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Solar eruptions and energetic events

Astrid M. Veronig

Kanzelhöhe Observatory & Institute of Physics,
University of Graz, Austria

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Lanzarote, 16 – 20 January 2017

Outline

1) Basic observational signatures

2) Models of coronal mass ejections (CMEs) & flares

3) Energy storage and release

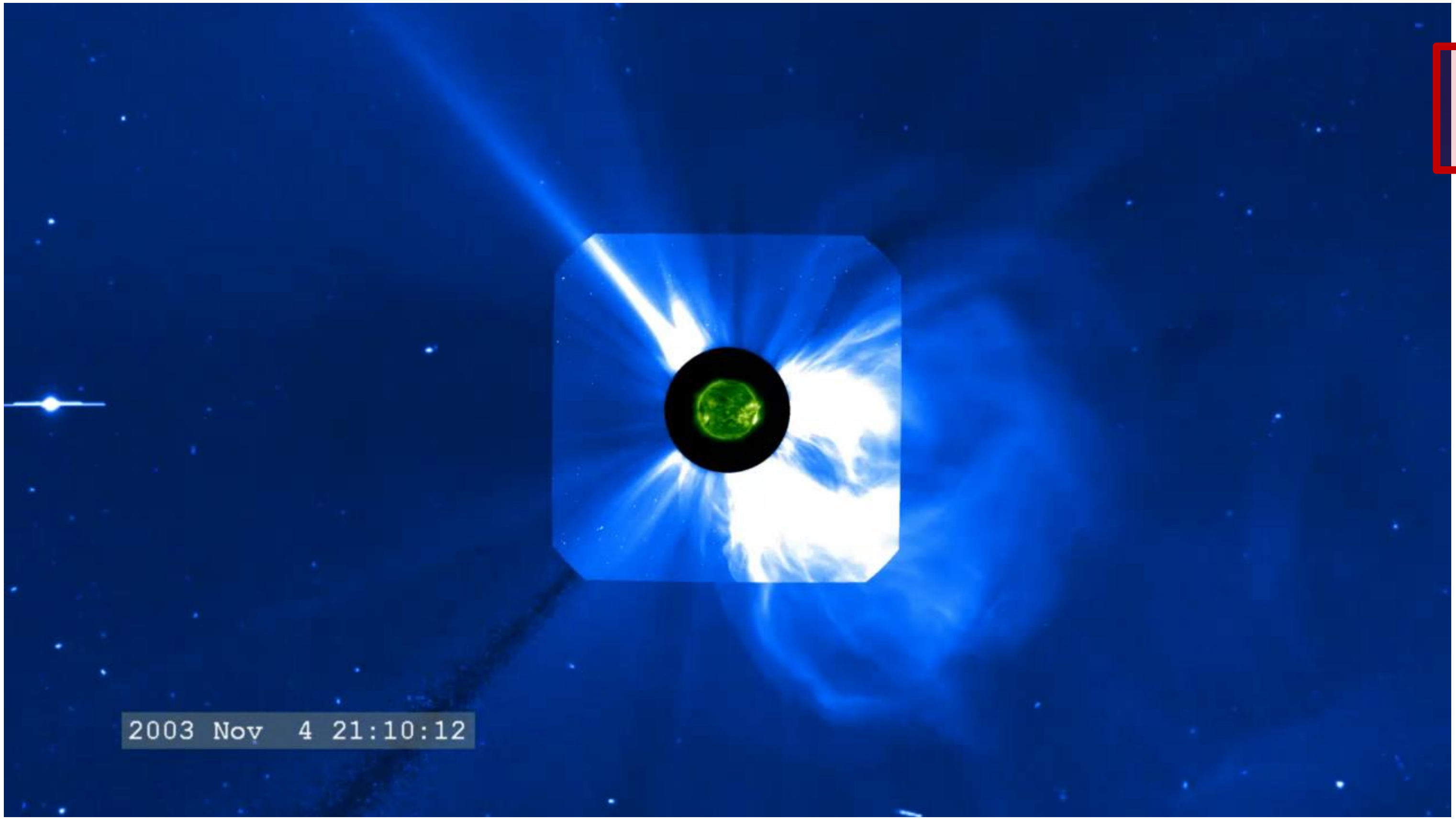
4) CME dynamics and relation to associated flare

5) Conclusions

Basic observational signatures

CMEs are expulsions of magnetized plasma with speeds of ~100 to ~3000 km/s.

Fastest CMEs may reach Earth in <1 day. Drive shock waves and accelerate solar energetic particles (SEPs) & may produce geomagnetic storms.

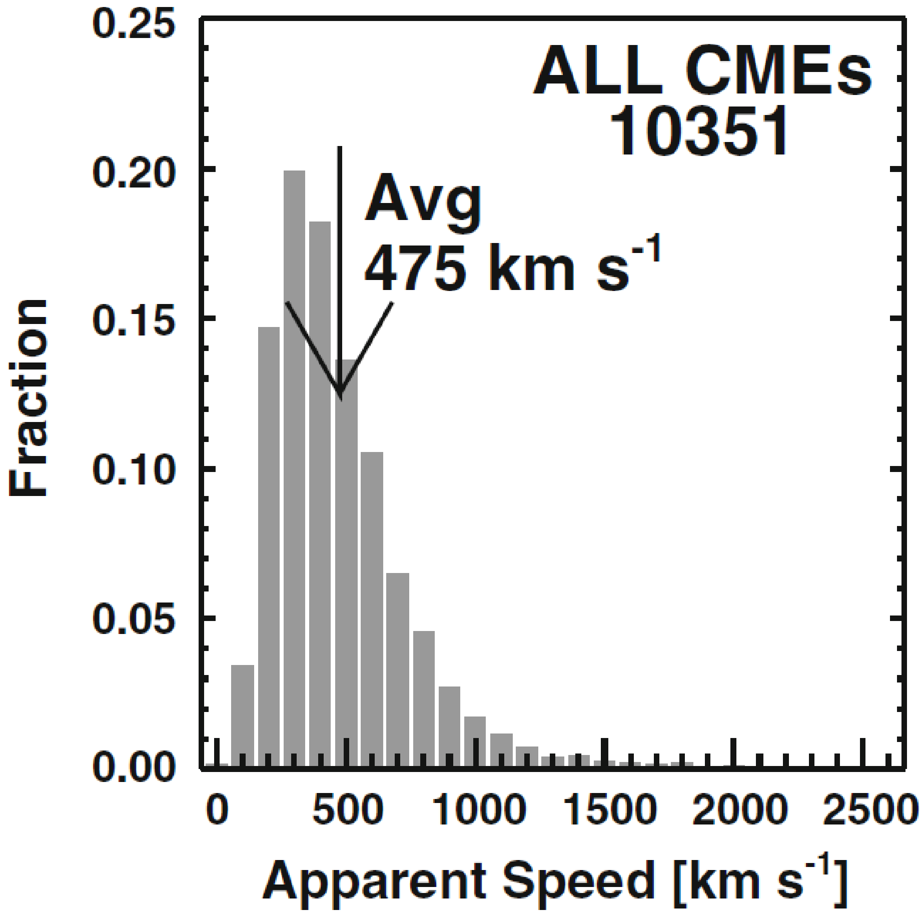


Space weather effects
⇒ Talk by Consuelo Cid

Basic observational signatures

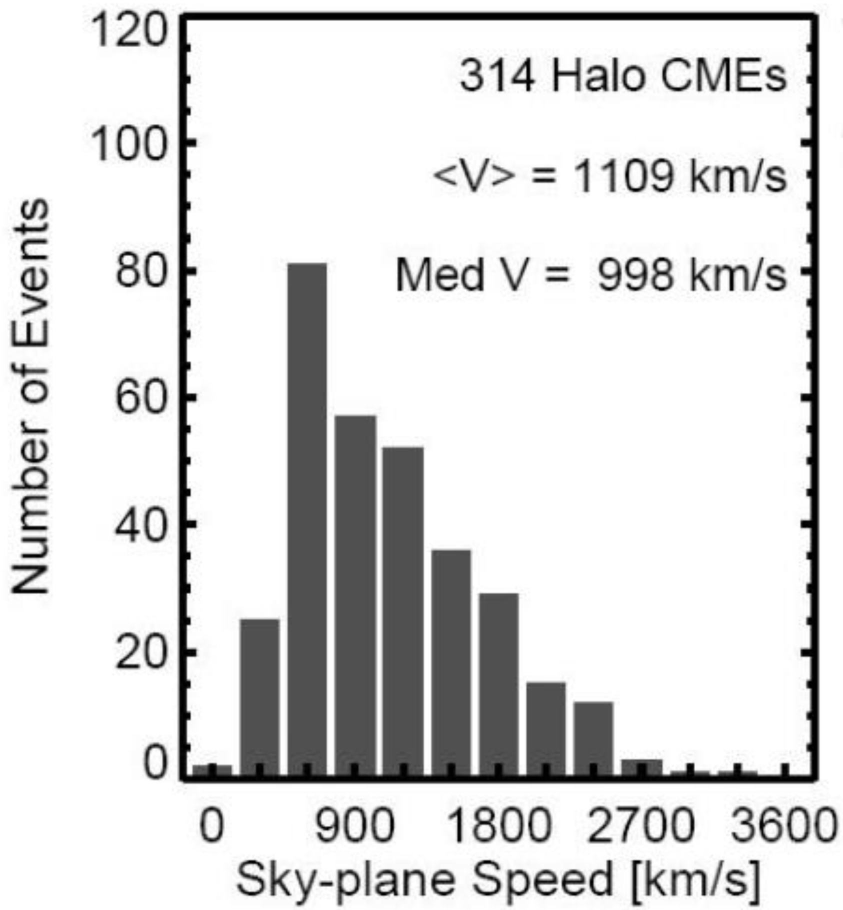
CME Speed distribution

All CMEs



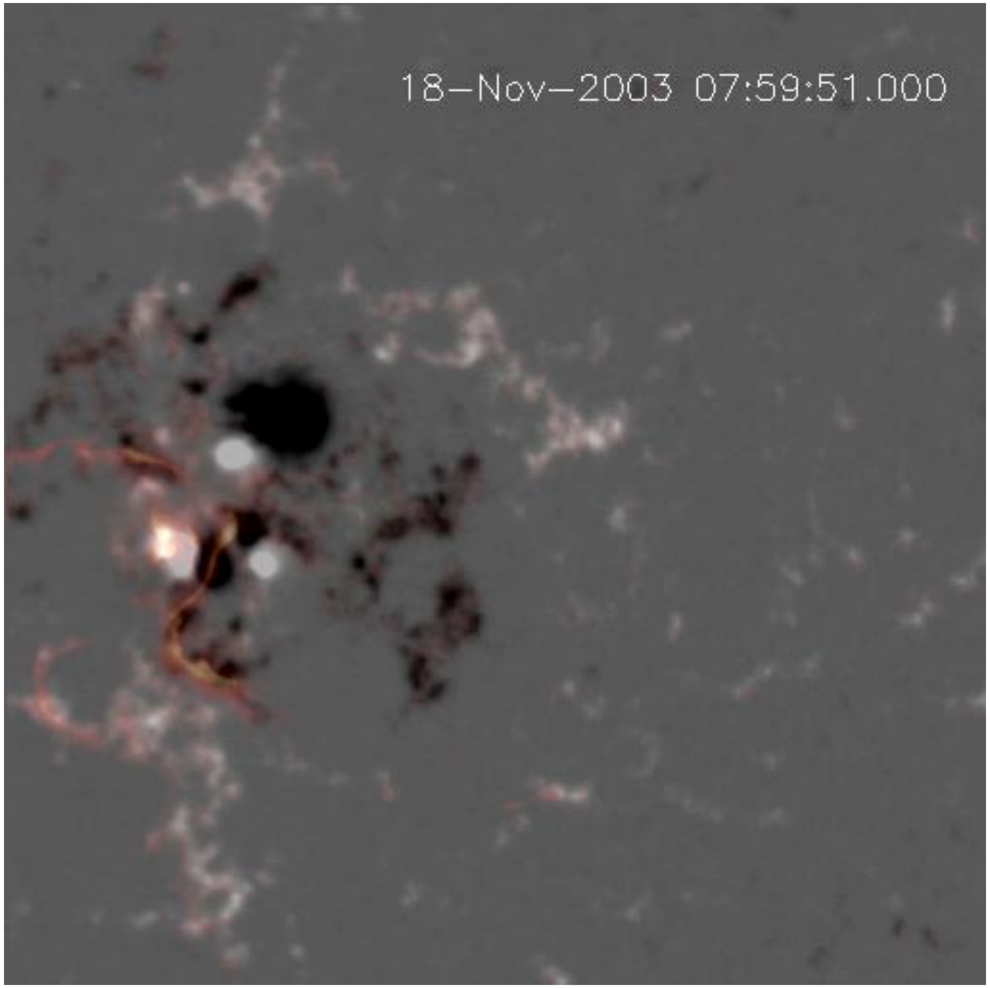
Gopalswamy et al., EMP 104 (2009)

Halo CMEs



Gopalswamy et al., S&G 5 (2010)

Basic observational signatures



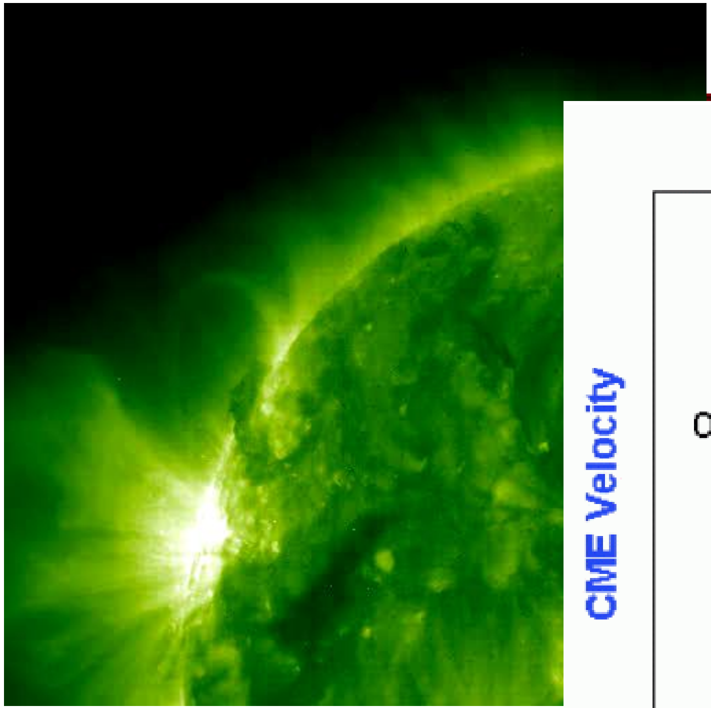
Miklenic et al., A&A 461 (2007)

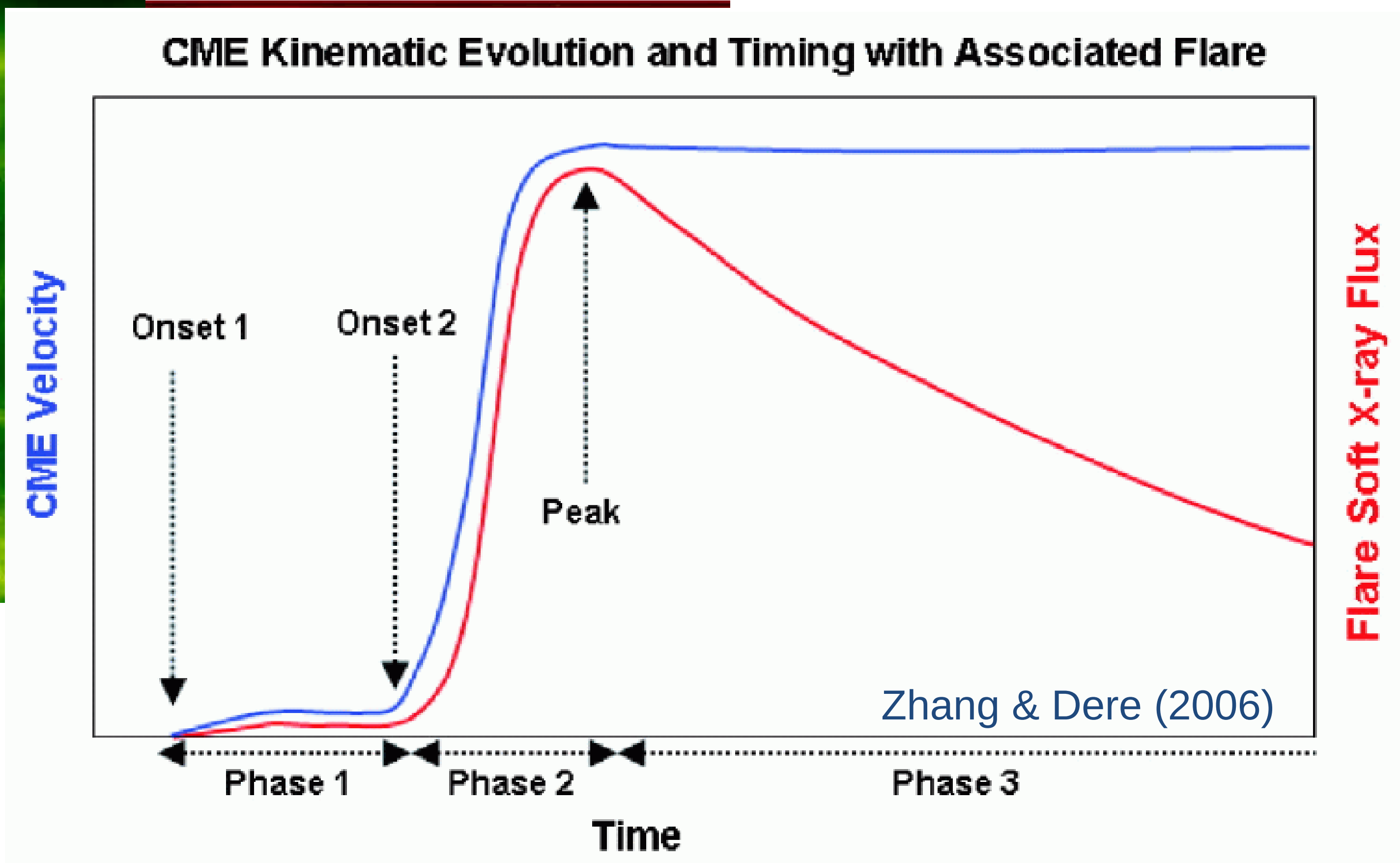
Flares are transient emission enhancements, in particular in chromosphere and corona.

