SOLAR ERUPTIONS:

Physical mechanisms and processes governing initiation and propagation of CMEs and shocks

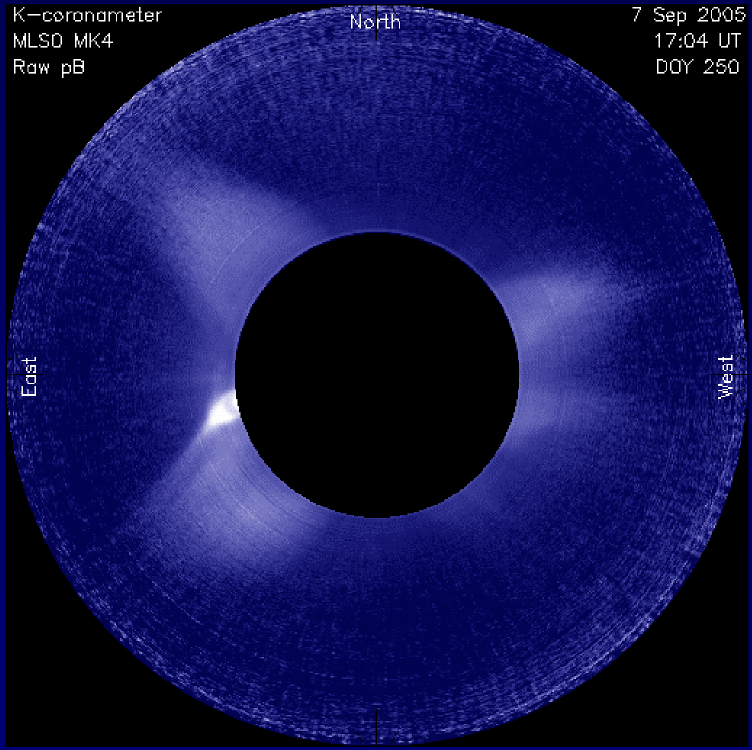
Bojan Vršnak

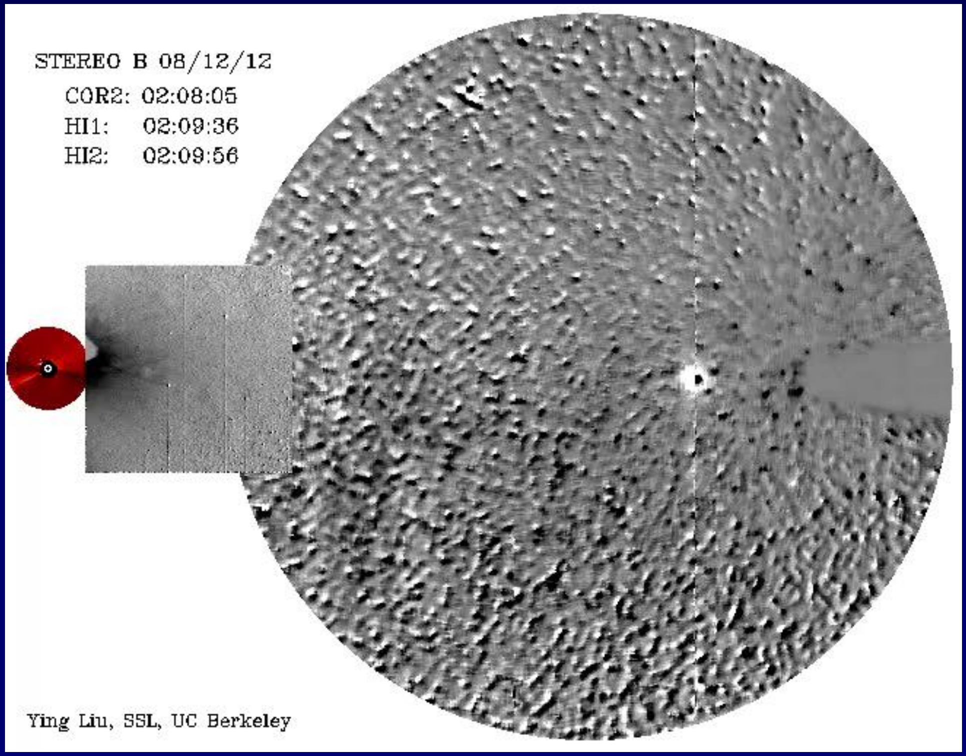
Hvar Observatory

Faculty of Geodesy, Kačićeva 26, HR-10000 Zagreb, Croatia

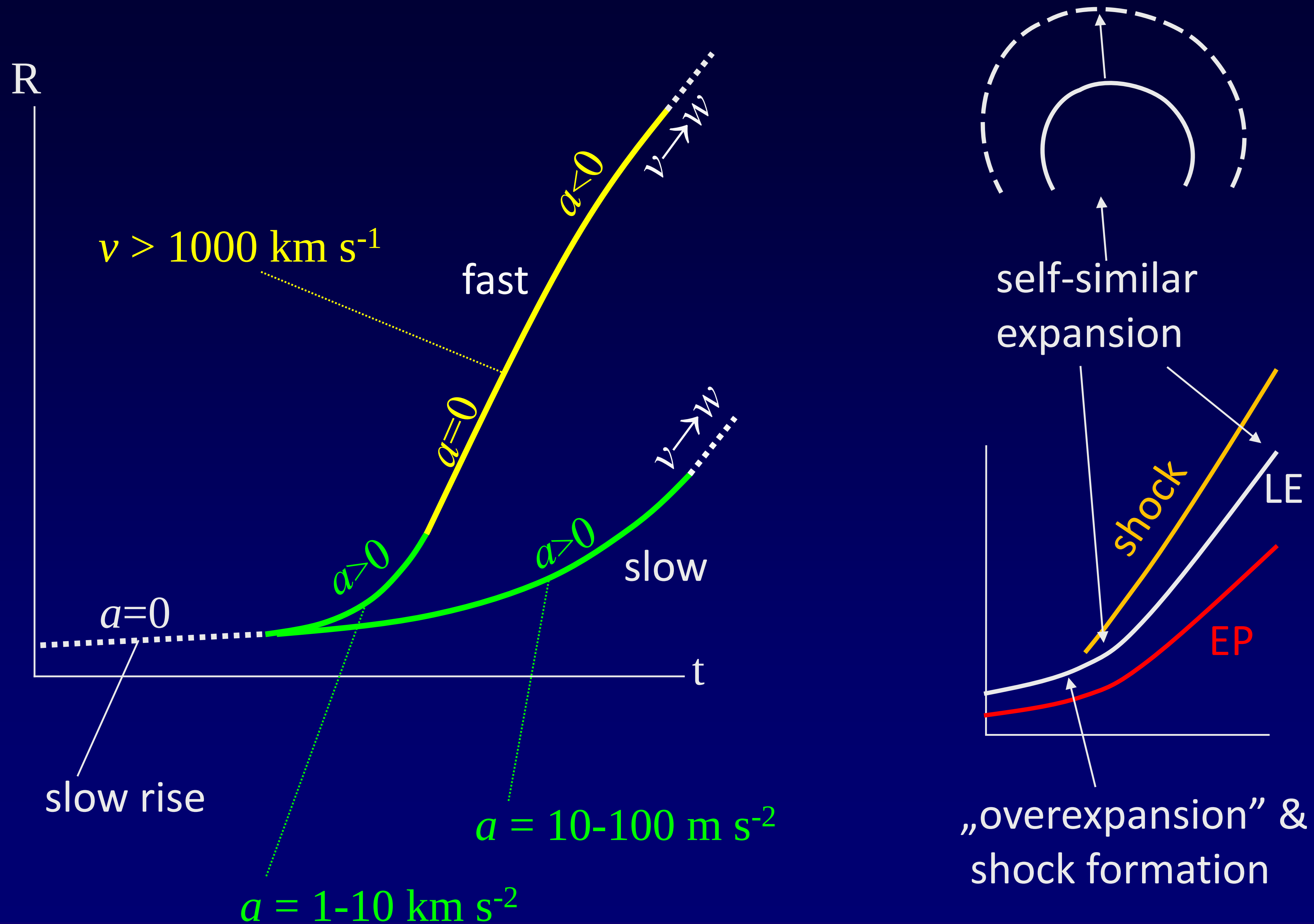
This work has been supported by *Croatian Scientific Foundation* under the project 6212 *„Solar and Stellar Variability“* (**SOLSTEL**).

