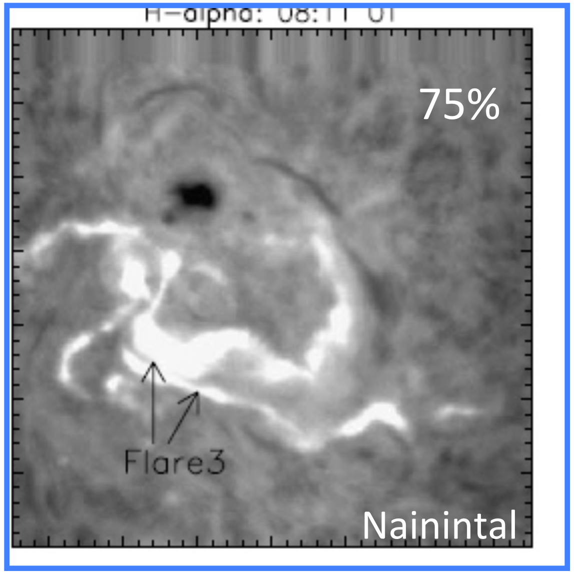
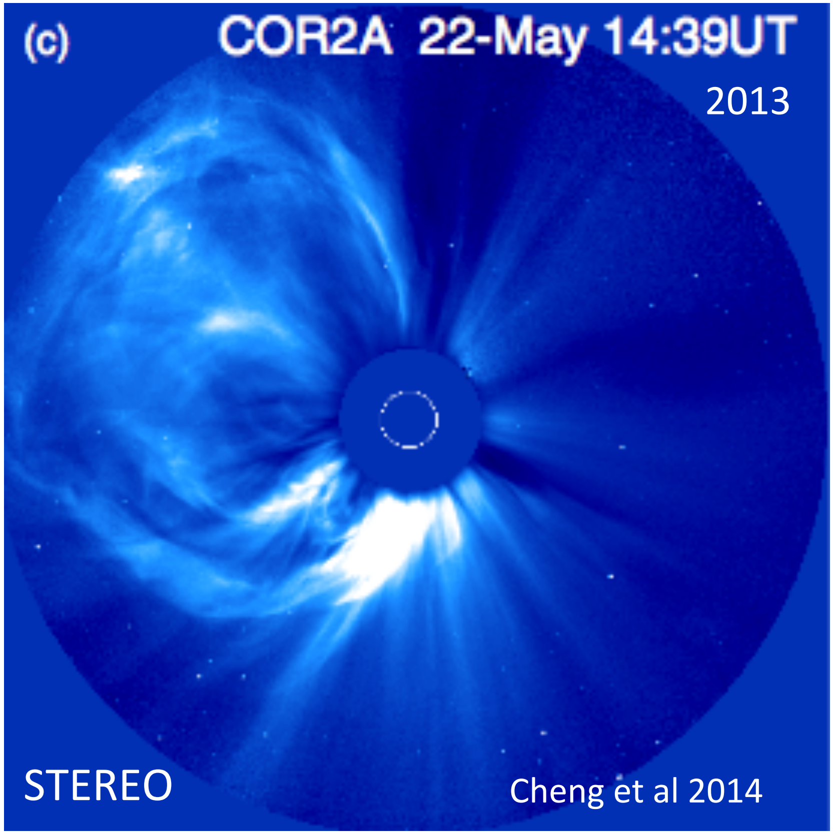
Flare-CME: triggering mechanisms

B.Schmieder

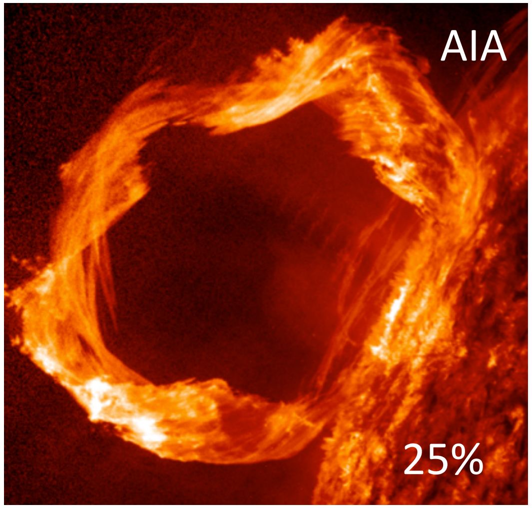
Observatoire de Paris, France

Collaboration: G.Aulanier





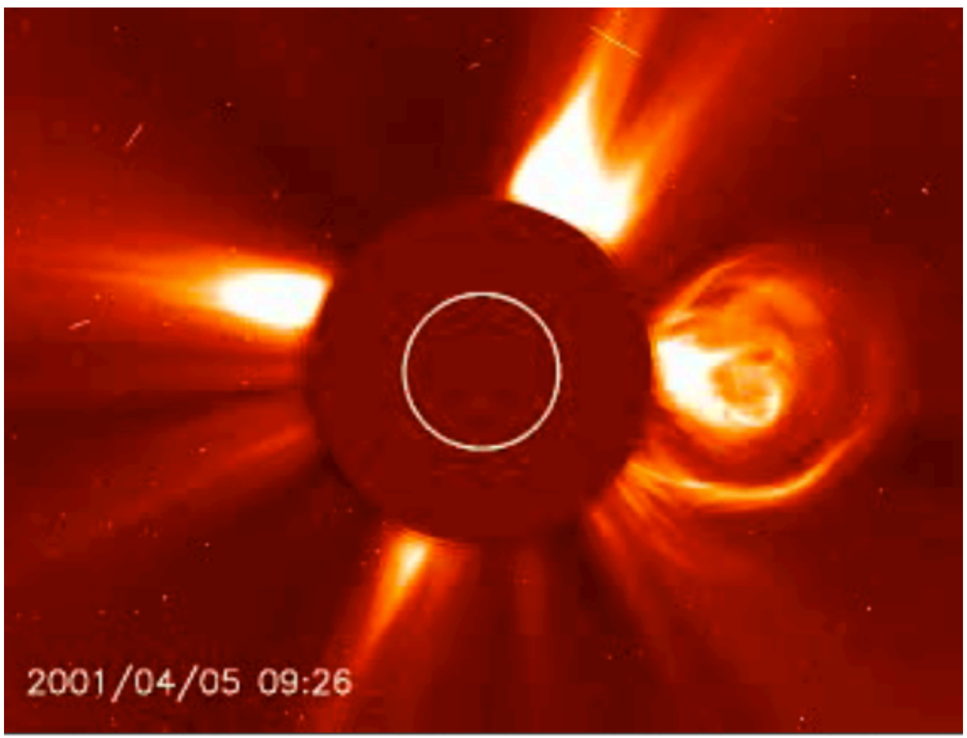
Statistics:
Subramanian &Dere 2000,Bein et al 2011,
Reviews: Chen 2011, Webb2012,Aulanier2014

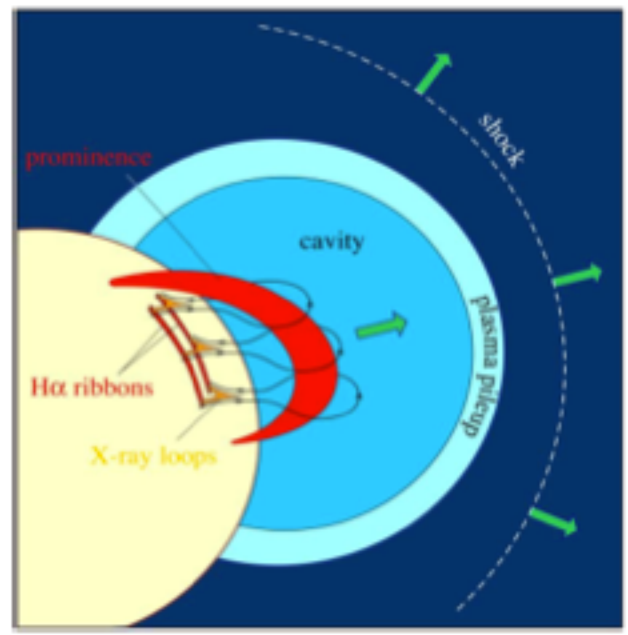


Nature of the CME

Observations in white light from the photospheric radiation
Thomson-scattered by free electrons in the corona,

Three parts (Schwenn 2006): Core (filament..) ,Cavity; weak density
Front : pile up of mass due to compression (Forbes 2000)

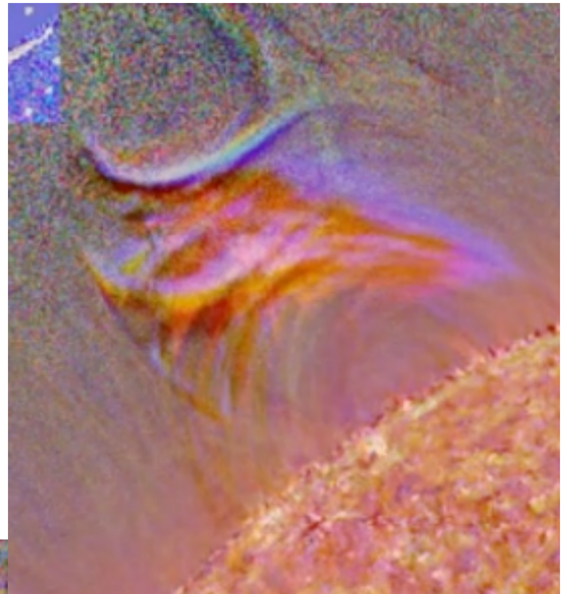


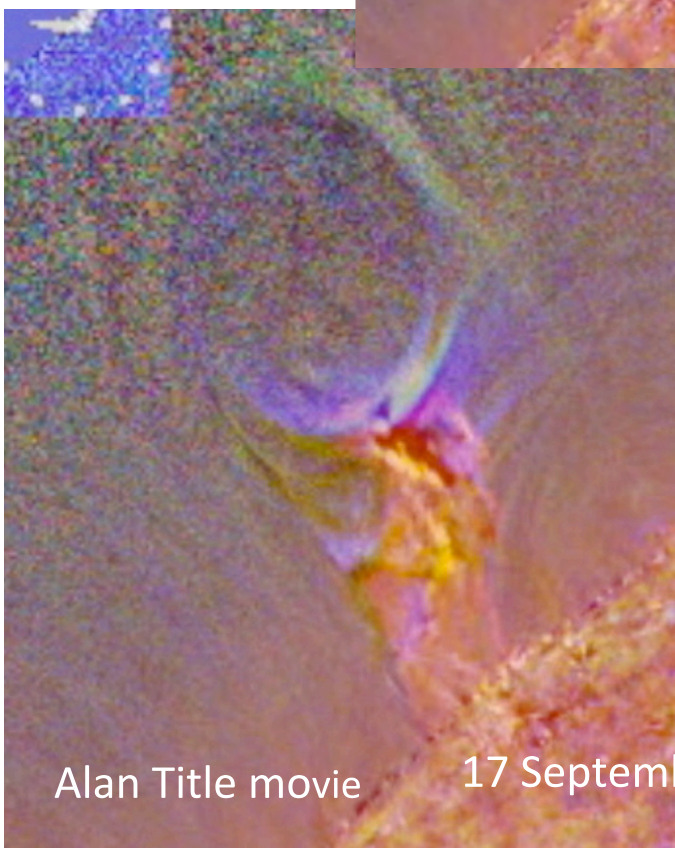


Forbes 2000

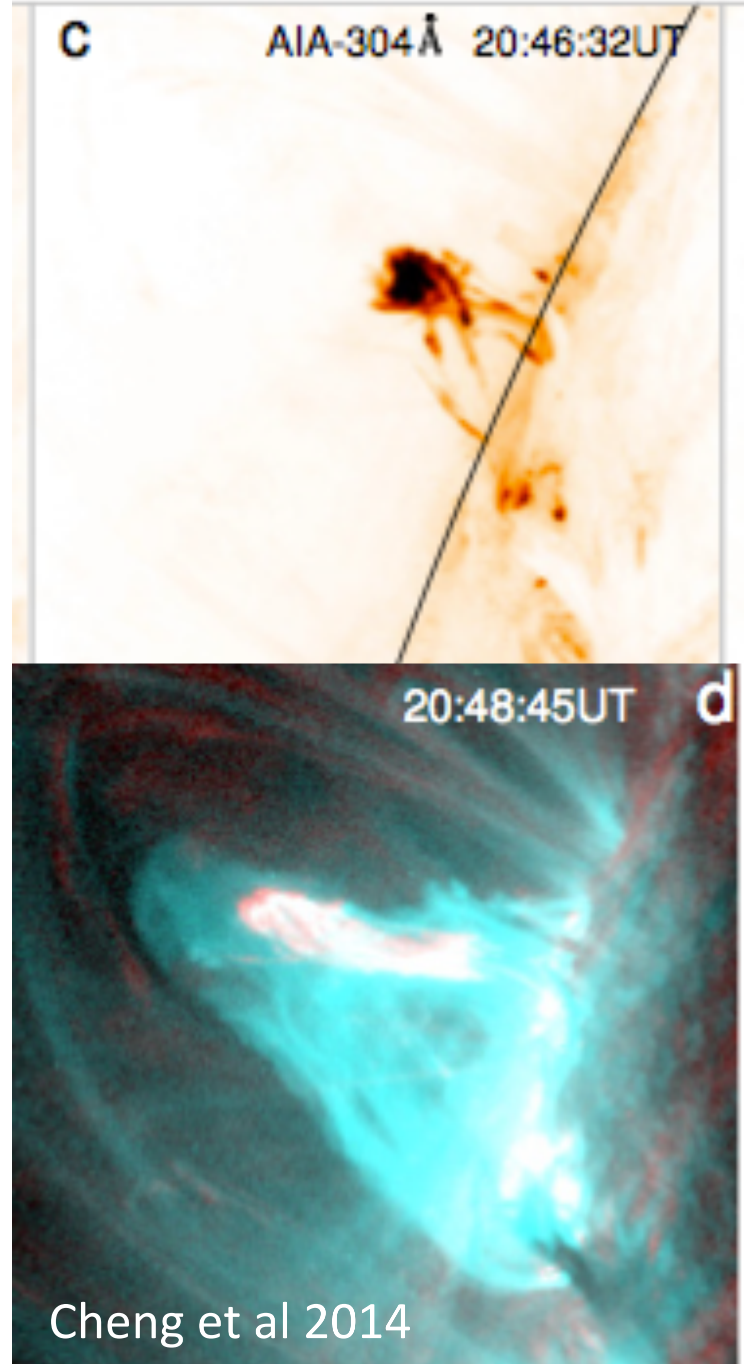
Flux Rope

AIA filters





Eruption



Flux Rope

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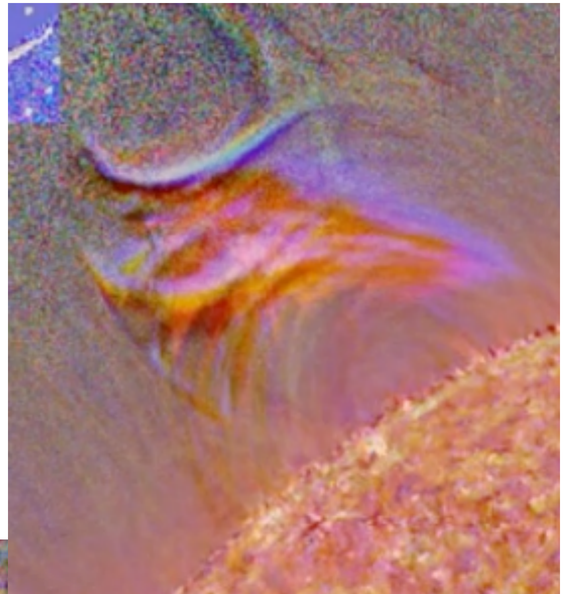

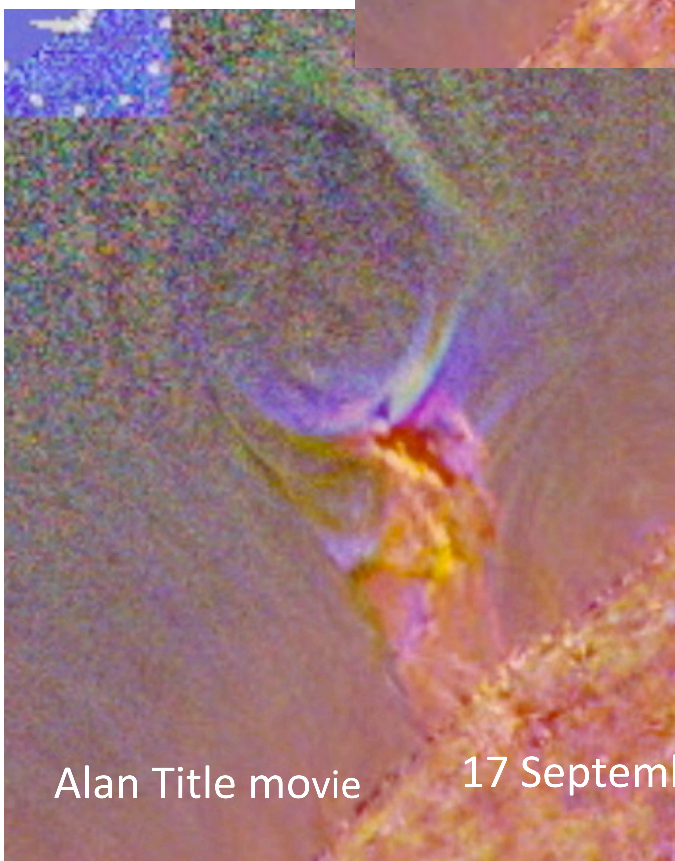

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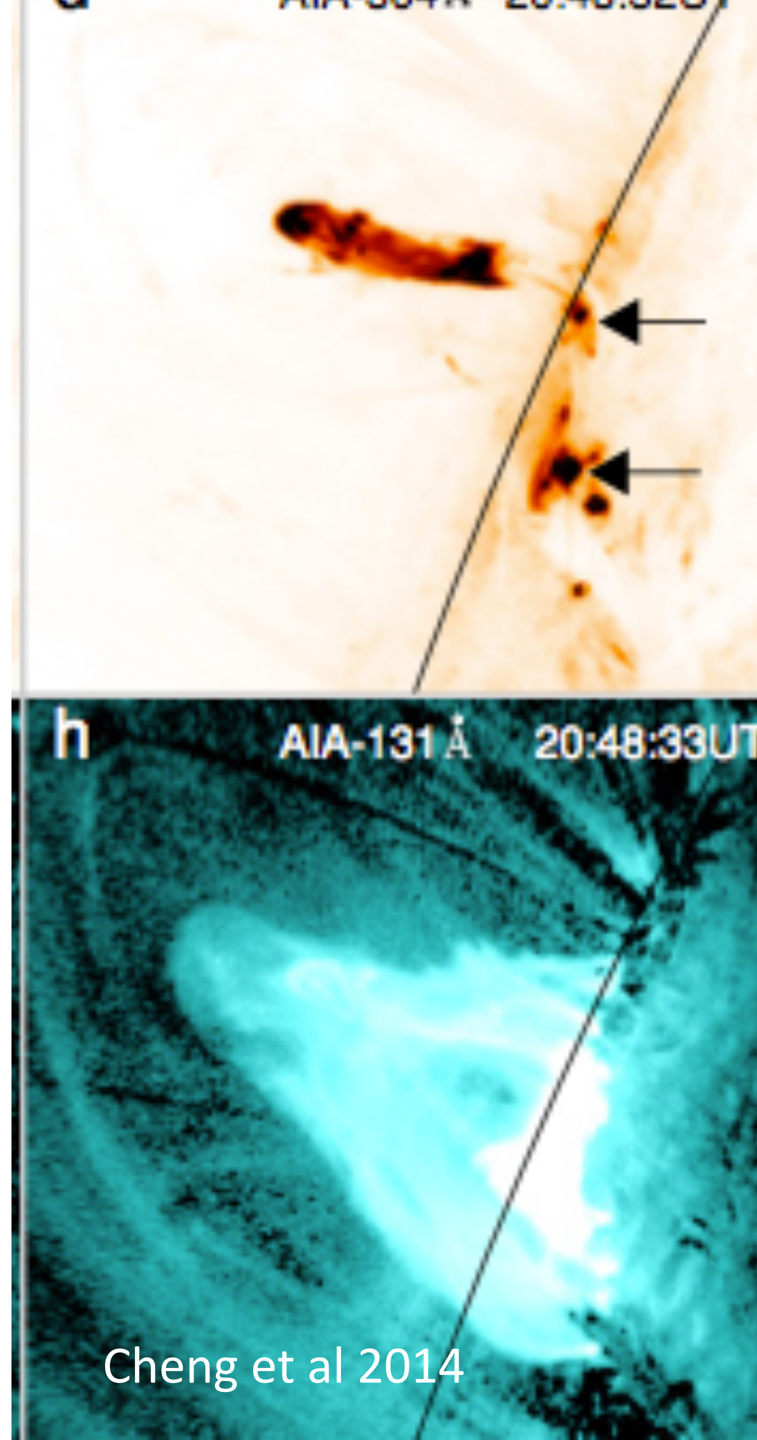
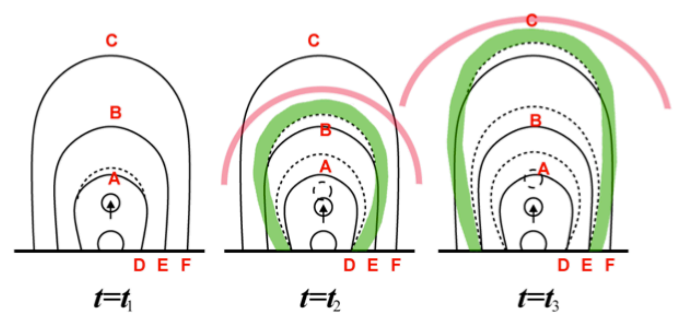


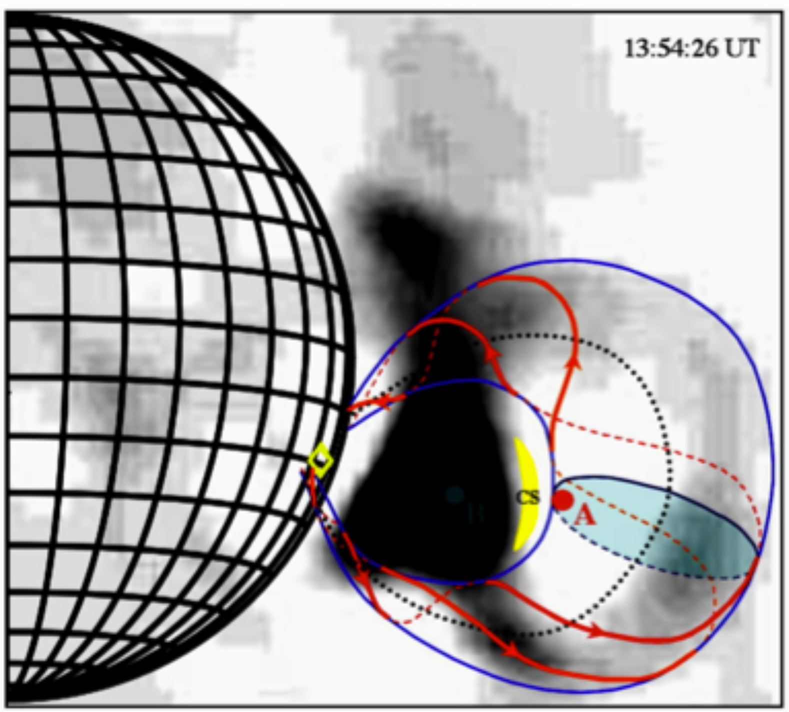
Flux Rope- radio CME

EIT wave and CME front are cospatial.
Compression over each loop
responsible of the density enhancement

