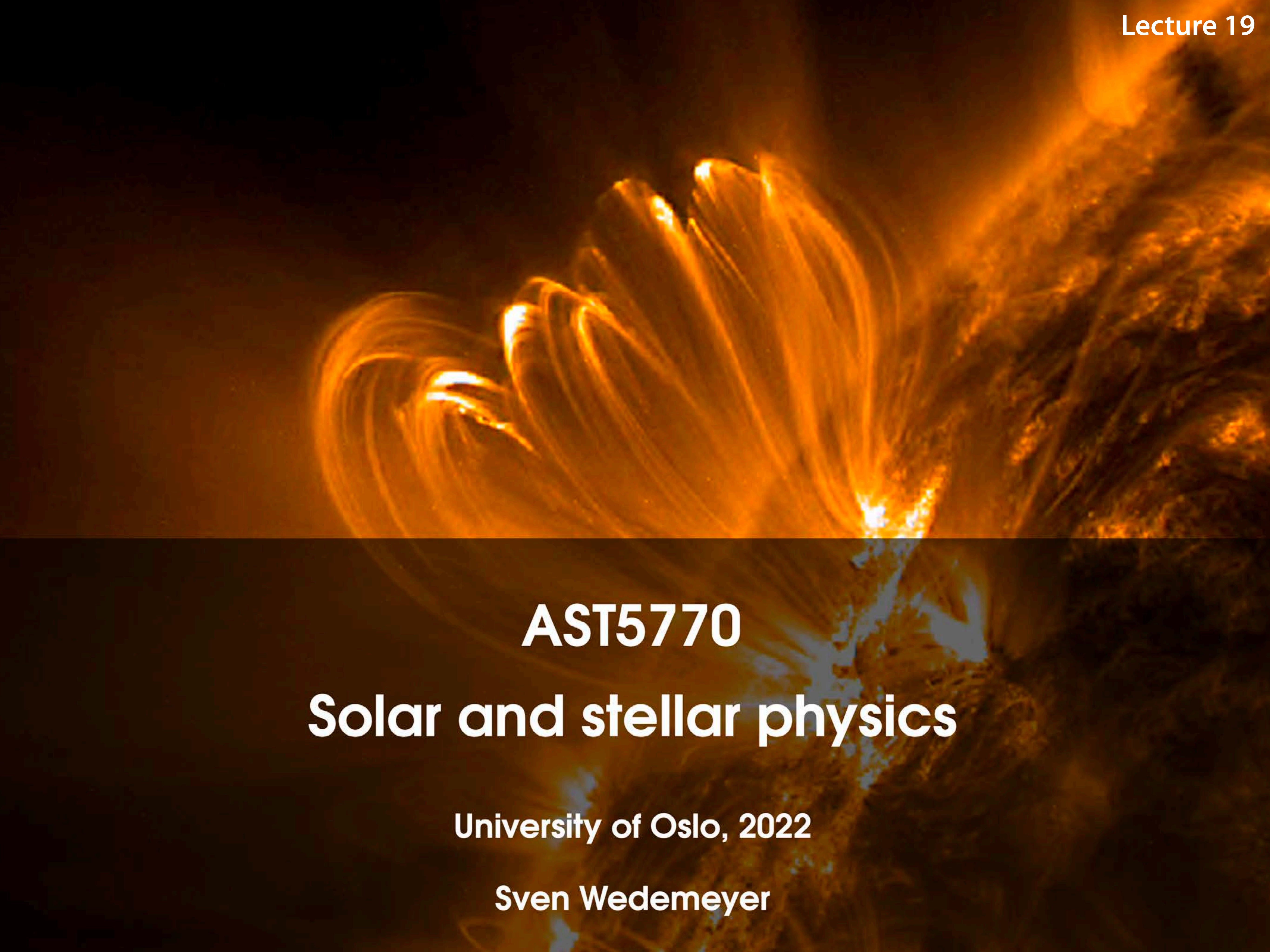


AST5770

Solar and stellar physics

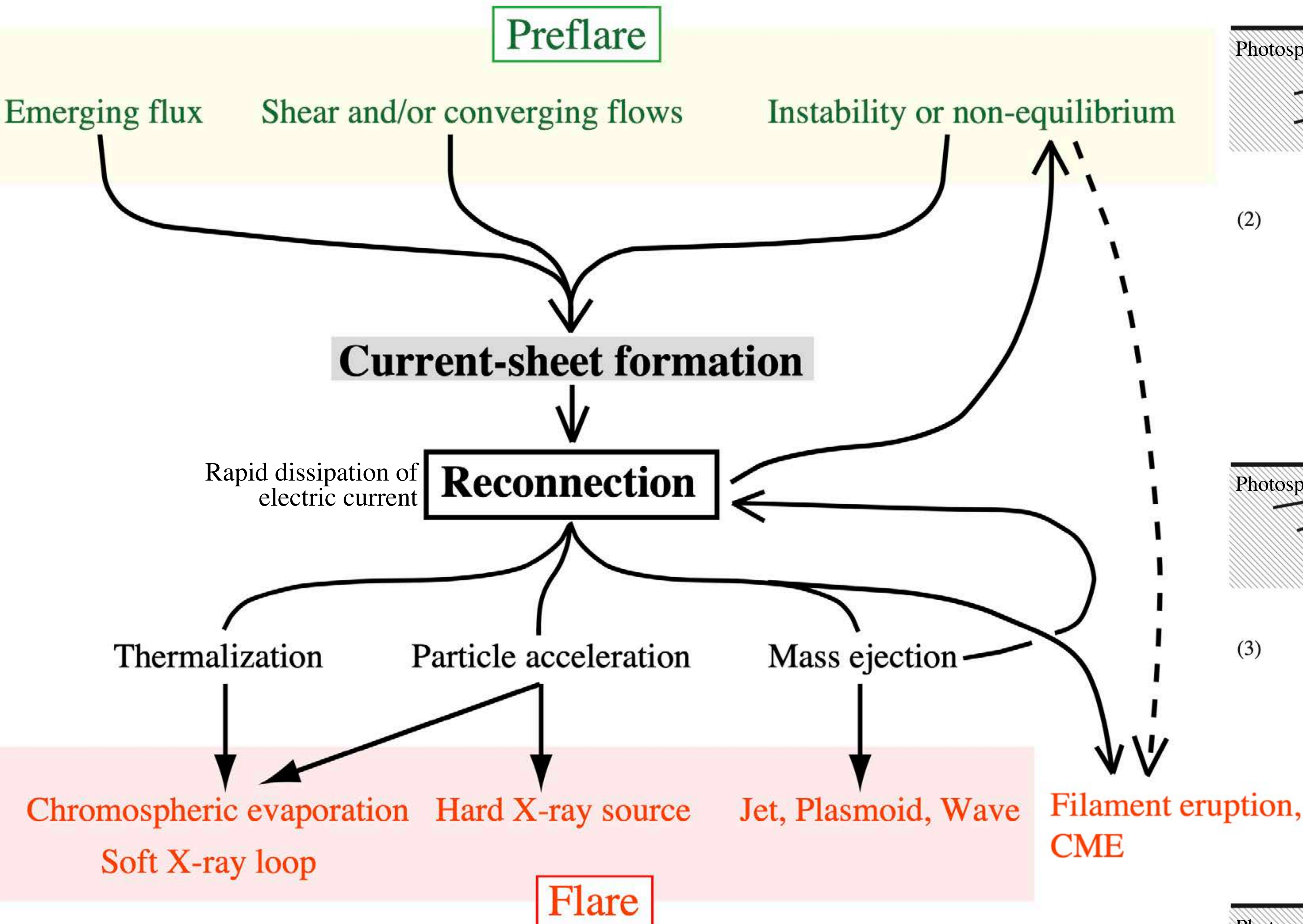
University of Oslo, 2022

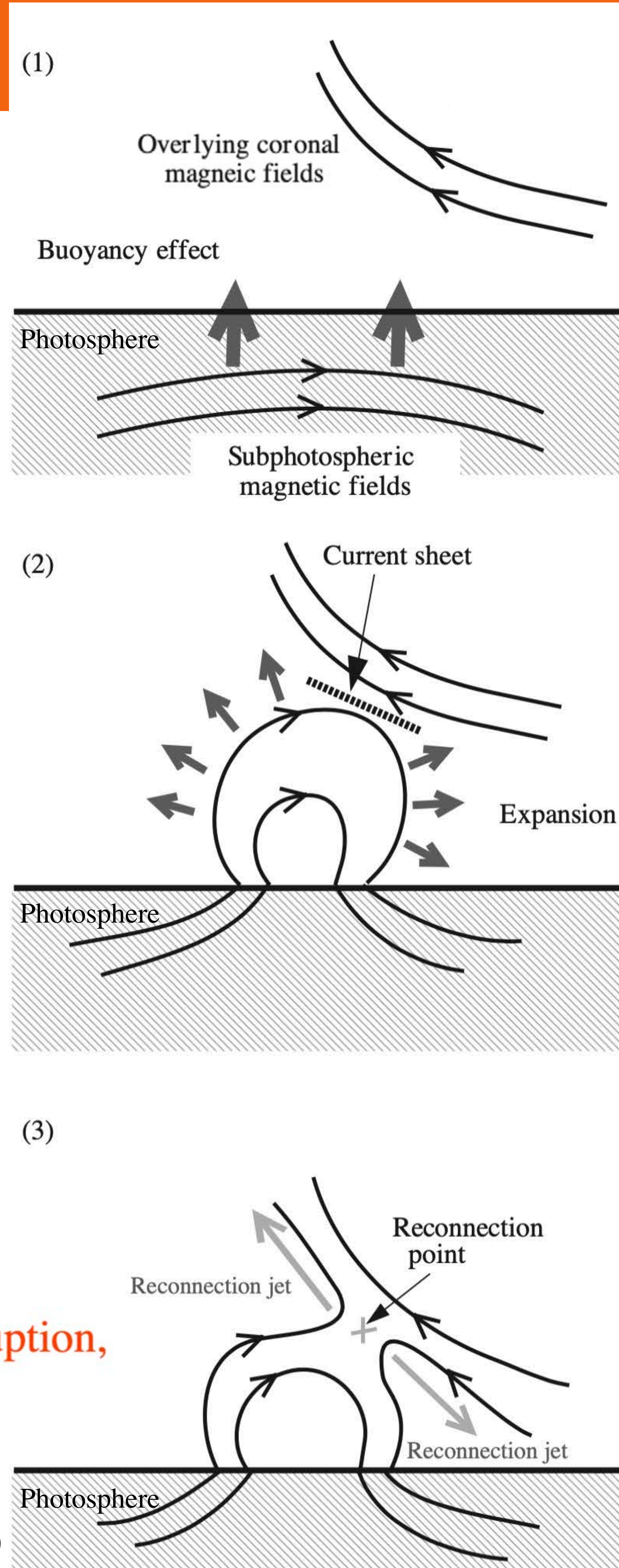
Sven Wedemeyer

Solar flares

Flares

Physical mechanism — overview

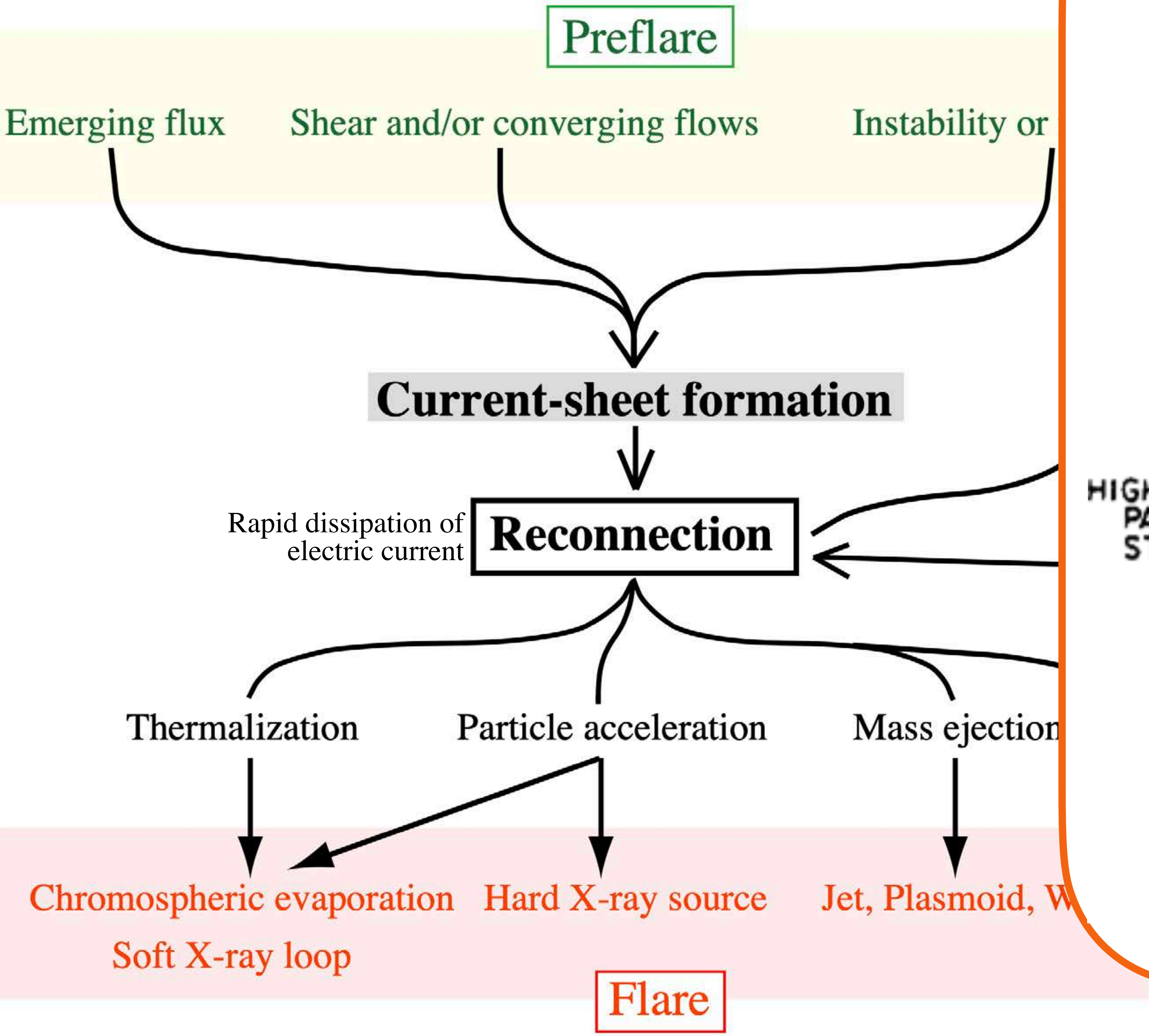




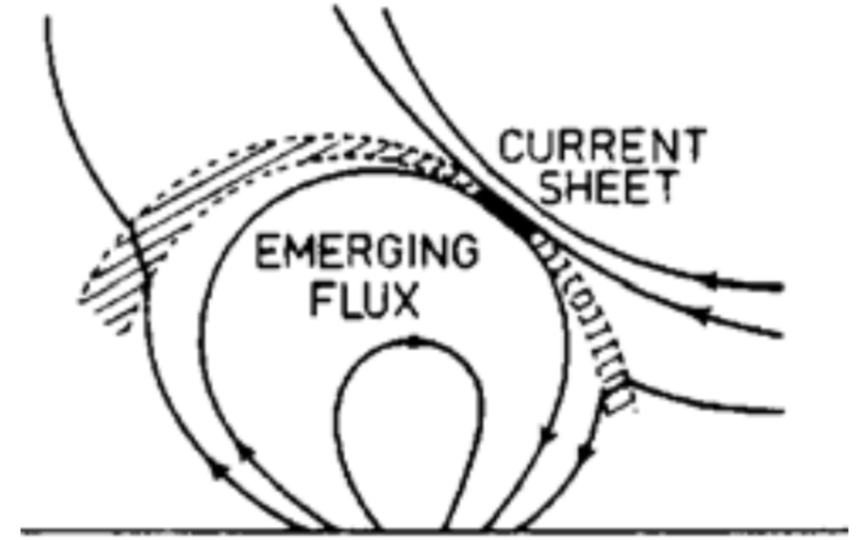
Shibata & Magara (2011)

Flares

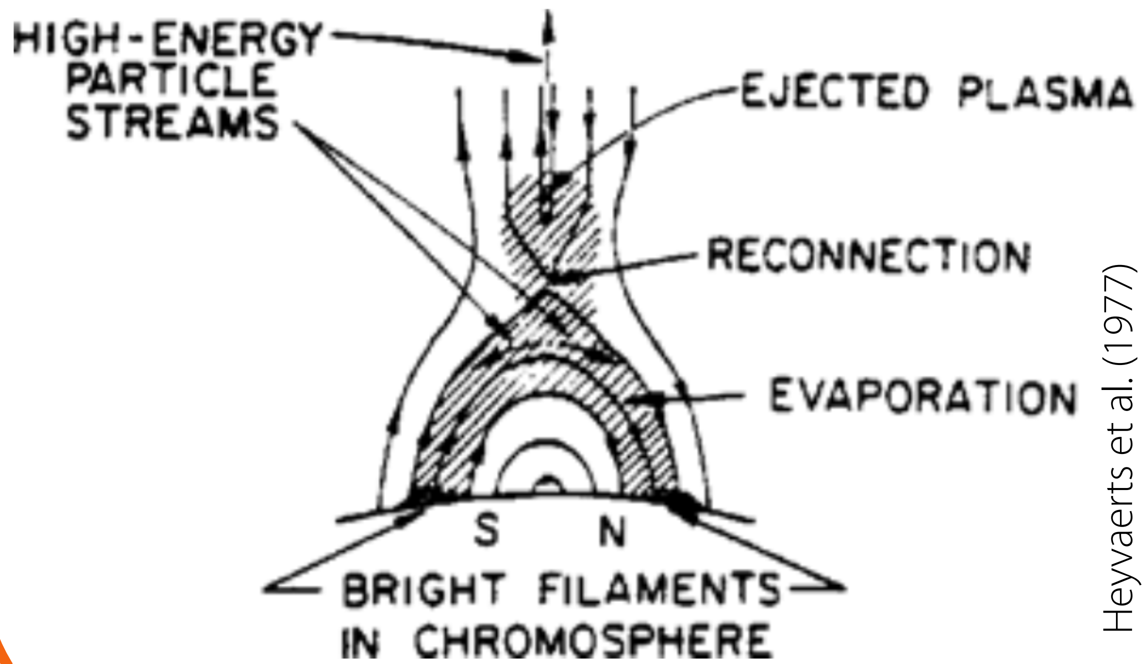
Physical mechanism — overview



Different possible configurations



Sturrock (1980)