High-energy particles and heating of solar atmosphere to >10 MK.

TRACE UV flare ribbons blended on MDI LOS magnetic field map: motion away from magnetic polarity inversion line.

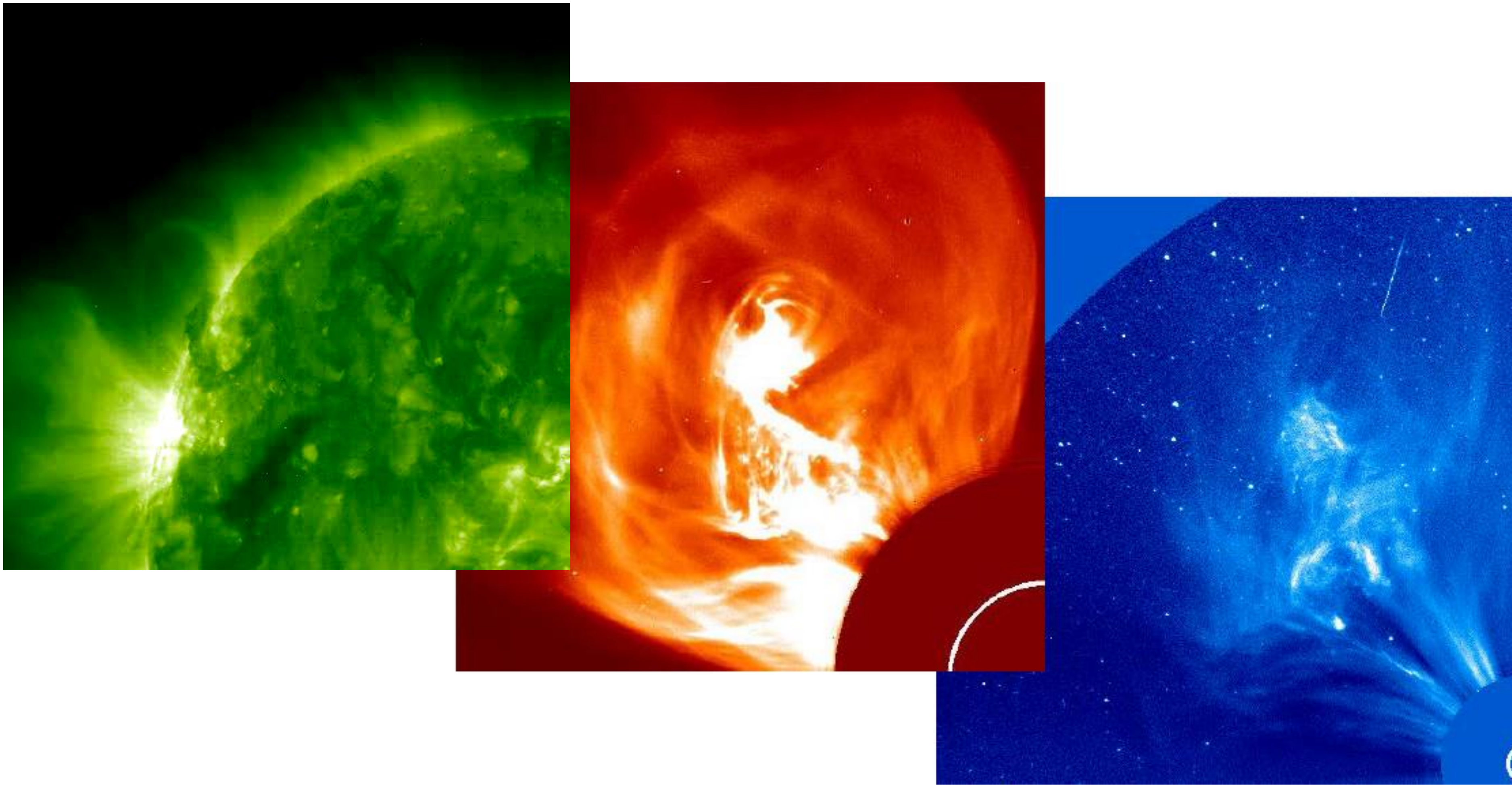
Basic observational signatures





Instaneous CME onset & rapid initial acceleration & impulsive flare energy release: energy storage & release model

Basic observational signatures



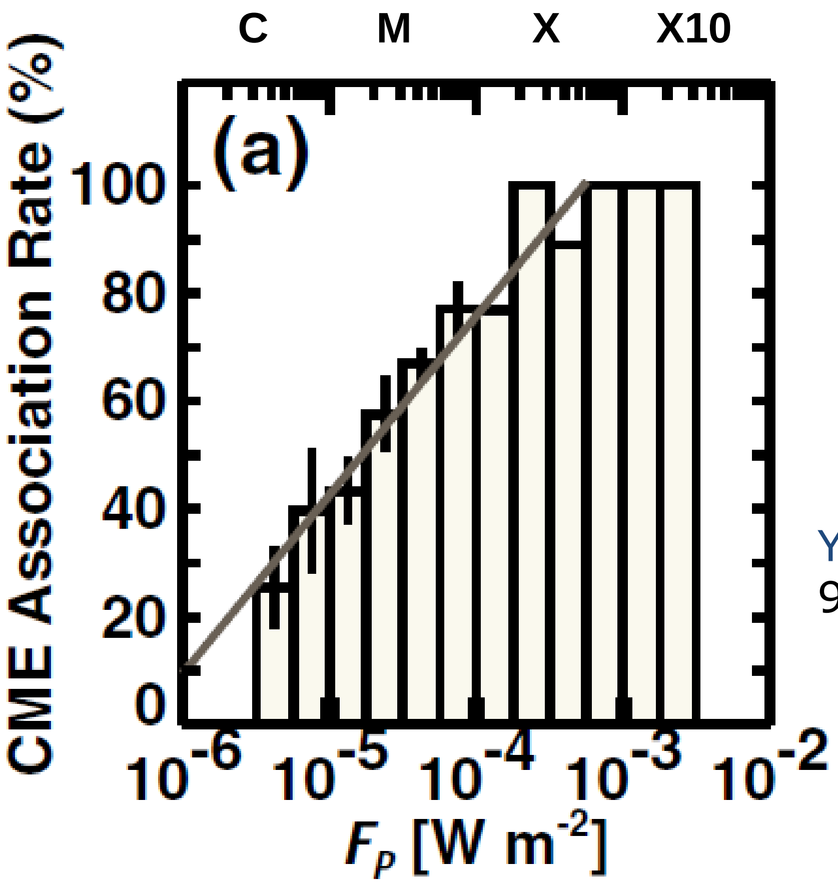
In large events: all three signatures occur together:
Flare – coronal mass ejection (CME) - prominence

$\Rightarrow$ Different observational signatures of one (complex) process

Basic observational signatures

Eruptive flares versus confined flares:

CME association rate is a steeply increasing function of flare class



Yashiro et al. (2006): statistics of 98 X, 692 M, 575 C flares

CME models

Prominence eruption

+

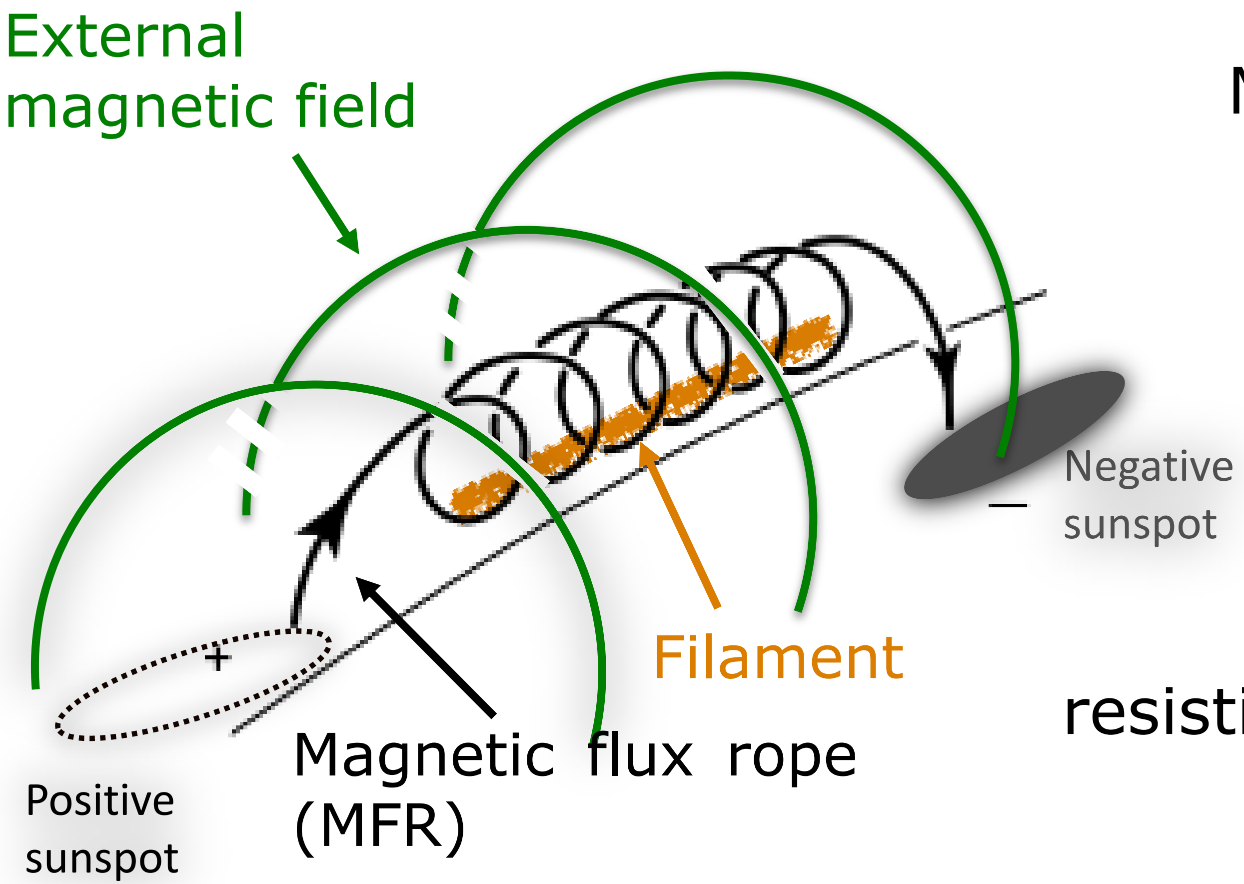
Coronal mass ejection (CME)

+

Flare

= Large-scale coronal instability

CME models



Courtesy of Francesco Zuccarello

Loss of equilibrium:

Magnetic tension

vs

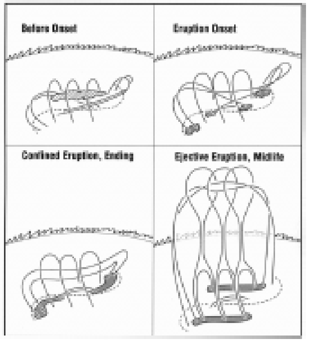
Magnetic pressure of MFR

ideal-MHD instability

resistive instability

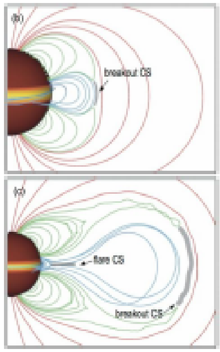
CME models

Tether Cutting (1992):
"runaway" reconnection
inside magnetic arcade



Moore et al. 2001 ApJ

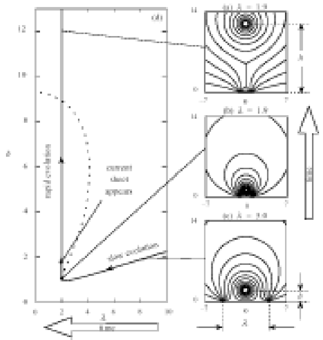
Magnetic Breakout (1999):
"breakout" reconnection
above triple magn. arcade



Karpen et al. 2012 ApJ

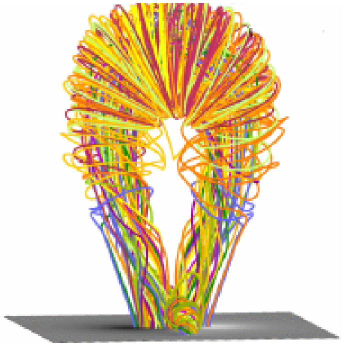
Flux rope forms
after CME onset

Flux Rope Catastrophe (1978):
end point in equilibrium
sequence & jump



Forbes & Priest 1995 ApJ

Flux Rope Instability (1978):
ideal MHD instability
(torus & kink instabilities)



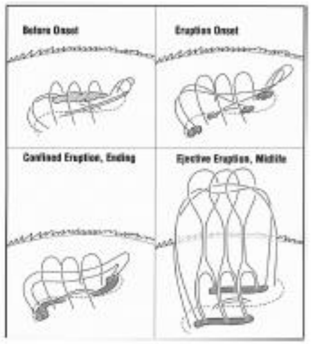
Kliem & Török 2006 PRL

Flux rope exists
prior to CME onset

Courtesy of Bernhard Kliem

CME models

Tether Cutting (1992):
“runaway” reconnection
inside magnetic arcade



Moore et al. 2001 ApJ

Magnetic Breakout (1999):
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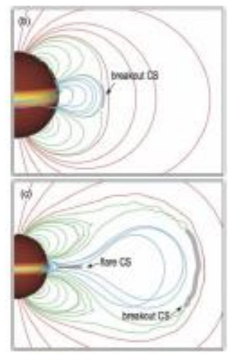
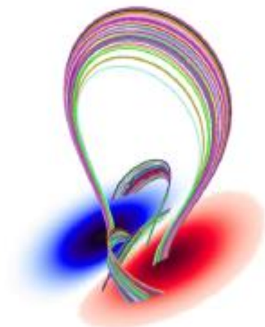
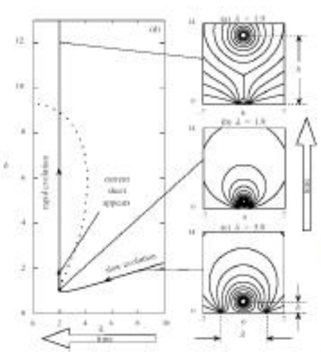


Karpen et al. 2012 ApJ

Flux Cancellation (2000)
photospheric reconnection
forms flux rope



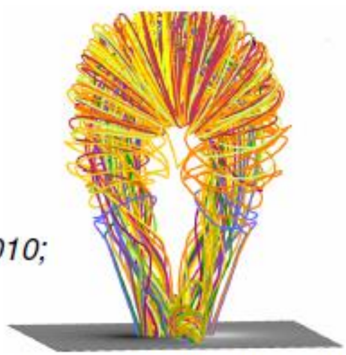
Flux Rope Catastrophe (1978):
end point in equilibrium
sequence & jump



Forbes & Priest 1995 ApJ

Flux Rope Instability (1978):
ideal MHD instability
(torus & kink instabilities)

