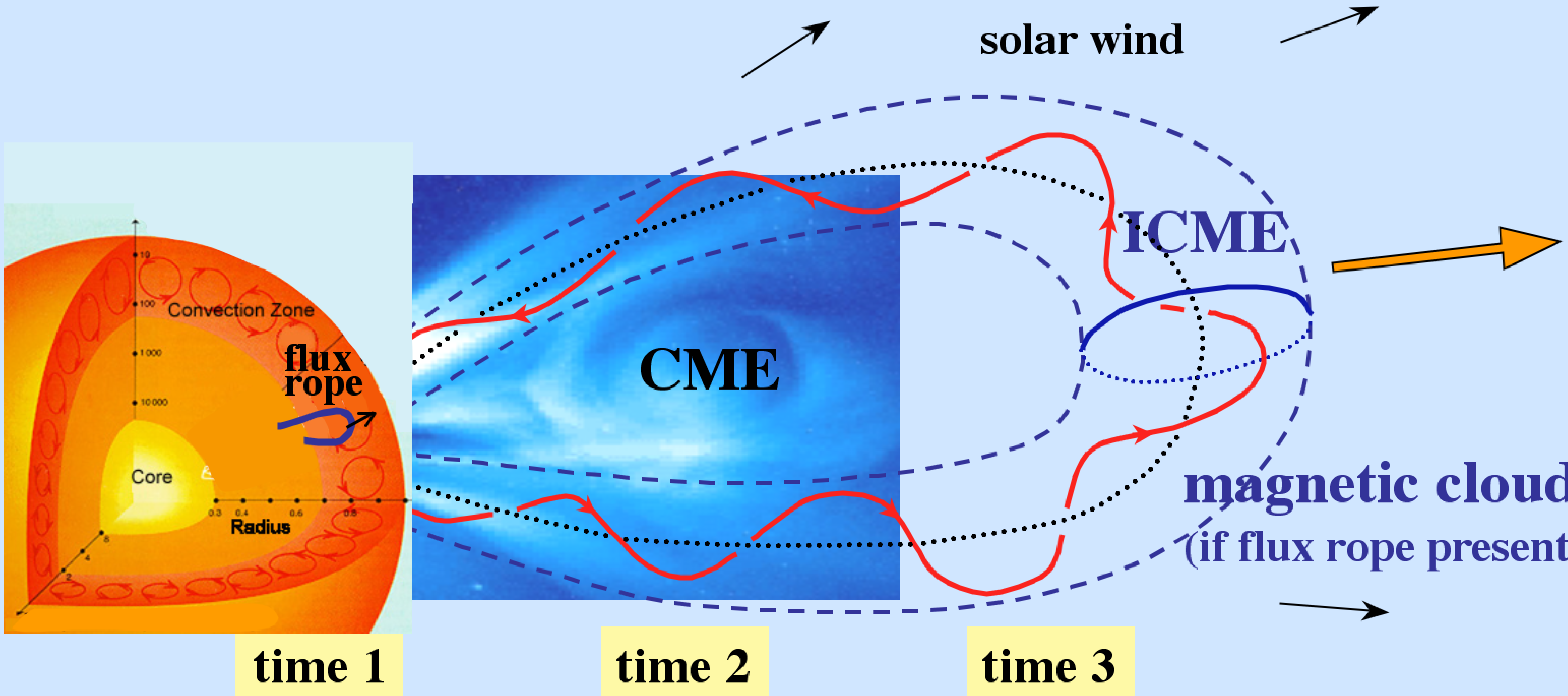
Relations between CME, ICME and Magnetic Clouds

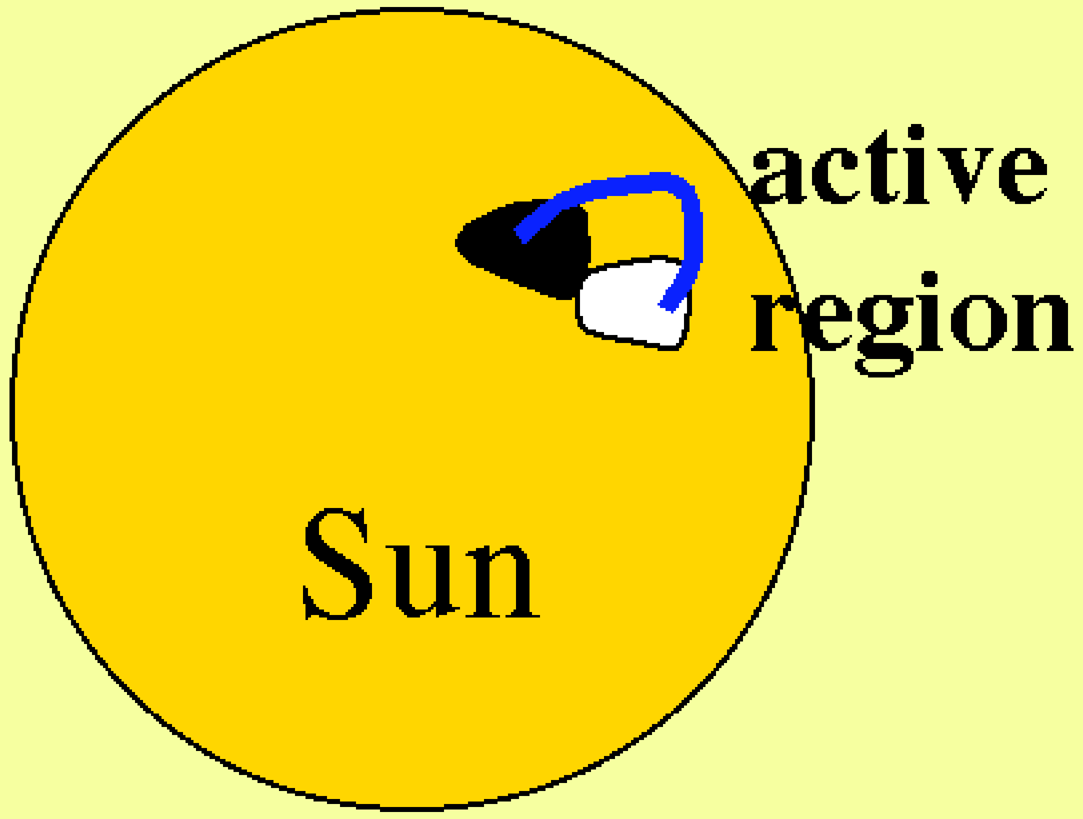


flux rope = twisted magnetic flux tube

flux rope in CZ ≠ flux rope in the CME / ICME

l'Observatoire de Paris LESIA

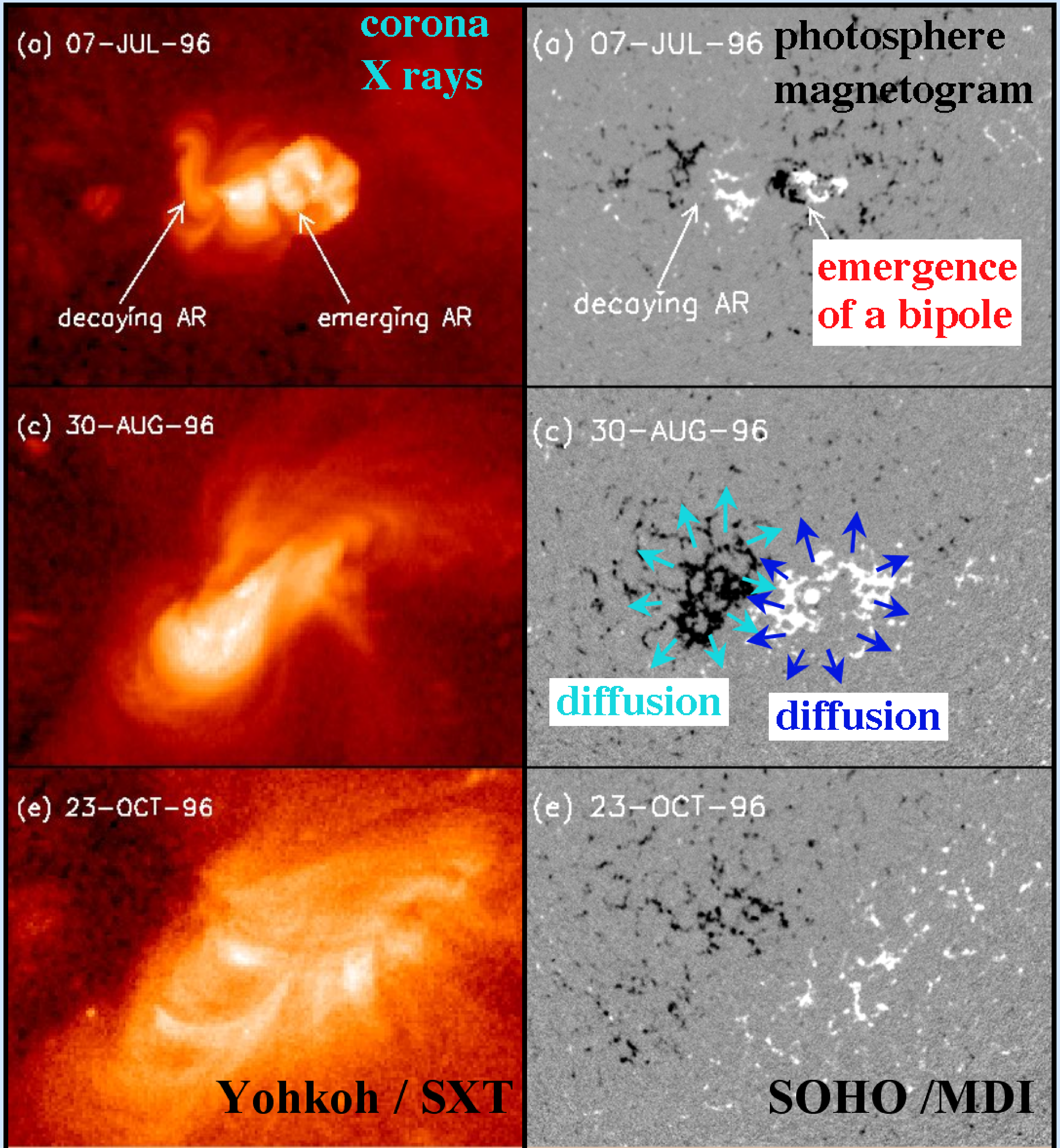
Pascal Démoulin



Emergence of magnetic field at the photospheric level

=> build up of coronal magnetic field

Emergence & dispersion of an Active Region



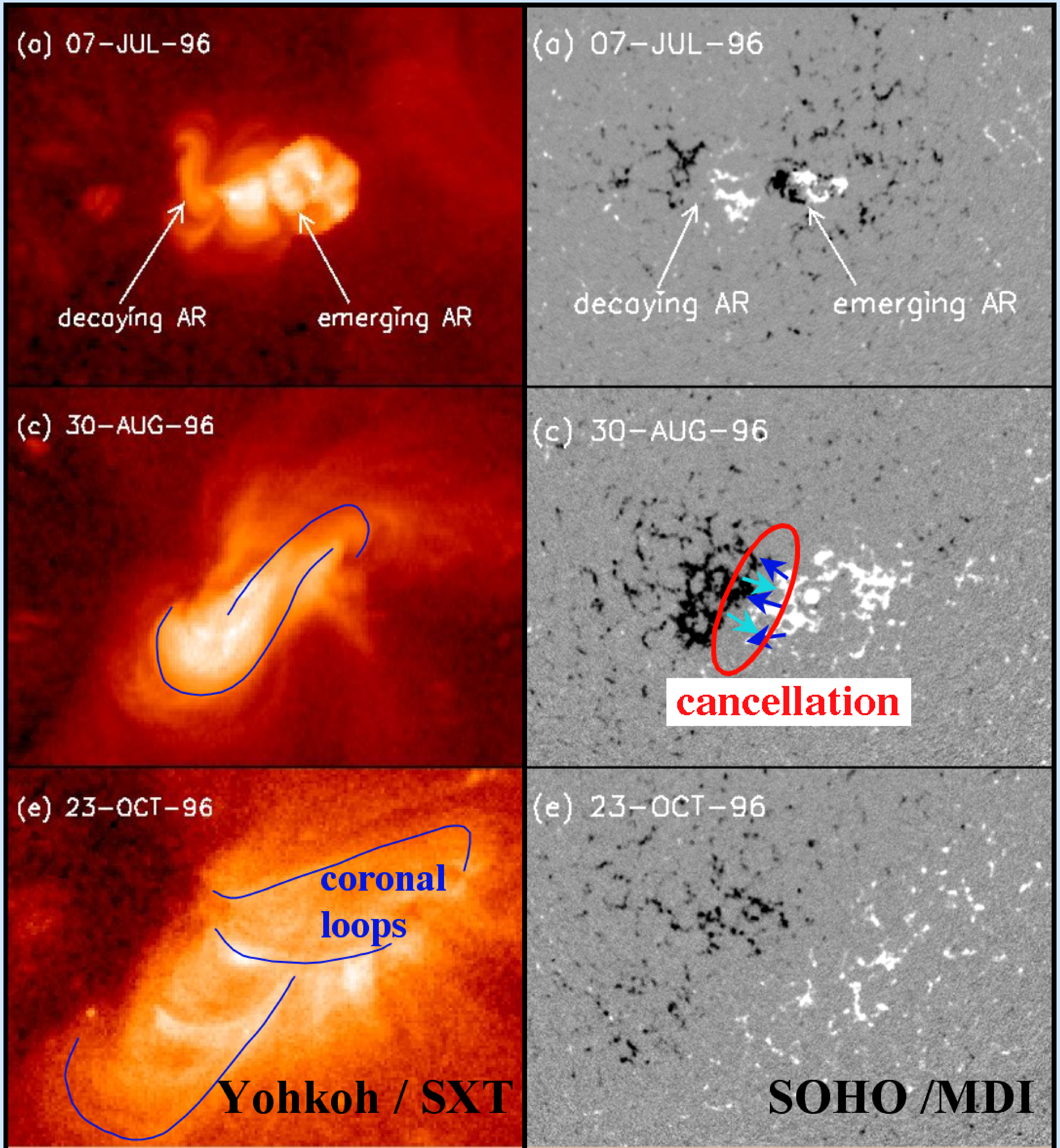
Same active region
1 image every 2 solar rotations

Emergence of
sheared / twisted
magnetic fields
=> free magnetic energy

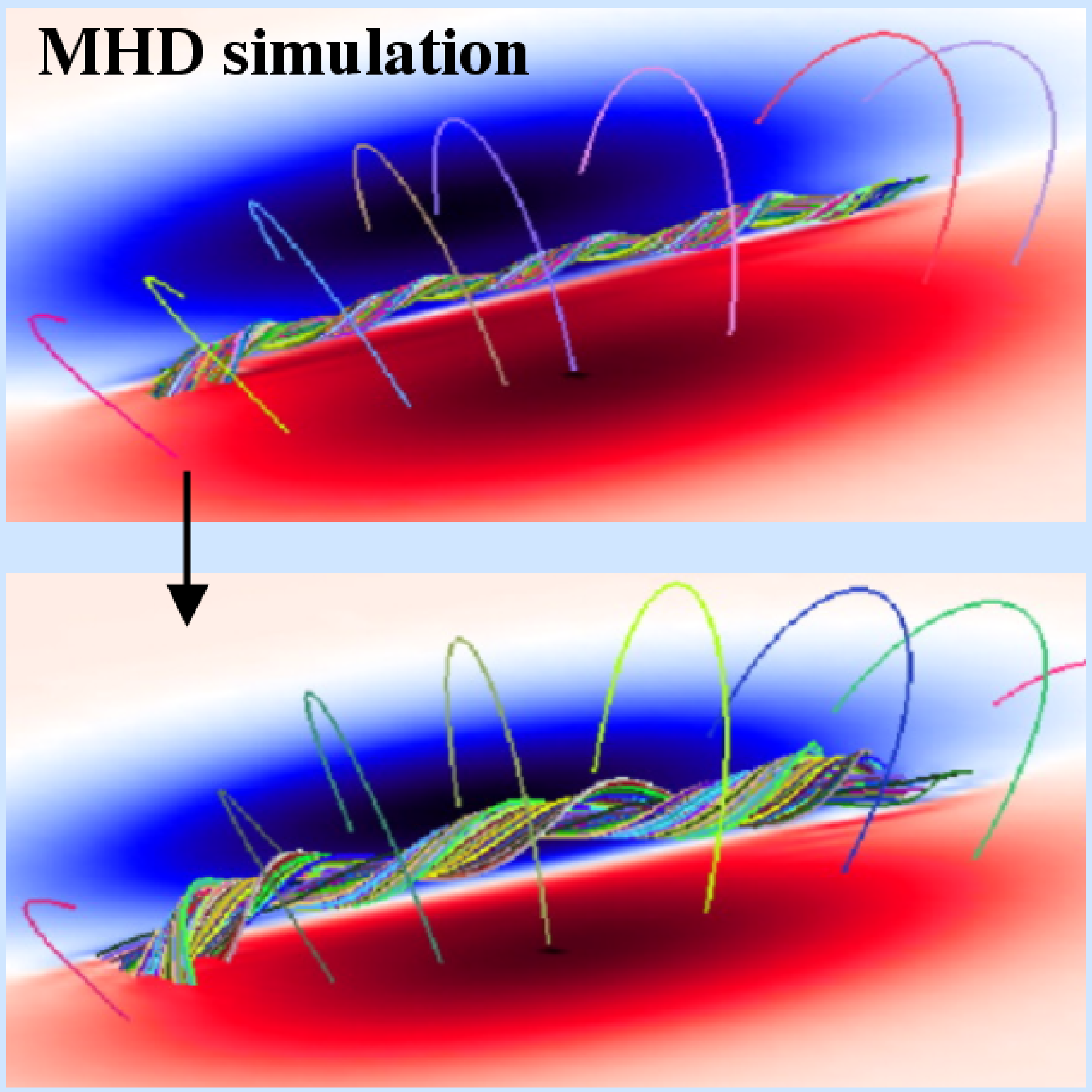
flux tubes transported
by convective cells
=> magnetic flux dispersal
(diffusion)

Martin et al. (1985),
Livi et al. (1989)
Démoulin et al. (2002),
van Driel Gesztelyi et al. (2003),
Schmieder et al. (2008)
...

