Magnetic Evolution, Reconnection, and Particle Acceleration in Solar Flares

Insights from RHESSI

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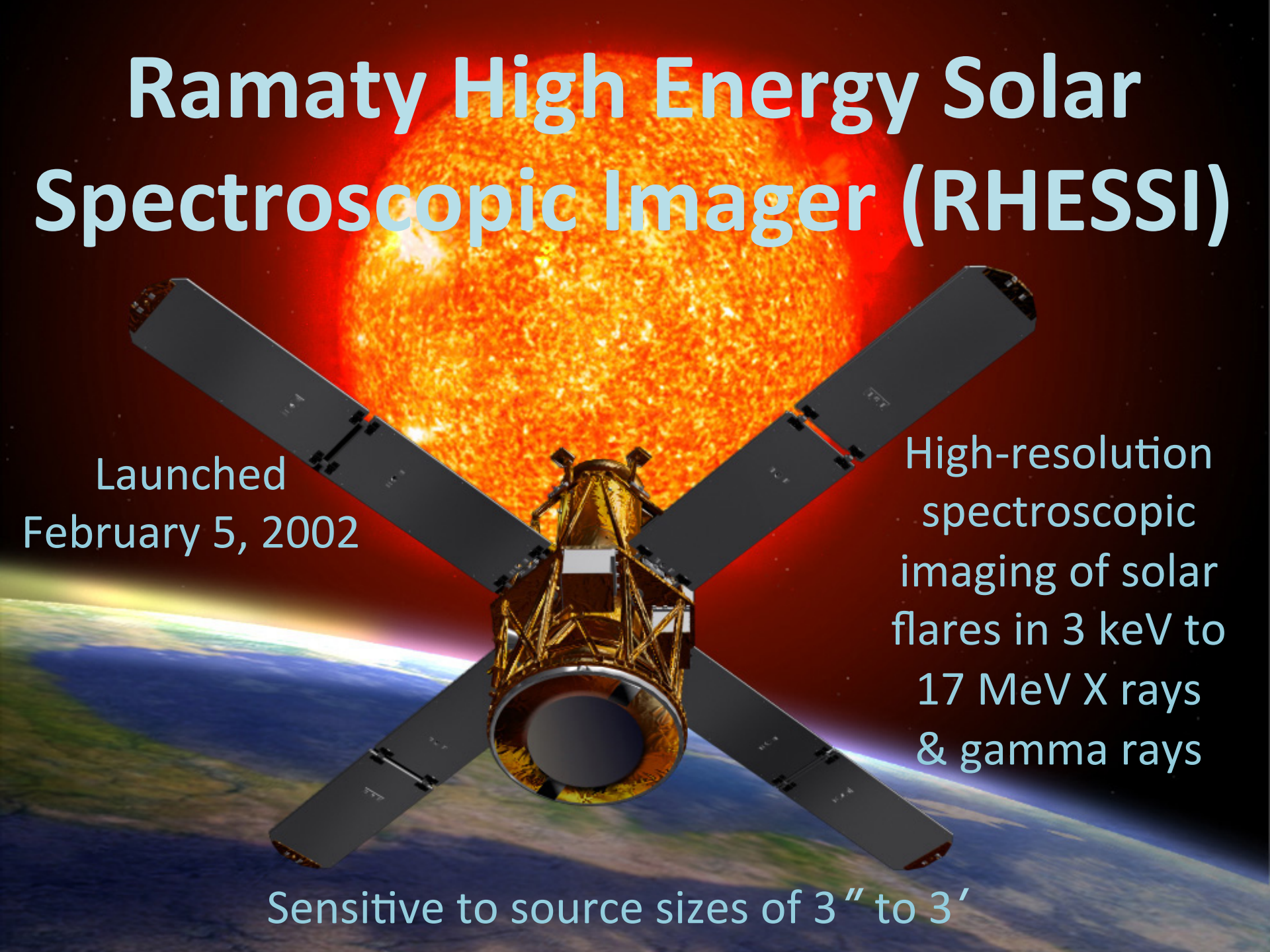
Ramaty High Energy Solar Spectroscopic Imager (RHESSI)

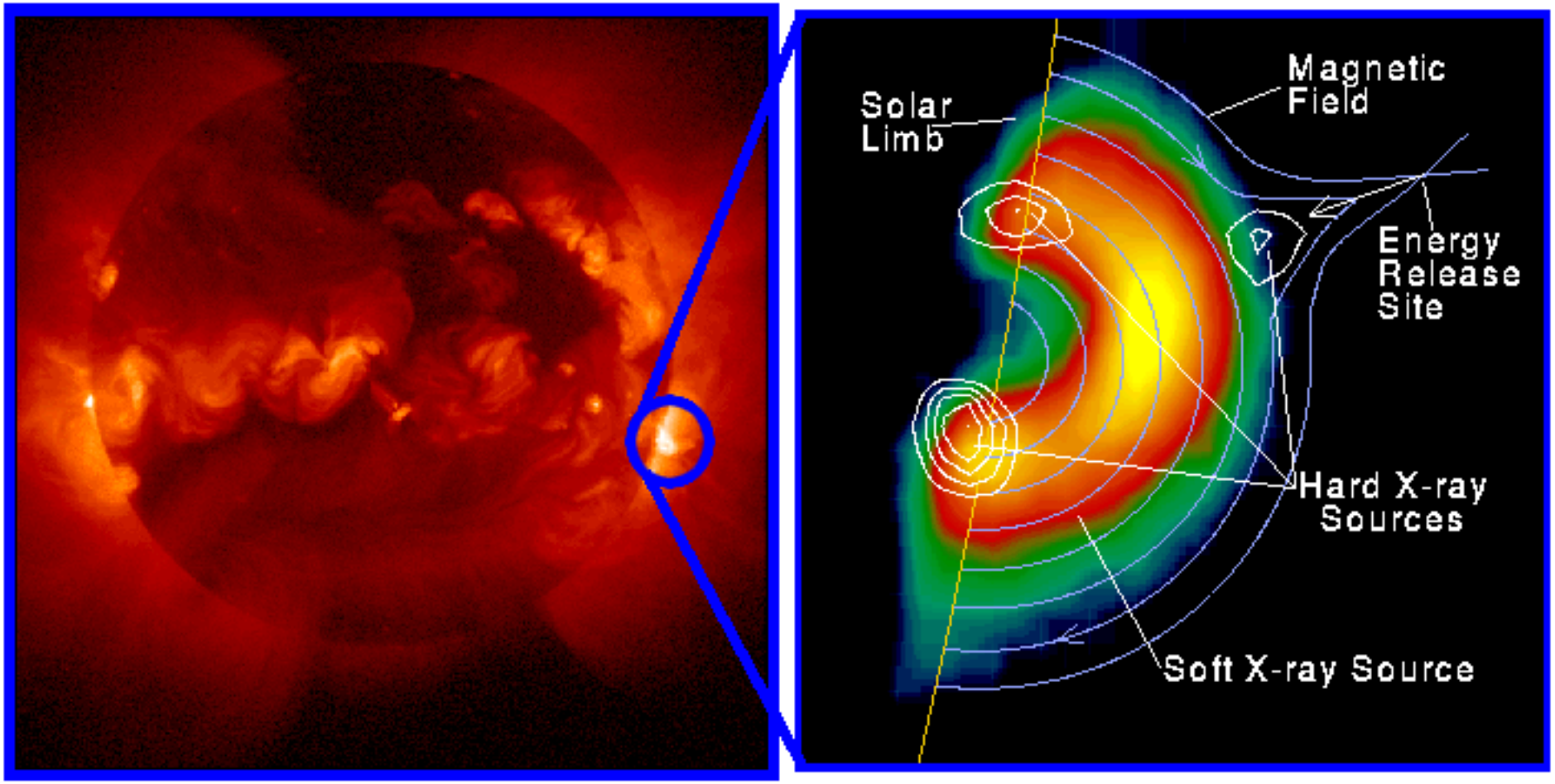


Launched
February 5, 2002

High-resolution spectroscopic imaging of solar flares in 3 keV to 17 MeV X rays & gamma rays

Sensitive to source sizes of 3″ to 3′

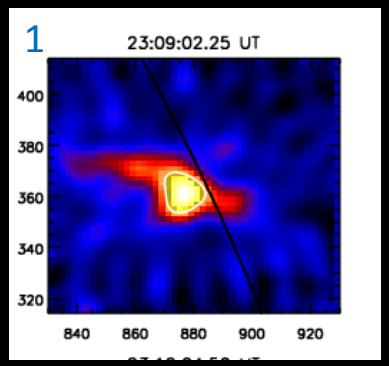
The “Masuda” Flare
Yohkoh - 1992 January 13