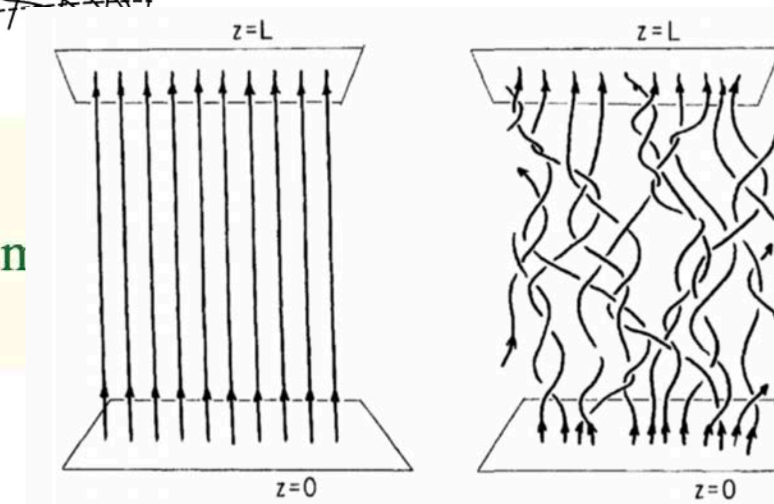


Heyvaerts et al. (1977)

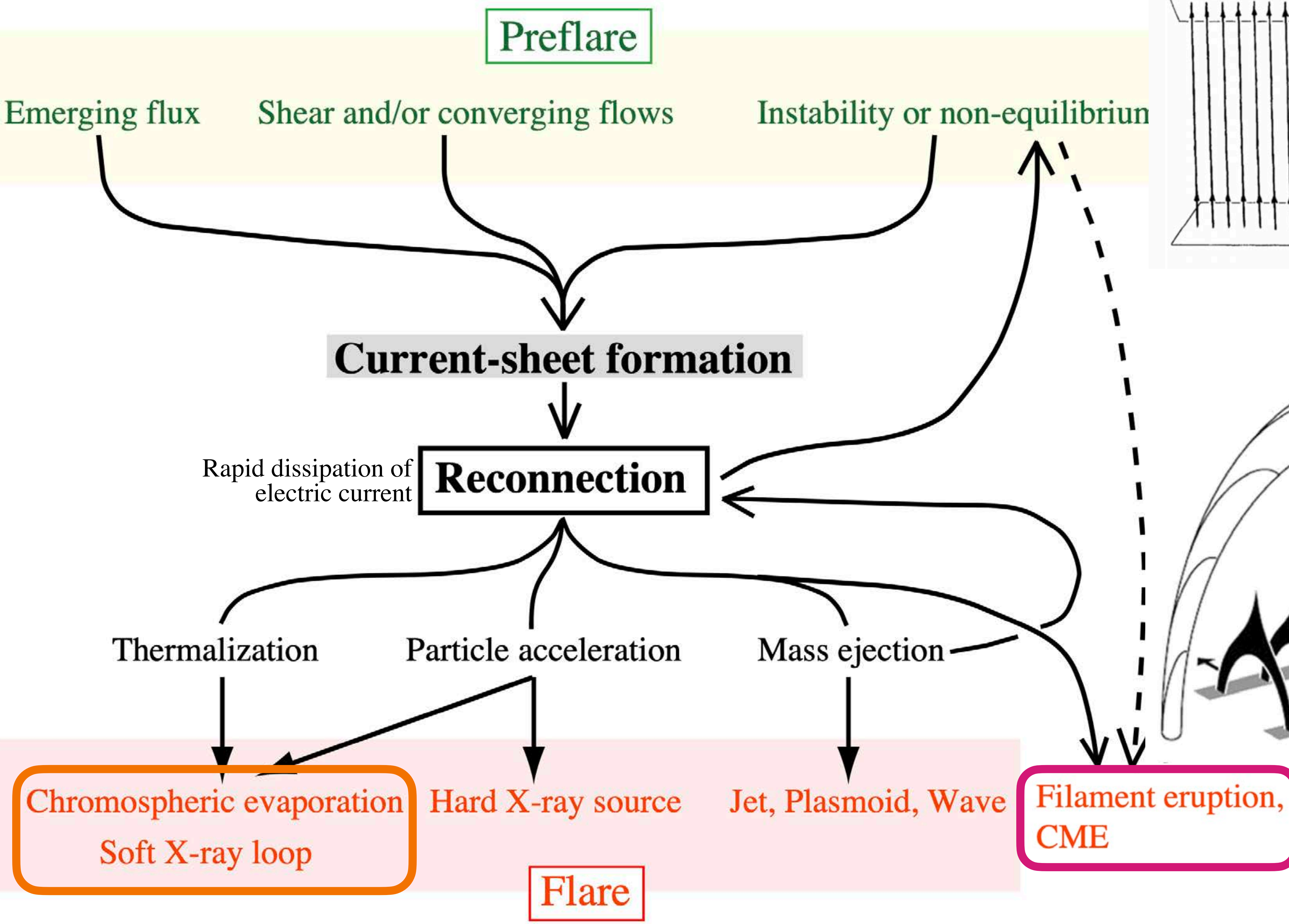
Shibata & Magara (2011)

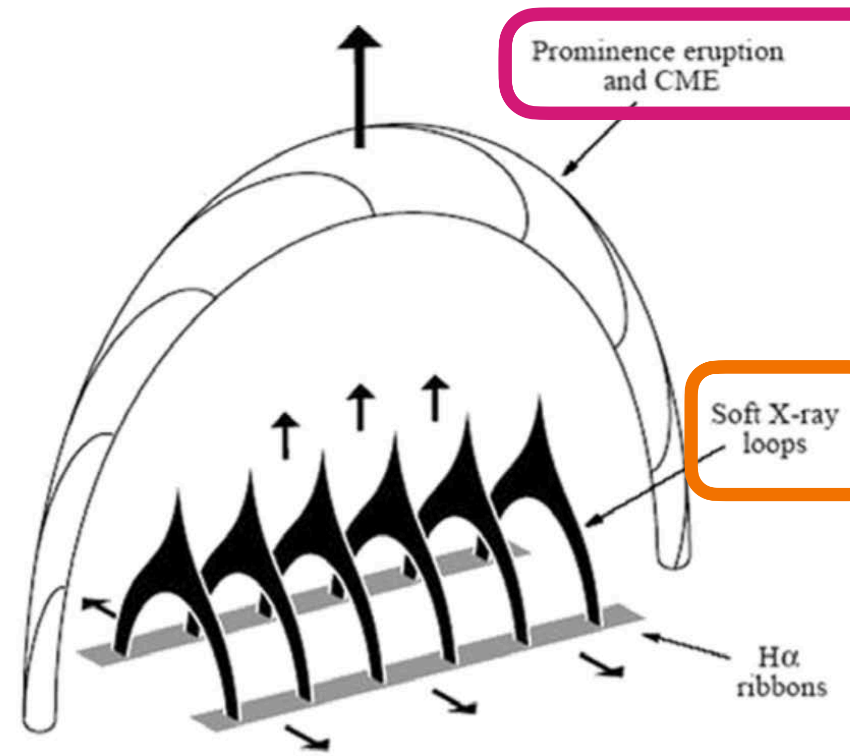
Flares

Physical mechanism — overview



Parker (1994)



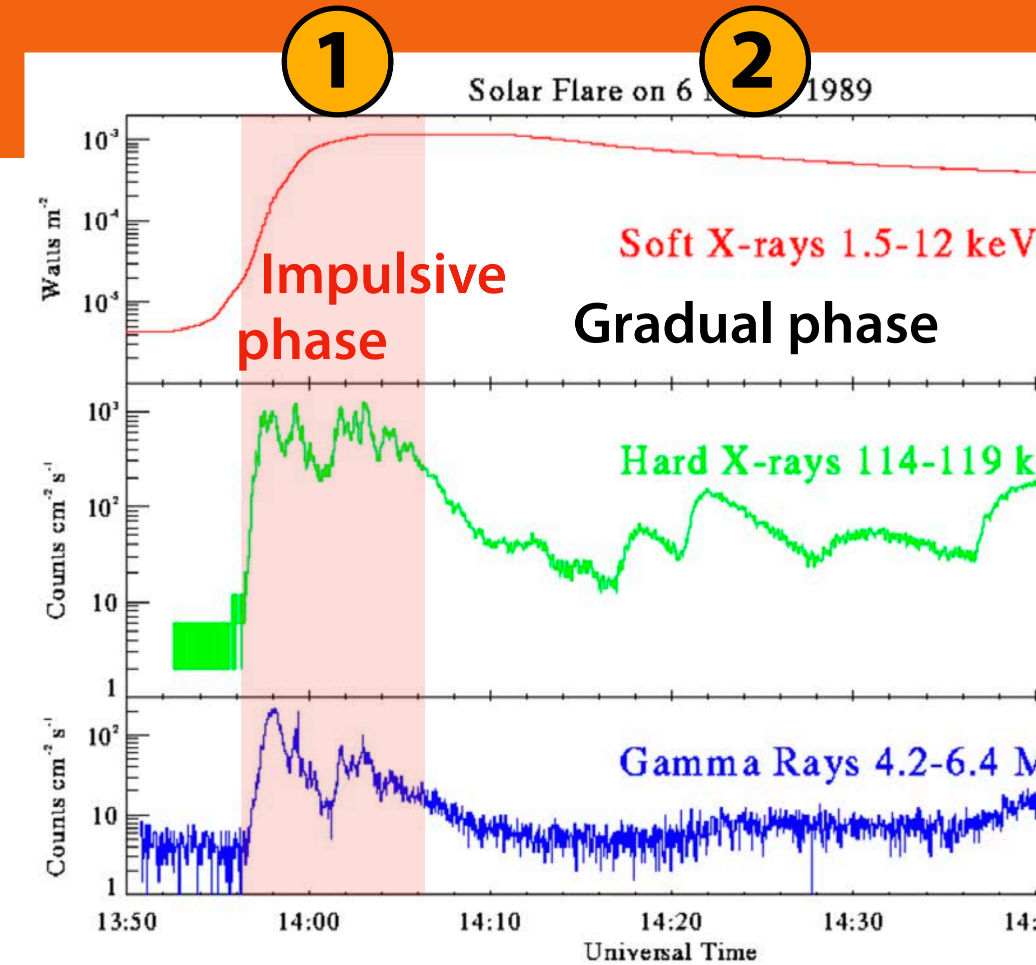


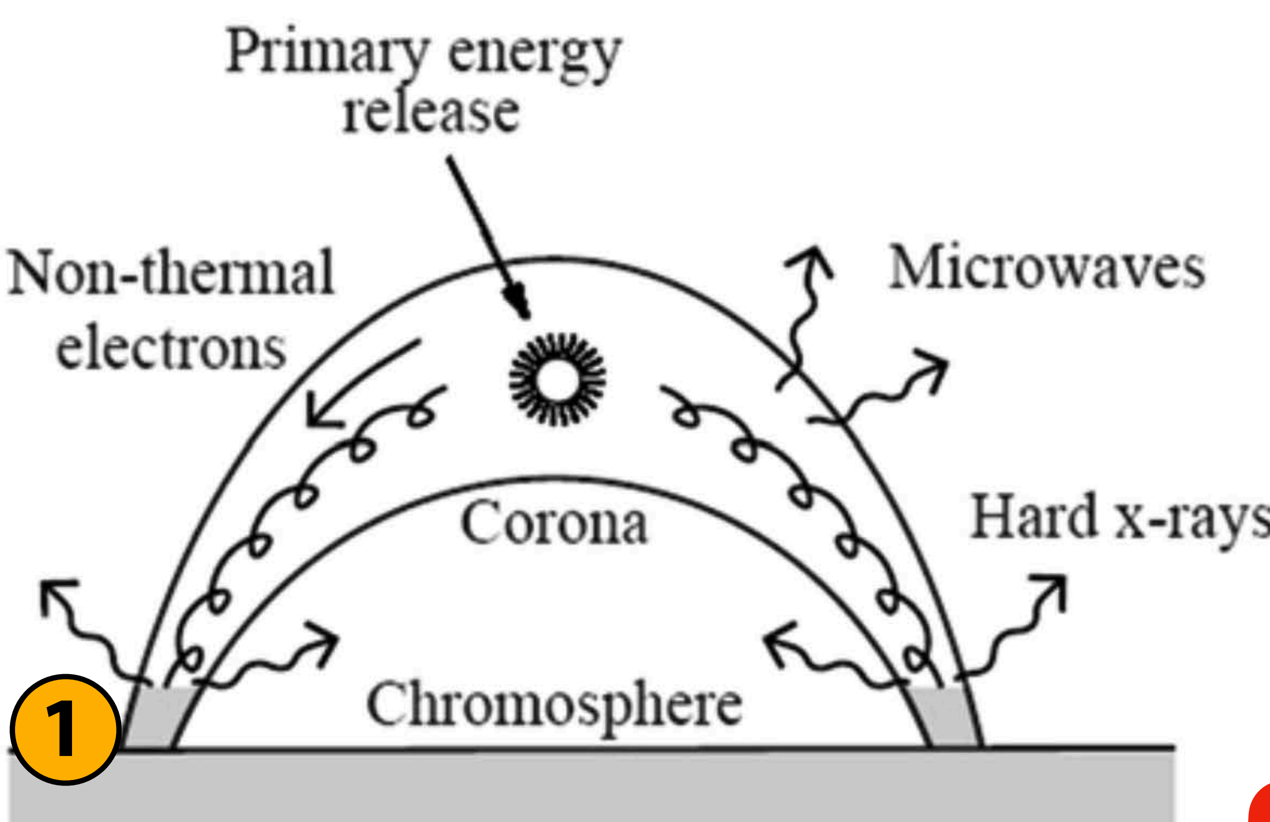
Shibata & Magara (2011)

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

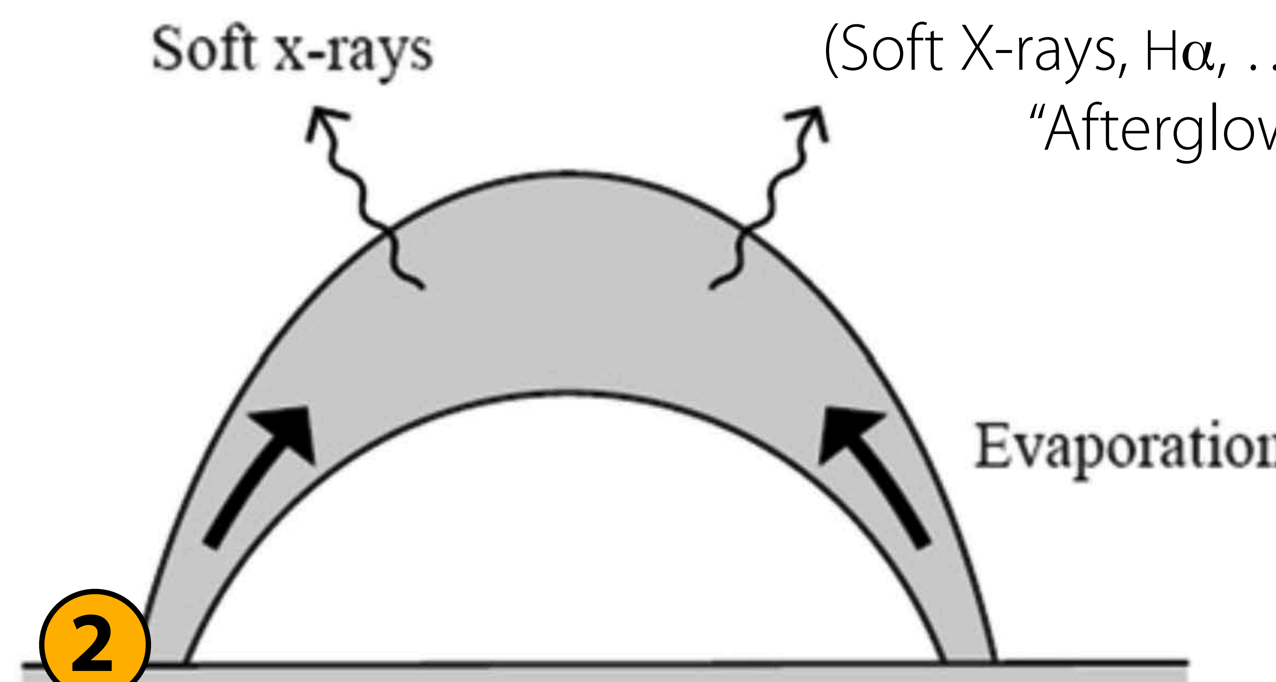




Thermal emission dominates

(Soft X-rays, Hα, …)

"Afterglow"

