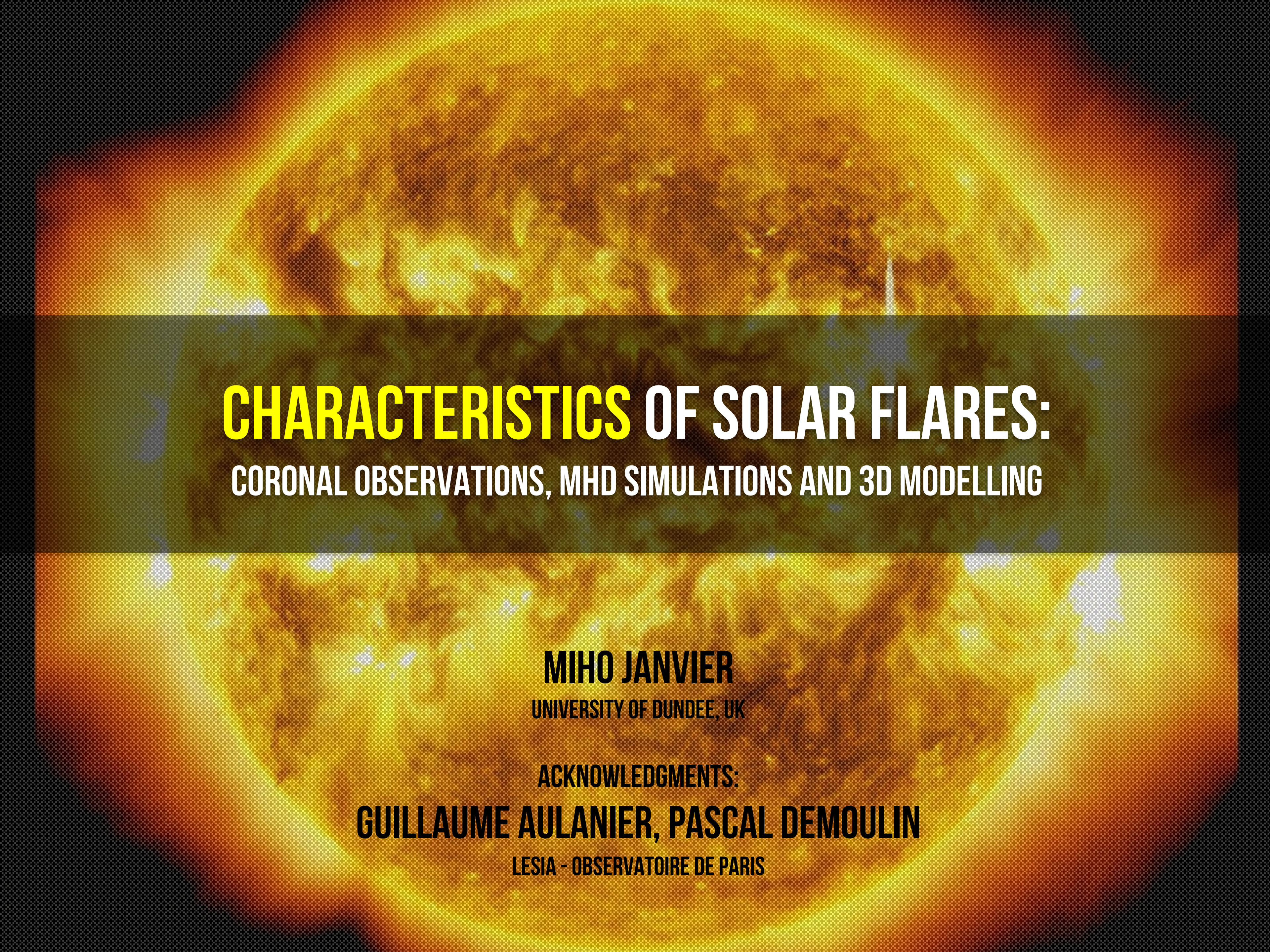


CHARACTERISTICS OF SOLAR FLARES:

CORONAL OBSERVATIONS, MHD SIMULATIONS AND 3D MODELLING

MIHO JANVIER

UNIVERSITY OF DUNDEE, UK

ACKNOWLEDGMENTS:

GUILLAUME AULANIER, PASCAL DEMOULIN

LESIA - OBSERVATOIRE DE PARIS

WHAT ARE FLARES?

(Def? Observations?)

ARE THEY ALL THE SAME?

(Differences confined/eruptive flares)

LINK WITH TOPOLOGY

How/where does magnetic reconnection occur?

NUMERICAL MODELS VS OBSERVATIONS

How do they complement each other?

OUTLINE

Flares (confined, eruptive): definition and observations

$\Longmapsto$ *What happens?*

Confined/eruptive flares: difference in drivers

$\Longmapsto$ *What drives flares?*

The topology of flares

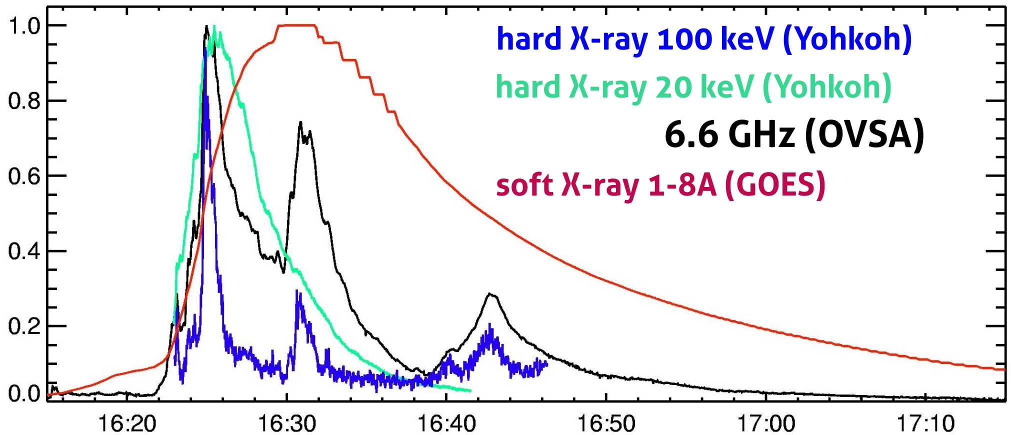
$\Longmapsto$ *Location of energy release?*

Prediction from models

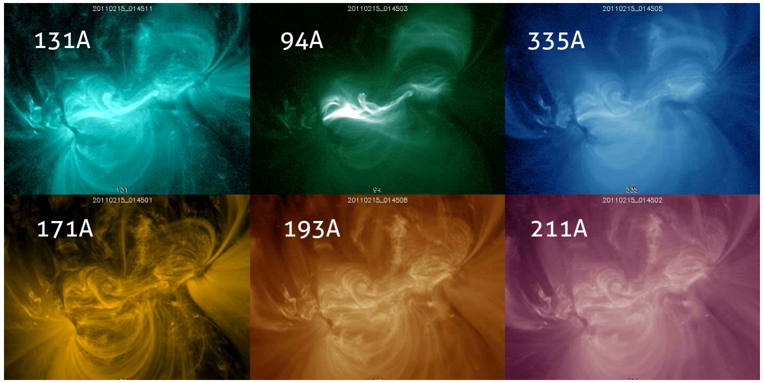
$\Longmapsto$ *What to look for?*

WHAT IS A FLARE?

