Solar flares and coronal mass ejections

Astrid Veronig & Yang Su

University of Graz, Austria

List of HESPE papers with Graz contribution:

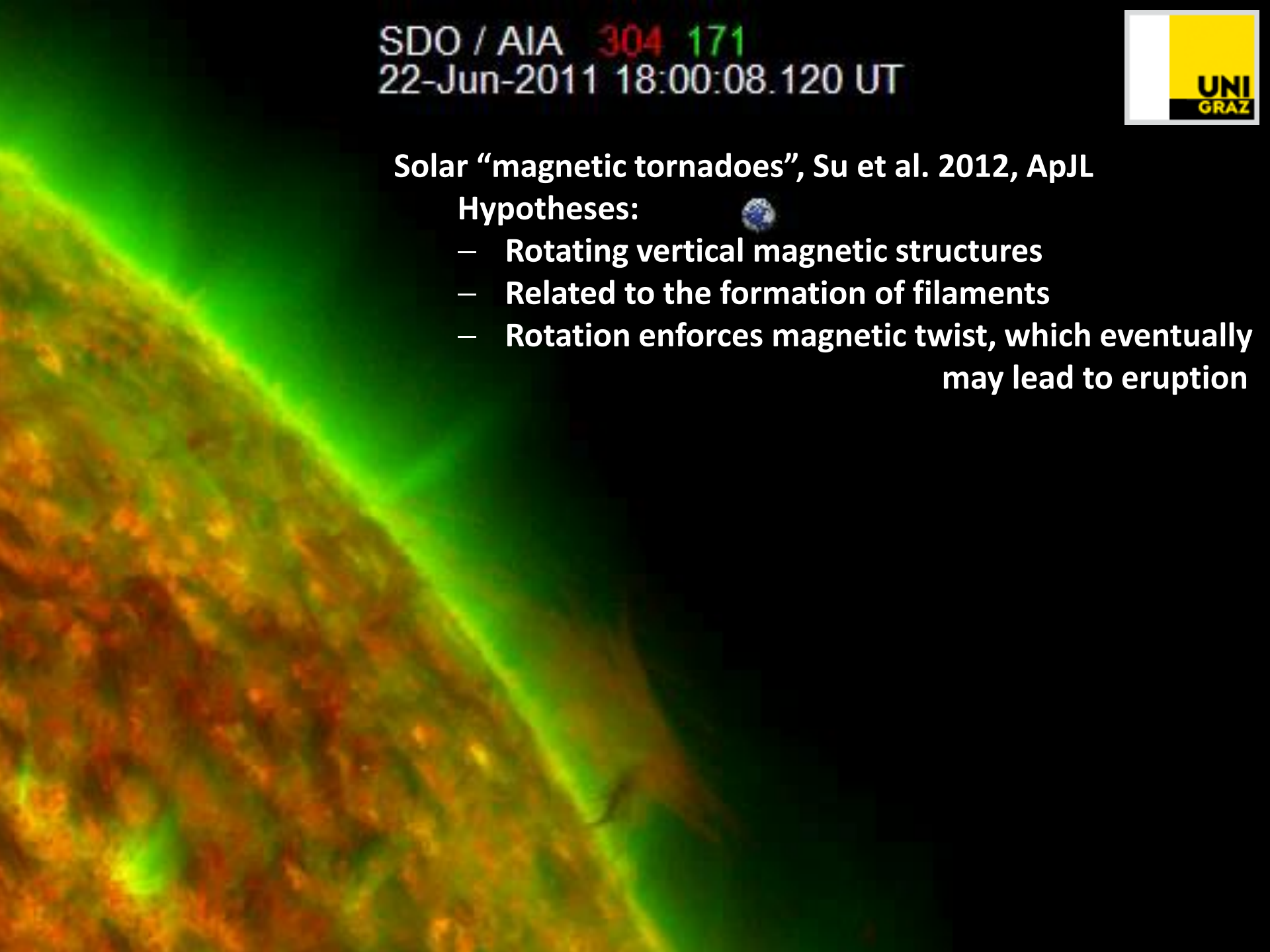
- Pre-flare activity and magnetic reconnection during an eruptive flare
  Joshi, Veronig, Lee, et al. 2011, ApJ
- Two-stage eruption, secondary heating
  Su, Dennis, Holman et al. 2012, ApJL
- Relation between CME dynamics and non-thermal flare cheracteristics
  Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ
- Solar “tornadoes” and filament formation
  Su, Wang, Veronig, Temmer, Gan, 2012, ApJL
- Multiple flare activity and filament eruption related with HXRs
  Joshi, Kushwaha, Cho, Veronig 2013, ApJ
- Imaging of magnetic reconnection
  Su, Veronig, Holman et al. 2013, Nature Phys.
- Energy partitioning
  Feng, Wiegelmann, Su et al. 2013, ApJ
- Motions in CME-Flare Current Sheet
  Gao, Wang, Lin et al. 2013, submitted to New Astronomy

1) Solar “magnetic tornadoes”
   - Su, Wang, Veronig, Temmer, Gan, 2012, ApJL
   - Ongoing work

2) Magnetic reconnection and energy release in flares
   - Su, Veronig, Holman et al. 2013, Nature Phys.

3) Relation between CME dynamics and flare characteristics
   - Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ
   - Su, Dennis, Holman et al. 2012, ApJL

1) Solar „magnetic tornadoes“



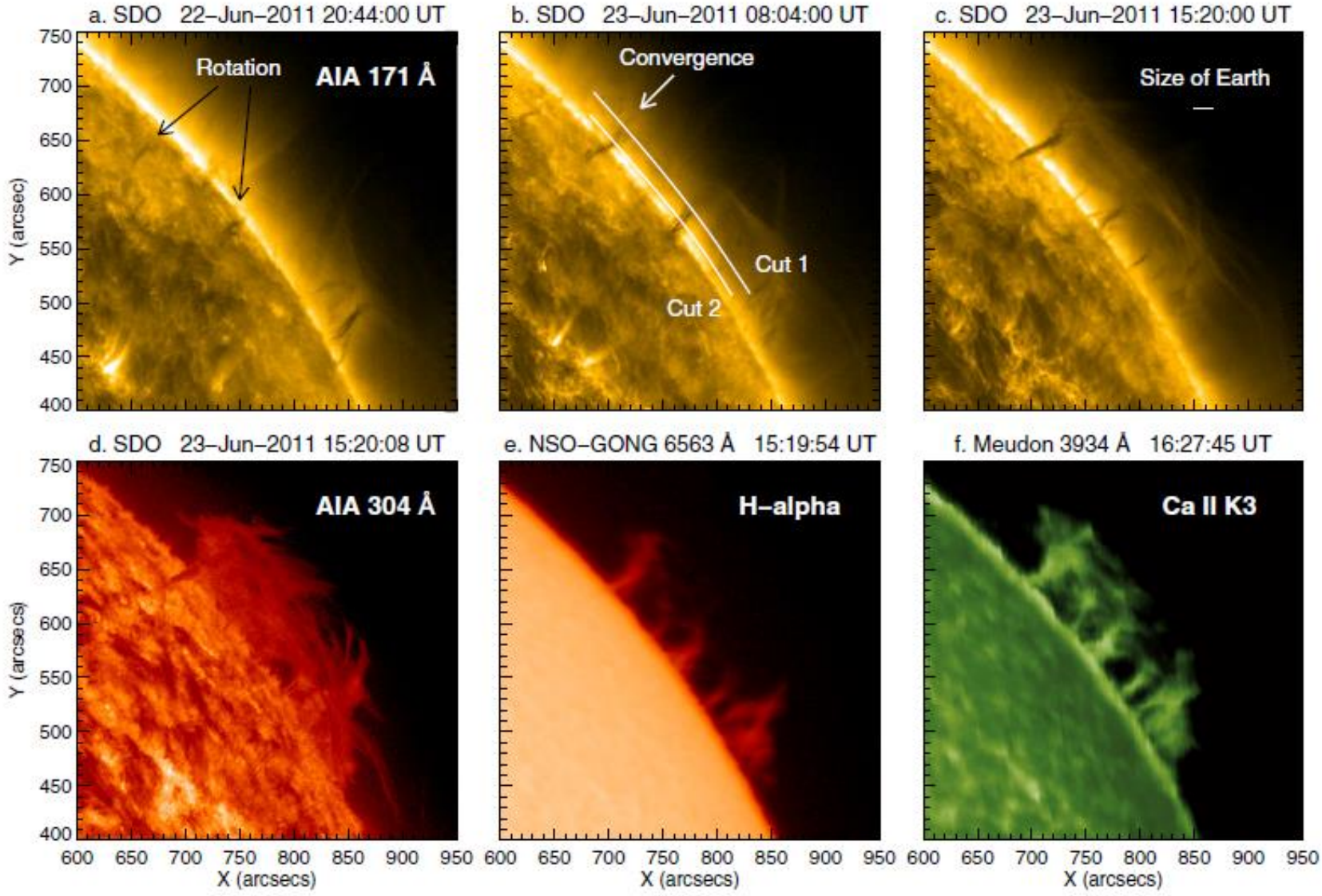
Solar “magnetic tornadoes”, Su et al. 2012, ApJL

Hypotheses:

- **Rotating vertical magnetic structures**
- **Related to the formation of filaments**
- **Rotation enforces magnetic twist, which eventually may lead to eruption**

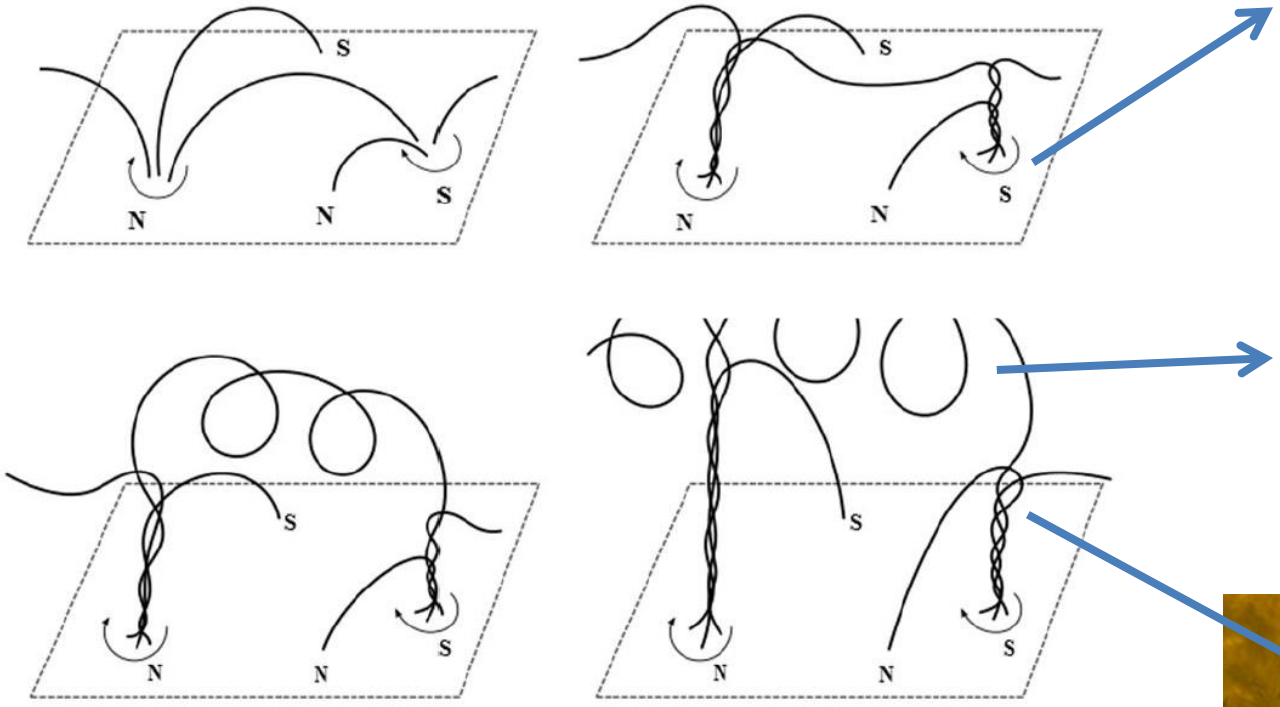
Solar “magnetic tornadoes”
Su, Wang, Veronig, Temmer, Gan, 2012a, ApJL

Relation to filament barbs and filament formation.