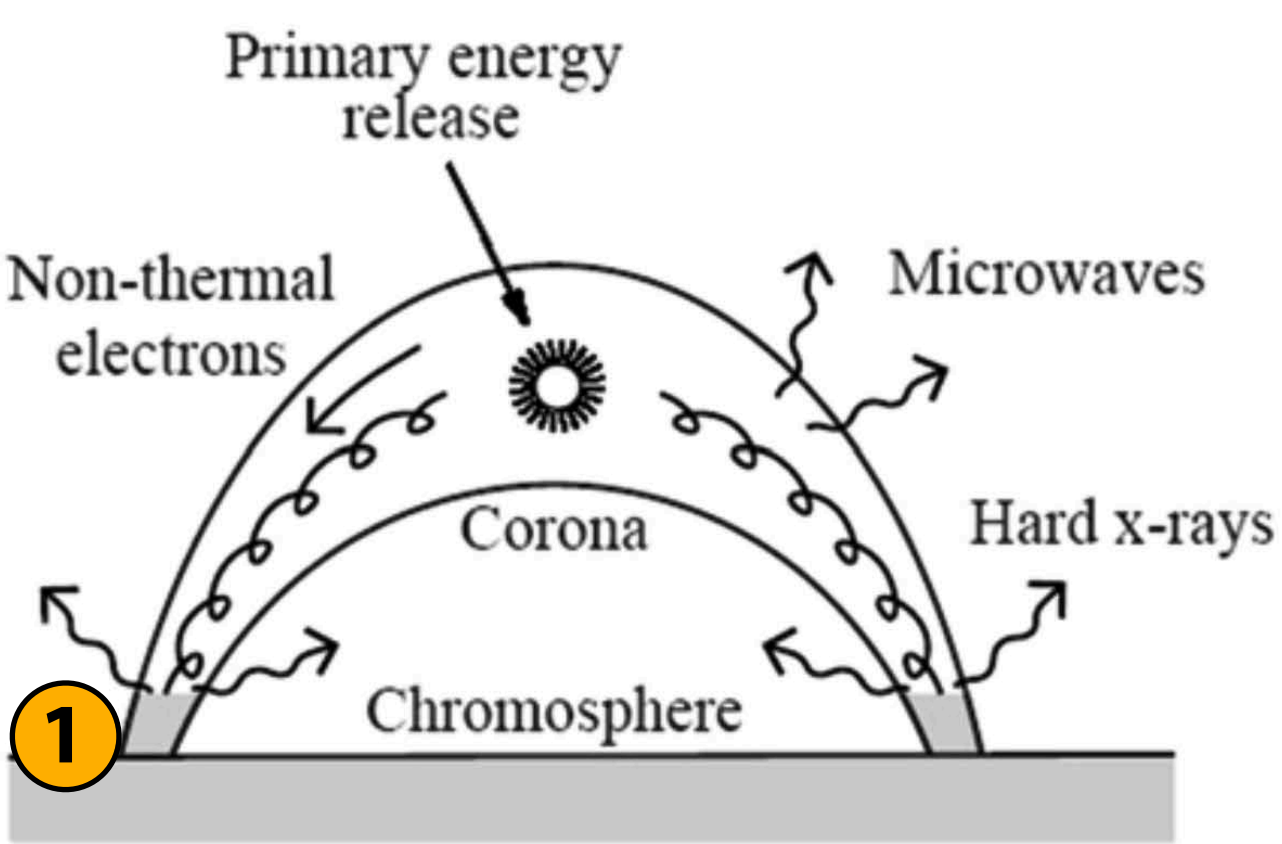


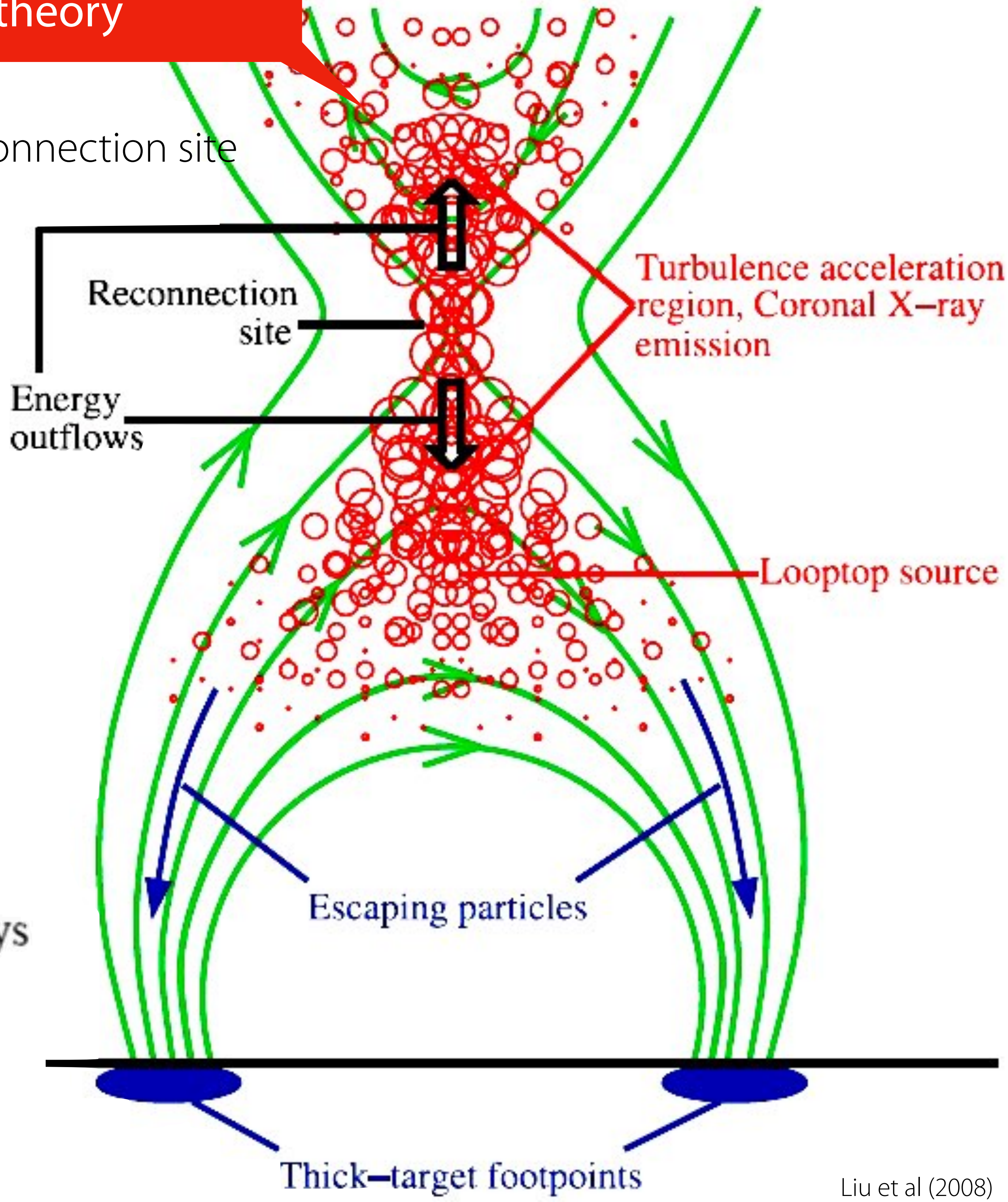
Correct model? Thin target model? Still debated.

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

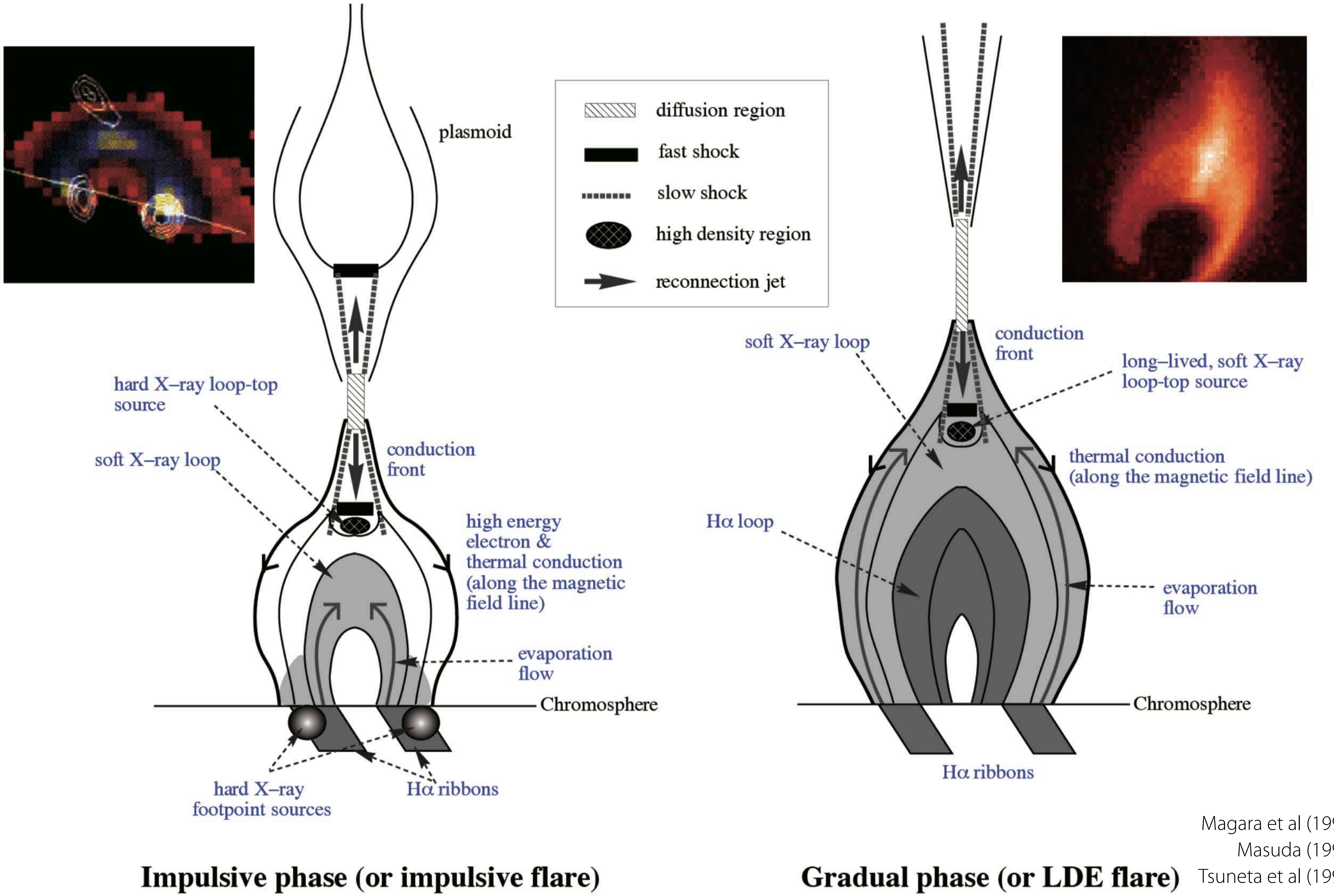




Liu et al (2008)

Flares

Impulsive and gradual phase

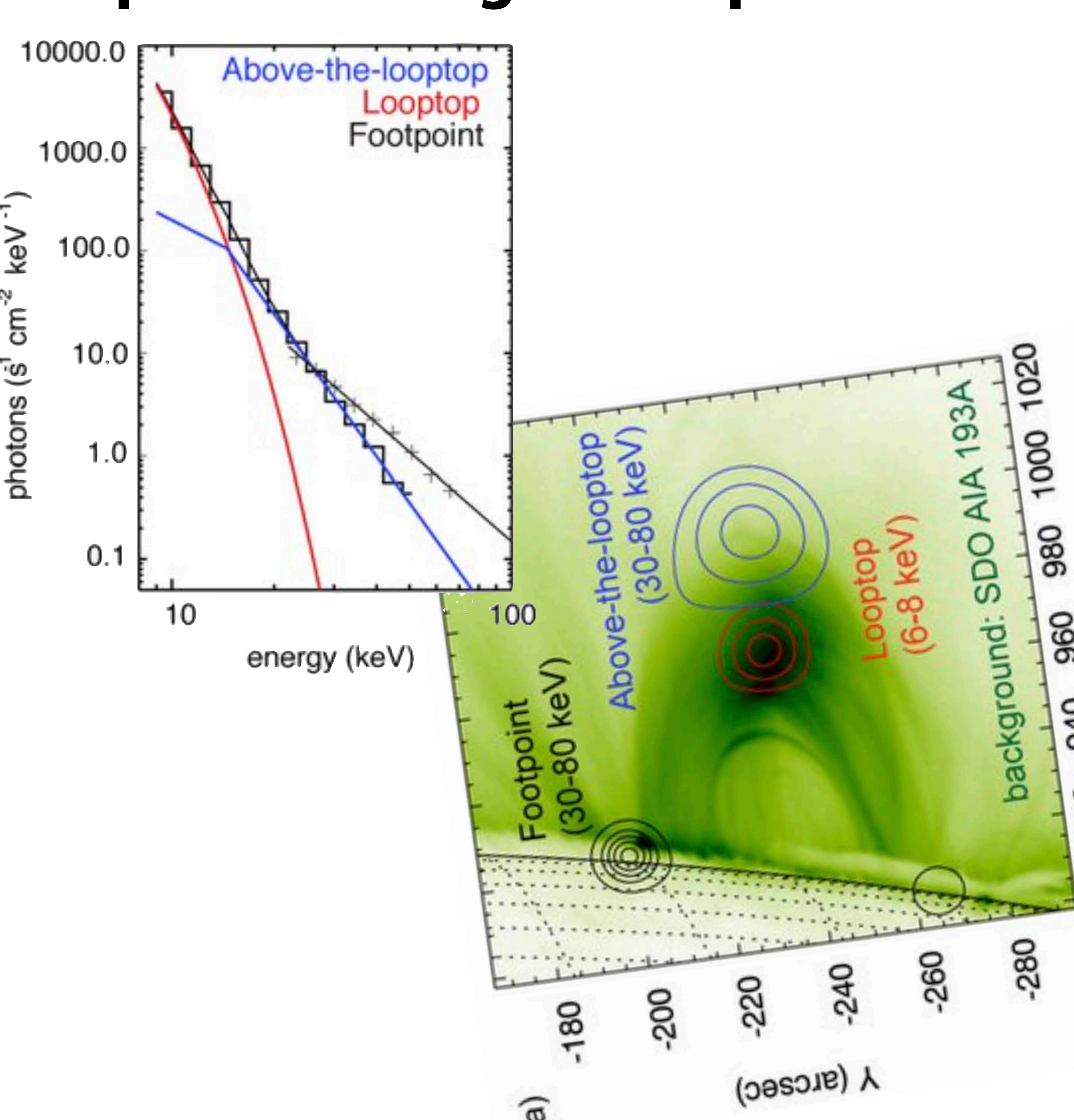


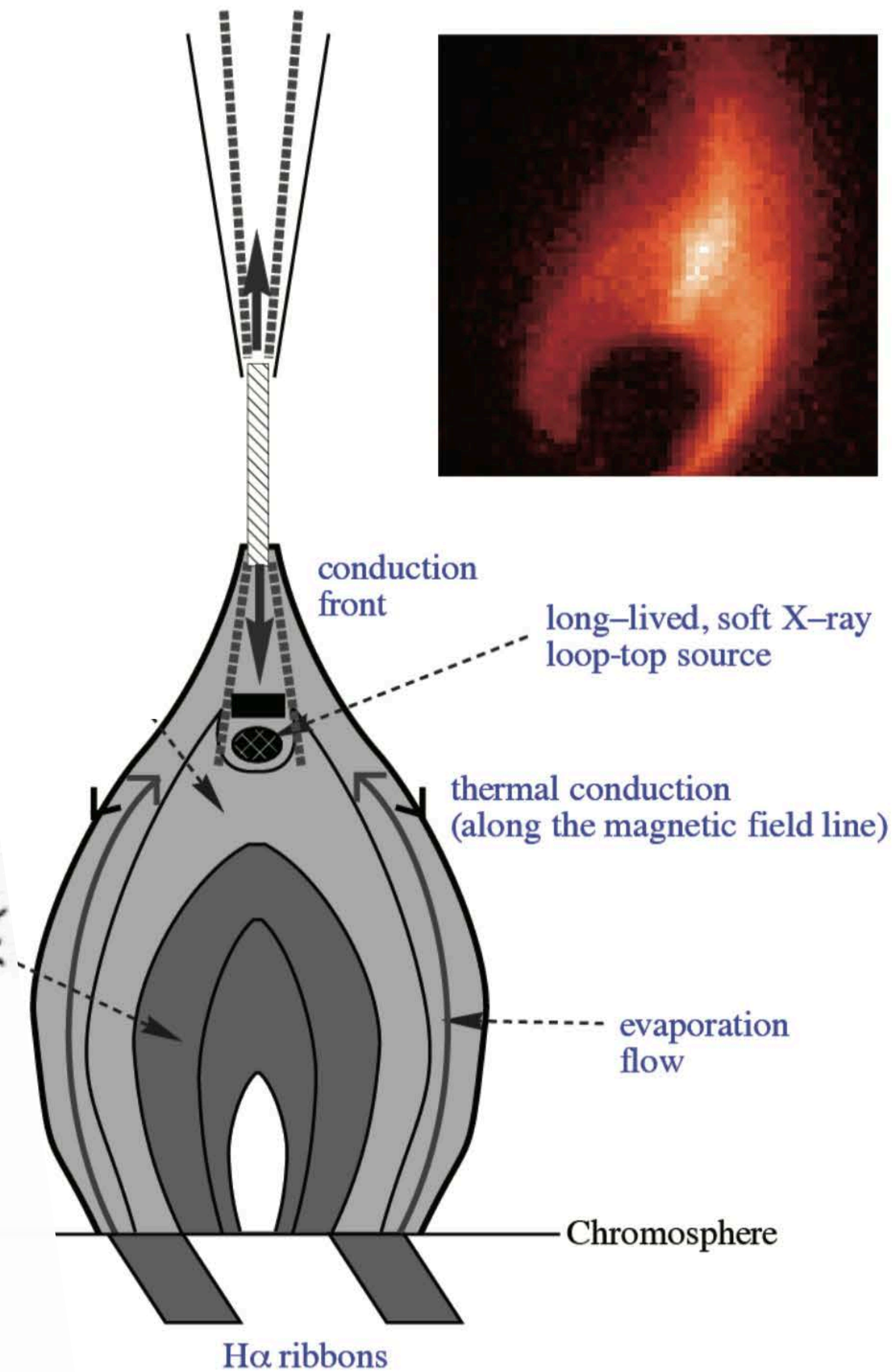
Magara et al (1996)
Masuda (1994)
Tsuneta et al (1992)