« Flare »: sudden brightening in solar atmosphere



Qiu et al. (2004)



Schrijver et al. (2011), 15/02/11 X-class flare

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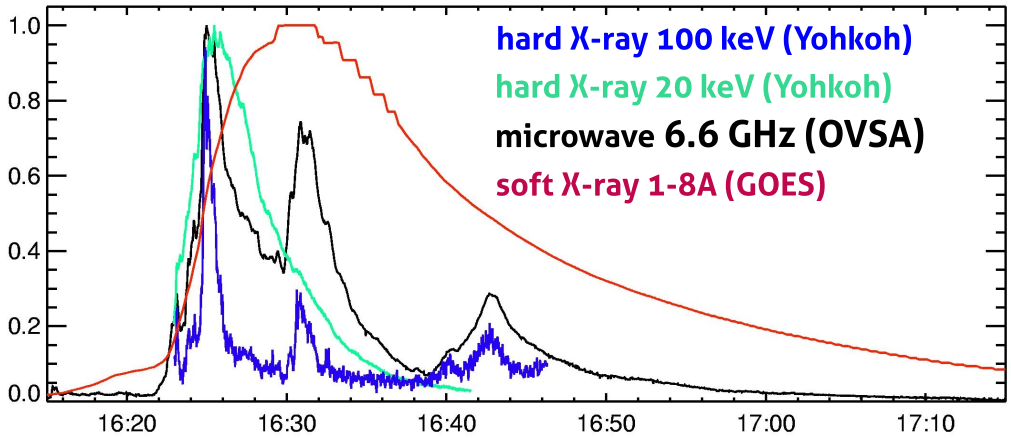

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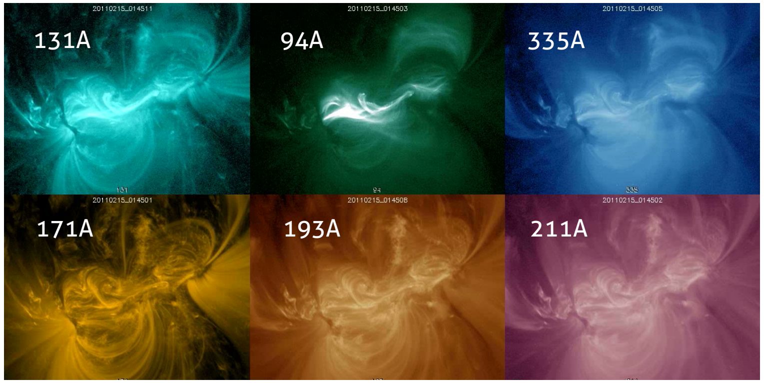

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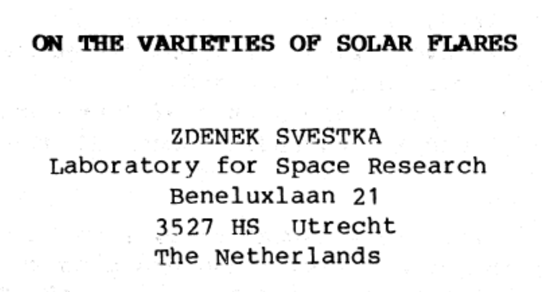
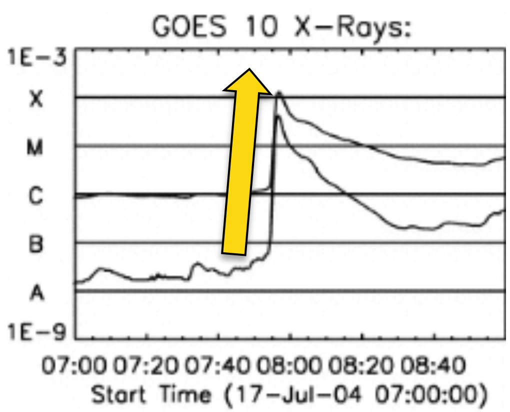
Flares can be **eruptive** or **confined**

Svestka (1986): «confined» and «ejective»

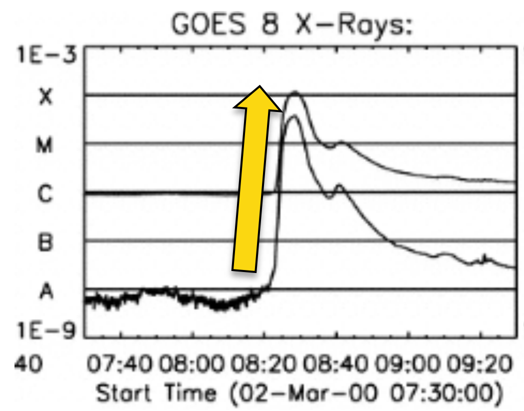


ON THE VARIETIES OF SOLAR FLARES

ZDENEK SVESTKA
Laboratory for Space Research
Beneluxlaan 21
3527 HS Utrecht
The Netherlands



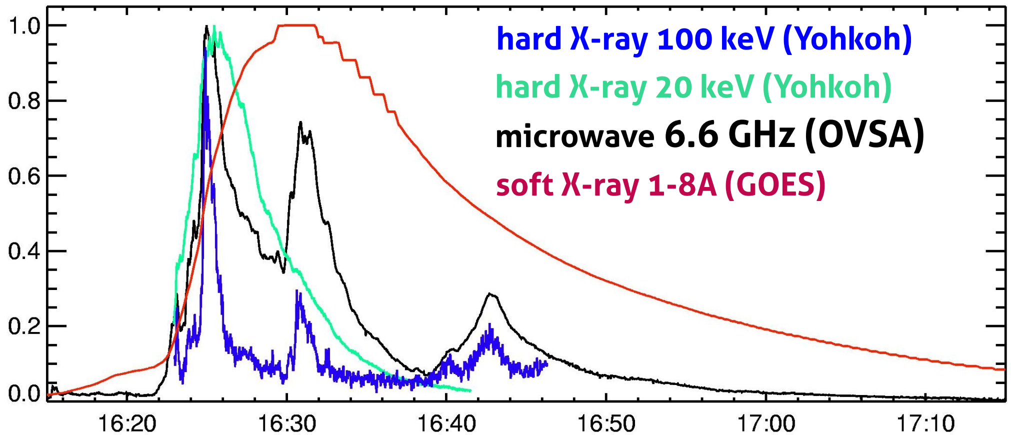
Confined flares



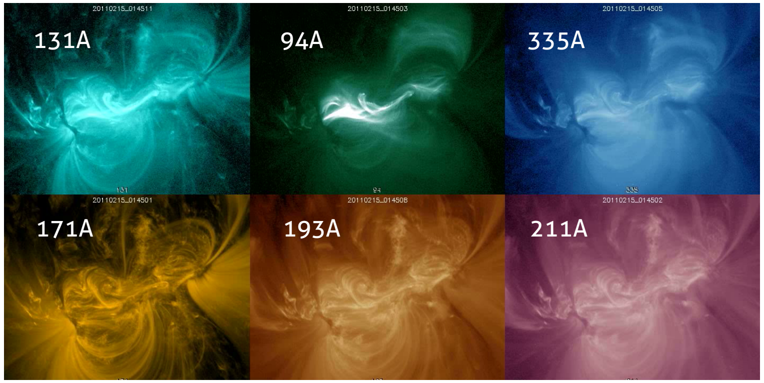
Eruptive flares

WHAT IS A FLARE? CONFINED VS ERUPTIVE

« Flare »: sudden brightening in solar atmosphere



Qiu et al. (2004)



