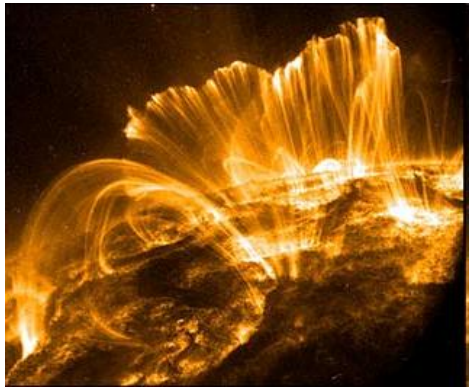
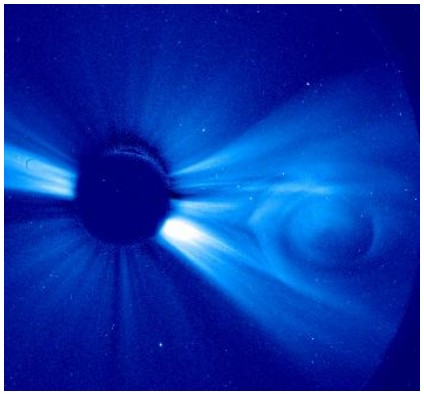
The Flare-CME Connection in Cycle 24:

The Quest for Harmony





Angelos Vourlidas

Some material based on reviews by Benz '08, Krucker et al '09, Hudson '08, Schrijver '09

The Cradle of Solar Explosions…

- 19th Century: Visual Disk Observing
  - Flares are photospheric explosions

- Mid-20th Century: Hα Disk Observing
  - No! Flares are chromospheric explosions

- 1970's – now: X-Ray Disk Observing
  - No! Flares are coronal explosions

- 1980's – now: Visual Coronal Observing
  - No! CMEs are the real explosions

- 21st Century: Full Sun Observing (almost)
  - Neither Flares, nor CMEs…Magnetic field explosions

…Leads to a Controversy Importance

- **1970's – 80's: CMEs are the coronal response to flaring**
- **1990's: The "Solar Flare Myth" debate**
  - Gosling (1993): CMEs (not flares) are responsible for interplanetary and geoeffective phenomena.
    "*CMEs have no fundamental association (in terms of cause and effect) with flares*".
  - Svestka (1995): "Eruptive" flares (not all flares) are the sources of CMEs. Realization of the difference between Ha and Soft X-ray flares.
  - Harrison (1996): "Flares and CMEs are manifestations of the same magnetic "disease". The do not cause one another but are closely related".
- **Late 1990's: The Flare-CME relationship is hotly debated.**
  - But the general features for both phenomena have been identified:
    spatial scale differences, post-flare x-ray loops, relative timing, filament-flare-CME relations, etc
- **21st Century: Flares and CMEs are closely connected**
  - Both phenomena are increasingly viewed within a common framework:
    - *Evolution of the coronal magnetic field*

Key Advances (1996-2007)

- **White Light CMEs are finally studied with synoptic cadence.**
- **EUV Flares are regularly observed.**
  - Many new phenomena are discovered and studied (waves, dimmings, brightenings) .
  - These observations provide links to CMEs
- **Hard X-Ray Flares are regularly observed.**
  - Many new phenomena are discovered and studied (separate ion/electron acceleration sites, high corona sources, etc) .
  - These observations provide links to CMEs
- **Radio imaging observations of both CMEs and Flares became routine.**
  - Imaging of CME & CME-flare related emissions
  - Observe the intial evolution of CME with unsurpassed cadence.

Where do we stand at the start of Cycle 24?

- **CMEs and flares are still treated as separate phenomena**
  - **Issue #1: "Flare" has become a generic, ever-expanding term**
  - **Issue #2: Mismatch of observations in temporal/spatial scales**
  - **Issue #3: CMEs link Sun-Heliosphere-Earth-Planets; flares remain a solar physics subject**
  - **Issue #4: "Historical inertia"**

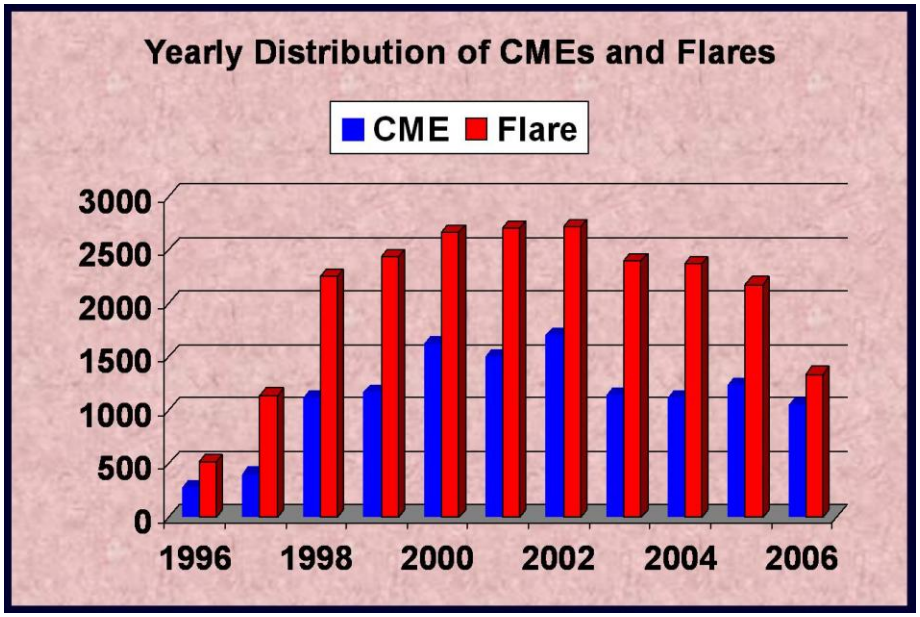
- **Solution → System approach:**
  - **flares and CMEs are the signatures of the same physical phenomenon:**

Relaxation of the solar magnetic field
through reconnection
producing
light change (flare) & plasma motion (CME)

Cycle 23: CME Statistics

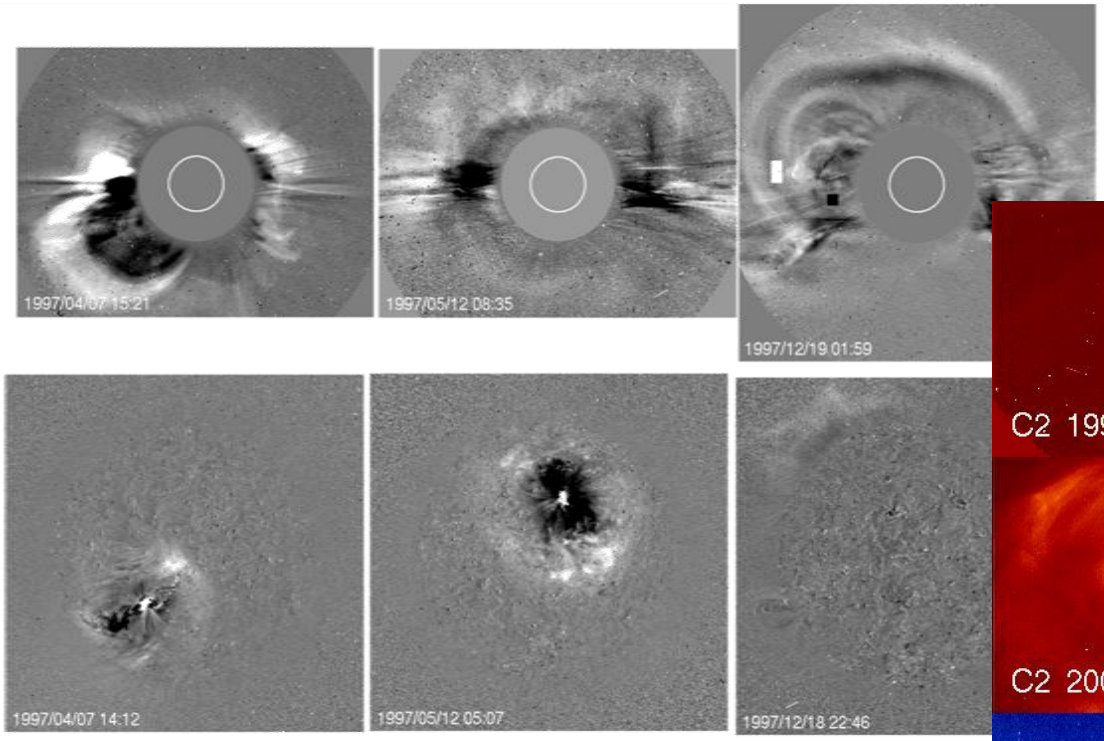
- **CME observations over a FULL solar cycle with improved sensitivity, duty cycle**