Flares

Impulsive and gradual phase

Oka et al. (2018)

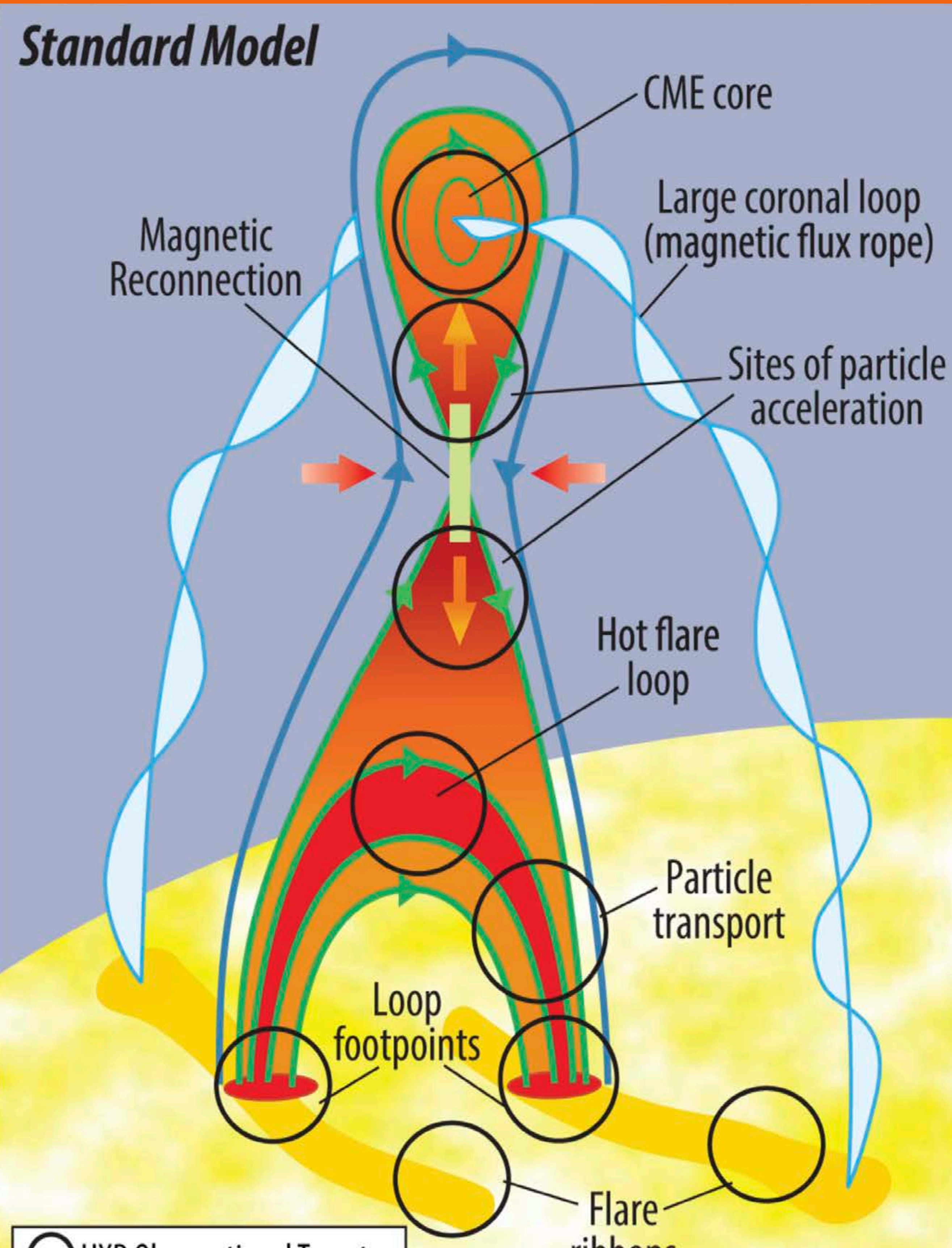




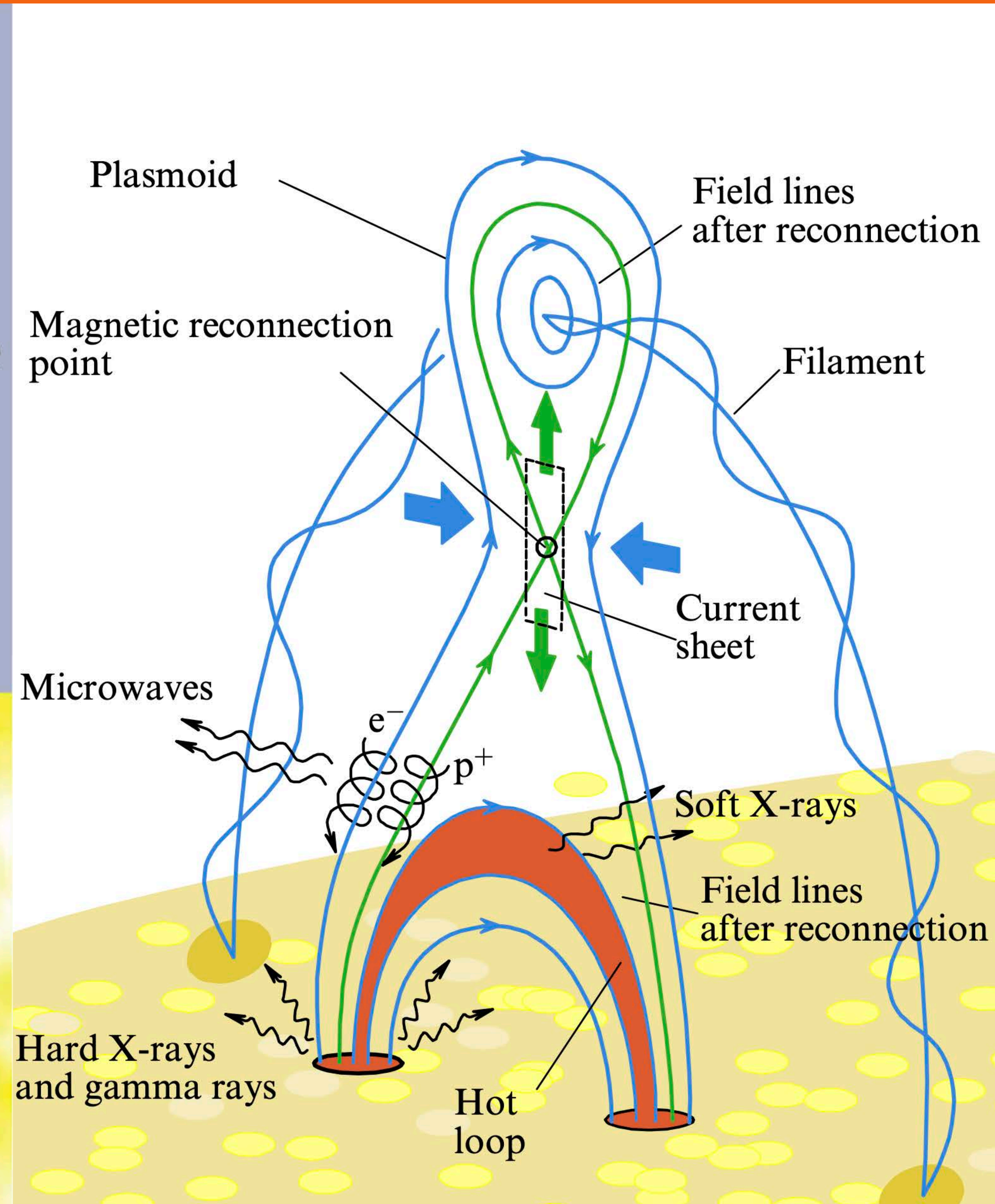
Gradual phase (or LDE flare)

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

Flares



Christe et al. (2017)

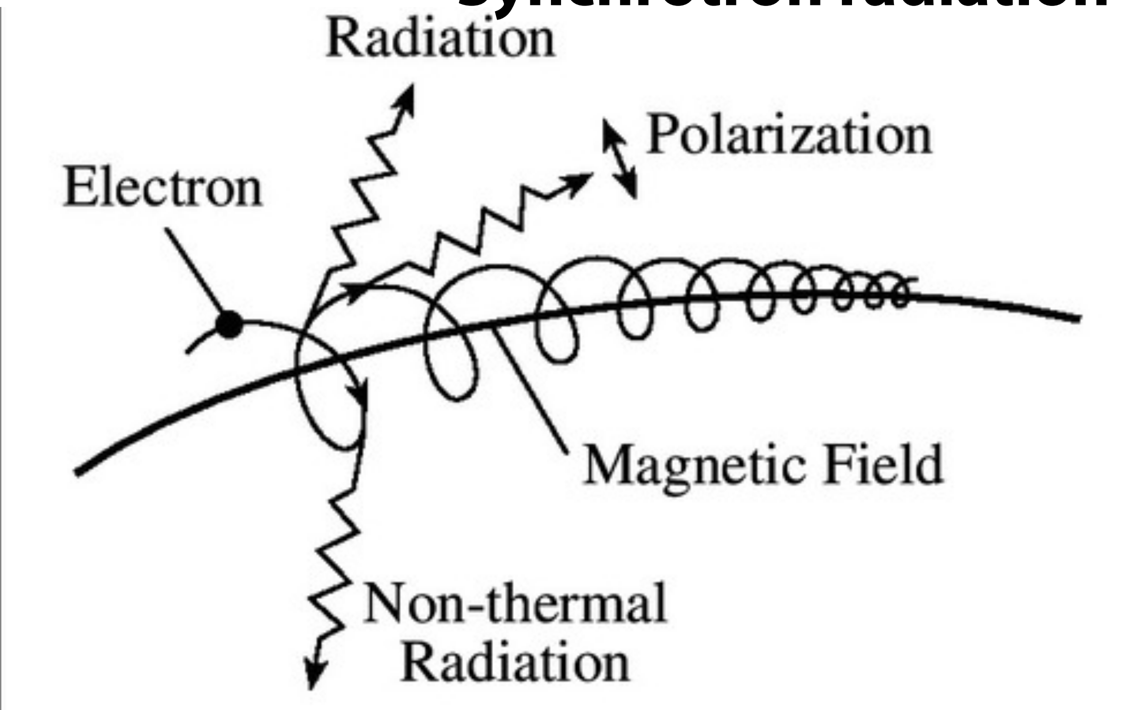


Lysenko et al. (2020)/Shibata et al. (1995)

Flares

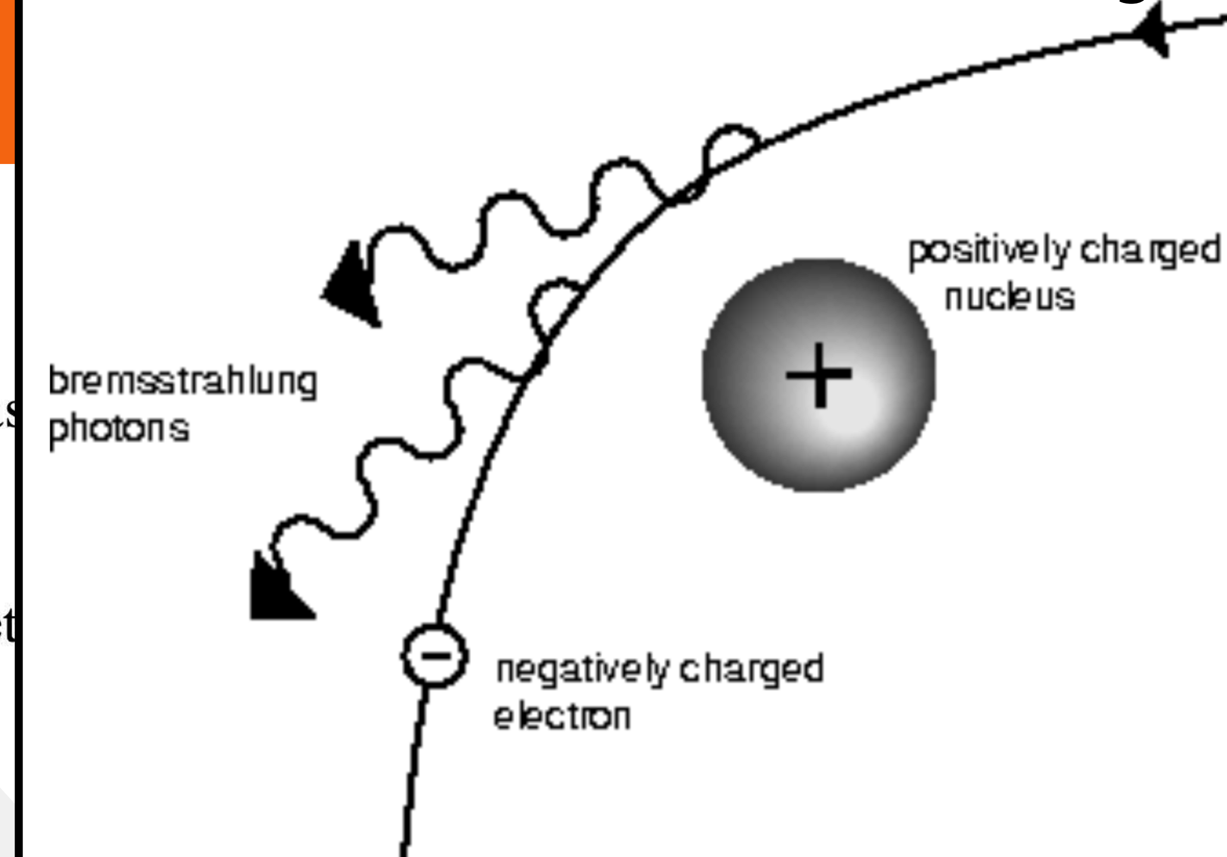
Emission mechanisms

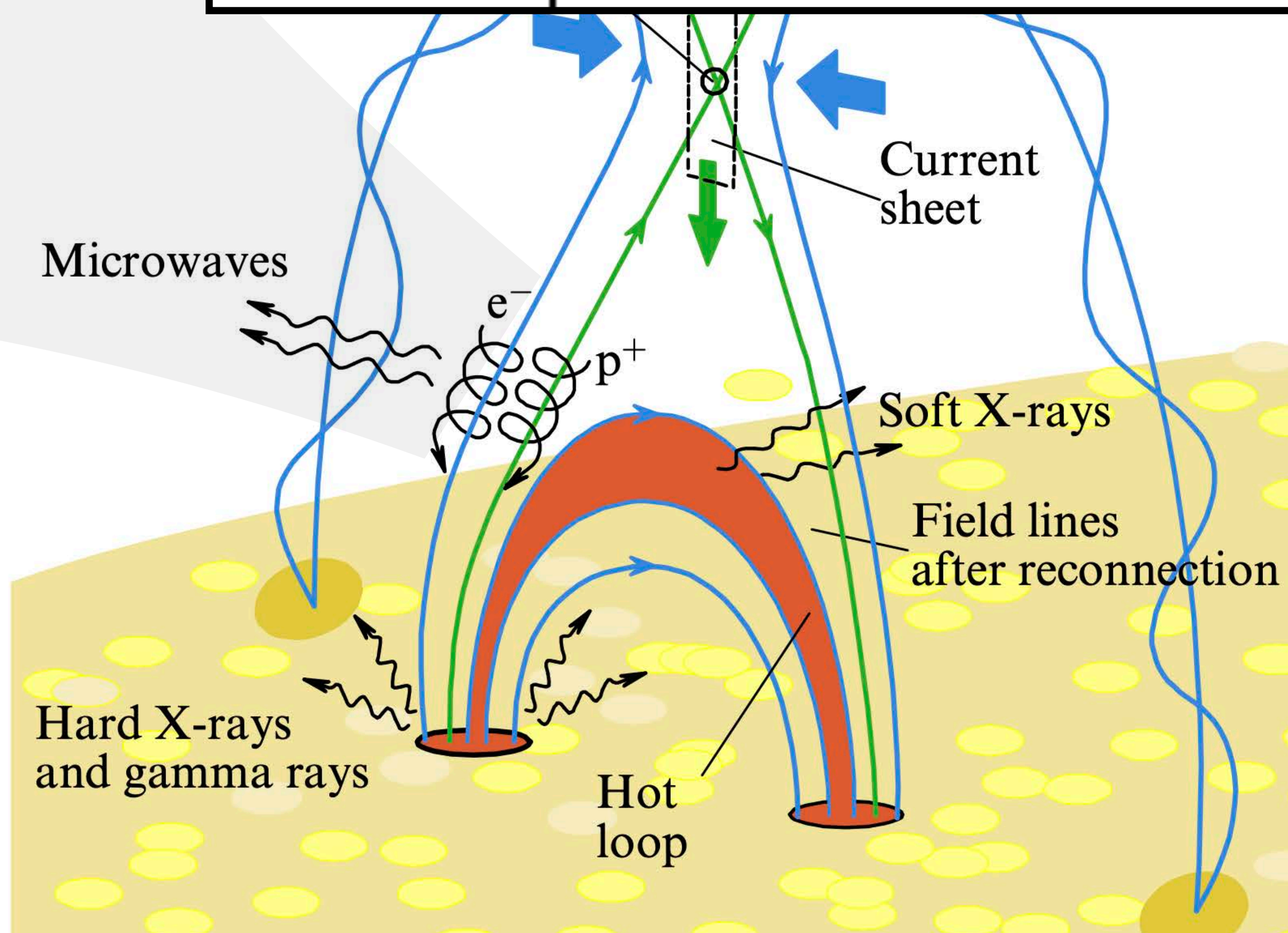
Non-thermal radiation — Synchrotron radiation