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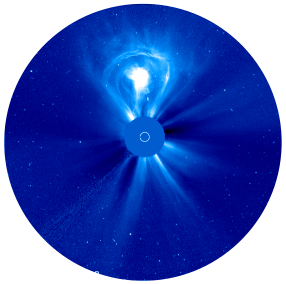
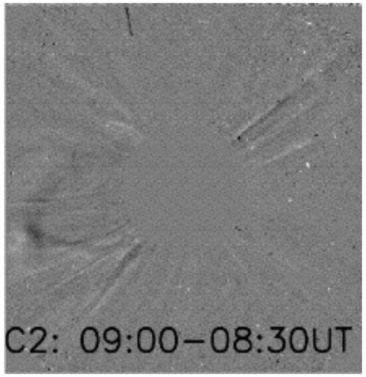
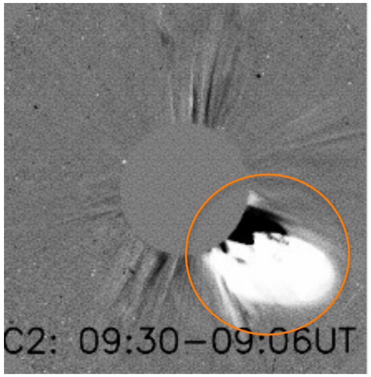


Eruptive flares:
associated with a CME



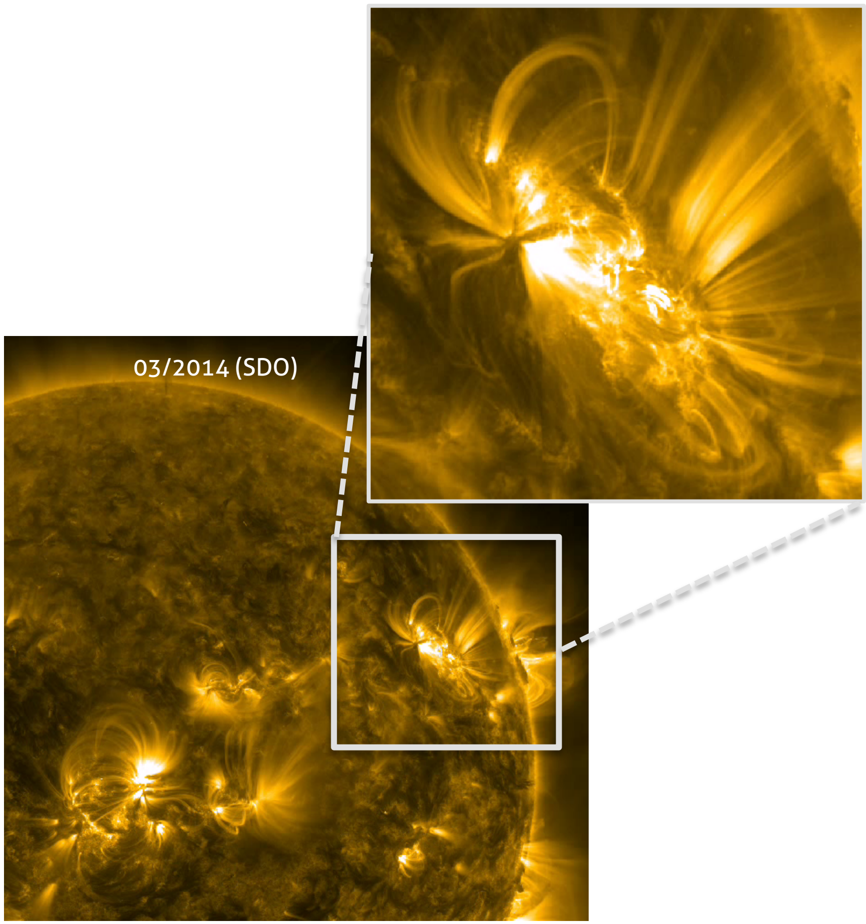
Confined flares

≠

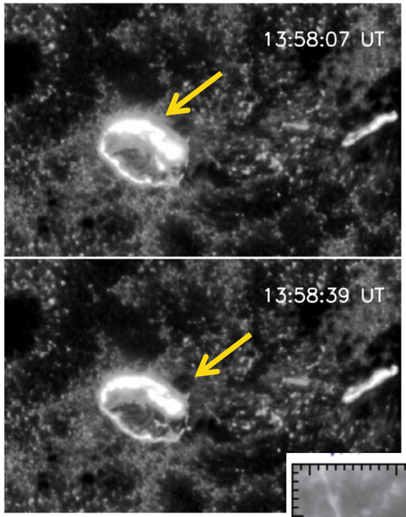


Eruptive flares

Flare - Emission & Loops



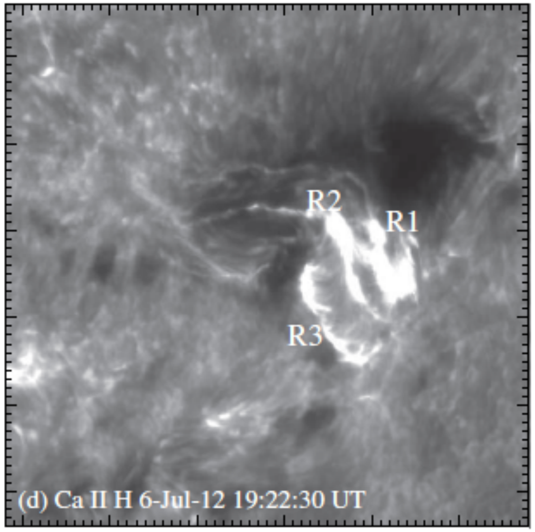
Flare ribbons



- ❖ Circular ribbons

Masson et al. (2009)