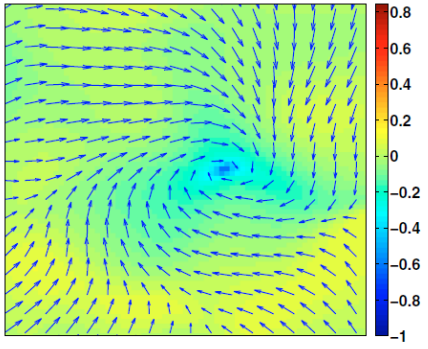


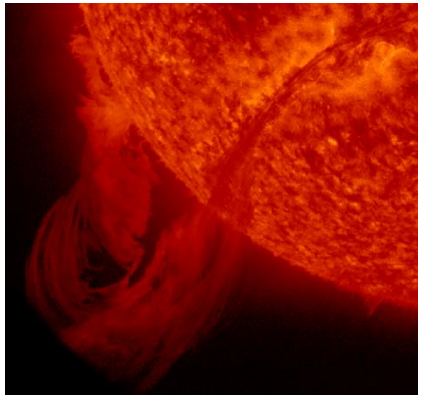
Solar “magnetic tornadoes”
Su, Wang, Veronig, Temmer, Gan, 2012a, ApJL

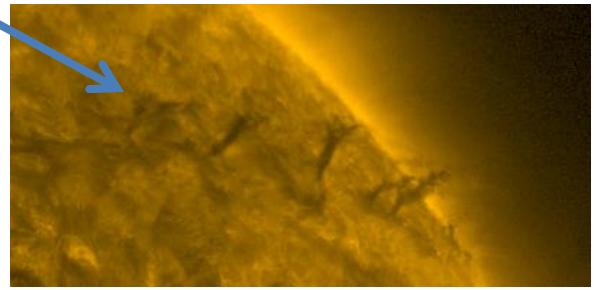
Idea of vortex-driven filament formation and eruption.

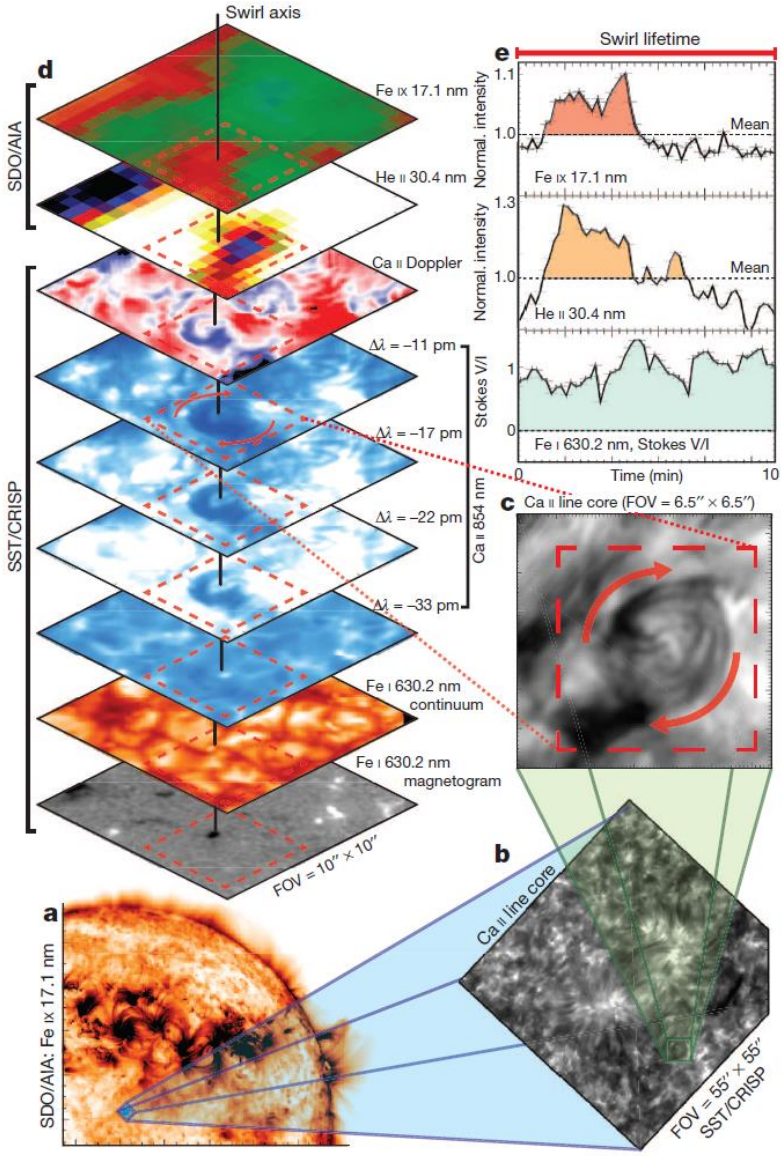


Vortex at supergranular junctions
Attie et al. (2009)







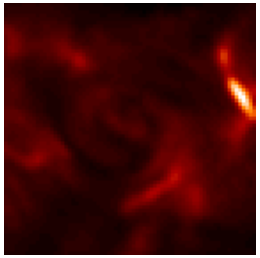


Wedemeyer-Böhm et al. (2012):

Magnetic tornadoes are related to vortex motions in lower layers („chromospheric swirls“)

Transport energy to corona (heating)

http://www.solartornado.info/



SST / CRISP observations

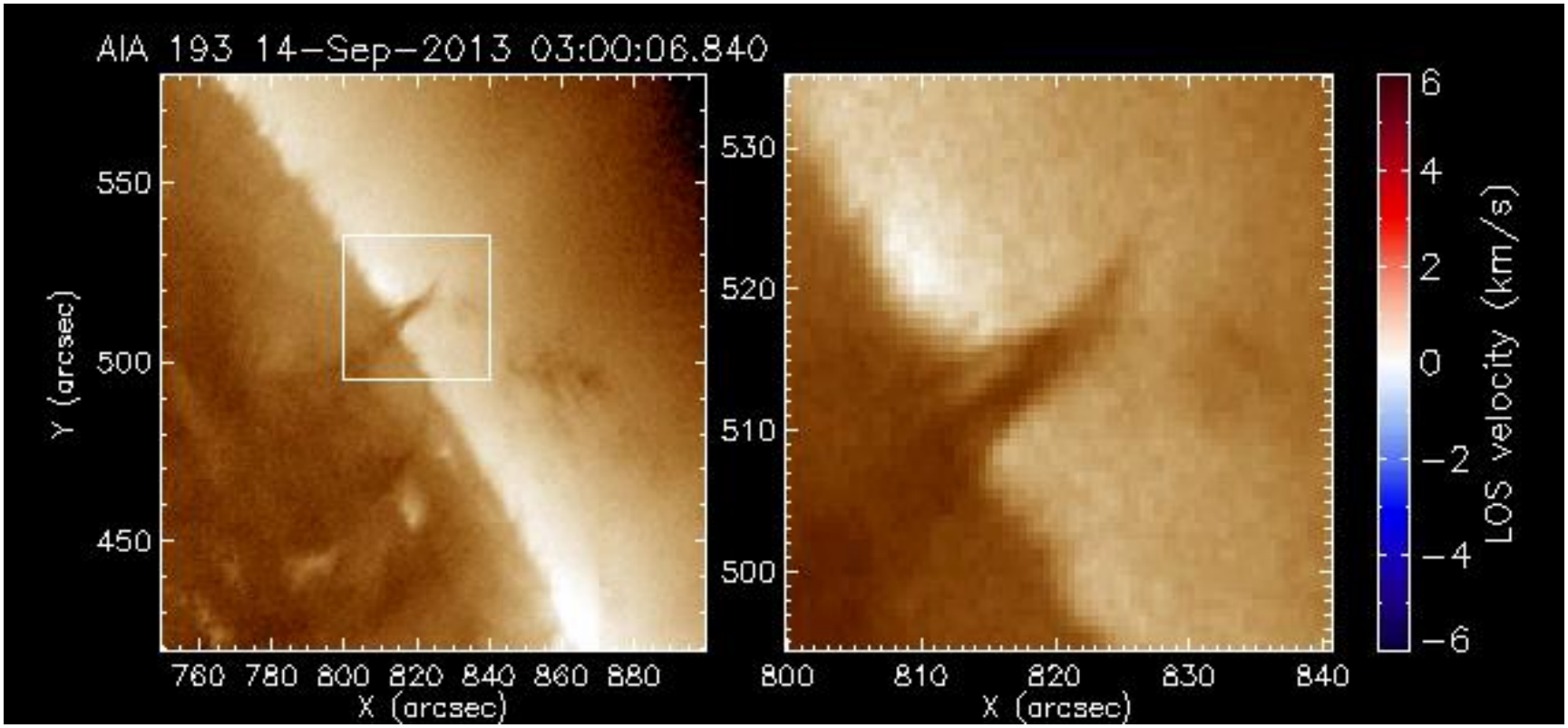
Solar “Tornadoes”
Su, Wang, Veronig, Temmer, Gan, 2012a, ApJL

Related papers & controversial discussion:

- Solar “Tornadoes”
  - Wedemeyer-Böhm et al. 2012, Nature (detection and simulation of solar tornadoes; relation to coronal heating)
  - Su et al. 2012, ApJL (connect vortex motion, solar tornadoes, and filament barbs and formation)
  - Li, X. et al. 2012, ApJL (plasma motion)
- Latest support for rotating barbs:
  - Orozco Suárez et al. 2012, ApJL (Evidence for rotational motions in the feet of a quiescent solar prominence)
  - Wedemeyer et al. 2013, ApJ (Giant tornadoes as rotating legs of solar prominences)
- Objections:
  - Panasenco et al. 2013, Solar Phys. (plasma motion, oscillation or projection; not rotation)

Solar “magnetic tornadoes”
Su et al., ongoing study

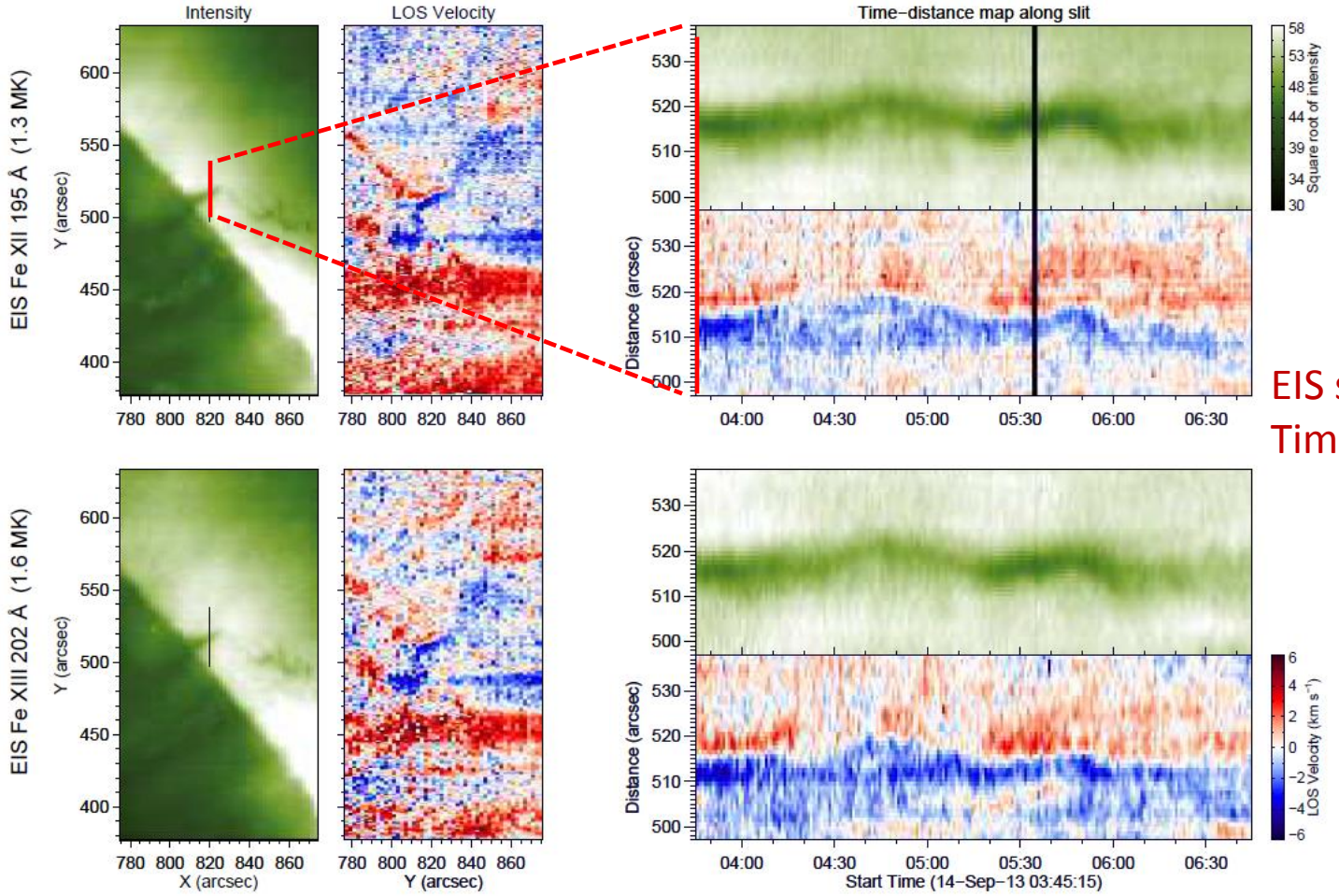
- Evidence of rotational motion in tornado-like barbs via EIS/Hinode spectroscopy
  - Systematic red/blue shift pattern



Solar “magnetic tornadoes”
Su et al., ongoing study

- Evidence of rotational motion in tornado-like barbs via EIS/Hinode spectroscopy
  - Systematic red/blue shift pattern
  - Signs do not change for at least 3 hours → **not oscillation but rotation**