CME/day: 0.5 – 4.5
Flare/day: 1.5 – 7.5

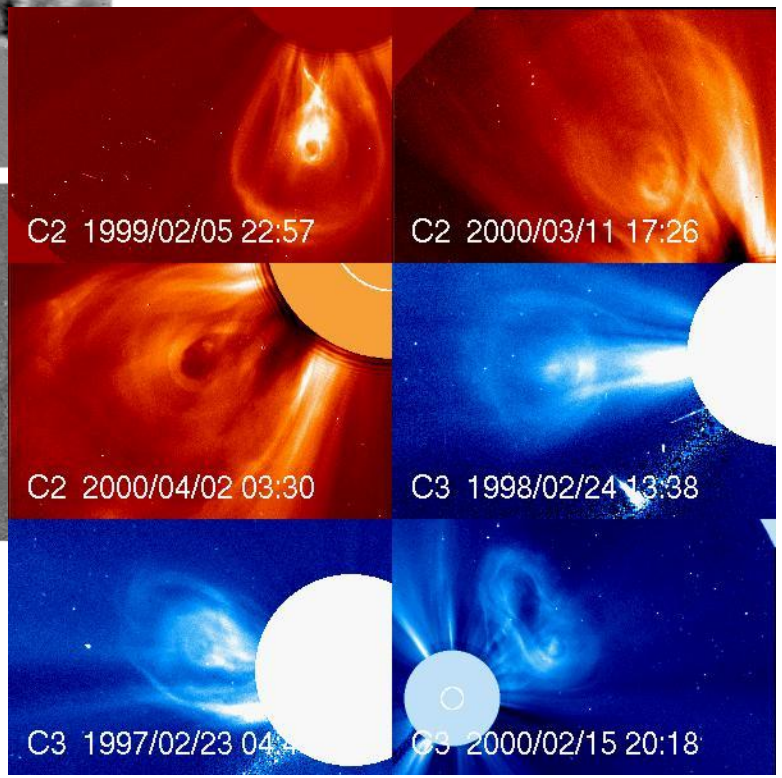


Flares & CMEs have similar occurrence rates

Cycle 23: CME Sources & Morphology

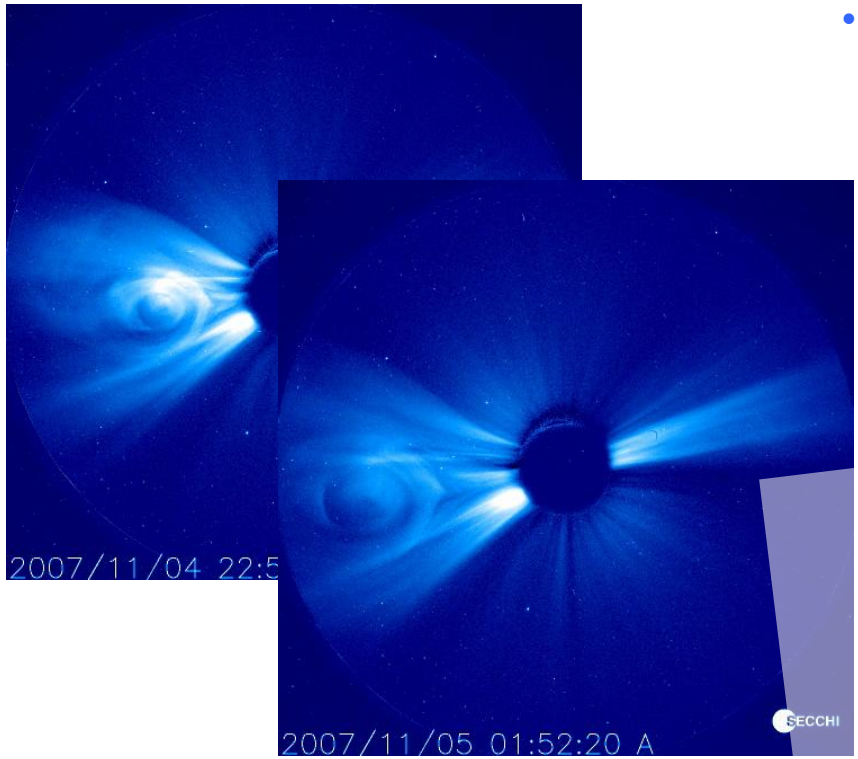


Association between CME EUV flaring region

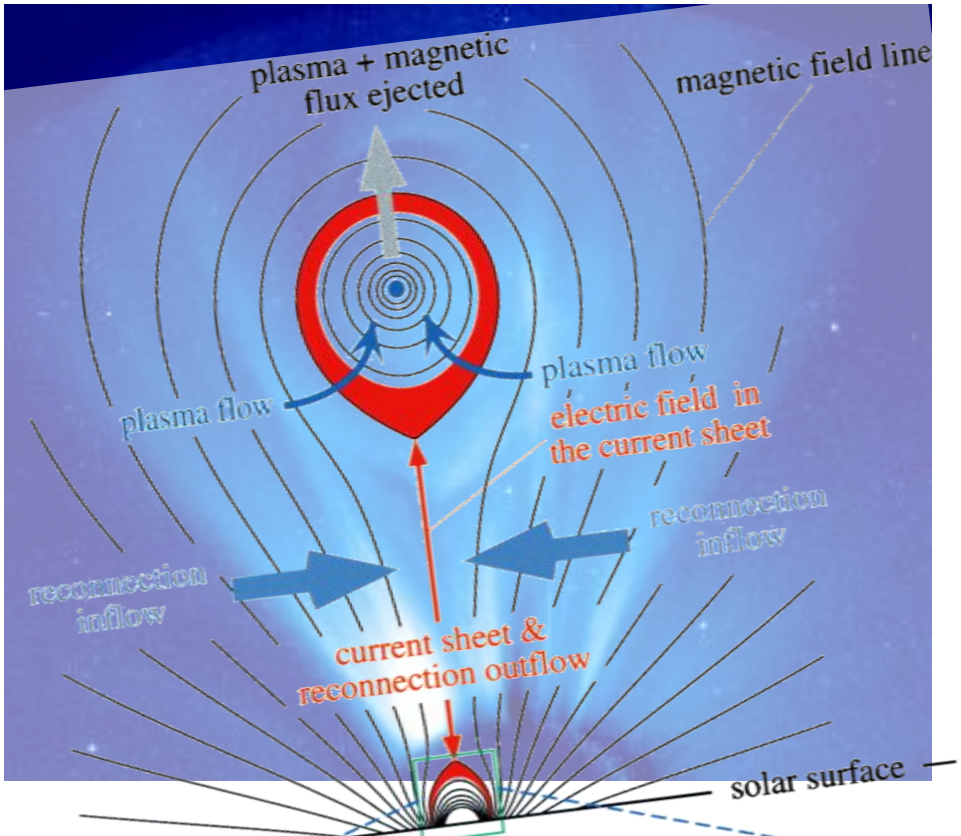


Most CME have fluxrope structures

CME Internal Structure

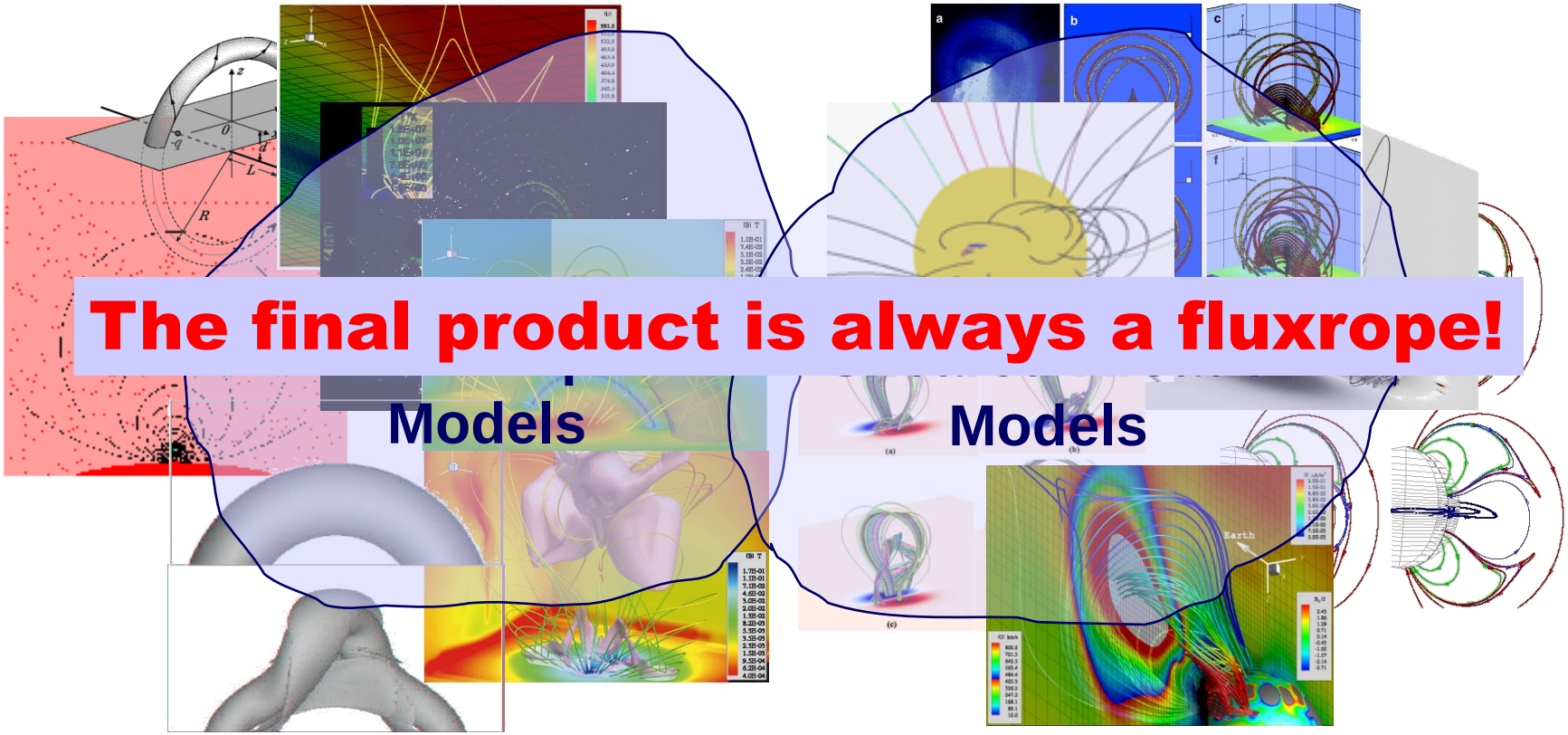


- **The tip of the post-CME current sheet is visible.**
  - **The current sheet should be visible in the low corona.**

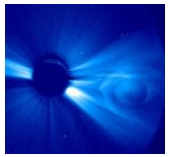


CME Initiation Models (quite a few but…)

(from I. Roussev's ESPM 2008 presentation)



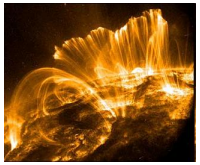
Amari *et al.* (2000, 2003, 2007); Antiochos *et al.* (1999); Forbes & Isenberg (1991); Gibson & Low (1998); Kliem *et al.* (2004); Lin *et al.* (2001); Linker *et al.* (2001); Lynch *et al.* (2005); Manchester *et al.* (2003, 2004); Moore *et al.* (2001); Sturrock *et al.* (2001); Titov & Démoulin (1999); Tokman & Bellan (2002); and Roussev *et al.* (2003, 2004, 2007).



Cycle 23: Review of CME Advances

- Measurement of CME Properties over a full solar cycle (& 10,000's of events)
- Detailed investigation of relation to coronal phenomena (flares, filament eruptions)
- Discovery of low corona CME counterparts (EUV-waves, dimmings)
- CME role in Sun-Earth Connection is established and extensively analyzed.
- Theory converges towards fluxrope as the ejected structure
  - 3D MHD modeling captures the main CME features (shock, core, speed, width)
- Clear understanding of CME images (shock, core, front, streamers)

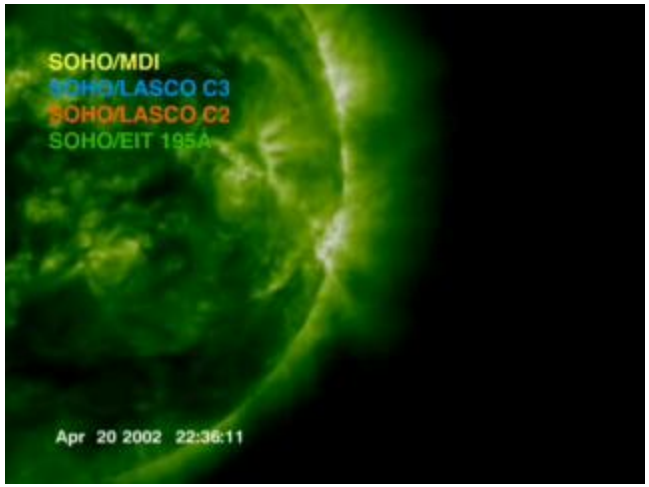
- But we don't know
  - size, direction, entrained magnetic field, initiation mechanism, energy partition, relation to extended corona, SEP accelerations



Flares (…with CMEs)

“Typical” Flare

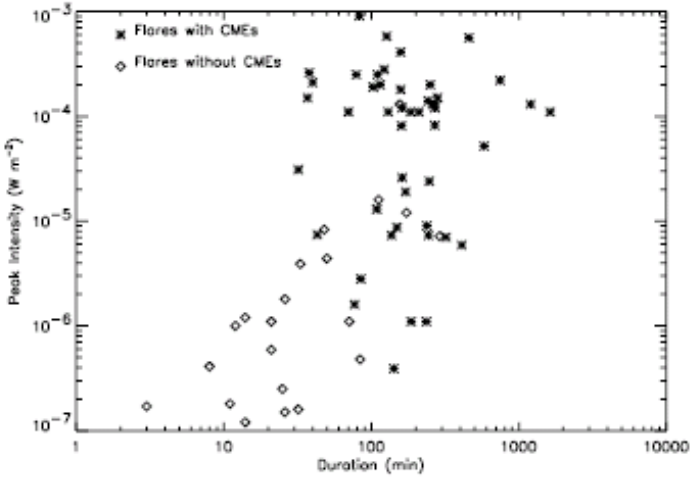
“Typical” Flare (in proper context)



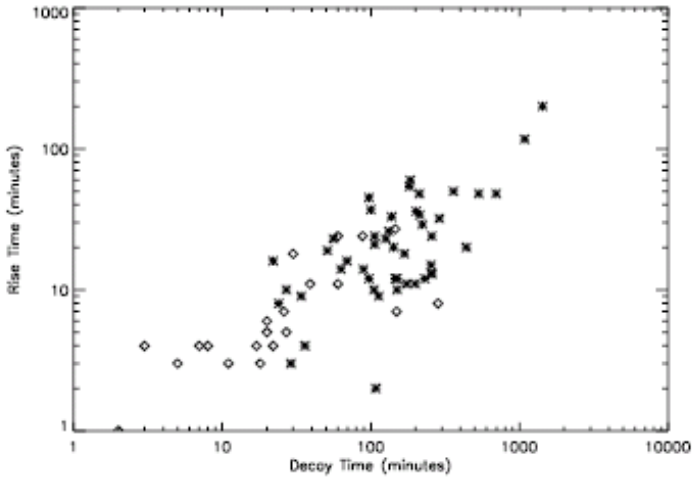
Flare-CME Statistics: Flare perspective

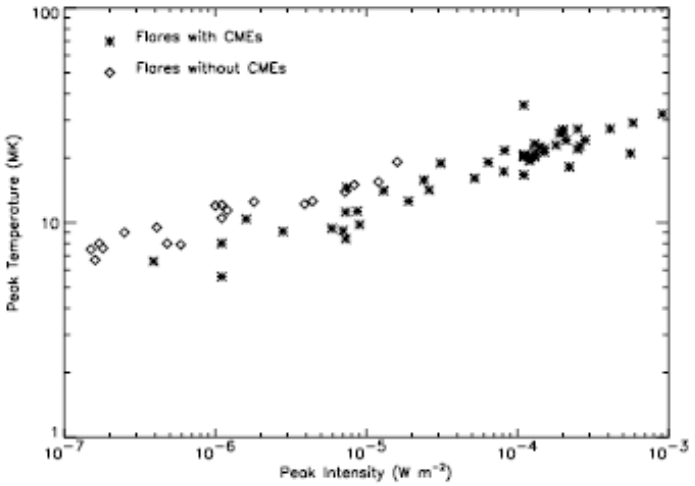
- Kay et al (2003): Flare Study
  - Flares with CMEs have longer duration, higher peak T, lower rise
  - Sample: 48 CME, 21 non-CME