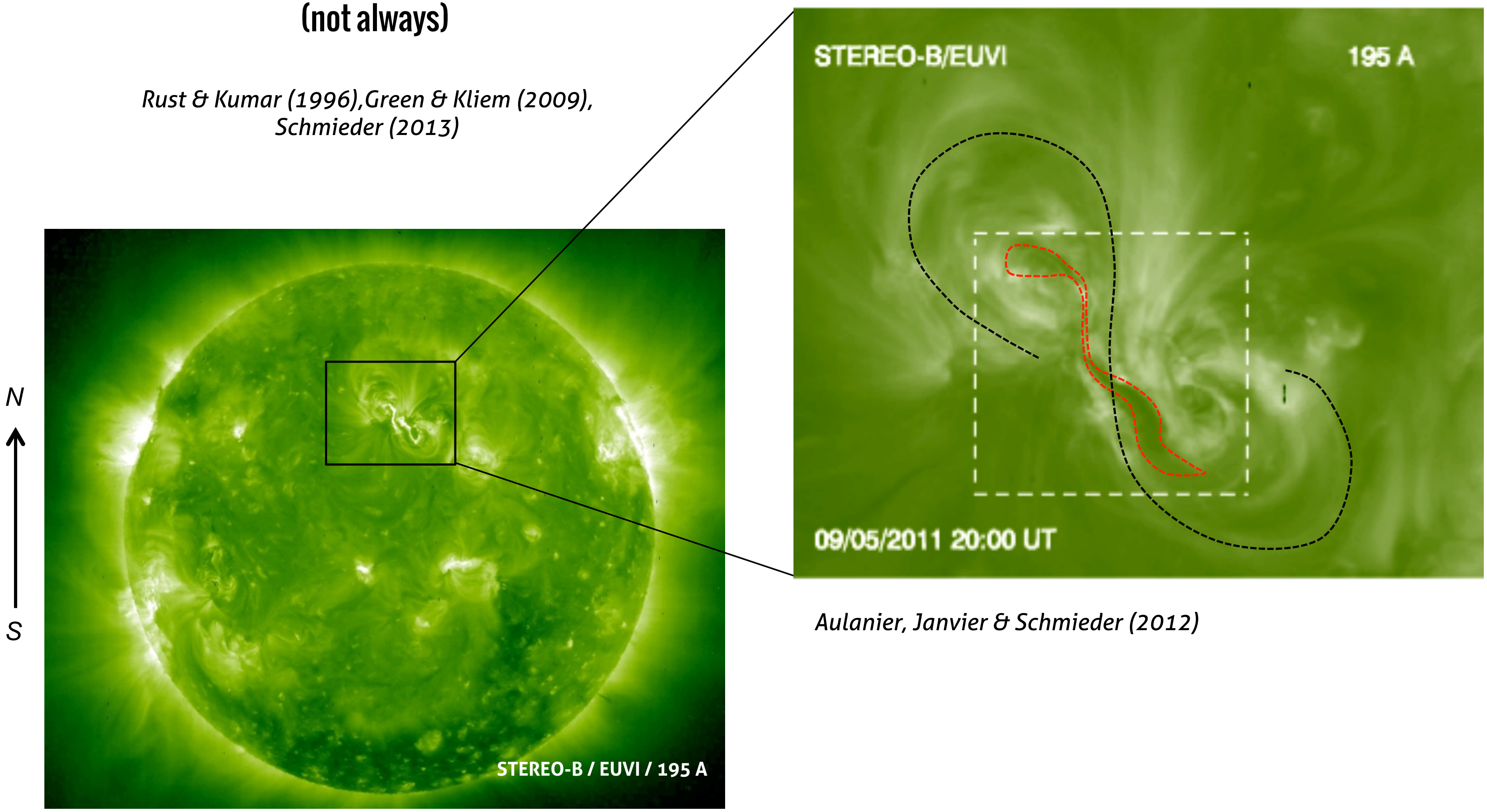
- ❖ Several ribbons



Wang et al. (2014)

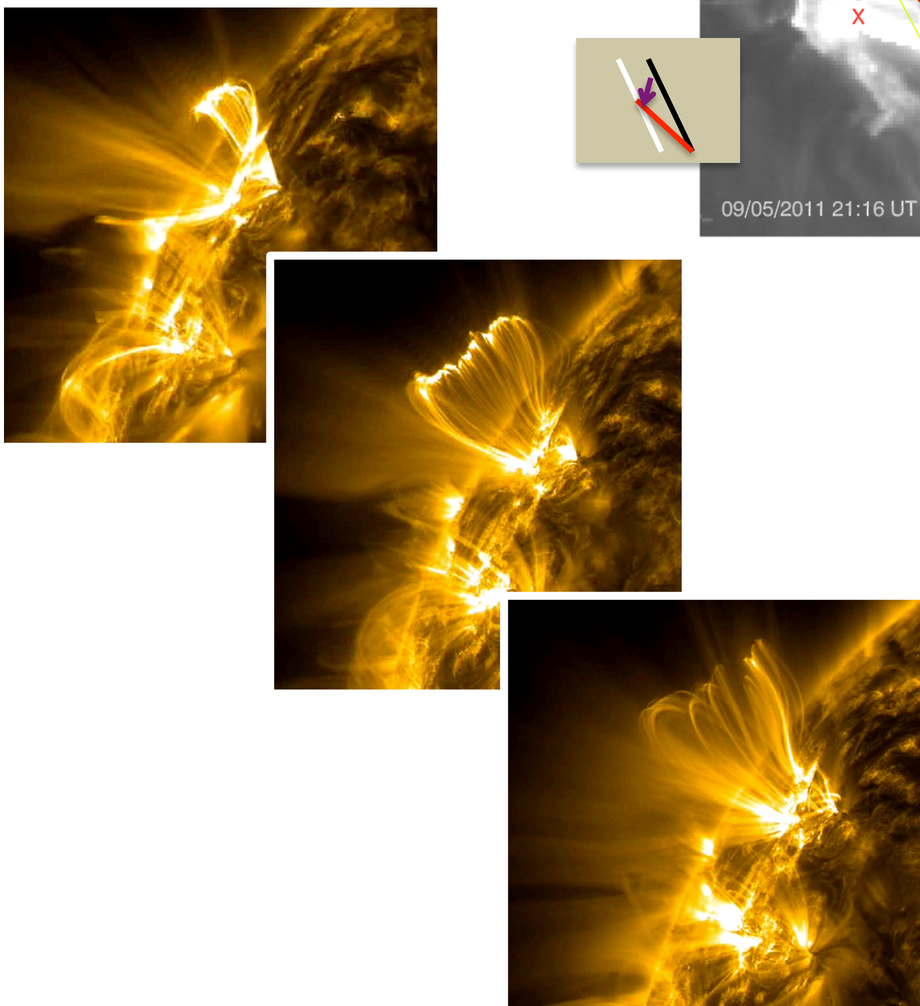
Pre-eruptive sigmoid & filament
(not always)

Rust & Kumar (1996),Green & Kliem (2009), Schmieder (2013)



Aulanier, Janvier & Schmieder (2012)

Flare loops



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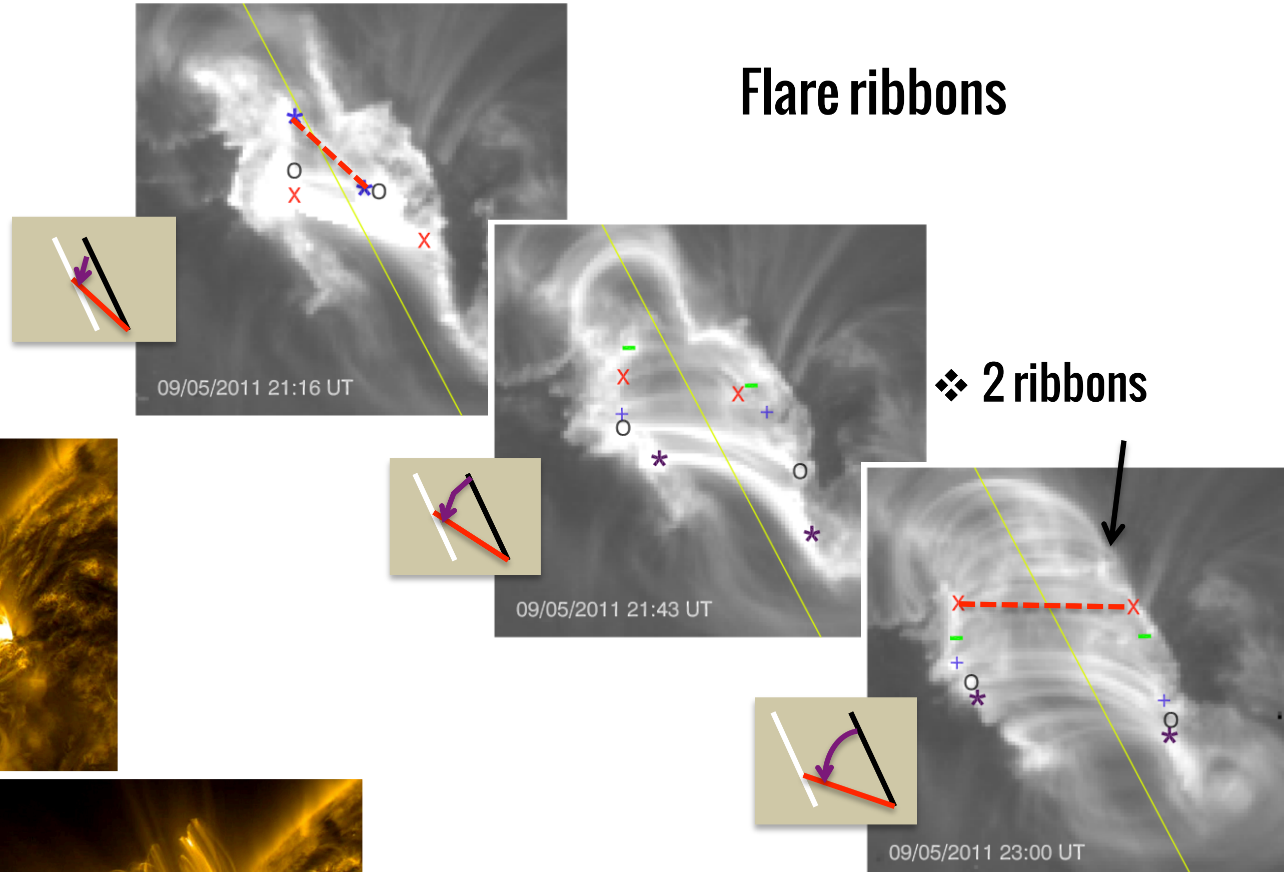