Emergence & dispersion of an Active Region



sheared arcade field lines
\+ cancellation
⇒ build up of a flux rope



then CME …

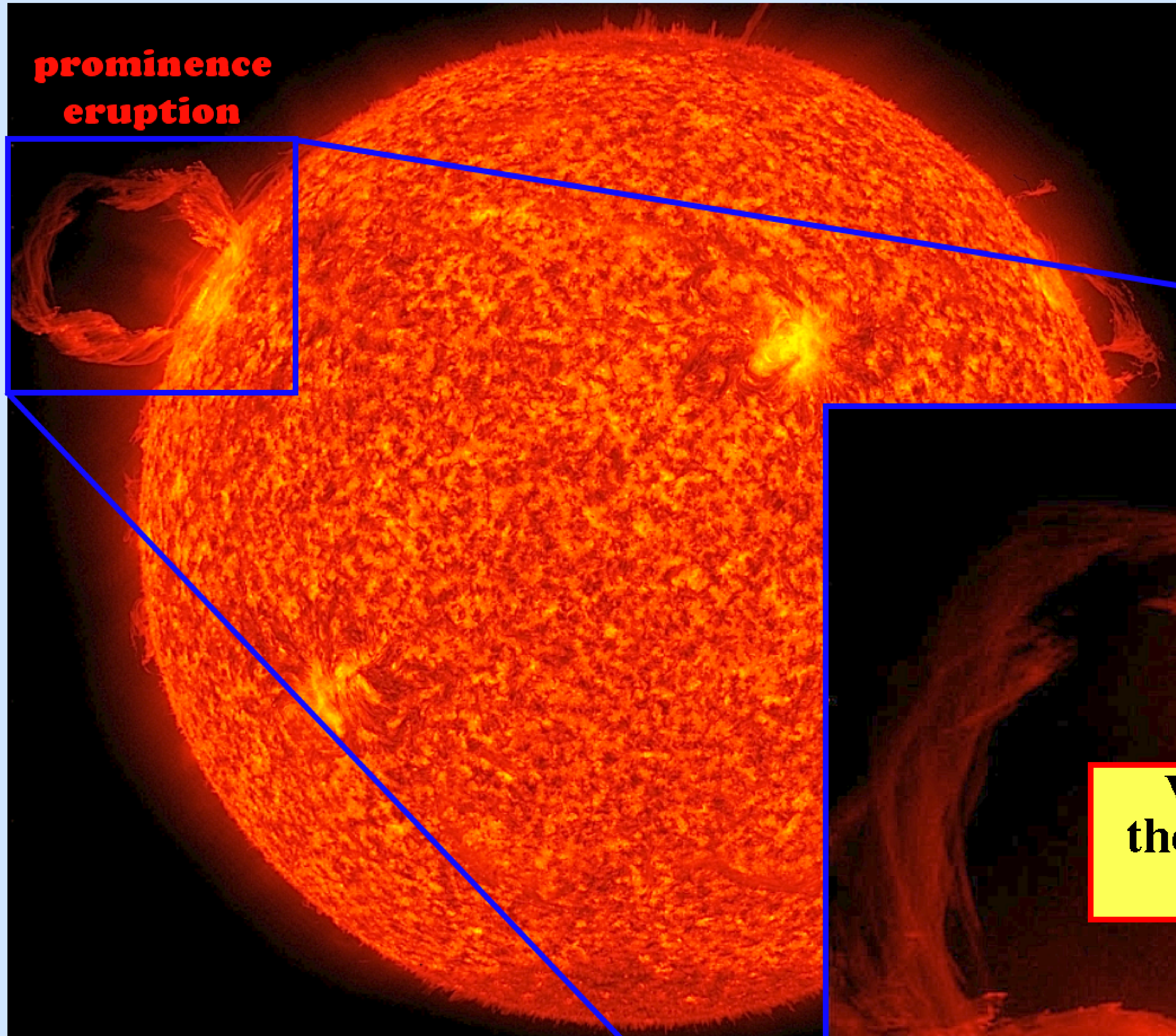
van Ballegooijen & Martens (1989),
Amari et al. (2003)
MacKay & van Ballegooijen (2006)
Aulanier et al. (2010)

What else ?

What else ?

Yes ! **But also …**

Solar Dynamics Observatory (SDO), NASA



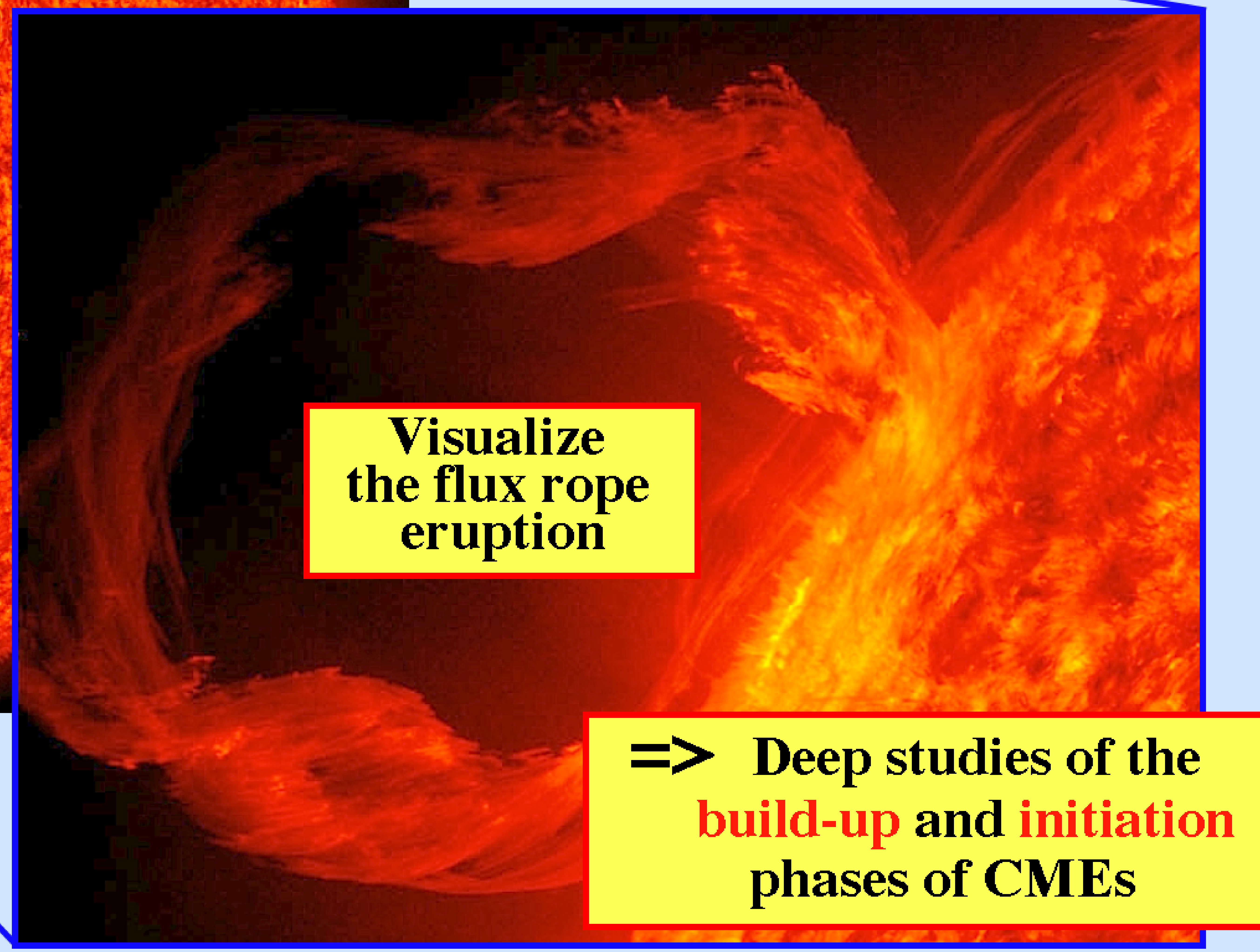
AIA: 4 telescopes

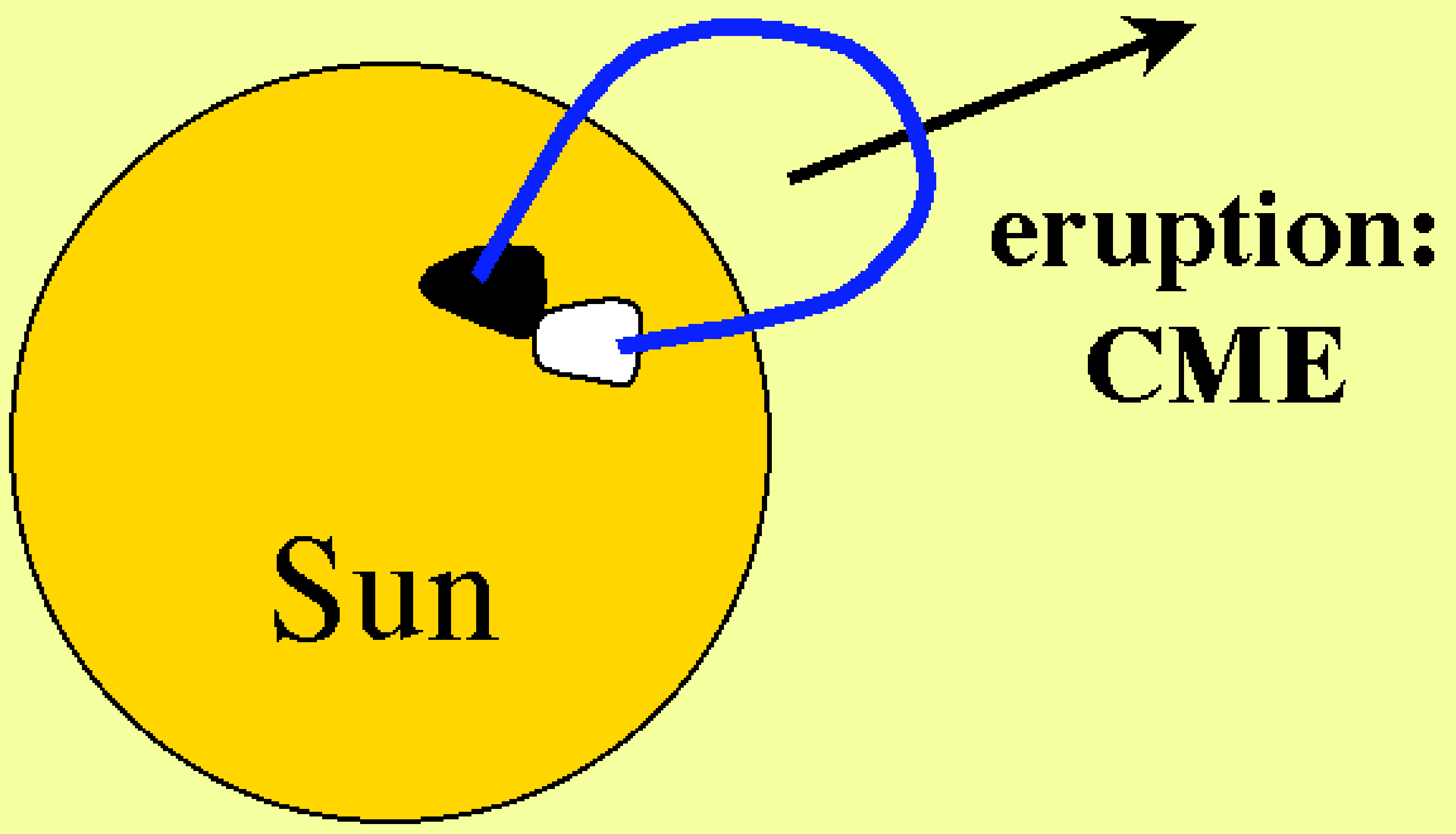
Full Sun at 0,6" (CCD 4096 x 4096)

8 wavelengths in 12 s

Temperature range: 5000 K - 20 MK

Continuously observing

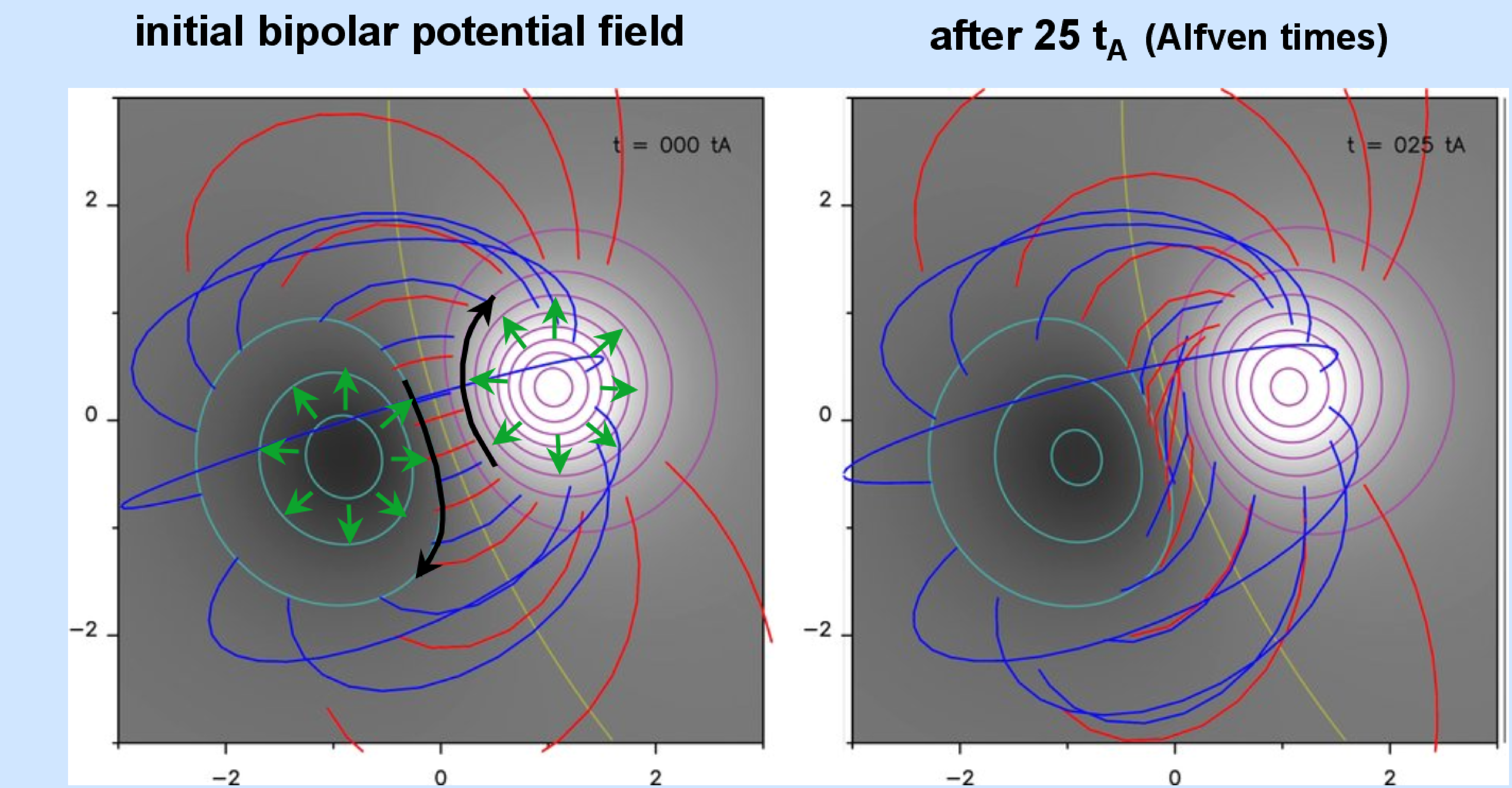




Eruption of the magnetic configuration

=> Coronal Mass Ejection (CME)

