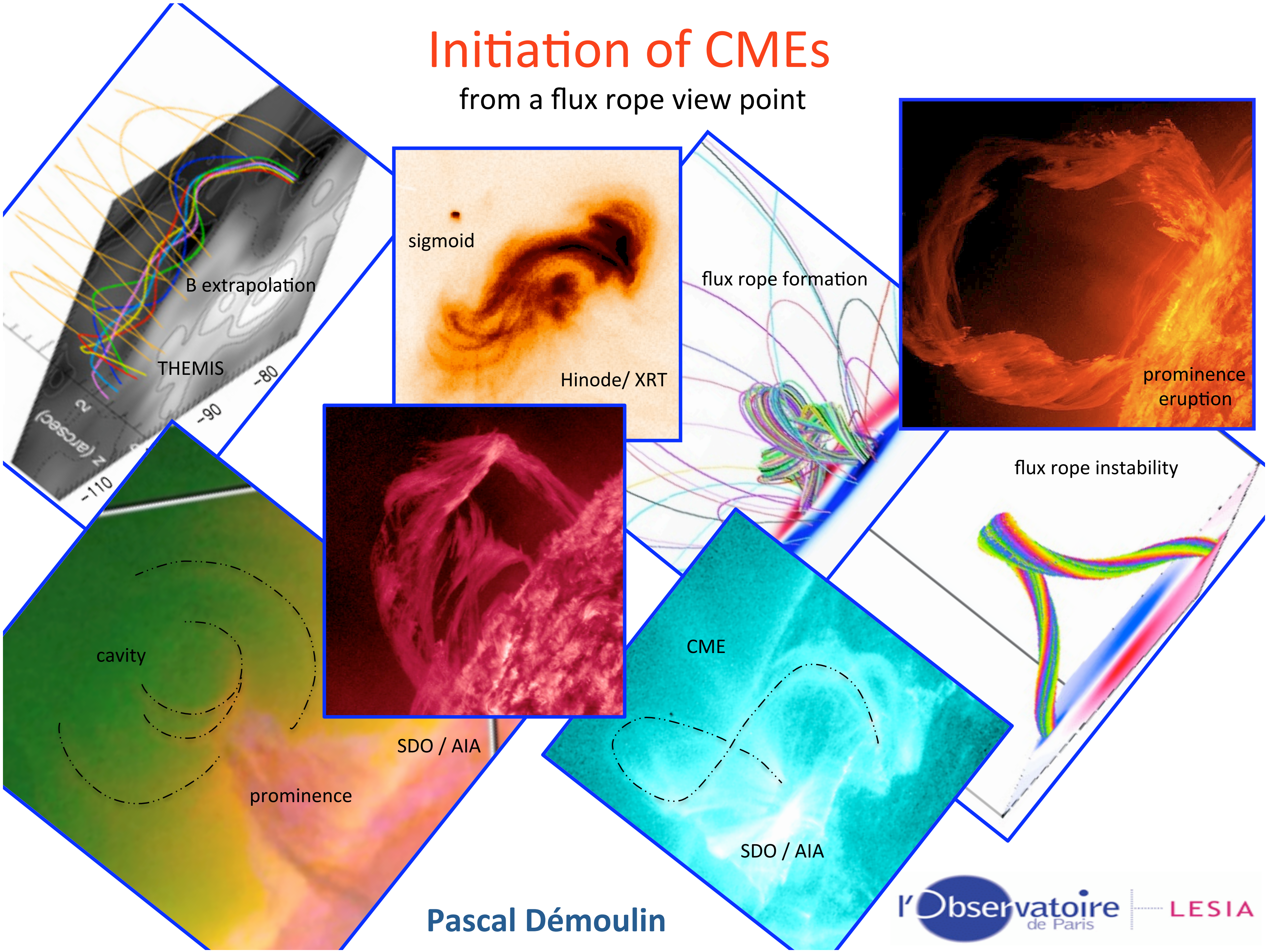
Initiation of CMEs

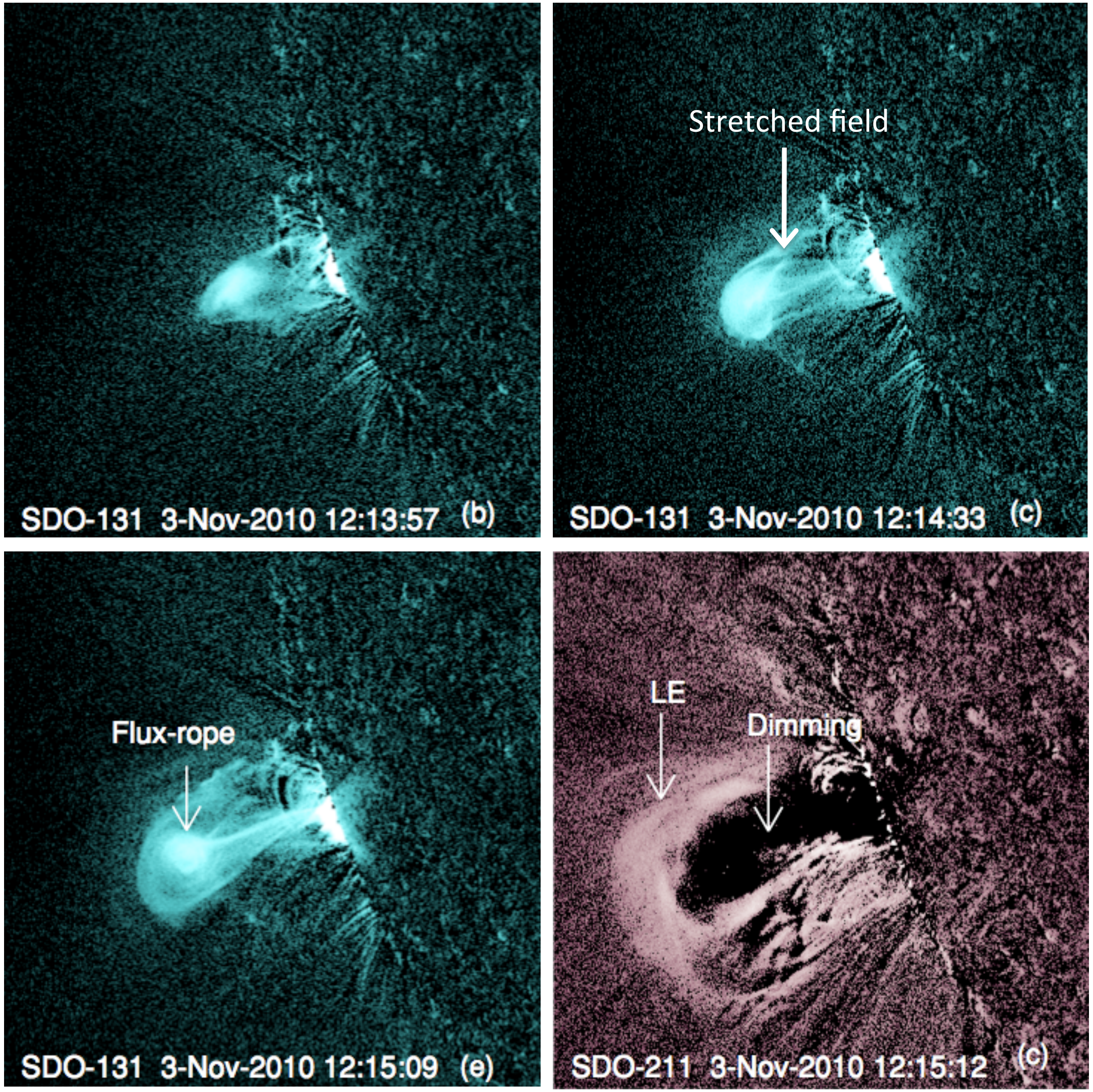
from a flux rope view point



Pascal Démoulin

l'Observatoire de Paris | LESIA

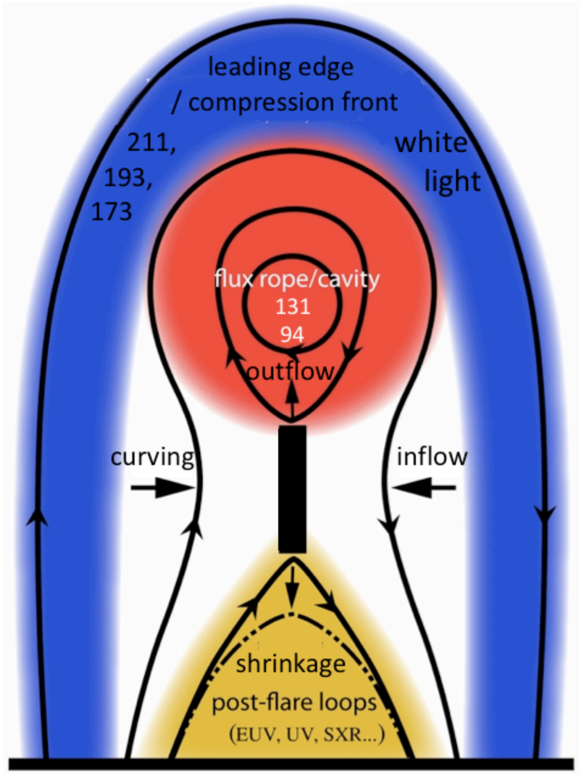
Flux rope eruption (at the limb)



Visualize a classical flux rope eruption, as in models !

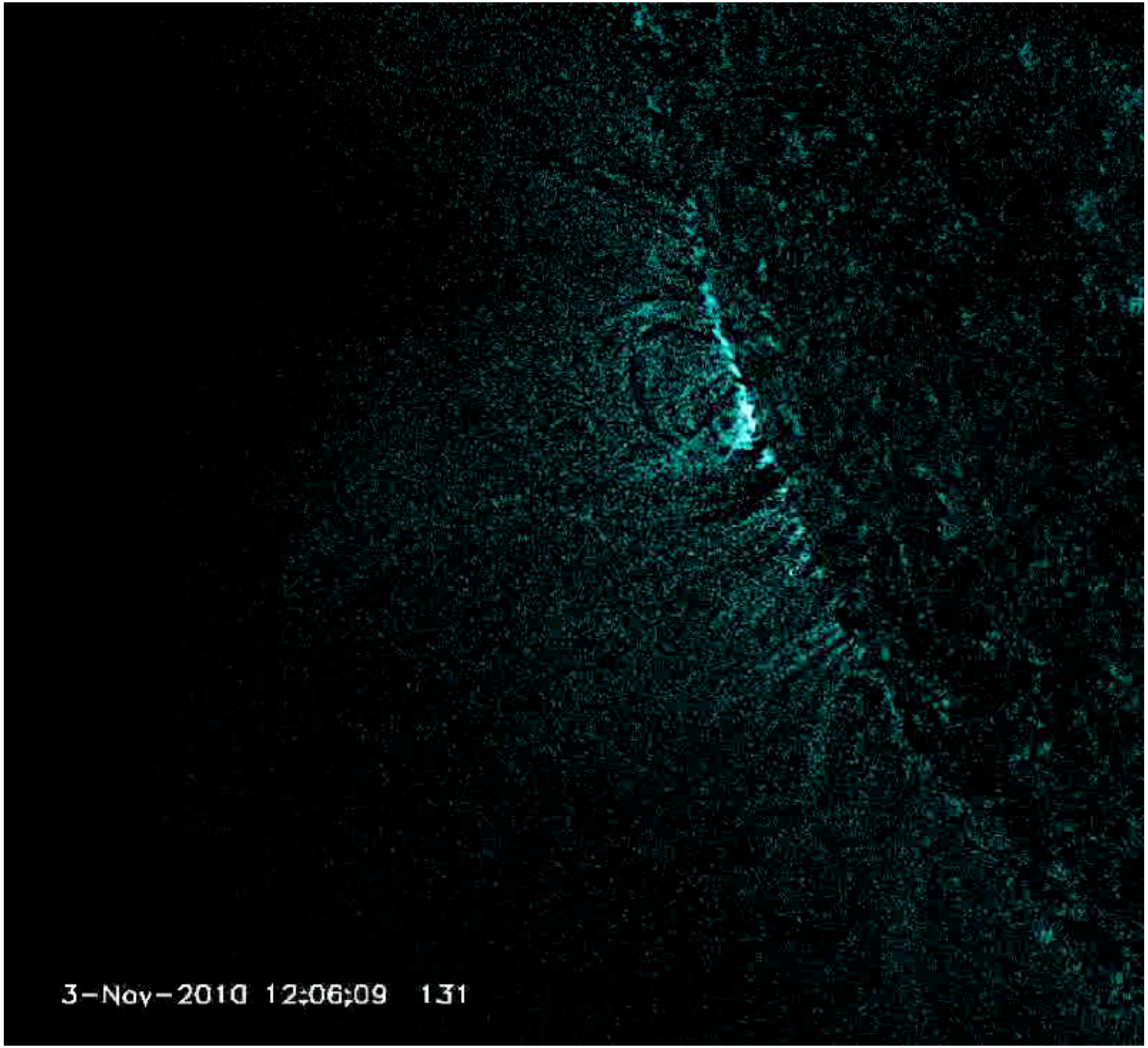
(Forbes et al. 2001, 2006, Vrsnak 2008 ….)

- Flux rope grows due to flare reconnection
- Very hot flux rope : 7-11 MK !



