Update on Hard X-Ray production in a solar failed eruption

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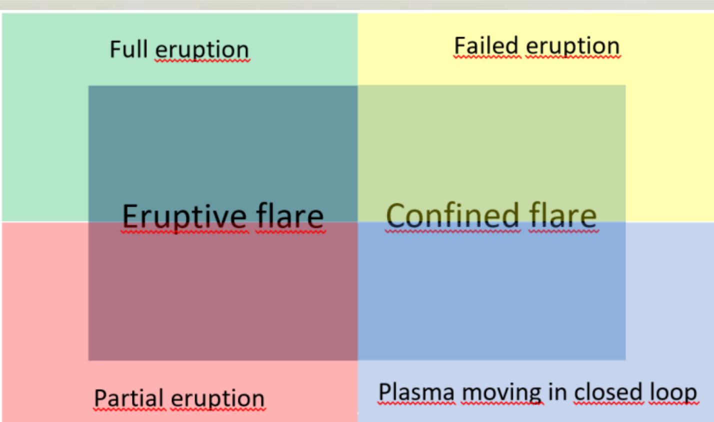
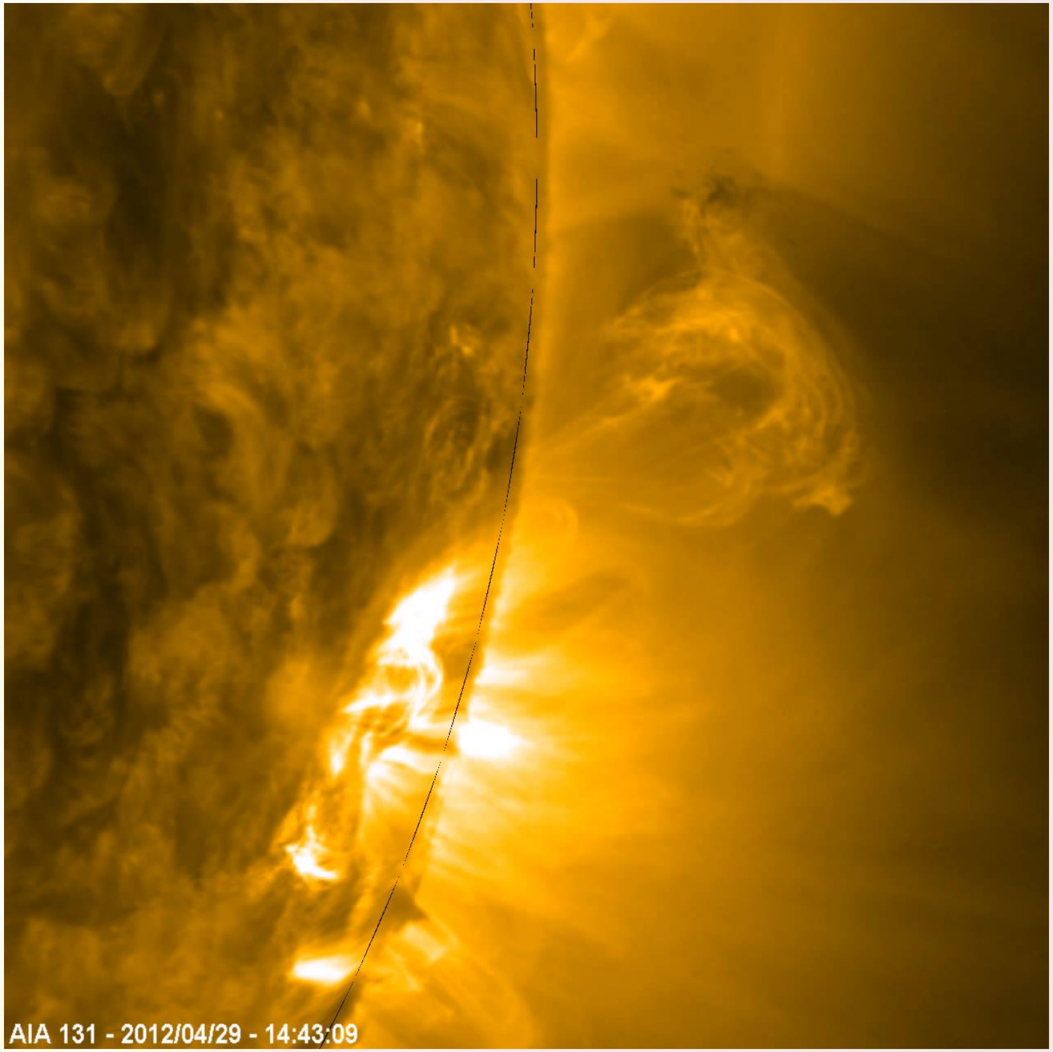
Failed eruptions

Gilbert, H. R., Alexander, D., & Liu, R. 2007, Sol. Phys., 245, 287:

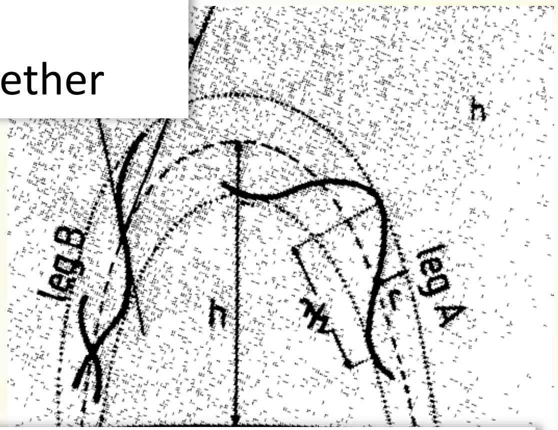
1. ***Full*** - most (≥ 90%) of filament mass and magnetic structure is erupted.
2. ***Partial***:
   - class A – the eruption of the entire magnetic structure with small amount or even no mass.
   - class B – the partial eruption of magnetic structure with some or none mass.
3. ***Failed*** - neither of mass nor magnetic structure escapes from the Sun. (No CME) – eruption stops after initial acceleration.





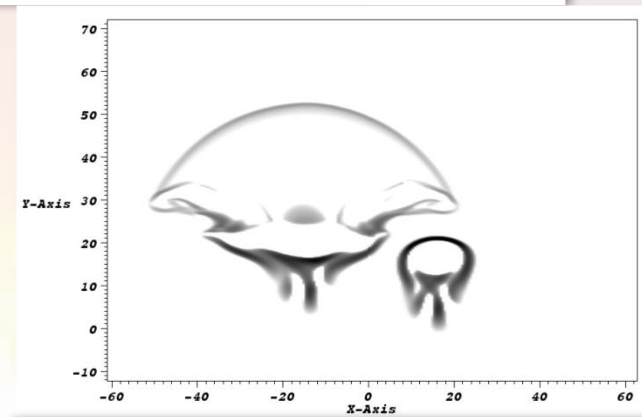
Braking mechanisms

Too strong confining tether



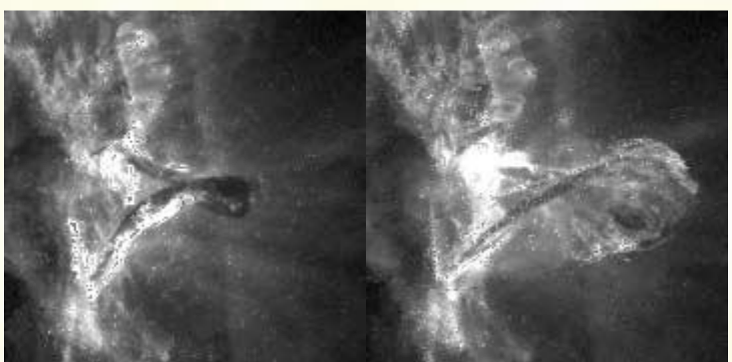
Vrsnak, B. 1990, Solar Phys. 129, 295

New flux emergence



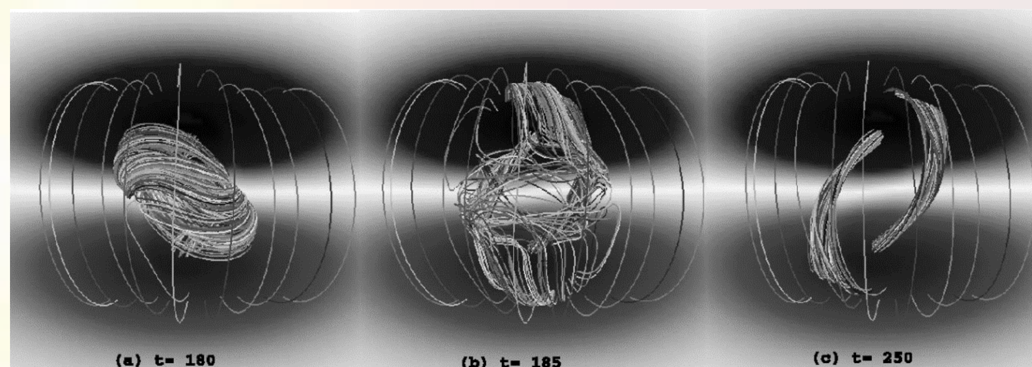
Archontis, V., et al. 2007, A&A 466, 367

Kink/toroidal instability



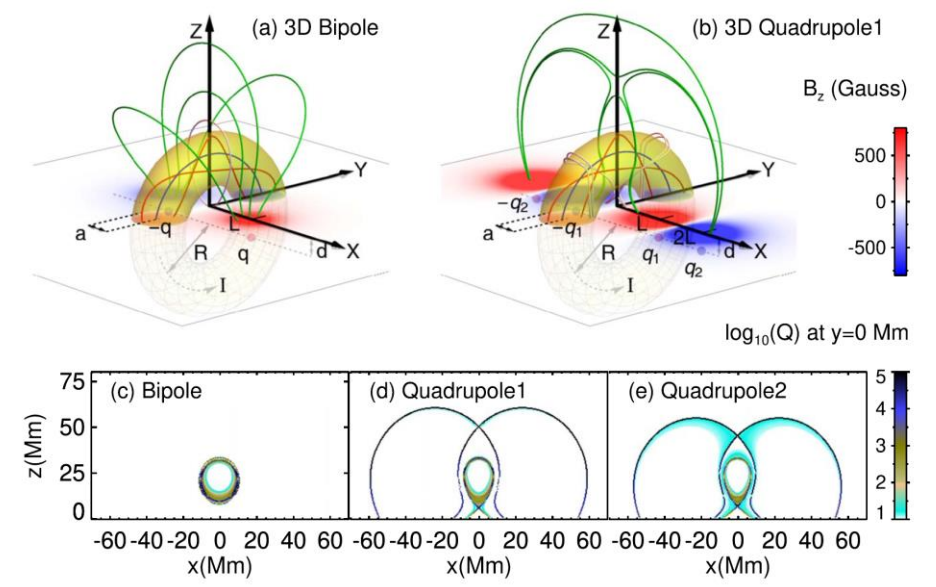
Ji, H. i in. 2003, ApJ, 595, L135

Barrier collision

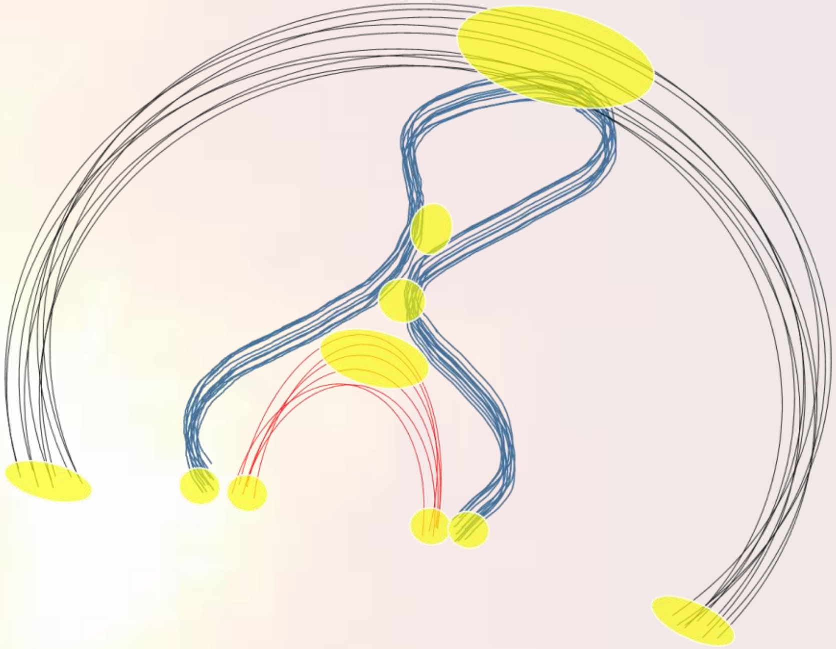


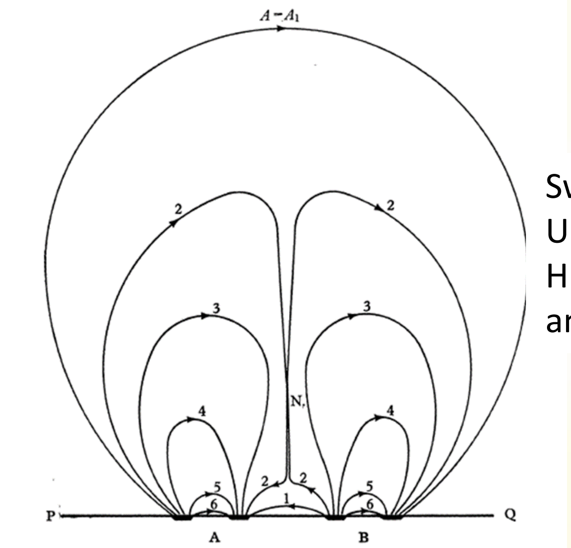
Amari, T., & Luciani, J.F. 1999, ApJ 515, L81

Magnetic configuration



Chen et al. 2023, ApJL 951, 35





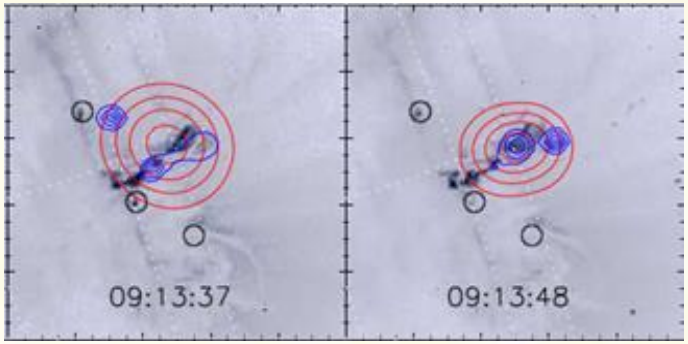
Sweet P.H. 1958,
Uchida et al. 1999,
Hirose et al. 2001,
and others

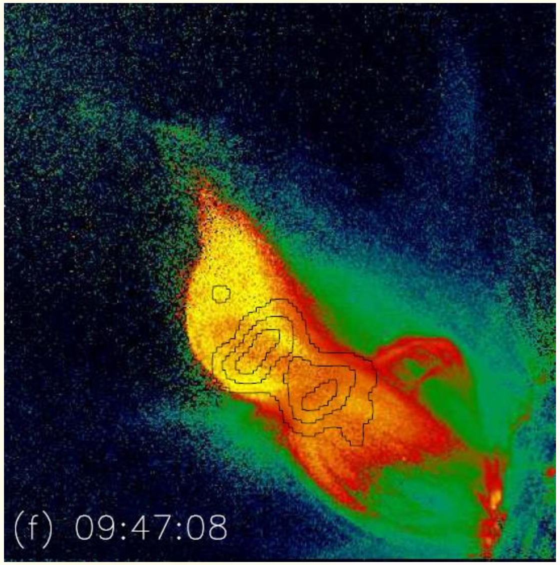
The quadrupolar model describes observed features of solar flares in a more natural way.

The „standard" model is cherry-pick. The surrounding magnetic structures give context and are crucial to the process of eruption.

Sometimes, overlying magnetic structures may lead to occurence of new types of HXR sources.

