AST5770

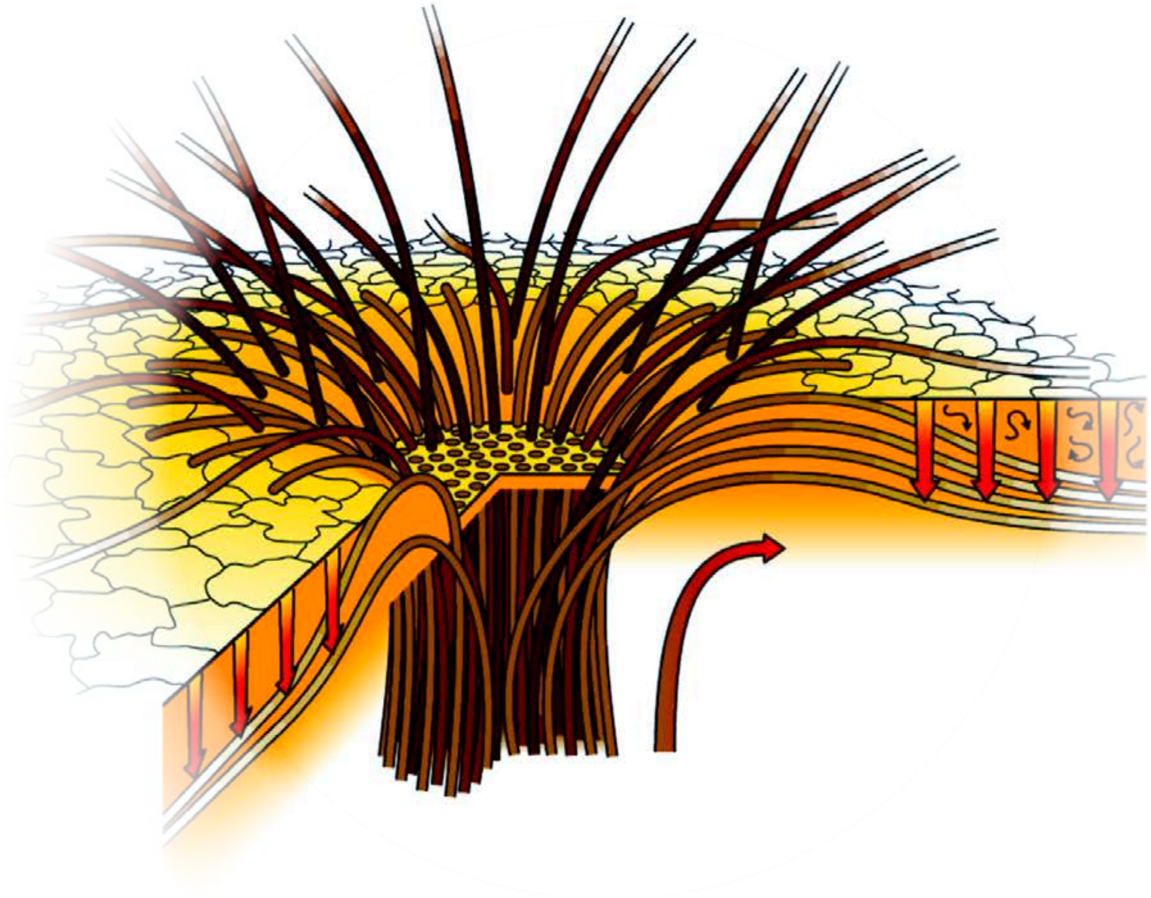
Solar and stellar physics

Sven Wedemeyer, University of Oslo, 2023

Sunspots

Sunspots

Recap



1. How big are sunspots typically?
2. How long do sunspots "live" typically?
3. What is uncombed penumbra?
4. What is the equipartition field strength and how it help to explain the magnetic field strengths observed in magnetic flux concentrations (e.g. sunspots)?
5. What is dominant oscillation period in the photosphere in Quiet Sun region (i.e. regions with relatively little magnetic flux)?
6. Why do we observe different oscillation periods in the chromosphere and inside sunspots?
7. How can we explain the appearance of umbral dots and lightbridges? What are those?

Think 1-2 min about the answers. You may discuss with your neighbours.

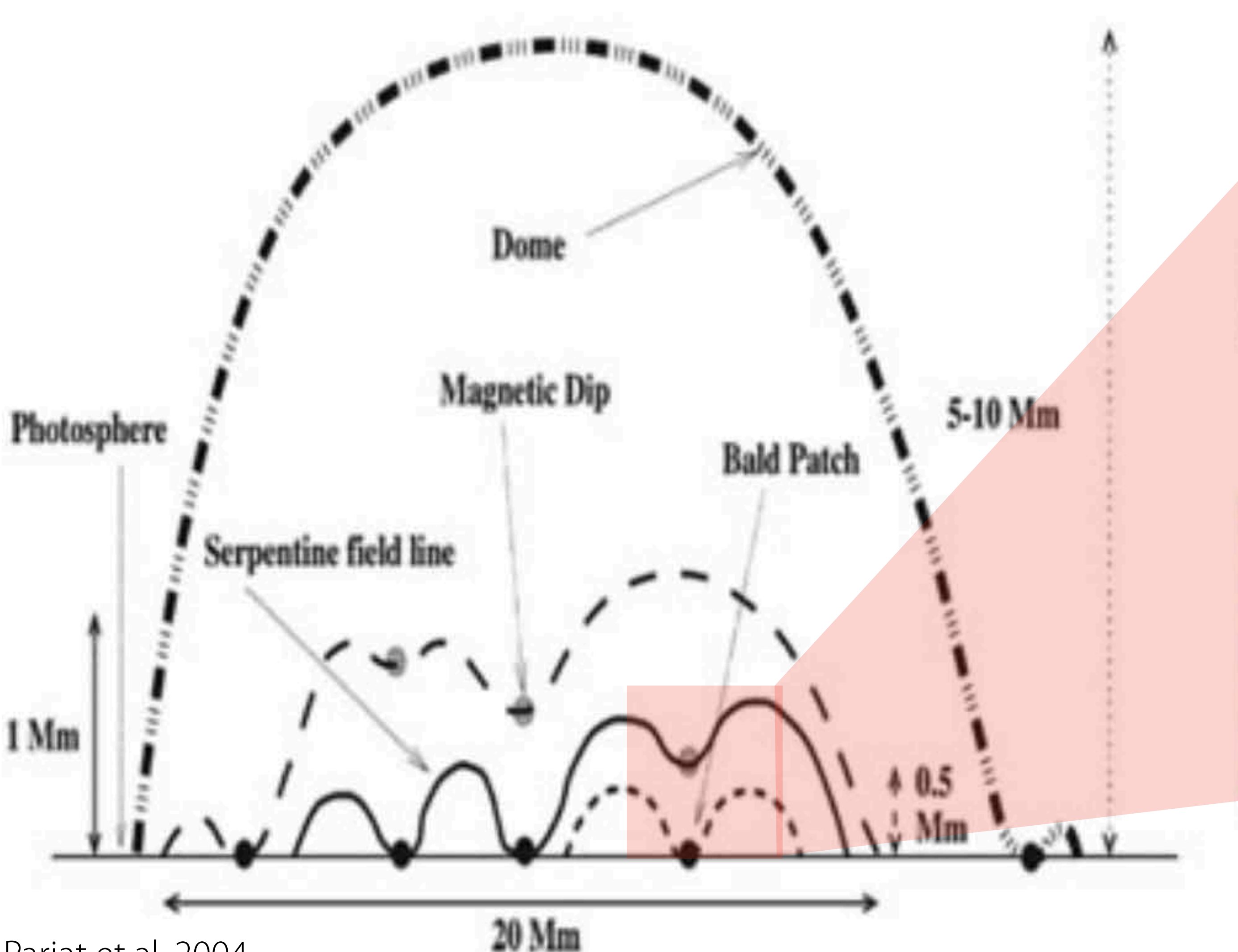
Energetic phenomena
Active Regions

Energetic phenomena in Active Regions

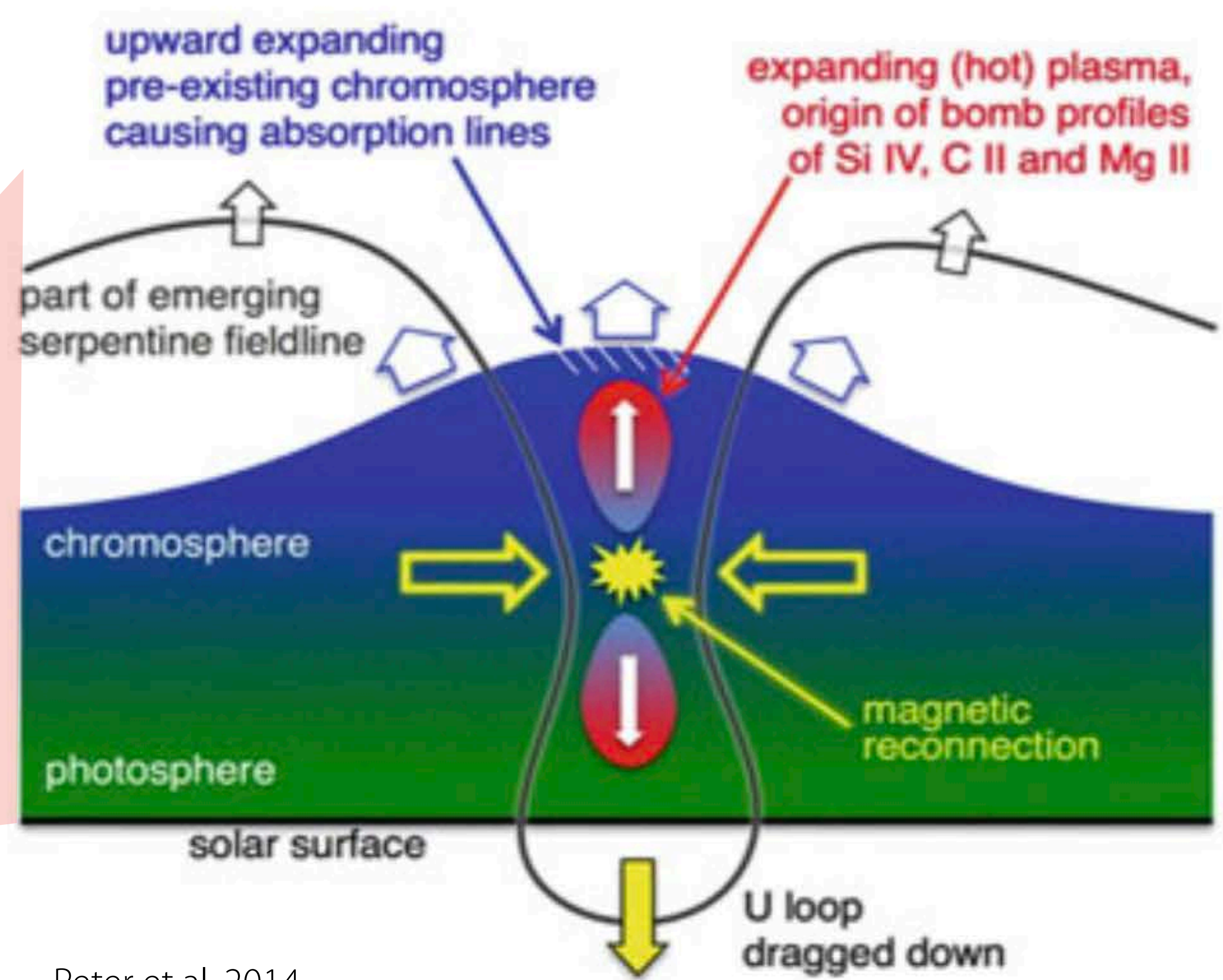
Magnetic reconnection

- Plasma motions in penumbra drag down magnetic field
- Serpentine field lines, magnetic dips, and "bald patches"
- If pushed too close, **magnetic reconnection** can occur

➡ **Reconfiguration** of magnetic field into an energetically preferable configuration and (explosive) **release of energy** (previously stored in magnetic field)