❖ 2 ribbons

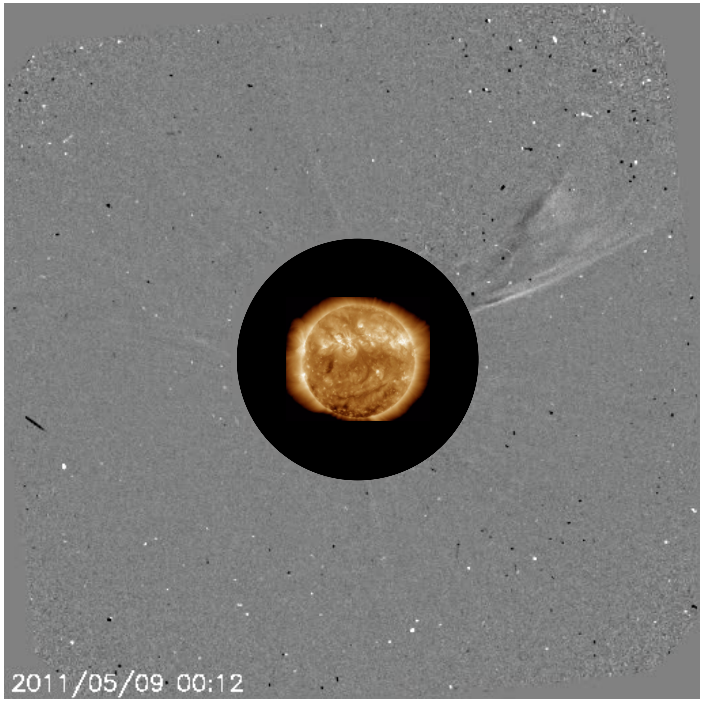
Aulanier, Janvier & Schmieder (2012)

⟹ Low-to-high altitude loop brightening

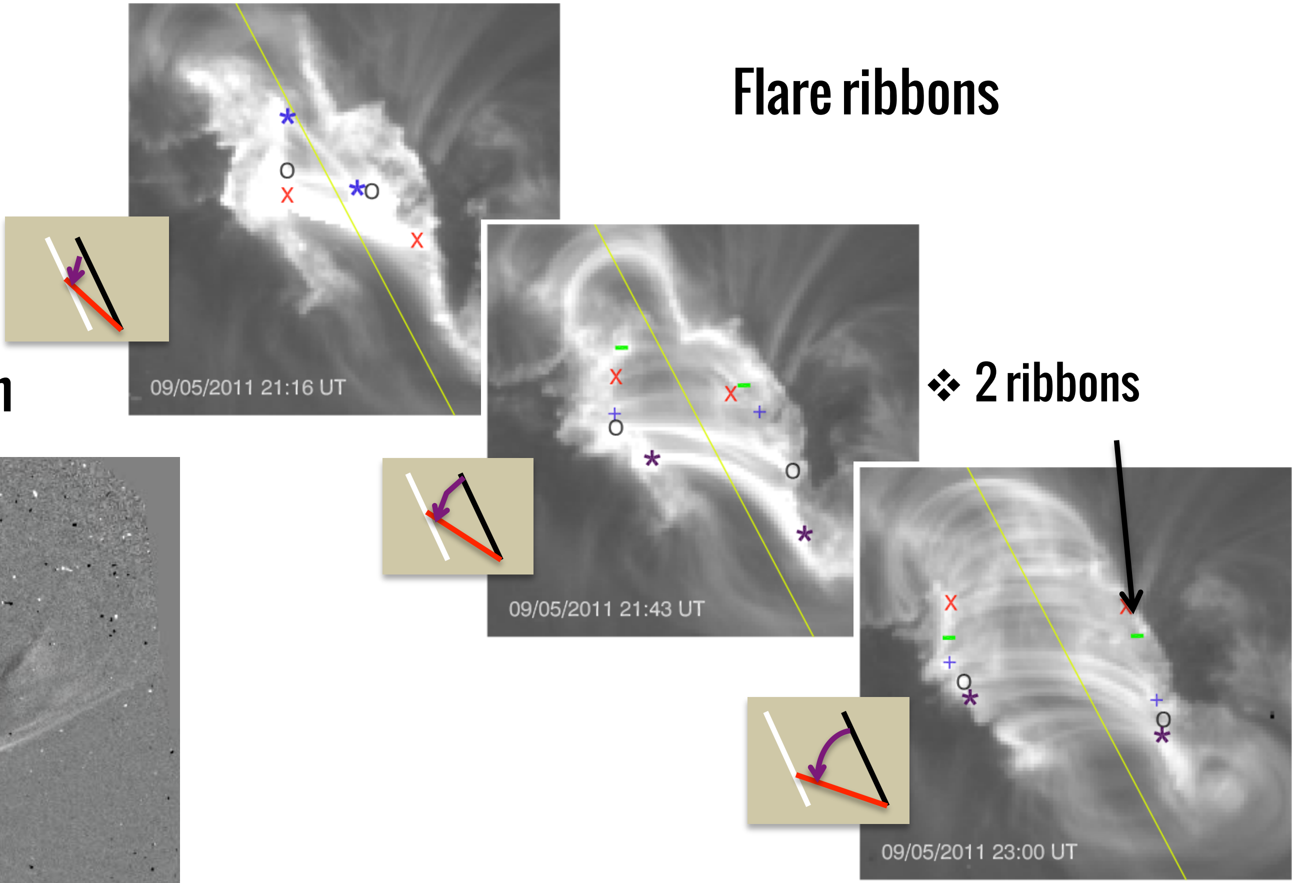
⟹ Strong-to-weak shear transition

OBSERVATIONAL CHARACTERISTICS – ERUPTIVE FLARES

Coronal Mass Ejection



Flare ribbons



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OUTLINE

Flares (confined, eruptive): definition and observations

⟾ *What happens?*

Confined/eruptive flares: difference in drivers

⟾ ***What drives flares?***

The topology of flares

⟾ *Location of energy release?*

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HOW TO EXPLAIN THE ENERGY RELEASE?