MHD simulation of CME launch (I)



slow photospheric **shearing motions**

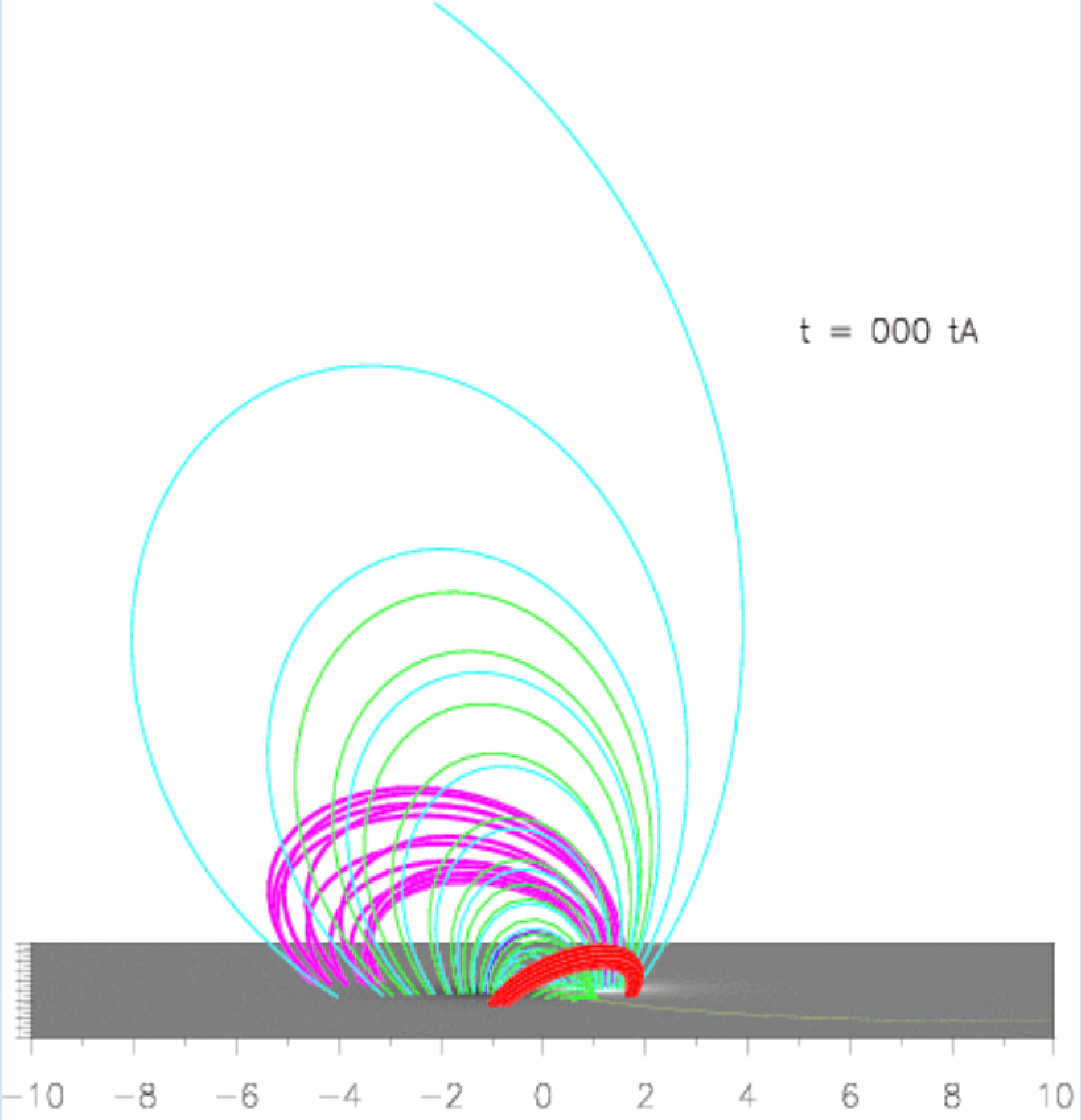
$<M_{A,phot}> \sim 0.025$, $t_{1\ turn} = 125\ t_A$

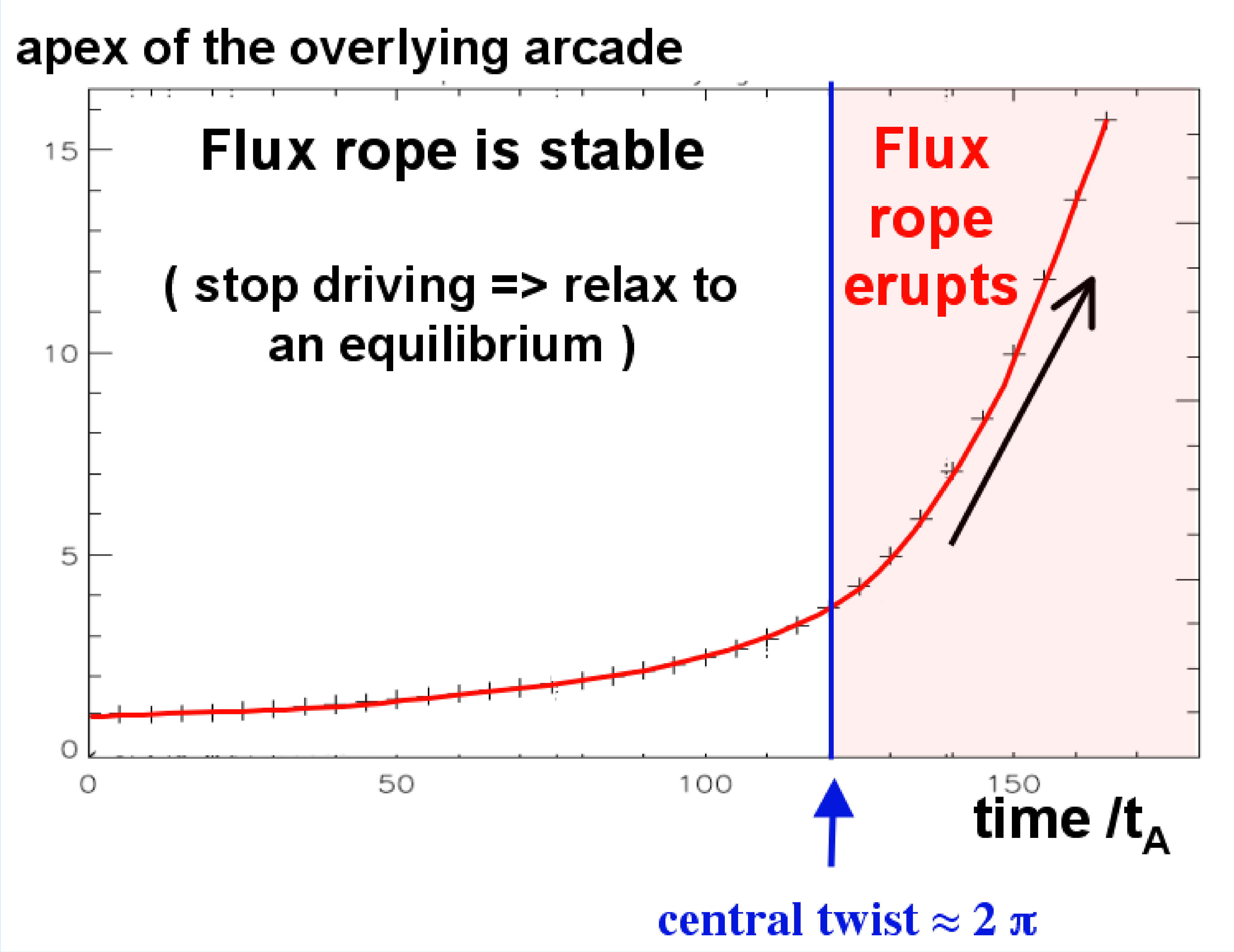
slow photospheric **diffusion of Bx,y,z**

$t_{diff} = 280\ t_A$

build a strongly sheared arcade
+ photospheric reconnection
--> build a flux rope

MHD simulation of CME launch (II)





Eruption occurs because the slowly rising flux rope eventually gets unstable

Aulanier et al. (2010)

photospheric diffusion

=> B drop + flux cancellation & coronal tether-cutting

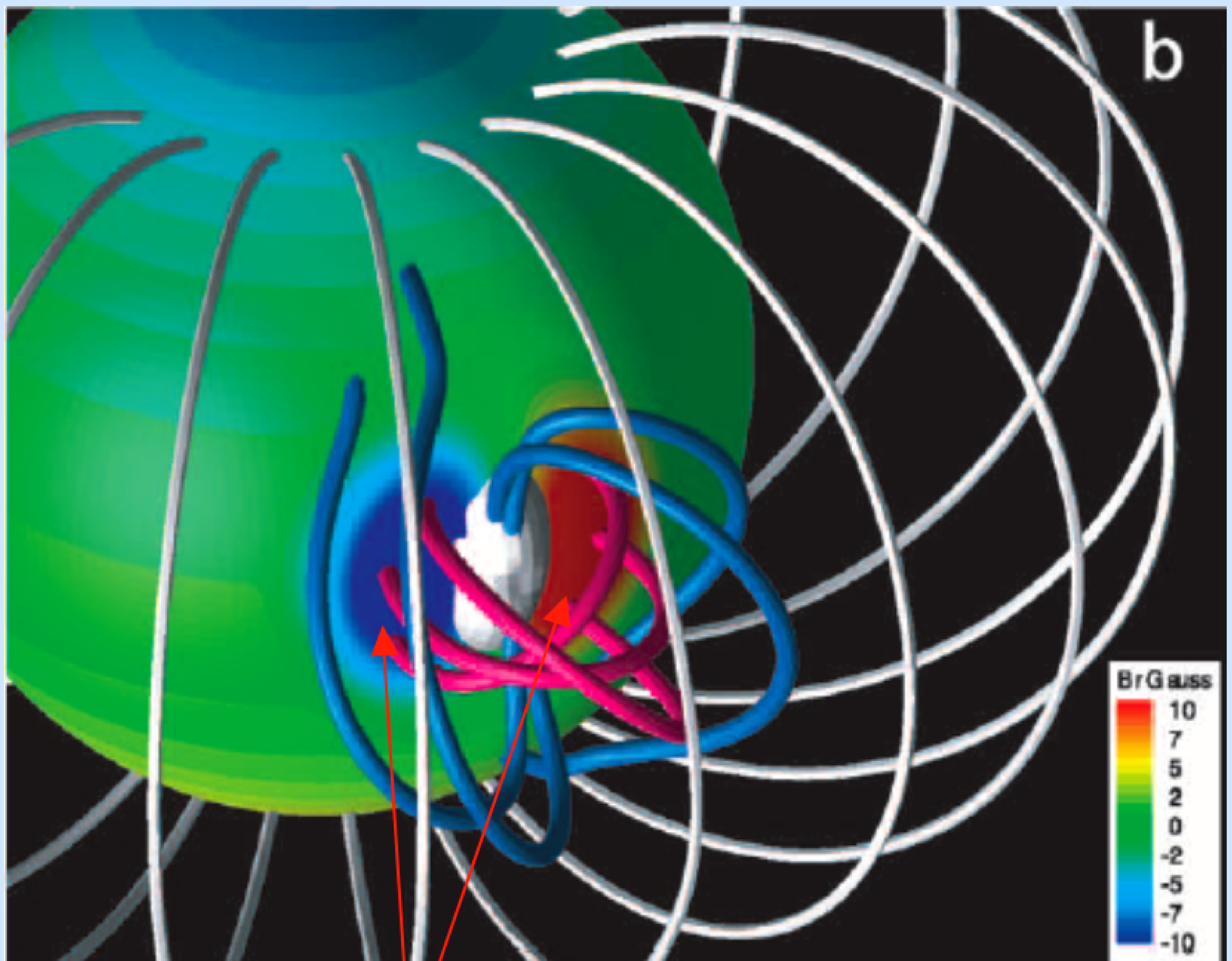
only responsible for flux rope formation and slow growth

3D MHD simulations

* Steady SW (fast/slow at high/low latitude)
* Global bipolar field **+ add** Gibson & Low (1998) configuration

no equilibrium => ejection

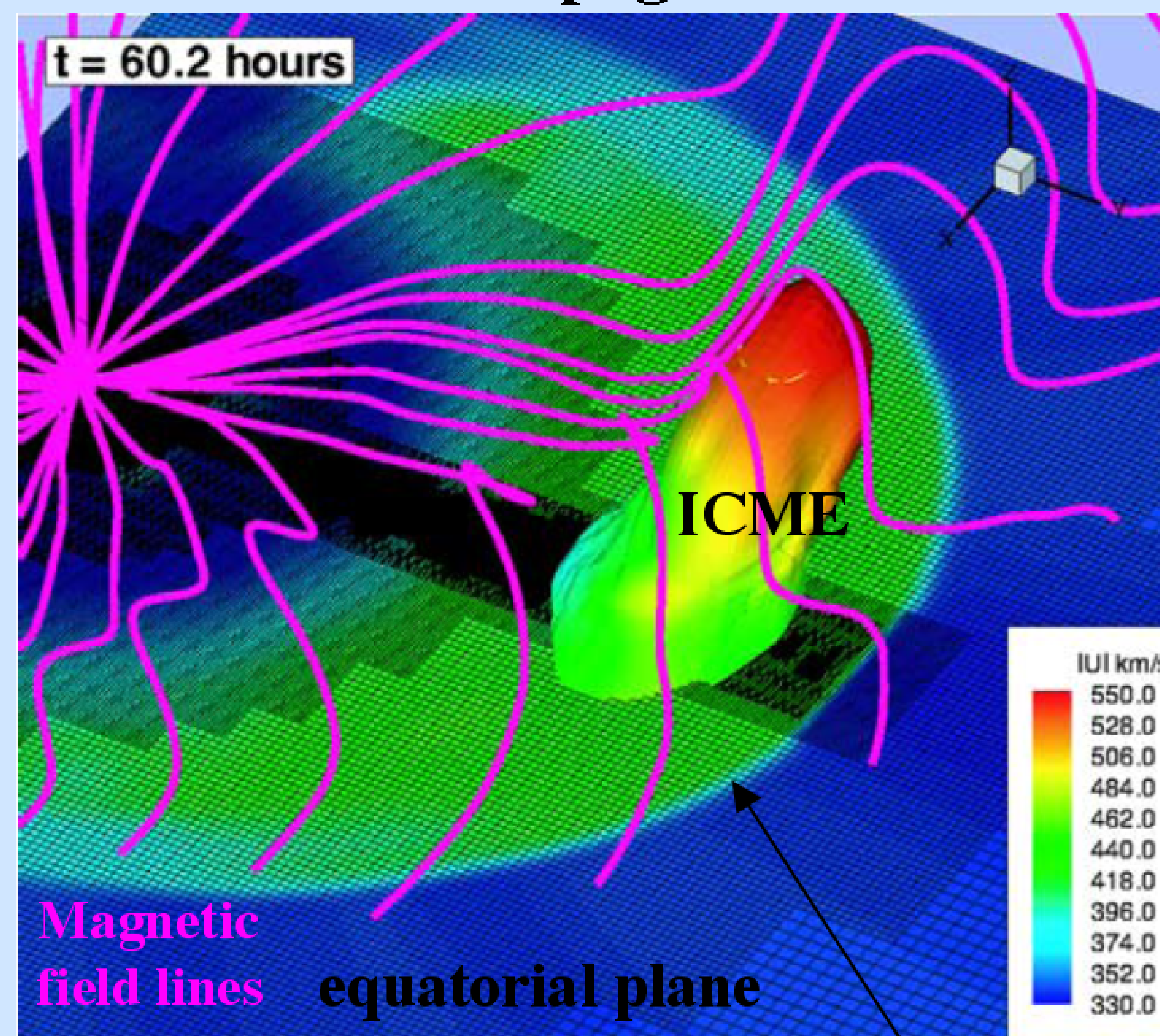
Initial magnetic configuration



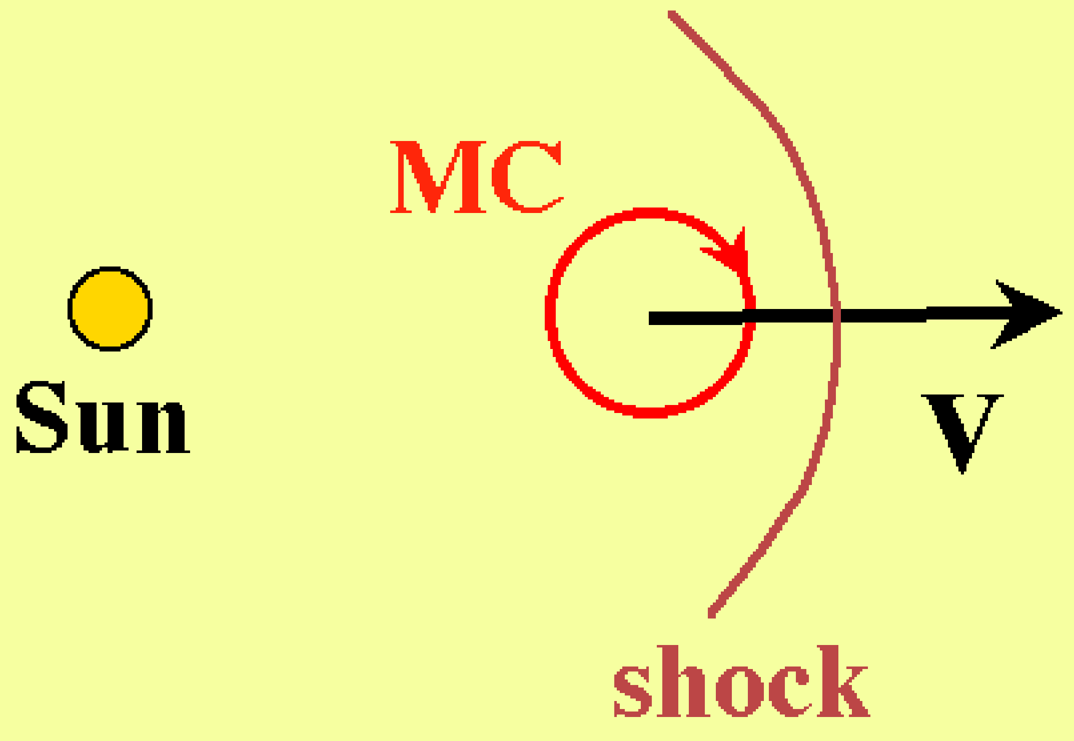
Simulate a strongly sheared magnetic field of an active region

