Processes and Mechanisms Governing Initiation and Propagation of CMEs

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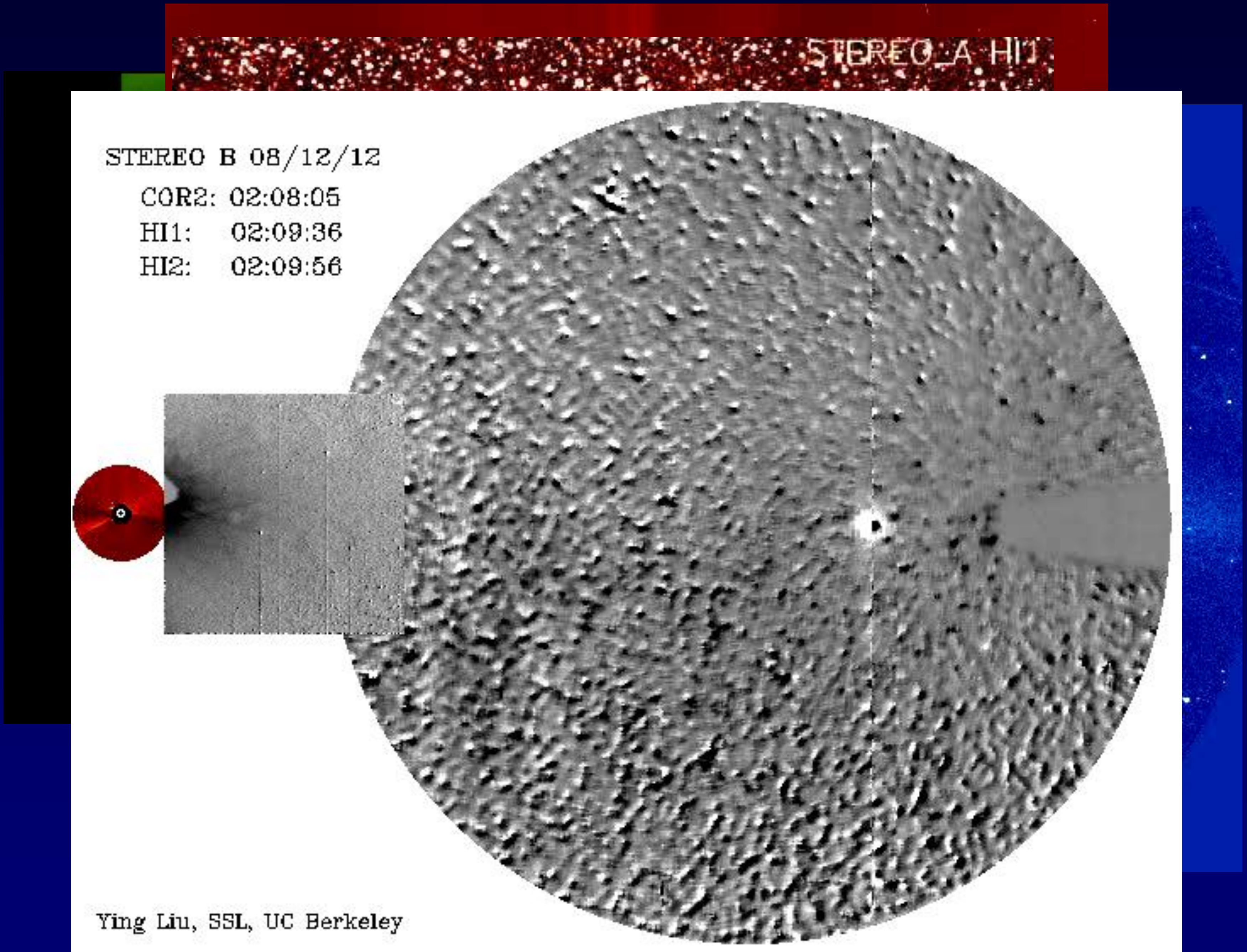
Observations:

(facts, requirements, constraints, guidelines)

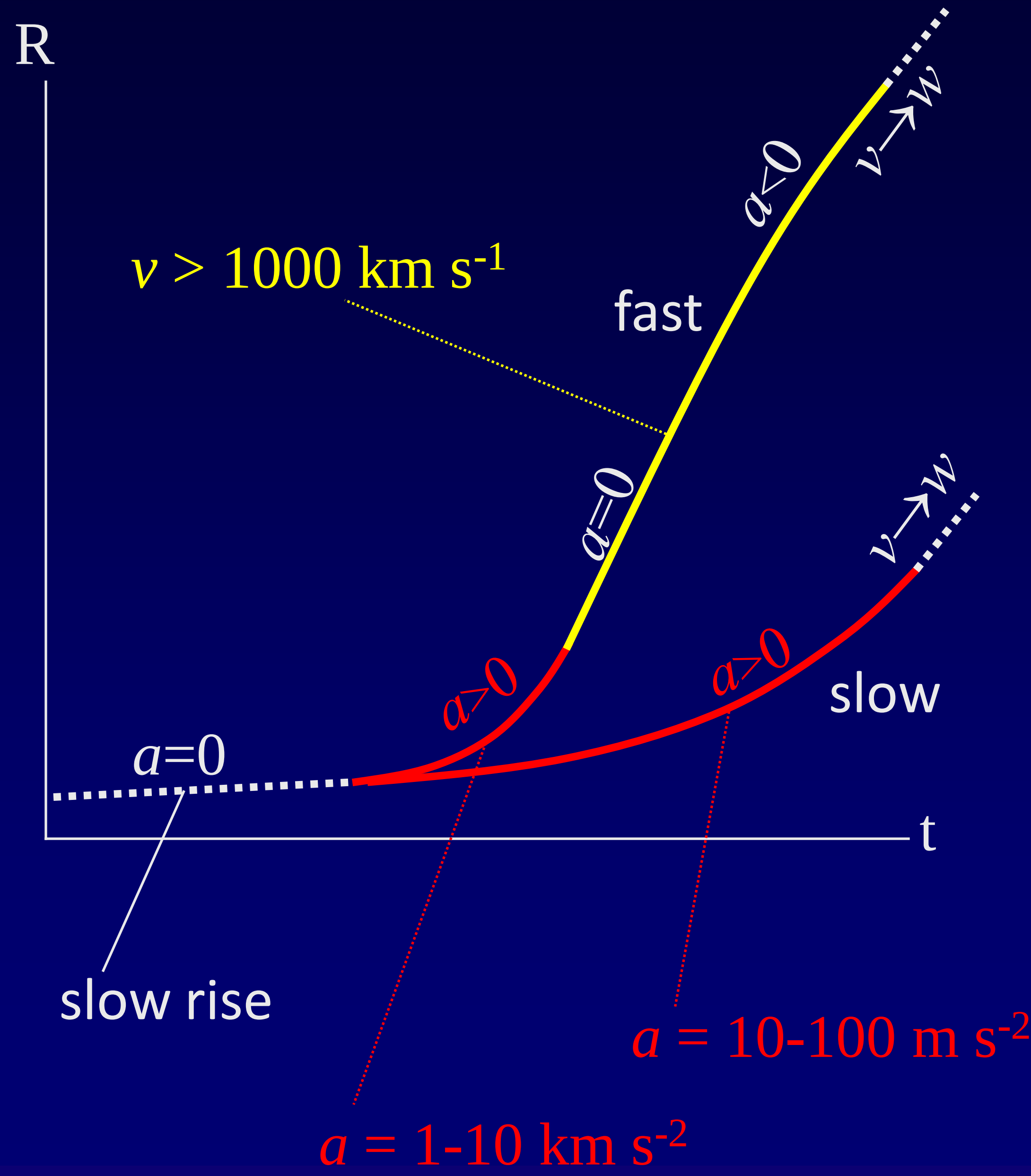
Theory:

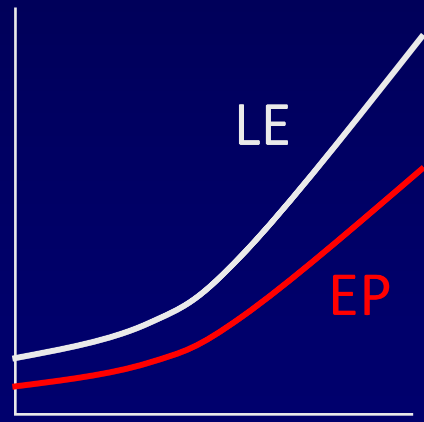
(general principles, concepts -> modeling)

Theory/Observations


STEREO_A HI1
STEREO B 08/12/12
COR2: 02:08:05
HI1: 02:09:36
HI2: 02:09:56
Ying Liu, SSL, UC Berkeley