Introduction

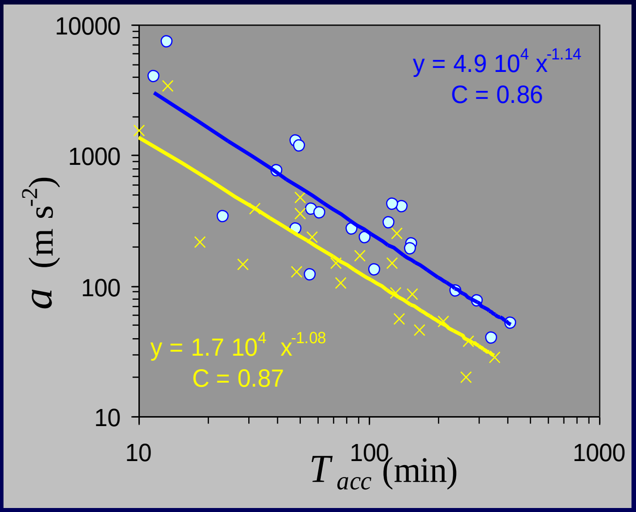


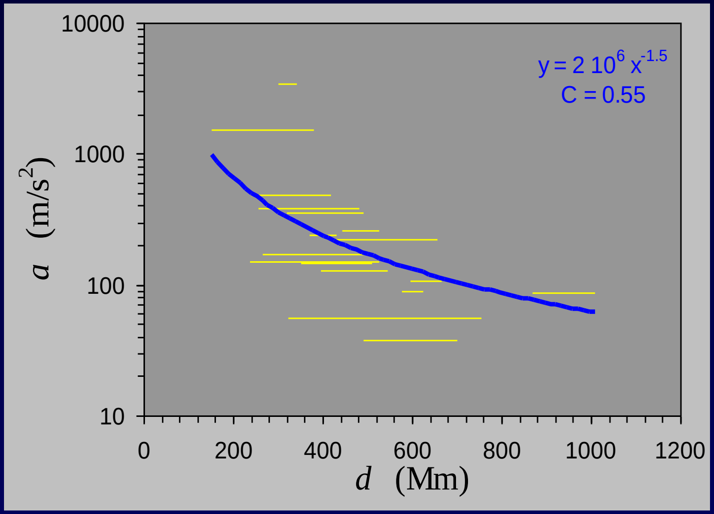


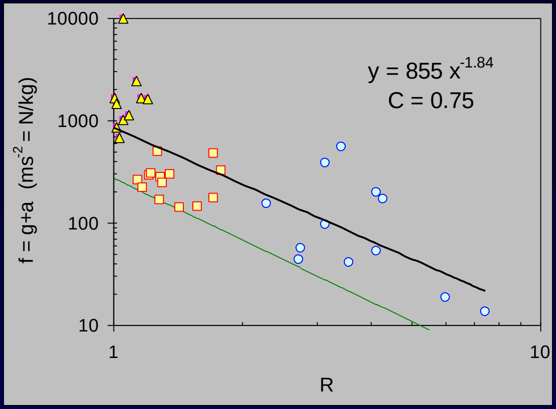
Observations: kinematics

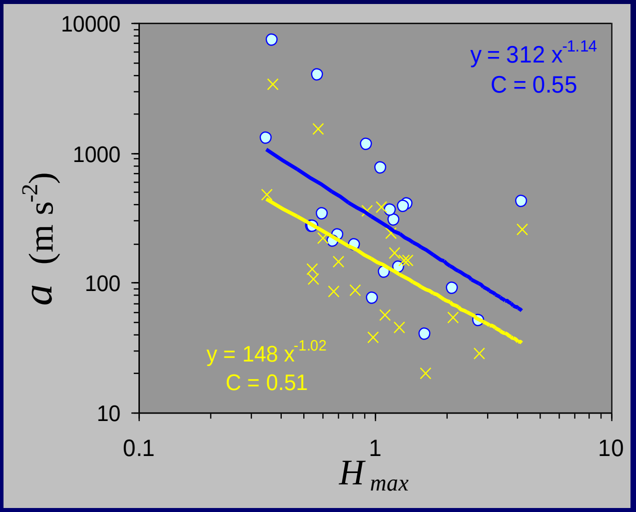


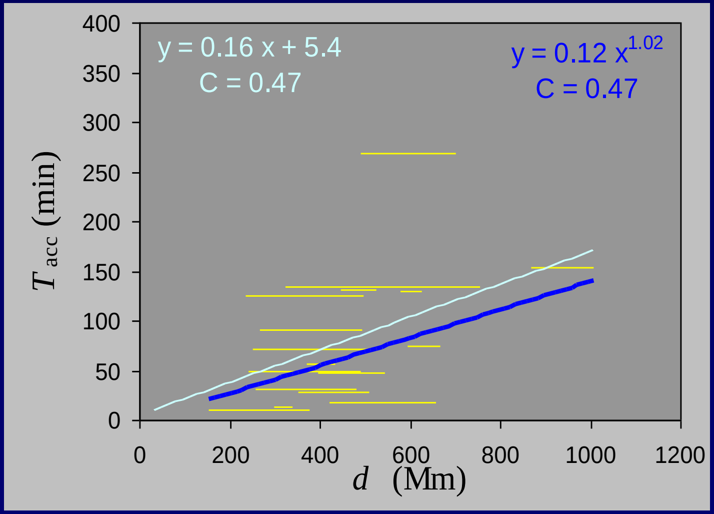
Observations: acceleration scaling

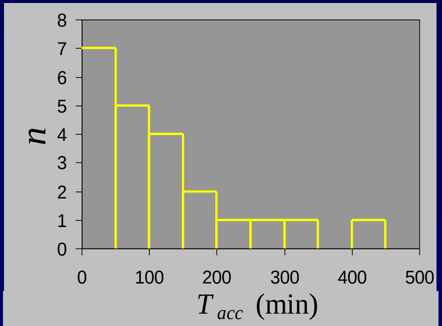


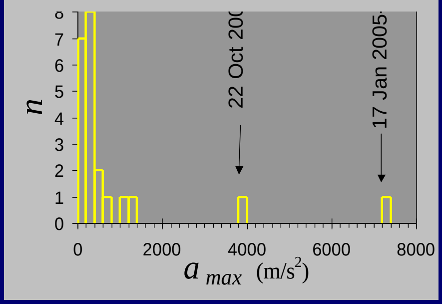












Scalings

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

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

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

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

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

AR

$d = 10^5$ km, $v_A = 1000$ km/s

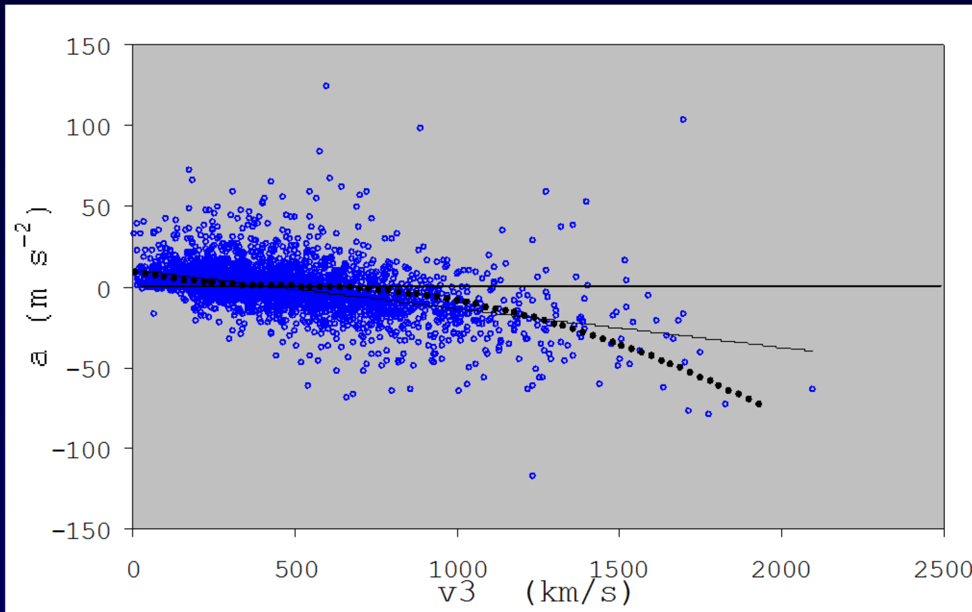
$a = 10$ kms^{-2} ; $\tau = 100$ s ; $\lambda = 10^5$ km