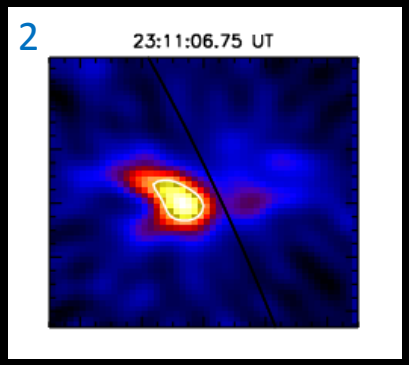


After Masuda, S., Kosugi, T., Hara, H., Tsuneta, S., & Ogawara, Y. 1994, Nature, 371, 495

Evolution of a Solar Flare in X-Rays

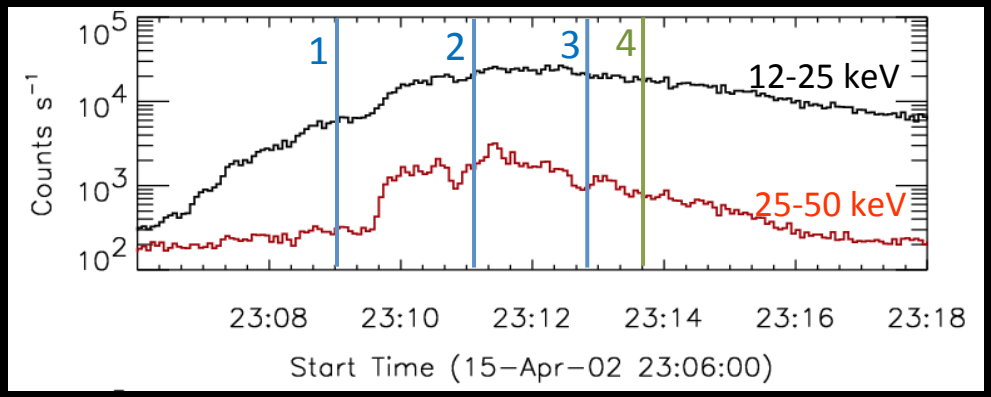
Sui & Holman, ApJL, 2003

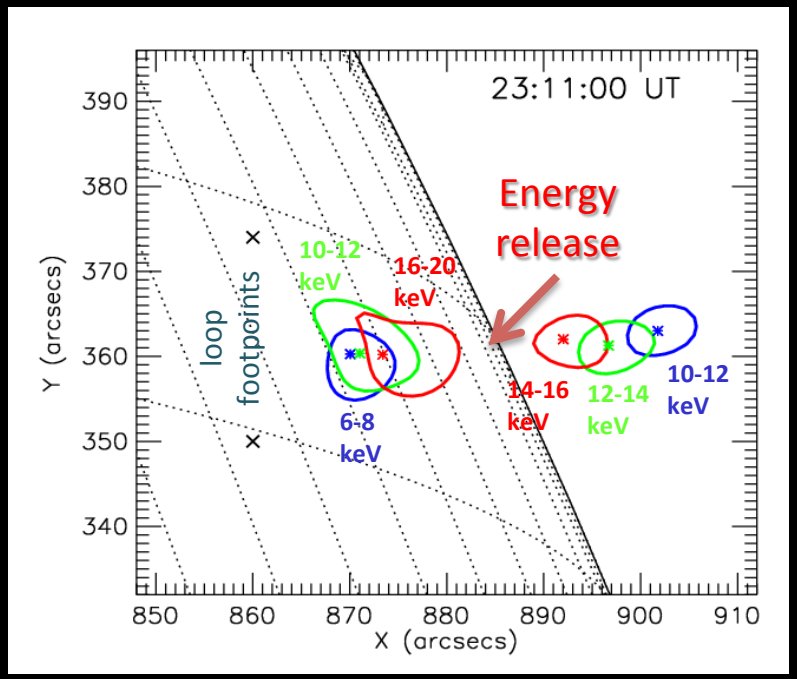


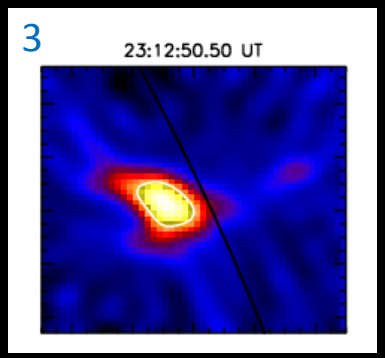


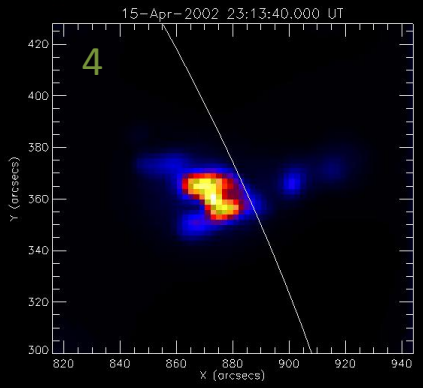
RHESSI 10-25 keV Images: Loop + Compact Coronal Source (1 – 3)

RHESSI Light Curves





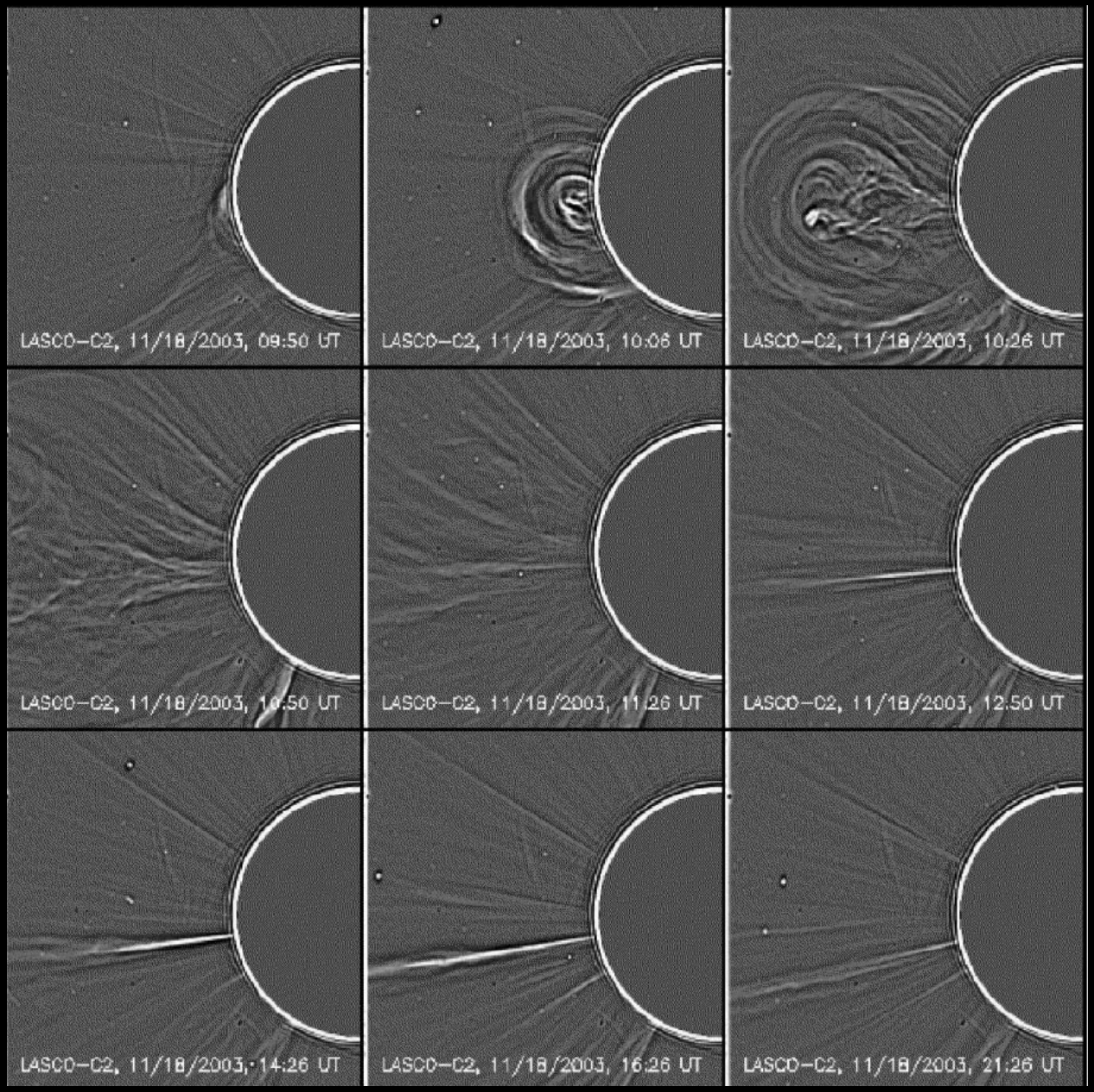




New Coronal Sources along current sheet (4)

2003 November 18 CME: Enhanced LASCO C2 Images

Post-CME Current Sheet!



