The height evolution and distribution of double-source X-ray emission during the flare on August 28 2022

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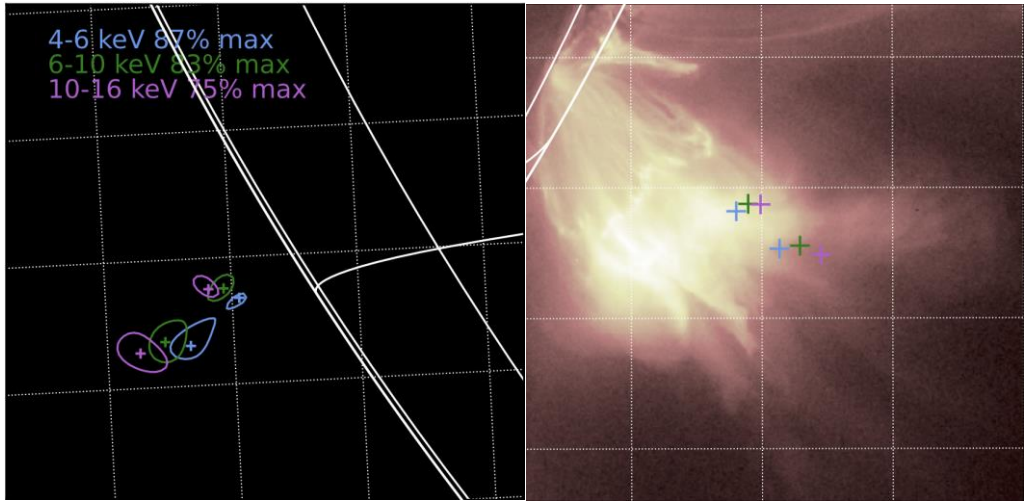
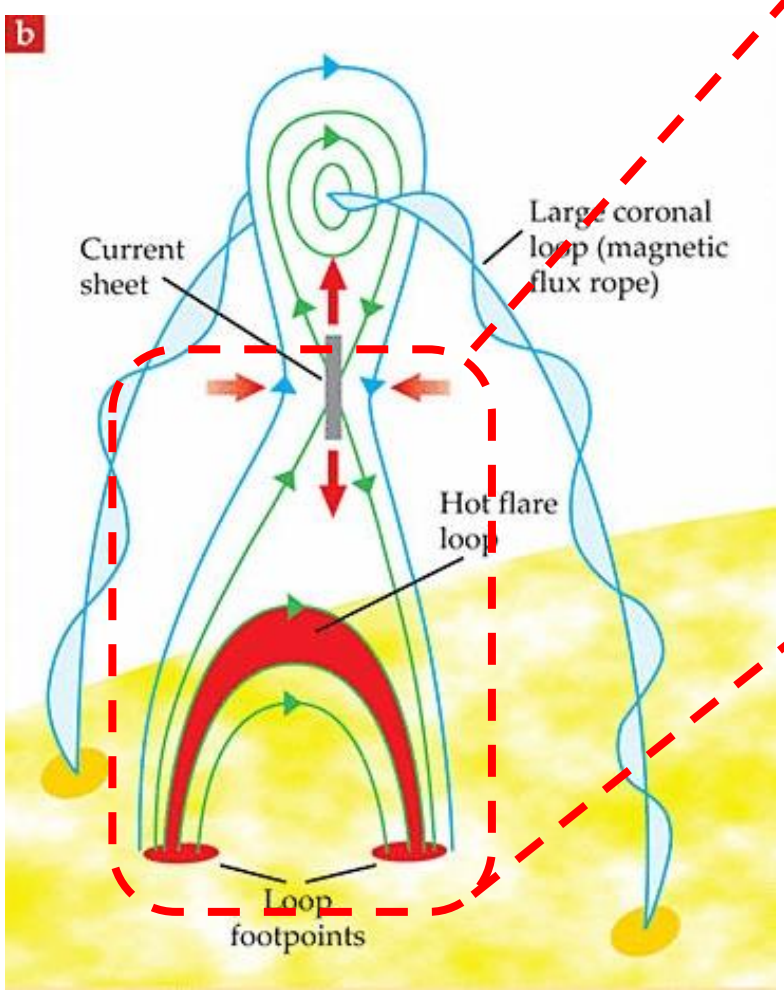


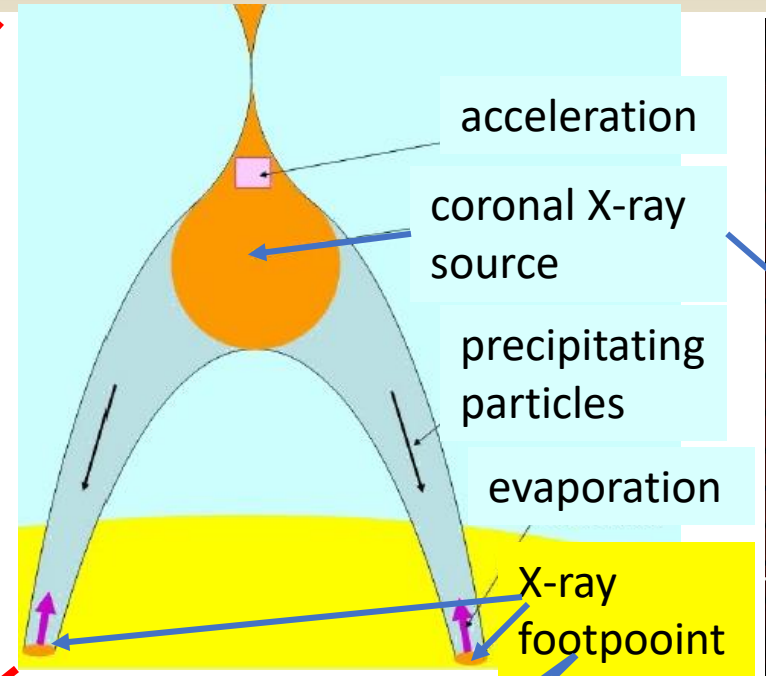
Outline

- Background
- Instruments and Methods
- Flare on August 28th , 2022
  - Event overview
  - X-ray source height estimation
  - the nature of the source
- Summary and the next step
- Some problems to discuss

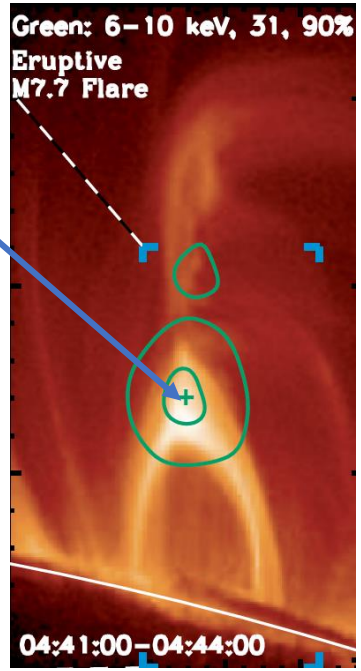
Reconnection, current sheet



Holman 2012

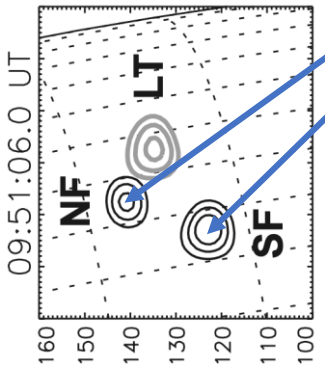


Benz 2017



Liu 2013

double-source:
Loop-top (LP) &
Above-loop-top (ALP)

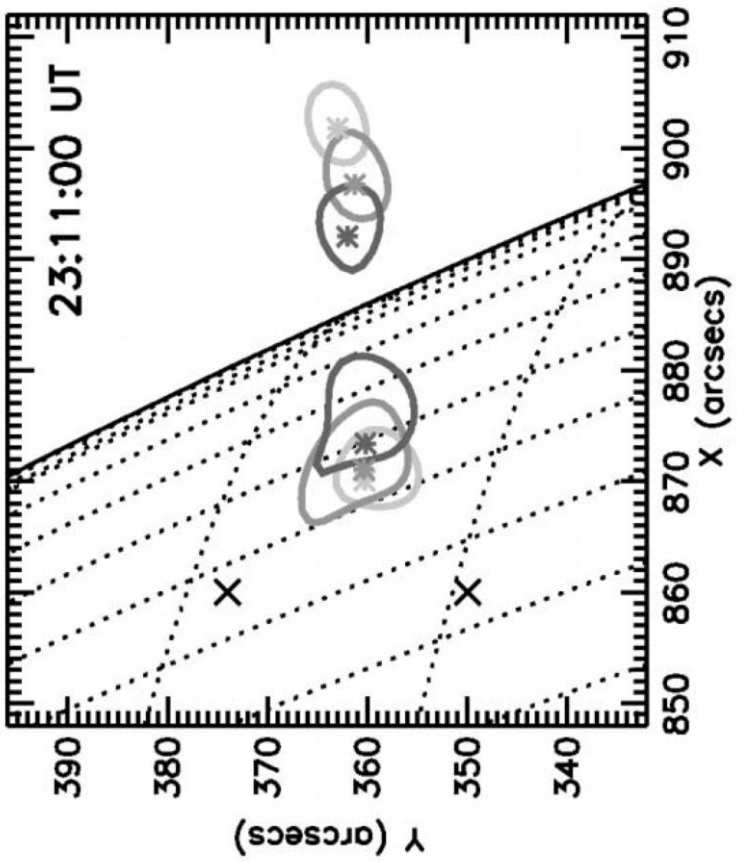


Veronig 2006

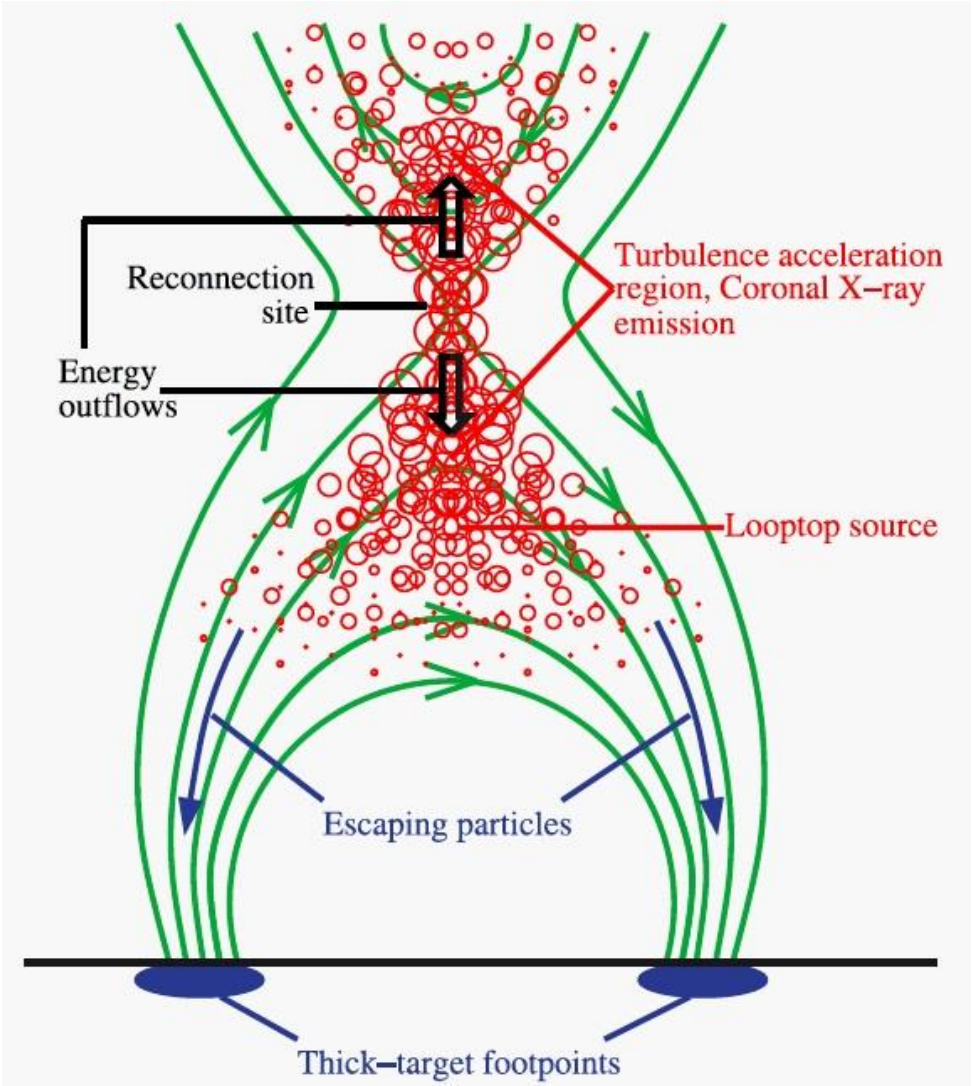
- HXR (and sometimes γ-ray) sources:
  - at two footpoints of the newly reconnected magnetic loops via bremsstrahlung.
  - **at or above the top** of bright EUV/SXR flare arcades *(Masuda et al. 1994; Veronig et al. 2006; Krucker & Battaglia 2014).*

Double-source/LP and ALP

contour line shade from light to dark
6–8, 10–12, and 16–20 keV



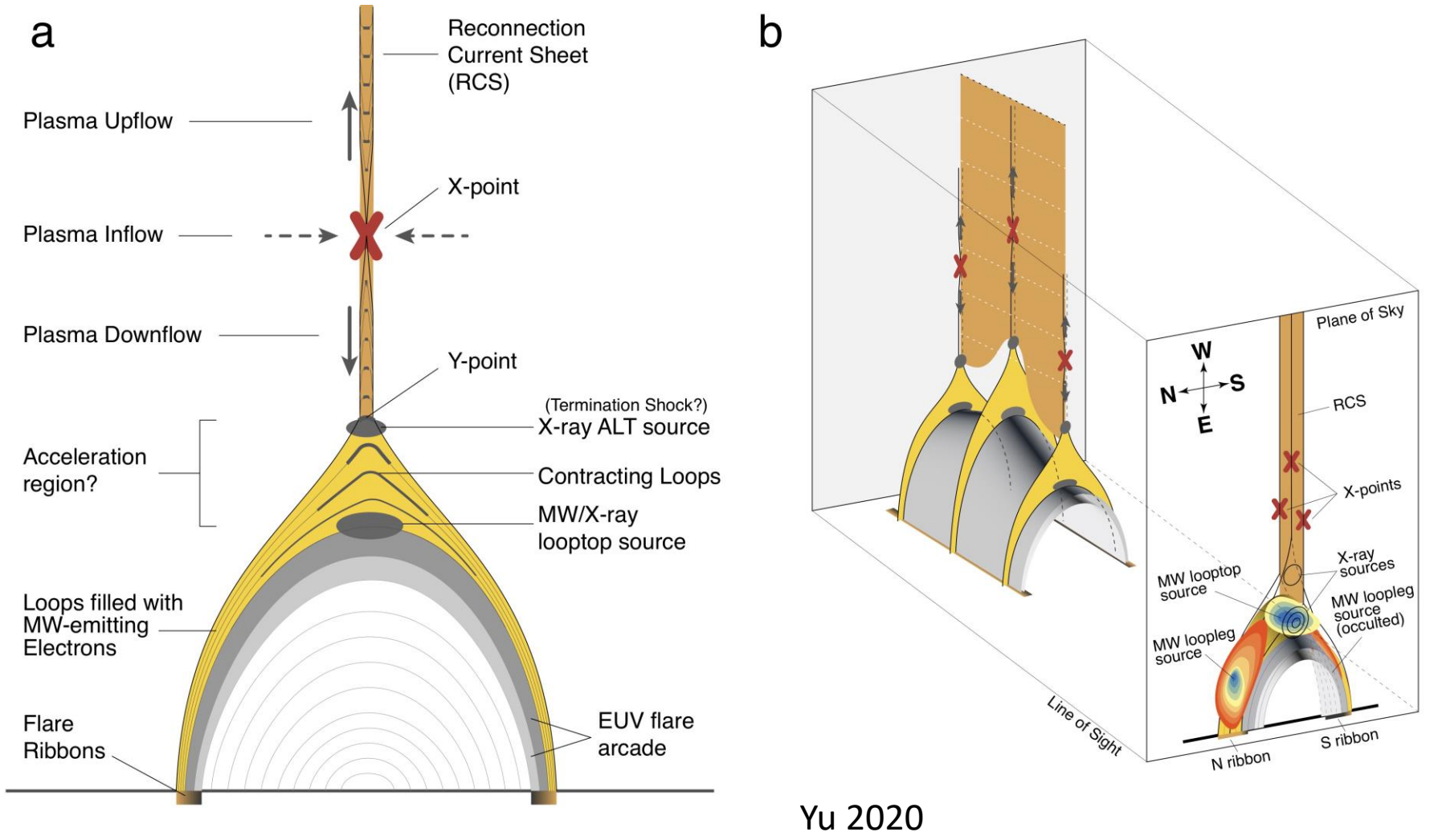
Sui 2003



Liu 2008

- Explanation 1: the bremsstrahlung at another side of the reconnection site.