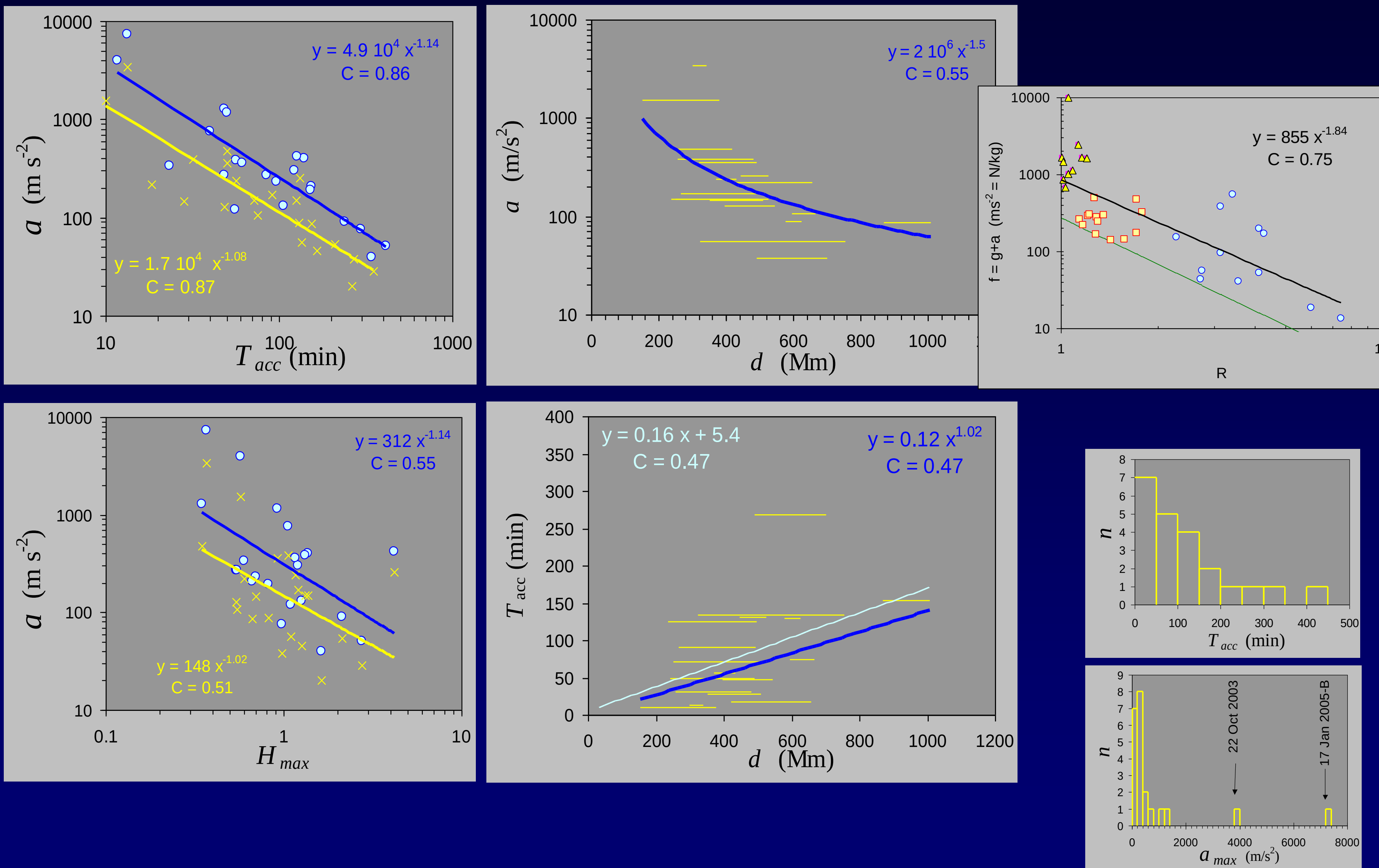
Observations: a) kinematics





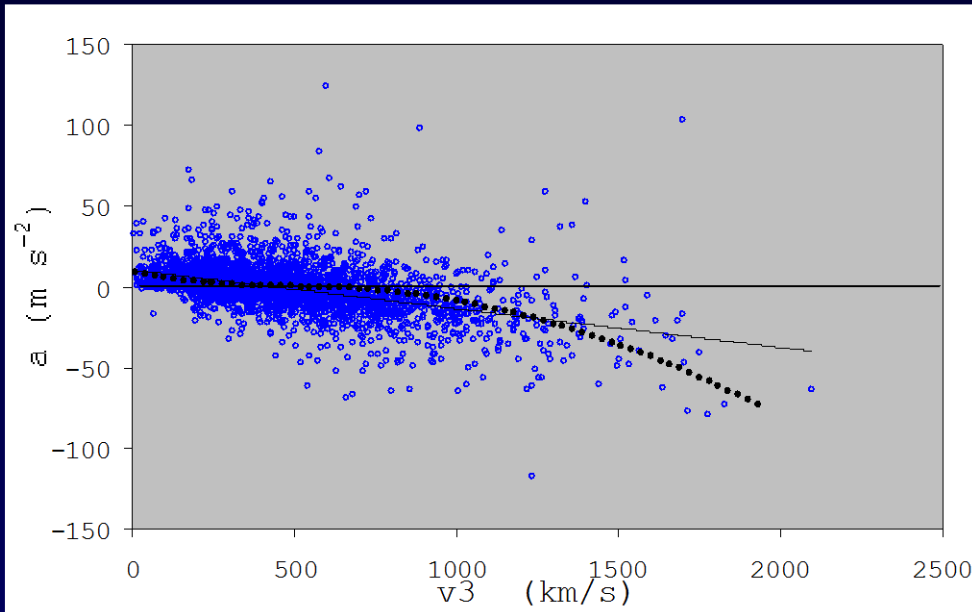
self-similar expansion

Observations: b) acceleration scaling



Vršnak et al., 2006 SPh, 241, 85

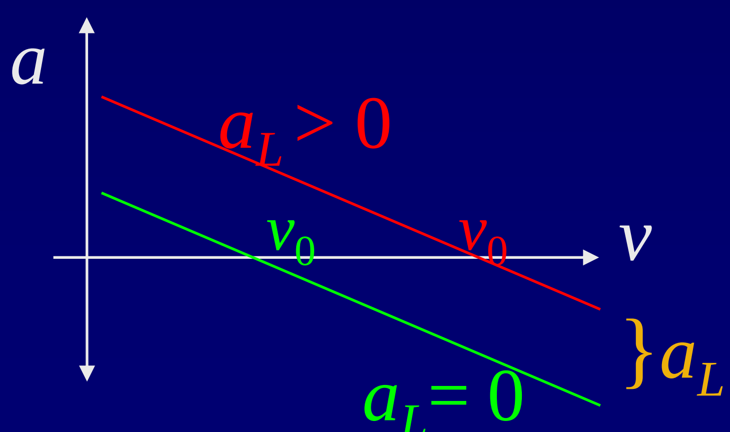
Observations: c) propagation phase

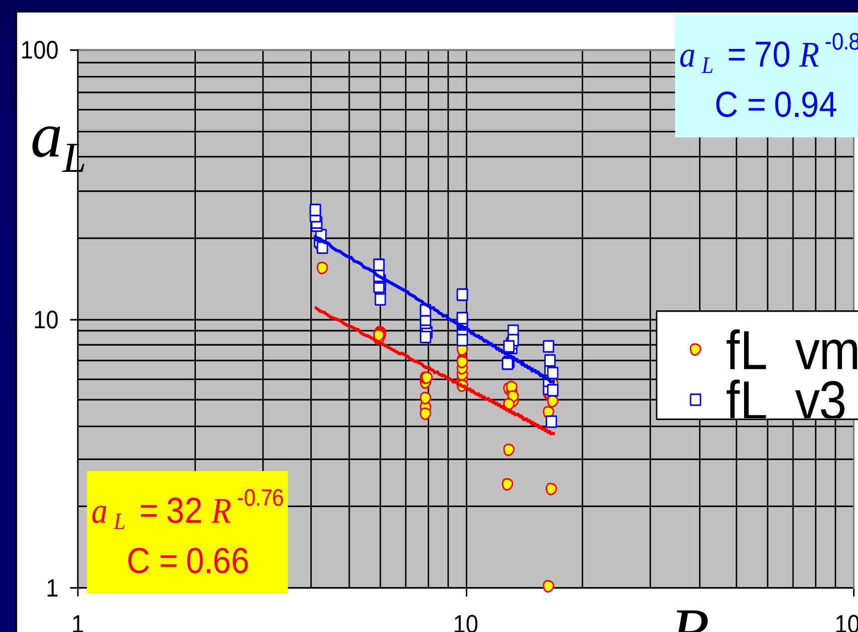


$$v_0\,(a_L > 0) \;>\; v_0\,(a_L = 0)$$

$$a_L = k\,\Delta v_0$$

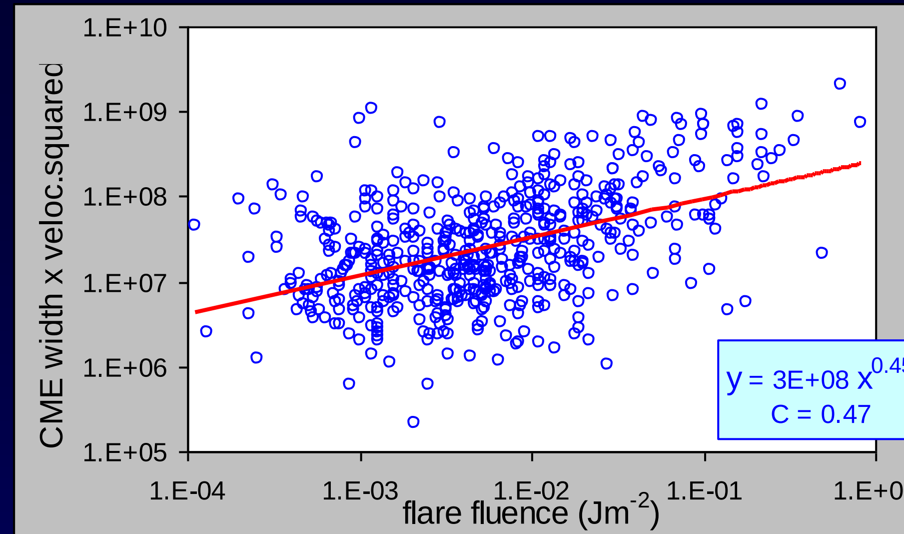
Vršnak et al. 2004, A&A 423, 717

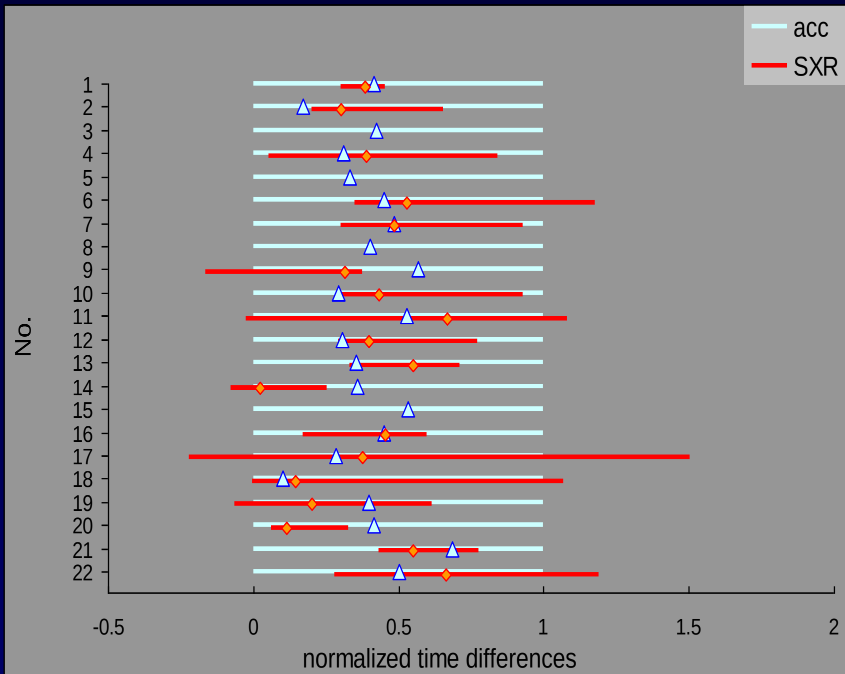




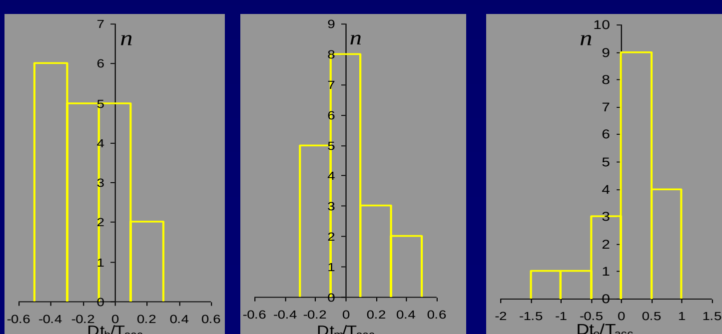
Observations:
CME/flare relationship

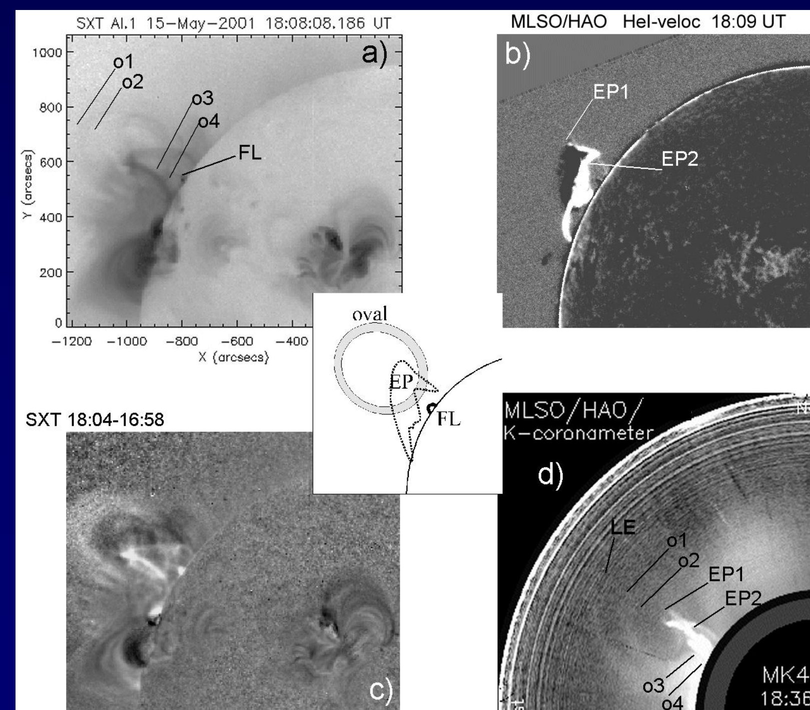
Vrsnak et al. 2005, A&A 435, 1149