Pariat et al. 2004

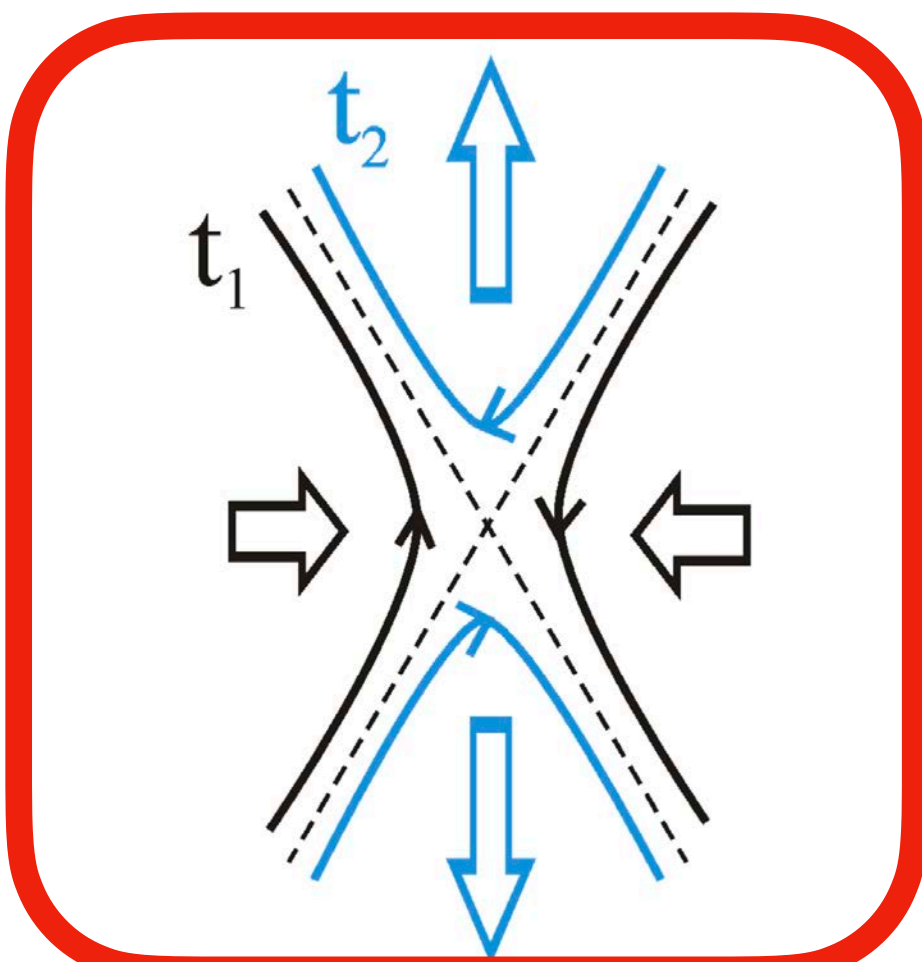


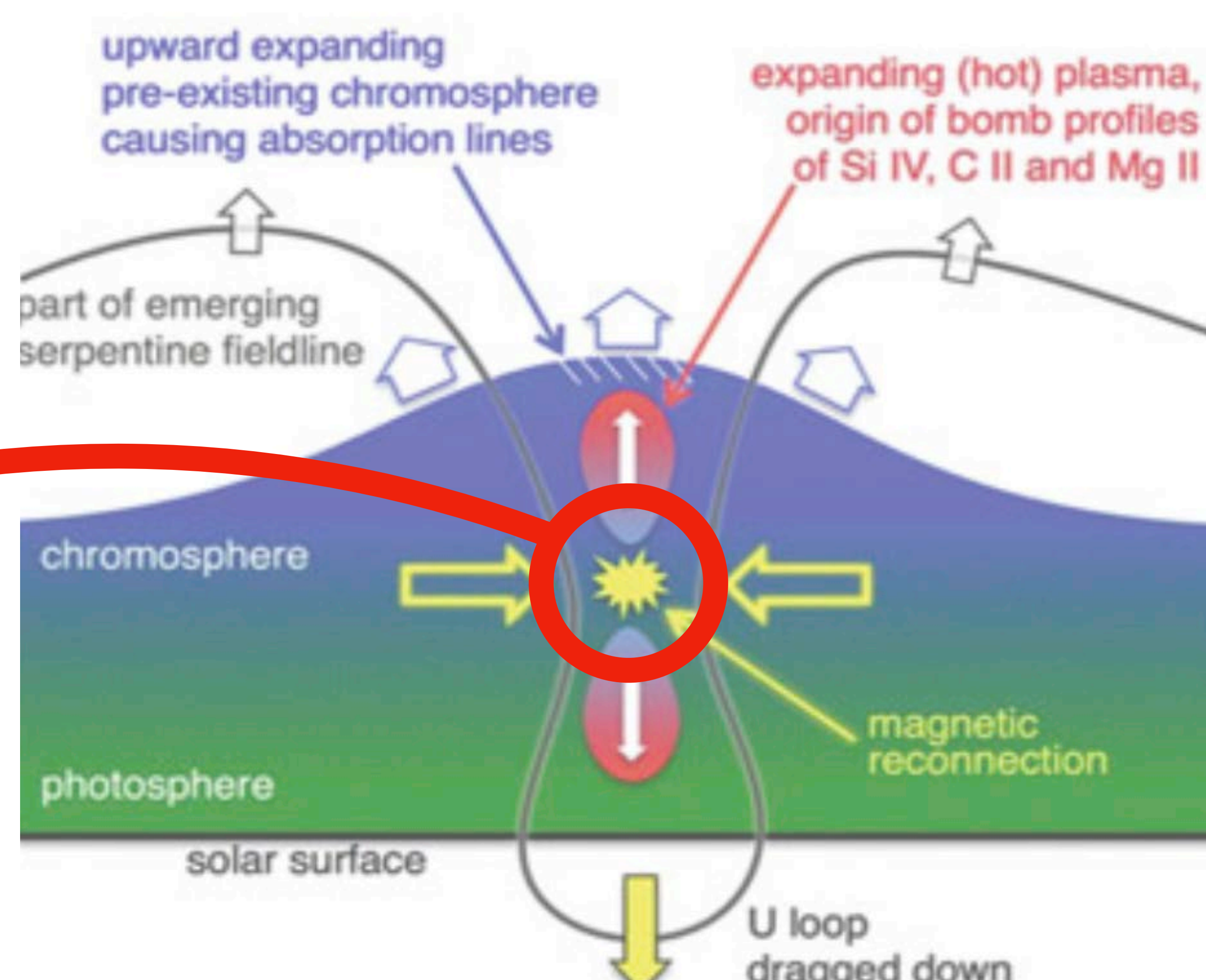
Peter et al. 2014

Energetic phenomena in Active Regions

Magnetic reconnection

- Antiparallel magnetic field lines disconnect at an X point and reconnect with other field lines
- Converts magnetic energy into kinetic energy — plasma is heated and accelerated
- Plays a critical role for a large number of phenomena on a large range of scales (e.g., solar flares, CME, geomagnetic storms at Earth…)



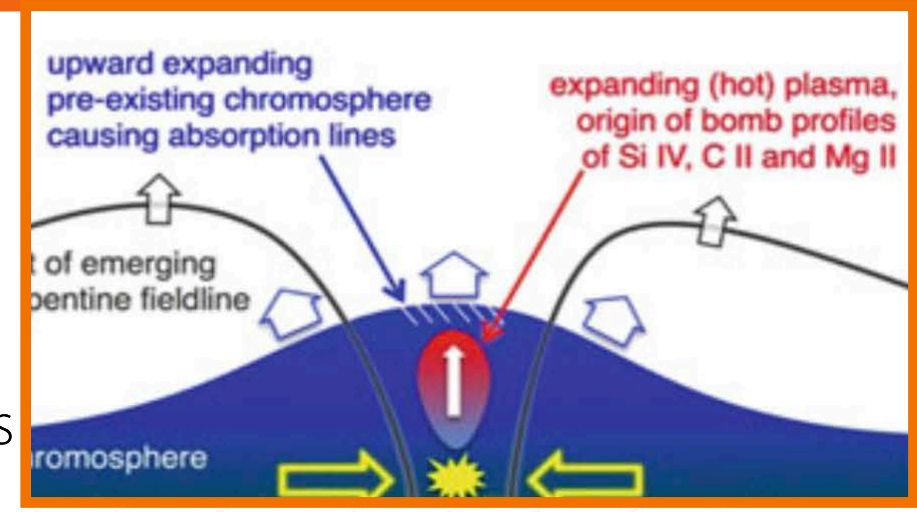


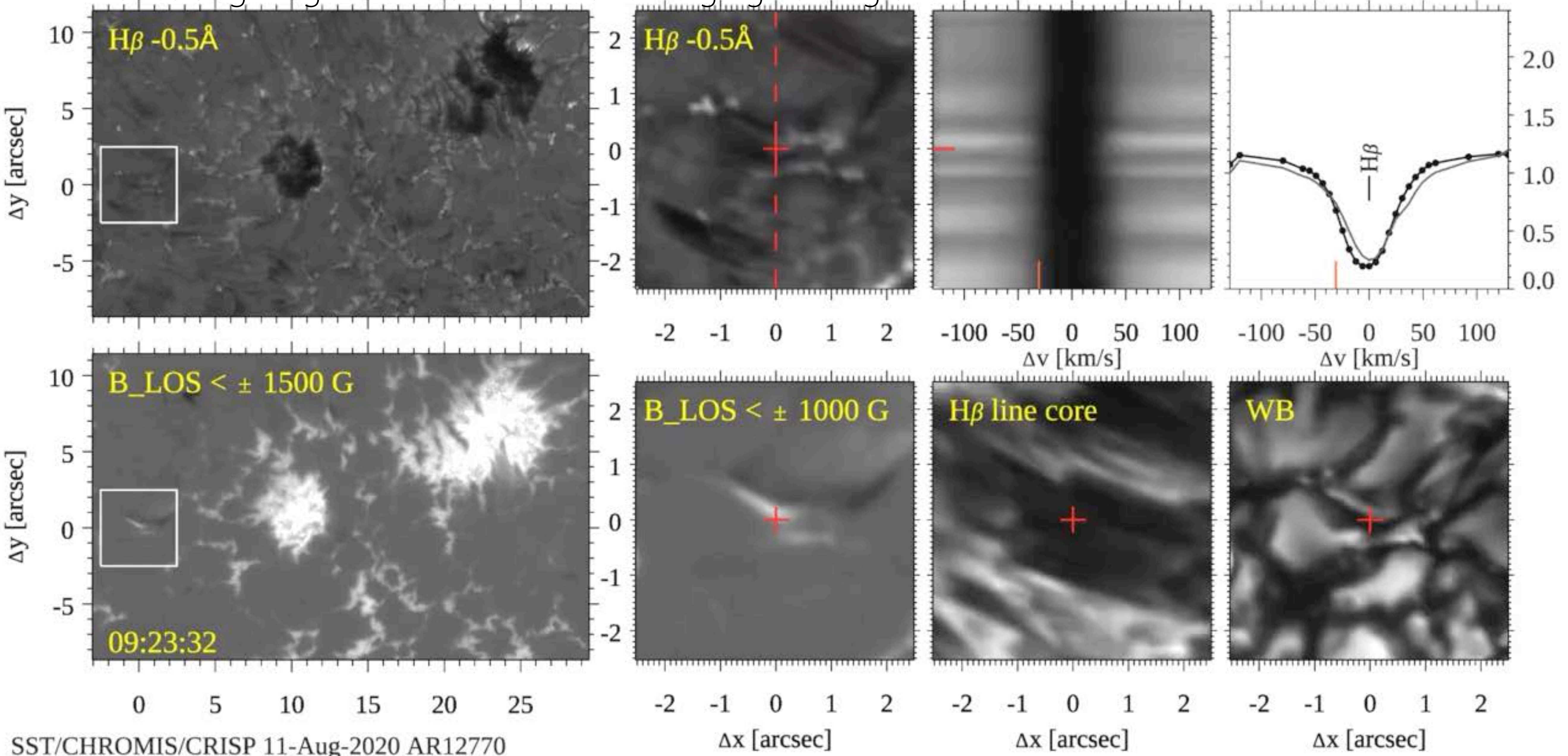
Peter et al. 2014

Energetic phenomena in Active Regions

Ellerman bombs (Discovered by Ellerman 1917)

- Bidirectional outflow from reconnection region causes a double-hump in spectral line profiles of Si IV, C II, and Mg II
- Cool material in atmosphere above causes absorption line
- Observed as <u>small-scale brightenings</u> in low chromosphere in areas with strong magnetic fields and near emerging flux regions

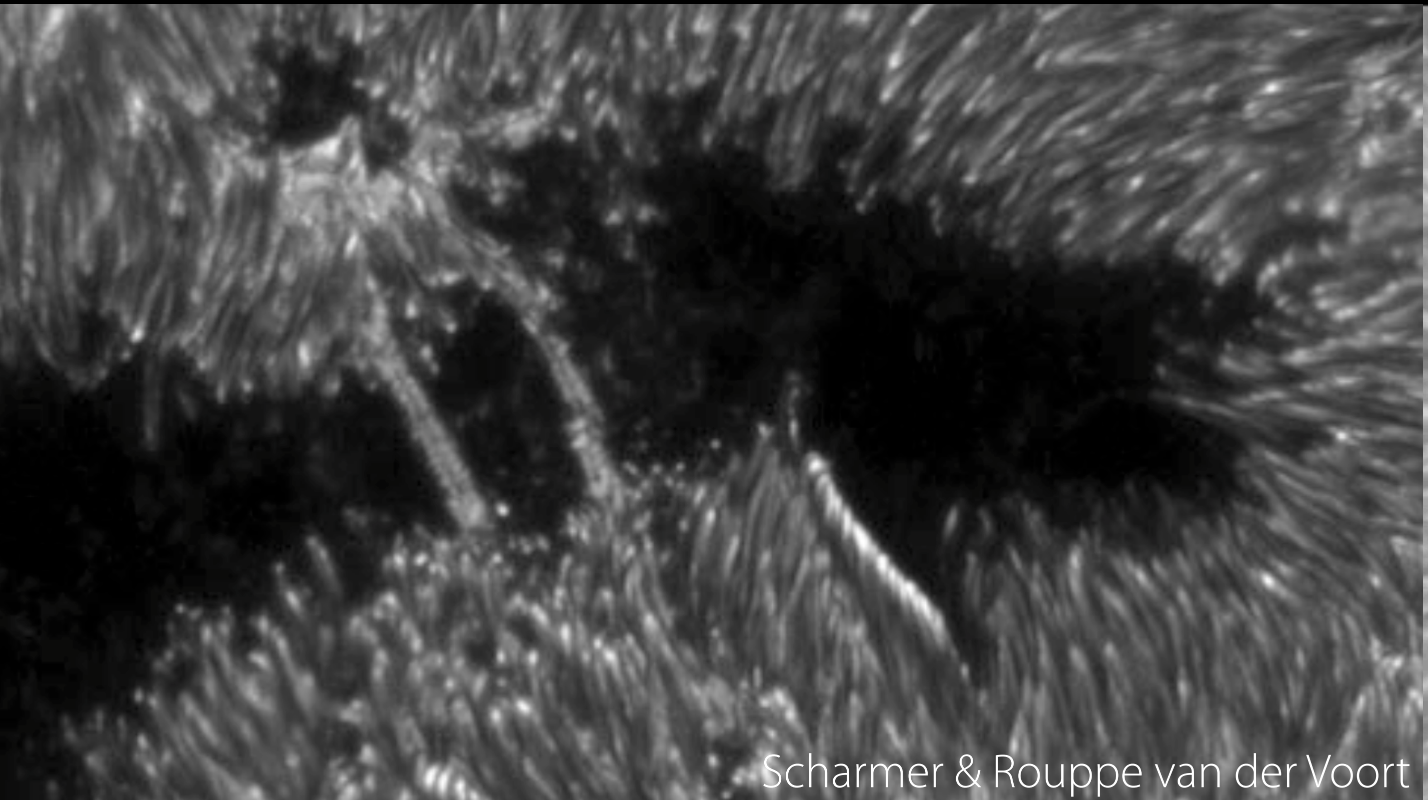


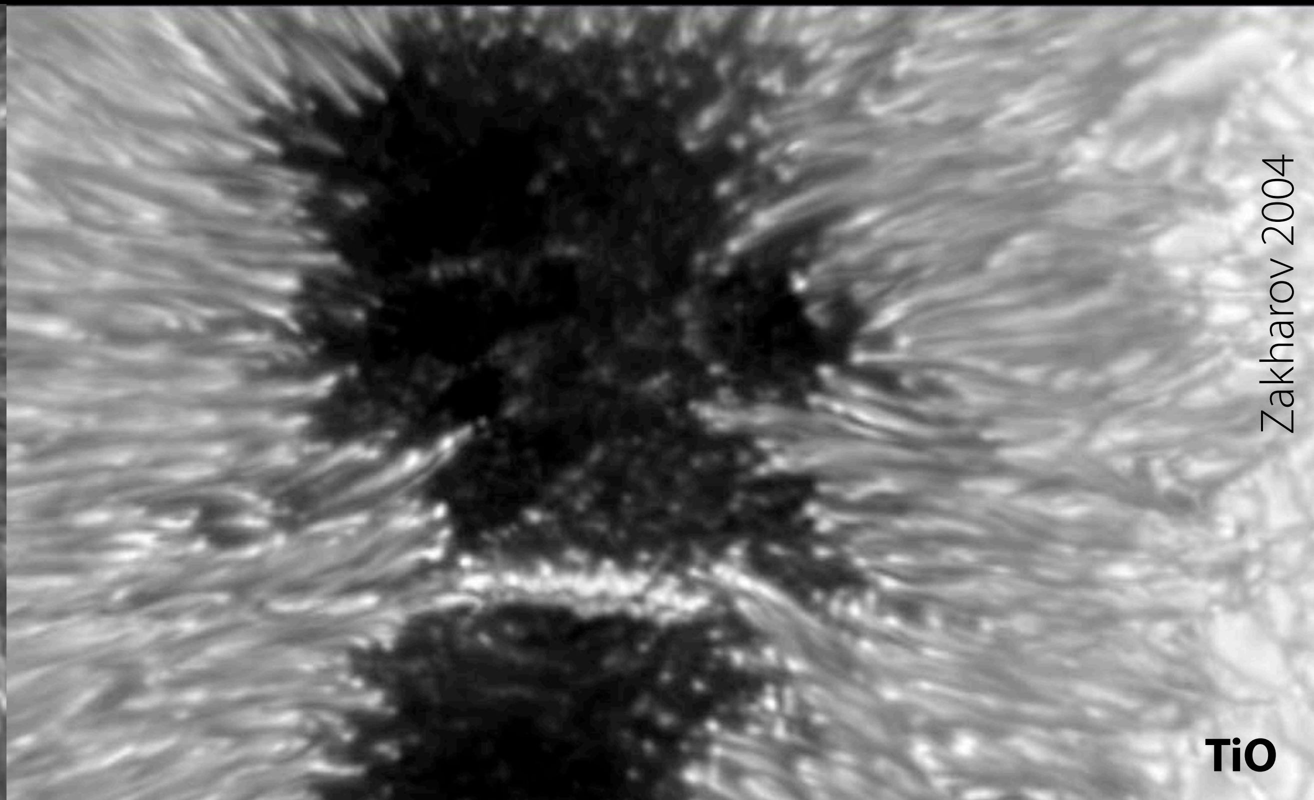


Energetic phenomena in Active Regions

Light bridges

- Observed: Plasma ejections along a light bridge of a stable and mature sunspot (e.g., in Hα surges, EUV jets at 171 Å)
  - Likely a by-product of magnetic reconnection