QP

$d = 10^6$ km, $v_A = 400$-1000 km/s

$a = 100$-1000 ms^{-2} ; $\tau = 15$-40 min ; $\lambda = 10^6$ km

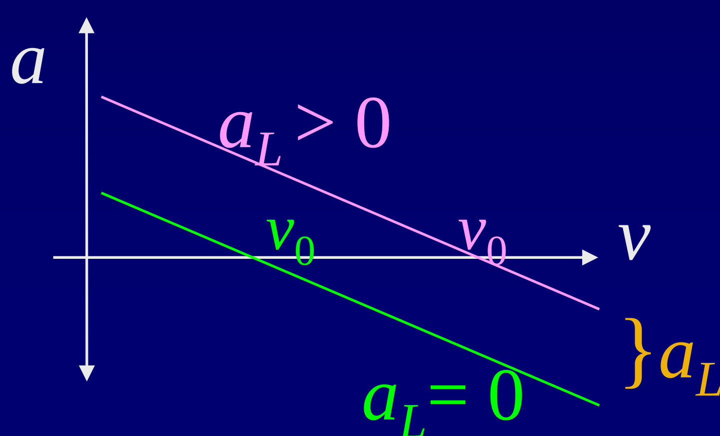
Observations: propagation phase

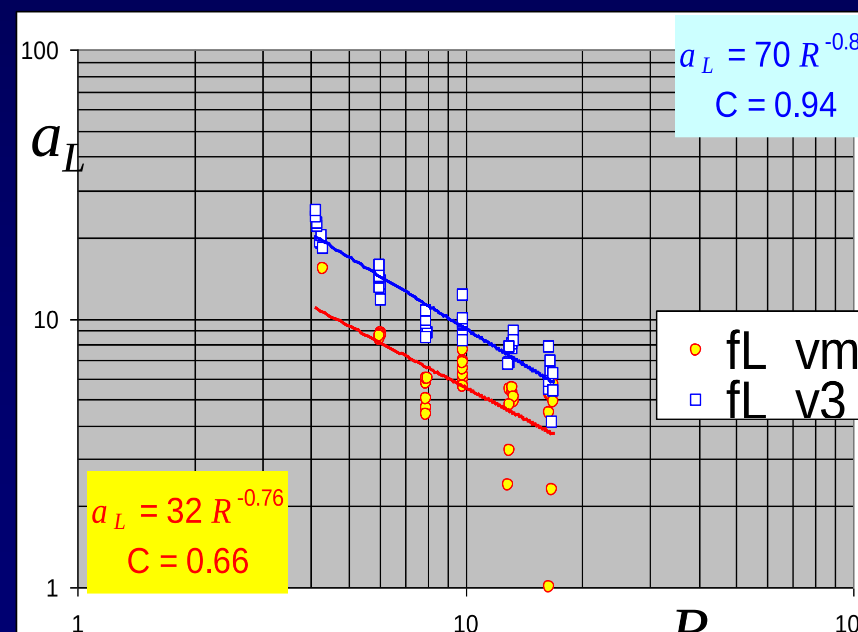


$$a = a_L - \gamma\,(v-w)|v-w|$$

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

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

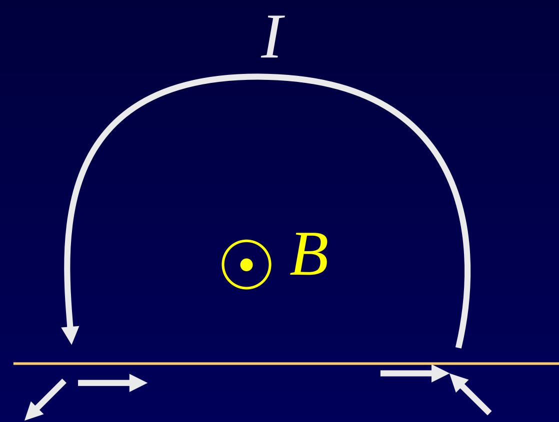




General concept:
Forces & Energies

Free energy of non-potential magnetic field $\Rightarrow$ $\boxed{\text{Electric current, } I}$

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



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

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

$$\Rightarrow \Delta F_{\text{L}}/\Delta R < 0$$

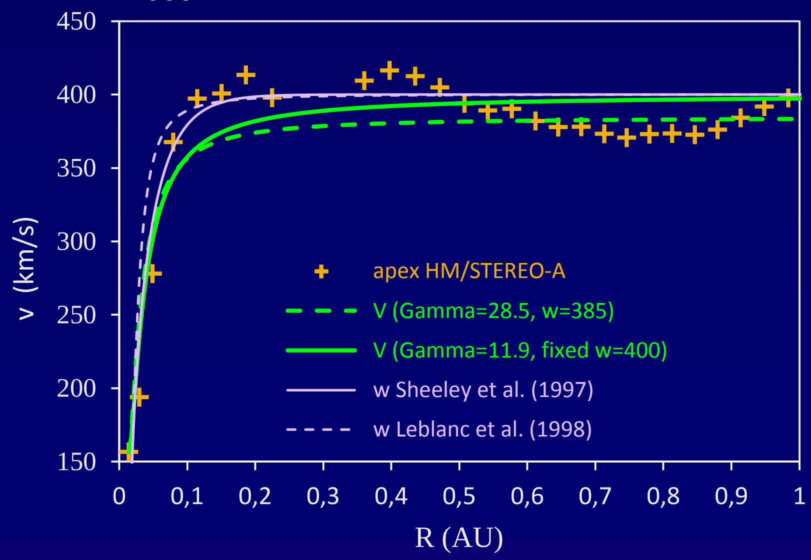
$$\Rightarrow \Delta W/\Delta R < 0$$

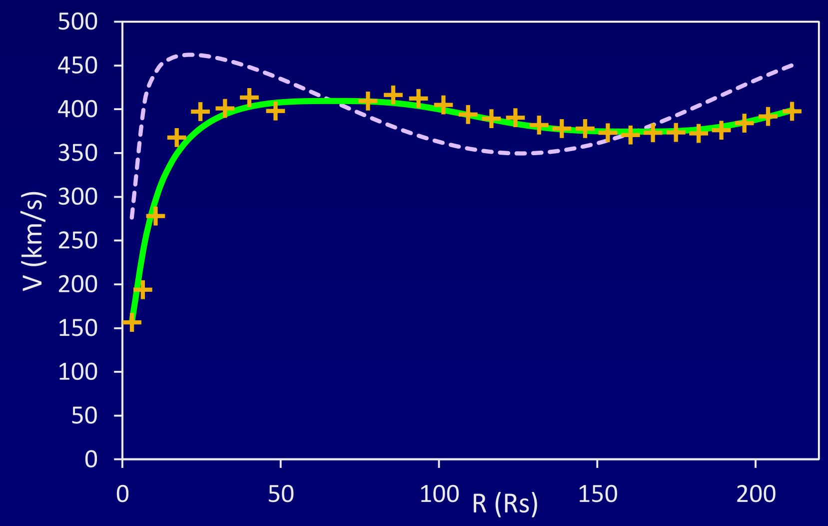
$$\Delta E_{\text{mag}} = \Delta E_{\text{kin}} + \Delta E_{\text{pot}} + W_{\text{drag}}$$

IP propagation

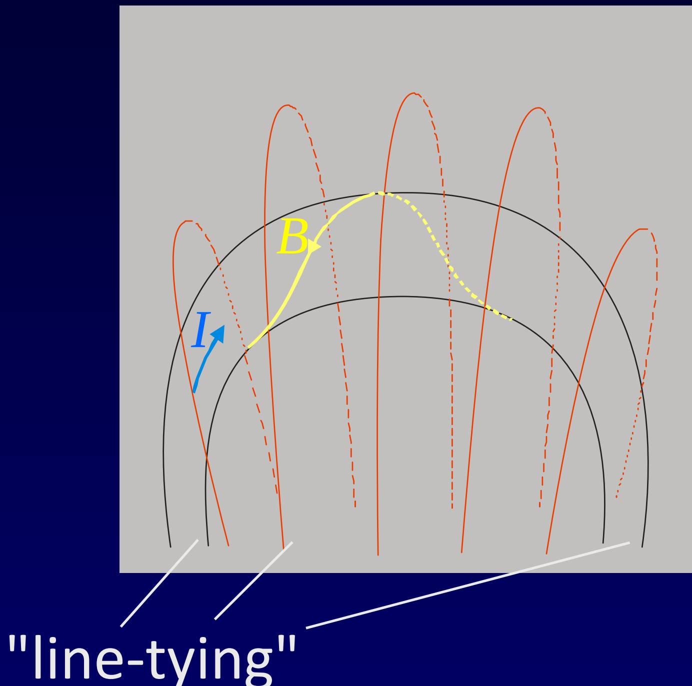
- fast CMEs decelerate, slow CMEs accelerate
- deceleration of massive CMEs is weaker than in case of light CMEs
- deceleration is weaker when a CME propagates in high-speed solar wind
- CME cross section deforms („pancaking”, deformations related to high-stream streams)
- …