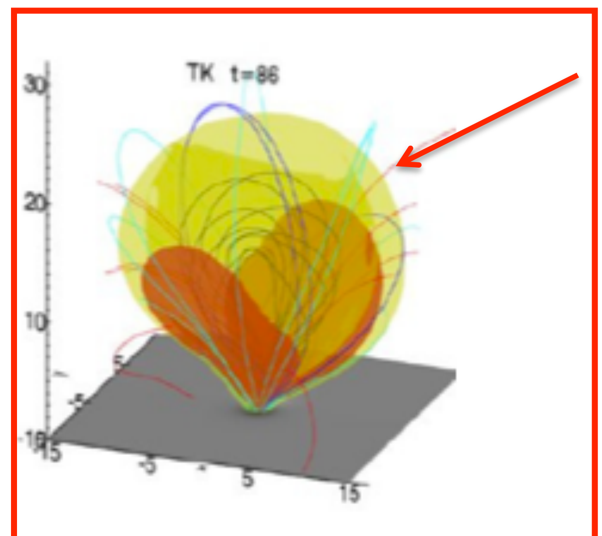
Compression



Chen 2011



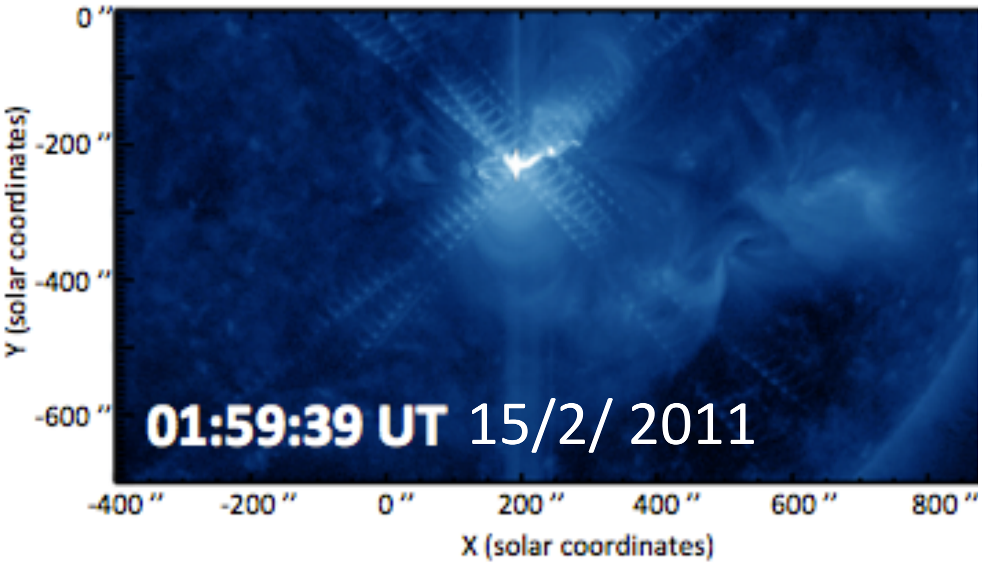
Demoulin, Pick et al 2012,

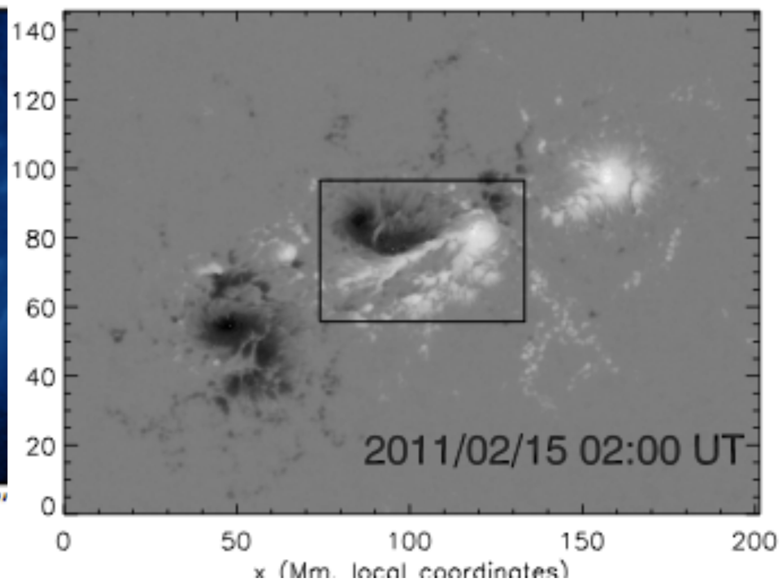


Current-
shell:
Front edge
of the CME

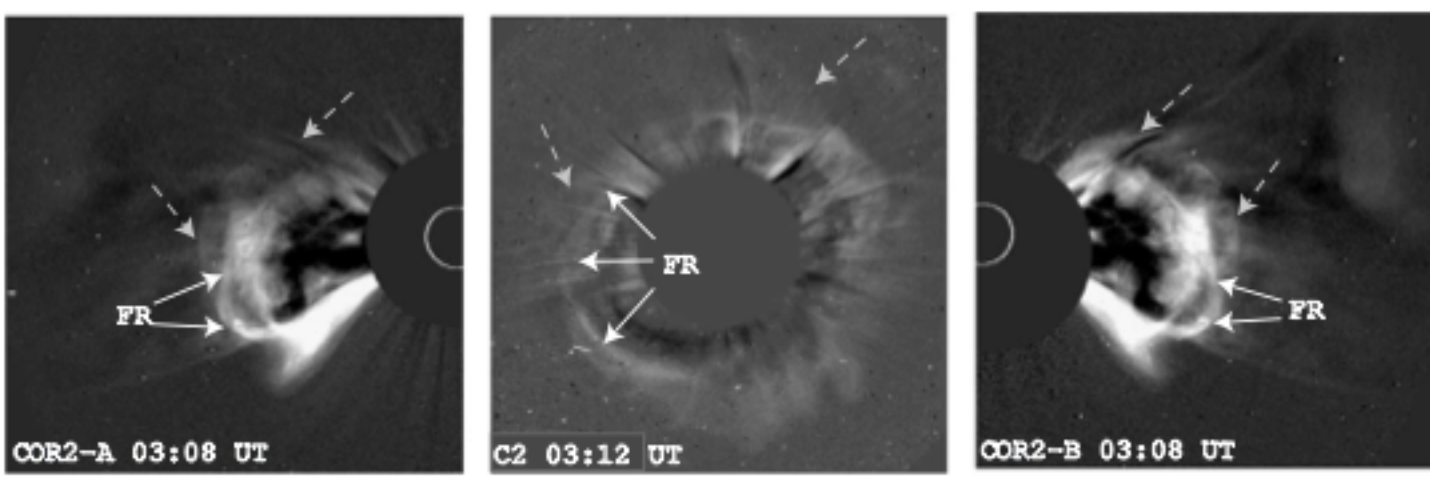
Delannee et al 1999, 2008, 2014

Halo CME in LASCO





Janvier et al 2014



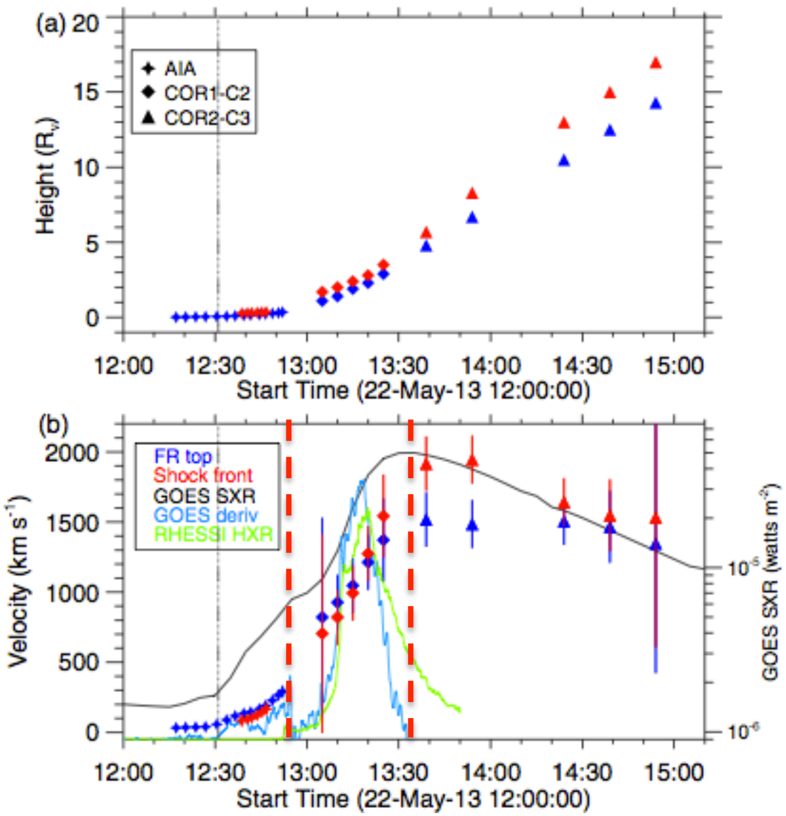
15 February 2011

Vourlidas et al 2013
Schrijver et al 2011

Properties of CMEs

Chen P.F. 2011

Velocity of the CME compared to SXT (GOES)   from 20 to 2000 km/s.



It depends on the magnetic field strength (Alfven speed) and the total reconnection flux

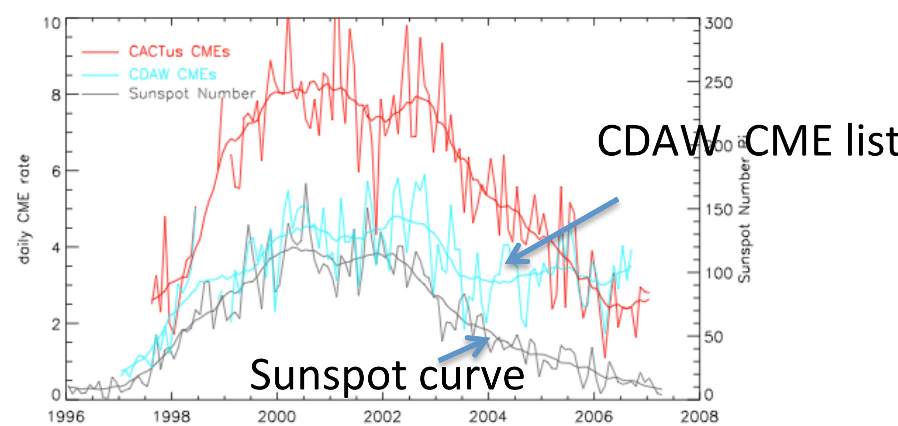
Accelerated or decelerated in the Solar Wind

Mass 0.1-4 10**13 Kg (Gopalswamy and Kundu 1992, Vourlidas 2002, 2013)

Occurrence rate 0.5 during minimum activity
6 during maximum activity

Impulsive phase

Cheng et al 2014, Zhang et al 2001



What did we learn from modeling eruptions ?

- The clear & physical **eruption**
- **driving** mechanisms

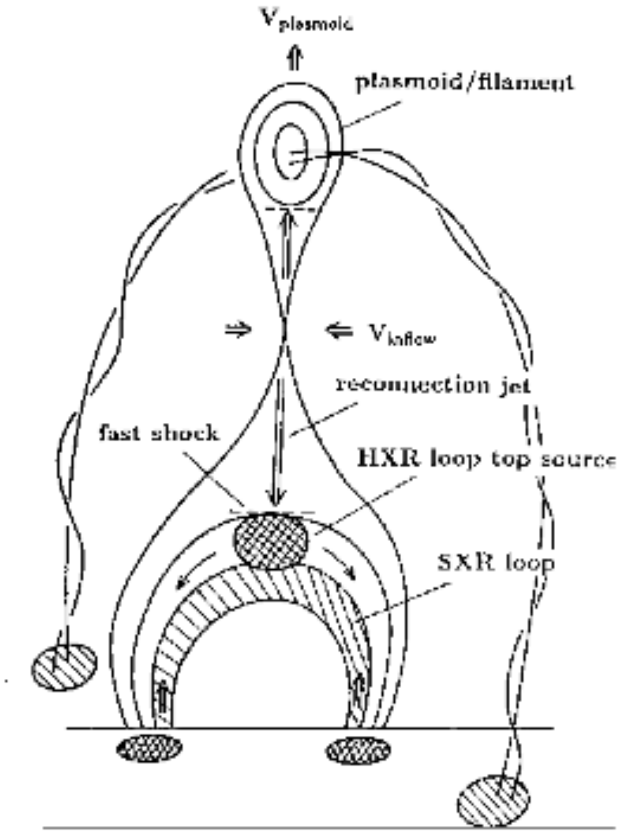
1. Breakout reconnection above rope

2 Localized flux decrease

3 Torus instability

- Phenomena that could also **drive**

  - Side reconnection
  - Tether-cutting from below
  - Converging motions (ideal)
  - Twist emergence into B-free/weak corona-kink
  - Flux cancellation through B^{phot} diffusion



Shibata 1998

Free energy and twist , currents, shear , decrease the tension

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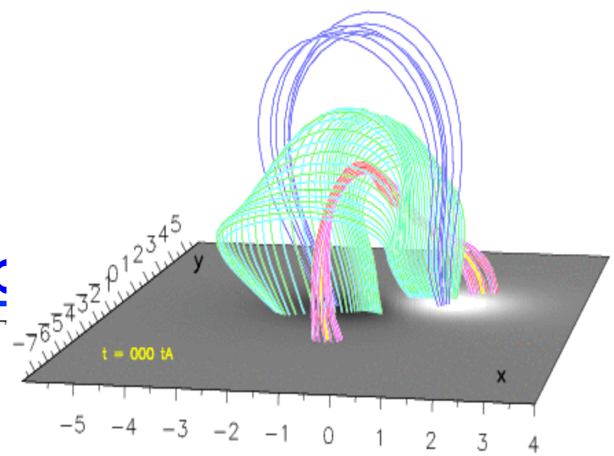

(Aulanier, Török, Démoulin & DeLuca, 2010)

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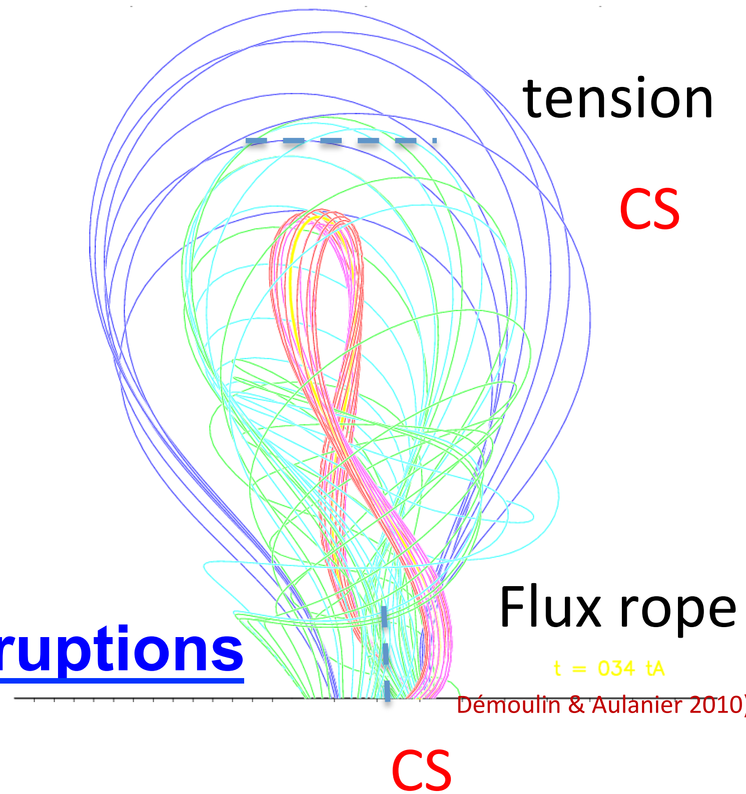

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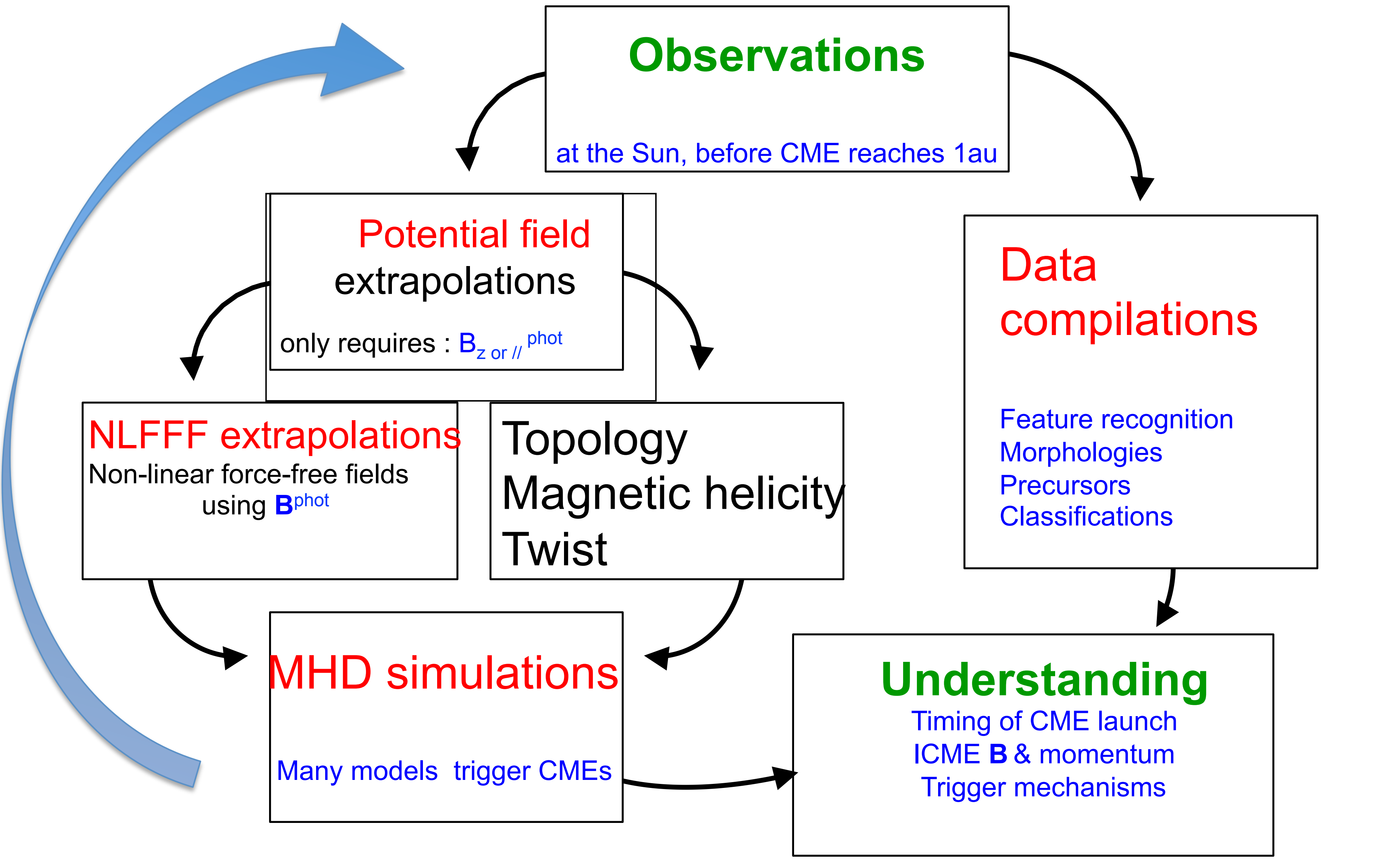
Free energy and twist , currents, shear , decrease the tension

What are the constraints given by the Observations ?



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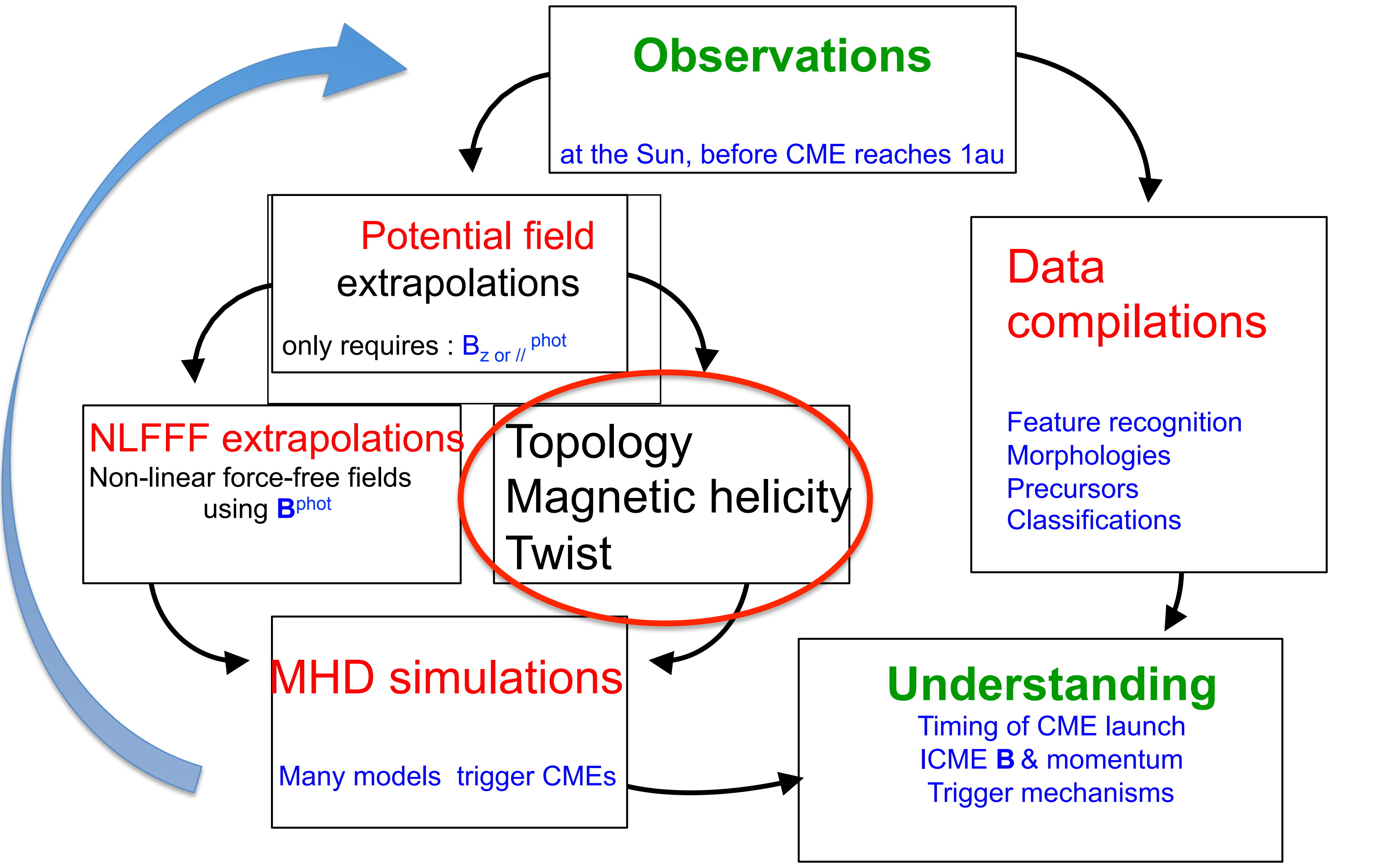
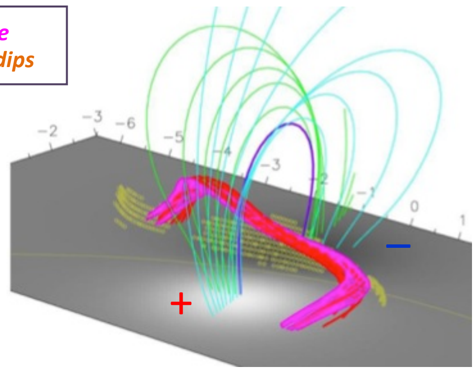
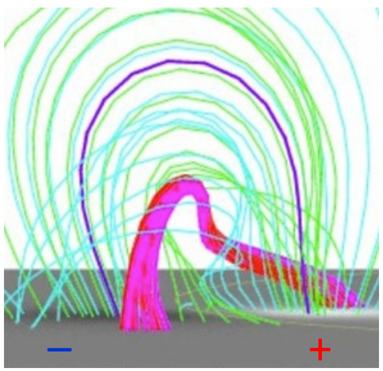


1. Clear-cut evidences of J // B in three different events

Flux rope
Magnetic dips



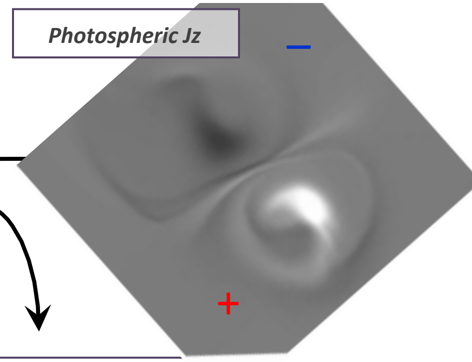
Tear-drop shaped arcades

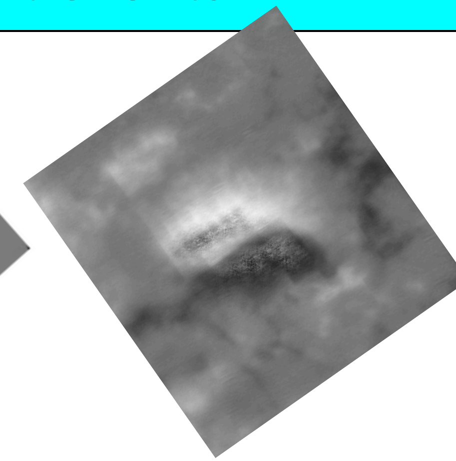


Aulanier et al. (2010)

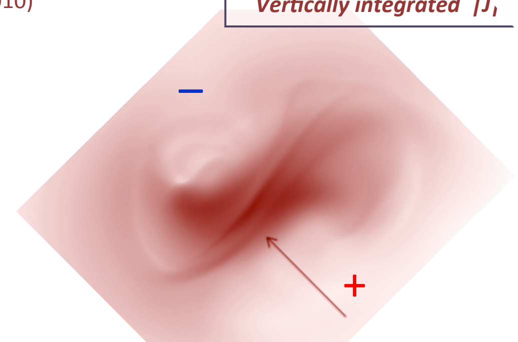
MHD simulation
sheared bipole

Photospheric Jz

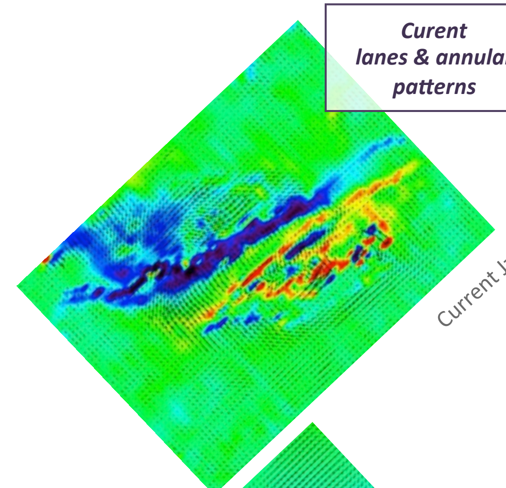




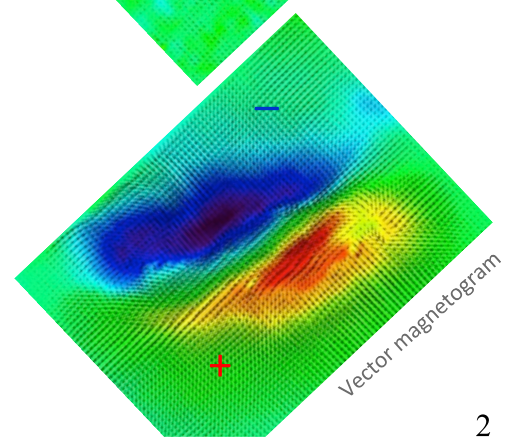
Vertically integrated |J|



Curent lanes & annular patterns

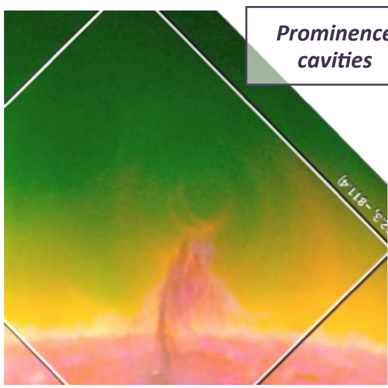


THEMIS / MTR



Canou et al. (2009),Li et al 2008

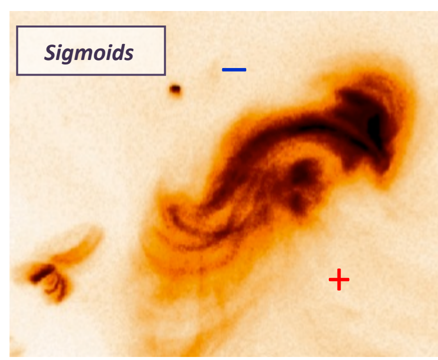
Prominence cavities



SDO / AIA
EUV 211A, 171A, 304A

From « suntoday » web page

Sigmoids

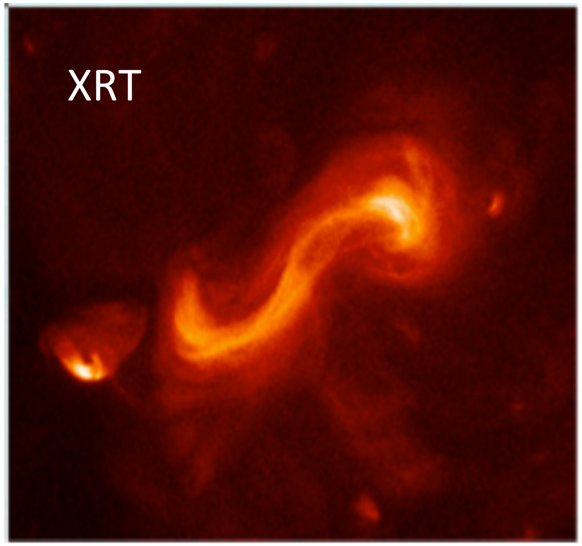


Hinode / XRT
SXR Al-Poly filter

McKenzie & Canfield (2008), Savcheva et al. (2009)
Green & Kliem (2009)

l'Observatoire de Paris | LESIA

Formation of current-carrying B fields



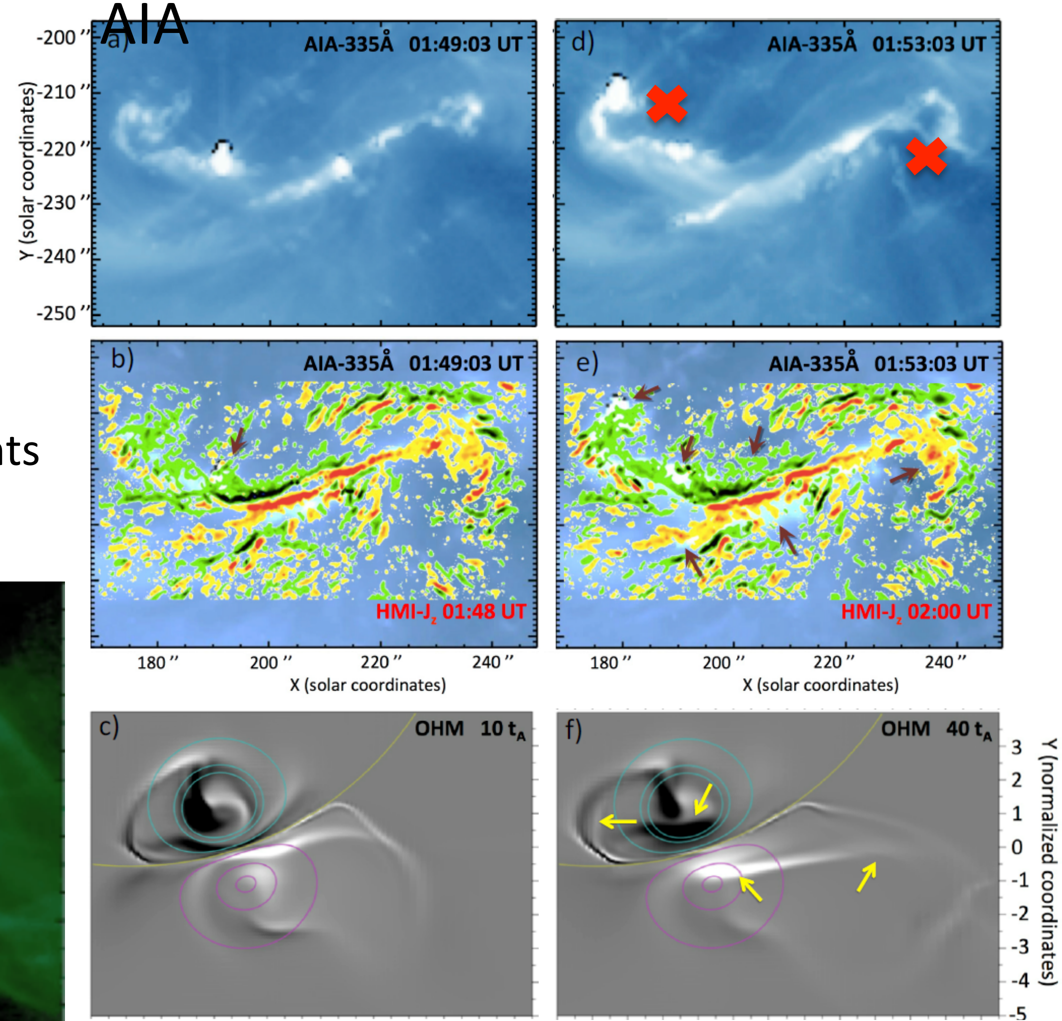
Savcheva, Pariat,van Ballegooijen, Aulanier & DeLuca (2012)