Energy of a flare

$10^{28} \sim 10^{33}$ erg

Schrijver et al. (2012)

Where does the (free) energy come from?

Studies of magnetic field show right orders to explain flaring regions

Ex: Metcalf et al. (2005), but limited use of extroplation: see De Rosa (2009)

MAGNETIC FIELD FREE ENERGY

$\Longrightarrow$ Heat, kinetic energy, energetic particles

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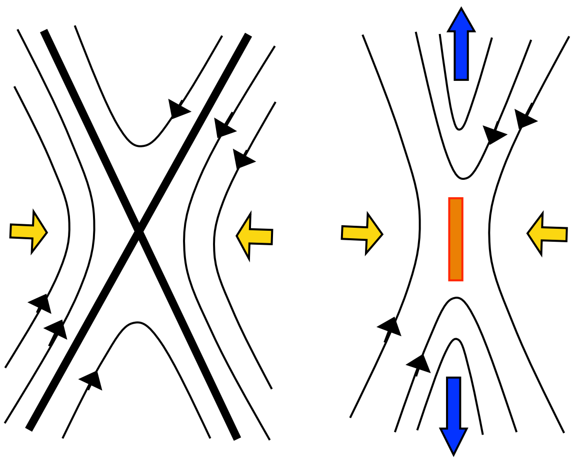
MAGNETIC FIELD FREE ENERGY

What process?

60s: Sweet and Parker proposed: **magnetic reconnection**

Separatrices in 2D → current sheet → reconnection



Early developments by:
Parker (1957, 1963), Sweet (1958), Syrovatskii (1981)

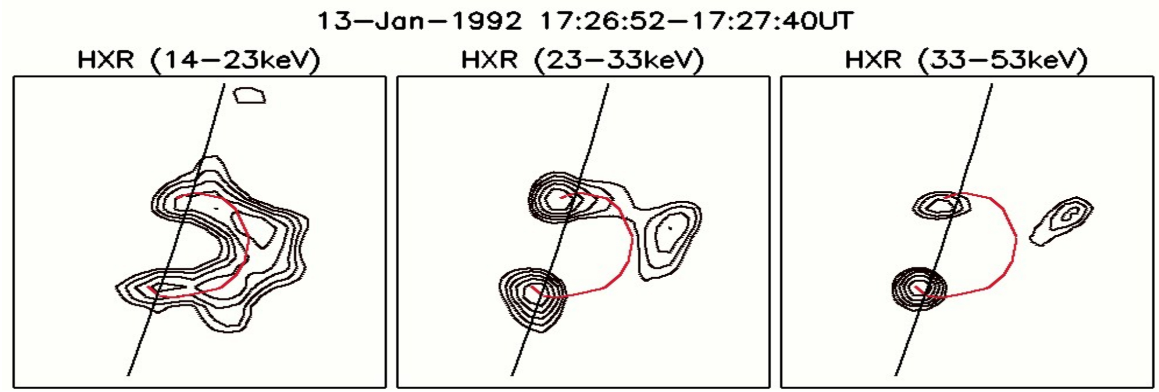
⟹ Heat, kinetic energy, energetic particles

RECONNECTION: OBSERVATIONAL EVIDENCES

Hard X-ray source above the loop top:

particle acceleration at reconnection site

Masuda et al. (1994), Hudson et al. (2001), Sui et al. (2003)

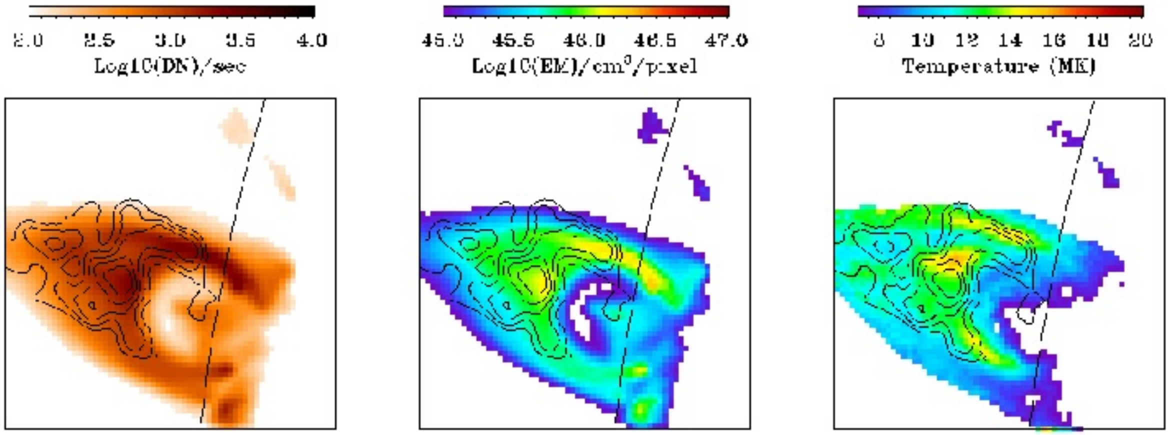


★ See Oka's talk (Today)

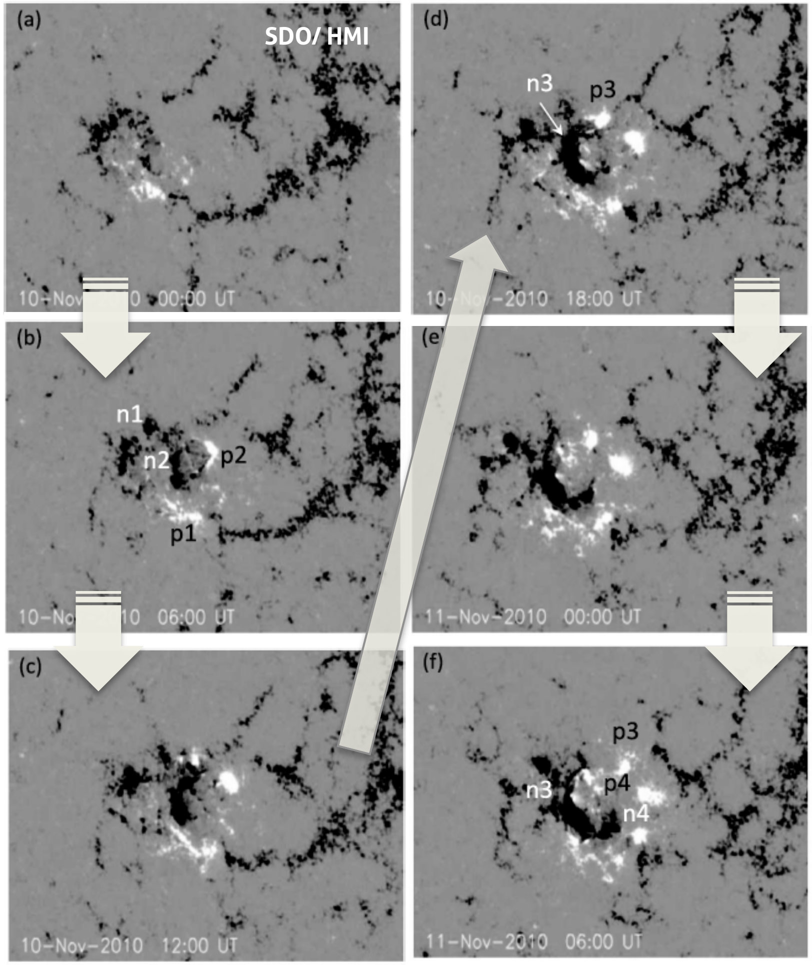
SXR high temperature ridges along outer or newly formed loops:

heating takes place

Tsuneta et al. (1996)