Maričić et al. 2007, SPh 241, 99





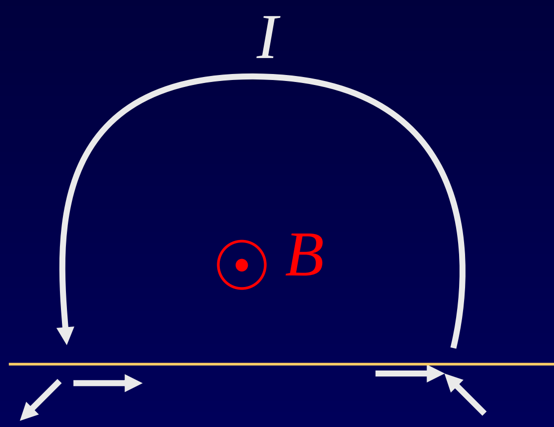
Vrsnak et al. 2004, SPh 225, 355

General concept

Forces & Energies

Free energy of non-potential magnetic field $\Rightarrow$ Electric current, I

$$E_{mag} = L\, I^2/2$$



$$\left.\begin{array}{l}\Phi = L\, I \\ \Phi \approx \text{const.}\end{array}\right\} \Rightarrow I \propto L^{-1}$$

$$\left.\begin{array}{l} I \propto L^{-1} \\ L \propto R \end{array}\right\} \Rightarrow \Delta I/\Delta R < 0,$$

$$\Rightarrow \Delta F_L/\Delta R < 0$$

$$\Rightarrow \Delta W/\Delta R < 0$$

$$\Delta E_{mag} = \Delta E_{kin} + \Delta E_{pot} + W_{drag}$$

Scalings

non-pot. **B** !
(free energy)