Démoulin & Aulanier 2010;
Kliem et al. 2014



Kliem & Török 2006 PRL

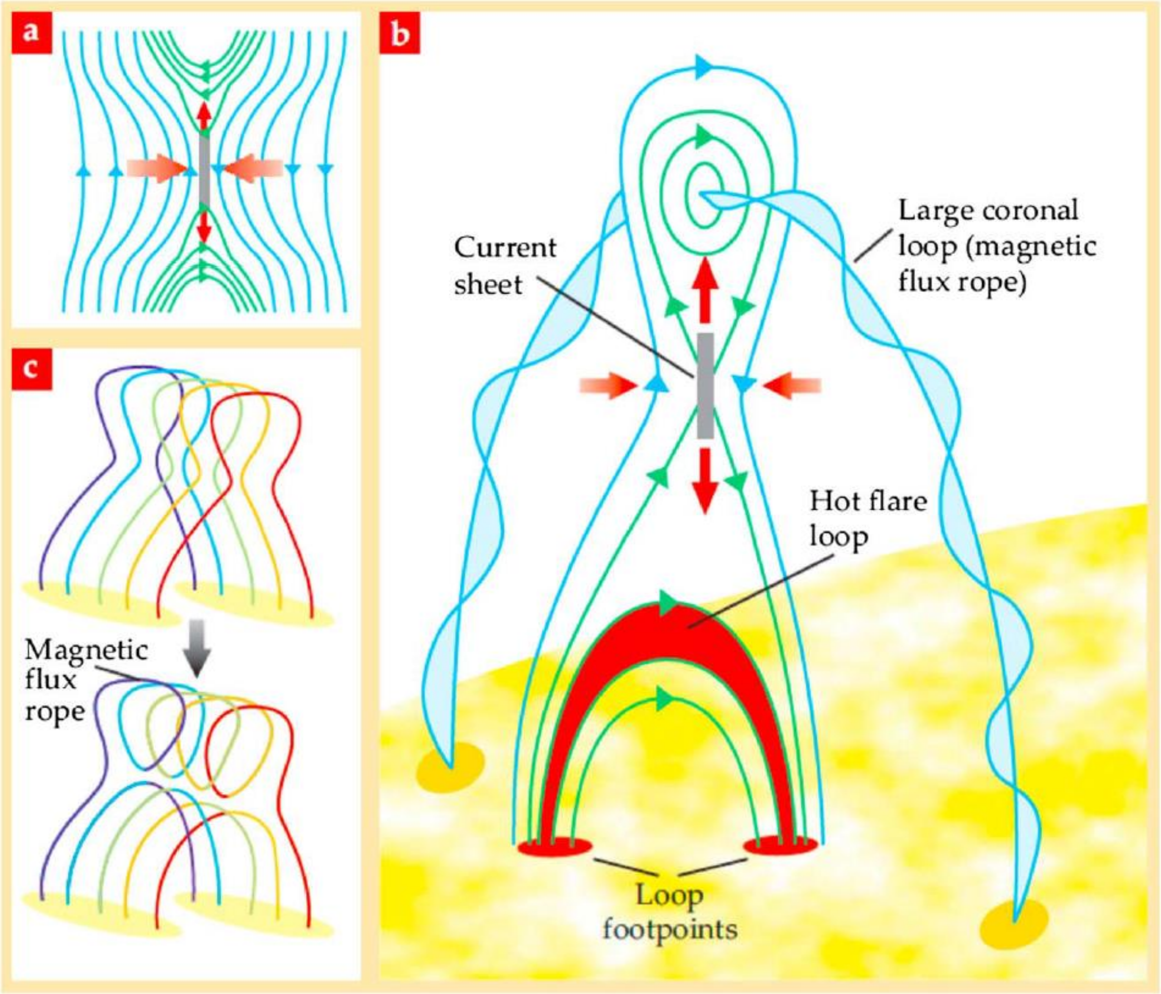
Flux Cancellation (2000)
flux rope
is unstable

Savcheva et al. 2012;
Kliem et al. 2013
Fan & Gibson (2007)

Linker et al. 2003 Phys. Plasmas

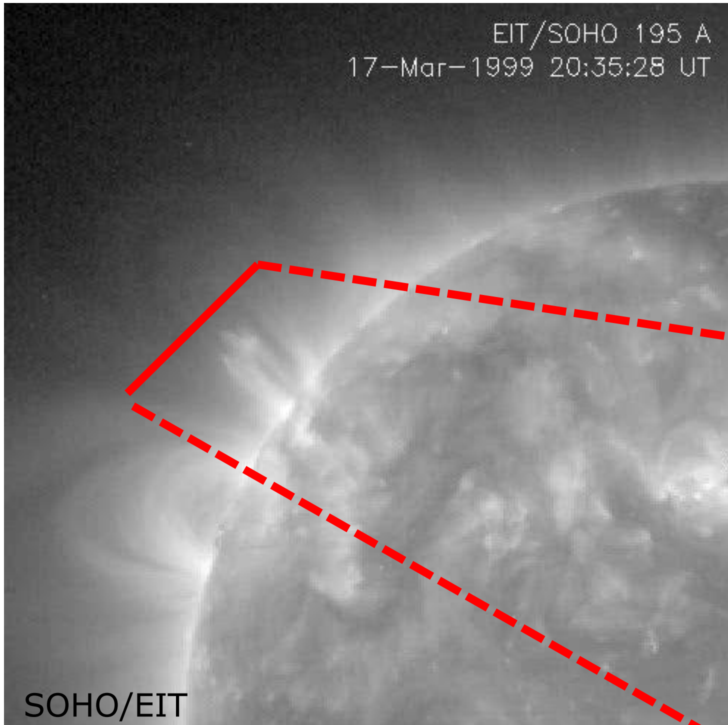
CME models

Standard eruptive flare model (tether cutting) – cartoon



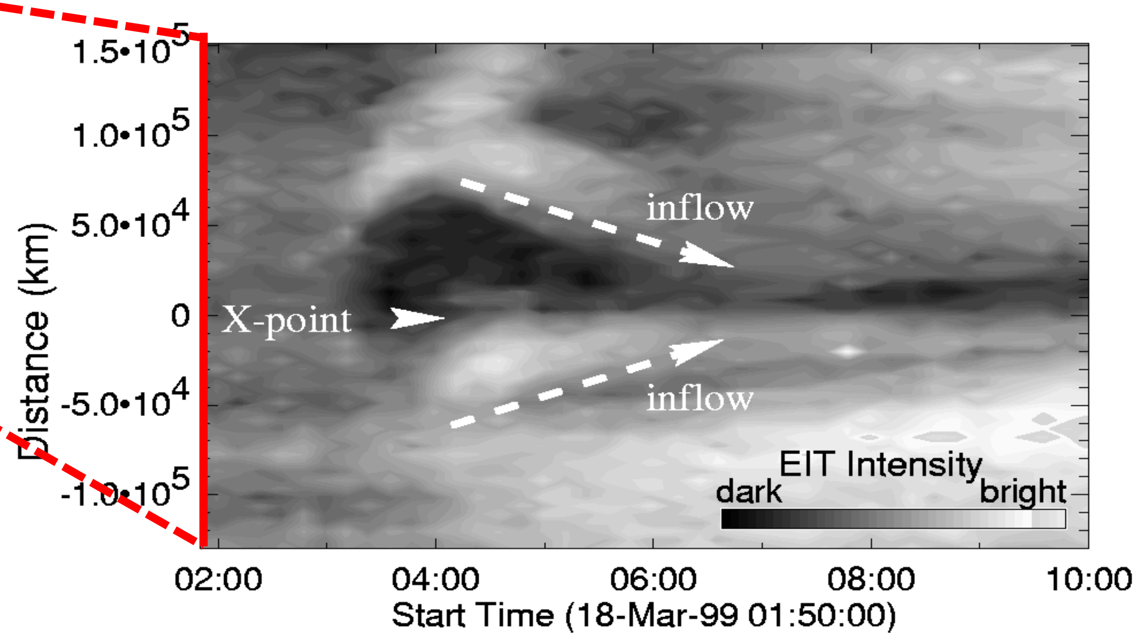
Holman (2016)

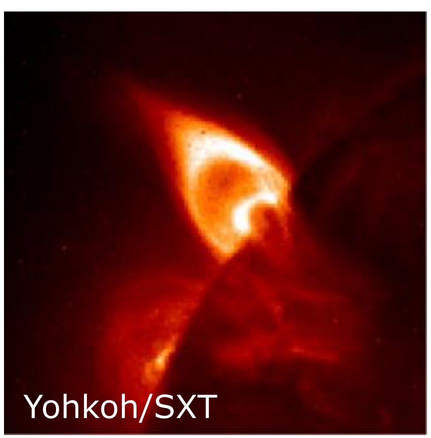
CME models



Reconnection inflow behind erupting CME.

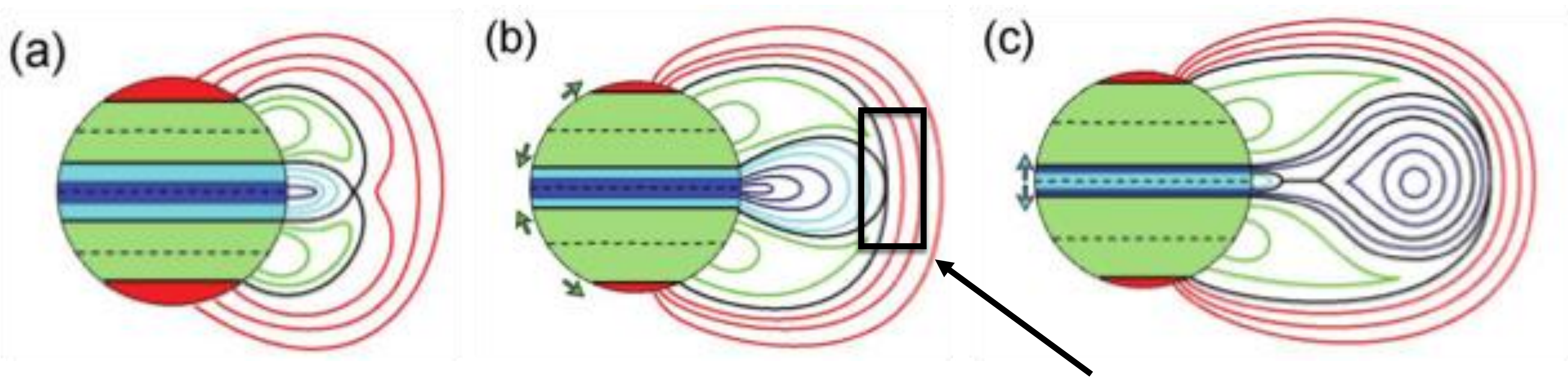
Yokoyama et al., ApJL 546 (2001)





CME models

Breakout model (Antiochos et al. 1999):



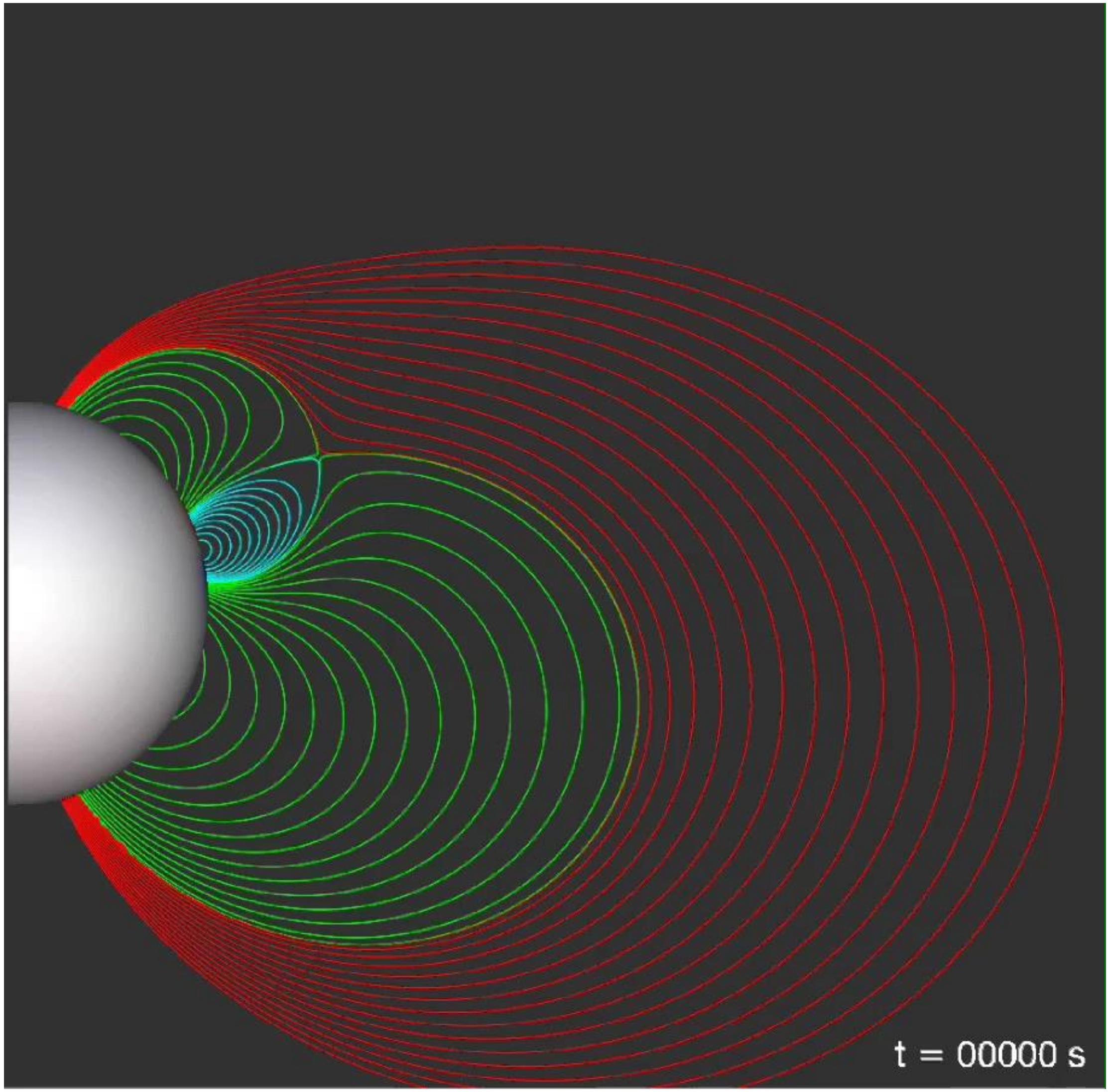
Multipolar topology + null point + highly sheared arcade

The onset of resistive instability leads to fast removal of unsheared overlying flux and eruption of the sheared arcade

Courtesy of Francesco Zuccarello

CME models

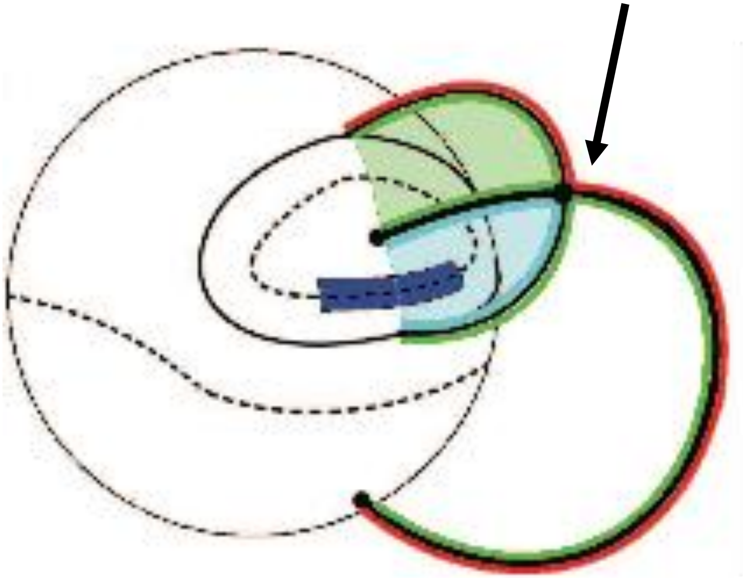
Lynch et al. (2008)



