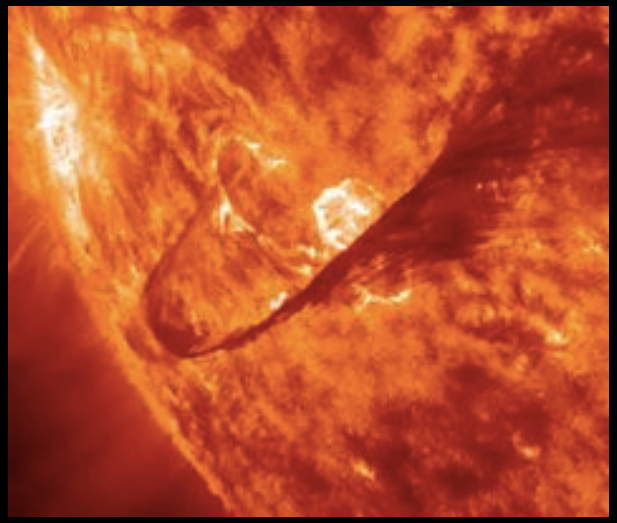
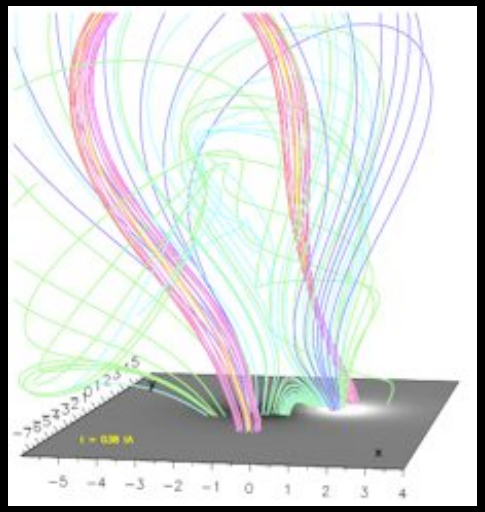
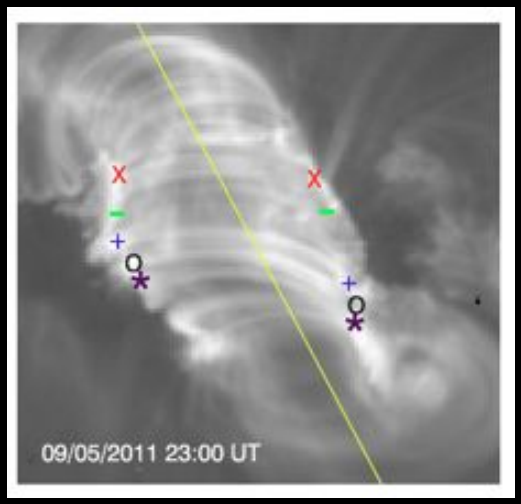
SDO



OHM



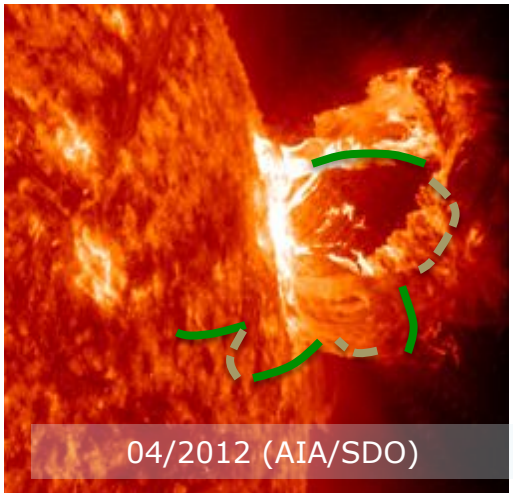
STEREO

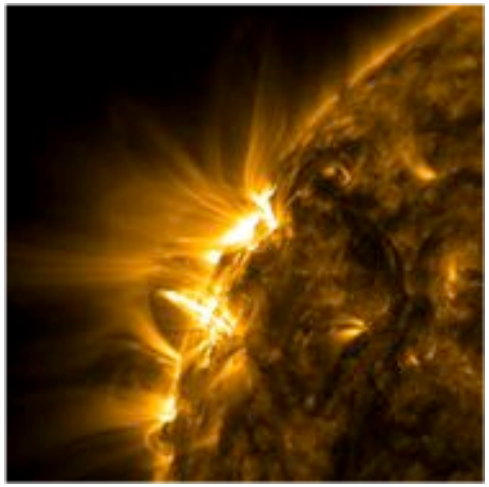



# Cohérences entre les observations et le modèle standard 3D d'éruptions solaires

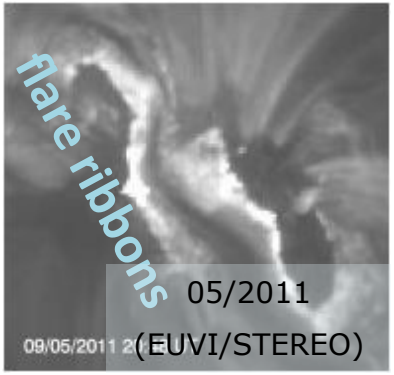
**Miho Janvier**
University of Dundee, UK
G. Aulanier, V. Bommier, P. Démoulin, E. Pariat, B. Schmieder
LESIA - Paris Observatory
J. Dudik
DAMTP, University of Cambridge

# Eruptive flares: observational characteristics



[Schmieder et al. 1995, Moore et al. 1995, Asai et al. 2003, Fletcher et al. 2011, Zhang et al. 2011]



Characteristics of eruptive flares:

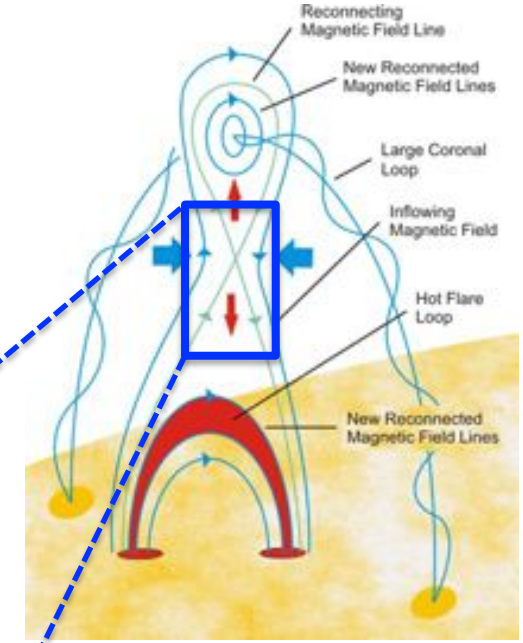
- Flare loops: regions of high density and temperature (X/UV rays)
  ➔ **they can be seen** (≠ pre-eruptive field)
- Ribbons: collisional region between descending particles and higher density chromosphere
- Flux rope: twisted magnetic structure that can support a prominence

## Standard 2D model of flare loops formation: (CSHKP model)

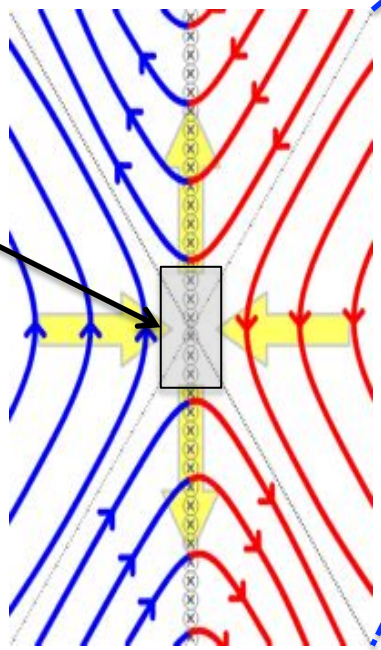
- **Magnetic reconnection leads to:**

⇛ **Flux rope + post-flare loops**

⇛ **Two flare ribbons**




**High current density layer**



*Carmichael (1964)*
*Sturrock (1966)*
*Hirayama (1974)*
*Kopp & Pneumann (1976)*

*Forbes & Malherbe (1986)*

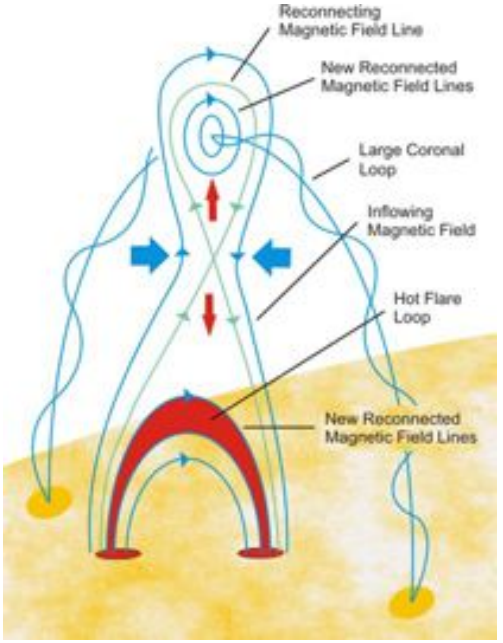
# Eruptive flares: 2D model & limitations

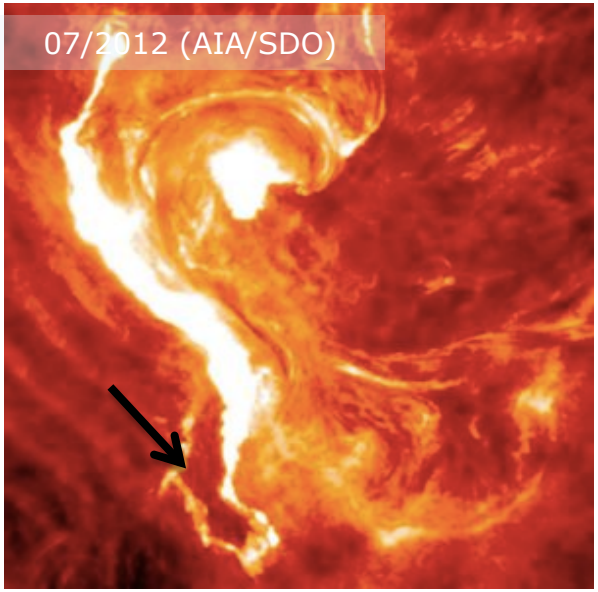
## Standard 2D model of flare loops formation: (CSHKP model)

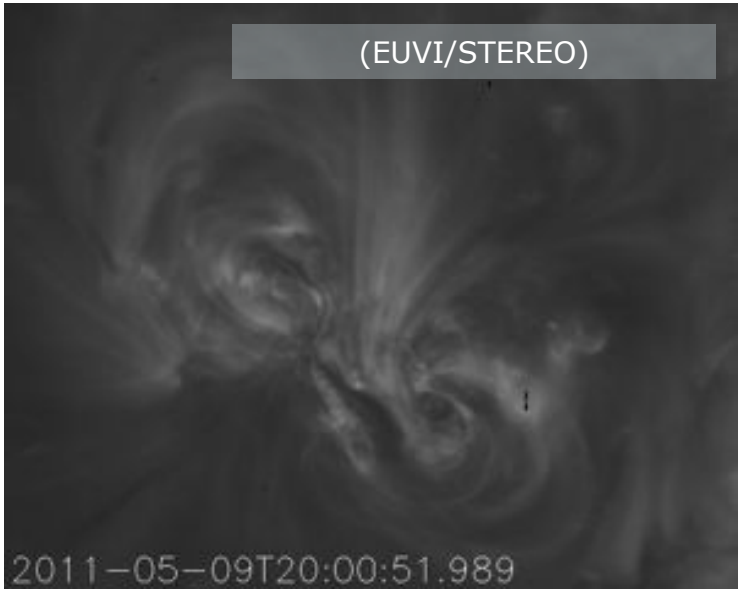
- **Magnetic reconnection leads to:**

⇛ **Flux rope + post-flare loops**

⇛ **Two flare ribbons**




*Carmichael (1964)*
*Sturrock (1966)*
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*Kopp & Pneumann (1976)*

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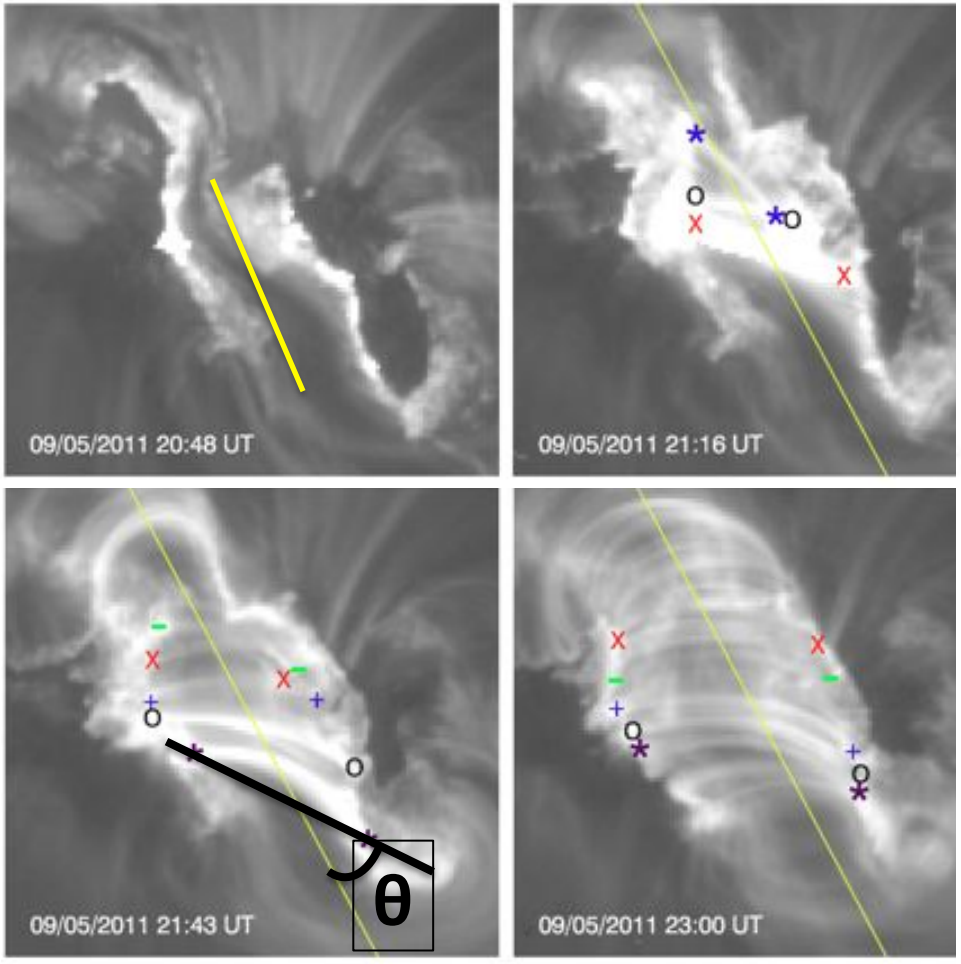
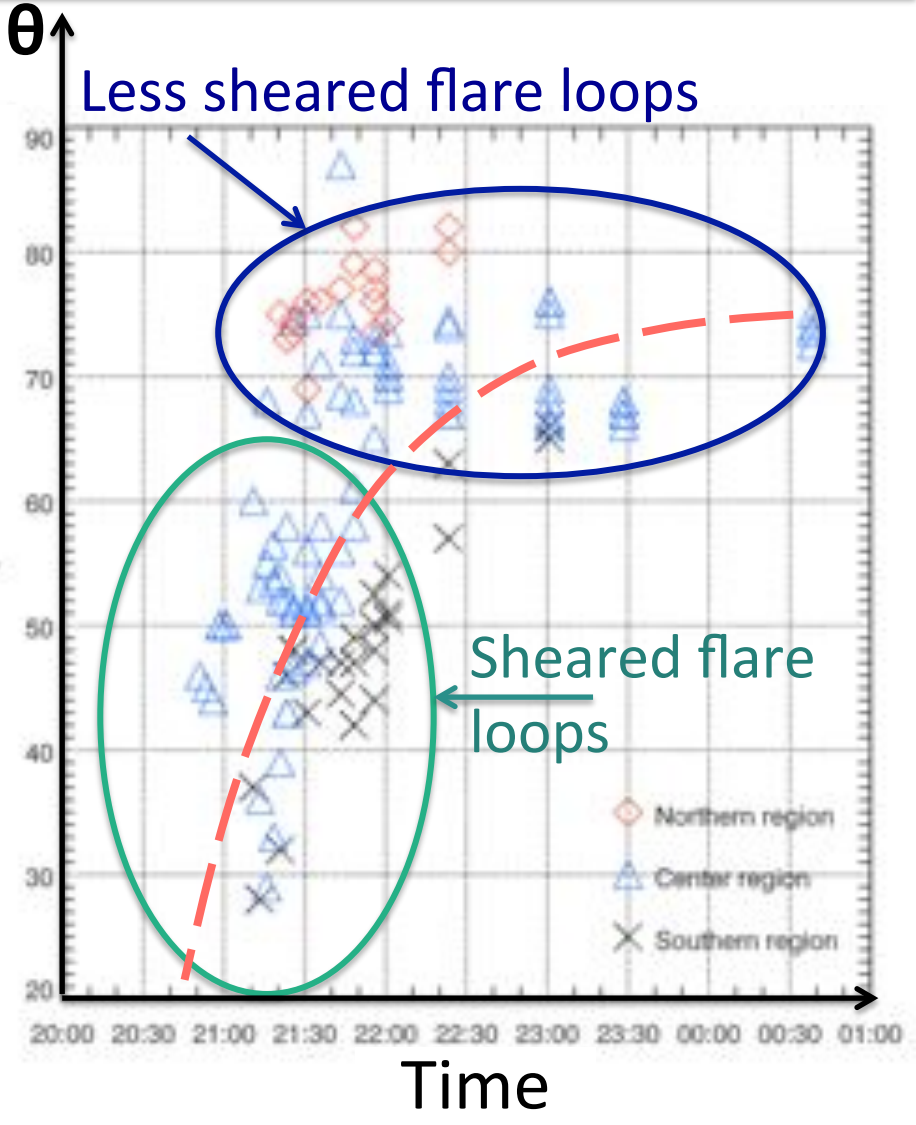
# Eruptive flares: shear evolution