Double-source/LP and ALP



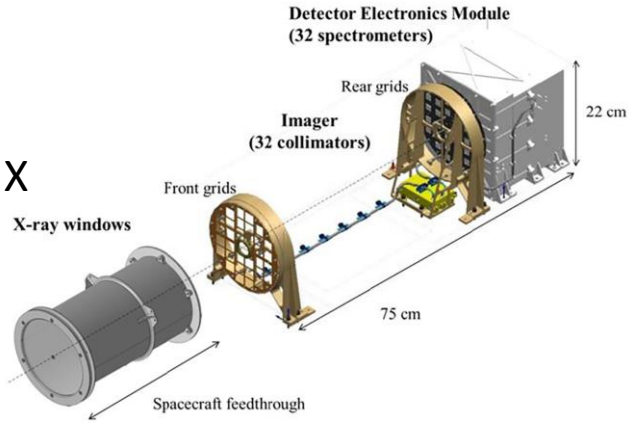
Yu 2020

- Explanation 1: the bremsstrahlung at another side of the reconnection sight.
- Explanation 2: emission from the termination shock, lying at the same side with the loop-top source

Instruments and Methods

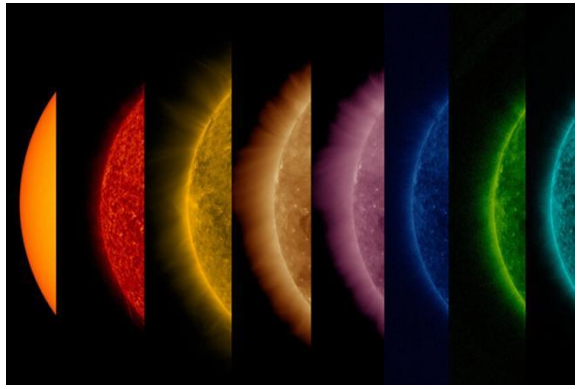
- Solar Orbiter (SolO/Spectrometer Telescope for Imaging X-rays (STIX): **for X-ray spectrum and imaging**
- Solar Dynamics Observatory (SDO)/Atmospheric Imaging Assembly (AIA): **for ultraviolet images**
- Other instruments: SolO/EUI (ultraviolet images), SOHO/LASCO (white-light coronagraph)

SolO/STIX

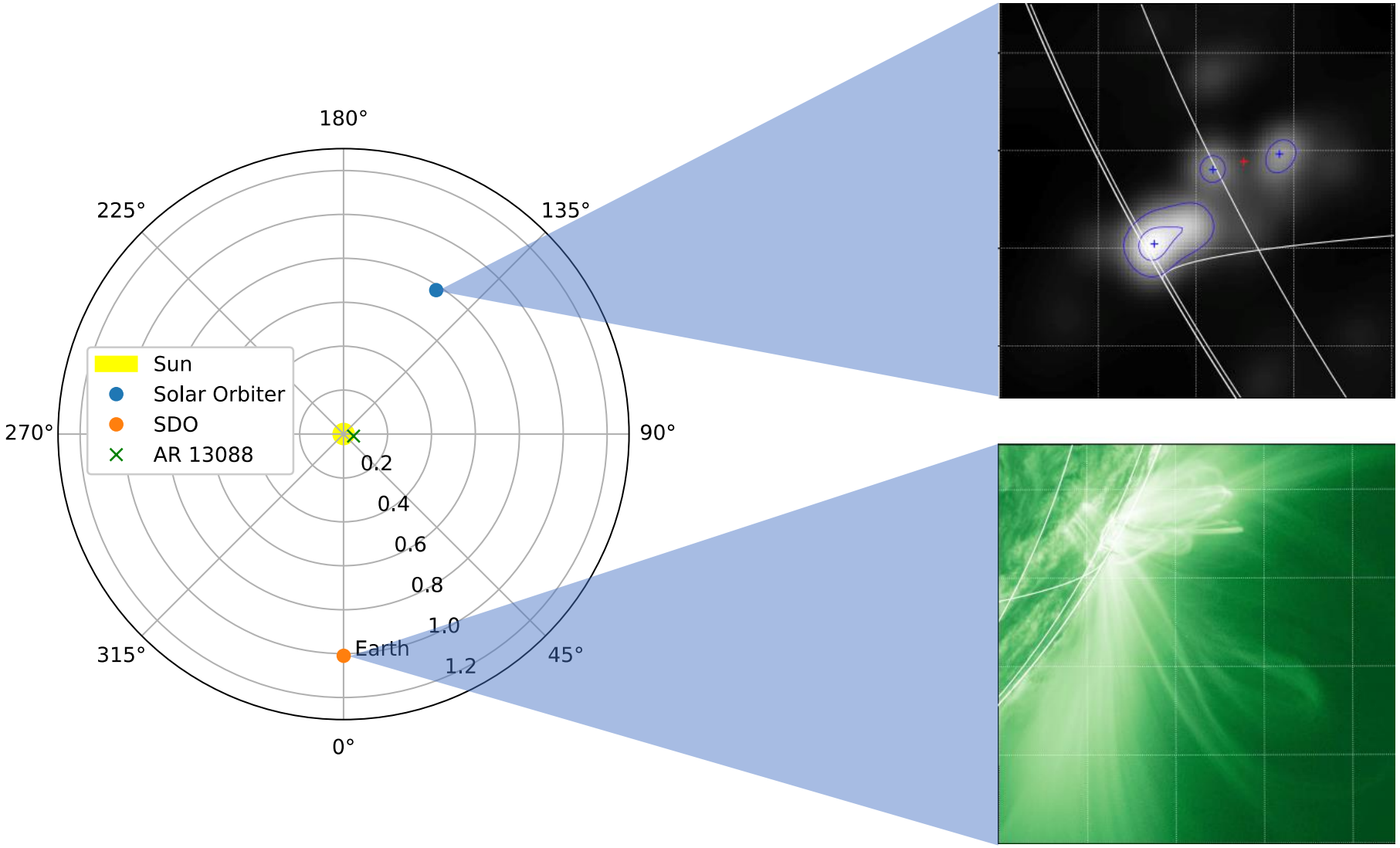


- Methods for X-ray imaging reconstruction:
  - CLEAN (Högbom 1974)
  - EM (Massa et al. 2019)
  - MEM_GE (Massa et al, 2020)
- Methods for obtaining thermal properties:
  - DEM (Su et al. 2018; Cheung et al. 2015)

SDO/AIA



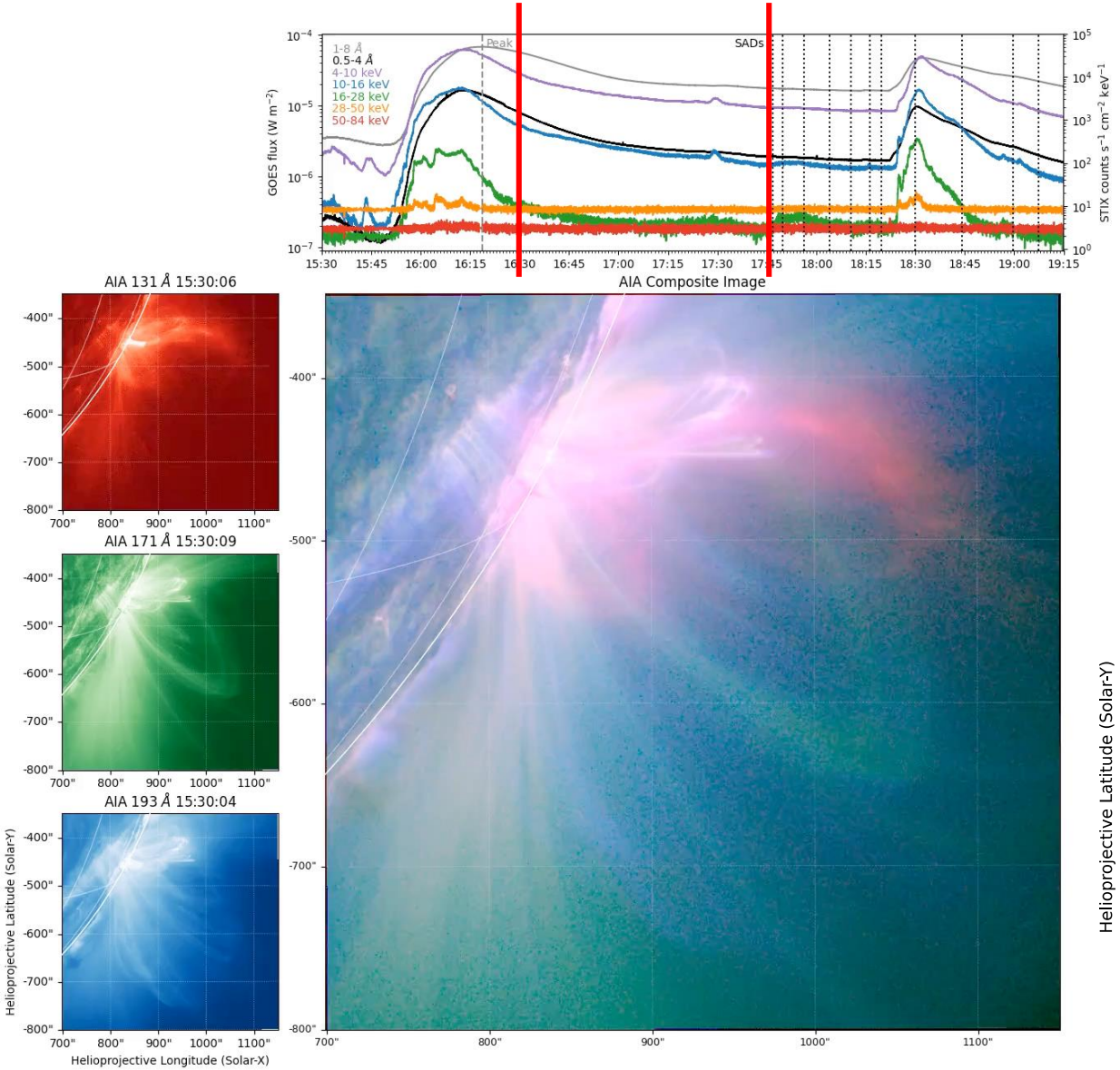
Flare on August 28th, 2022



SolO/STIX

SDO/AIA

Event Overview

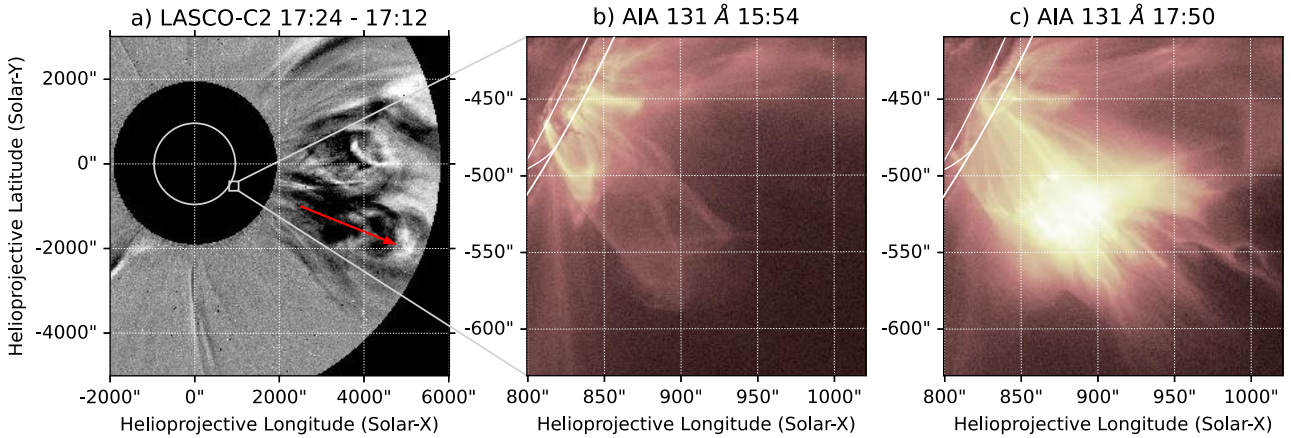


131, **171**, **193** and the **composite** image

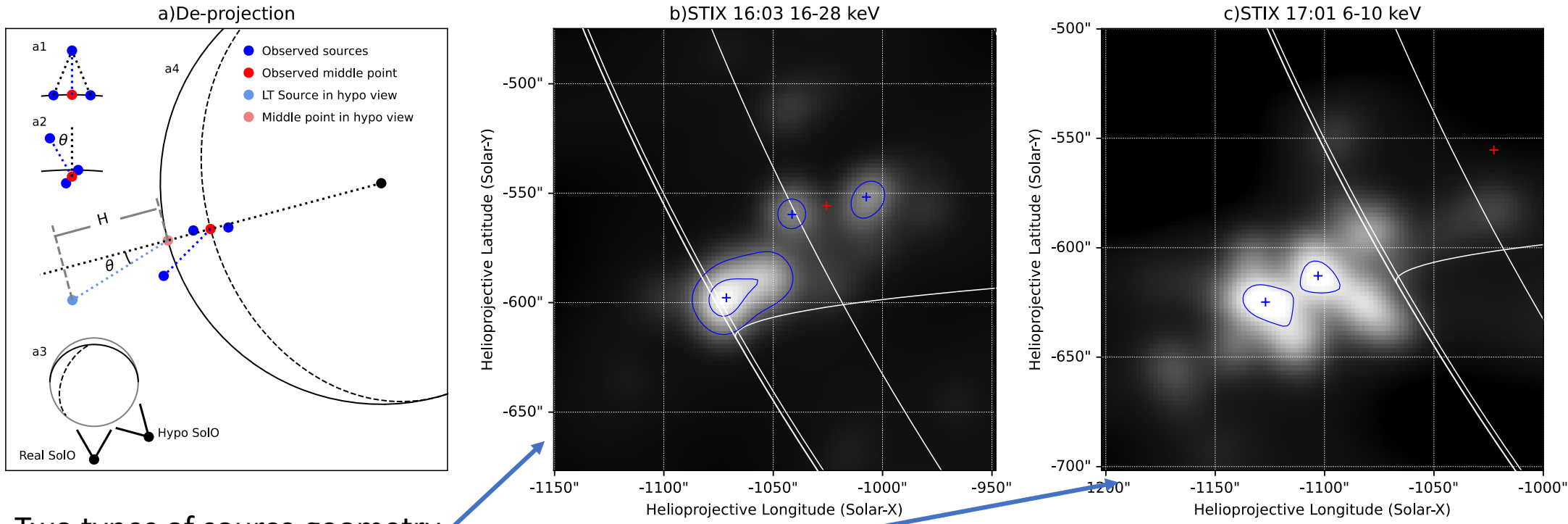
- **Impulsive phase: 15:50-16:30**
  - In 131, the erupted structure has crossed legs, likely to be a flux rope.
  - In 171 and 193, several loops (cold) enclose the 131 flux rope (hot).