EIS raster

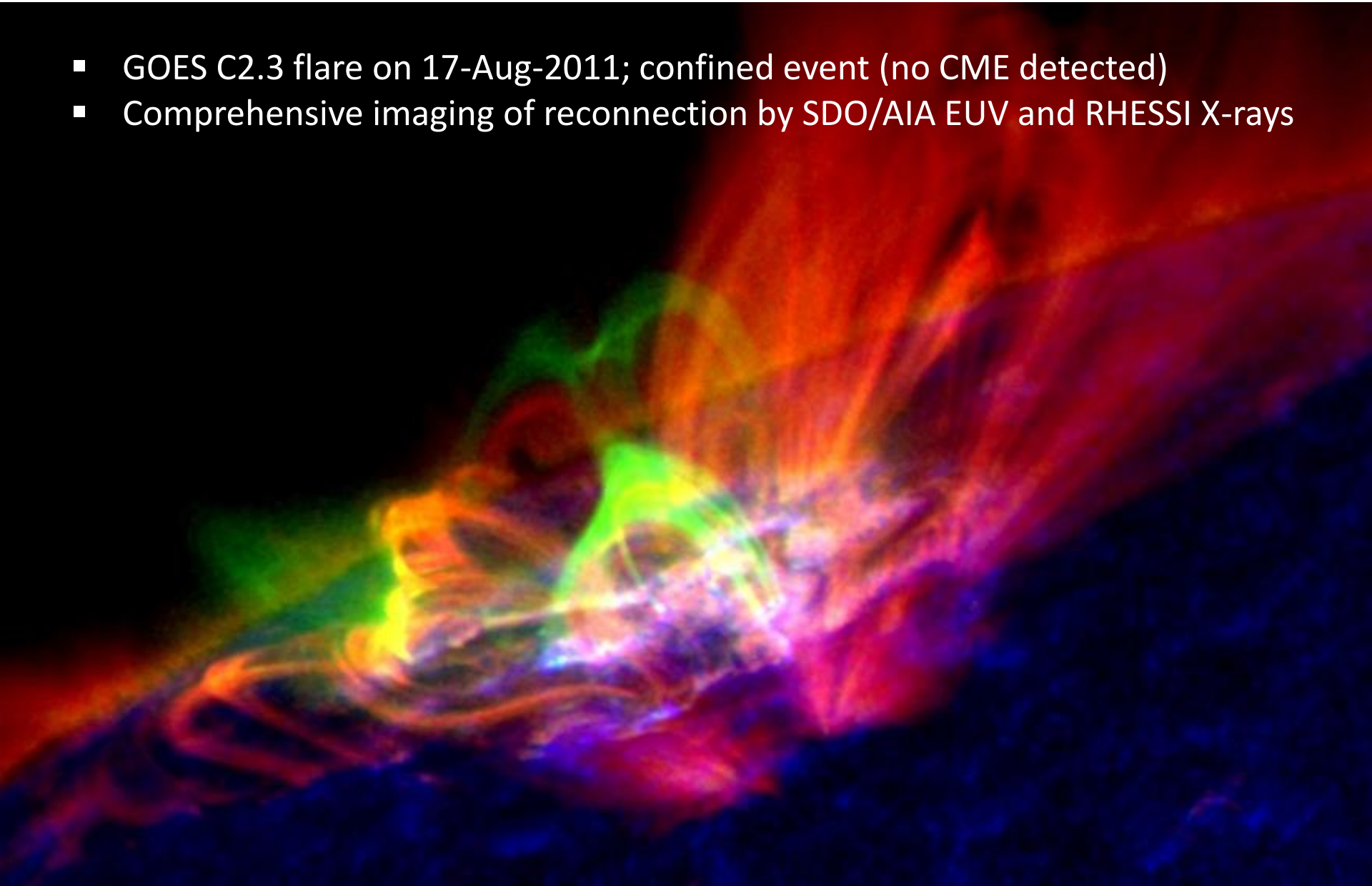


EIS slit ->
Time evolution

2) Magnetic reconnection and energy release

Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

- GOES C2.3 flare on 17-Aug-2011; confined event (no CME detected)
- Comprehensive imaging of reconnection by SDO/AIA EUV and RHESSI X-rays



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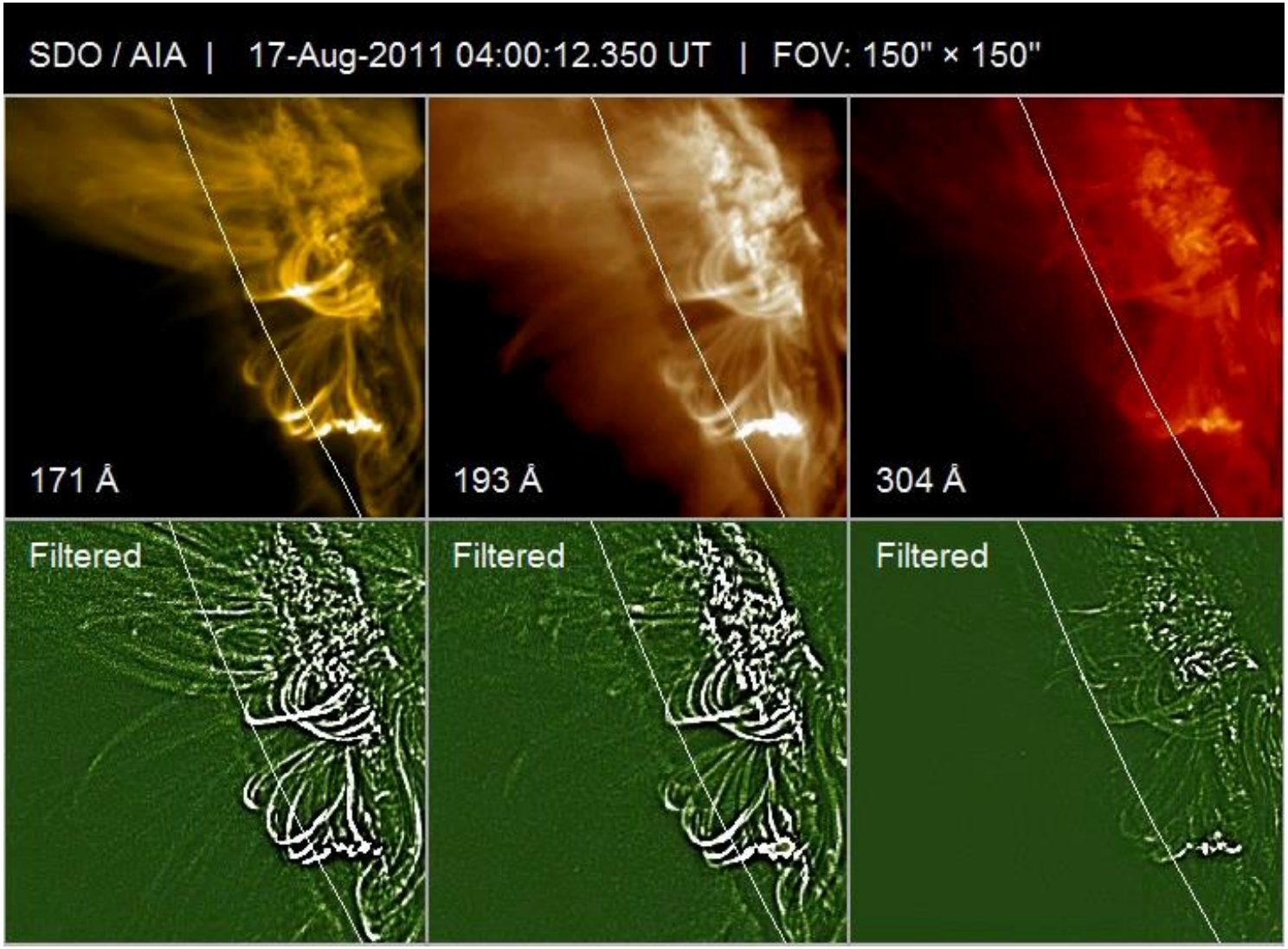
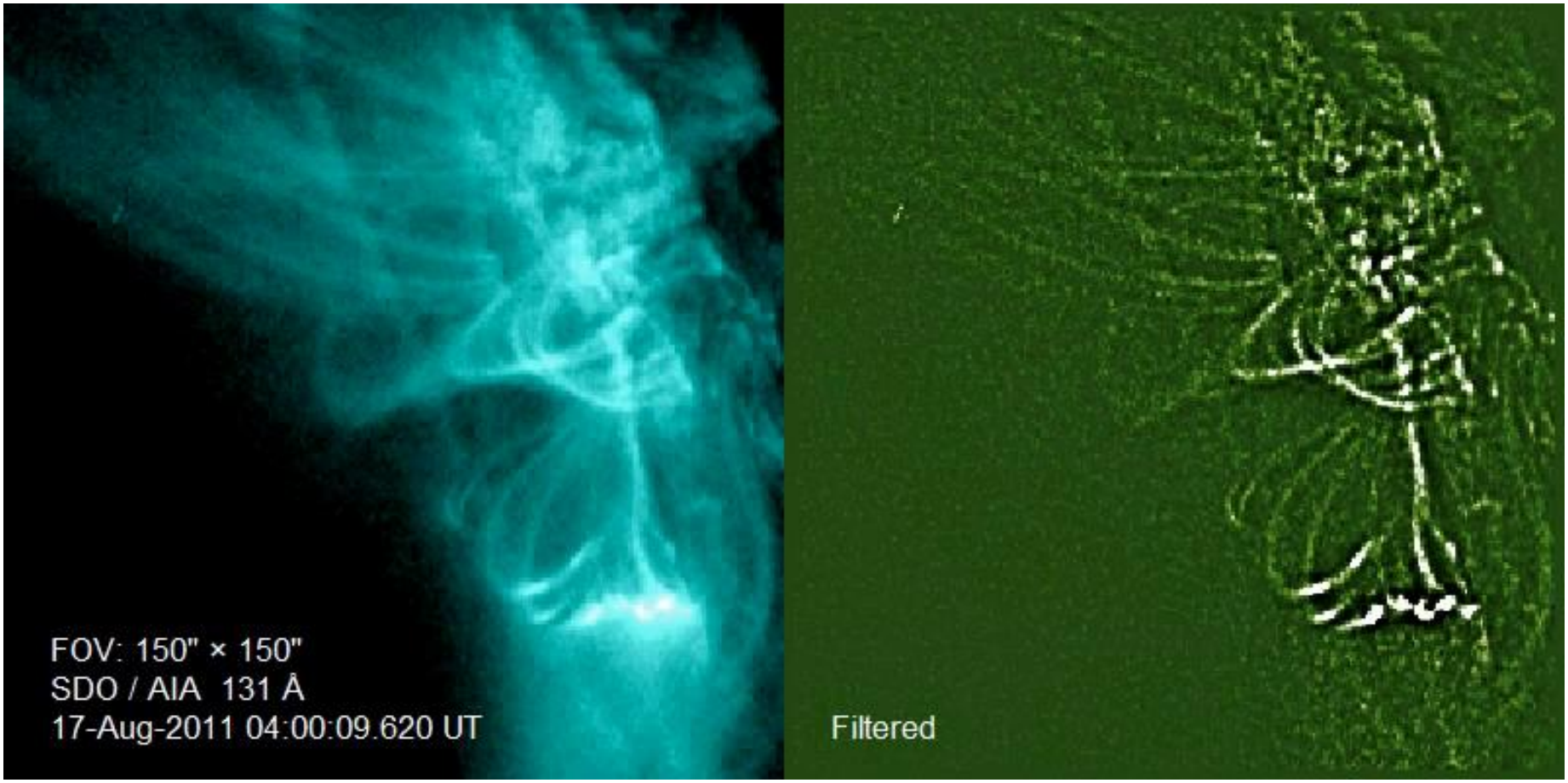
Su, Veronig, Holman, et al. 2013, Nature Phys.

Cool loops merge and disappear.



Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

- AIA 131 Å images show plasma at ~10 MK in newly formed loops (re-connected).