[Asai et al. 2003, Su et al. 2006, Warren et al. 2011]




**Time evolution of loop orientation**



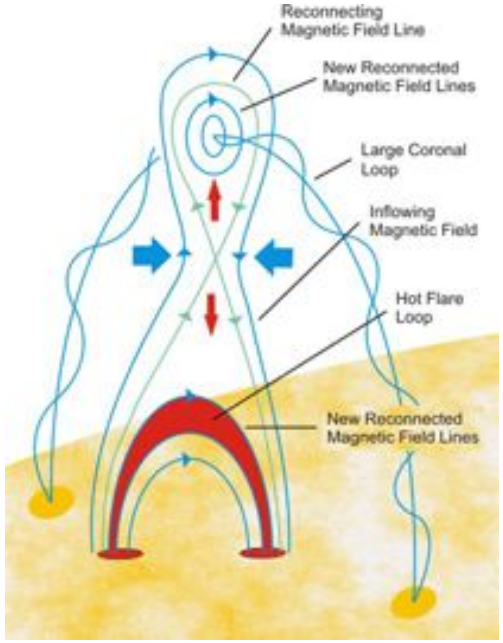

[Aulanier, Janvier, Schmieder, A&A 2012]

# Eruptive flares: 2D model & limitations

## Standard 2D model of flare loops formation: (CSHKP model)

**But 2D does not relate with 3D effe[illegible]D dynamics, geome[illegible] effects: shear and torsion)**

**Why are post-flare loops s[illegible]red? W[illegible]y is there a J-shape for the flare r[illegible]on? What about the flux rope?**




*Carmichael (1964)*
*Sturrock (1966)*
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# 3D MHD Simulation: the basic ingredients

✧ **O**bservationally-driven **H**igh-order **M**HD Code (**OHM**)

3D, non uniform mesh,
finite difference,
predictor-corrector

[Aulanier, Démoulin, Grappin 2005]

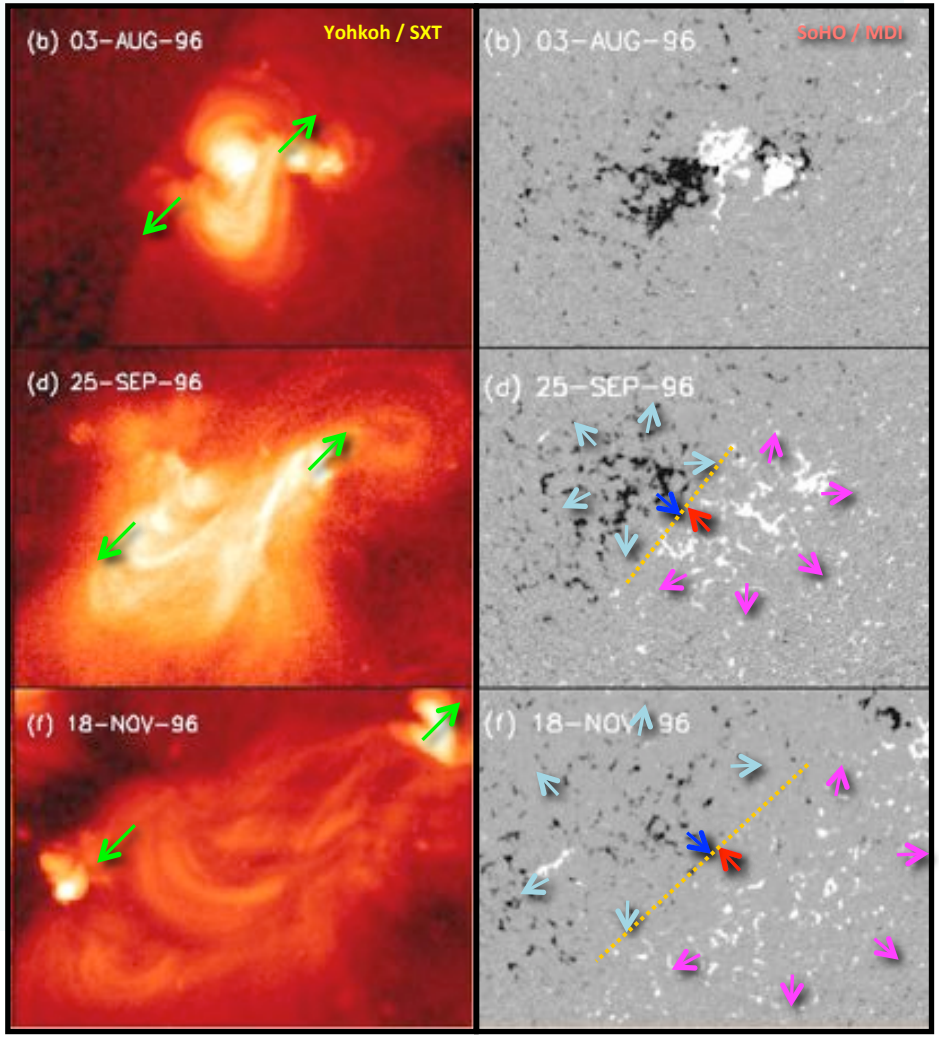
✧ Visco-resistive, $\eta_{coronal}$ = cst,
$\beta = g = 0$

✧ **line-tied** at photosphere (z=0)

- Shearing coronal loops
- Converging motions at PIL
- Flux dispersal and B decrease
- Flux cancellation at PIL

[Schmieder et al. (2008), Green et al. (2011), Démoulin et al. (2002), van Driel Gesztelyi et al. (2003)]

Long-term evolution of active regions



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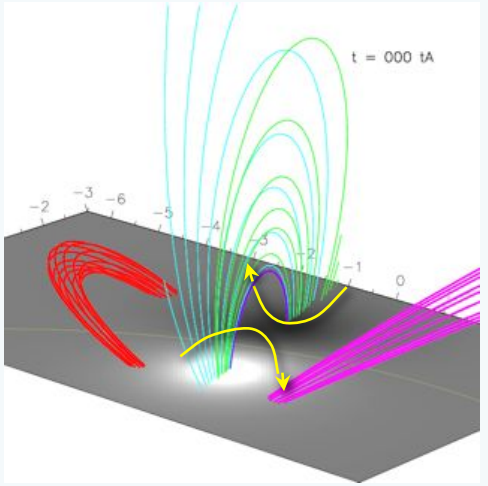
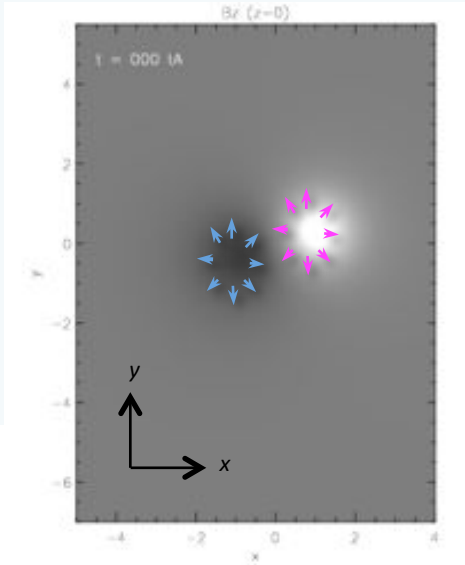



## STEP 1:

❖ Asymmetric bipolar arcade

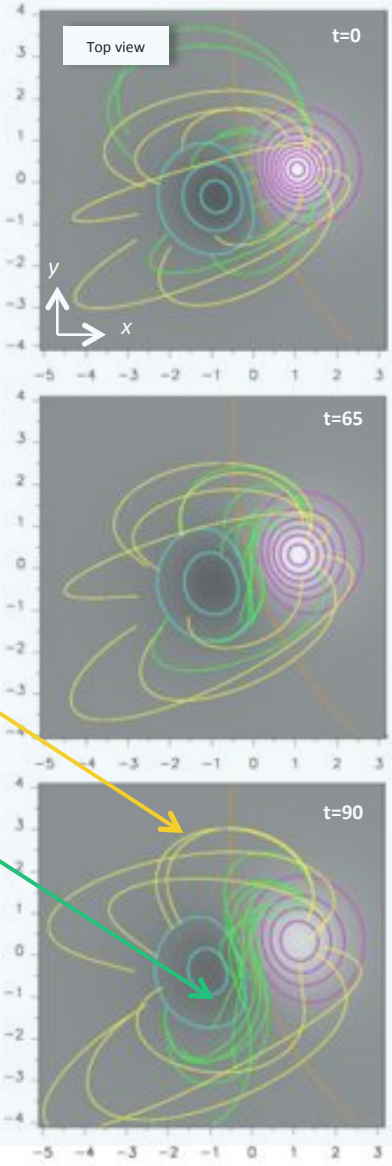
❖ Photospheric magnetic diffusion of $B_{x;y;z}$

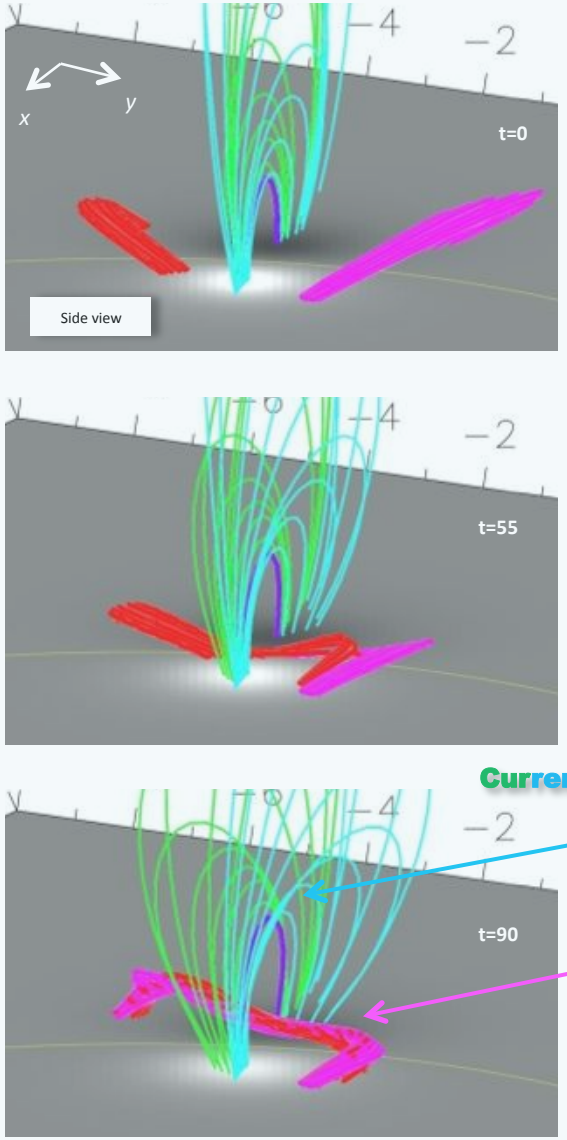
❖ Photospheric shearing motions $u_{x;y}$



# 3D MHD Simulation: the unstable flux rope

[Aulanier, Török, Démoulin & DeLuca 2010]