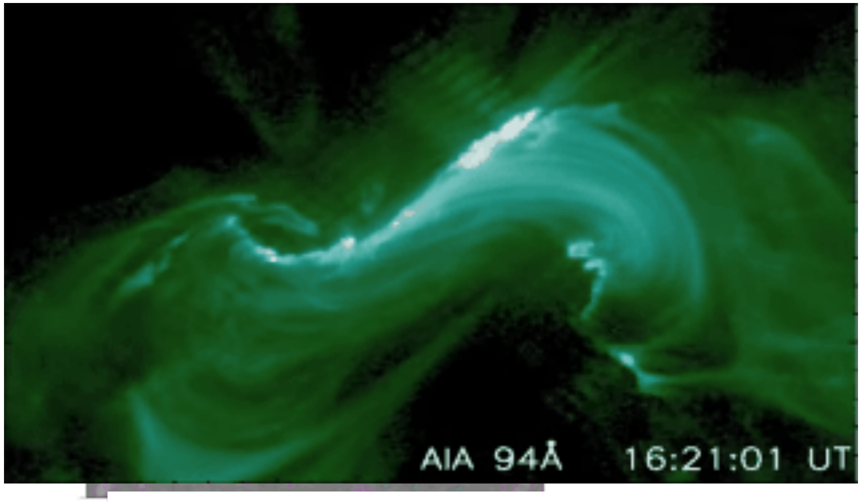
On the disk: J, Sigmoids

15 February 2011

AIA

Currents (HMI)





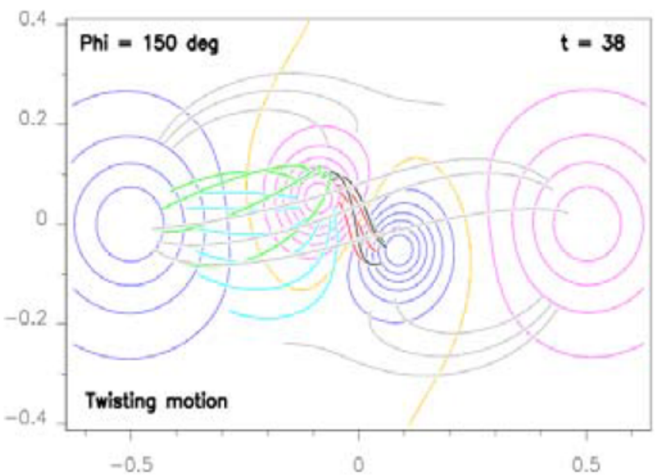
Dudik et al 2014

Janvier et al 2014

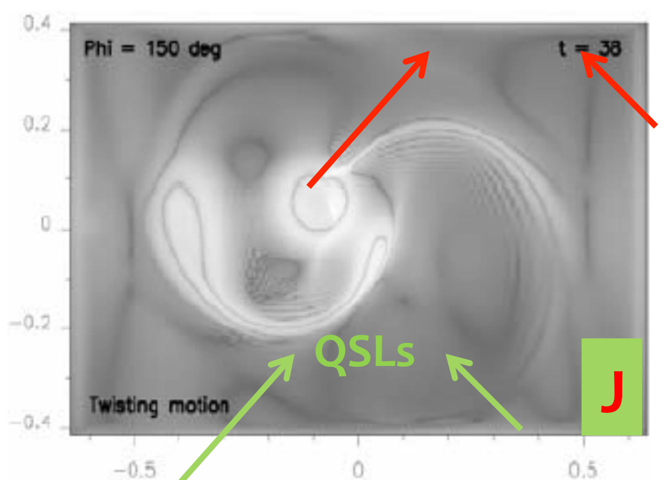
Efficient energy release in 3-D magnetic configurations

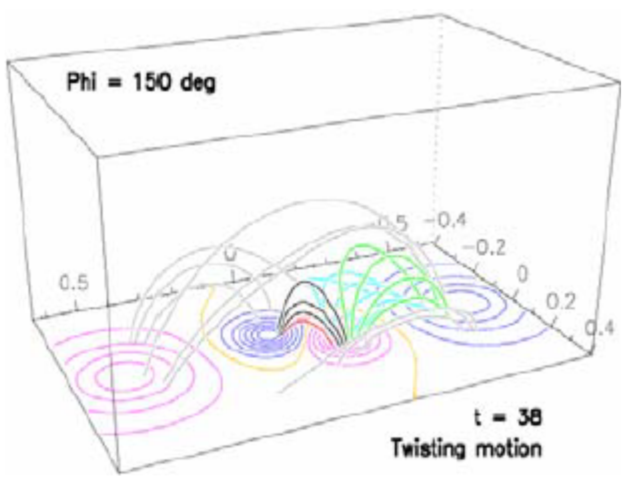
Topology

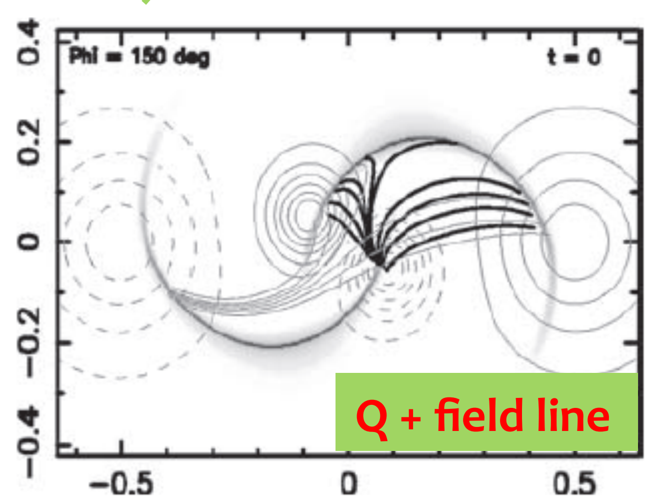
Aulanier, Pariat and Demoulin 2005



Current sheet







Separatrices:
-sites of connectivity of the field lines
-sites of intense currents
-sites of reconnection
(Faster on the Alfven time scale)

Quasi separatrices (QSL)

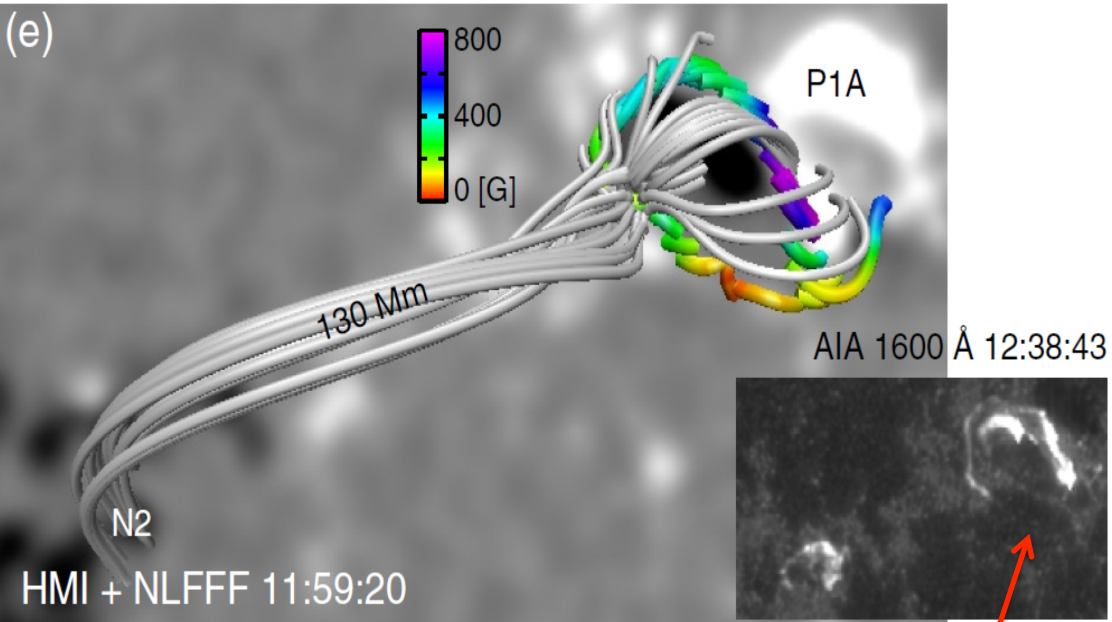
Parameter:
Squashing degree Q

Hyperbolic flux tube volume

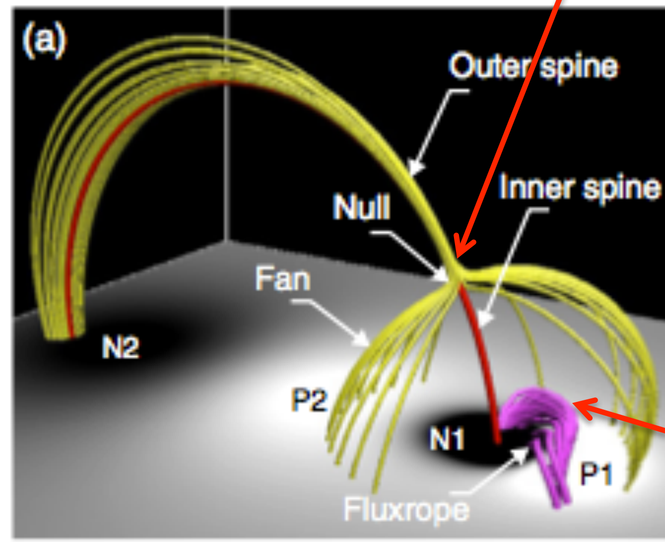
Efficient energy release in 3-D magnetic configurations

Classical locations: null point, separatrices

Null point

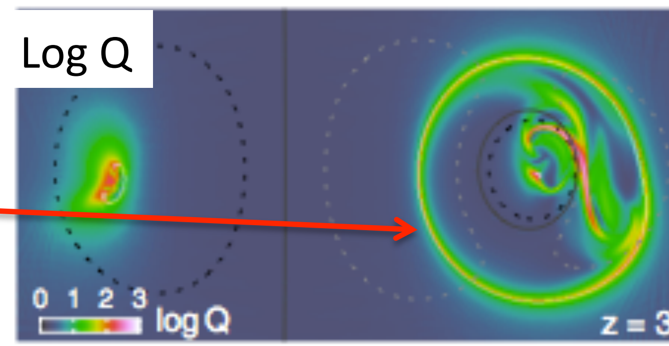


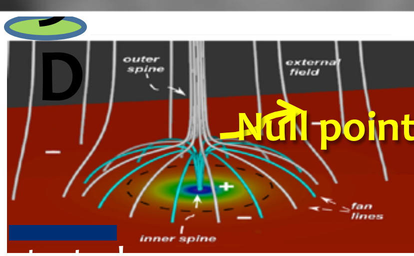
AIA 1600 Å 12:38:43



Flux rope

Log Q





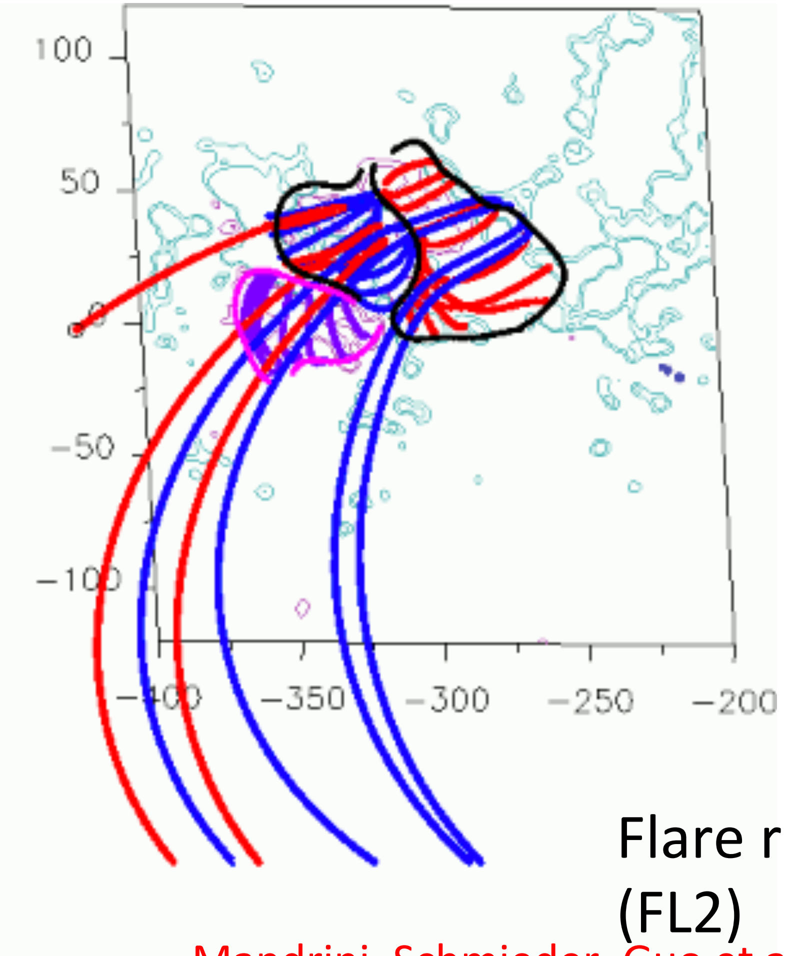
Jet

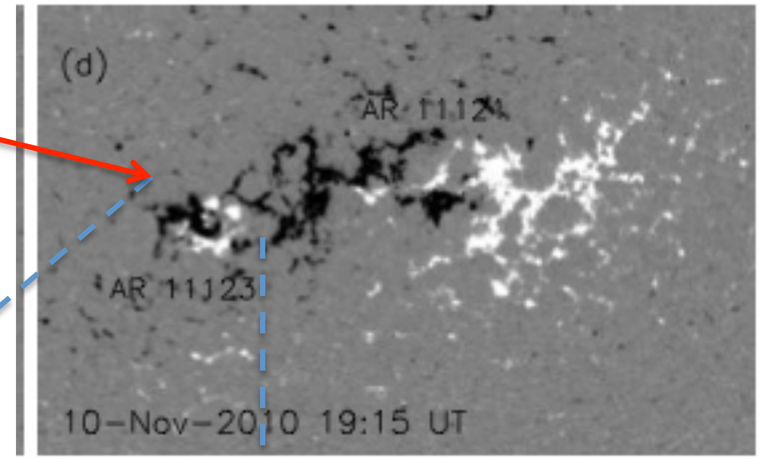
Pariat et al 2009, Torok et al 2009, Wang & Liu 2012

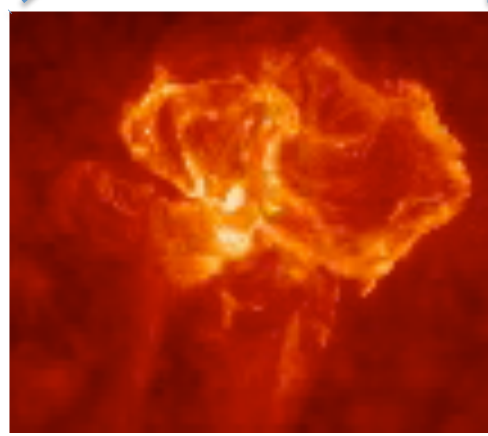
Sun, Hoeksema,Liu,Aulanier et al 2013
Savcheva et al 2012

Separatrices and QSLs in the AR 11123

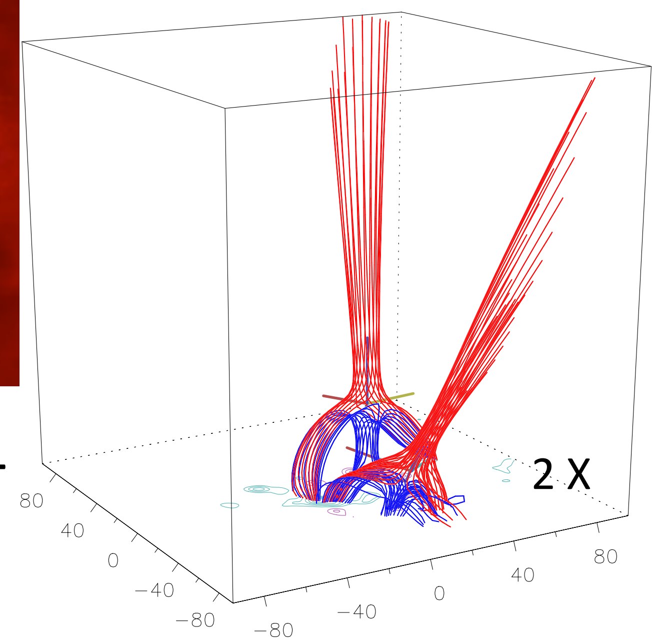
Emerging flux







Flare ribbons at 07:25 UT
(FL2)