SXR Peak Intensity vs Flare duration



Flare Rise Time vs Decay Time



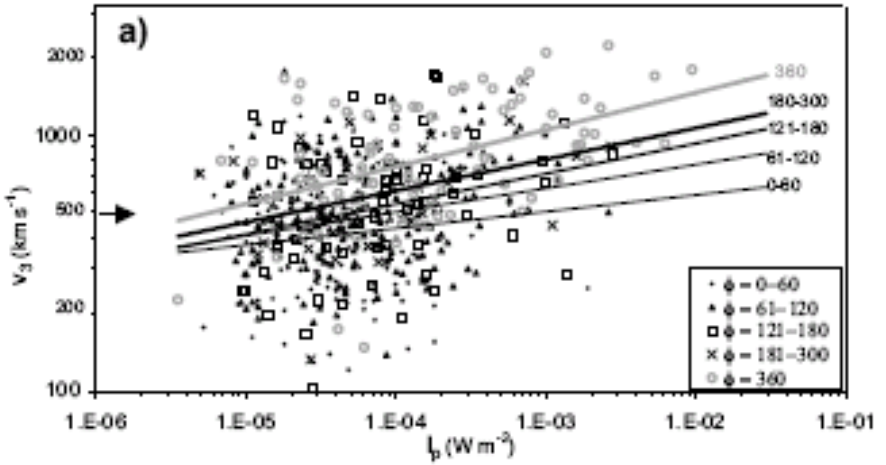


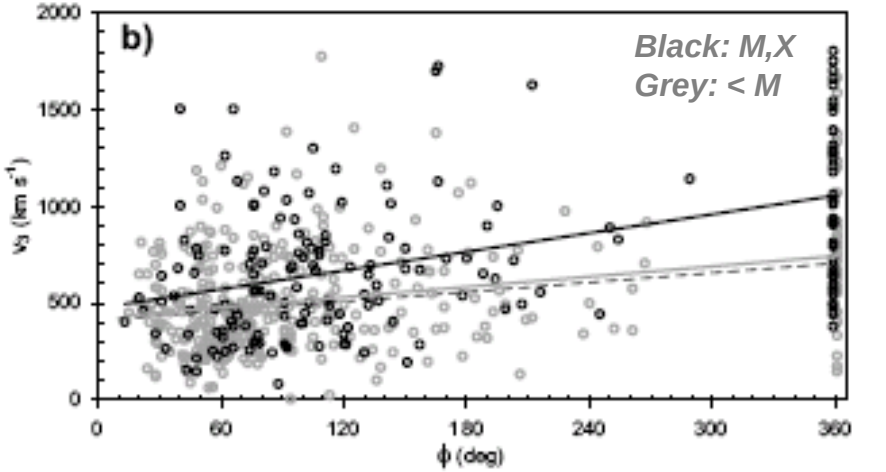
SXR Peak Temperature vs Peak Intensity

Flare-CME statistics: CME perspective

- Vršnak et al (2005): Kinematic study.
  - No bimodal distribution found (speed or acceleration).
  - Continuous spectrum of events
  - Wider CMEs are faster
  - Weak-flare (B,C) CMEs similar to non-flare CMEs

Velocity vs SXR Peak Flux

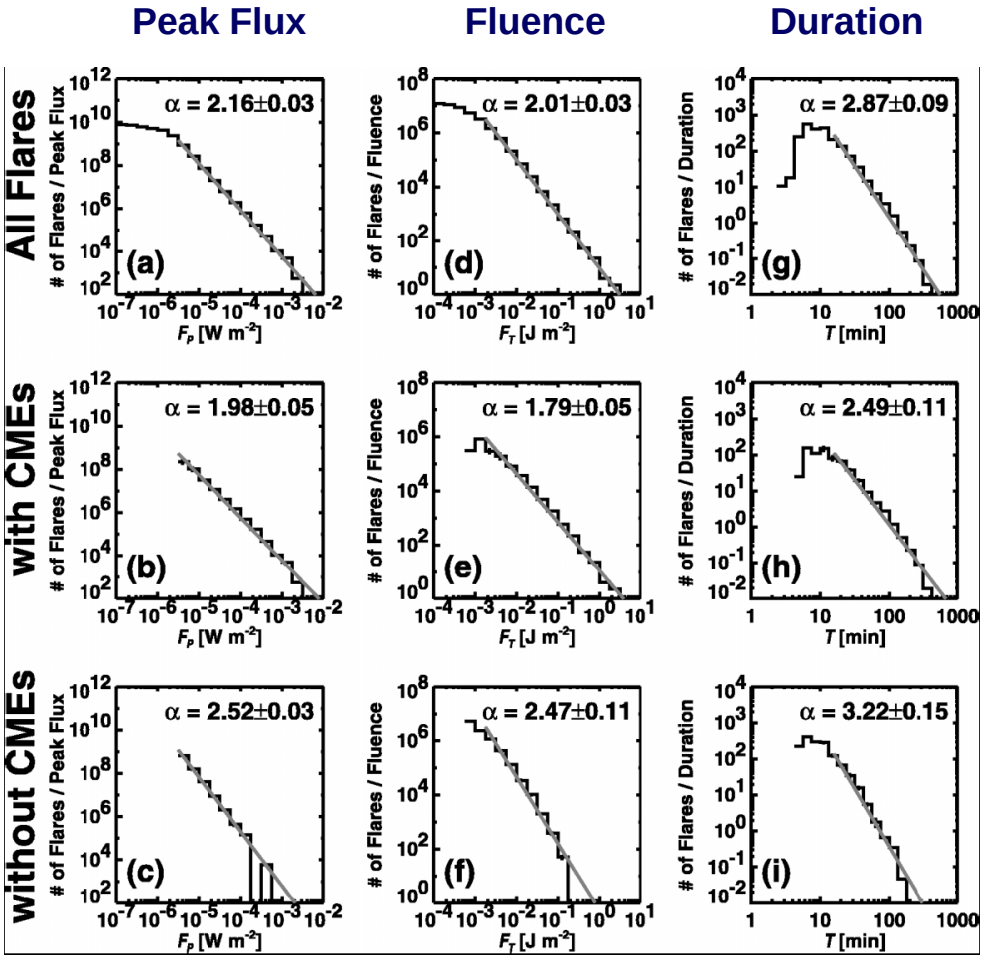


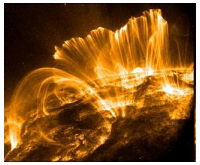


Velocity vs CME Width

Flare-CME Statistics: Power-Laws

- Yashiro et al (2006):
  - Bimodal distribution in flare indices.
  - Flares without CMEs dominate at small energies.
    - More energy to heat the corona?
  - Sample: 98 X, 692 M, 575 C

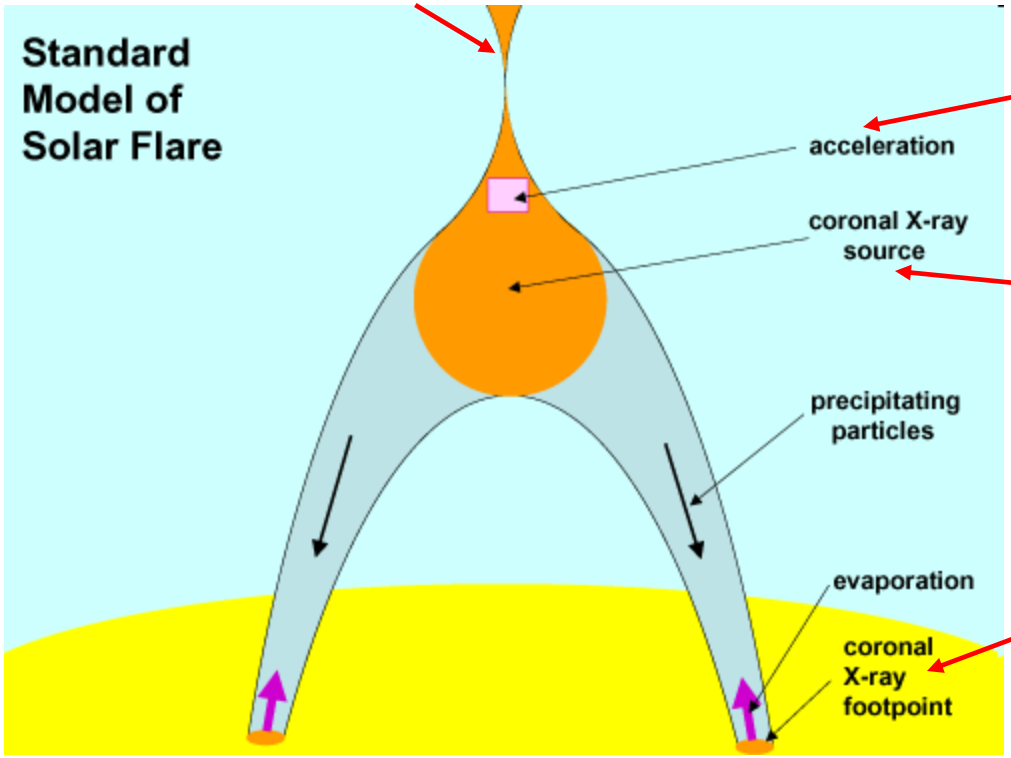




The ‘Standard’ Flare Concept in Cycle 23

- **Still standing**
- **New observations suggest connection to CME**

High Corona
HXR sources



Too many electrons
(10^{38} = 10^{15} gr)!

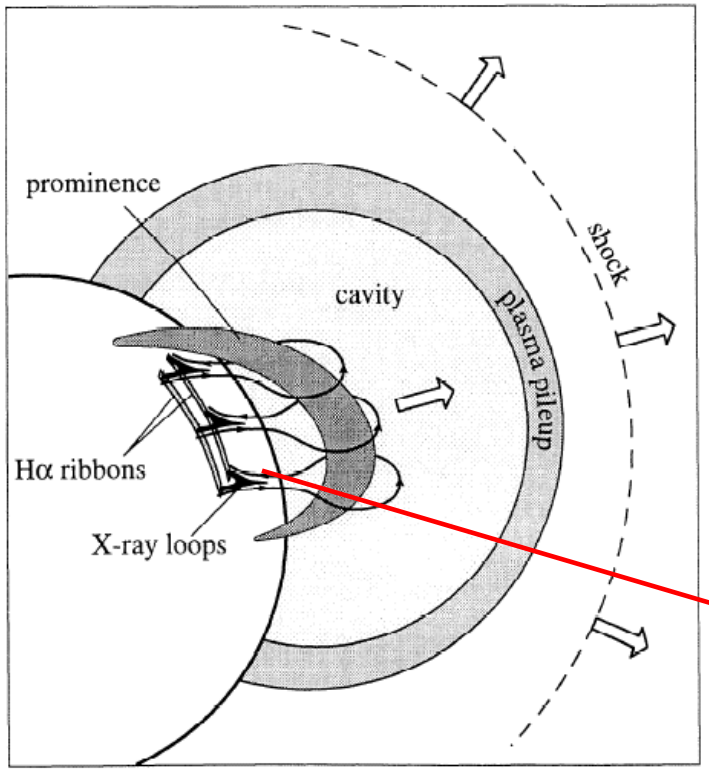
SXR source appear
before footpoints!

Different for Electrons
& ions!

From Benz (2008)

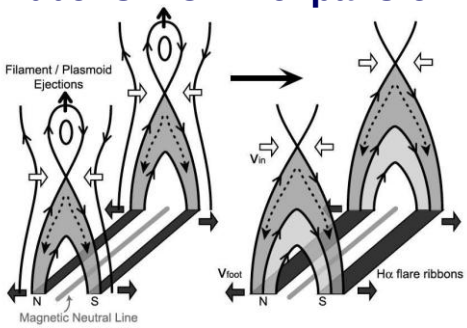
The "Standard" Flare-CME Concept

Still at cartoon level (pick your favorite from *solarmuri.ssl.berkeley.edu/~hhudson/cartoons*)