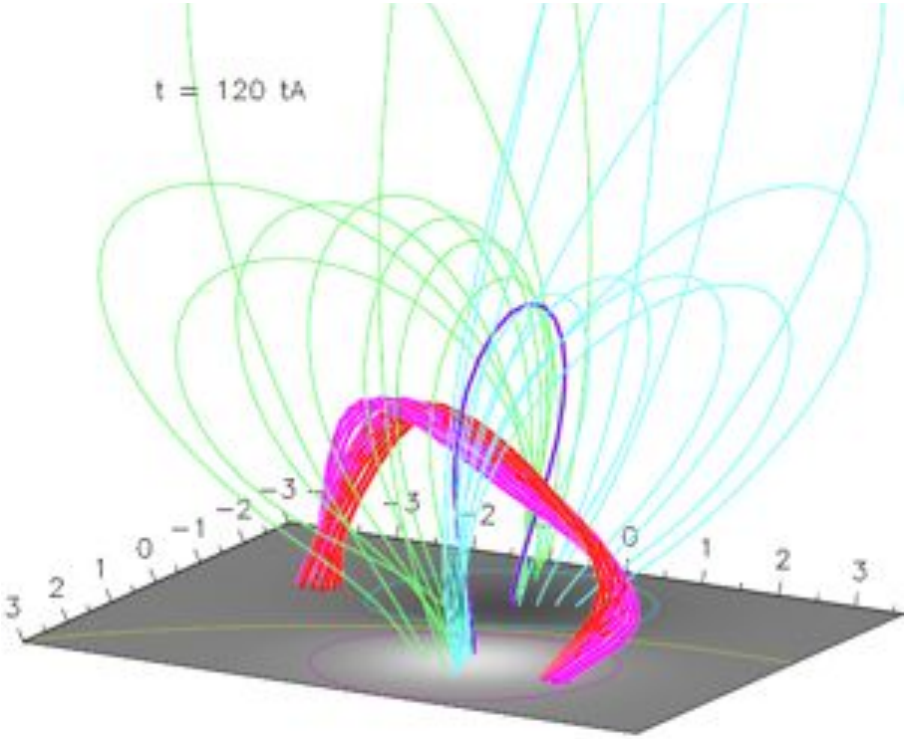

Current-almost-free arcades

J- and S- shaped loops

Current-almost-free arcades

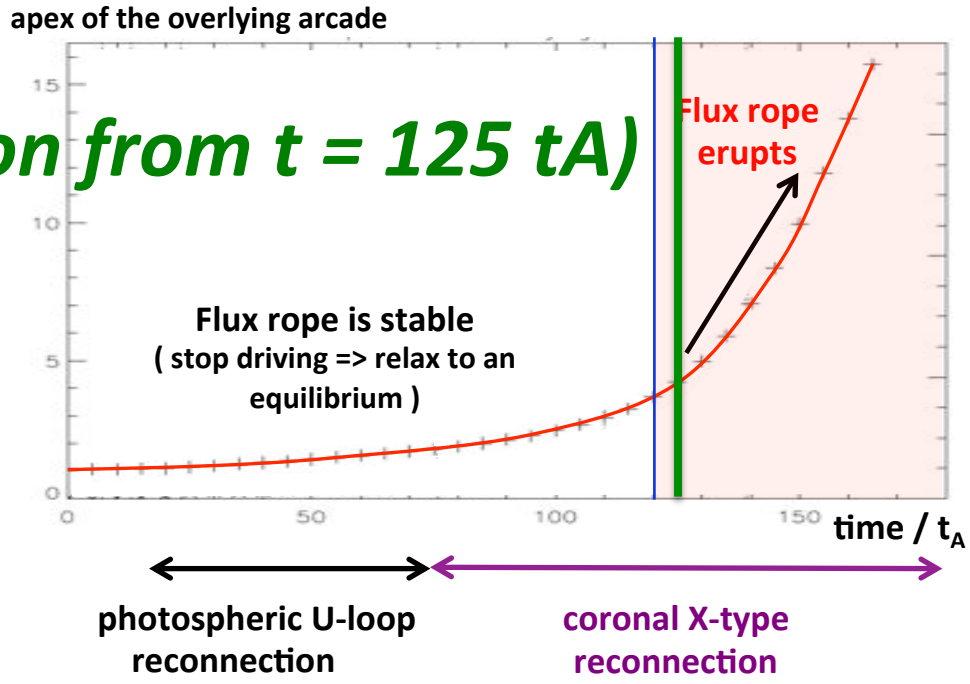
Flux rope

# 3D MHD Simulation: the unstable flux rope




[Aulanier, Török, Démoulin & DeLuca 2010]

## *(relaxation from t = 125 tA)*




**CME eruption caused by:**

➔ **TORUS INSTABILITY**

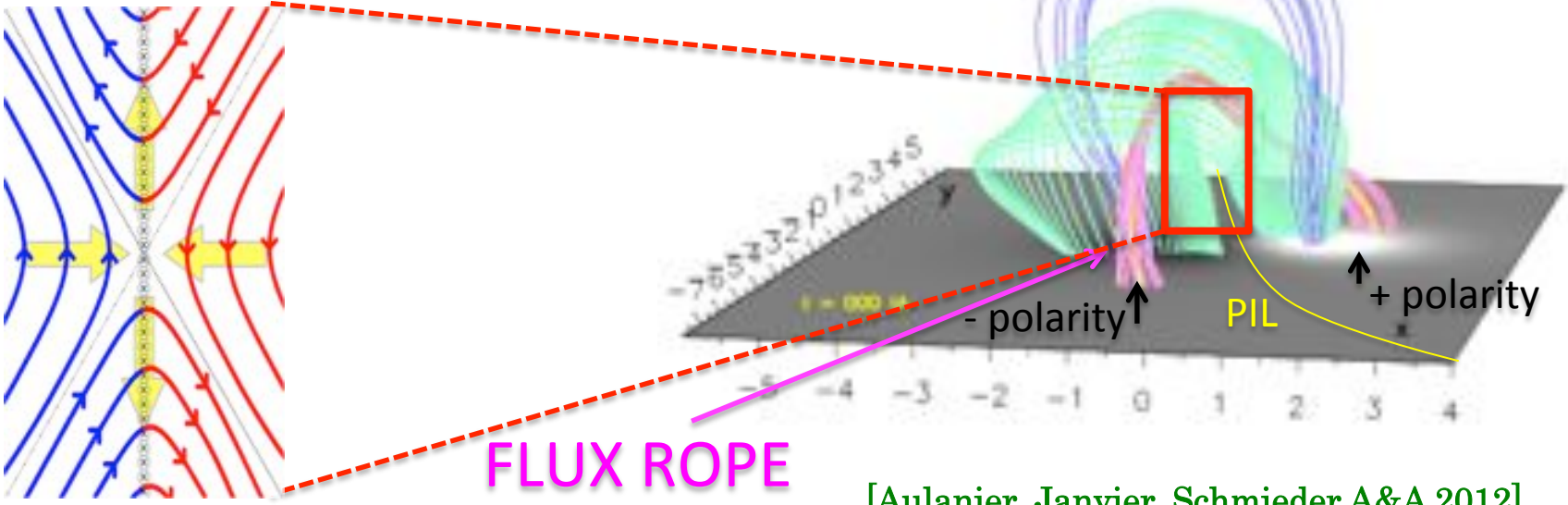
# 3D MHD Simulation, part 2: flux rope expansion

**OHM** code:

- ✧ t=0, « torus » unstable
- ✧ At t>0, **no forcing**
- ✧ line-tied at photosphere (z=0)

⇛ FLUX ROPE EXPANSION

⇛ Magnetic reconnection




[Aulanier, Janvier, Schmieder A&A 2012]

# 3D MHD Simulation, part 2: flux rope expansion

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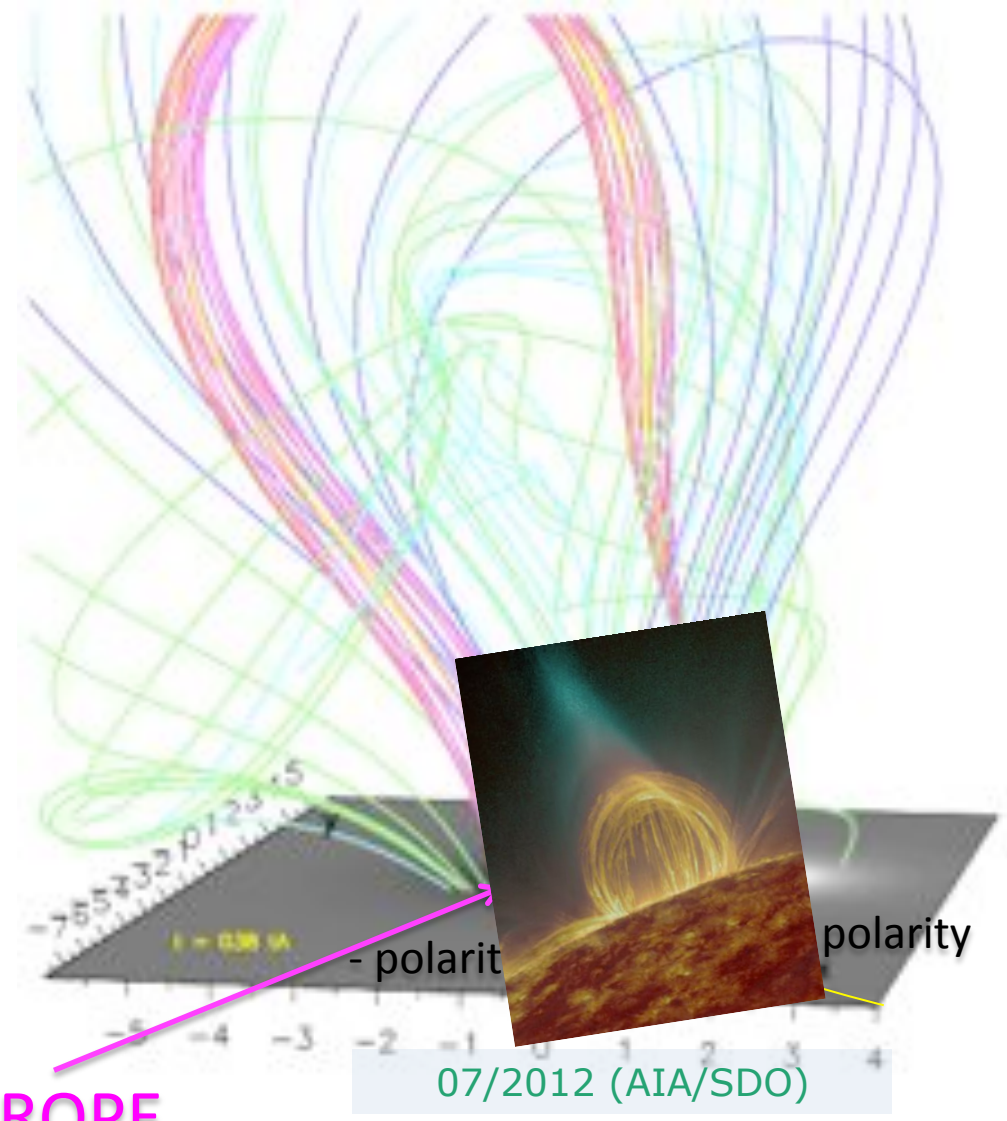


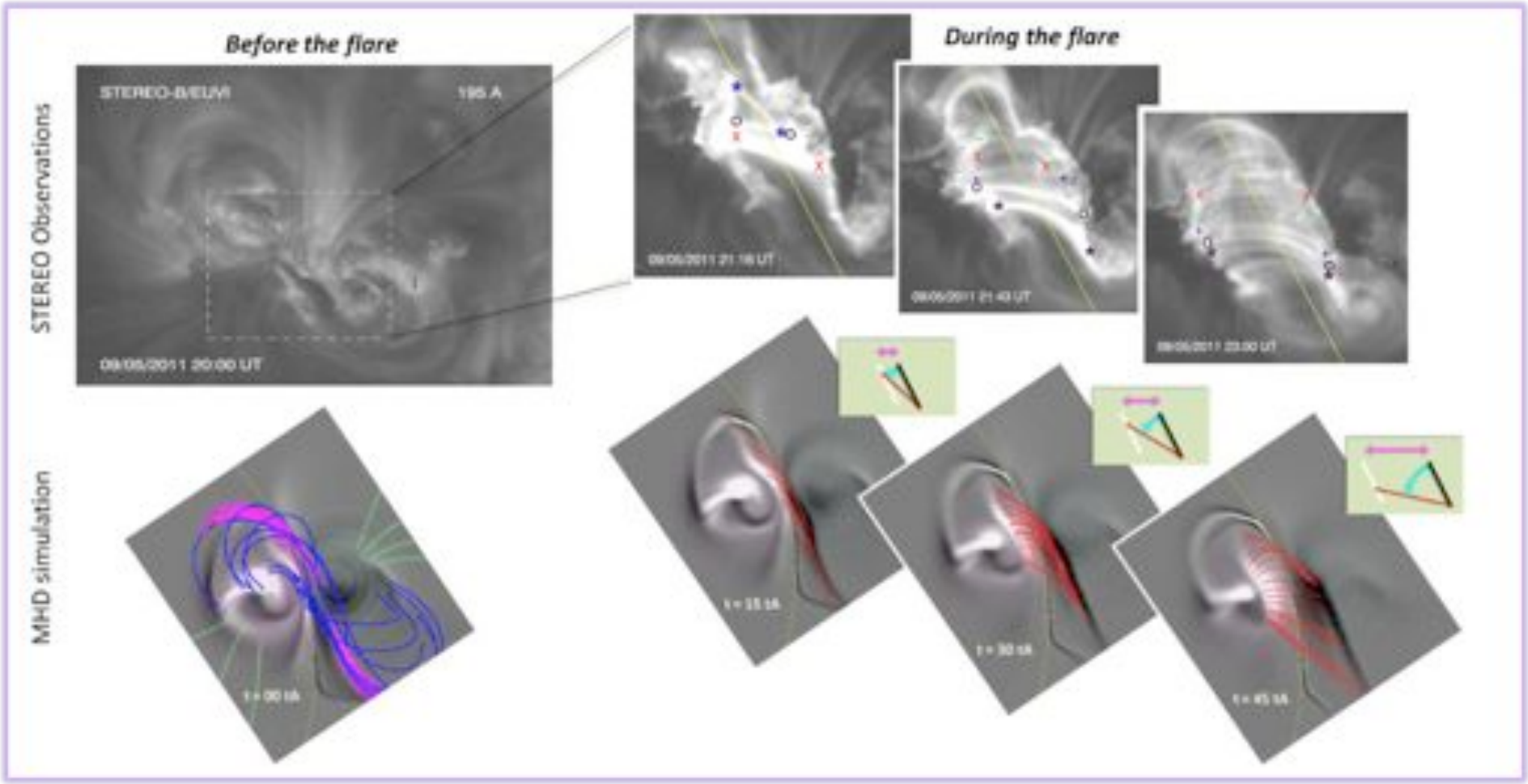

[Aulanier, Janvier, Schmieder A&A 2012]

# Flux rope relaxation: MHD & EUV comparison (flare loops)

Similar evolution of flare loops in observations and MHD simulation:

⇛shearing of loops

⇛flare ribbons

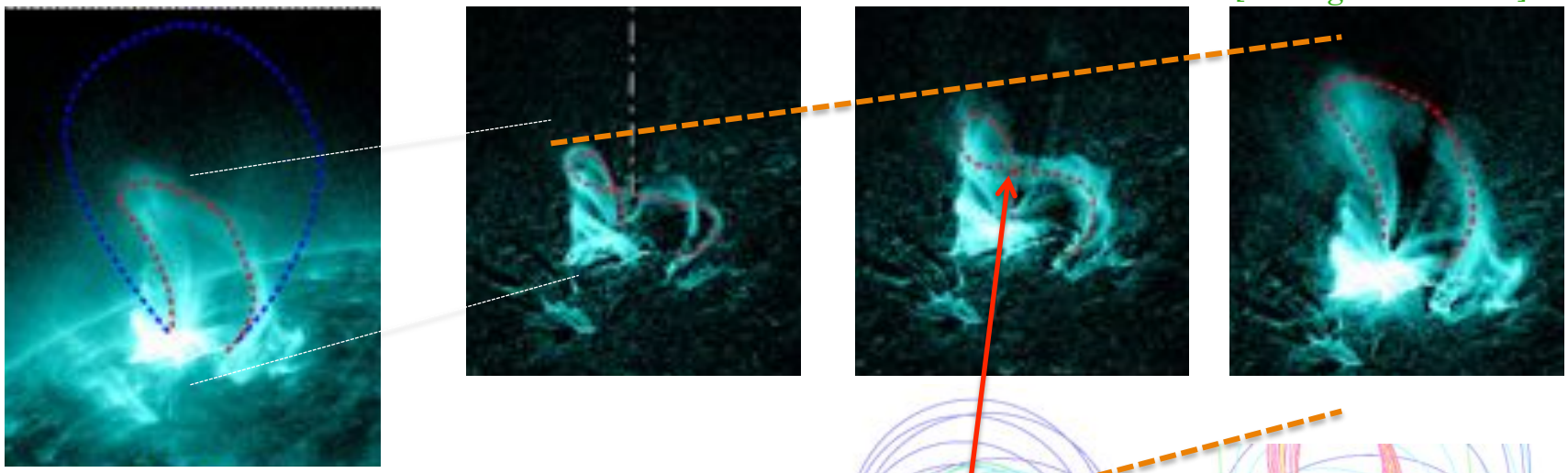


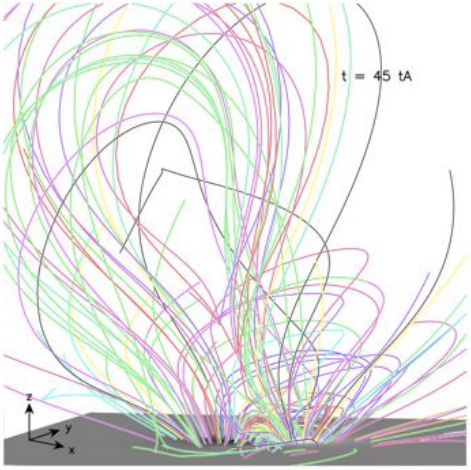

[Aulanier, Janvier, Schmieder A&A 2012]