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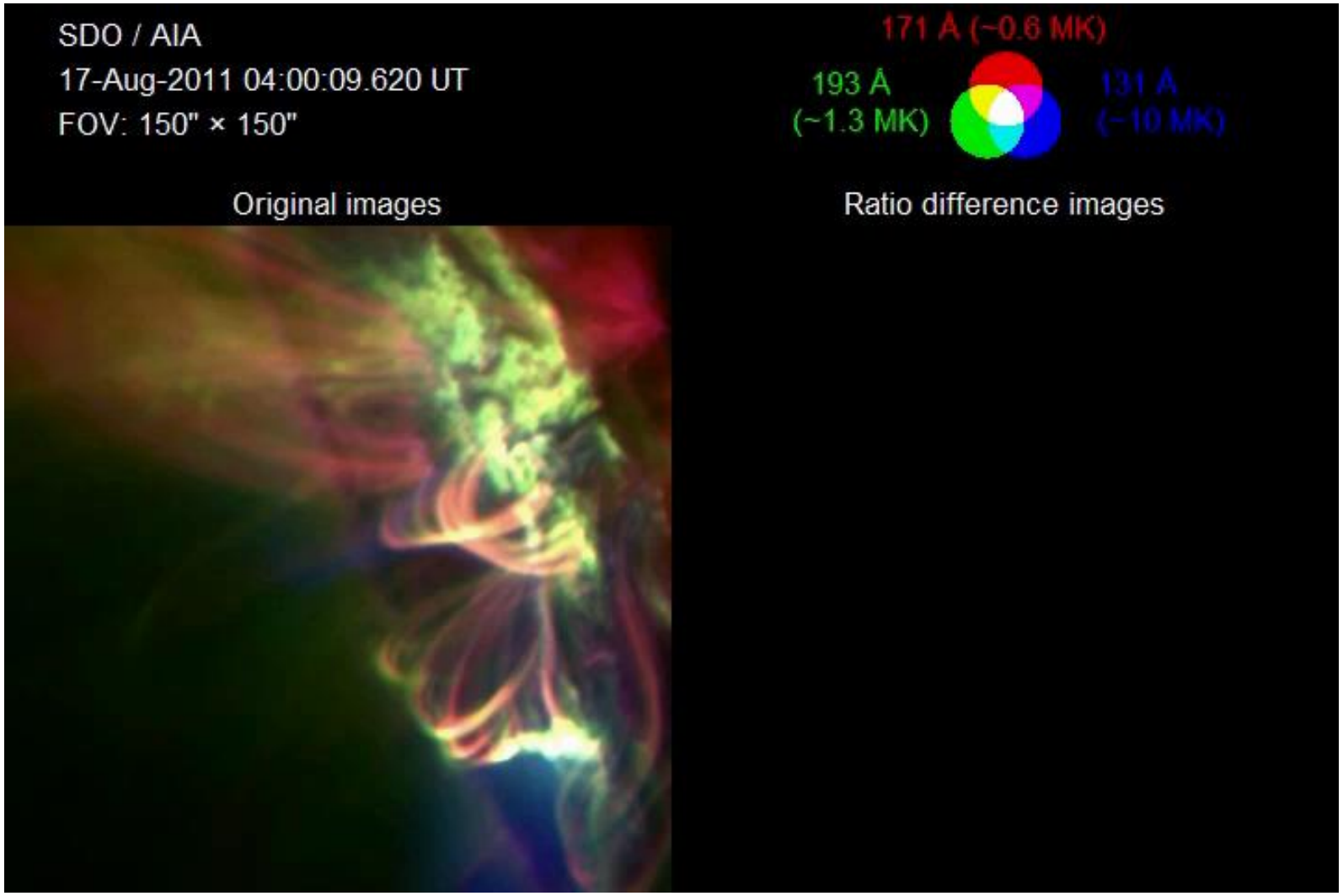
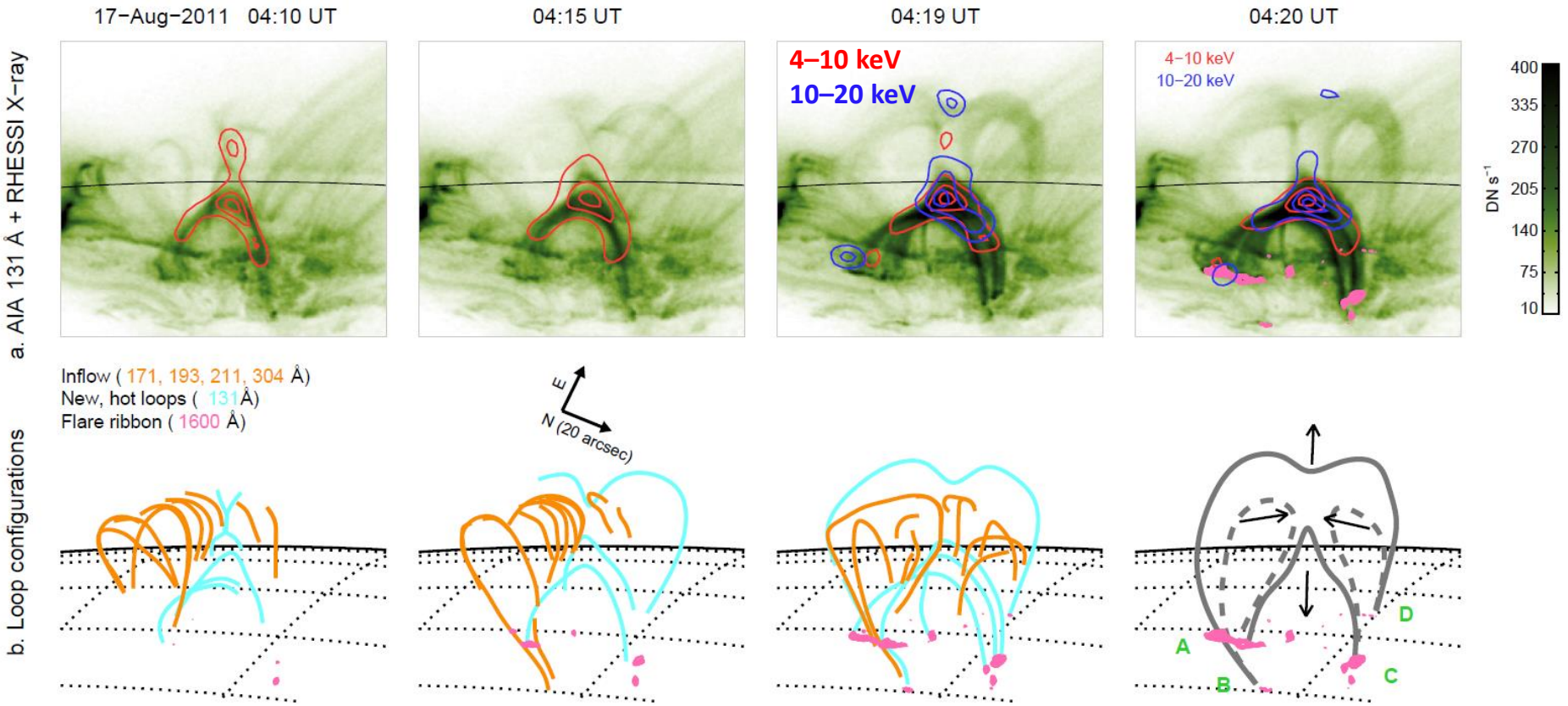


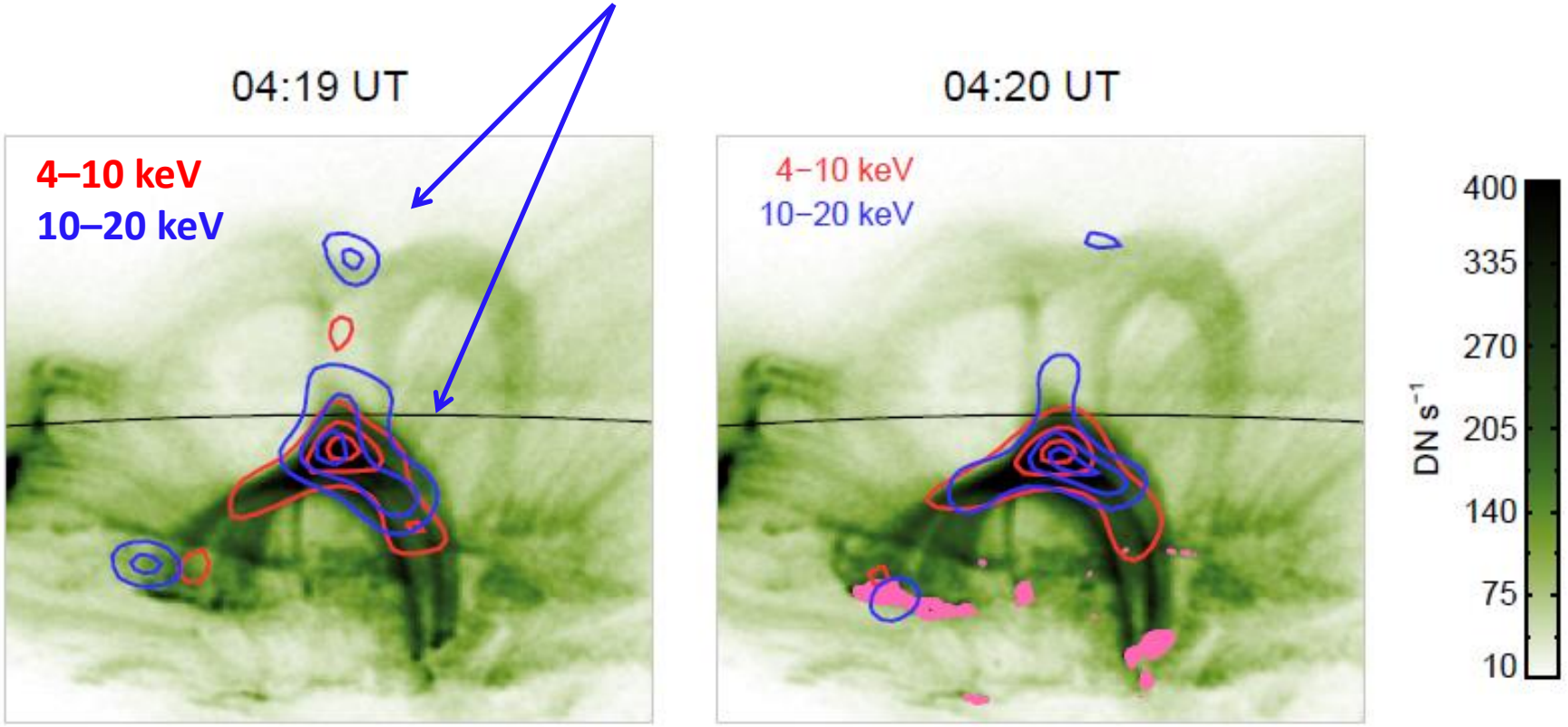
Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

- Magnetic reconfiguration: A-B and C-D → A-C (shrinking) and B-D (expanding)
- Inflow loops, outflow loops, flare ribbons and X-ray sources:
  comprehensive picture of reconnection & energy release from AIA and RHESSI



Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

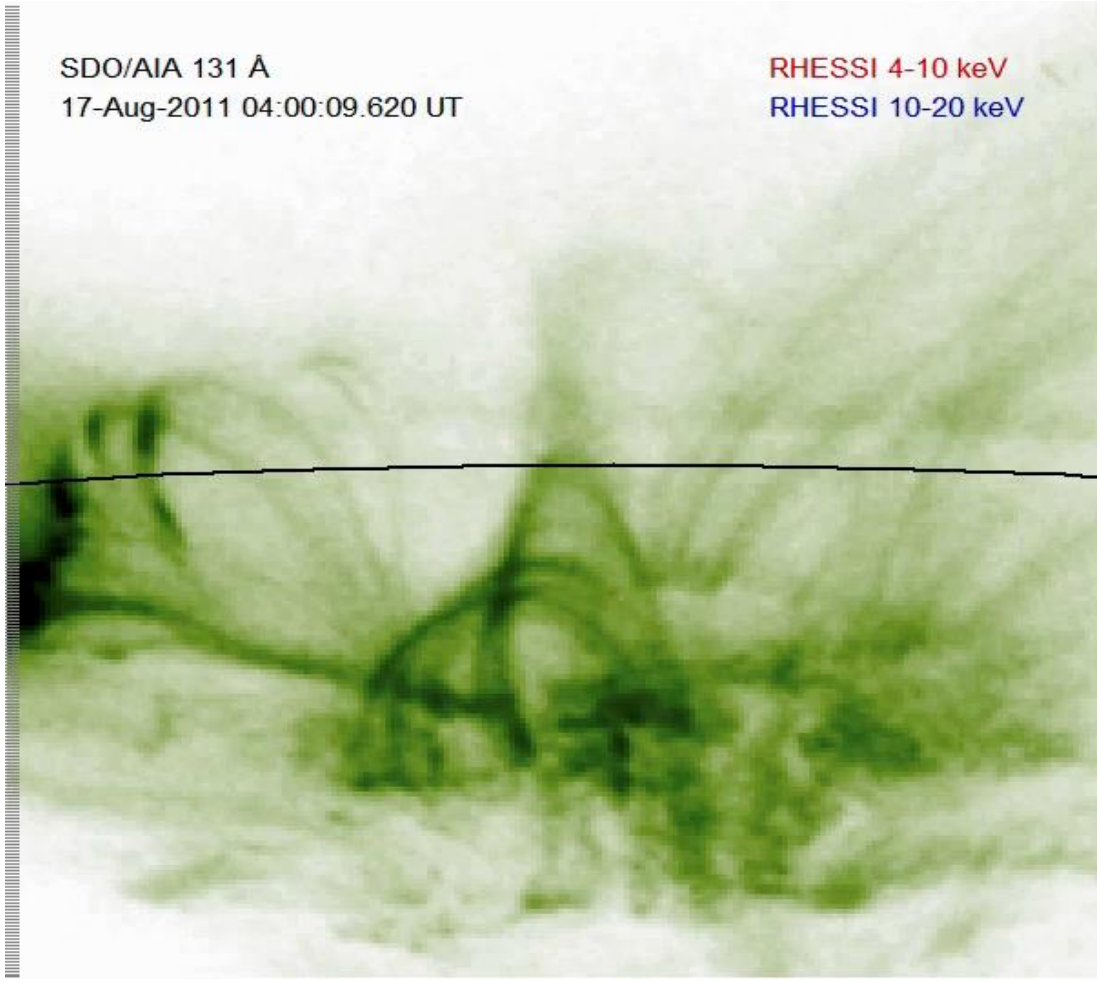
Double coronal X-ray sources: first seen in RHESSI data alone
(Sui & Holman 2003, Veronig et al. 2006)