(Manchester et al. 2004, Lugaz et al. 2005, Chané et al. 2006, Xiong et al. 2007, …)

Propagation



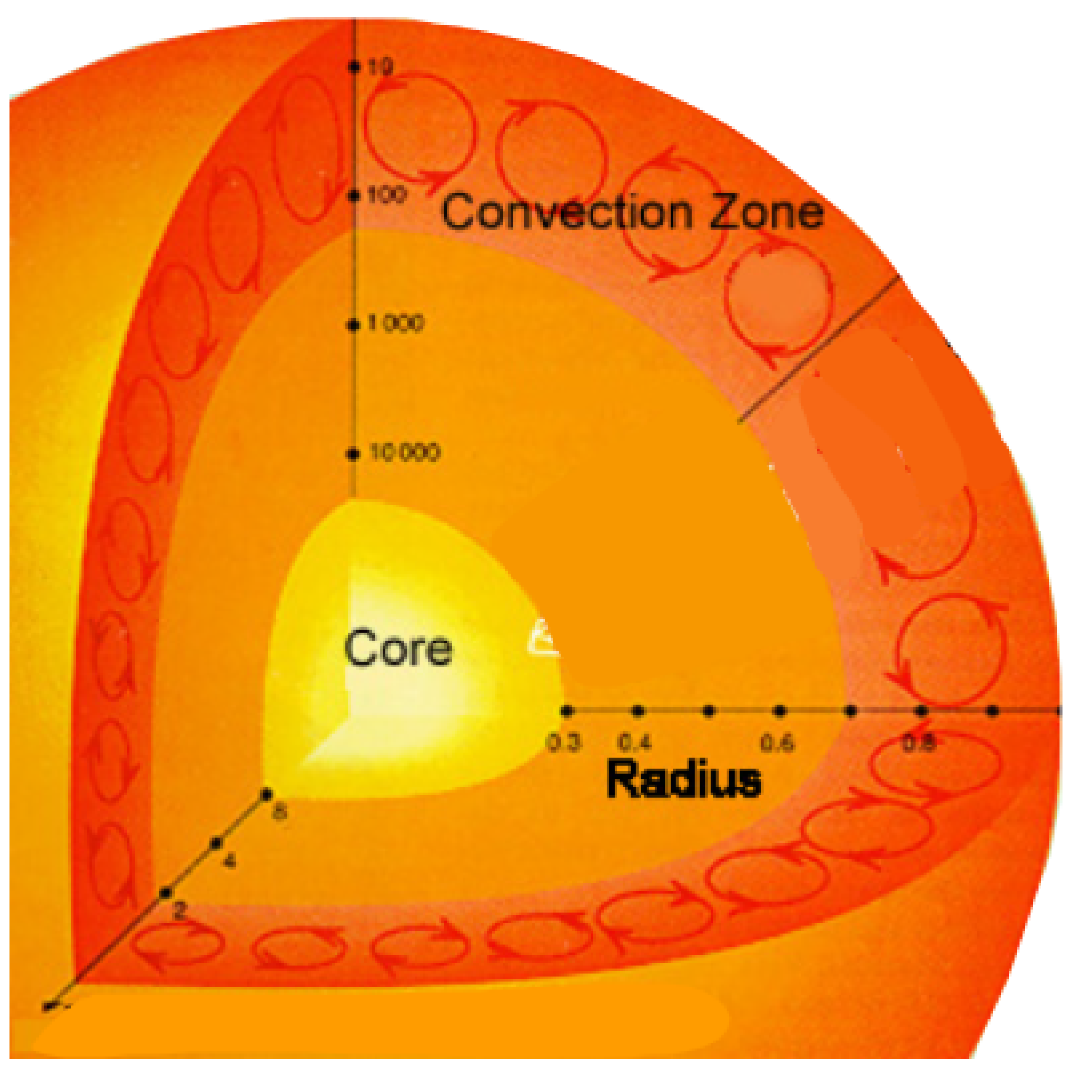
shock

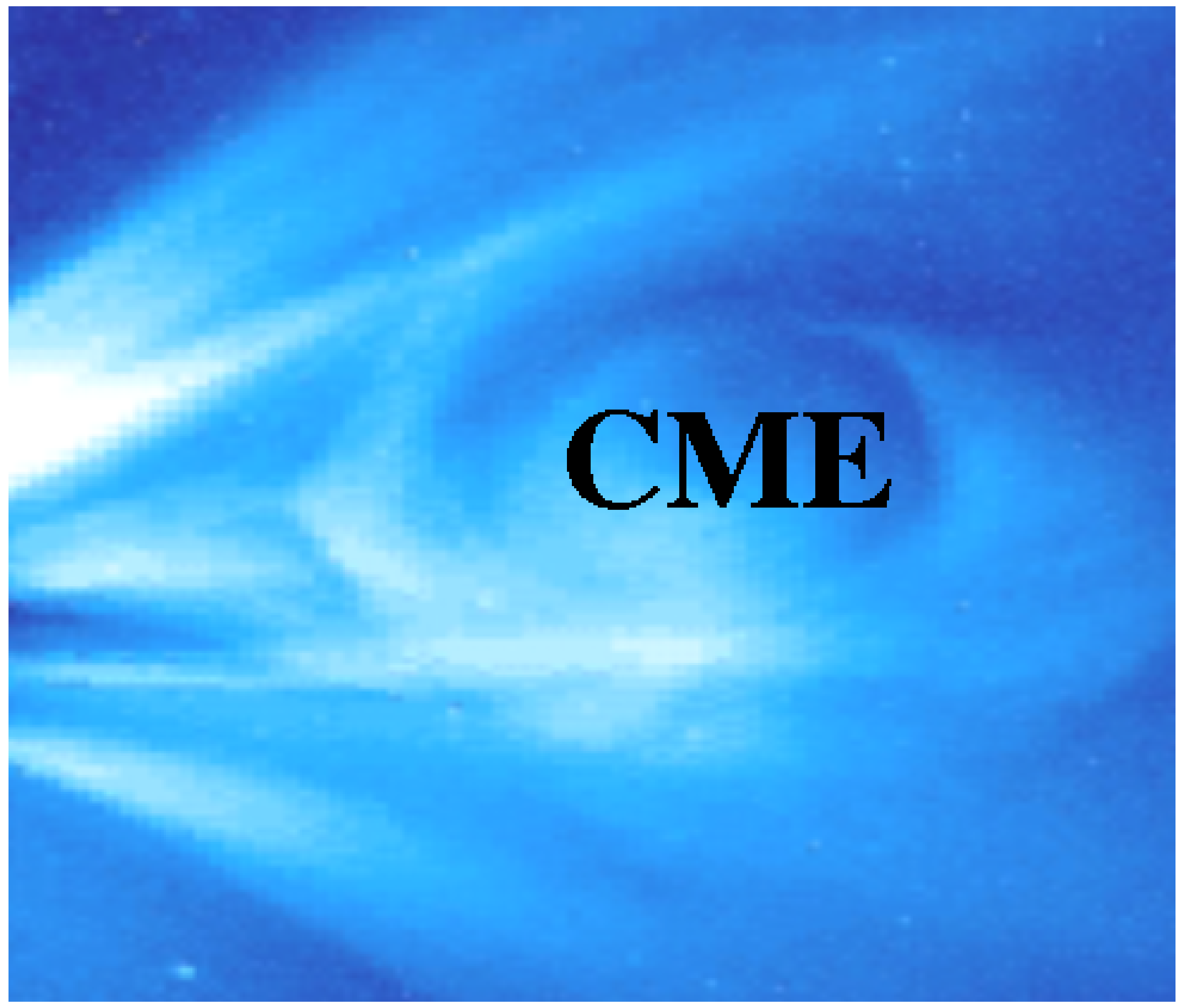


Propagation of ICME / MC

in the interplanetary space

Global view of CME / MC relationship

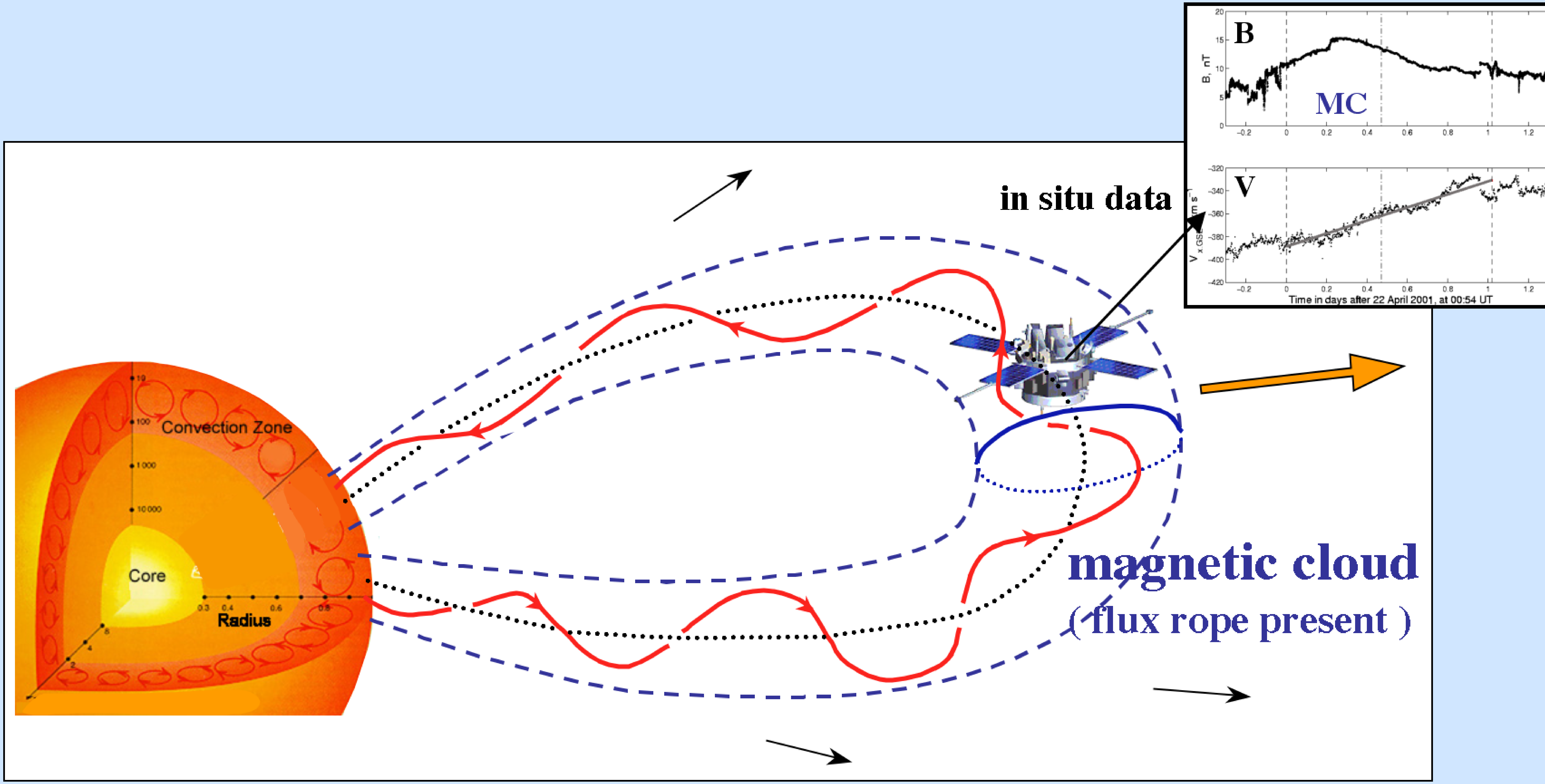




CME observed with a coronagraph

SOHO / LASCO

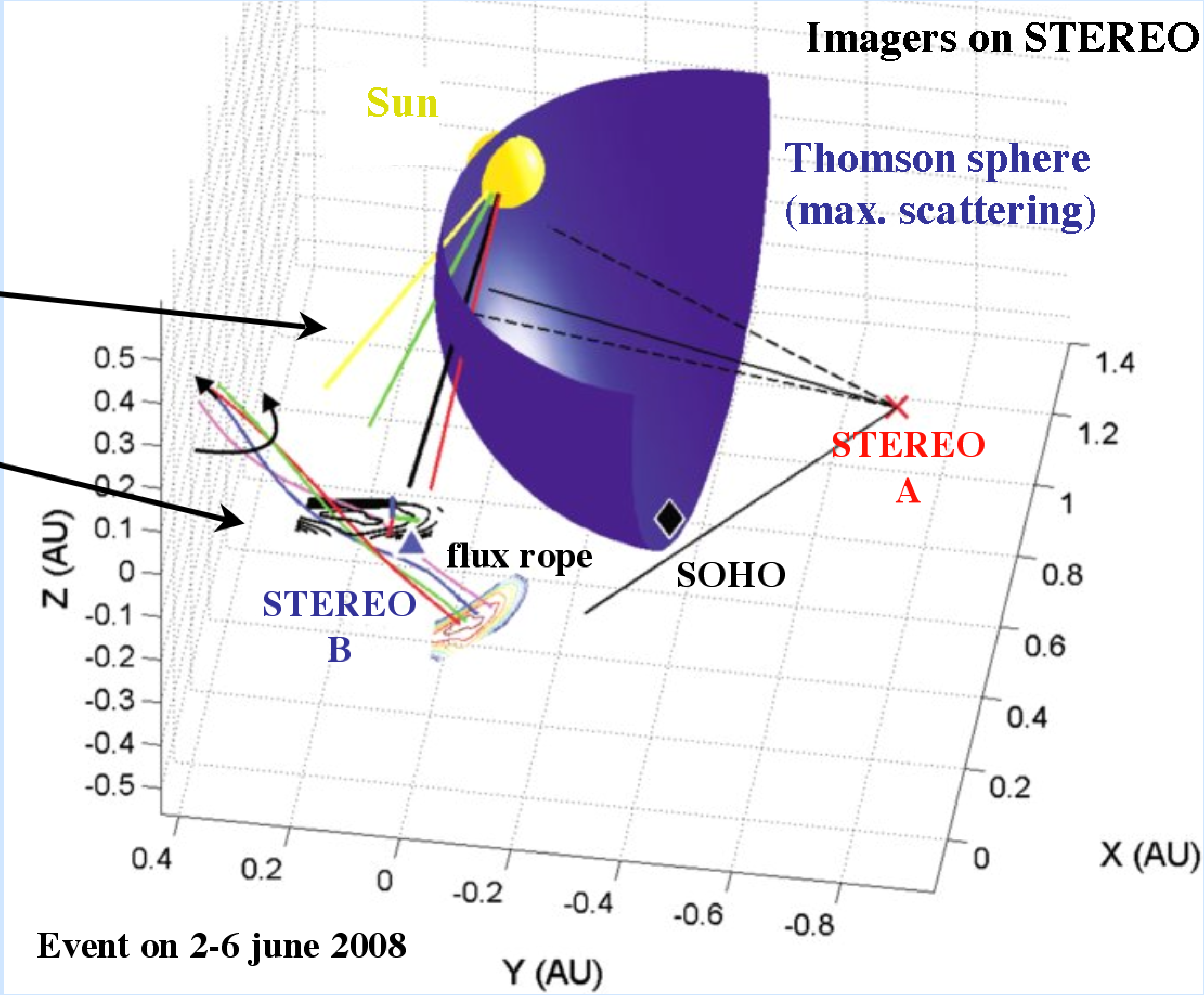
Global view of CME / MC relationship



Wind, ACE, Ulysses

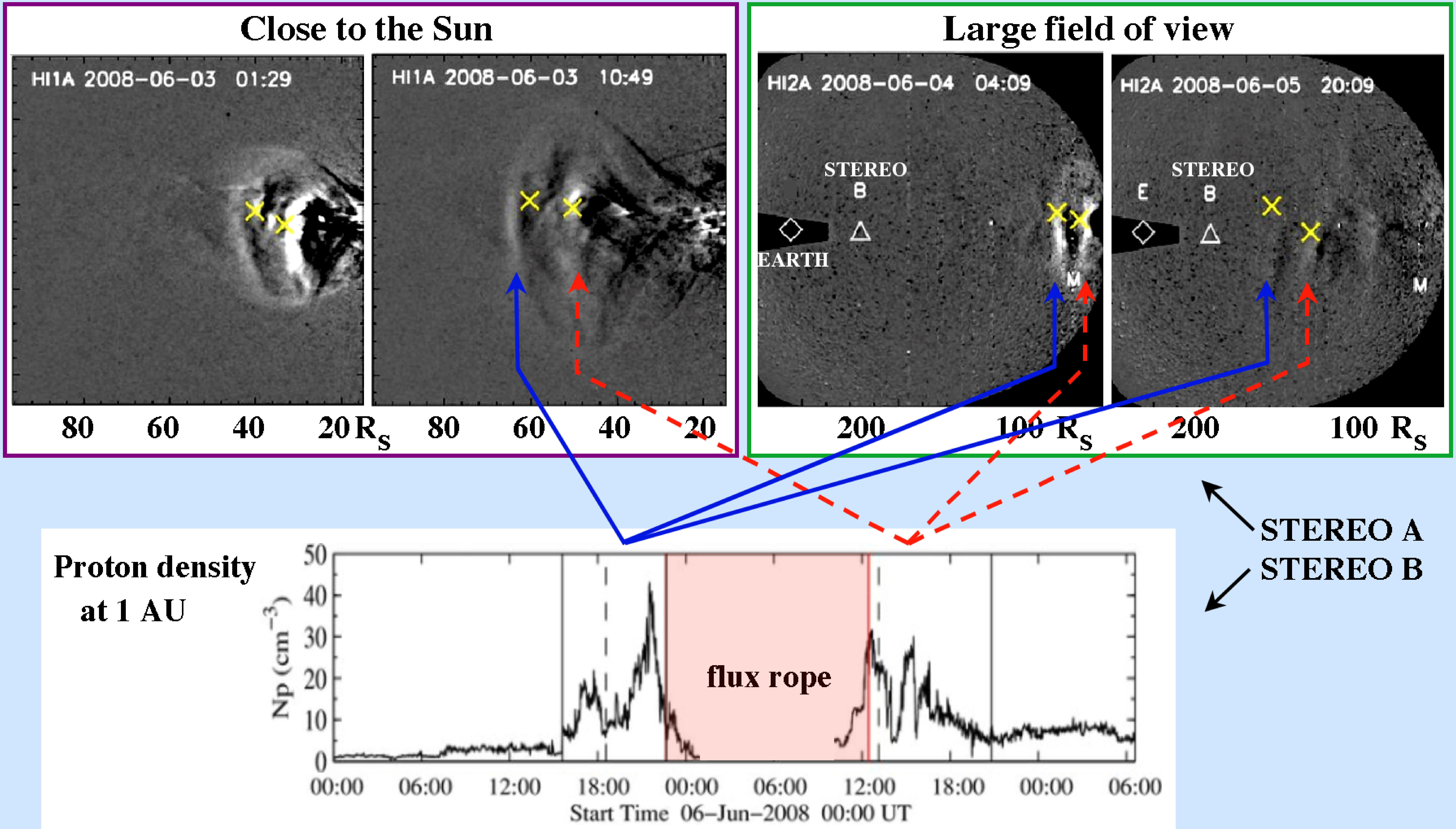