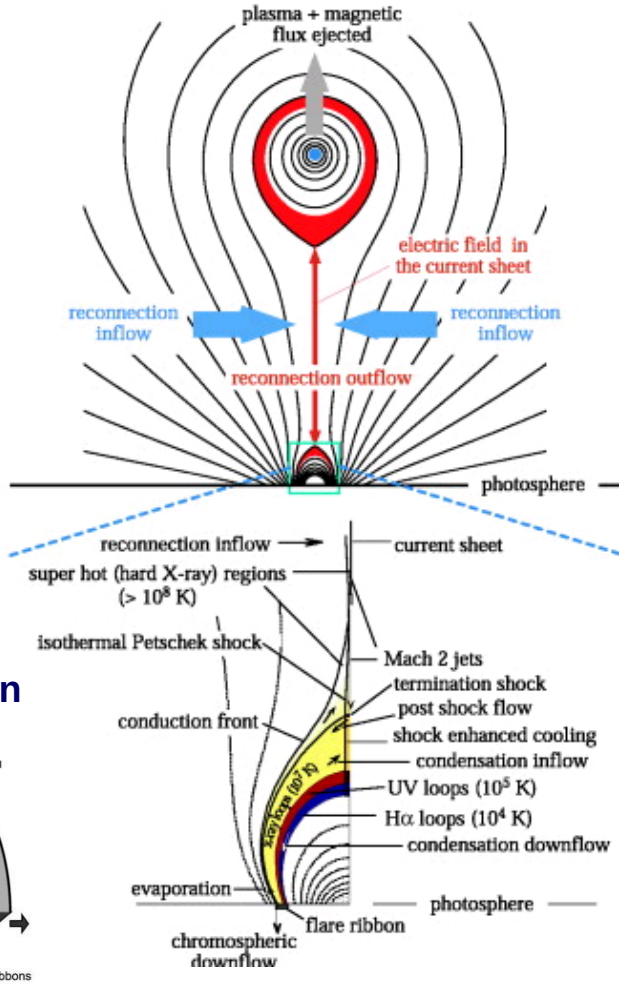


Forbes 2000

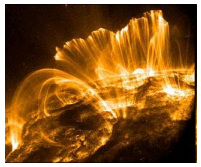
Ribbons = CME expansion



Asai et al 2006

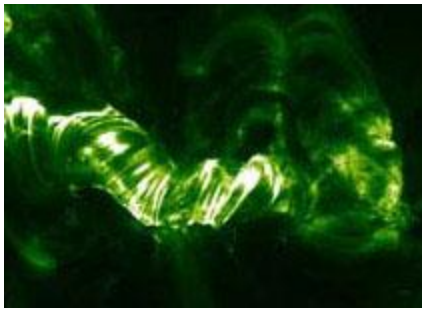


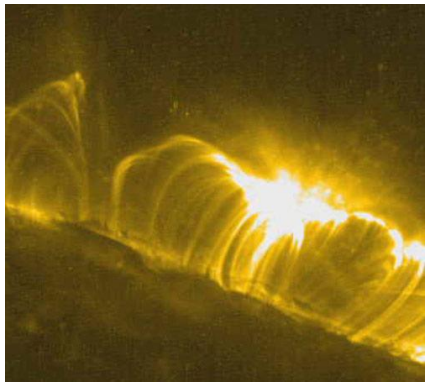
Lin & Forbes 2002

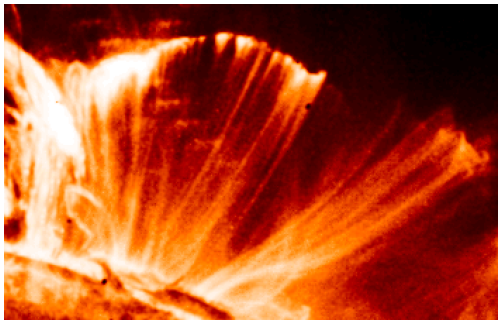


Flare-CME Connection: Post-Eruption Arcades

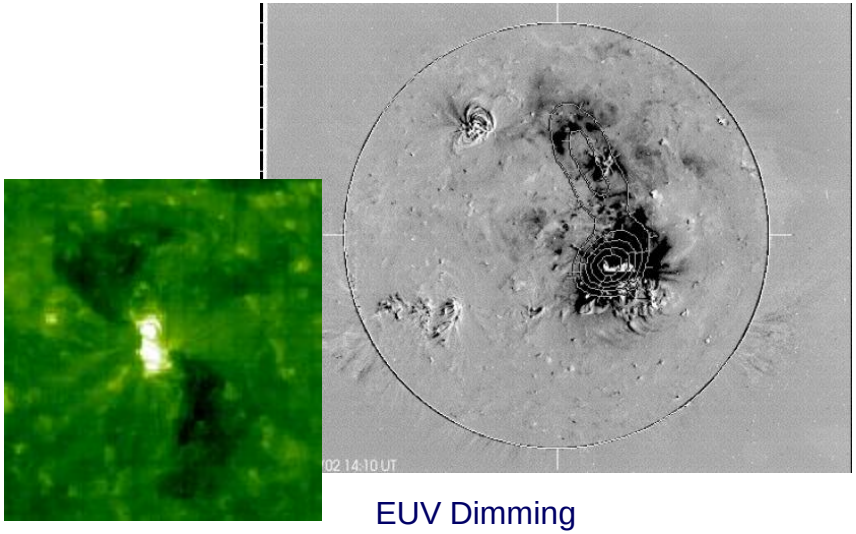
Post-flare loops → Post-CME loops → Size of the erupted Fluxrope



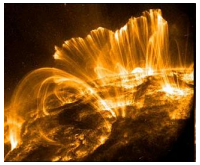




Coronal Dimmings map the ejected corona and the footpoints of the fluxrope (?)

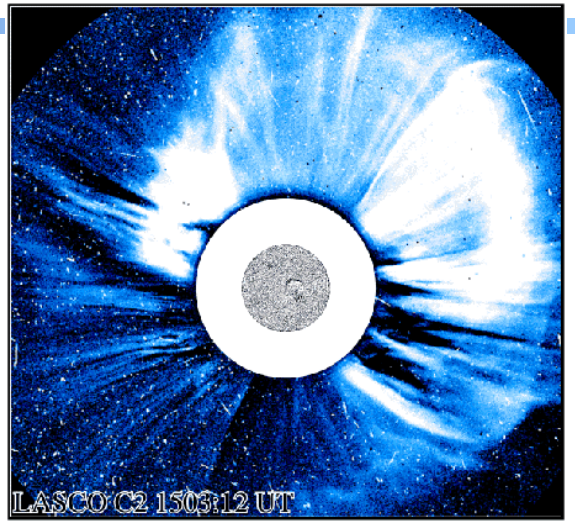


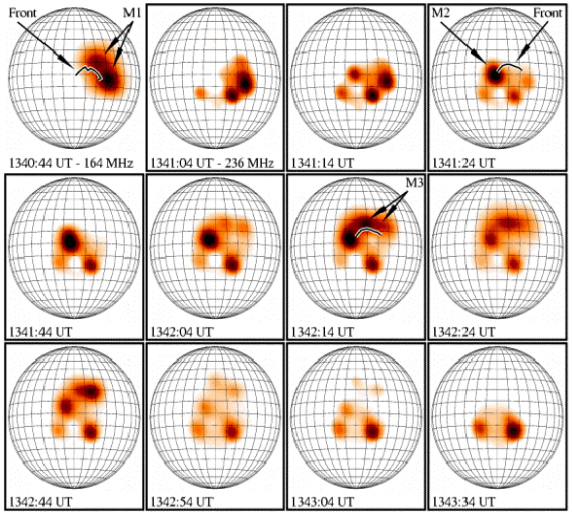
EUV Dimming



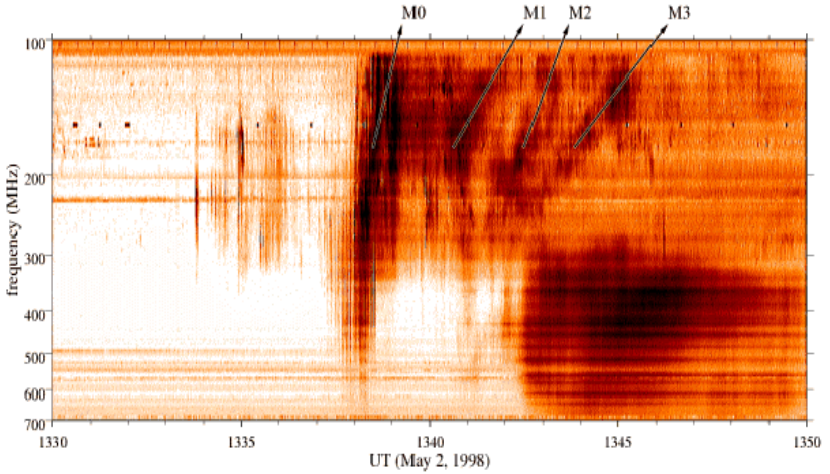
Flare-CME Connection: Flares and Ejecta

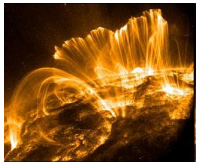
- **Radio observations reveal a direct connection between flaring & plasma ejections**



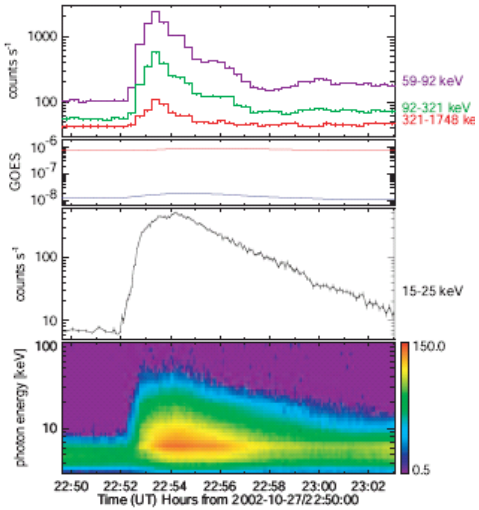


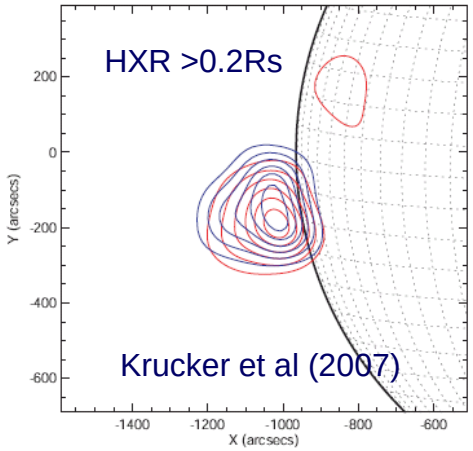
Pohjolainen et al. 2001





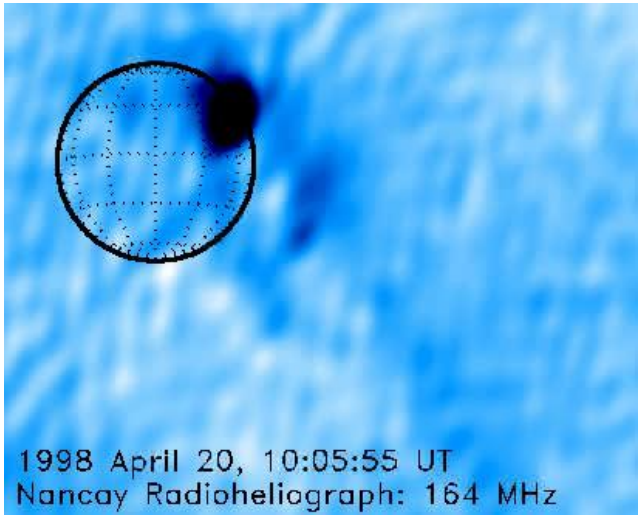
Flare-CME Connection: High Corona Hard X-Rays





Radio observation of non-thermal electrons from occulted sources (Bastian et al 2001; Maia et al 2007):

B_{CME} ~0.1-few G, E ~ 0.5-5MeV, n_{th} ~10^7 cm^{-3}

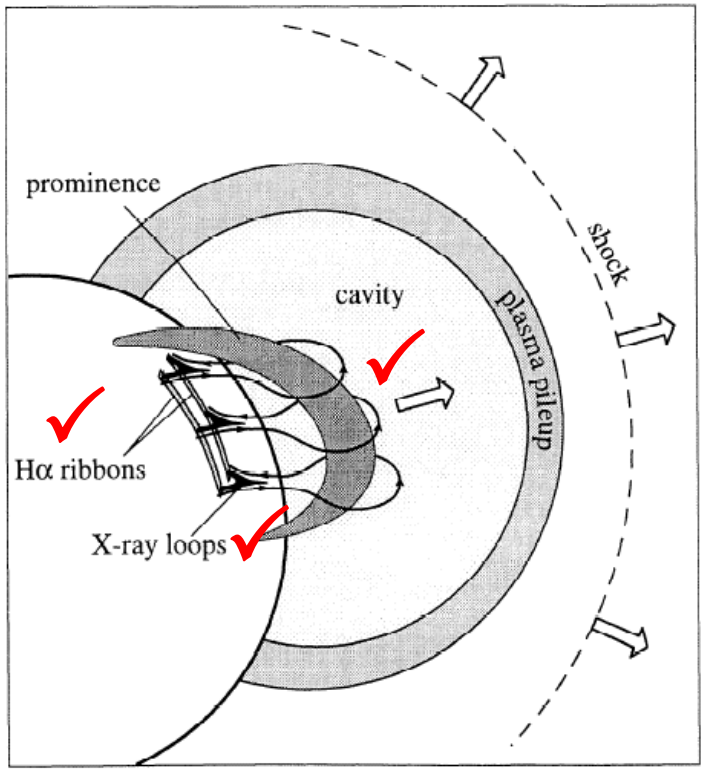


- HXR sources above ~0.2 R seem common
(e.g., Hudson et al 2001; Krucker et al 2007)
- Associated with CMEs
- Occur at the impulsive phase
- Long-lived
- Require occulted source, large SNR

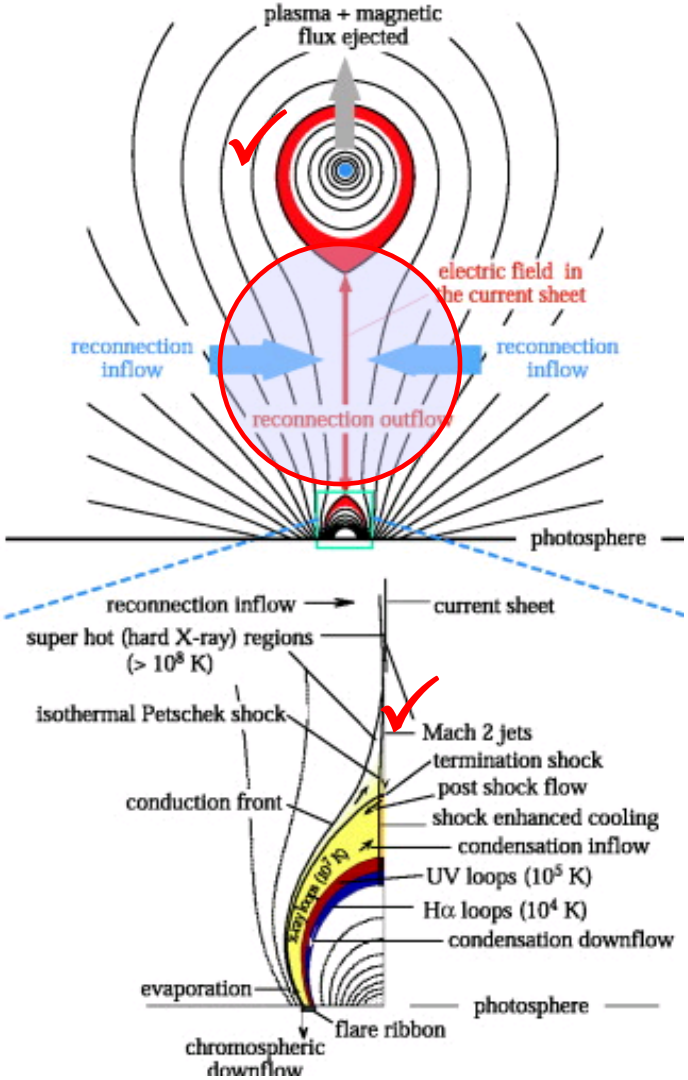
Q: Do we observe the same populations?