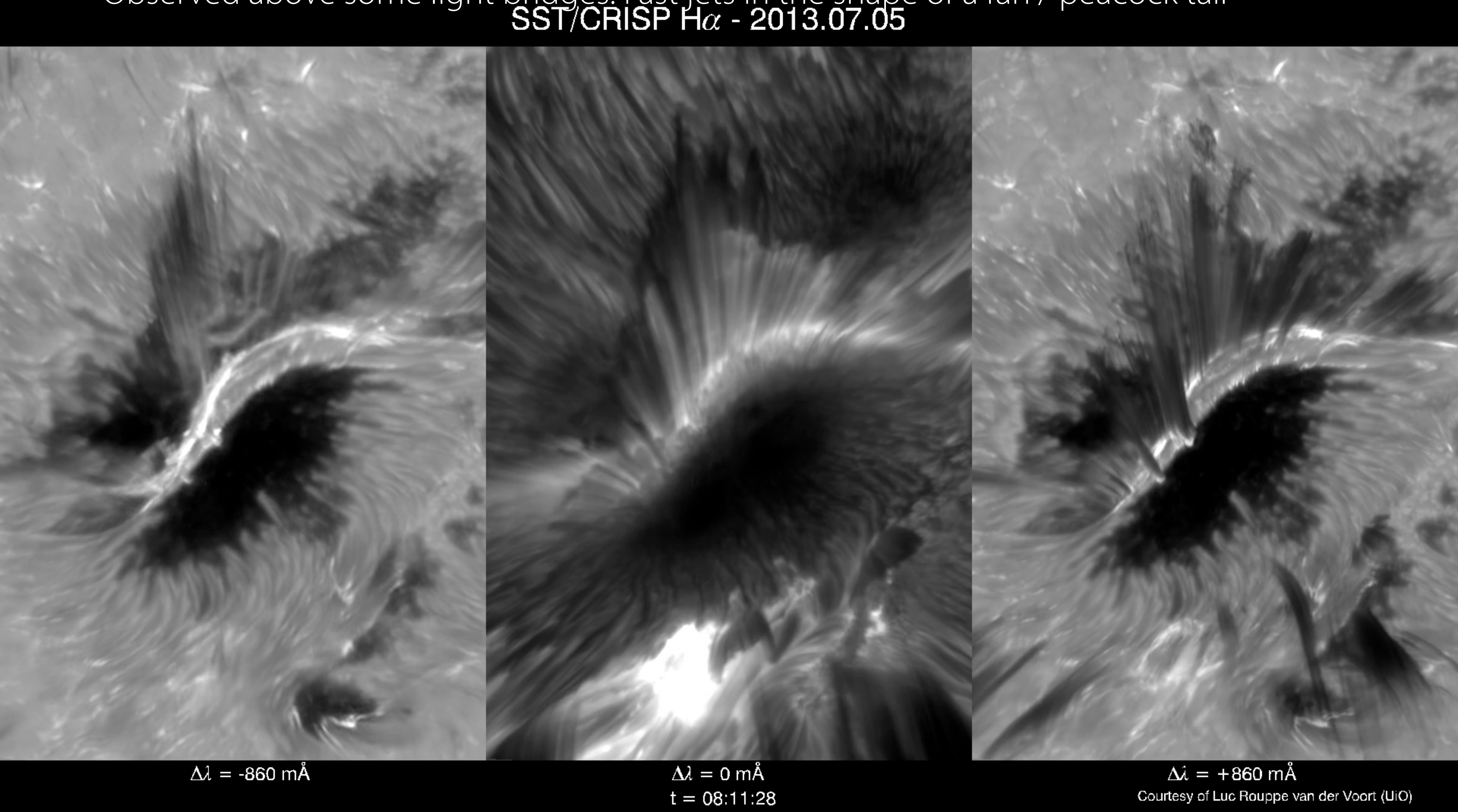




Energetic phenomena in Active Regions

Peacock jets / Fan-shaped jets

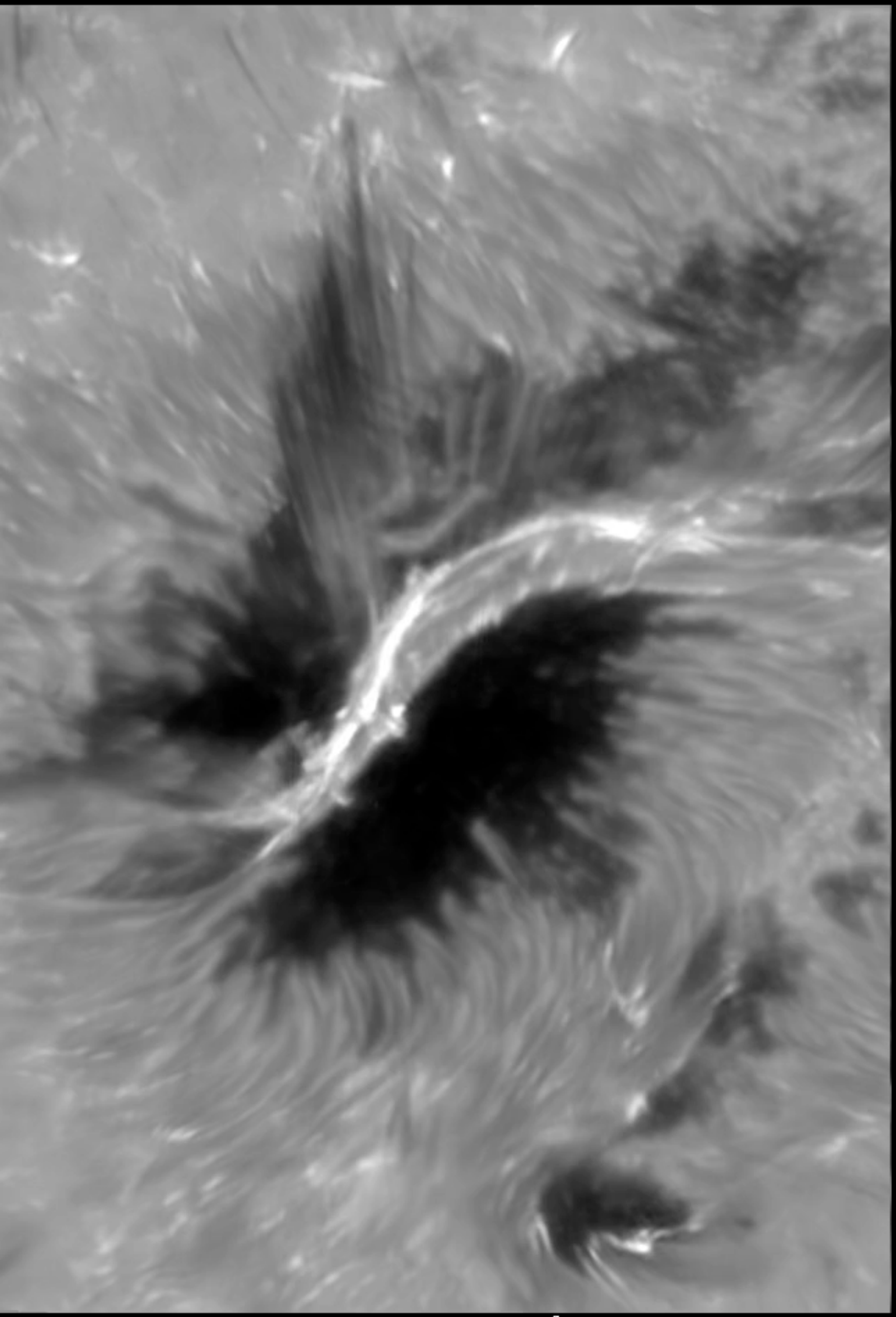
- Many dynamic phenomena in chromosphere above light bridges
- Observed above some light bridges: Fast jets in the shape of a fan / peacock tail



Energetic phenomena in Active Regions

Peacock jets / Fan-shaped jets

- Many dynamic phenomena in chromosphere above light bridges
- Observed above some light bridges: Fast jets in the shape of a fan / peacock tail



$\Delta\lambda$ = -860 mÅ

- Cool material (<15 000 K)
- Maximum speeds of up to 175 km/s !
- Extend up to 50 Mm.
- Accelerate upwards for an extended amount of time until reaching max. velocity at height between ~7 to ~50 Mm.
- Influence of the magnetic field clearly seen in the acceleration/deceleration (in contrast to gravity alone)
- Please note the length of jets (or any feature) may appear different for various diagnostics as they are sensitive to different formation height ranges / plasma properties
- **Likely explanation:** Horizontal field aligned along the light bridge shear with the pre-existing vertical field in umbra

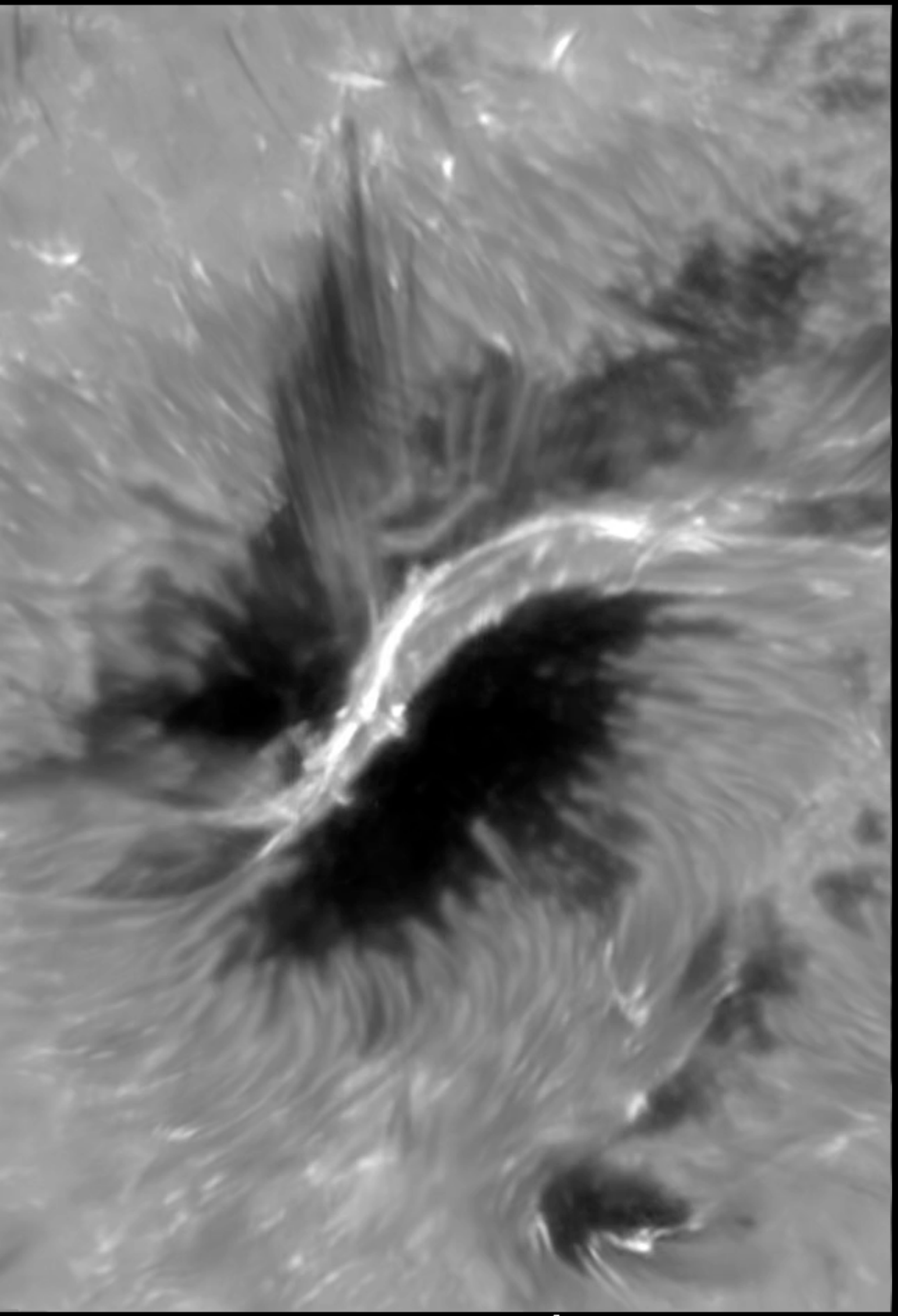
➡ **Magnetic reconnection**

➡ Acceleration of plasma upwards along magnetic field

Energetic phenomena in Active Regions

Peacock jets / Fan-shaped jets

- Many dynamic phenomena in chromosphere above light bridges
- Observed above some light bridges: Fast jets in the shape of a fan / peacock tail



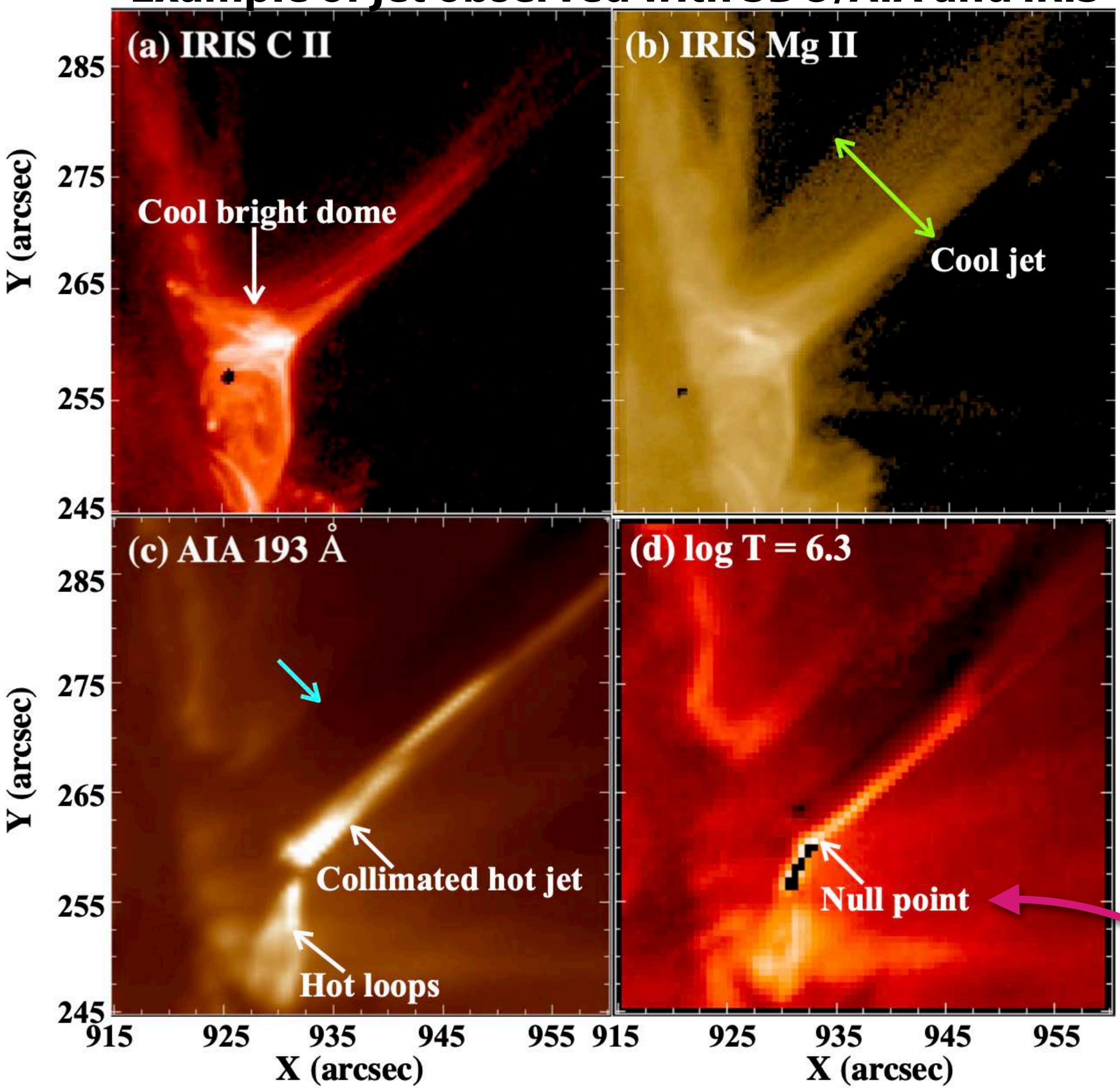
$\Delta\lambda$ = -860 mÅ

- 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)