3D MHD simulation

Fast (~Alfvén speed) eruption without pre-existing flux rope

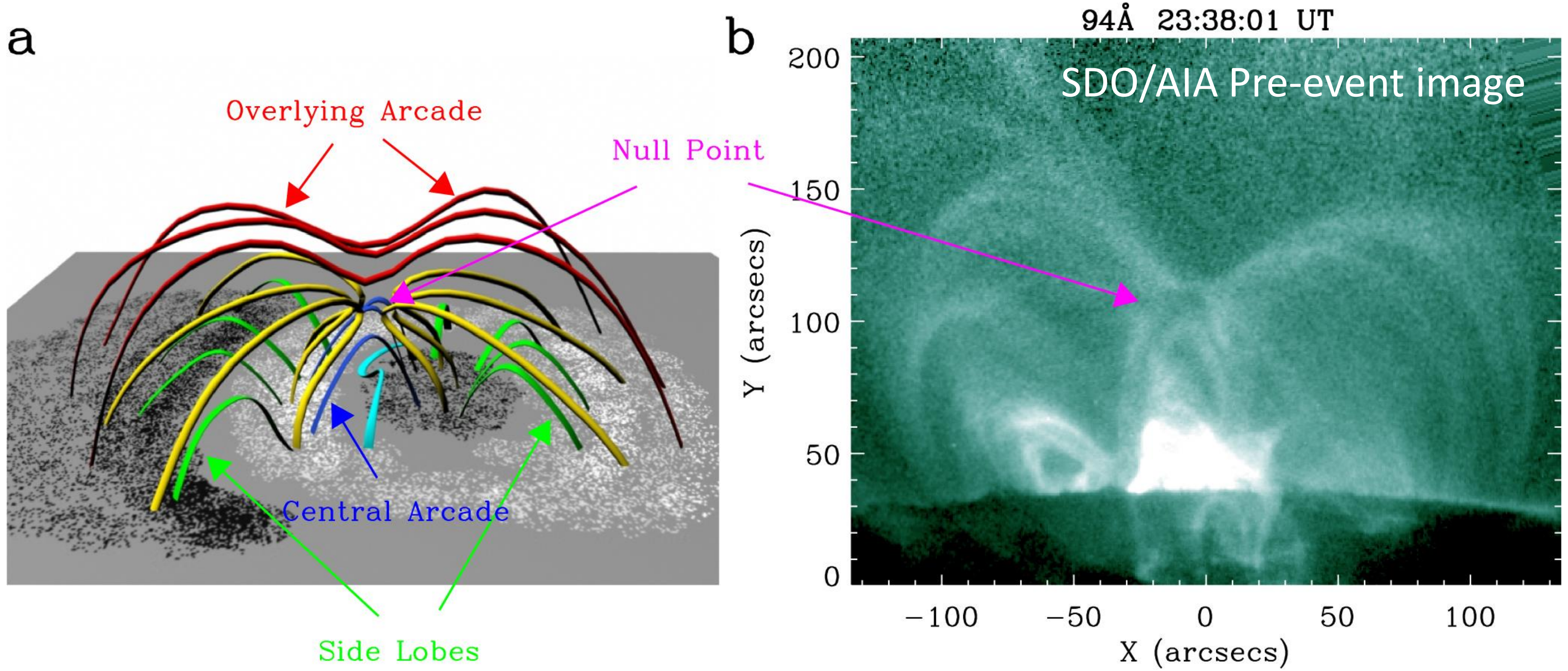
Null-point



Courtesy of Francesco Zuccarello

CME models

Imaging observations of magnetic break-out reconnection by SDO/AIA

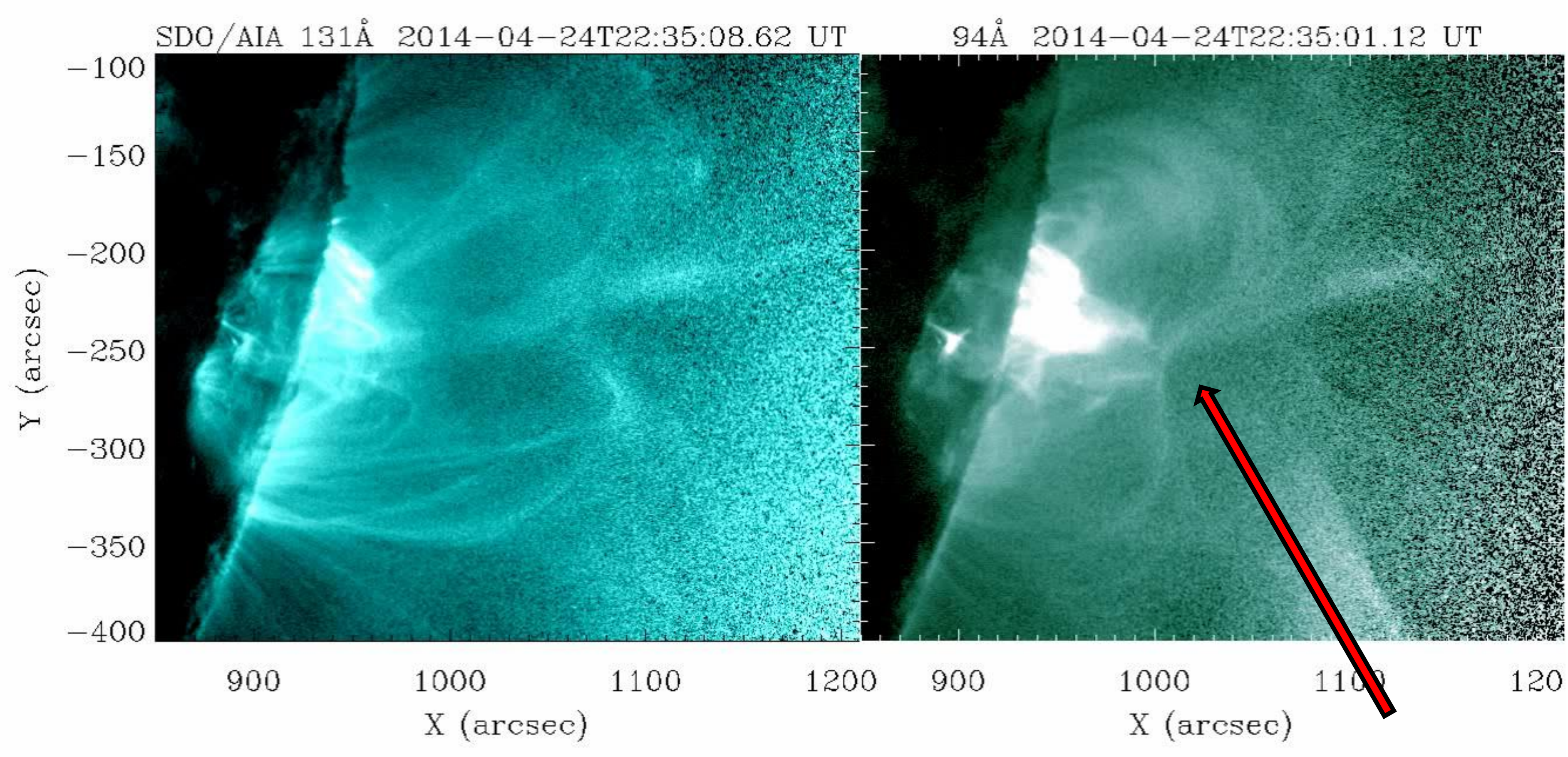


Magnetic field sketch

Chen et al. (2016)

CME models

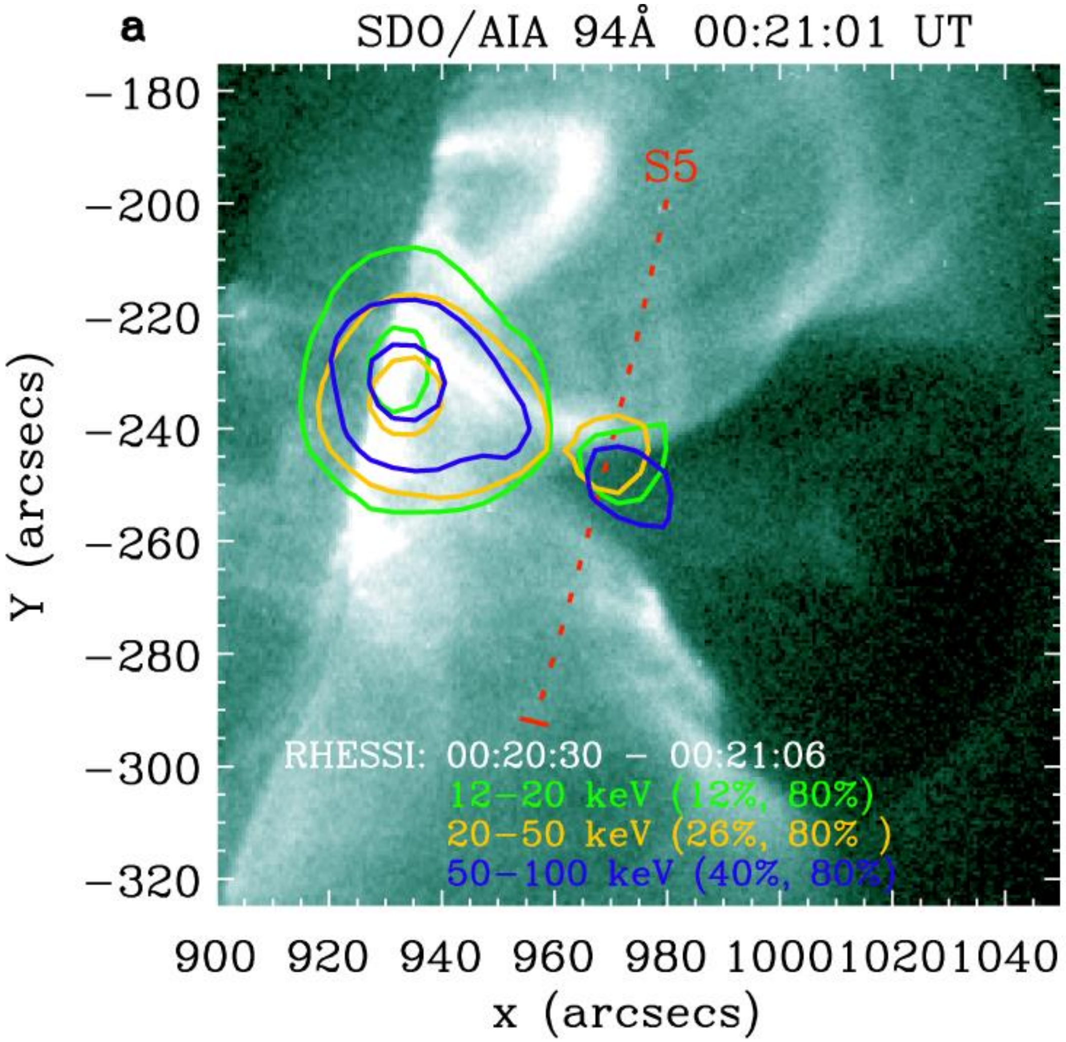
Imaging observations of magnetic break-out reconnection by SDO/AIA.



Chen et al. (2016)

CME models

RHESSI X-ray observations of flare energy release in break-out reconn.



Chen et al. (2016)

CME models

Flux rope instabilities: torus instability, kink instability
(Török & Kliem 2005, 2006, Fan & Gibson 2007)

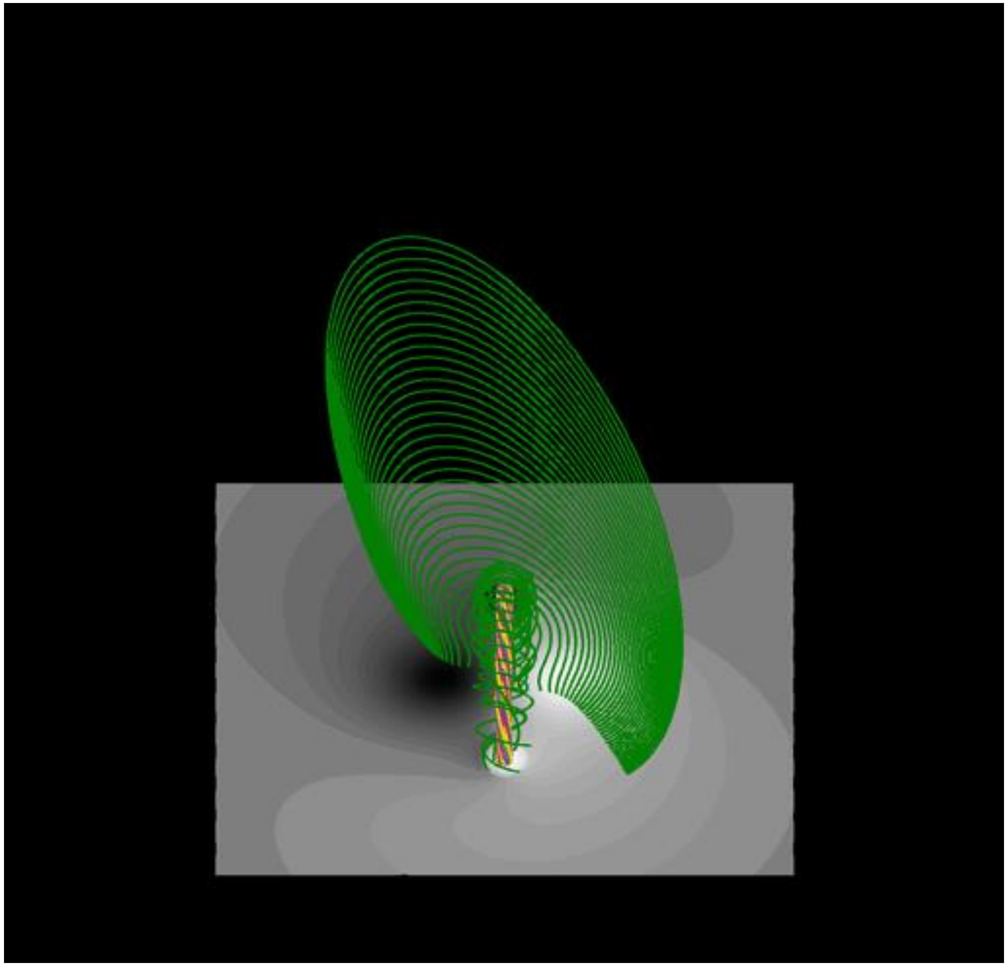
Torus instability:

Eruption depends on the stratification of the overlying field

Critical decay index:

$n = -\mathrm{d}(\ln B_{ex}) / \mathrm{d}(\ln z) > 1.5$

Ideal instabilities play important role as trigger for CMEs.



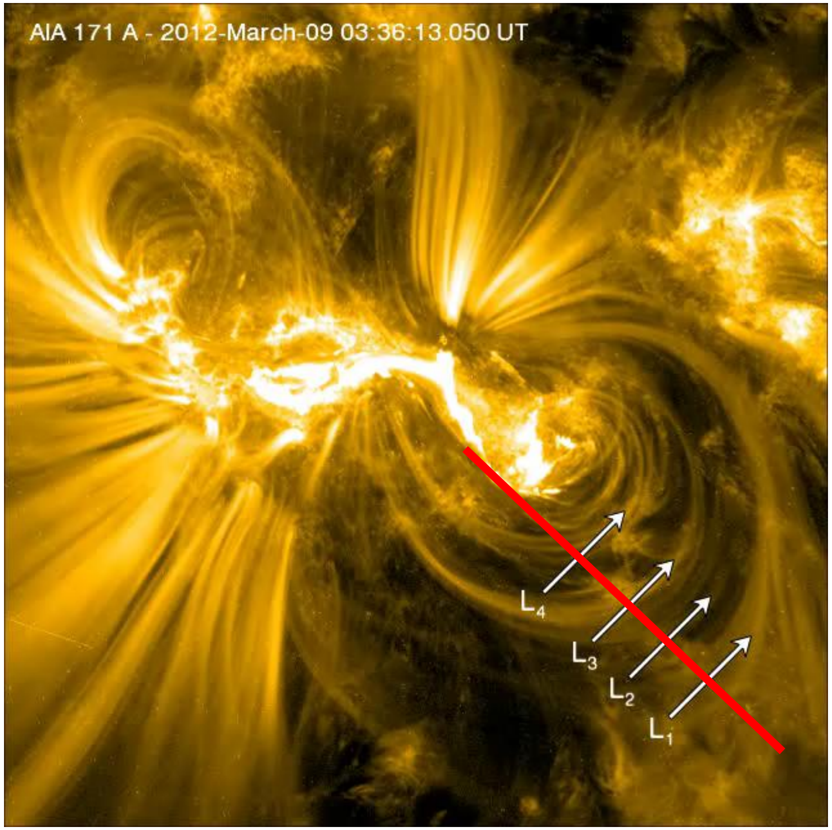
Török & Kliem (2006)

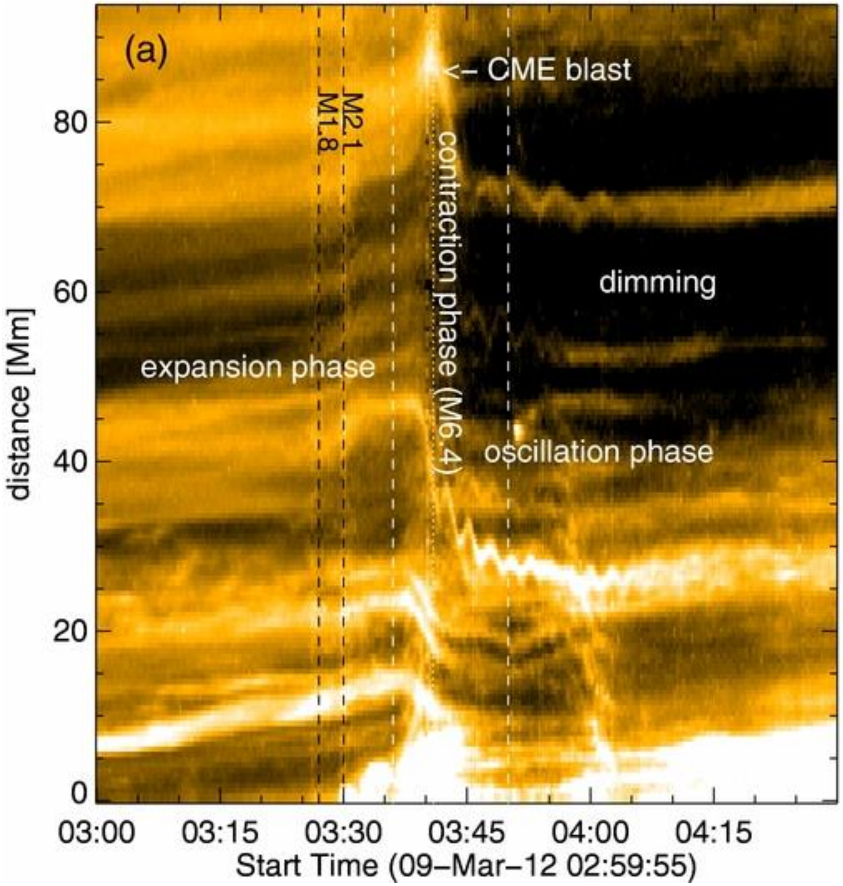
Energy storage and release

The energy that drives a flare/CME comes from parallel current systems in the corona, driven from below.