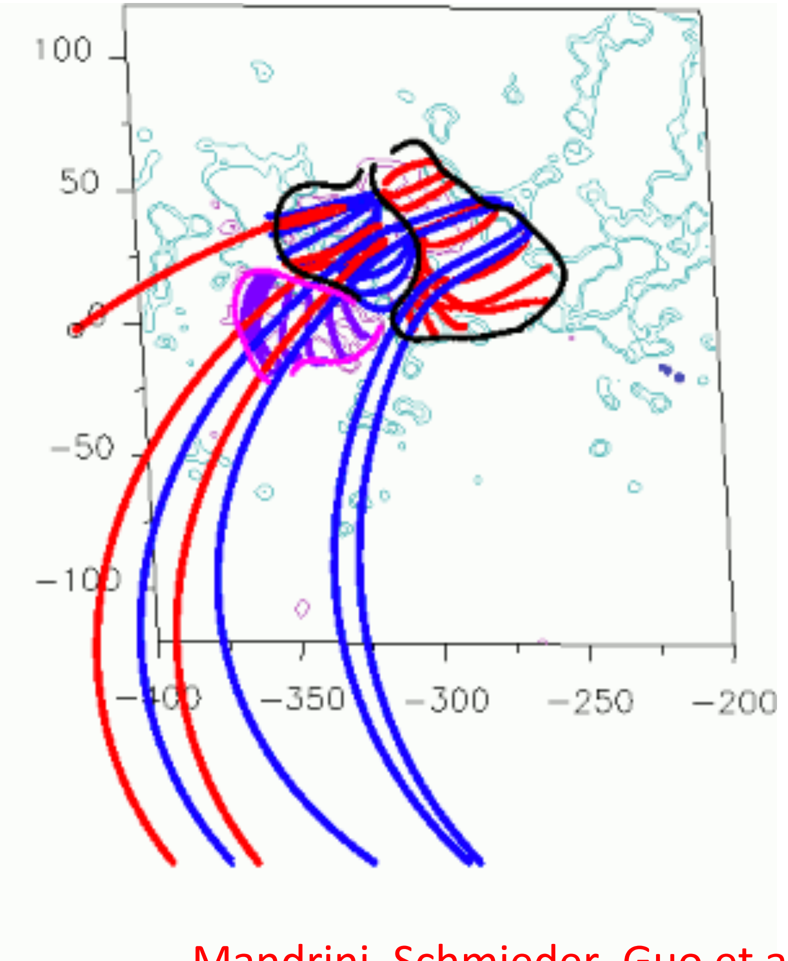


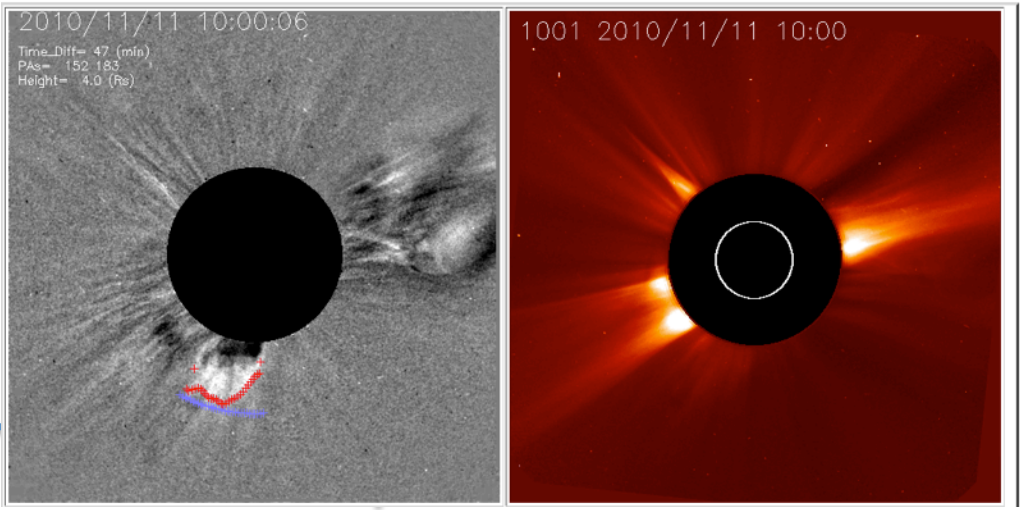
2 X

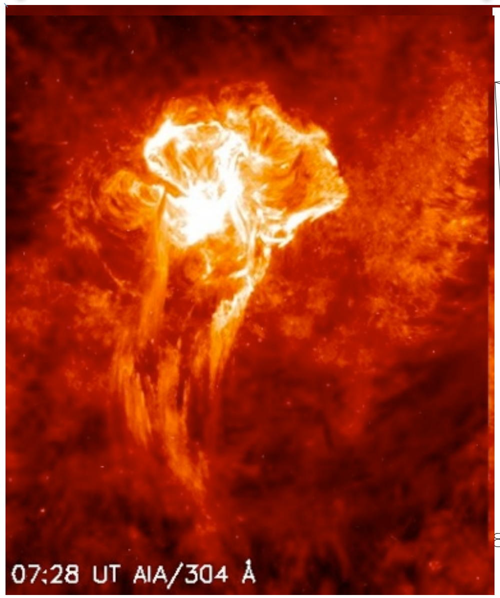
Mandrini, Schmieder, Guo et al 2014

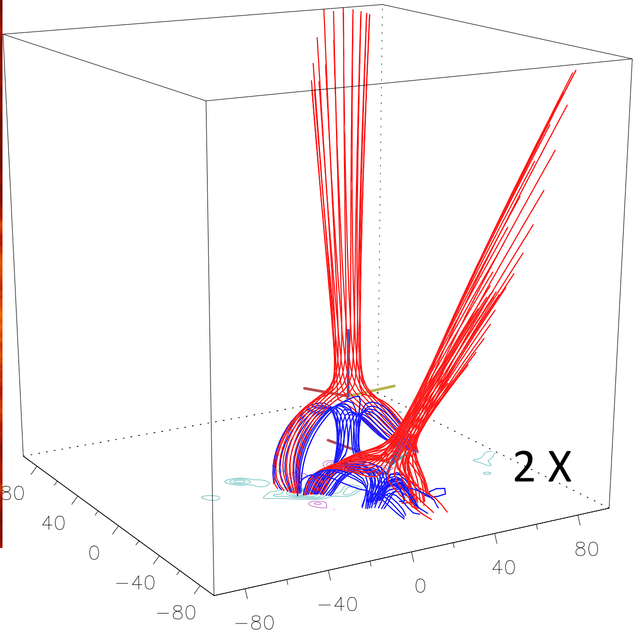
Separatrices and QSLs in the AR 11123

CME_Flare_0740



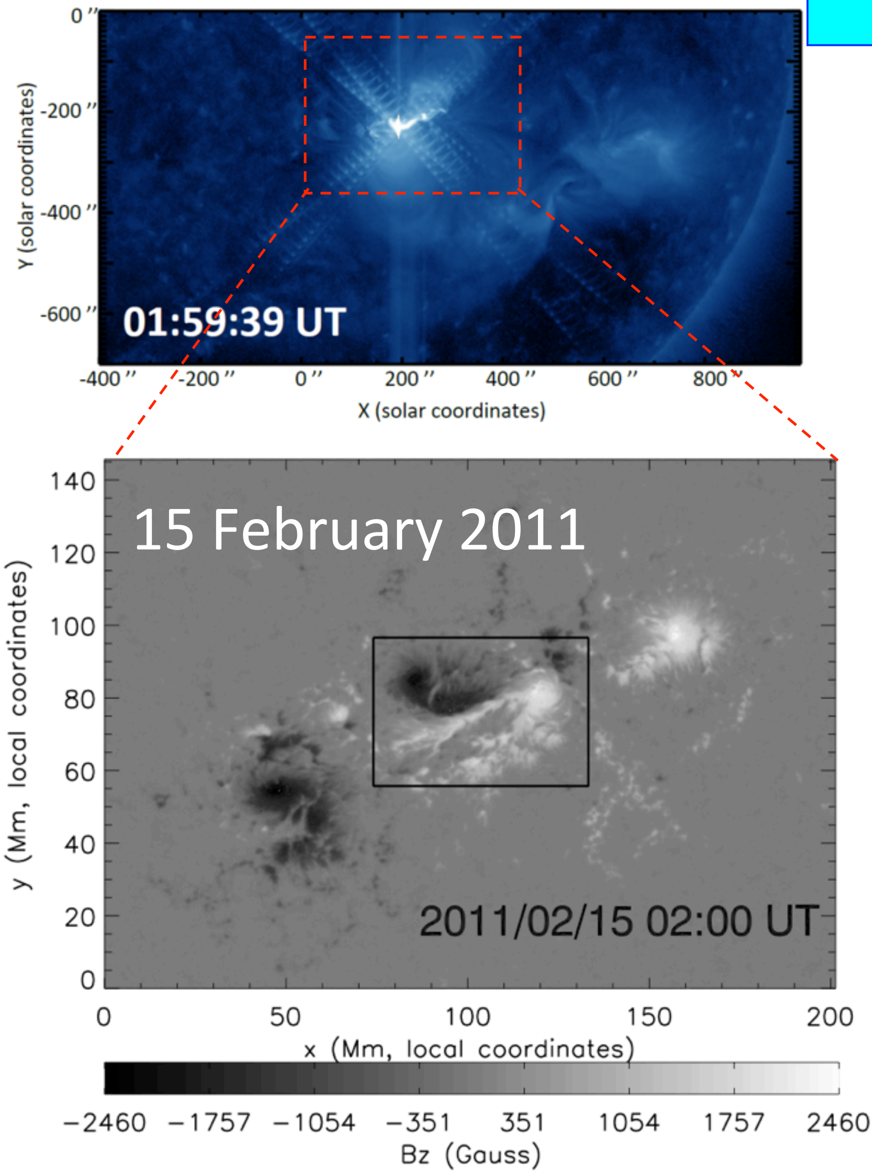




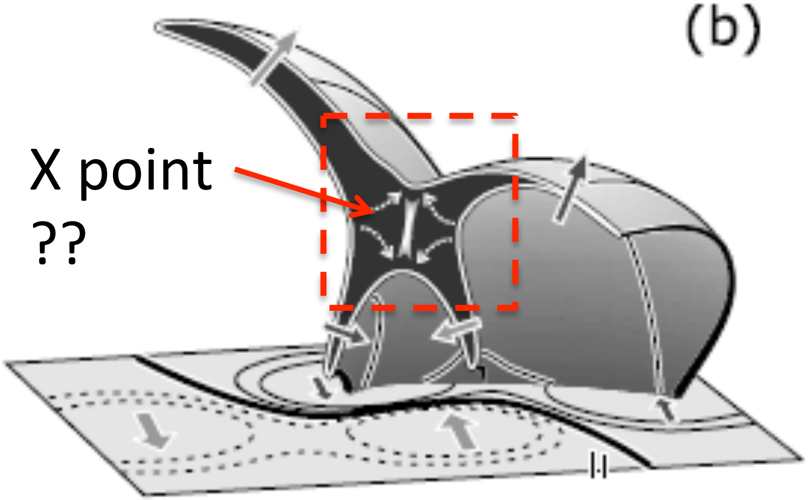


Mandrini, Schmieder, Guo et al 2014

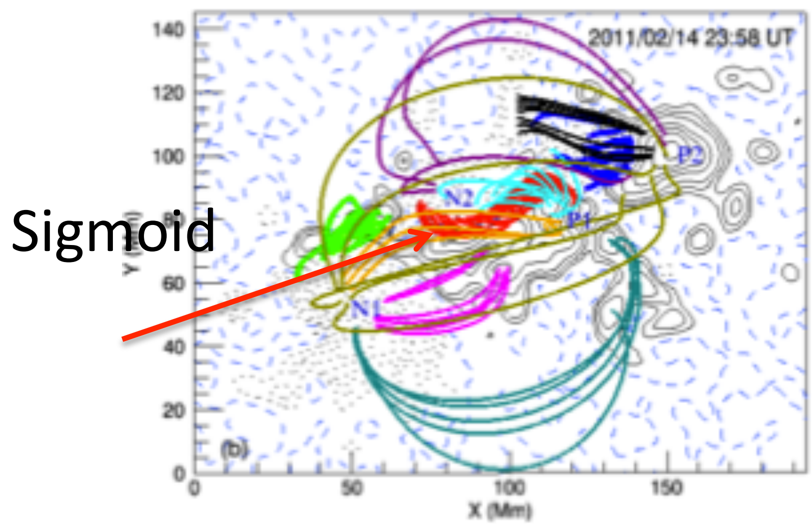
Hyperbolic flux tube



Janvier et al 2014



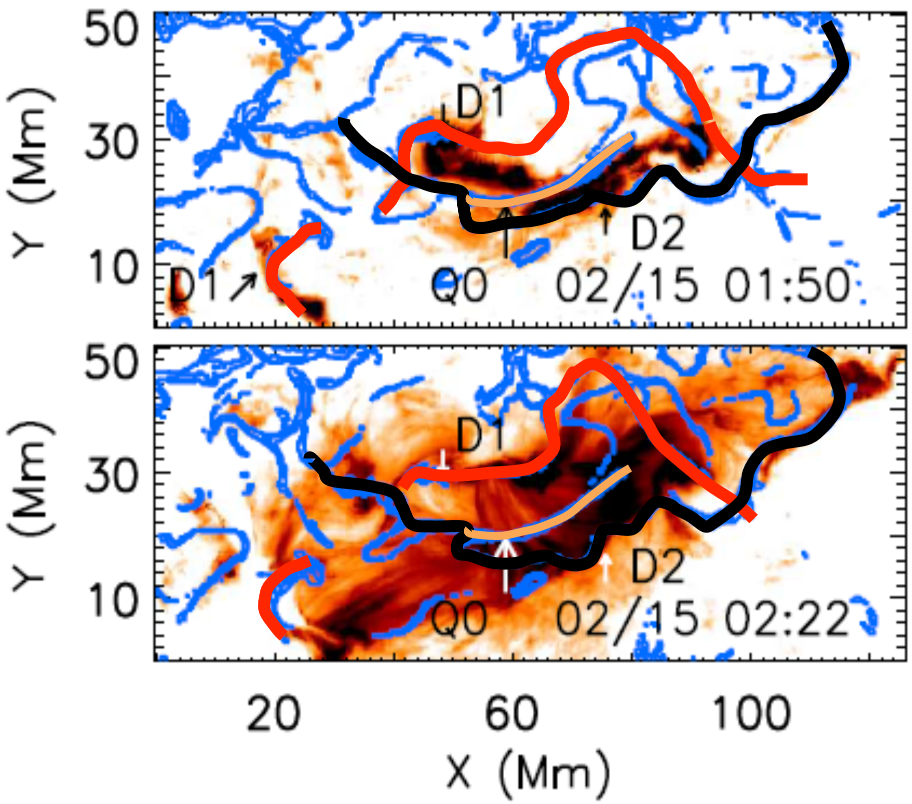
Titov 2003



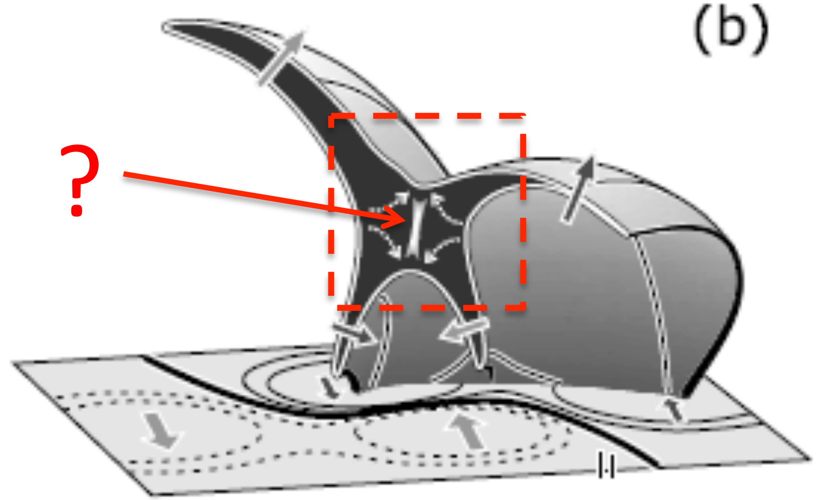
Zhao et al 2014, Sun et al 2012

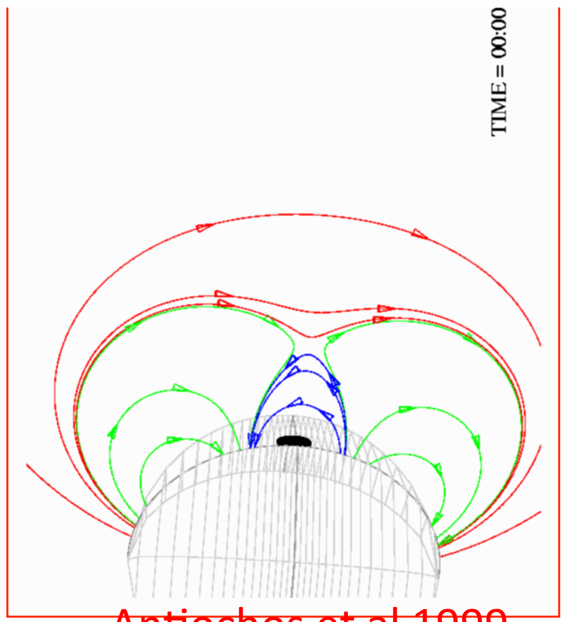
Break out reconnection?

AIA/304 + quasi separatrix QSL



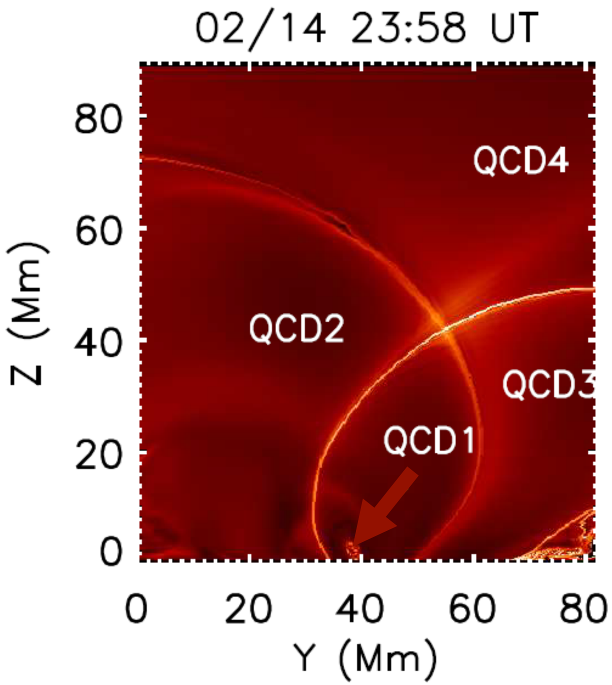
Zhao, Pariat, Schmieder, Guo, Li, 2014



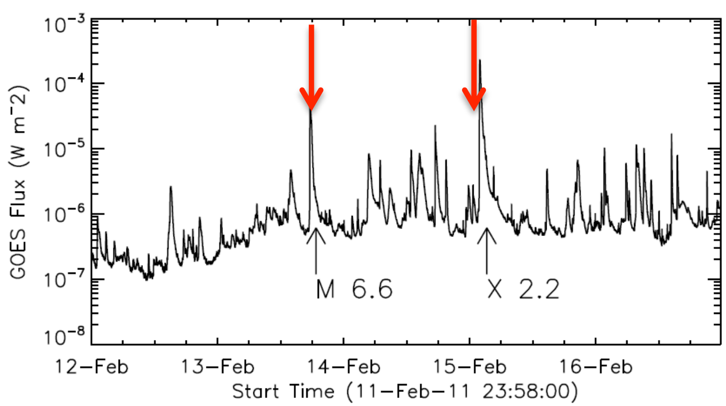


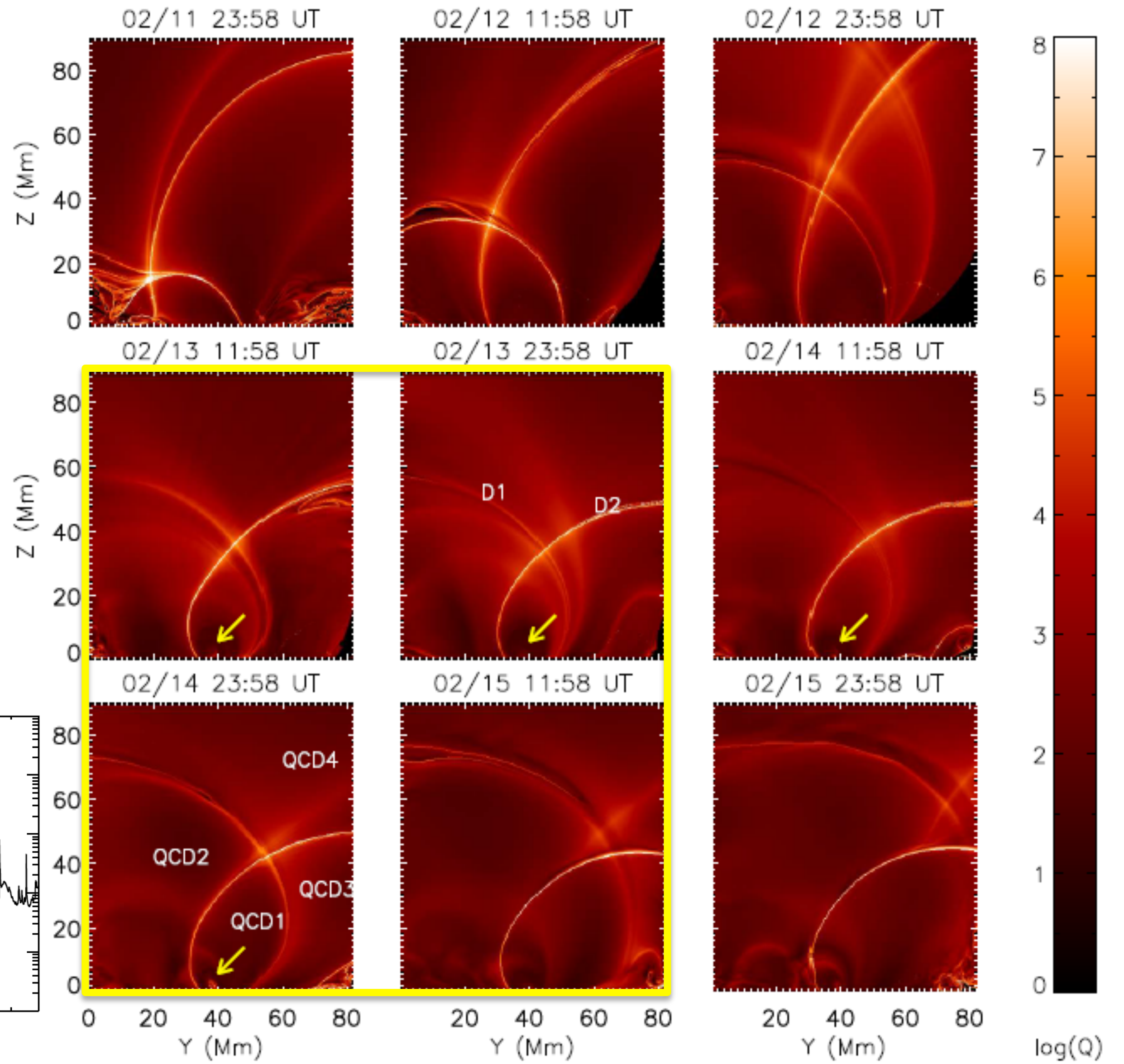
Antiochos et al 1999

Hyperbolic flux tube: no changes!!

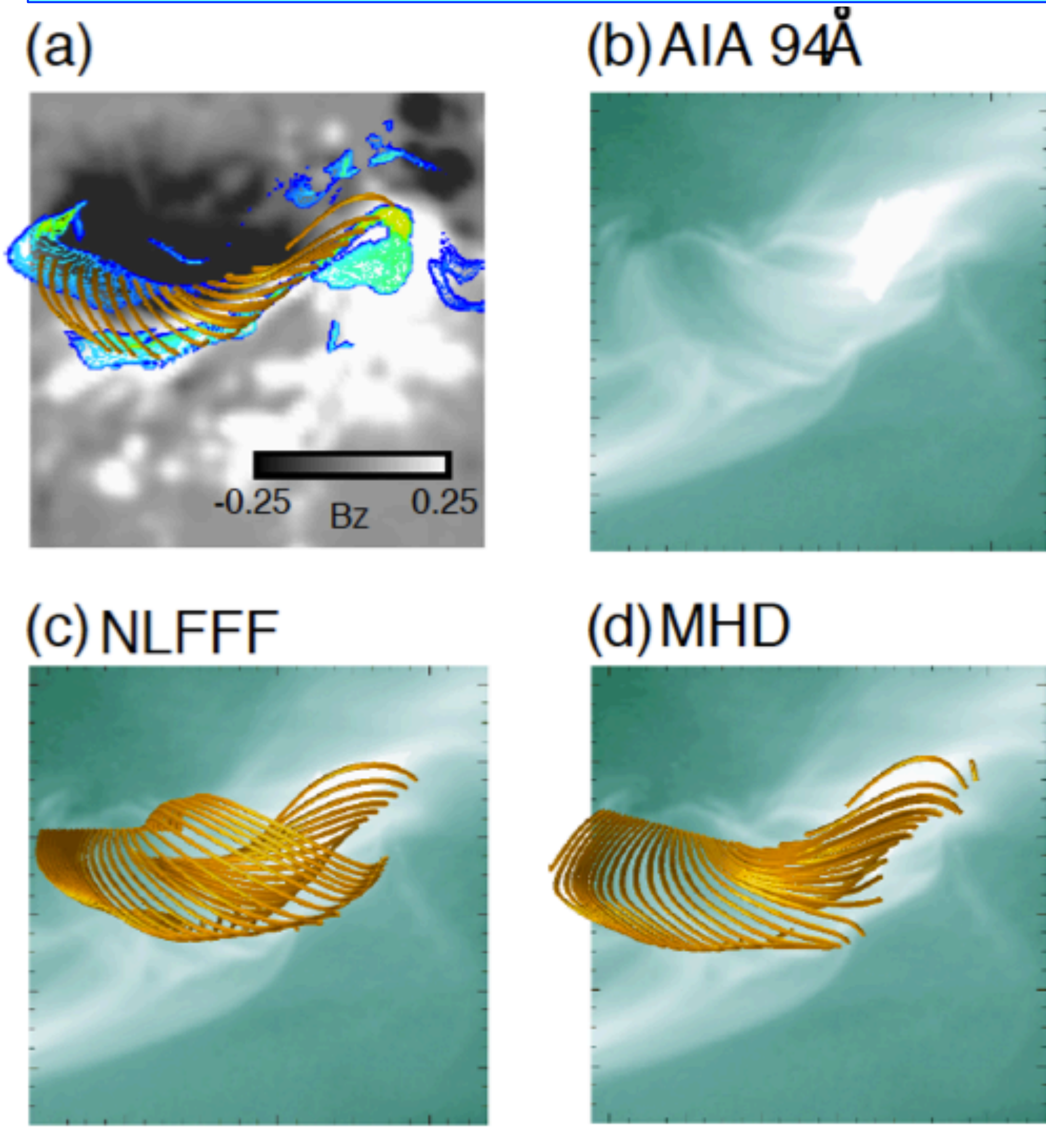


Zhao, Pariat, Schmieder,Li 2014



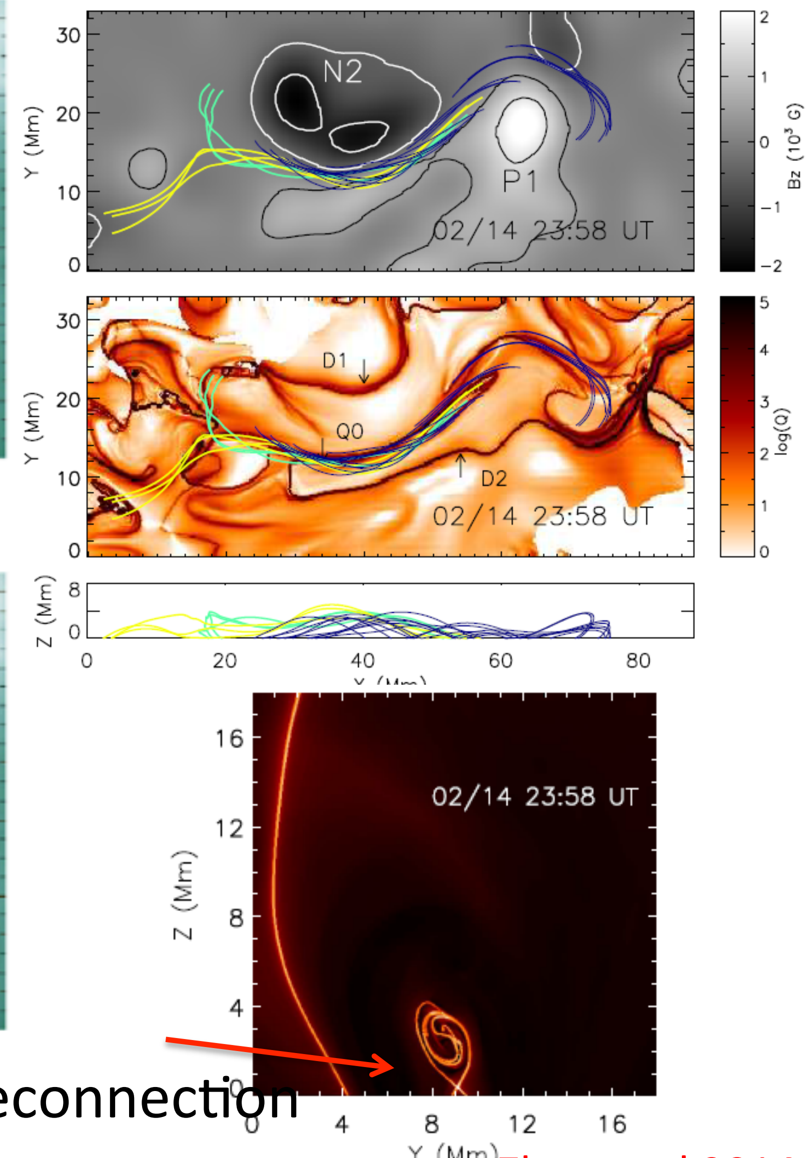


Reconnection by tether cutting



Inoue et al 2014

Low and small HFT



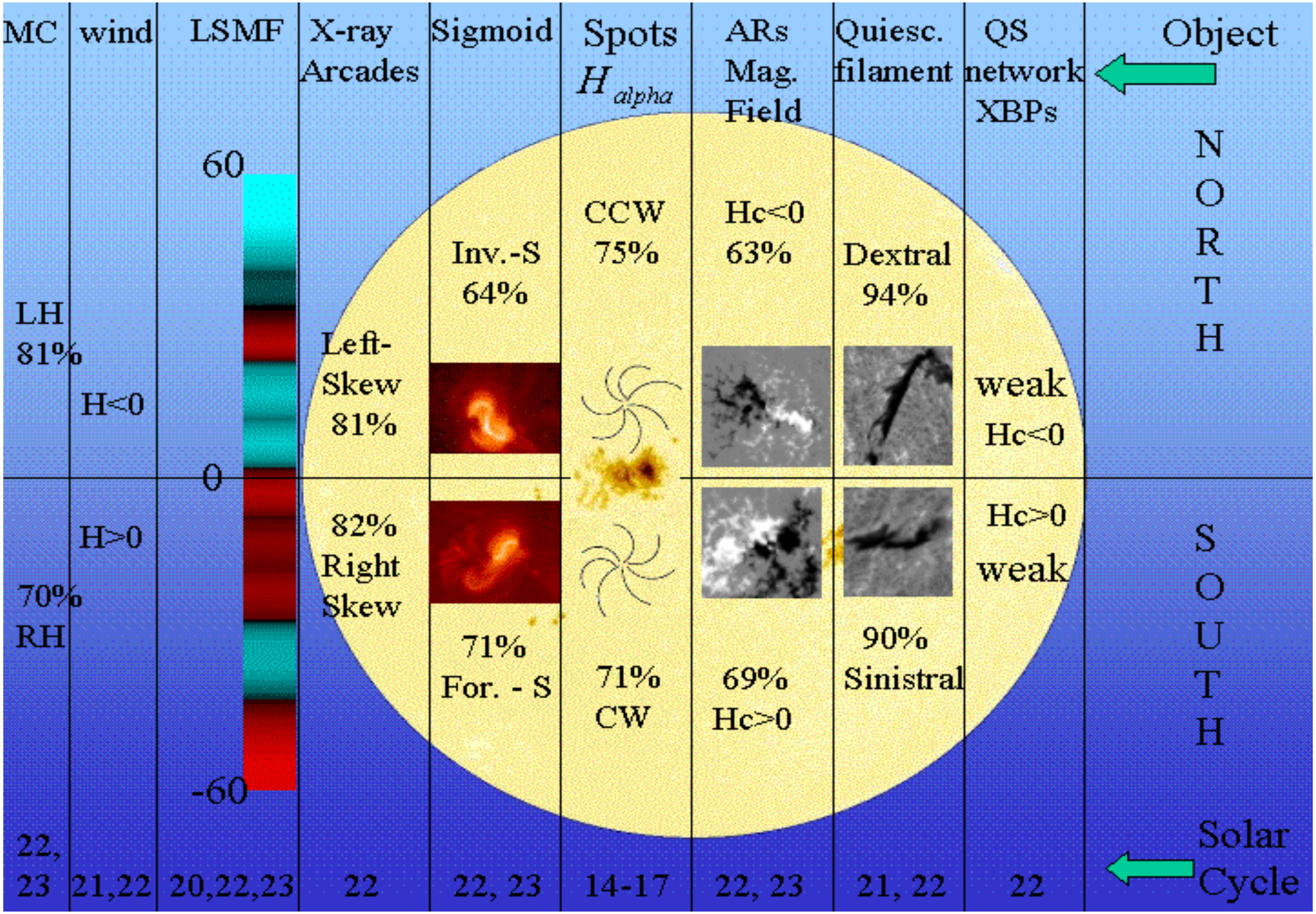
Zhao et al 2014

Magnetic Helicity conservation (Hemispherical rules)

dominance

H < 0

H > 0

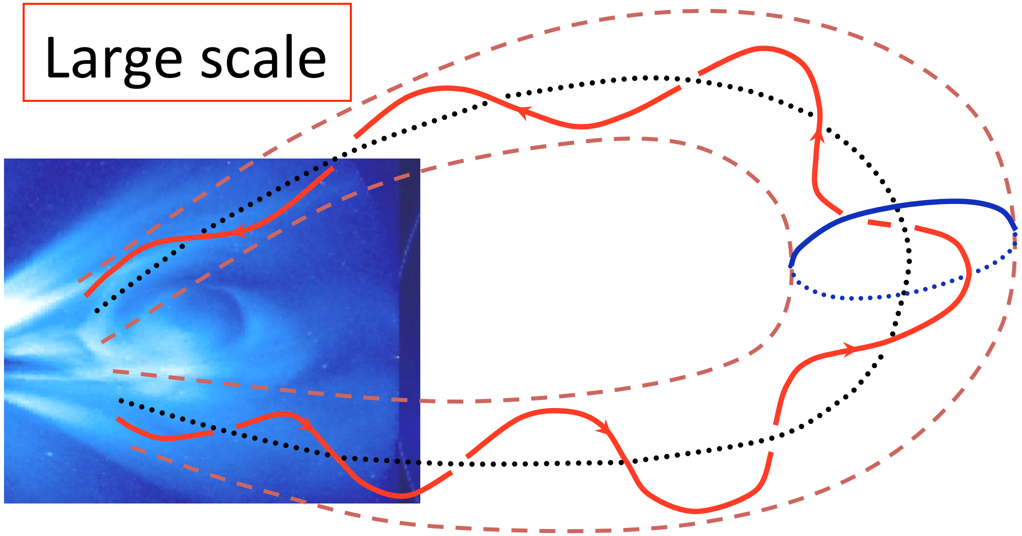


independent of solar cycle

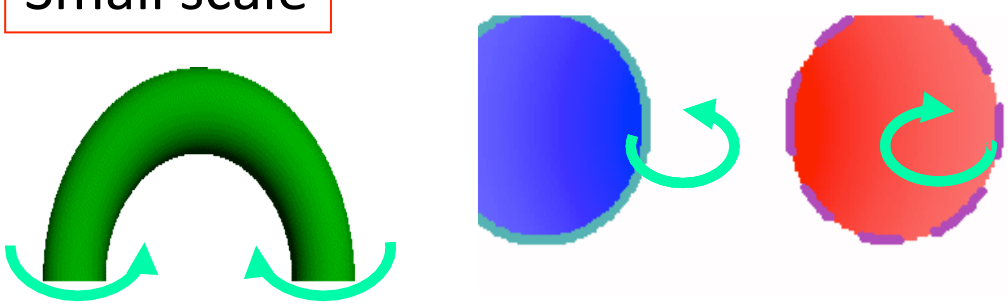
(Pevtsov 2002)