3D observations of CMEs / ICMEs (I)

CME direction found from:
- Triangulation
- Forward modelling
- Elongation Fitting
- Kinematic fixed ϕ
- In situ modeling



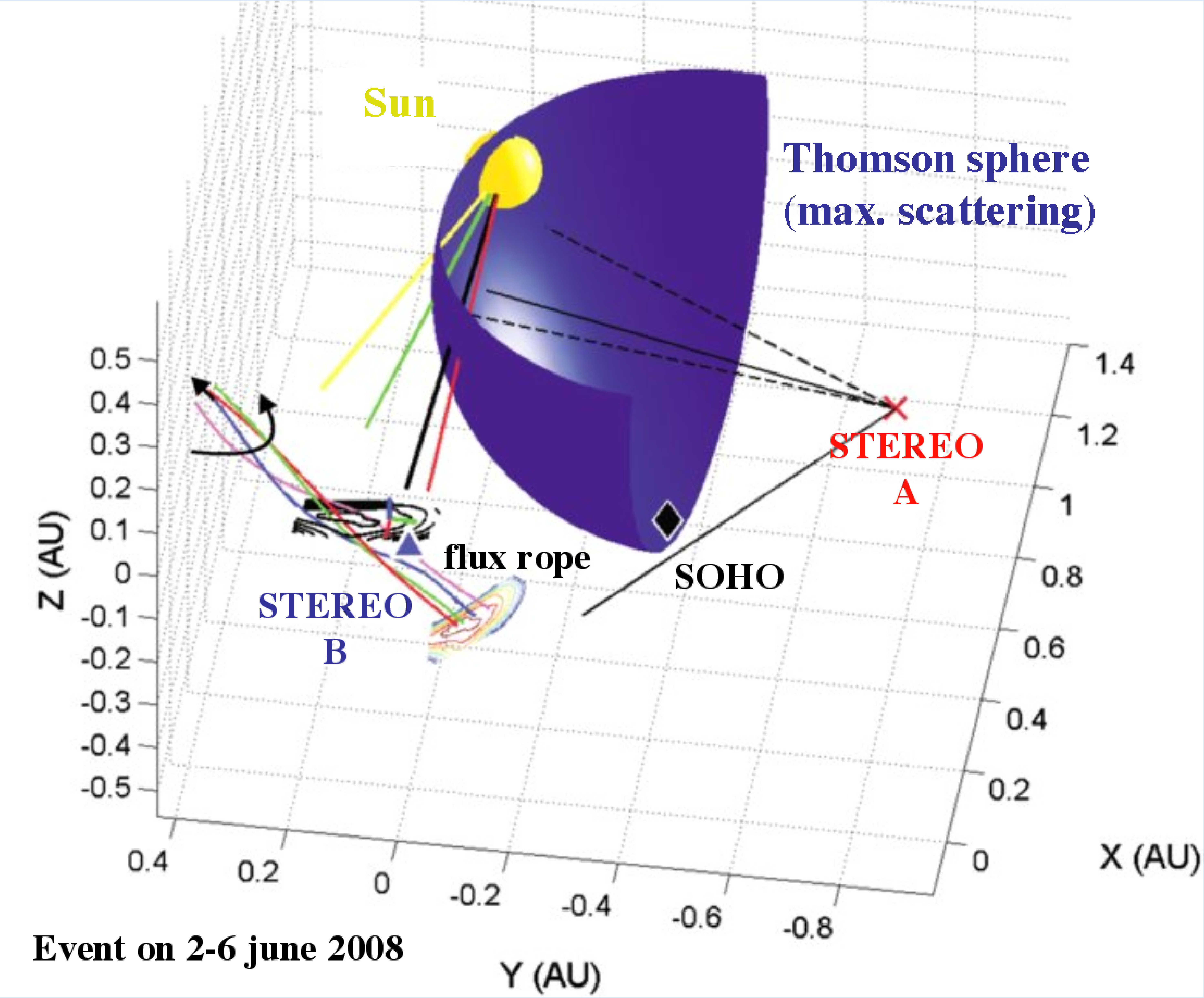
(Liu et al. 2009, Mostl et al. 2009, Rouillard et al. 2009, 2010)

3D observations of CMEs / ICMEs (II)



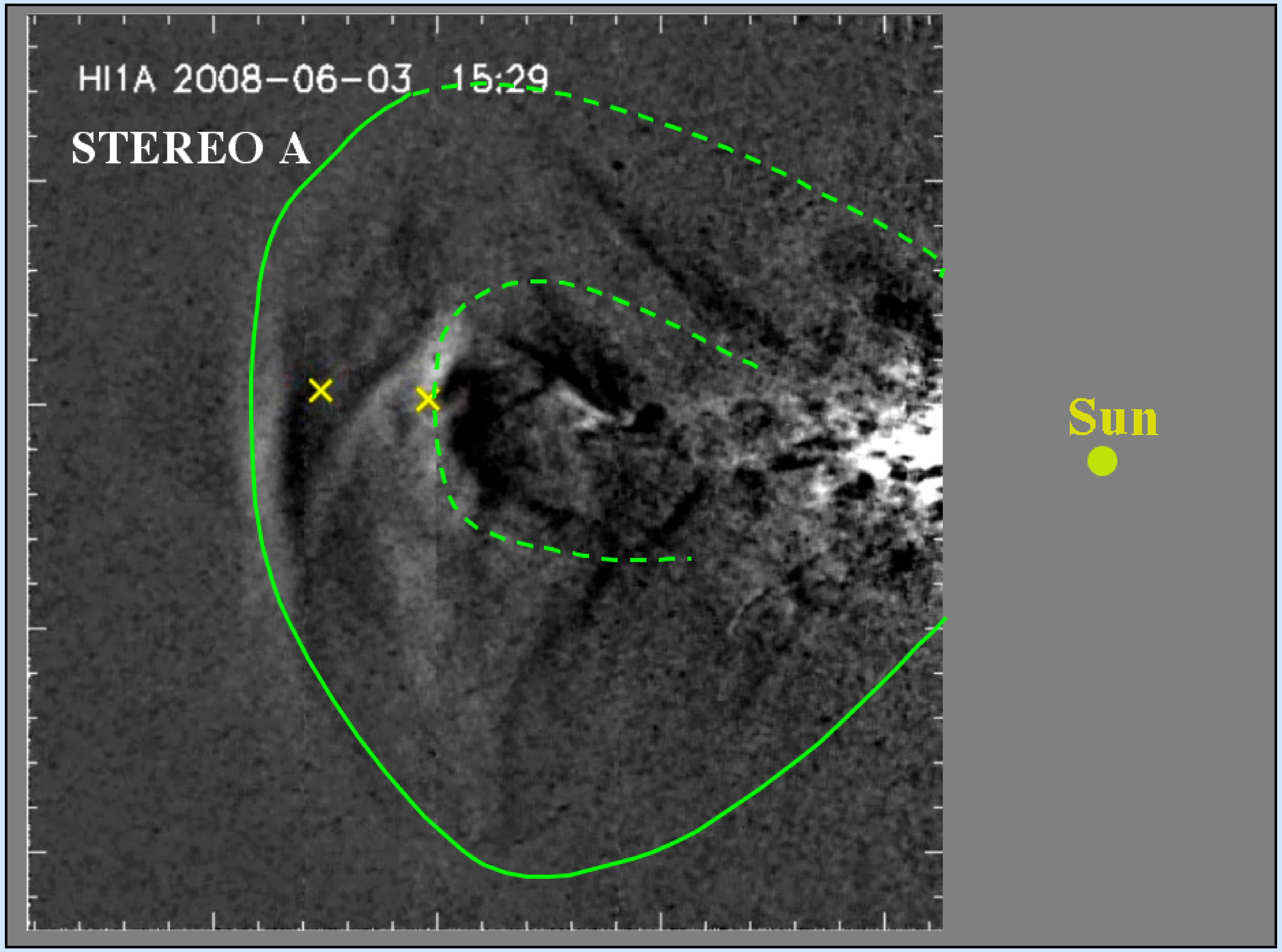
(Mostl et al. 2009)

3D observations of CMEs / ICMEs (III)

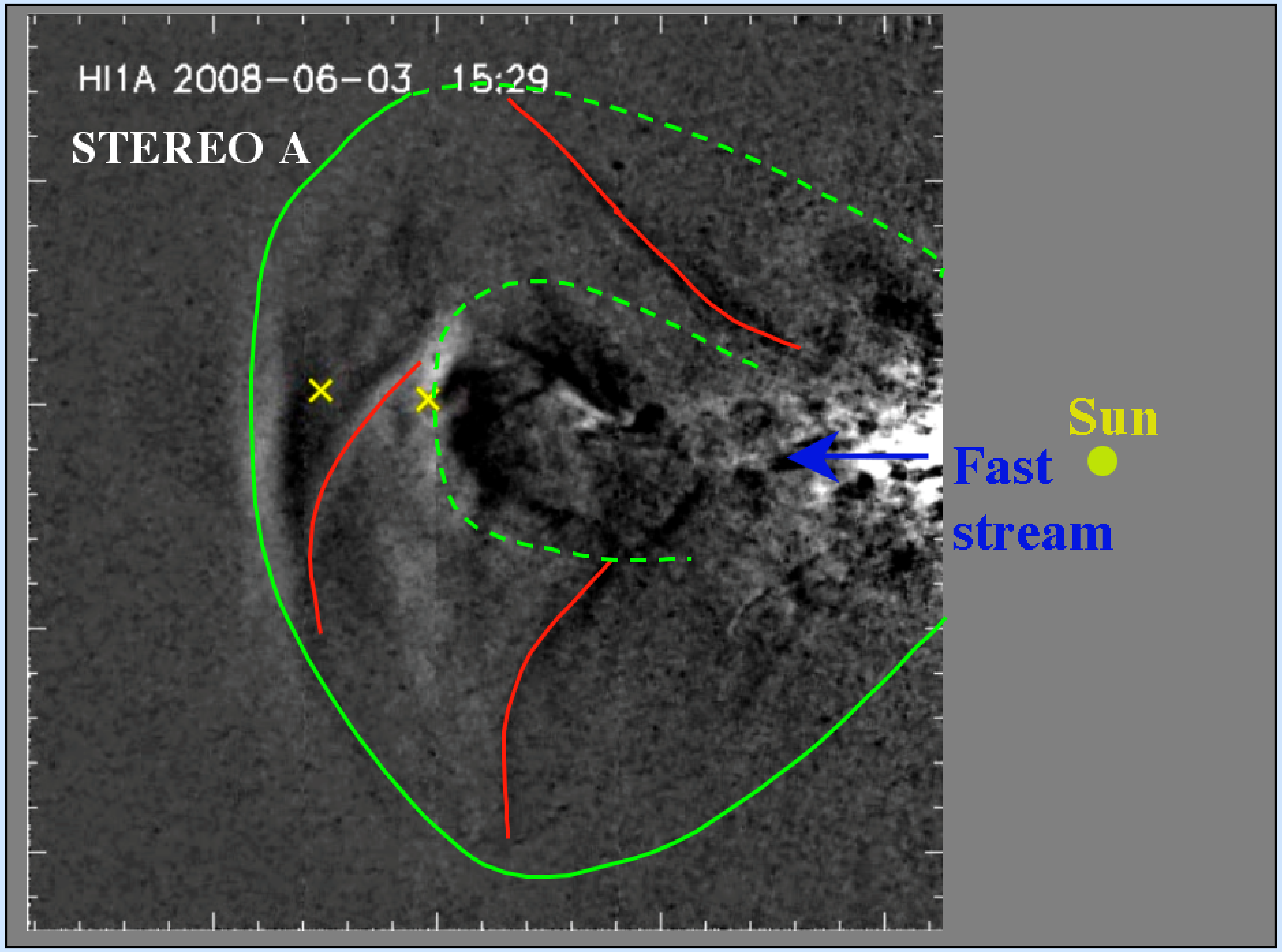


(Mostl et al. 2009)

3D observations of CMEs / ICMEs (III)



3D observations of CMEs / ICMEs (III)