★ See van Driel-Gesztelyi's and Pinto's talks (Tuesday)



LARGE SCALE FLUX EMERGENCE

New polarities emerging in older region

⟾Several B-connectivity domains involved

Photospheric diverging motions

⟾Coronal loop expansion

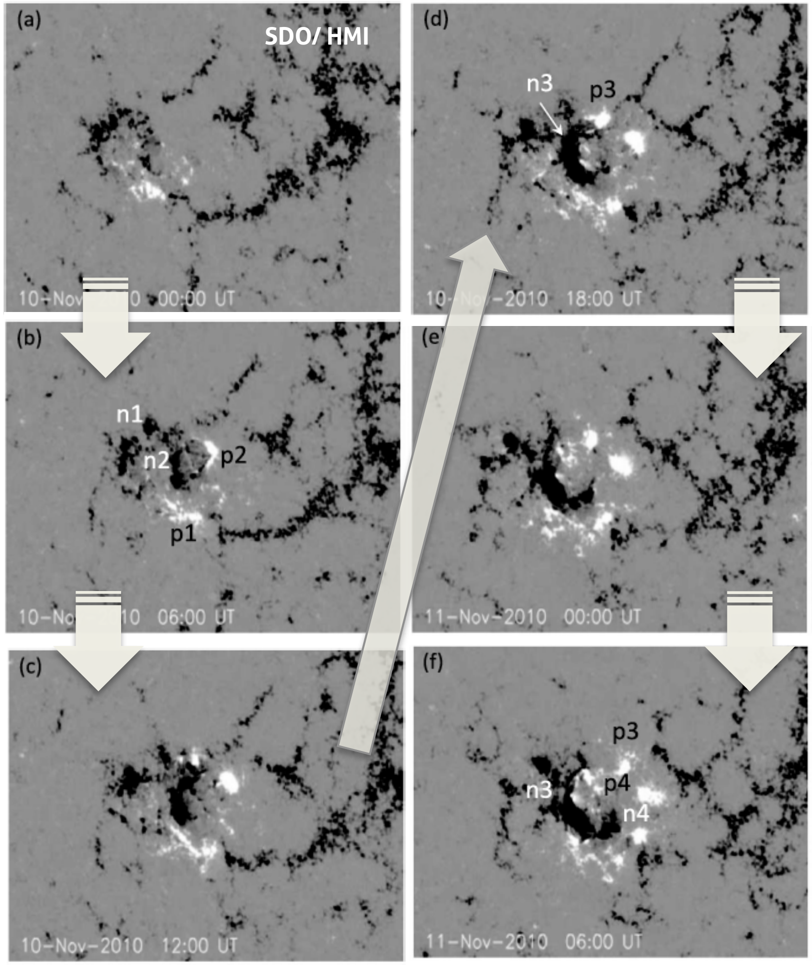
Favorable conditions for mag. reconnection

AR 11123: magnetic flux ↗ 70%/1 day

Mandrini et al. (2014)

★ See Mandrini's talk (Thursday)

CONFINED FLARES DRIVERS: OBSERVATIONS



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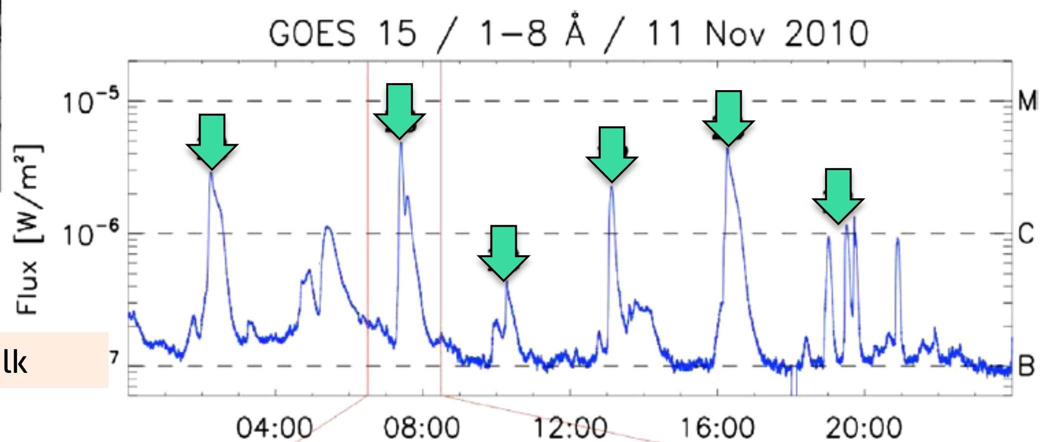
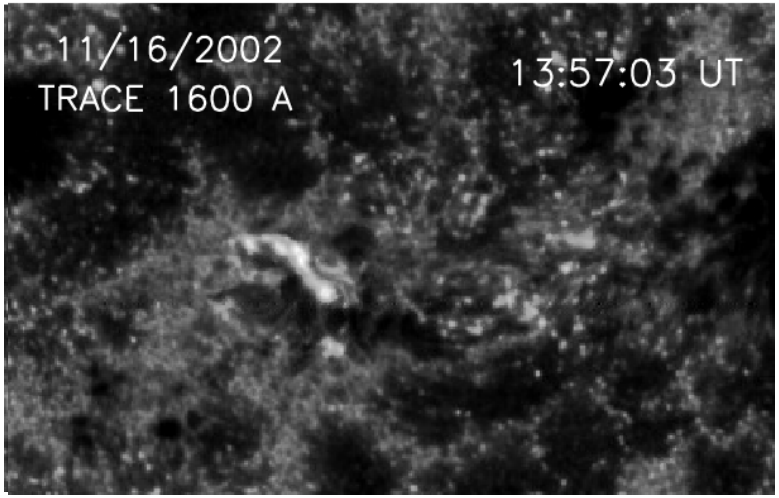


EVOLUTION OF CONFINED FLARES? OHM code

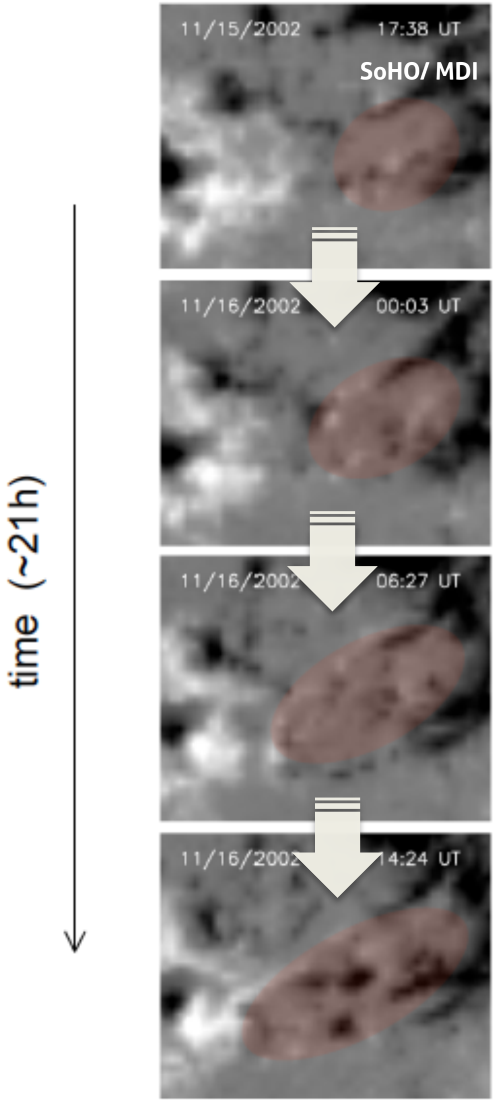
- **O**bservationally-driven **H**igh-order **M**HD **code**