The "Standard" Flare-CME Concept

Where is the a direct physical connection between CME and Flare?



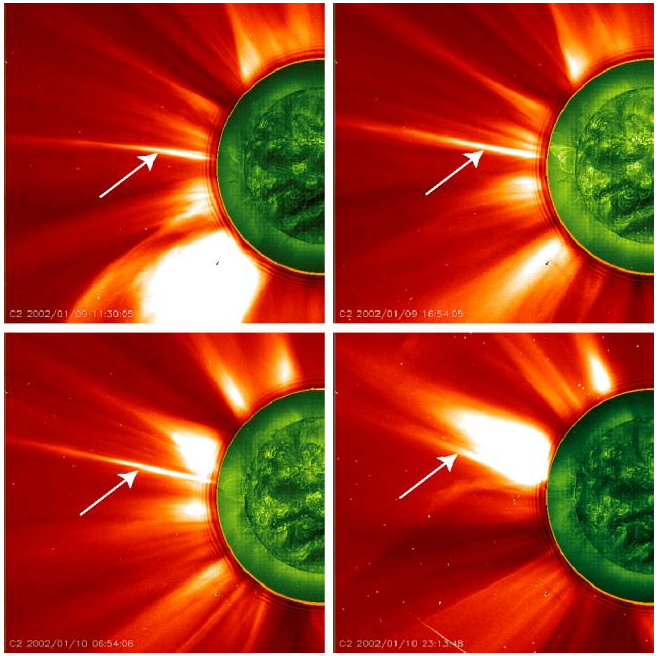
Forbes 2000

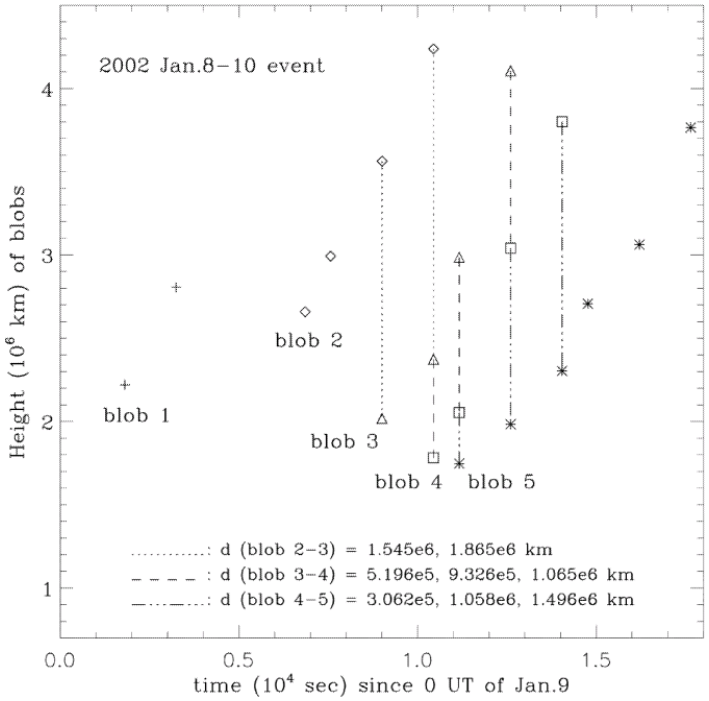


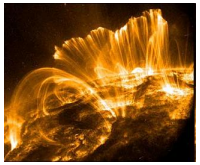
Lin & Forbes 2002

The direct link: Current Sheets

- **EUV detection of the long sought current sheet behind the CME! (e.g.,** *Ciaravella et al, '02; Ko et al '03; Lin et al '06, '07; Bemporad et al '06; Vsnak et al 2009*)
- **The "missing link" between CMEs and flares.**

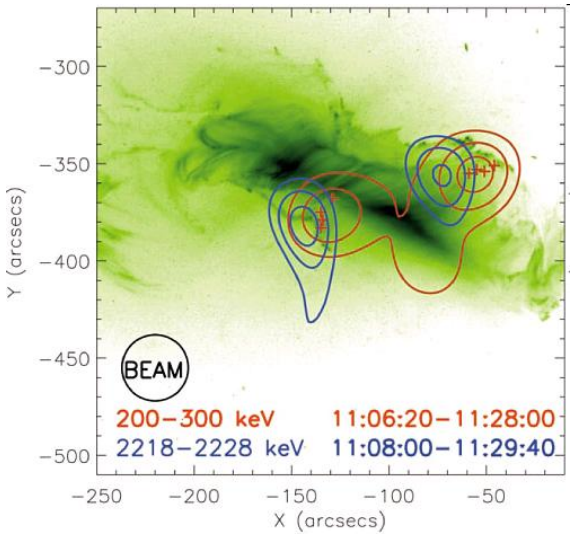






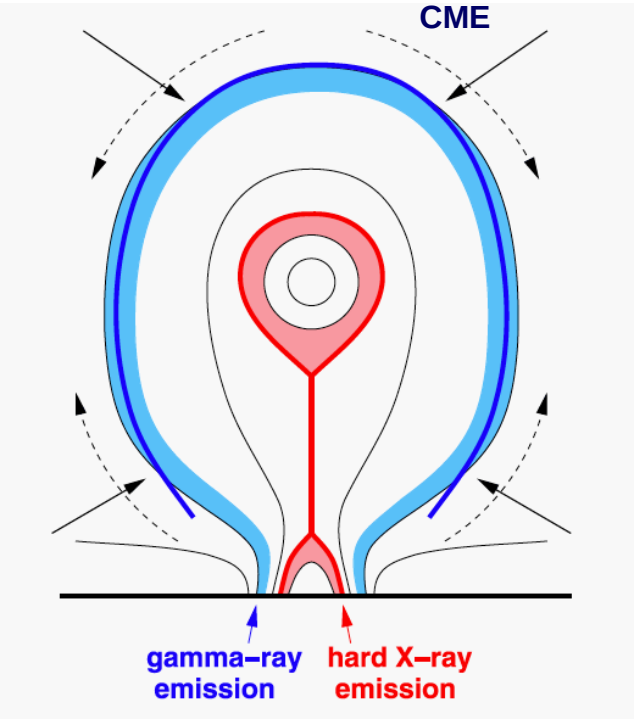
Flare-CME Connection: Ions don't like Electrons?

- **Ions & electrons seem to be accelerated at different sites**
  - **Different loop sizes? (Emslie et al 2004)**



Hurford et al (2006)

But if we look at the big picture….

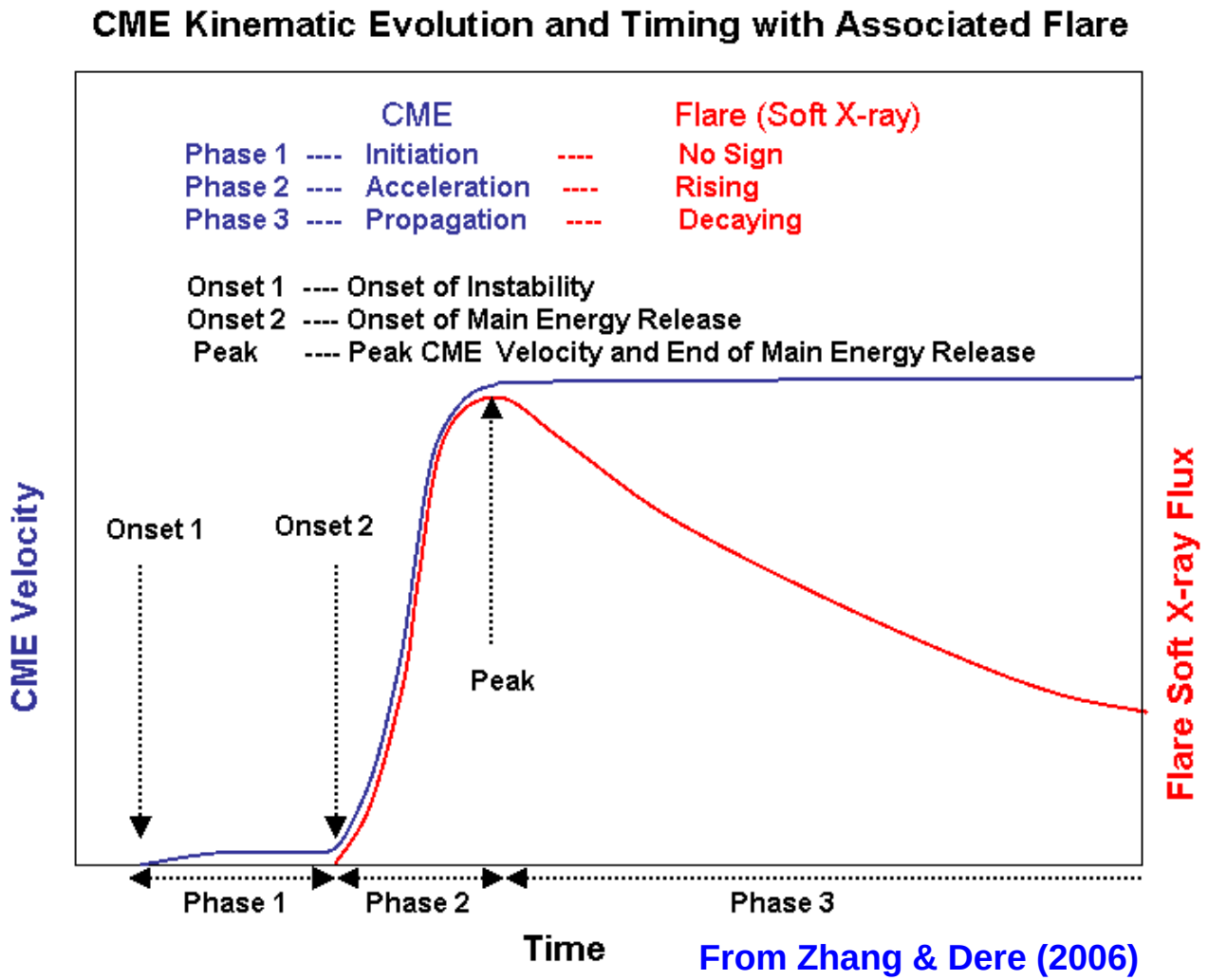


Pomoell et al (2008)

Flare-CME Connection: CME Acceleration

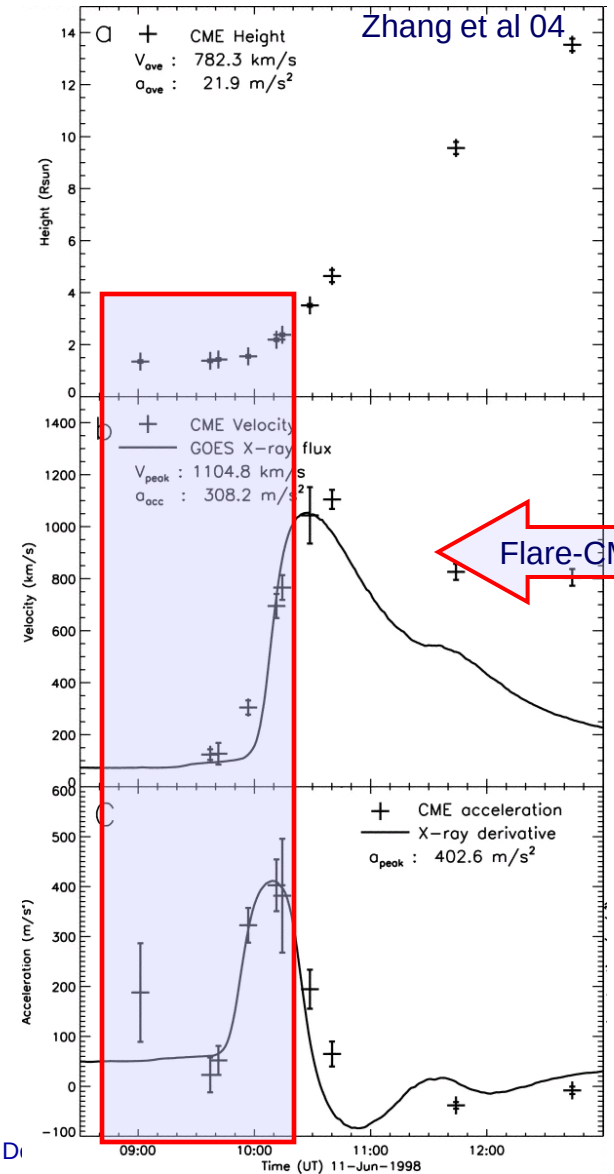
(from J. Zhang's SHINE 2007 presentation)