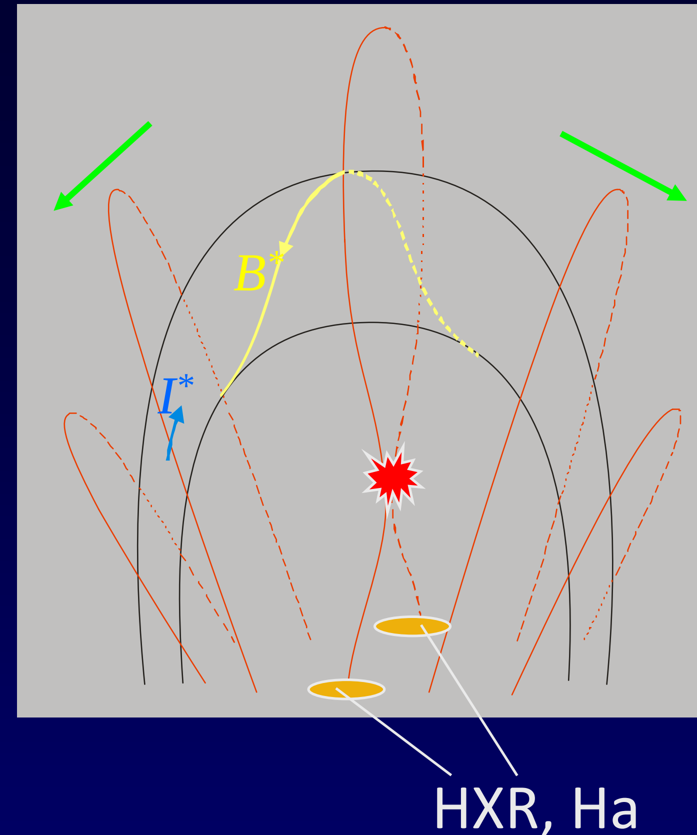
„MHD-aerodynamic” drag

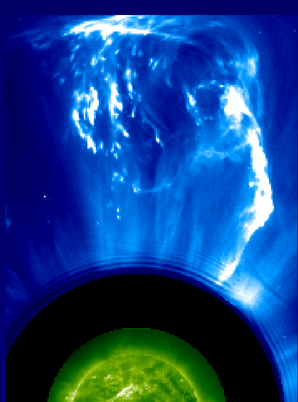




3-D flux-rope models

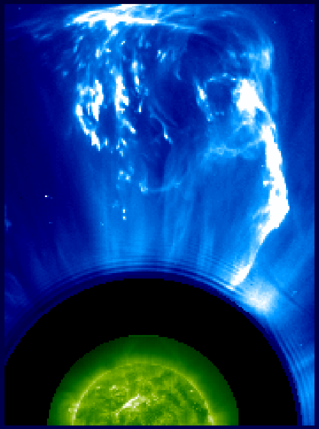


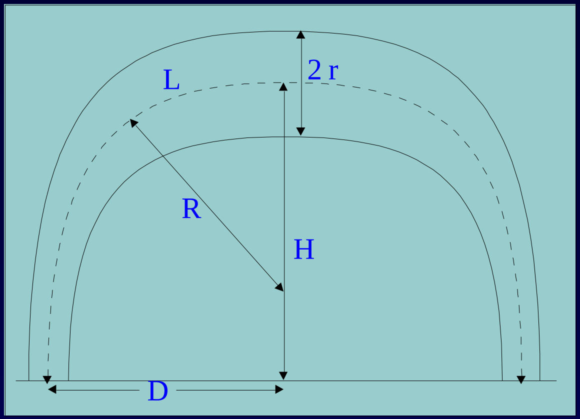


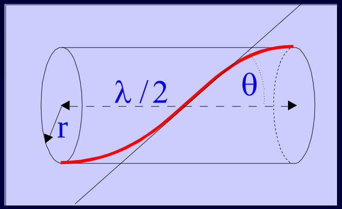


Mouschovias & Poland, 1978, ApJ 220, 675
Anzer & Pneuman, 1982, SPh 79, 1
Chen, J. 1989, ApJ 338, 453
Vrsnak, B. 1990, SPh 129, 295
Chen, J., Krall, J.: 2003, JGR 108, 1410
....

Driving force







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

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

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

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

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

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

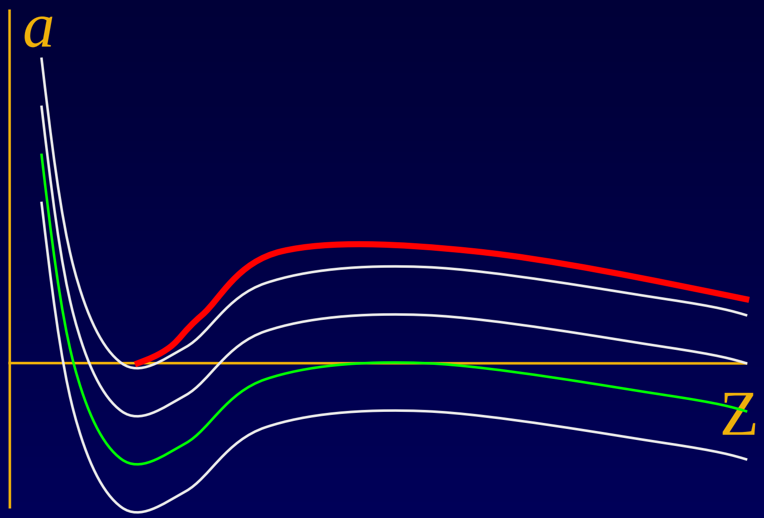
in the absence of reconnection:

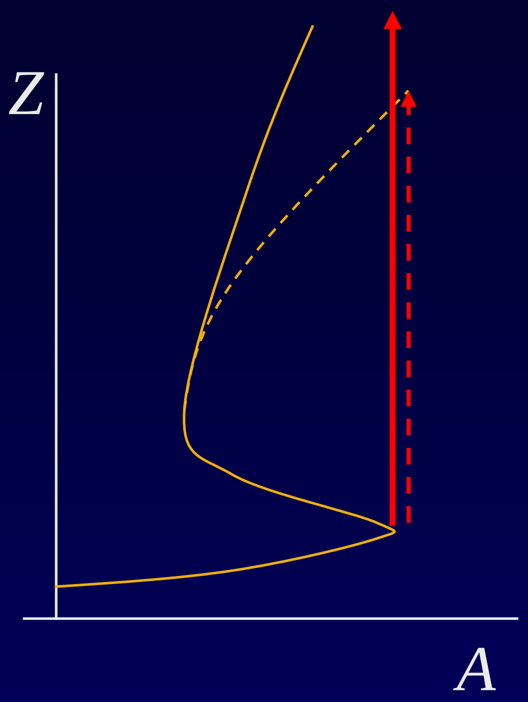
$$\Phi_\mathrm{e} = \text{const.} \propto I\,l\,[\ln(8R/r) - 2]$$