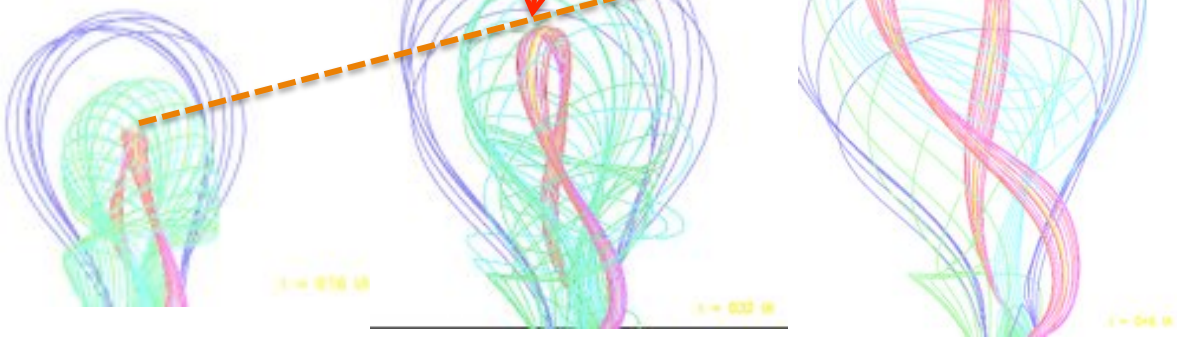
# Flux rope relaxation: MHD & EUV comparison (flux rope)

Similar evolution of the flux rope in observations and MHD simulation:
⇛writhe, twist, expansion

[Zhang et al. 2011]

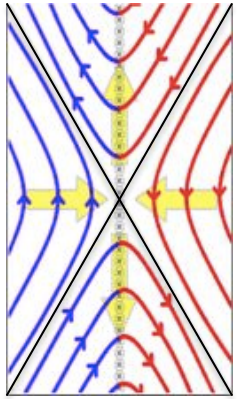




# 3D reconnection: underlying mechanism

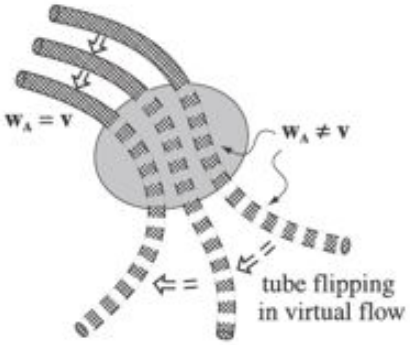
Classical image in 2D, with null points and separatrices:



Not necessarily true in 3D:
**Strong distortion of magnetic field ⇛ Current layer**
Ideal MHD can still break down in those finite-J regions.

[Priest & Démoulin 1995, Démoulin et al. 1996-1997]

3D reconnection without null points:
⇛ **Slipping reconnection**
(continuous change of connectivity)



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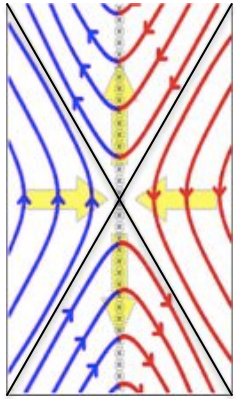

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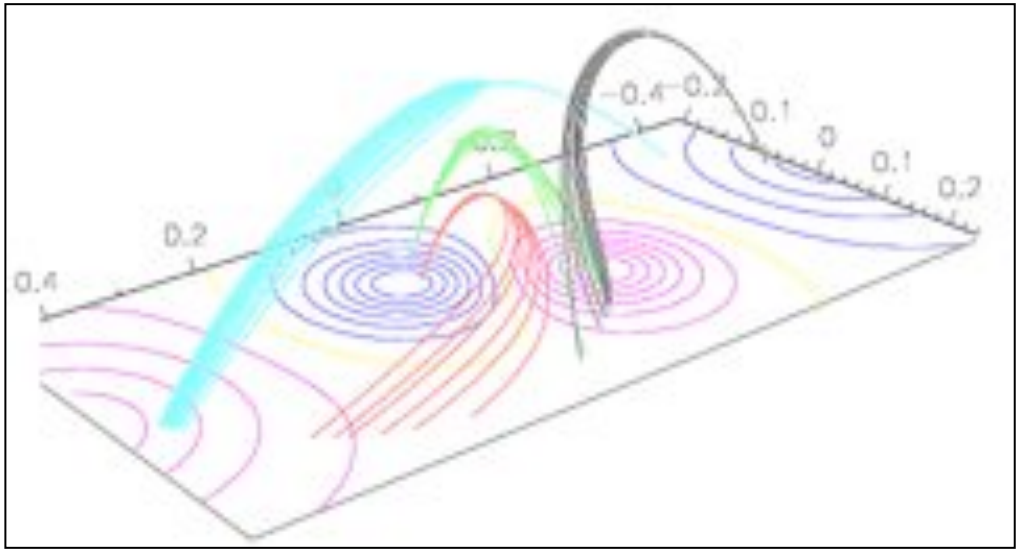


[Aulanier et al. 2005]
See also [Aulanier et al. 2007] for observational evidences

3D reconnection without null points:
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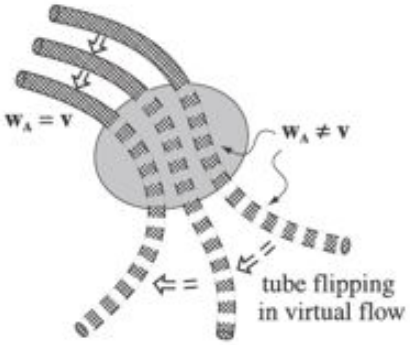
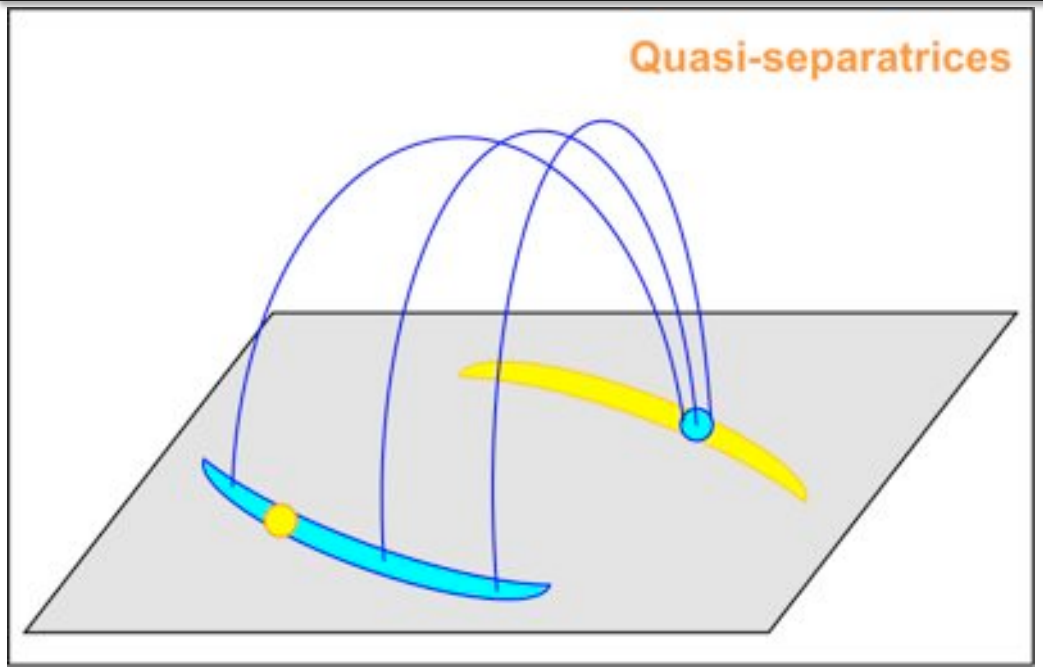
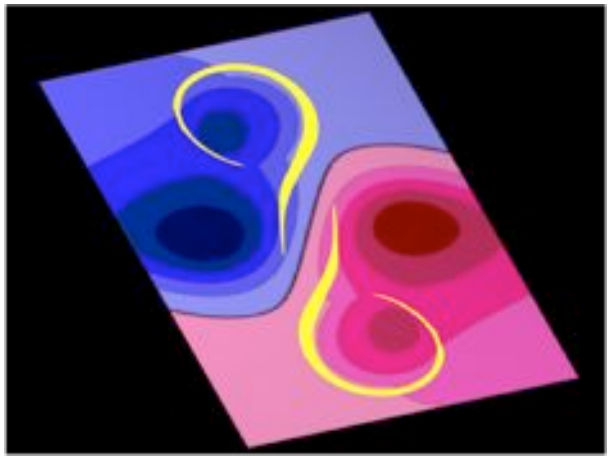


# 3D reconnection: Quasi-Separatrix Layers



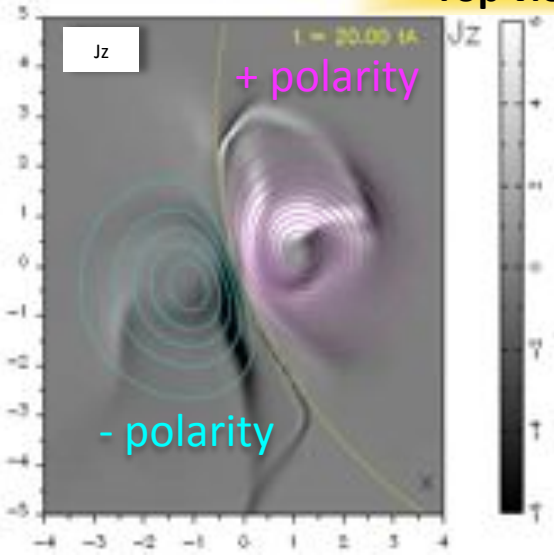

Démoulin et al. (1995, 1996, 2006)
Titov et al. (2002), Pariat et al. (2012)

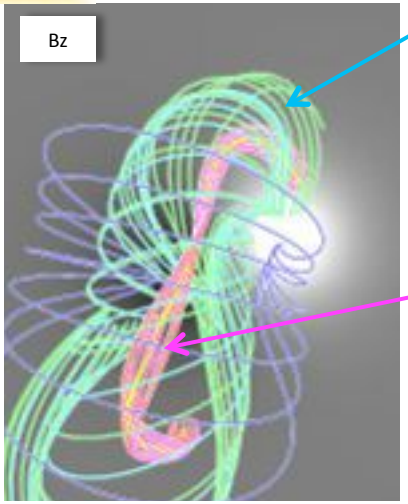
Quasi-separatrix Layers (QSLs): measure the strong variations of the magnetic connectivity

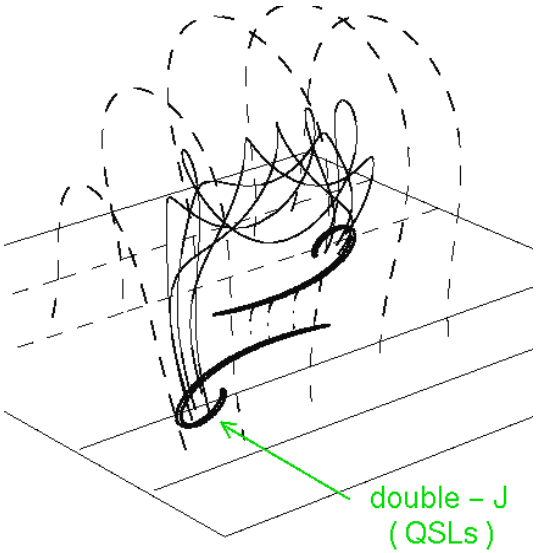


# Flux rope legs: J-shaped QSL and current footpoints

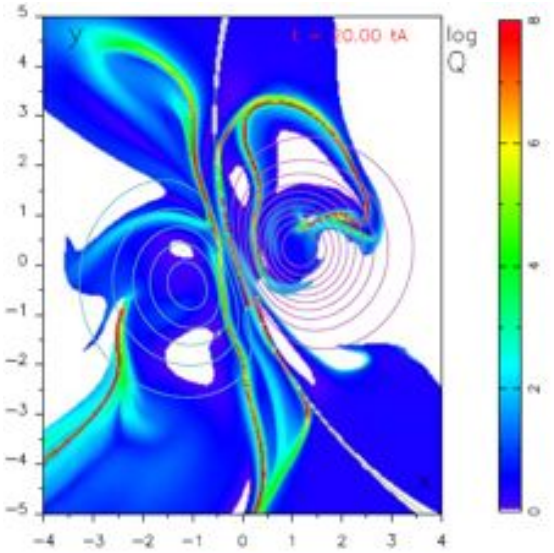
**Top views**

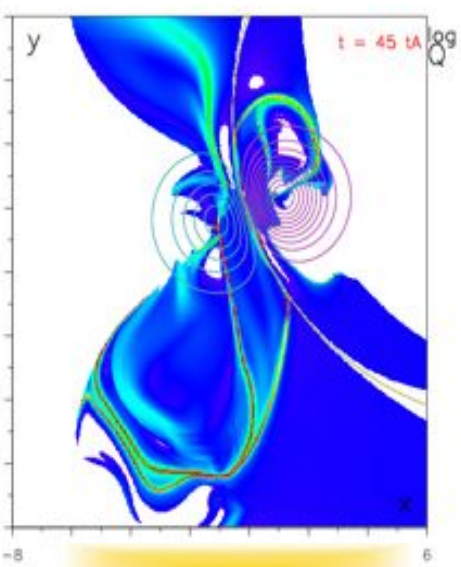


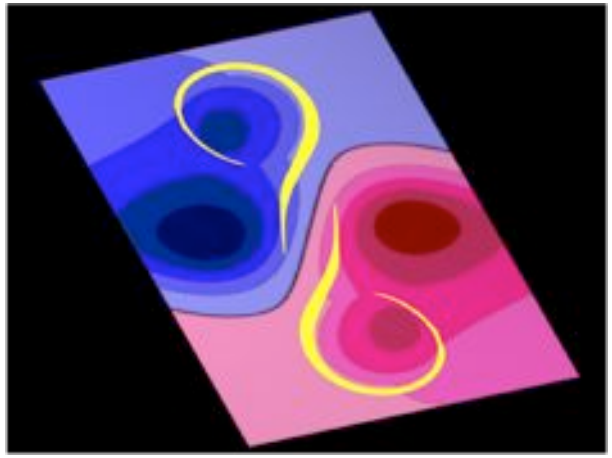




[Démoulin, Priest & Lonie 1996]