K. R. Lang, Tufts University

Thermal radiation — Bremsstrahlung





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

- Electrons accelerated to relativistic speeds

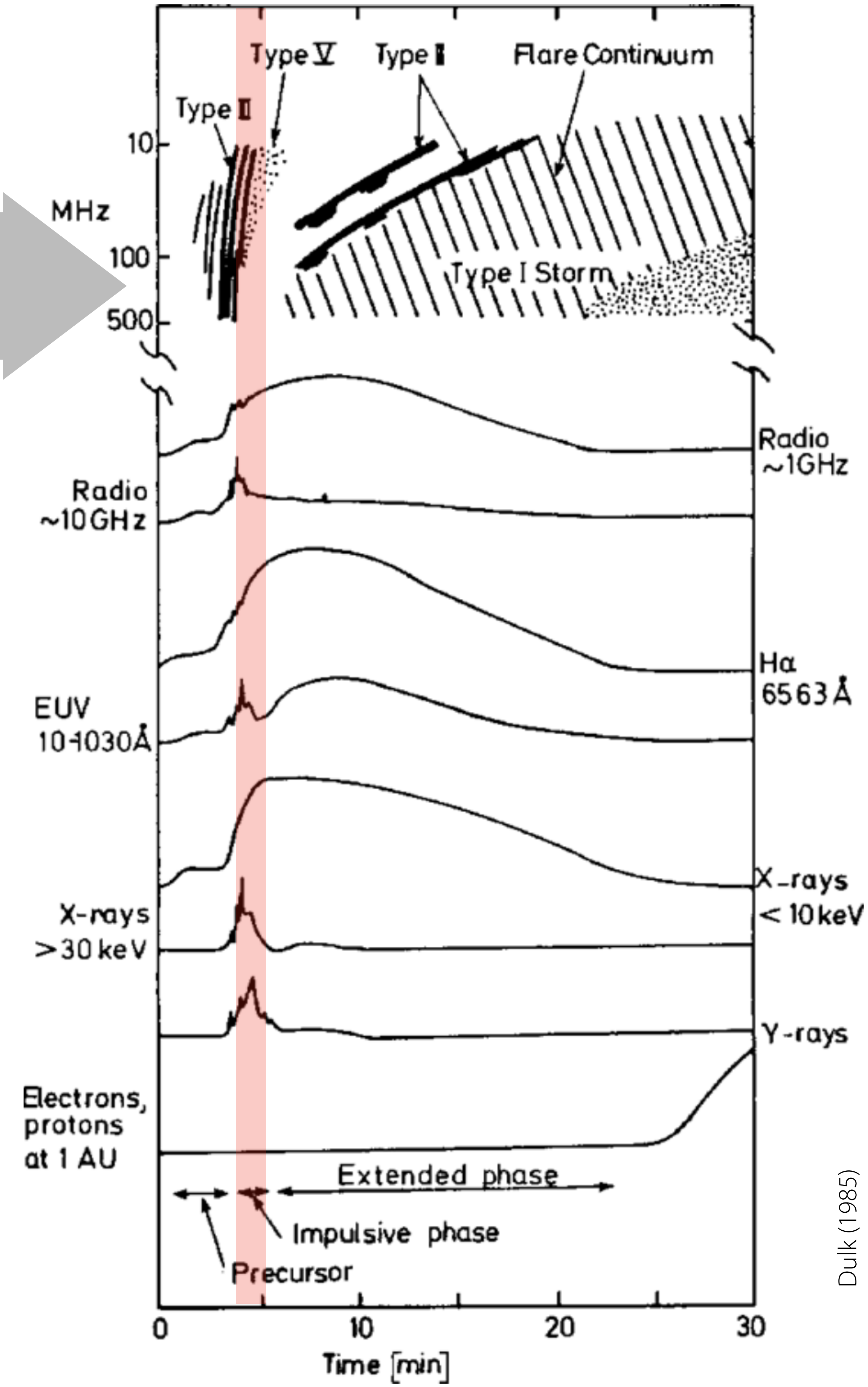
➡ Synchrotron radiation becomes beamed for electrons moving at relativistic speeds

- 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.

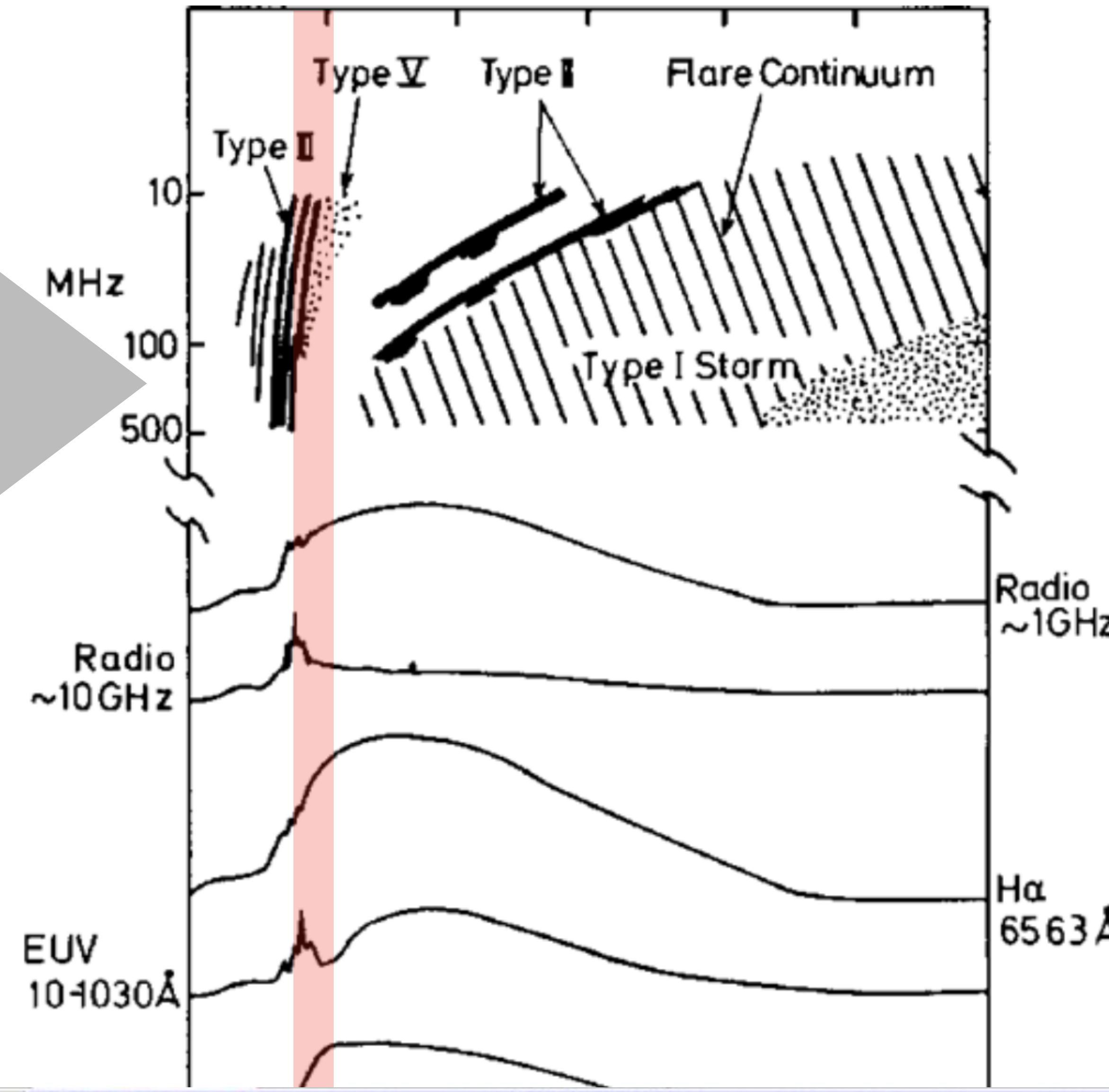


Dulk (1985)

Flares

Radio Bursts

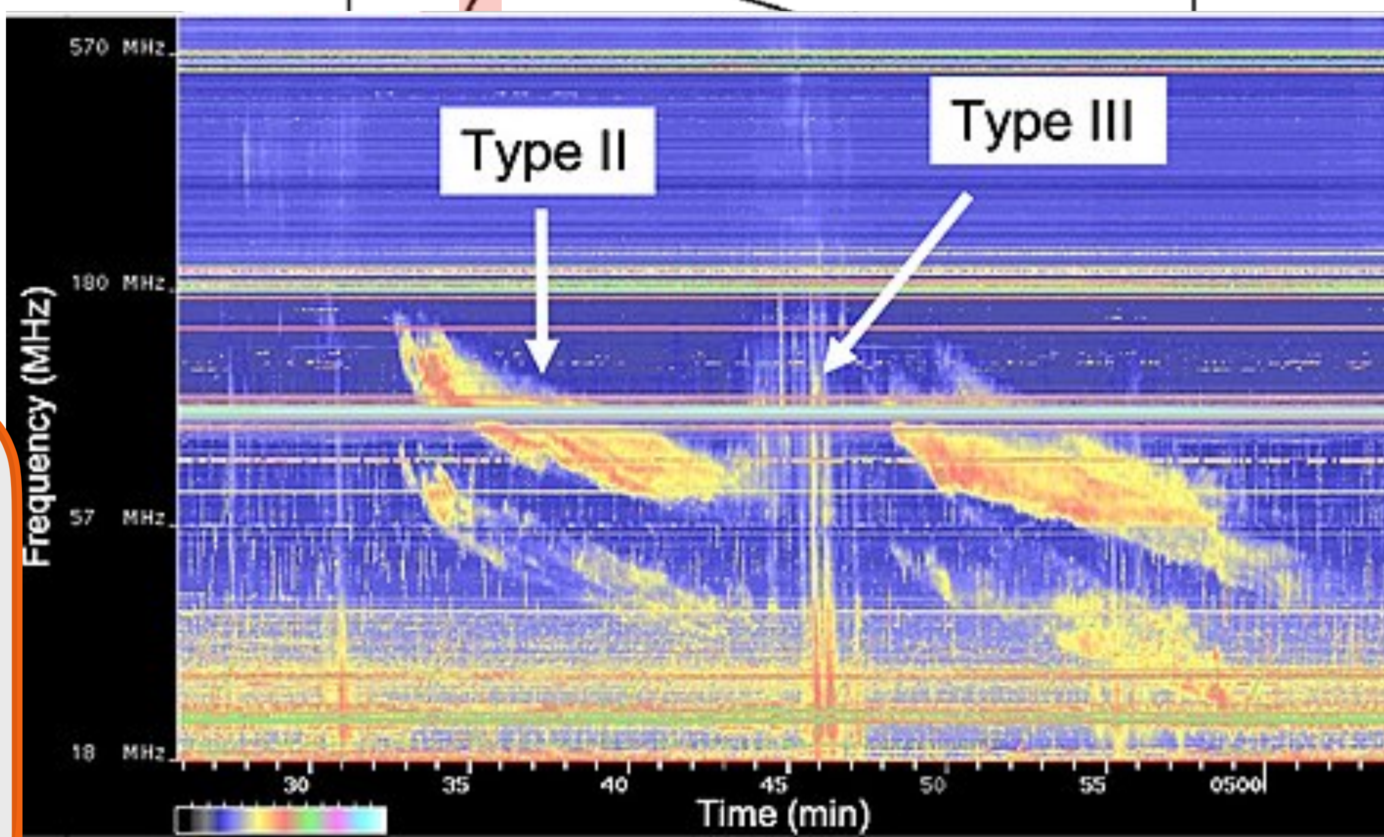
- **Radio wavelengths > 0.1 m** : eruptive events recorded since first discovery of solar radio signals (~1942)
- Many radio bursts associated with flares
- **Classification: Types I to V** (Wild 1959).
- Types II and III most characteristic due to banded structure in a frequency-time diagram.
- Lowest (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

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

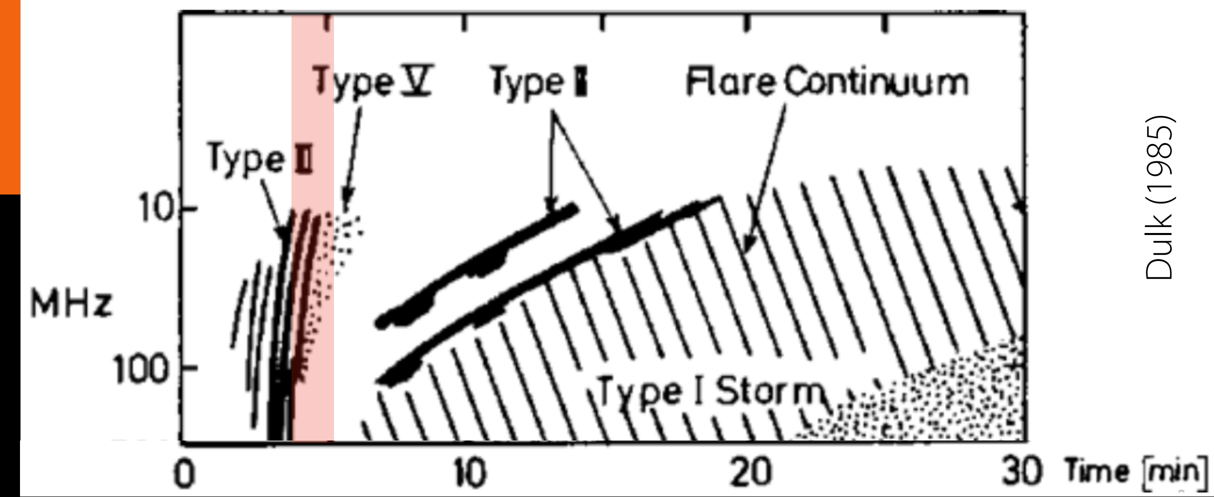
Electromagnetic waves with frequency < ν_P cannot propagate, will be absorbed or reflected



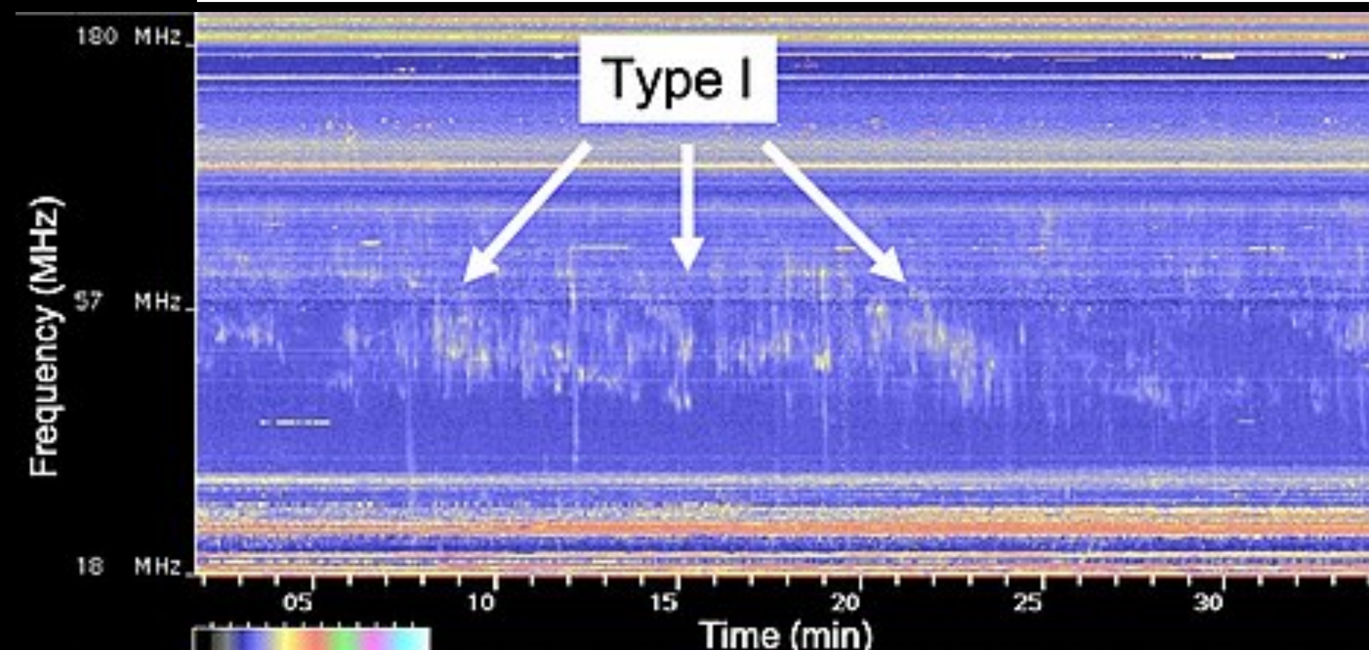
Flares

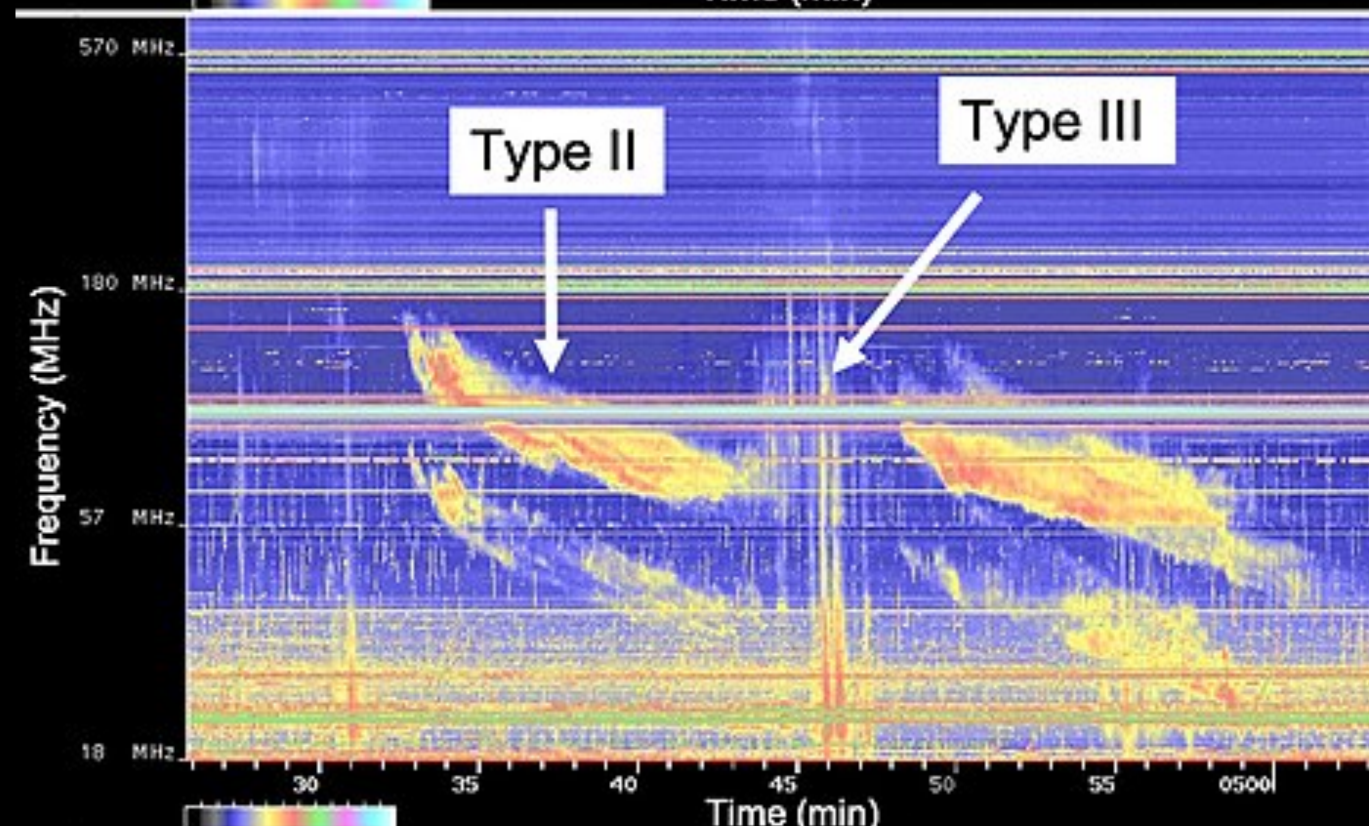
Radio Bursts

- **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 ~ 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