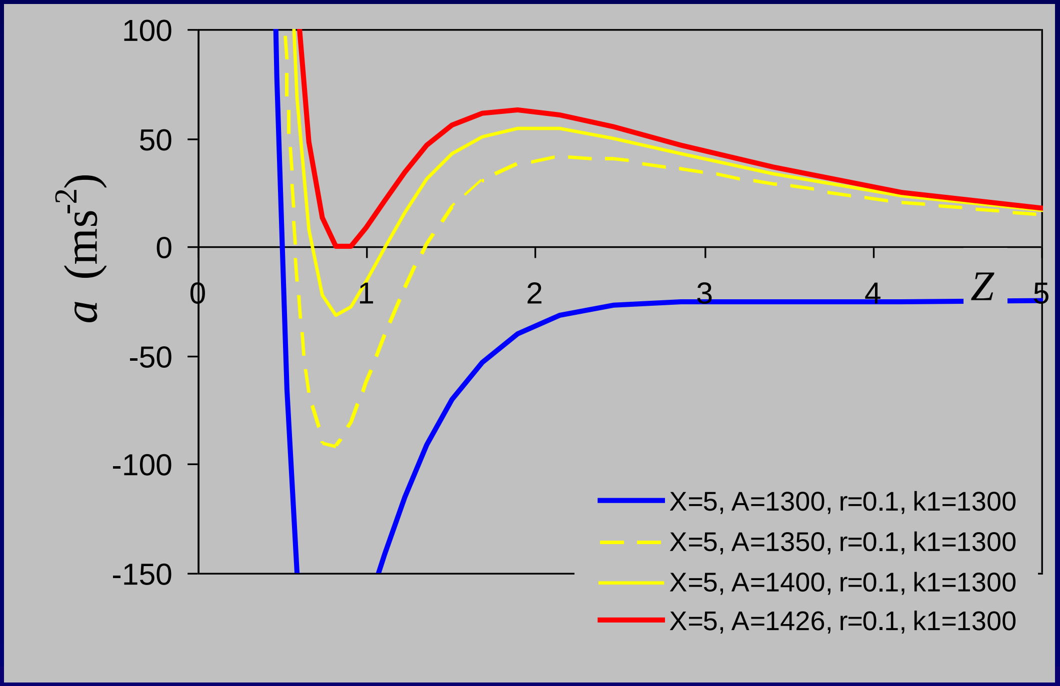
$$\Phi_\mathrm{i} = \text{const.} \propto I\,l$$