(Cheng et al. 2011, Reeves & Golub 2011)

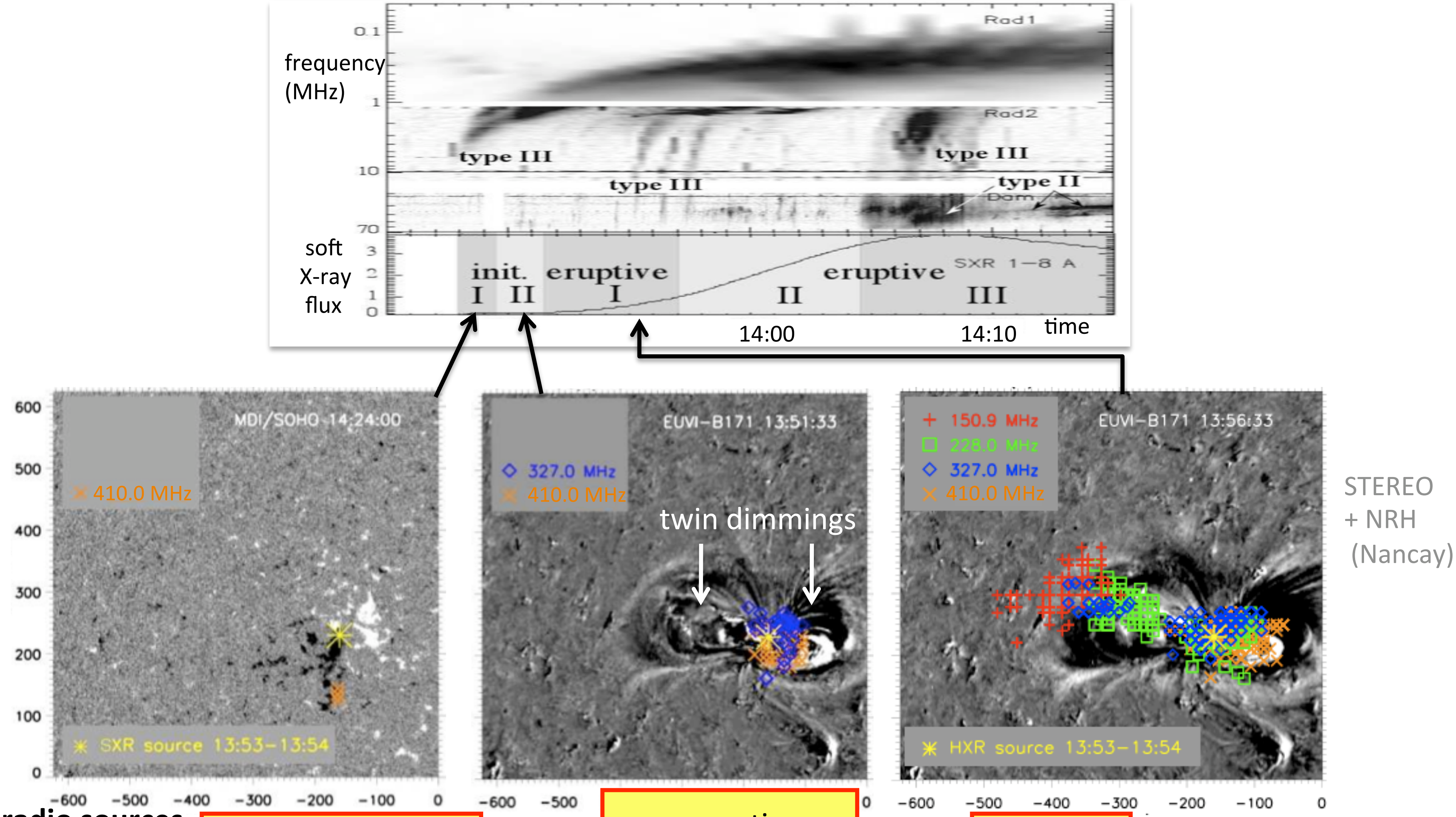
Flux rope eruption (at the limb)



AIA 131 Å

(Cheng et al. 2011)

Flux rope eruption (on the disk)



radio sources trace:

side reconnection

with open field lines => type III bursts

reconnection behind flux rope

At later times, flux rope models of coronagraph observations

flux rope

(Huang et al. 2010; Cheng et al. 2010)

(Thernisien et al. 2009; Wood & Howard 2009)

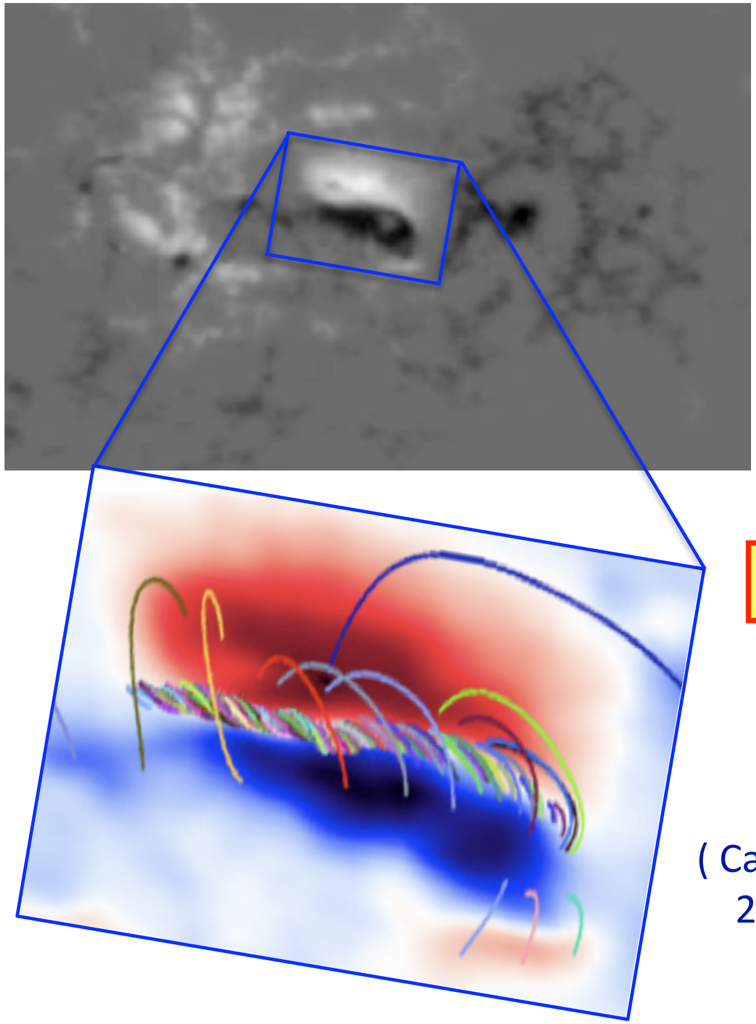
Is a twisted flux tube (flux rope) present <u>before</u> the eruption ?

Evidence of flux ropes

Magnetic extrapolations are able to reconstruct a flux rope even within a complex B topology

(Valori et al. 2010)

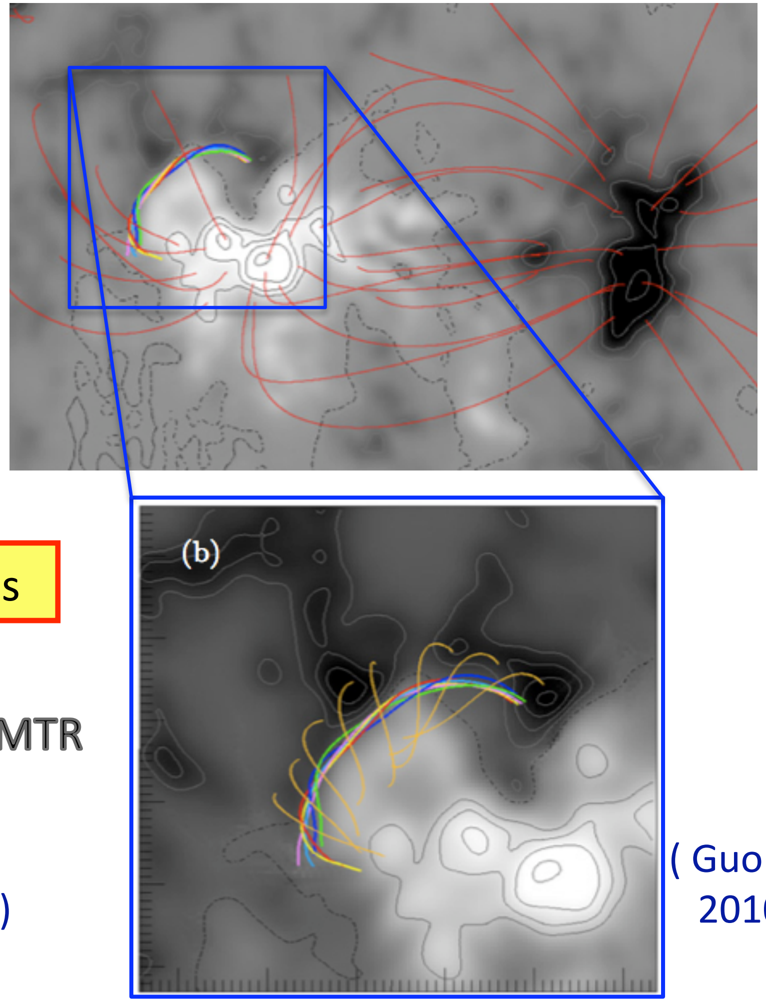
Non-linear force-free magnetic field computations from vector magnetograms



flux ropes

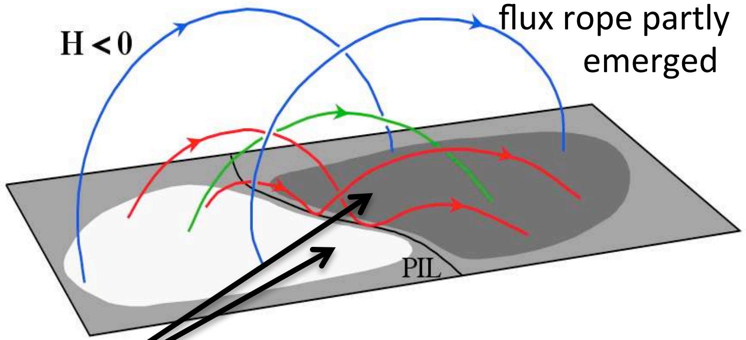
THEMIS/MTR

(Canou et al. 2009, 2010)



(Guo et al. 2010)