Sunspots / Active Regions — Jets

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

Example of jet observed with SDO/AIA and IRIS

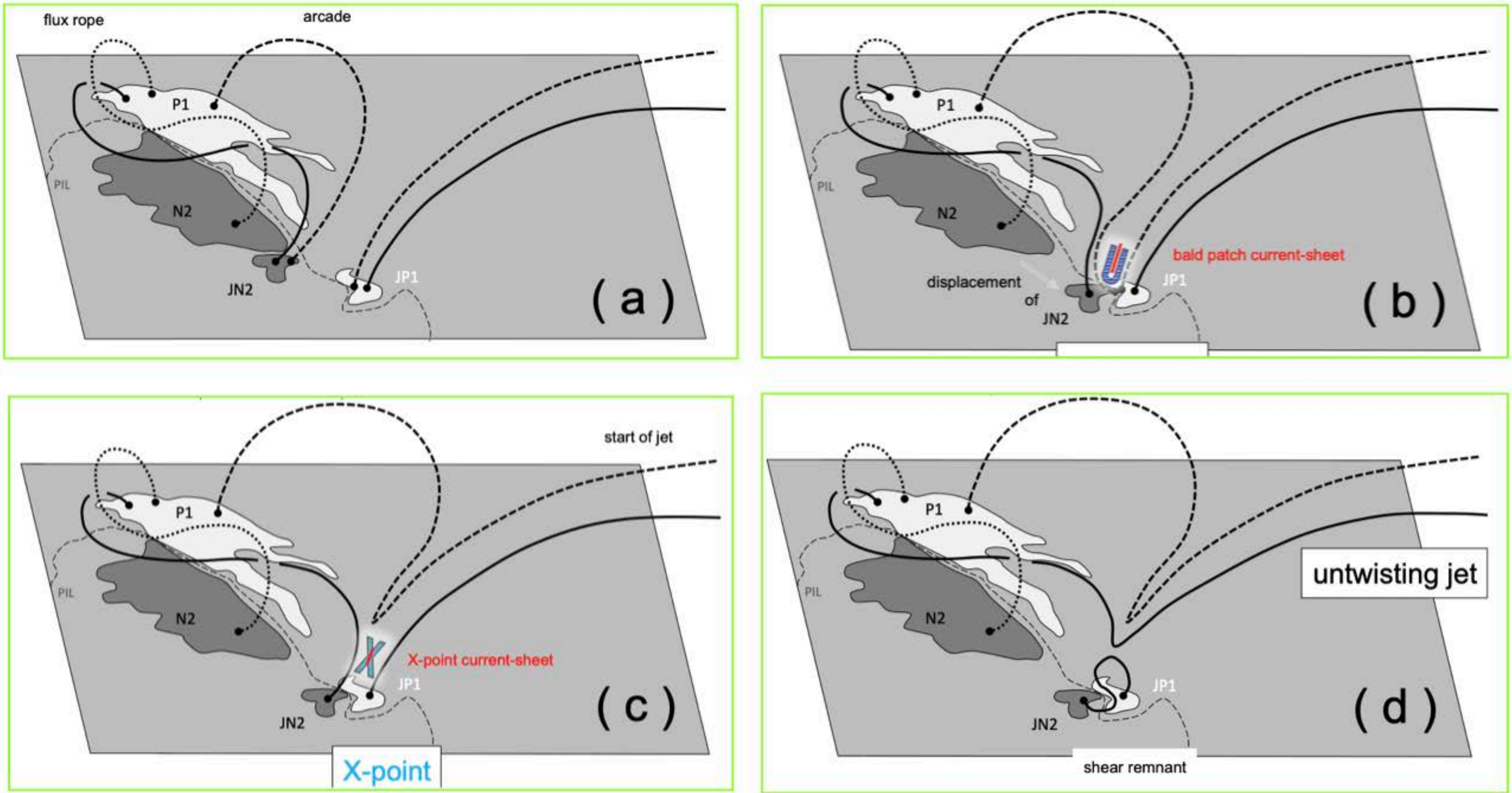


Joshi et al. (2020)

- 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)

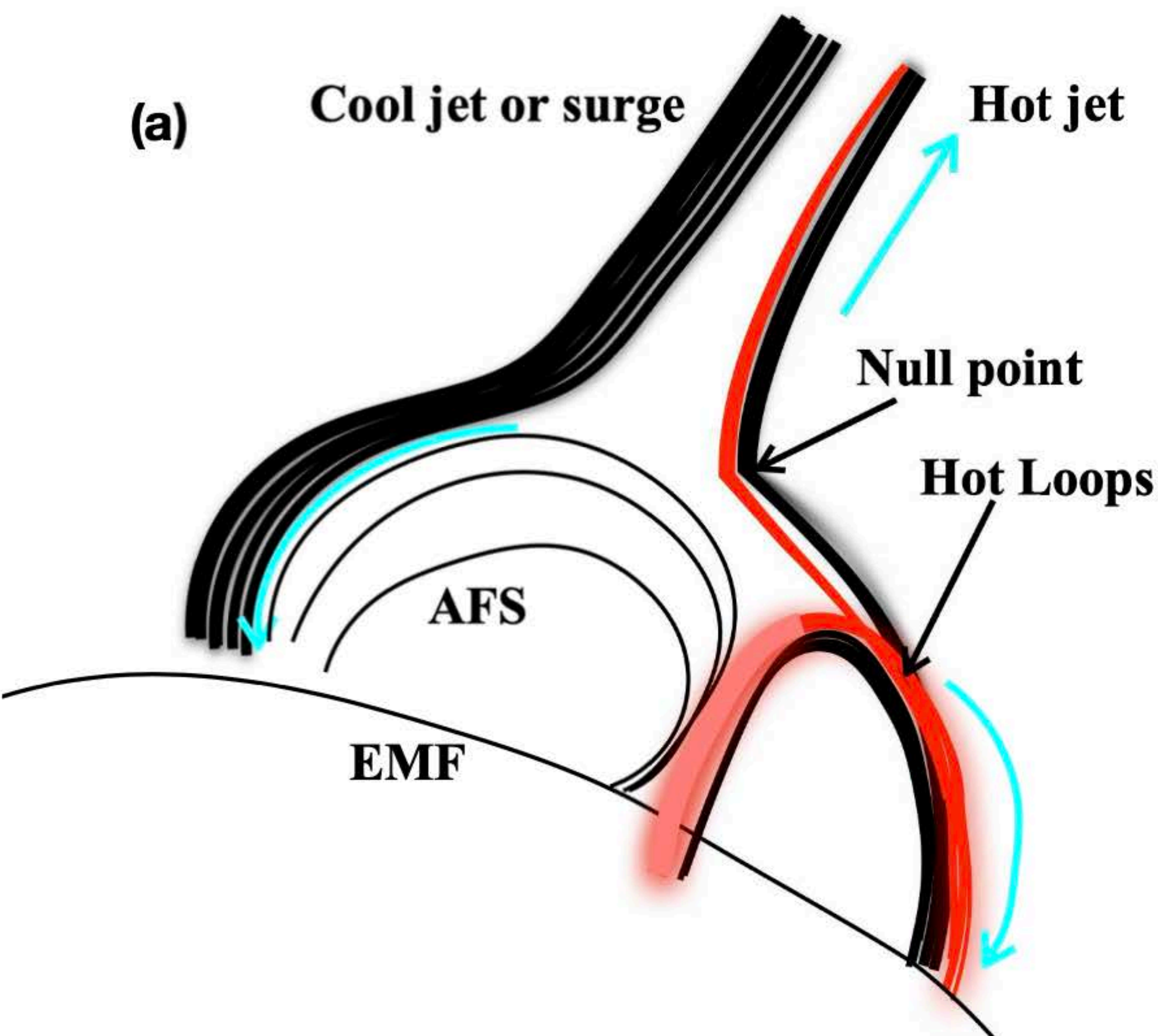
- Panel a: Magnetic configuration before the reconnection.
- Panel b: Formation of the bald patch current sheet.
- Panel c: X-point current sheet.
- Panel d: Untwisting jet after the reconnection and the remnant twist in the bipole.

Sunspots / Active Regions — Jets

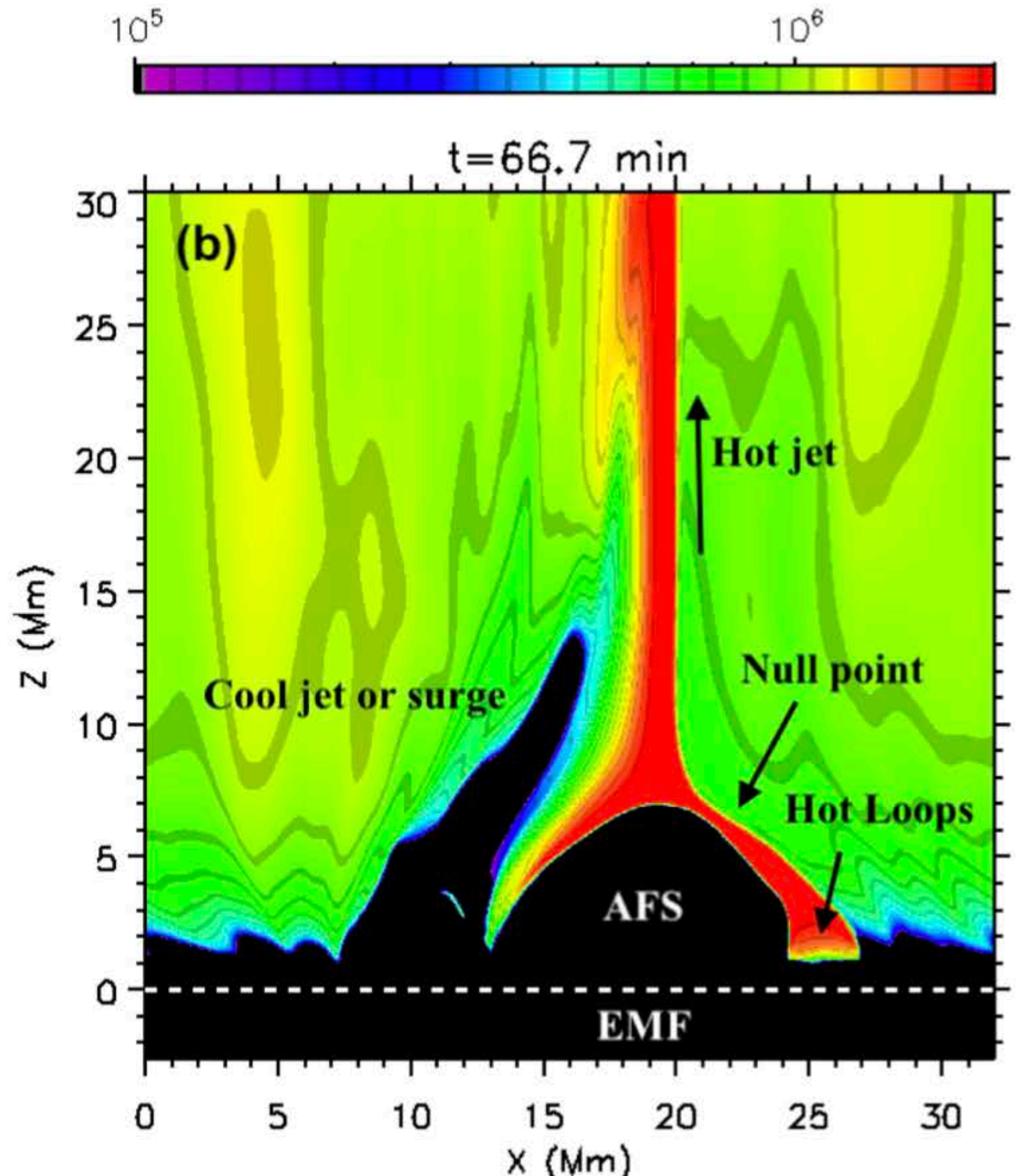
Small-scale surface motions and the twist in the solar jet

Joshi et al. (2020)

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



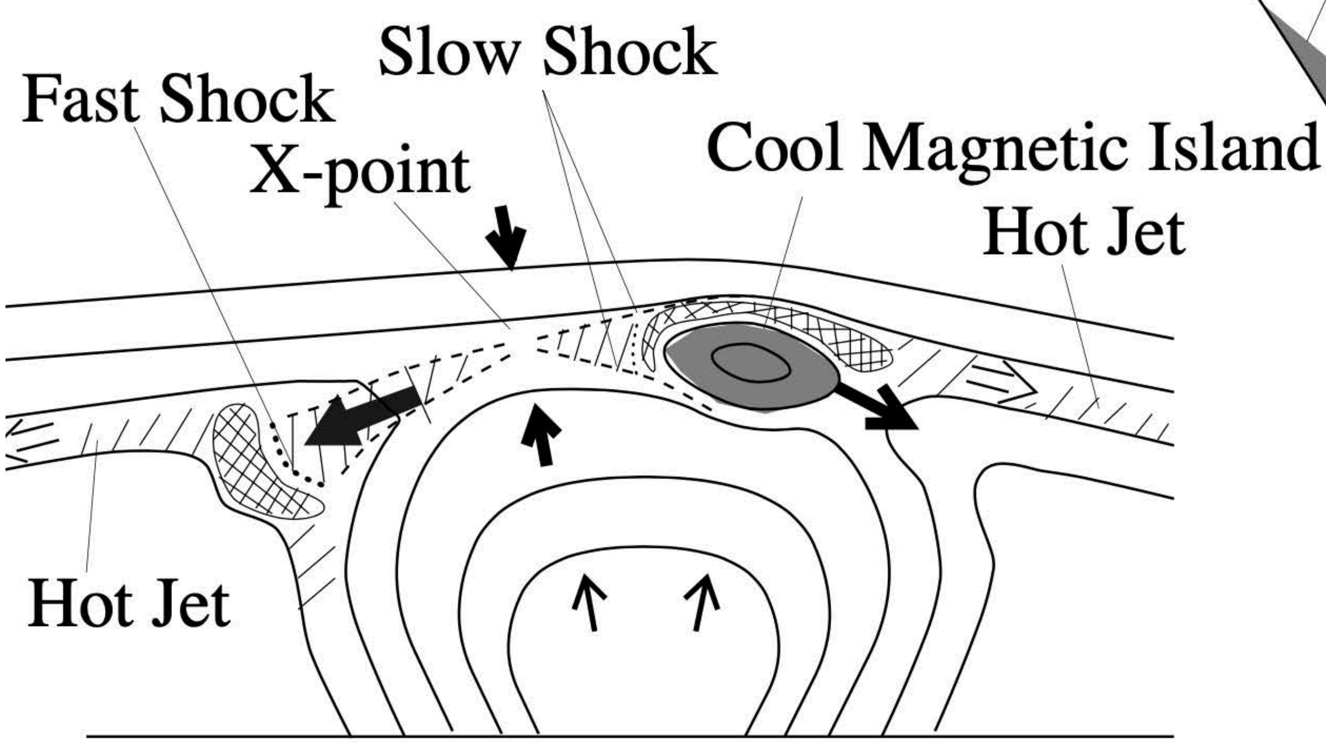
Numerical simulation (temperature)
(Nóbrega-Siverio et al. 2017, 2018)