- **The post-flare loops and the supra-arcade fan developed; it produced a CME: 16:30-17:45**
  - supra-arcade fan and spikes

- **A series of supra-arcade downflows: 17:45-19:15**



X-ray source height estimation



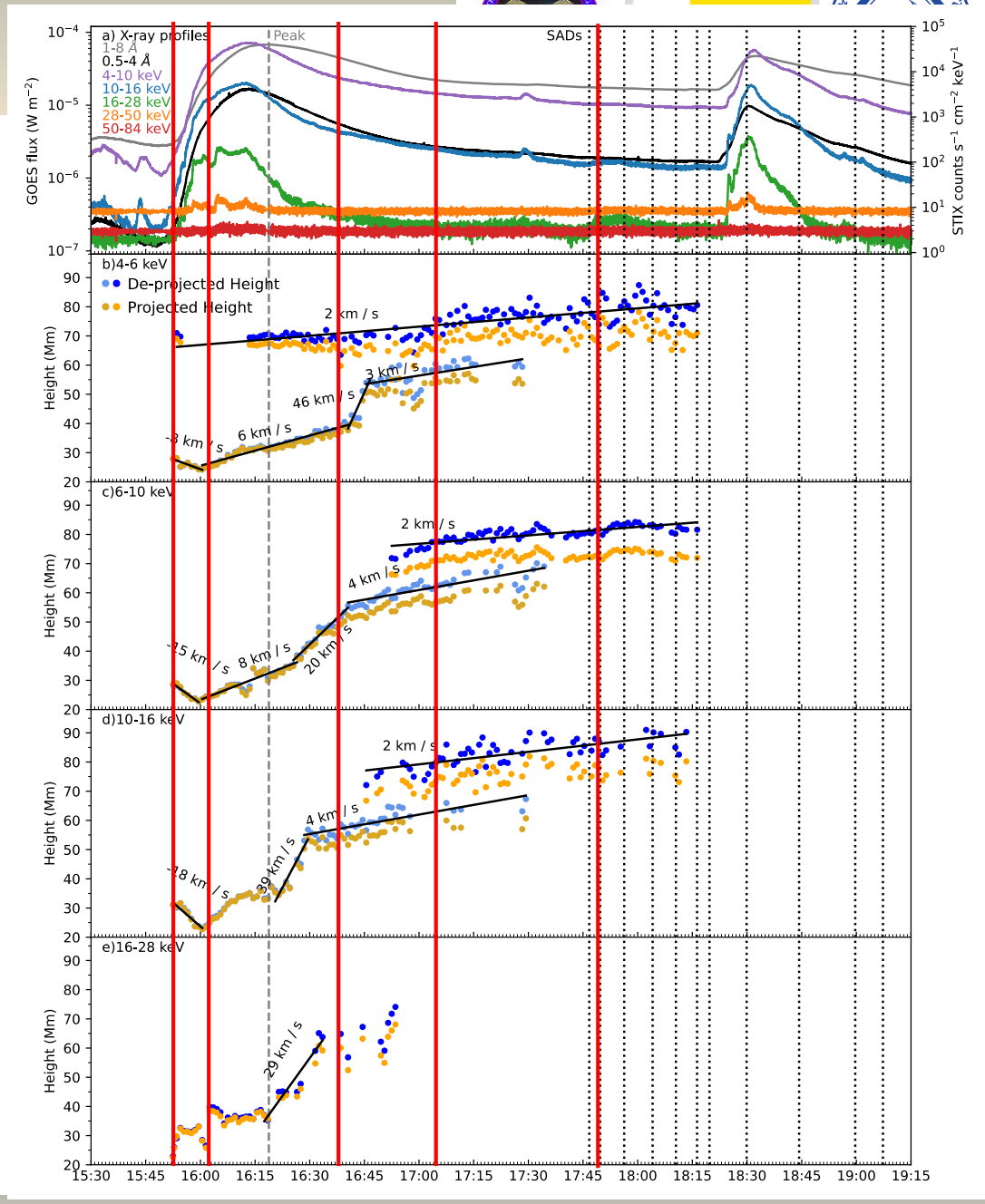
- Two types of source geometry
  - with footpoint sources
  - without footpoint sources
- Basic idea of estimating the height of the sources above the surface:
  - determine a base point at the solar surface
  - convert the distance between the base point & the above-surface source to an estimate height (based on several assumptions on source geometry)

h vs time

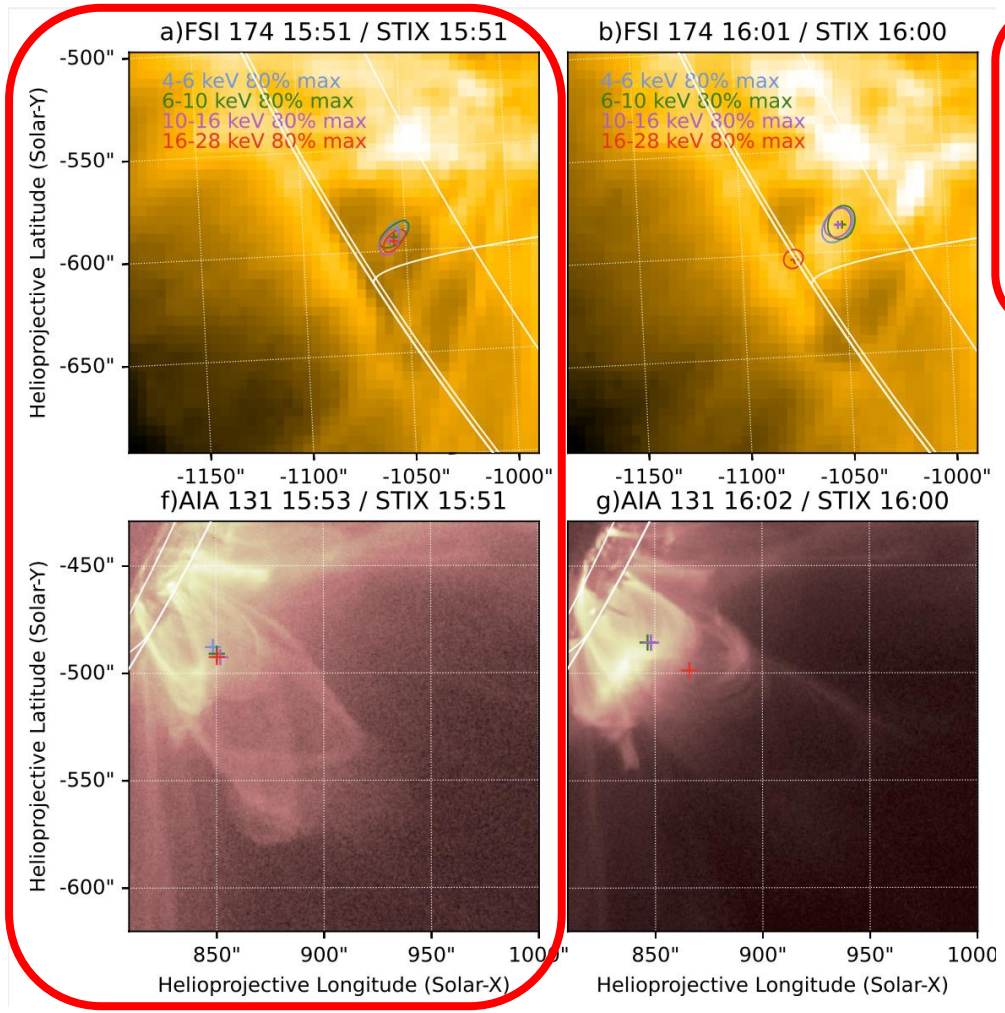
h vs energy

Height vs time

- General feature:
  - A long-term height trace of a double X-ray sources.
  - Multi-phase for the LT source: a pre-flare downward motion (except 16-28 keV); a gradual rise; a quick rise; a gradual rise.
  - The quick rise period started earlier in higher energy ranges.
  - Slowly rising of the ALT source: about 2 km s^{-1}.

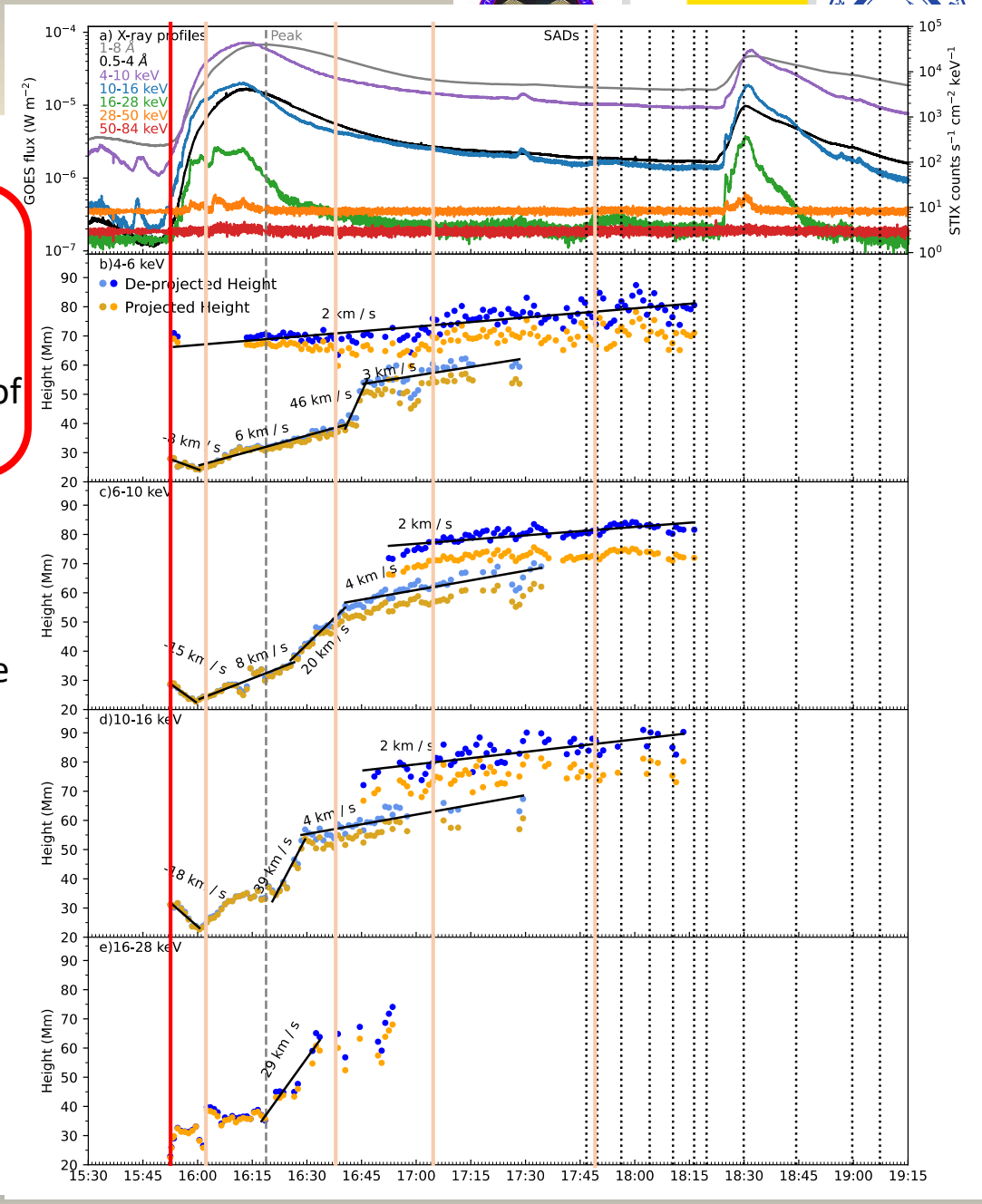


Height vs time: source evolution



- 15:51
- single source
- the same height
- 16-28 keV at the stem of the erupting flux rope

- 16:00
- still single source
- 16-28 keV rose with the erupting flux rope



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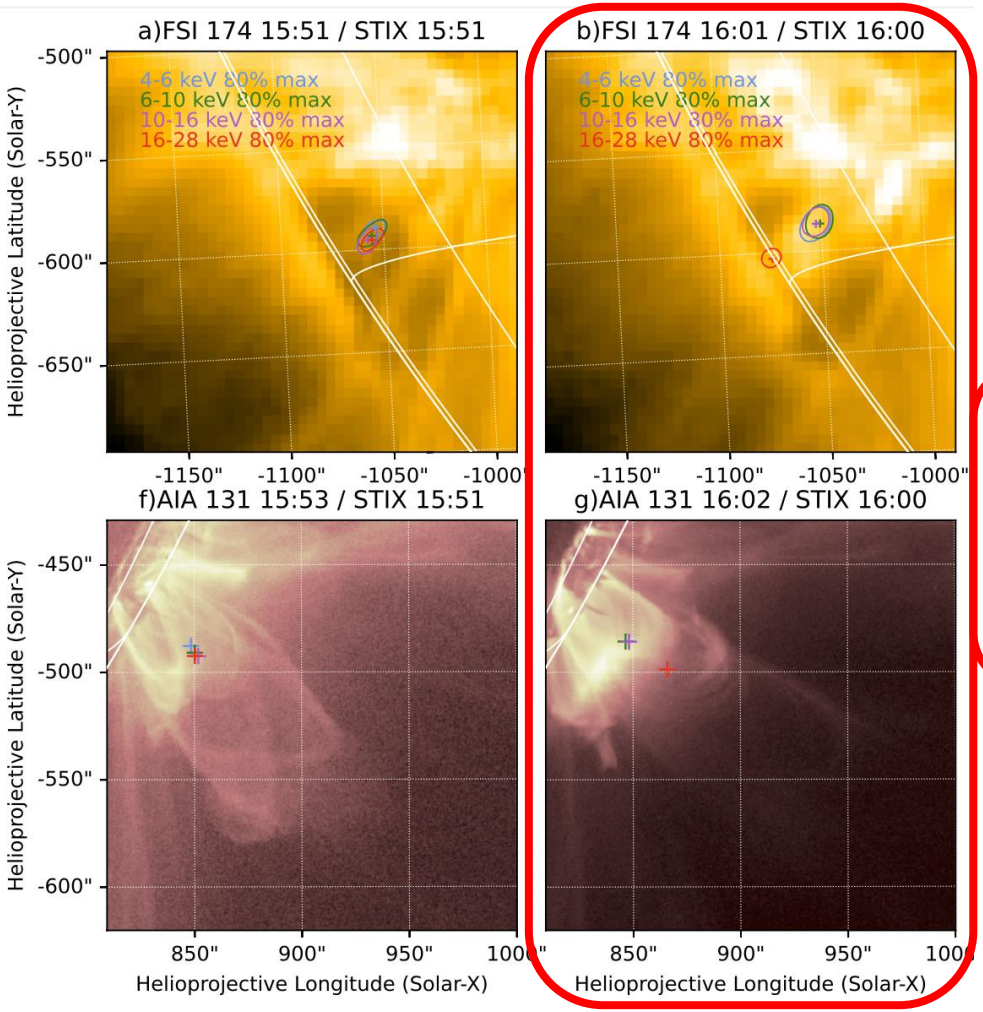

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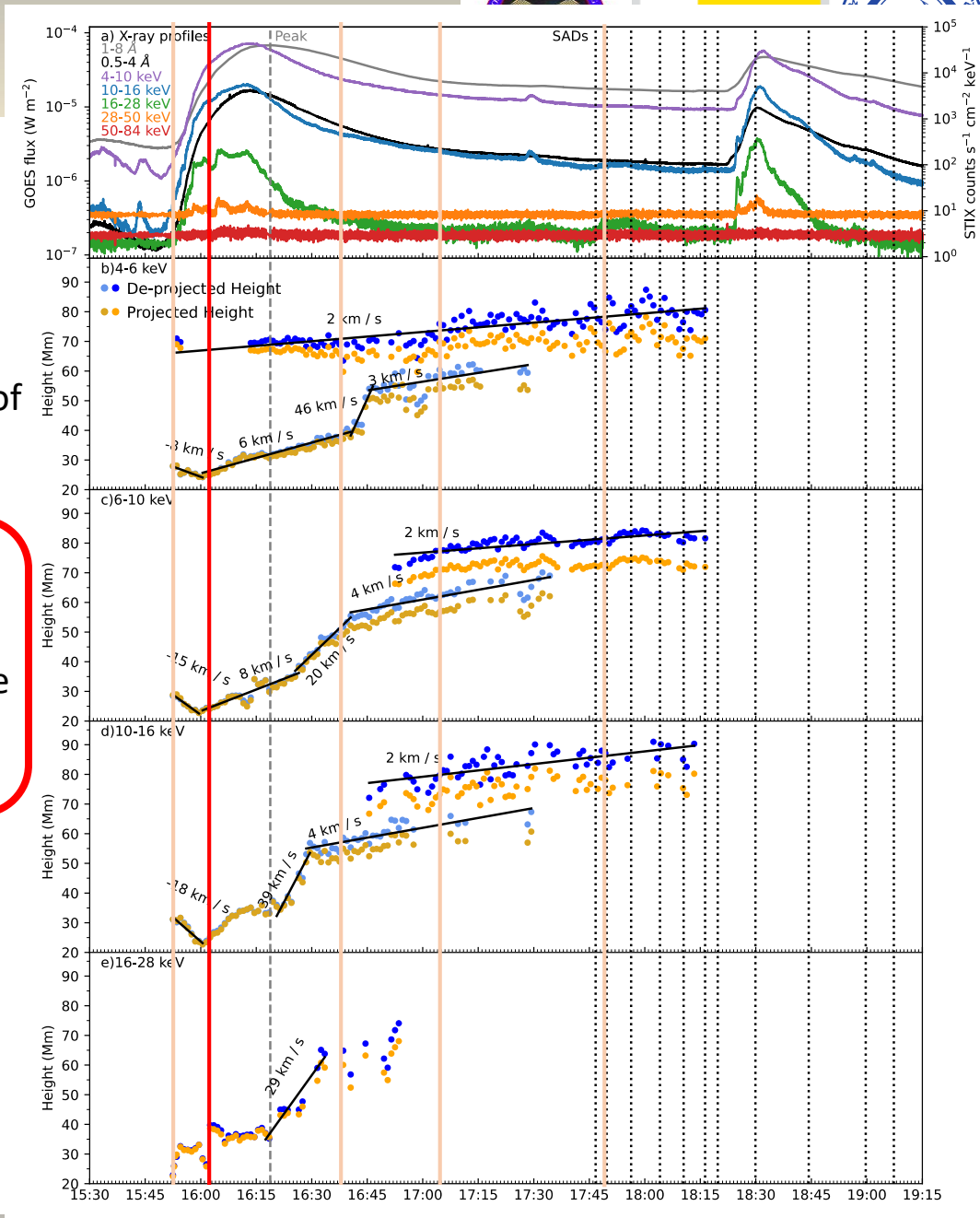