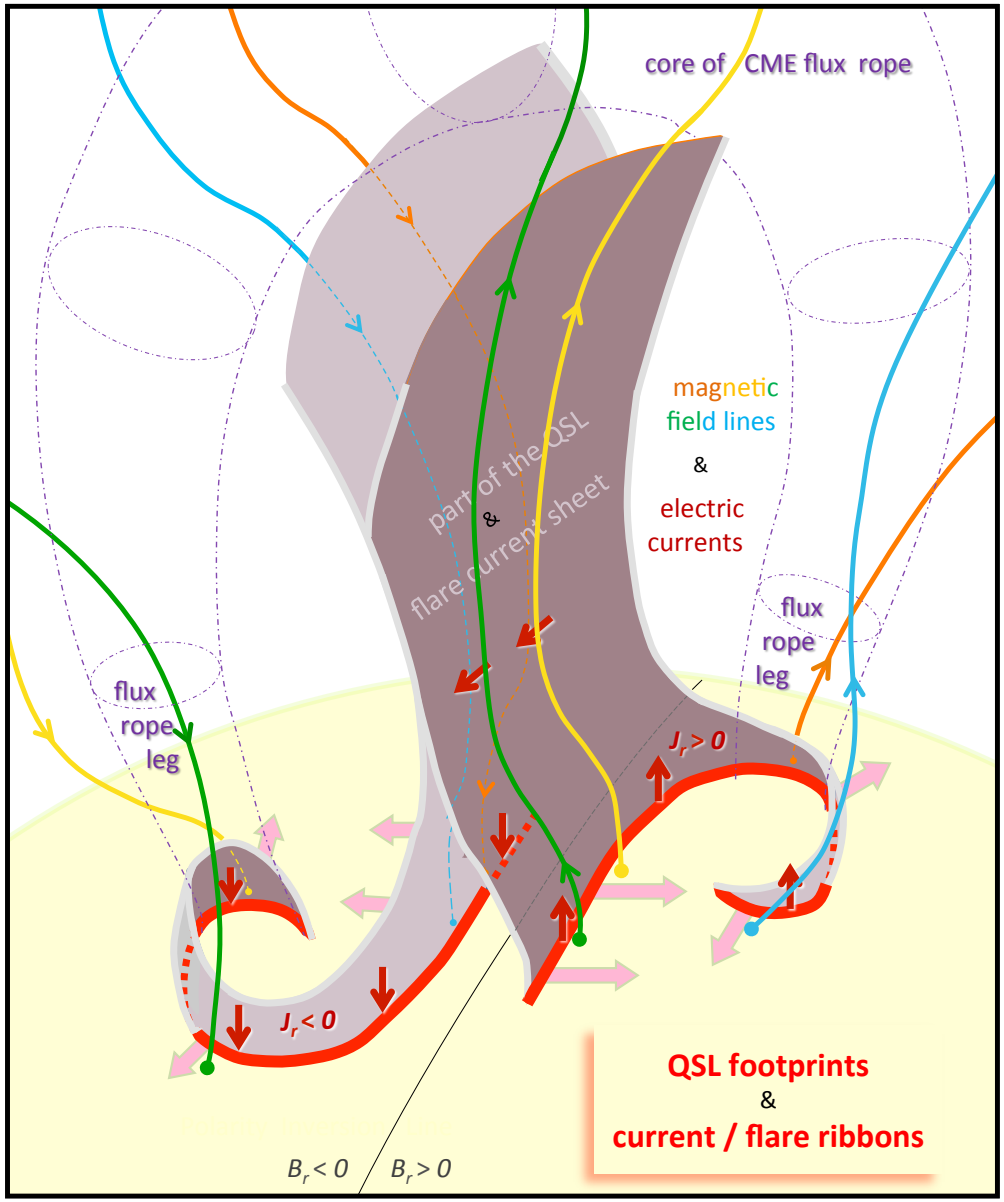


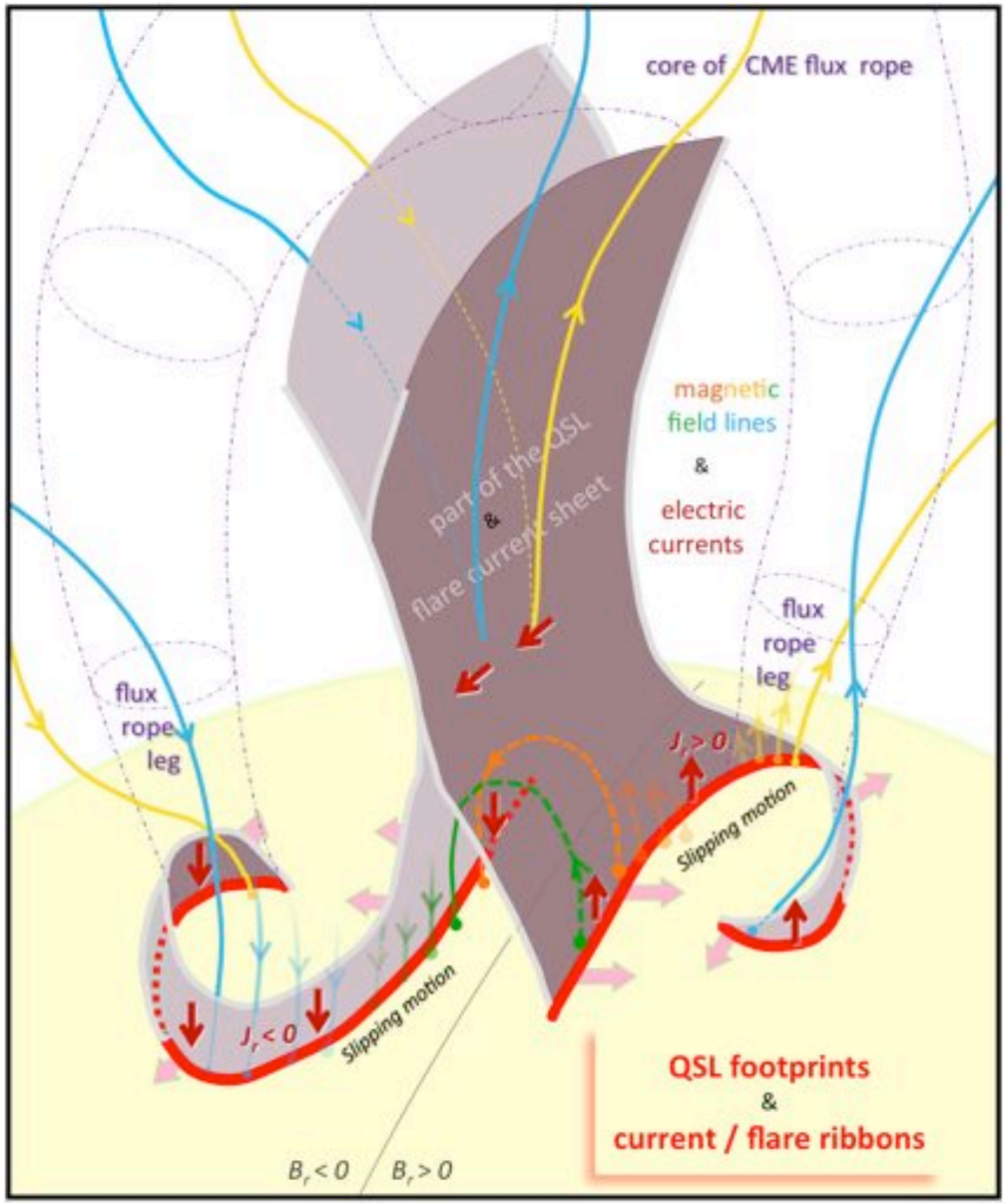

**Zoom out**



# 3D model for eruptive flares – early flare phase

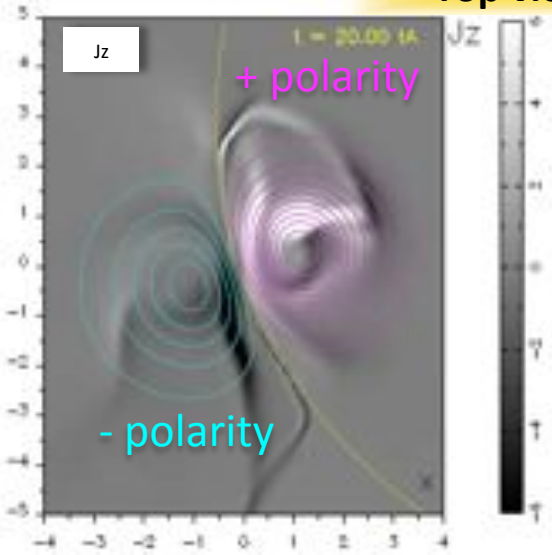


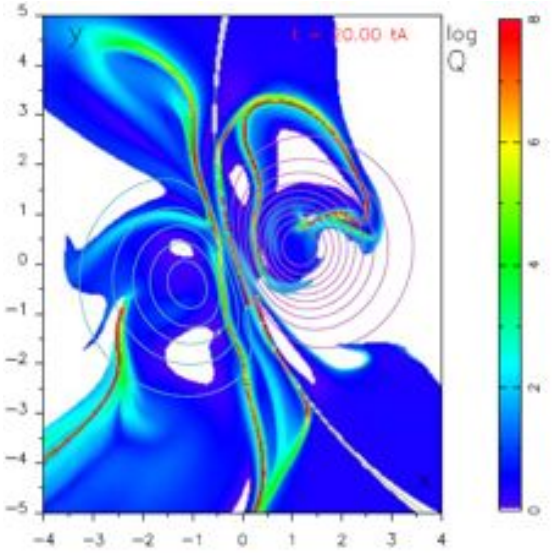
# 3D model for eruptive flares – late flare phase



# 3D model: reconnection and slipping

**Top views**



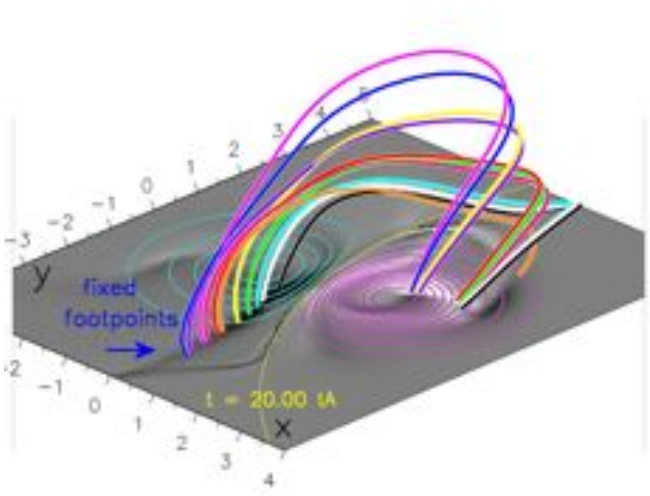




Build-up of **intense electric current** sheet at QSLs = **preferential location for reconnection**

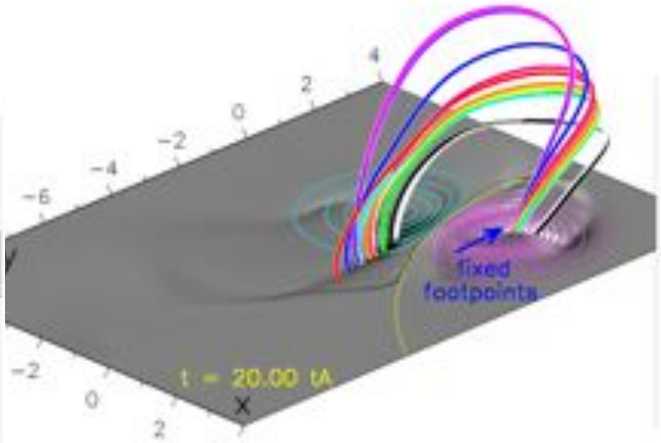
[Démoulin et al. 1996, Maclean, Büchner, Priest 2009]

➔ **Slipping of field lines**

**Flare loops** formation



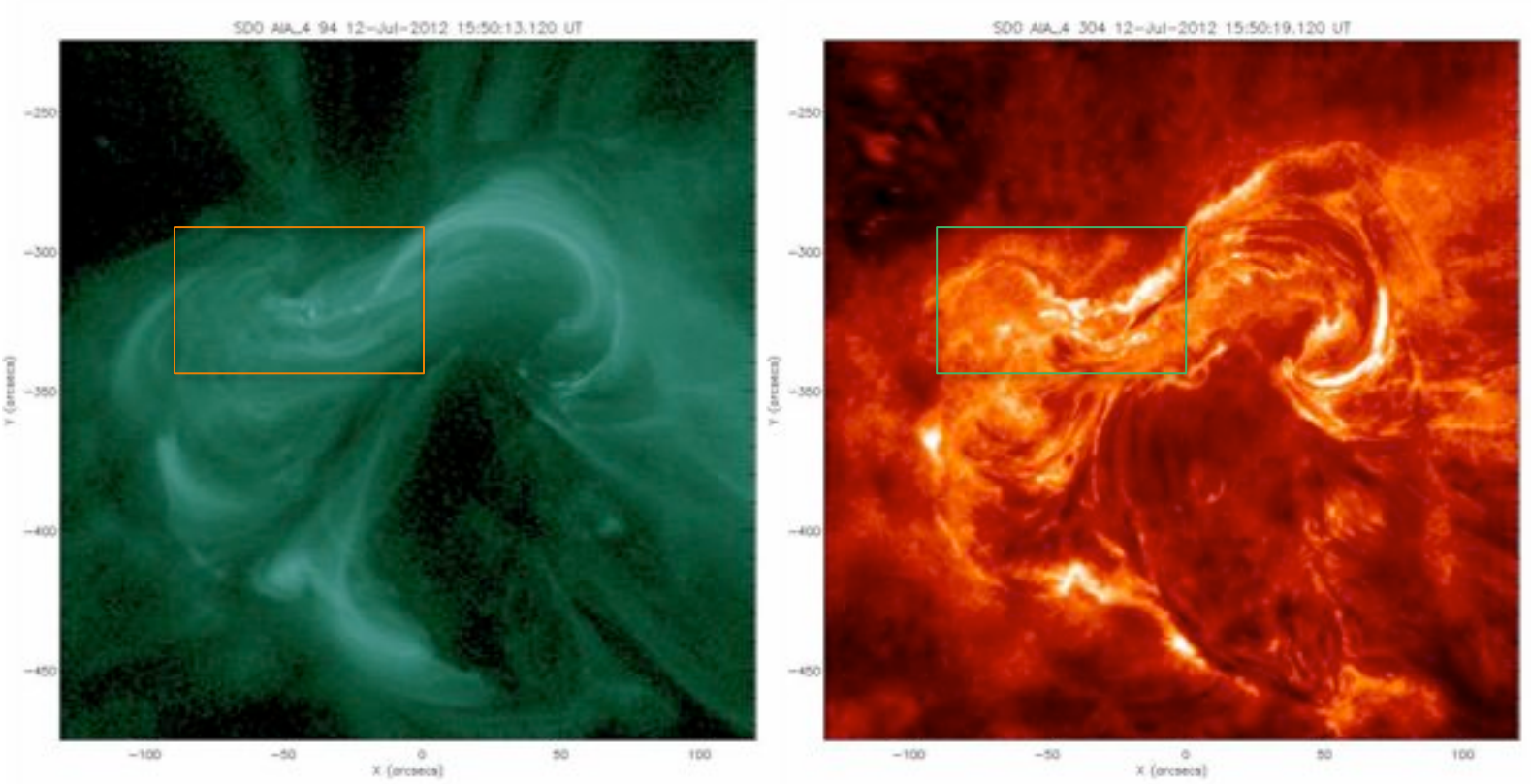

**Flux Rope** formation




[Janvier et al. A&A 2013]