Lin, J., Ko, Y.-K., Sui, L., Raymond, J. C., Steinborg, G. A., Jiang, Y., Zhao, S. & Mancuso, S., 2005, Ap. J. 622, 1251

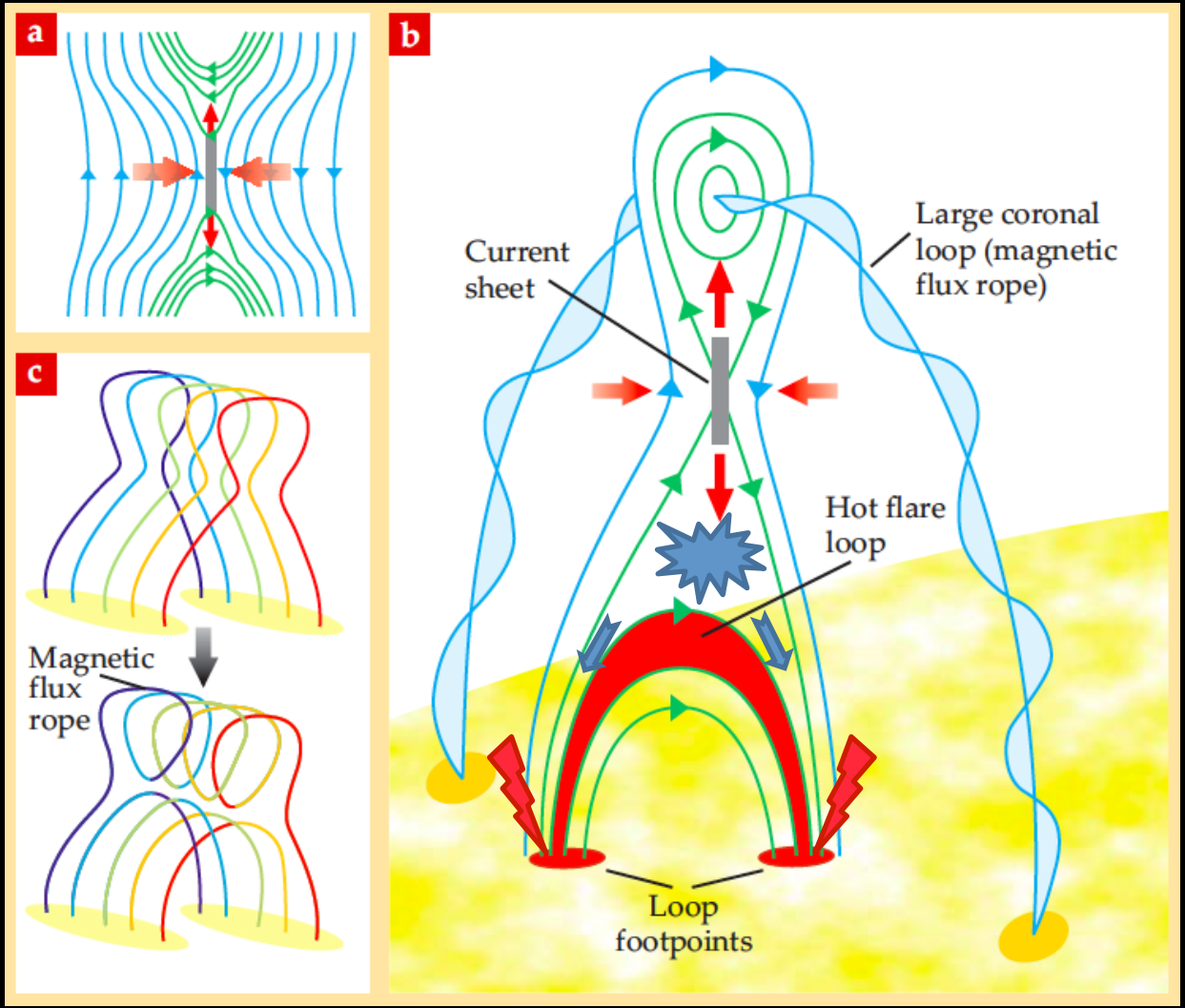
Implications

- Energy release site located in corona between the two multi-thermal X-ray sources
- X-ray source above energy release site travels outward as part of a coronal mass ejection (CME)
- Extended, narrow current sheet remains behind the CME
- Energy release and electron acceleration rates greatest when energy release region (current sheet) is compact
- New, compact sources can develop within the extended current sheet

The Standard Model for Solar Eruptive Events (SEEs)

As the ribbons are sheared

- Footpoints separate
- Loop tops expand upward
- Loops collapse inward and reconnect



Electron Acceleration

Electron Propagation

Thick-Target Brems-strahlung X-Rays and Chromospheric Evaporation

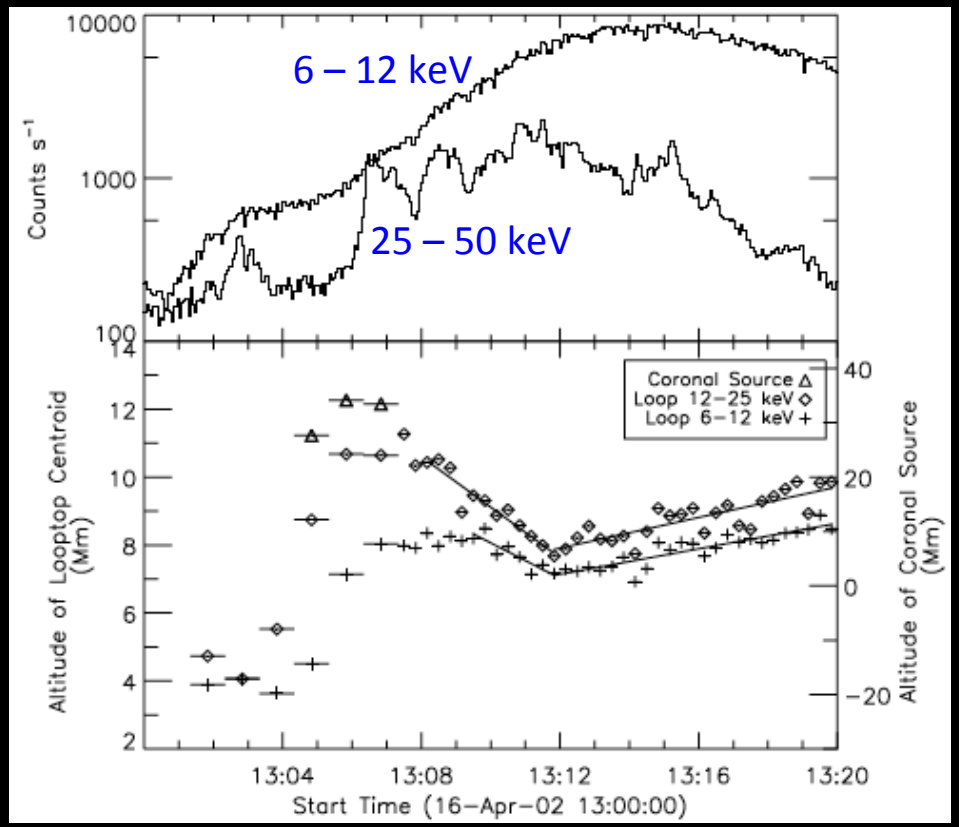
Holman, G. D. 2012, *Physics Today*, April issue