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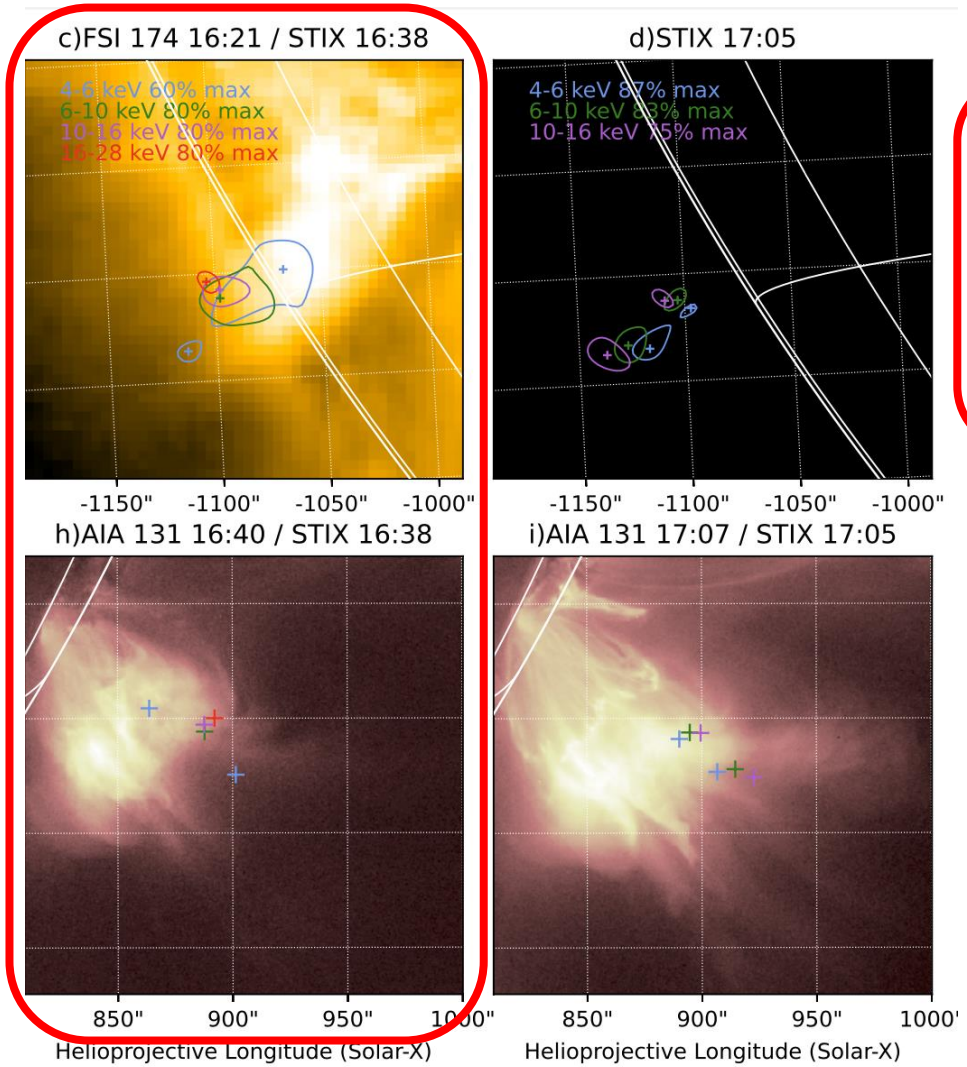
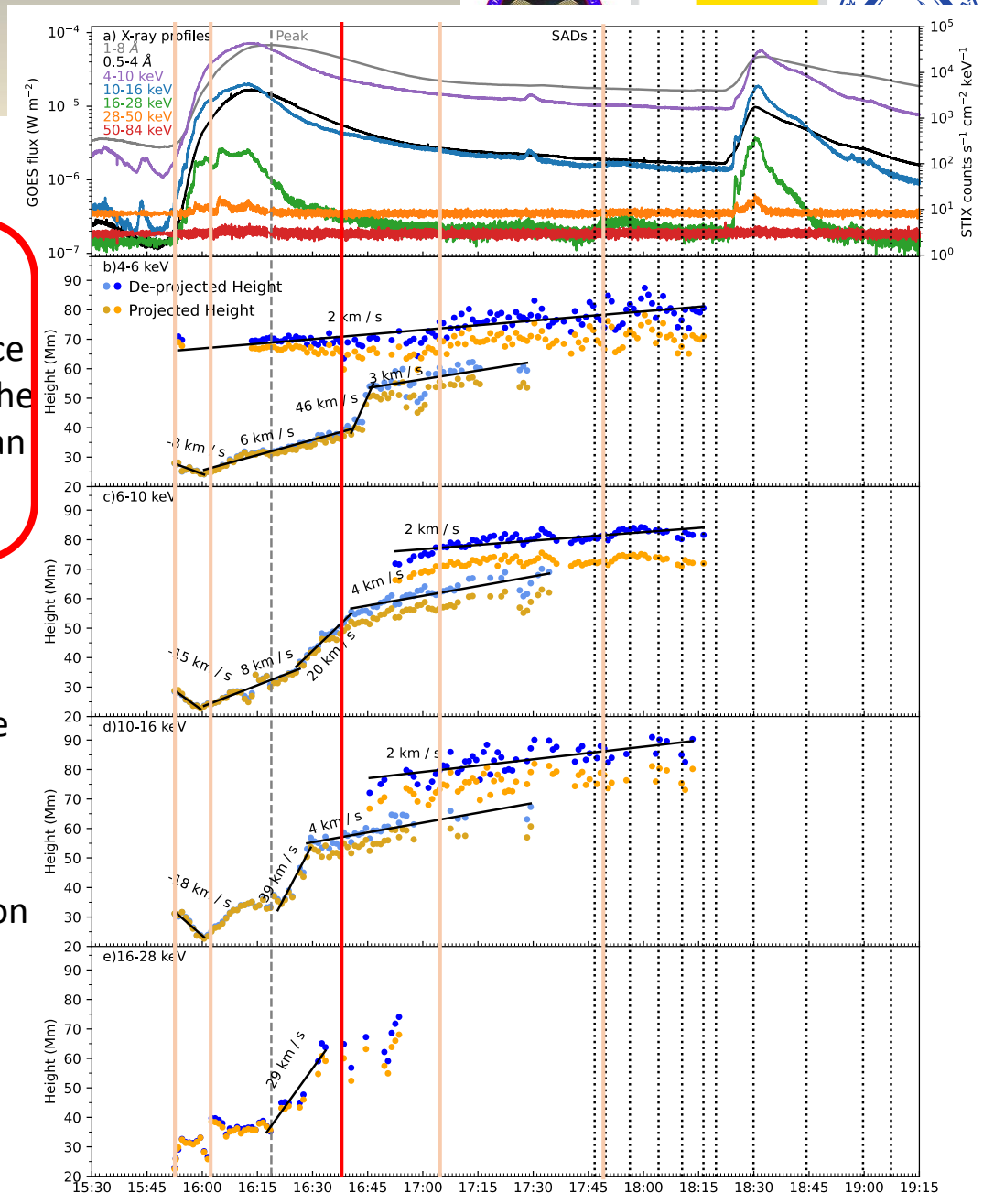


- 16:38
- 4-6 keV double source
- others, still single source
- 4-6 keV ALT source at the thinner supra-arcade fan region which shows “spikes”.

- 17:05
- double source for three low energy ranges
- 16-28 keV disappeared
- source with higher energy in higher location
- LT sources at dense supra-arcade fan
- ALT sources at thinner supra-arcade spikes



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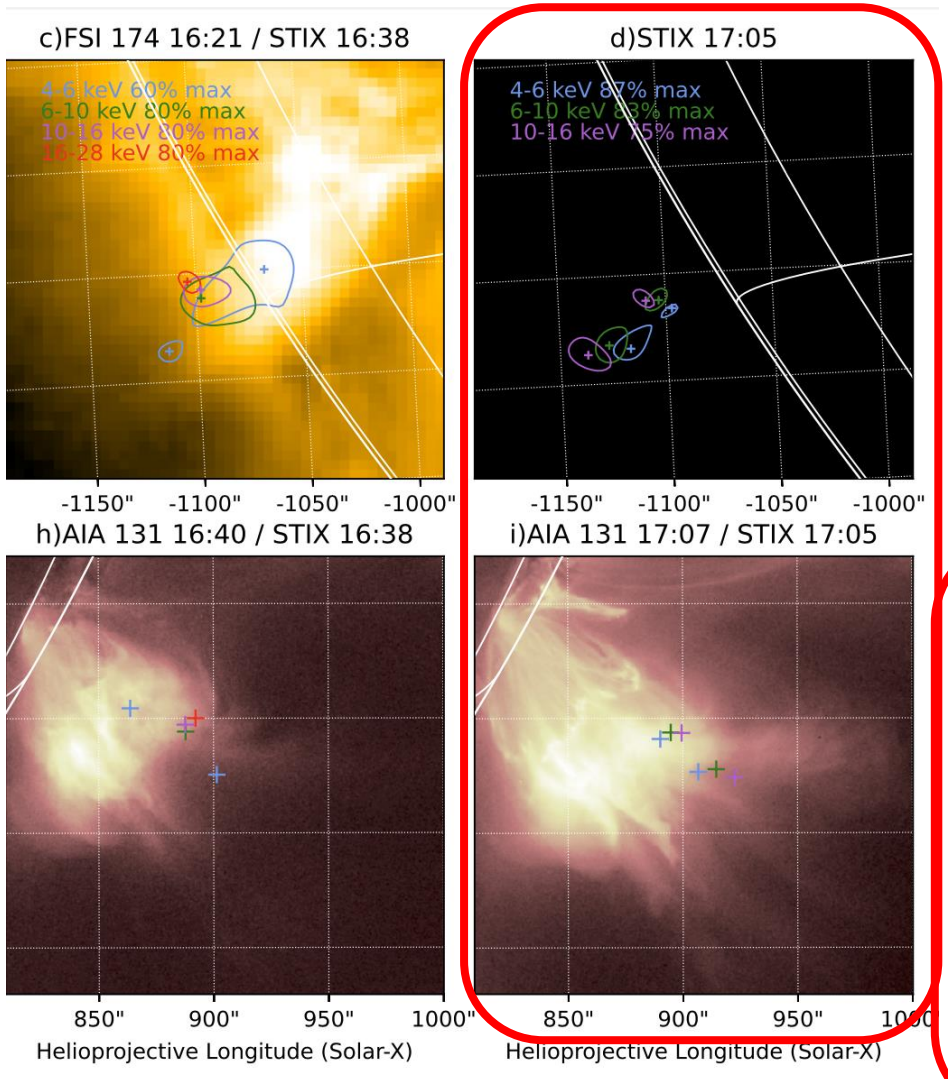
Height vs time: source evolution



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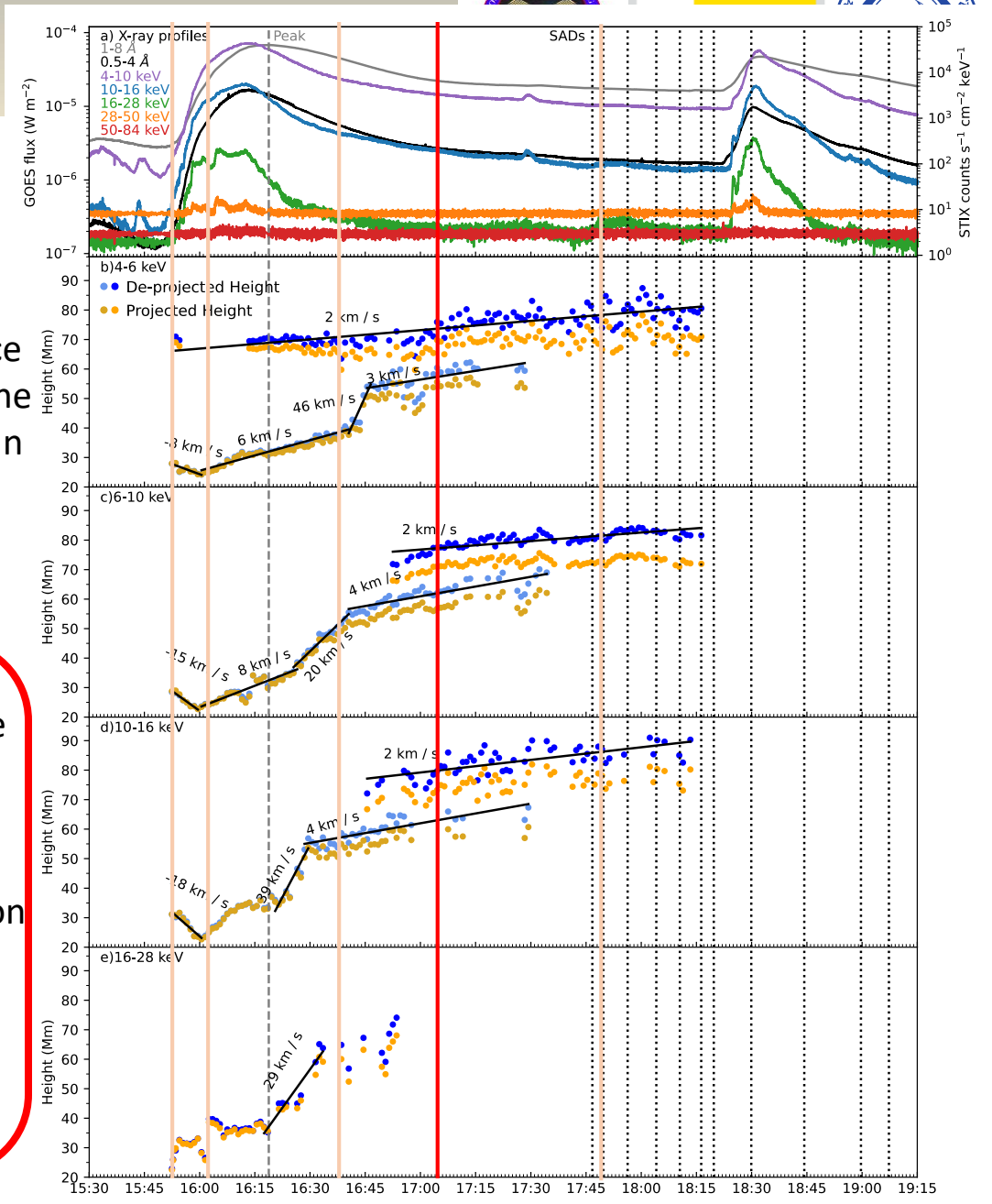

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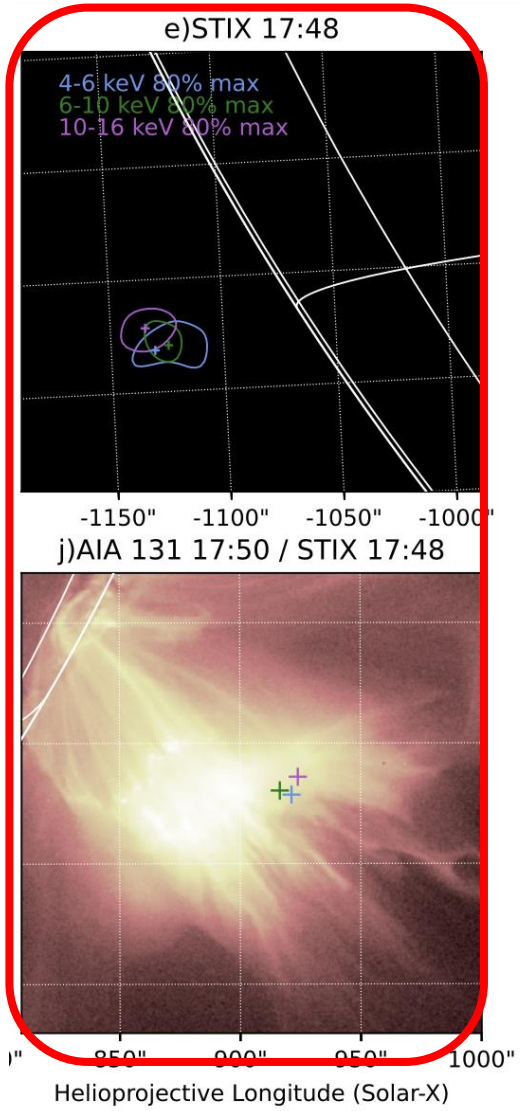
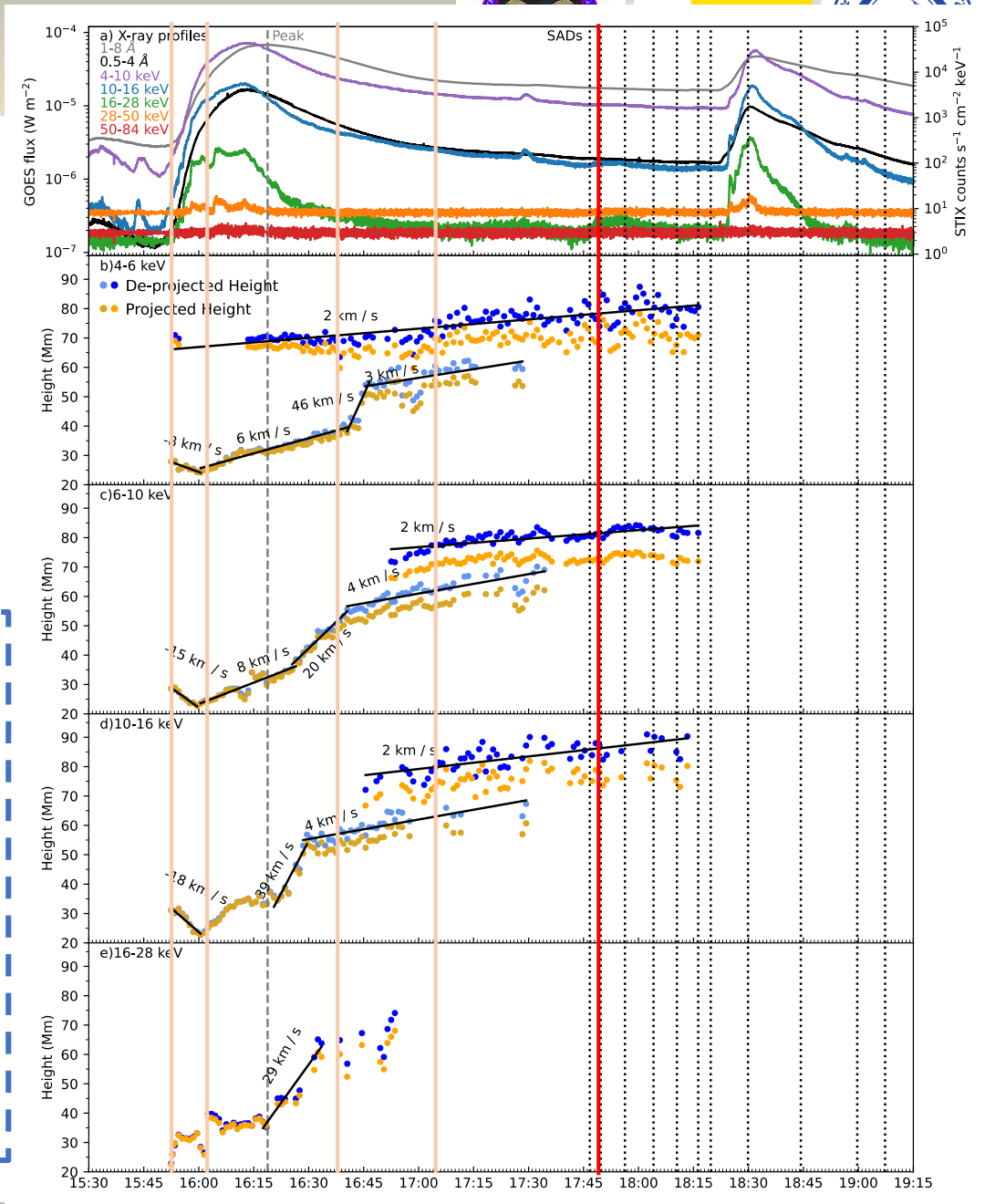
Height vs time: source evolution