Magnetic helicity

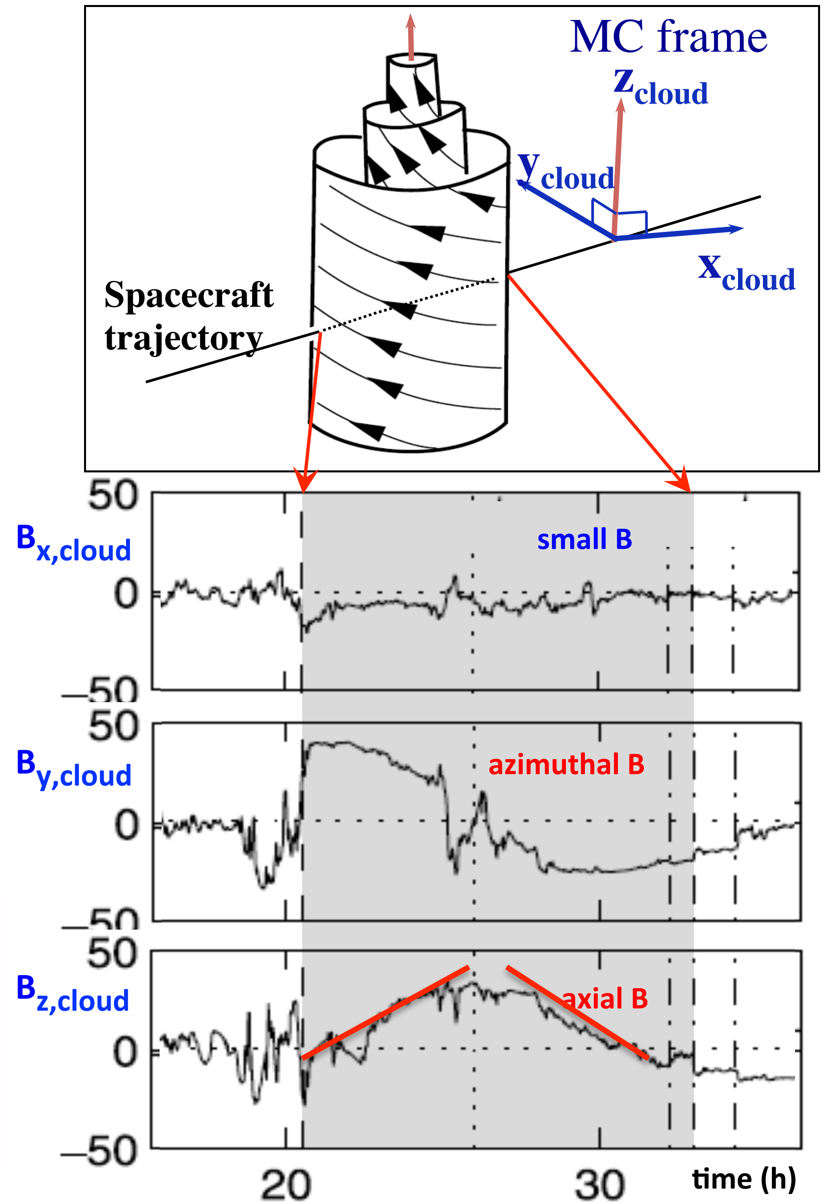
Large scale



Small scale



Loops in AR (Pariat 2007, Dalmasse 2013)



H<0 (Bothmer 1999)

CME on Nov 18 2003 MC on NOV 2003   Dst =-457 nT

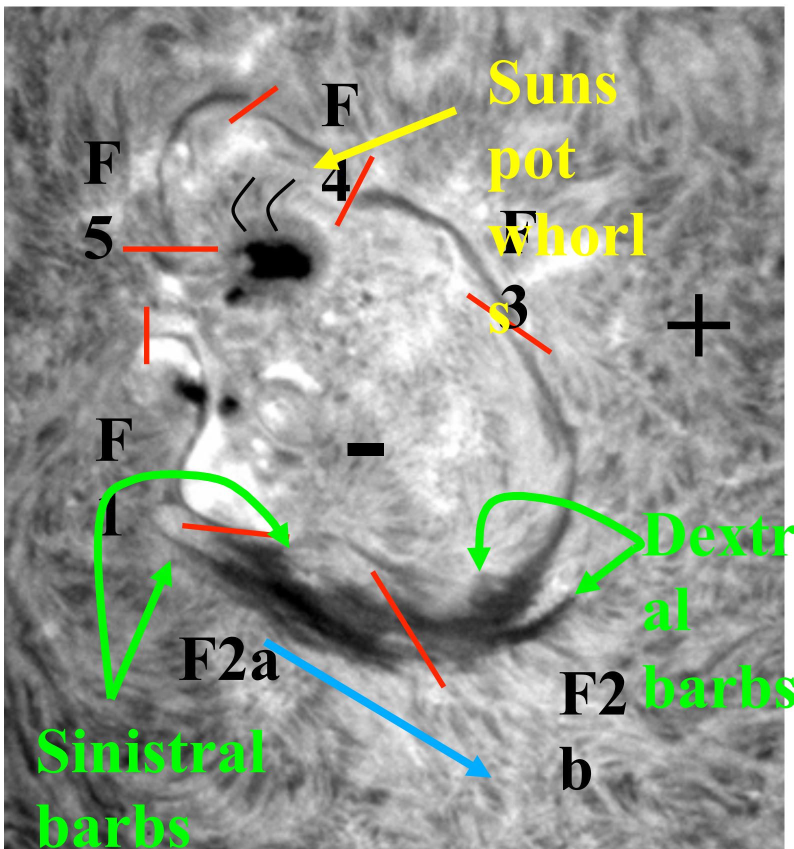
Magnetic helicity of the filament F2 a

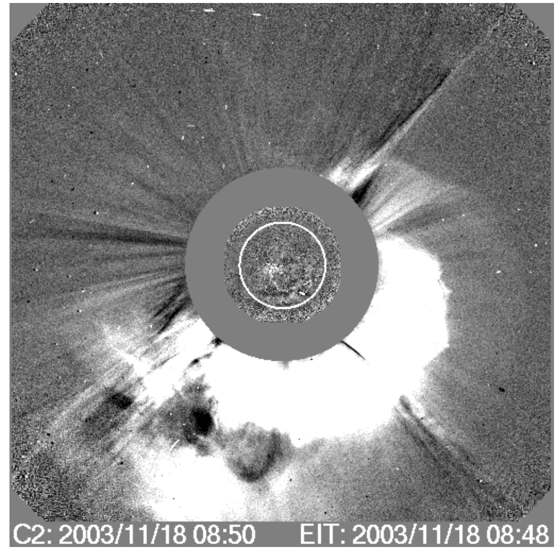
=

Magnetic helicity of the MC

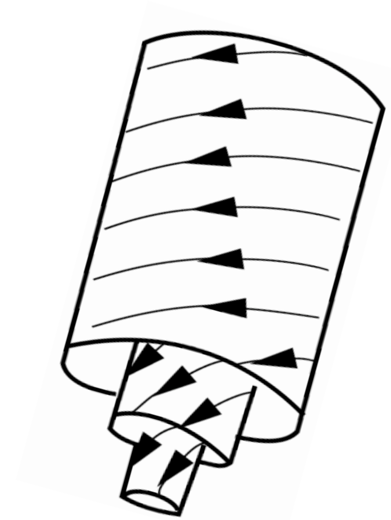
Chandra et al 2010

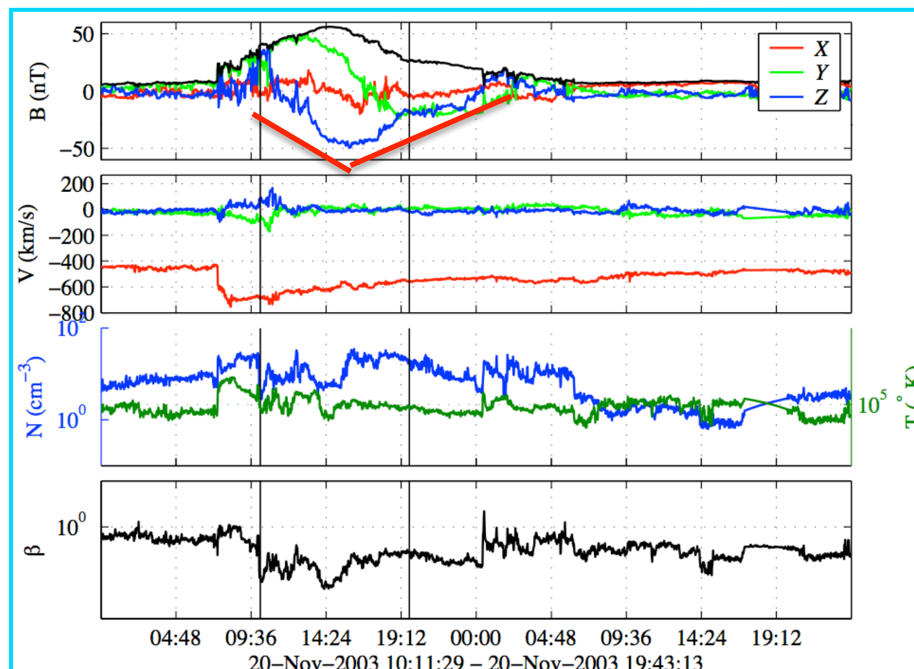
H>0





H>0





CME on Nov 18 2003 MC on NOV 2003 Dst =-457 nT

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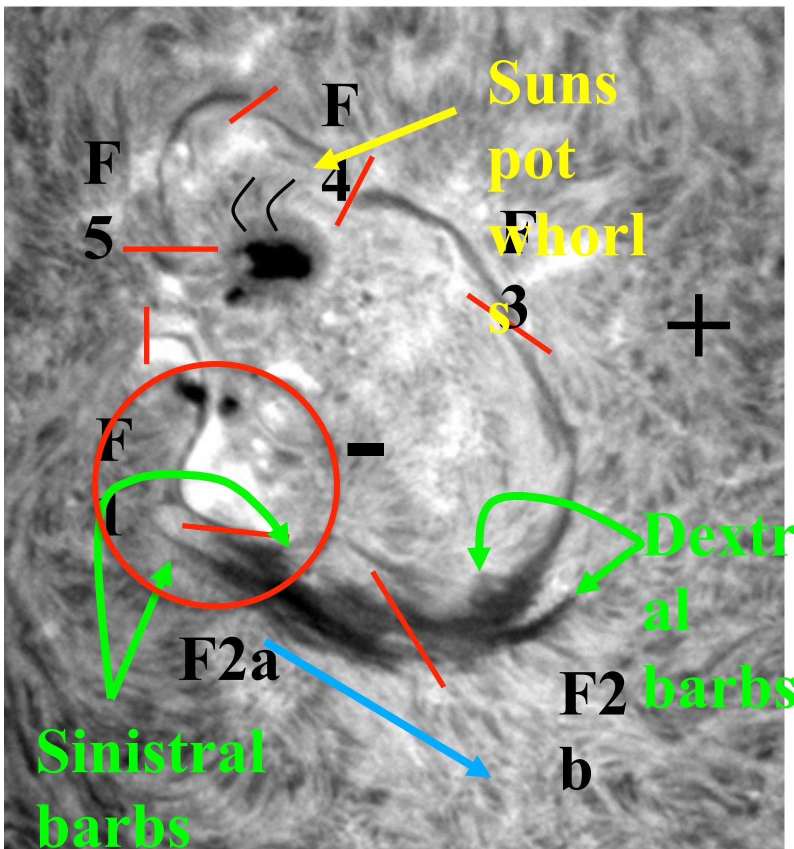
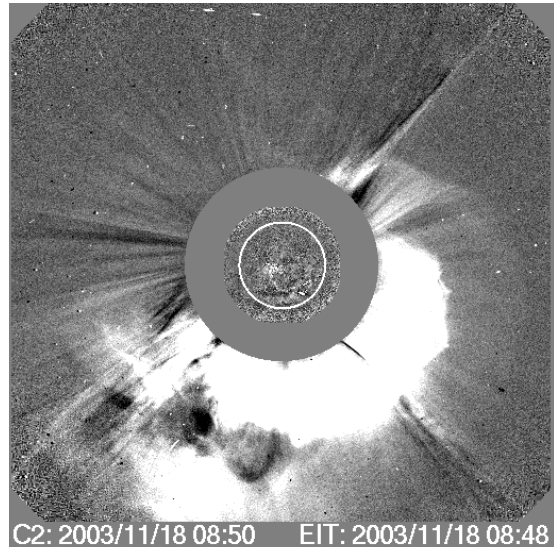
Magnetic helicity of the MC

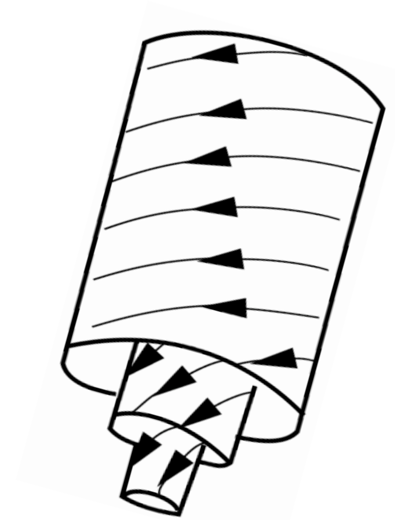
Chandra et al 2010

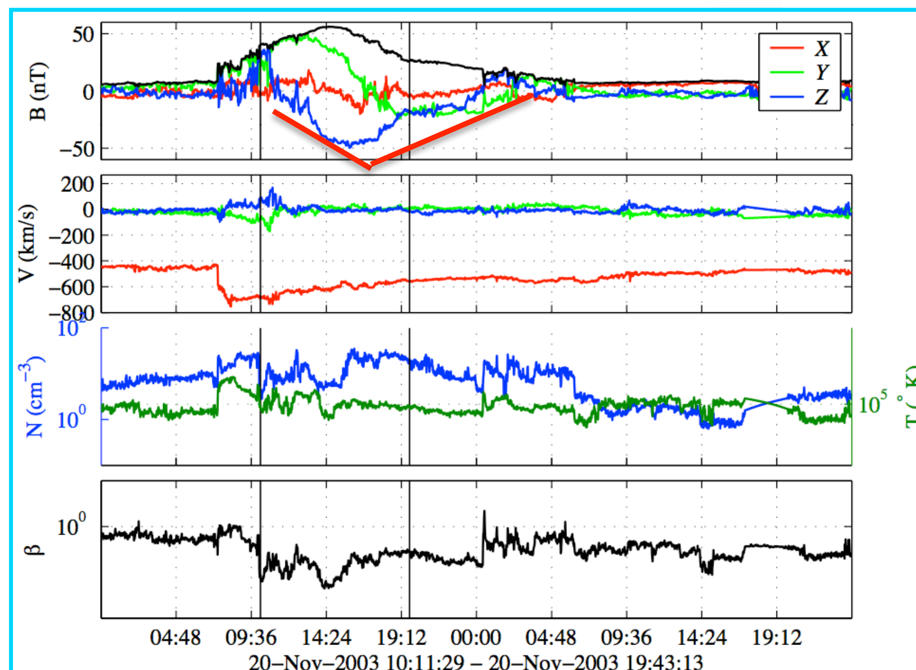
H>0



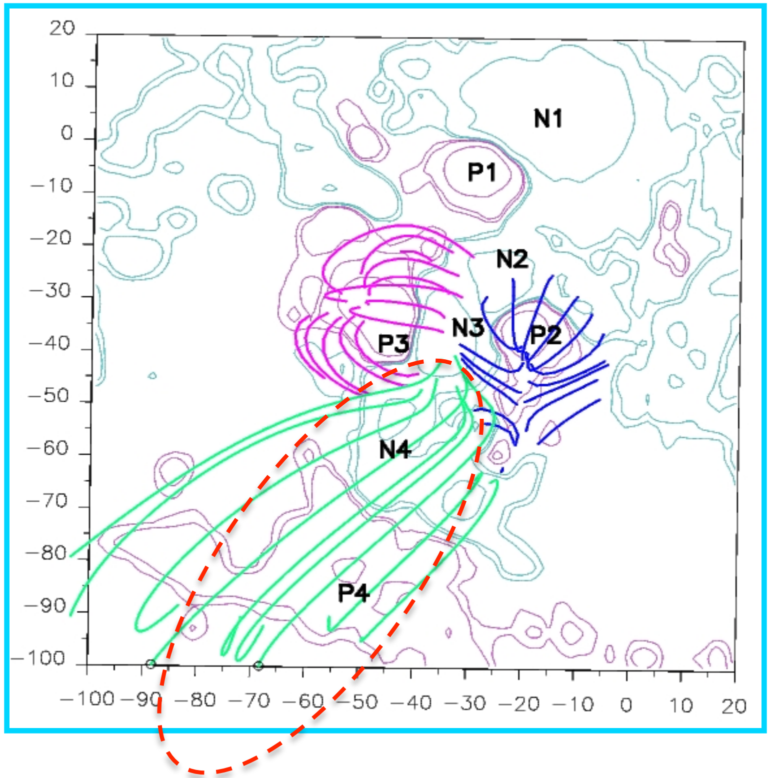


H>0





Localized helicity injection : small scale loops



Connectivity domains where H injection is positive:

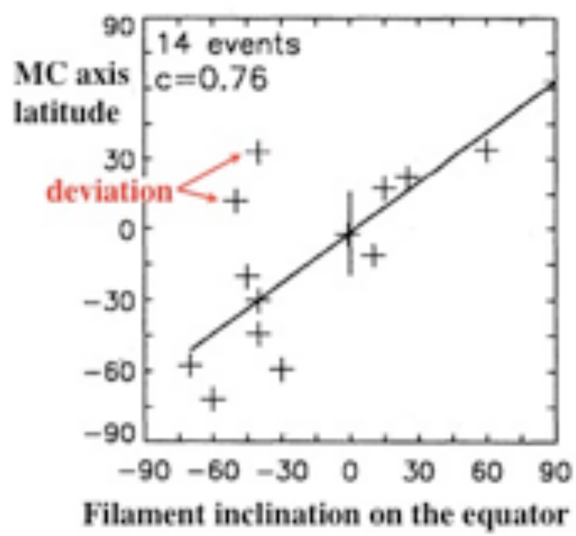
N4-P4 → H injection positive, 3 10^{41} Mx^2 for ~48 hours, if so during ~6 days, enough for the MC.

(Chandra, Schmieder, Mandrini, Demoulin, Pariat 2010)

Large scale: Invariant in a volume

CMEs expell the excess of magnetic helicity

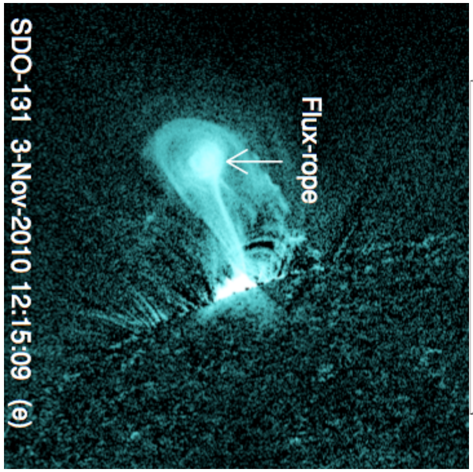
Same sign of magnetic helicity: flux rope and magnetic cloud

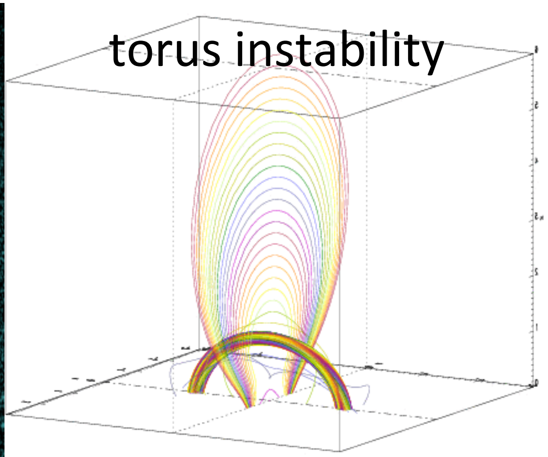


(Zhao & Hoeksema 1998)

Triggering mechanisms for CMEs: kink, torus

Török et al. 2005, Williams et al. 2005
Kliem et al 2010





Cheng et al. 2011,Kliem & Török 2006, Török & Kliem 2007

- **TD** (Titov-Demoulin) **flux rope can erupt due to:**

  kink instability → critical twist (>2.5 turn)

  torus instability → critical drop of overlying field

  → **semi-circular flux rope shape**

- **start with KI- and TI-stable TD configuration**
- **Trigger instabilities ?** **Flare reconnection (emergence, shear…)**

Theory ⇄ observations

1. Preflare- Existence of flux tubes: currents

2. Topology of the Active region (X,QSL,HFT)

3. Magnetic helicity conservation: eruption, MC

4. Eruption/CME drivers

Loss of equilibrium (Forbes 2000,Longcope Forbes 2014)

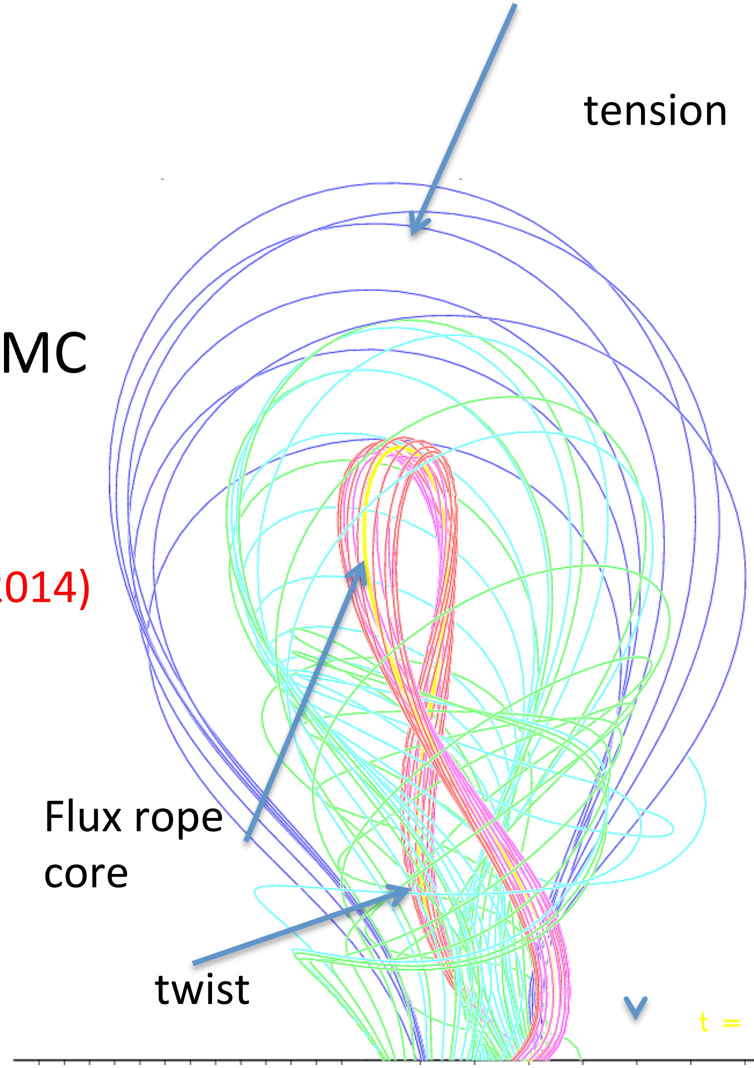
Break-out (Antiochos 1999, Karpen et al 2012)

Diffusion of the magnetic field (Amari et al 1999)

Tether cutting (Moore 2001,Zhao2014,Inoue2014)

Instability of the flux rope: kink, torus

(Torok, Kliem et al 2005, 2007,2010, Chen et al 2014)



Aulanier et al 2010

Where are we now, after >30 years of observations and theory ?

- The clear & physical **eruption driving** mechanisms

  - Breakout reconnection above rope
    => At null point & separator
    => Works *only if* not too much magnetic flux at high altitudese

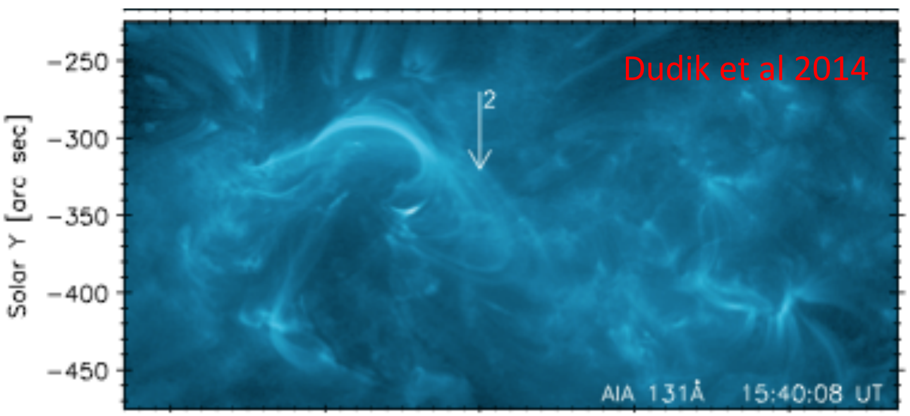
  - Localized flux decrease
    => Clear and firm *theoretical* explanation based on open field energy
    => Ongoing discussion about *physical* validity

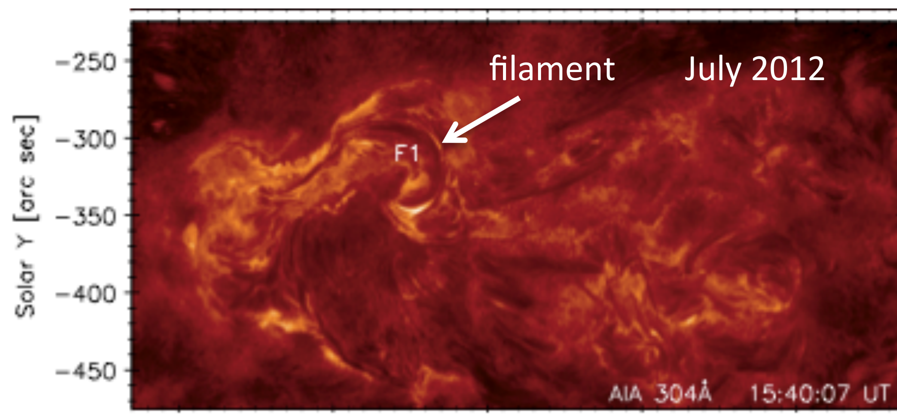
  - Torus instability (TI)
    => Identical to line-current loss of equilibrium (Démoulin & Aulanier 2010)
    => Connection between *electric wire* approach and *MHD* paradigm

- Phenomena that could also **drive eruptions** or
- **lead to one of the above** ?