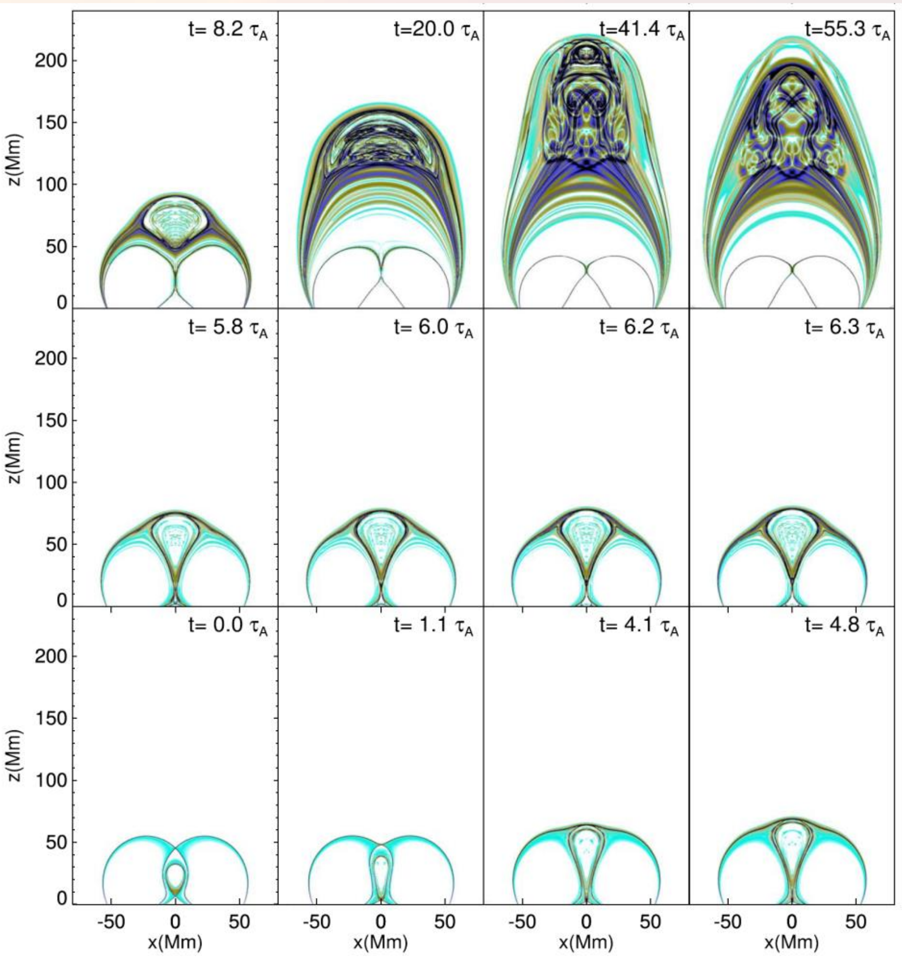
Reconnection sites (possible cause for hot plasma in FE)





Observations of hot plasma (not only X-rays):

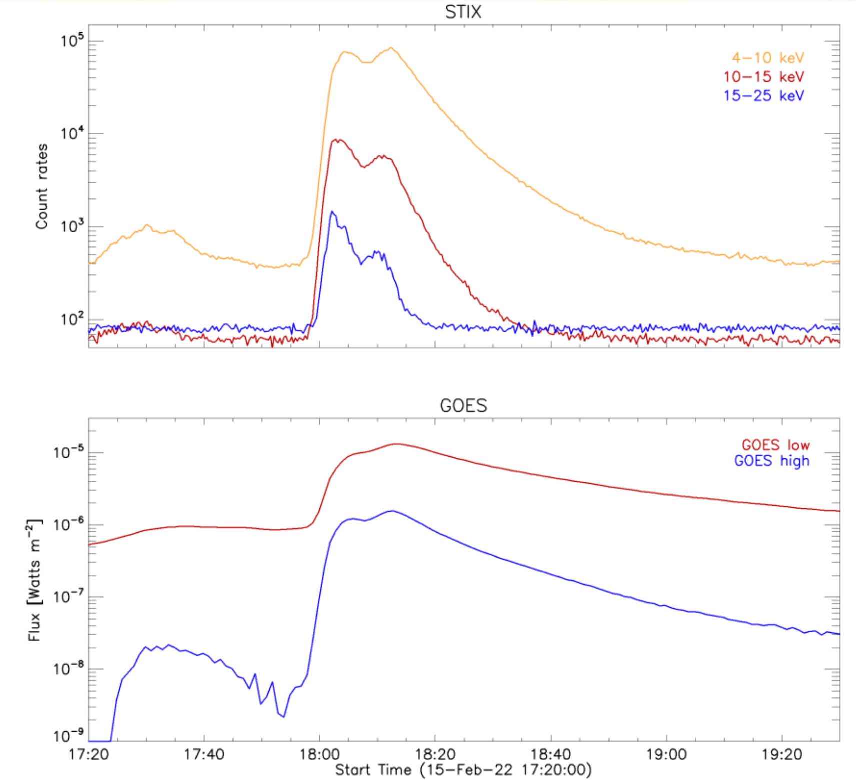
Alexander, D. et al. 2006, ApJ 653, 719
Netzel, A. et al. 2012, A&A 548, id.A89
Song, H. Q. et al 2014 ApJ 784 48



Models (reconnection below nad/or over the failed eruption):

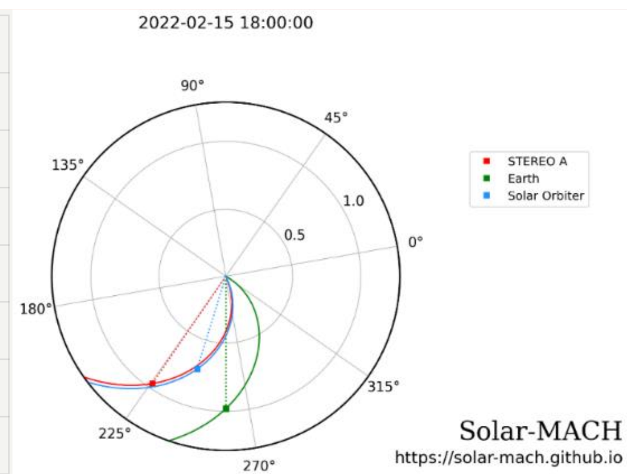
Amari & Luciani 1999, ApJL 515, 81
Hassanin, A. & Kliem, B., 2016, ApJ 832,106
Wang, C. et al. 2022, ApJL 933, 29
Chaowei, J. et al. 2023, MNRAS

The flare (GOES M1.3, STIX data estimated C8.0)

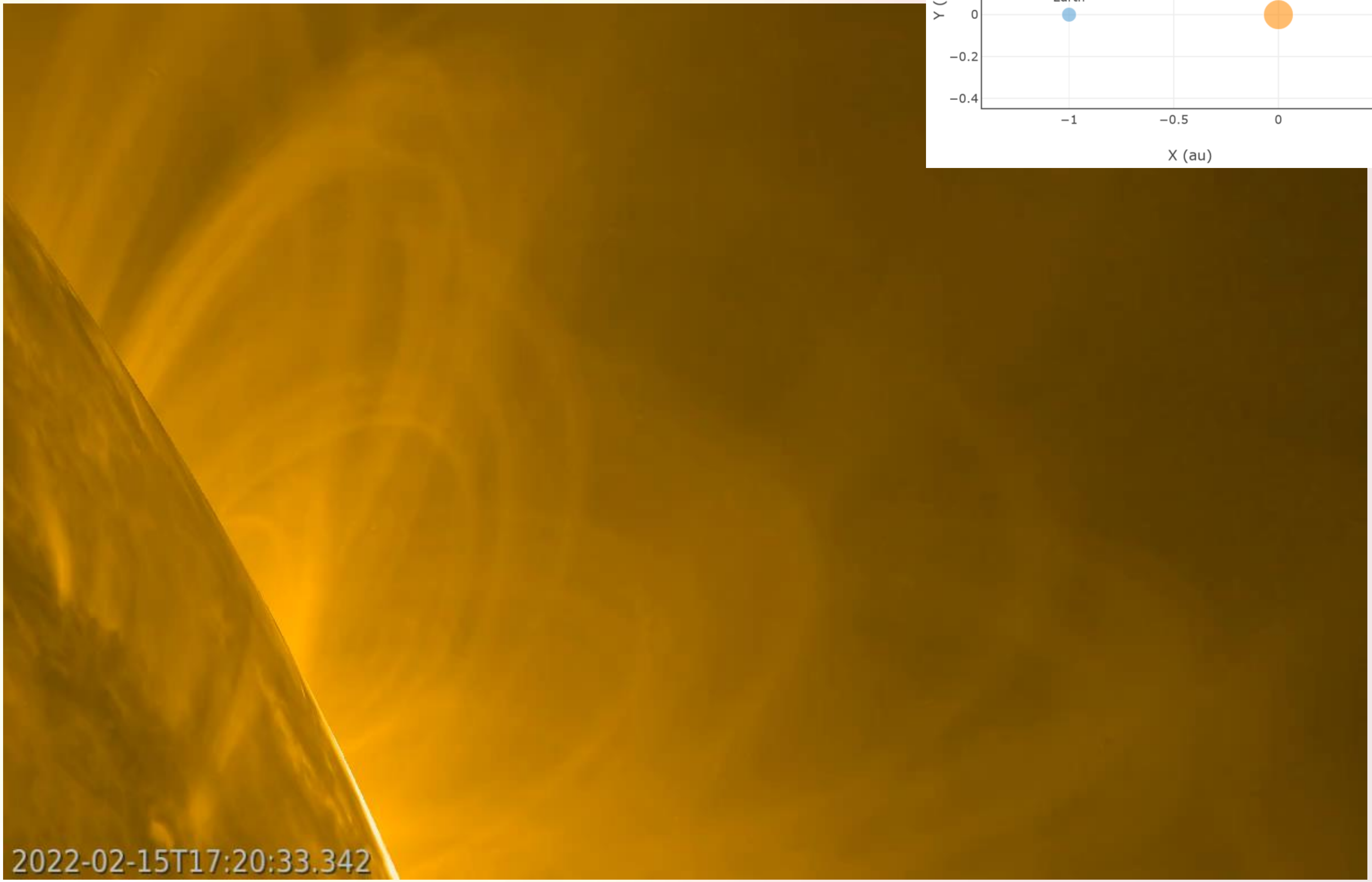


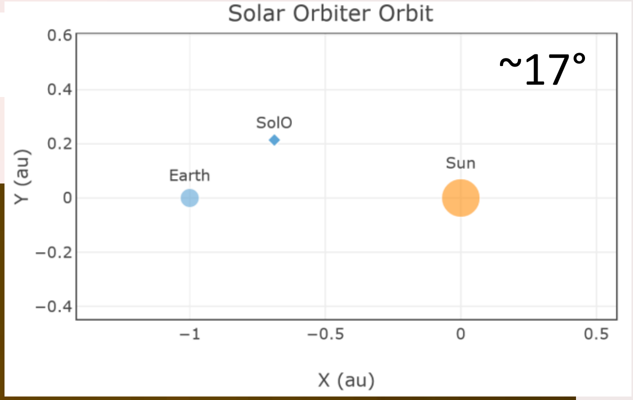
Observed by SO/STIX, SO/EUI FSI, SDO/AIA, PROBA2/SWAP, STEREO A

	STEREO A	Earth	Solar Orbiter
Carrington longitude [°]	225.6	260.0	242.8
Carrington latitude [°]	-4.4	-6.9	-3.1
Heliocent. distance [AU]	0.97	0.99	0.72
Longitud. separation to Earth longitude [°]	-34.4	0.0	-17.2
Latitud. separation to Earth latitude [°]	2.4	0.0	3.7
Solar wind speed [km/s]	400	400	400
Magnetic footpoint Carrington longitude [°]	285.8	321.1	287.9

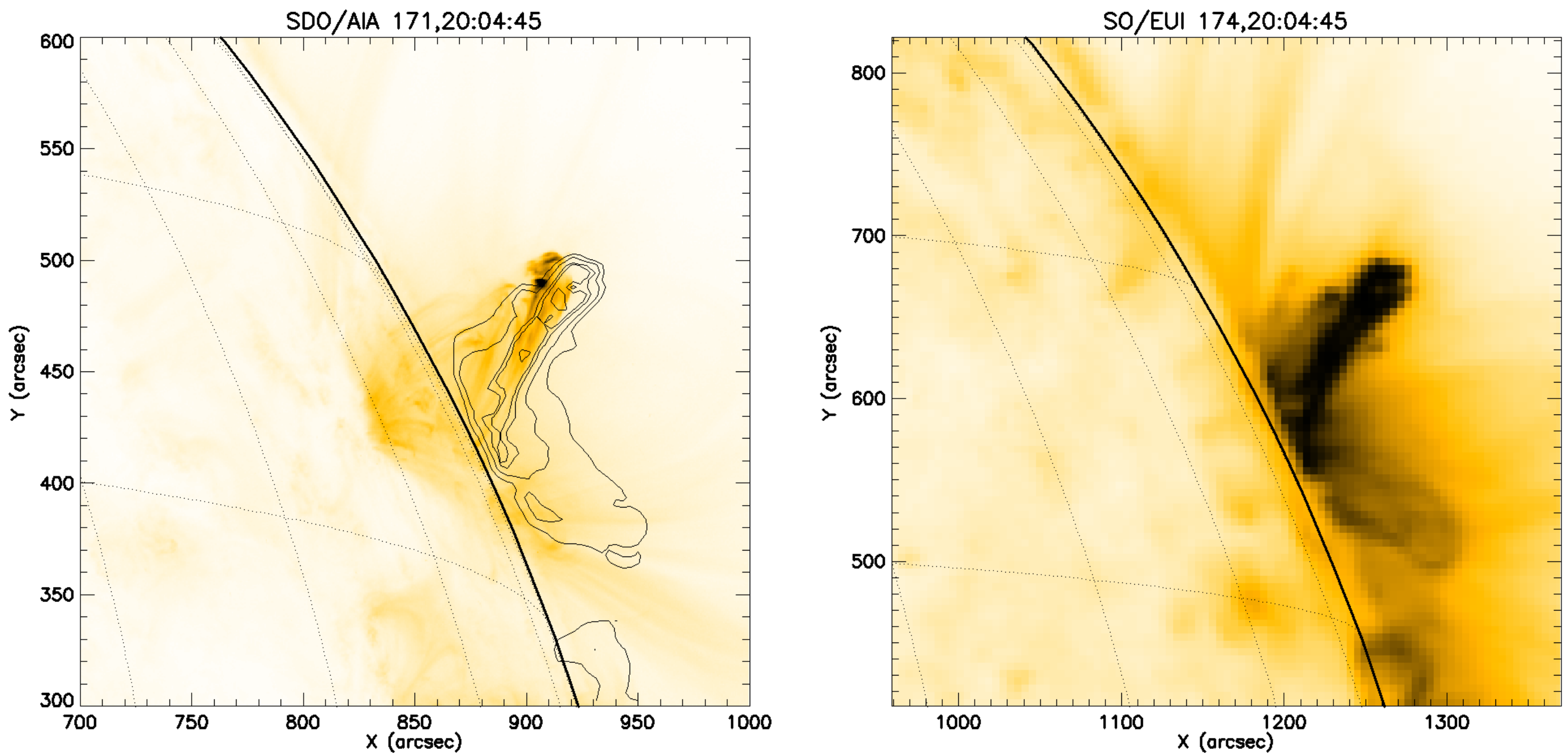


Failed eruption (SO perspective), 171 Å





SO-SDO perspectives

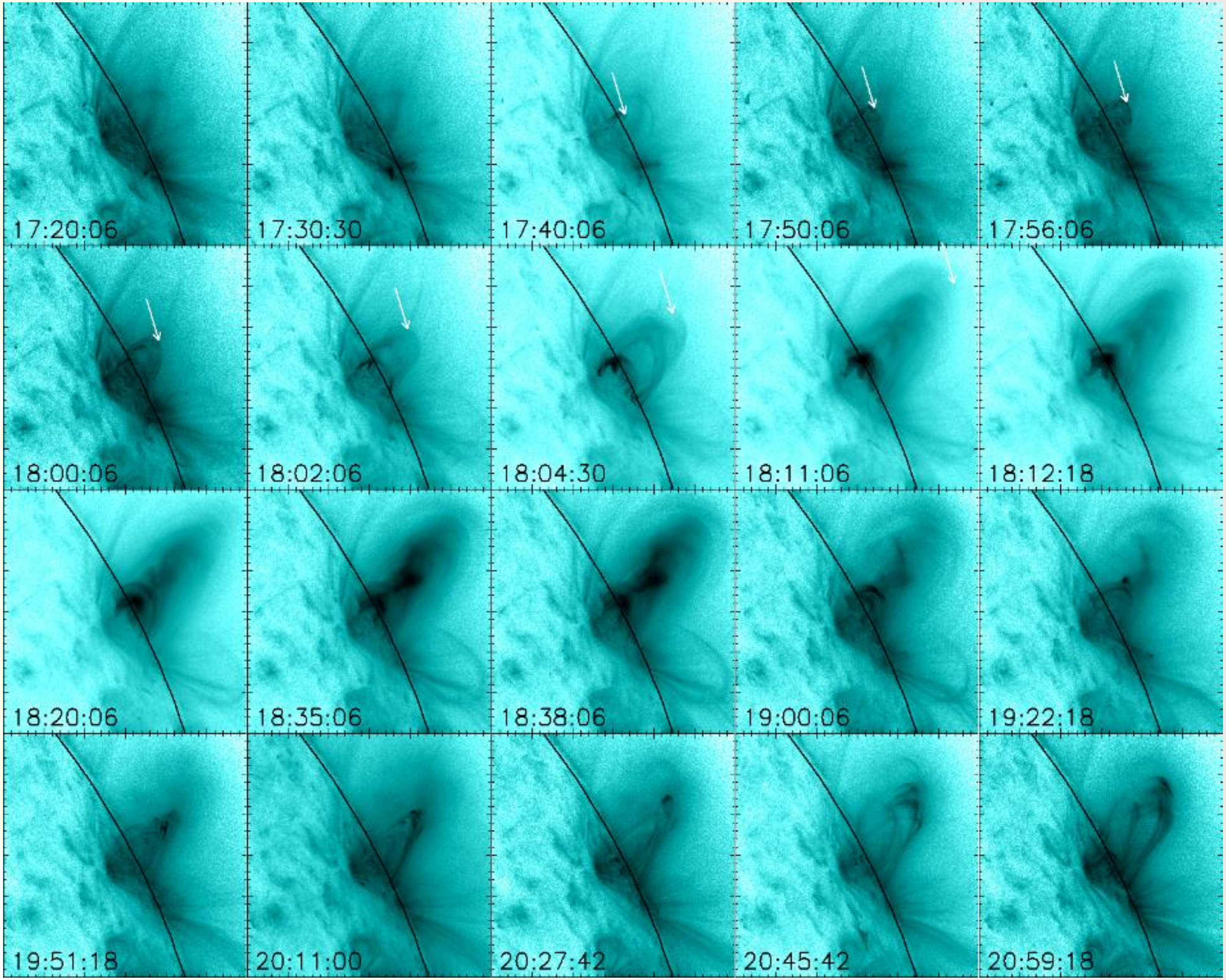


EUI (contours) overlayed on AIA (image). SO pointing used, no additional shifts/rotations.

- SO-SDO longitude separation = -17.2°,
- Footpoints of the eruption seen by AIA: 78°W and 80°W.
- Comparison with EUI shows that both perspectives are symetrical with regard to solar limb.