RHESSI images: MEM NJIT

Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

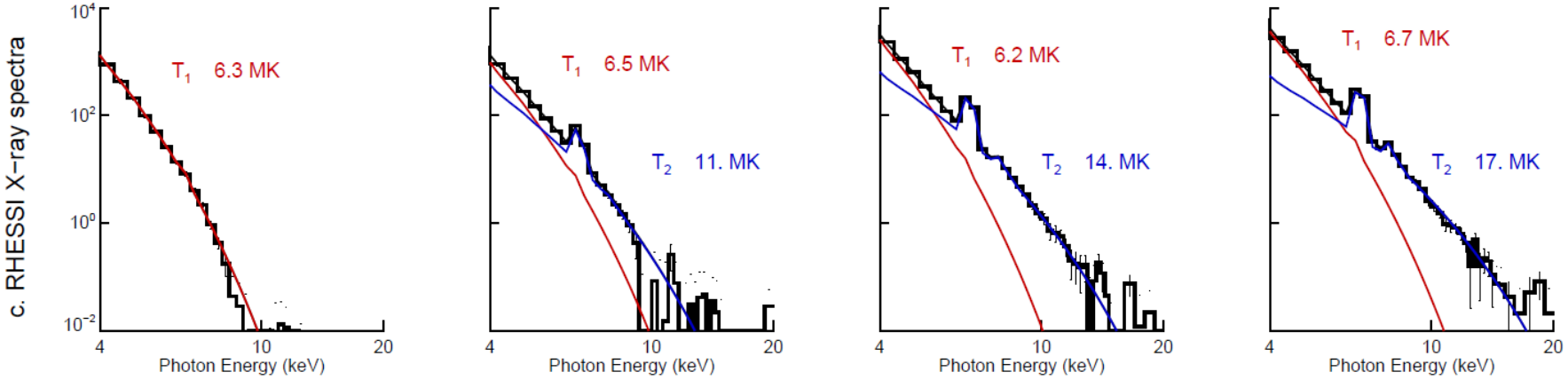
AIA 131 + RHESSI

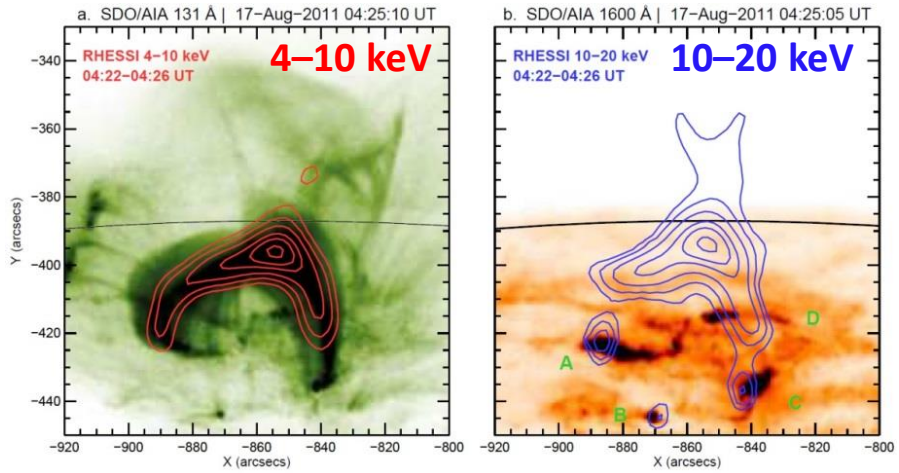


Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

RHESSI X-ray spectra:

- Fitting model: two isothermal component
- May indicate a small contribution of heating from non-thermal electrons.

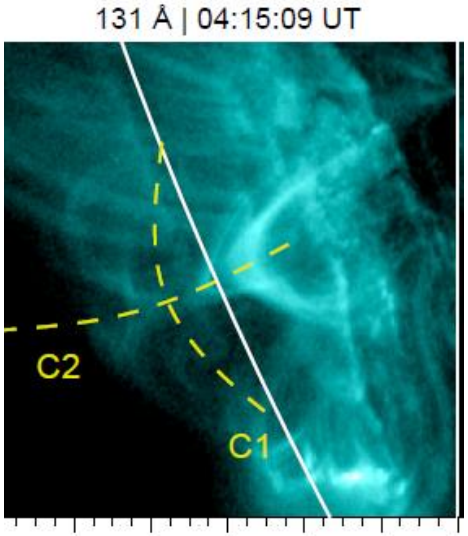


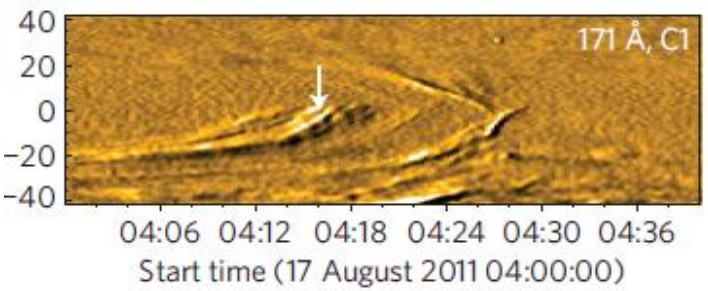


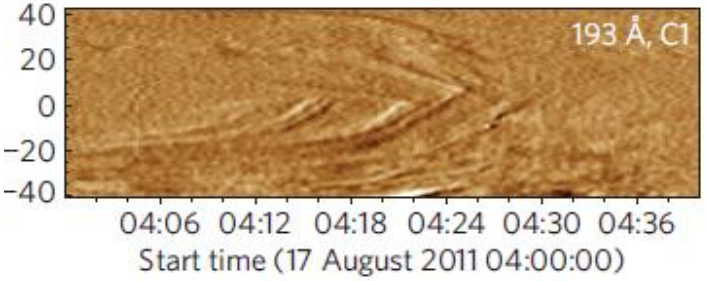
Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

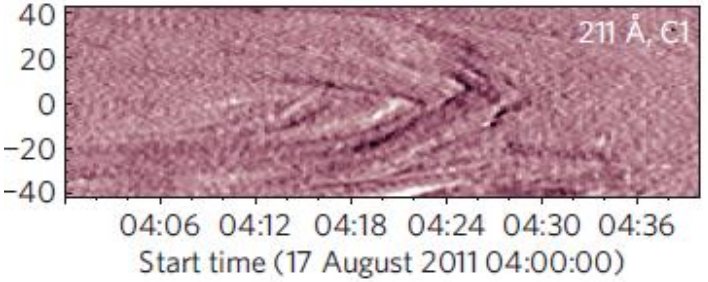
Inflow profiles (along C1)

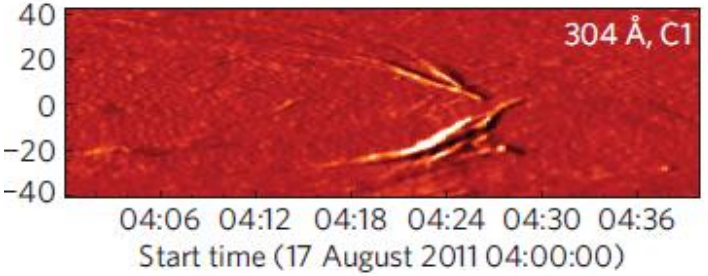
Outflow profiles (along C2)











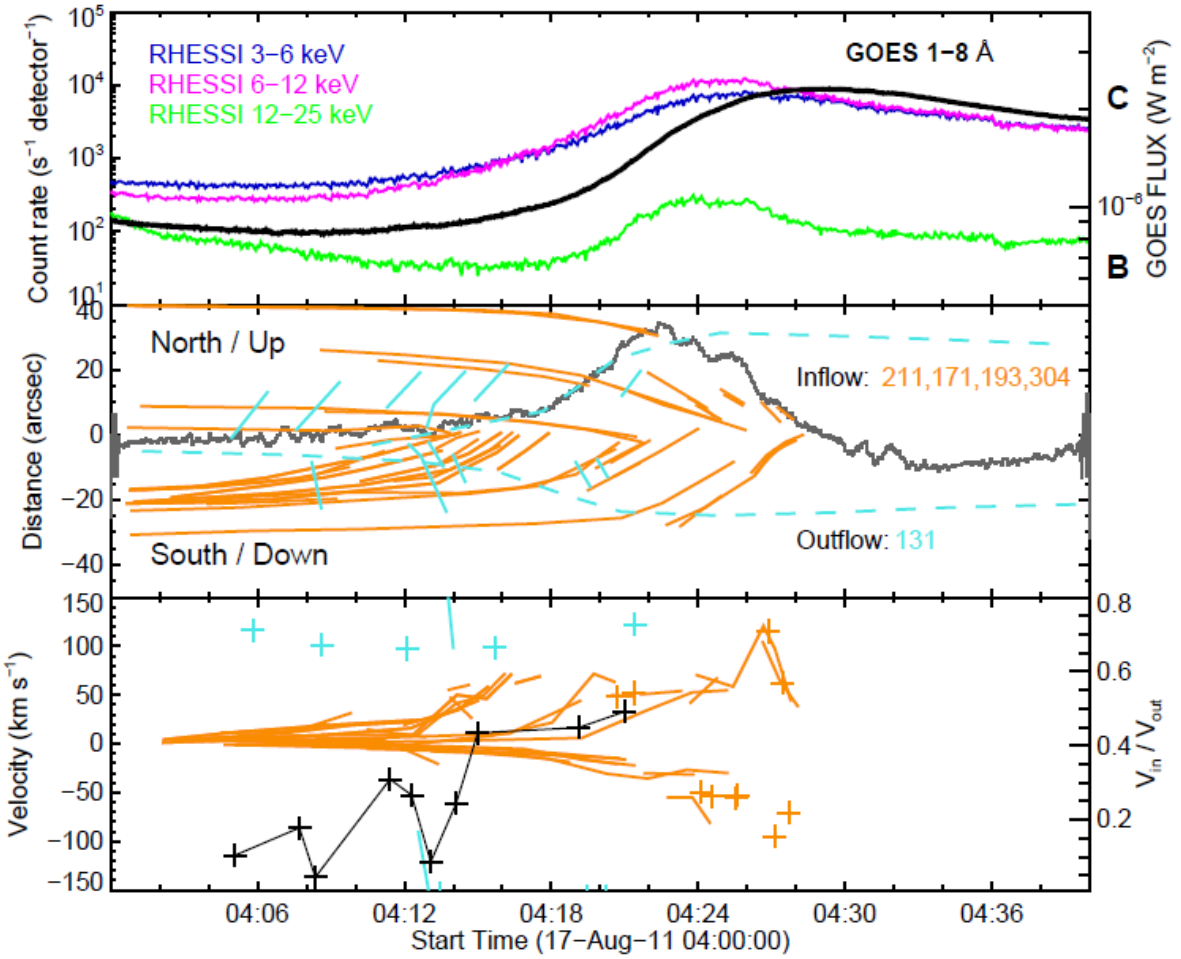
Imaging observations of magnetic reconnection
Su, Veronig, Holman, et al. 2013, Nature Phys.

Inflow:

- accelerating
- non-uniform
- non-steady
- asymmetric

GOES flux started decreasing after last inflows were seen
→ Energy input stopped

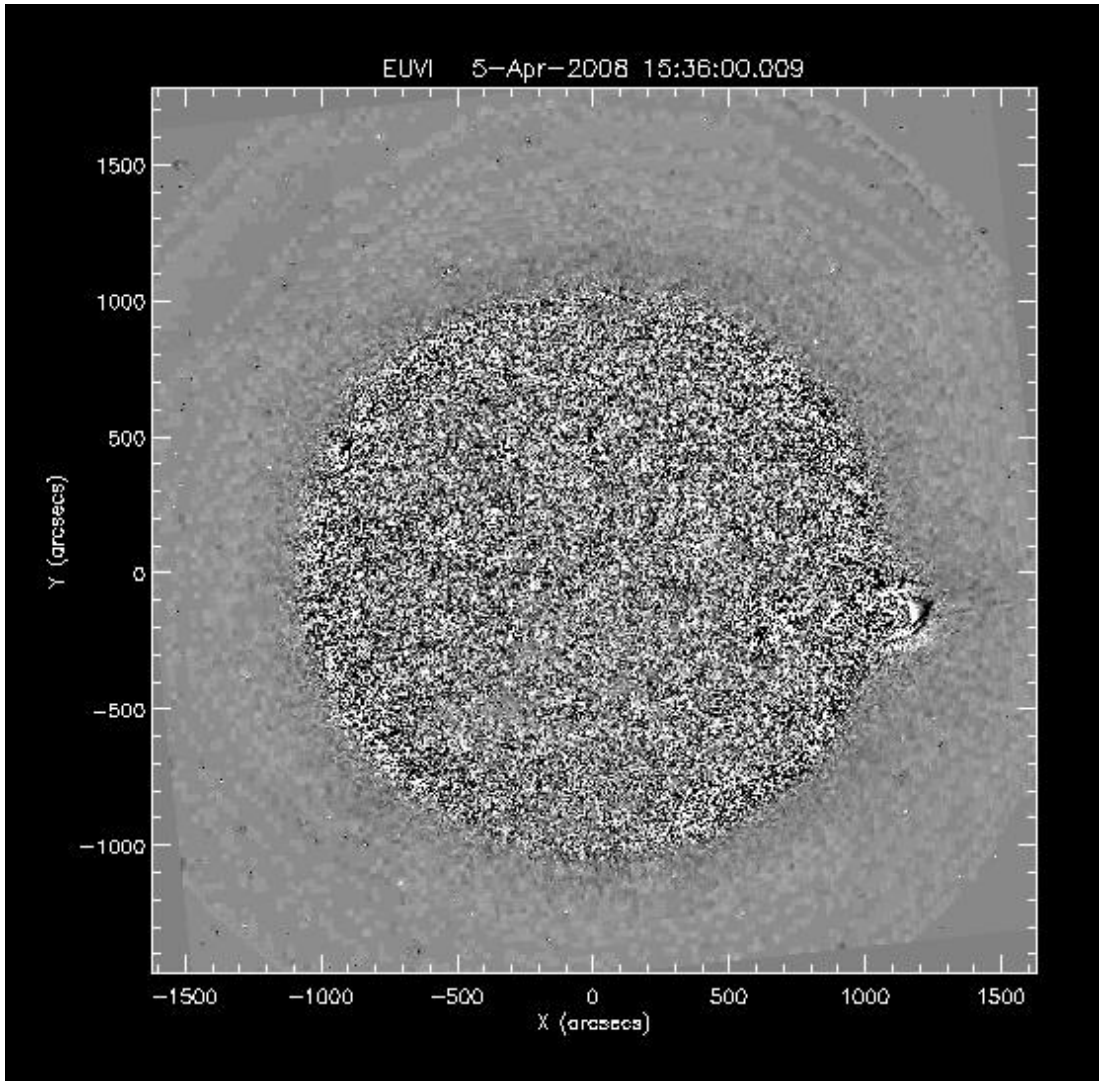
Estimated reconnection rate changes with time:
~0.05-0.5