  - Side reconnection => Tension weakening **?**
  - Tether-cutting from below => Tension transfer ? Accel' by recon' jet **?**
  - Converging motions (ideal) => Building-up pressure below **?**
  - Twist emergence into B-free/weak corona => Mass drainage, shear flows **?**
  - Flux cancellation through B^{phot} diffusion => Leads to TI (Aulanier, Török, Démoulin & DeLuca, 2010)

Flux rope- Cavity-Sigmoids

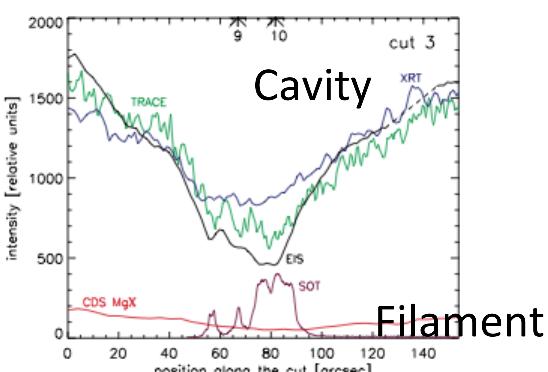




Hot loops around the filament: flux rope

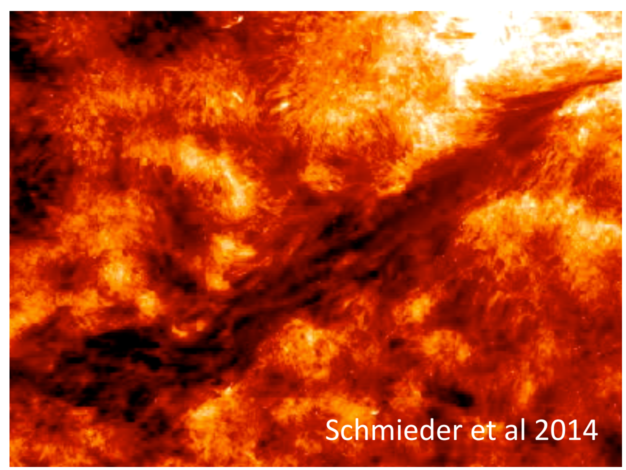
AIA cavity

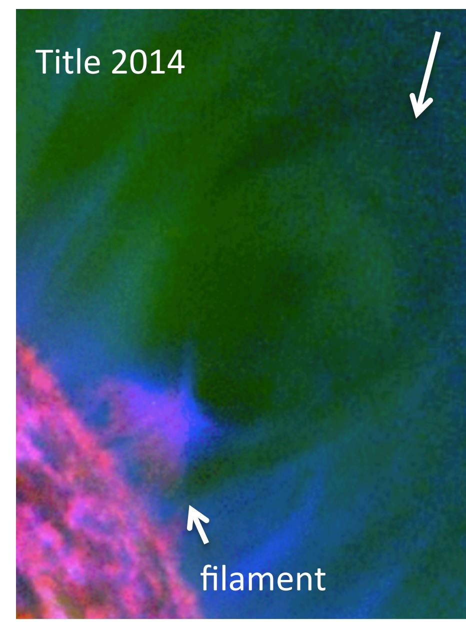
From the limb



Heinzel et al 2008

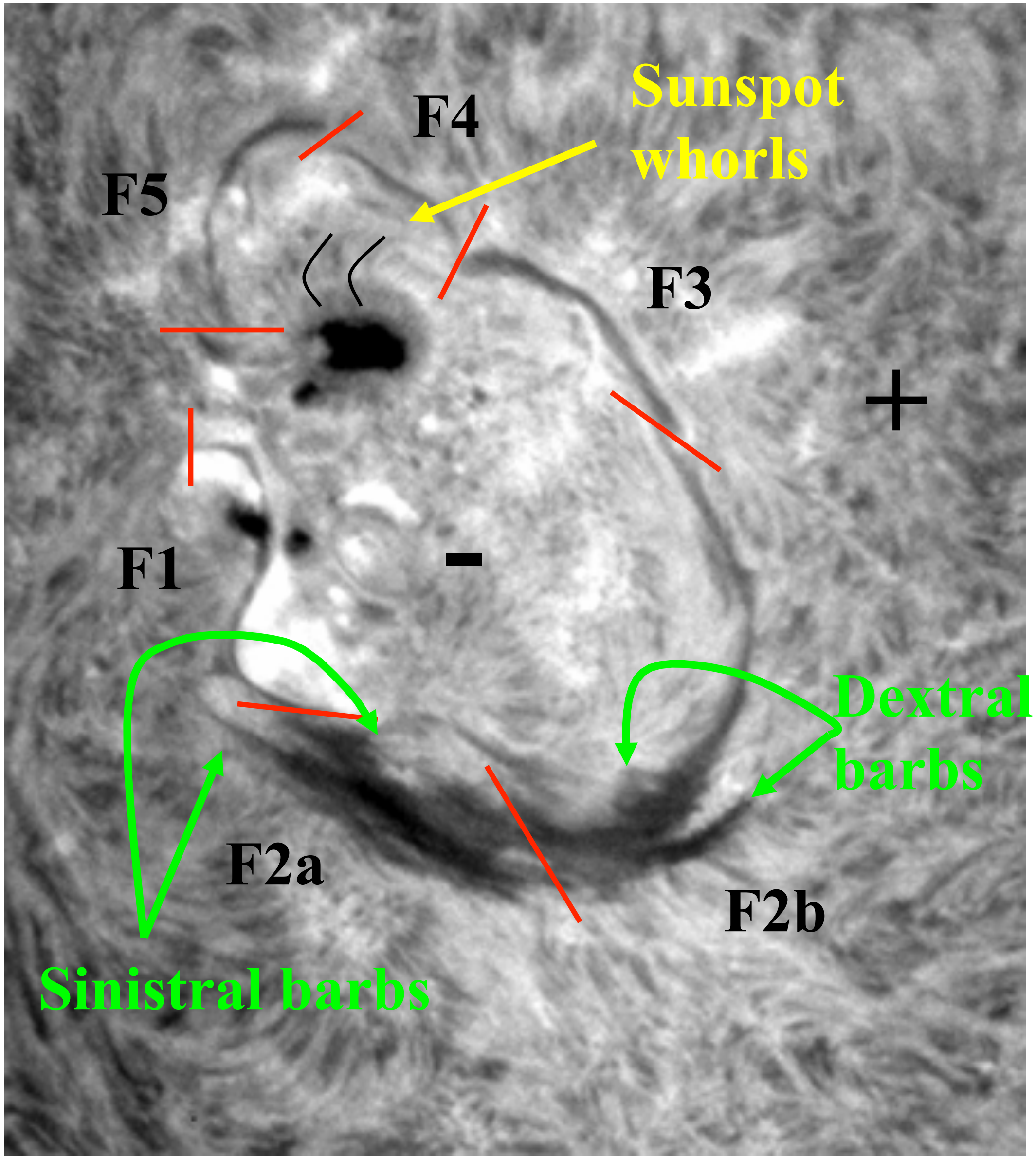
AIA Filament channel

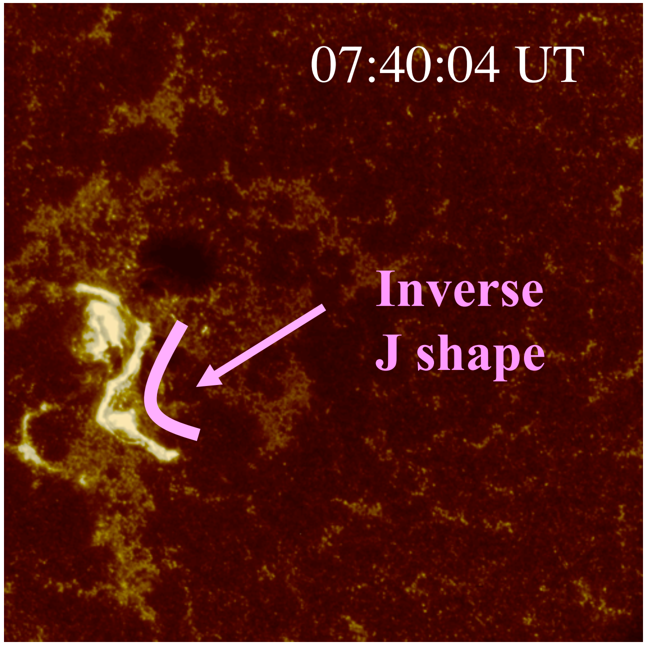




- 2. Topology of the active region
- Null point, separatrices

Observational clues – AR helicity sign <0





Sunspot whorls → $H_{AR} < 0$

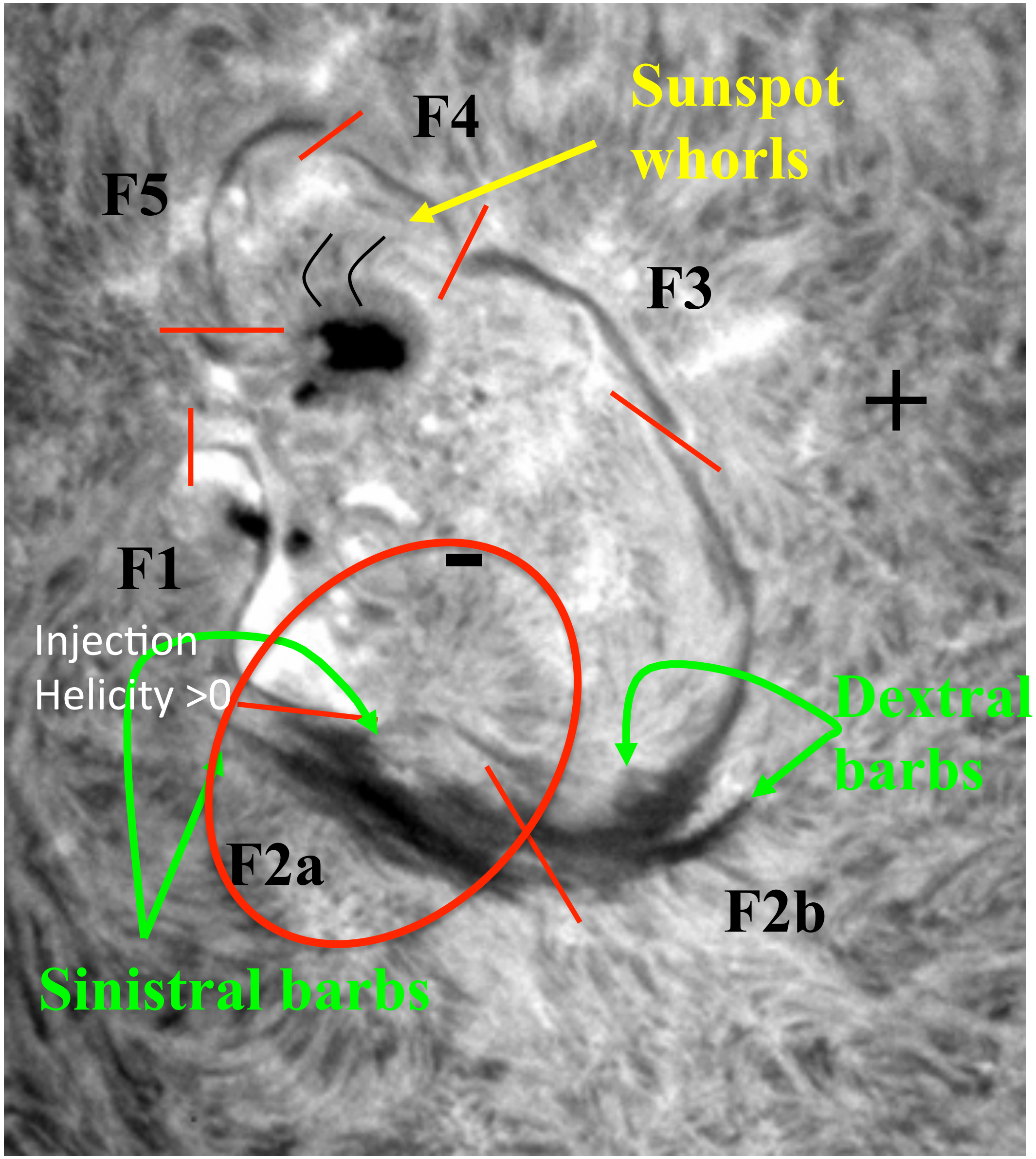
Dextral barbs → $H_{AR} < 0$

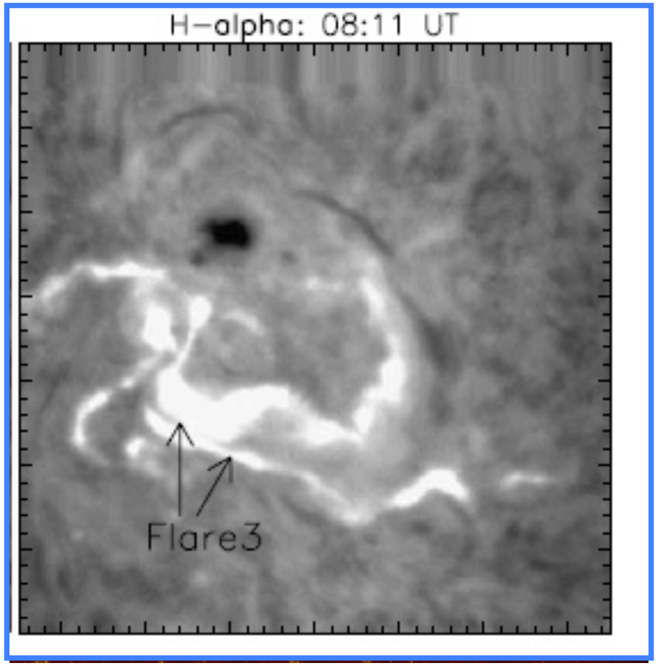
Inverse J shape ribbons → $H_{AR} < 0$

Sinistral barbs → $H_{AR} > 0$

Chandra, Schmieder, Mandrini, Pariat et al 2010

Observational clues – AR helicity sign –EMF>0





Sunspot whorls → $H_{AR} < 0$

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Inverse J shape ribbons → $H_{AR} < 0$

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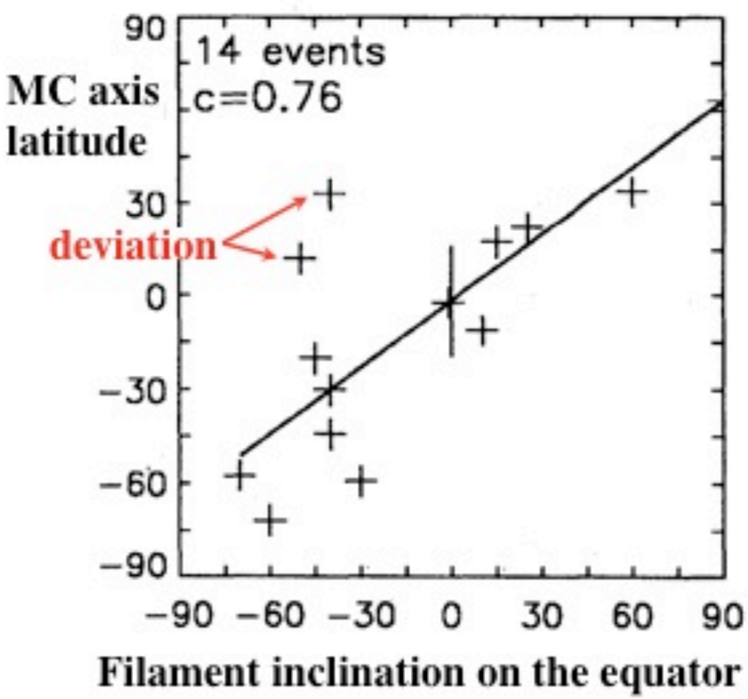
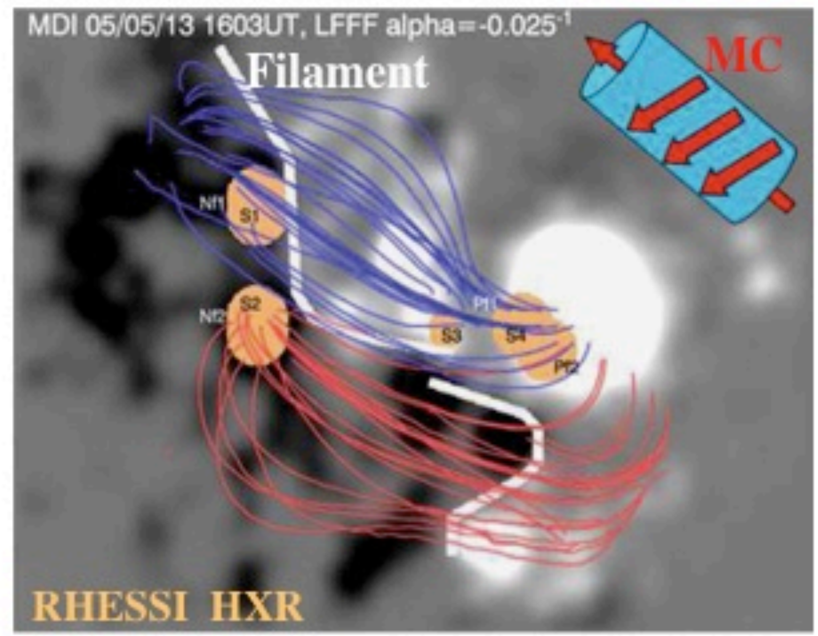
Chandra, Schmieder, Mandrini, Pariat et al 2010

Magnetic helicity

Invariant in a volume: CMEs expell the excess of magnetic helicity
Same sign of magnetic helicity: flux rope and magnetic cloud





(Zhao & Hoeksema 1998)

(Yurchyshyn et al. 2006)

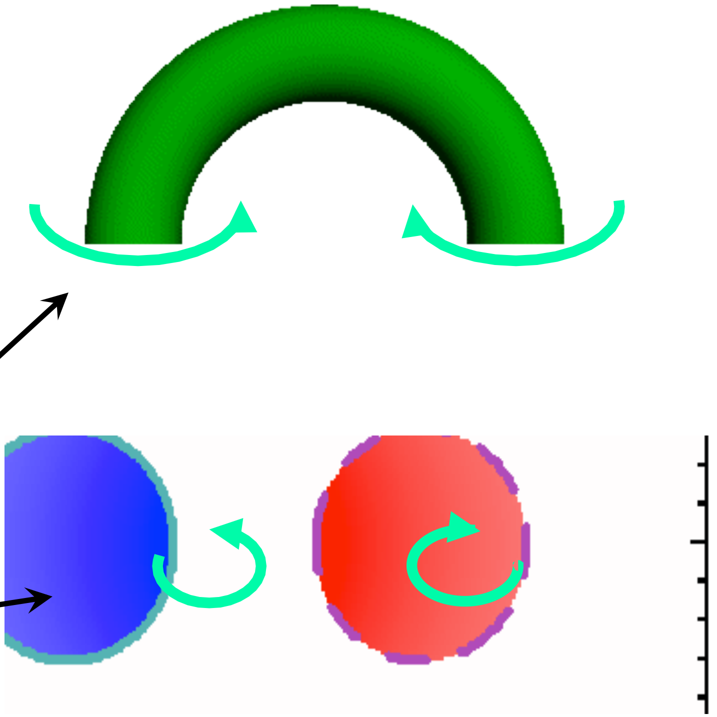
The flux rope as it expands , becomes gradually more and more twisted in order to conserve both azimuthal and axial magnetic flux (Parker 1979)

Localized helicity injection

G_θ is better suited to study the local injection of H than previous definitions of the helicity flux density function. But:

G_θ also induces fake polarities, e.g.

- Rotation in a whole of a flux tube without twisting
  - theoretically → no injection of helicity.
  - G_θ → opposite sign polarities at the footpoints.



(Pariat et al, 2005)

G_Φ: observational application, only applied to theoretical & numerical simulations studies (eg, Pariat et al. 05, 07; Dalmasse et al. 13)

$$\boxed{G_\Phi(\boldsymbol{x}_{a_+}) = \frac{1}{2}\left(G_\theta(\boldsymbol{x}_{a_+}) + \left|\frac{B_n(\boldsymbol{x}_{a_+})}{B_n(\boldsymbol{x}_{a_-})}\right| G_\theta(\boldsymbol{x}_{a_-})\right)}$$

Is used for the first time
For region of February 2011…
Dalmasse et al 2014

CONCLUSION

Unification of the scenario for getting flare-CMEs

1. Existence of a flux tube- presence of currents

Sigmoids, twist flux rope

Due to shear, rotation , EMF

Magnetic helicy conservation

2. Loss of equilibrium (Lin, Forbes, Isenberg 2001)

Break-out , cancellation

Diffusion of the magnetic field .

Tether cutting

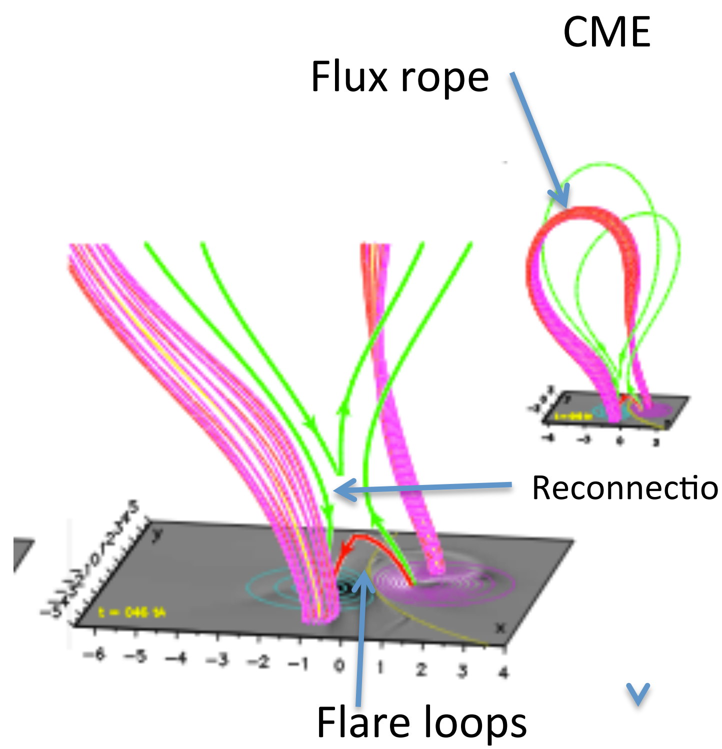
3. Reconnection in current sheet below the flux tube

X null point, separatrices, HFT

4. Instability of the flux rope: kink, torus

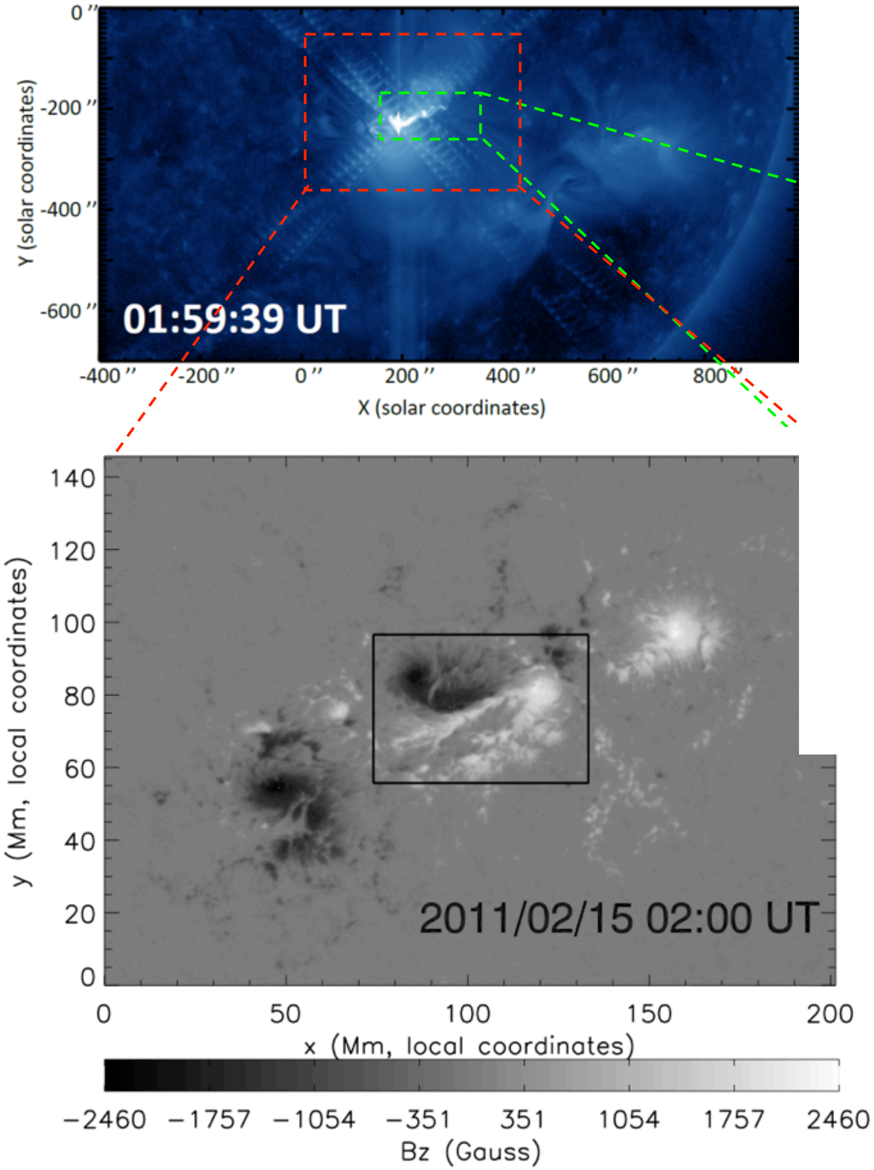
Catastrophe, loss, instability..