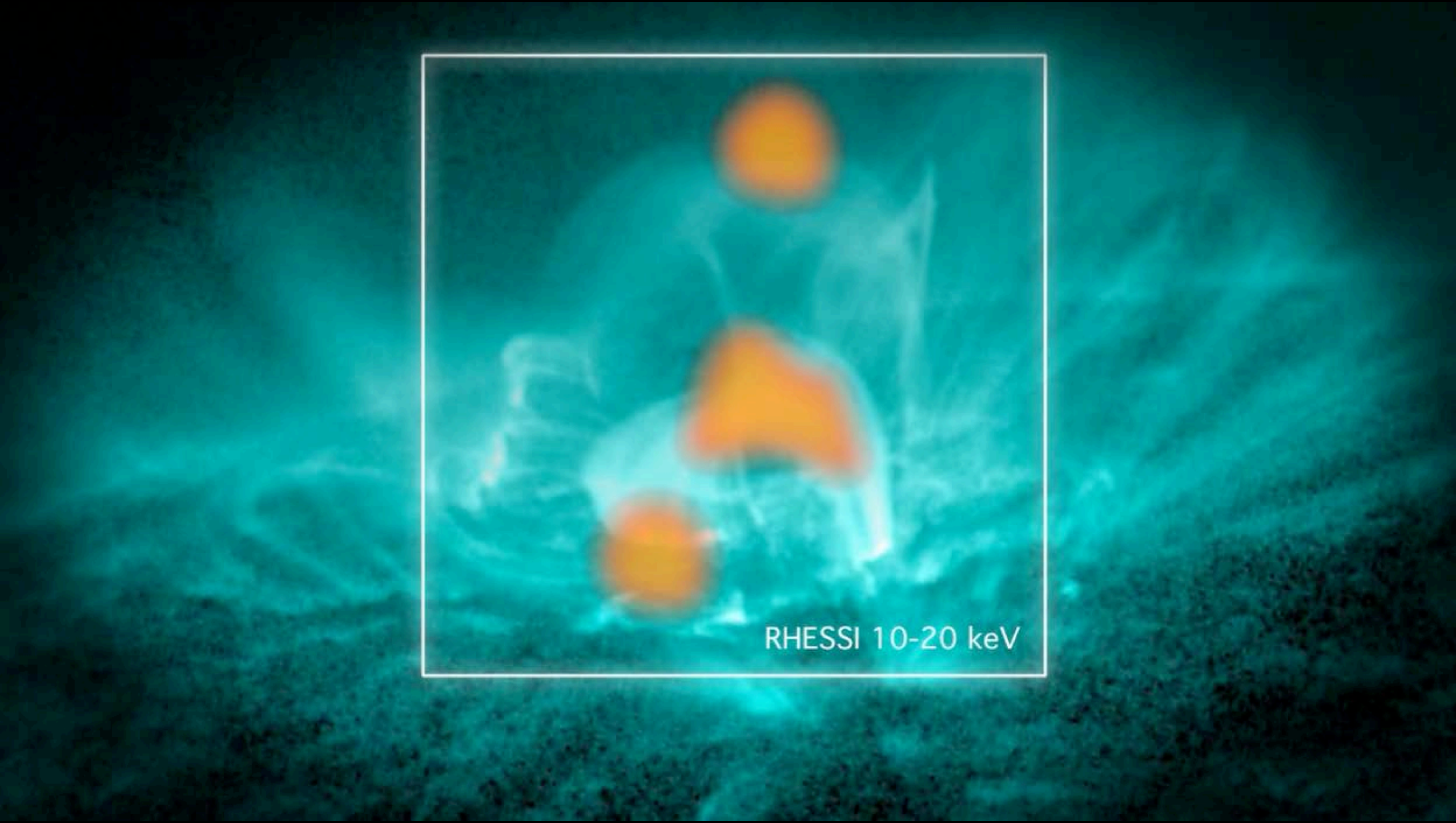
Dulk (1985)





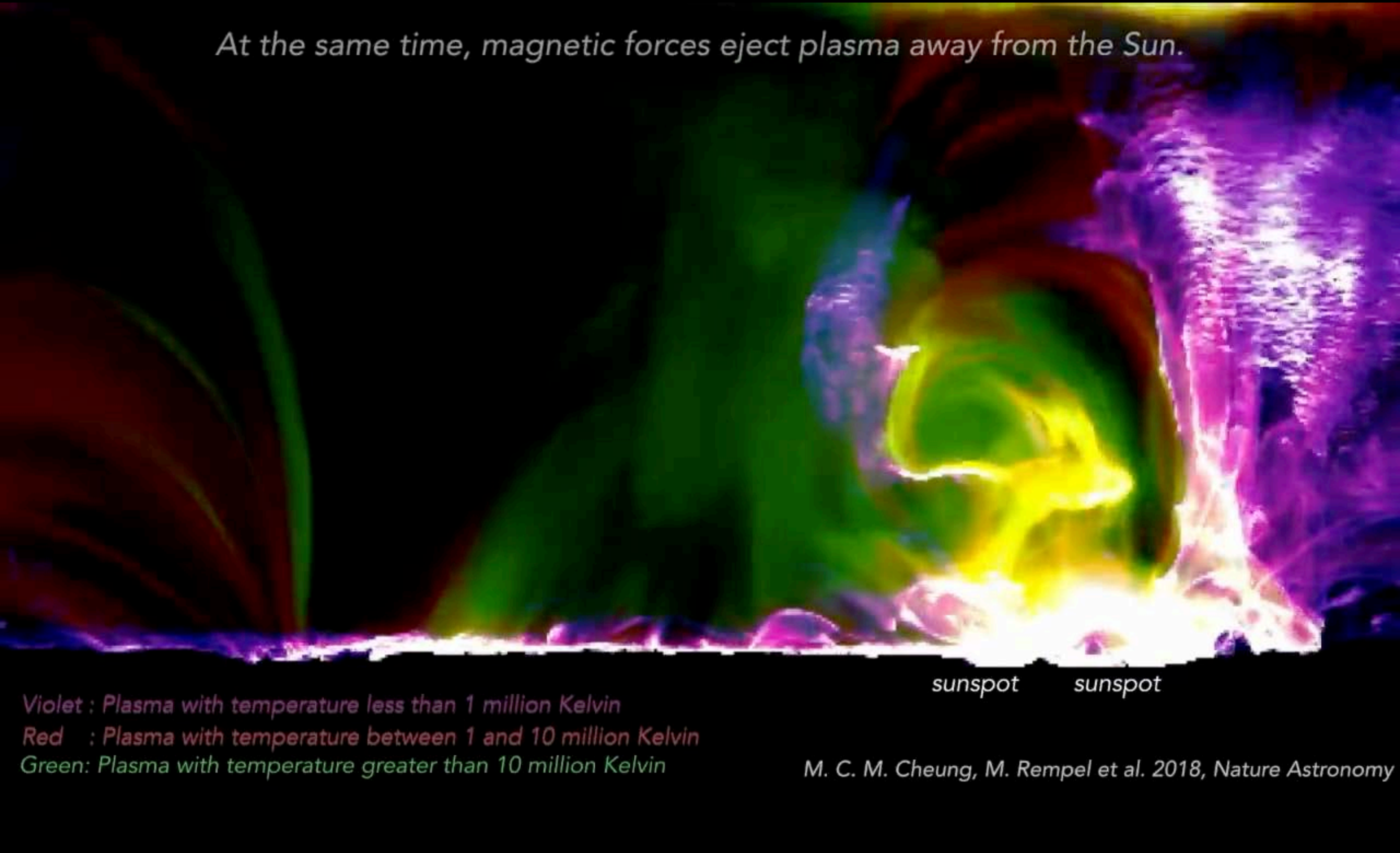
Flares

Observational evidence for reconnection



Flares

Numerical simulations



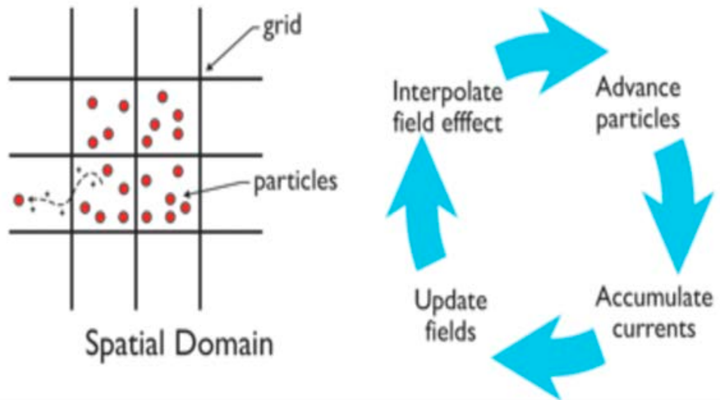
Flares

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)

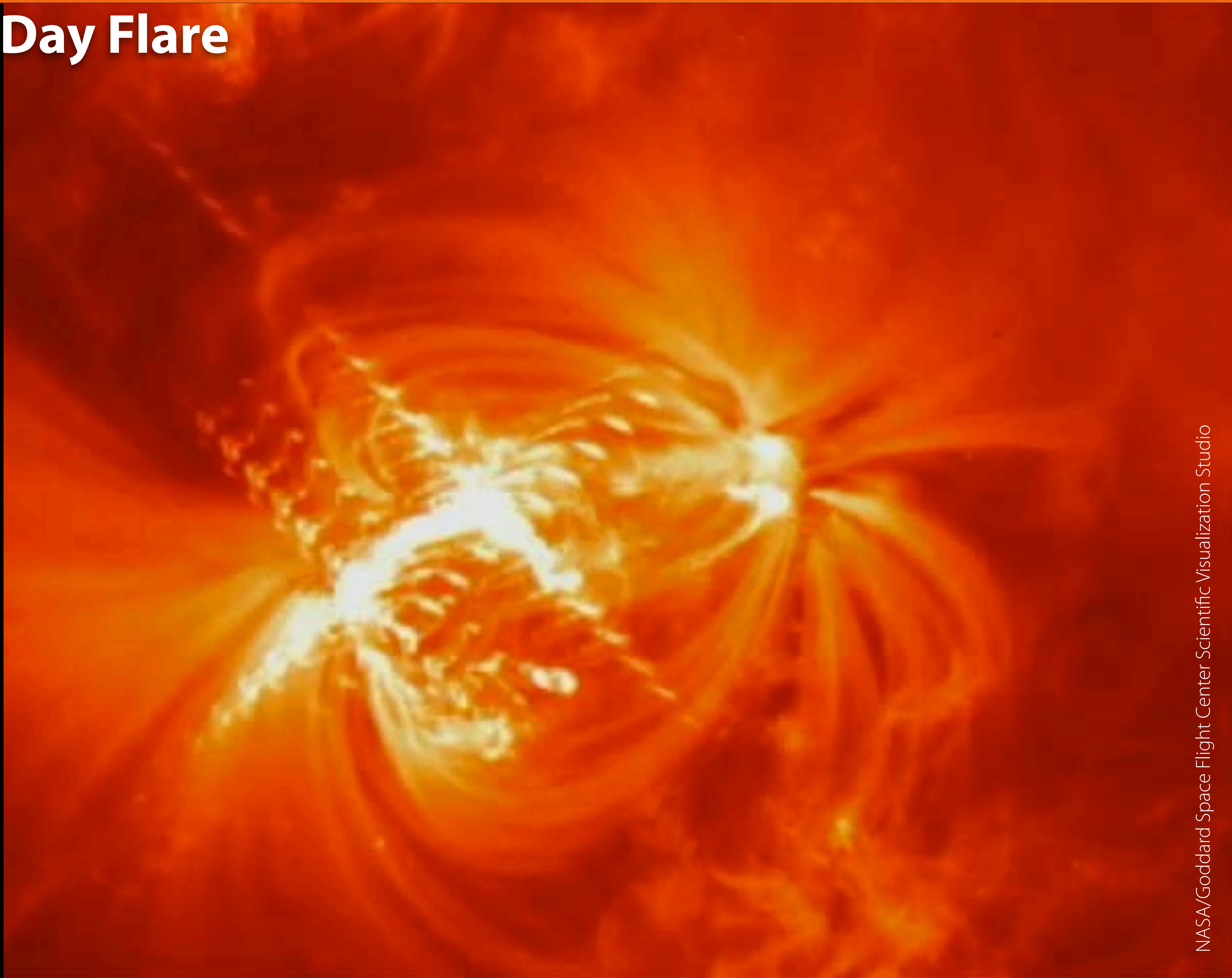
- **Current numerical approach**:
  - Simplifying assumptions and approximations needed to render problem computationally feasible
  - Particle-in-cell (PIC) method
    - Iterative method for solving the evolution of a system of particles (here: charged particles in a magnetic field)
    - Uses macro-particles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