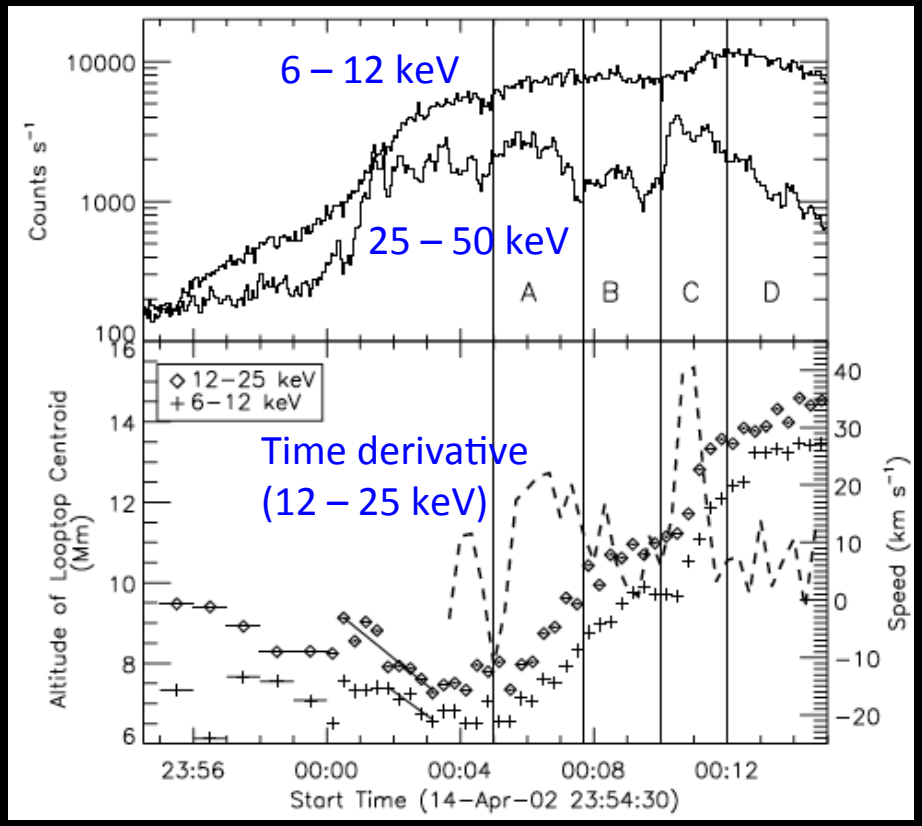
Evolution of Accelerated Electrons

- A co-spatial return current resupplies electrons to the acceleration region and stabilizes the beam of streaming electrons
- Return-current energy losses distort X-ray spectra and heat coronal plasma

- See *Poster 121*: Evidence for a Co-Spatial Return Current in RHESSI Solar Flare Spectra (Meriem Alaoui & Gordon Holman)

X-Ray Loop-Top Height Time Evolution Observed by *RHESSI*

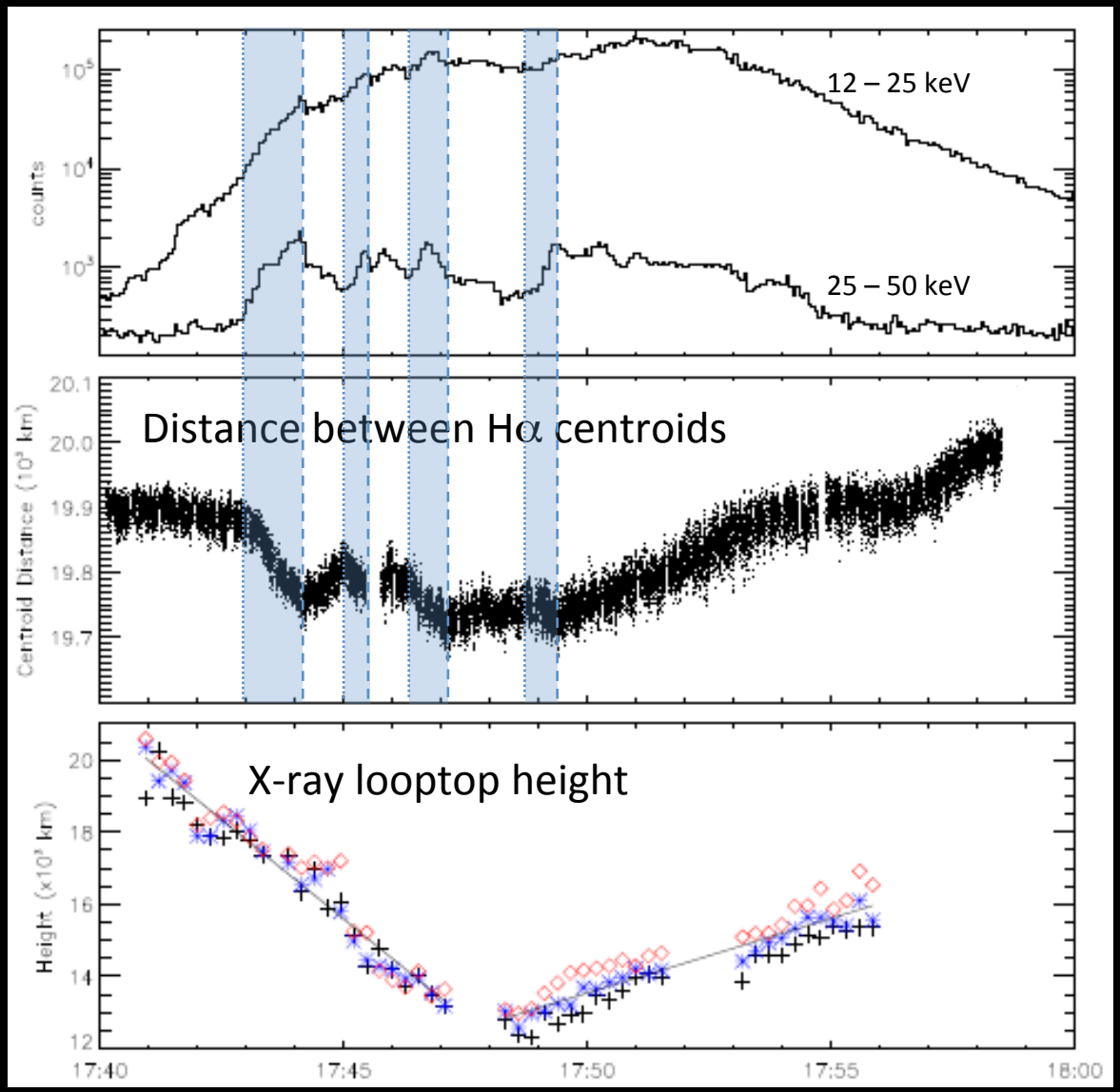




- Up – Down – Up evolution
- Plasma temperature increases with height
- Electron acceleration correlated with evolution

Sui, Holman & Dennis, ApJ, 2004

Correlation of Looptop and Footpoint Motions and X-ray Flux



Electron acceleration rate correlates with rate at which distance between footpoints decreases