A flare or CME requires a *"magnetic implosion"* to release the energy (Hudson 2000):

$$\int_{\text{Before}} \frac{B^2}{2\mu_0} dV > \int_{\text{After}} \frac{B^2}{2\mu_0} dV$$

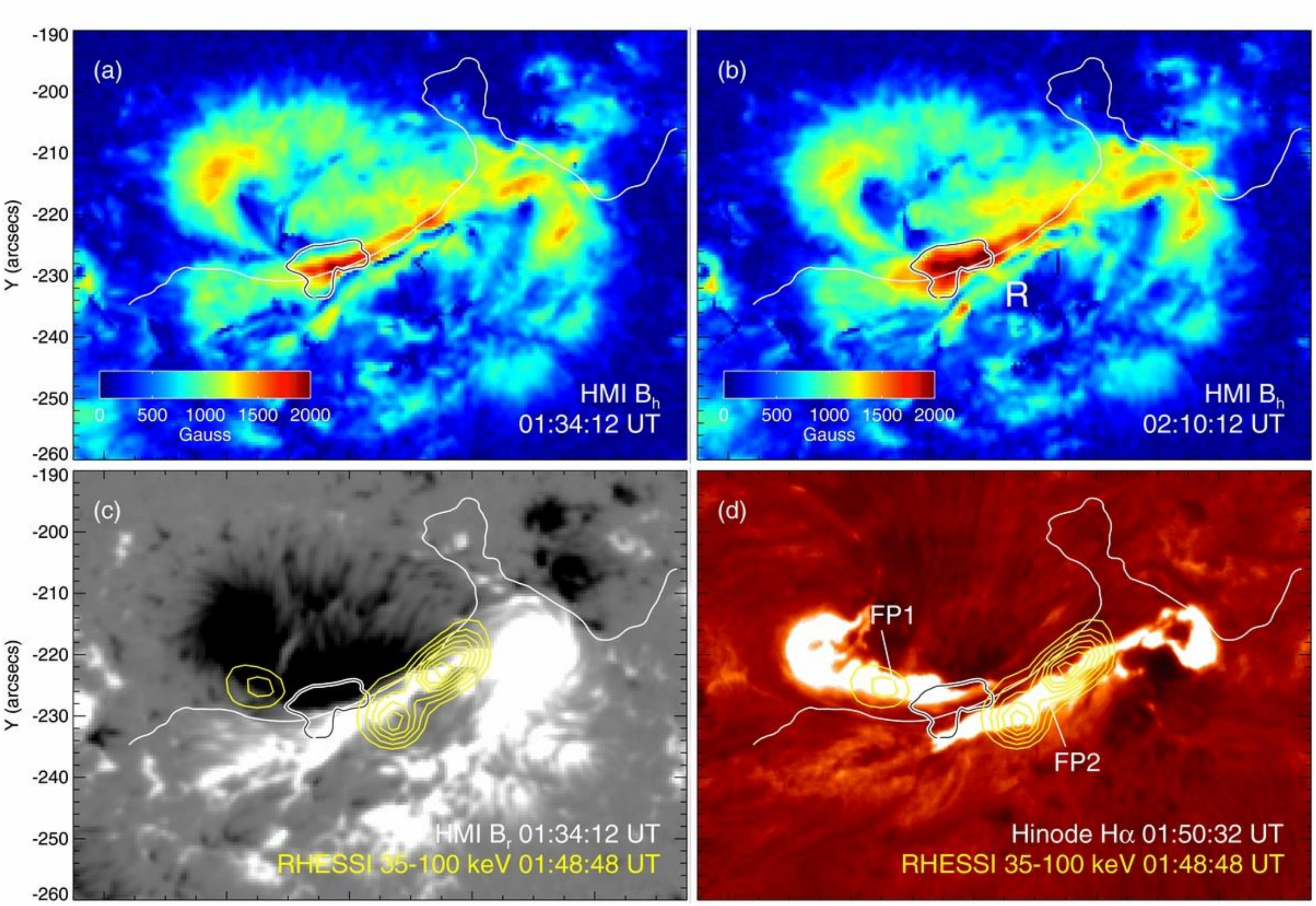




Simoes et al. (2013)

Energy storage and release

The collapse of coronal loops during flare/CME is accompanied by an increase of the horizontal component of the photospheric field (Wang et al. 2012, Liu et al. 2012, Gosain 2012) - corona to photosphere back-reaction (Fisher et al. 2011)



Change of horizontal field over PIL in X2.2 flare/CME

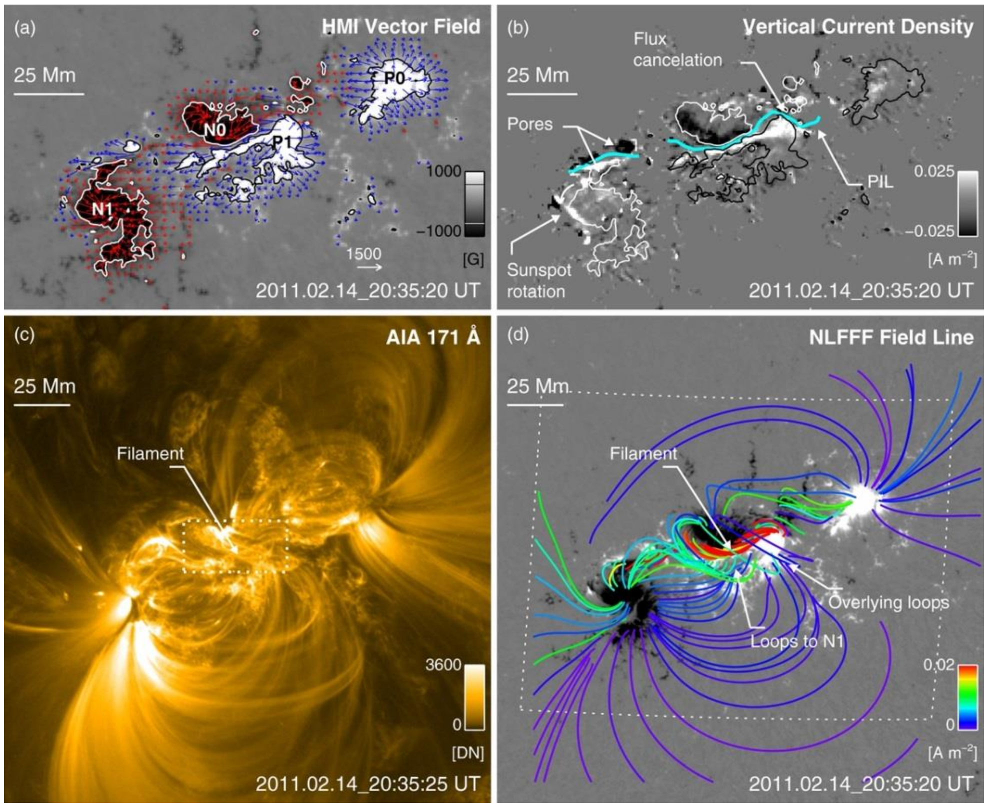
See also Poster in S4 by Peter Gömöry

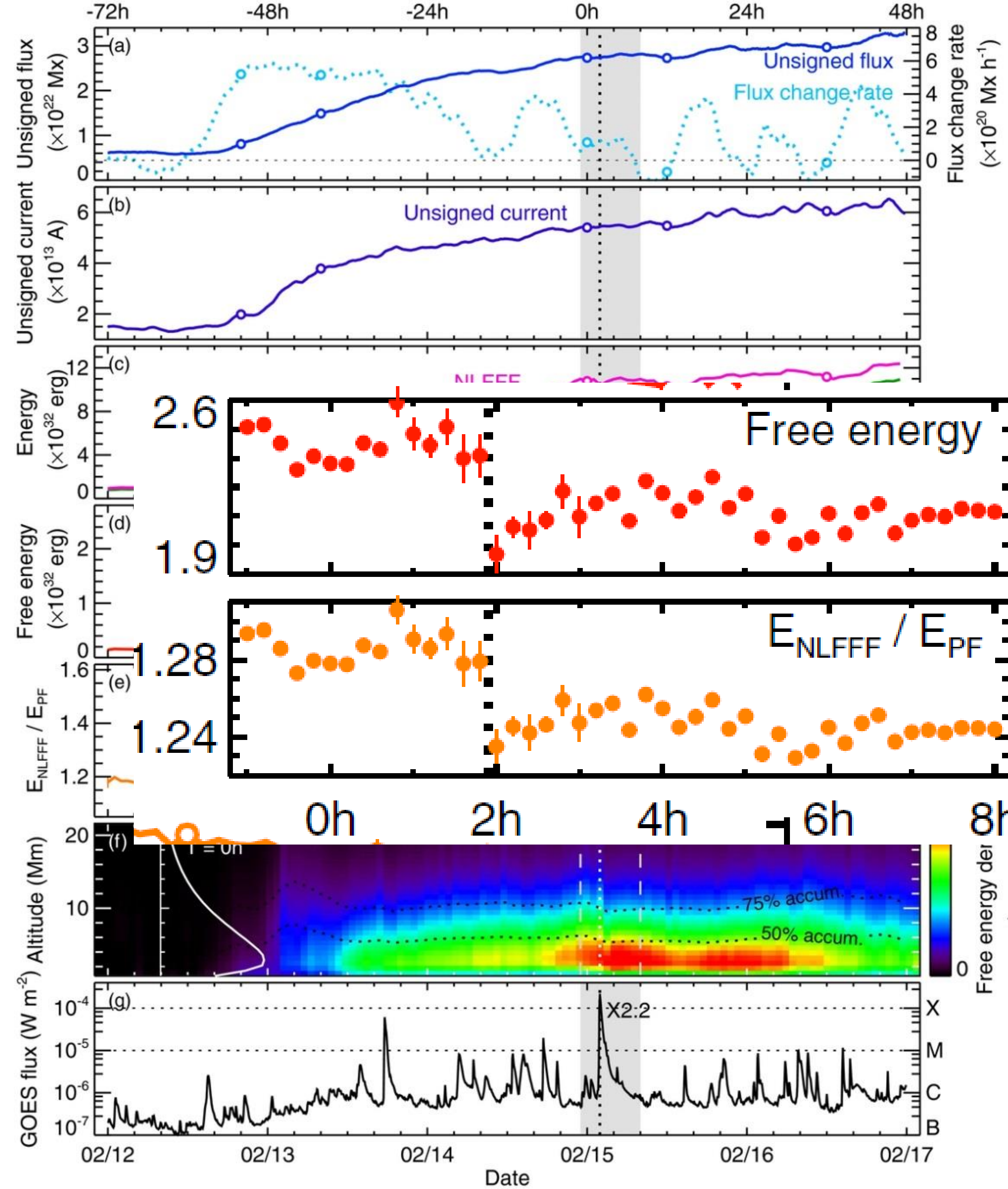
Wang et al. (2012)

Energy storage and release

Evolution of magnetic field and coronal free energy in AR 11185

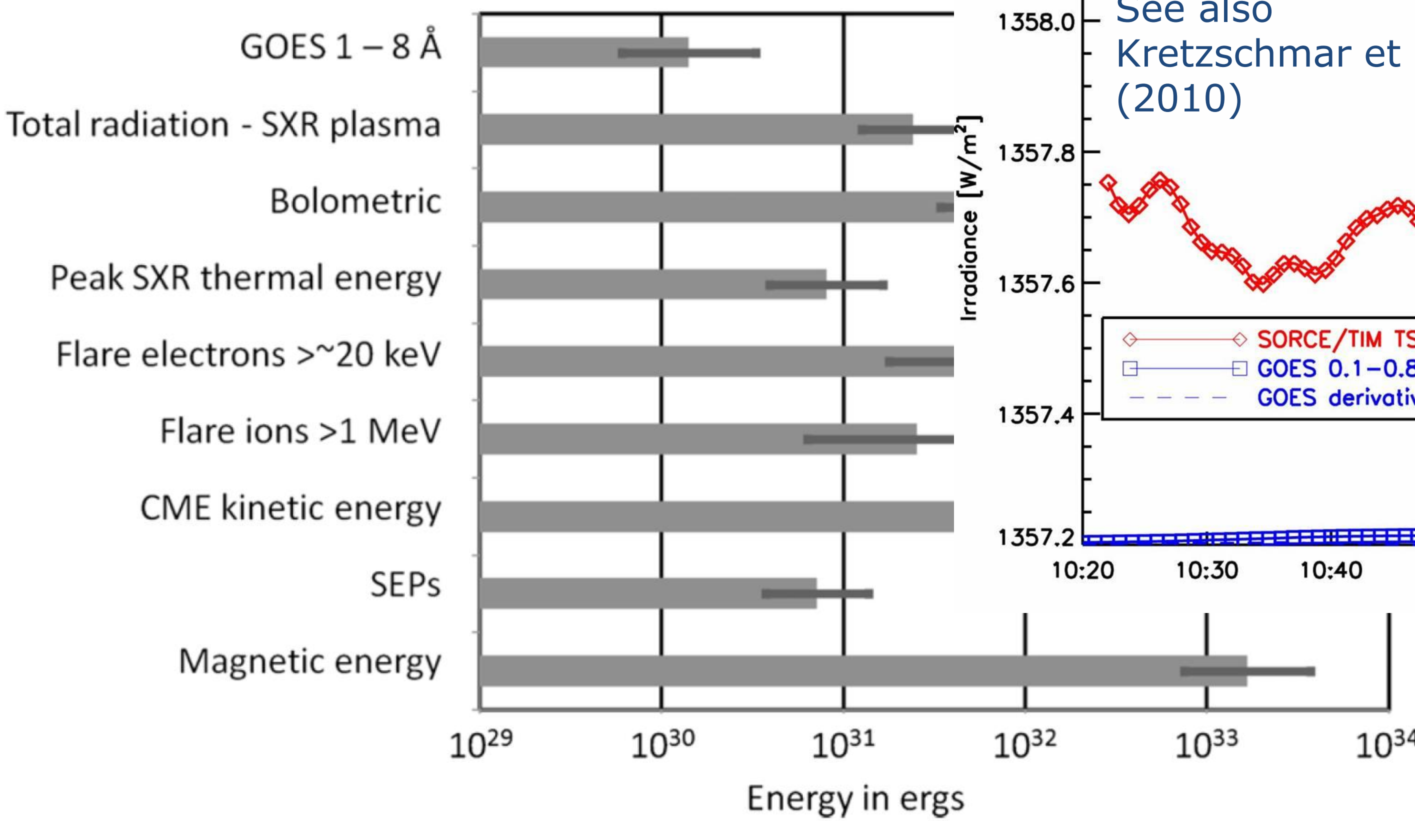
Sun et et al. (2012)

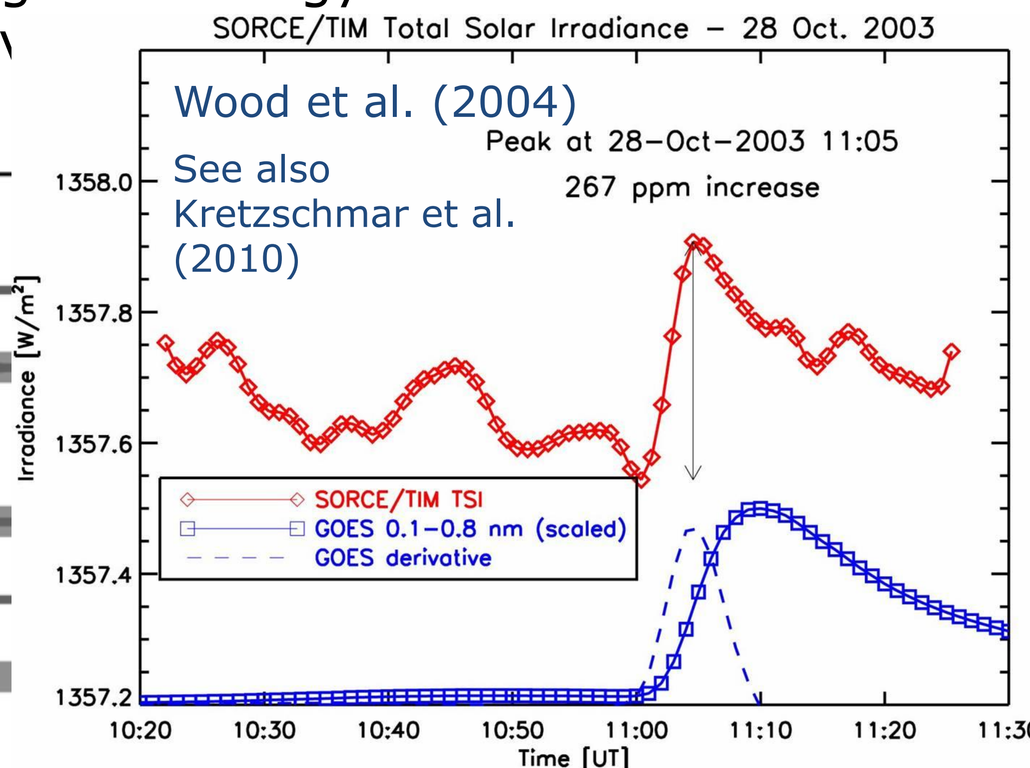




Energy storage and release

Comparison of various energy components: flare (particles, radiation), CME kinetic energy and AR free magnetic energy derived from 38 strong CME-flare ev





Wood et al. (2004)

See also Kretzschmar et al. (2010)

Emslie et al., ApJ 759 (2012)

Energy storage and release

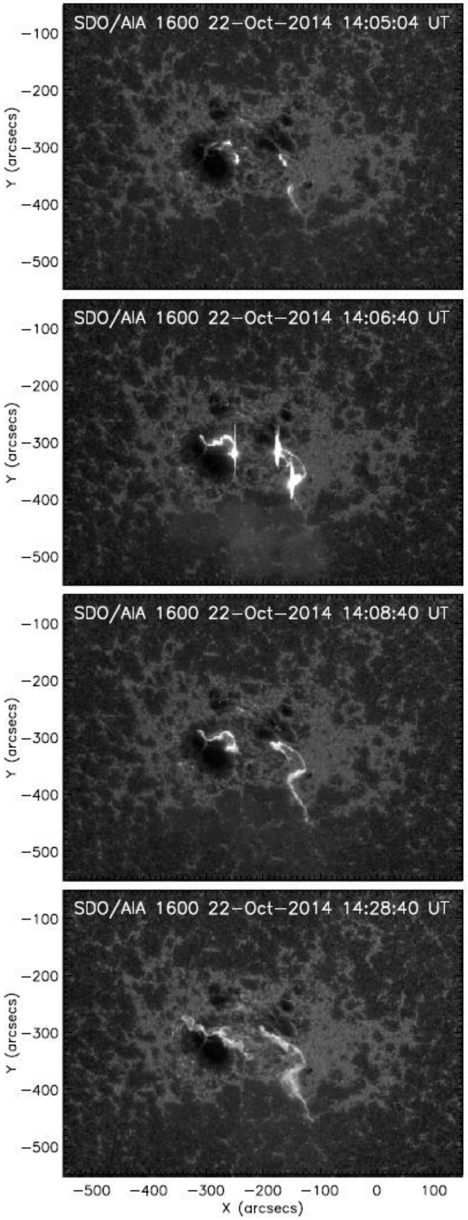
Calculation of magnetic reconnection rates and fluxes