max. velocity: $\rho v^2/2 \le B^2/2\mu \quad \Rightarrow \quad v \le v_A$

acceleration: $\rho a \le B^2/2\mu r \quad \Rightarrow \quad a \le v_A{}^2/2r$

acc. time: $\tau = v/a = 2r/v_A \quad \Rightarrow \quad \tau = \tau_A = d/v_A$

acc. length: $\lambda = v^2/2a = r \quad \Rightarrow \quad \lambda = r$

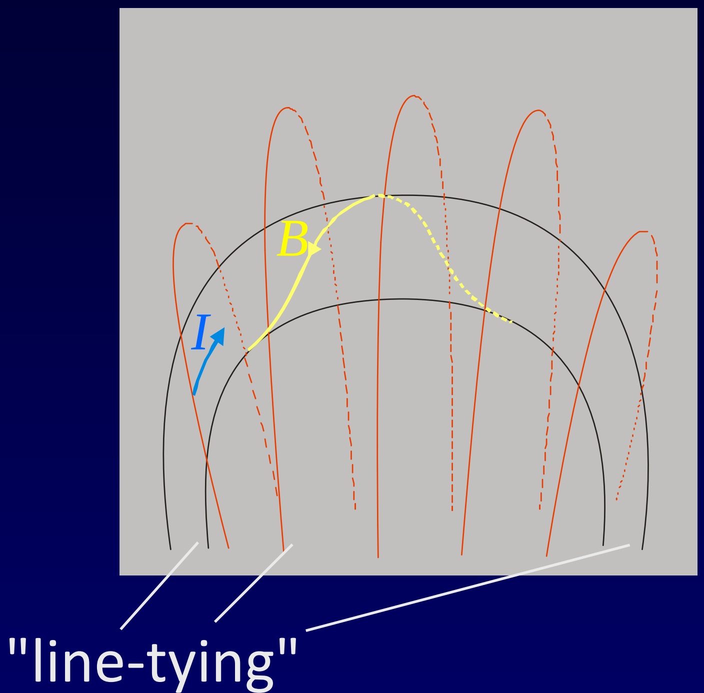
AR

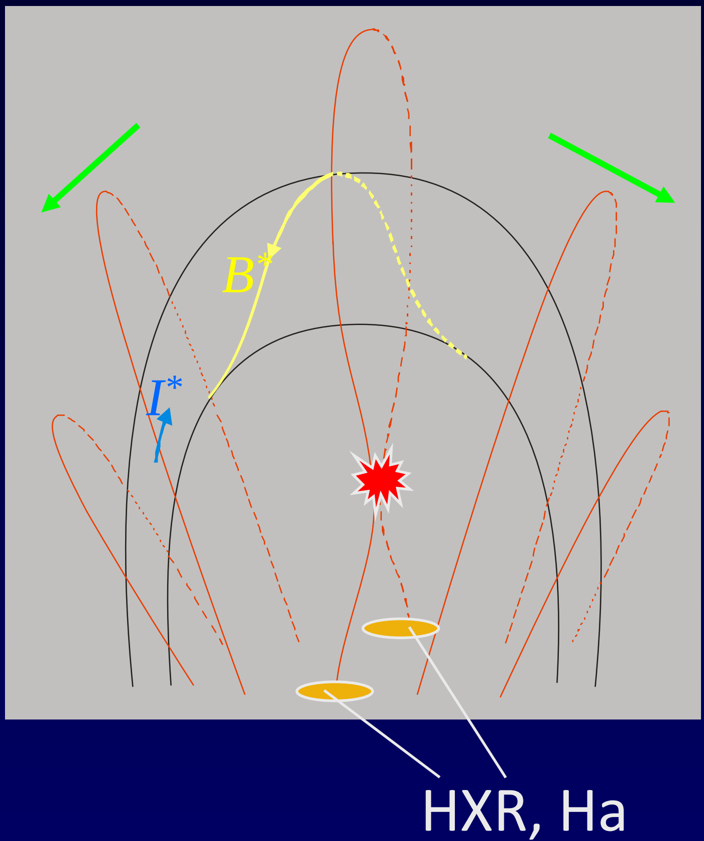
$d = 10^5$ km, $v_A = 1000$ km/s
$a = 10$ kms^{-2} ; $\tau = 100$ s ; $\lambda = 10^5$ km

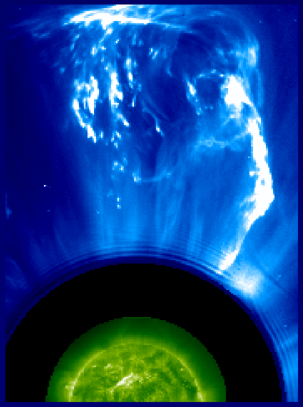
QP

$d = 10^6$ km, $v_A = 400$-1000 km/s
$a = 100$-1000 ms^{-2} ; $\tau = 15$-40 min ; $\lambda = 10^6$ km

3-D flux-rope models

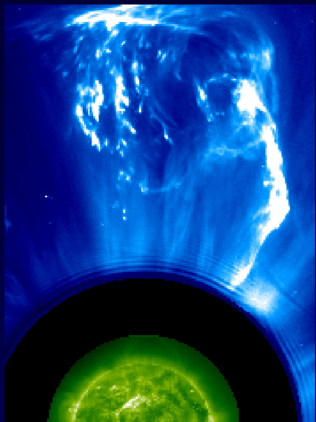


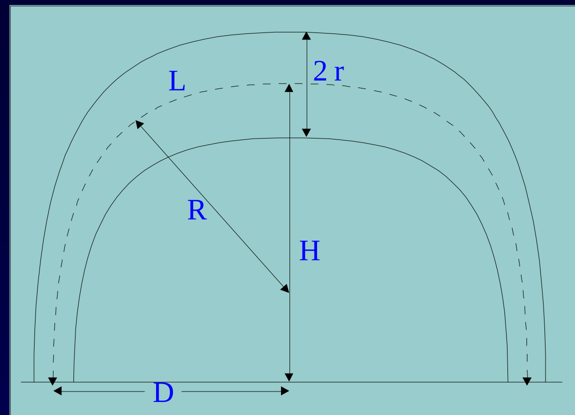


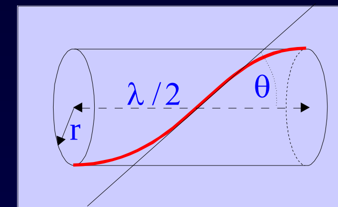


Mouschovias & Poland, 1978, ApJ 220, 675
Anzer & Pneuman, 1982, SPh 79, 1
Chen, J. 1989, ApJ 338, 453
Vrsnak, B. 1990, SPh 129, 295
Chen, J., Krall, J.: 2003, JGR 108, 1410
....

The driving force







Vršnak, 1990 SPh, 129, 295

$$X = \mathrm{tg}\,\theta = B_\phi / B_{//}$$

$$\Phi = l\,X/r, \quad n = \Phi/2\pi$$

$$n = l/\lambda, \quad n = const.$$

$$a = a_\mathrm{L} - g - a_\mathrm{d}$$

$$a_\mathrm{L} = A\,(l/h + l/R - 2l/RX^2) \pm kI/lr$$

$$A = \frac{\mu I^2}{4\pi M} = \frac{B_\phi^2}{\mu\rho l} = \frac{X^2 B_\parallel^2}{\mu\rho l} \approx \frac{v_A^2}{l} = \frac{l}{\tau_A^2} = l\omega^2$$

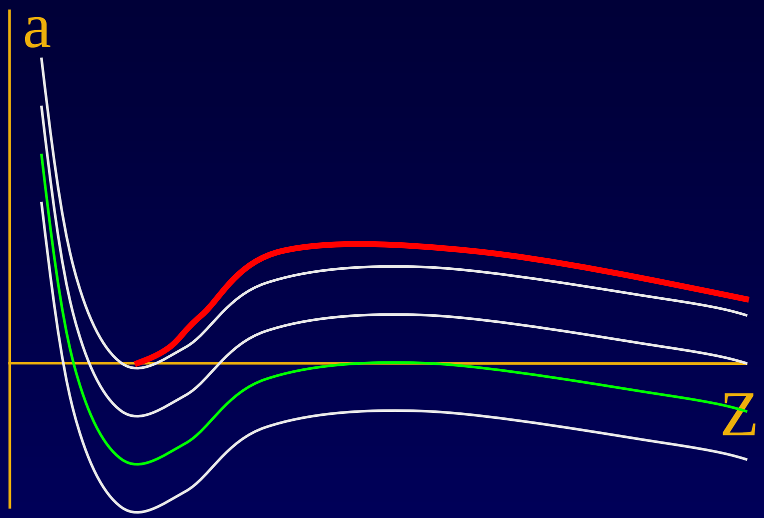
in the absence of reconnection:

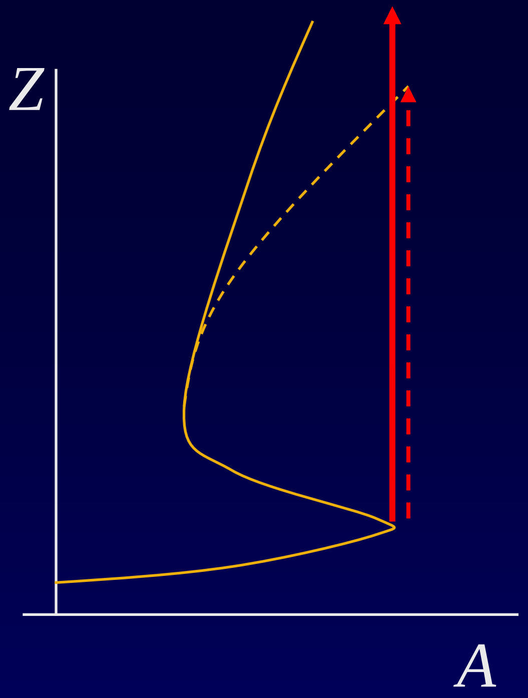
$$\Phi_\mathrm{e} = \text{const.} \propto I\,l\,[\ln(8R/r) - 2]$$

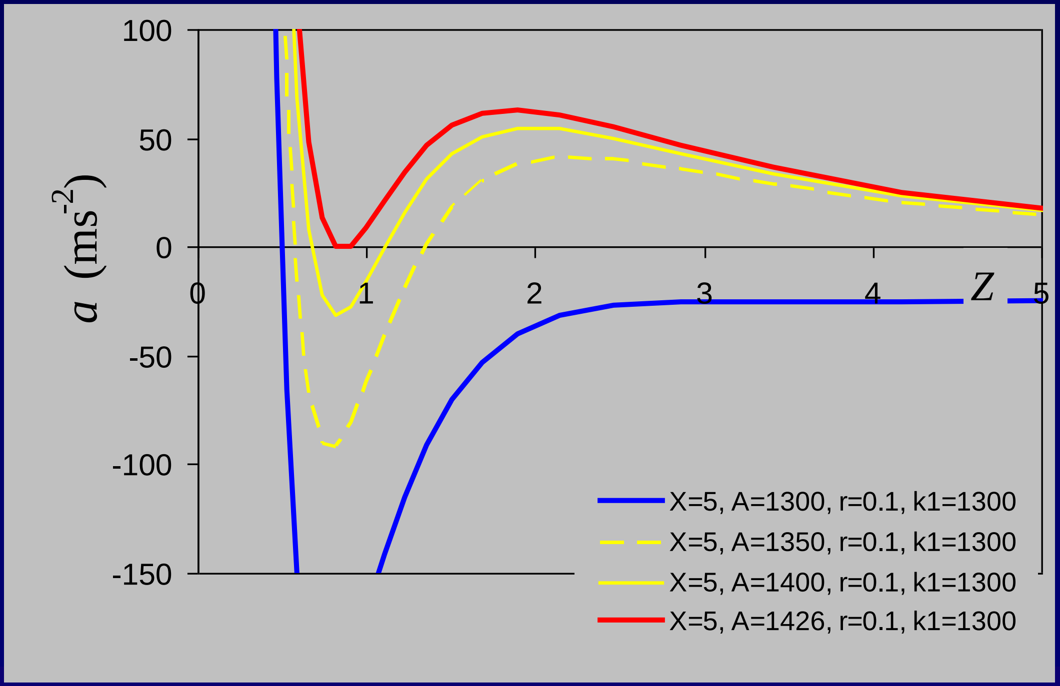
$$\Phi_\mathrm{i} = \text{const.} \propto I\,l$$