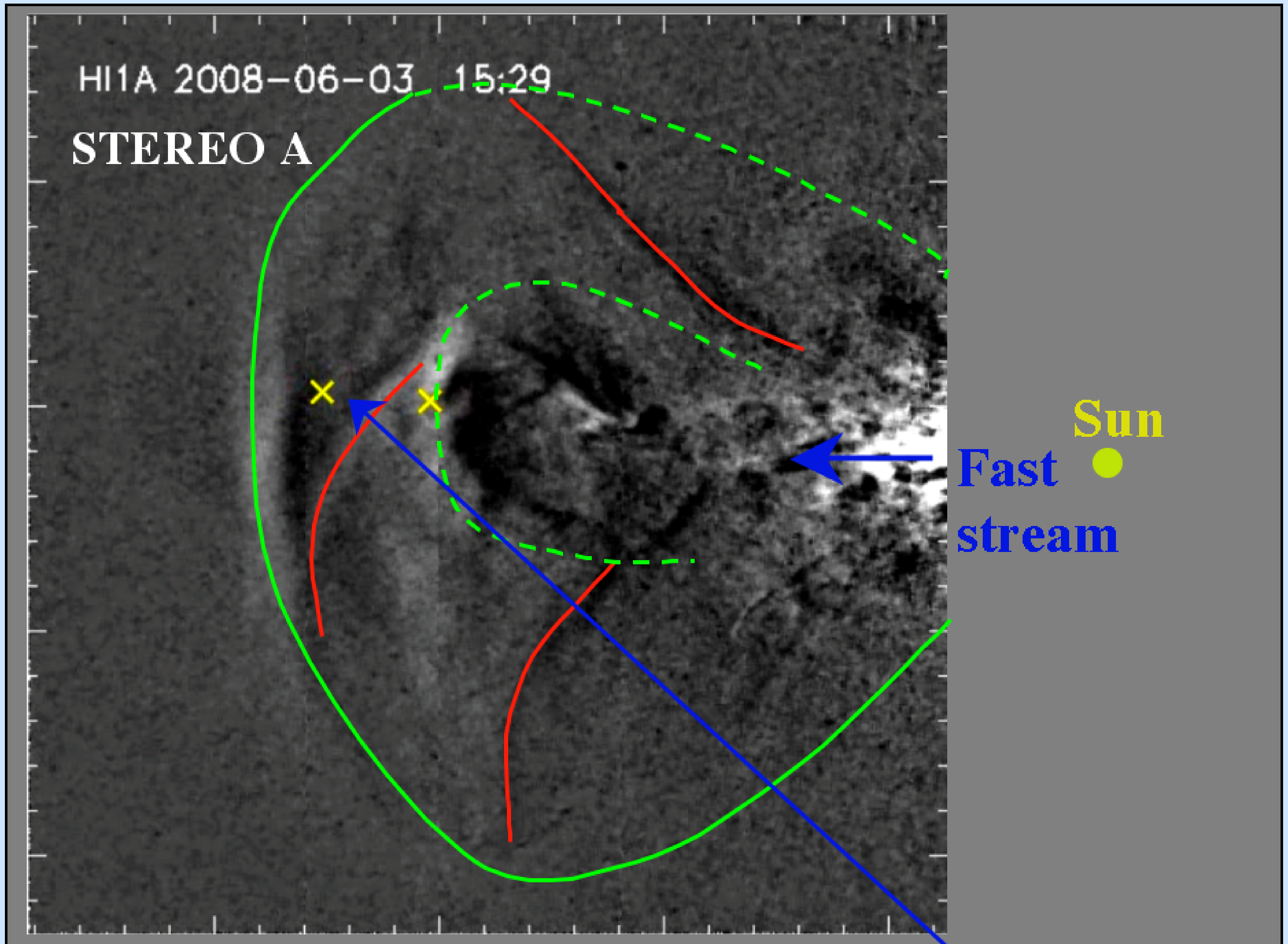


Evidence of a flux rope with imager

See better the side closer to STEREO A because closer to the Thomson sphere

=> right handed (H>0)

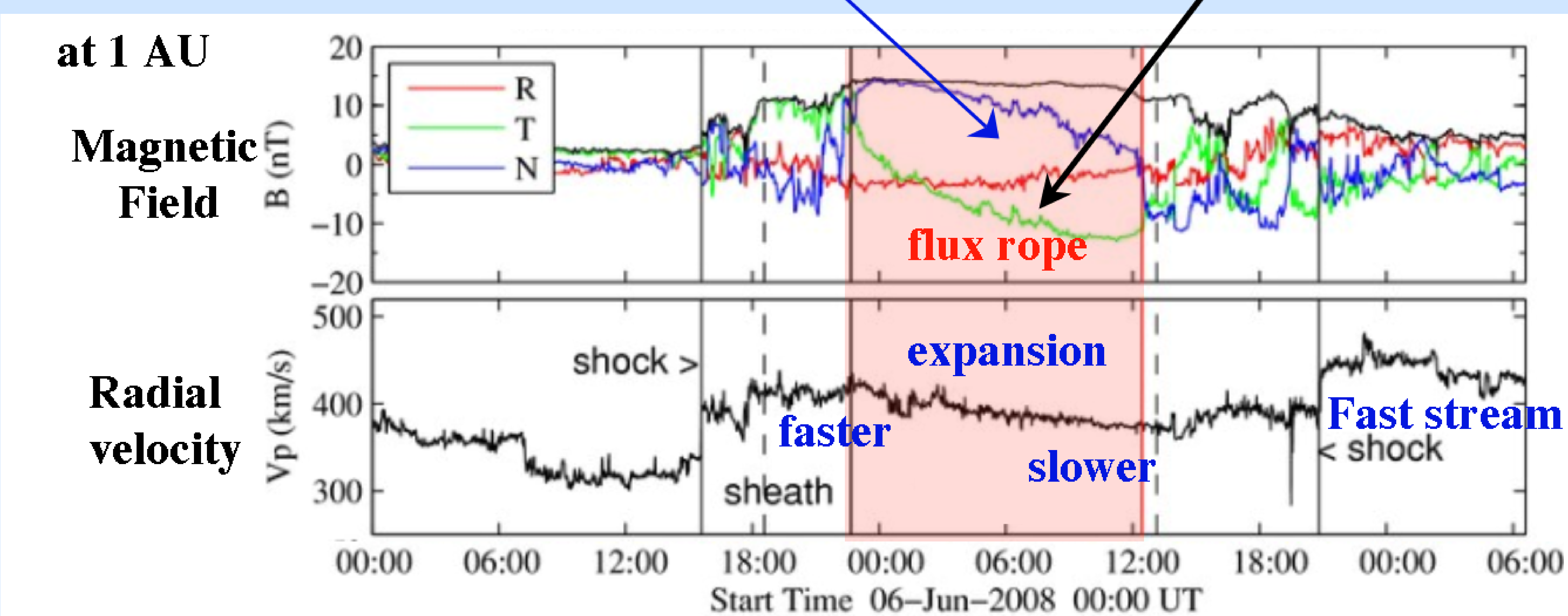
3D observations of CMEs / ICMEs (III)



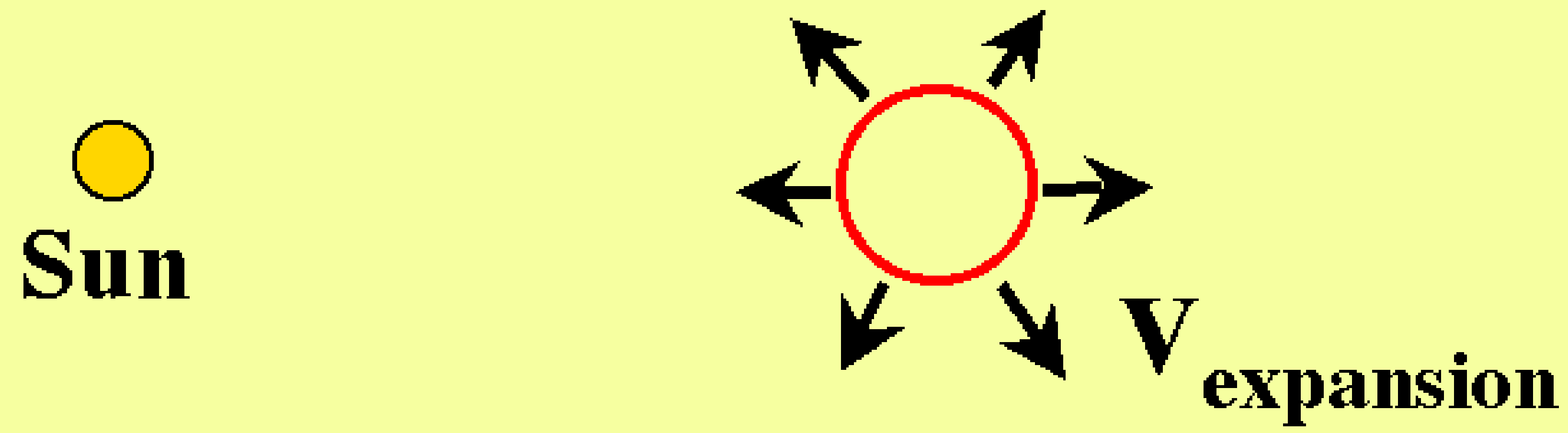
Evidence of a flux rope with imager and insitu data

See better the side closer to STEREO A because closer to the Thomson sphere
=> right handed (H>0)

Coherent with in situ rotation of B

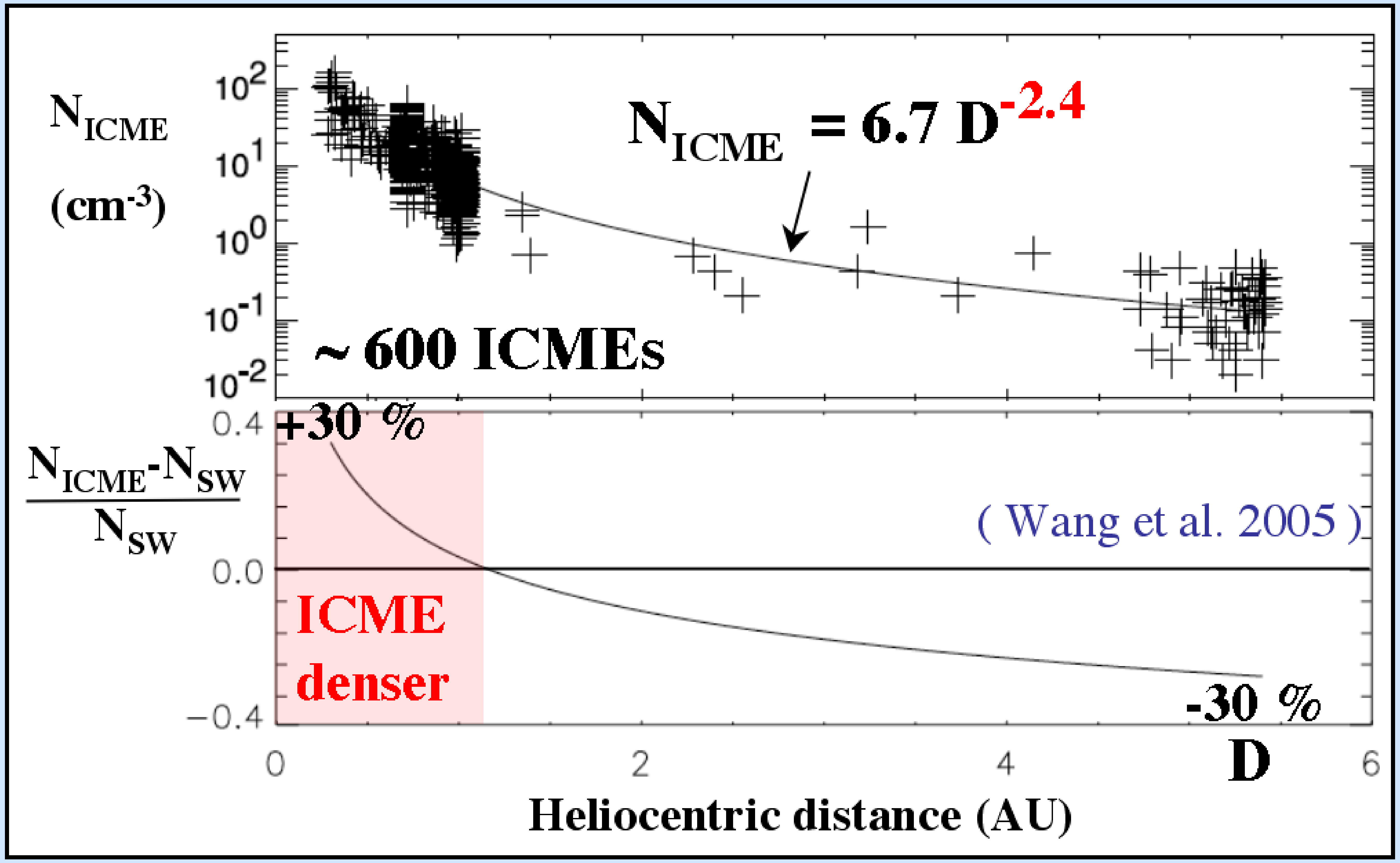


STEREO B



Expansion rate of ICMEs / MCs

Density (distance) in ICMEs



Faster decrease than in the SW

($N_{SW} \propto D^{-2}$)

=> 3D expansion of ICMEs

other studies:

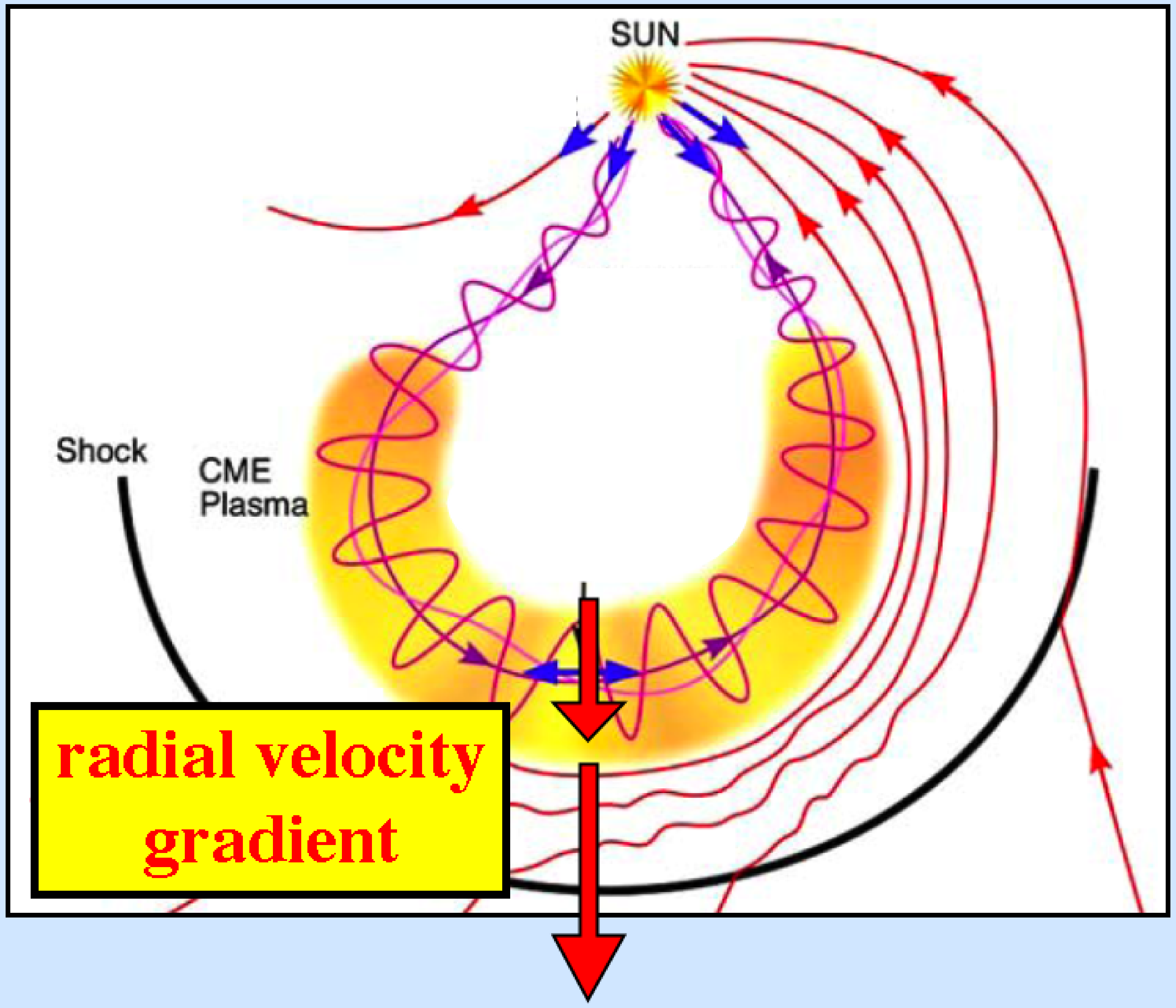
216 ICMEs: $N_{ICME} = 6.2\ D^{-2.3\ +/-0.07}$

(Liu et al. 2005)