Movie 1: newly brightened flare area (left) and cumulated flare area (right) on AIA 1600 images

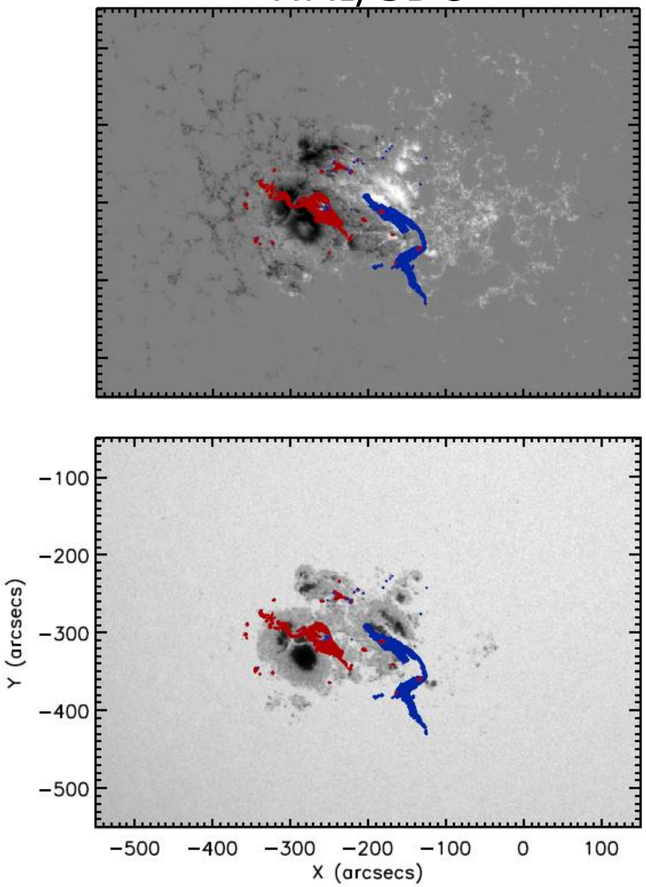
Movie 2: newly brightened flare area (left) and cumulated flare area (right) on HMI LOS magnetic field map

Veronig & Polanec (2015)

SDO AIA 1600



HMI/SDO



Energy storage and release

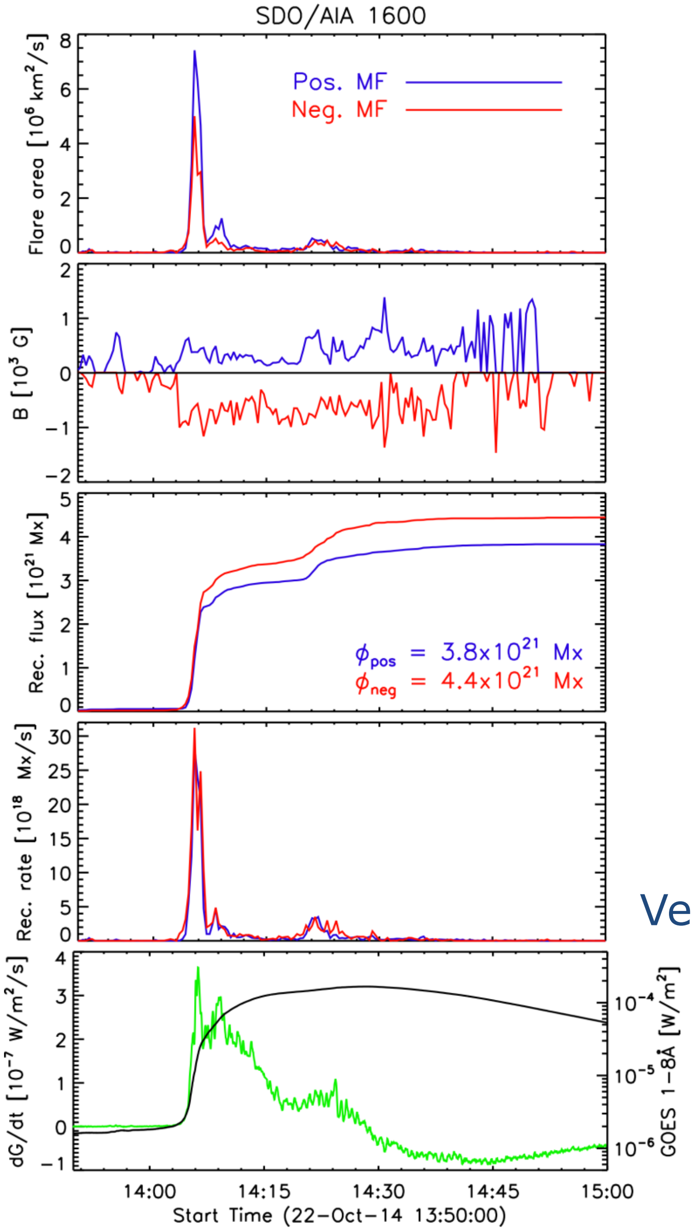
Newly brightened flare area A

Mean field strength in flare pixels <B>

Cumulated reconnection flux $\varphi(t)$

Reconnection rate $\frac{d\varphi}{dt}$

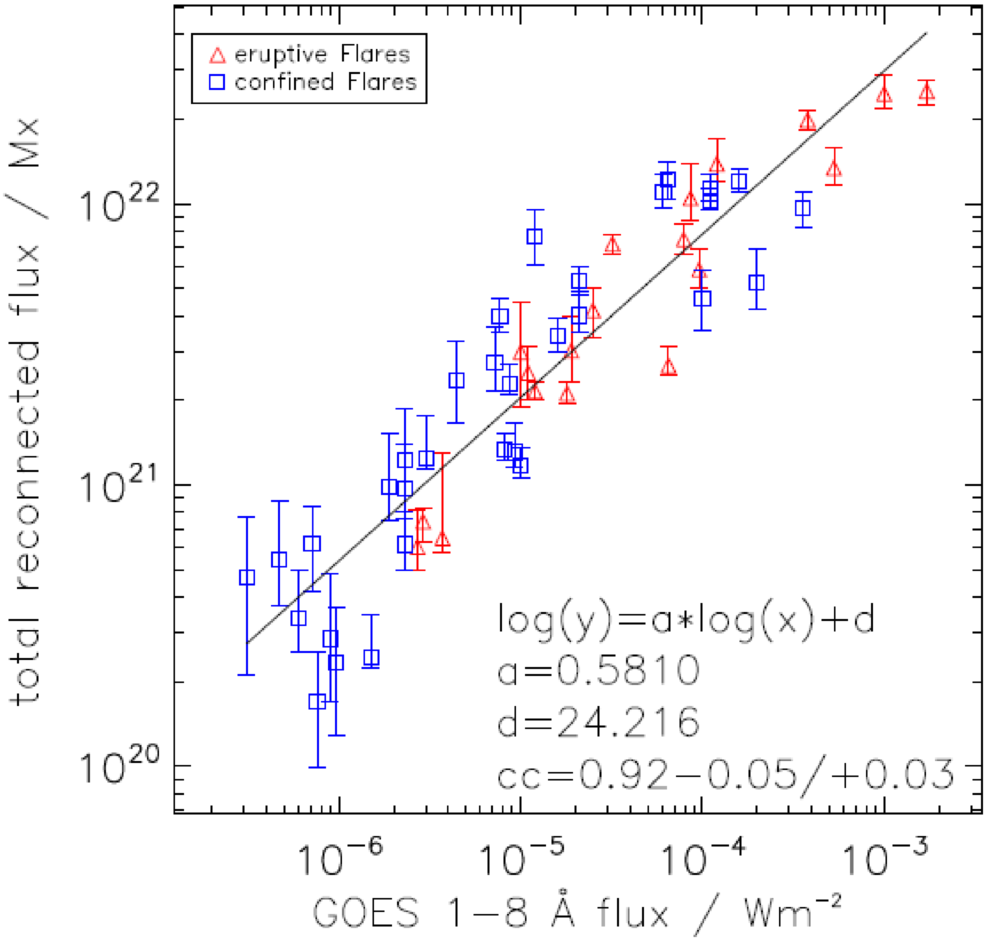
GOES X-ray flux and derivative



Veronig & Polanec (2015)

Energy storage and release

Reconnection flux (Mx) against GOES peak flux for set of 50 flares observed in Hα at Kanzelhöhe Observatory.

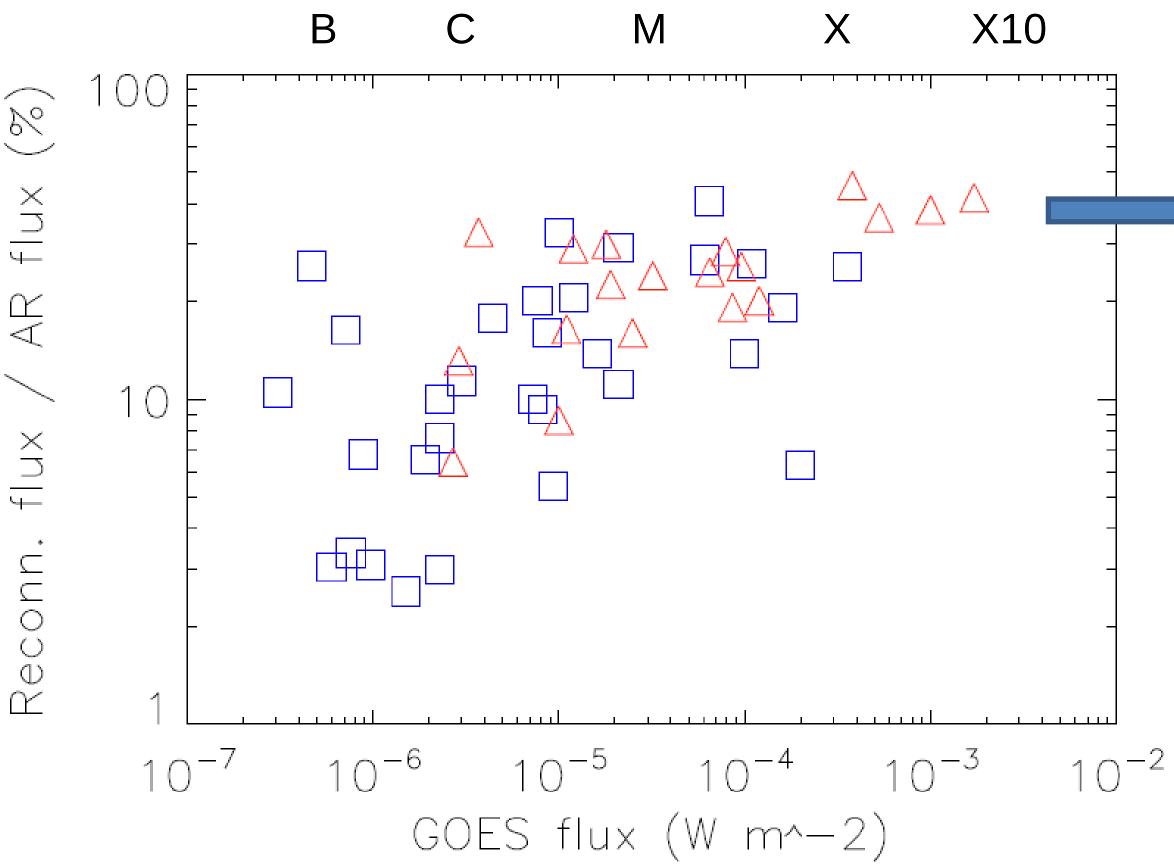


Red: eruptive flares
Blue: confined flares

Tschernitz, Veronig et al. (2017)

Energy storage and release

Percentage Reconnection flux / AR flux against GOES X-ray flare class



Red: eruptive flares
Blue: confined flares

Up to ~30% of AR flux is reconnected in largest events

Tschernitz, Veronig et al. (2017)

CME dynamics and flare relation

Forces acting on CMEs:

$a_{\mathrm{CME}} = a_{\mathrm{L}} - g + a_{\mathrm{d}}$ … Lorentz force, gravitation, aerodynamic drag

dominate close to Sun (acceleration phase)

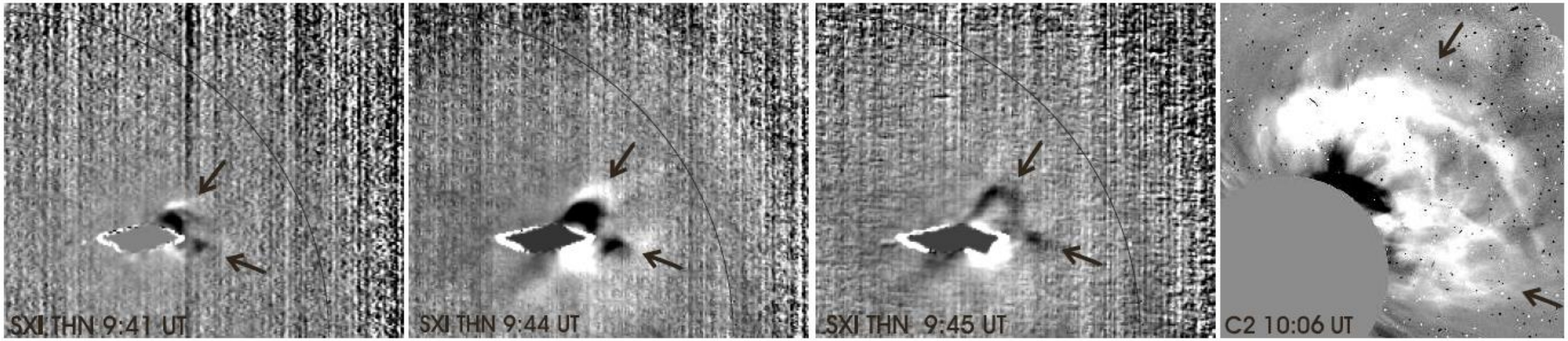
dominates in IP space (propagation phase)

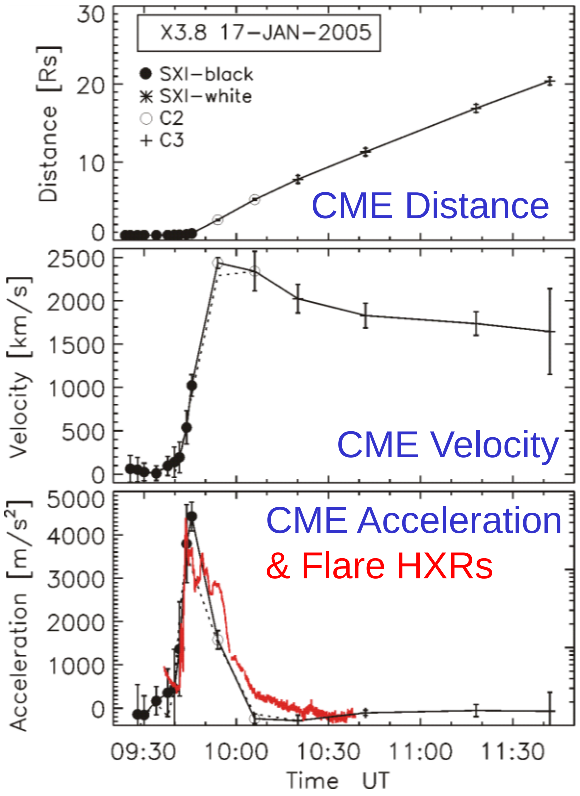
$a_{\mathrm{d}} = \gamma\,(v - w)\,|v - w|$ … aerodynamic drag: interplay of CME & solar wind

(Cargill et al., JGR 191, 1996; Vršnak et al., SoPh 285, 2013)