- 17:48
- the LT sources disappeared
- ALT at the region where the supra-arcade and the spikes meet

A brief summary of source evolution:

- In early period, the 16-28 keV source looks more related with the erupting flux rope.
- The sources in three low energy ranges are more connected to the hot supra-arcade fan as well as the spikes.



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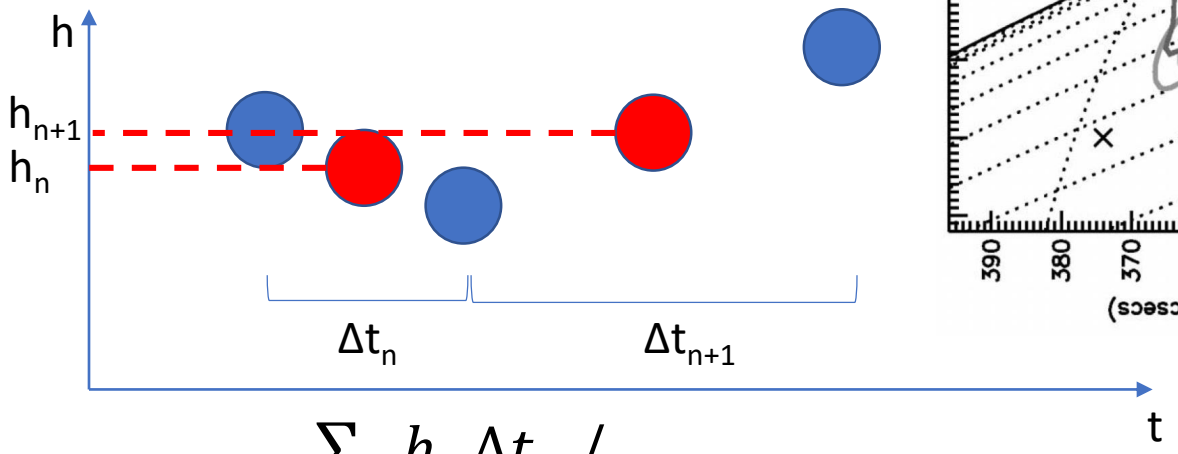
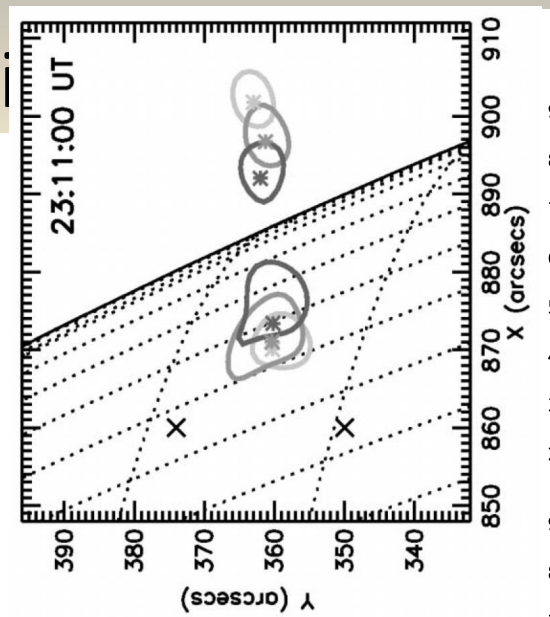
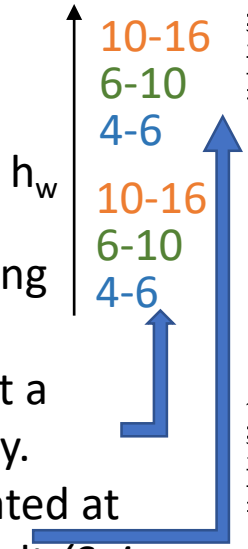
Height vs energy: Uncommon height distributi

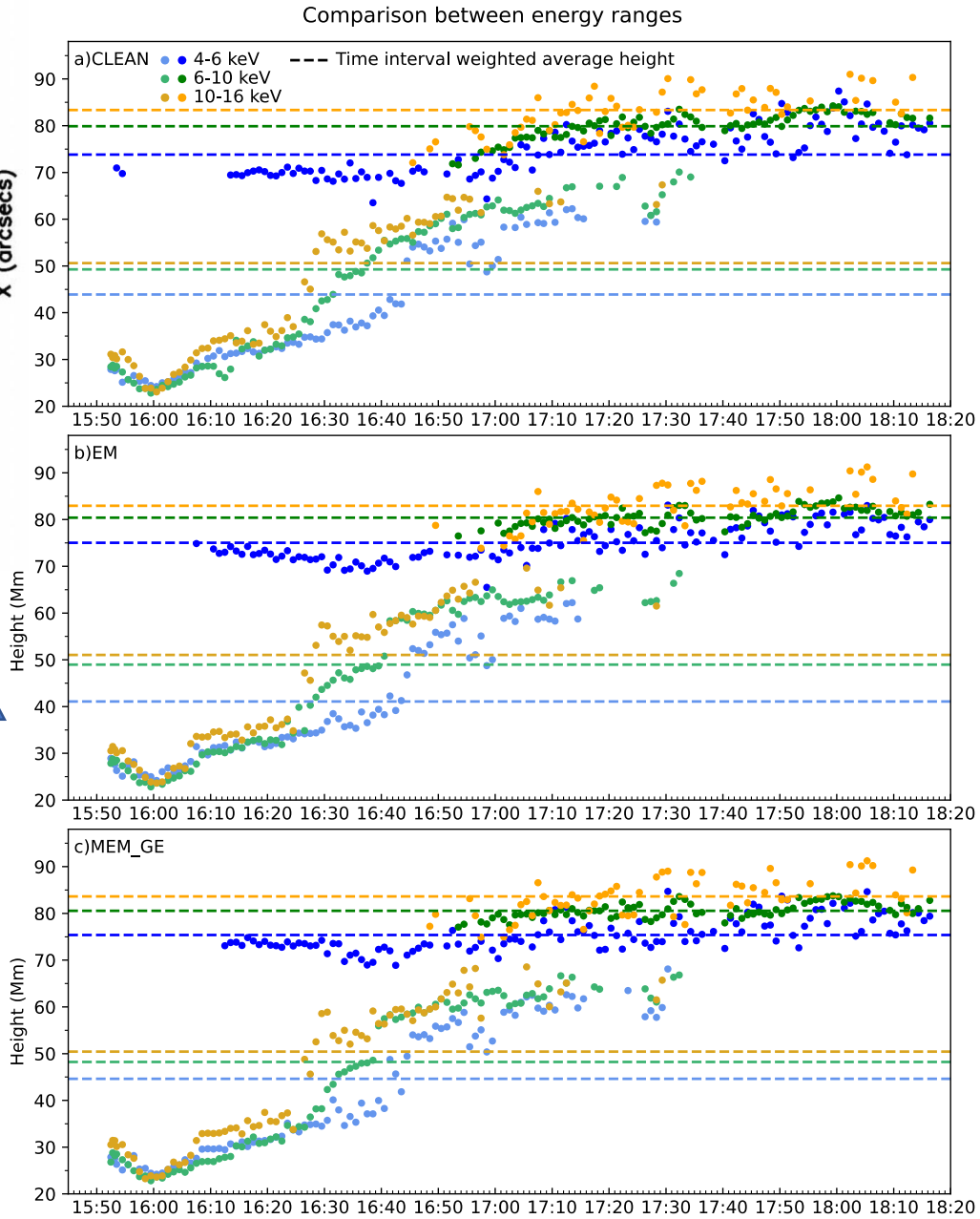
- Time interval weighted average height



$$h_w = \sum_n h_n \Delta t_n \Big/ \sum_n \Delta t_n$$

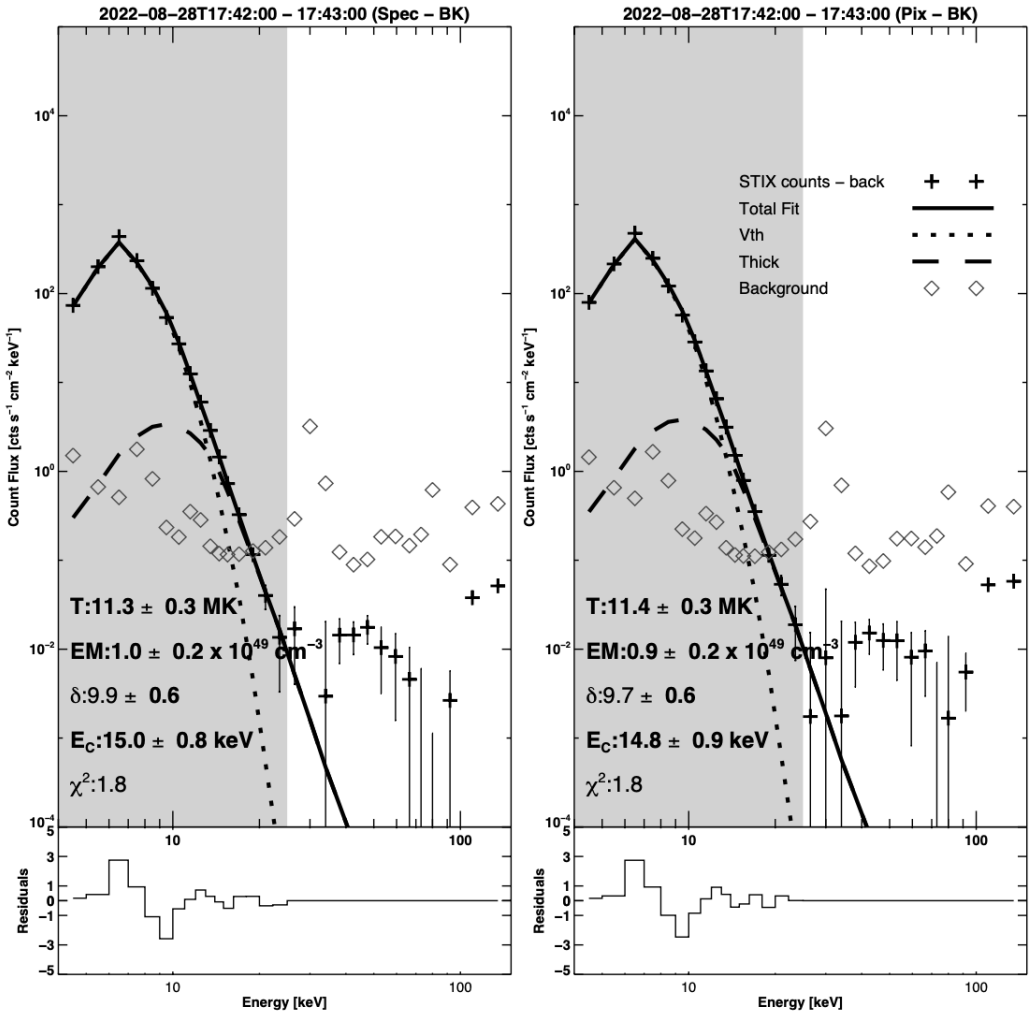


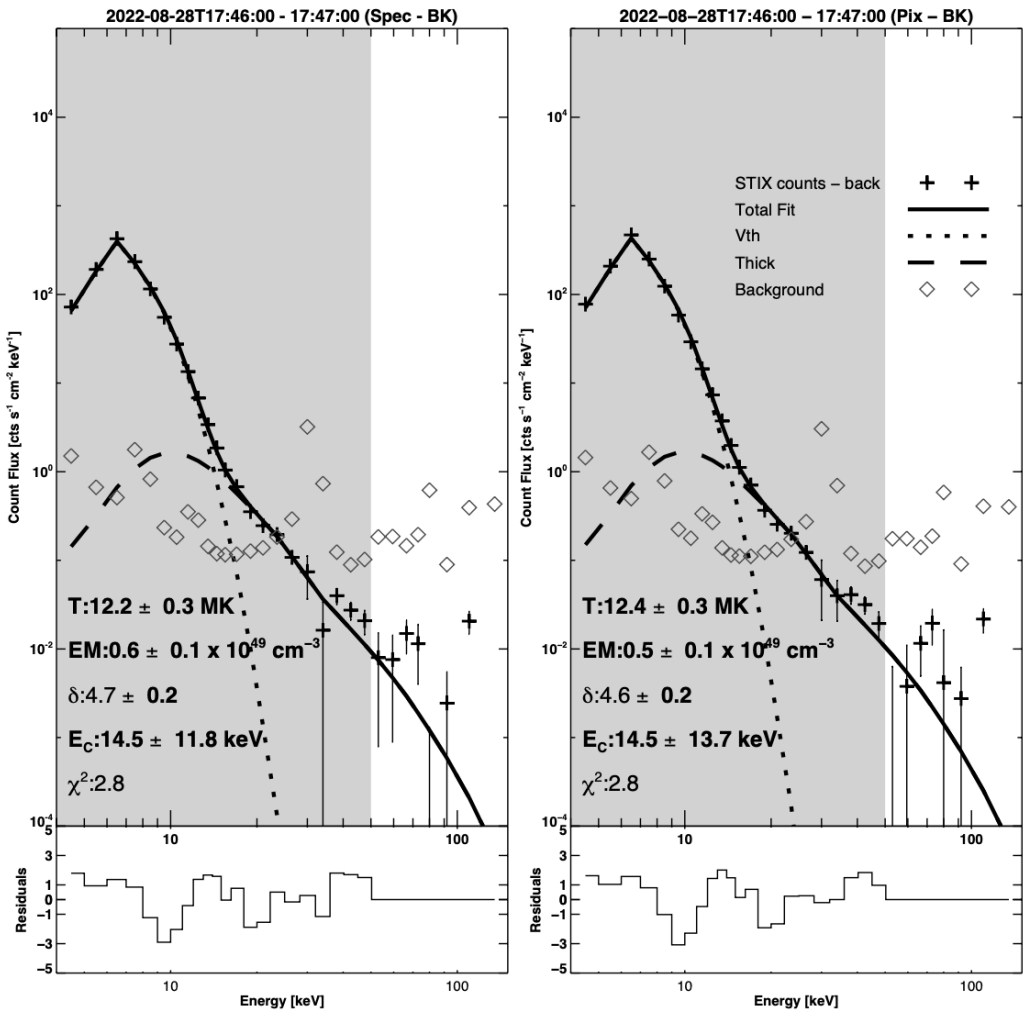




- The height distribution shows the same pattern in the imaging reconstruction results by all the three methods:
  - For LT sources, a source with higher energy is located at a higher location, which is commonly observed previously.
  - For ALT sources, a source with higher energy is still located at a higher location, which is opposite to the previous result *(Sui 2003, Liu 2008, 2013).*