CME main acceleration coincides with flare energy release phase

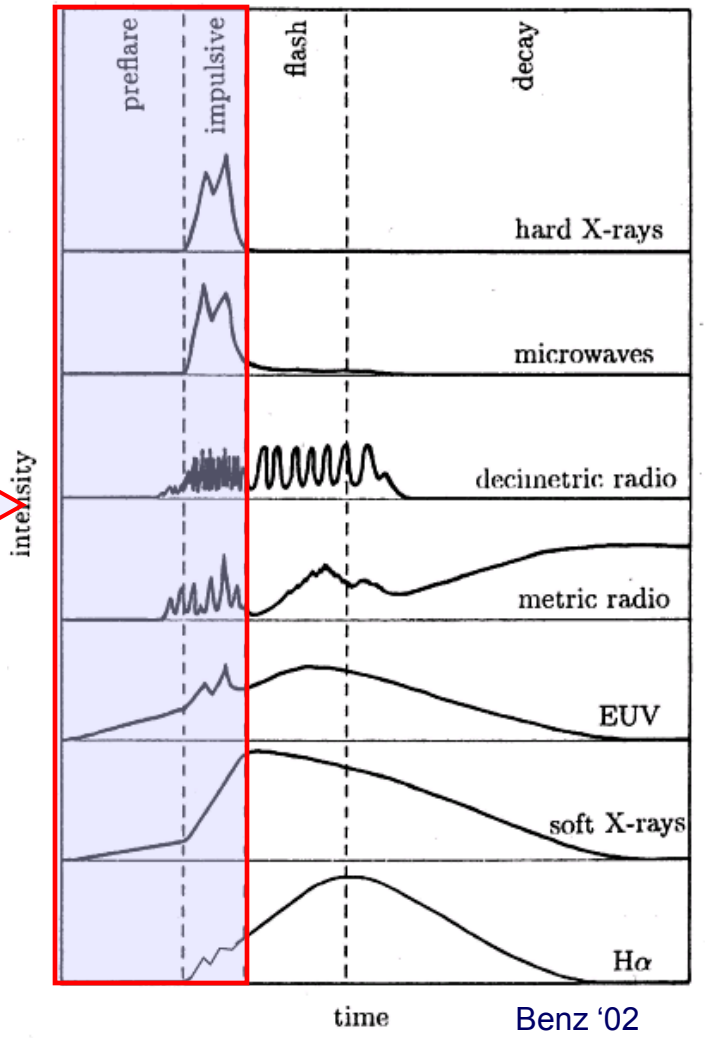


From Zhang & Dere (2006)

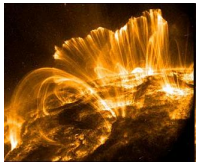
What's in the Time History of a Flare?



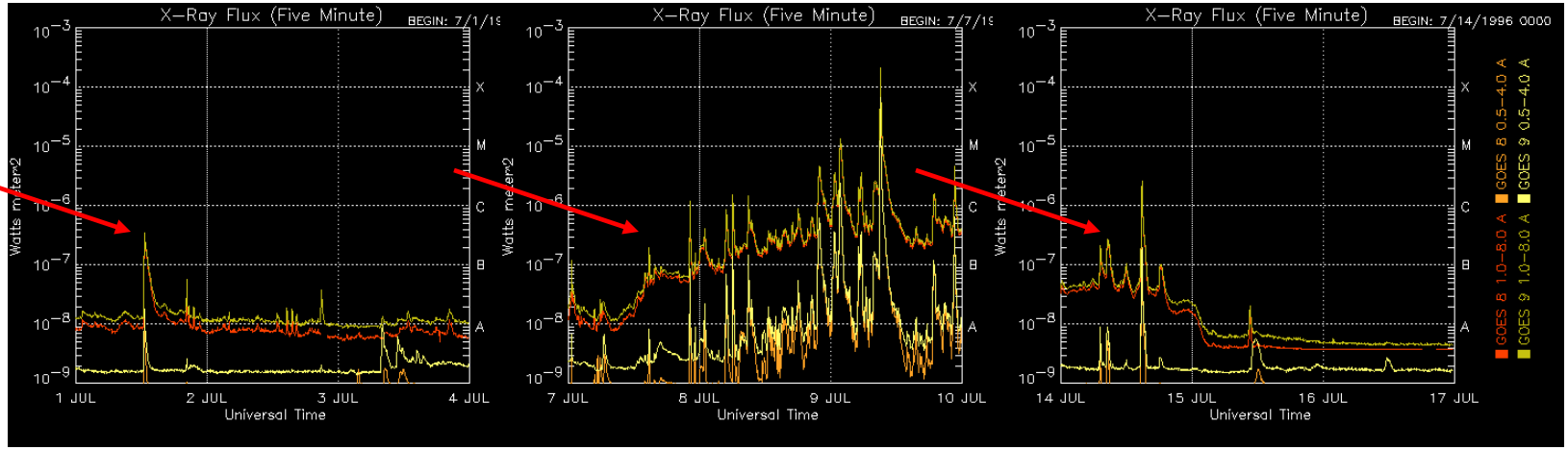
Flare-CME Connection



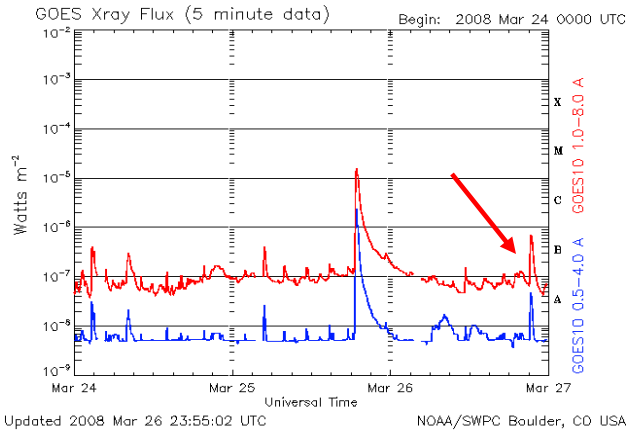
Benz '02

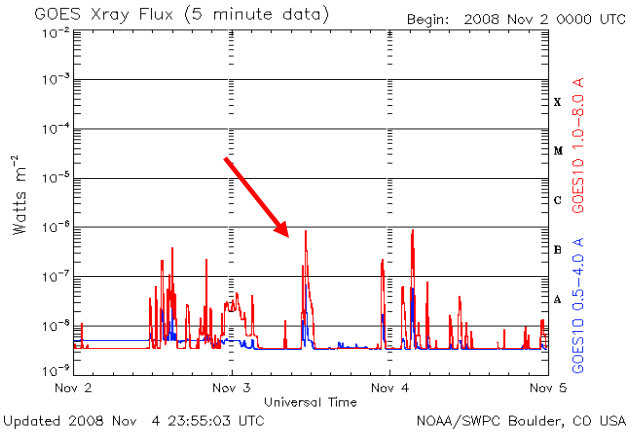


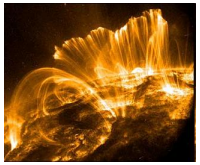
Can we trust the SXR Light Curves?



SXR Background Level effect on Preflare/Flare start times, rise times?

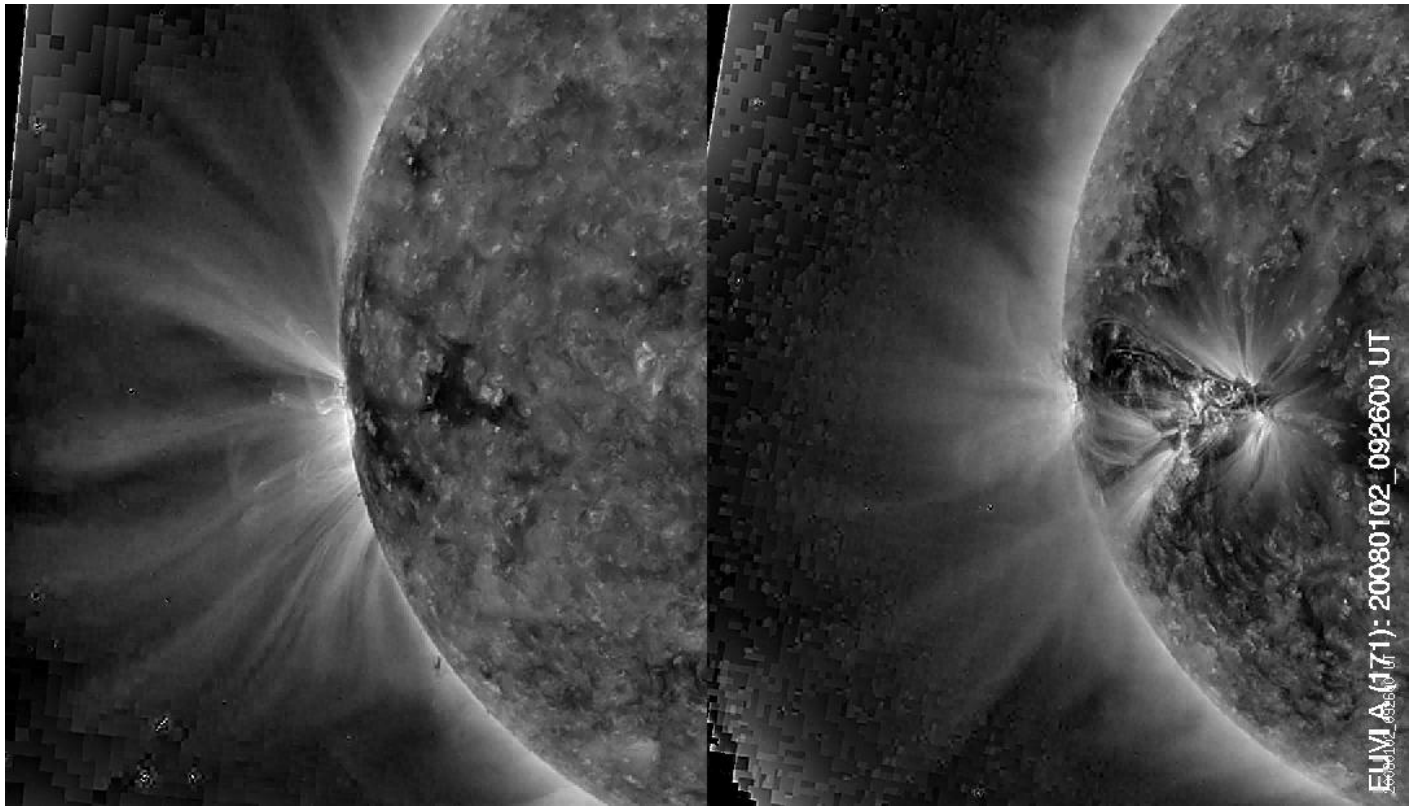


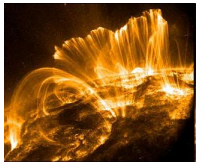




Can we trust the SXR Light Curves?

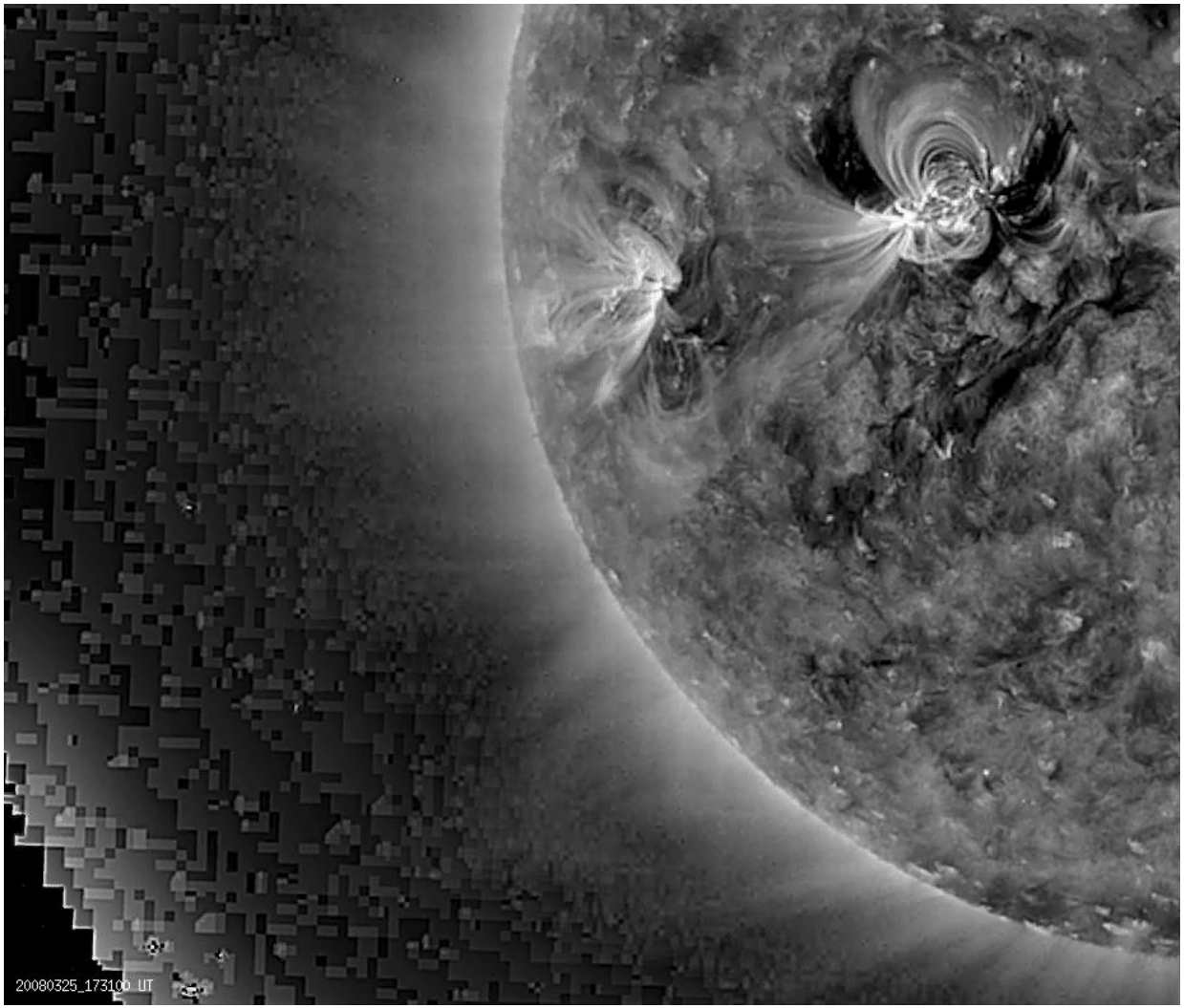
Source confusion from the spatially unresolved SXR curves!