IP propagation of CMEs
$\Rightarrow$ Talk by Marilena Mierla

CME dynamics and CME-flare relation



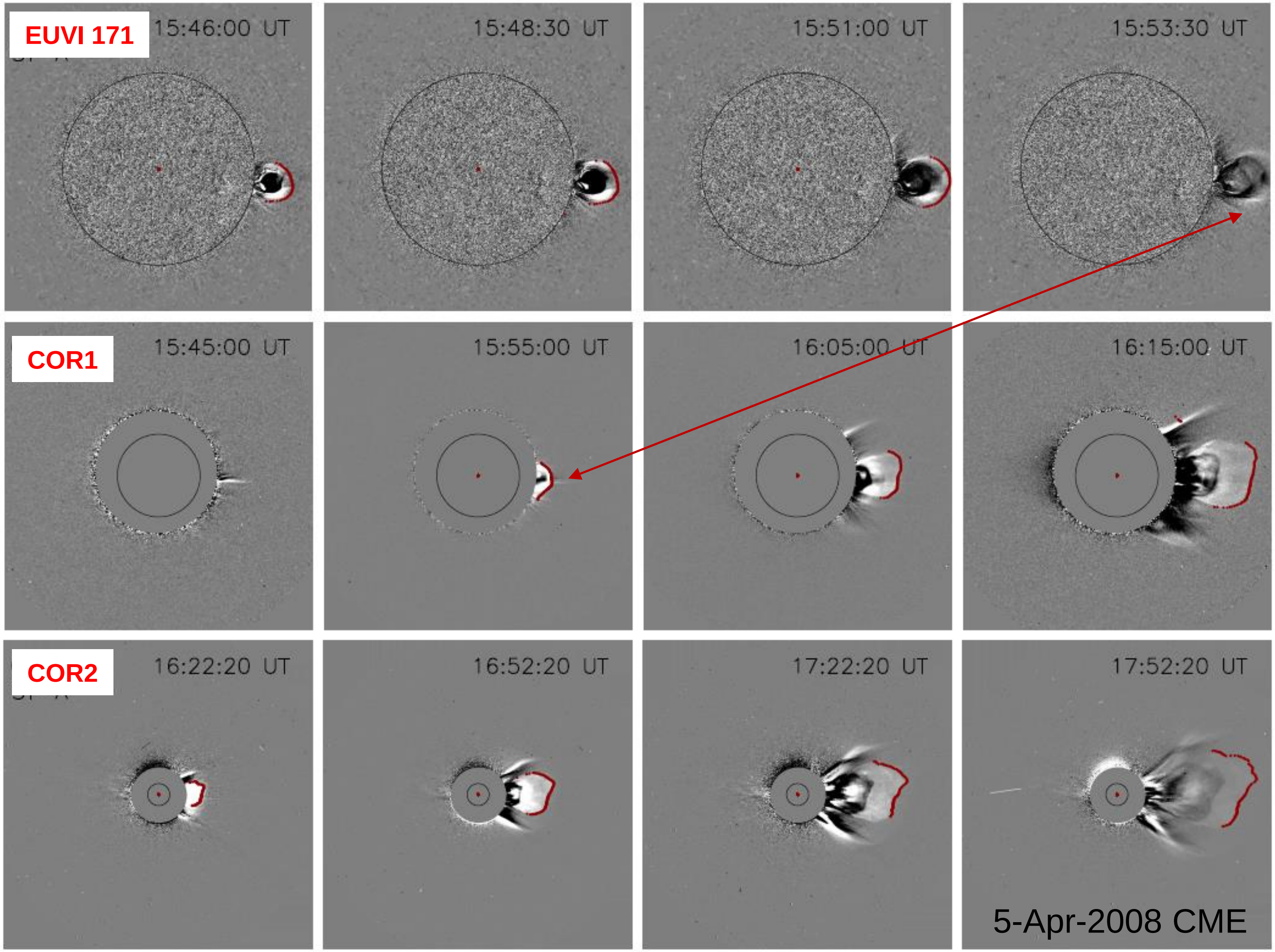


Combined CME observations low in the corona for a fast halo CME & associated flare hard X-rays.

… case studies

Temmer, Veronig, et al., ApJL 673 (2008)

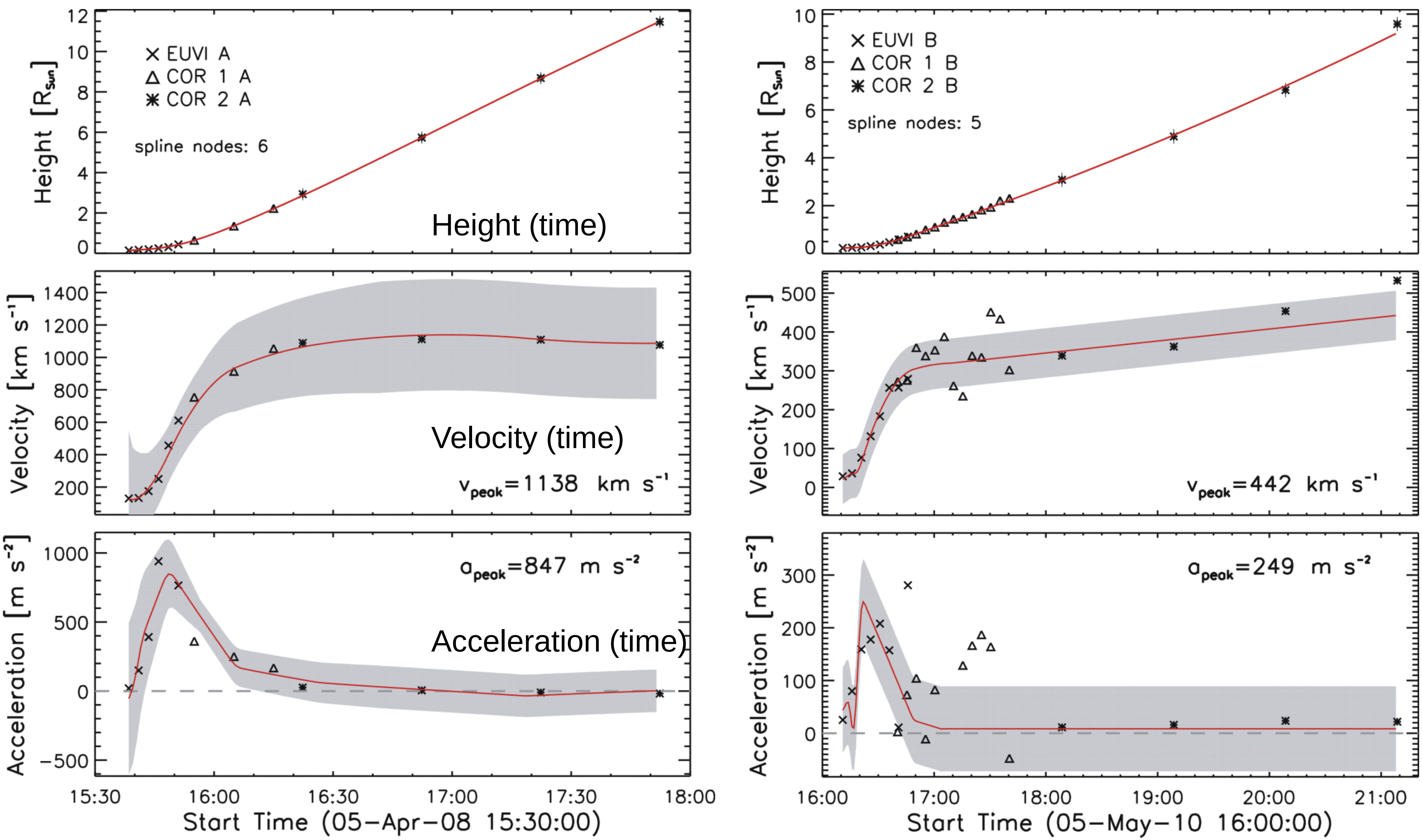
CME dynamics and CME-flare relation



STEREO EUVI & Cor1 & Cor2:
- overlapping FOVs
- high cadence

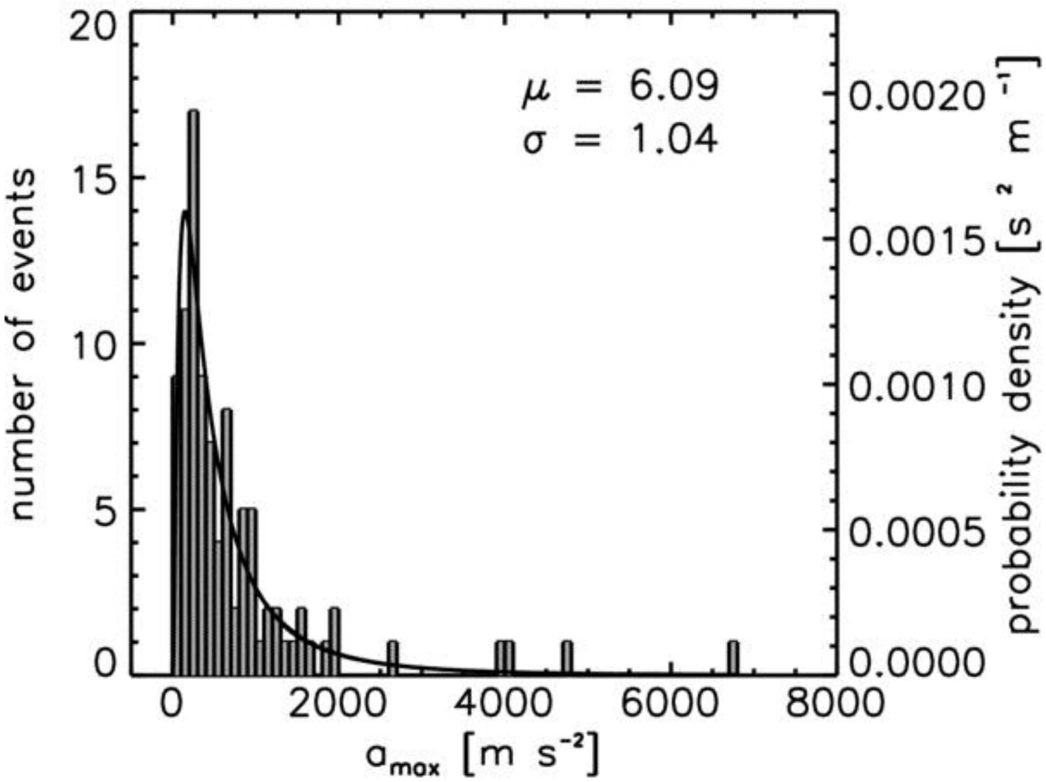
Bein et al. ApJ 738 (2011)

CME dynamics and flare relation

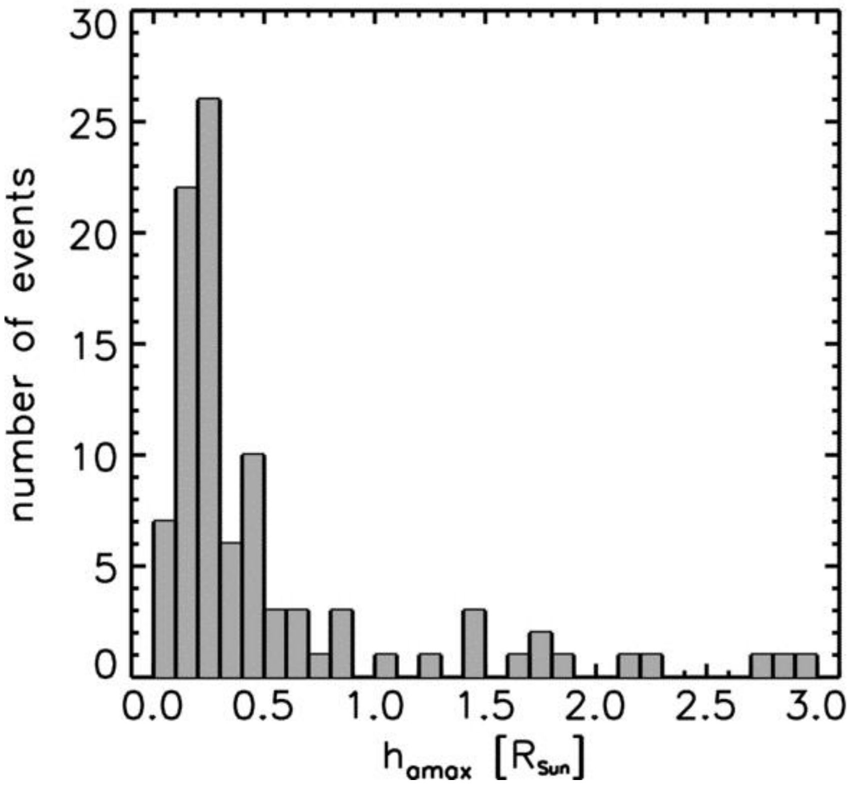


CME dynamics and flare relation

Distribution CME peak acceleration



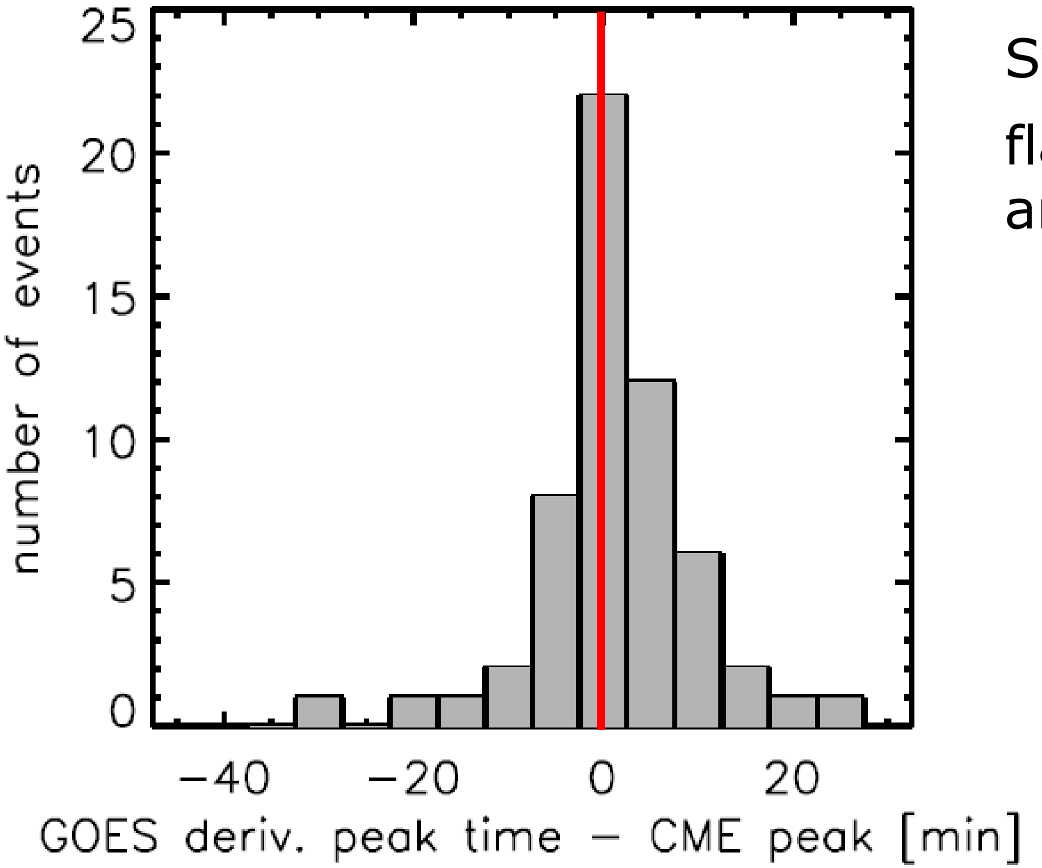
Distribution CME heights at peak accel.



Bein et al., ApJ 738 (2011)

Set of ~100 CMEs measured with STEREO EUVI/COR1/COR2.

CME dynamics and flare relation

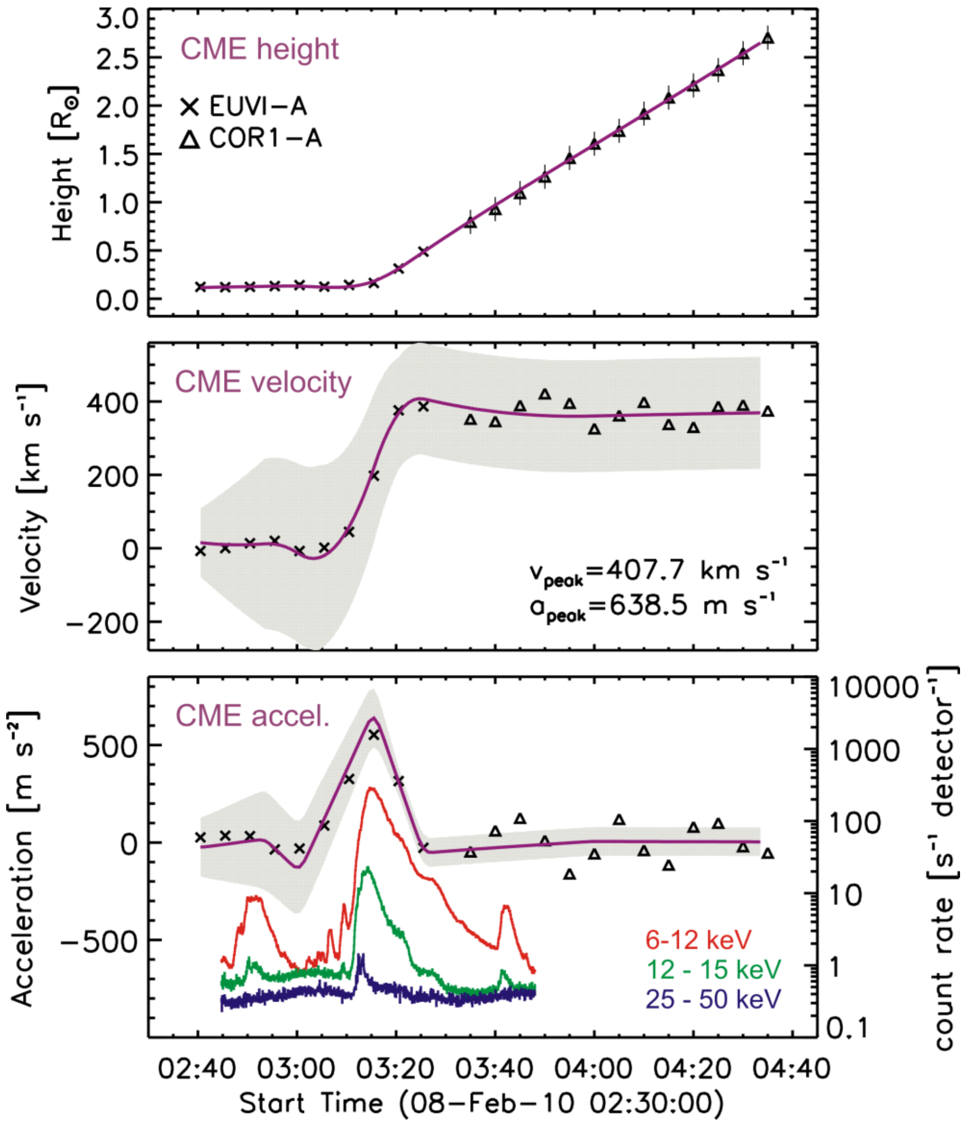


Bein et al., ApJ 738 (2011)