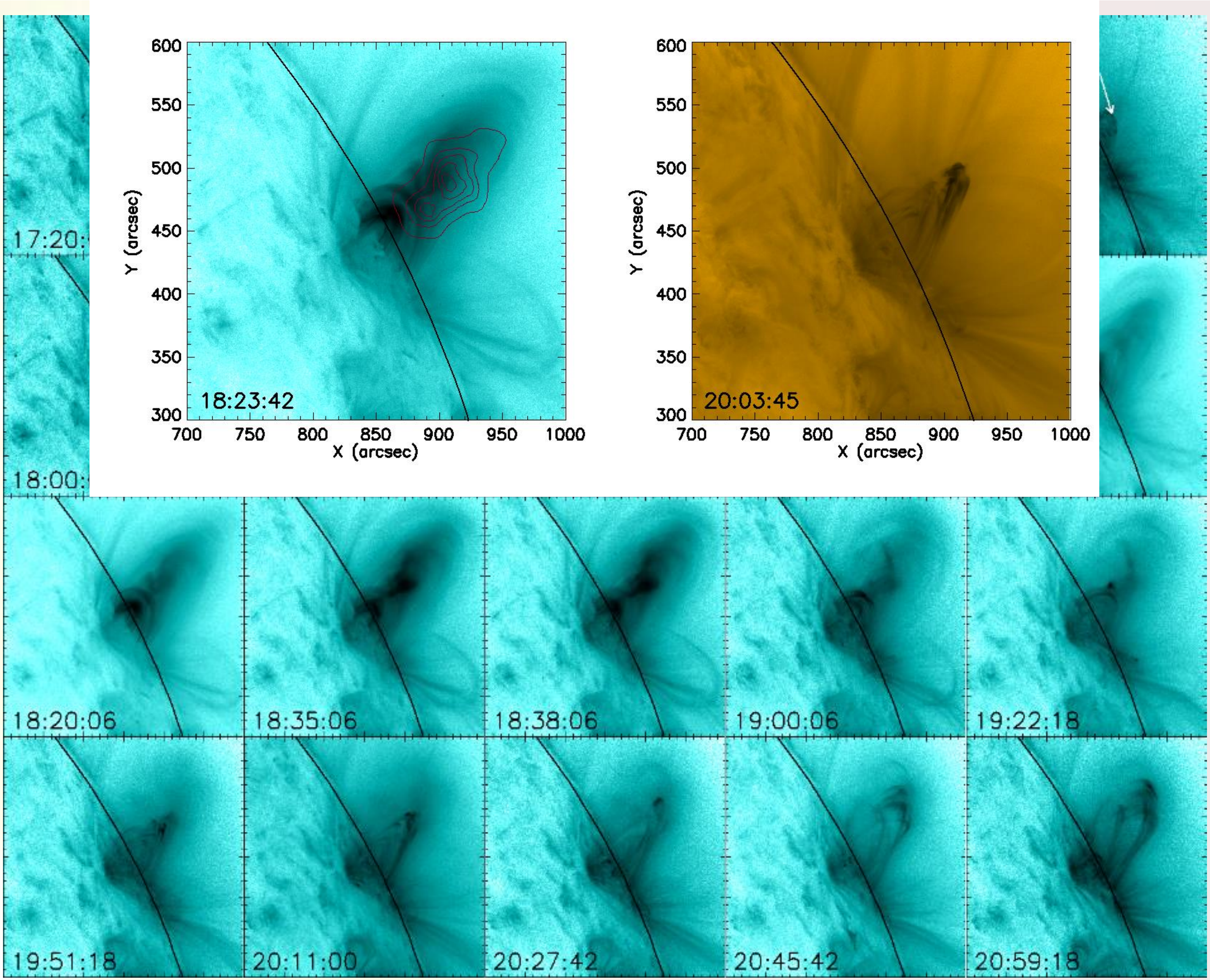
We assume that altitudes above the limb are almost the same (after correction for distance to the Sun) for both perspectives.

Evolution



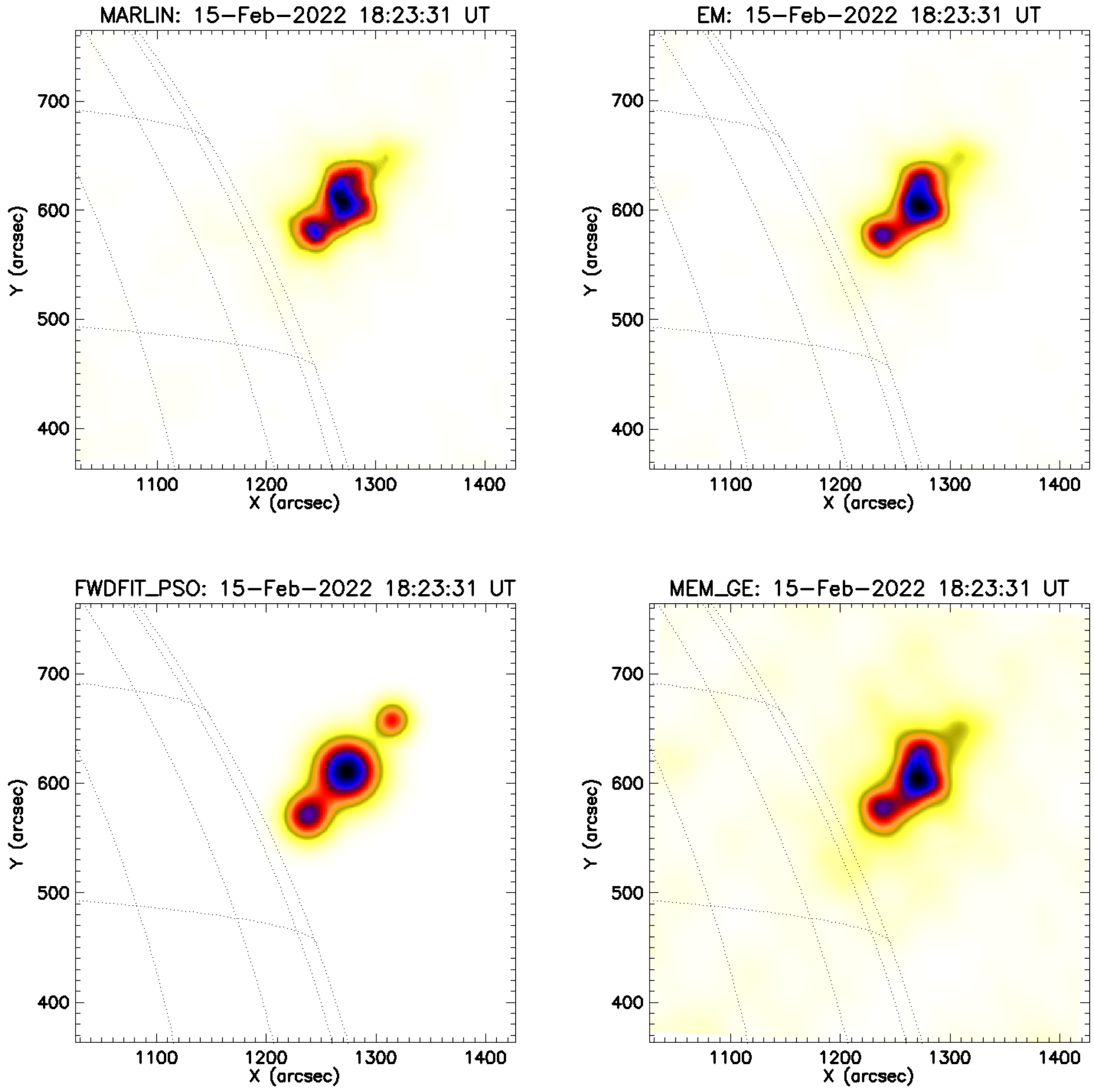
17:20:06
17:30:30
17:40:06
17:50:06
17:56:06
18:00:06
18:02:06
18:04:30
18:11:06
18:12:18
18:20:06
18:35:06
18:38:06
19:00:06
19:22:18
19:51:18
20:11:00
20:27:42
20:45:42
20:59:18

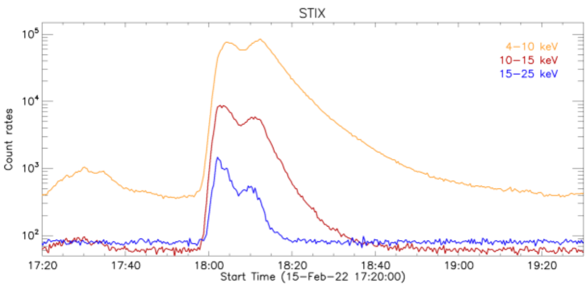
Evolution



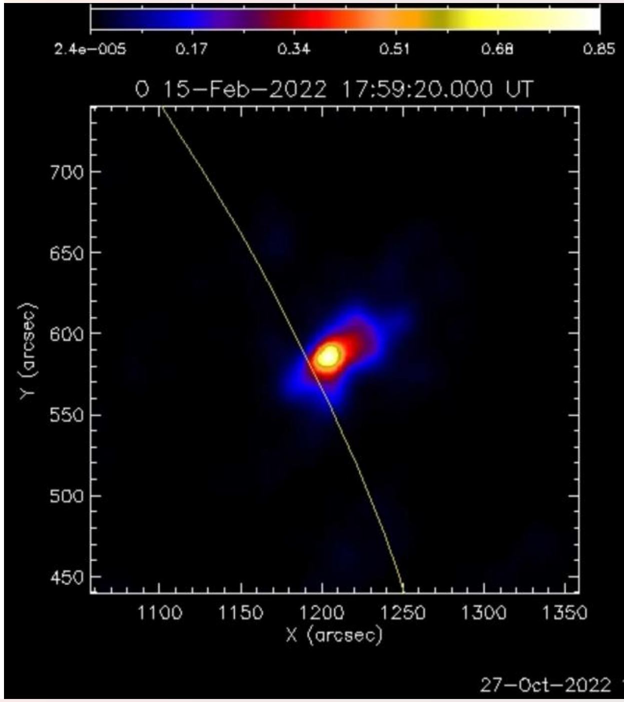
600
550
500
450
400
350
300
Y (arcsec)
700 750 800 850 900 950 1000
X (arcsec)
18:23:42
20:03:45
17:20:
18:00:
18:20:06
18:35:06
18:38:06
19:00:06
19:22:18
19:51:18
20:11:00
20:27:42
20:45:42
20:59:18

Three STIX sources

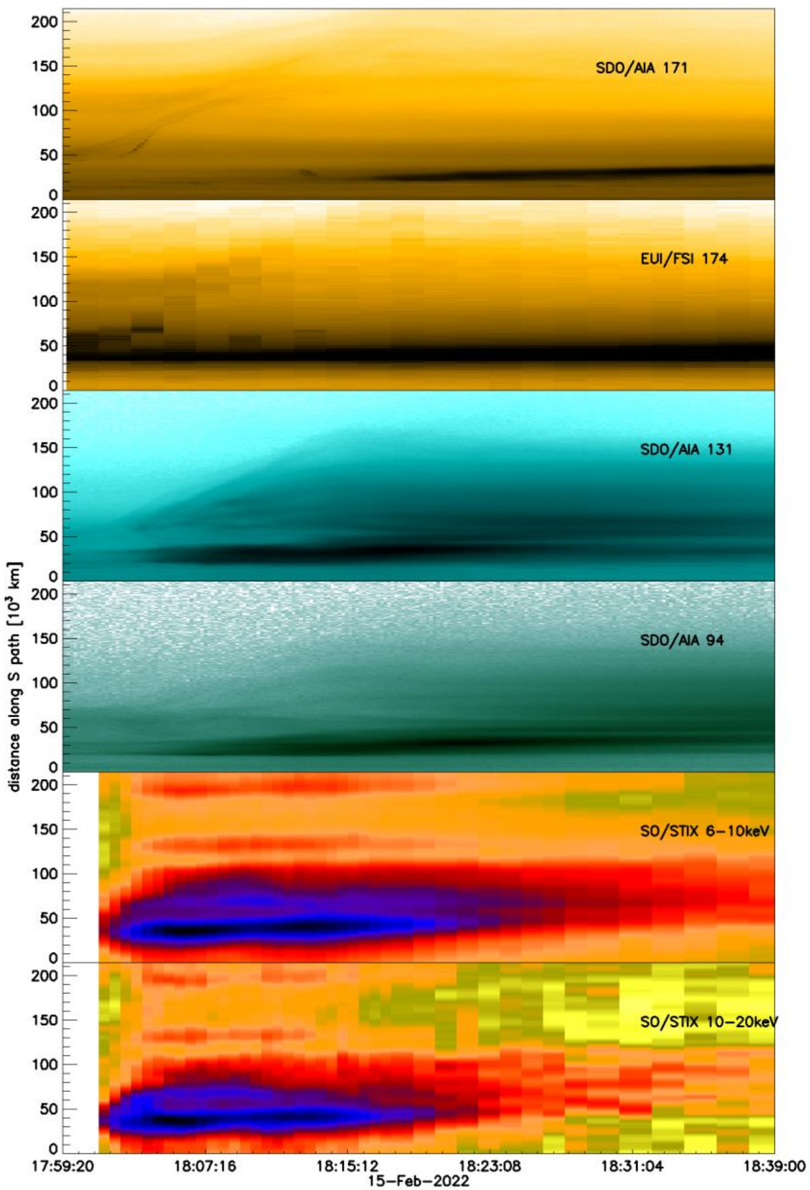


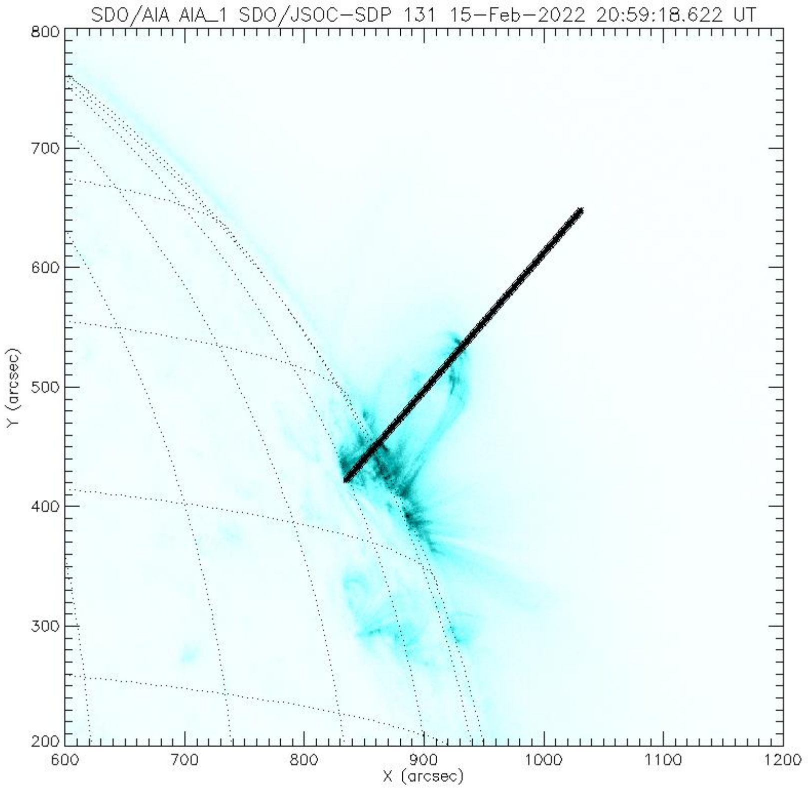


- All three sources are coronal.
- Foot points occulted by the limb (~10° behind)



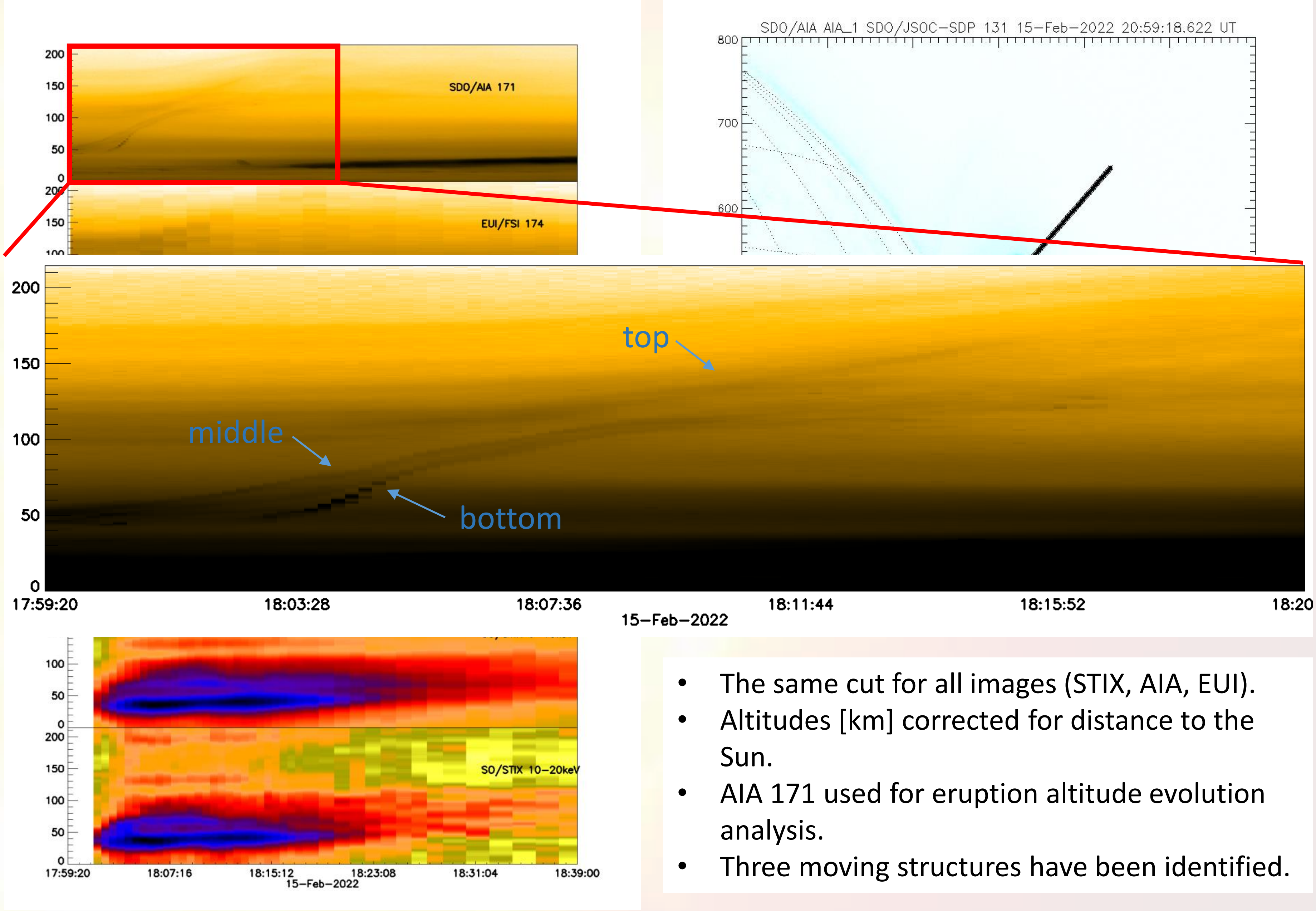
Kinematics





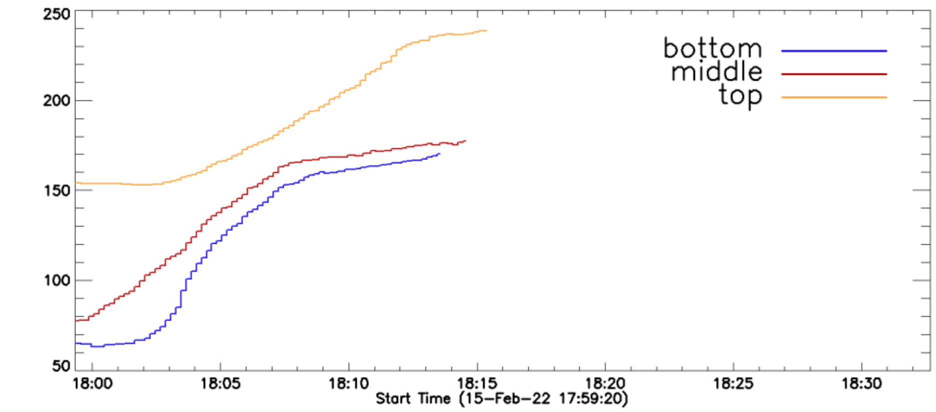
- The same cut for all images (STIX, AIA, EUI).
- Altitudes [km] corrected for distance to the Sun.
- AIA 171 used for eruption altitude evolution analysis.