Two examples





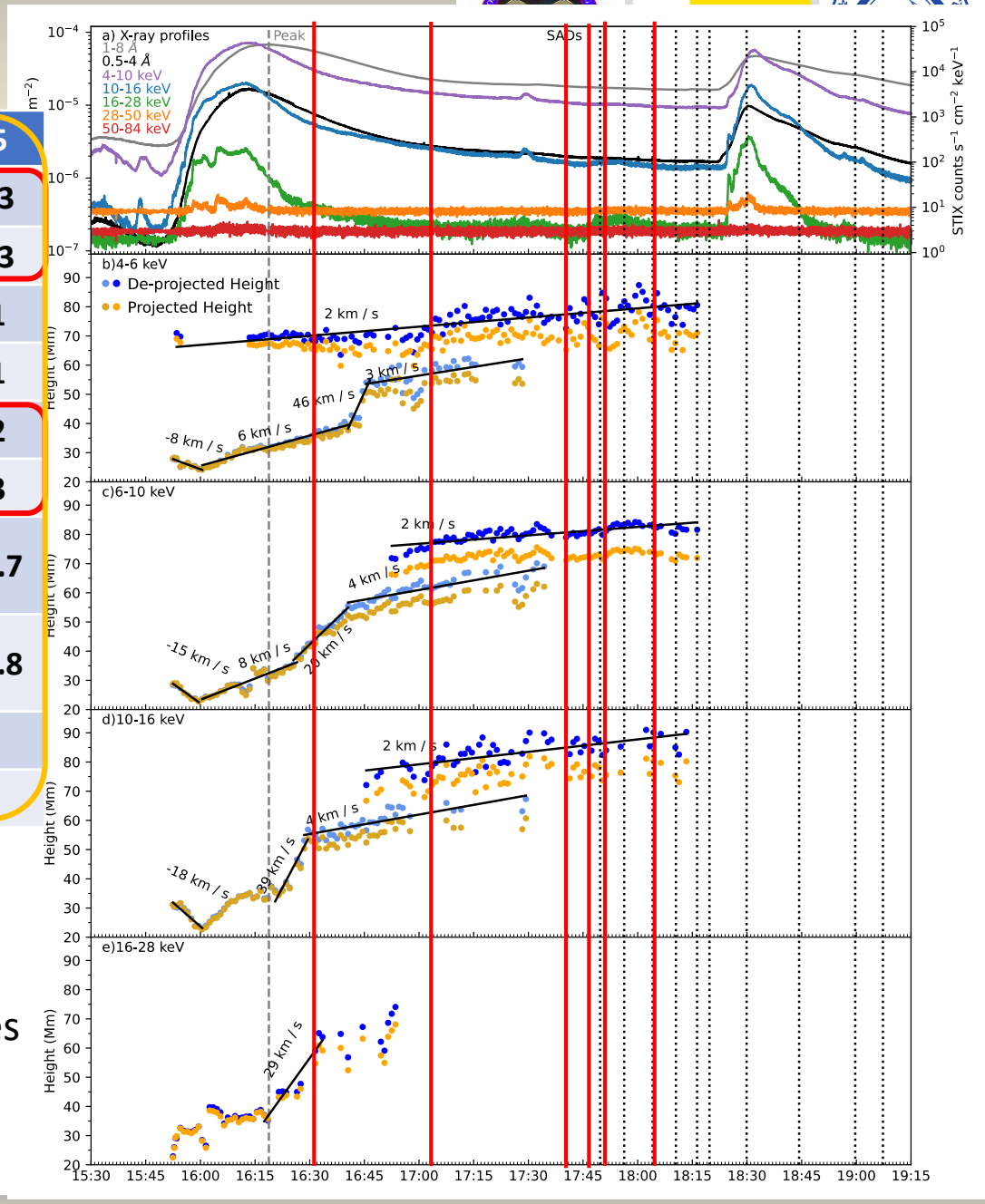
The nature of the above-loop-top source

	16:31-32	17:03-04	17:42-43	17:46-47	17:48-49	18:04-05
T (MK)	12.0 ± 0.3	12.4 ± 0.3	11.3 ± 0.3	12.2 ± 0.3	12.3 ± 0.3	12.4 ± 0.3
	12.2 ± 0.3	12.7 ± 0.3	11.4 ± 0.3	12.4 ± 0.3	12.3 ± 0.4	12.3 ± 0.3
EM (10^{49} cm^{-3})	3.1 ± 0.6	0.9 ± 0.1	1.0 ± 0.2	0.6 ± 0.1	0.5 ± 0.1	0.4 ± 0.1
	2.8 ± 0.5	0.8 ± 0.1	0.9 ± 0.2	0.5 ± 0.1	0.5 ± 0.1	0.5 ± 0.1
δ	10.9 ± 0.3	10.9 ± 0.5	9.9 ± 0.6	4.7 ± 0.2	4.8 ± 0.2	4.3 ± 0.2
	11.0 ± 0.3	10.9 ± 0.6	9.7 ± 0.6	4.6 ± 0.2	4.9 ± 0.2	4.7 ± 0.3
E_c (keV)	14.9 ± 0.5	15.3 ± 0.7	15.0 ± 0.8	14.5 ± 11.8	14.5 ± 10.7	14.8 ± 24.7
	15.2 ± 0.5	15.6 ± 0.8	14.8 ± 0.9	14.5 ± 13.7	14.4 ± 9.9	14.3 ± 18.8
χ^2	0.9	1.5	1.8	2.8	2.4	3.6
	0.8	1.3	1.8	2.8	2.1	3.8

double–source period SAD period

Temperature obtained from DEM results: ~ 11 - 13 MK

- Early: very high spectrum index ~ 10 -> thermal component dominates
- SAD period: decrease of the spectrum index
- The slight decrease and re-increase of temperature

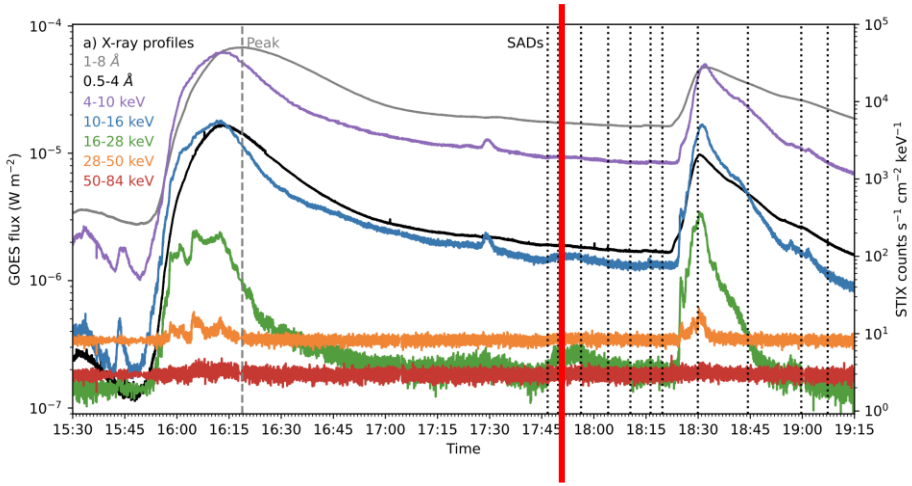


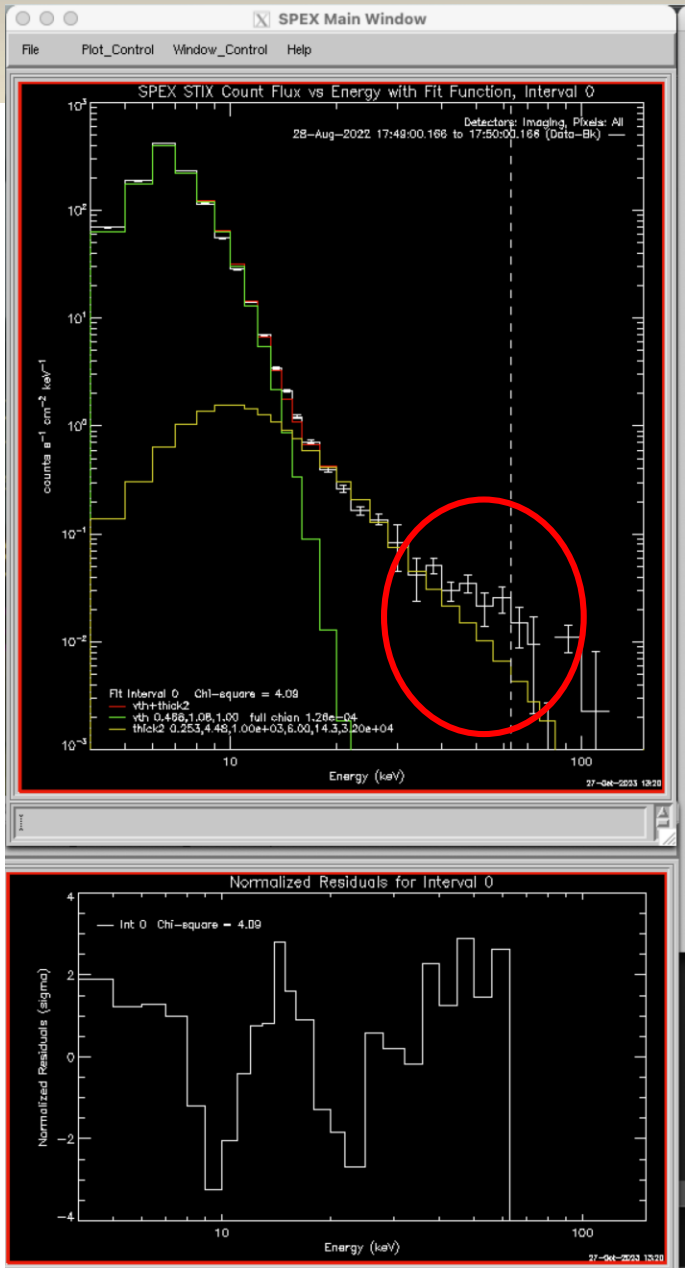
How to fit it?

17: 49-50
Index: 4.47
chi square ~ 4

Methods tried but failed:

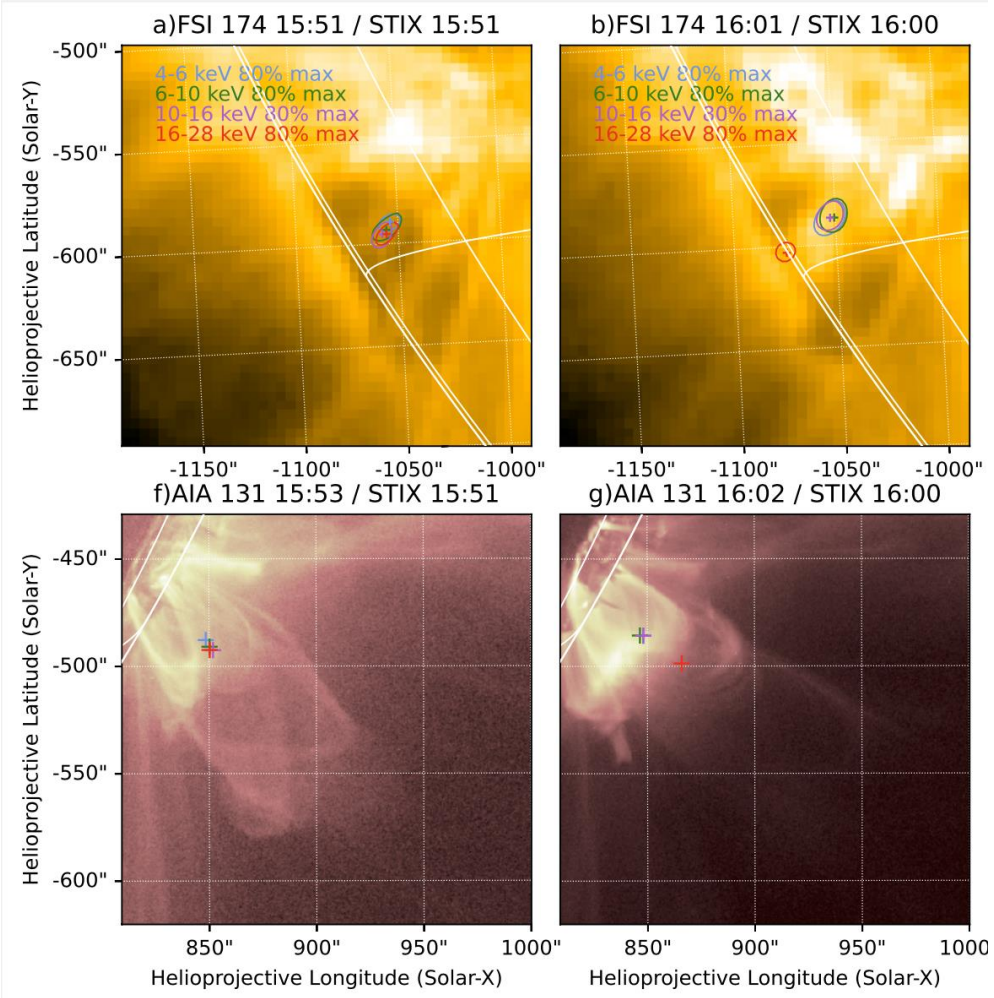
1. manually adjust the break energy
2. include background data for longer time range





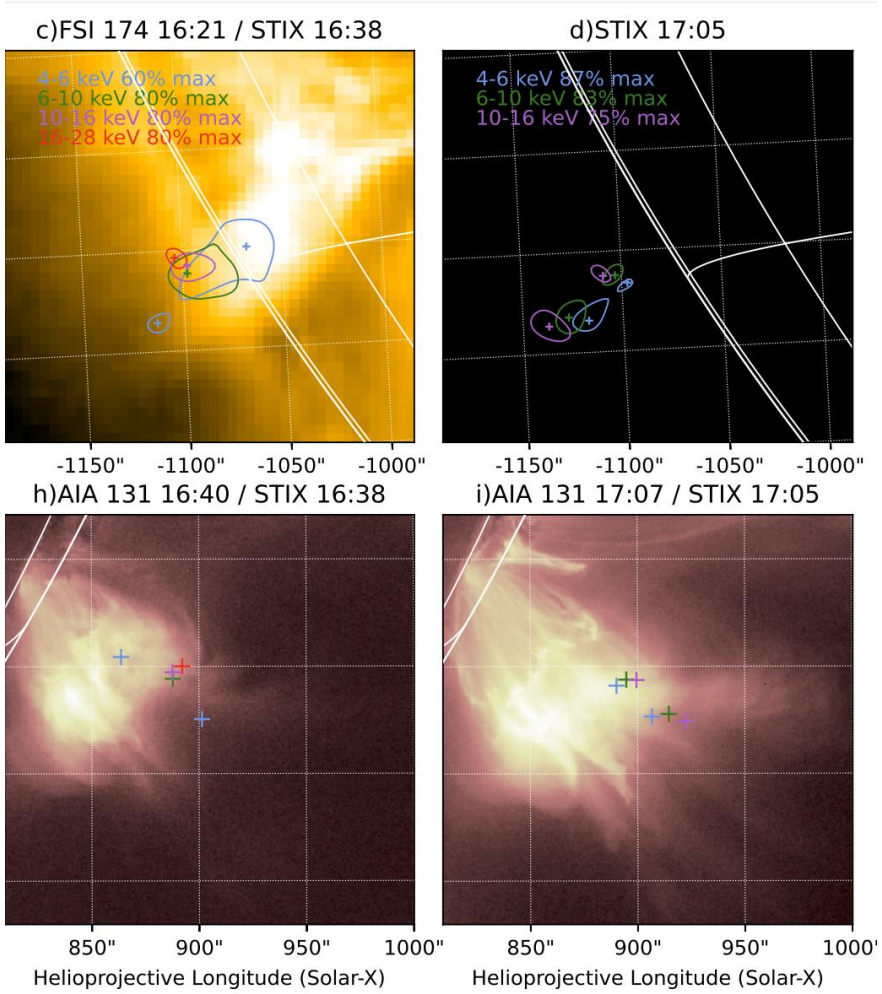
Discussion and integration

- A picture of the energy release during the flare:
  - 1.During the flare impulsive phase, non-thermal emission of X-ray was produced by the bremsstrahlung of accelerated electrons, with **the 16-28 keV source rising with the erupting flux rope** and disappearing soon after the intensive energy release due to magnetic reconnection.



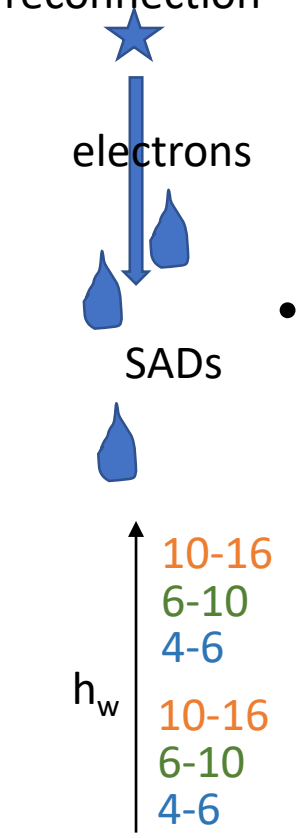
Discussion and integration

- A picture of the energy release during the flare:
  - 2.Heated plasma around the supra-arcade region generated thermal emission.
  - 3.With the development of finer supra-arcade structures, fan and spikes, two distinct X-ray sources formed, with one lying in the denser fan and one closer to the higher but thinner spikes.