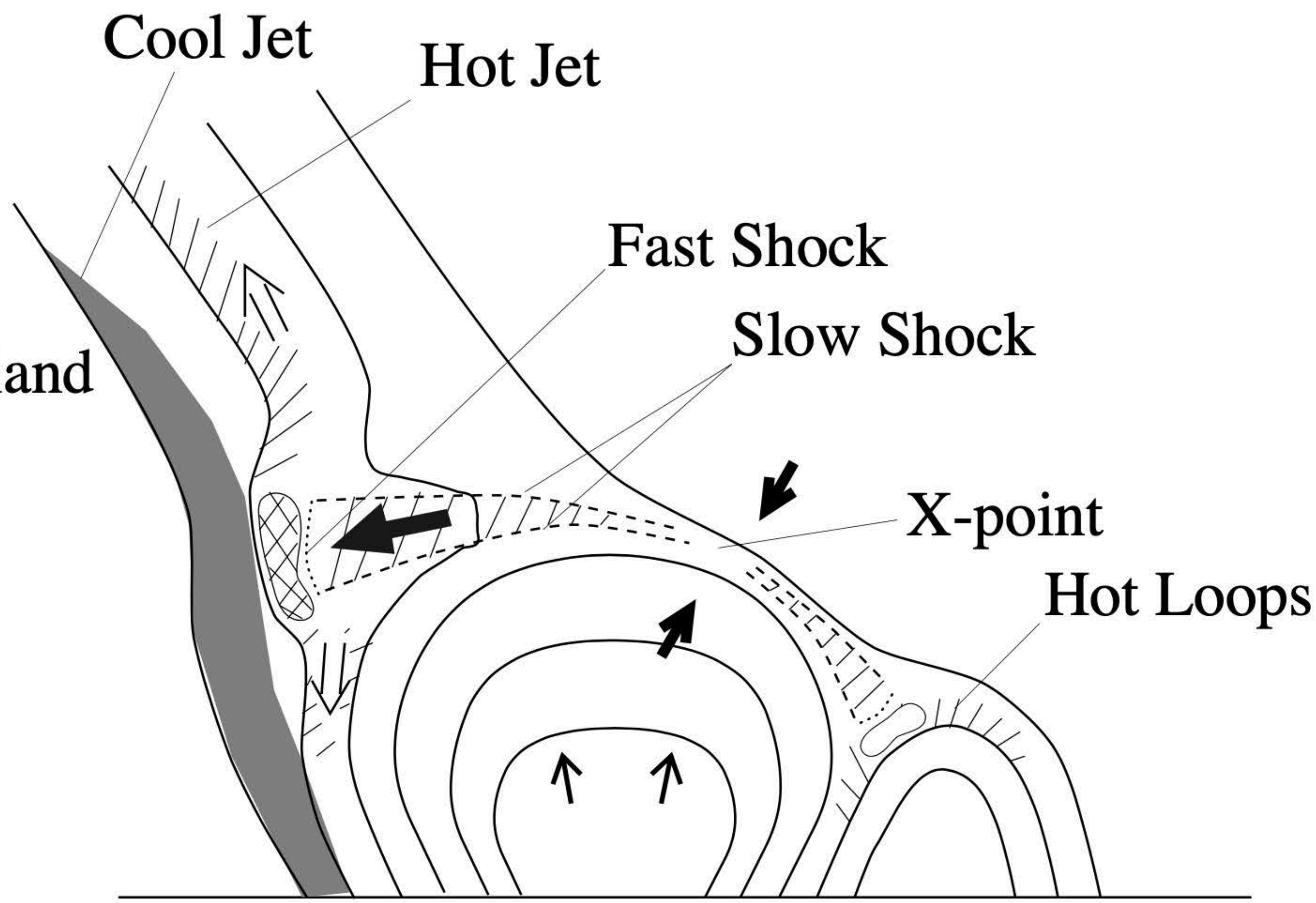
Sunspots / Active Regions — Jets

X-ray jets

Two sided-loop jet



Anemone-type jet



Yokoyama and Shibata (1996)

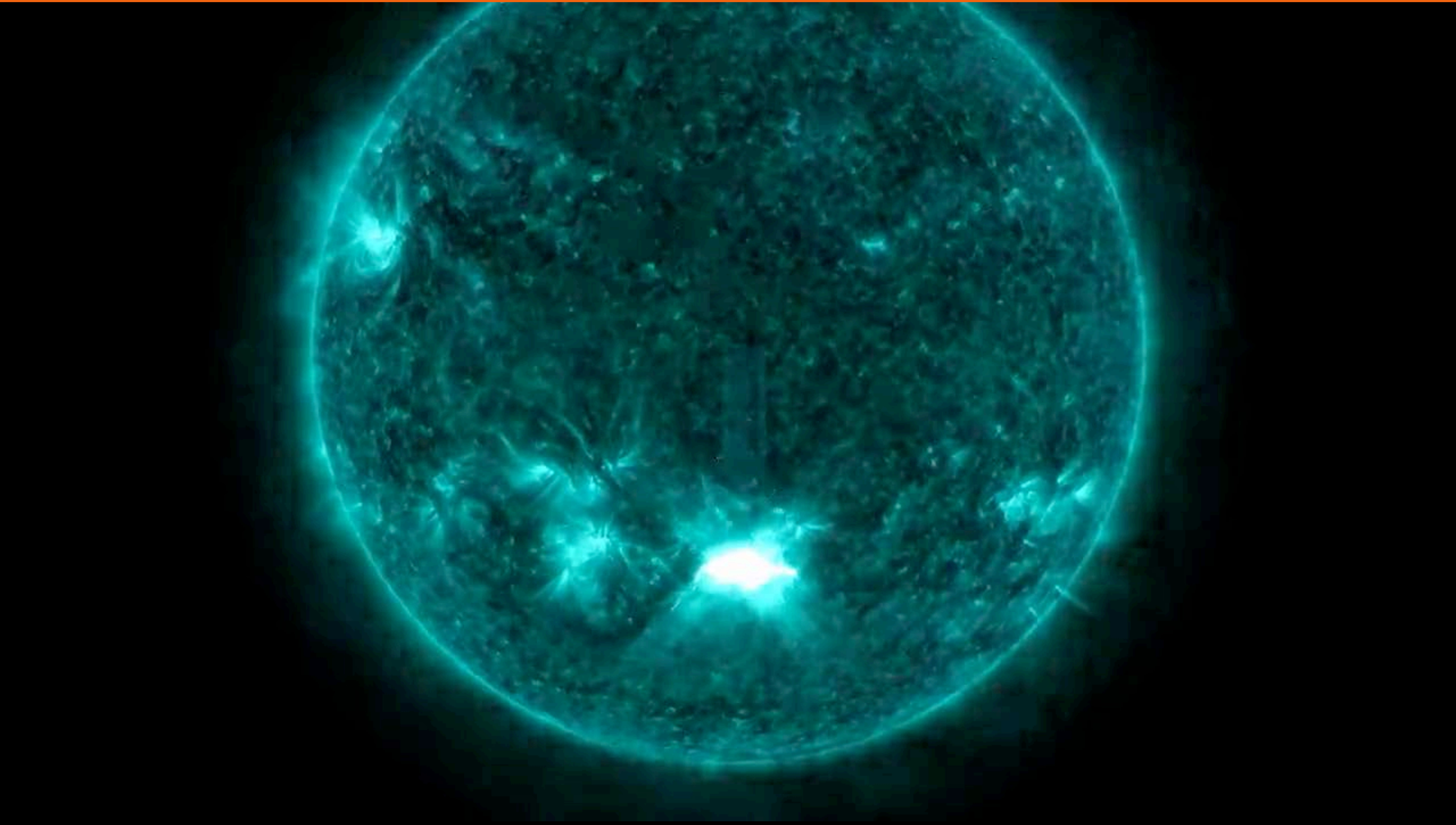
Energetic phenomena in Active Regions

Jet Surge

NASA/SDO

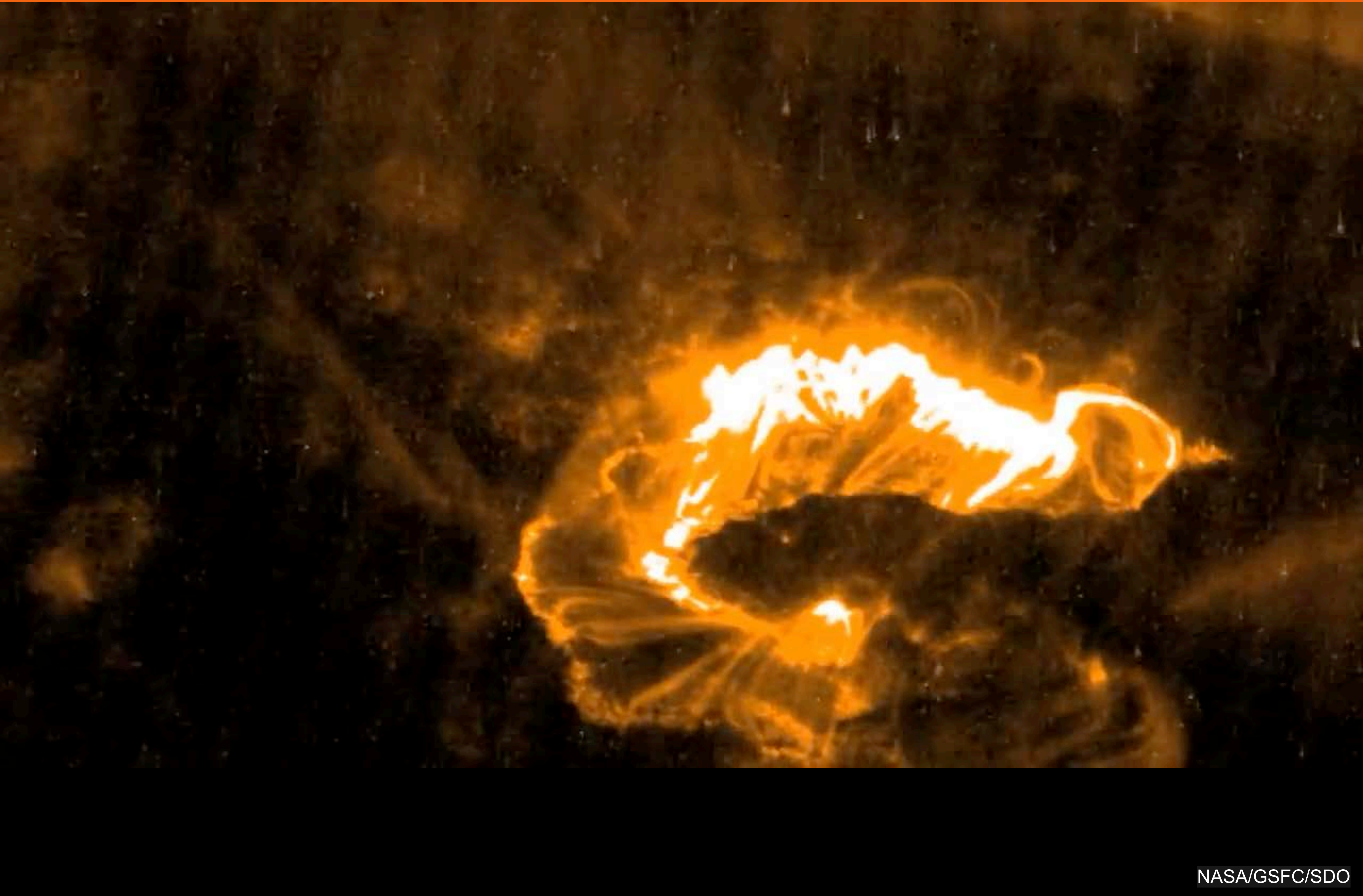
Solar flares

Flares



- Flares = Intense eruptions on the Sun with emission of radiation across the whole spectrum (γ- and X-rays, UV, visible / white light … radio) and energetic particles