Flares

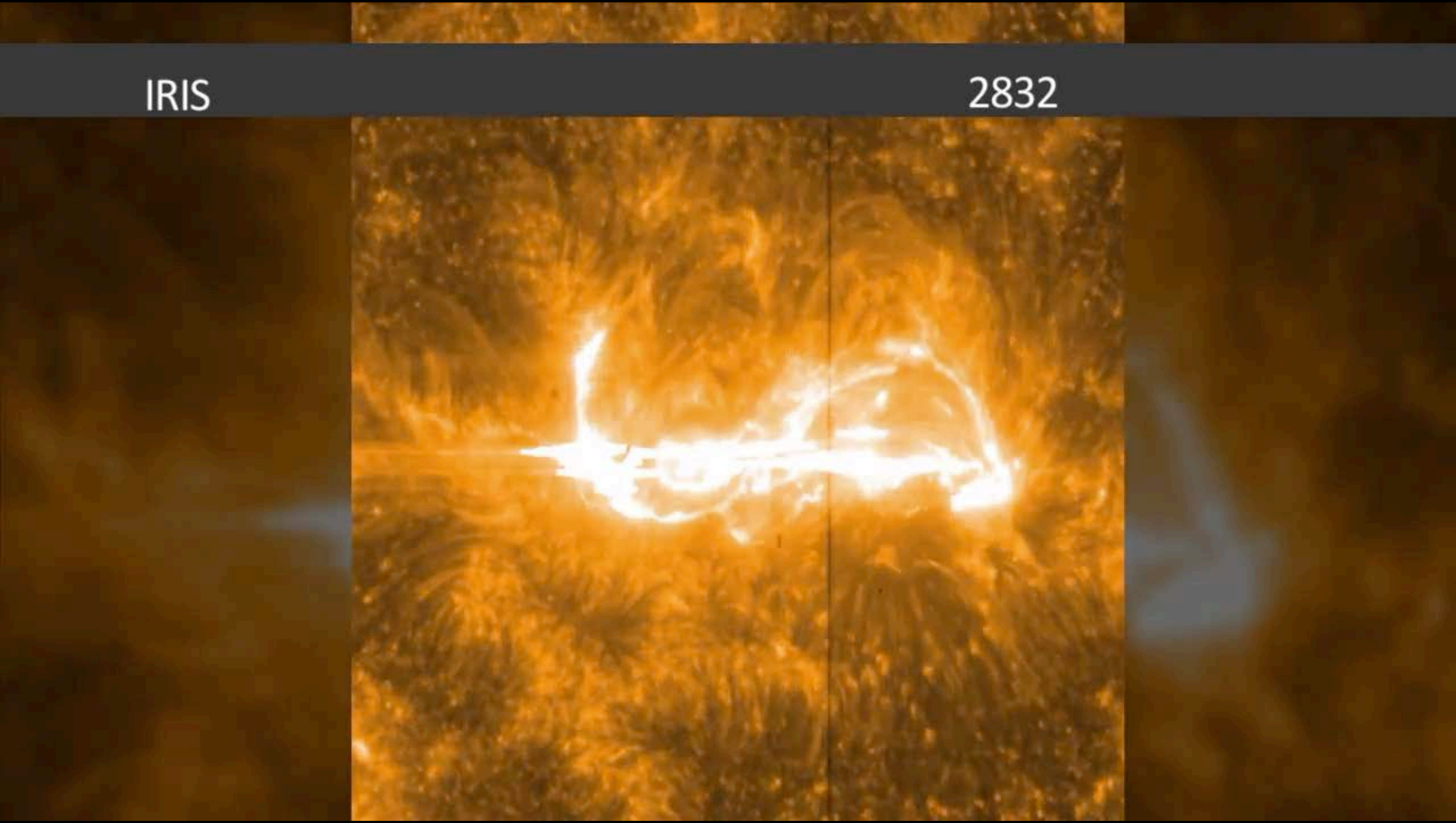
Bastille Day Flare

- 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

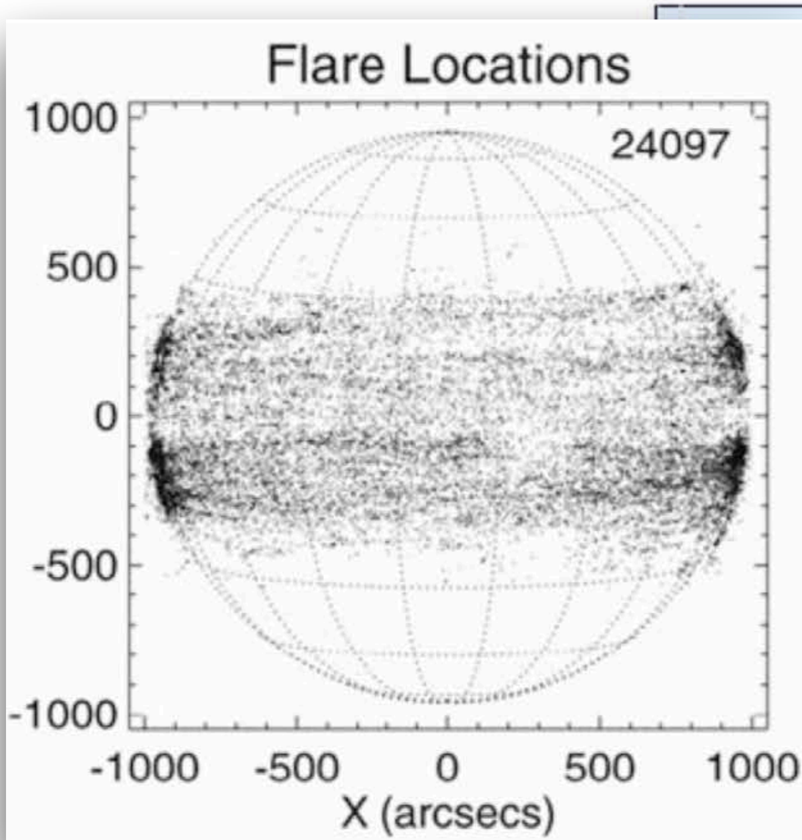


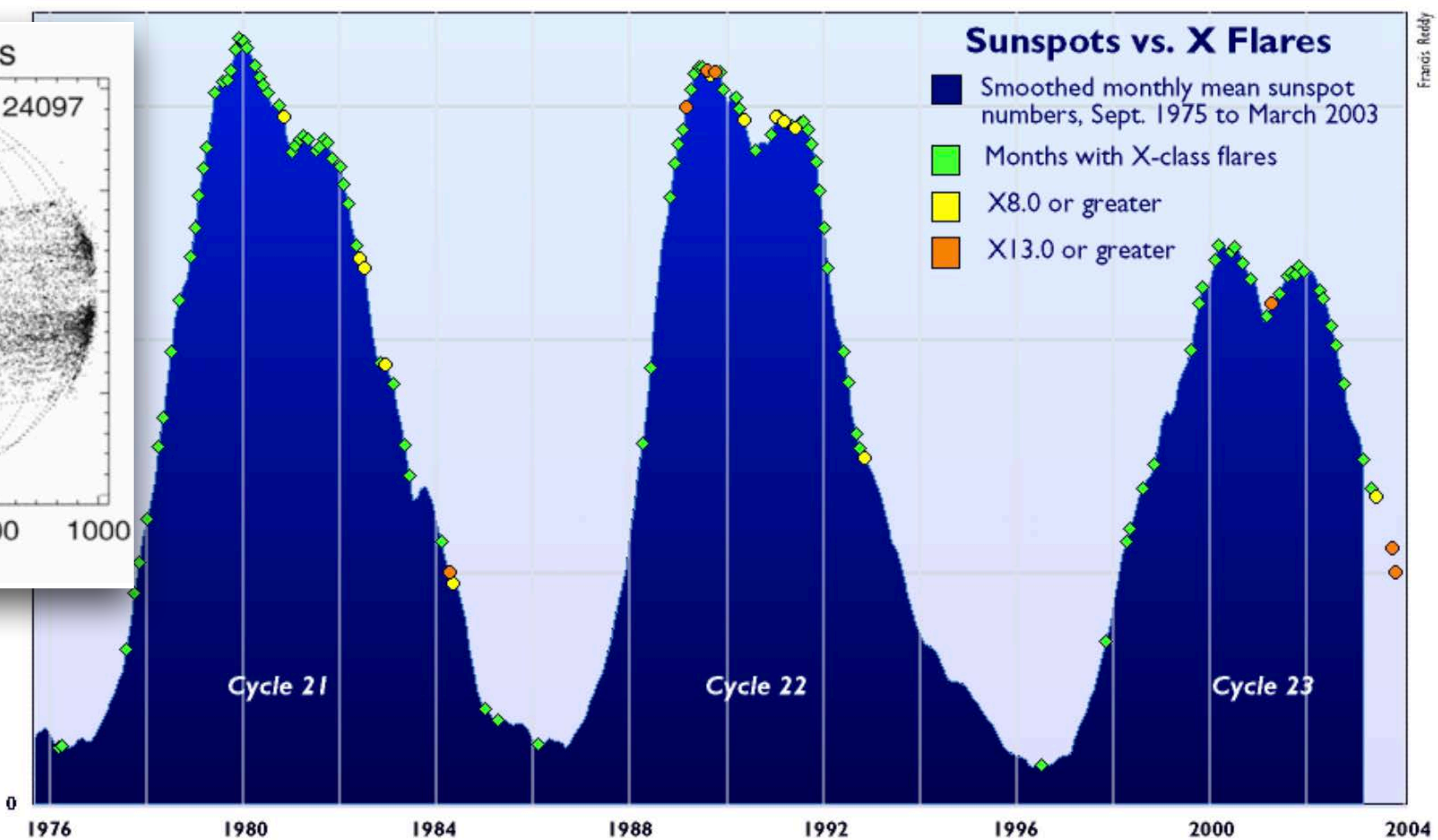
Flares

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

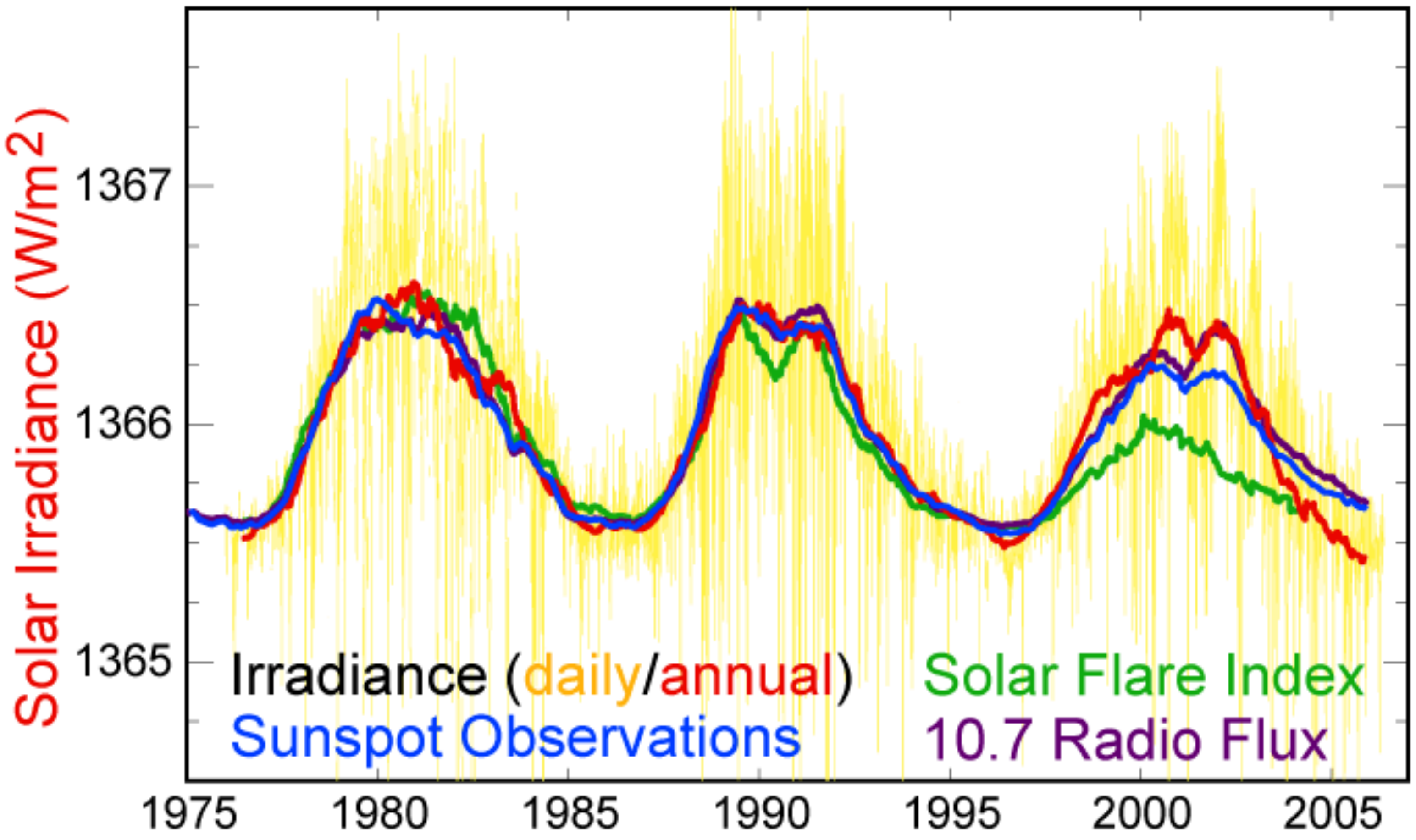




Flares

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.

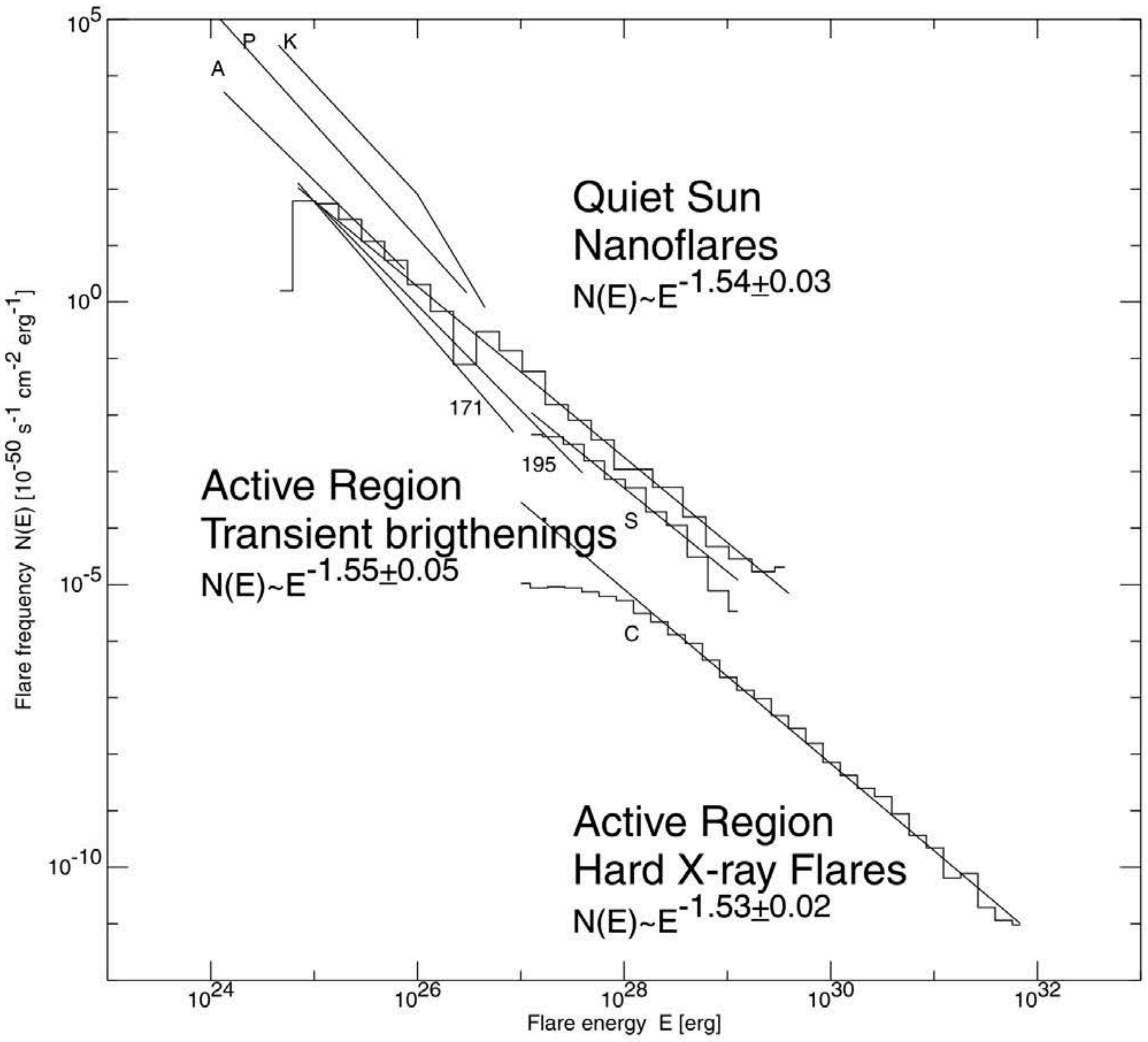


Solar flare index:
based on flare's brightness
and importance.

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)

Flares

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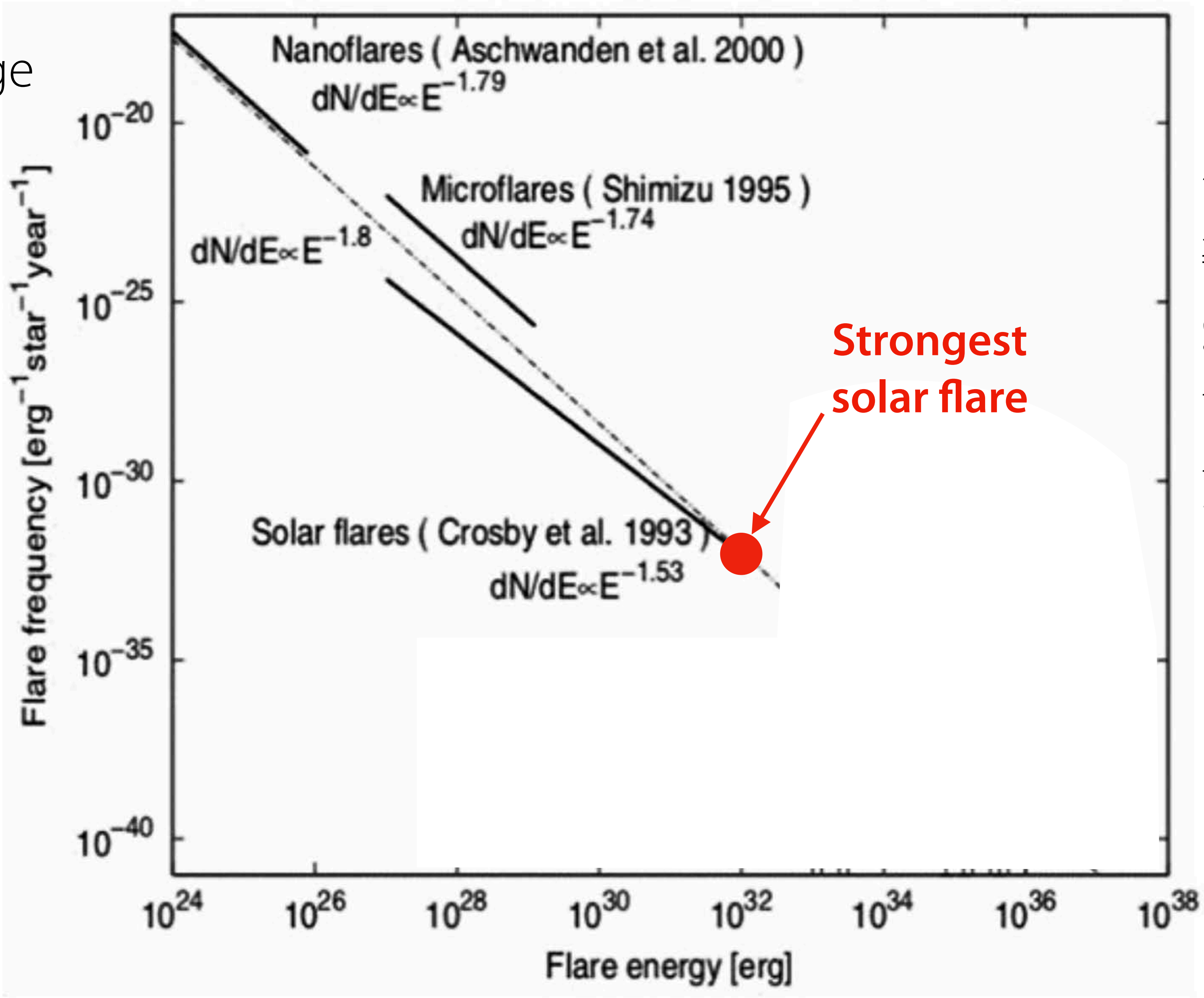
Observed on the Sun



Aschwanden & Parnell (2002)