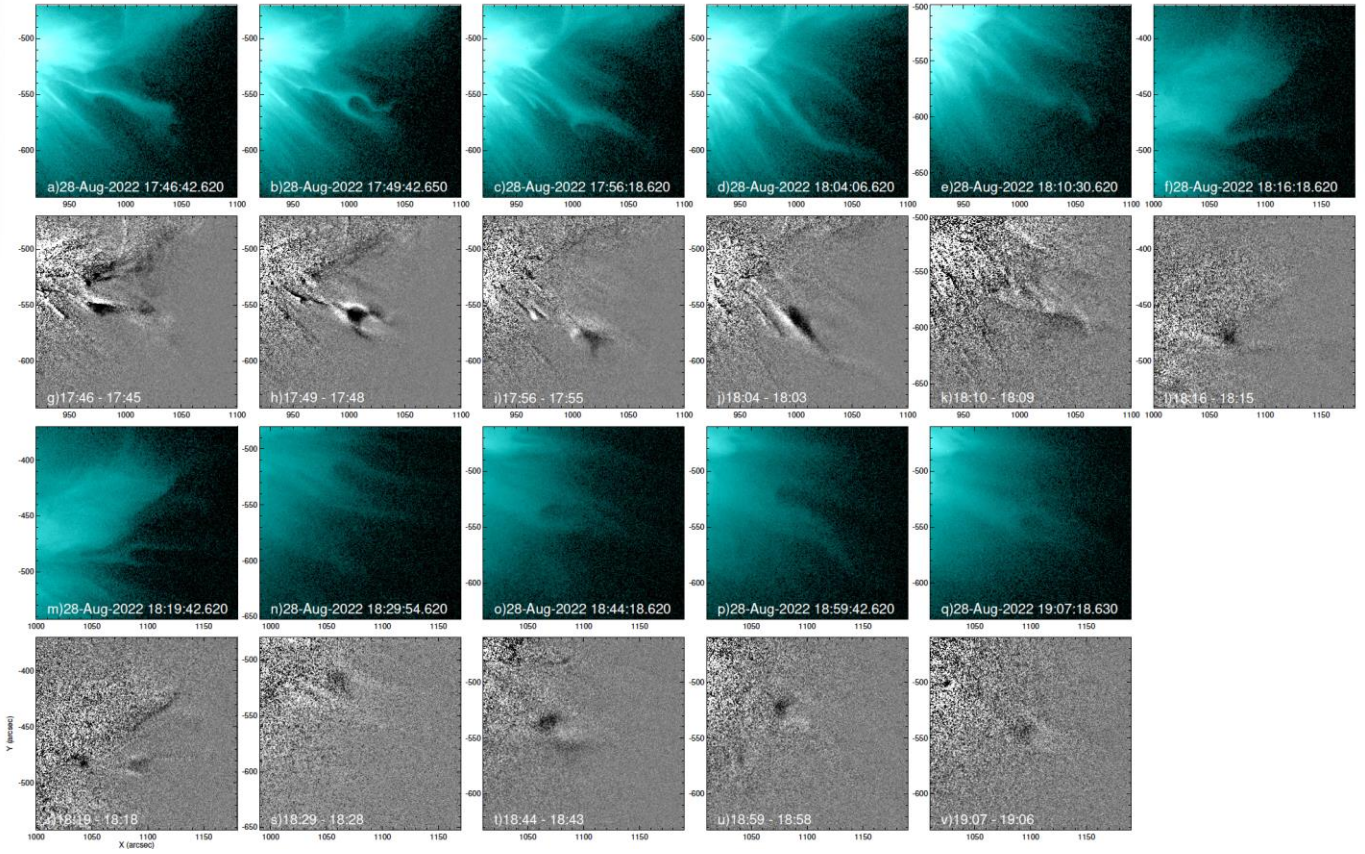


Discussion and integration

- A picture of the energy release during the flare:

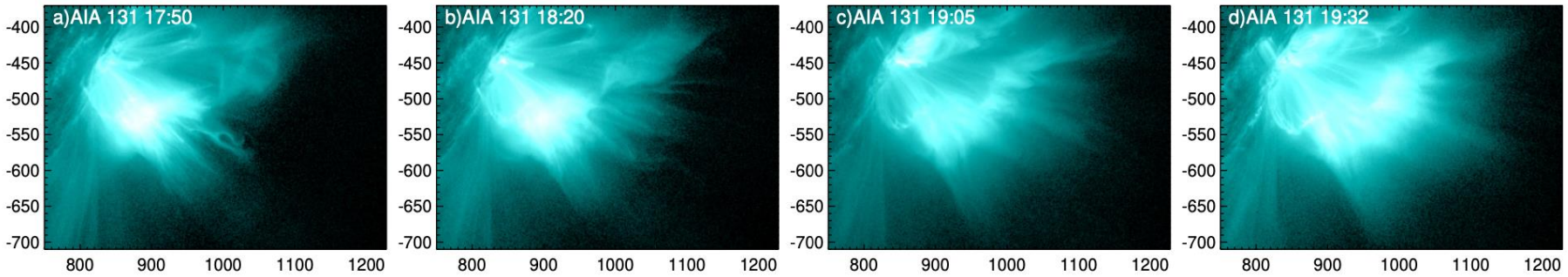


- 4.The reconnection process continued, producing supra-arcade downflows and hardening of X-ray spectrum in one period of flare decay phase.
- SADs come from somewhere higher than the observed X-ray sources, suggesting a reconnection sites lying higher, which is in agreement with the observed height distribution (higher energy closer to the reconnection site).



Discussion

- Question left: why is there a double distinct thermal source?
  - We could explain double non-thermal source by some previous models (e.g. Yu 2020).
  - Double thermal source indicates **two distinct magnetic structures** between which heat is not easy to transfer.
  - There is an observation of an **empty supra-arcade fan below some spikes** (Figure below). Do the two features have any connections? What insight could we get for understanding the post-flare geometry?



- Try: detailed analysis of DEM.

Summary and the next step

- We got a long-term observation of a double X-ray source during a flare for more than 2 hours, which is rarely obtained. This is also the first reported STIX double-source. Thanks STIX!
- We found an uncommon height distribution of X-ray sources along energy ranges. The nature and origin is worth investigation for understanding the post-flare magnetic geometry.

The next step

- A detailed analysis of DEM to investigate the reason of the long-term existence of the double source.

How to fit it?

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Index: 4.47
chi square ~ 4

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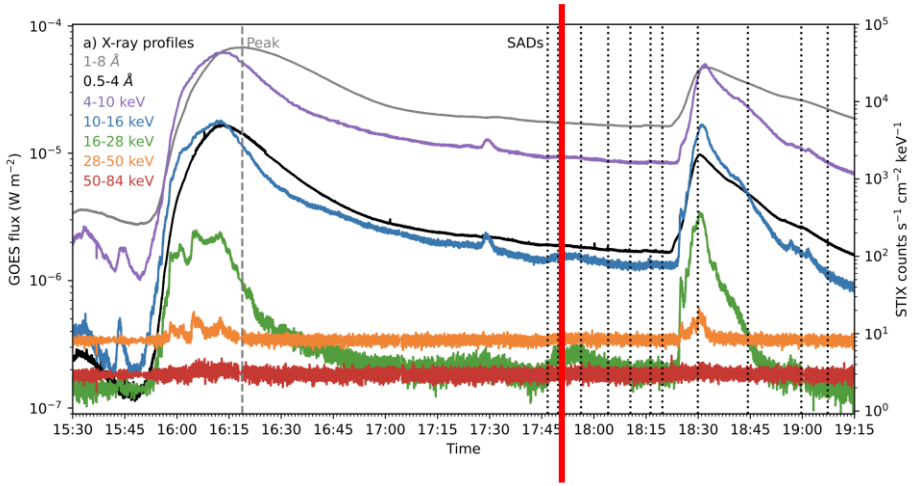
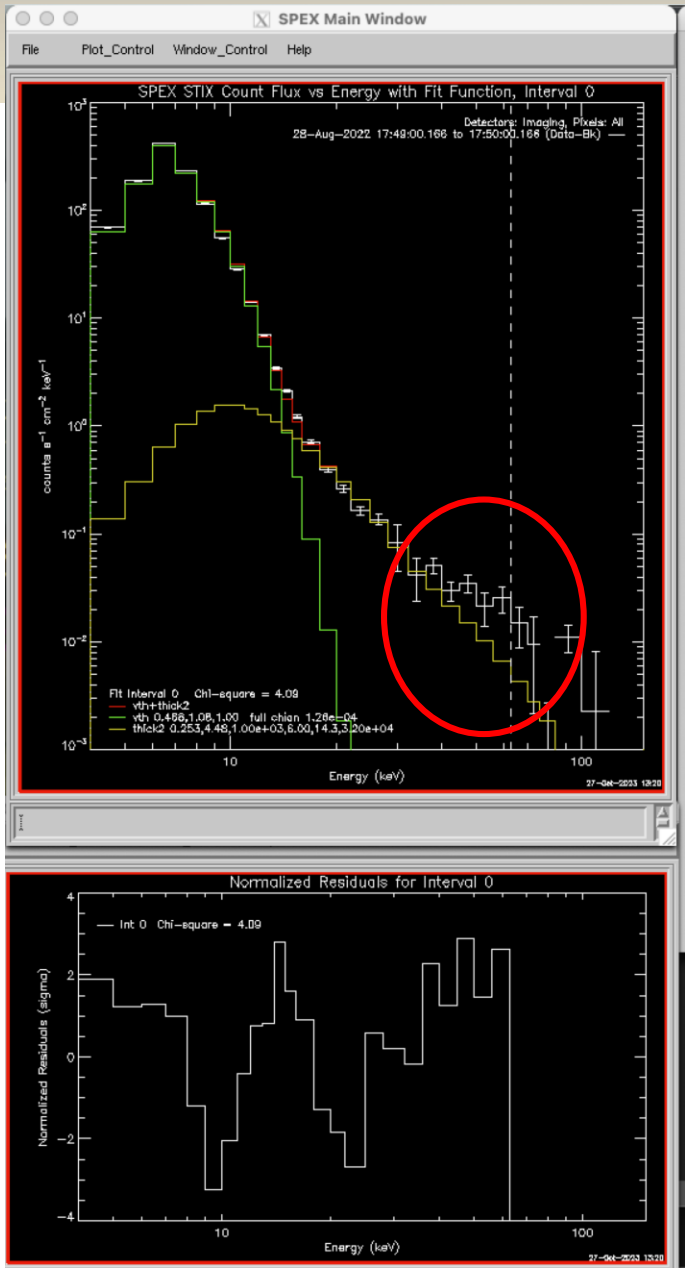
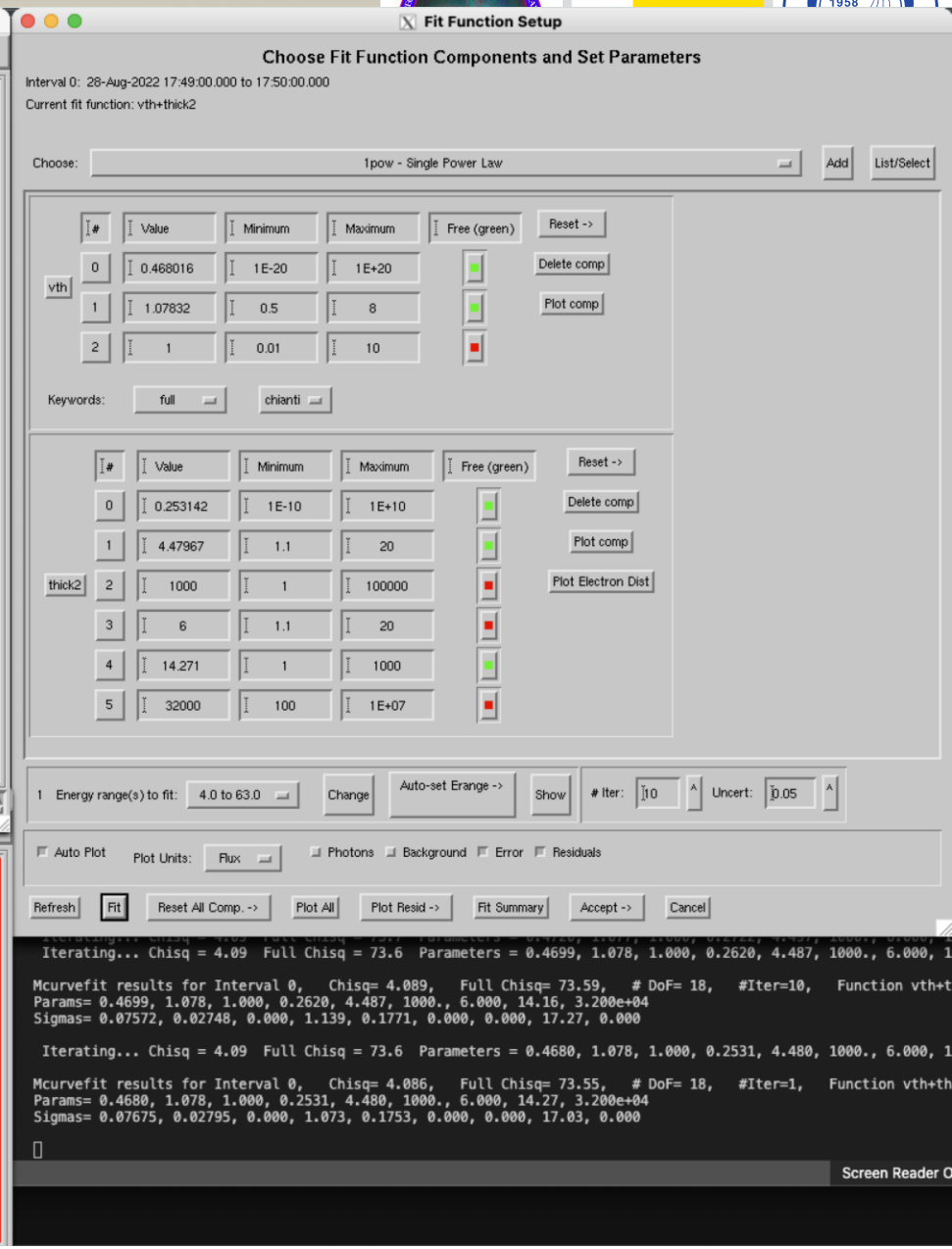