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

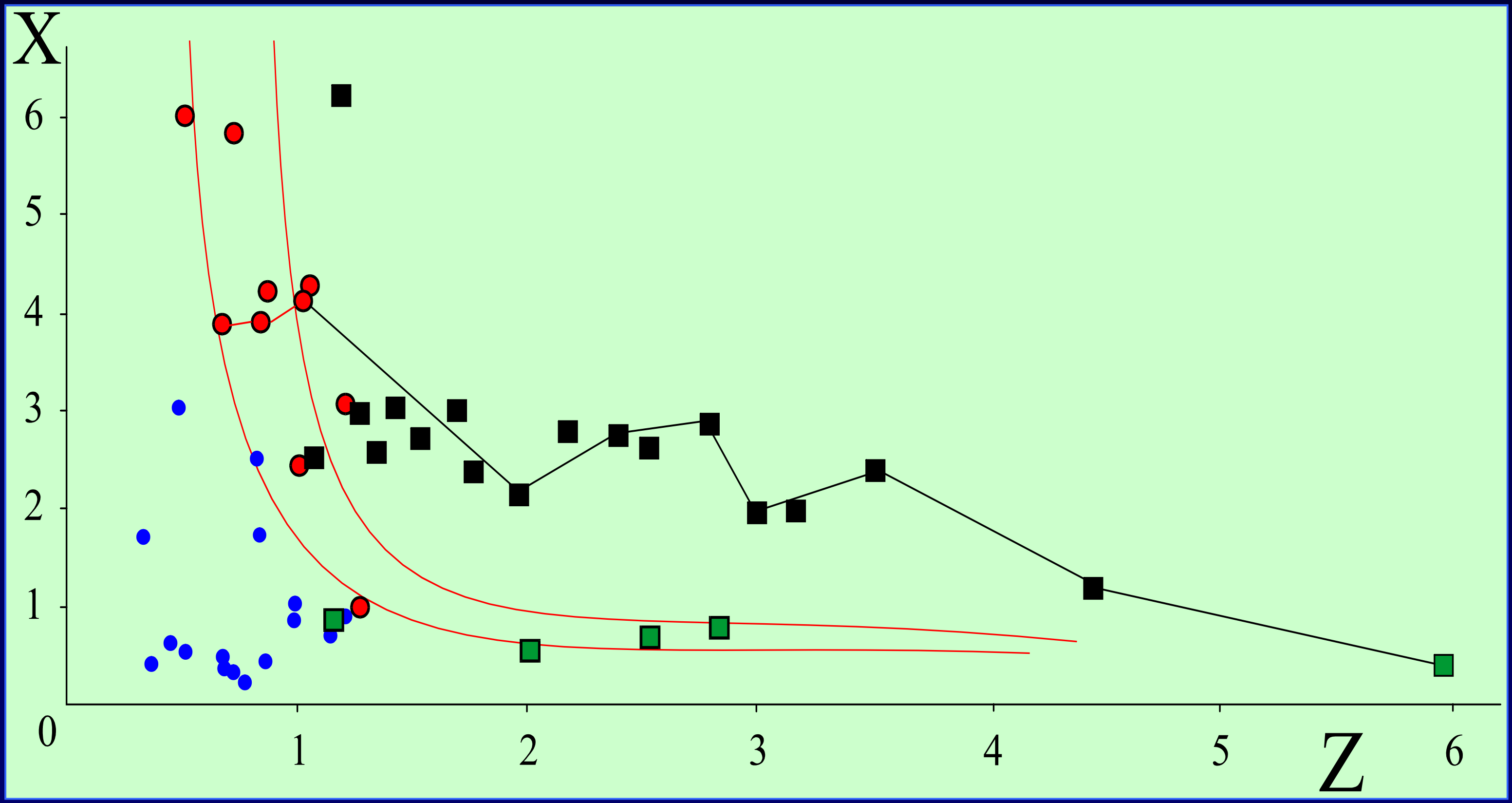
Loss of equilibrium



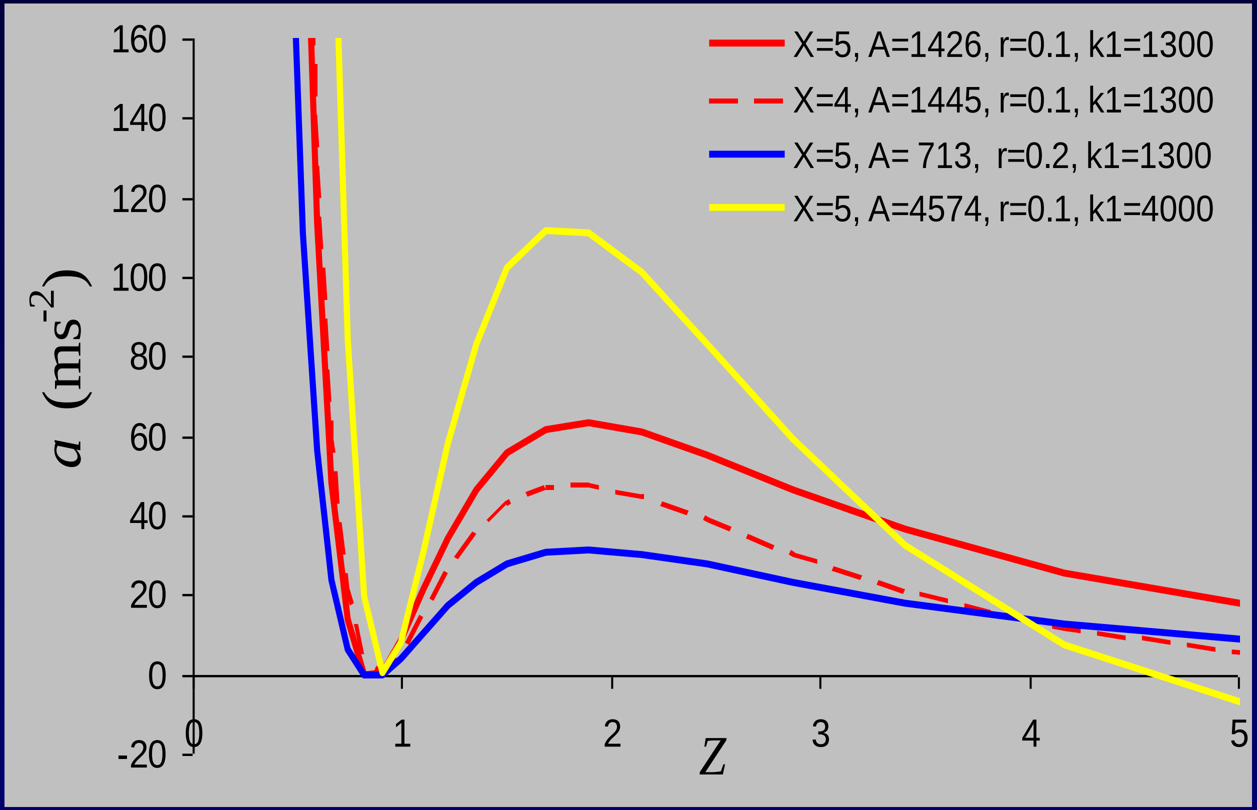




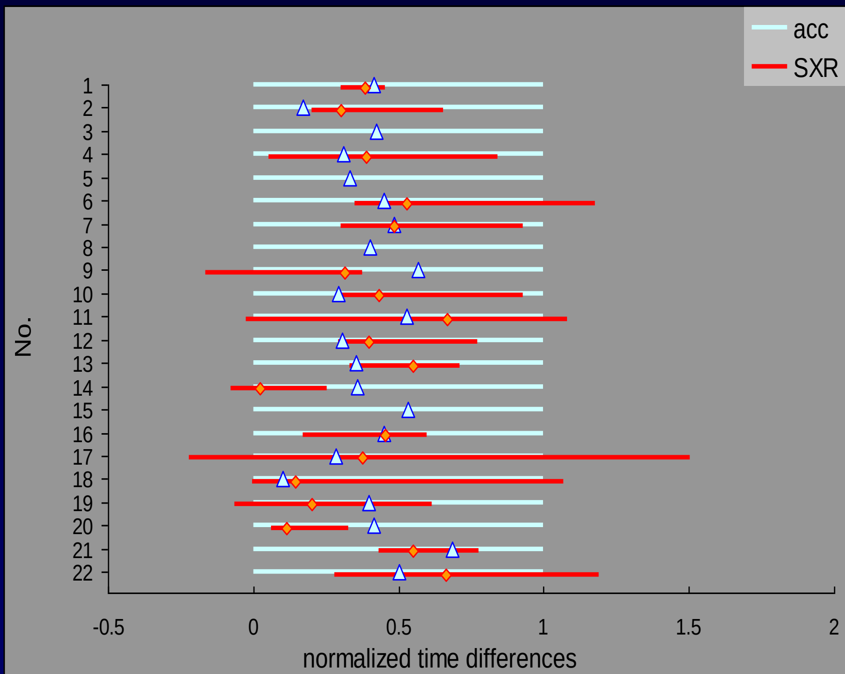
Loss of equilibrium (observations)

