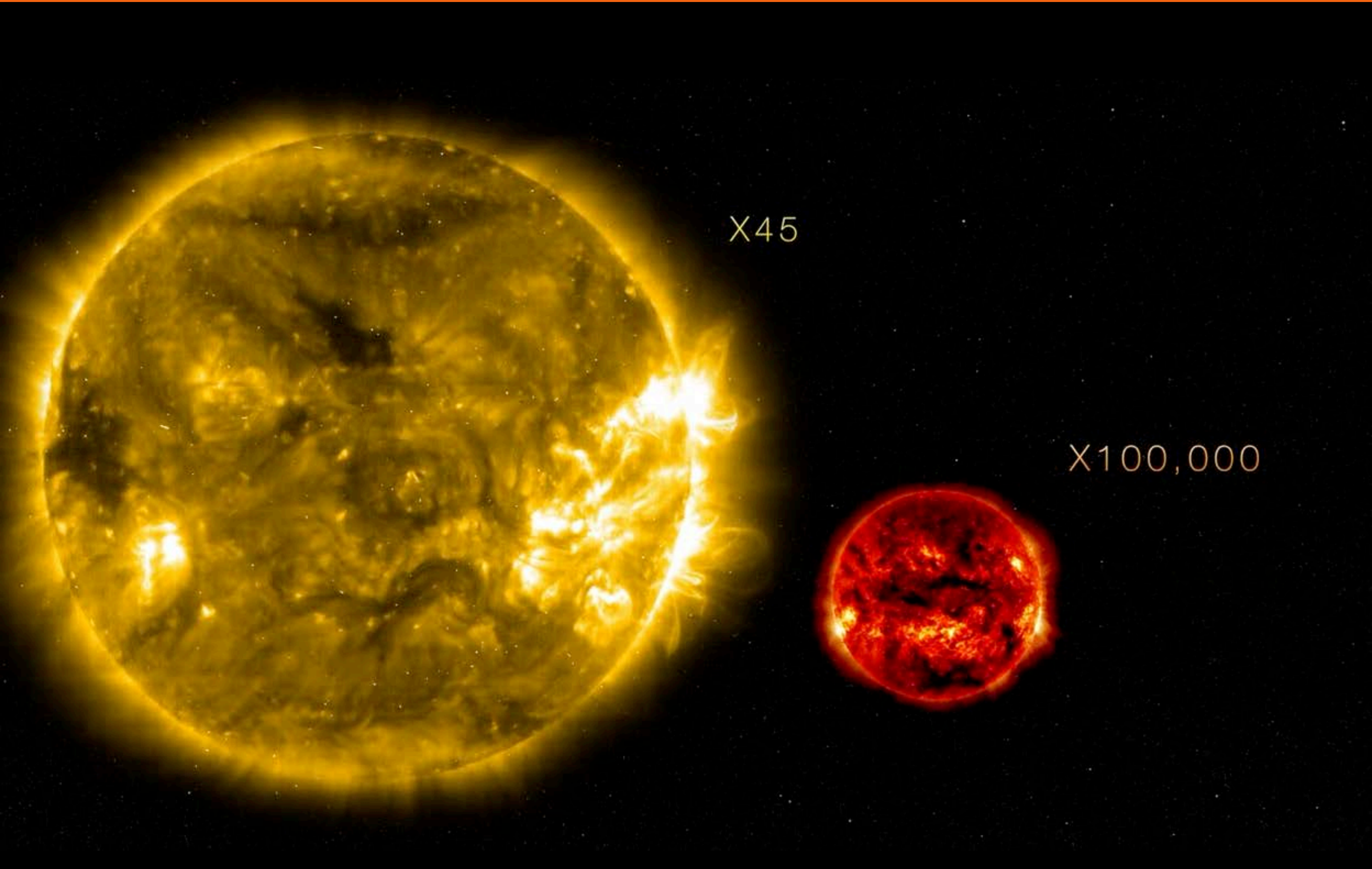
Maehara et al (2012)

- Kepler observations
- G-type main-sequence star KIC 9459362
  - Relative flux variation ($\Delta F/F_{av}$): 1.4%
  - Flare duration: 3.9 h
  - Total released energy: 5.6 10^{34} erg
- G-type main-sequence star KIC 6034120
  - Relative flux variation ($\Delta F/F_{av}$): 8.4%
  - Flare duration: 5.4 h
  - Total released energy: 3.0 10^{35} erg
- In total: 365 superflares from ~83000 stars observed over 120 days.

➡ Superflare occurring on a star once every ~350 yr.