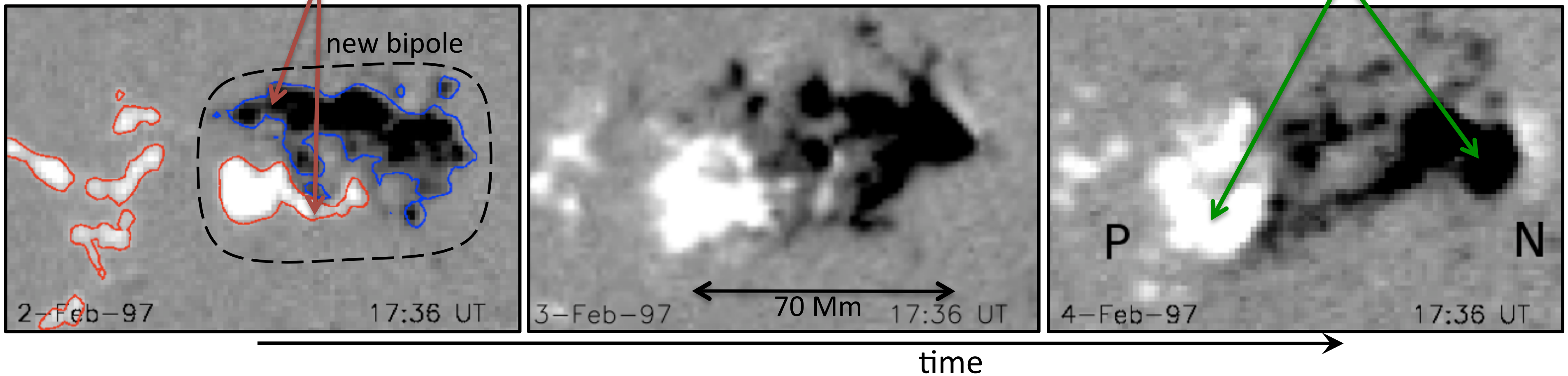
ARs formed by flux rope emergence



magnetic tongues: trace of **azimuthal B**

trace of: **axial B**

First days of an AR emergence

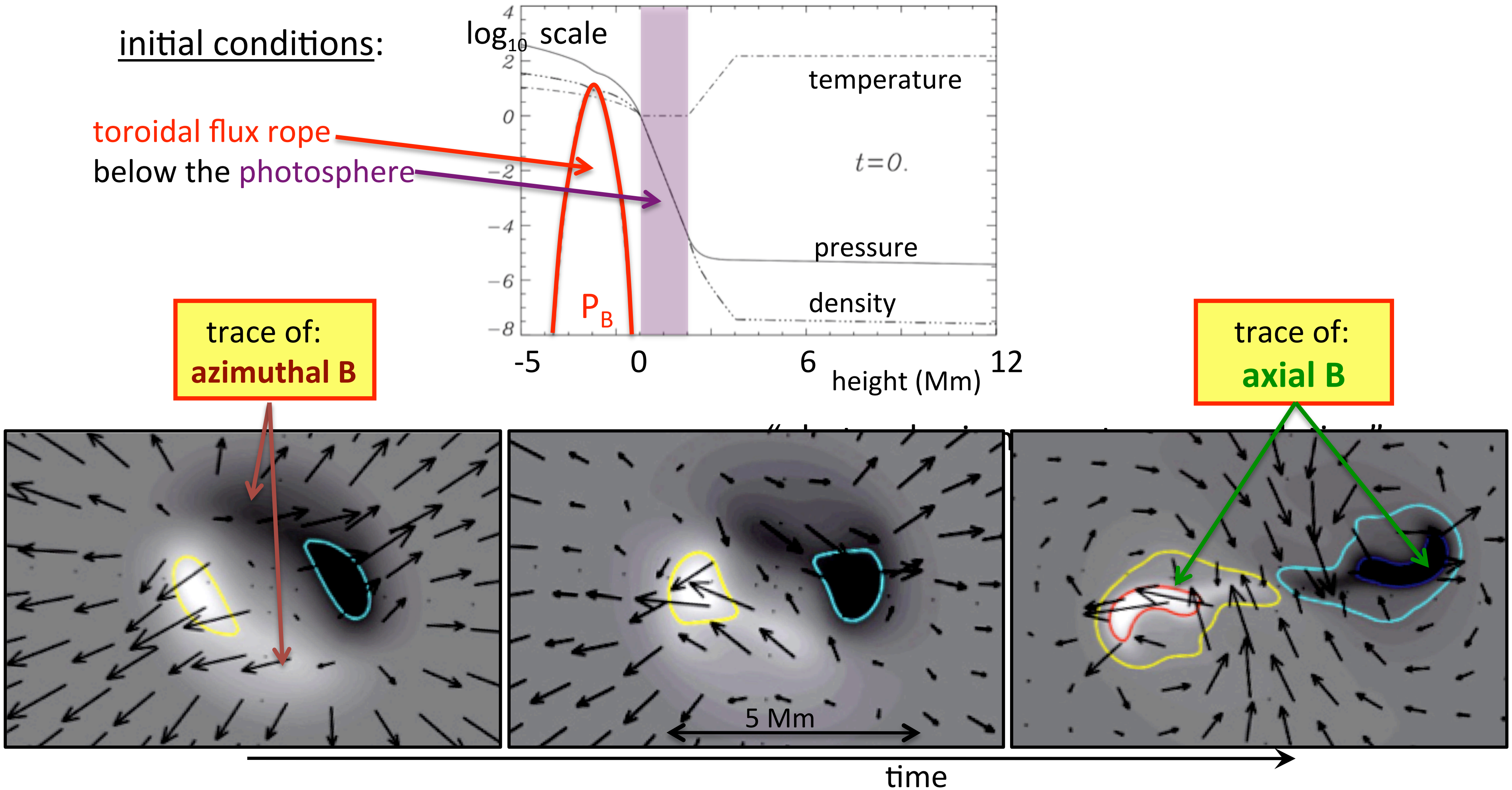


grey levels: magnetogram

=> apparent rotation of the AR

(Luoni et al. 2011,
Lopez Fuentes et al. 2000)

MHD simulation of emergence

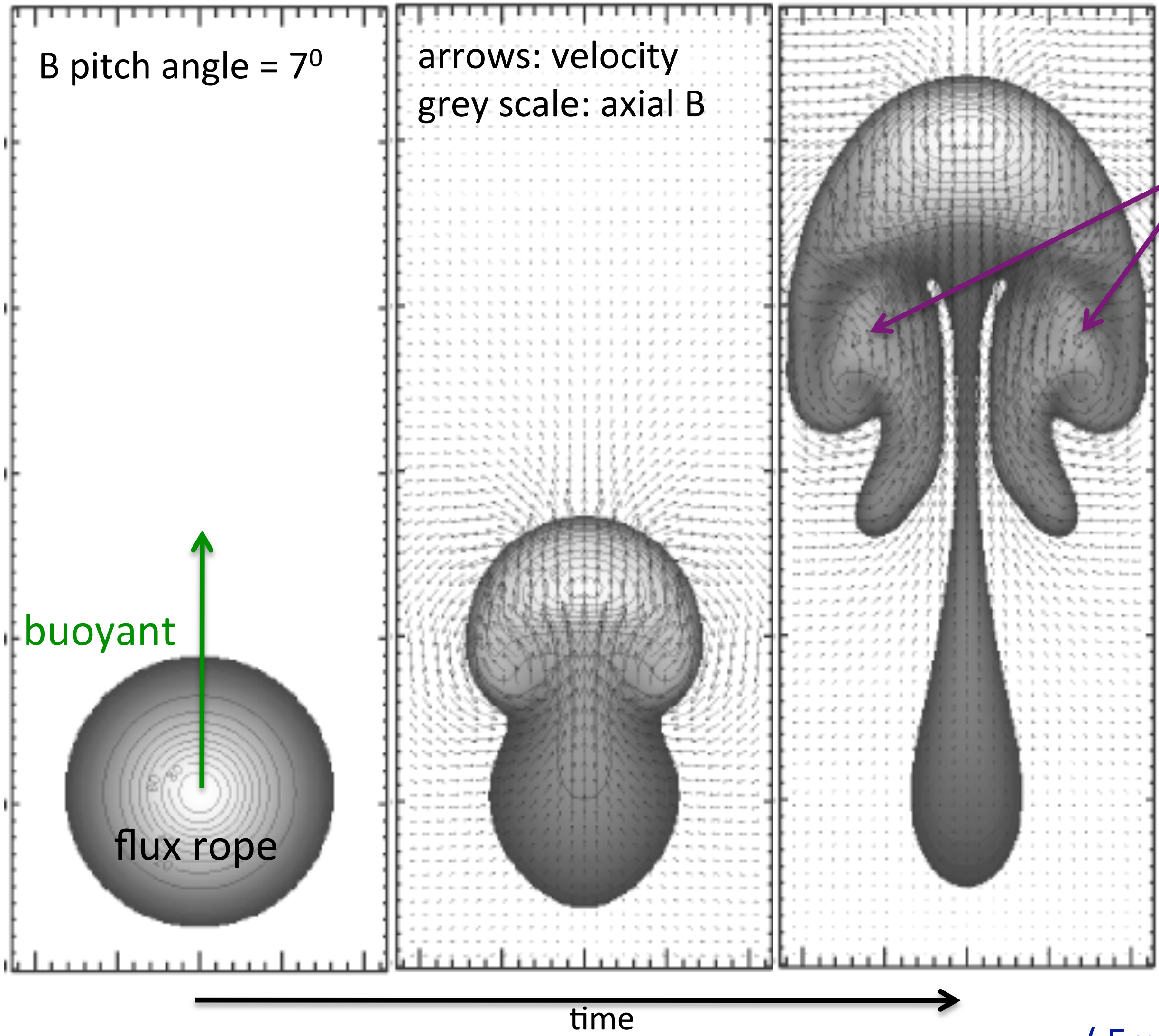


grey levels: “magnetogram”, arrows: plasma velocity

(Hood et al. 2009, Archontis & Hood 2010)

(Magara & Longcope 2003, Archontis et al. 2004, Manchester et al. 2004, Fan 2009, Murray & Hood 2008)

Crossing the convective zone



Hydrodynamic vortexes destroy the flux rope **if** it is not twisted enough

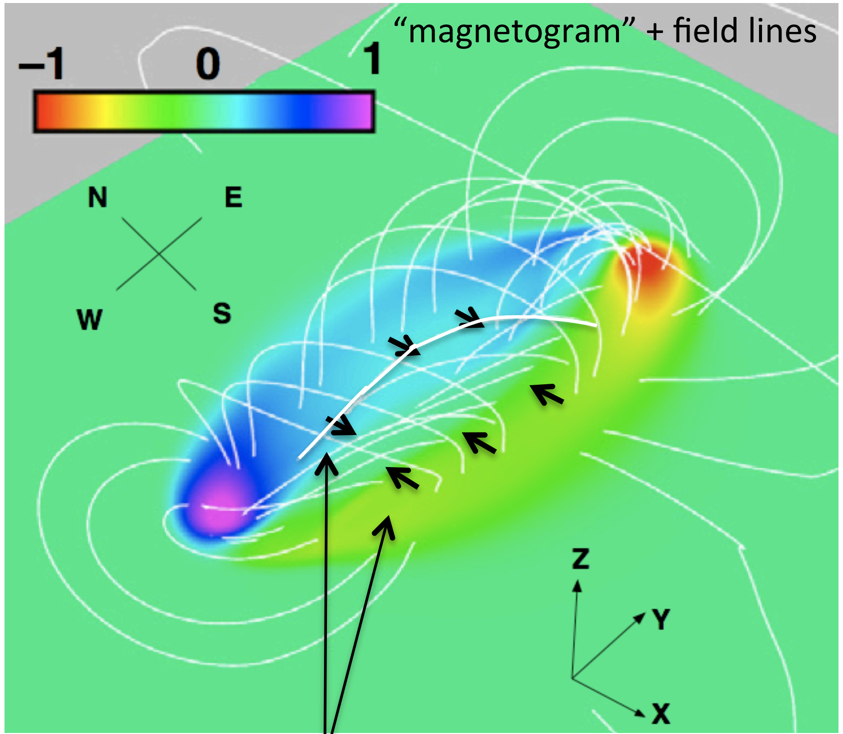
flux tubes need to be **significantly twisted** (typically > 1 turn) to cross the convective zone and to form active regions

Main dynamo: at the bottom of the convective zone

(Emonet & Moreno Insertis 1998, Cheung et al. 2006, Fan 2008)

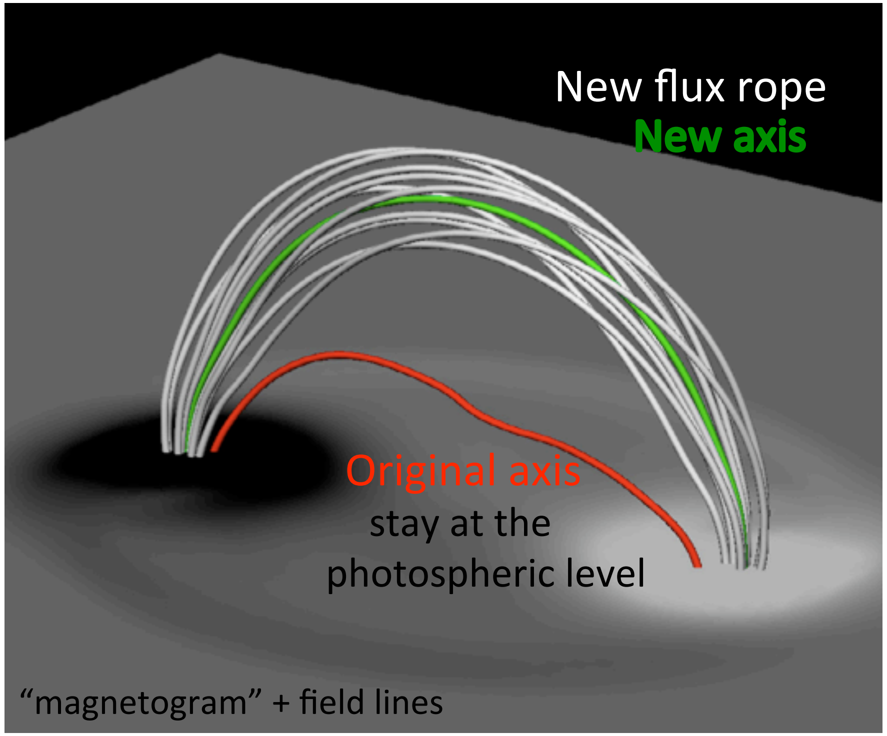
Formation of a new flux rope (above the photosphere)

emergence of the flux rope top
-> sheared arcade



pressure depression behind emerging field
=> converging flows
=> reconnection of arcades
=> new flux rope formation