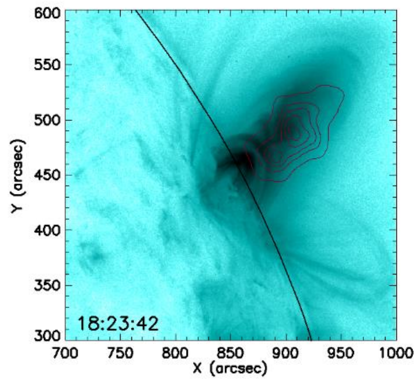
Kinematics

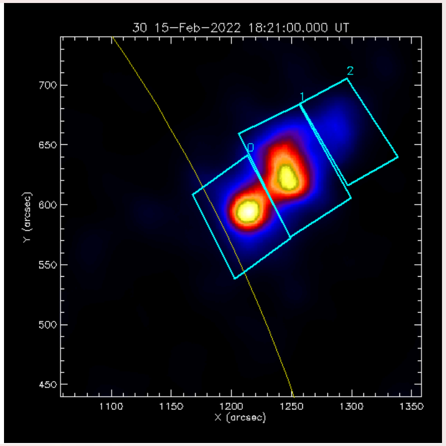


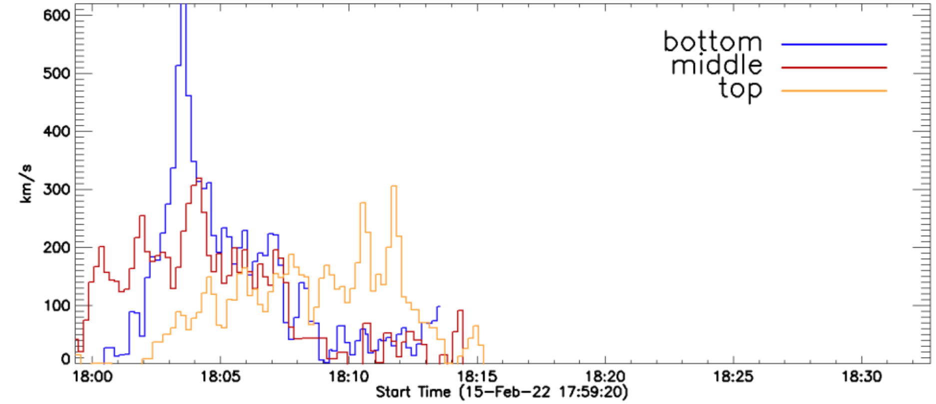
- The same cut for all images (STIX, AIA, EUI).
- Altitudes [km] corrected for distance to the Sun.
- AIA 171 used for eruption altitude evolution analysis.
- Three moving structures have been identified.

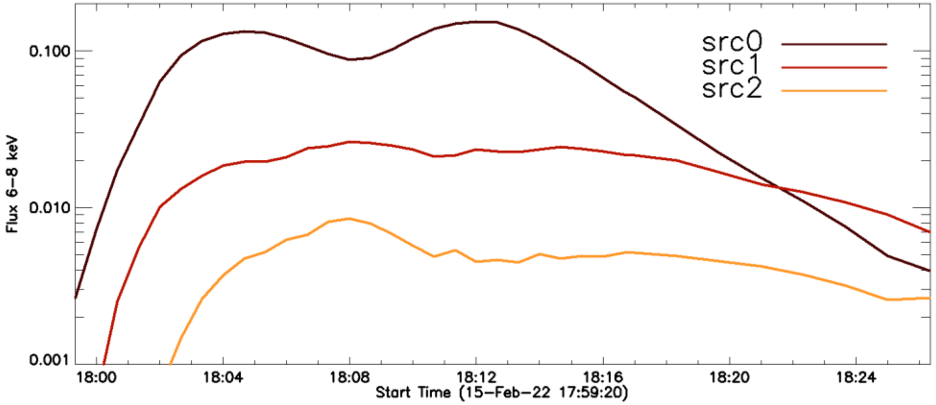
Kinematics





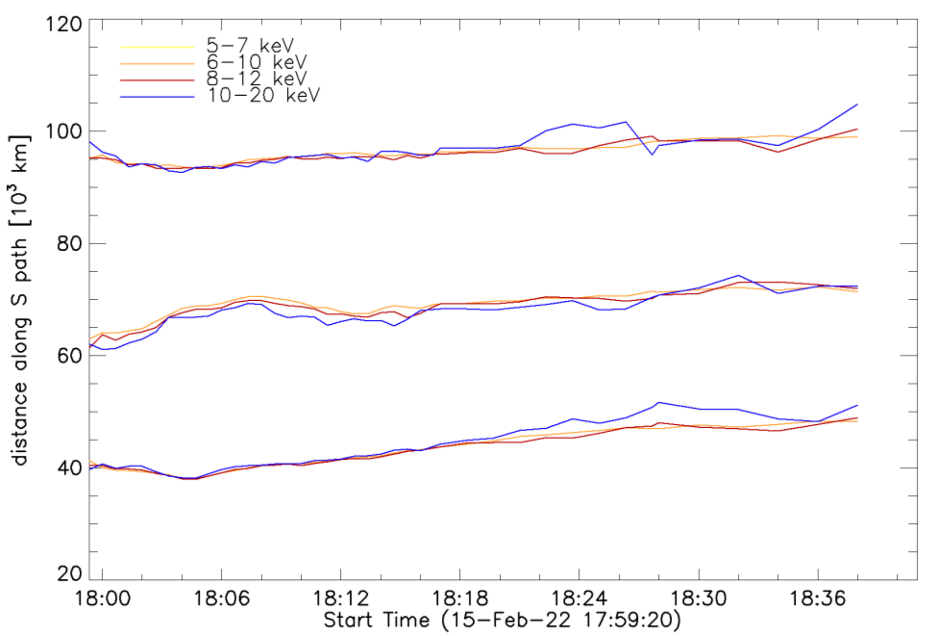


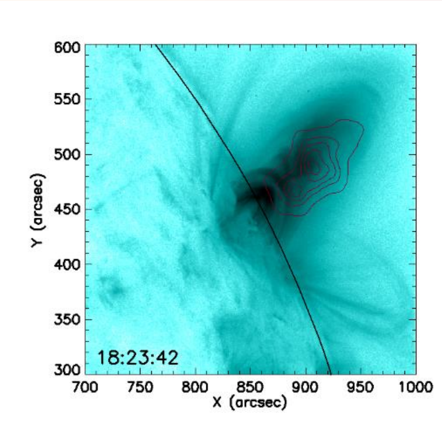


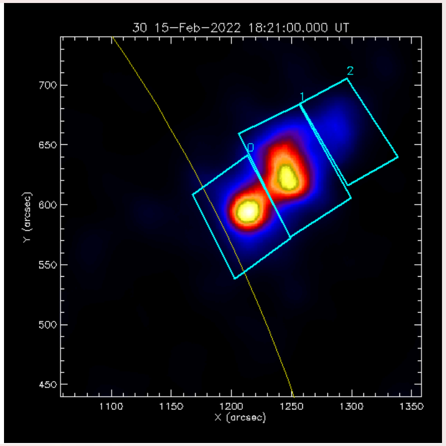


- SRC0 brightness rise phase is corellated with fast acceleration of bottom eruption front.
- First peak in the velocity curve of bottom front is repeated in mid and top with few dozen seconds time shift.
- SRC1 and 2 show brightness max after the first peak of SRC0.
- After strong deceleration of bottom front, brightness of SRC0 abruptly decreases.
- Top front maximum velocity is correlated with second max brightness of SRC0.

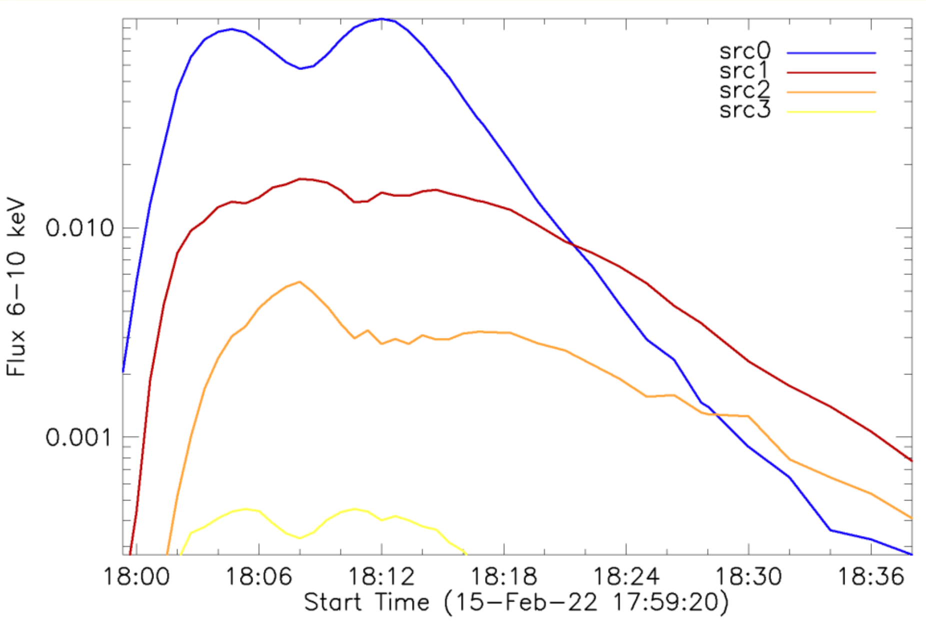
HXR sources

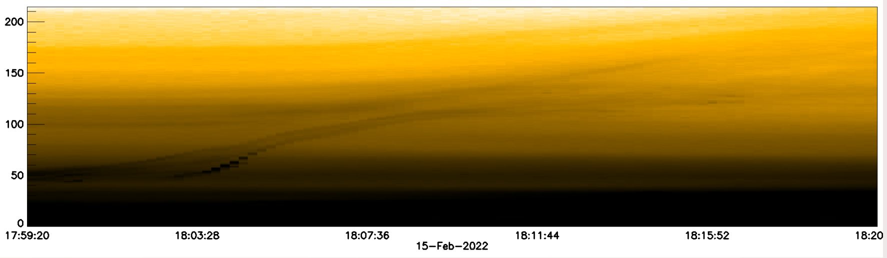




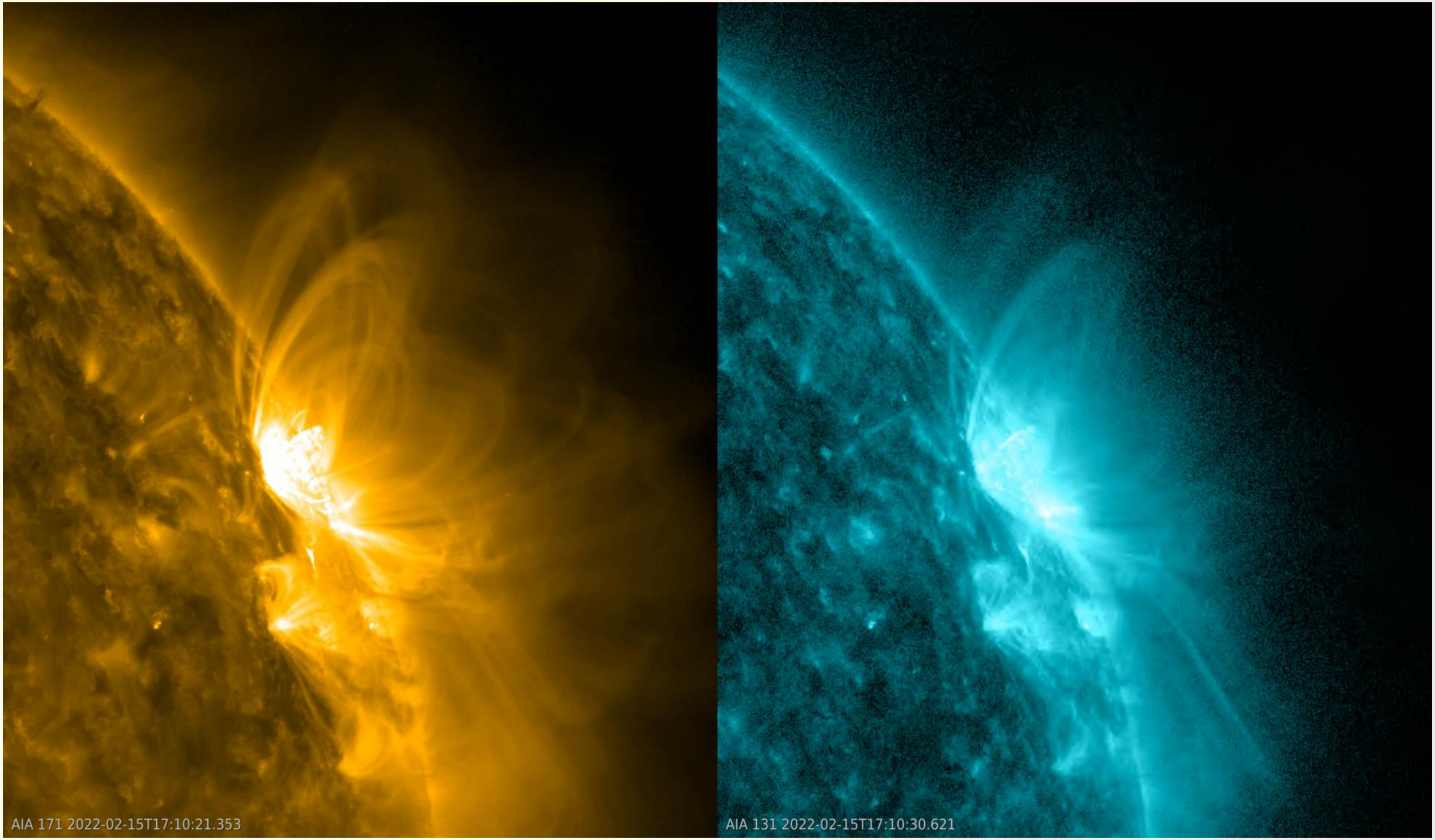


- Small changes of sources' altitudes.
- Only SRC0 behaves like typical loop top source: altitude decrease during impulsive phase, slow rising after with velocity < 5 km/s.
- SRC1 and 2 show changes of altitude within 5000 km range (V<1 km/s)