Synchronization of

flare energy release maximum and CME peak acceleration

CME dynamics and flare relation



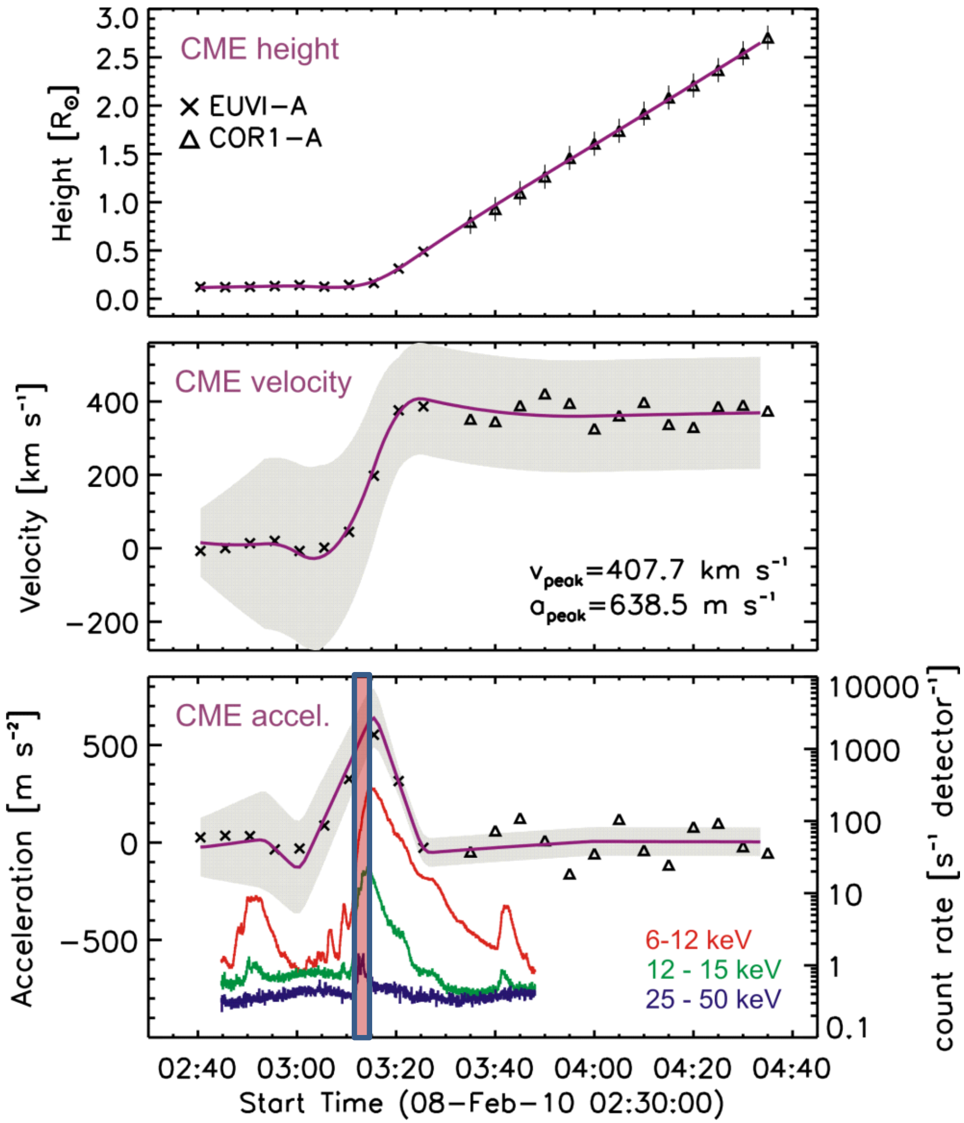
CME height vs time

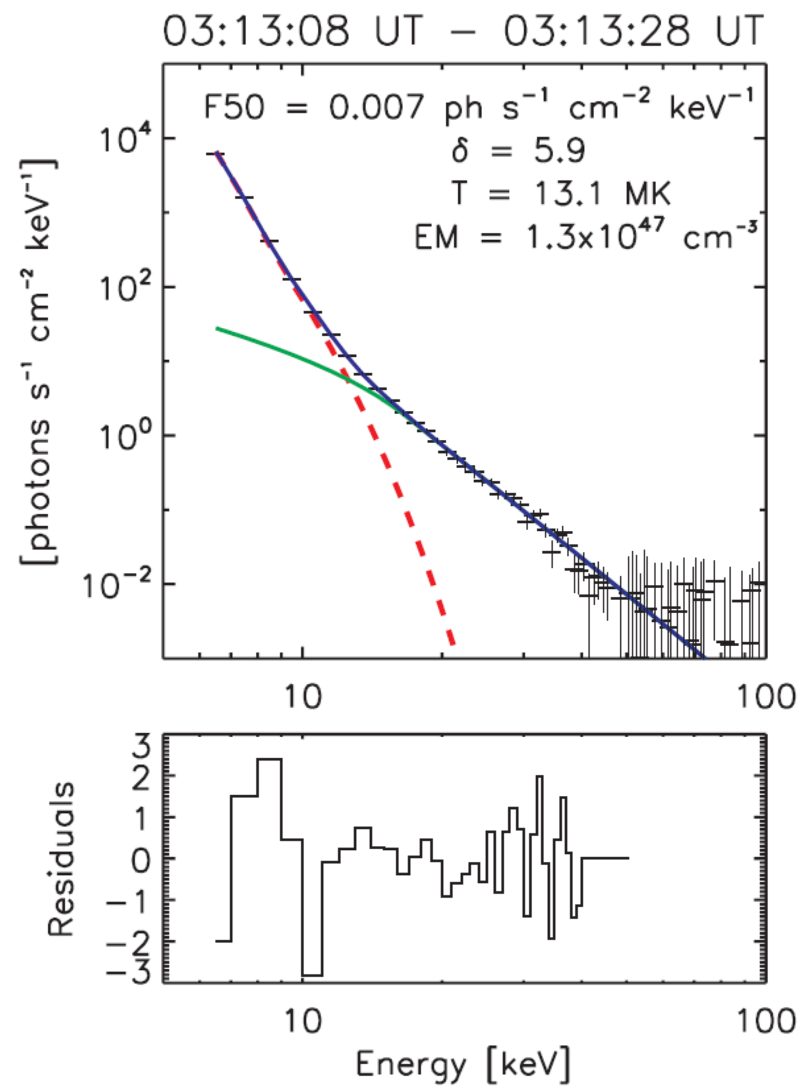
CME velocity vs time

CME acceleration vs time
&
Flare X-rays (RHESSI)

Berkebile-Stoiser, Veronig, Bein, Temmer, ApJ 753 (2012)

CME dynamics and flare relation

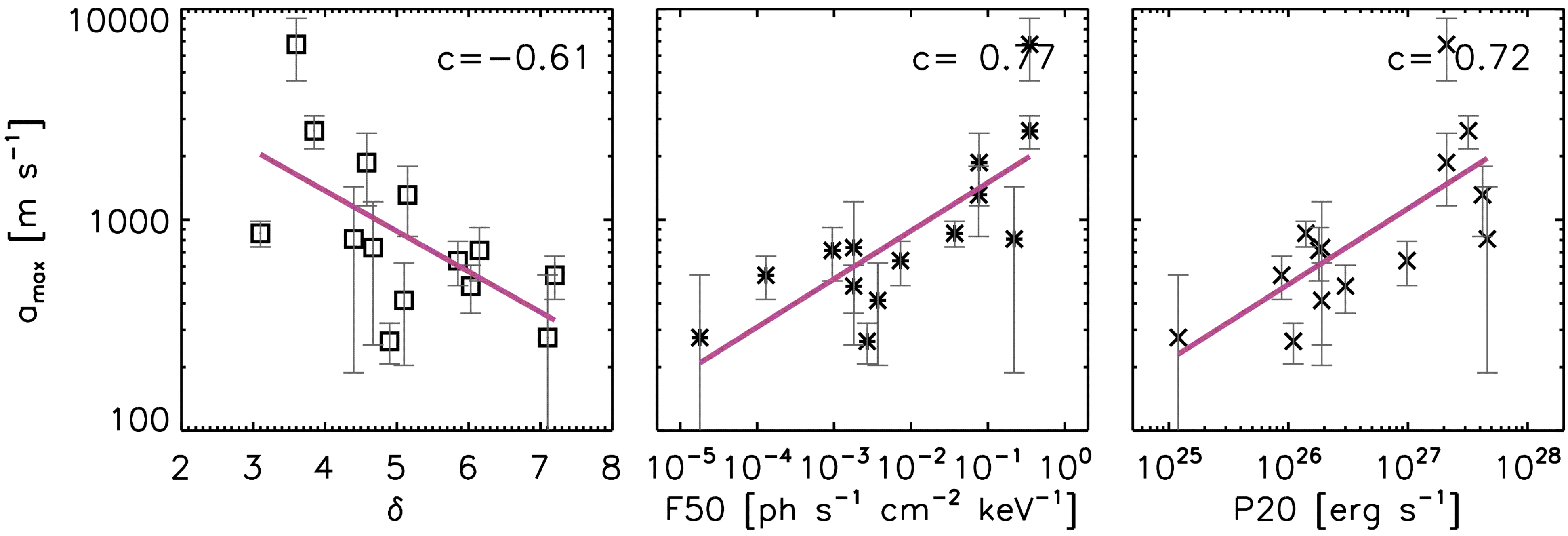




Berkebile-Stoiser, Veronig, Bein, Temmer, ApJ 753 (2012)

CME dynamics and flare relation

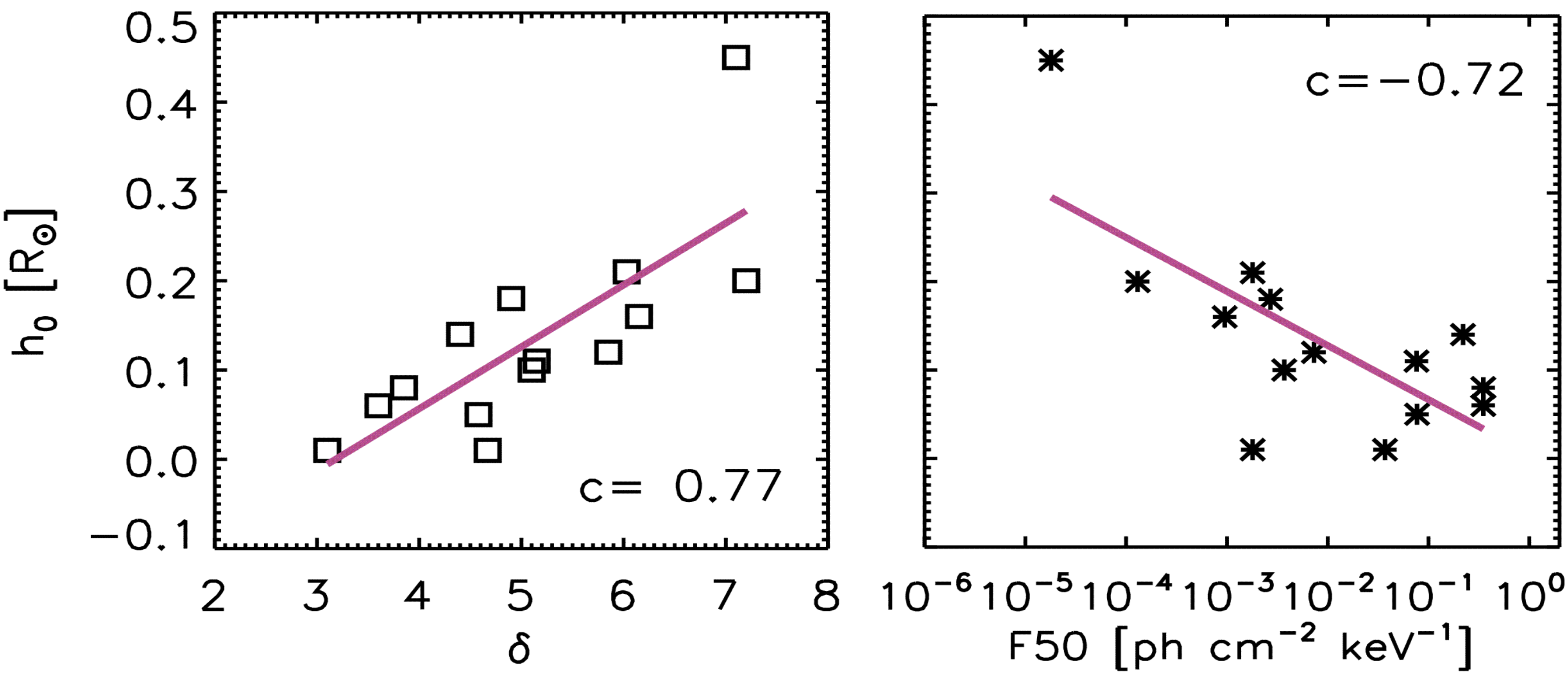
Berkebile-Stoiser et al., ApJ 753 (2012)



CMEs with larger peak accelerations are associated with flares with harder electron spectra, and larger electron and energy fluxes.

CME dynamics and flare relation

Berkebile-Stoiser et al., ApJ 753 (2012)



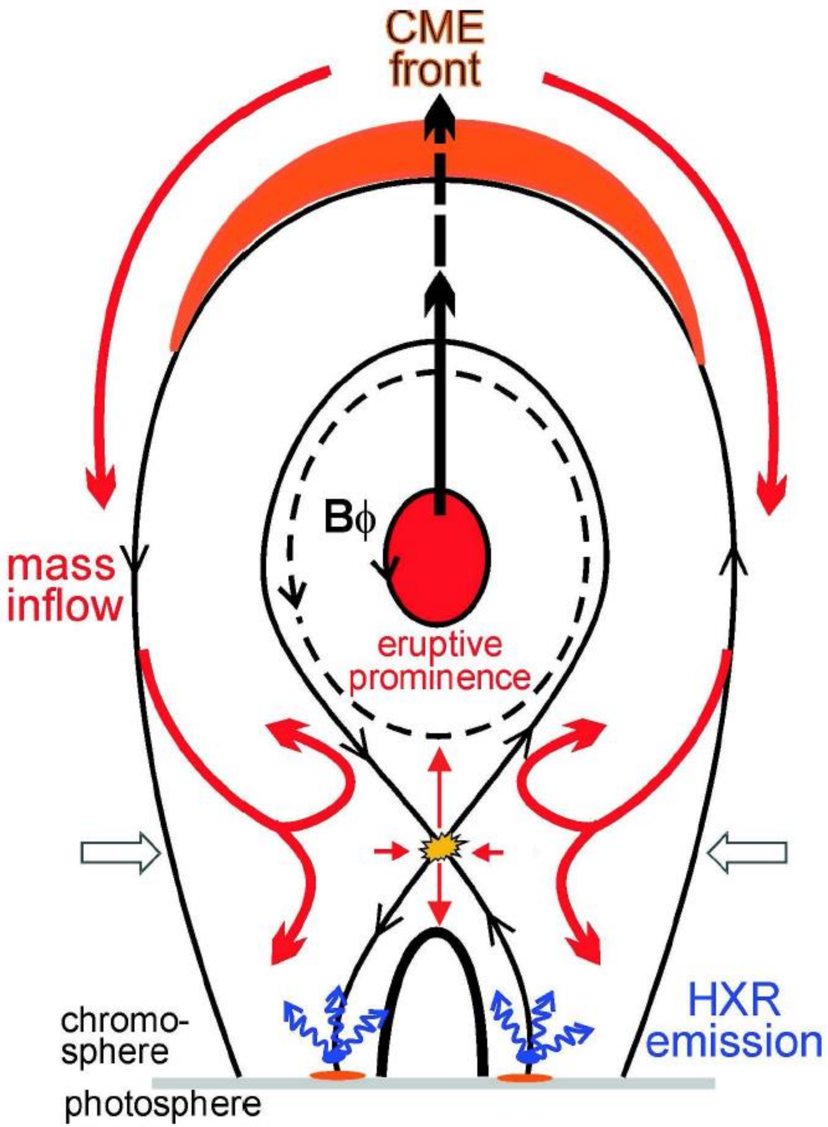
CMEs erupting from compact source regions are associated with flares with harder electron spectra and larger electron fluxes.

Source region lower in corona ⇒ stronger **B** field

CME dynamics and flare relation

Tight correlations between various CME and flare energy release parameters: timing, particle accelerations, source region characteristics, …

Suggests feedback relationship between large-scale CME dynamics and small-scale flare processes due to magnetic reconnection at current sheet behind erupting CME.



Temmer et al., ApJ 712 (2010)

Conclusions

- Close connection between CME dynamics and flare energy release from arious observational diagnostics
- Emphasizes the importance of non-ideal processes for impulsive CME acceleration
- Ideal processes (models) though are important for triggering the instability
- Magnetic reconnection fluxes are tightly correlated to flare size for both eruptive and confined flares.
  Allows us to estimate an upper limit of solar flare size from AR fluxes.