after "photospheric" reconnection

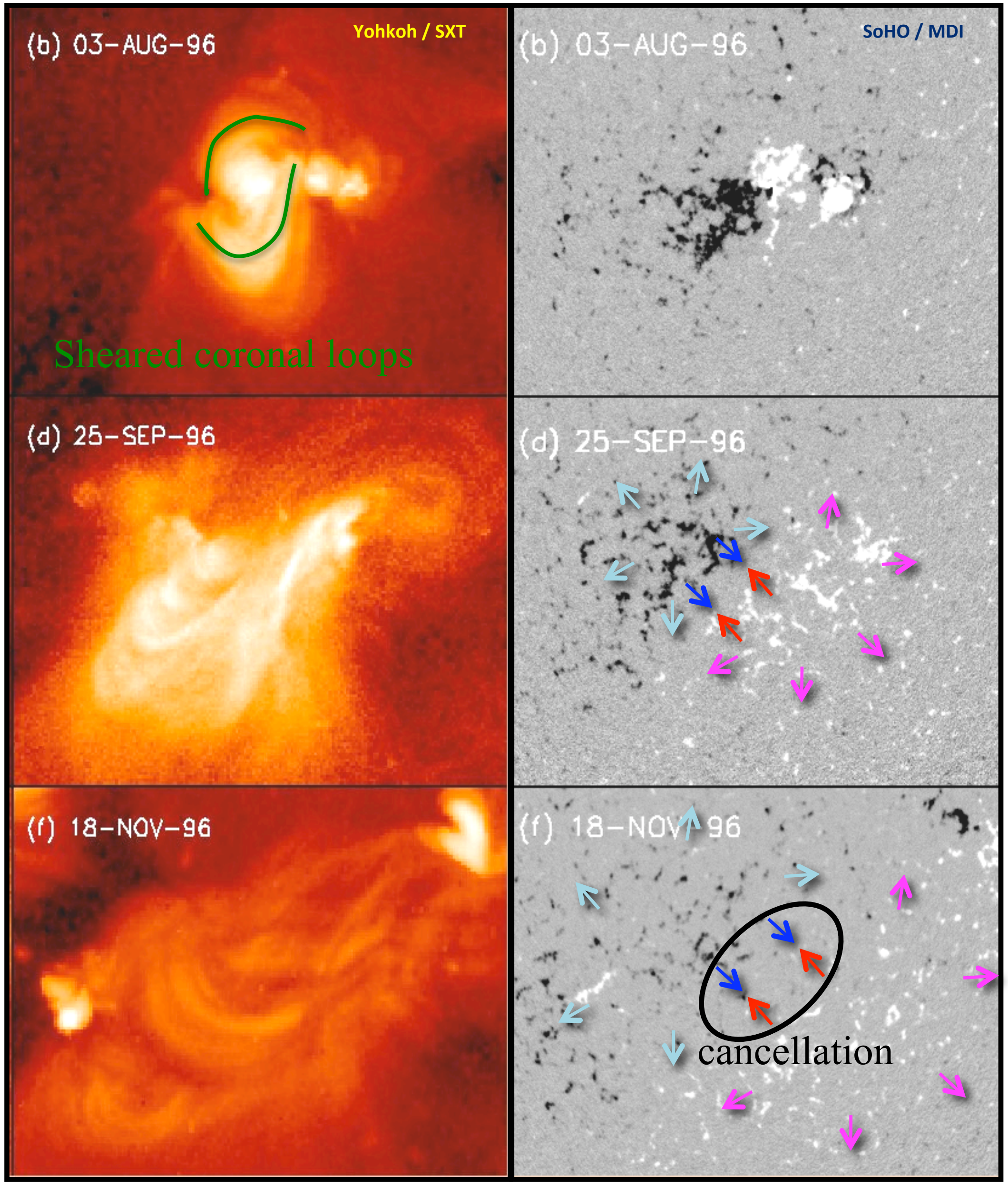


(with a larger B strength, the new axis can be below the original axis which emerges above the photosphere)

(Manchester et al. 2004,
Archontis et al. 2009
Mac Taggart & Hood 2009)

Formation of flux ropes also
in decaying active regions !

Many CMEs in decaying ARs !



Carrington rotations →

Flares : X , M , C , B

weaker flares but still CMEs !

(less than half of the CMEs occur during the first rotation)

Sheared coronal loops

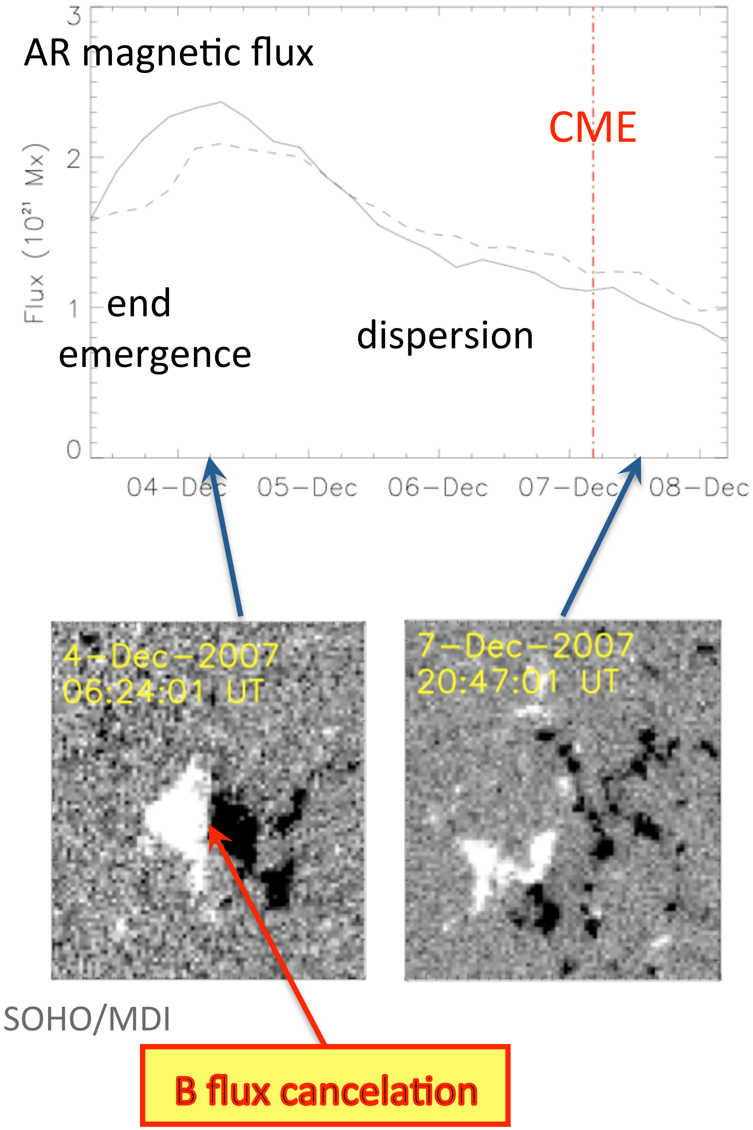
Flux dispersal and B decrease

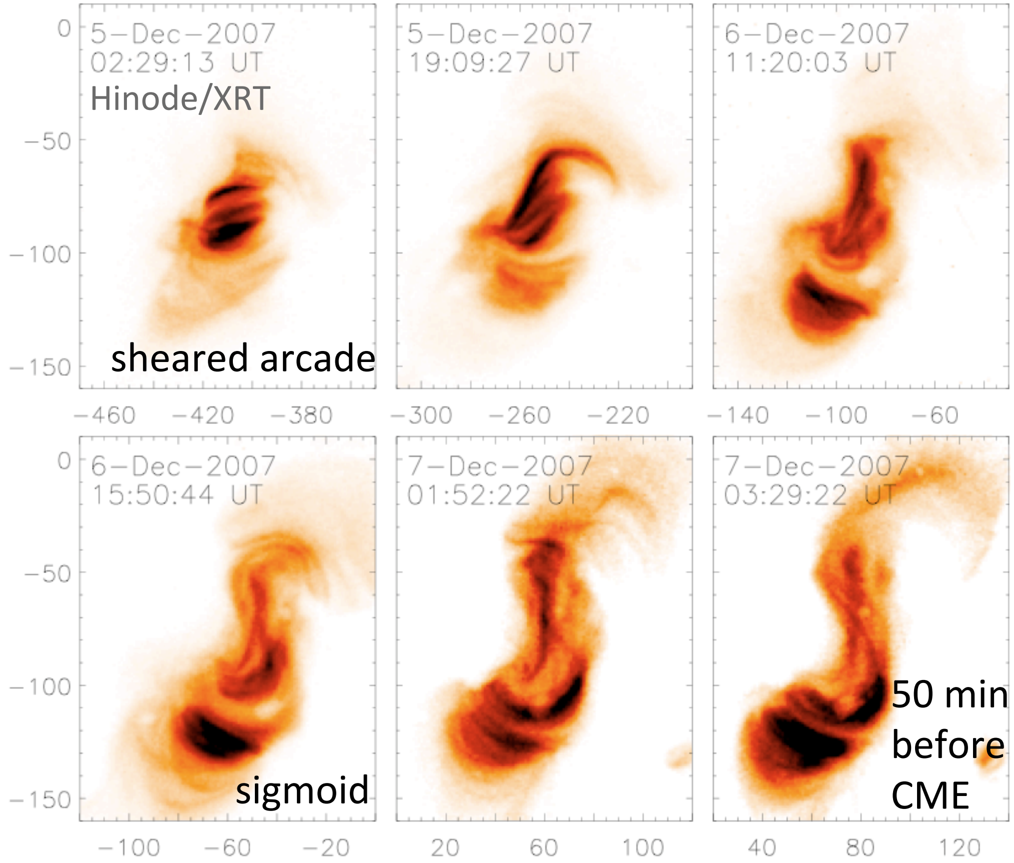
=> converging motions at PIL

=> Flux cancellation at the photospheric inversion line

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

Sigmoid formation before eruption





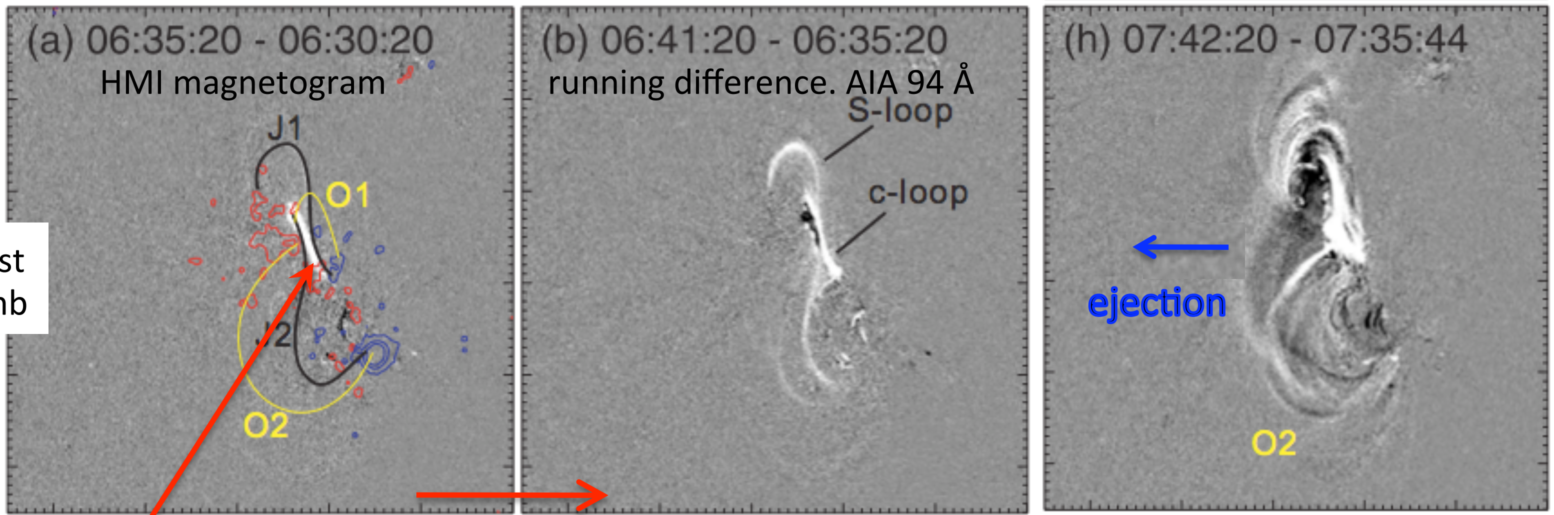
(Green, Kliem, Wallace 2011)

(Moore et al. 1995, Hudson et al. 1998,
Canfield et al. 1999, Glover et al. 2000,
Gibson et al. 2006, Tripathi et al. 2009 …)

Sigmoid formation & eruption

1h before eruption: reconnection J1 with J2 => S & c loops

east limb



evidence of flux-rope build up then ejection

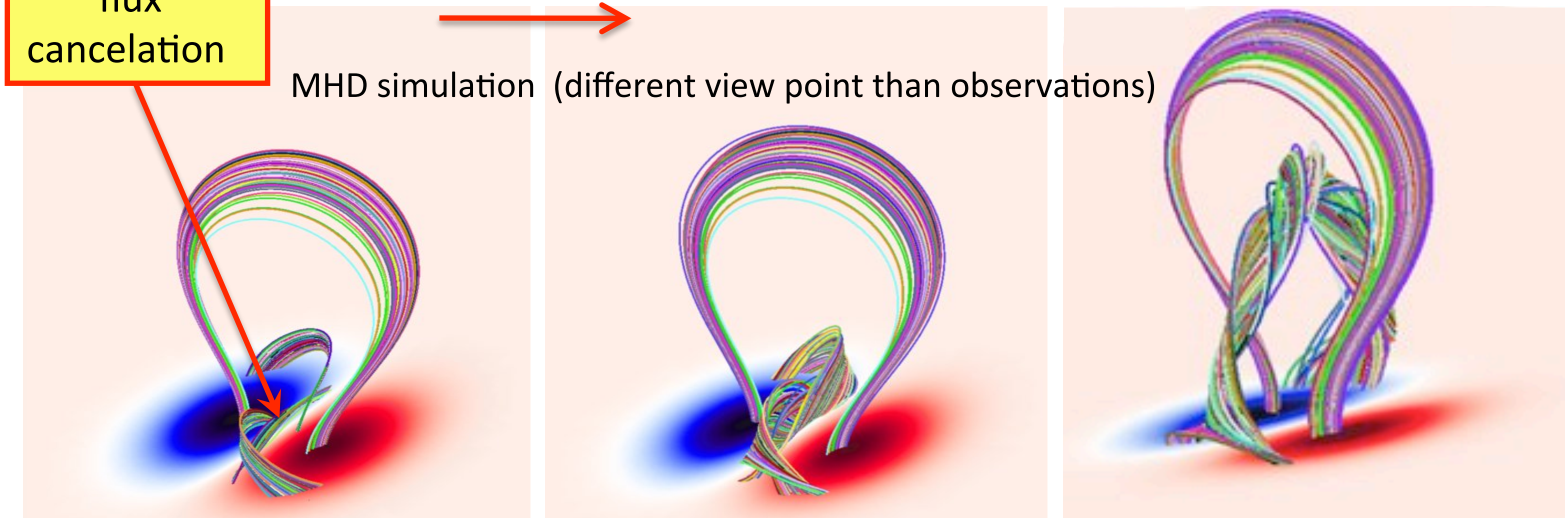
(Liu et al. 2010)