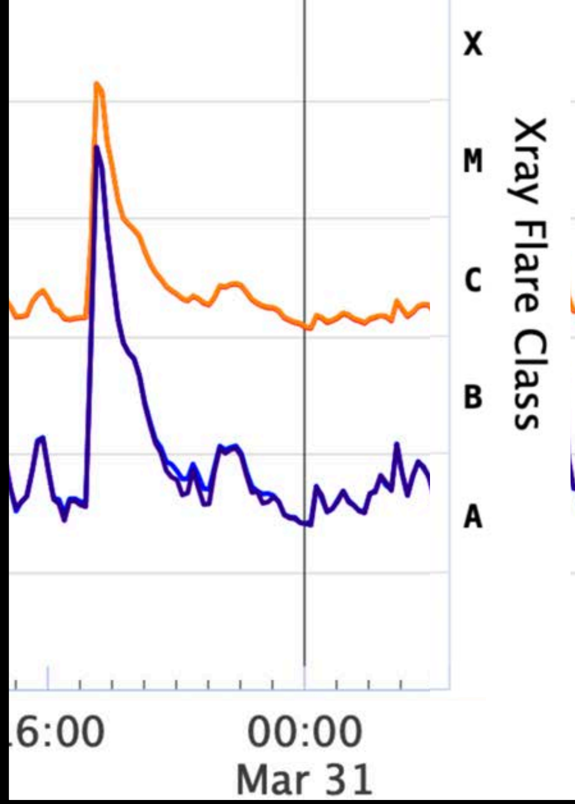
Flares

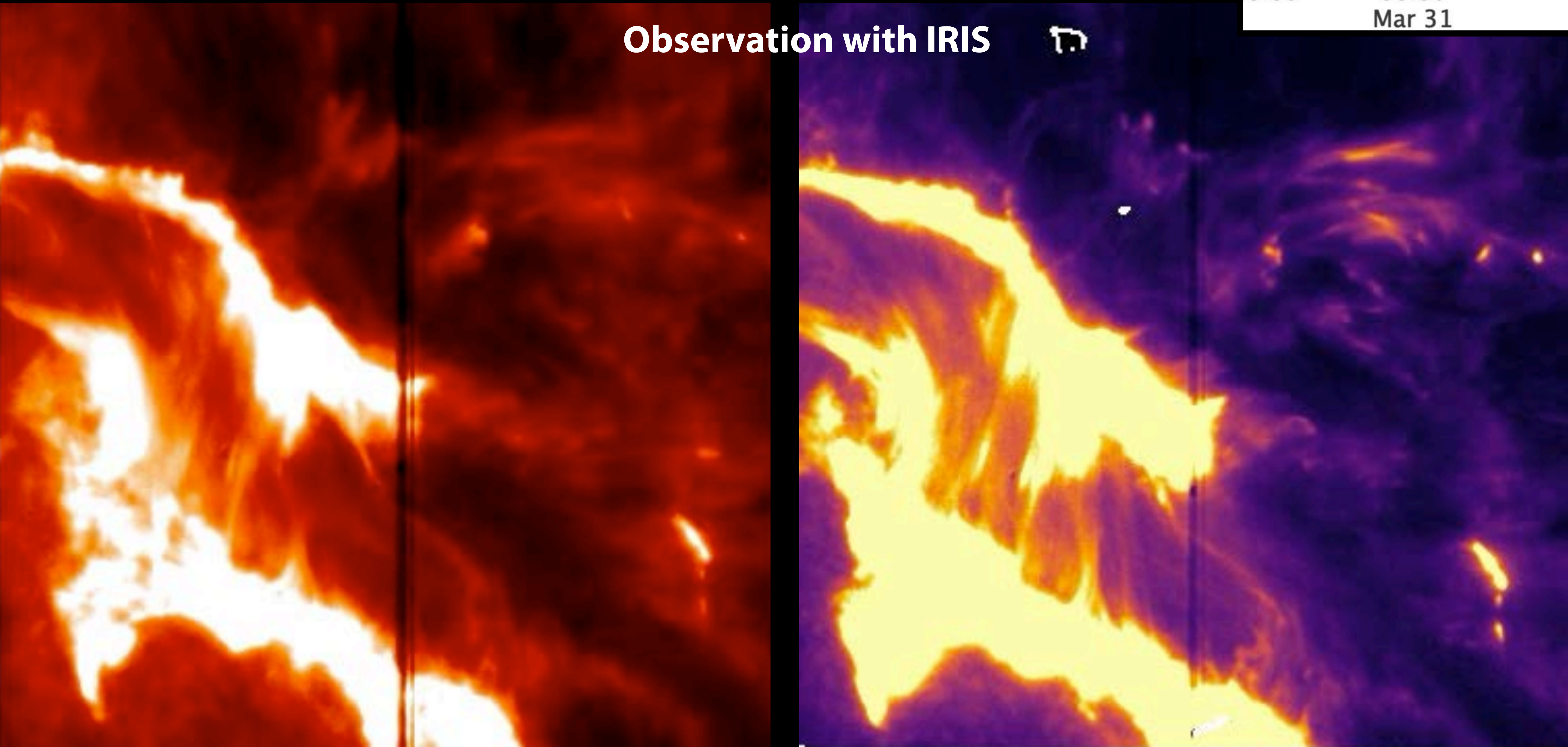


Flares

Recent example

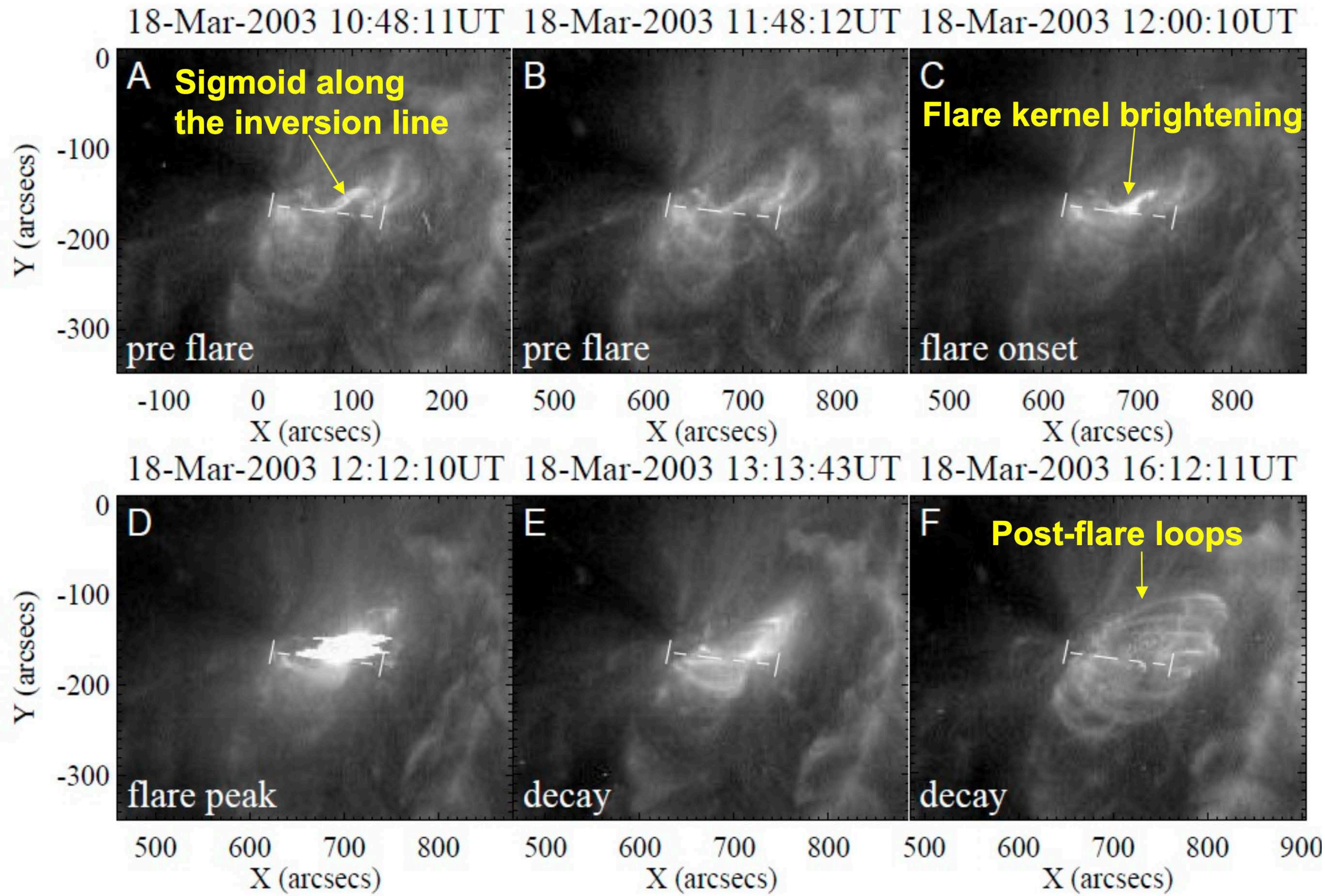
- Flare on March 30, 2022, 17:40UT — AR12975
- X1 class flare
- Check it out in jhelioviewer!





Flares

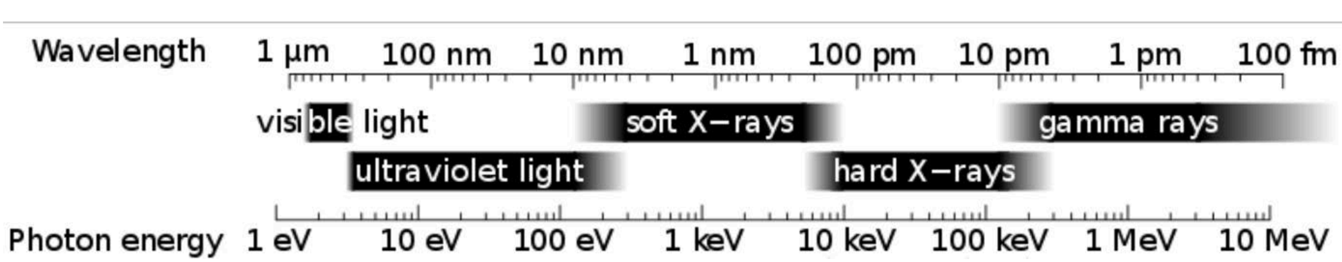
Typical evolution stages

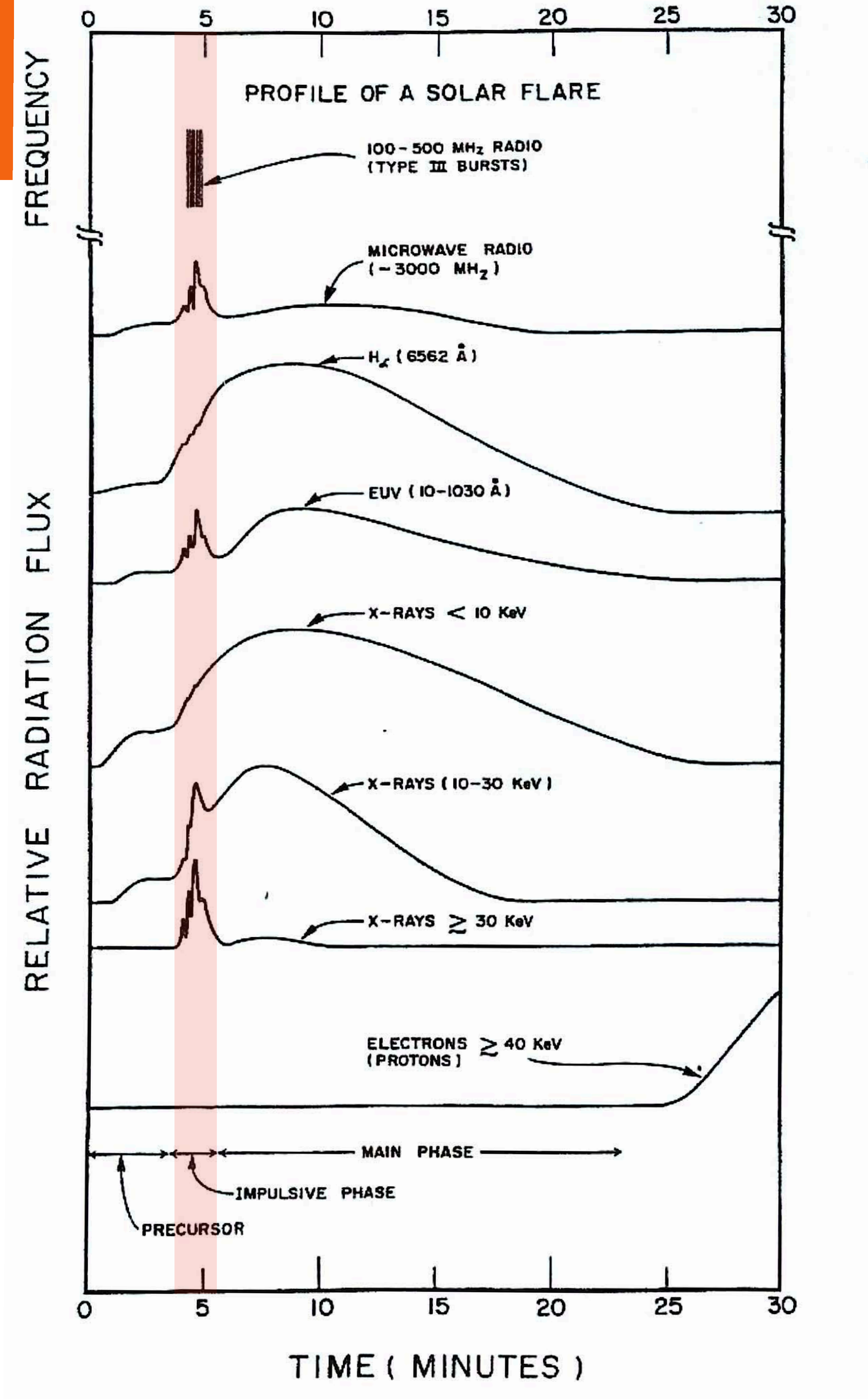


Flares

Temporal evolution

- Sudden brightening that involves all layers of the solar atmosphere
- Emission across the whole electromagnetic spectrum but different temporal variation (incl. rapid increase) depends on wavelength region
- Total energy released in flares varies from event to event
  - Range: 10^{27} - 10^{32} ergs, most of it emitted within a few 10min
  - For comparison: One H-bomb = 10 million TNT = 5 10^{23} ergs

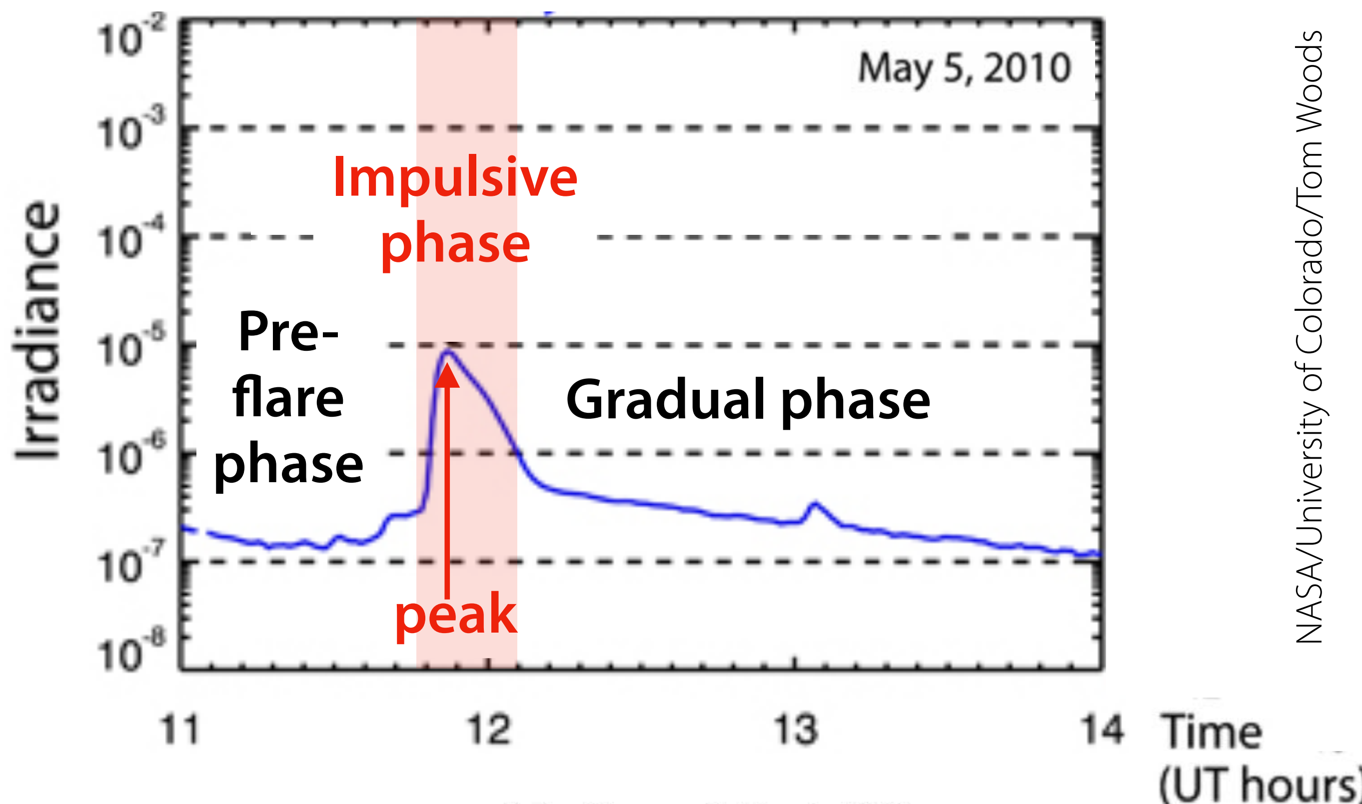


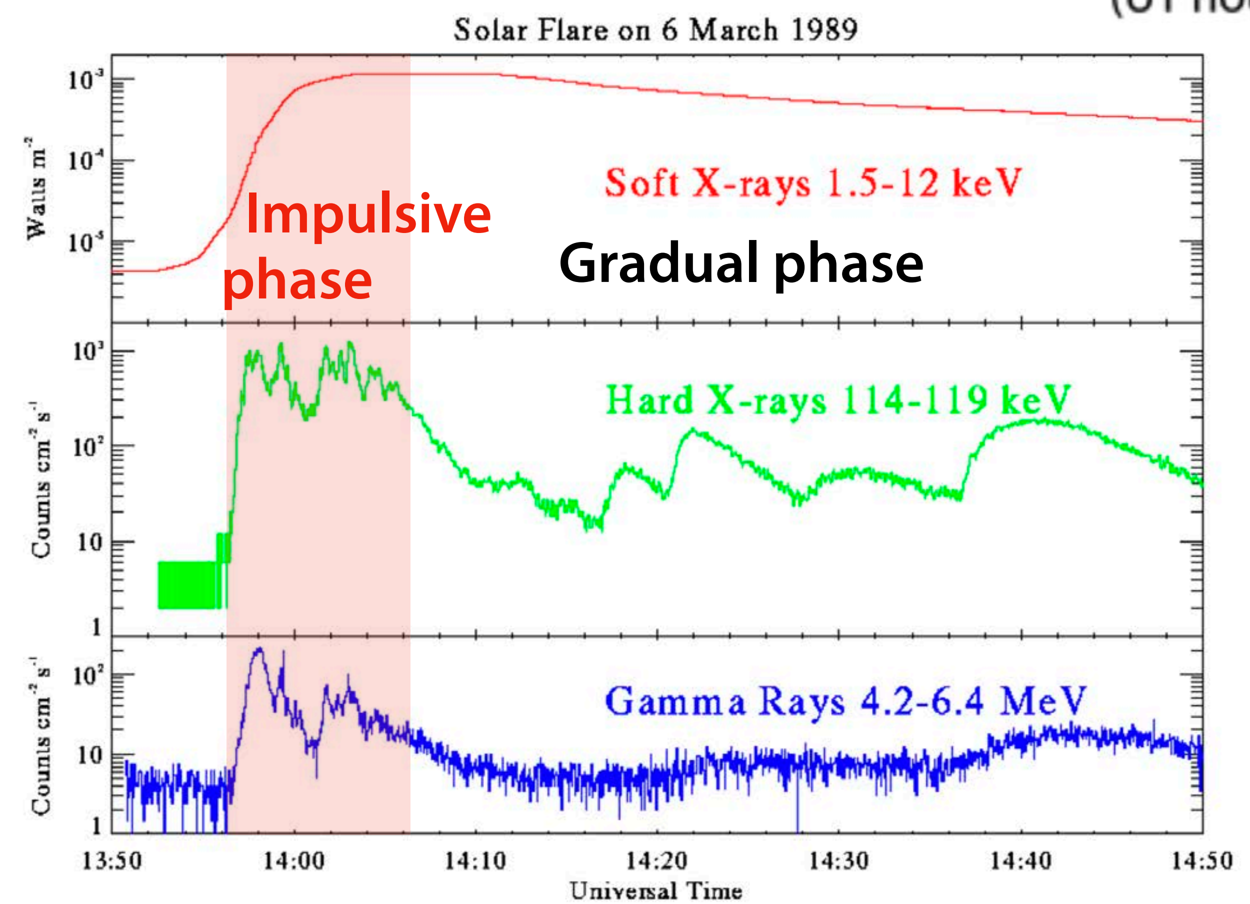


Flares

Three major phases

- **Pre-flare phase:** flare trigger phase leading to the major energy release
  - Slow increase of soft X-ray flux
- **Impulsive phase** (incl. peak): main rapid energy release phase
  - Most evident in increased hard X-ray, γ-ray, and millimetre/radio emission
  - Soft X-ray flux rises rapidly!
  - Short time-scales (1s and below), whole phase lasting for min - ~10min
- **Gradual phase** (post-flare)
  - Slow (or now) energy release / "afterglow" on longer time scales
  - No further emission in hard X-ray
  - Soft X-ray flux starts to decrease gradually.
  - Loop arcades (or arches) start to appear
  - Can last several hours