Kliem, Lin, Forbes, Priest, Torok 2014

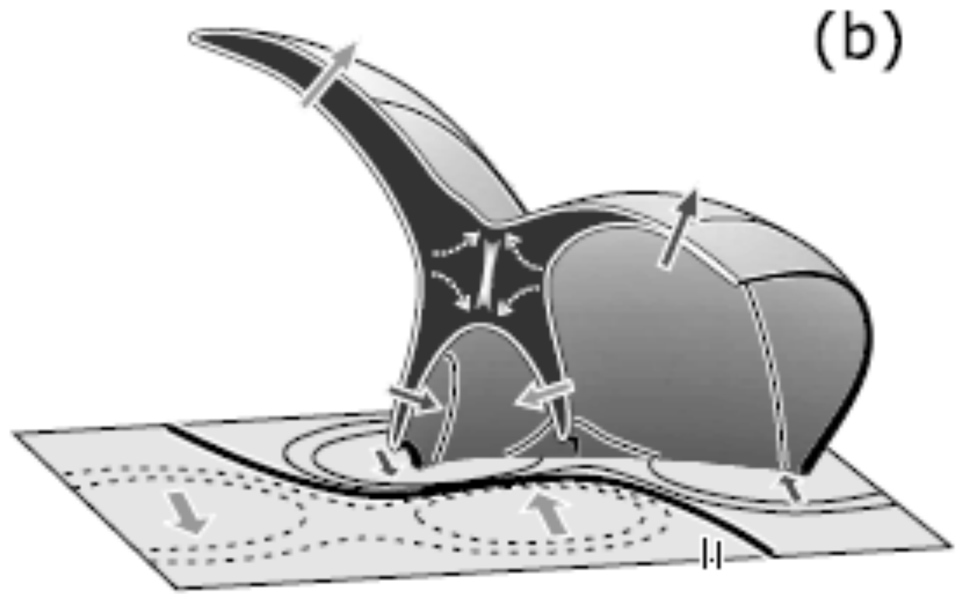


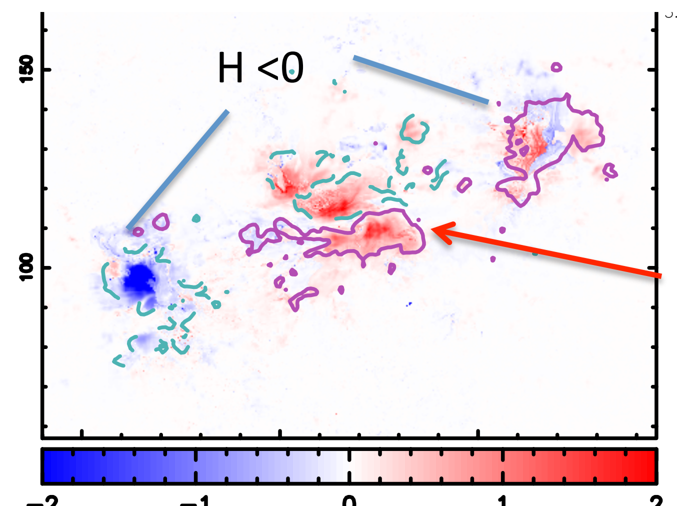
Aulanier et al 2010

X-class flare of Feb 15, 2011



Janvier et al 2014



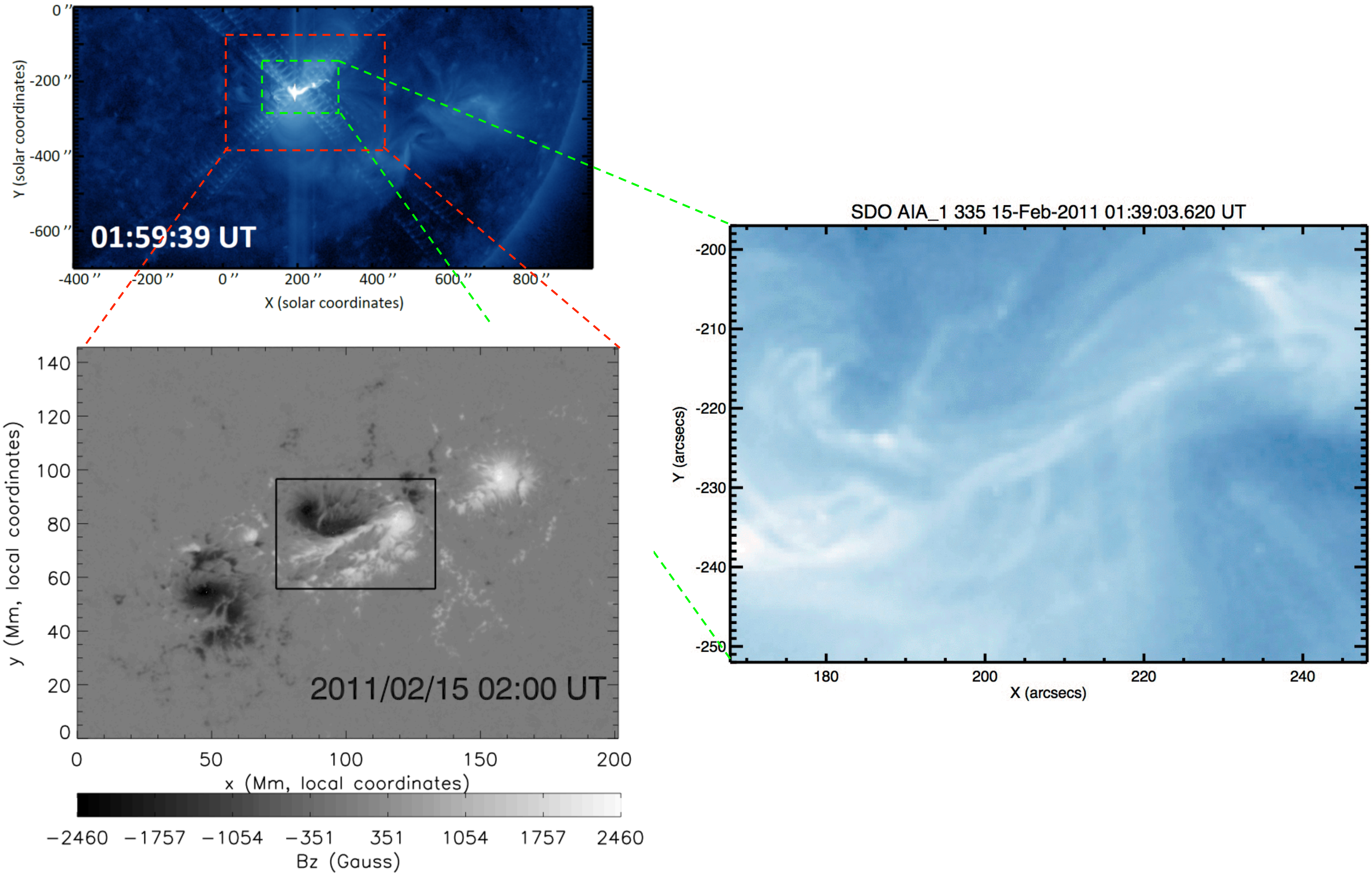


Inner system of positive Helicity

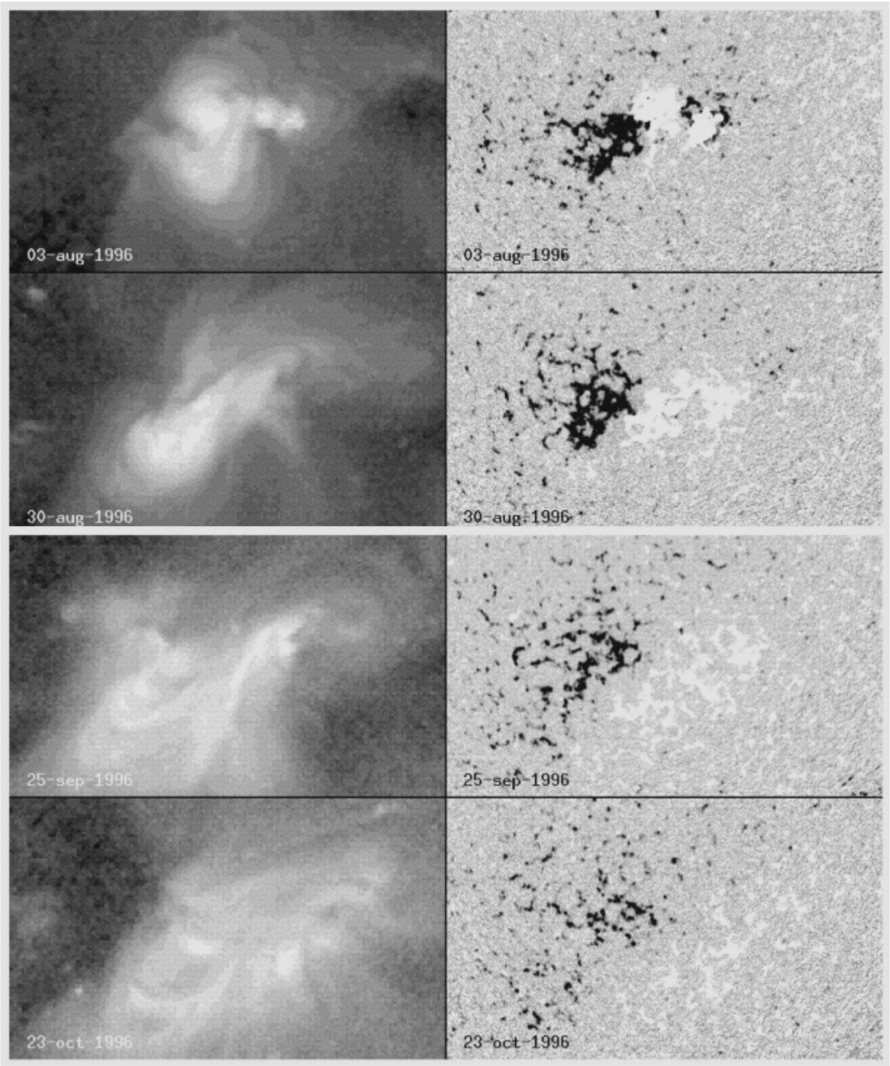
NLFF

Dalmasse et al 2013b

X-class flare of Feb 15, 2011



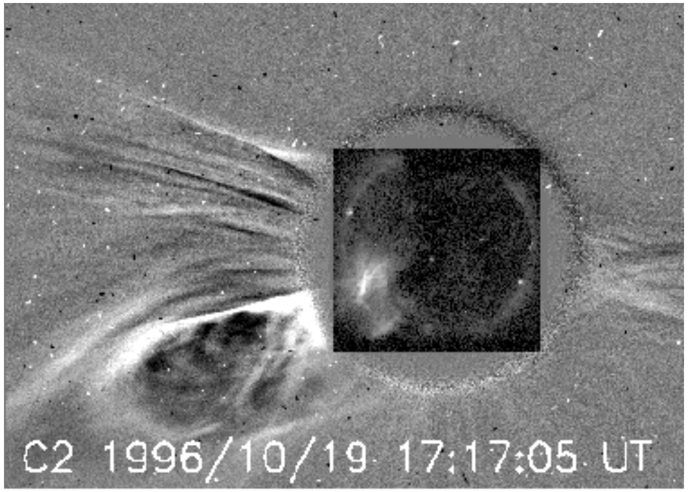
Observed flux cancellation & decay of solar active regions



- **Converging motions at PIL**
- **Flux = Σ Bz.dS** ↘

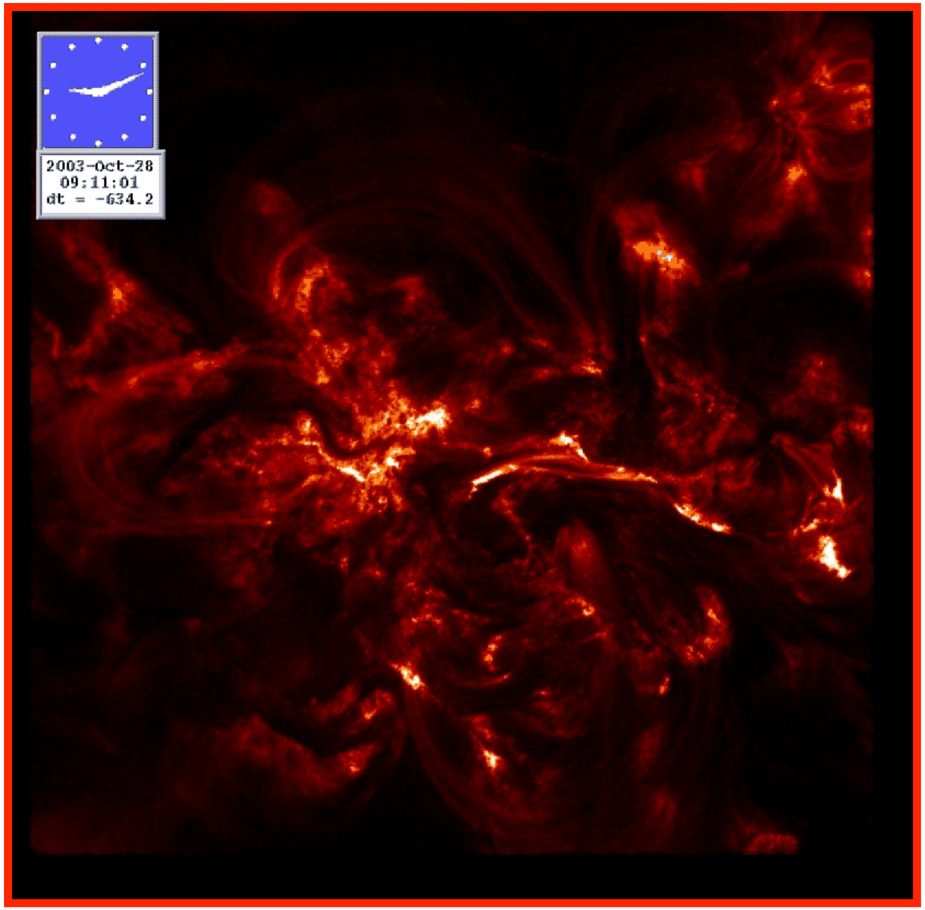
  due to cancellation at PIL

- flare rate ↘
- **CME rate** **~ const**

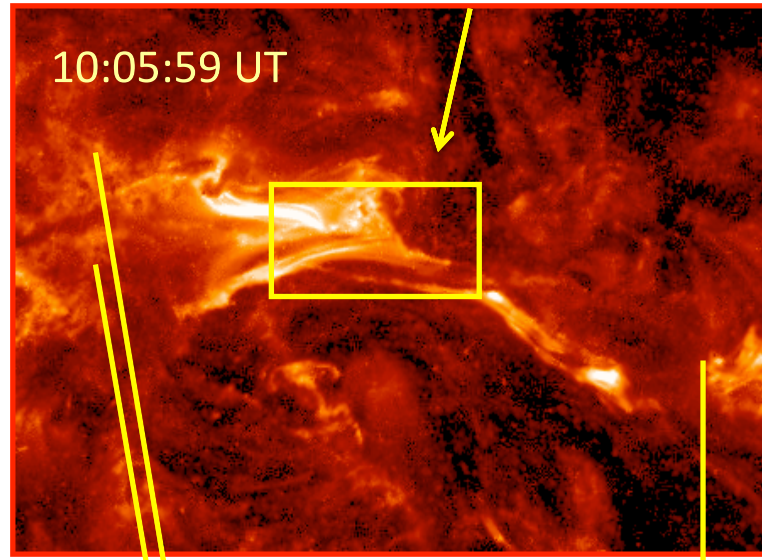


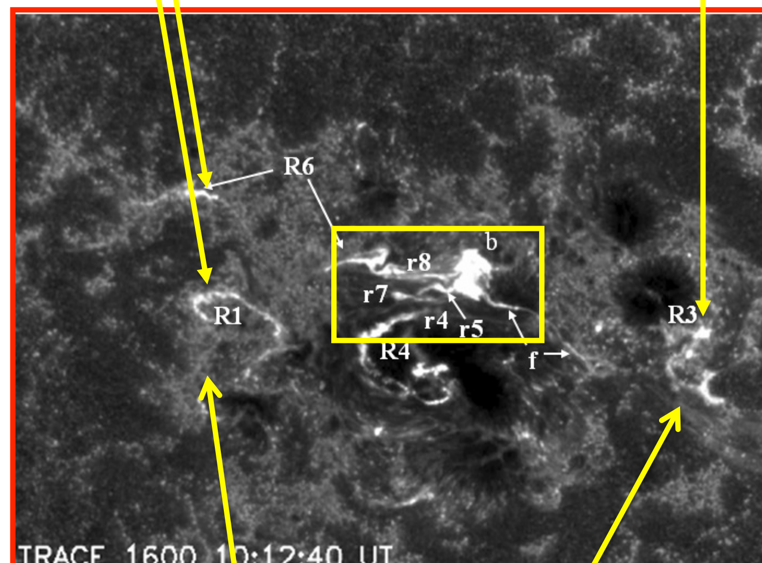
Martin et al. (1985), Démoulin et al. (2002), van Driel Gesztelyi et al. (2003), Schmieder et al. (2008), Park et al. (2010) …

Coronal observations



Emerging flux in the AR center



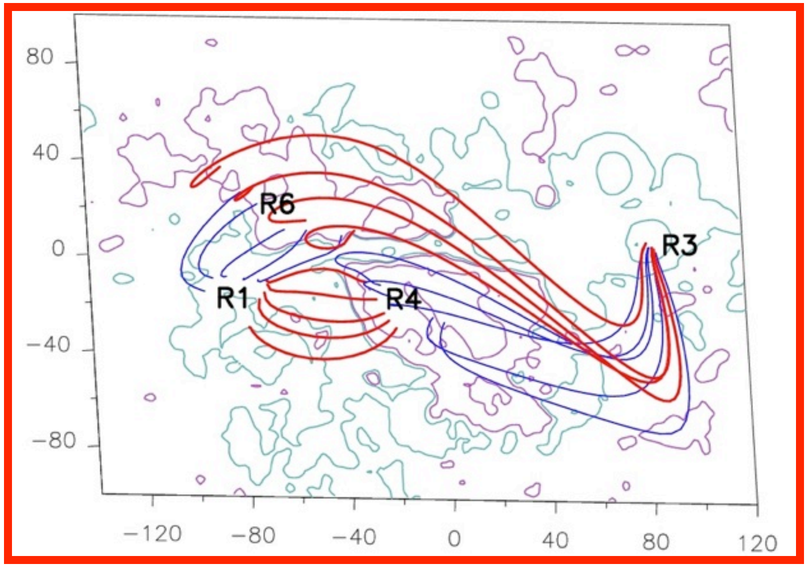


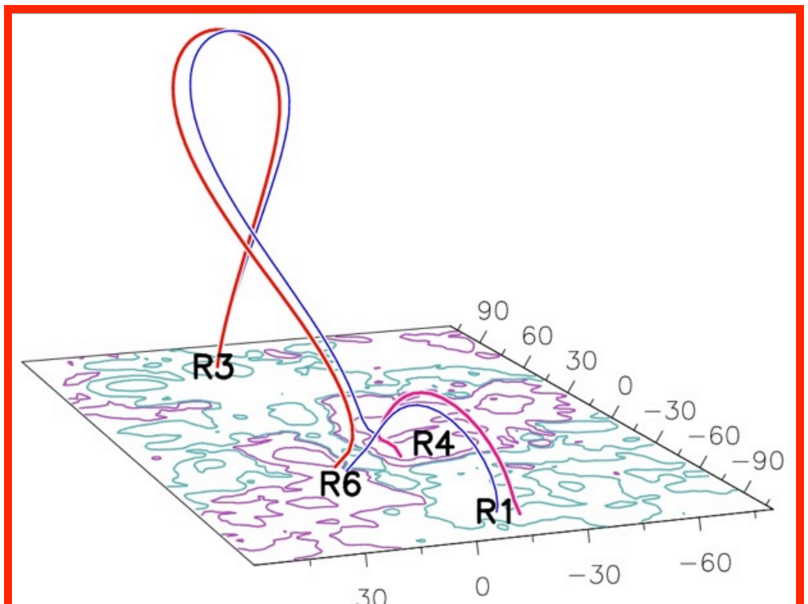
Secondary ribbons

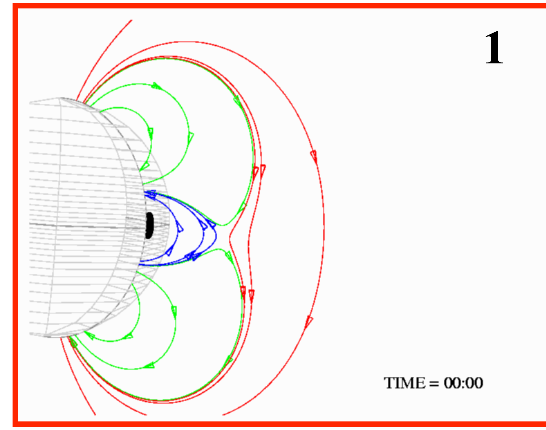
Transition Region and Coronal Explorer 195 Å
09:11 UT – 12:56 UT

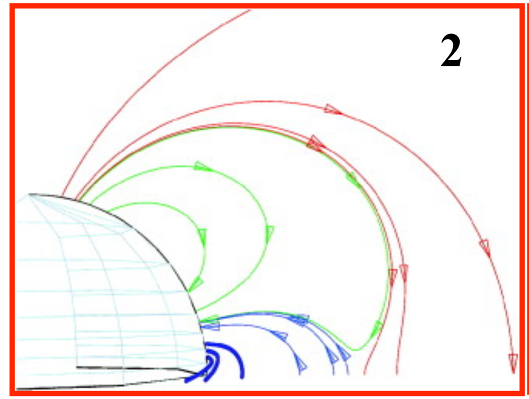
Mandrini et al 2006, Schmieder et al 2007

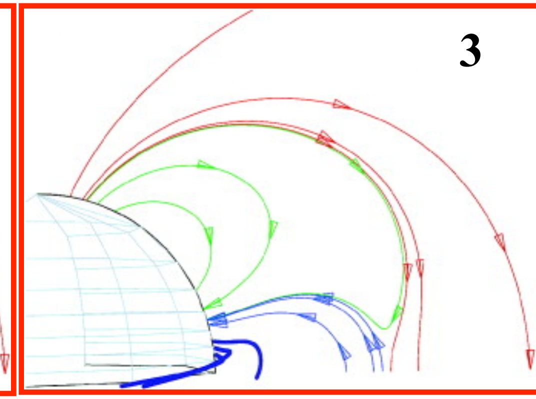
Magnetic field model

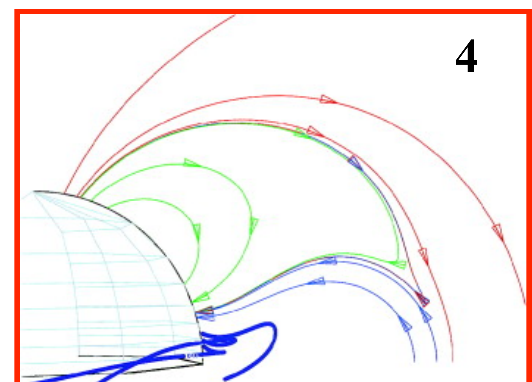












A topology similar to the "breakout" model for the origin of CMEs (lateral "breakout") → no magnetic null point present.

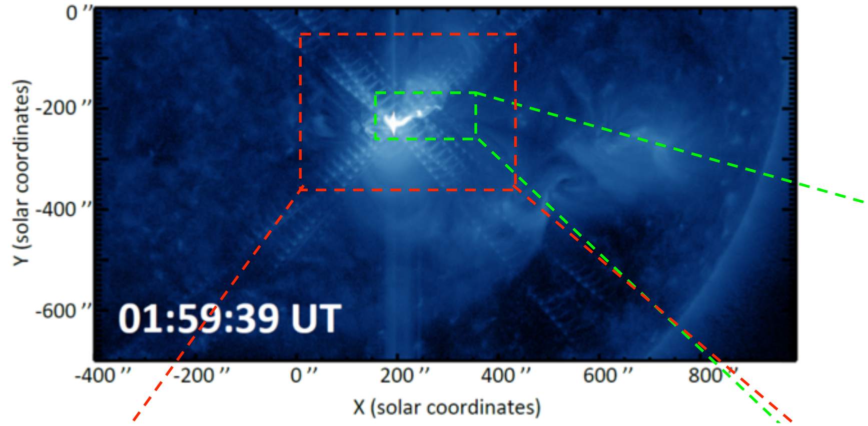
Antiochos et al. (1999)

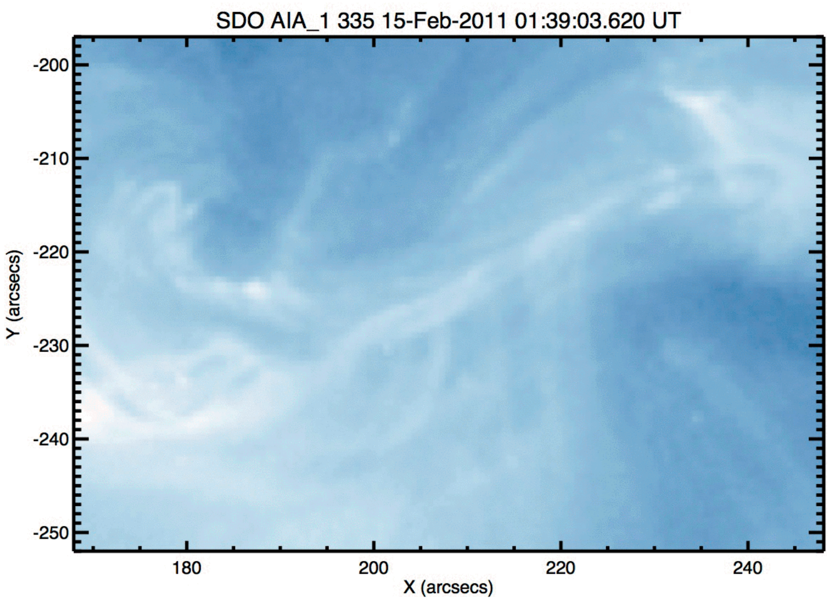
- 3. Loss of equilibrium

Reducing the tension:

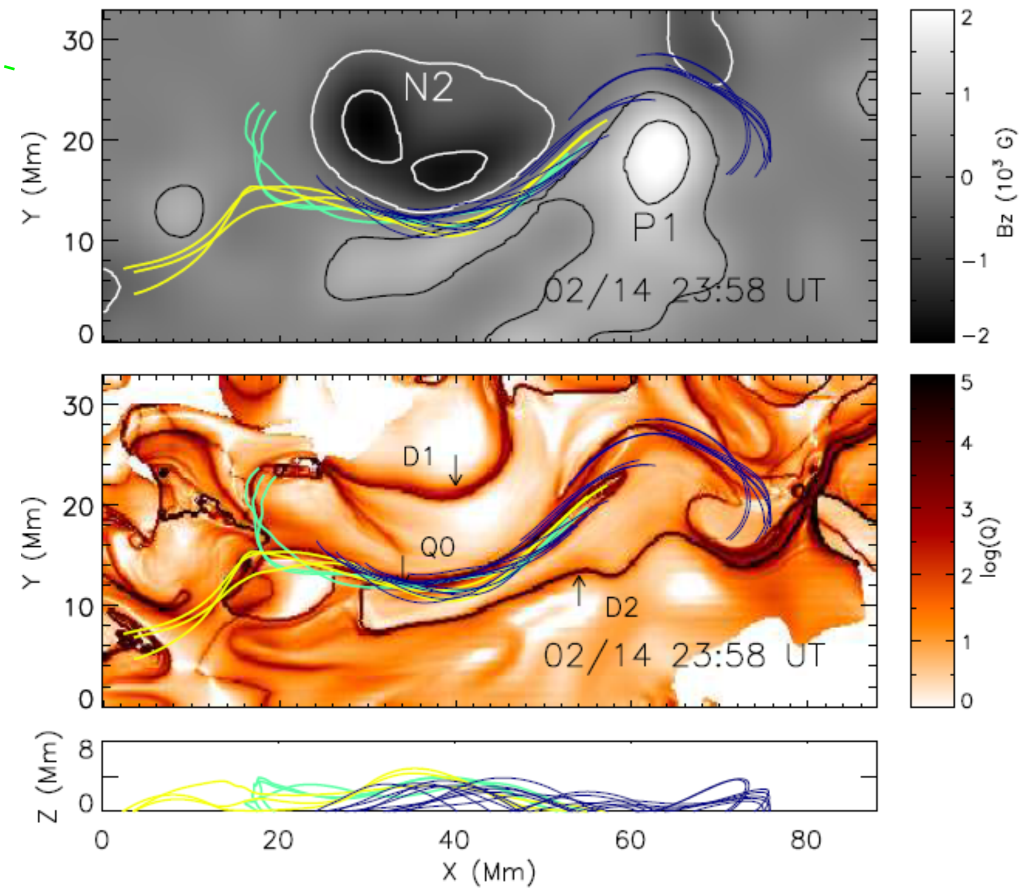
Break-out, tether-cutting..