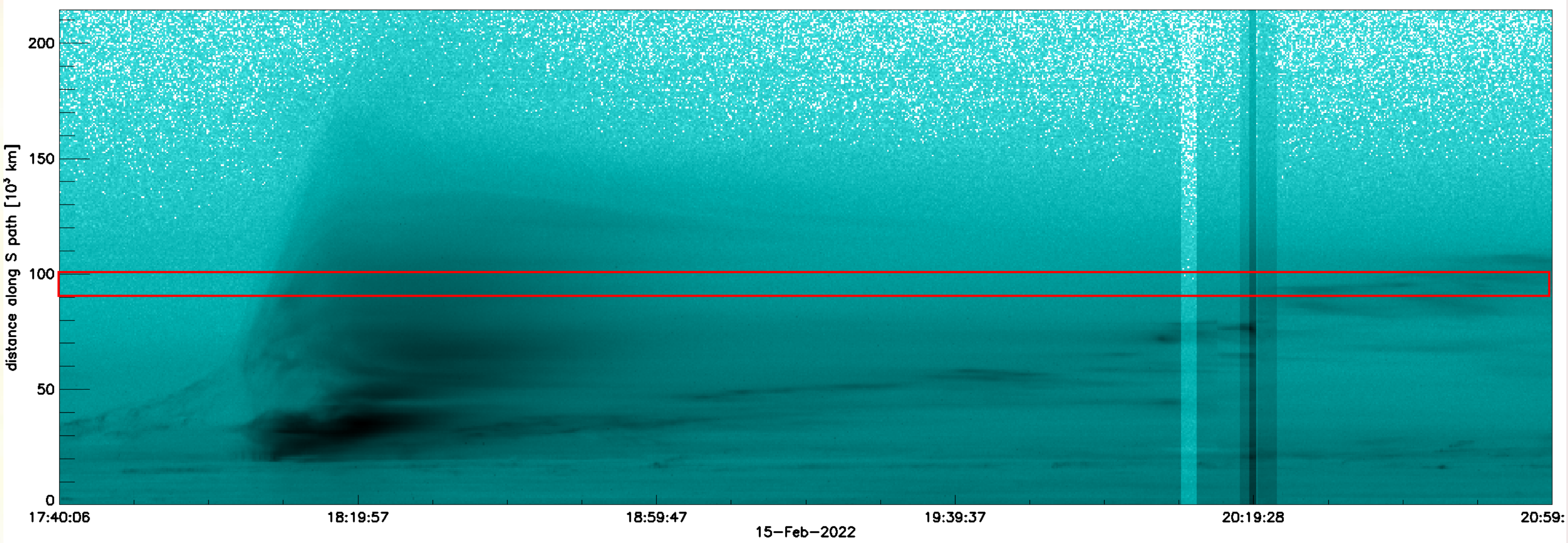


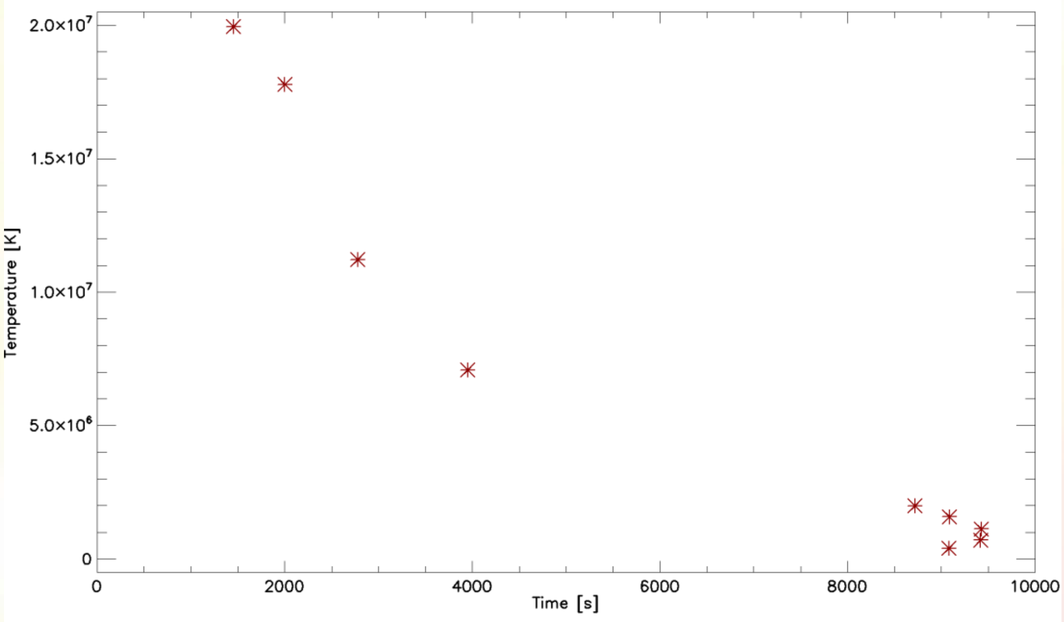
Cooling



Sources heated during eruption braking are visible ~2 hours later as systems of cool loops. They are not „post-flare loops" but rather structures disconnected from primary energy release site.

Cooling





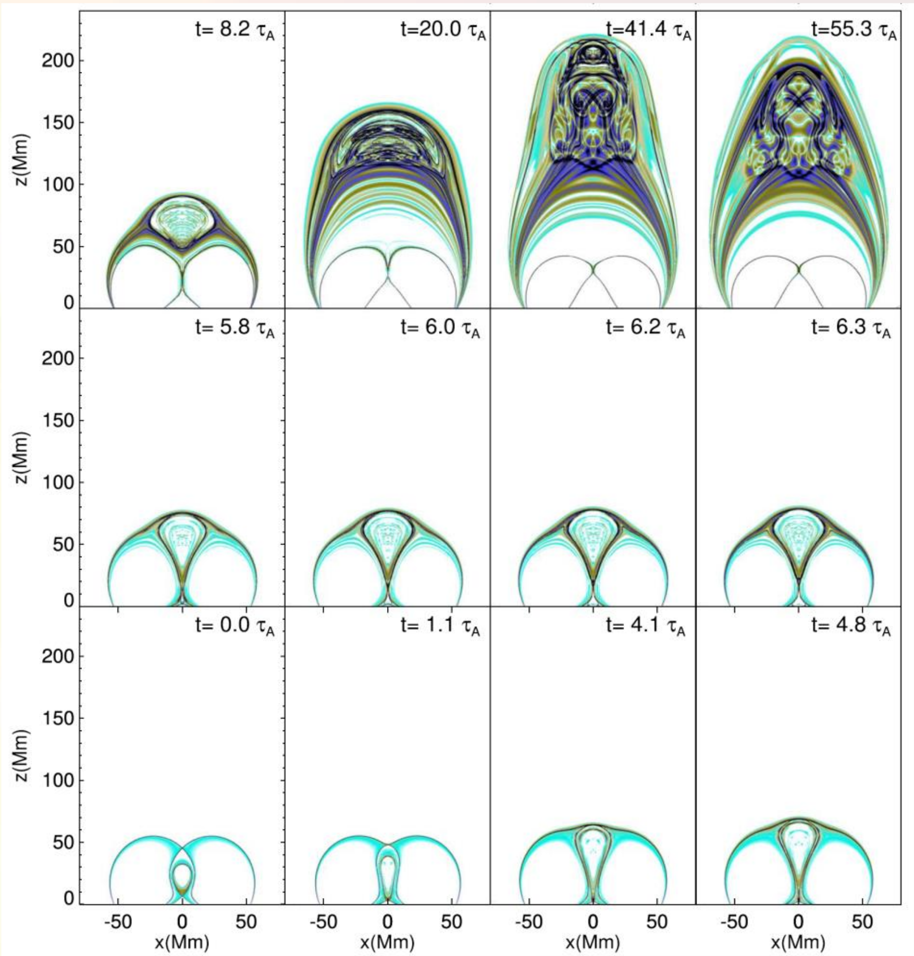
Case	λ_T (cm)	Cooling Sequence
I	$>2 \times 10^8$	Collisional Conduction → Radiation
II	5×10^6–2×10^8	Turbulent Conduction → Collisional Conduction → Radiation
III	3×10^5–5×10^6	Turbulent Conduction → Radiation
IV	$<3 \times 10^5$	Radiation

Bian et al., 2016, ApJ 833, 76
(λ_T – turbulent mean free path)

First stage of cooling is turbulence dominated conduction and after this radiation is present only.

Summary

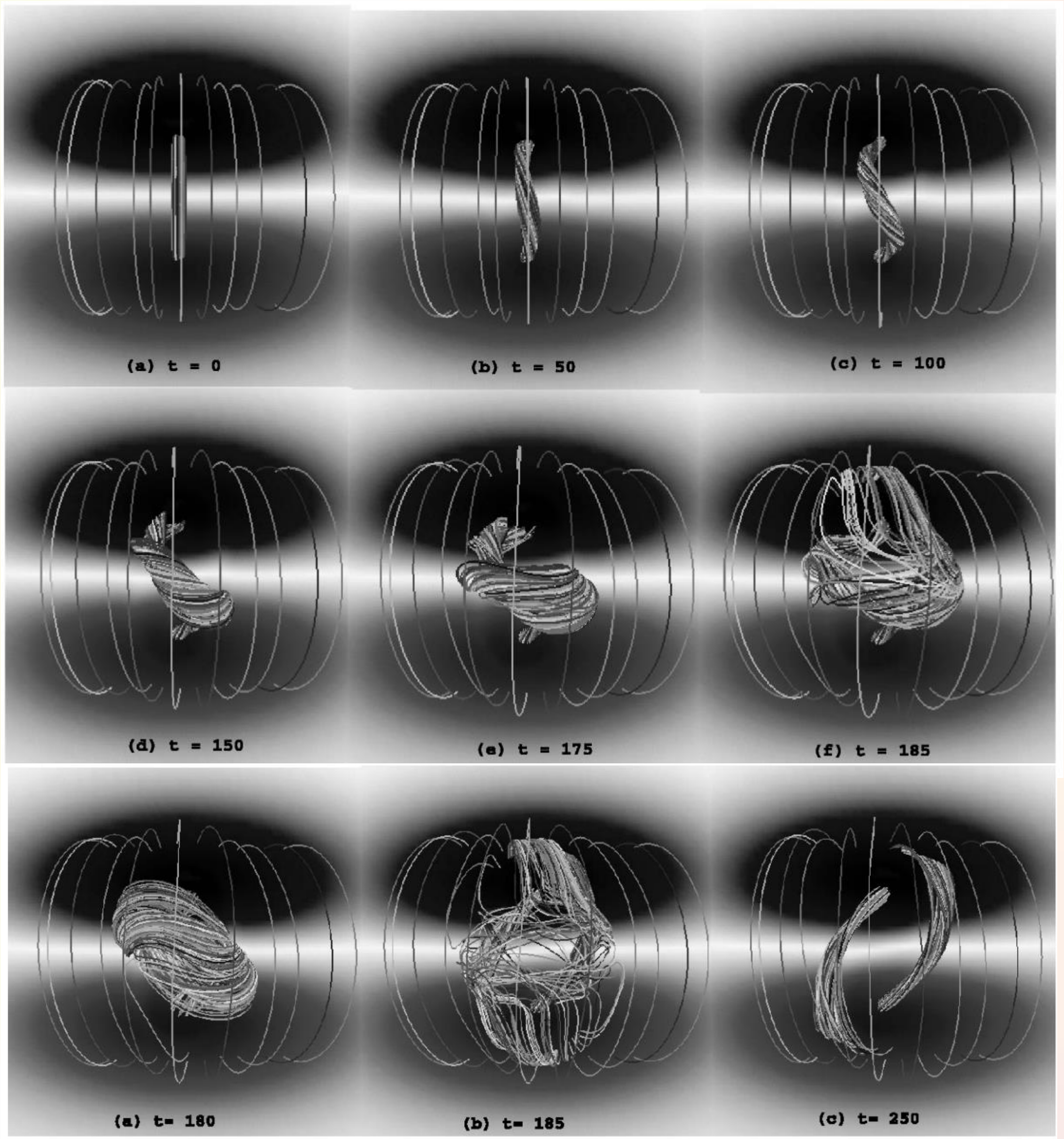
- At least three HXR sources visible in the solar corona
- They are „classical” flare-related sources (SRC0) as well as sources produced during eruption reconnection with overlying magnetic structures (SRC1 and 2).
- Lowest source experience two brightness maxima.
- Two higher sources reach maximum brightness after the SRC0 first maximum.
- The altitudes of SRC1 and 2 are relatively stable. They seem to be disconnected from the reconnection ongoing below the eruption.
- Imaging spectroscopy is needed – preliminary results suggest that sources are thermal, but some non-thermality is expected at least in the beginning (structures collisions).
- Structures cools from 20 MK to 500 kK in 10000 s which might be connected to strong turbulence at first stage of cooling. Tulbulence decrease efficiency of conduction and may add energy due to many small reconnections.

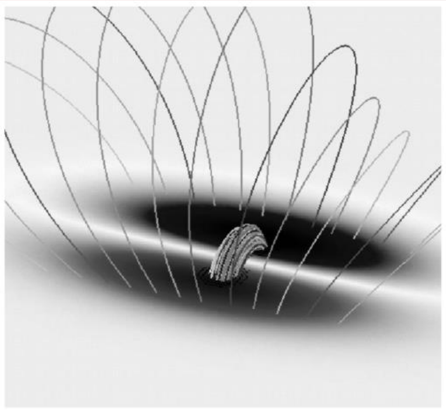


Chaowei, J. et al. 2023, MNRAS
Chen et al. 2023, ApJL

Backup slides

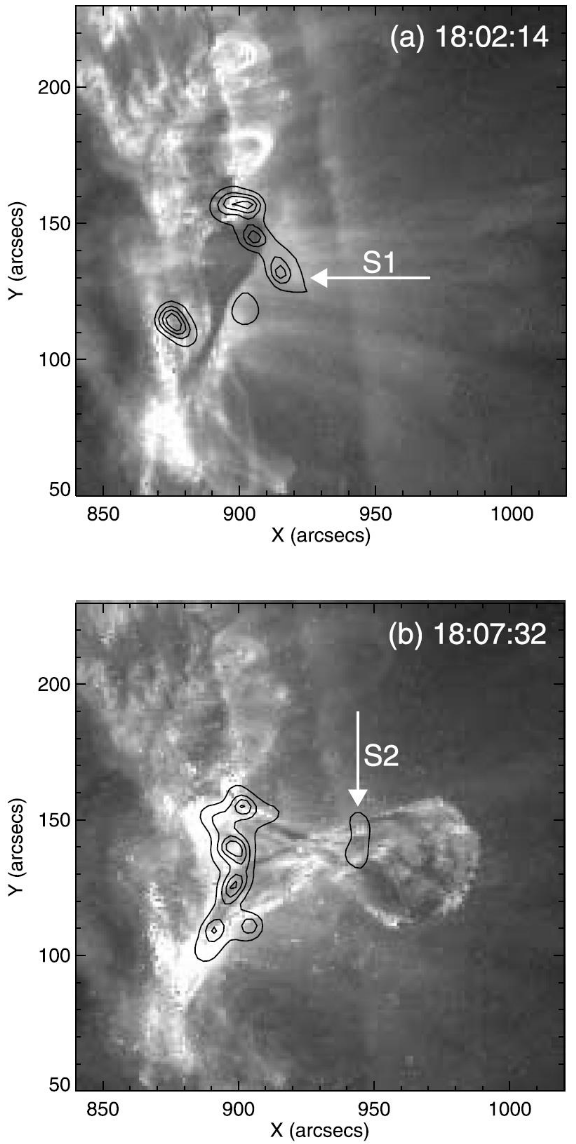
Failed eruption (Amari & Luciani 1999, ApJL 515, 81)





1. The configuration evolves slowly building up twist and magnetic energy. The overlaying confining arcade remains almost potential.
2. The system evolves through a dynamical phase during which the configuration experiences a disruption. The reconnection occurs through two “curtain-like” structures made of field lines that suggest the presence of current sheets.
3. The configuration reaches an equilibrium with two almost untwisted flux tubes and a closed overlaying arcade.

Failed eruption & HXRs (Alexander, D. et al. 2006, ApJ 653, 719)



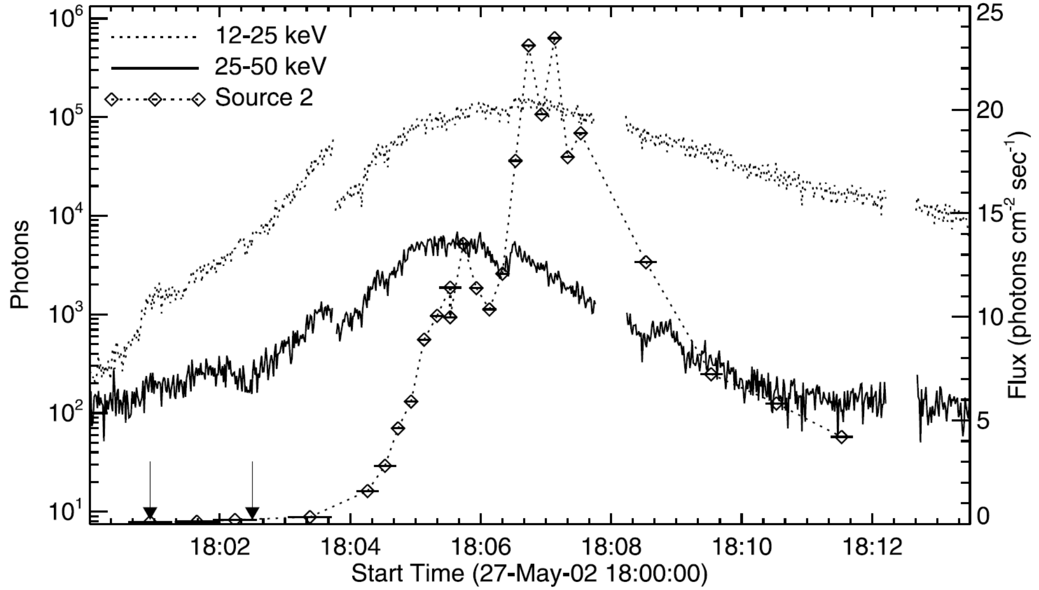
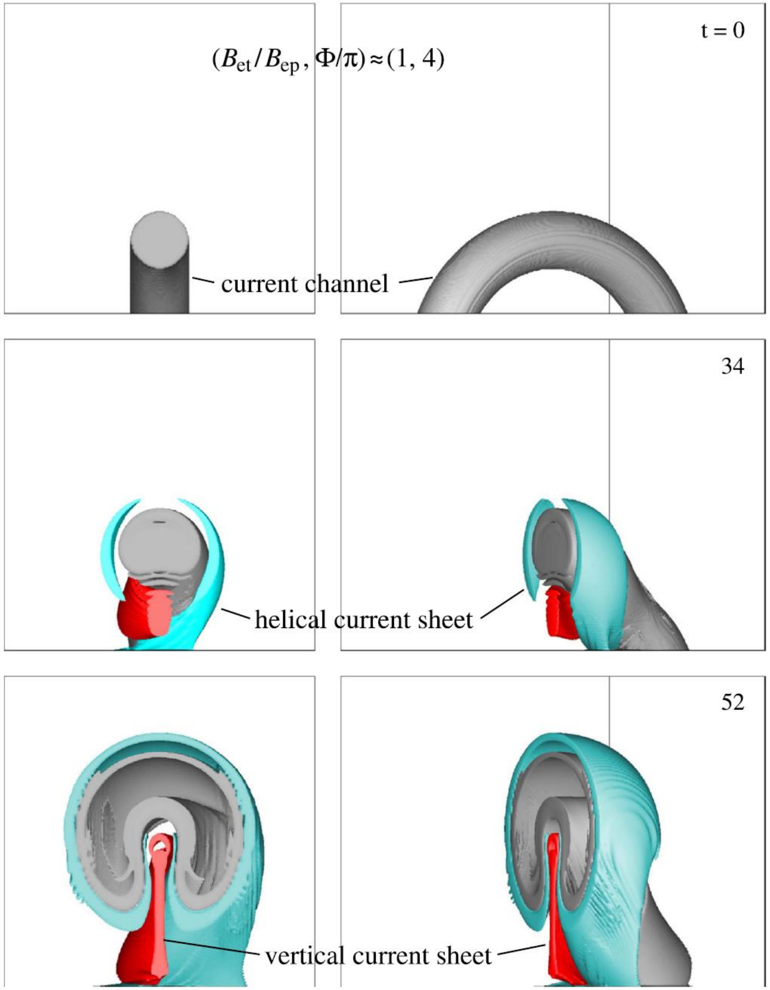