transformation :
double J => S shaped loops

ejection of the flux rope

flux cancelation

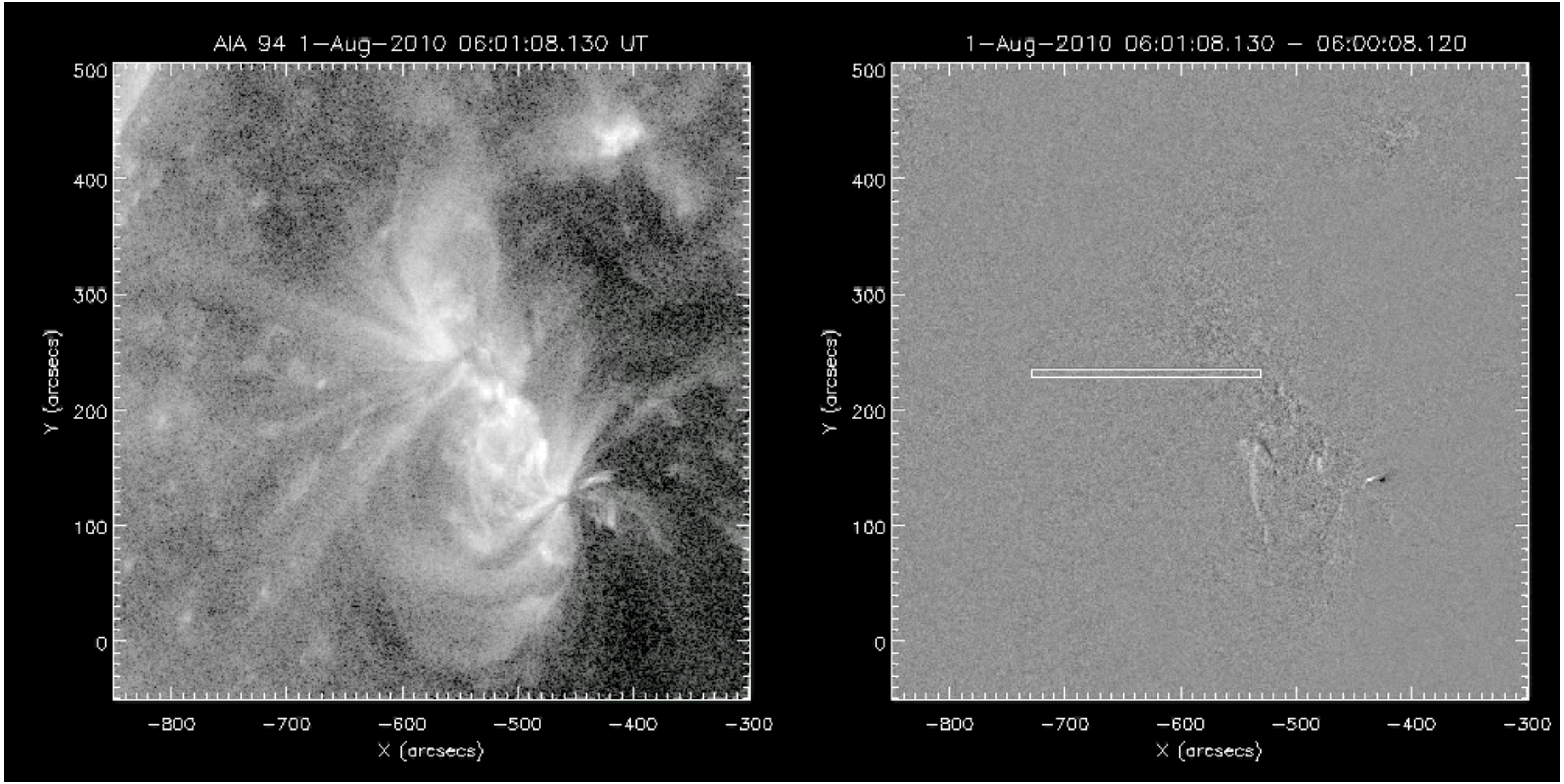
MHD simulation (different view point than observations)



(Amari et al. 2010)

Sigmoid formation & eruption

running difference. AIA 94 Å

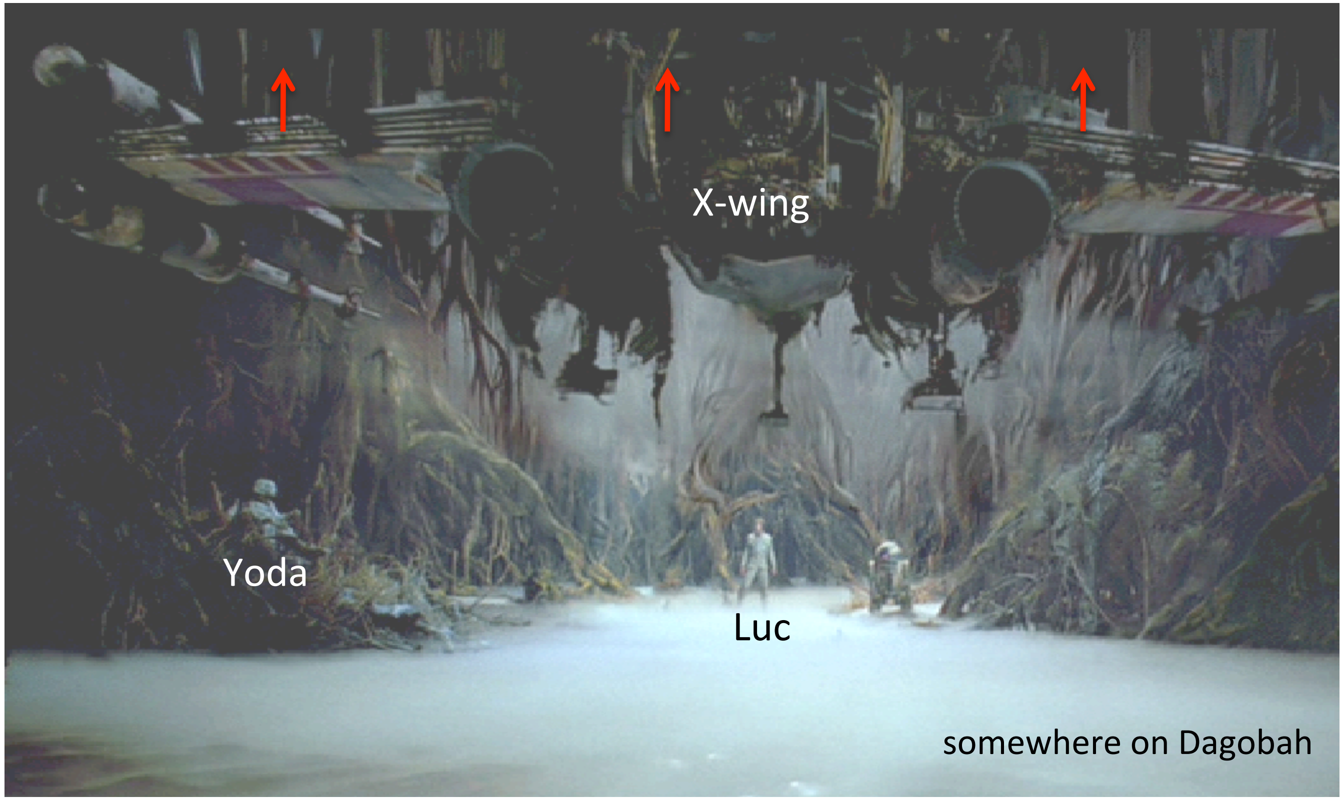


(Liu et al. 2010)

In agreement with previous studies (Manoharan et al. 1996, Moore et al. 2001, Gibson et al. 2002, Canfield et al. 2007 …)

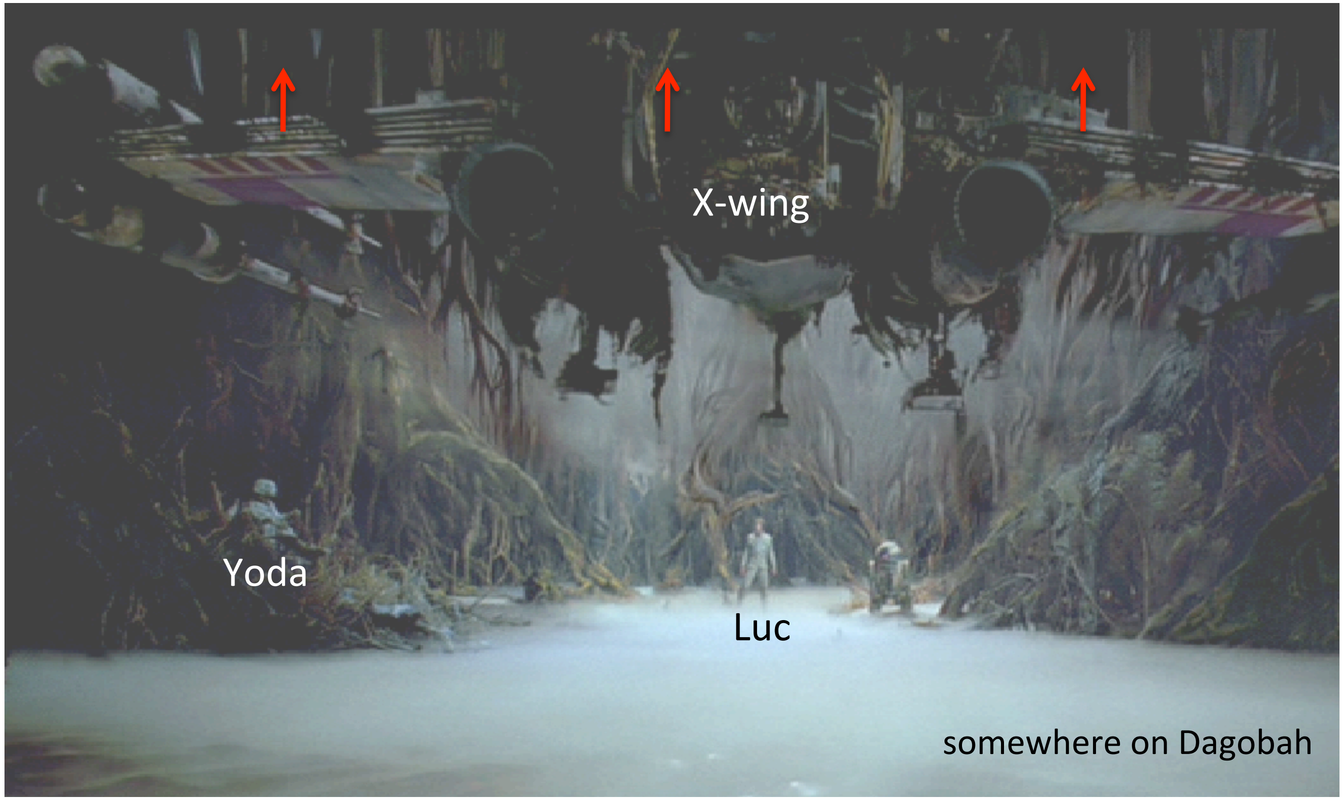
Mechanisms for CME initiation

Which force drives CMEs ?



Which force lifts up this huge mass ?

Which force drives CMEs ?



Which force lifts up this huge mass ?

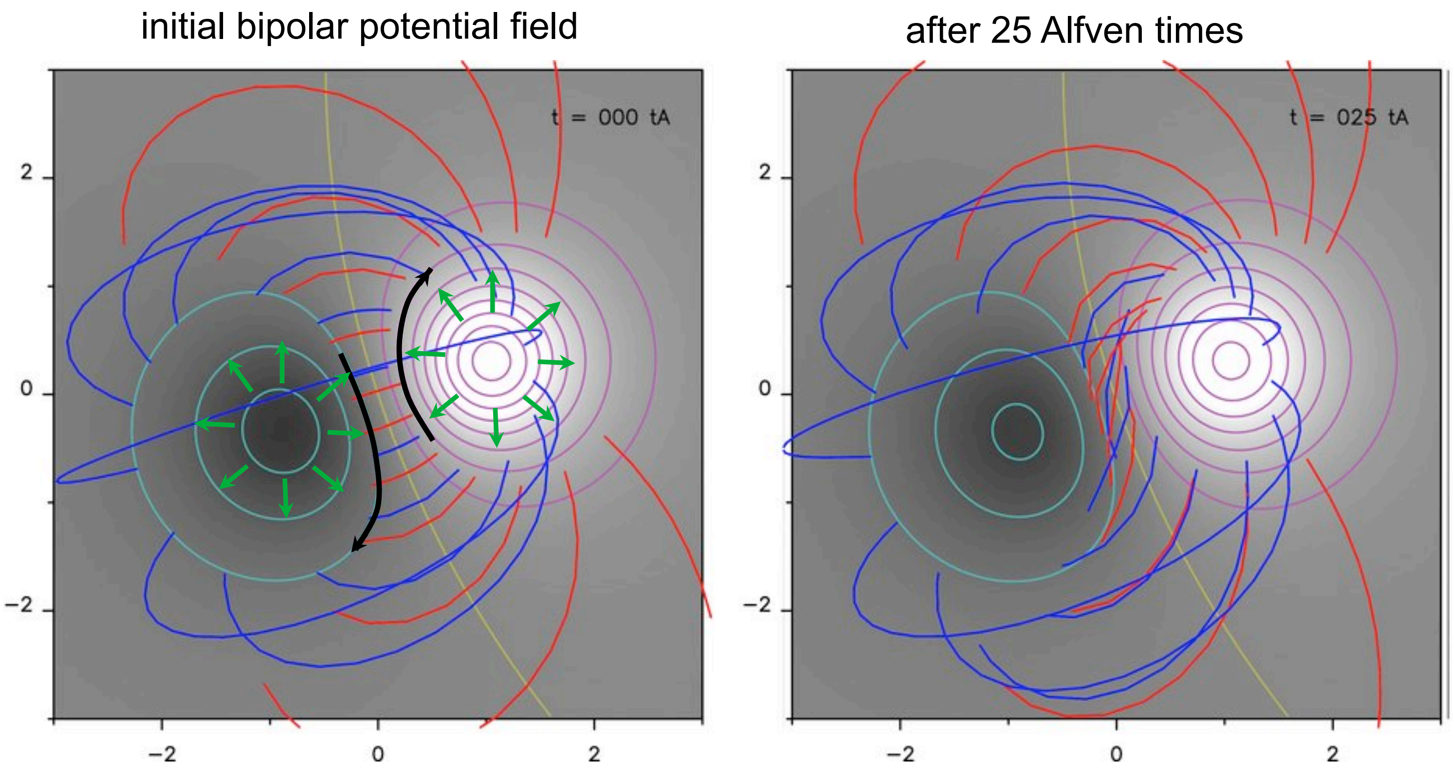
- Unloading ? The dense plasma mostly falls down after the prominence ejection starts
- Buoyant ? Different physics than in the convection zone: $(\rho - \rho_{ext})\, g \ll B^2/ 2\mu_0$

} not the mechanism !