X-class flare of Feb 15, 2011





Janvier, Aulanier et al 2014

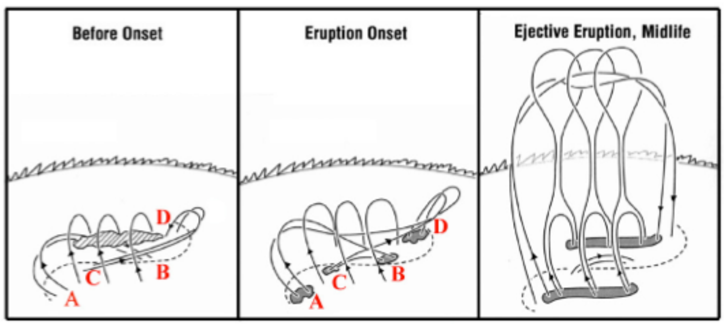


NLFFF (Wiegelmann):
Two systems of field lines: hell blue, dark blue

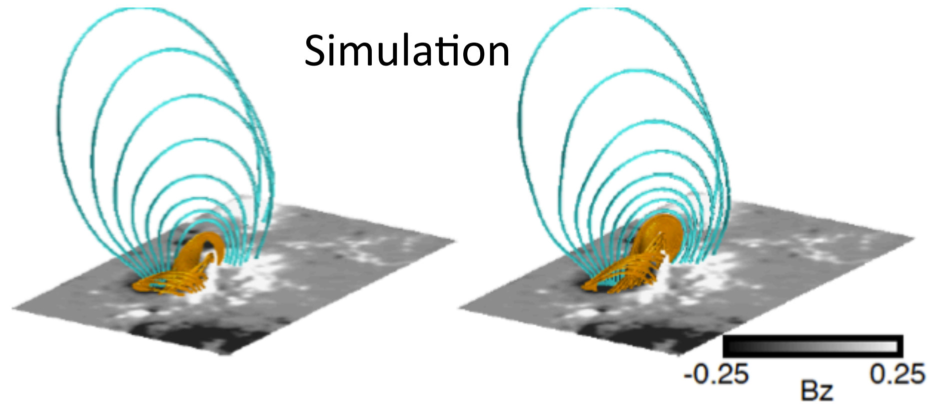
Zhao, Li, Schmieder, Pariat et al 2014

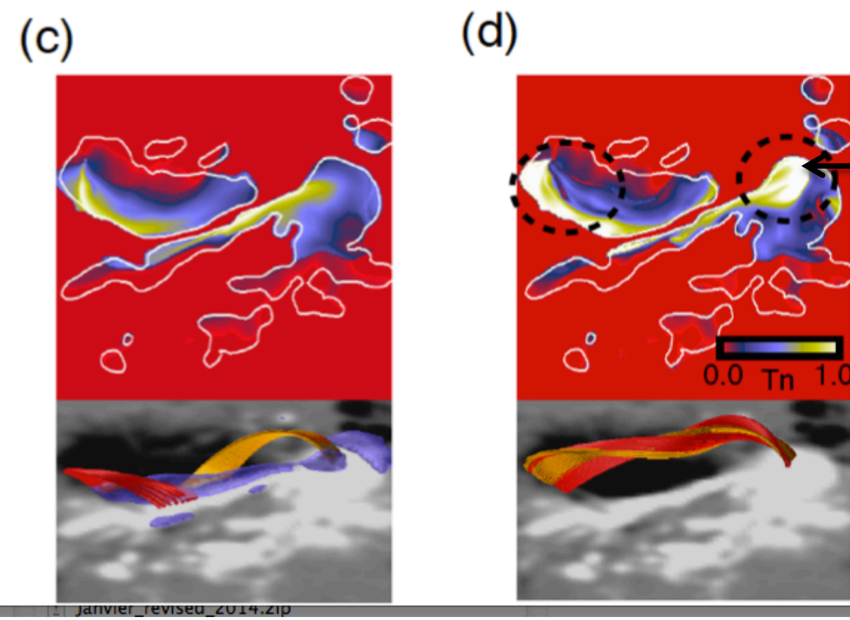
Tether- cutting

Moore 2001

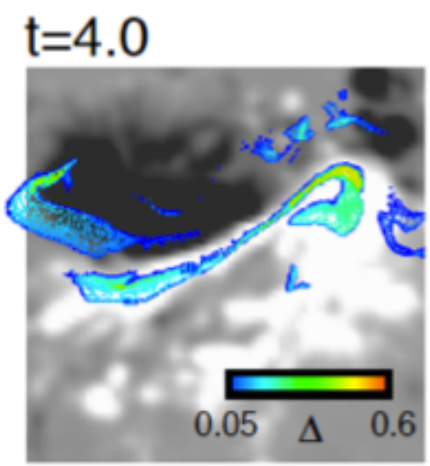


Simulation





Twist
(more
than
half –turn)



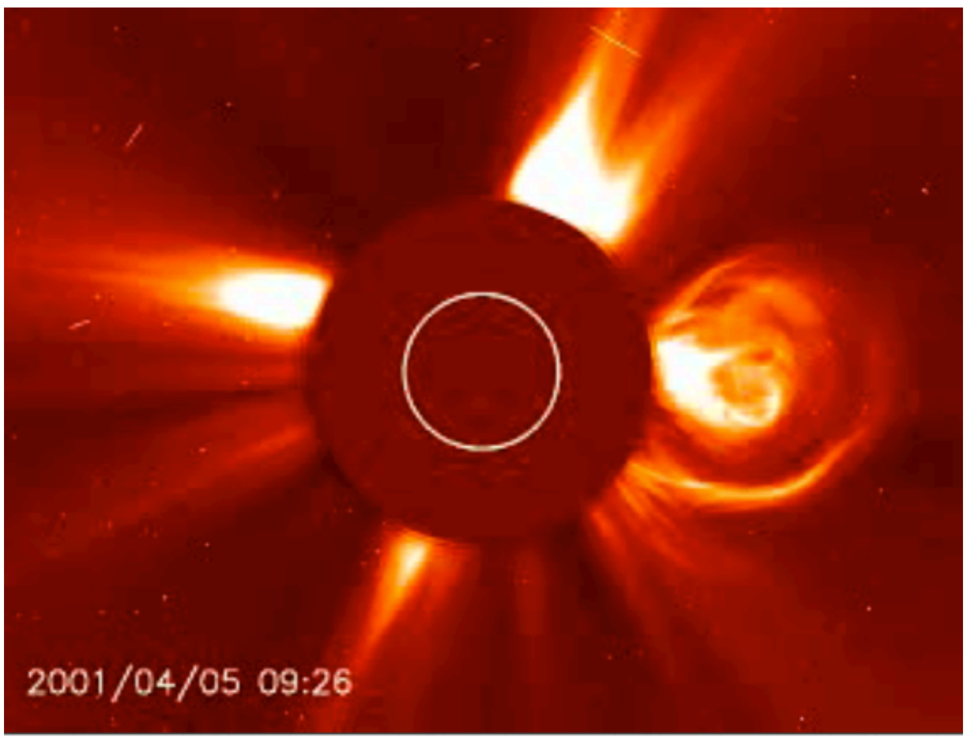
Ribbons

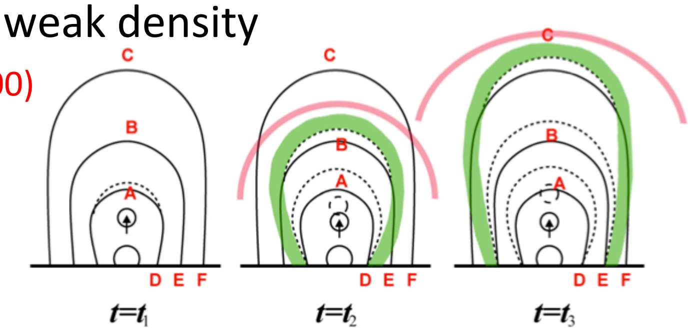
Inoue et al 2014

Nature of the CME

Observations in white light from the photospheric radiation
Thomson-scattered by free electrons in the corona,

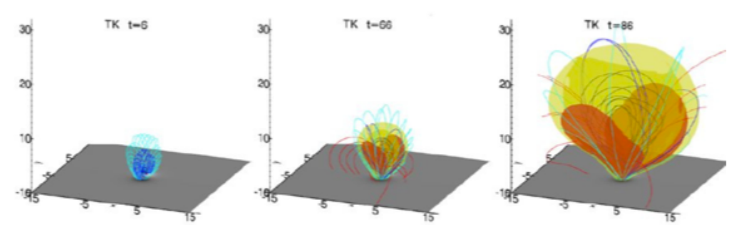
Three parts (Schwenn 2006): Core (filament..) ,Cavity; weak density
Front : pile up of mass due to compression (Forbes 2000)





EIT wave and CME front are cospatial.
Compression over each loop responsible of the density enhancement

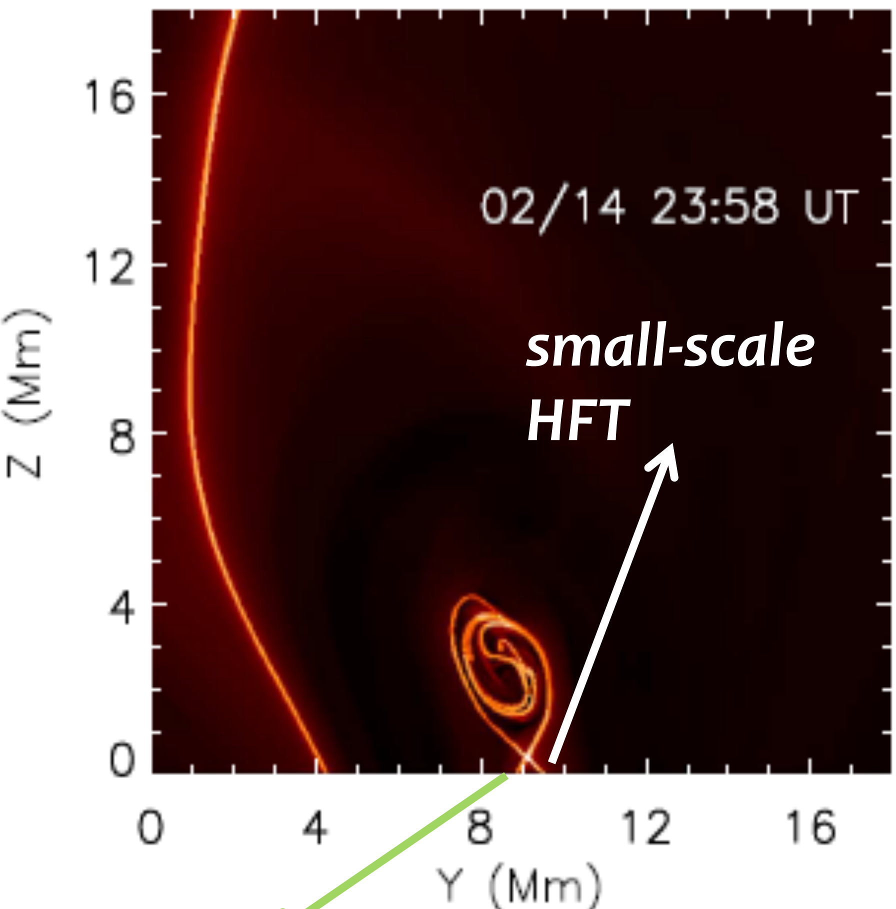
Chen 2011

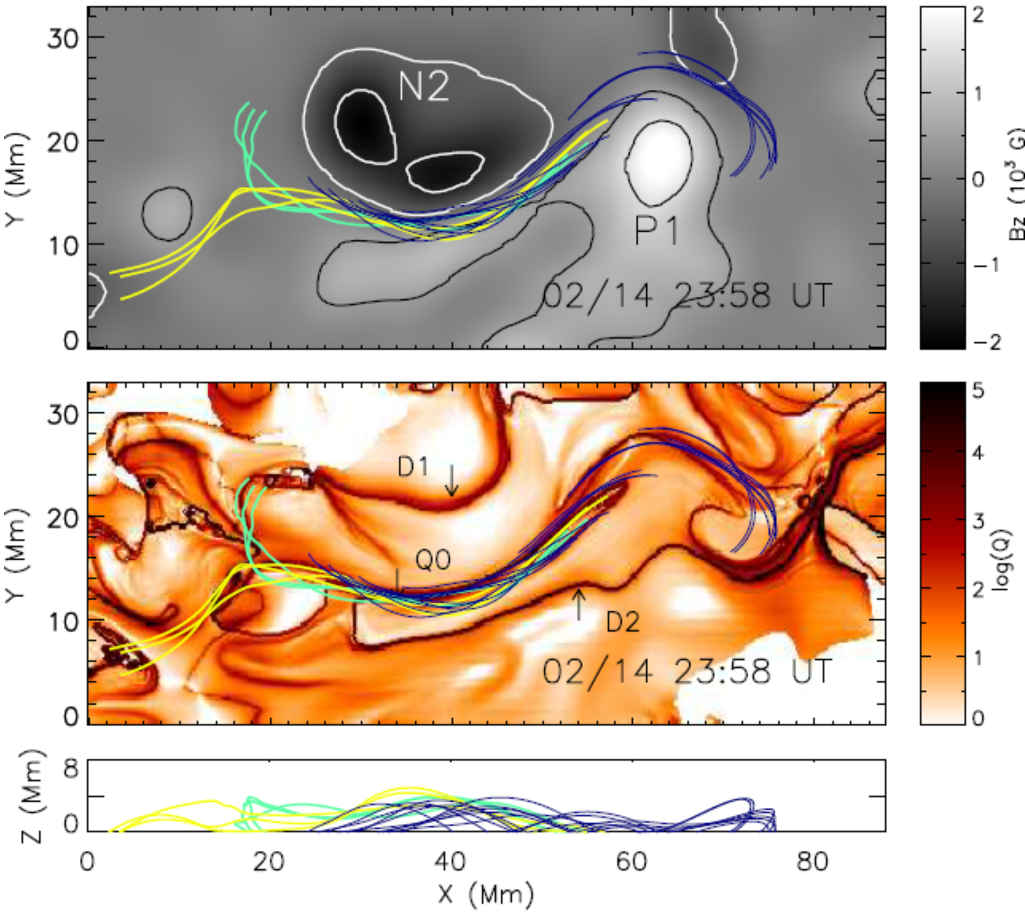


Current shell : front edge of CME

Delannee et al 2008,2014

reconnection in small scale HFT

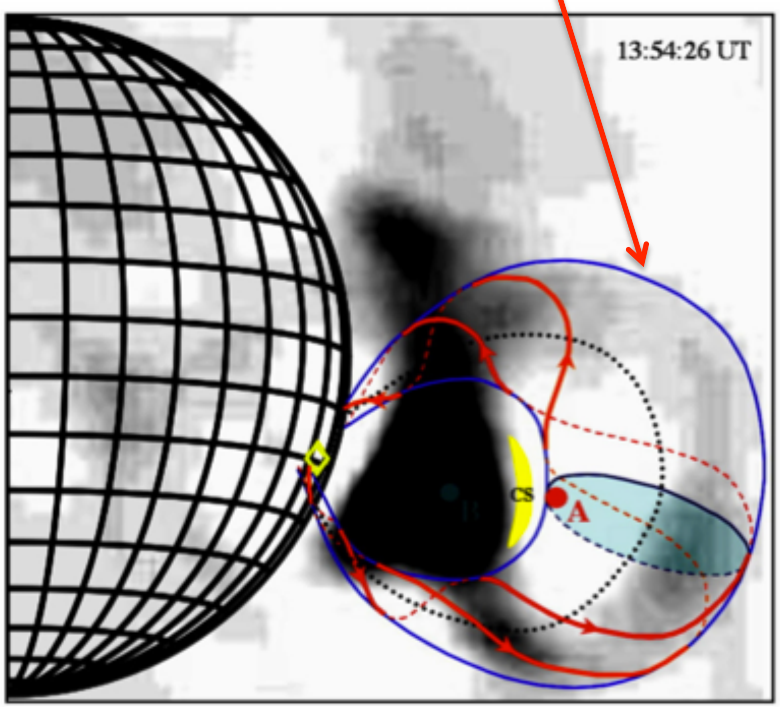




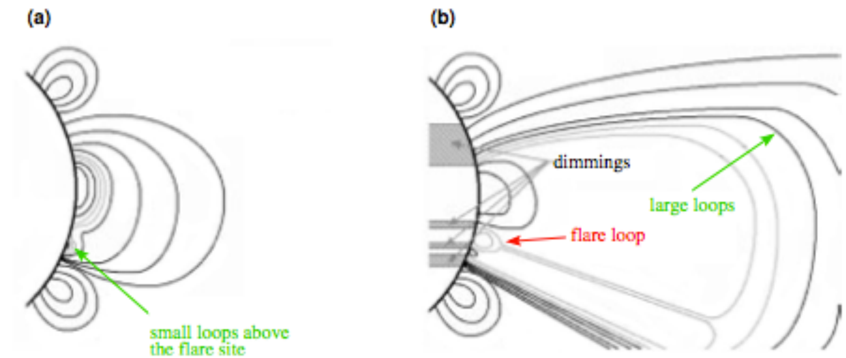
Reconnection

Flux Rope- radio CME

Radio CME : flux rope



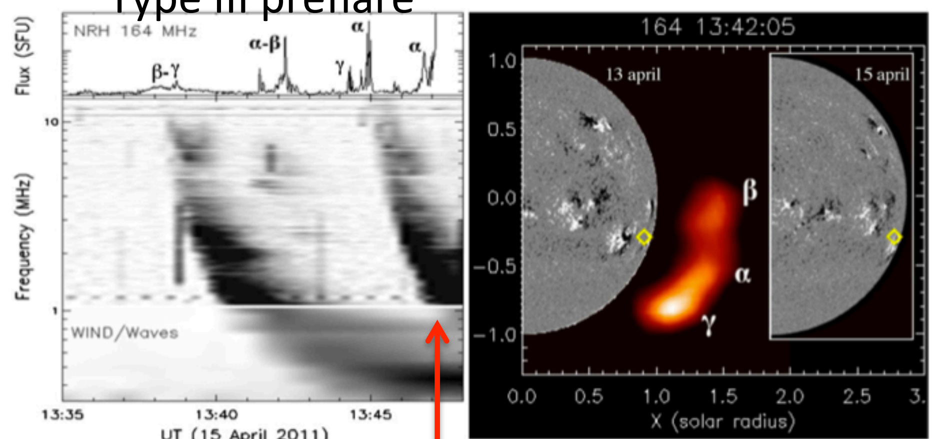
Démoulin et al 2012



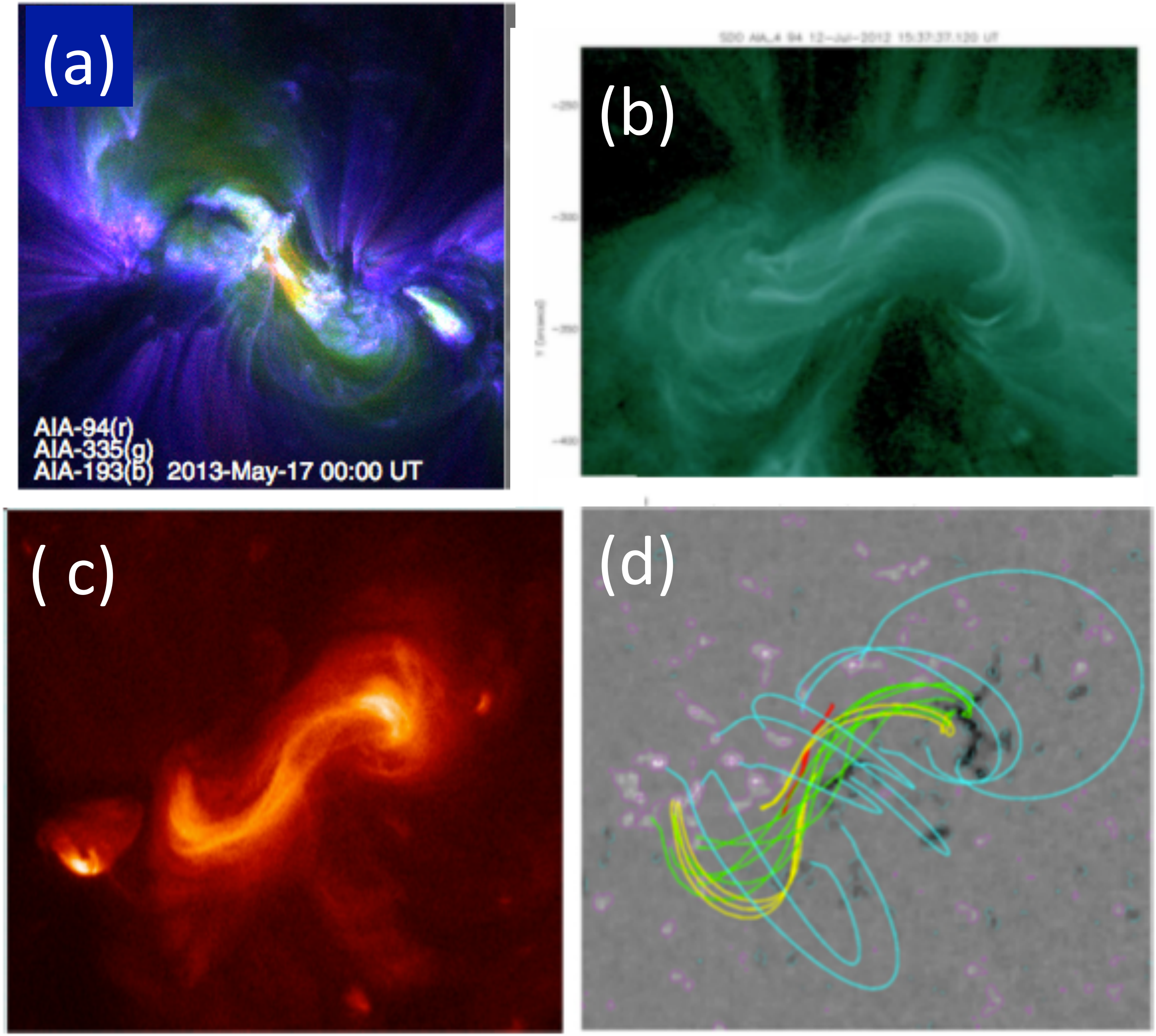
Lateral extension explains also the '' EIT waves ``

Delannée 1999

Type III preflare

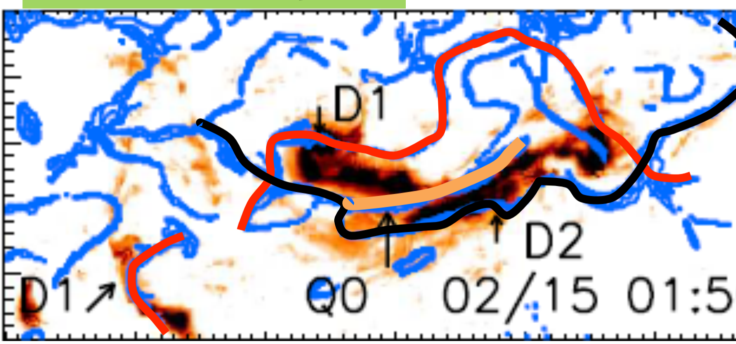


flare


(a)
AIA-94(r)
AIA-335(g)
AIA-193(b) 2013-May-17 00:00 UT
(b)
(c)
(d)

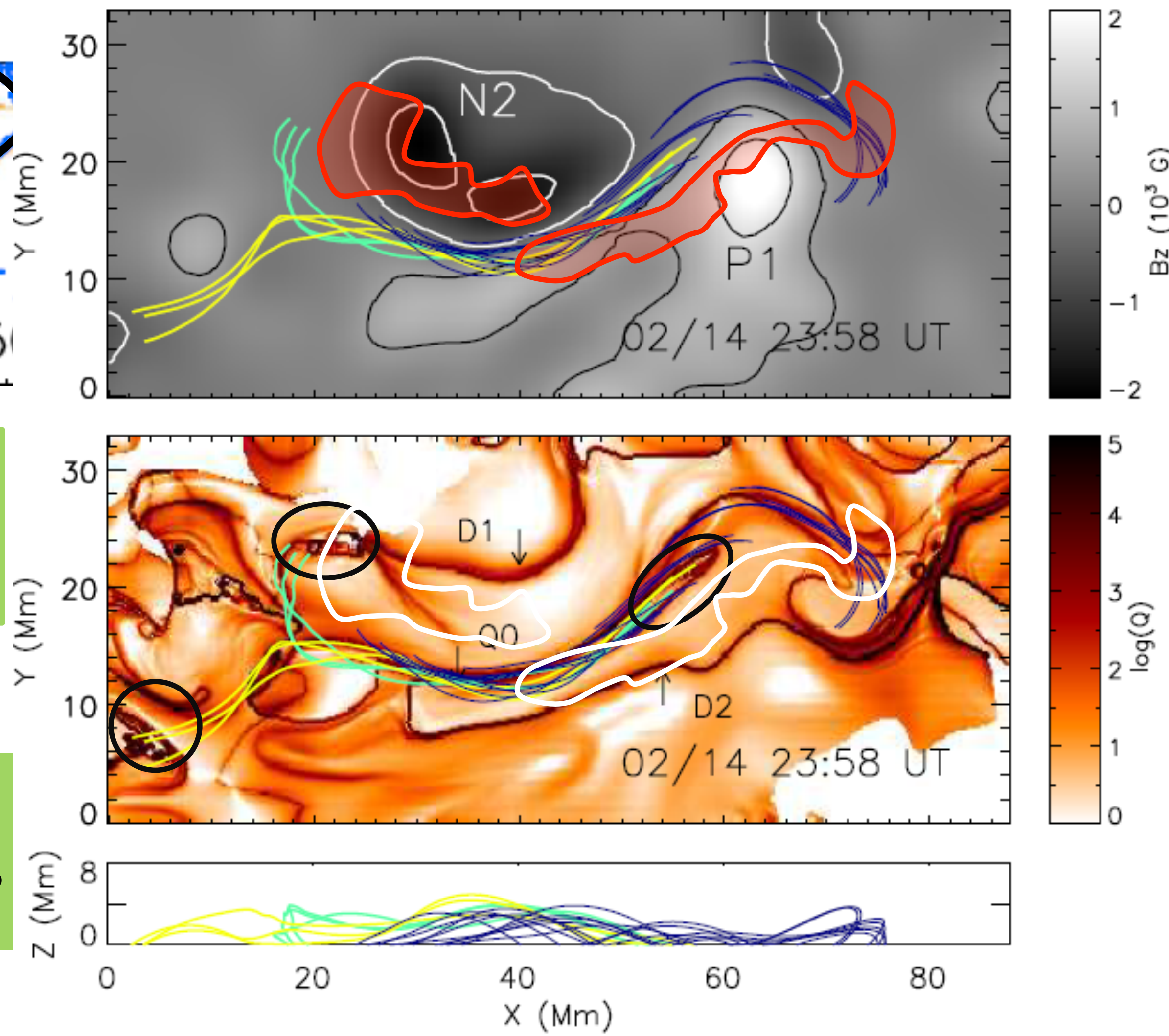
Magnetic topology related to X2.2 flare

AIA/304 + QSL



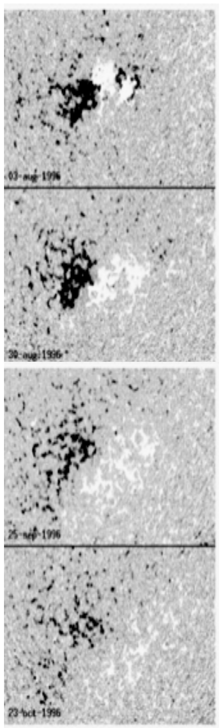
Flare ribbons are initially associated with QSL Q0

What is the field line connectivity around here?

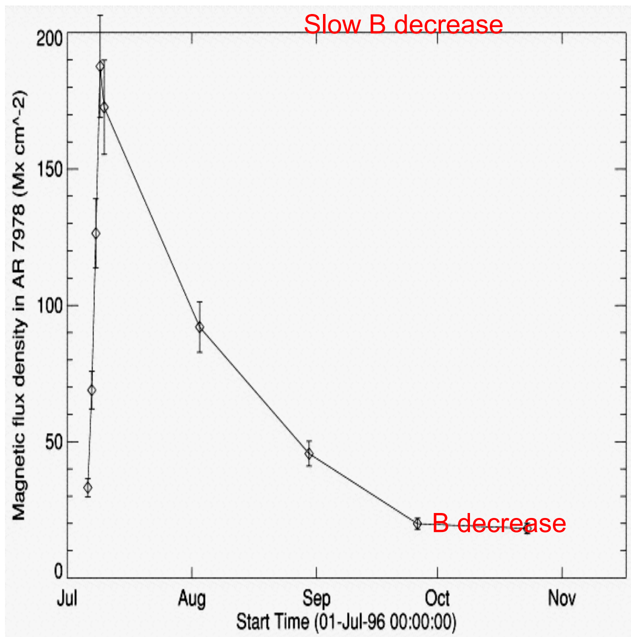


Observed B^{phot} diffusion or dispersal

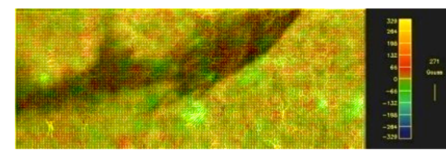
SoHO / MDI



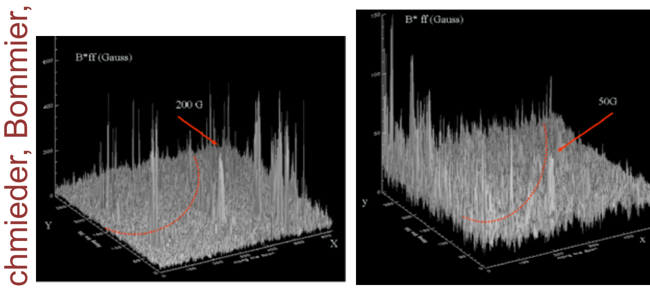
van Driel Gesztelyi et al. (2003)



Schmieder, Bommier, et al (2008)



THEMIS



Example I

Example II

Impossible d'afficher l'image. Votre ordinateur manque peut-être de mémoire pour ouvrir l'image ou l'image est endommagée. Redémarrez l'ordinateur, puis ouvrez à nouveau le fichier. Si le x rouge est toujours affiché, vous devrez peut-être supprimer l'image avant de la réinsérer.

Courtesy of A. title