130 MCs: $N_{MC} = 6.6\ D^{-2.6\ +/-0.07}$

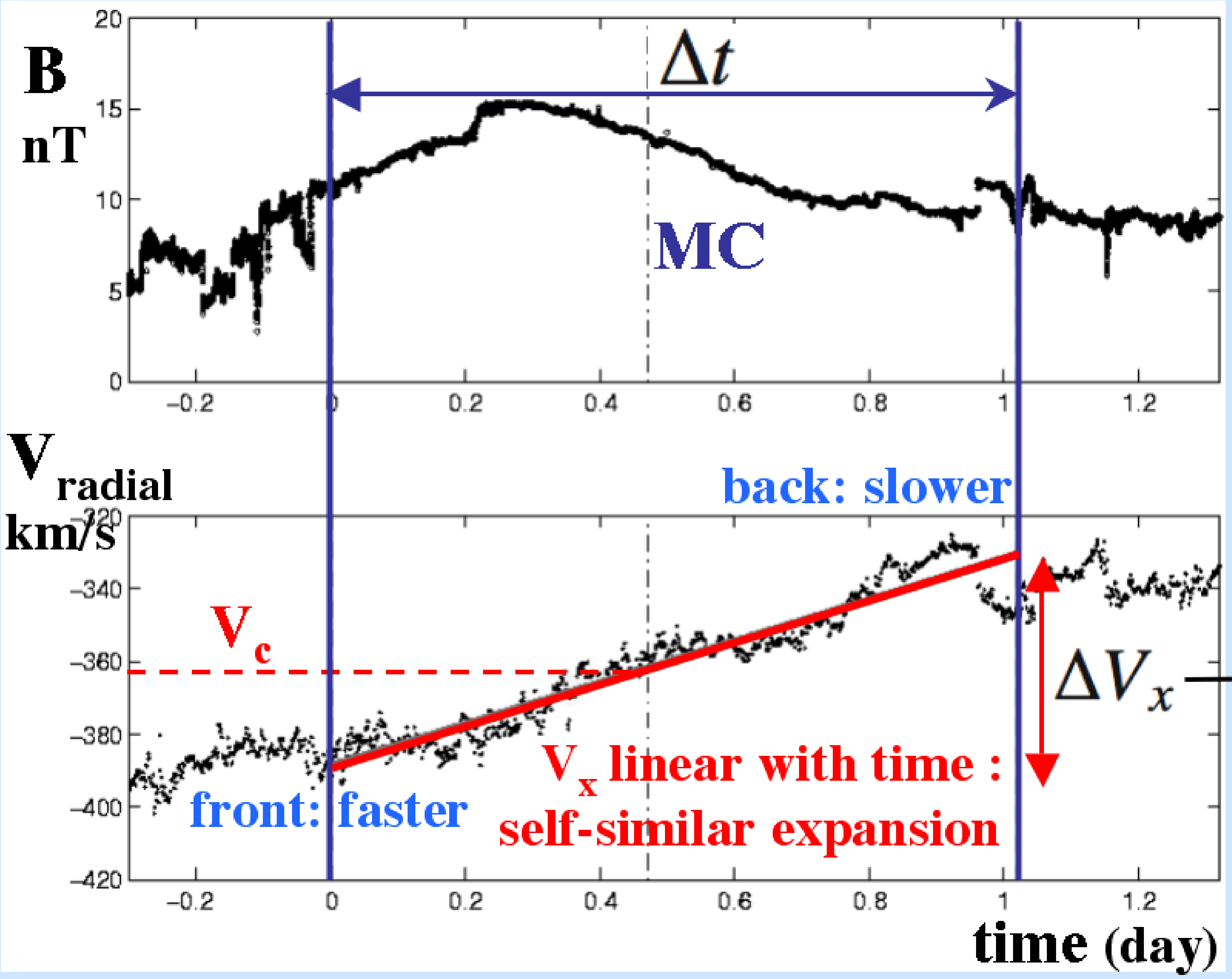
(Leitner et al. 2007)

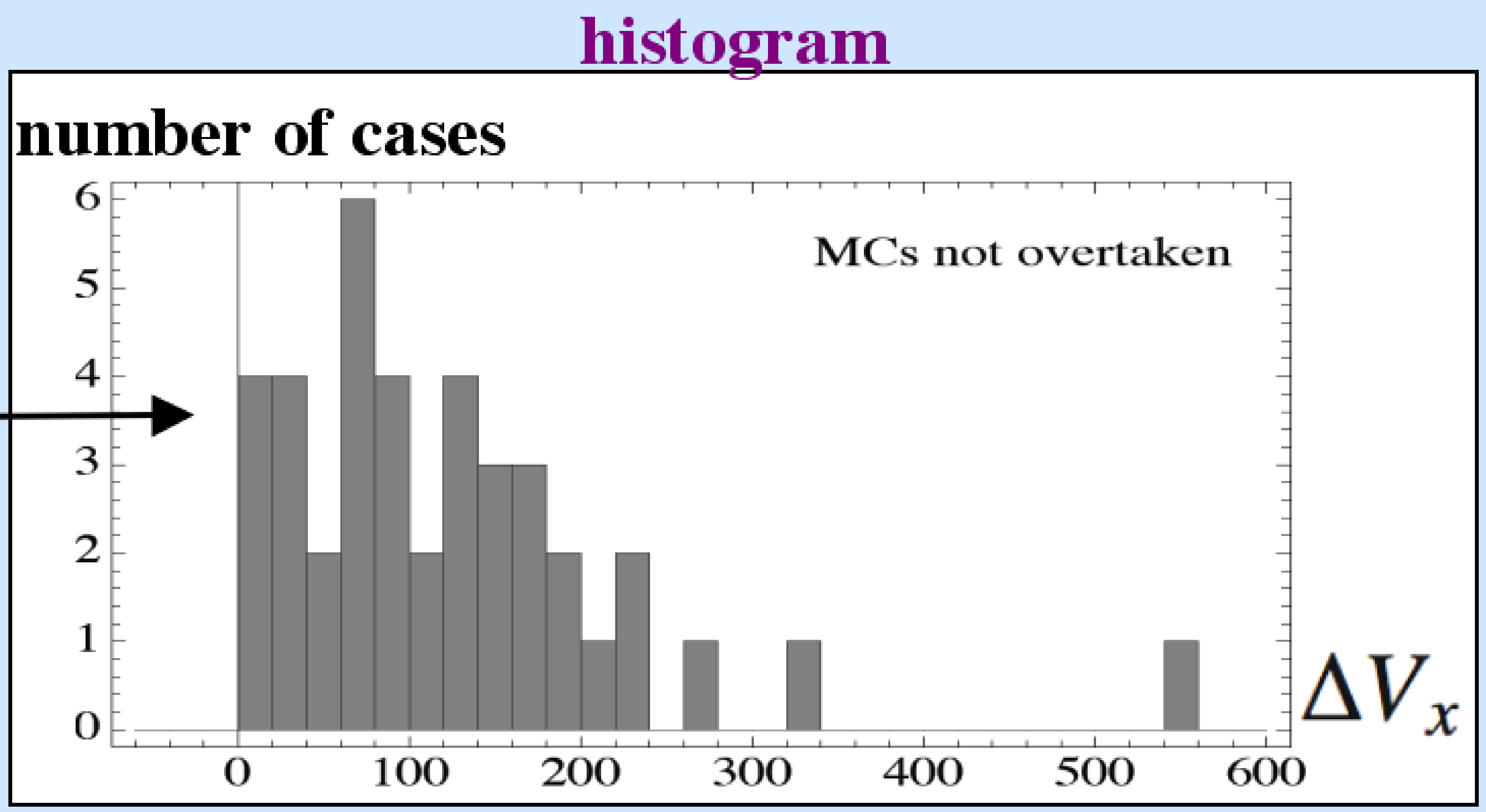
Expansion of ICMEs



observed in situ in most ICMEs

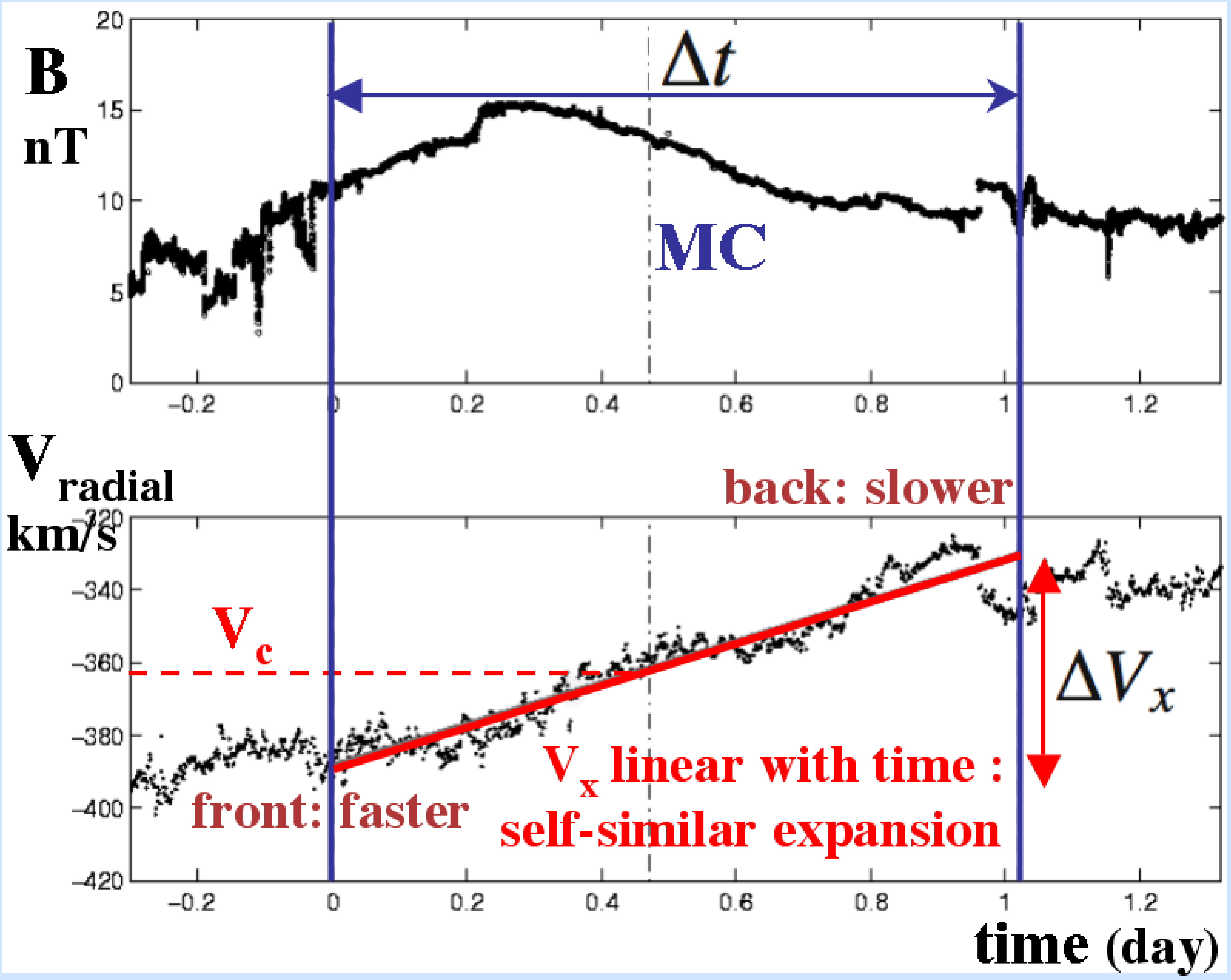
Expansion rate of MCs

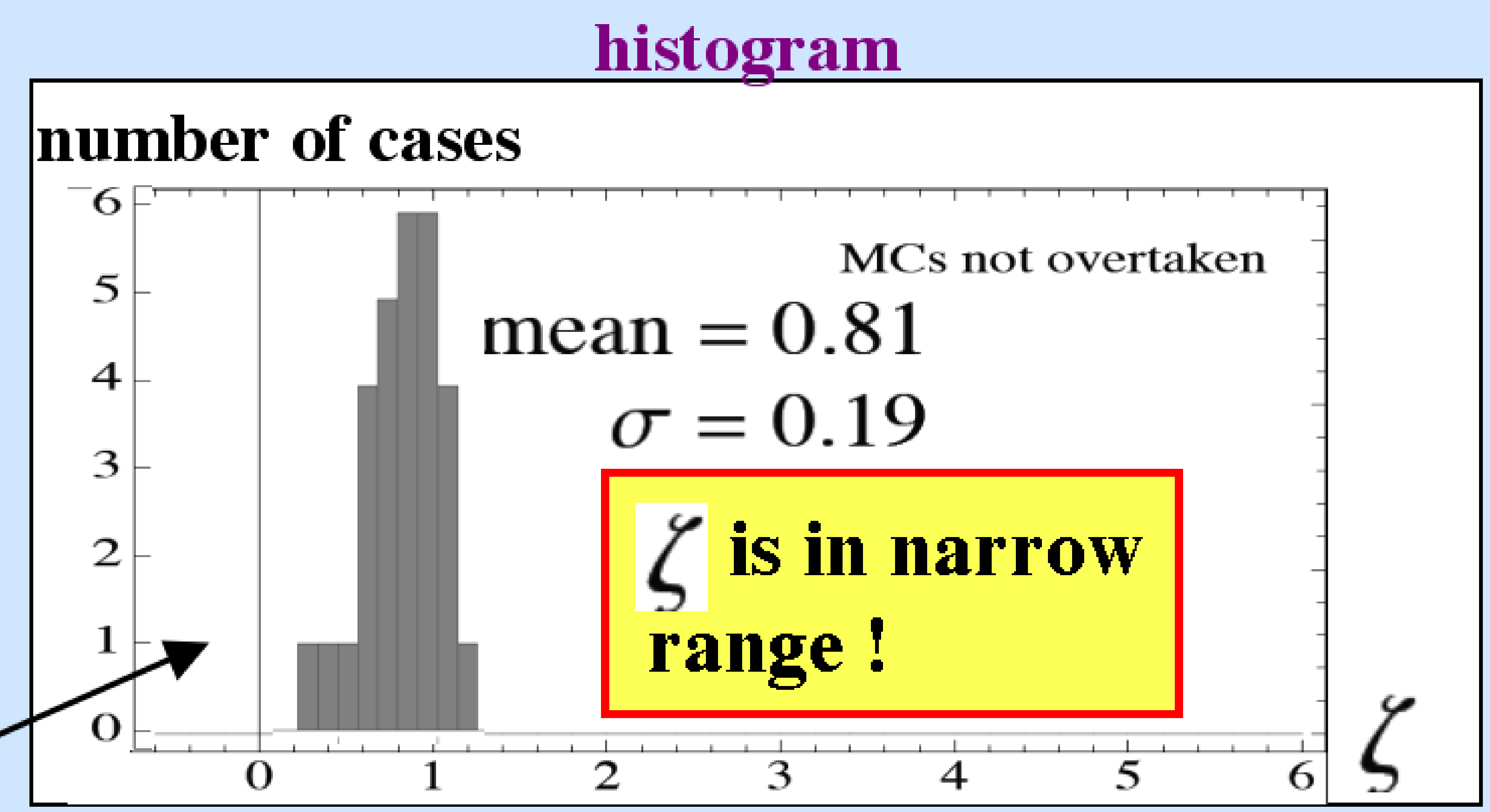




=> broad range of ΔV_x

Expansion rate of MCs





non dimensional expansion rate :

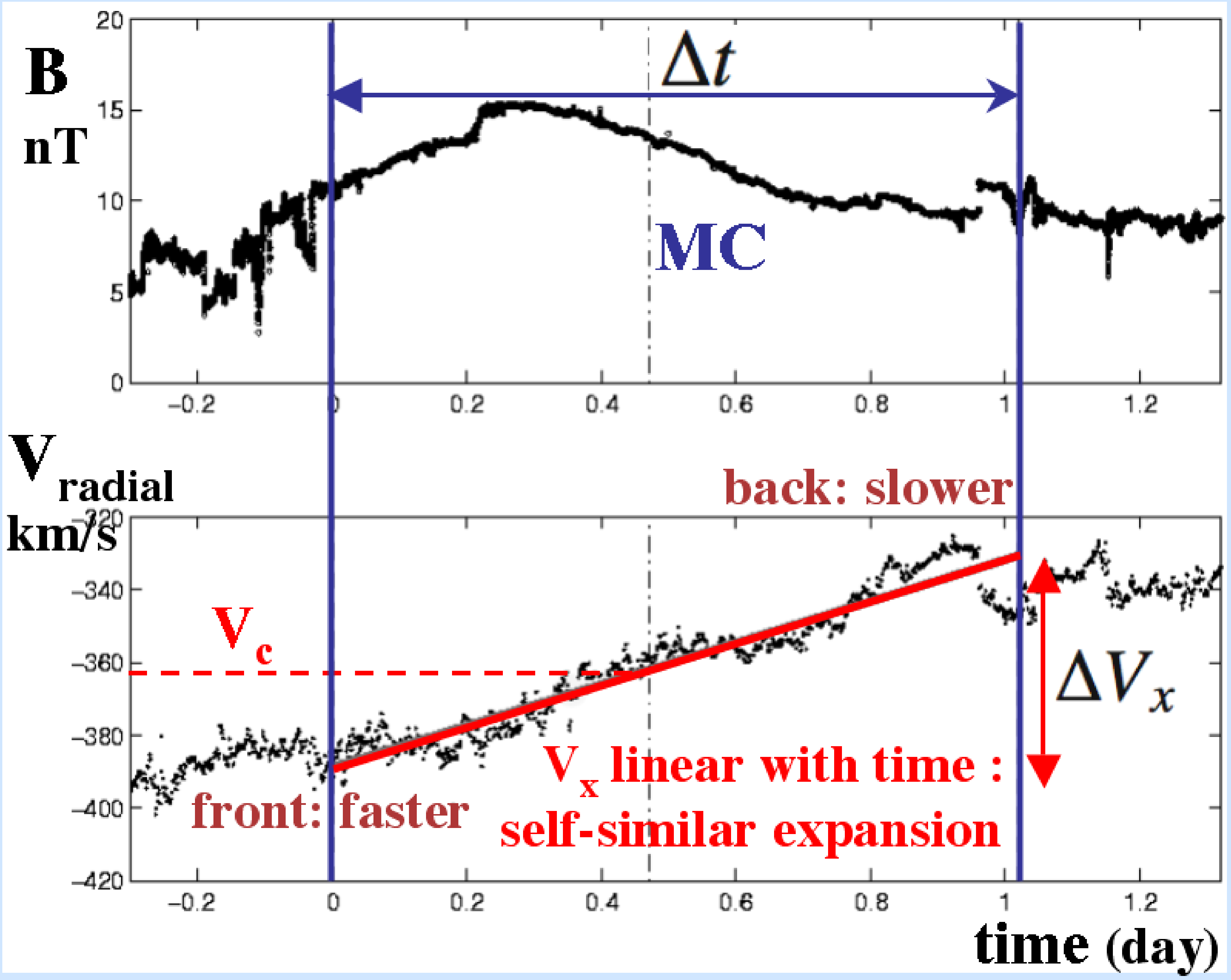
$$\boxed{\zeta = \frac{\Delta V_x}{\Delta t}\,\frac{D}{V_c^2}}$$