Stellar flares

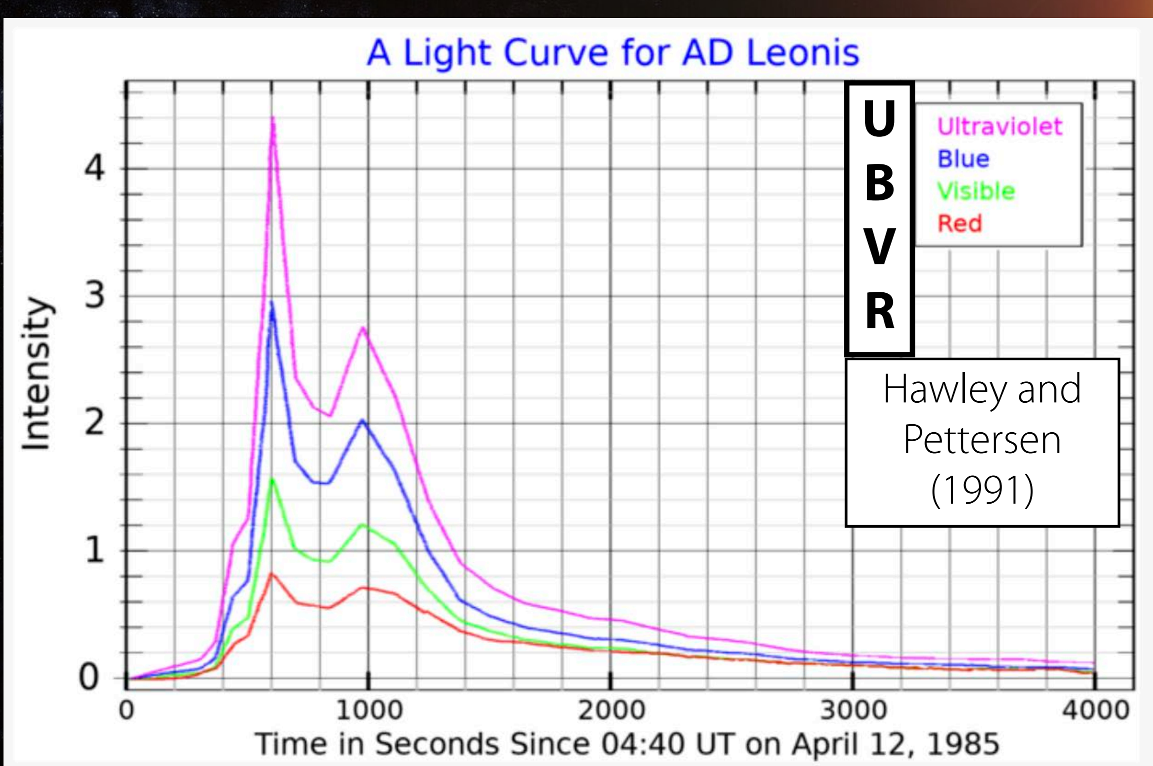


Credits: NASA's Goddard Space Flight Center/S. Wiessinger

Stellar flares

Megaflares

- Megaflares on M-dwarf stars:
  The flare can outshine the whole stars for minutes
- Prominent examples:
  - Proxima Cen: Flare on May 1, 2019, lasted just 7 seconds, brightest ever detected flare in millimeter and far-UV wavelengths.
  - AD Leo: Well-studied flare star.



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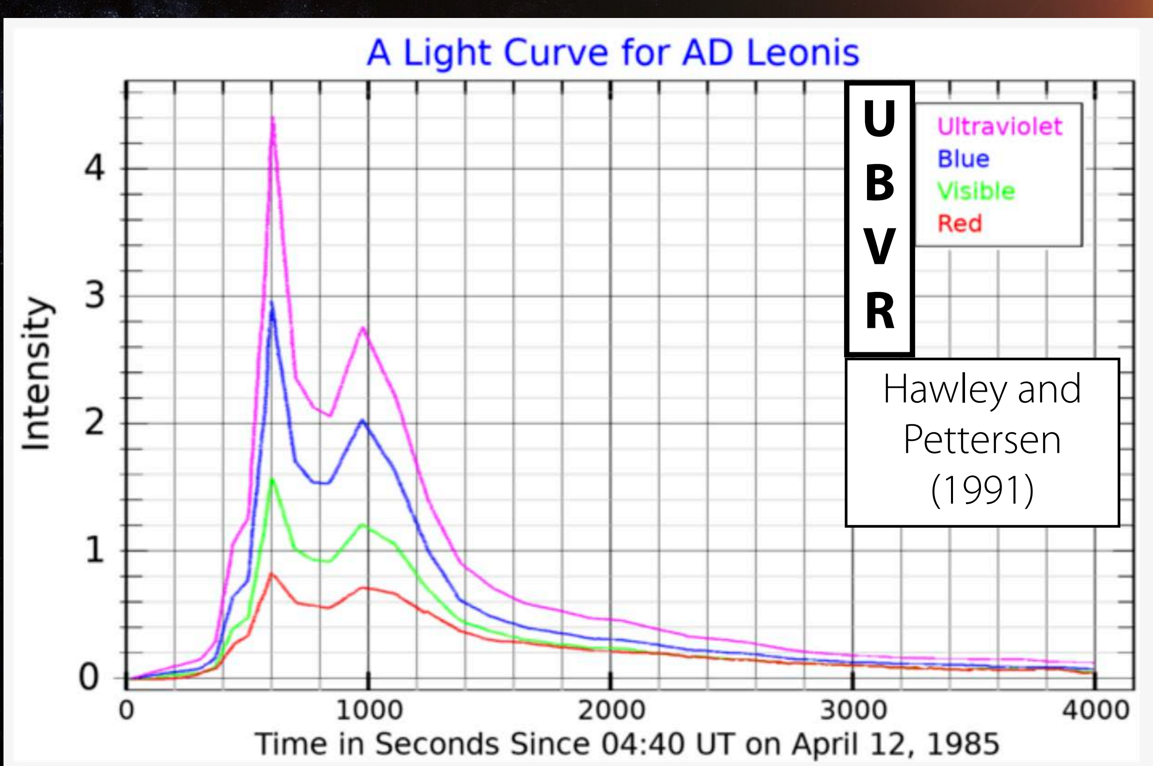