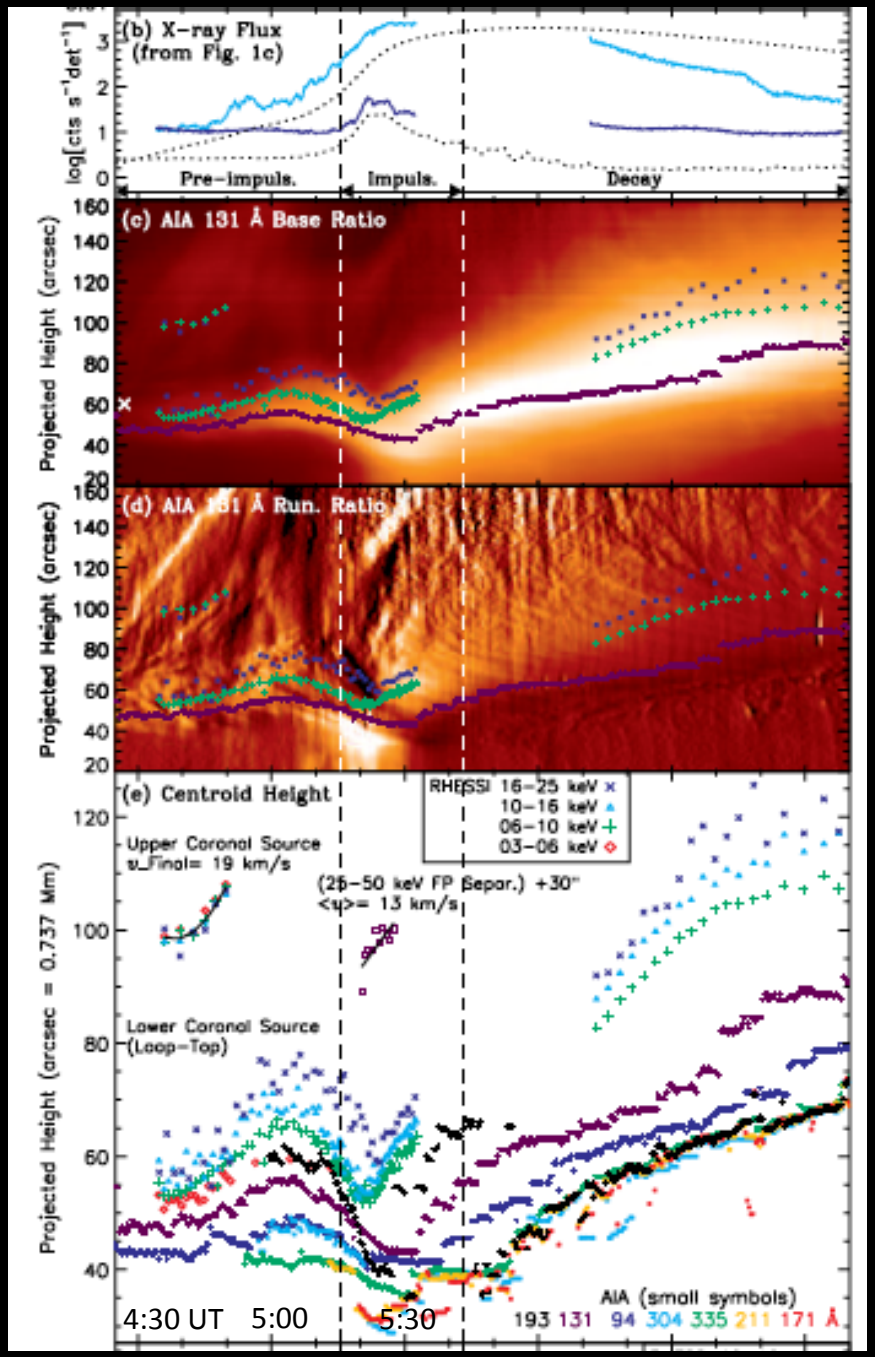
Shen, Zhou, Ji, Wang, Cao & Wang, ApJ, 2008

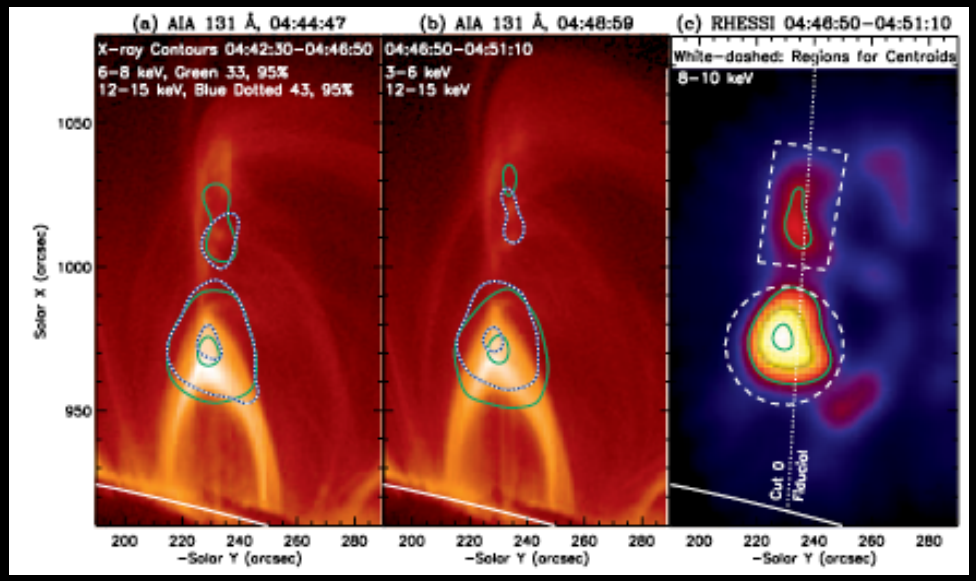
2012 July 19 Event

Below: *RHESSI* X-ray sources in the upper and lower reconnection jets

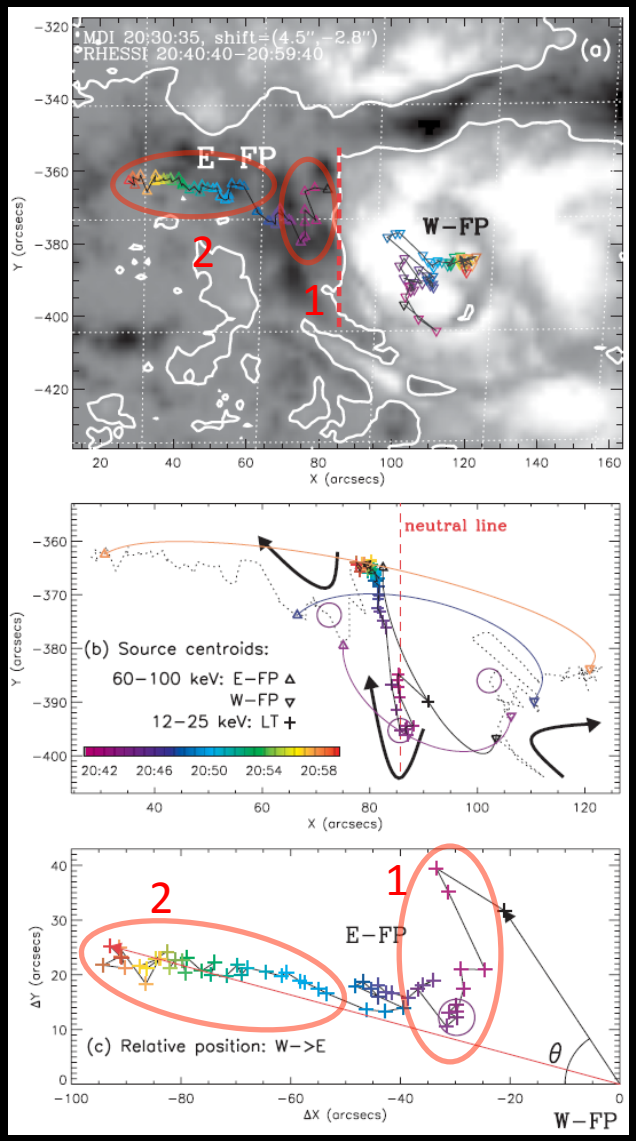
Left: Height-time plots showing the Up-Down-Up evolution of the loop-top emission from *RHESSI* and AIA