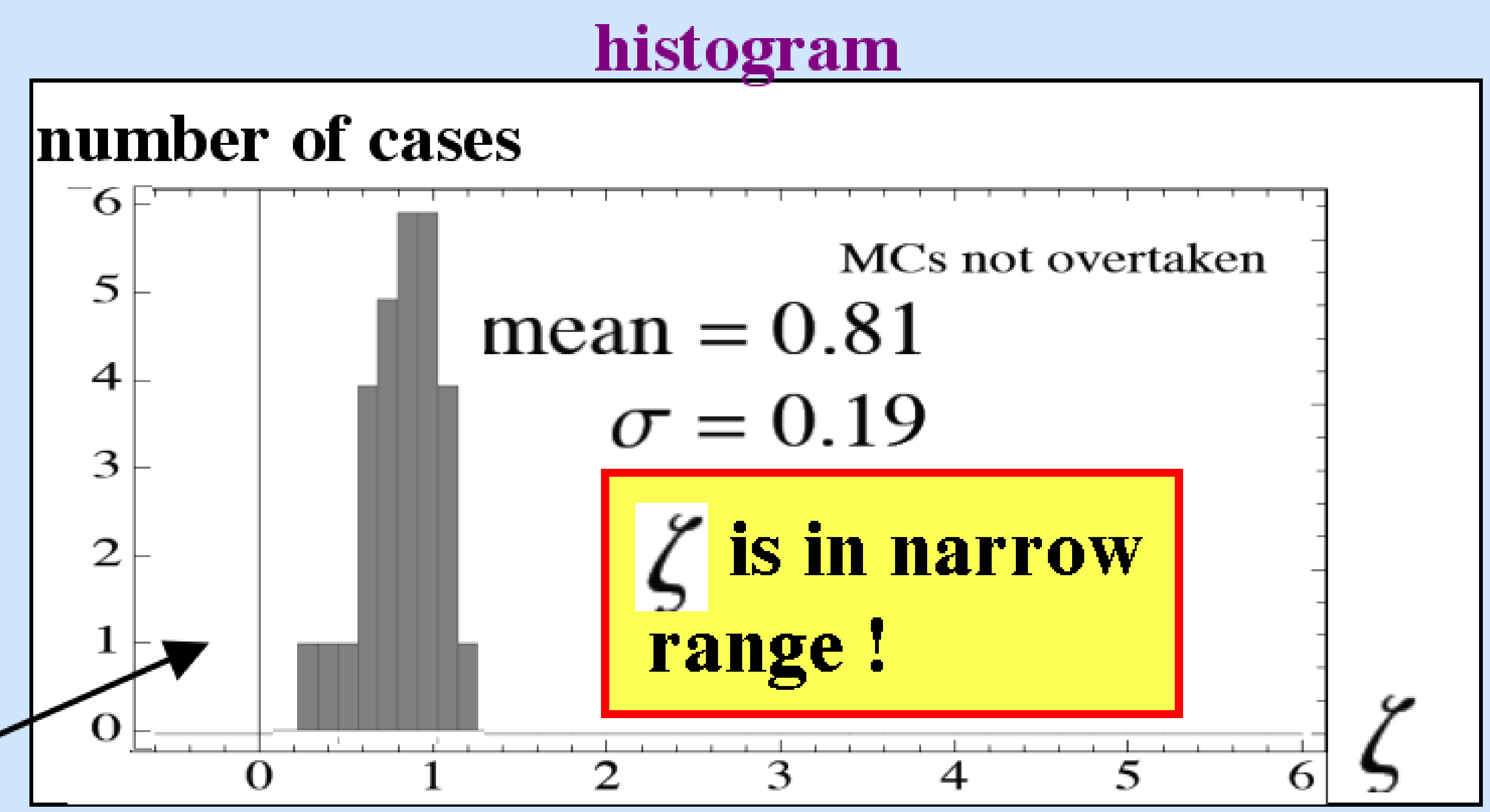
<u>meaning</u>: if ζ independent of D,

size = size$_0$ $(D/D_0)^{\zeta}$

(Démoulin et al. 2008, Gulisano et al. 2010)

Expansion rate of MCs





non dimensional expansion rate :

$$\zeta = \frac{\Delta V_x}{\Delta t} \frac{D}{V_c^2}$$

ζ independent of :
- B strength
- MC size

meaning: if ζ independent of D,

size = $\text{size}_0 \, (D/D_0)^{\zeta}$

=> MCs have a typical expansion rate !

(Démoulin et al. 2008, Gulisano et al. 2010)

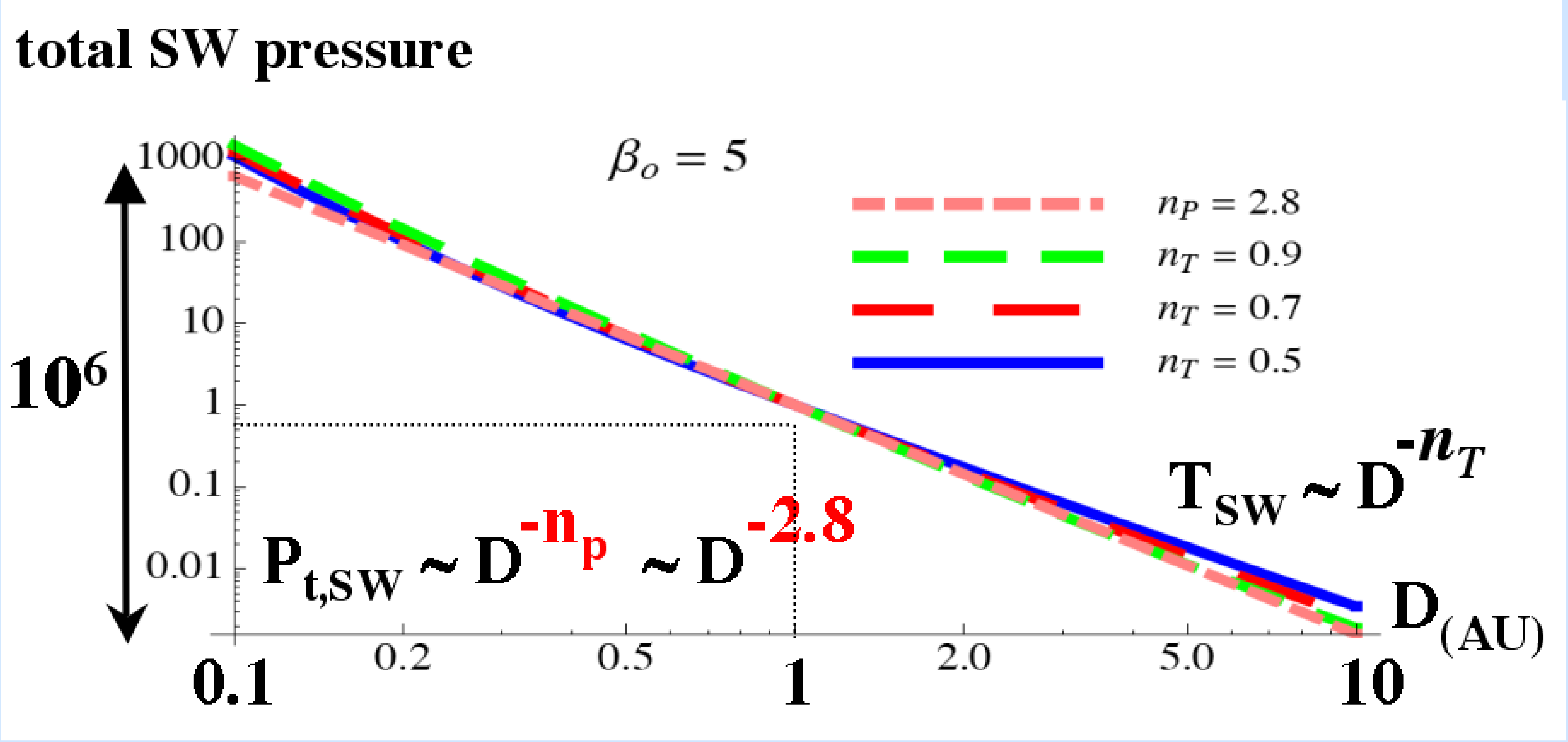
Why a typical expansion rate for MCs ?

simple estimation of the pressure balance :

$$P_{MC} \sim c \; P_{t,SW}$$

few units

main source of P_B evolution



=> self-similar expansion : $r = r_0 \, D^{n_p/4} \sim r_0 \, D^{0.7}$

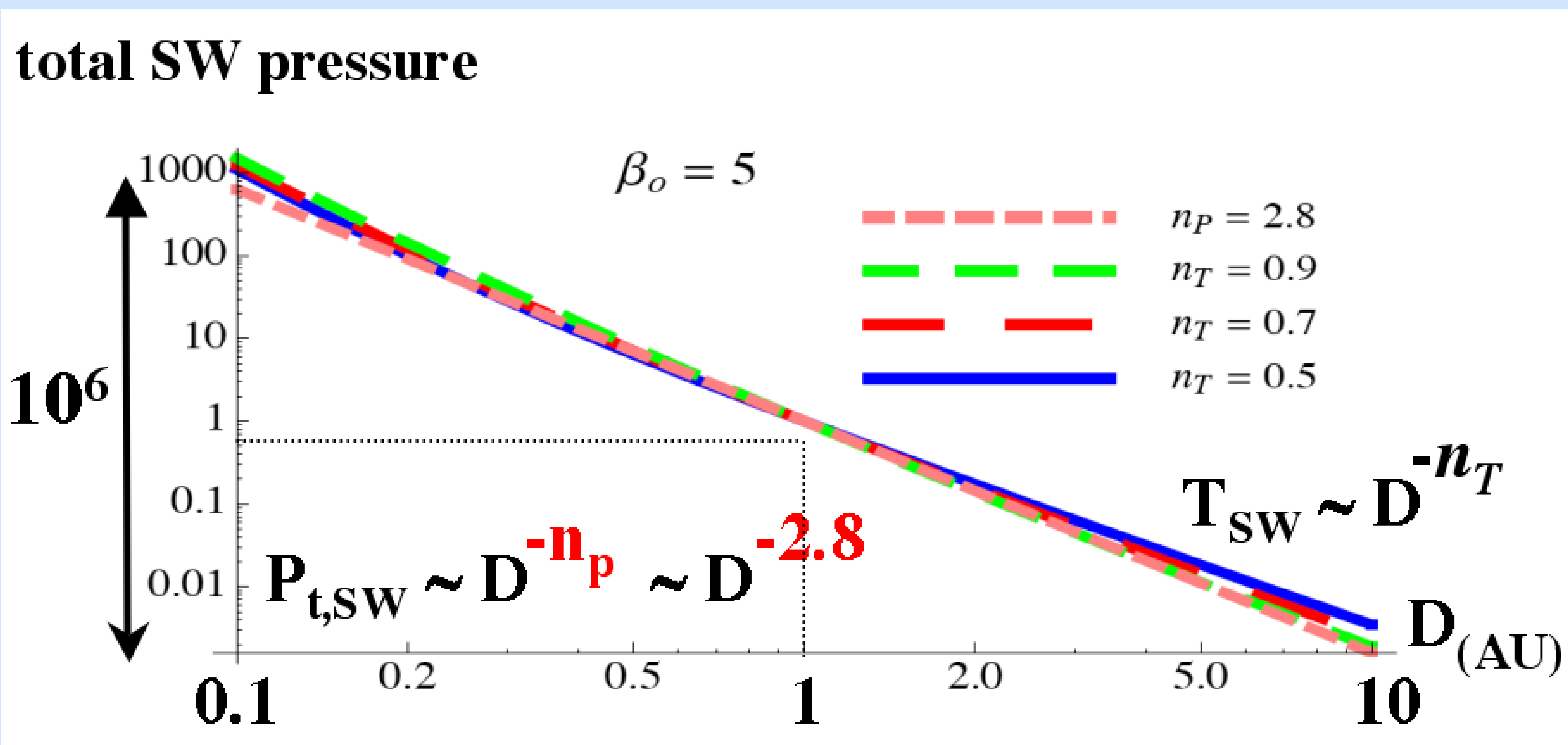
The SW total pressure defines the cross-section expansion rate

simple estimation of the pressure balance :

$$P_{MC} \sim \underset{\uparrow}{c}\ P_{t,SW}$$

few units

main source of P_B evolution

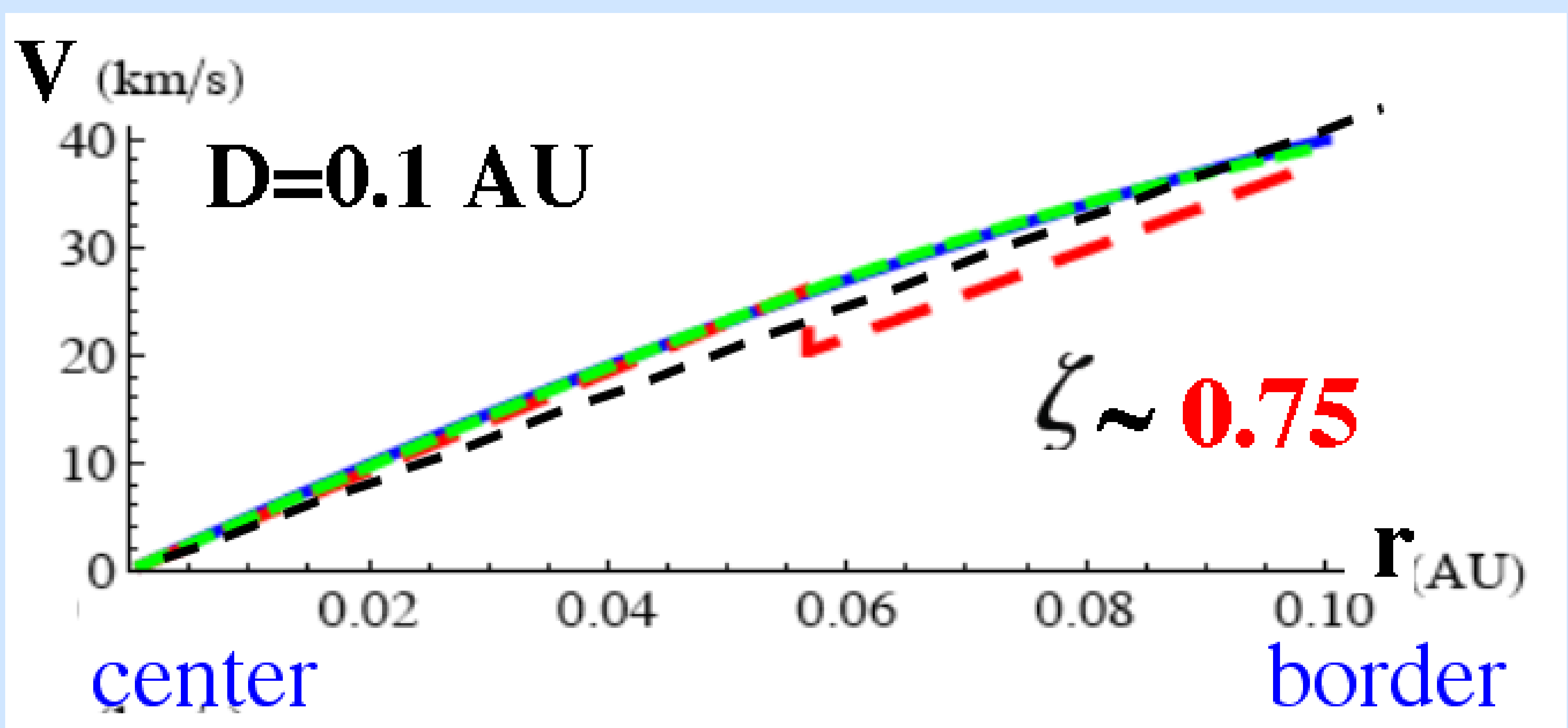


Model of flux rope evolution

ideal MHD + force-free field

$(V_{expansion} \lesssim V_A)$

Velocity profile across the flux rope



different field models : Lundquist, Gold & Hoyle, splitted

=> self-similar expansion : $r = r_0\, D^{n_p/4} \sim r_0\, D^{0.7}$

ζ and linear V profile as observed

(Démoulin & Dasso 2009)

Conclusion

Some achievements (almost baked)

- **Characterisation of erupting regions** (large magnetic shear, sigmoids flux cancelation, …)
- **Relate imager to in situ data**
- **Understand the magnetic cloud evolution** (expansion, …)

Conclusion

Some achievements (almost baked)

- Characterisation of erupting regions (large magnetic shear, sigmoids flux cancelation, …)
- Relate imager to in situ data
- Understand the magnetic cloud evolution (expansion, …)

Some challenges (need more coffee)

- Understanding the pre-eruptive phase
- When does an eruption start ?
- Quantitative link between coronal and interplanetary structures (e.g. magnetic flux & helicity)
- Do all ICMEs have a flux rope ?