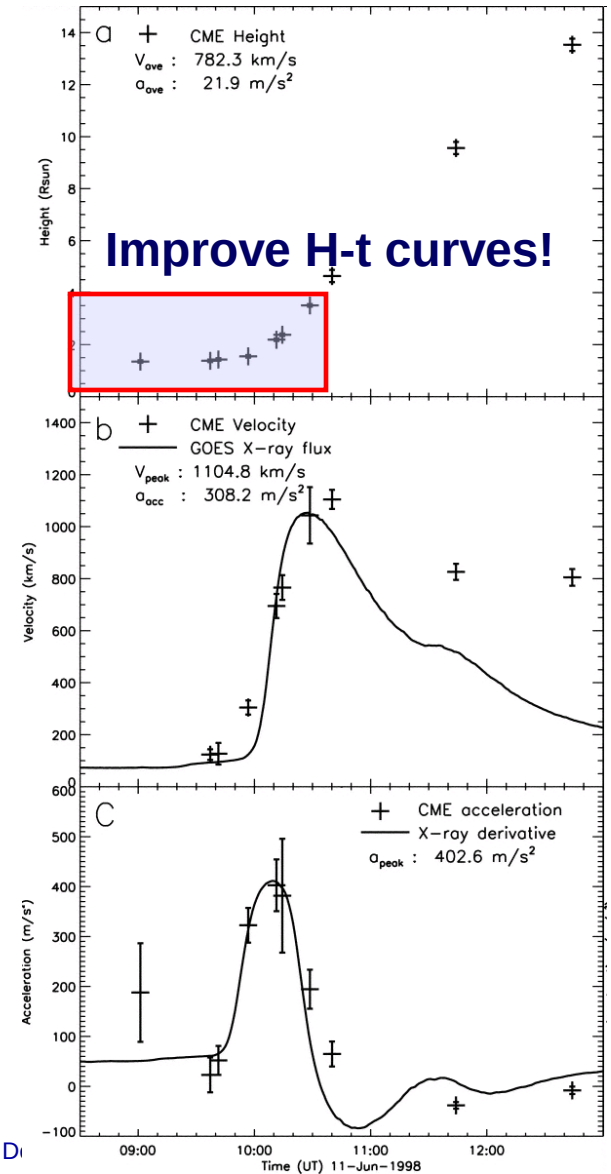


Can we trust the SXR Light Curves?

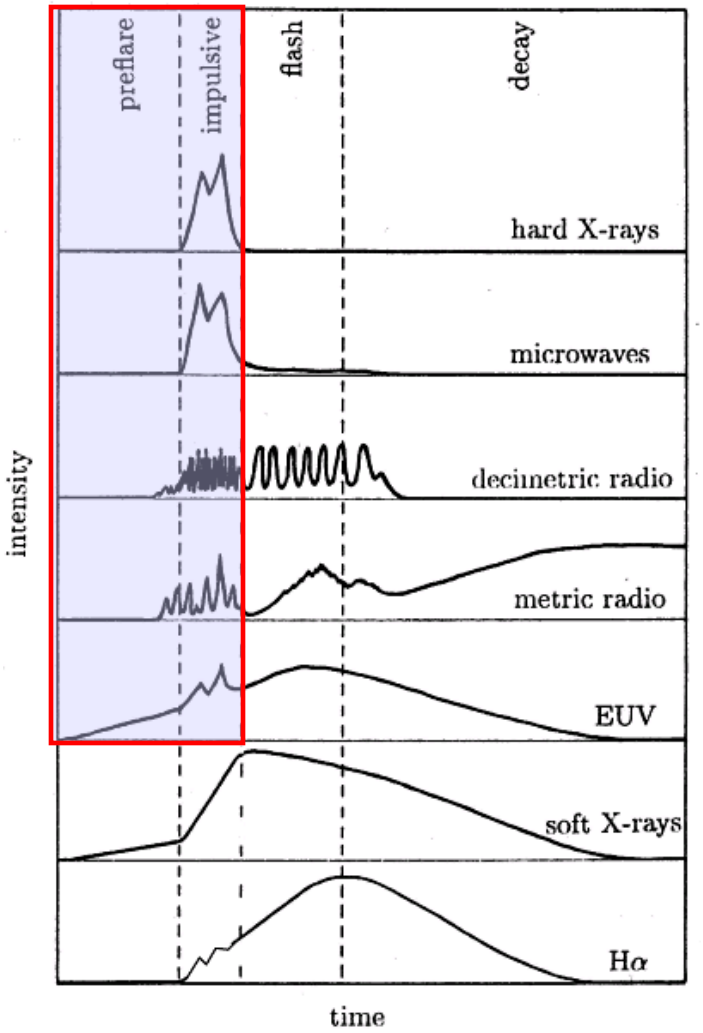
Source confusion from the spatially unresolved SXR curves!

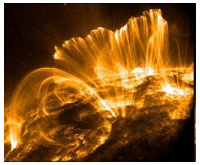


TODO in Cycle 24: Focus on Impulsive Phase



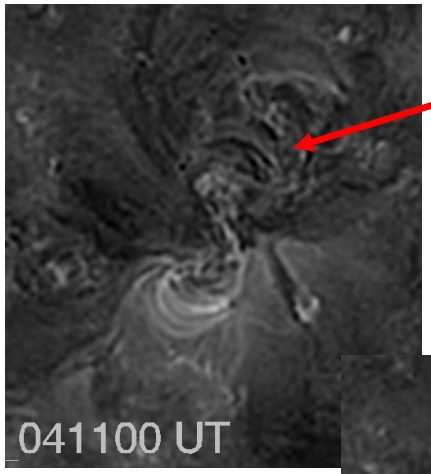
Improve preflare imaging!



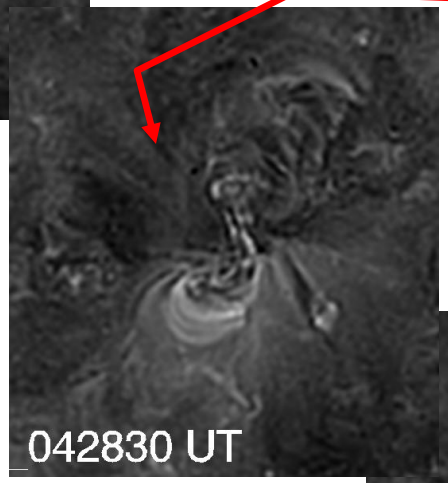


Implications from a STEREO/EUV Wave

EUVI 171A, 12/7/07 Event from Patsourakos et al 09

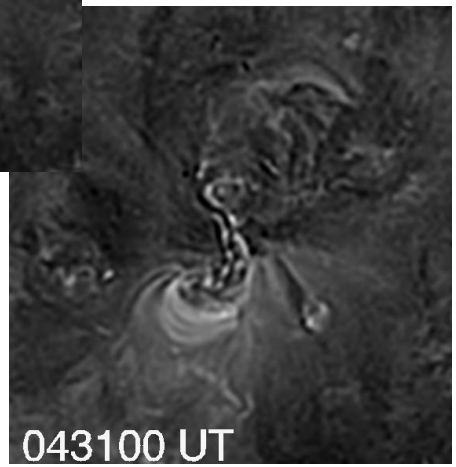


- **Loops start to rise**
  - **10 min BEFORE wave**



- **Wave appears**
  - **No flare!**
  - **Connection between wave & rising loops?**

Phase transition in 90 sec!!



- **Flare ribbons appear**
  - **Rising loops disappear**
  - **Wave accelerates or forms?**

Flares and CMEs Are Very Much Alike

	Size	Time	Side Effects	Energy	Particles	Filament	Wave	Ejecta	Extremes	Mag. Field Re-configuration
CMEs	Global	Slower	Low Corona	~10^{32}	Yes	Yes	Yes	Yes	Mini-CME	Global
Flares	Local	Faster	Outer Corona	~10^{32}	Yes	Yes	Yes	Yes	Nano-Flare	Local

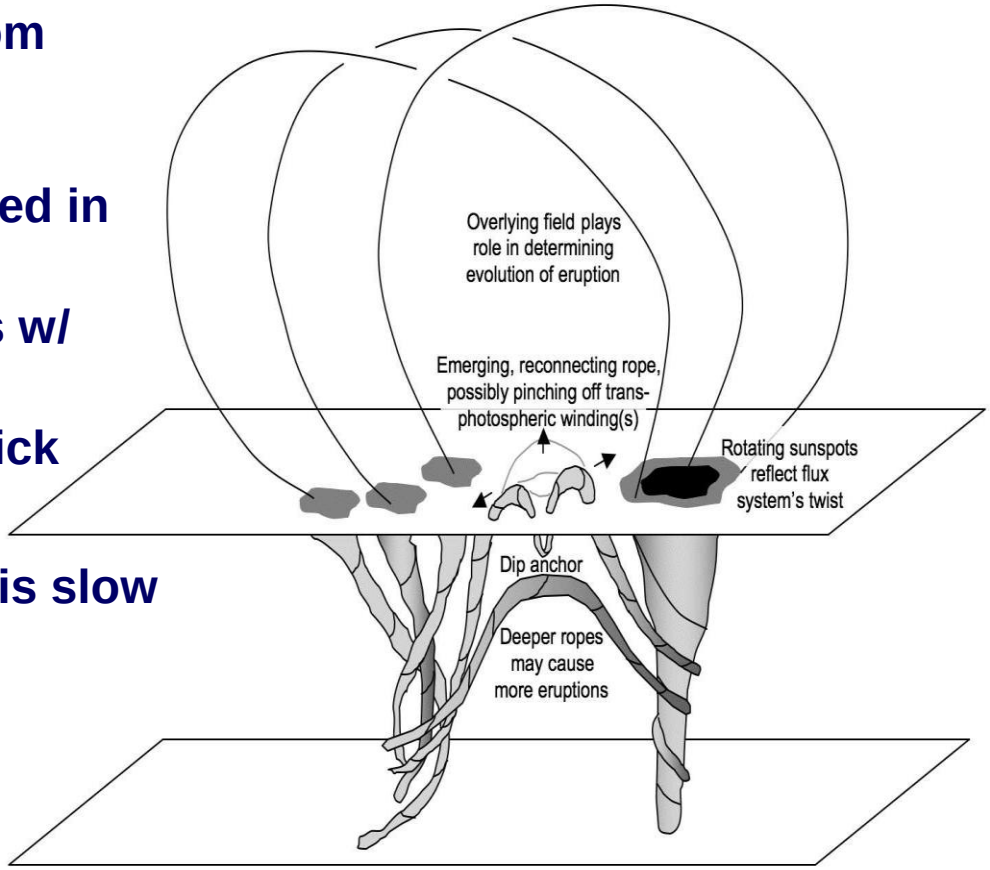
Impulsive CMEs have flares / Gradual flares have CMEs.