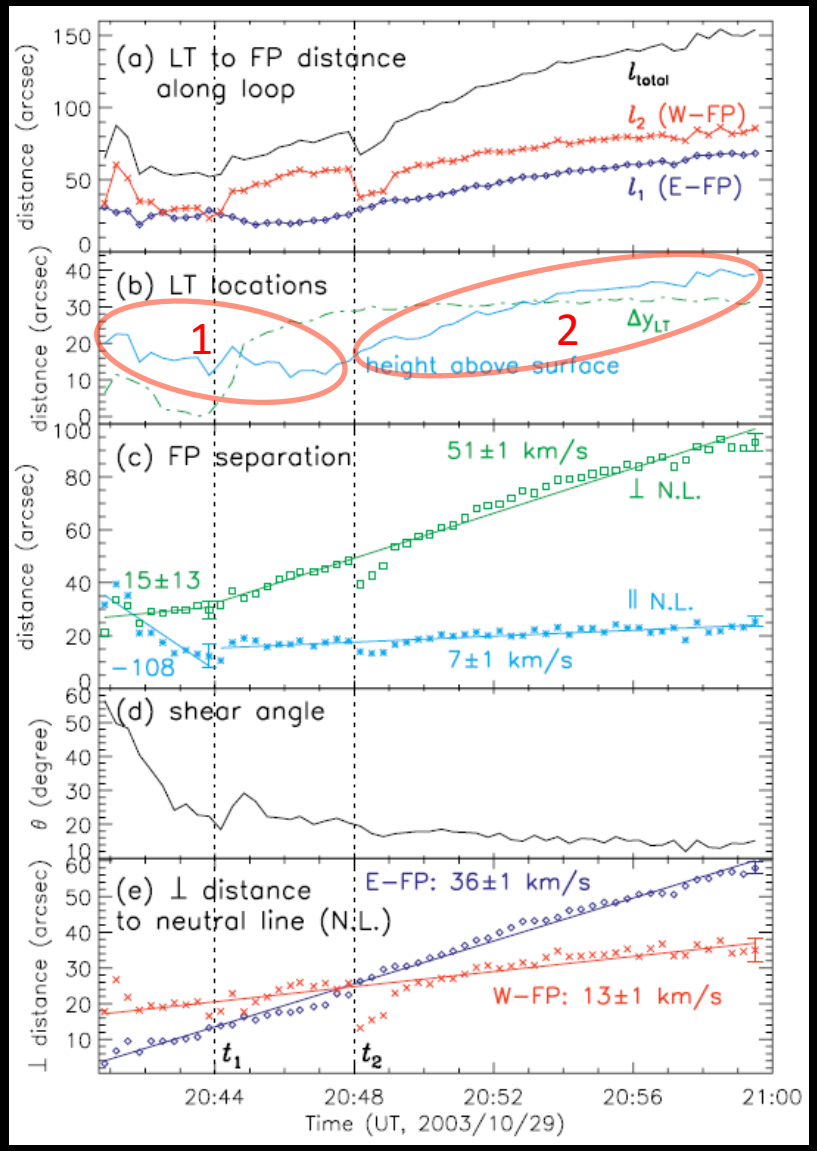
Liu, Chen & Petrosian, ApJ, 2013





X-ray Footpoint Motion Associated with Decrease in Magnetic Shear





Two-step reconnection: first along the neutral line, then upward.

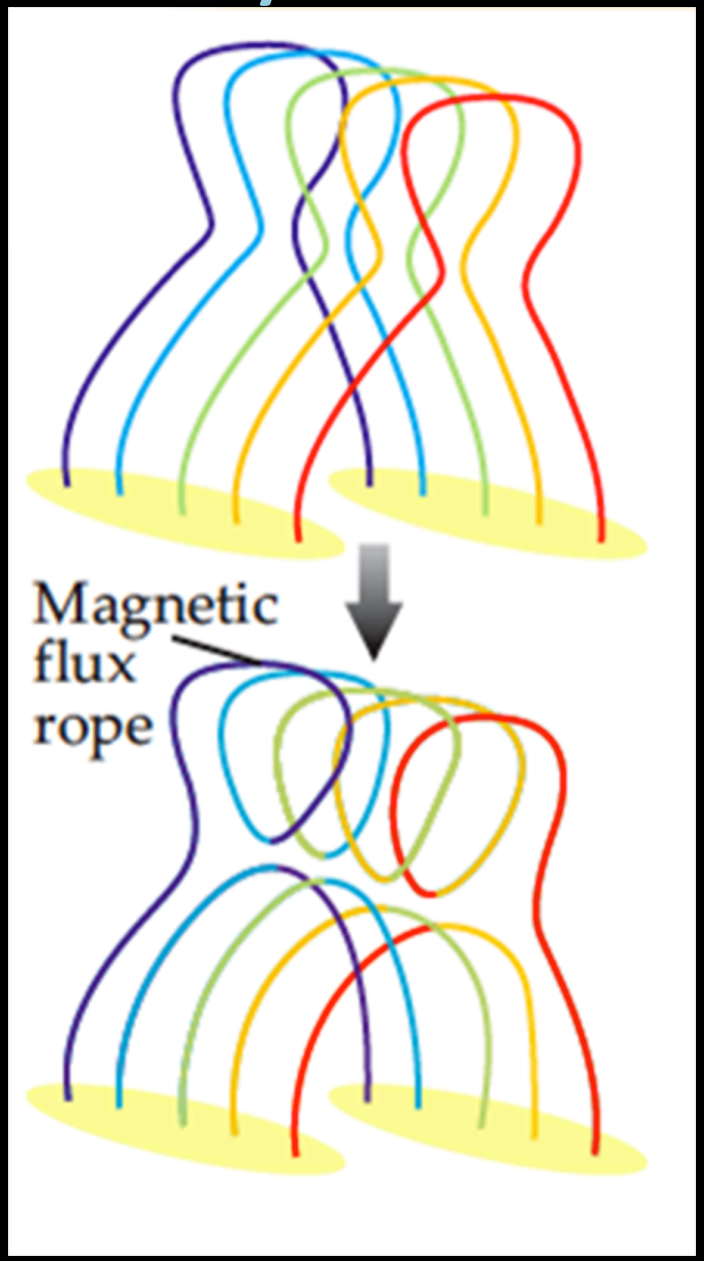
Understanding this requires a 3-D model, including propagation along arcade!

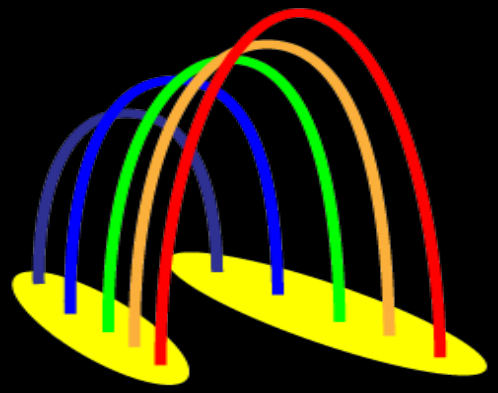
Liu, W., Petrosian, V., Dennis, B. R., & Holman, G. D. 2009, ApJ, 693, 847

Implications

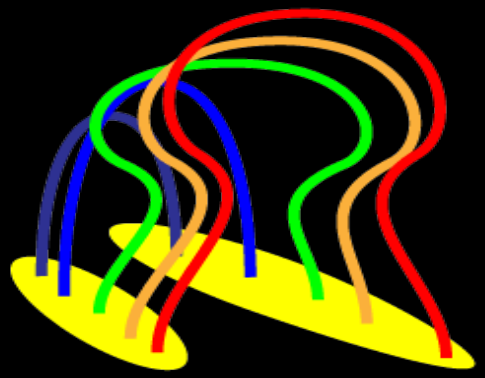
- An asymmetric, 3-D model is critical to understanding the evolution of solar eruptive events
- Downward loop-top motion is associated with the propagation of reconnection along the arcade
- Early upward motion is associated with shearing and expansion of original arcade and flux rope
- The electron acceleration rate is proportional to both the primary and "slipping" reconnection rates
- The onset of reconnection does not trigger the onset of impulsive flare emission. What does?

Asymmetric Arcade Reconnection



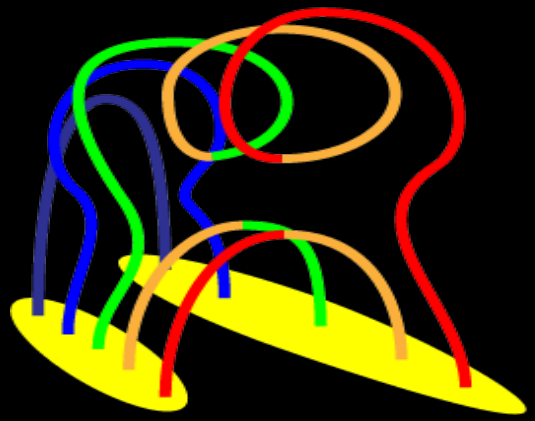


Early Upward Loop-Top Motion: Different length ribbons, loops at one end expand more