## Creation of new magnetic structures (here, the flux rope):

⇛ Recently, **AIA observations (SDO) have revealed the slipping motion** of field lines during an eruptive flare




July 12 2012, X-class flare, Dudík, Janvier et al. (ApJ in press)

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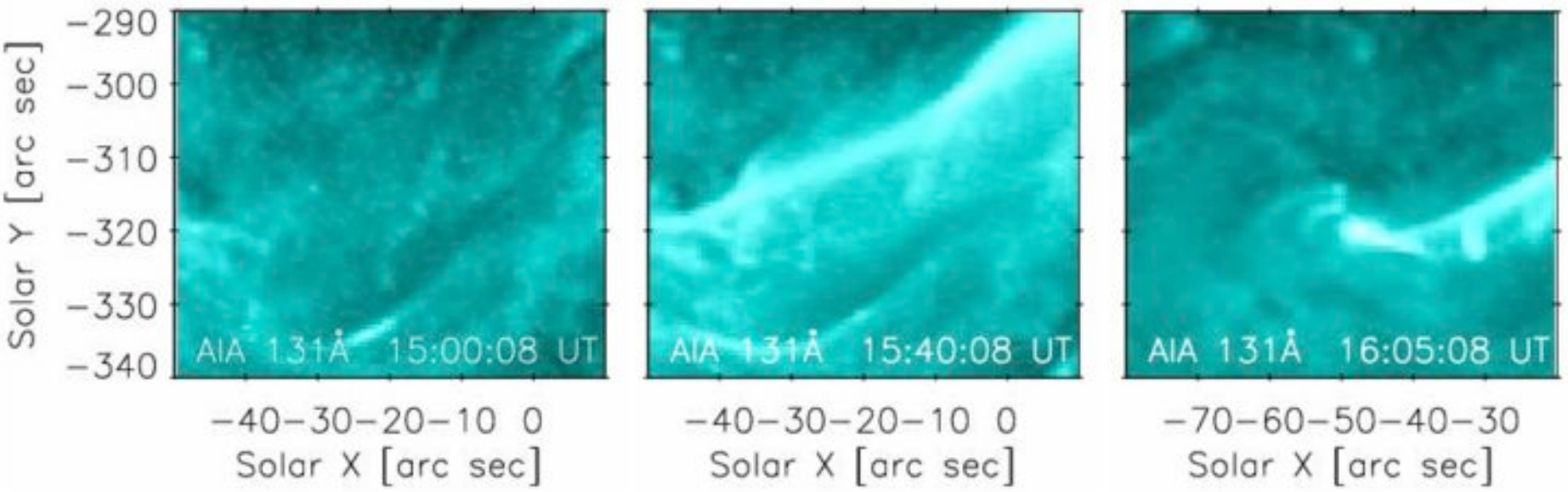


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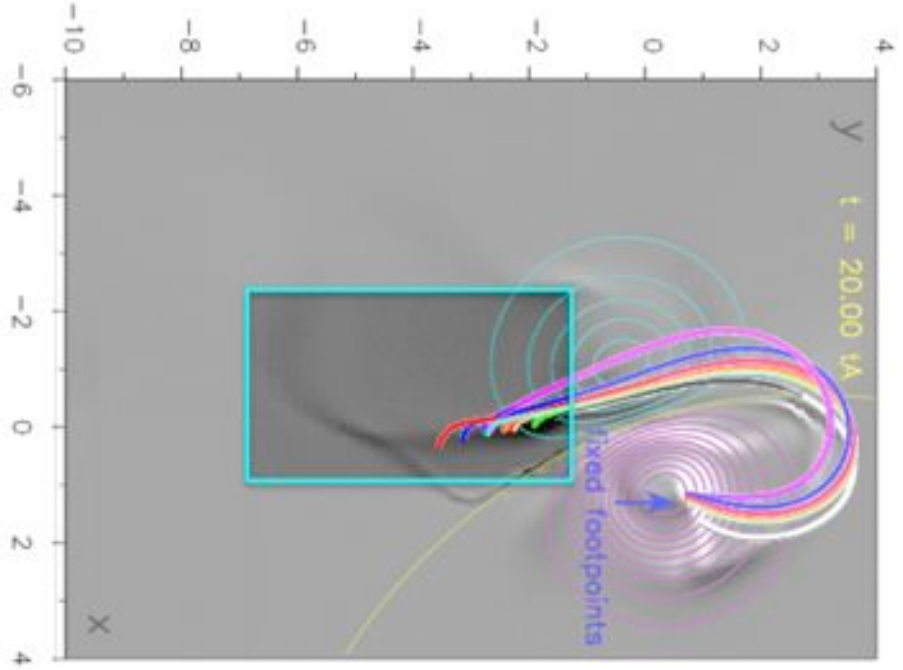
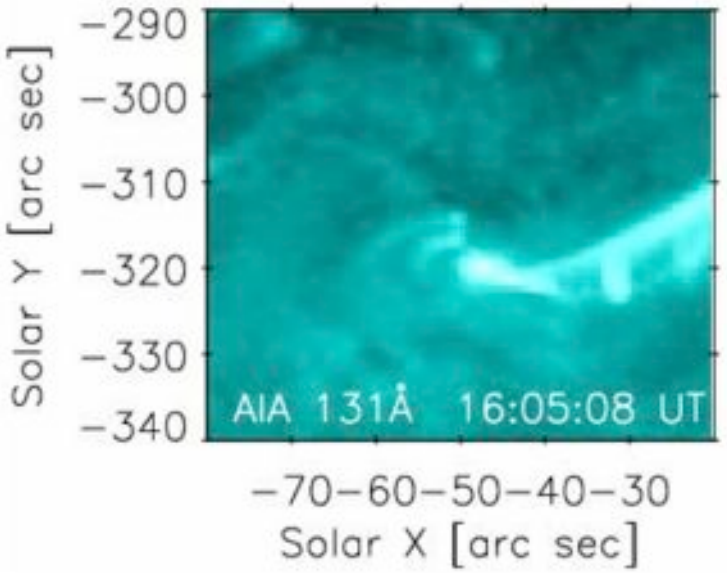
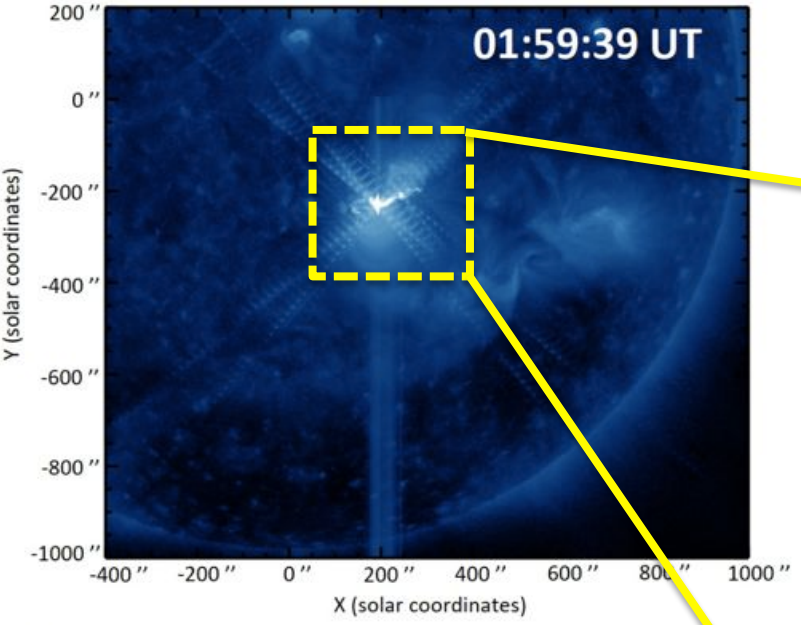
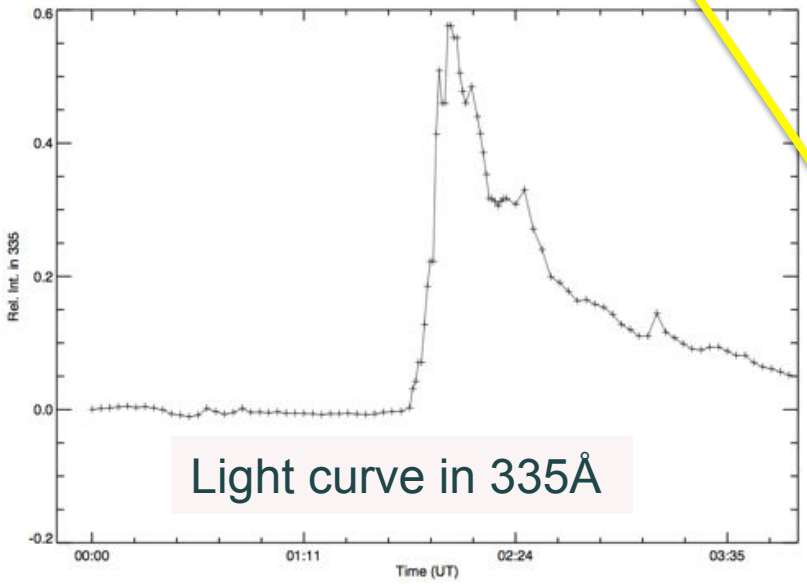



July 12 2012, X-class flare, Dudík, Janvier et al. (ApJ in press)

# Test case: AR 11158 & X2.2 class flare (15/02/2011)

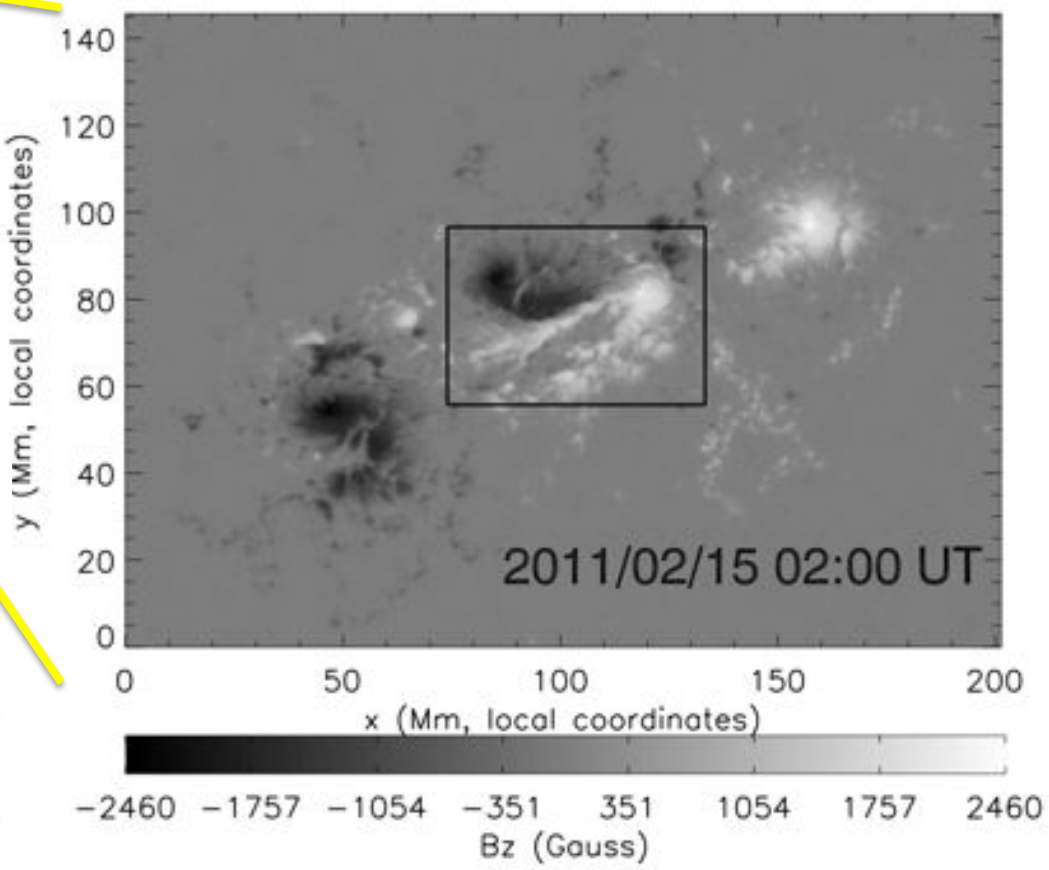



Light curve in 335Å

•Complex region but the flare occurs in the central part

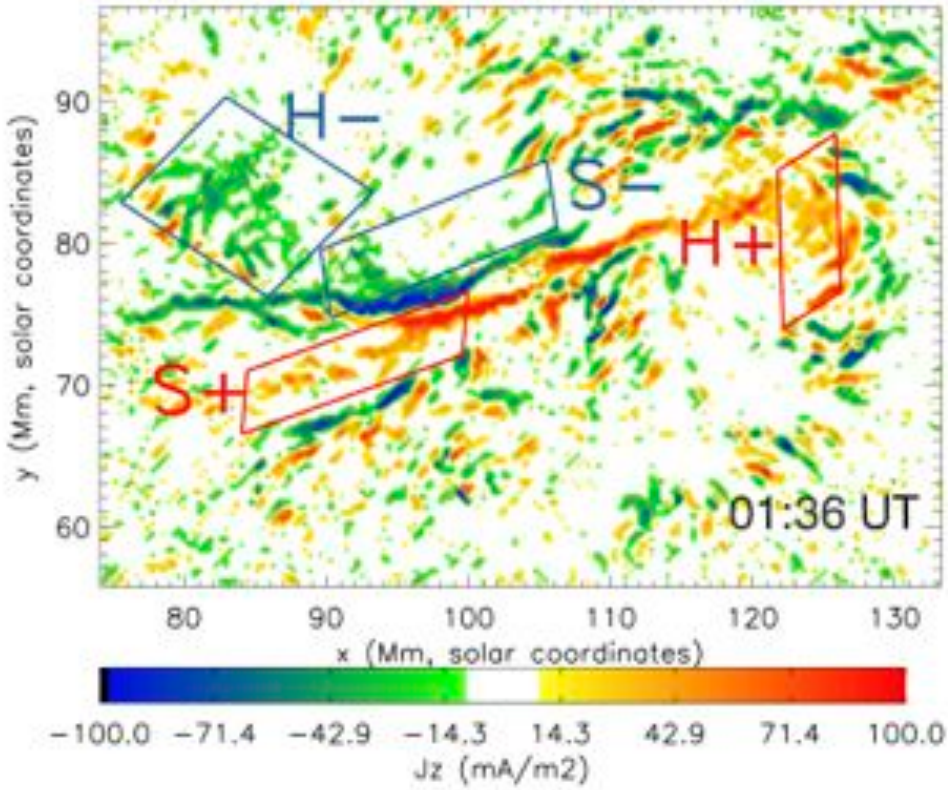
➔ **« Simple» bipolar structure**

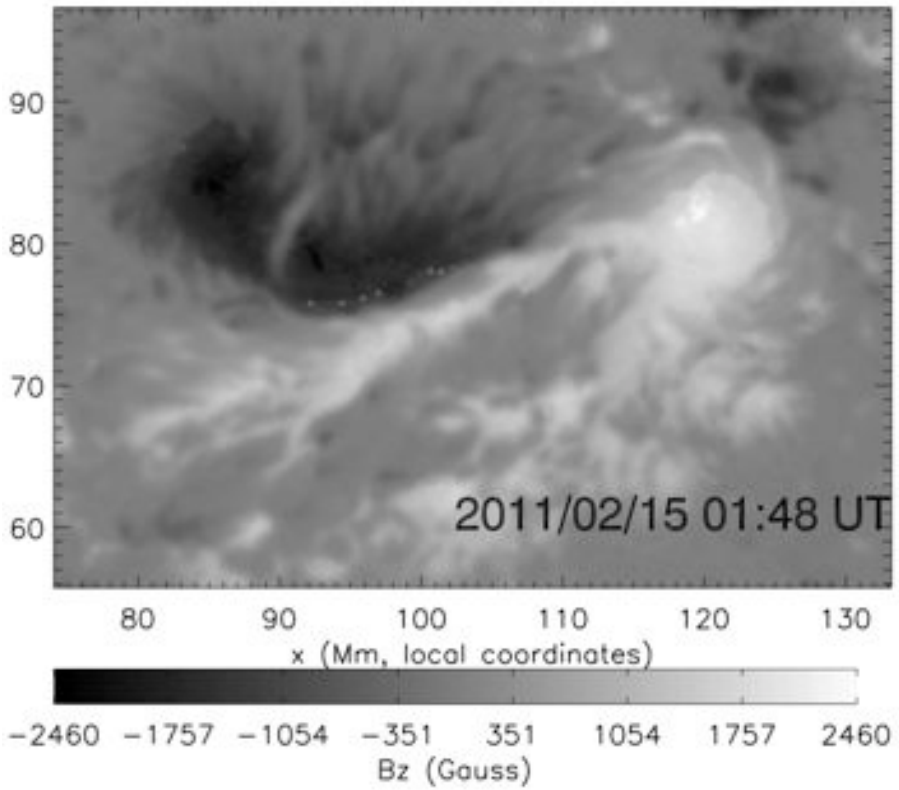


# How do photospheric currents evolve?

Inversion method: UNNOFIT Bommier et al. (2007)