- Low corona : low-β ($p \ll B^2/ 2\mu_0$) and sub-Alfvénic regime
  $B^2/ 2\mu_0$ dominates all other energies

eruption driven by magnetic forces

MHD simulation of CME launch



(Aulanier et al. 2010)

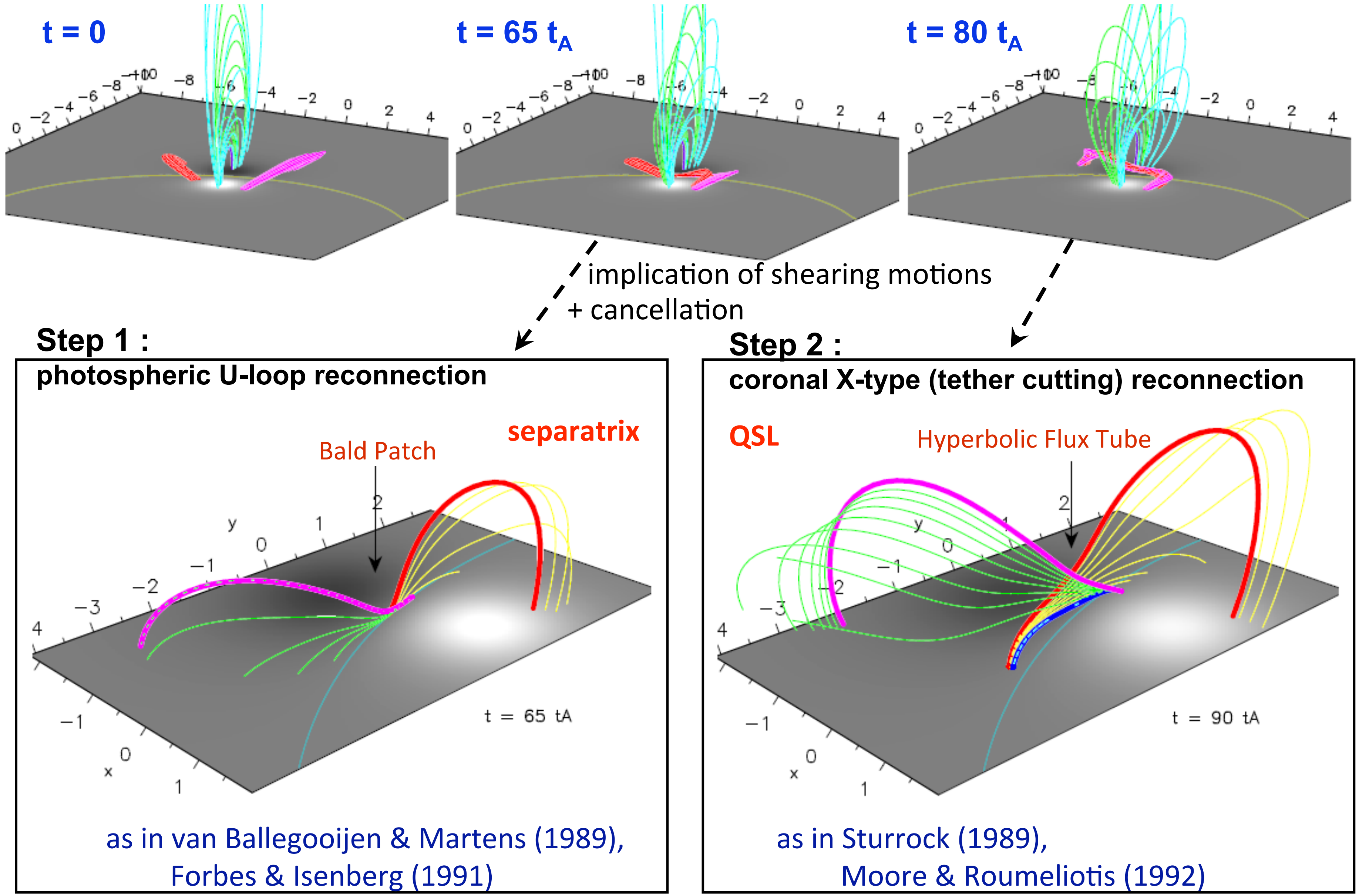
slow photospheric **shearing motions** & **diffusion of Bx,y,z**

build a strongly sheared arcade
+ photospheric reconnection
=> **build a flux rope**

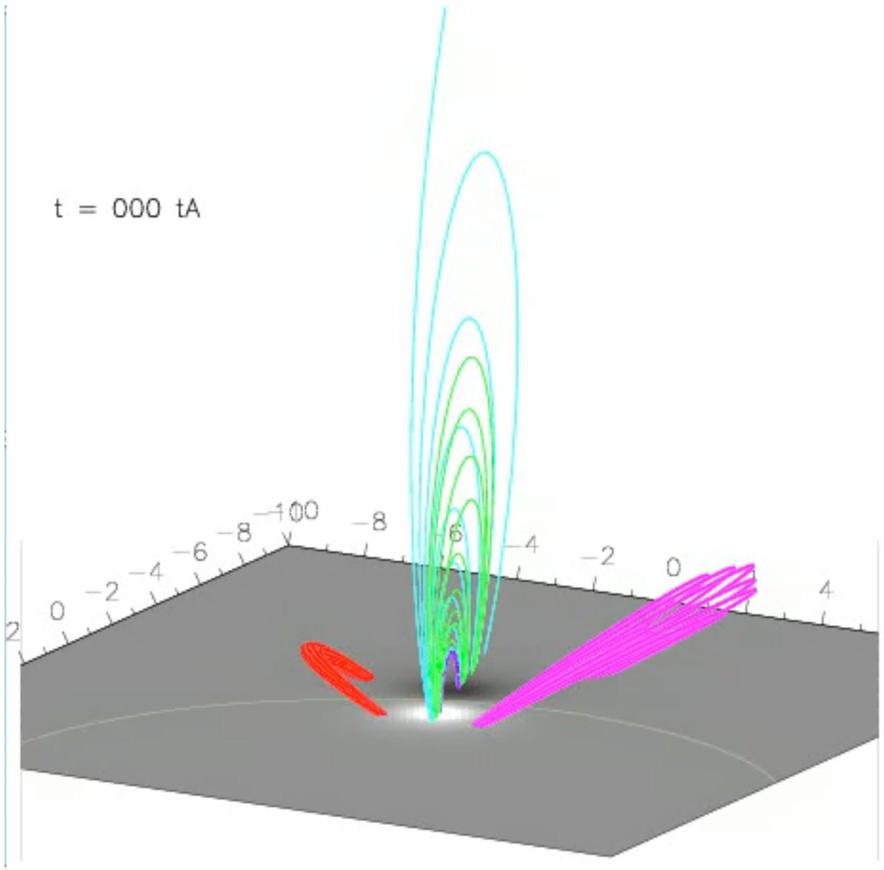
Similar to previous studies

(van Ballegooijen & Martens 1989, Forbes & Isenberg 1992, Amari et al. 2000, 2003, 2007, 2010, Fan & Gibson 2004, Mackay & van Ballegooijen 2006)

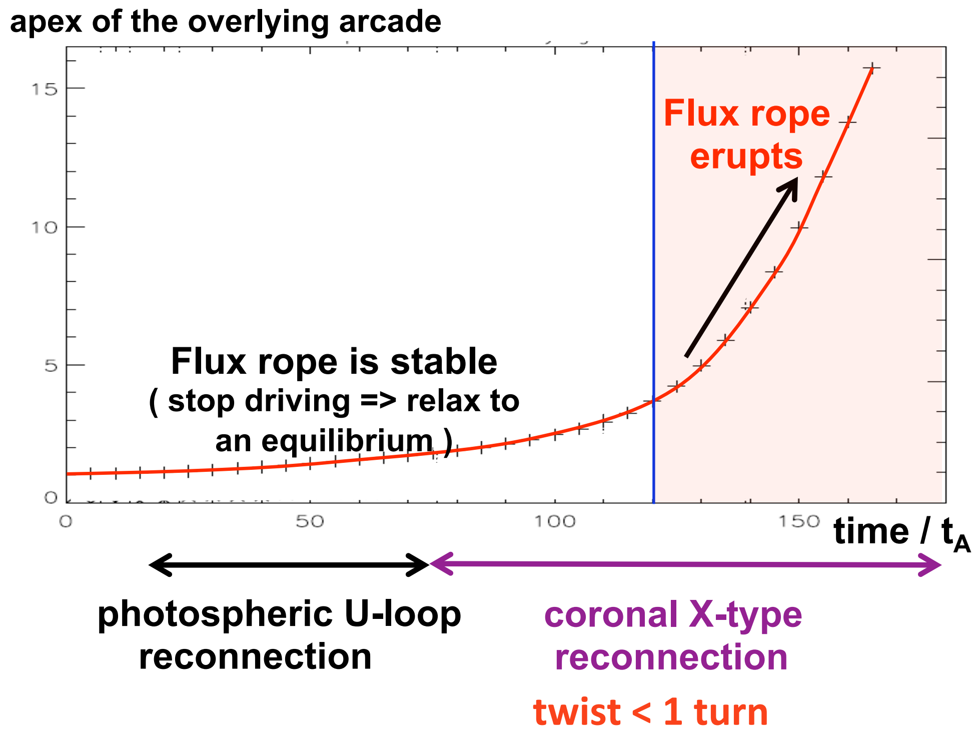
Flux rope formation and growth



Flux rope eruption & physical effects



When eruption starts :
max |B>0| ↘ by 50 %
max |B<0| ↘ by 30 %
B flux ↘ by 10 % only



Eruption is NOT caused by
- photospheric reconnection
- coronal tether-cutting reconnection
- loss of confining overlaying arcade

They are only responsible for rope formation and slow growth

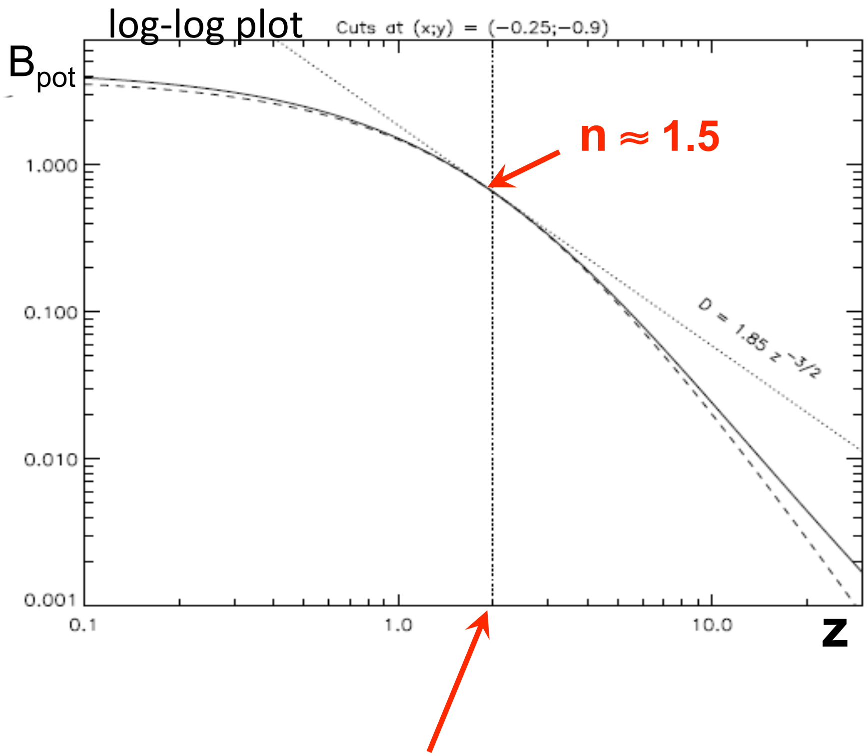
(Aulanier et al. 2010)