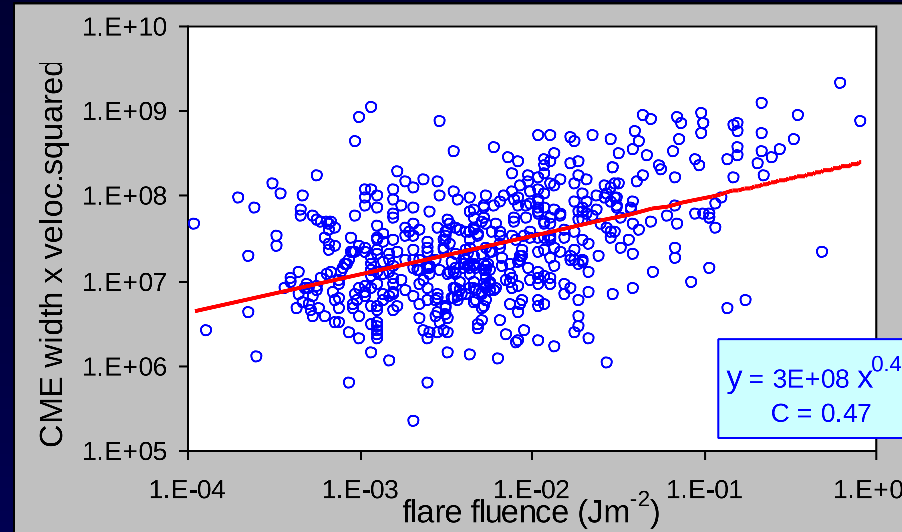


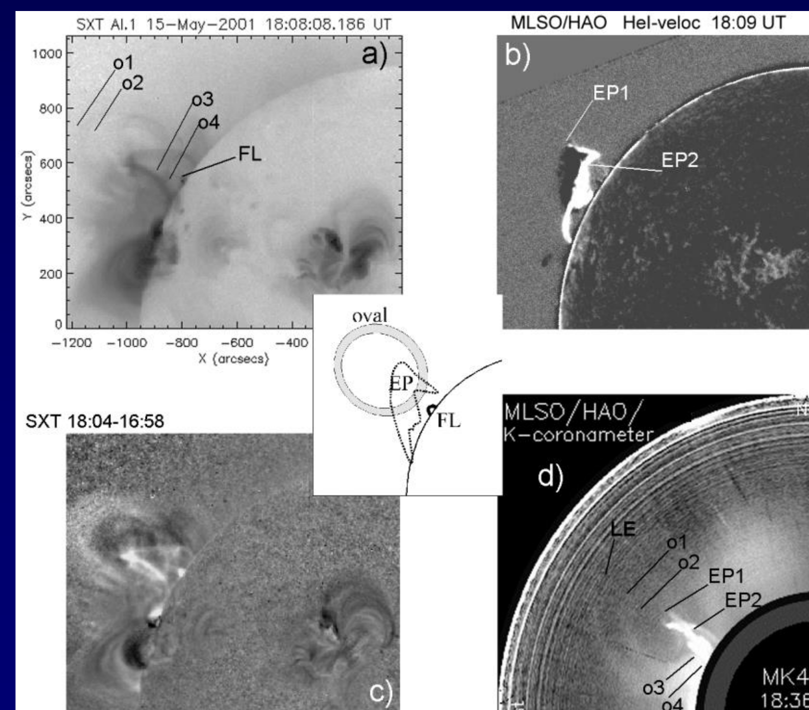
Eruption ***without*** reconnection

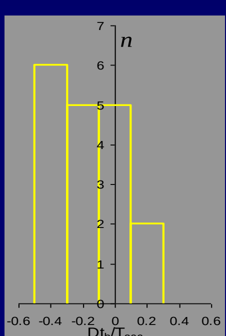


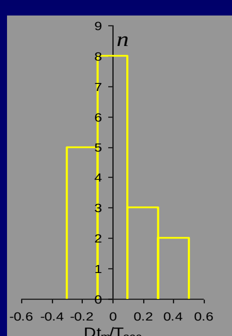
Observations:
CME/flare relationship

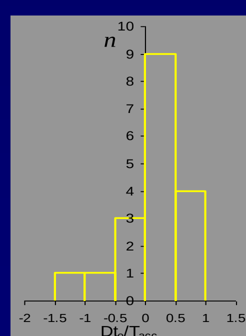






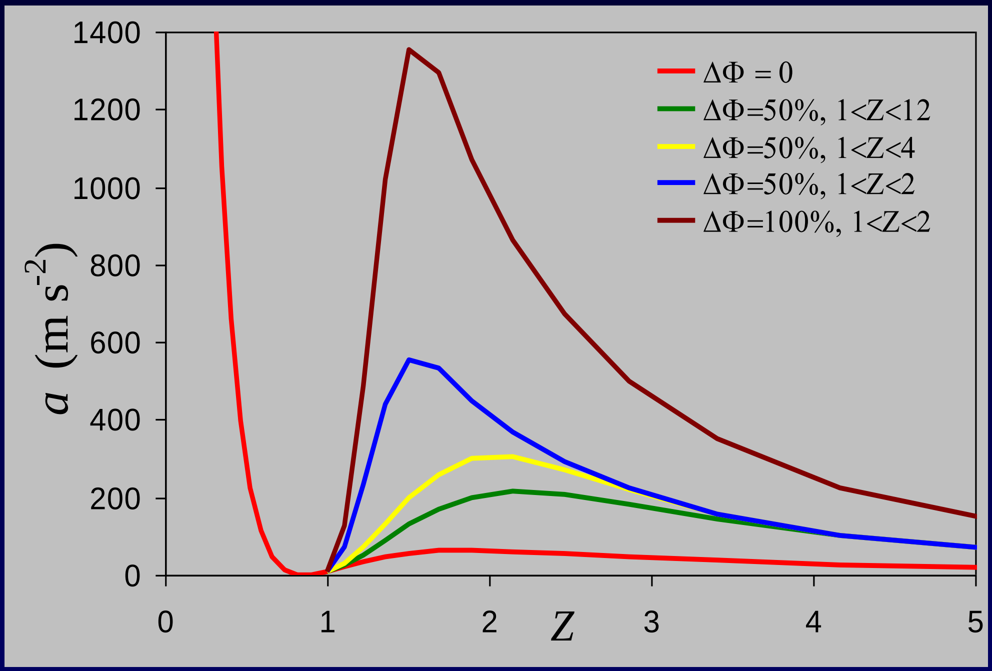


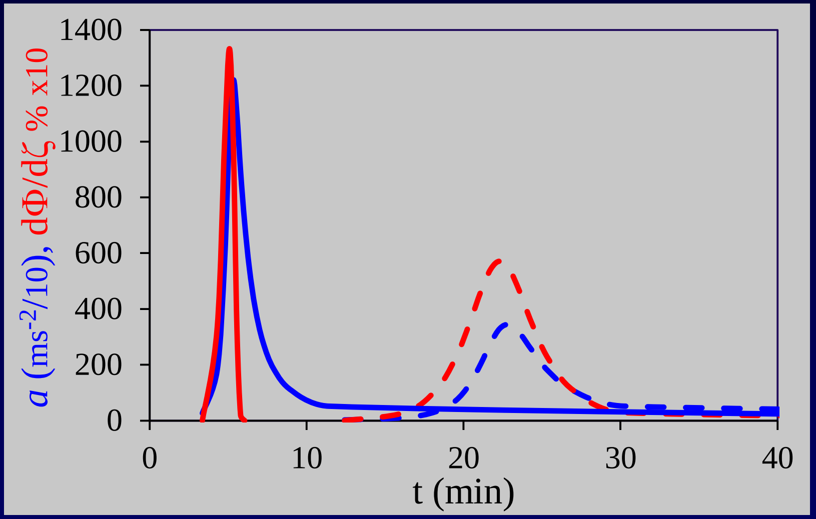


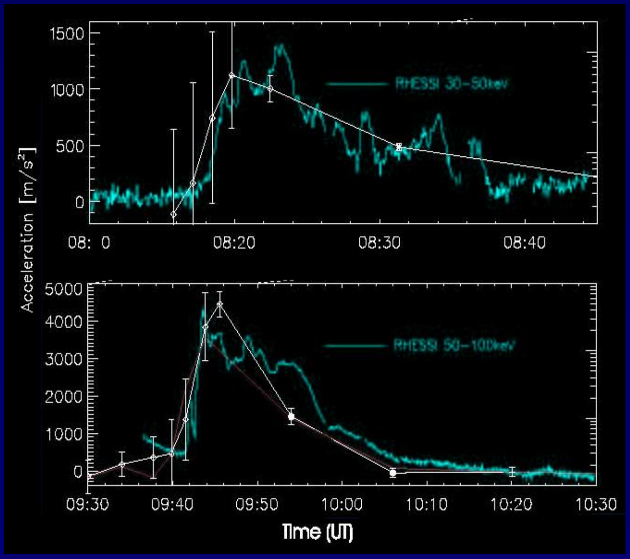


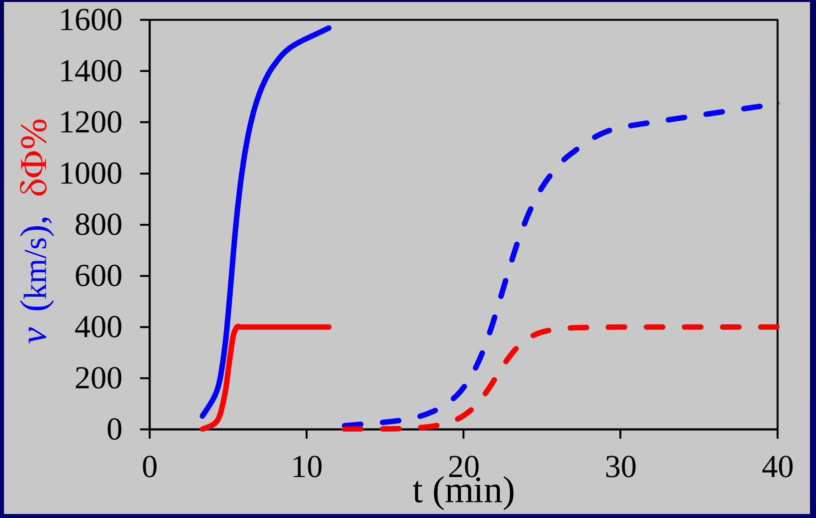
Eruption ***with*** reconnection

$\cancel{I \propto l^{-1}}$

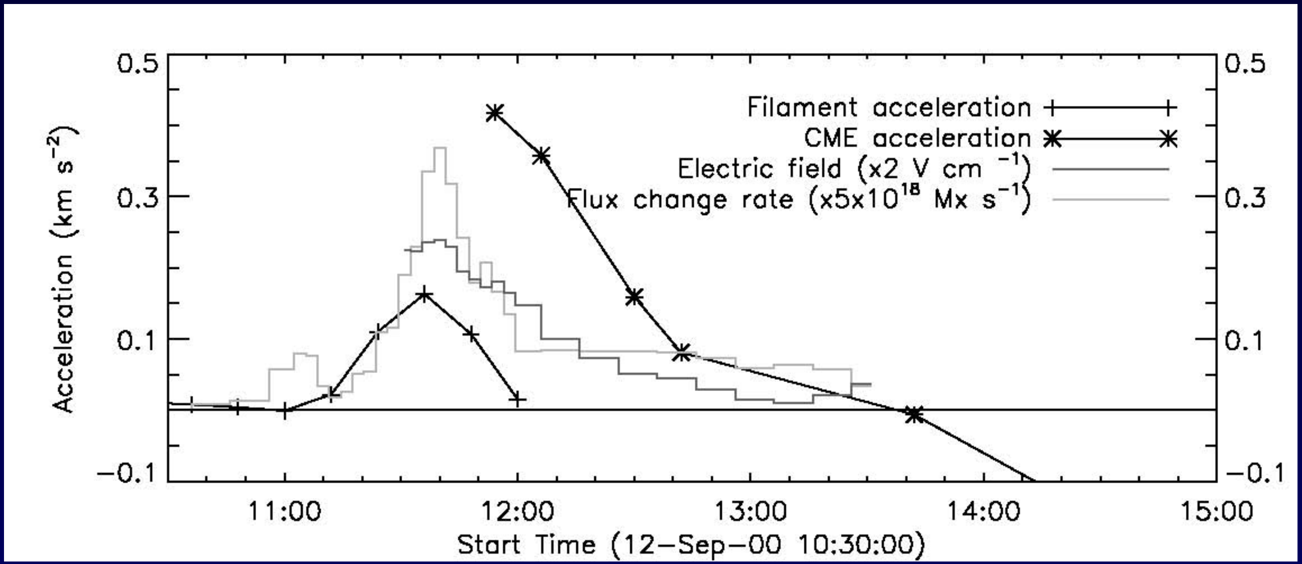


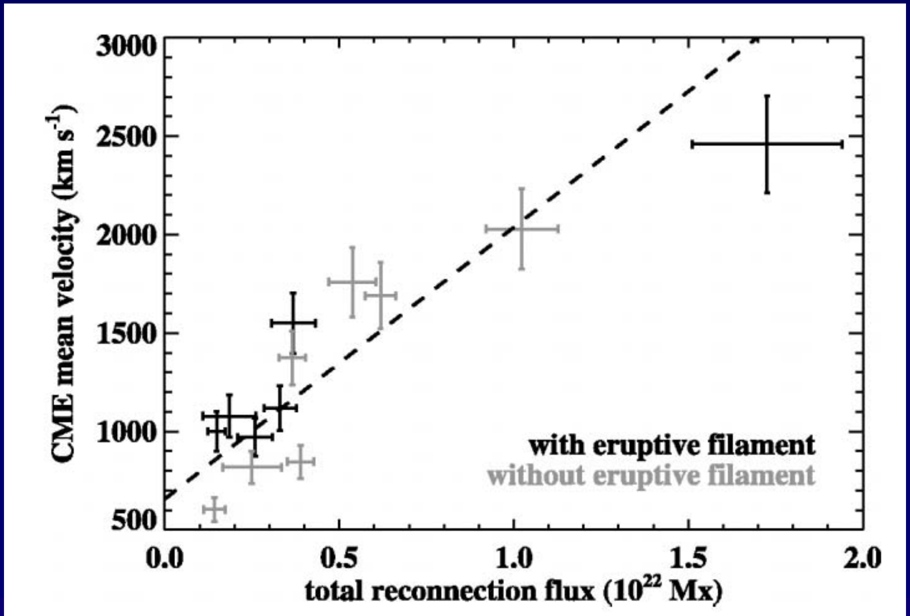






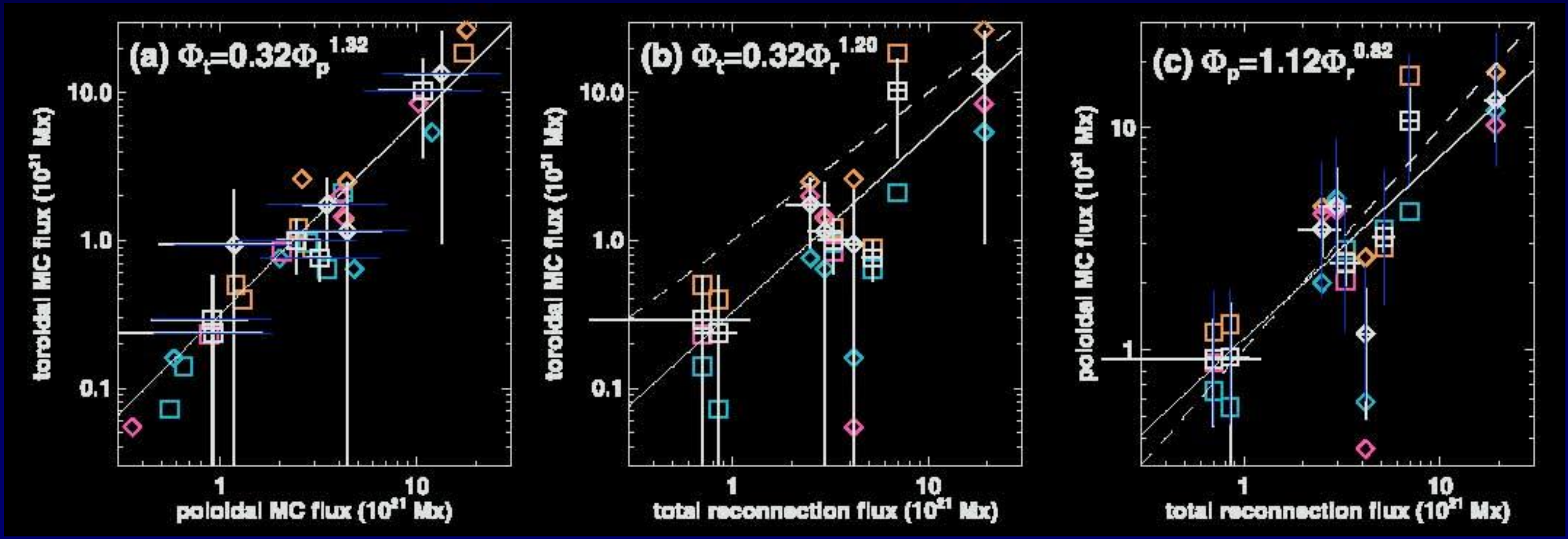
CME acceleration and ***v***x***B*** proxy



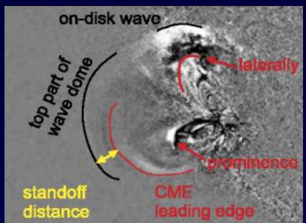


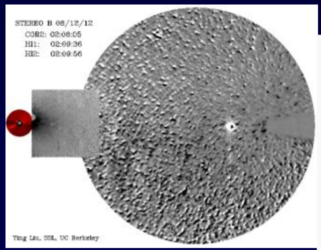
Sun - 1AU relationship