$$\Rightarrow \quad I \propto l^{-1}, \quad r \propto R, \quad X \propto r/l$$

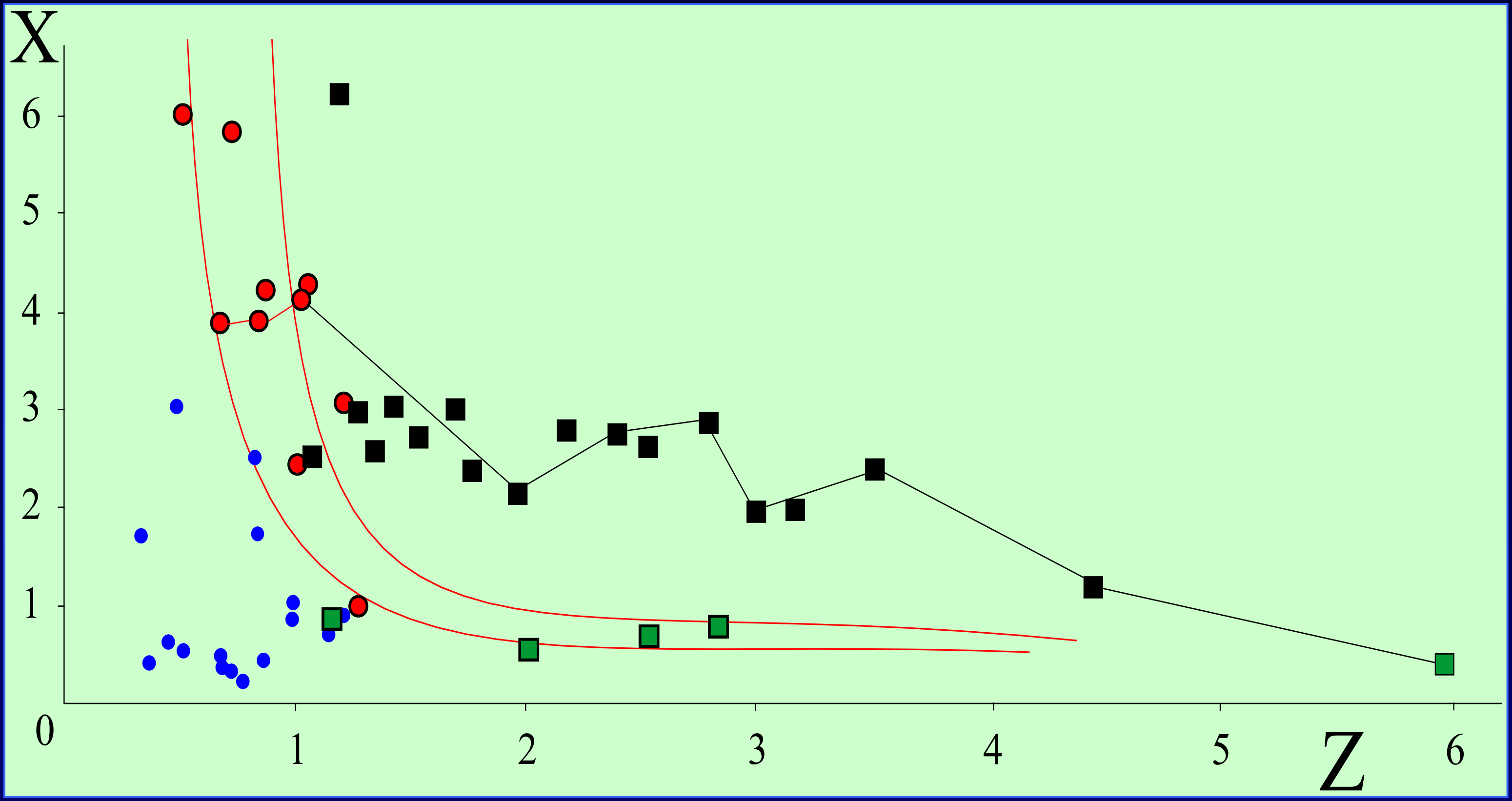
Loss of equilibrium





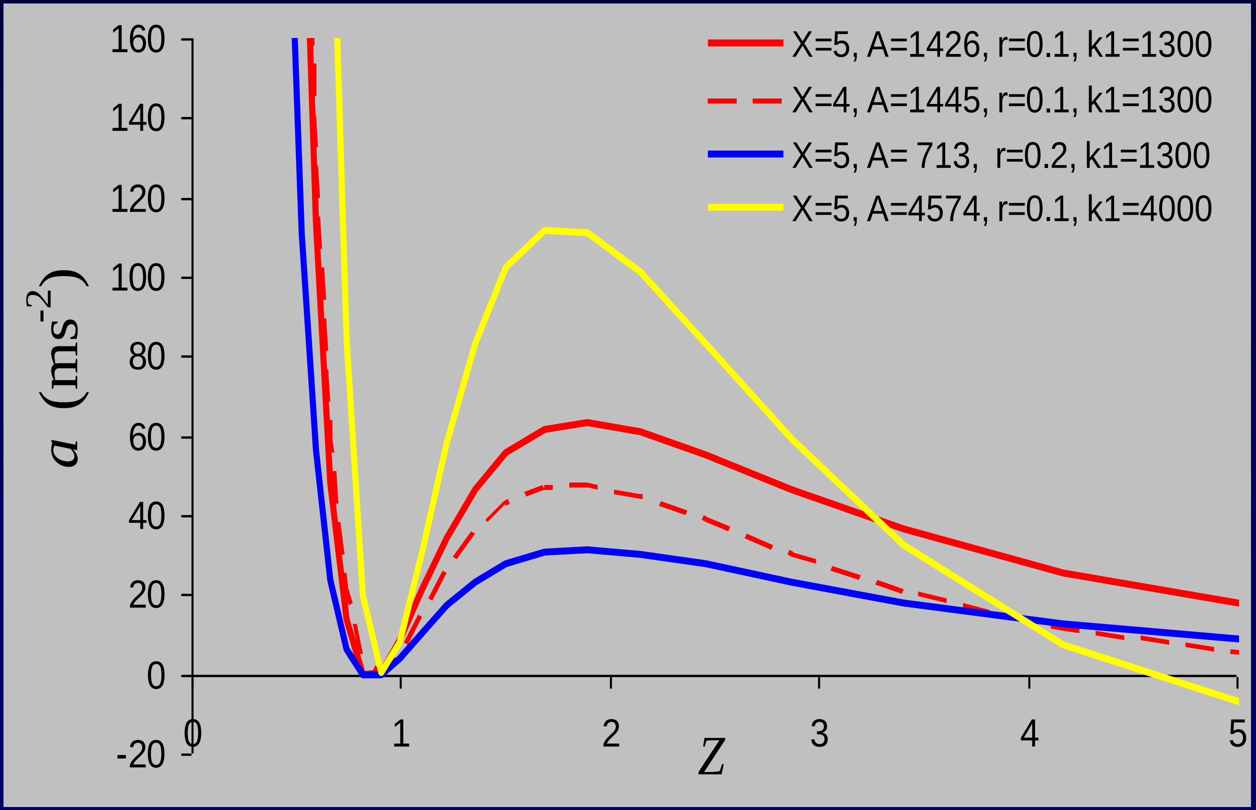


Loss of equilibrium: observations

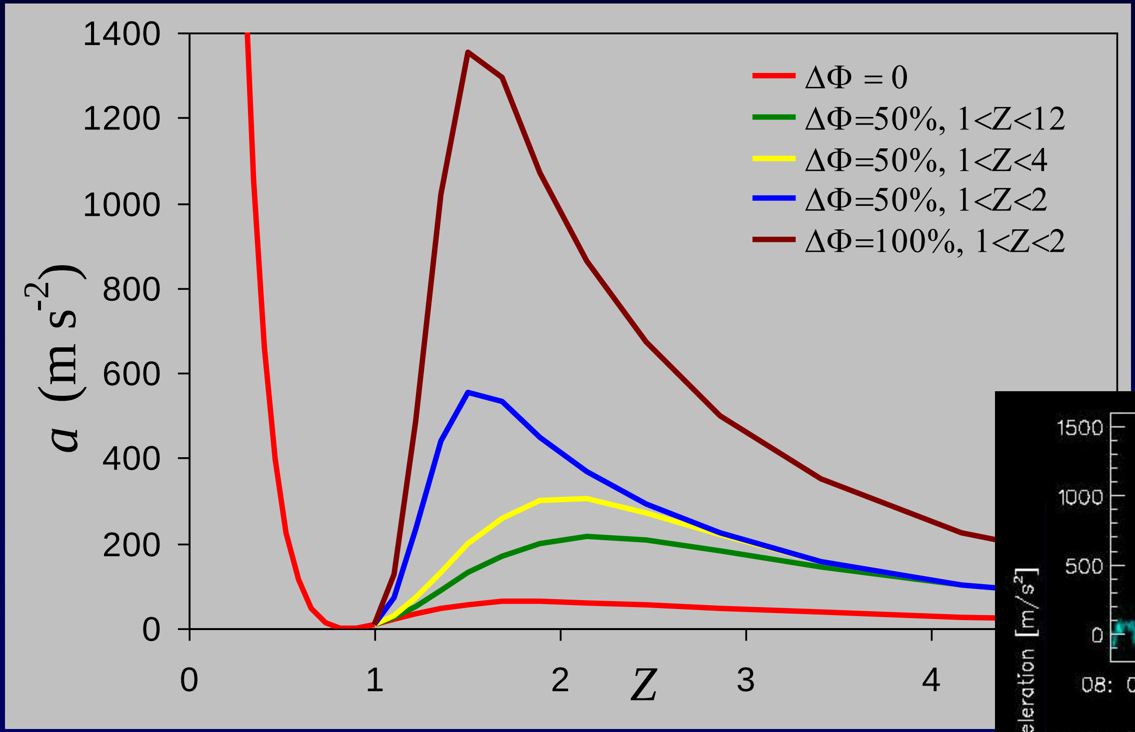


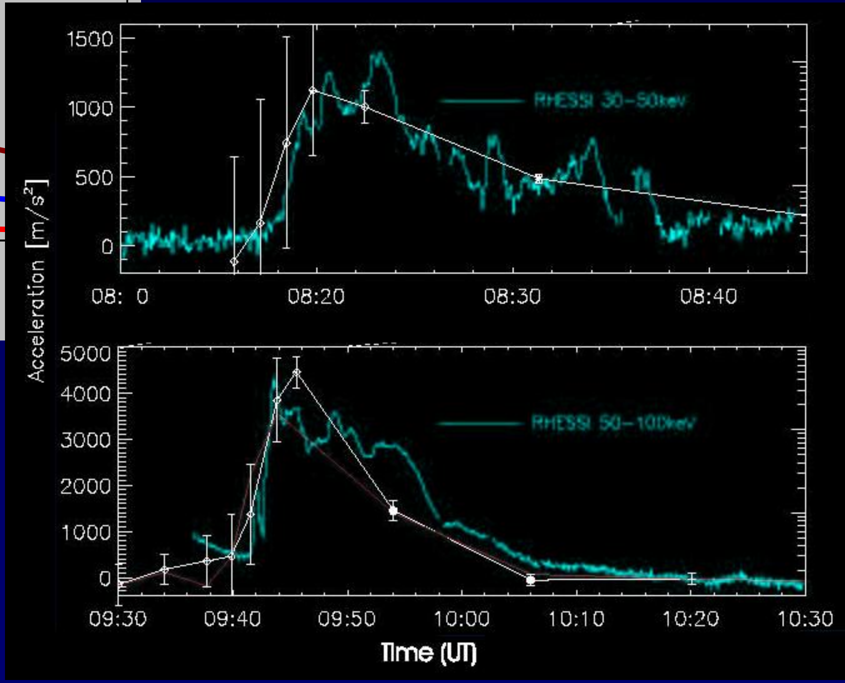
Vršnak, Ruždjak & Rompolt 1991, SPh 136, 151