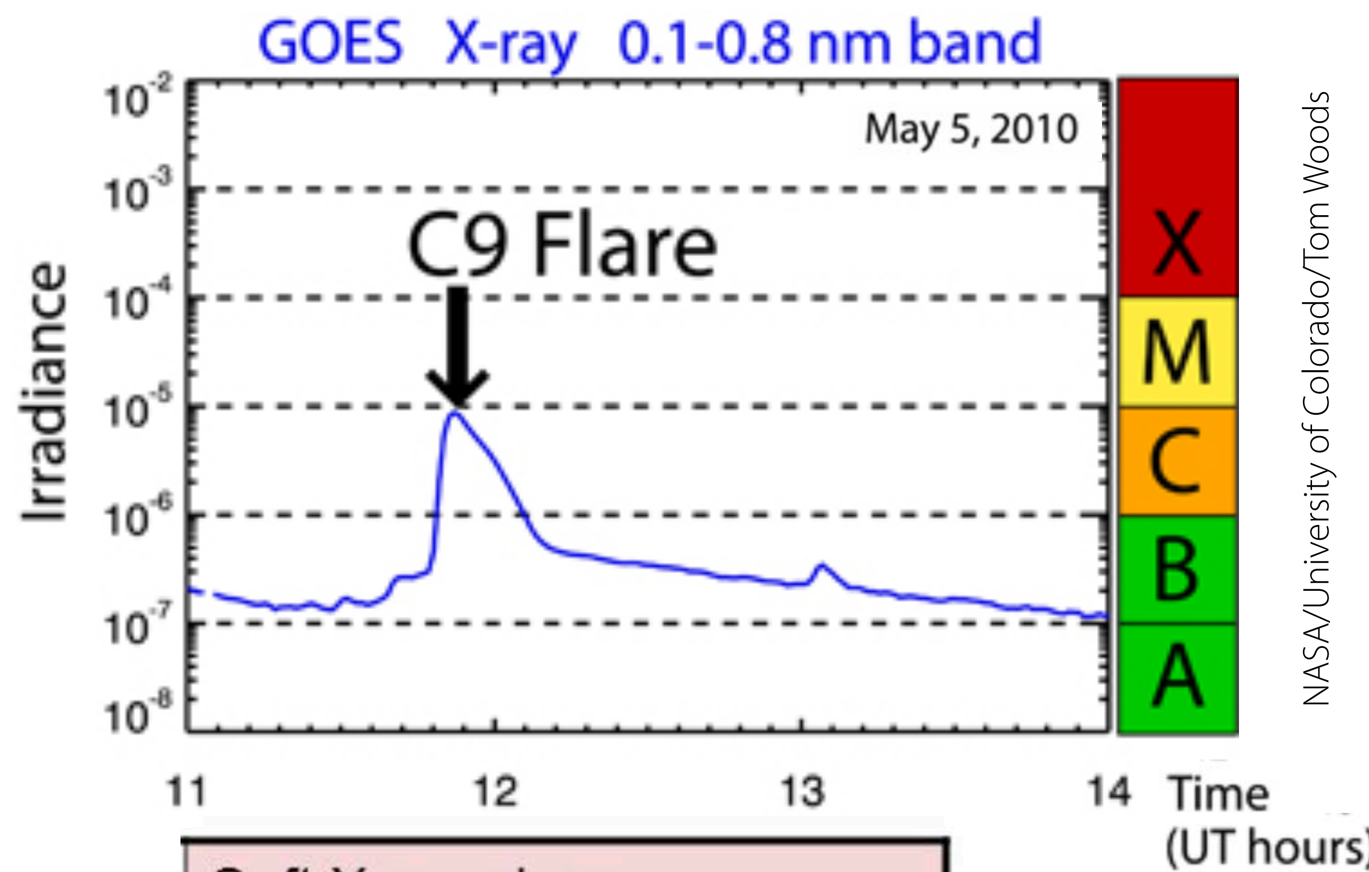




Flares

Classification

- **GOES** (Geostationary Operational Environmental Satellite): Several satellites
  - Measure (among many things) irradiance in several **X-ray** bands
  - Classification of a flare according to the measured peak irradiance



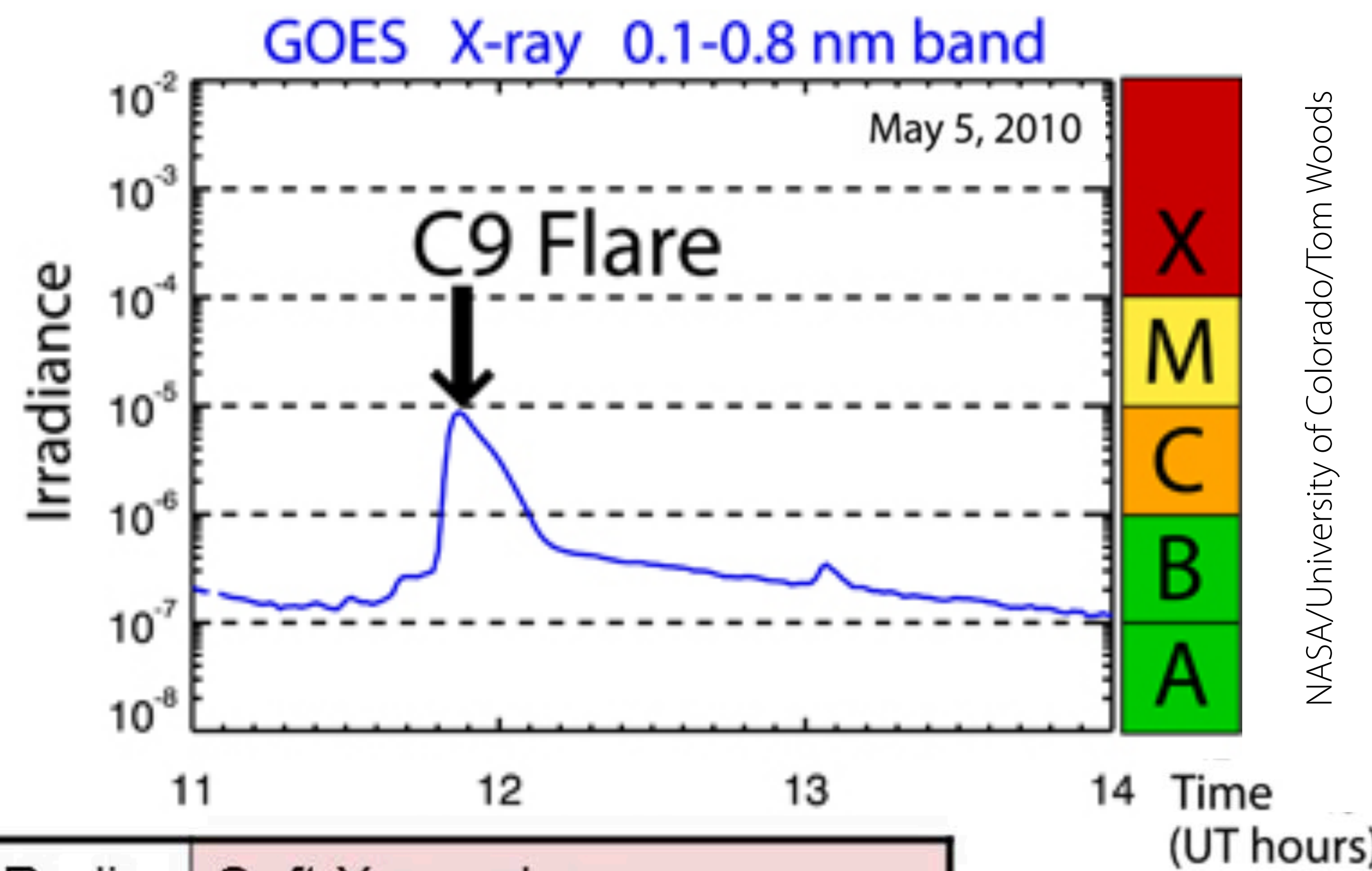
Soft X-ray class	
Importance class	Peak flux in 1-8 Å w/m^2
A	10^{-8} to 10^{-7}
B	10^{-7} to 10^{-6}
C	10^{-6} to 10^{-5}
M	10^{-5} to 10^{-4}
X	$>10^{-4}$

- Additional numbers after class letter:
  - X2 = 2 times as intense as an X1
  - X3 = 3 times as intense as an X1
  - …
- X10 (or stronger) are rare and unusually intense

Flares

Classification

- Alternative classifications schemes based on other measurable indicators, e.g.:
  - Radio flux at 5G Hz
  - Area with enhanced emission in Hα



Hα sub-classification by brightness: F – faint, N – normal, B – bright

Hα classification			Radio flux at 5000 MHz in s.f.u.	Soft X-ray class	
Importance Class	Area (Sq. Deg.)	Area 10^{-6} solar disk		Importance class	Peak flux in 1-8 Å w/m²
S	2.0	200	5	A	10^{-8} to 10^{-7}
1	2.0–5.1	200–500	30	B	10^{-7} to 10^{-6}
2	5.2–12.4	500–1200	300	C	10^{-6} to 10^{-5}
3	12.5–24.7	1200–2400	3000	M	10^{-5} to 10^{-4}
4	>24.7	>2400	3000	X	$>10^{-4}$