⇛ **B**(x,y) ⇛ Current maps $J_z(x,y) \sim \text{curl } |B|_z$ (12 min cadence w. HMI)




⇛4 regions: - 2 « straight part » of $J_z$
- 2 « hooks» des $J_z$

With $J_z$ positive and negative

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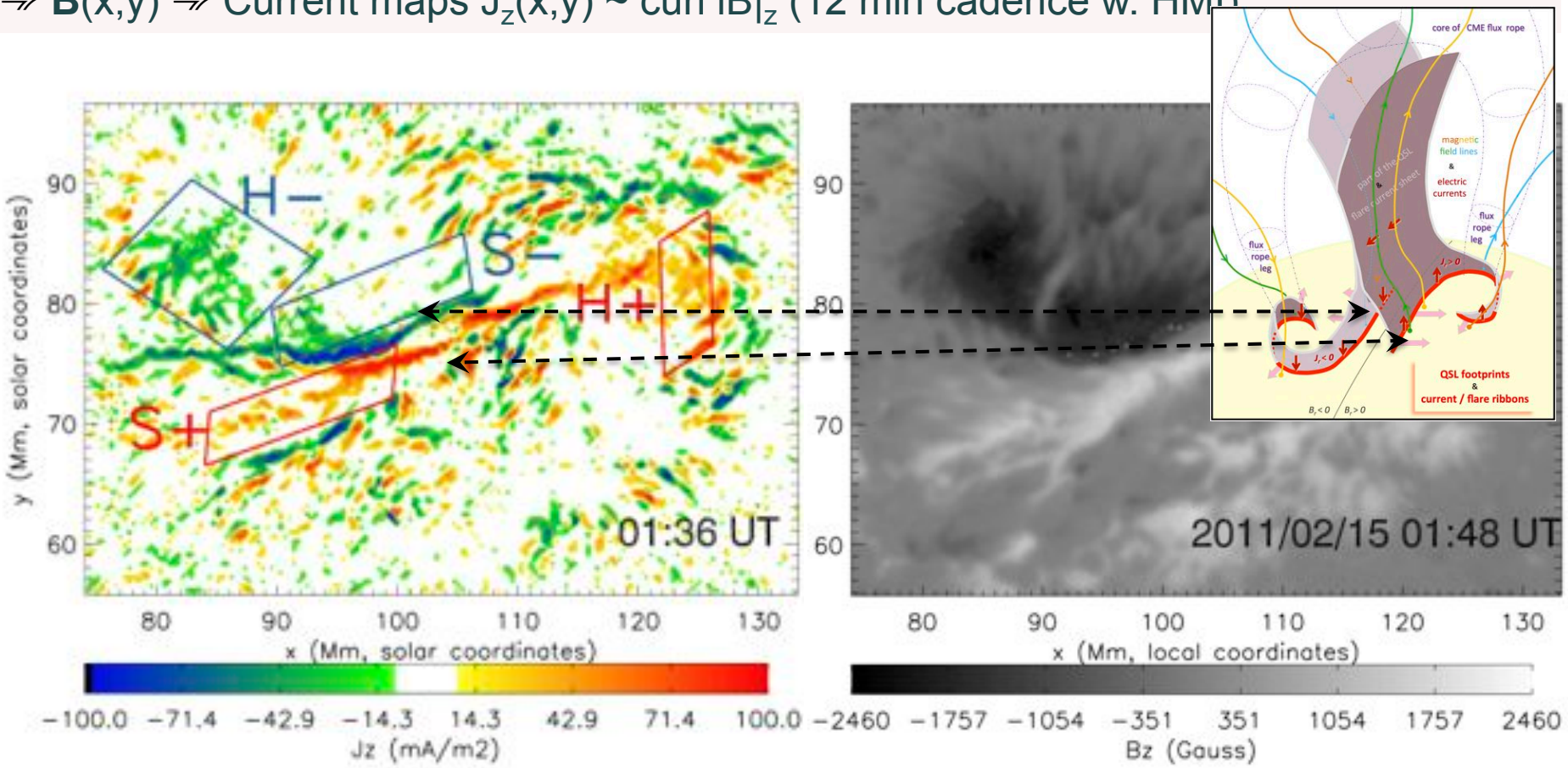


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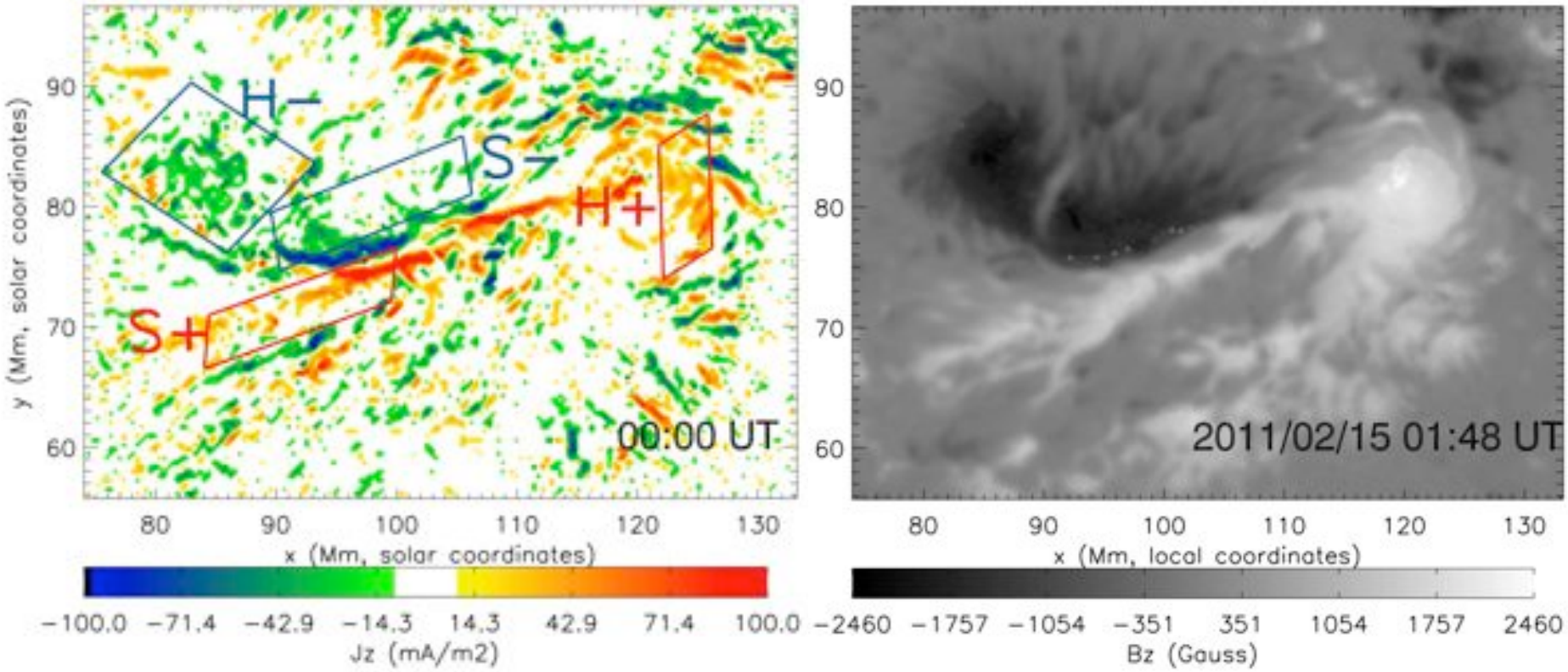


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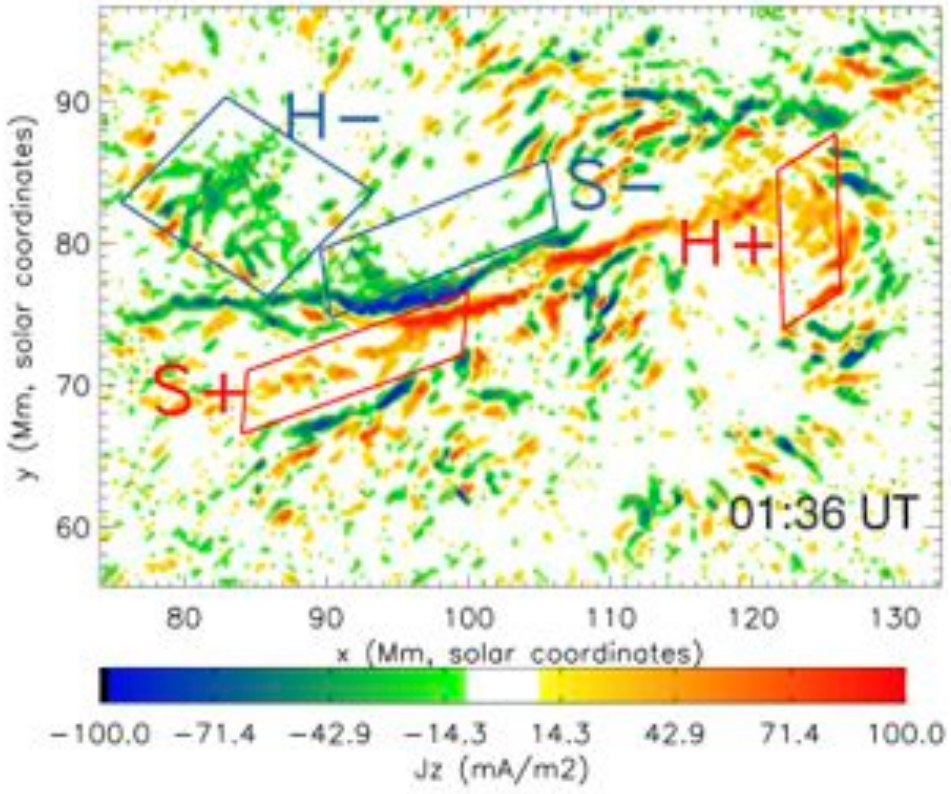
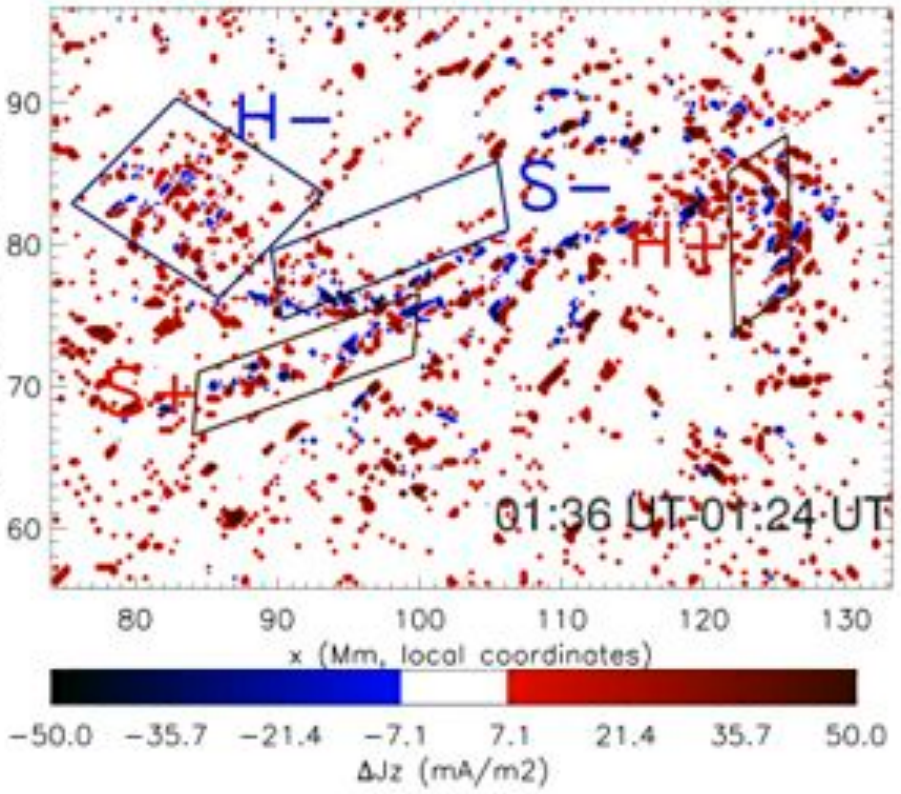
# How do photospheric currents evolve?