The higher, more sheared loops collapse and reconnect first

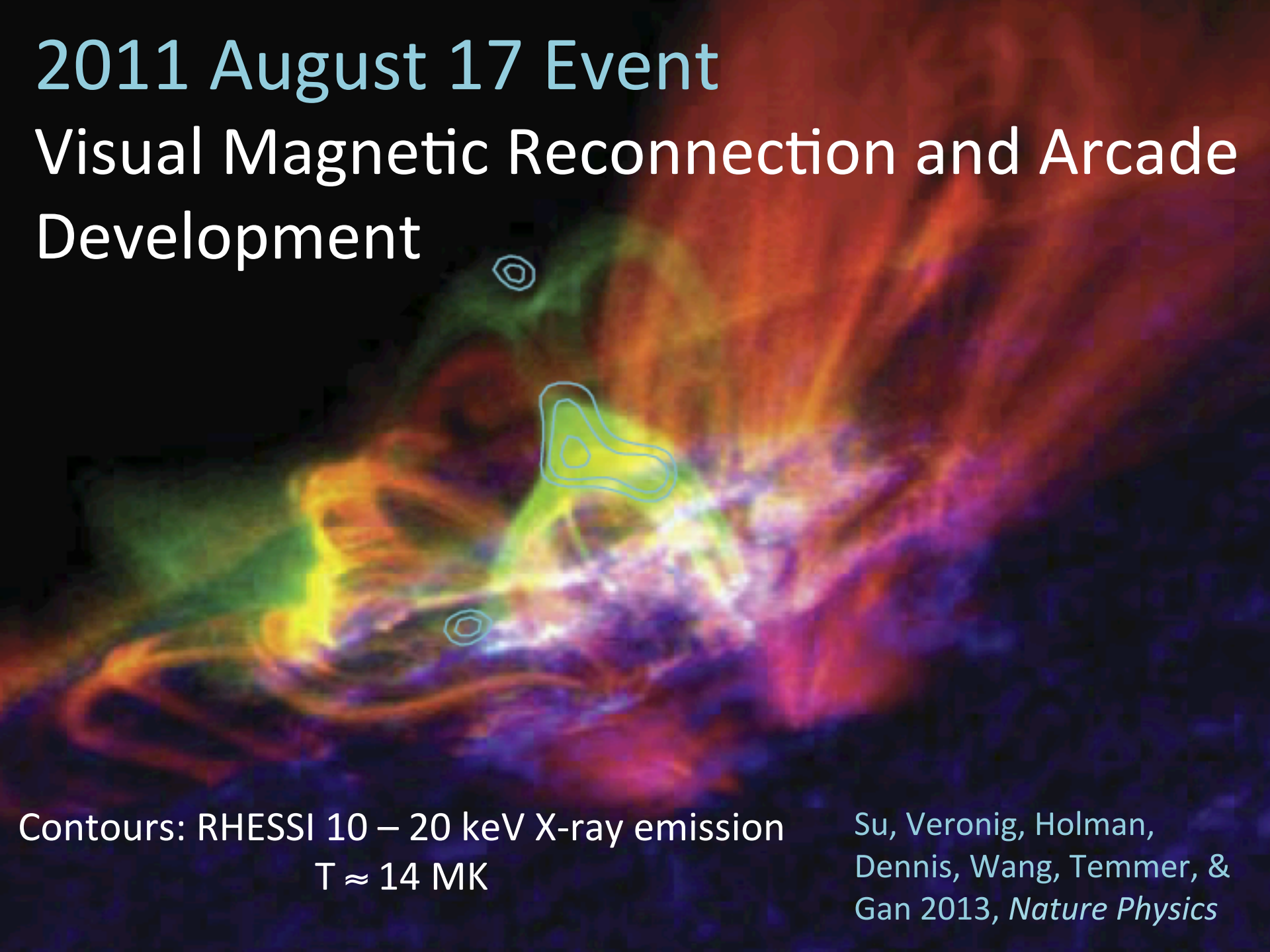
Downward Loop-Top Motion: Reconnection propagates along the arcade to the lower loops



Late Upward Loop-Top Motion: The arcade grows as reconnection continues above

2011 August 17 Event

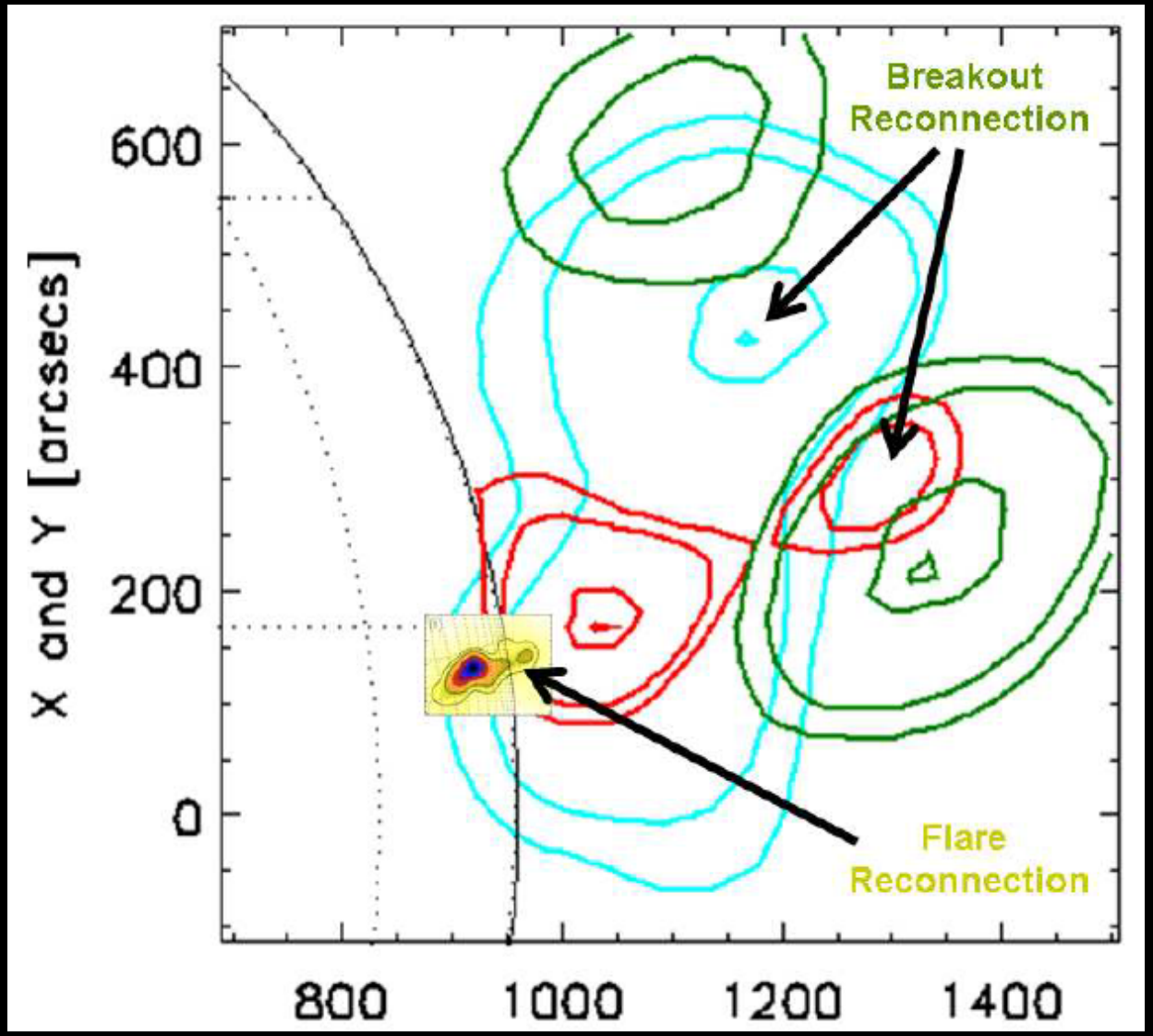
Visual Magnetic Reconnection and Arcade Development