1 s.f.u. = 10^4 jansky = 10^{-2} W m^{-2} Hz^{-1}

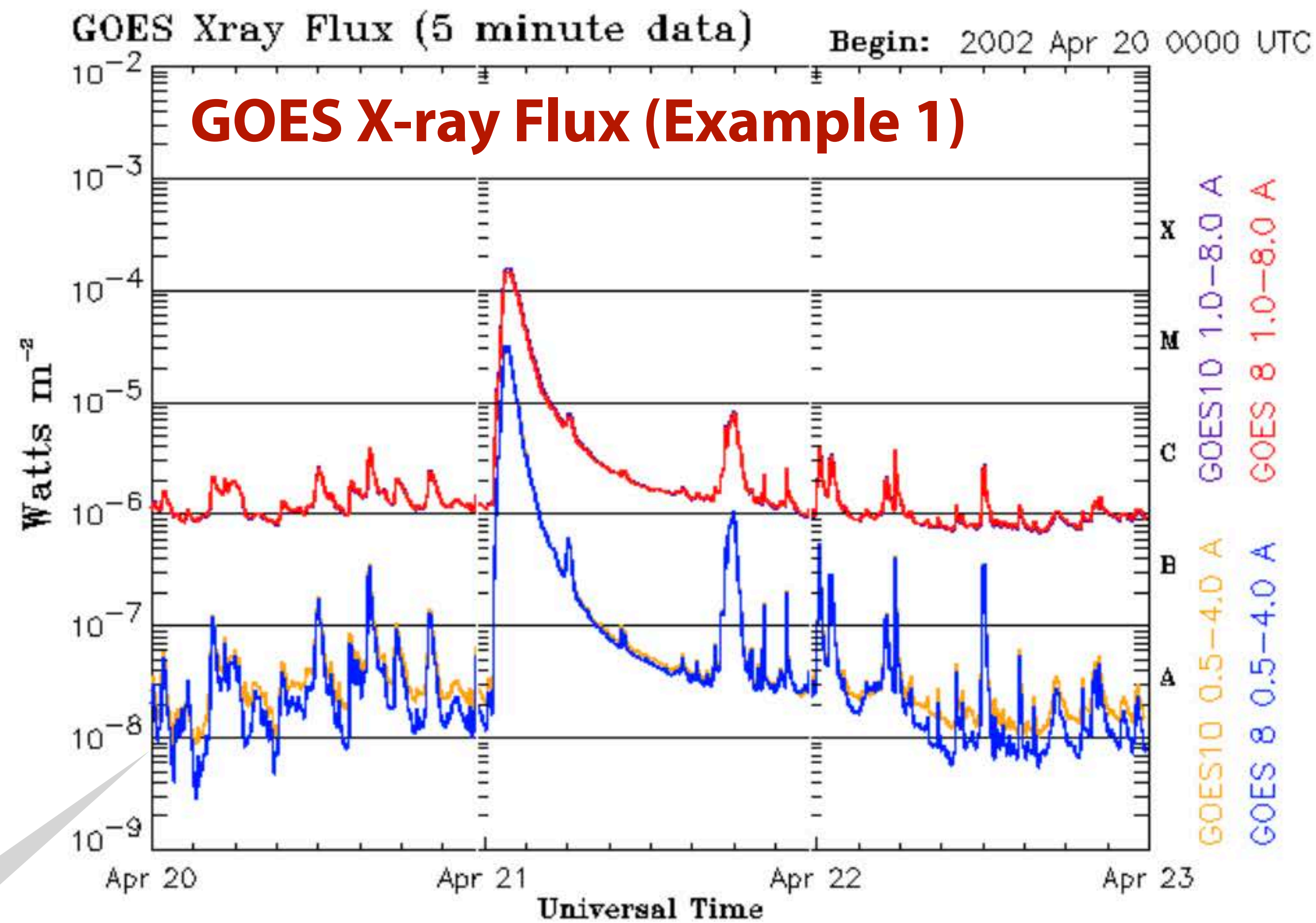
Flares

GOES observations

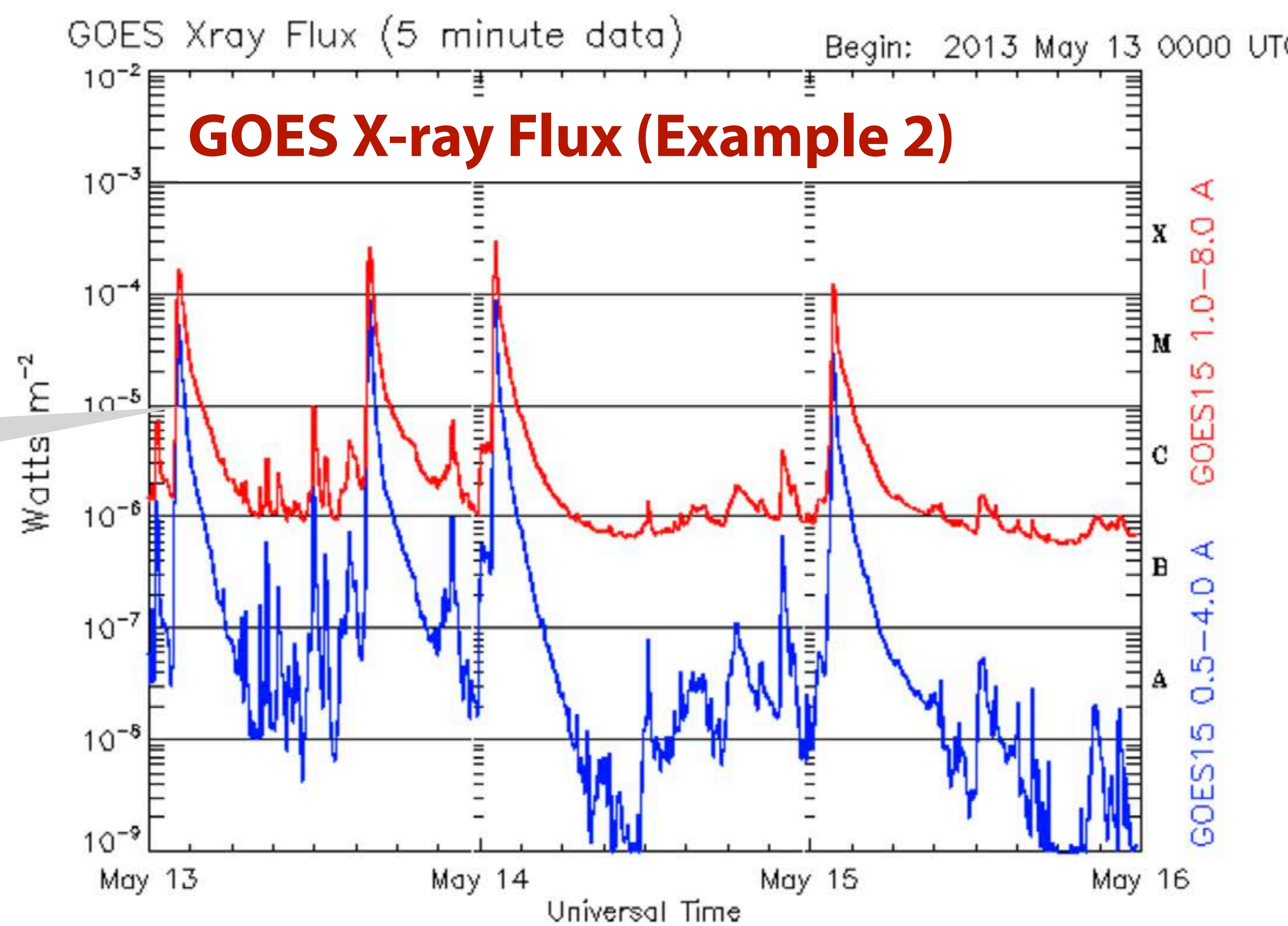
- GOES detects the X-ray irradiance of the whole Sun
- A single flare significantly varies the detected X-ray irradiance despite affecting only small region on the Sun!

Different colors = different bands

GOES class according to **0.1-0.8nm band (red)**



Sequence of several flares including 4 X-class flares within 3 days

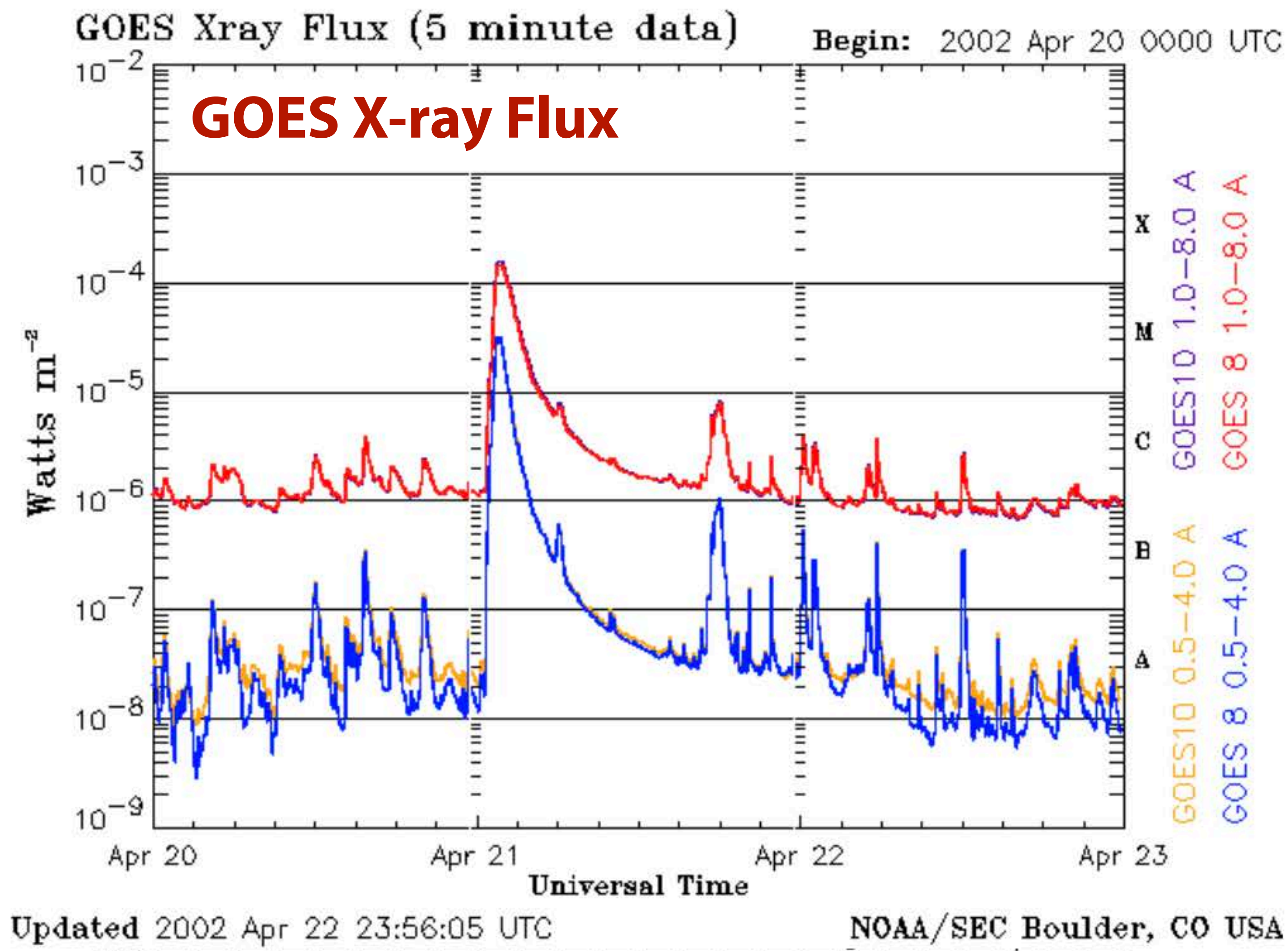


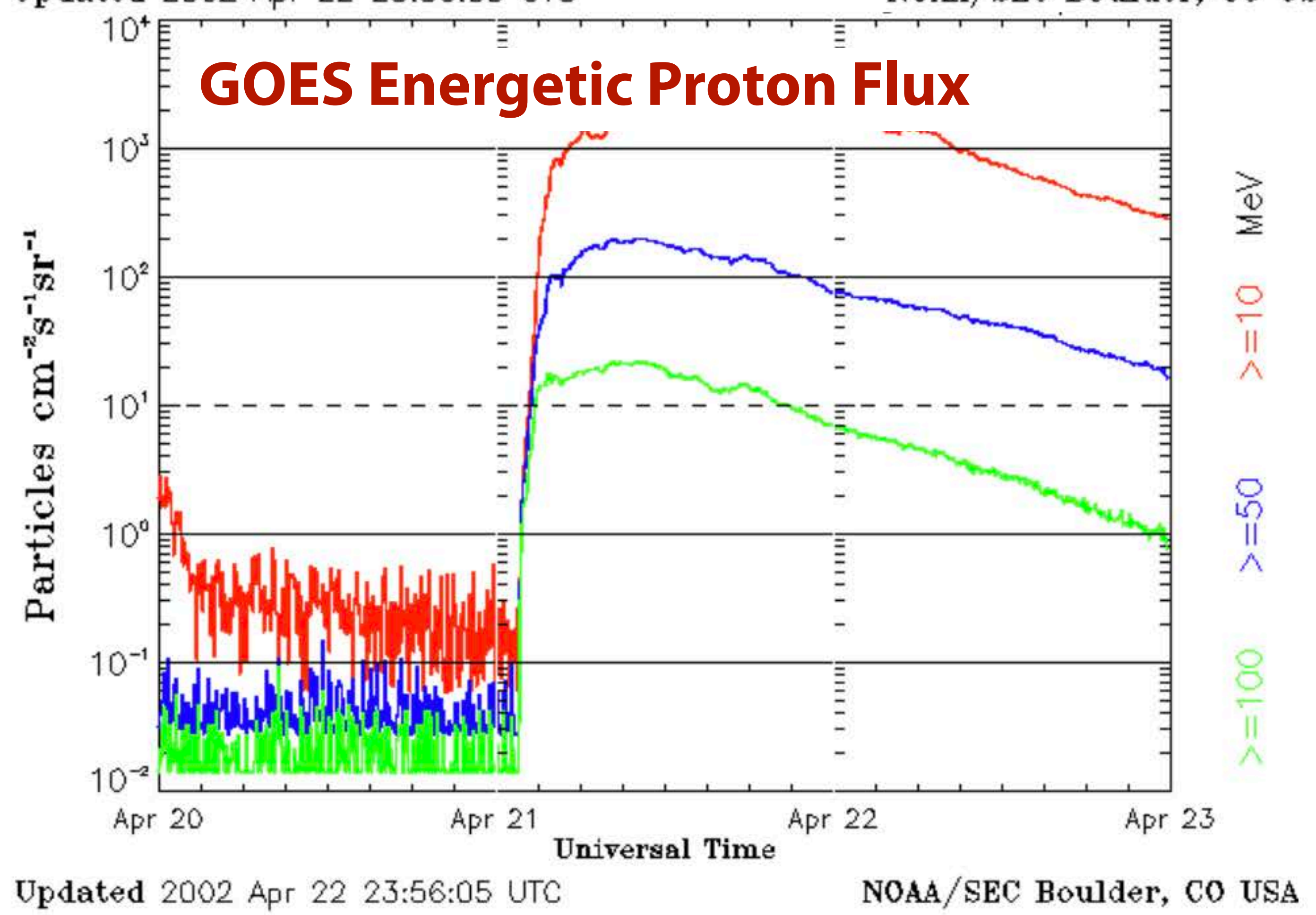
Flares

GOES observations

- GOES detects the X-ray irradiance of the whole Sun
- A single flare significantly varies the detected X-ray irradiance despite affecting only small region on the Sun!

- Flares also produce energetic particles, some ejected into interplanetary space
- GOES measures energetic proton flux

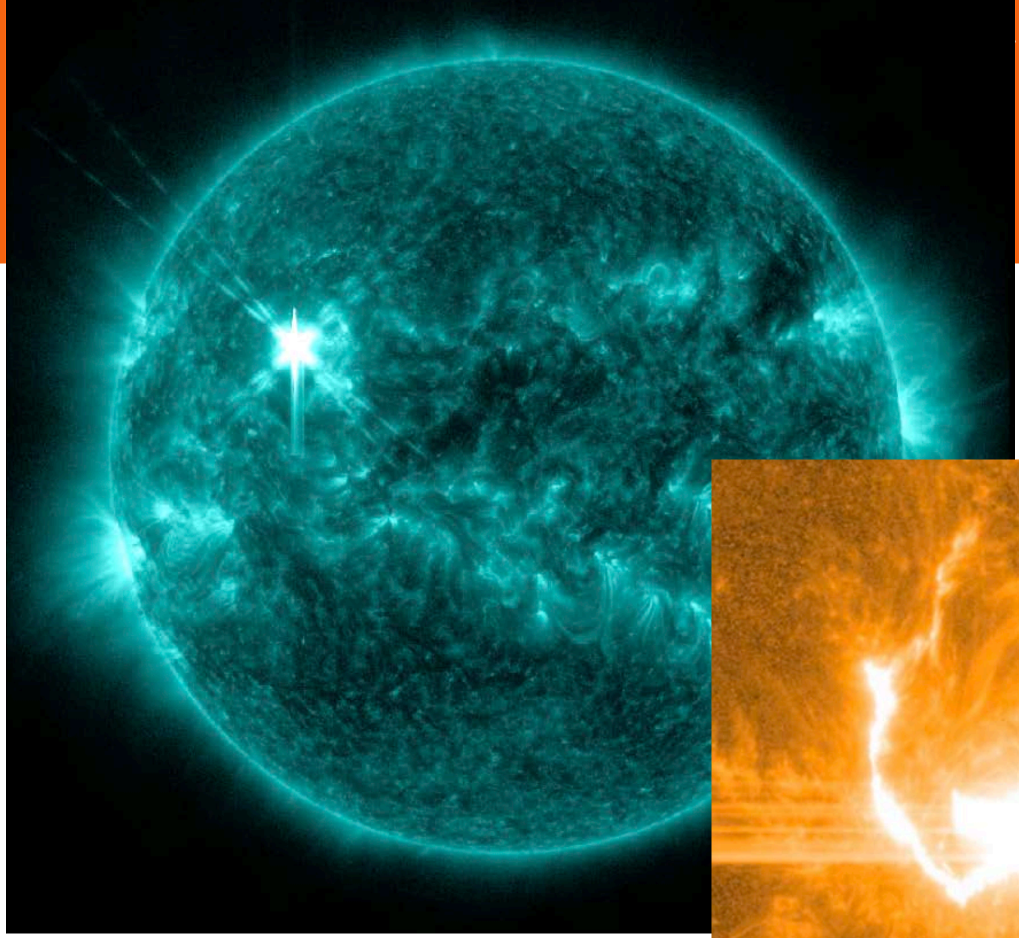




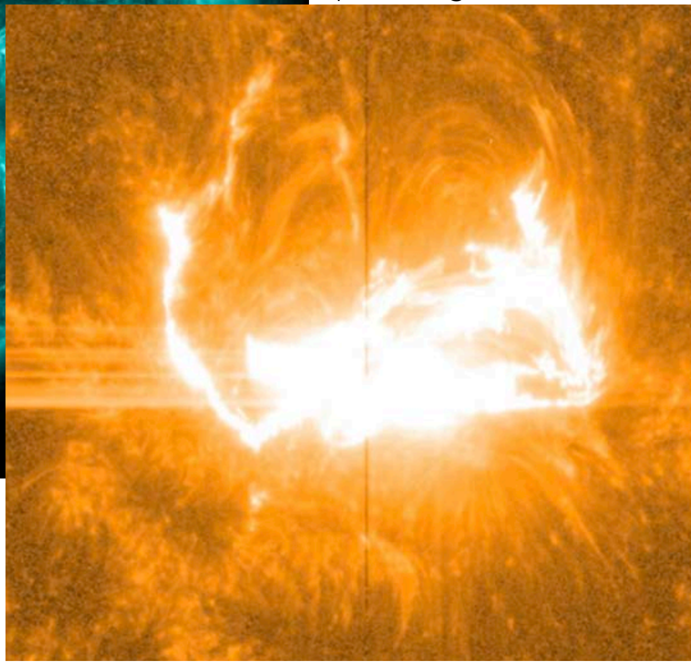
Flares

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