Eruption **WITHOUT** reconnection



Eruption **WITH** reconnection

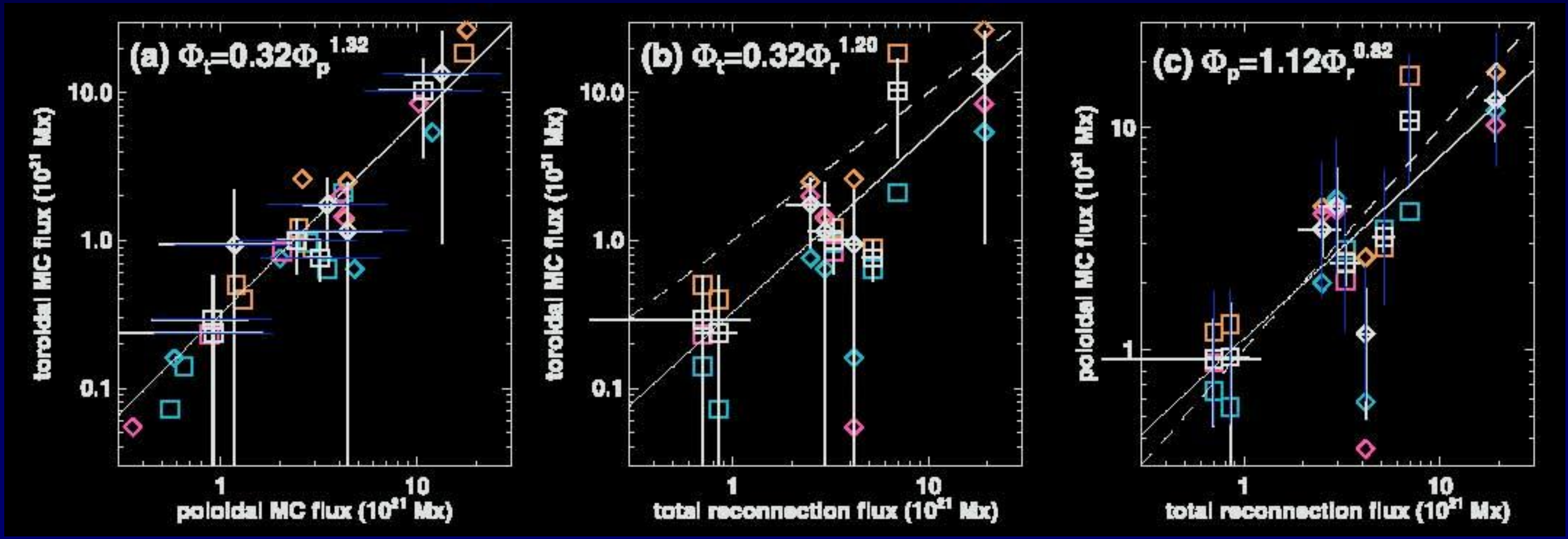




Temmer et al. 2007

Sun - 1AU relationship

Qiu et al. 2007, ApJ 659, 758 : Φ_{recon} *versus* Φ_{1AU}



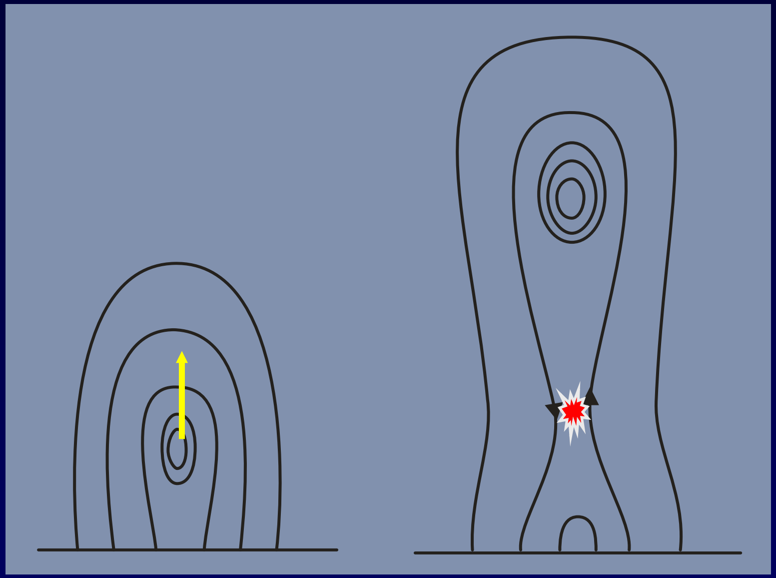
The End

Thank You

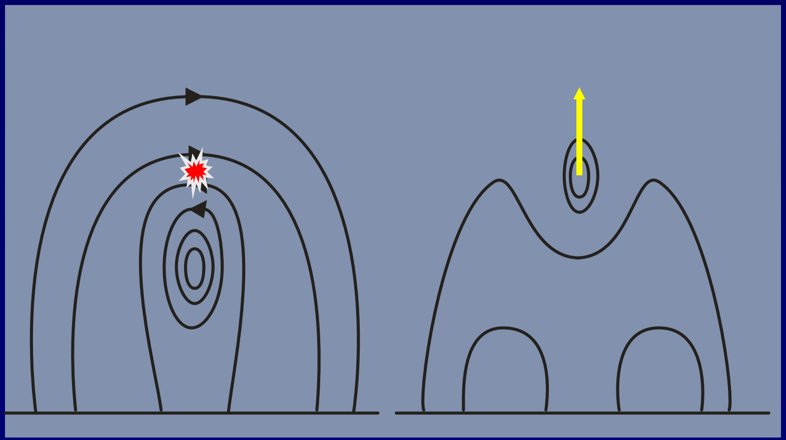
For Your Attention!

2-D models: no eruption without reconnection!

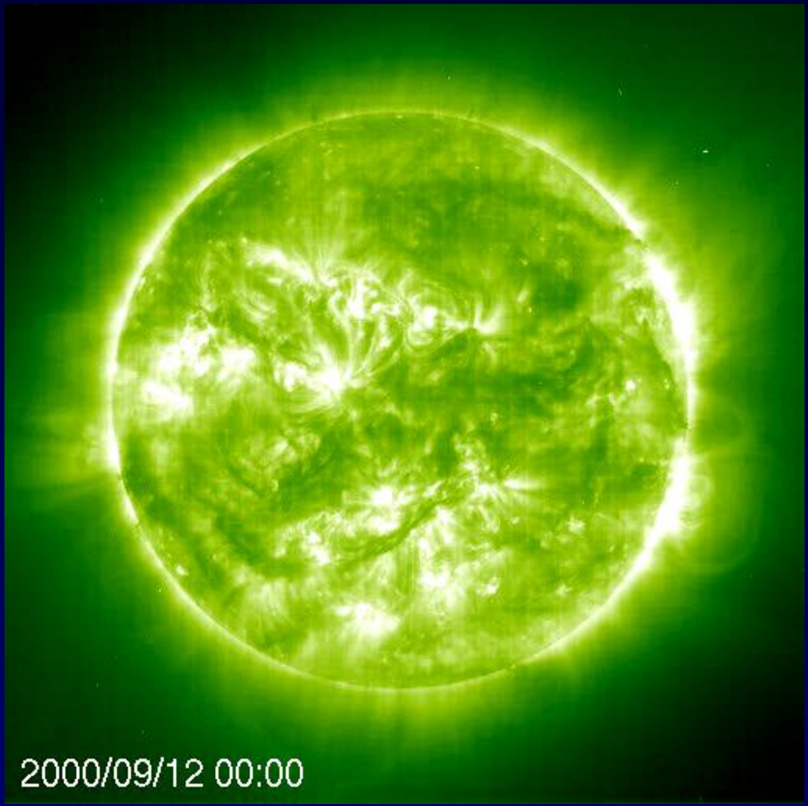
Tether-cutting models (reconnection below ejection):
Reduces magnetic tension of the overlying field and increases magnetic pressure below CME; enlarges the flux rope ($d\Phi_p/dt > 0$)

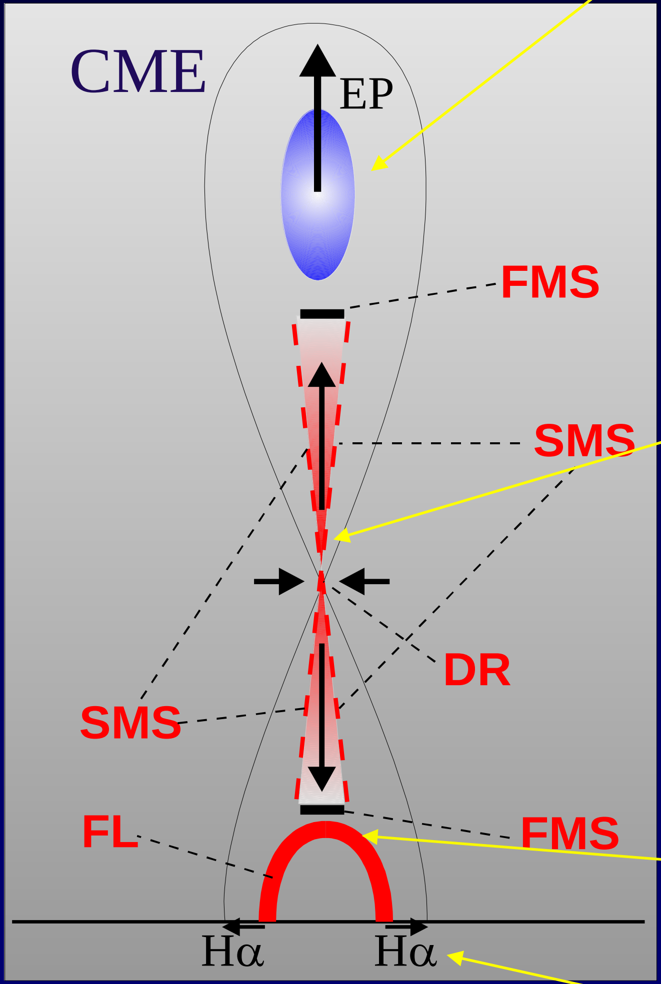


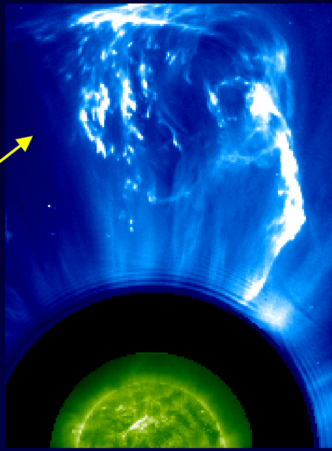
Break-out models (reconnection above ejection):
Reduces magnetic tension and pressure of the overlying field; reduces the flux rope ($d\Phi_p/dt < 0$)