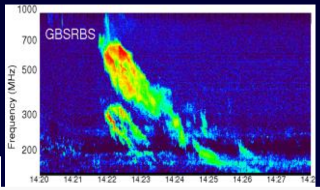
Φ_{recon} versus Φ_{1AU}

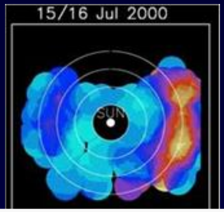


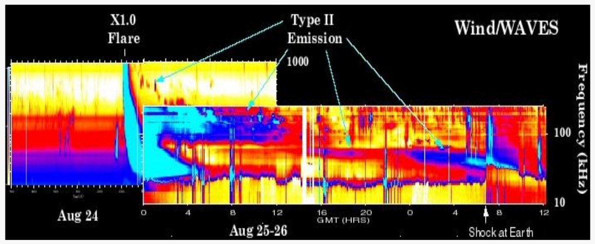
Shock formation & propagation

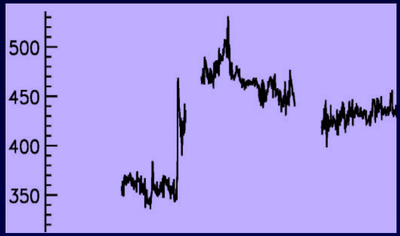


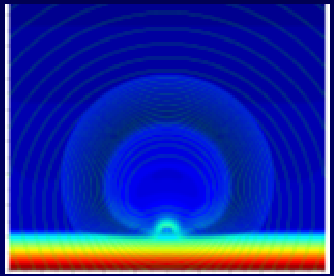


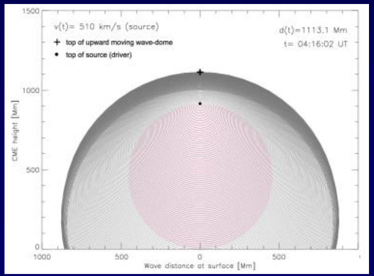


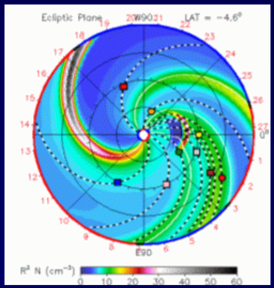


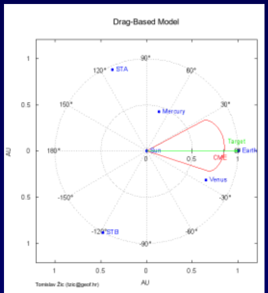












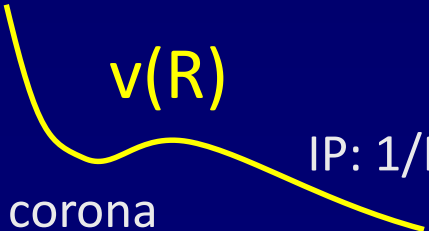
Formation:
3D piston („explosion phase”; „overexpansion”)

Coronal propagation:
- lateral (piston-driven -> freely propagating)
- upward (driven: piston/bow)

IP propagation

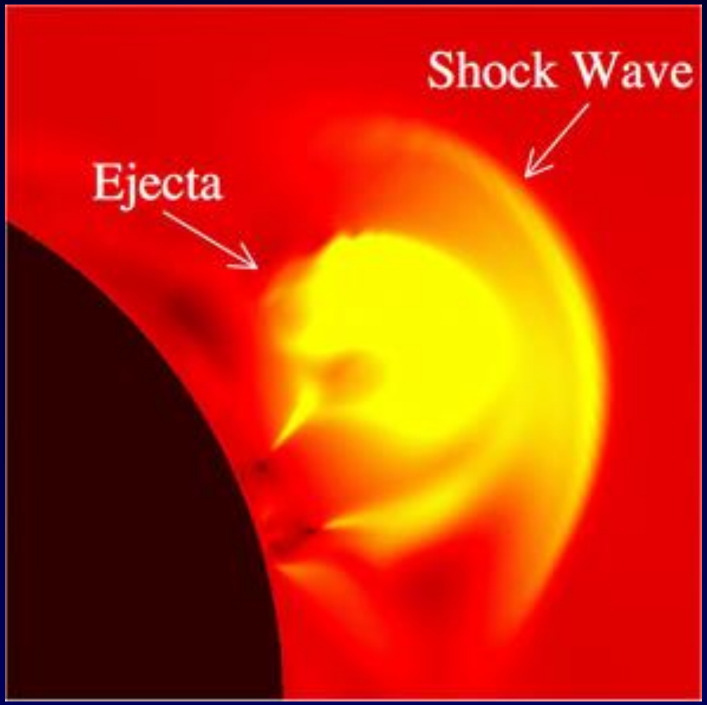
CME-driven (piston/bow)

freely propagating (V_{CME} ~ V_{SW})



The End

Thank You
For Your Attention!


Shock Wave
Ejecta