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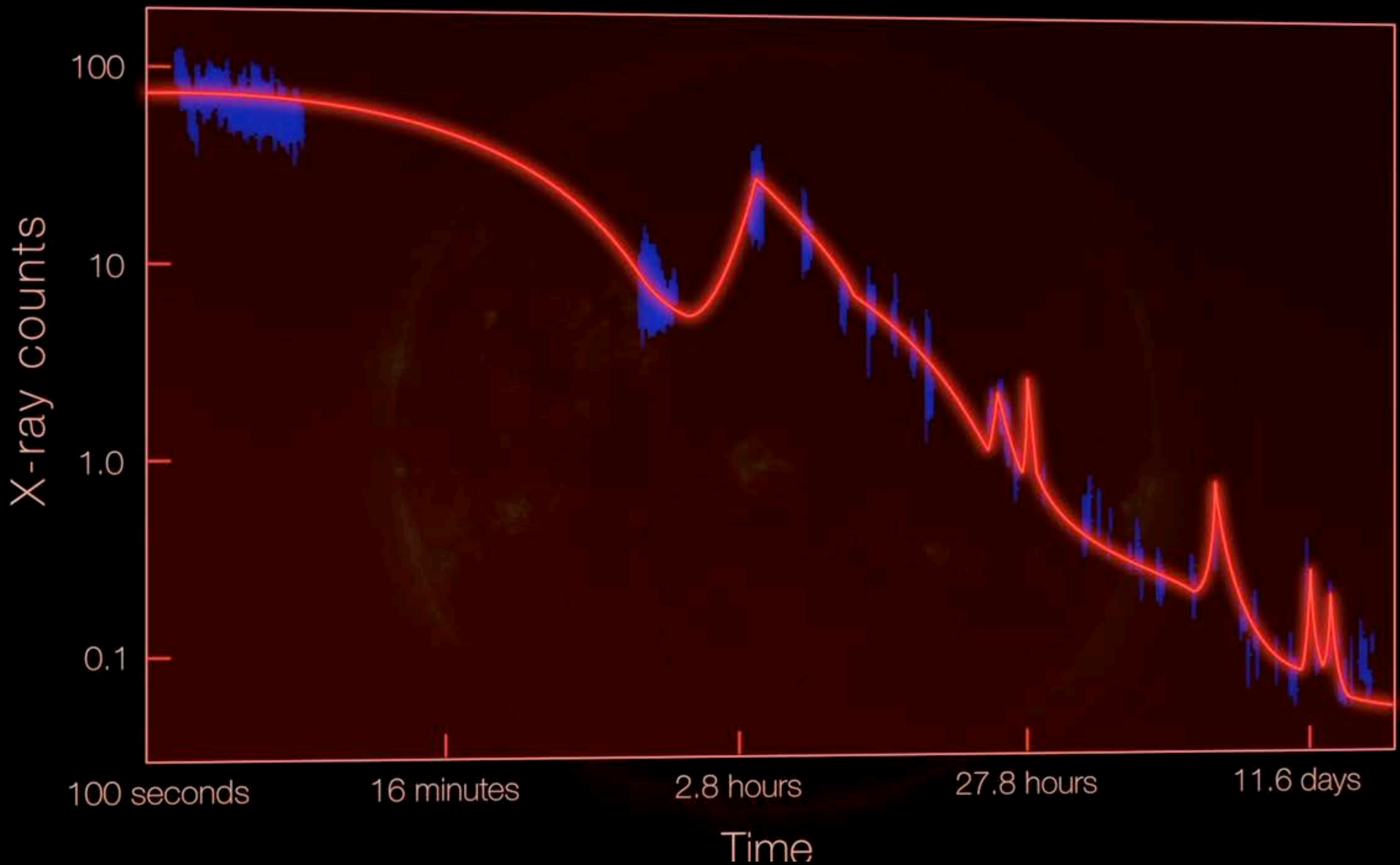
Stellar flares



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