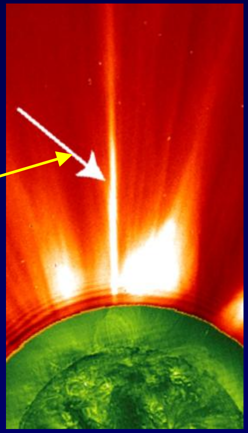


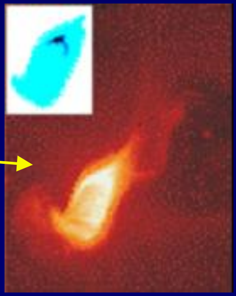
CME/flare process





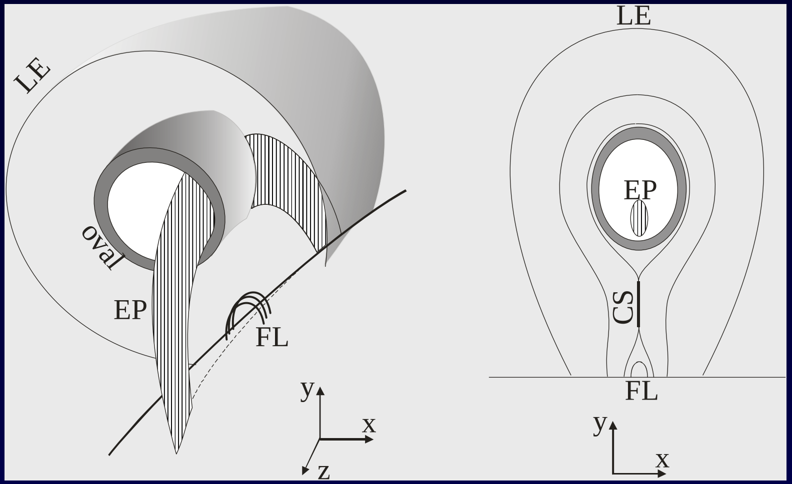


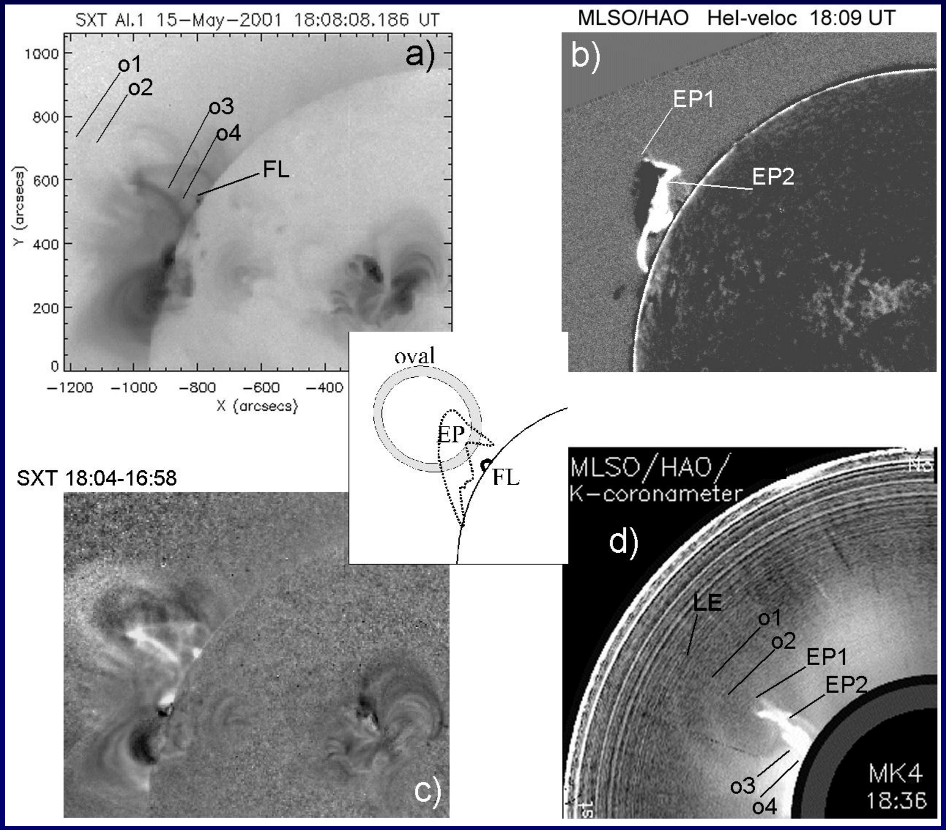


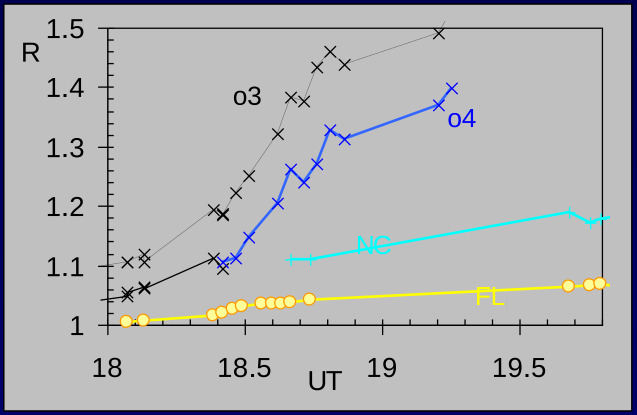


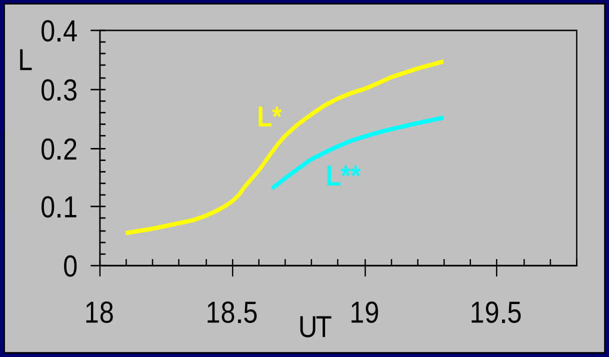
Current sheet signatures:

a) CME/flare of 15 May 2001



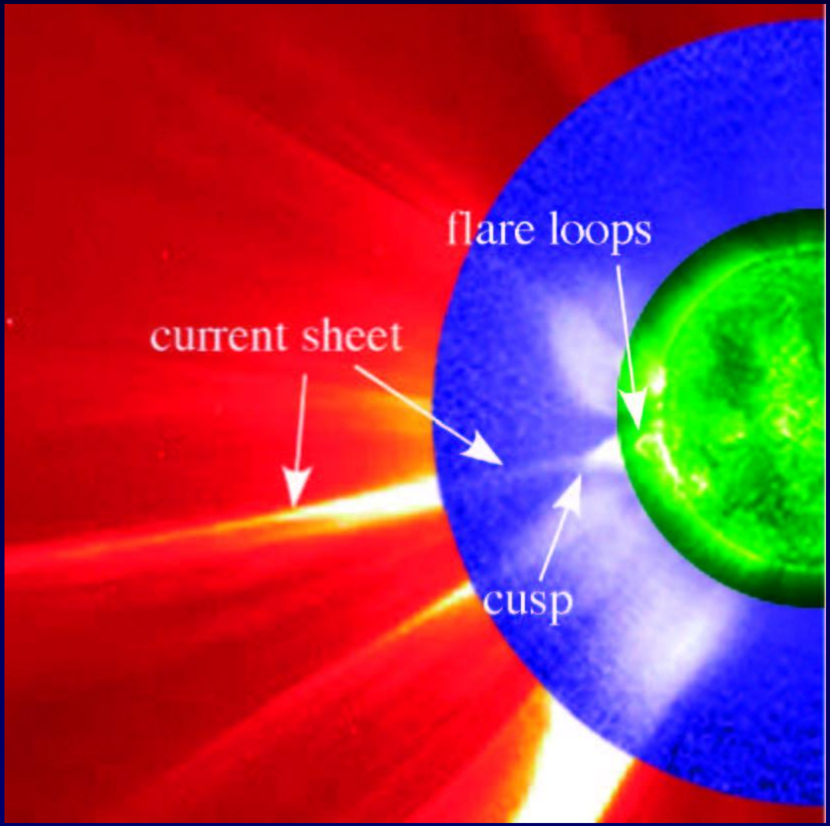






Vrsnak et al. 2004, SPh 225, 355

Current sheet signatures: b) "Rays"



SoHO-LASCO-C2/C3,
MLSO-MK-IV & EIT obs.:
(e.g., Lin et al. 2005, ApJ 622, 1251 and references therein)
reconnection inflow (UVCS Lyα):
v_{in} = 10-100 km/s

SoHO-UVCS obs. (e.g., Bempoard et al. 2006, ApJ 638, 1110; and references therein):
$T_{CS}/T_c = 5 \rightarrow 3$ & $n_{eCS}/n_{ec} = 7 \rightarrow 5$
in 0.3 → 2.3 day interval (increasing β with height?)

Why reconnection is needed?