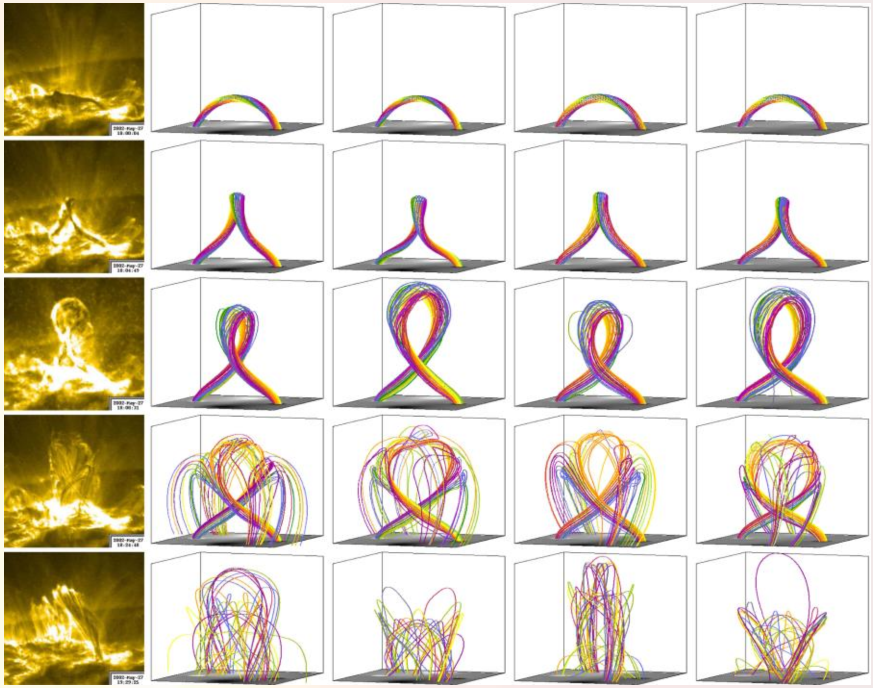
FIG. 3.—Light curves of *RHESSI* hard X-ray emission. The dotted and solid lines show the time evolution of the 12–25 and 25–50 keV emission, respectively, from the whole flare (in photons). The diamonds indicate the time evolution of the 12–25 keV coronal source (S2; photons cm^{-2} s^{-1}). The arrows delimit the time over which the hard X-ray coronal source (S1) was detected. The gaps in the whole flare light curves are due to attenuator switches in *RHESSI*.

- Sources preceeding eruption (tether cutting?)
- Sources in the X-point of kinked structure

Failed eruption & HXRs (Hassanin, A. & Kliem, B., 2016, ApJ 832,106)

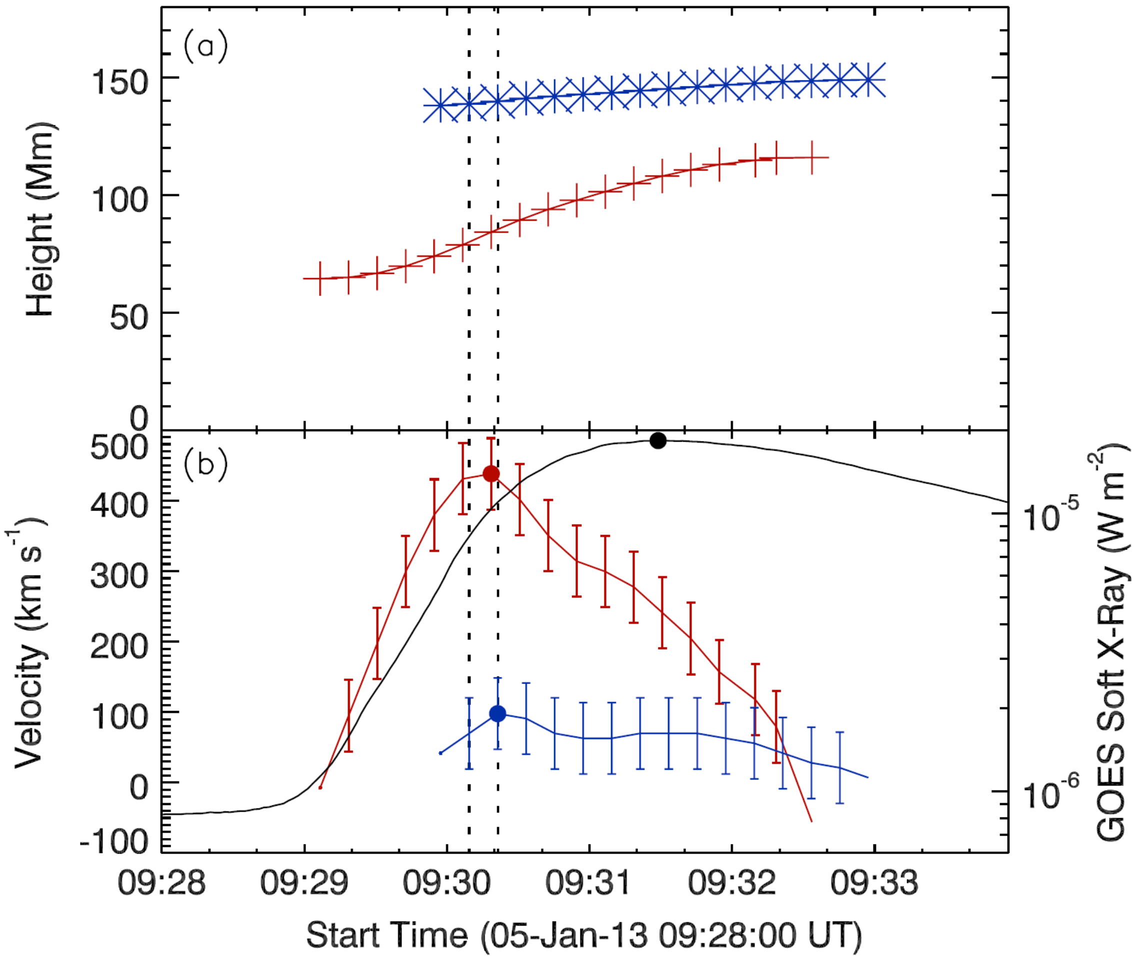


Two distinct phases of strong magnetic reconnection can occur. First, the erupting flux is cut by reconnection with overlying flux. Second, the resulting flux bundles may subsequently reconnect in the vertical current sheet between them.

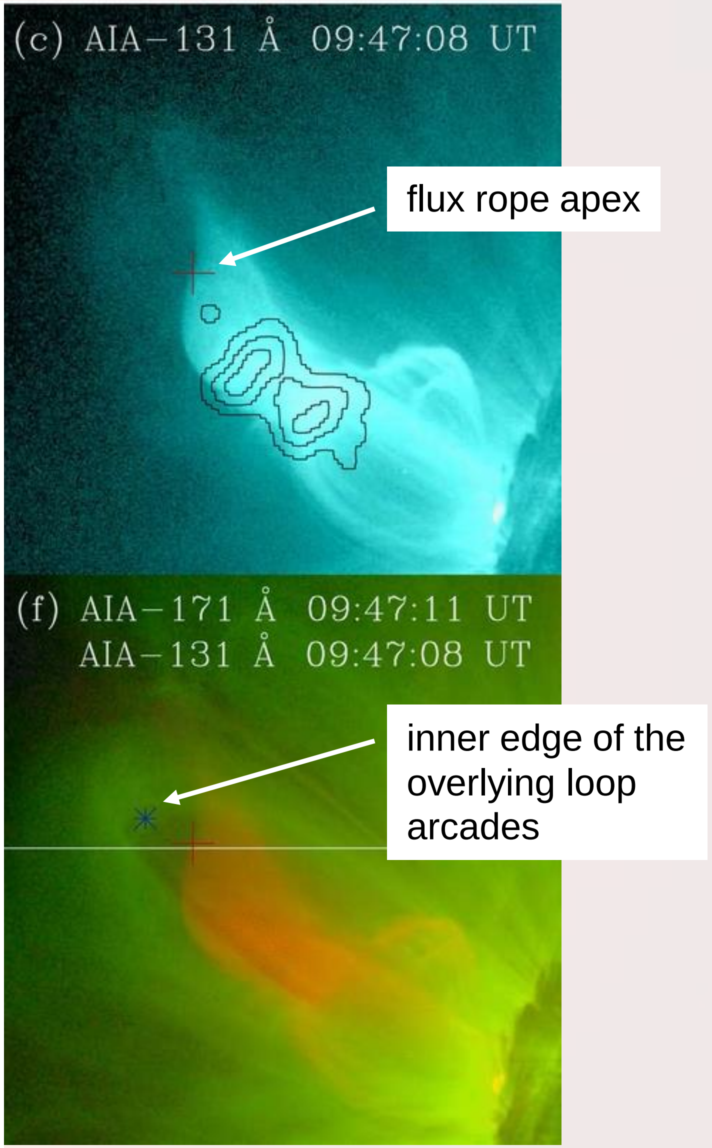


- Well observed filament eruption on 2002 May 27 has been MHD modeled compromising all phases of the event.
- Good agreement with confinement, terminal height, writhing, distortion, and dissolution of the filament, and the flare loops.
- **Simulations do not include the acceleration of particles, but a link to the HXR emissions is given by the observation that the time of the peak reconnection rate in eruptions is associated with the peak flux of the high-energy emissions.**
- **Modeled reconnection sites are assumed to be locations of HXR sources**.

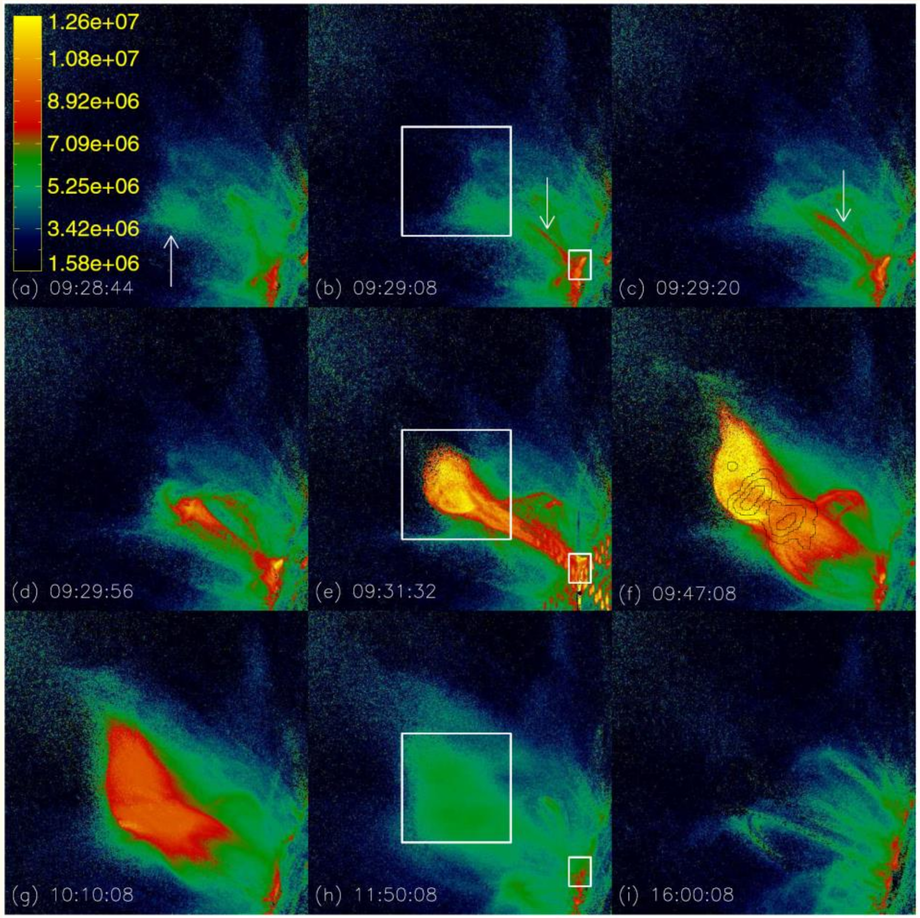
Hot plasma in a failed eruption (H. Q. Song et al 2014 ApJ 784 48)

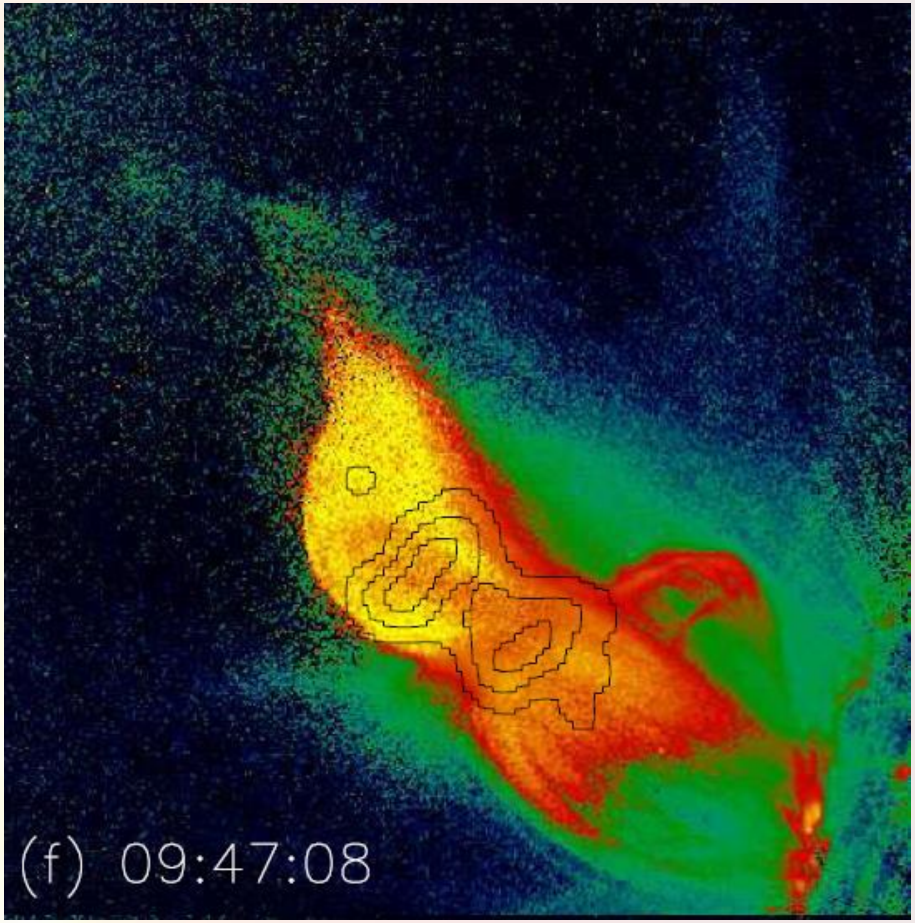


(a) Height–time profiles of the flux rope (red) and the loop arcade (blue). (b) The velocity-time profiles of the flux rope (red) and the loop arcade (blue), along with the profile of GOES soft X-ray 1–8 Å flux.



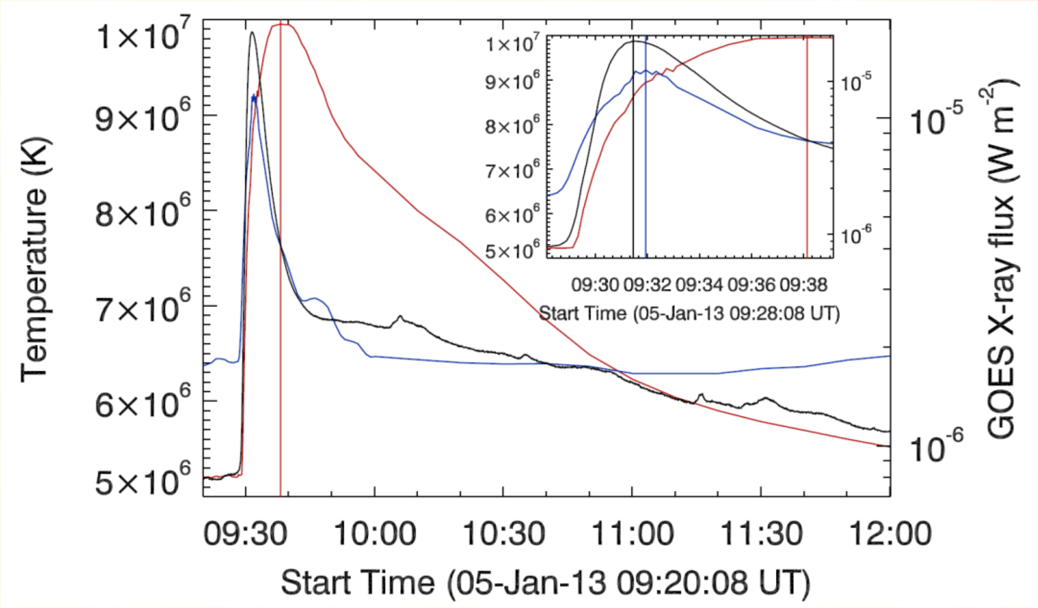
Hot plasma in a failed eruption (H. Q. Song et al 2014 ApJ 784 48)





- RHESSI show a double X-ray source. The region of magnetic reconnection should be between the two X-ray sources (e.g., Liu et al. 2008).
- It seems that the magnetic reconnection separates the flux rope structure into two parts: the upper part and the lower parts (similar, for partial eruption, has been reported in several studies: Gilbert et al. 2000; Gibson & Fan 2006; Tripathi et al. 2007, 2013; Sterling et al. 2011).