Gradual CMEs do not have flares / Impulsive flares do not have CMEs

Putting it all together

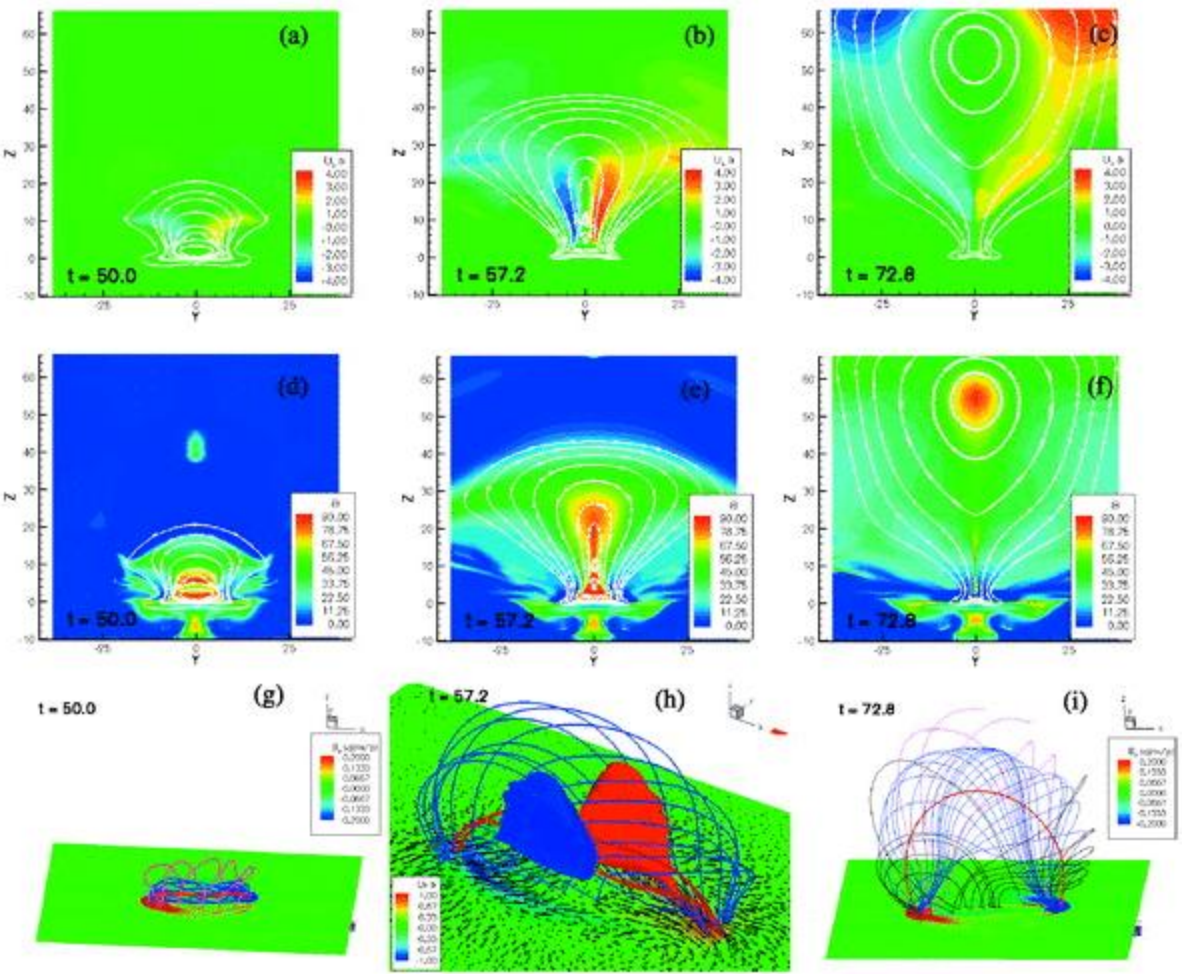
A possible scenario (see Schrijver 2009):

1. **Magnetic field rises as fluxrope from convection zone**
2. **Top of fluxrope bursts through the chromosphere; rests stays anchored in photosphere**
3. **The new coronal fluxrope interacts w/ background:**
   1. **Flare only if reconnection is quick**
   2. **Flare+CME if enough E_{mag}**
   3. **Eruption only if energy release is slow**



Putting it all together

MHD models support such scenario



From Manchester et al 2004

Time to Rethink our Definitions?

'CME' = Ejection of organized (*as fluxrope*) coronal magnetic flux detected by the plasma advected/entrained in the field

'Flare' = EUV/X-Ray brightenings marking locations of electron acceleration

***Flare + CME = FME* (Flaring Magnetic Eruption)**

or

relaxation of the coronal magnetic field through reconnection leading to ejection of magnetic flux (CME), electron acceleration (flare), coronal heating (post-CME loops), *…*

Outstanding Issues

- **Why are there two types of flares (eruptive/implusive)?**
  - **What decides the flare type?**
    - **Available magnetic energy (We need to measure Free Magnetic Energy)**
    - **Access to open field lines**
- **Do the flare-accelerated particles have access to the CME?**
  - **How do they escape?**
  - **How many are there?**
- **What is the connection between the CME acceleration – Flare light curve?**
- **When does the CME fluxrope form?**
- **Is there a single initiation mechanism?**

Wish List for Cycle 24

- **Focused observations of the physical connections between CME and Flare**
  - **Behind the CME/above the flare**
  - **HXR and radio imaging**
  - ***Wish: Eclipse-like visible imaging of the corona (0.03 – 3 Rs)***
- **Reliable estimation of the field non-potentiality**
  - **Improved extrapolation codes**
  - ***Wish: Magnetic field observations above canopy into TR***
- **FME Initiation:**
  - **High cadence EUV observations (< 1min), during the early phase (<10 min), at low heights (<1.5 Rs) .**
- **Improved energy measurements.**
  - **Better flare energy estimates.**
  - **CME composition measurements in early phase (e.g., Lee et al 09).**

Questions for Working Groups

Q1: Does the erupting fluxrope preexist? Is this a valid question?

Q2: What can we learn from the CME acceleration profile?

Q3: What is the role of B_{bkg} in flares/CMEs?

Q4: Are there flares without CMEs (incl. any plasma ejection)?

Q5: What is the role of non-magnetic forces in the eruption?

Q6: Do we understand 3D reconnection? Topologies, energy release/partition?

Q7: How can we reliably measure the 'free' magnetic energy? What about helicity?

Q8: Role of multipolar systems in flares/CMEs?

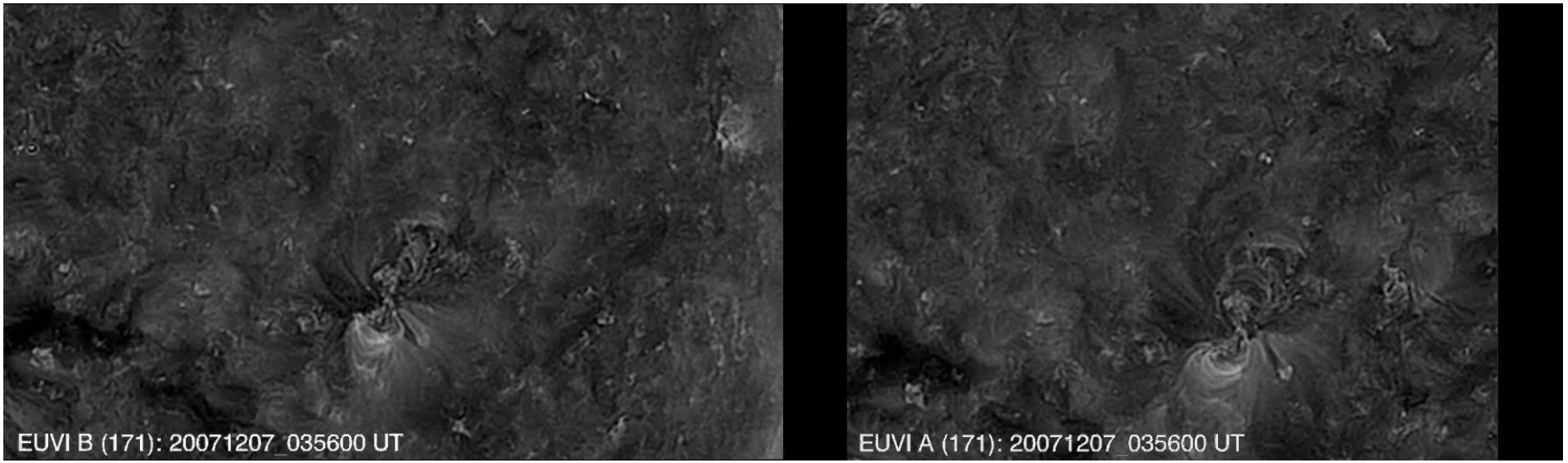
Q9: How reliable are the GOES SXR curves?

BACKUP SLIDES

Nugget 2: EUV Wave Structure/Evolution

- A-B separation = 42 deg
- Cadence = 2.5 min
- Mild wavelet enhancement

- First EUV wave with
  - High cadence (< 2.5 min)
  - Multi-temperature (4 wavelengths within minute)
  - Stereoscopic (EUVI-A, -B, EIT)



Statistical Studies

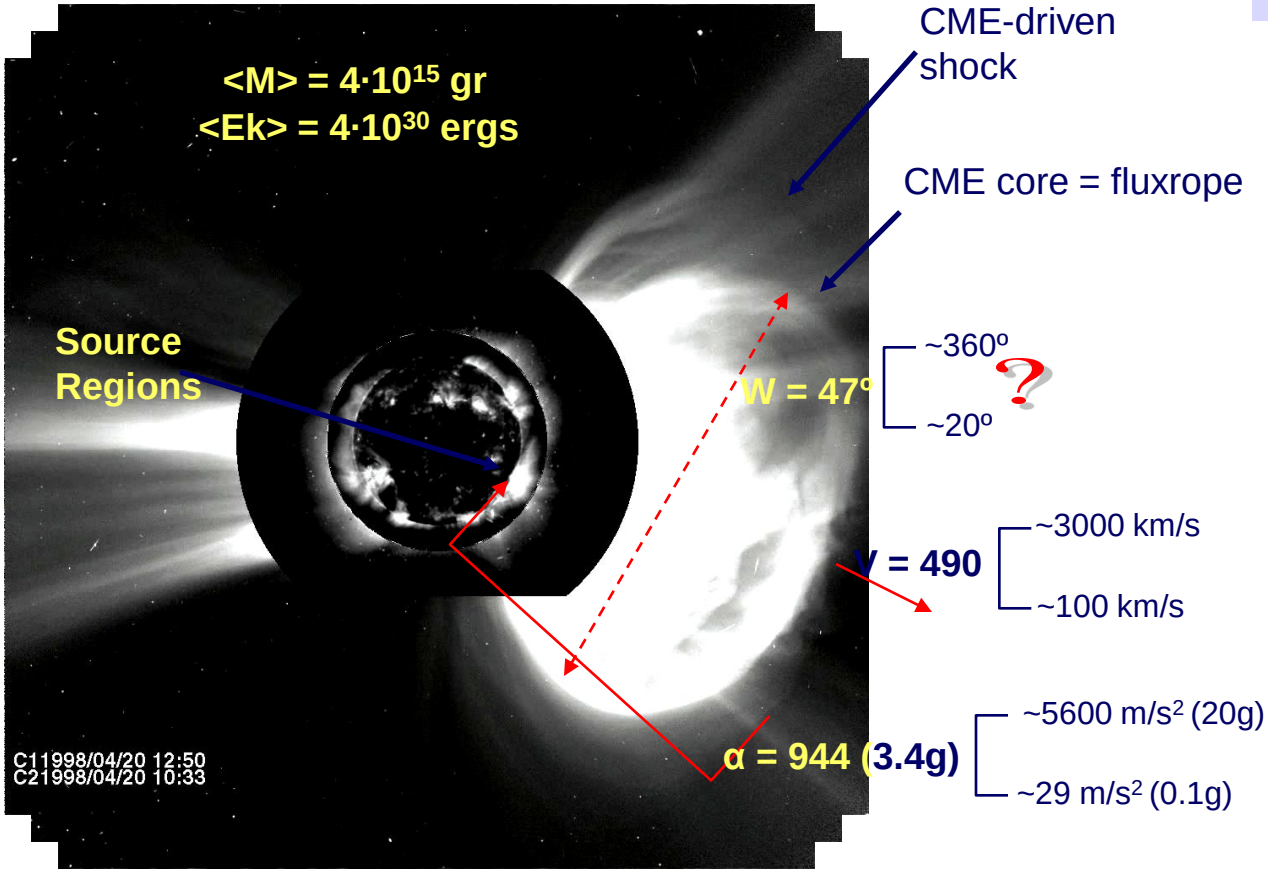
1. Moon, Y.-J. et al. 2002, ApJ, 581, 694
2. Moon, Y.-J. et al. 2003, J. Korean Astron. Soc., 36, 61
3. Andrews, M. D. 2003, Sol. Phys., 218, 261
4. Nindos, A., & Andrews, M. D. 2004, ApJL, 616, L175
5. Moon, Y.-J. et al. 2004, ApJ, 615, 1011
6. Jing, J. et al. 2004, ApJ, 614, 1054
7. Vršnak, B, Sudar, D., & Ruždjak, D. 2005, A&A, 435, 1149
8. Yashiro, S., et al. 2006, ApJL, 650, 143

9. **Burkepile, J. T., et al. 2004, JGR., 109*

CMEs in the LASCO Era (3)

- **With >15,000 Events recorded, the basic CME properties are well-known**

Tendency for
Slow CMEs to Accelerate
and
Fast CMEs to Decelerate



CME-driven shock

CME core = fluxrope

W = 47° ~360° ~20° ?

V = 490 ~3000 km/s ~100 km/s

α = 944 (3.4g) ~5600 m/s² (20g) ~29 m/s² (0.1g)