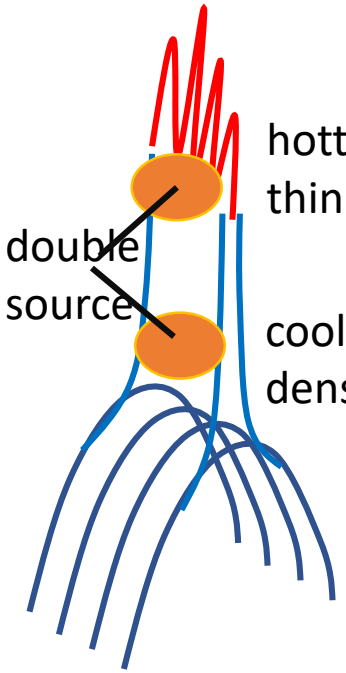


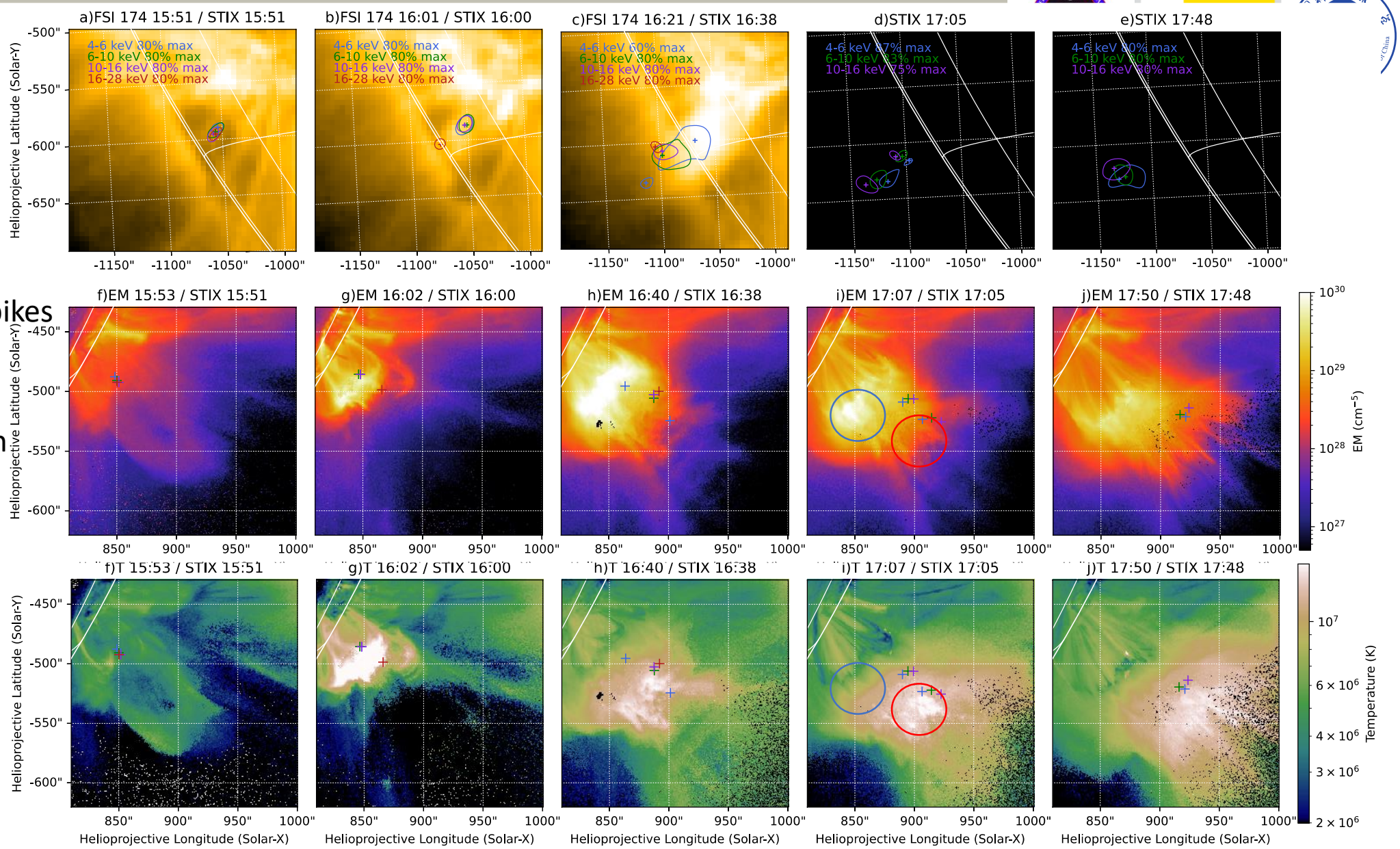

esa
STIX
SOLAR ORBITER

UNI
GRAZ

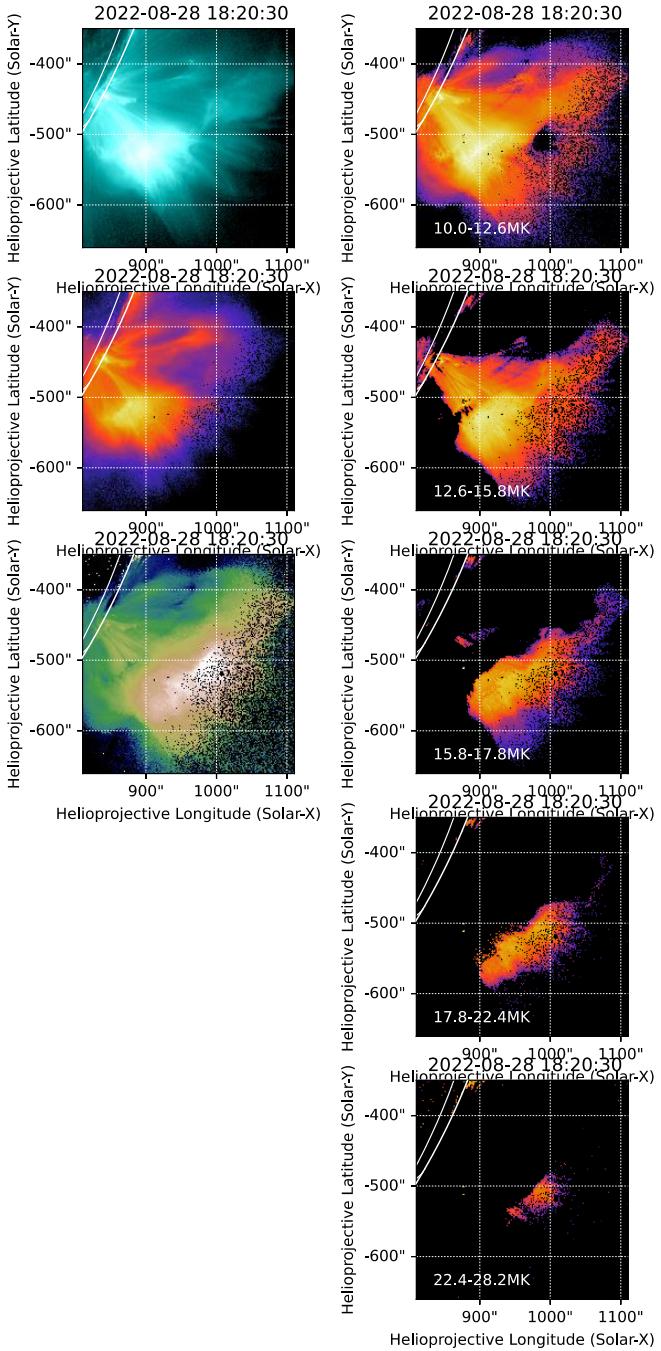
1958

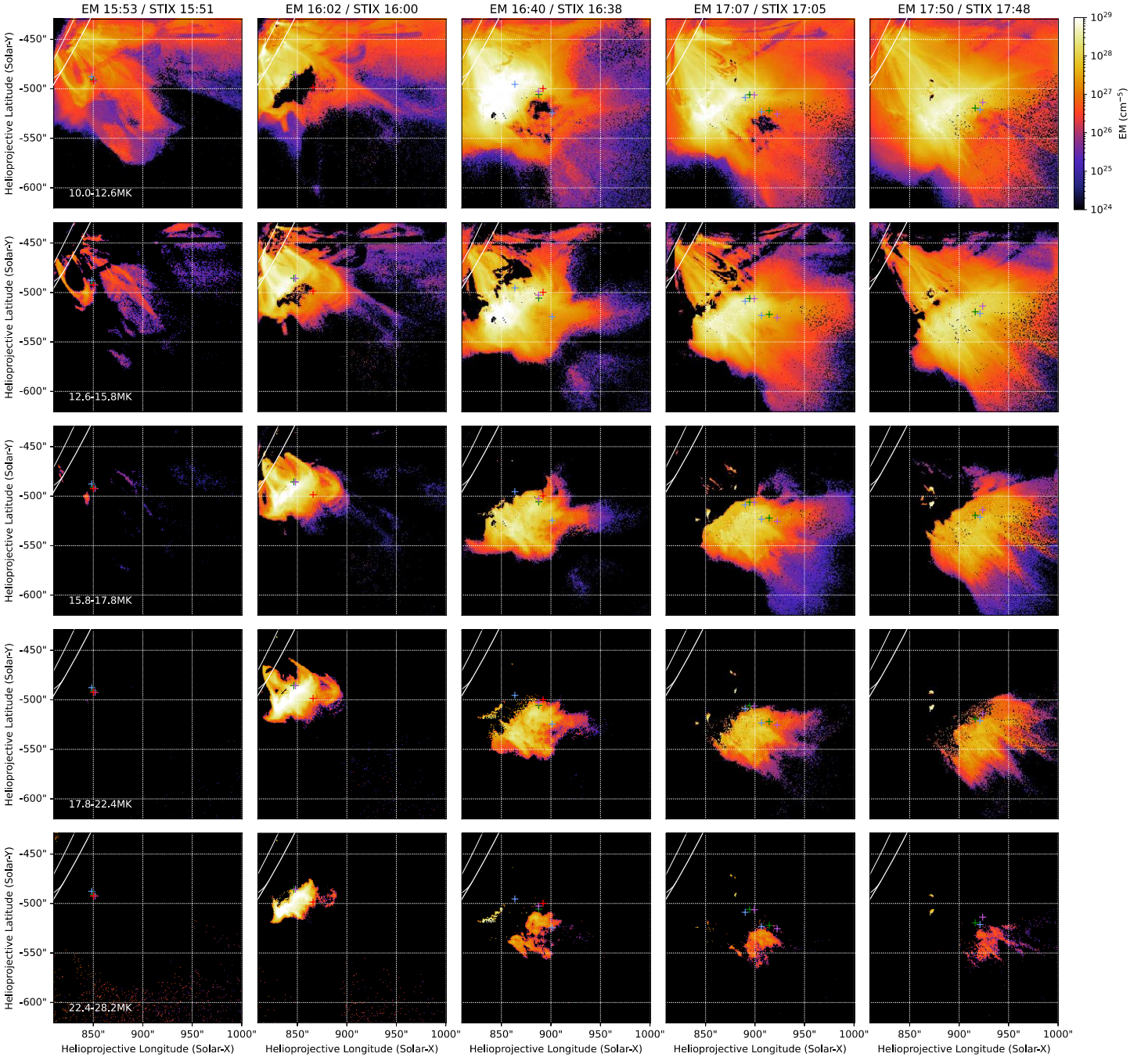
Discussion


hotter,
thinner spikes
double
source
cooler,
denser fan

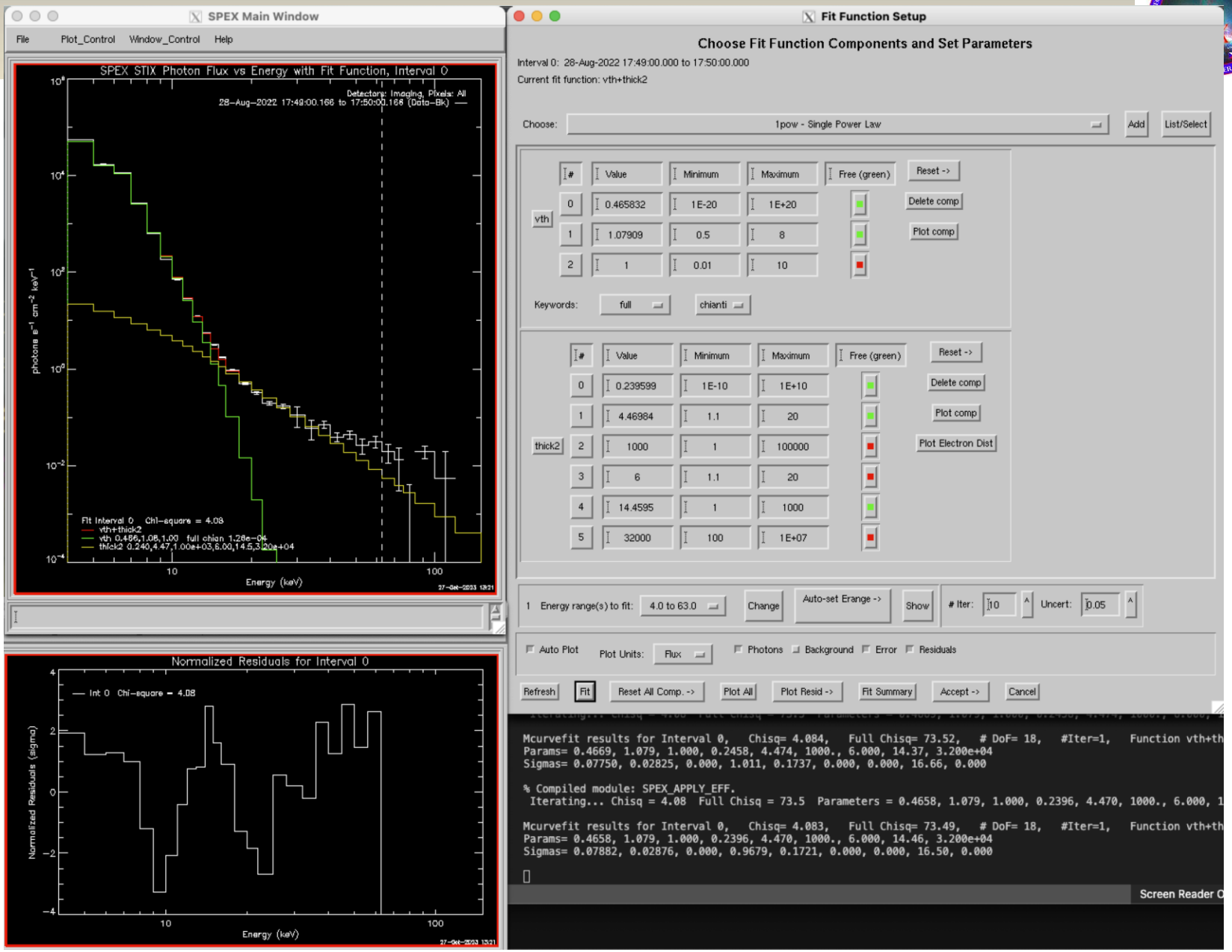

a)FSI 174 15:51 / STIX 15:51
b)FSI 174 16:01 / STIX 16:00
c)FSI 174 16:21 / STIX 16:38
d)STIX 17:05
e)STIX 17:48
4-6 keV 30% max
6-10 keV 30% max
10-16 keV 80% max
16-28 keV 80% max
Helioprojective Latitude (Solar-Y)
f)EM 15:53 / STIX 15:51
g)EM 16:02 / STIX 16:00
h)EM 16:40 / STIX 16:38
i)EM 17:07 / STIX 17:05
j)EM 17:50 / STIX 17:48
EM (cm⁻⁵)
f)T 15:53 / STIX 15:51
g)T 16:02 / STIX 16:00
h)T 16:40 / STIX 16:38
i)T 17:07 / STIX 17:05
j)T 17:50 / STIX 17:48
Temperature (K)
Helioprojective Longitude (Solar-X)

Discuss

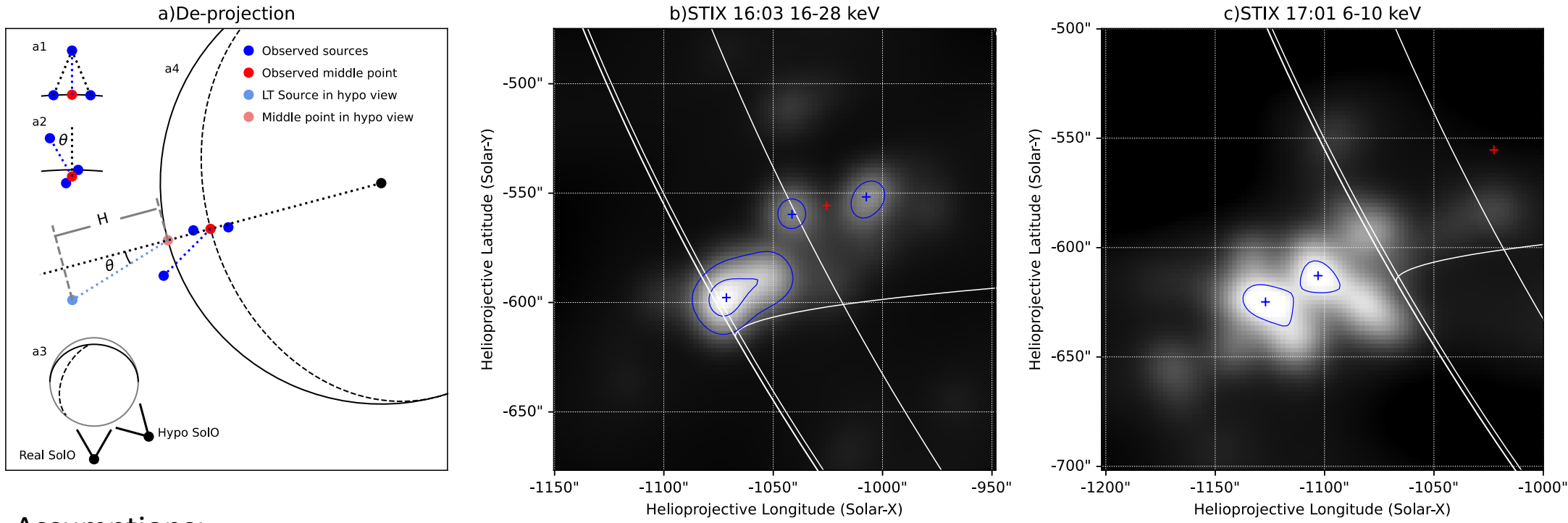

2022-08-28 18:20:30
10.0-12.6MK
12.6-15.8MK
15.8-17.8MK
17.8-22.4MK
22.4-28.2MK
Helioprojective Latitude (Solar-Y)
Helioprojective Longitude (Solar-X)


EM 15:53 / STIX 15:51
EM 16:02 / STIX 16:00
EM 16:40 / STIX 16:38
EM 17:07 / STIX 17:05
EM 17:50 / STIX 17:48
10.0-12.6MK
12.6-15.8MK
15.8-17.8MK
17.8-22.4MK
22.4-28.2MK
Helioprojective Latitude (Solar-Y)
Helioprojective Longitude (Solar-X)
EM (cm^{-5})

17: 49-50
Index: 4.47



X-ray source height estimation



- Assumptions:
  - The two footpoint sources: at the surface of the sun (h=0 Mm).
  - The triangle formed by the three sources is isosceles; the two footpoint sources: the two feet (a1).
  - The line connecting the triangle top (blue) and the middle point at the bottom (red) has a certain inclination angle θ (a2).
  - In SolO's view, the ellipse arc where the red middle point lies is perpendicular to the associated radius (the black dotted line in a4). The third assumption states that such ellipse arc is vertical to the plane determined by the footpoint sources and the sun center.

h vs time

h vs energy