Base difference: $J_{direct}(t) - J_{direct}(01:24\ UT)$
Red: increase, Blue: decrease



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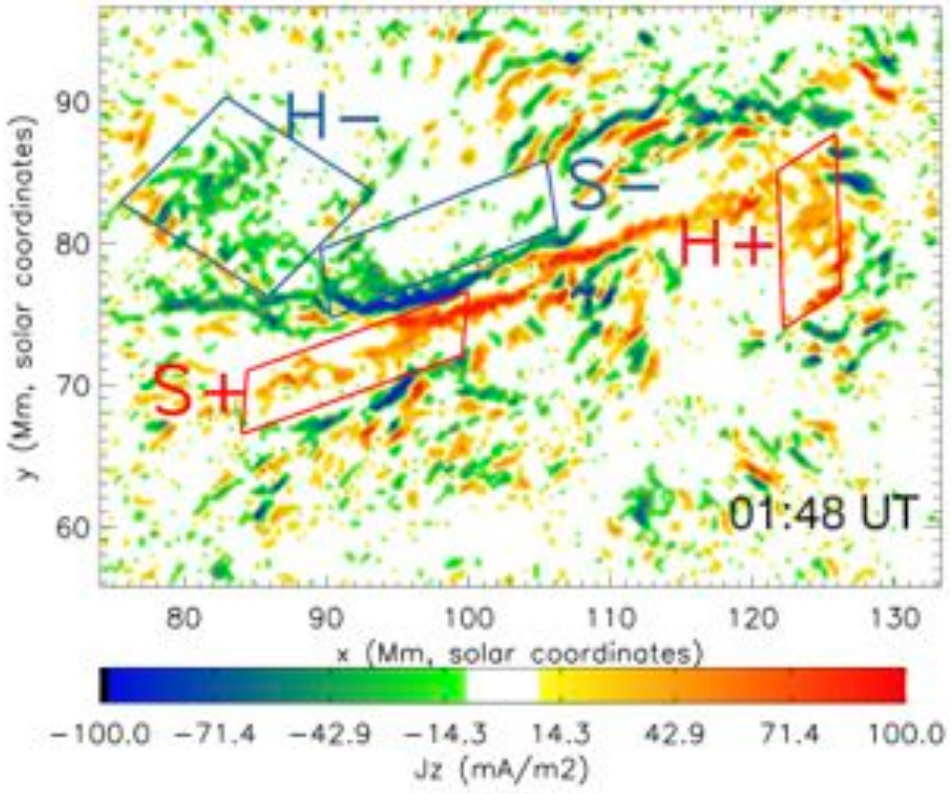


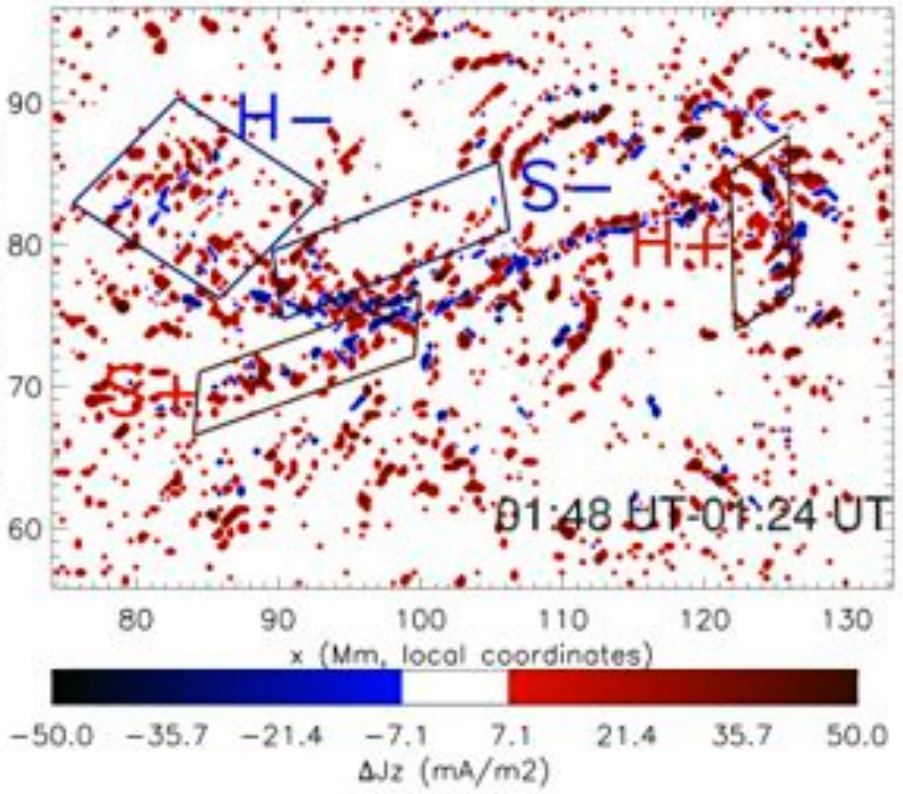

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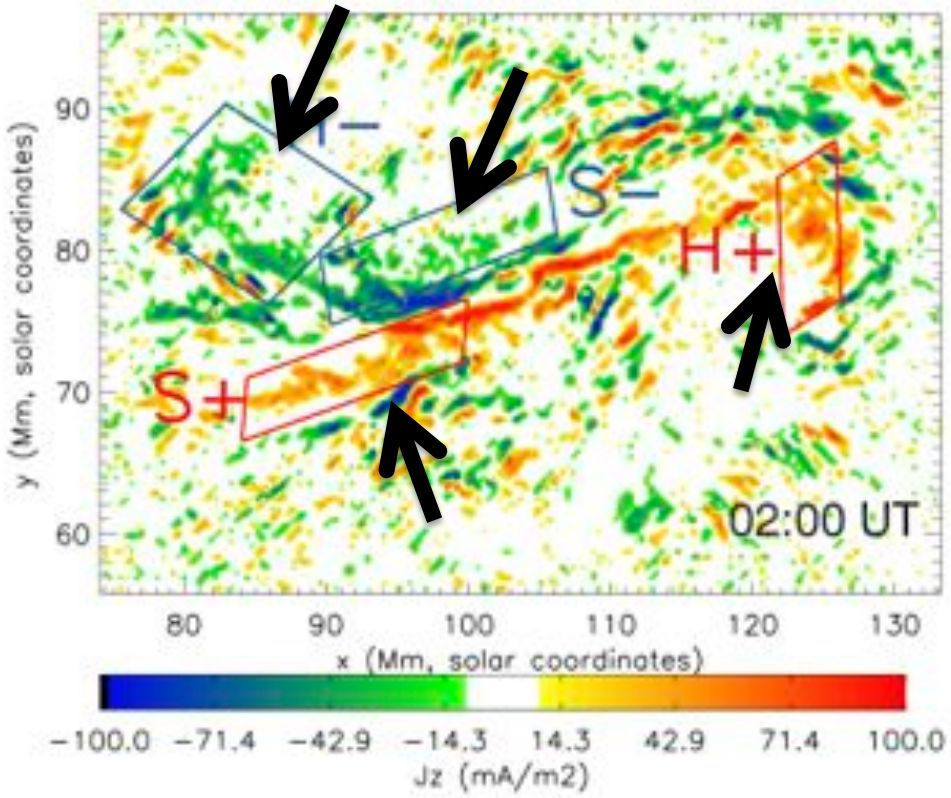


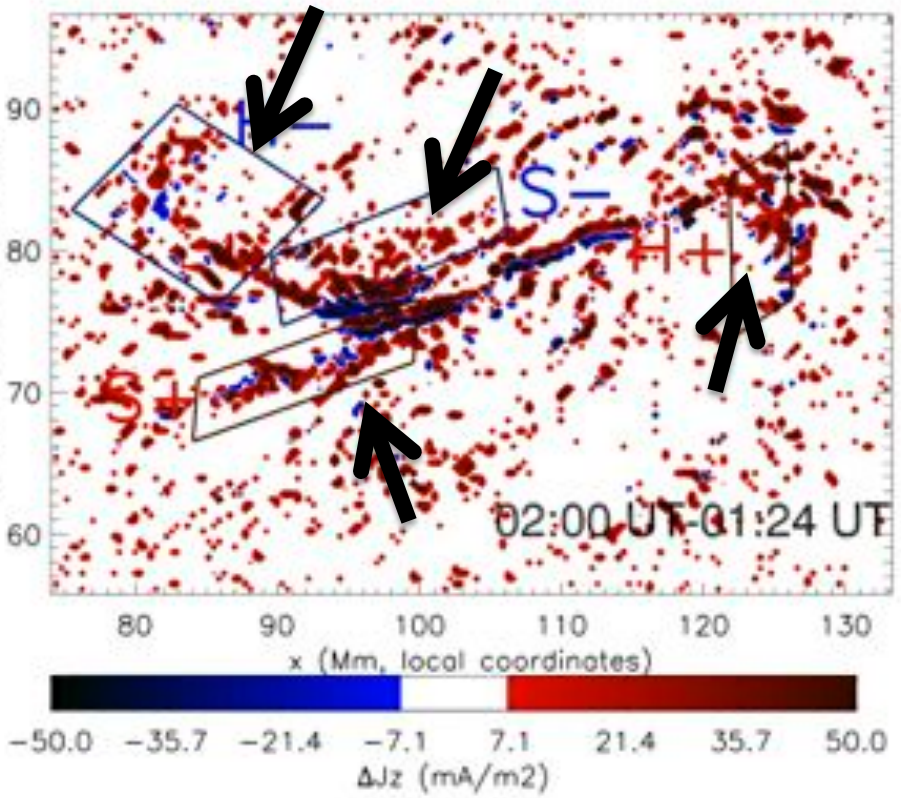

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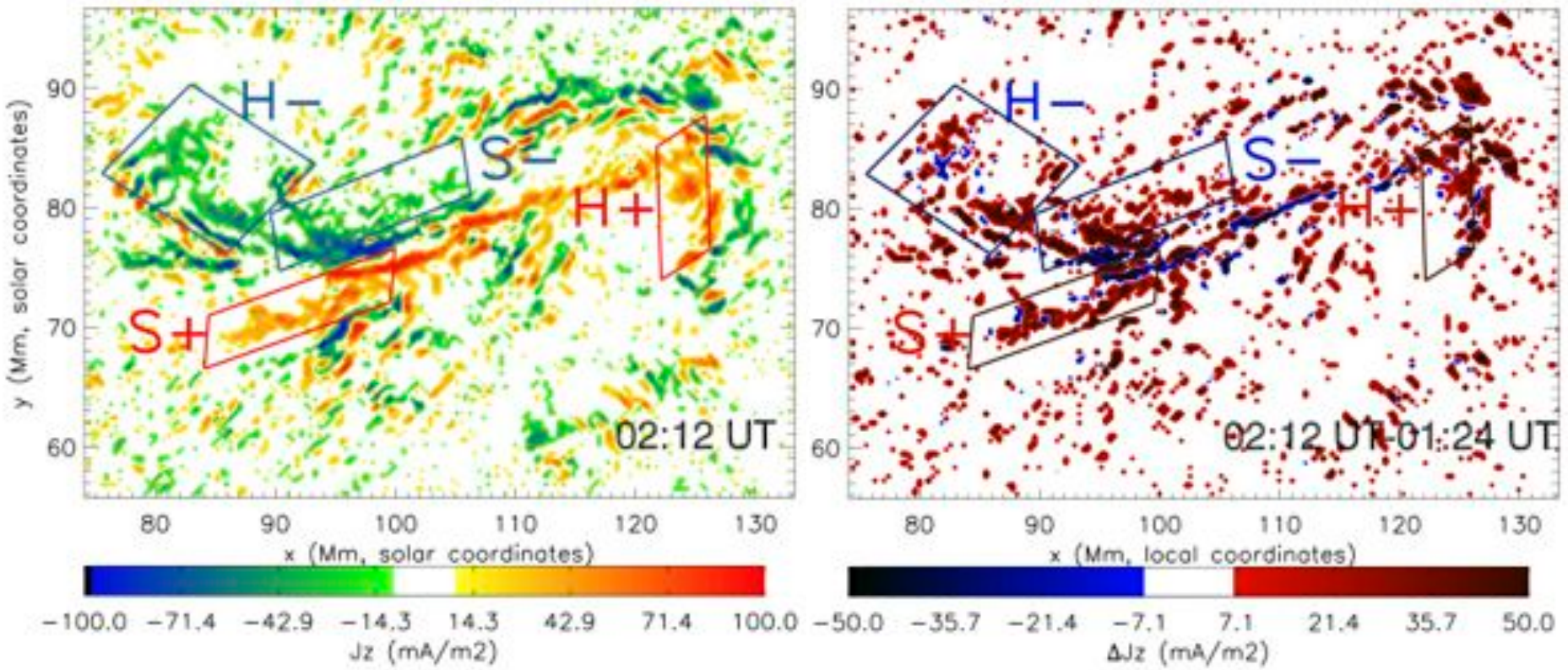
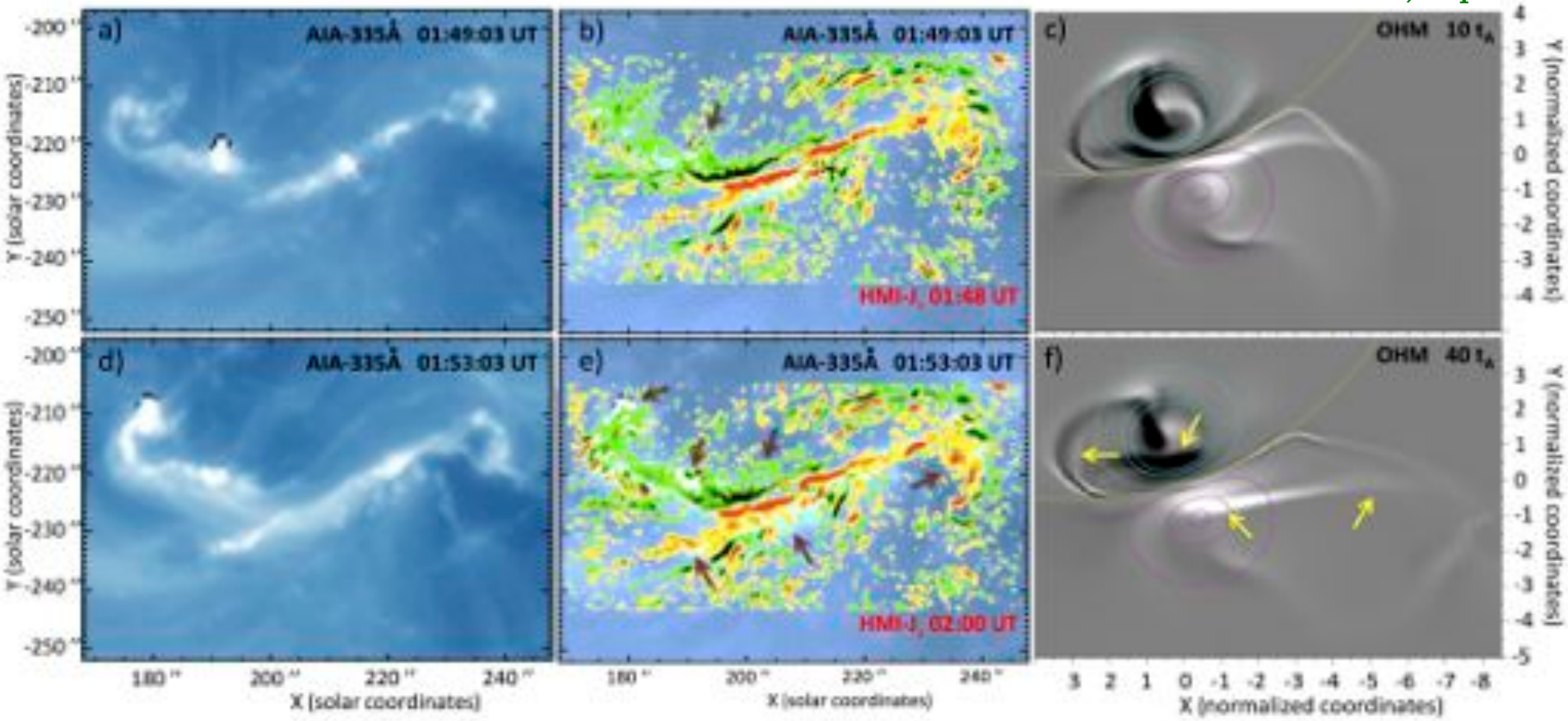


# Flare ribbons vs Photospheric currents vs OHM prediction

In the same event, we also followed the evolution of the flare ribbons

⇛Superposed $J_z$ – maps (HMI) with EUV images (AIA)

[Janvier et al., in press]




We find the same characteristics, predicted in OHM simulations, for the flare ribbons and the photospheric currents

**⇛ VALIDATION of PREDICTIONS of OHM's PHYSICS**