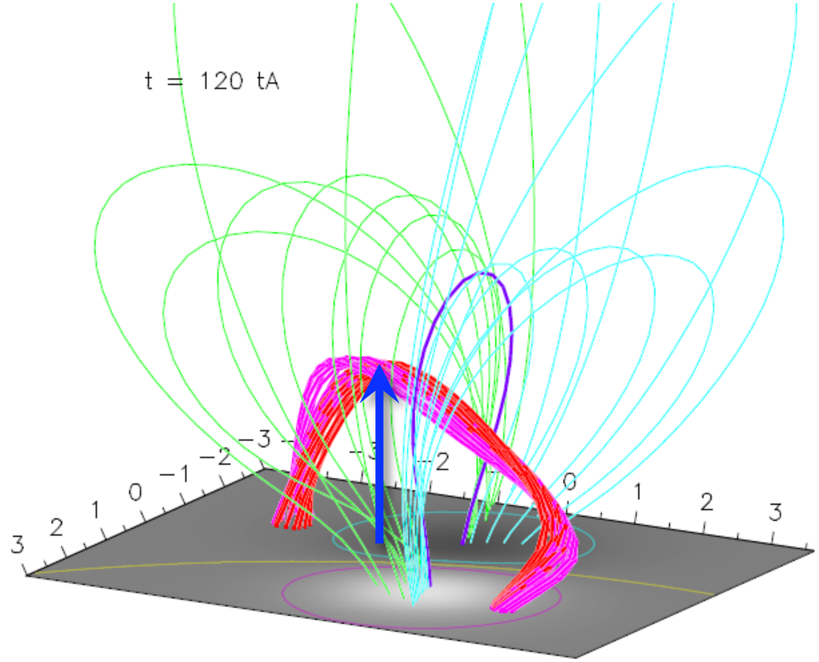
The role of the external field drop-off with height

At the eruption time, measure the critical decay index n(z) of the potential field B_{pot}

(approximation of the external field)

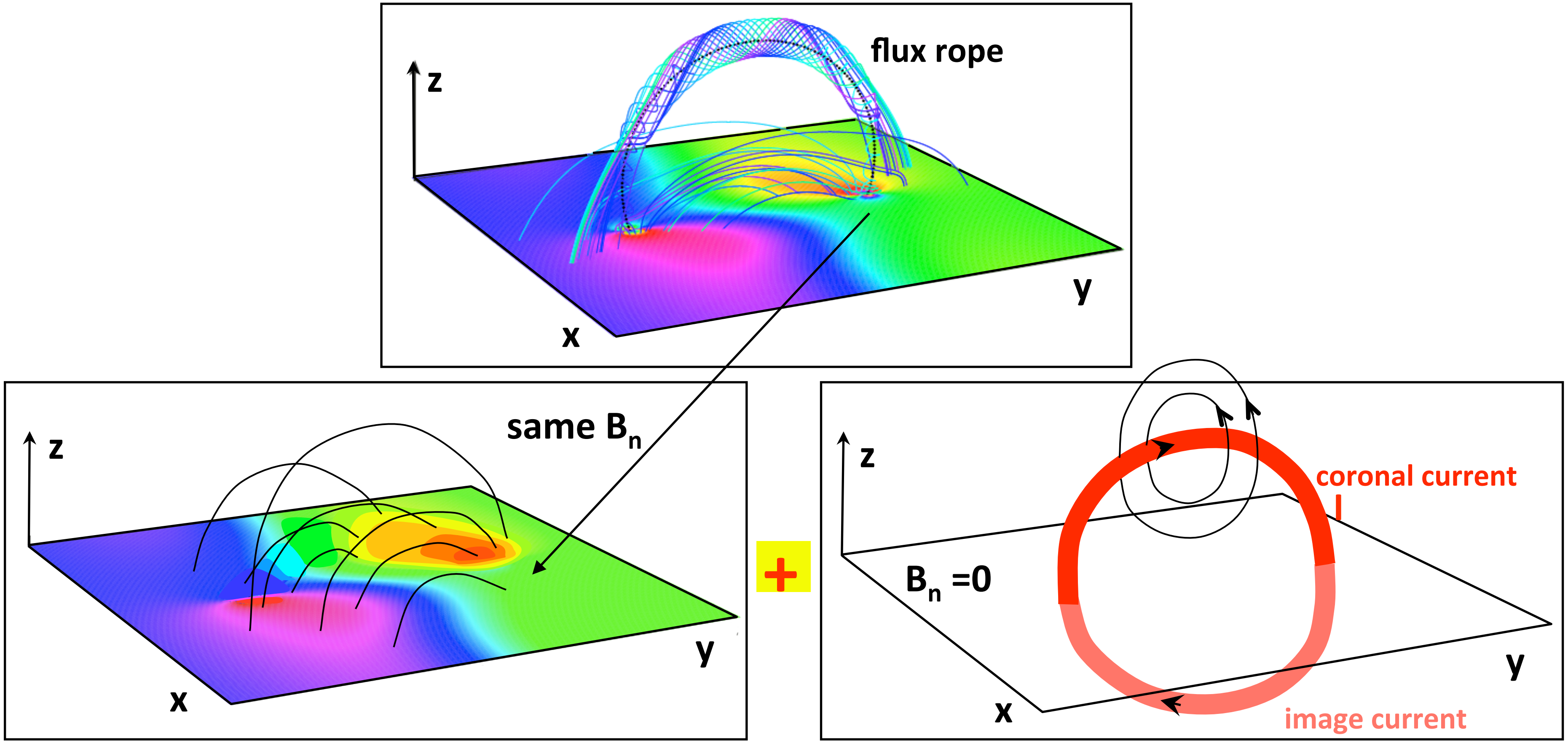
$$n(z) = - d(\log B_{pot}) / d(\log z)$$





Eruption occurs because the slowly rising rope eventually gets *unstable:* torus instability when $B_{phot} \propto z^{-1.5}$

Analytical model



potential magnetic field | **magnetic field created by the coronal net current + its image**

$$f_z = B_{pot,x}(h)\, I + r_c\, I^2$$

Laplace force due to potential field	image current + hoop force

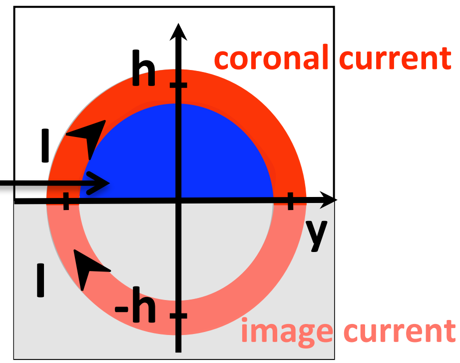
Bateman (1978), Kliem & Török (2006)
Isenberg & Forbes (2007)
Olmedo & Zhang (2010)

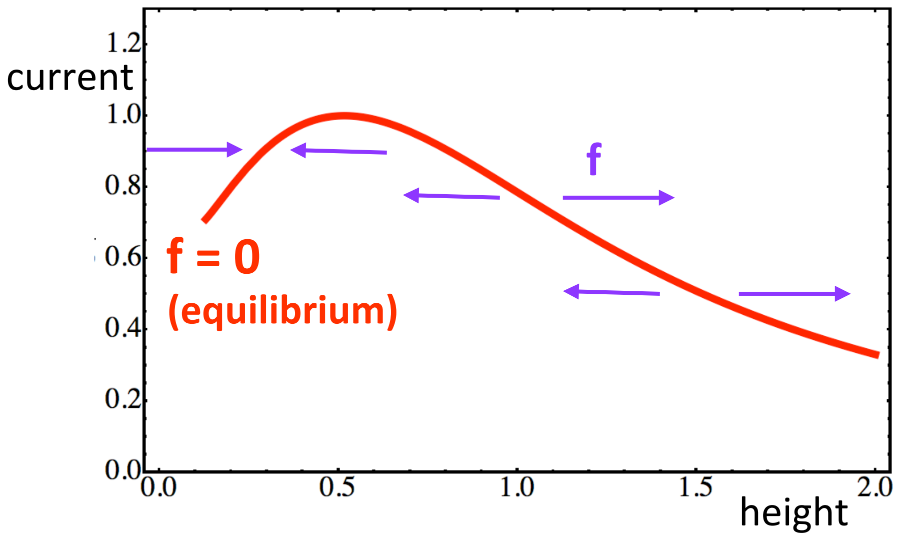
van Tend & Kuperus (1978), Molodenski & Filippov (1987)
Démoulin & Priest (1988), Martens & Kuin (1989), Forbes (1990),
Lin et al. (2001),

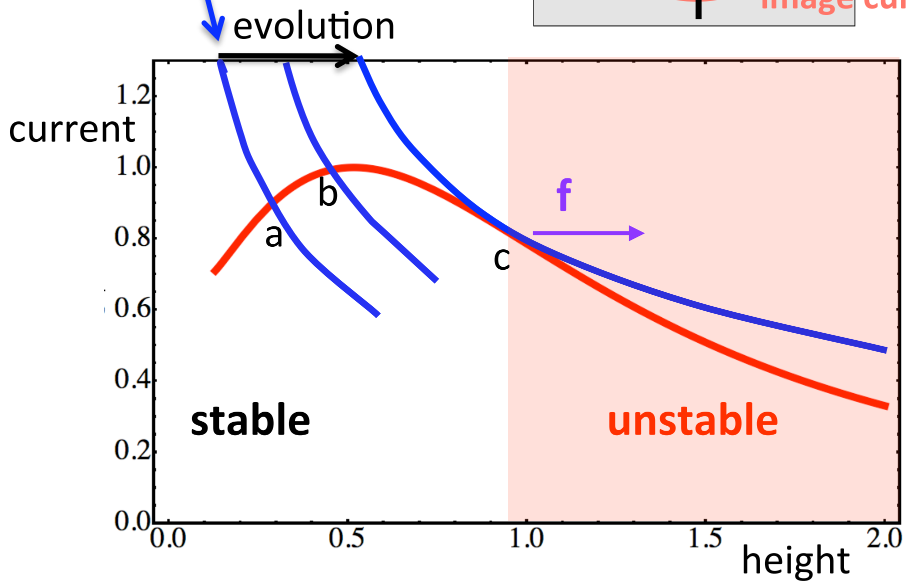
Loss of equilibrium <--> torus instability

evolution : e.g. by converging motions

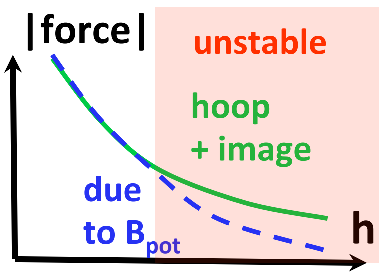
perturbation: ideal MHD : preserve the **B flux** between the flux rope and the photosphere







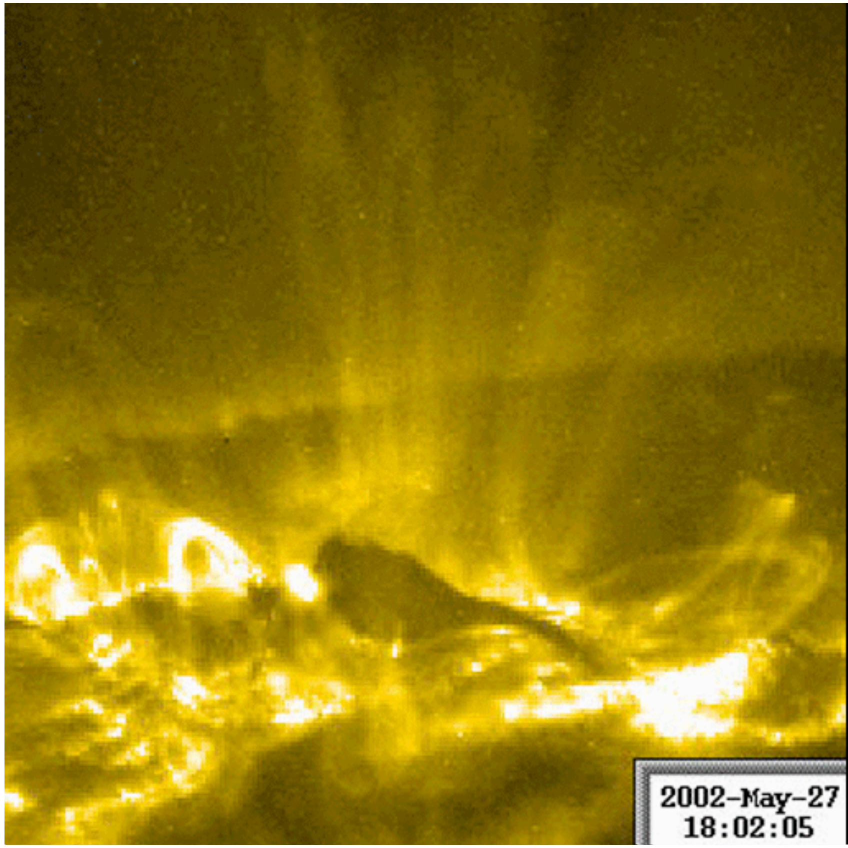
loss of equilibrium & torus instability
are two views of the same physical mechanism