Flares

Flares as a scalable phenomenon

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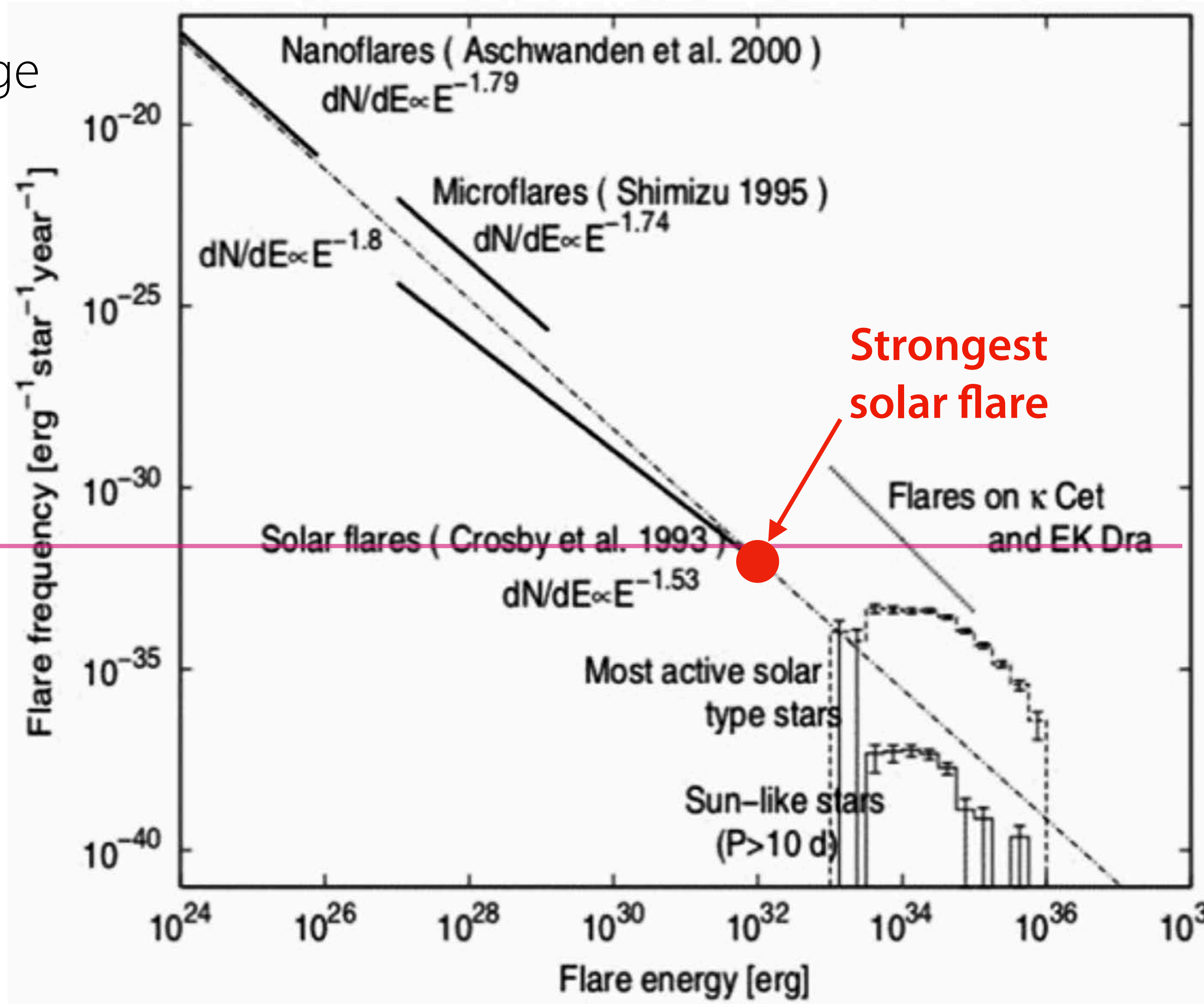
- From small to large:
  - Nanoflares
  - Microflares
  - (normal) flares
  - **Superflares**
  - **Megaflares**

Observed on the Sun



Aschwanden & Parnell (2002)

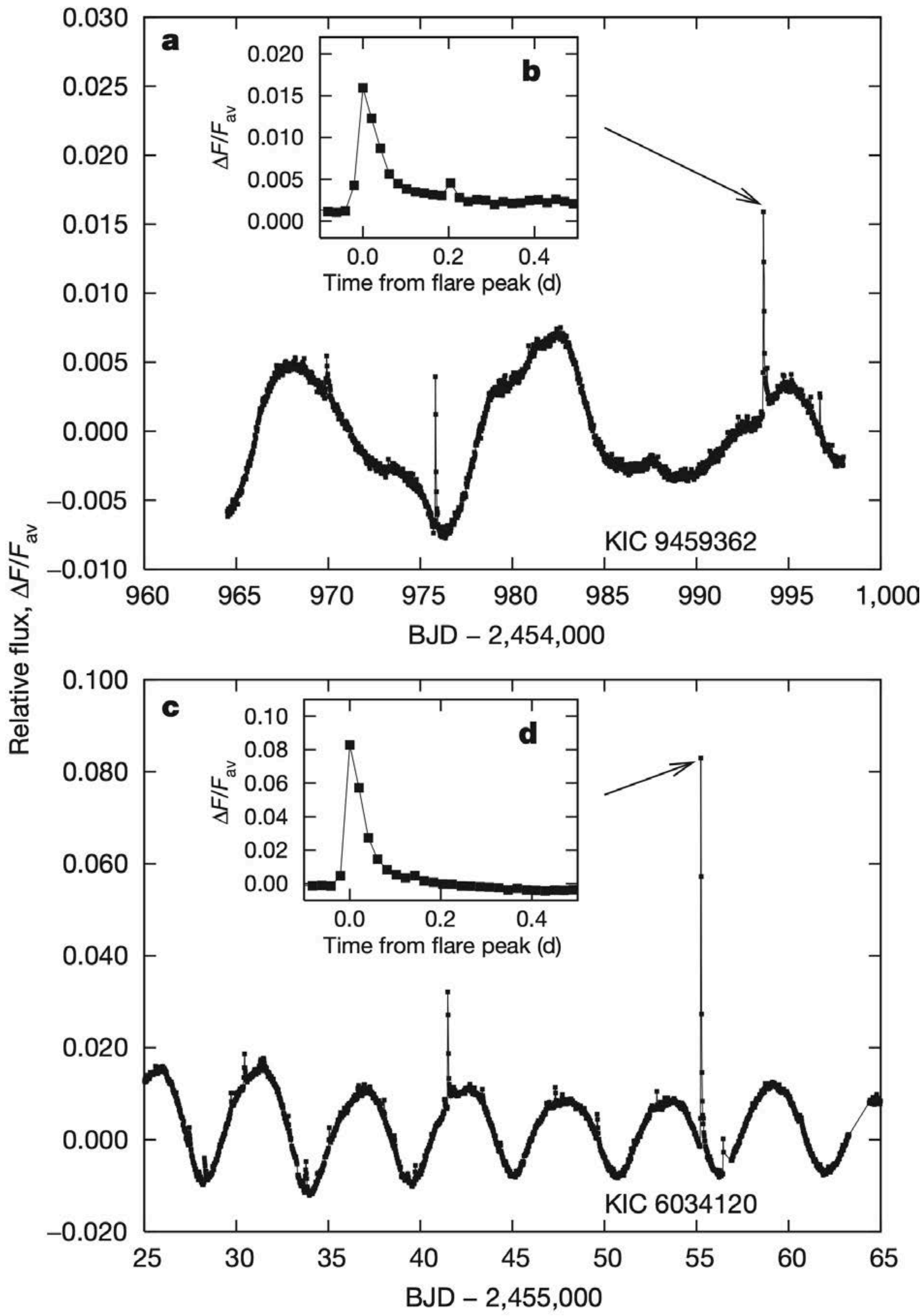
Stellar flares

Superflares

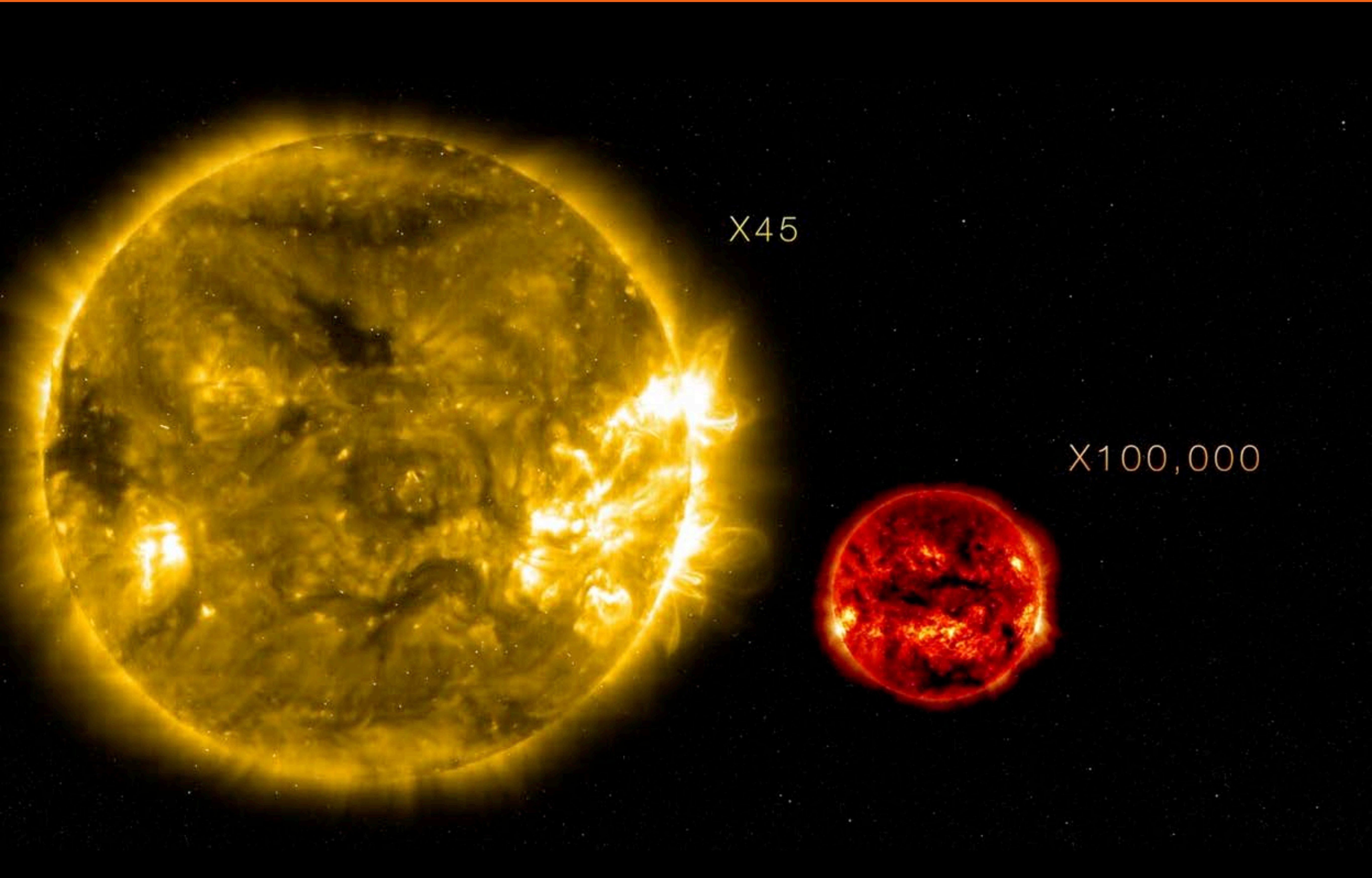
Maehara et al (2012)

- 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

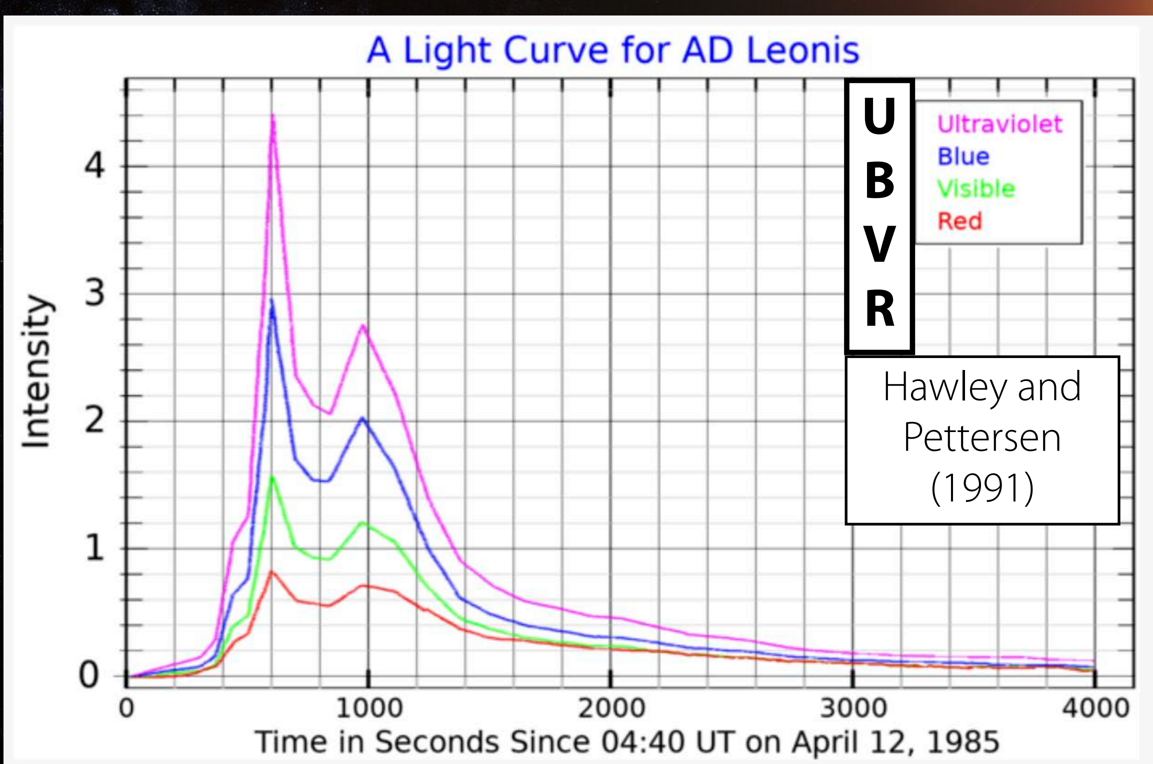


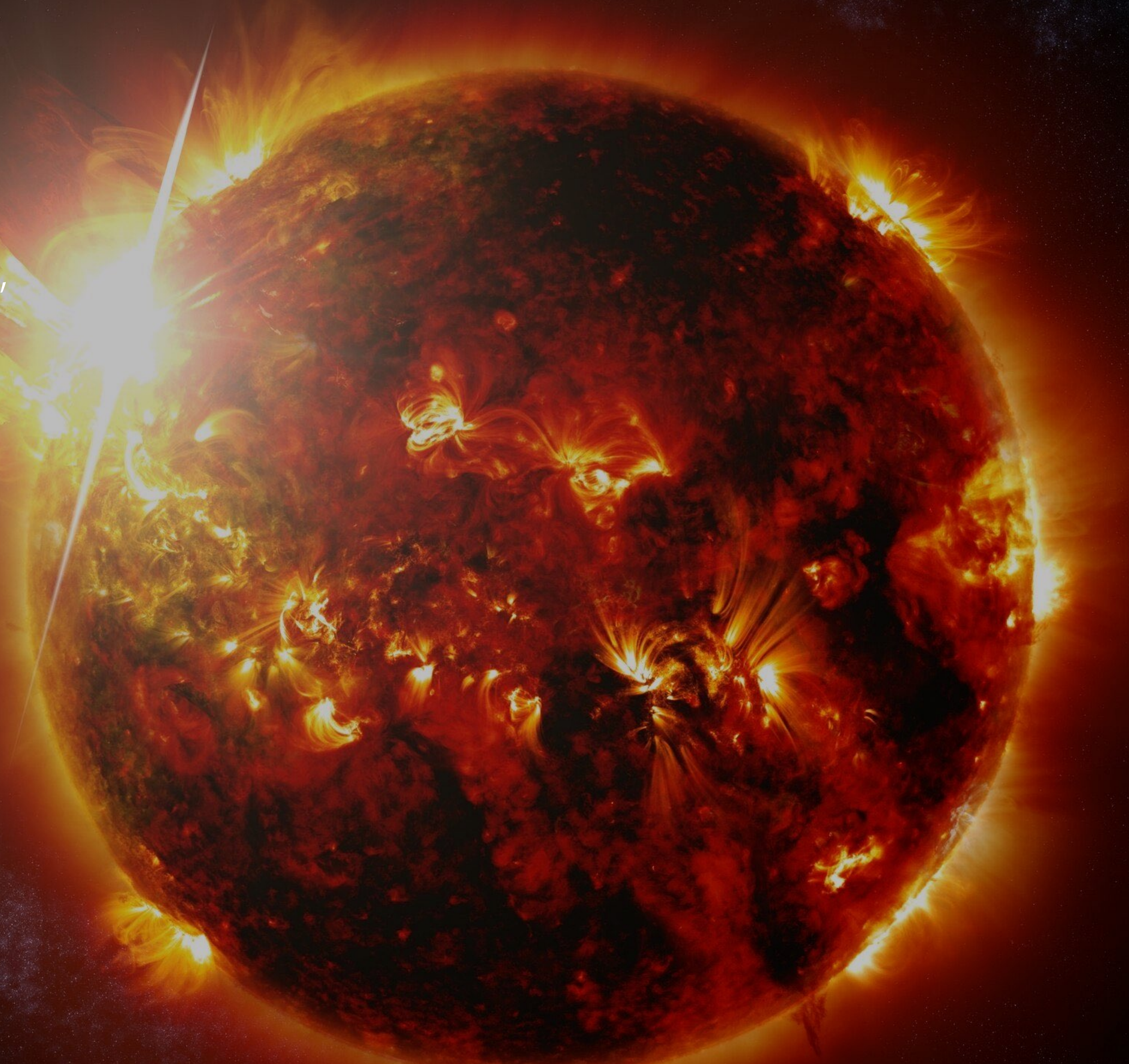
Credits: NASA's Goddard Space Flight Center/S. Wiessinger

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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