Contours: RHESSI 10 – 20 keV X-ray emission
T ≈ 14 MK

Su, Veronig, Holman, Dennis, Wang, Temmer, & Gan 2013, *Nature Physics*

Reconnection at the Top: A Solar Eruptive Event in Radio Emission

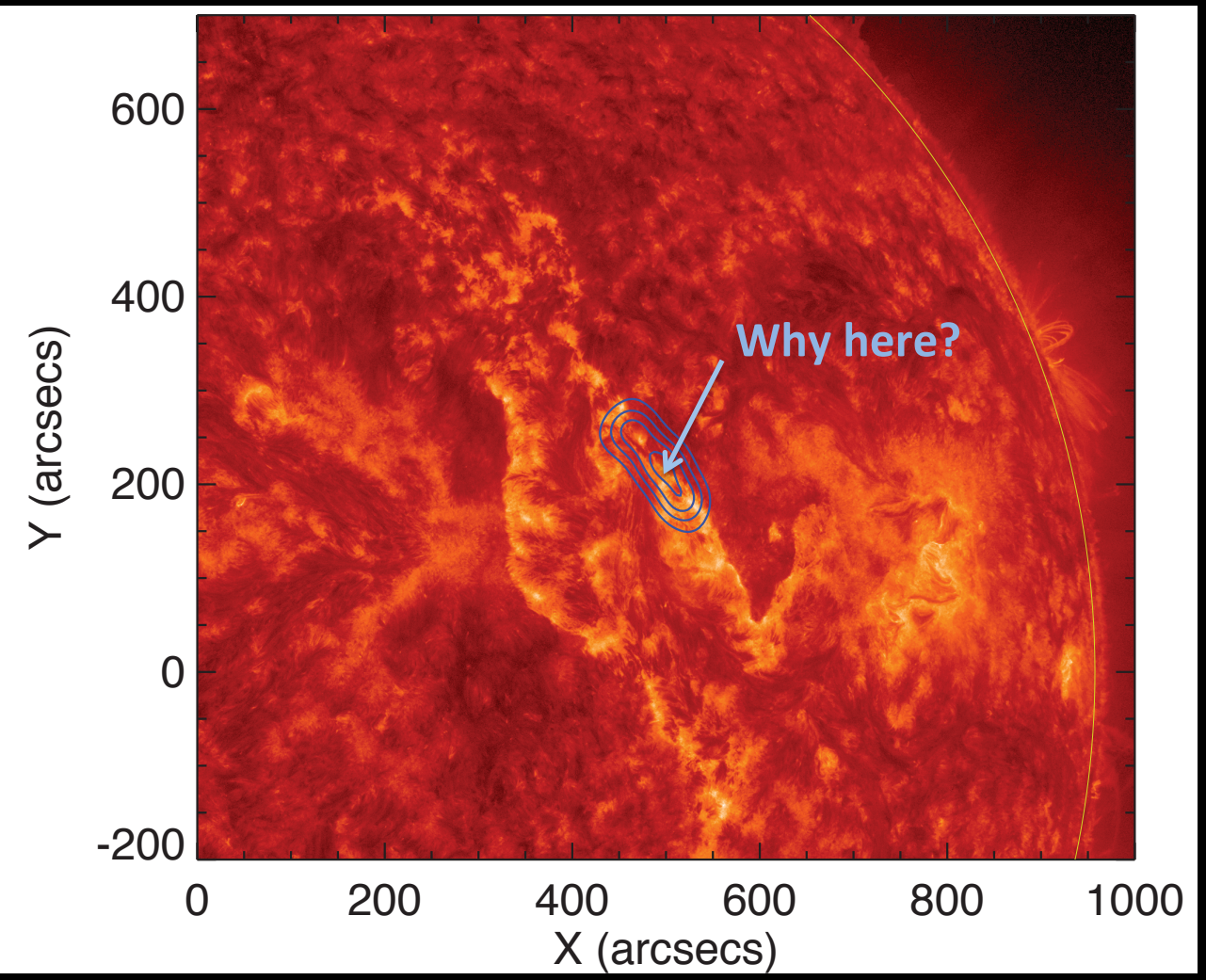


Red: 410 MHz
Cyan: 327 MHz
Green: 236 MHz

Breakout reconnection at the top of a stationary magnetic flux rope

Aurass, Holman, Braune, Mann, & Zlobec, A&A, 2013

2013 Quiescent Filament Eruption

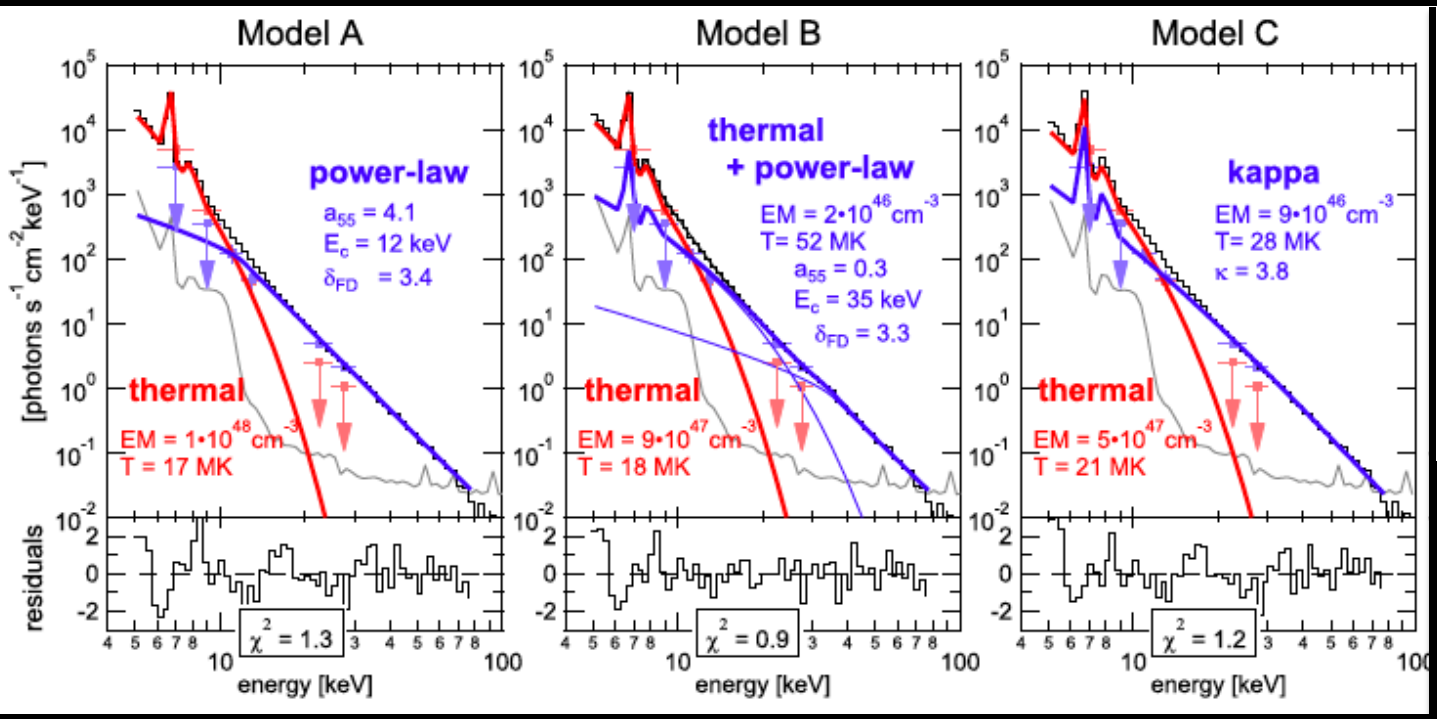


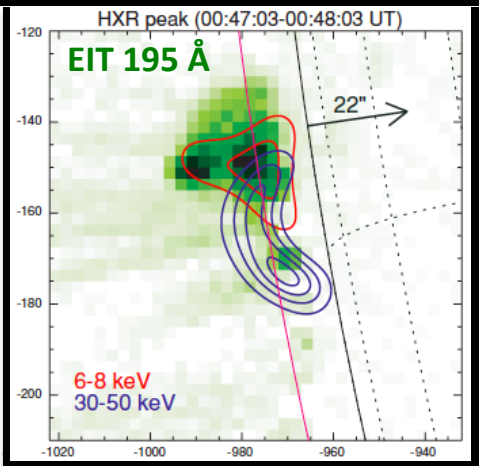
"… microflares strongly resemble more energetic flares in most respects: they occur solely within active regions …"
Hannah et al. 2011, Space Sci. Reviews

Why Does RHESSI See X-rays?

See *Poster 323*: Observations of a Solar Flare in Association with a Quiescent Filament Eruption (Adi Foord & Gordon Holman)

Three Spectral Models – Three Conclusions





2007 Dec 31
Coronal X-Ray Sources
(from Krucker et al. 2010, ApJ 714, 1108)

Non-thermal Fractions of Electron Number/Energy Densities in the Southern Source

Type of Density	Model A (Power Law without Thermal Core)	Model B (Power Law with Thermal Core)	Model C (Kappa)
Number density	44 % (>5%)	>2%	20 ± 1%
Energy density	88% (>32%)	>12%	52^{+3}_{-2}%

A: Almost all accelerated B: < 10% accelerated C: half of energy in accelerated electrons

M. Oka , S. Ishikawa , P. Saint-Hilaire , S. Krucker, and R. P. Lin 2013, ApJ 764, 6

SUMMARY

- RHESSI observations have contributed greatly to understanding the evolution of, and energy release in, solar eruptive events
- To understand energy release in SEEs, the propagation of reconnection along the magnetic arcade must be understood
- Need imaging spectroscopy of spectral lines sensitive to ~10 – 50 MK temperatures and greater dynamic range in X-rays to determine the fraction of energy in accelerated electrons