$$M_A = V_{in}/V_A \cong V_{in}/V_{out}$$

3) Relation between CMEs and flares

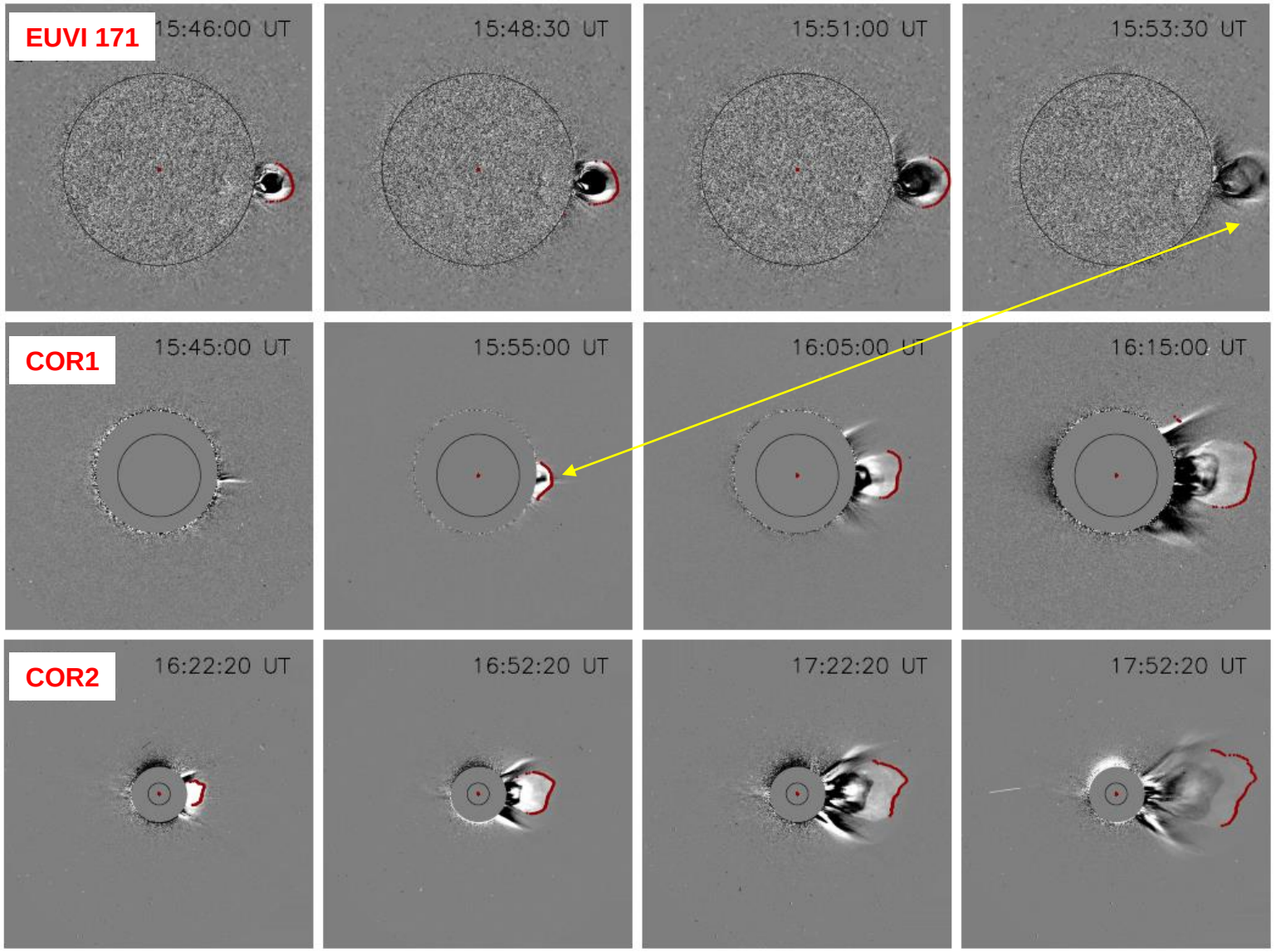
CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ



CME kinematics from combined STEREO EUVI, COR1, COR2 observations.

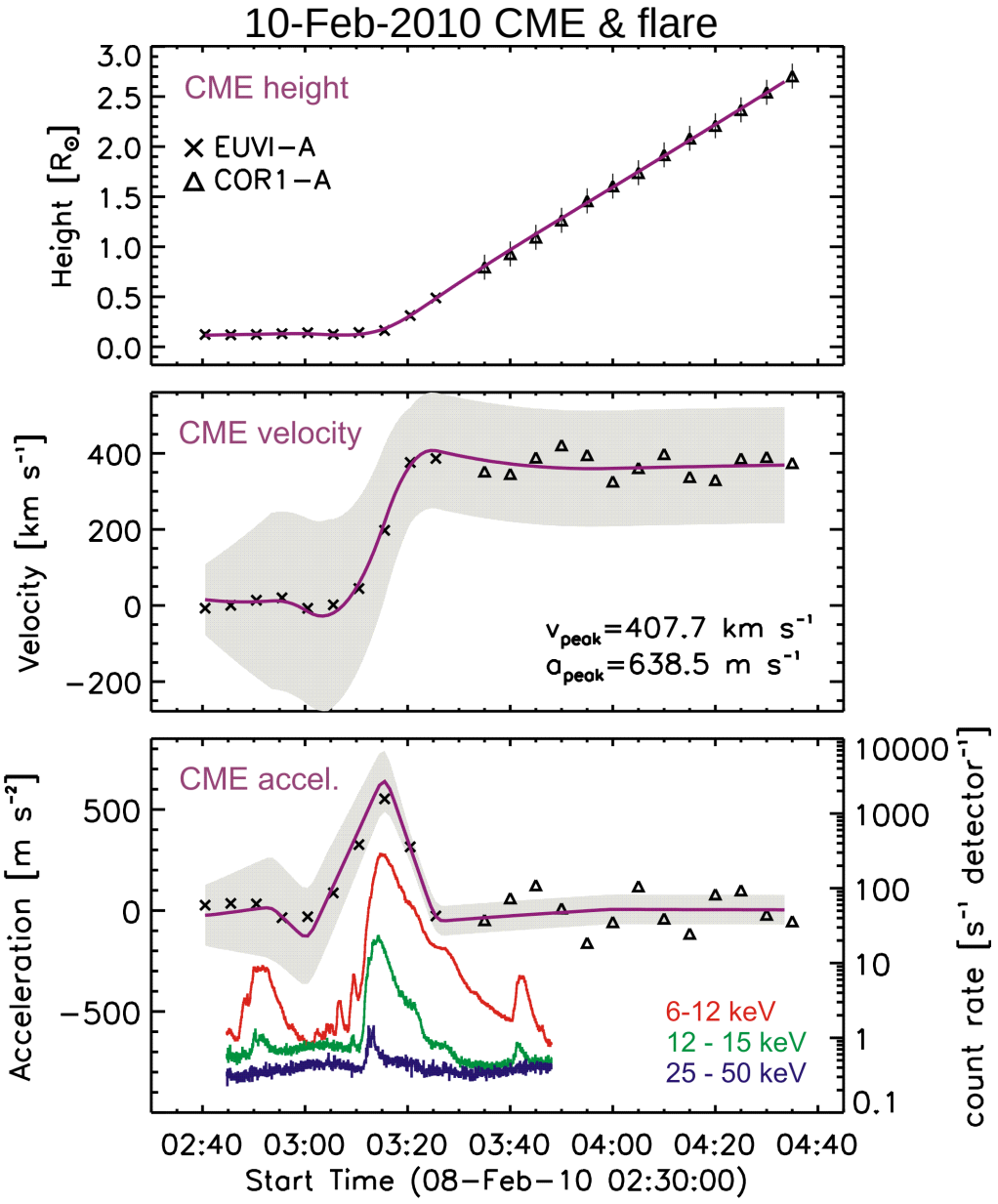
CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ

5-Apr-2008 CME



STEREO EUVI & COR1 & COR2:
- overlapping FOV
- high cadence

CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ



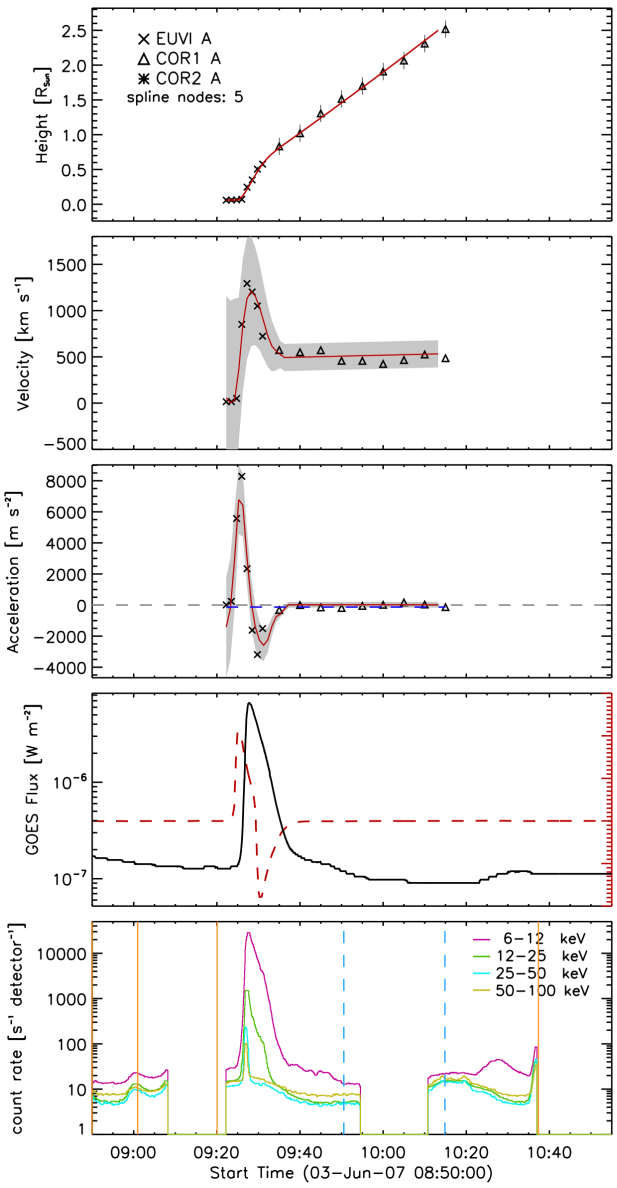
CME height vs time

CME velocity vs time

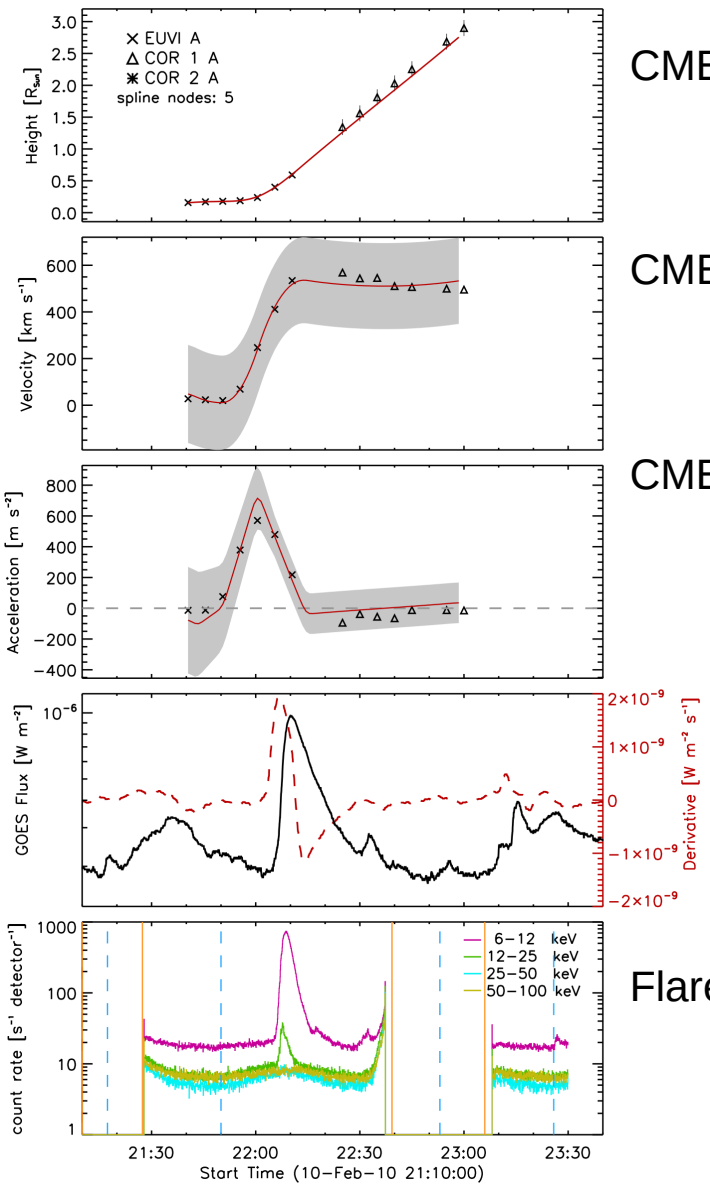
CME acceleration vs time
&
RHESSI flare X-rays

CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ

3-Jun-2007



10-Feb-2010



CME height vs time

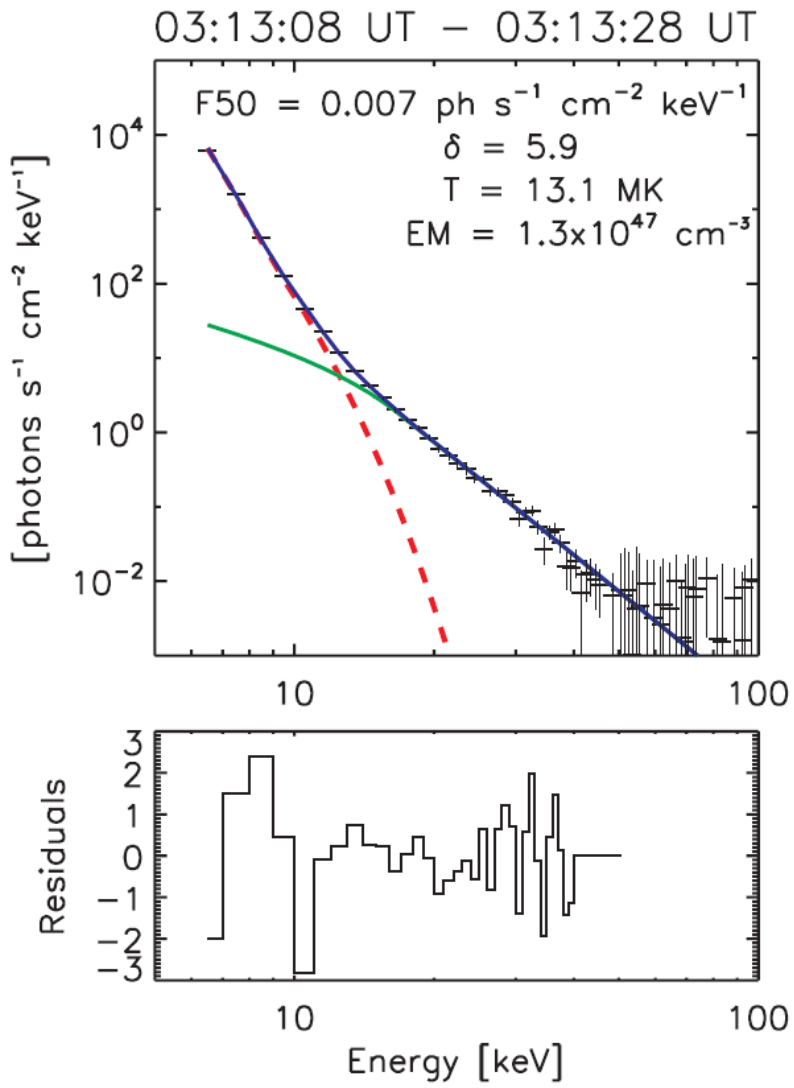
CME velocity

CME acceleration

Flare GOES SXR & derivative

Flare RHESSI HXR flux

CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ

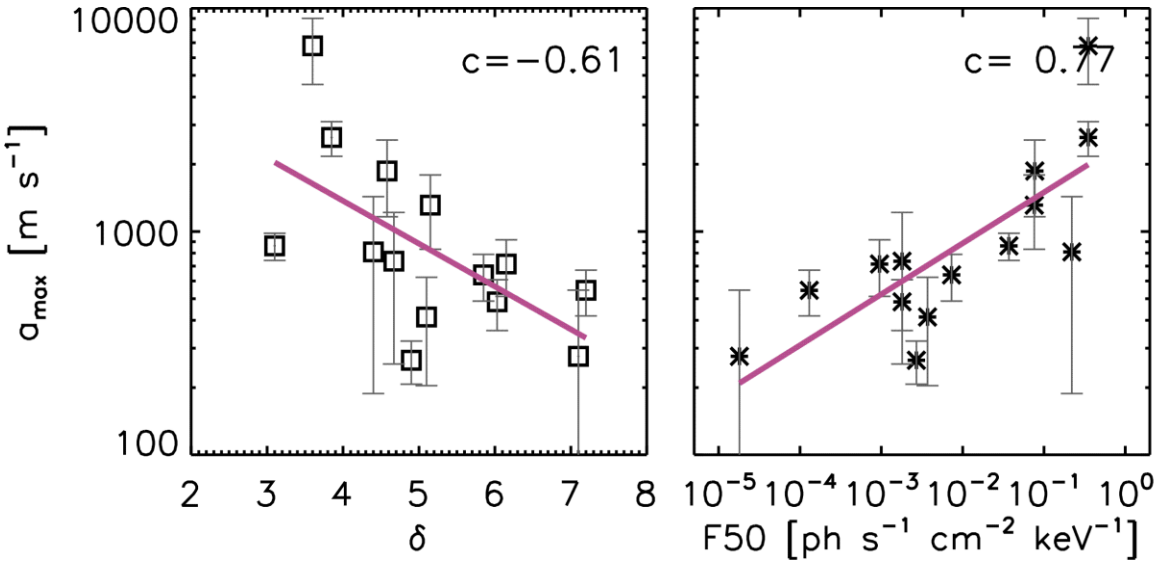


1) CME kinematics: h(t), v(t), a(t); v(h), a(h).

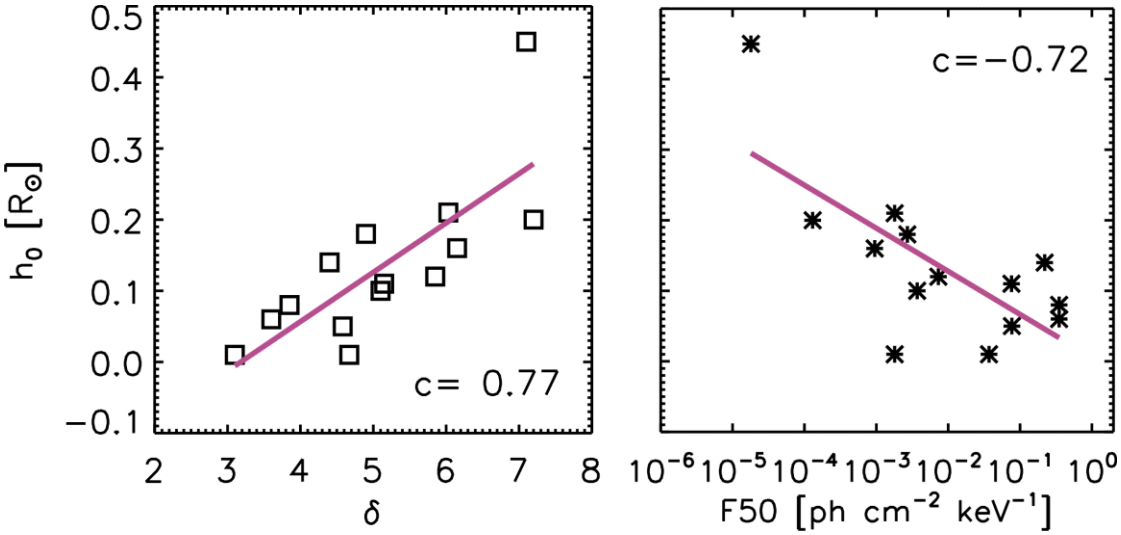
2) Derived and fitted RHESSI spectra during peak of the associated flare.

3) Statistical relation between CME and flare properties.

CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ

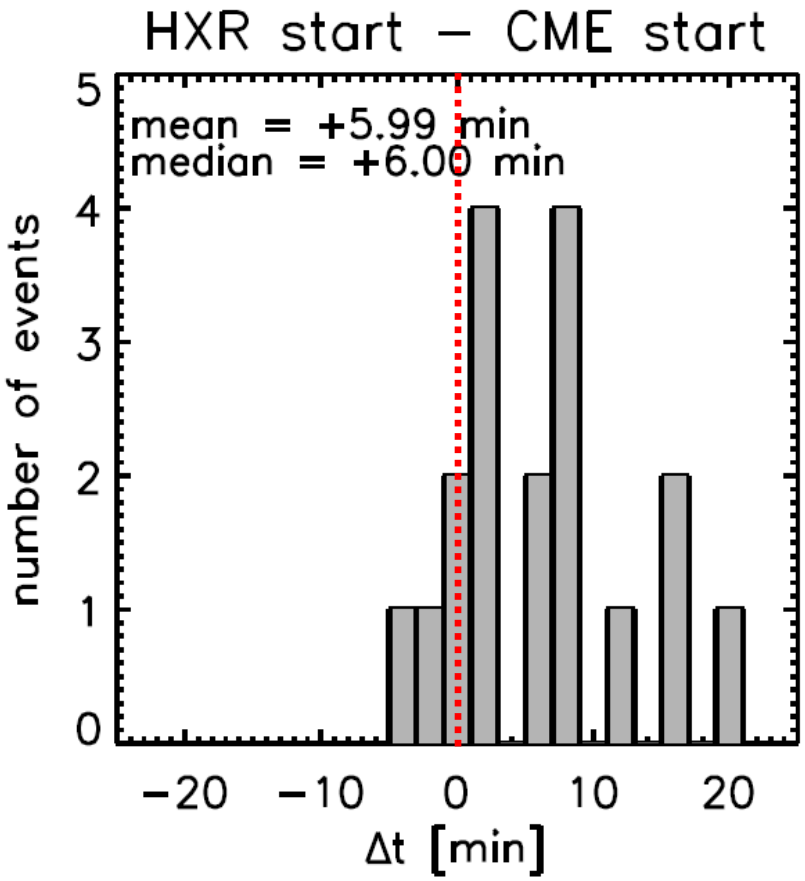


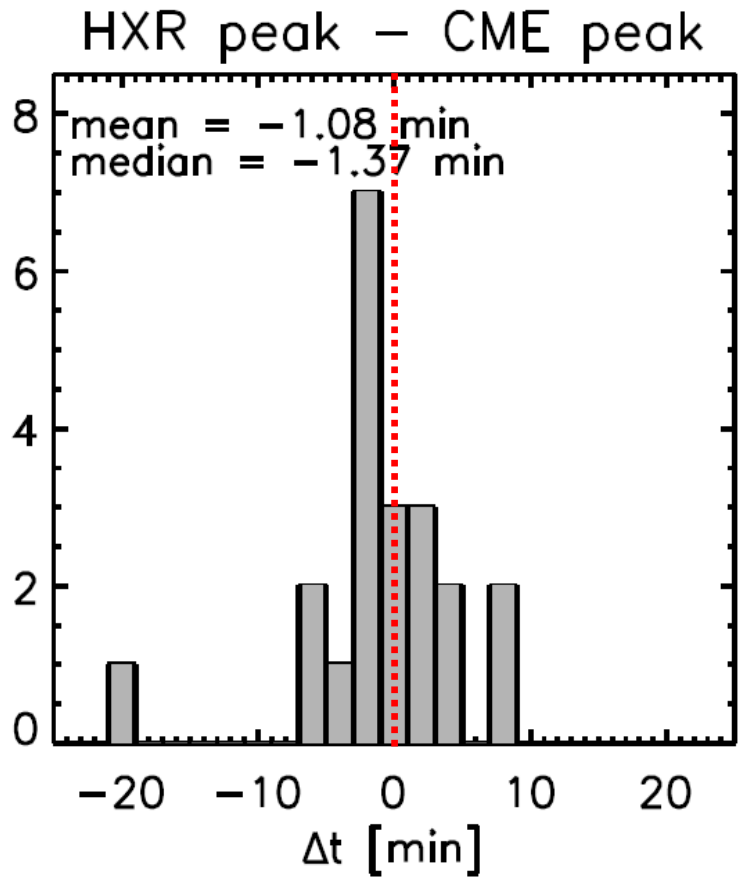
- CMEs with larger peak acceleration are associated with flares with harder electron spectra and larger electron fluxes.