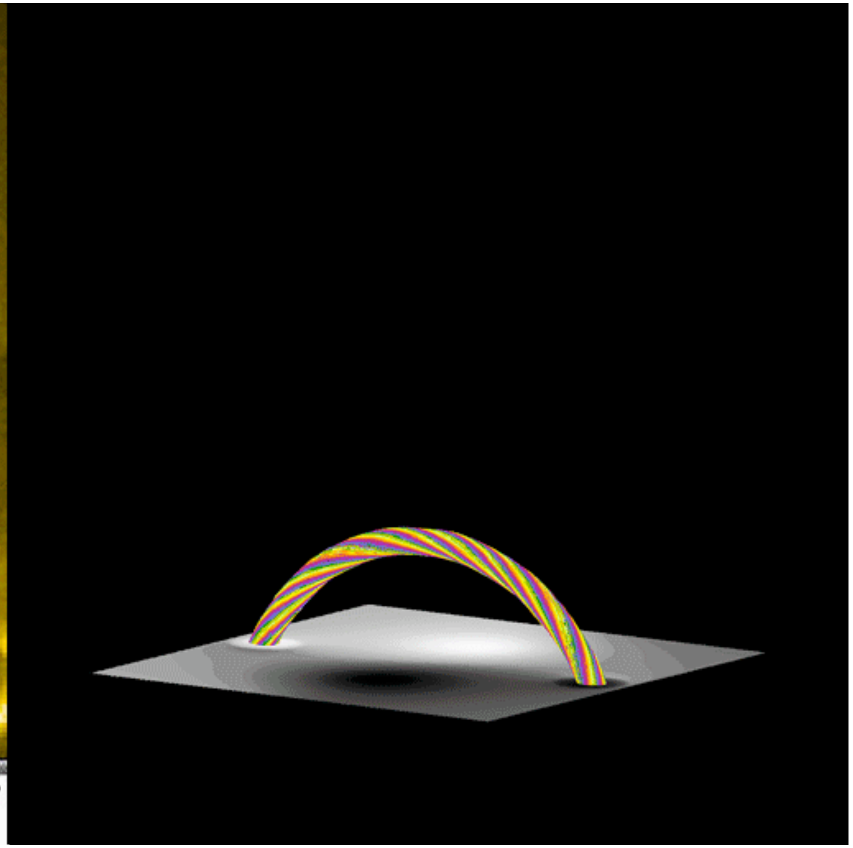
(Démoulin & Aulanier 2010)

Kink instability

TRAC E 195



MHD simulation



(Ji et al. 2003,   Török & Kliem 2005)

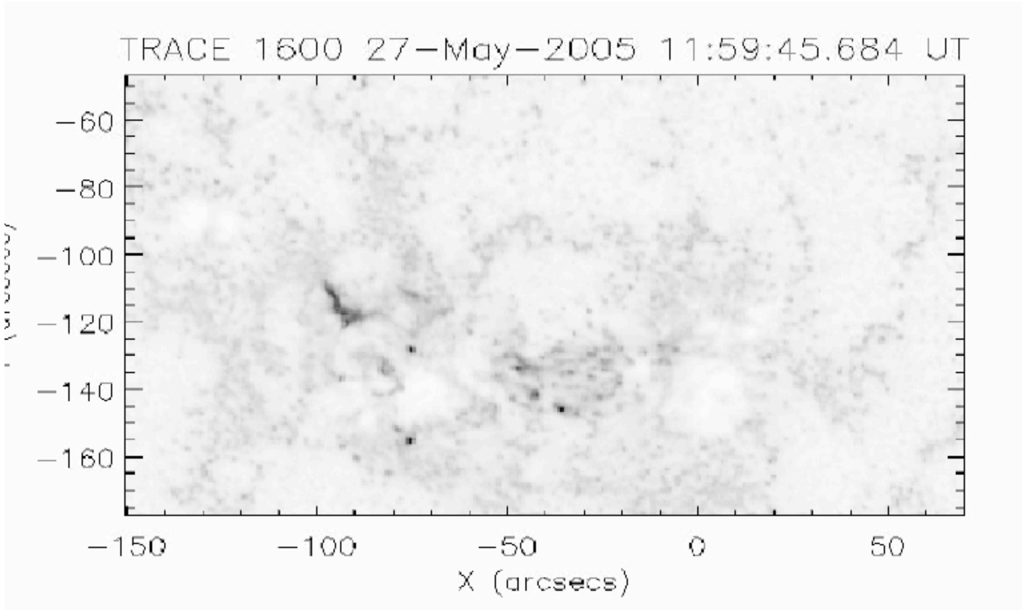
Instability present when :

twist > 2.5 to 3.5 π

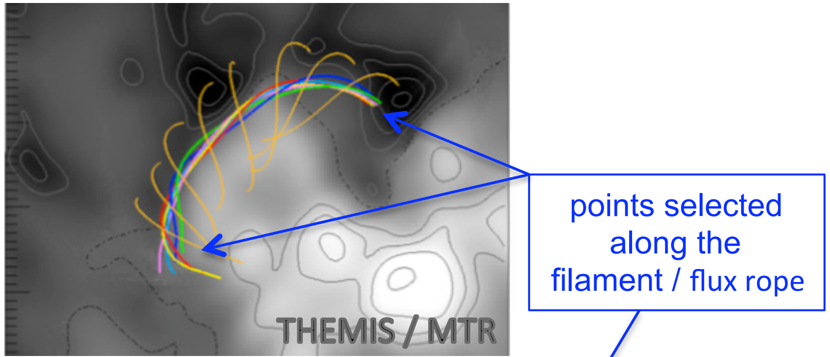
(Hood & Priest 1981, ... Amari et al. 1999,
Fan & Gibson 2004, Török et al. 2004)

-> Large writhing
(helical deformation of the flux rope)

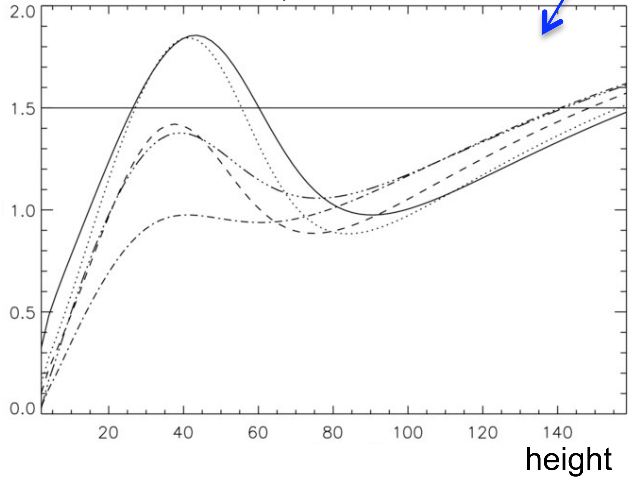
Kink instability: confined eruption



ribbons + filament eruption (writhing)



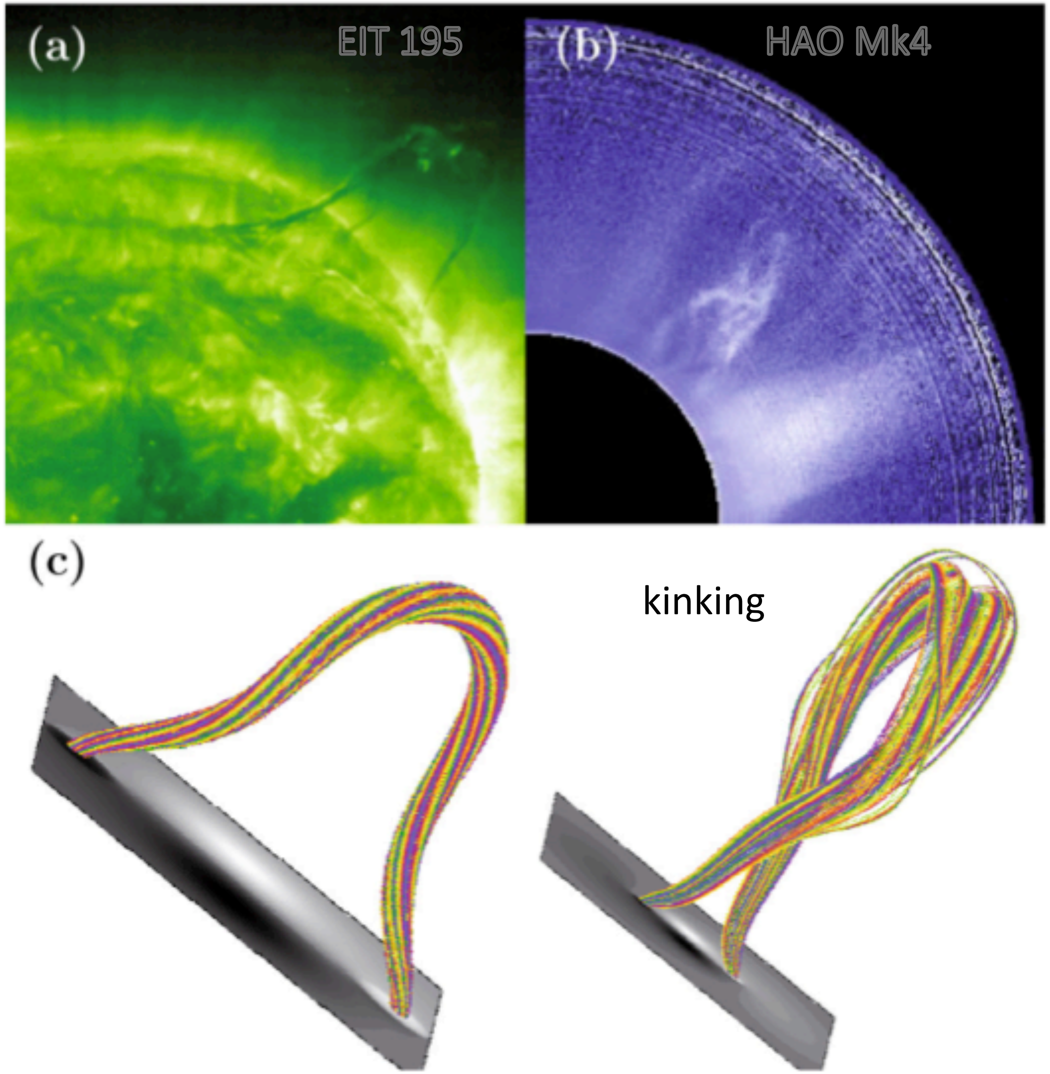
decay index = - d(log B_{pot}) / d(log z)



(Guo et al. 2010)

decay index too low
for loss of equilibrium / torus instability
=> **confined eruption**

Kink instability triggering a CME



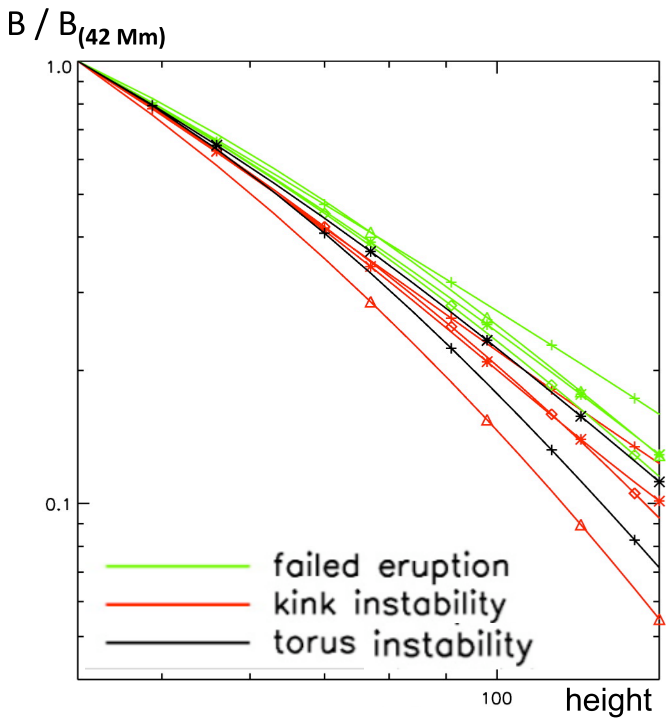
kink instability + upward perturbation
=> flux rope moving upward

If B decreases fast enough with height
=> loss of equilibrium / torus instability

the kink instability could bring the flux rope high enough to trigger the loss of equilibrium / torus instability
=> CME

(Török et al. 2010)

Testing the field decay index for eruptions



(Liu 2008)

- compute the potential field of eruptions,
- how does it decrease with height ?

failed eruptions :
decay index < 1.7
successful eruptions :
decay index > 1.7

Theory:
loss of equilibrium / torus instability
if decay index > 1.5 to 1.9

(Kliem & Török 2006,
Fan & Gibson 2007,
Aulanier et al. 2010)

(eruptions studied by: Williams et al. 2005,
Green et al. 2007, Schrijver et al. 2008)

Also: stronger field (factor 3) at low altitude
in **failed eruptions**
compare to **successful eruptions**

Simplified conclusion

- diffusion of B photospheric
- cancellation of flux at/above the inversion line
- increasing B shear

} build up a flux rope

- emergence of small bipoles
- lateral reconnection
- quadrupolar reconnection

} weaken the overlying arcade

Evolution of the configuration
Not the eruption mechanism

- kink instability — alone : failed eruption

- loss of equilibrium
- torus instability

} same physics, main eruption mechanism

<u>During the eruption</u>: large amount of flux reconnected below the flux rope
=> further build up of the flux rope
observed in situ as a magnetic cloud (or a hot flux rope)

To test with more examples / challenge with SDO/AIA and other instruments !

END