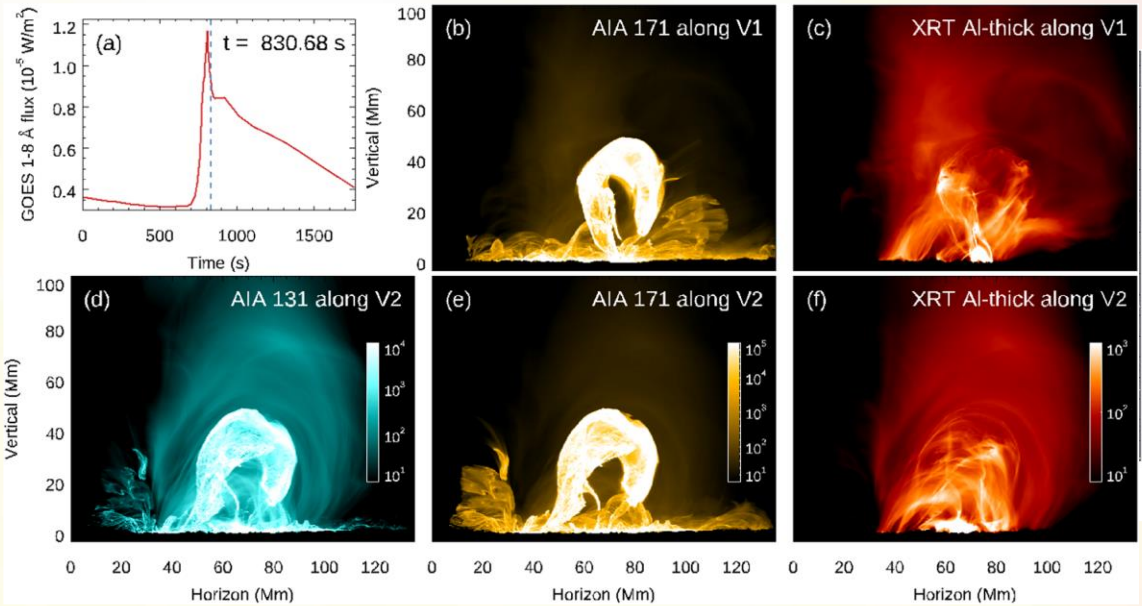
Hot plasma in a failed eruption (H. Q. Song et al 2014 ApJ 784 48)

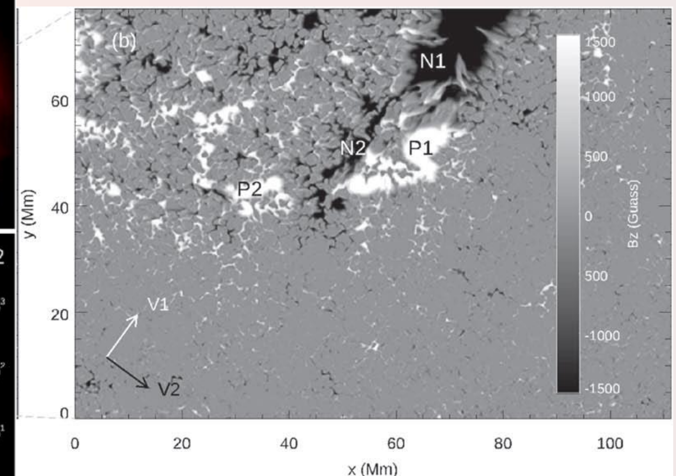


Temperature-time profiles of the high-lying flux rope (red) and the low-lying flare loops (blue), along with the profile of GOES soft X-ray 1–8 Å flux (black).

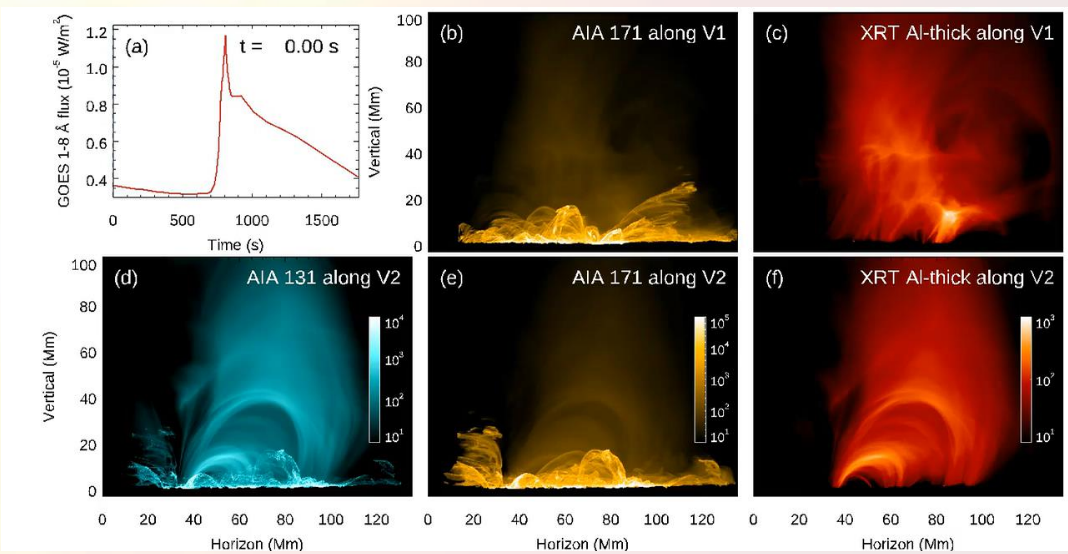
- The **failure of the eruption was caused by the strapping effect** of the overlying magnetic loop arcade , or the tension force of the line tying field.
- The failure of the eruption resulted in **less energy converted to the kinetic energy of the bulk plasma** from the released magnetic energy. Remained energy heat the flux rope trapped in the corona (**"fire ball" sitting in the corona for more than two hours**).
- The **flux rope should be heated directly** by the thermal energy generated at the reconnection site through the thermal conduction **without the chromospheric evaporation.**

Failed eruption & HXRs (Wang, C. et al. 2022, ApJL 933, 29)

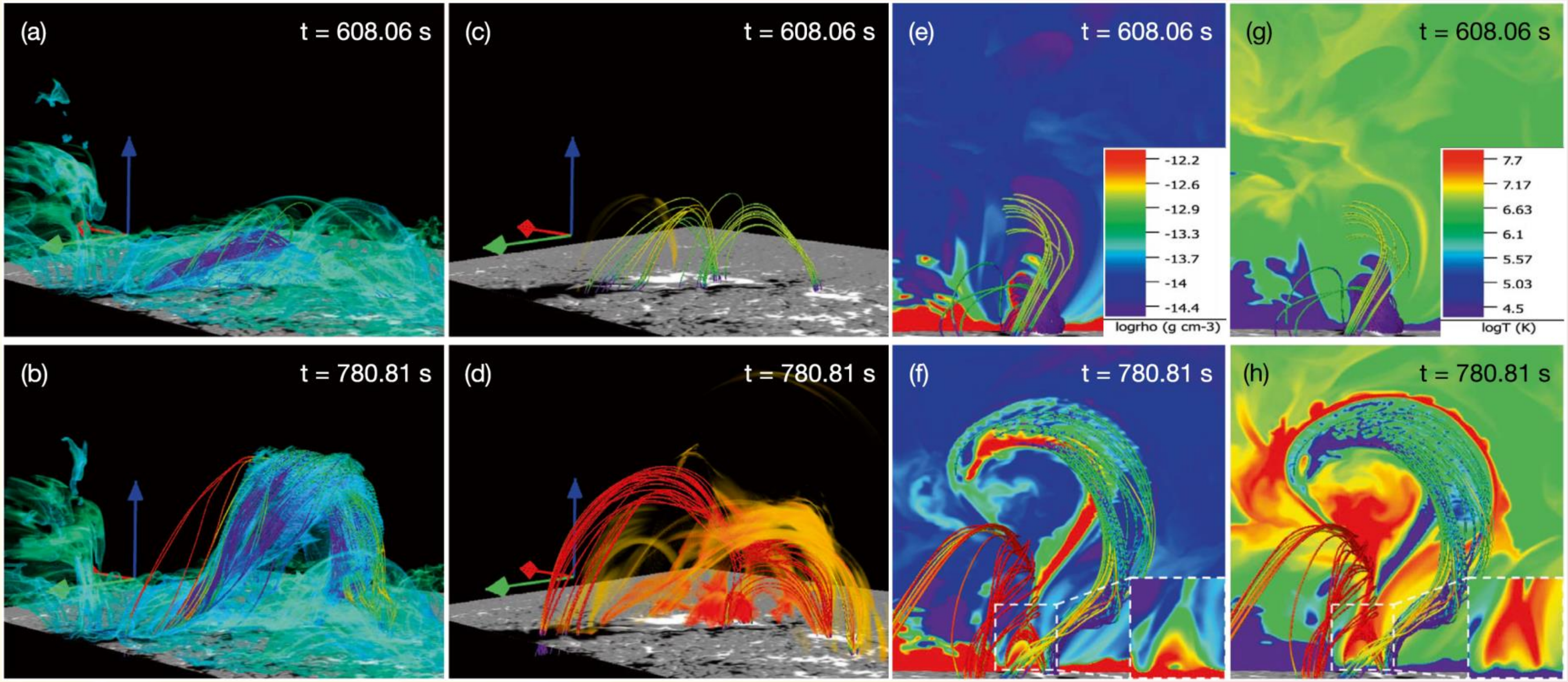




(a) Synthetic GOES 18 Å flux in the selected region. The blue dotted line indicates the time instance (t = 830.68 s) of the image shown in (b)–(f). (b) Synthetic AIA 171 Å image seen along V1 showing a rising bright arch. (c) Synthetic XRT Al-thick image seen along V1, showing a bright semicircular structure under the arch in (c). (d) Synthetic AIA 131 Å image seen along V2. (e) Similar to (b) but along V2. (f) Similar to (c) but along V2.

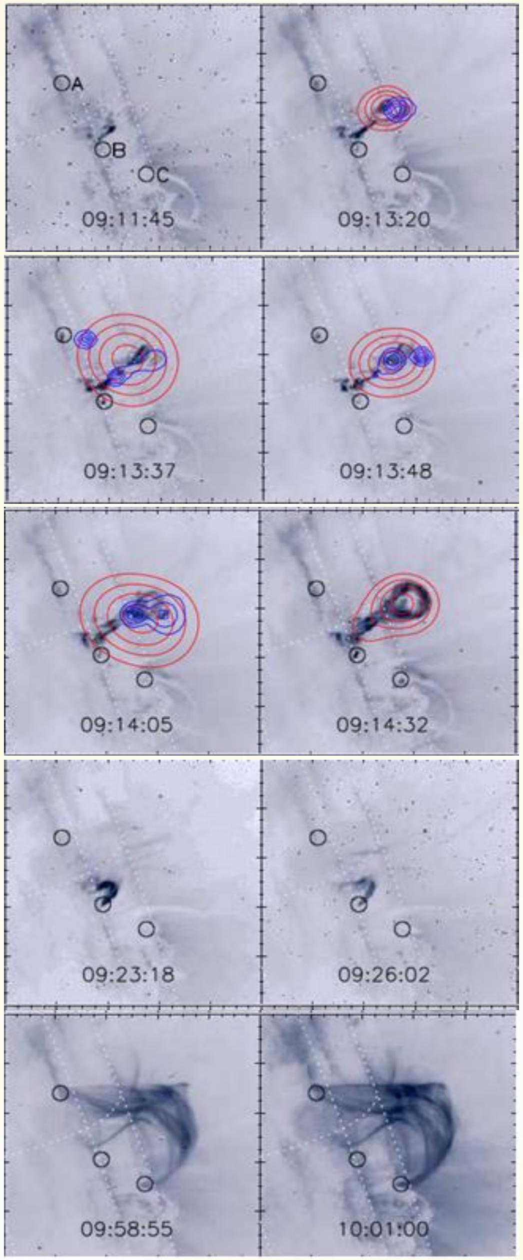


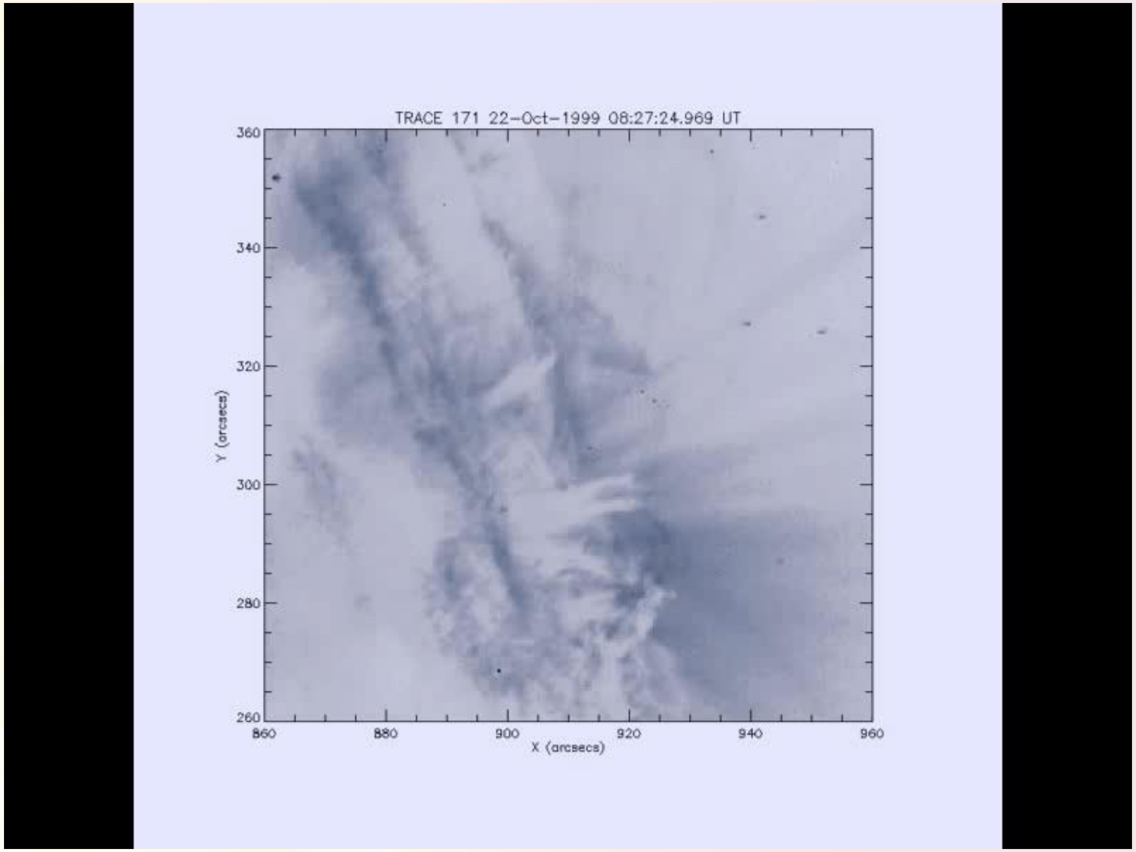
Failed eruption & HXRs (Wang, C. et al. 2022, ApJL 933, 29)



- Overplotted are selected magnetic field lines characterizing the event (flux rope in purple, low-lying arcades in yellow, and reconnected lines in red).
- (a)-(b) EM in the temperature range of 0.03–1 MK
- (c)-(d) EM in the temperature range of more than 10 MK
- (e)-(f) Distribution of plasma density on the selected slice
- (g)-(h) Distribution of plasma temperature on the selected slice.
- **The plasmas with the highest temperature of more than 10 MK mainly appear at the current sheet below the flux loop, the current shell around it, and the postflare loops.**

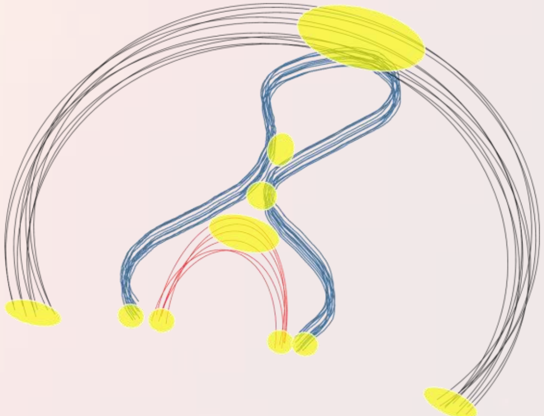
Failed eruption & HXRs (Netzel, A. et al. 2012, A&A 548, id.A89)



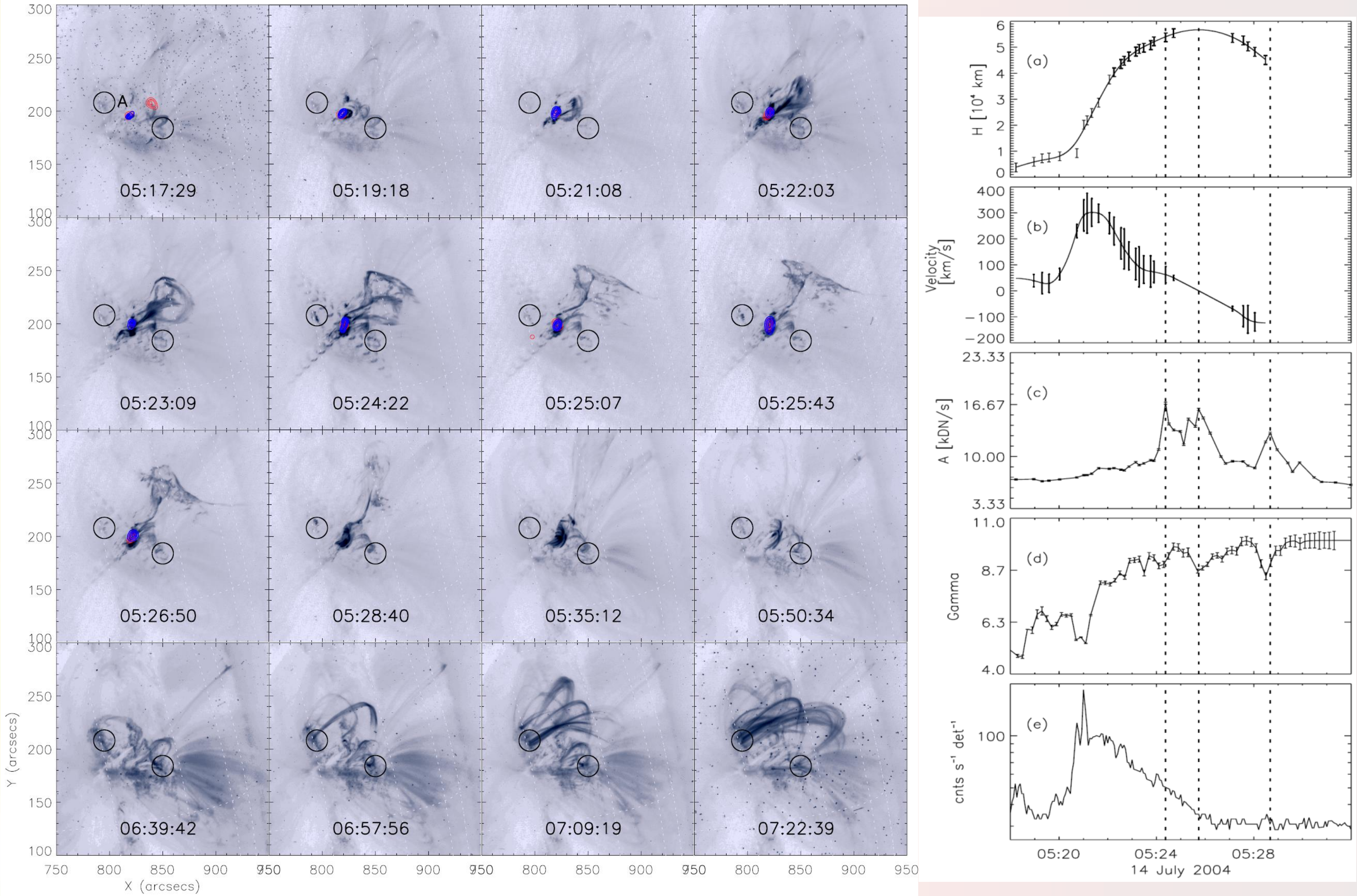


Possible HXR sources produced during the eruption:

- Footpoints of overlying magnetic structures
- Eruption's front interacting with overlying magnetic field

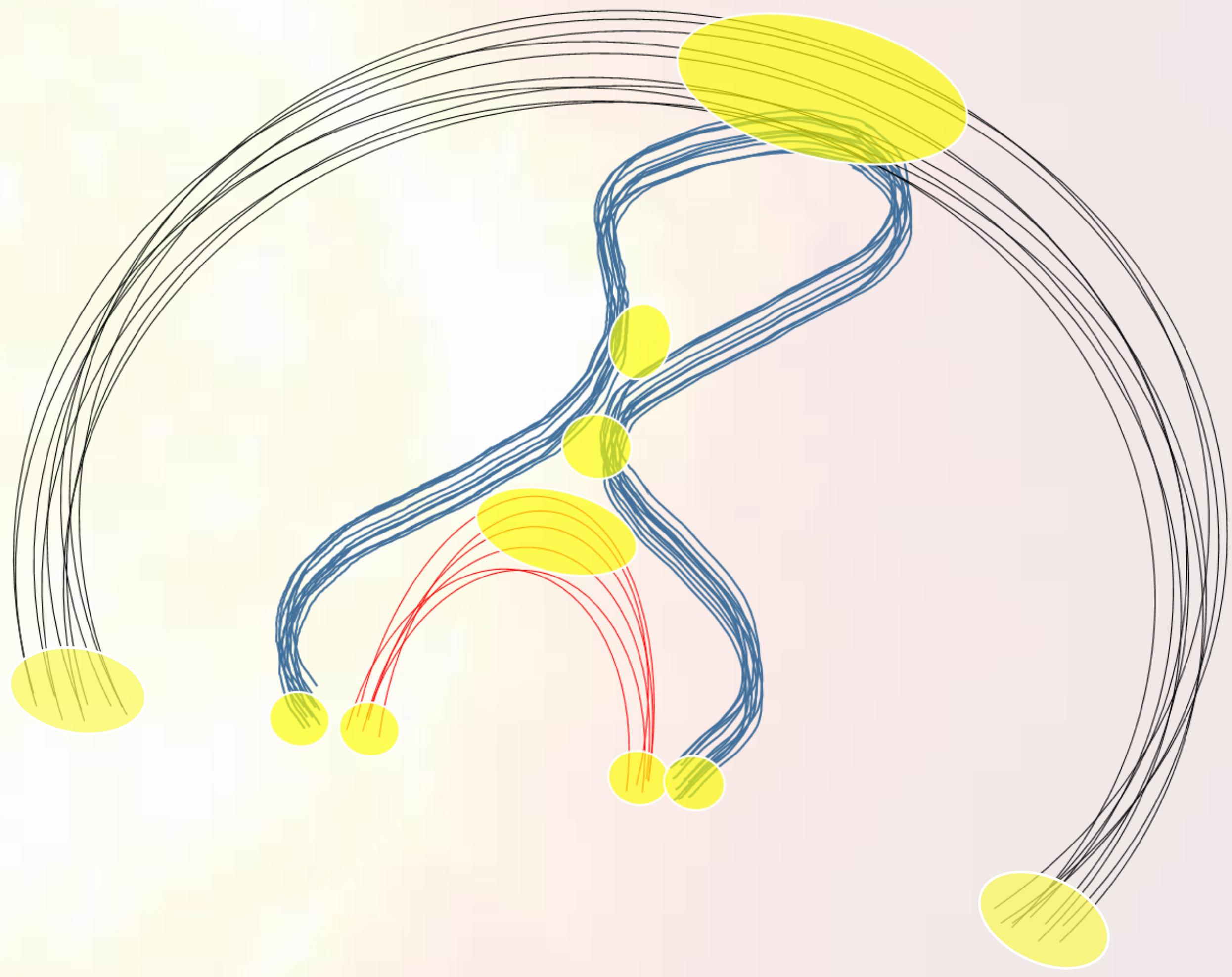


Failed eruption & HXRs (Netzel, A. et al. 2012, A&A 548, id.A89)



Can STIX show us such sources?

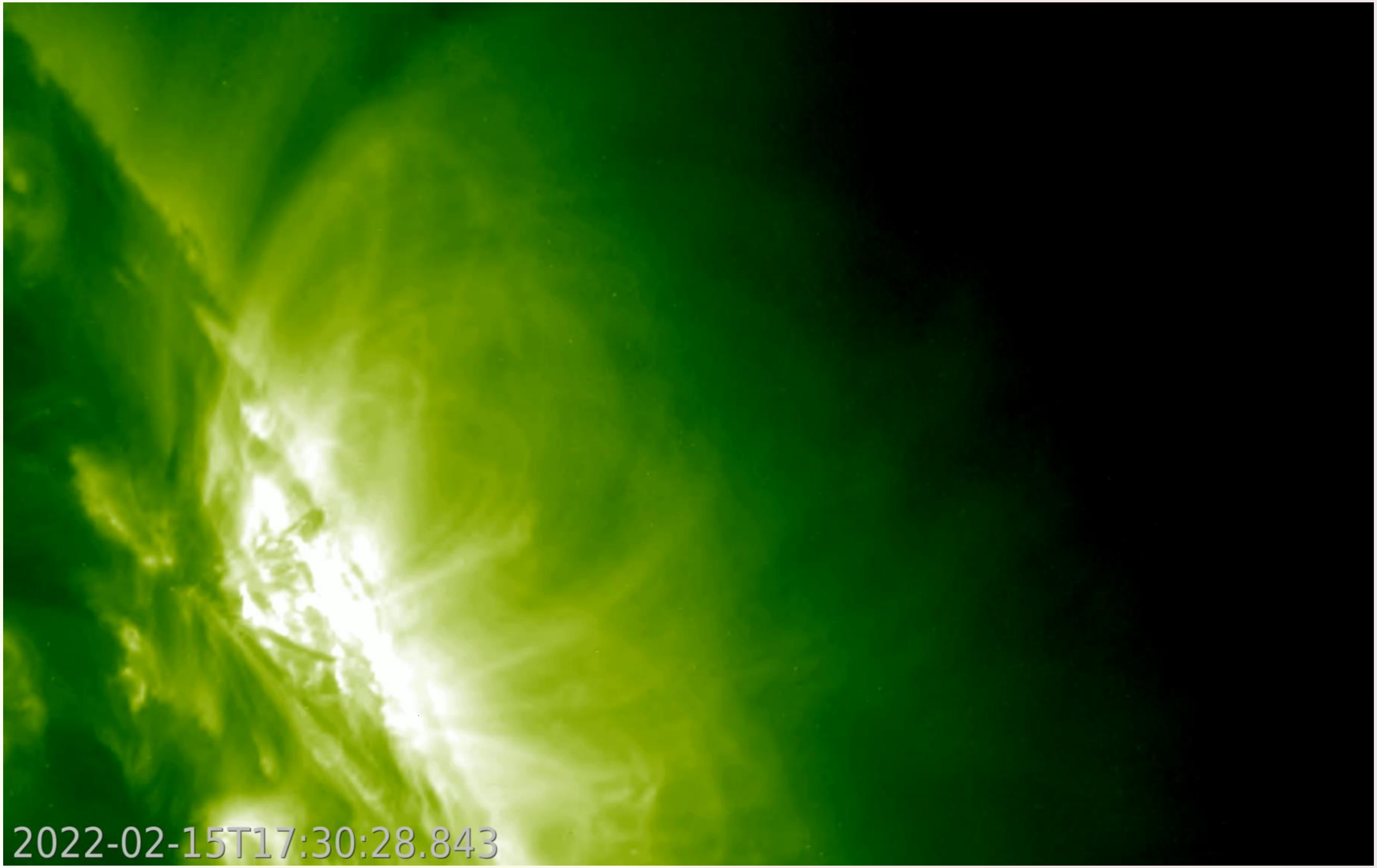
- Hot plasma appear at the **current sheet below the flux loop, the current shell around it, and the postflare loops** .
- The failure of the eruption resulted in less energy converted to the kinetic energy of the bulk plasma. **Remained energy heat the flux rope trapped in the corona producing source visible for more than two hours.**
- The **flux rope should be heated directly** by the thermal energy generated at the reconnection site through the thermal conduction without the chromospheric evaporation.



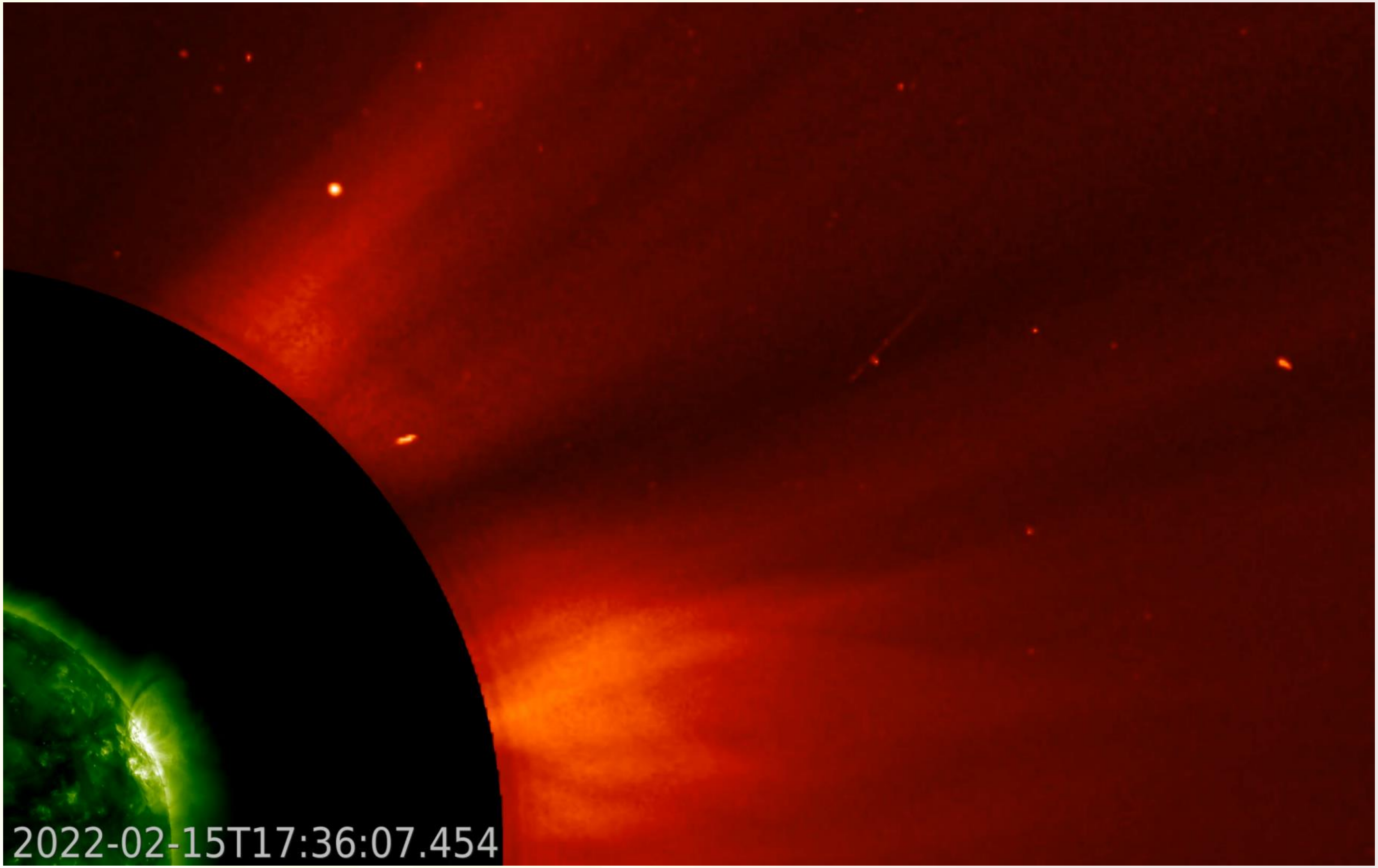
Failed eruption (SO perspective), 131 Å (hot structures)

STIX perspective (6-10 keV)

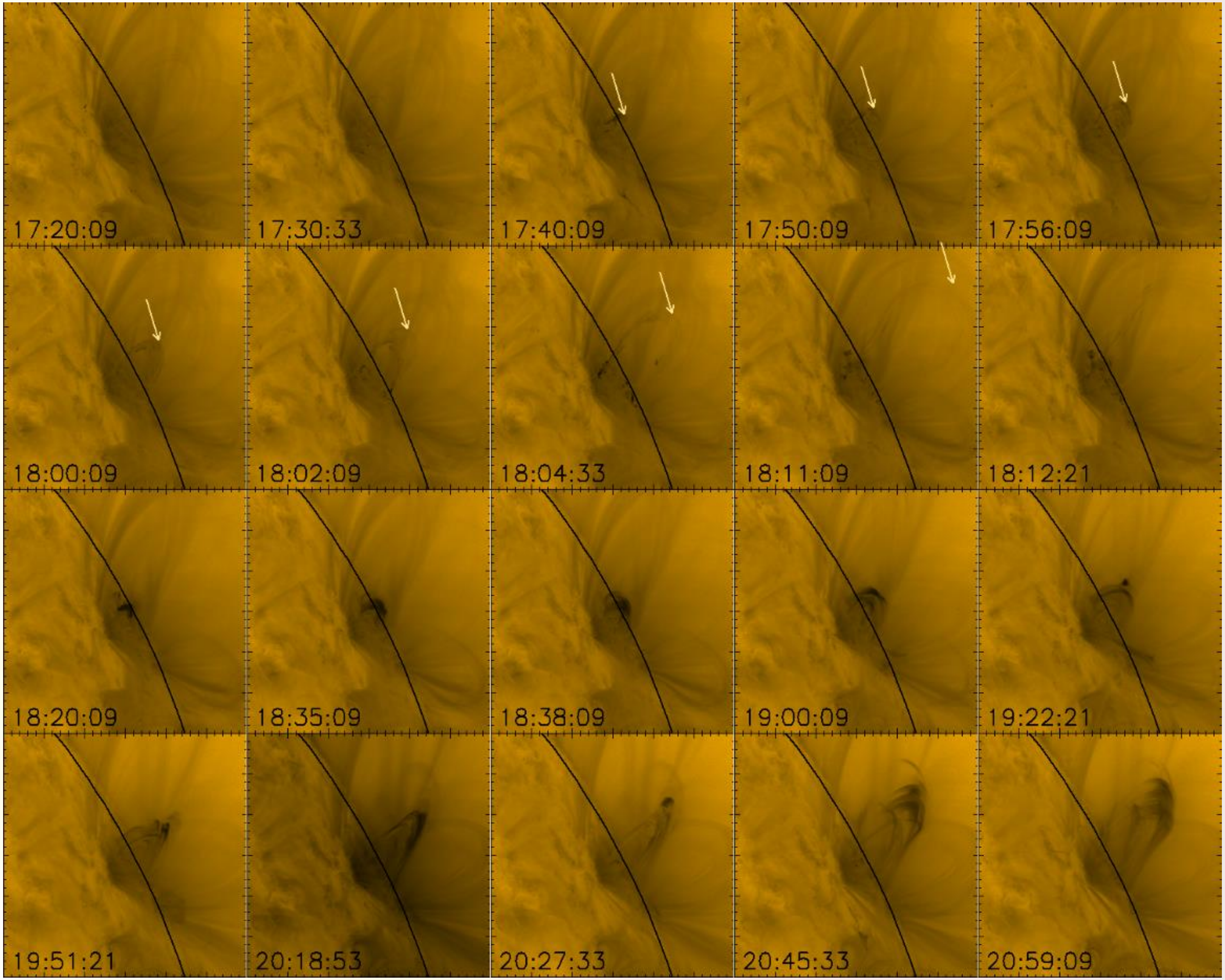
Failed eruption (SDO/AIA perspective), 193 Å, 17:30 – 22:00 UT



Failed eruption (SO+SOHO perspective)



Evolution



17:20:09
17:30:33
17:40:09
17:50:09
17:56:09
18:00:09
18:02:09
18:04:33
18:11:09
18:12:21
18:20:09
18:35:09
18:38:09
19:00:09
19:22:21
19:51:21
20:18:53
20:27:33
20:45:33
20:59:09

EUI perspective (174 Å, 17:20 – 20:36 UT)