- CMEs erupting from low in the corona (stronger fields) are associated with flares with harder electron spectra and larger electron fluxes.

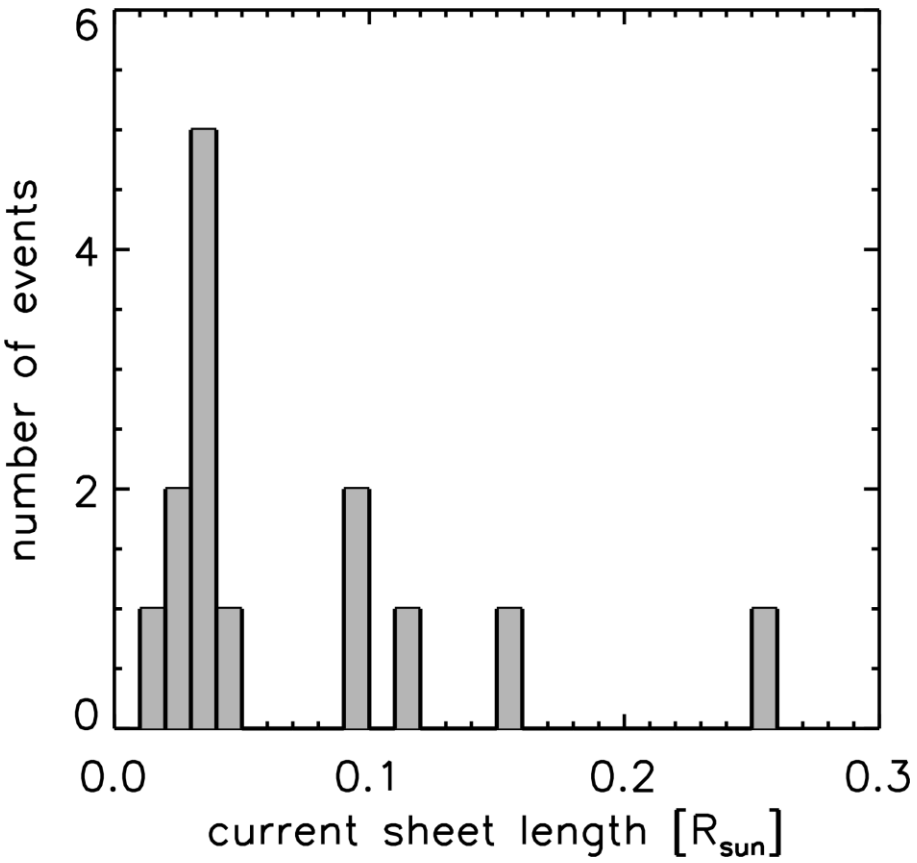
CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ





- CME acceleration starts before fast particle acceleration in associated flare (~85%).
- Peak of CME acceleration and flare energy release occur closely synchronized in impulsive CMEs, in 75% $|\Delta t| < 5$ min

CME dynamics and nonthermal flare characteristics
Berkebile-Stoiser, Veronig, Bein, Temmer, 2012, ApJ

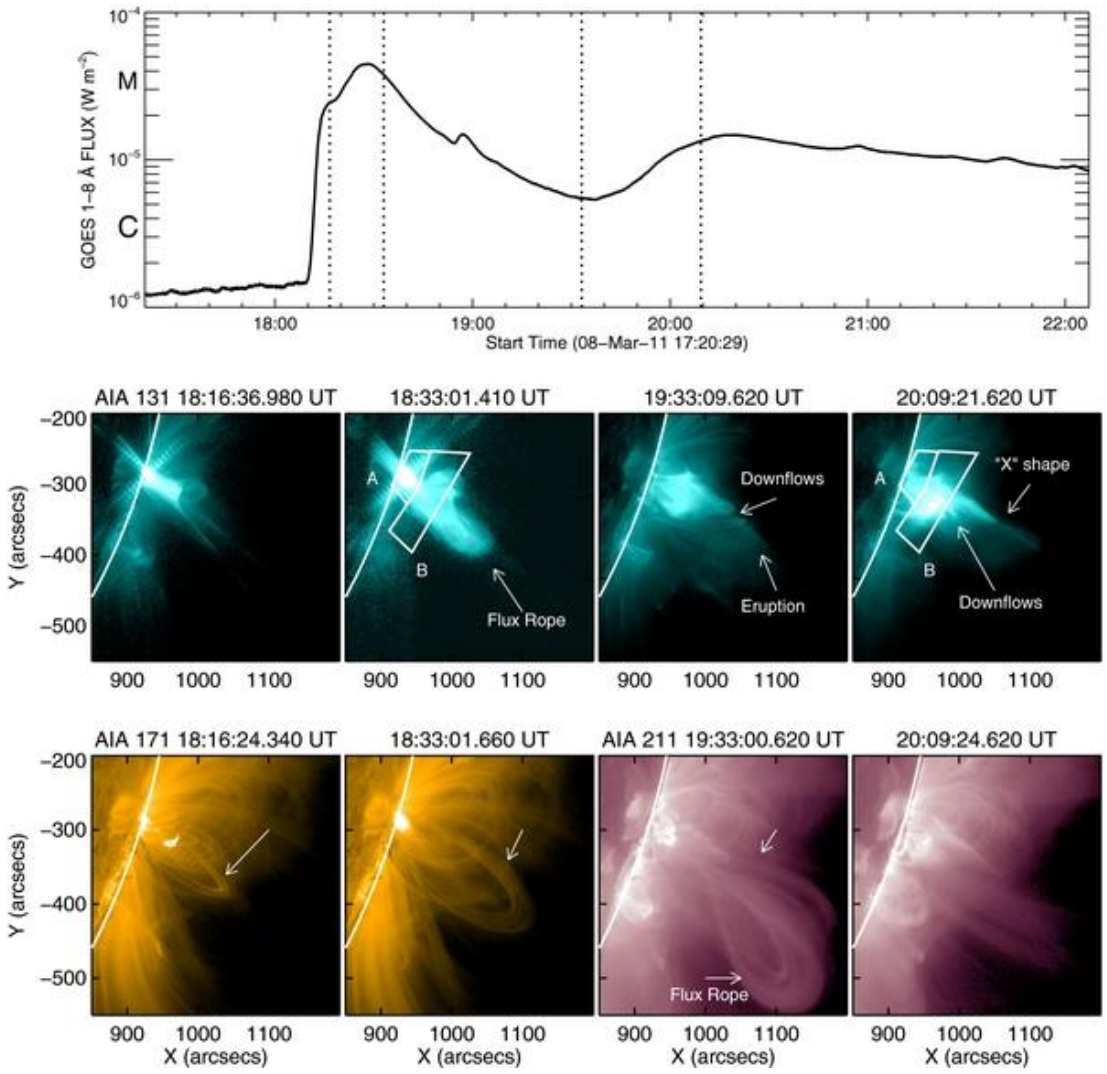


$H \sim 21 \pm 7$ Mm

- Estimate of the current sheet length at the onset of impusive magnetic reconnection and particle acceleration.

Two-stage eruption, secondary heating
Su, Dennis, Holman et al. 2012b, ApJL

Case study: Secondary heating phase in flare is related to delayed CME eruption.



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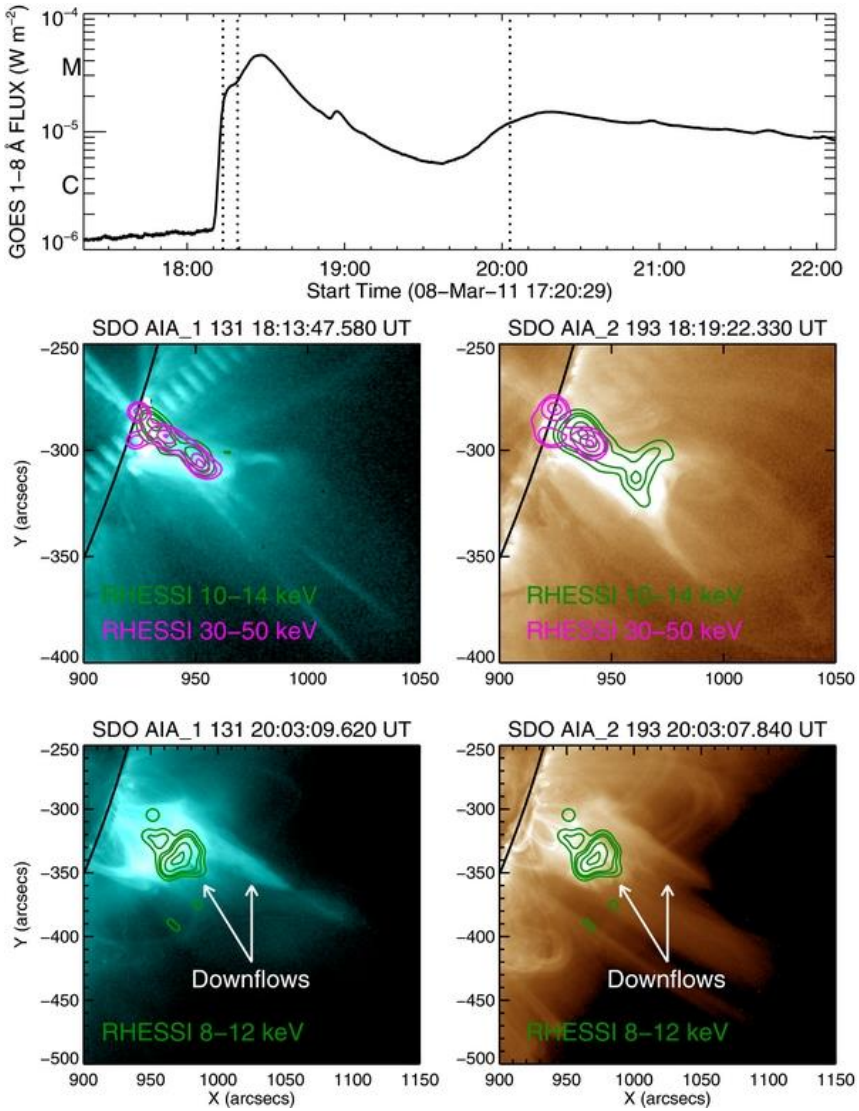

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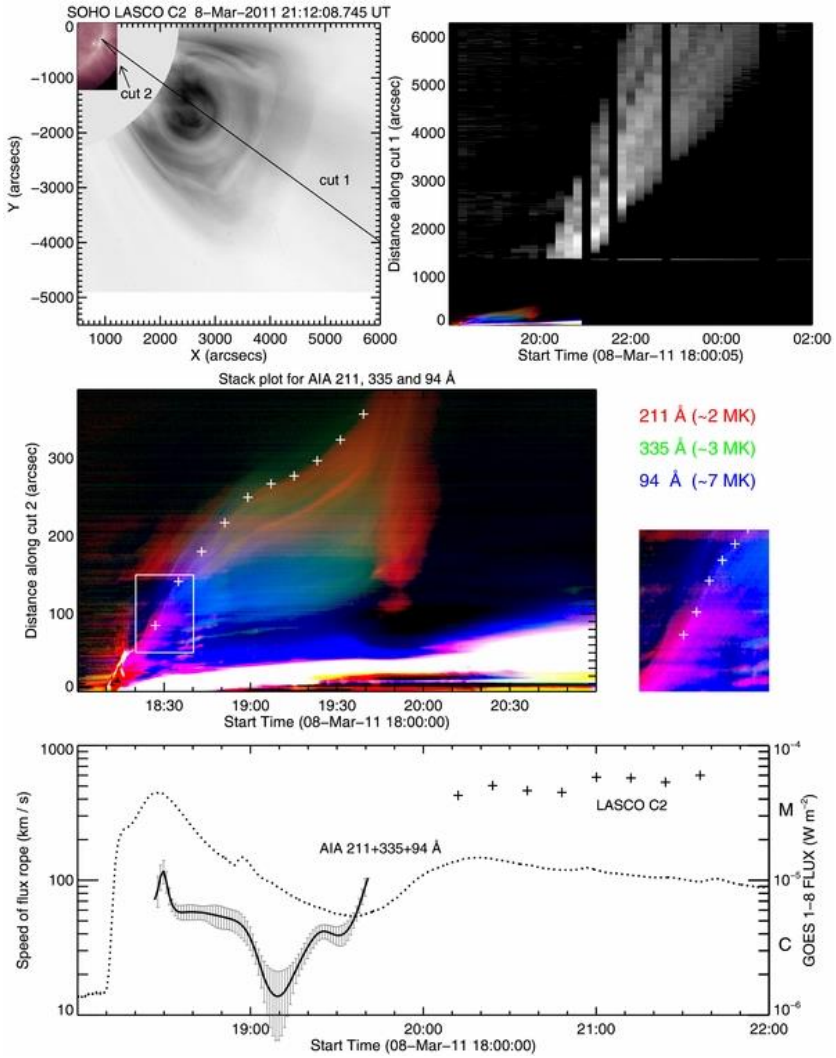

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