  3D, non-uniform mesh, finite difference, predictor-corrector
  g = 0

Aulanier, Démoulin & Grappin (2005)



Masson et al. (2009)



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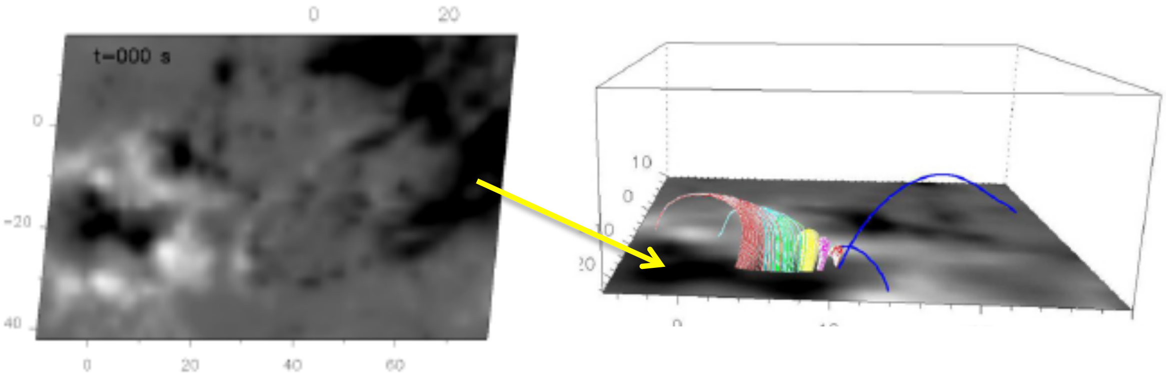
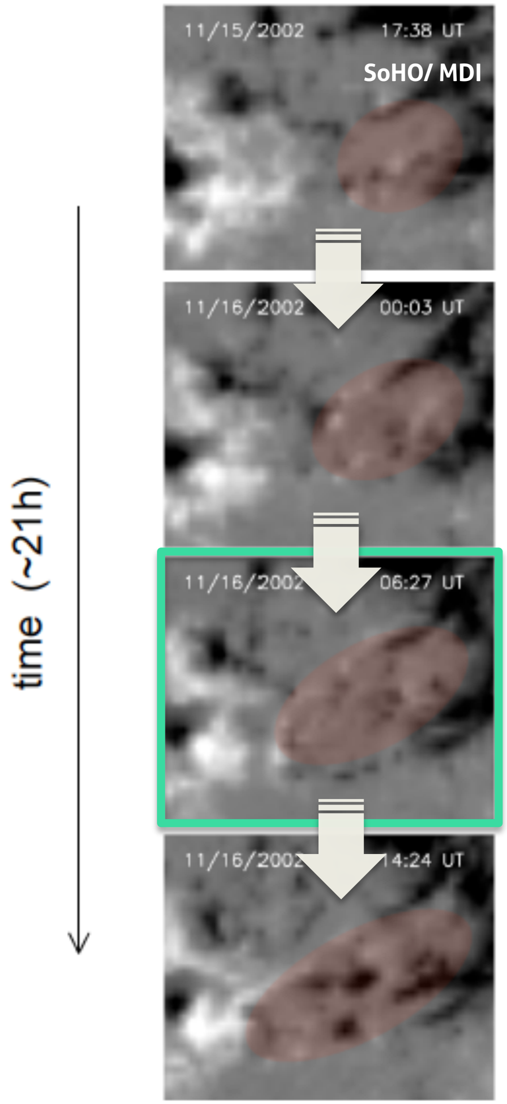
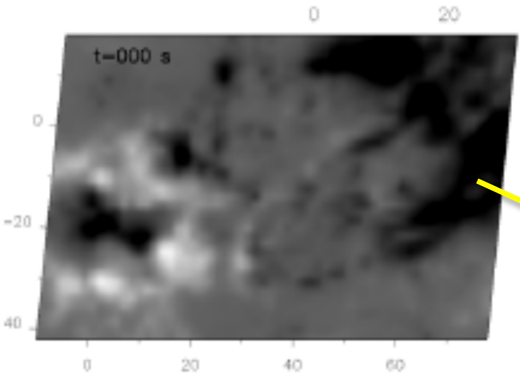


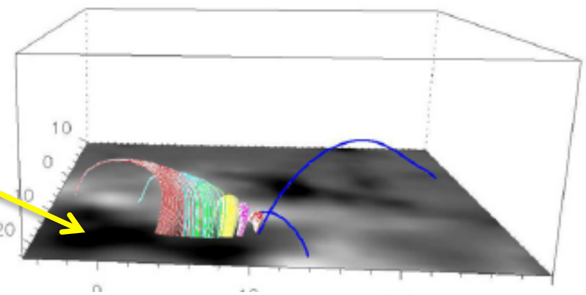


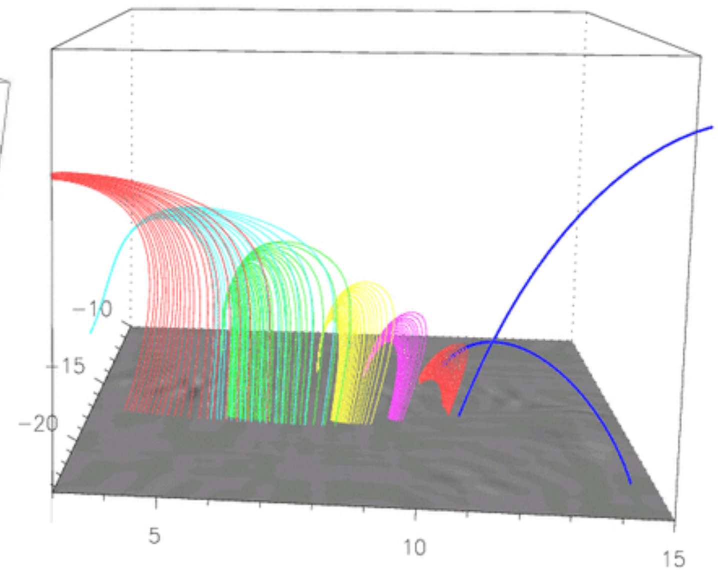
- Data-driven (from potential extrapolation)
- Physical regime: $\eta_{coronal}$ = cst, $\beta \neq 0$
- Photospheric diverging motions (as observed)

Masson et al. (2009)

EVOLUTION OF CONFINED FLARES? OHM code







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- Physical regime: $\eta_{coronal}$ = cst, $\beta \neq 0$
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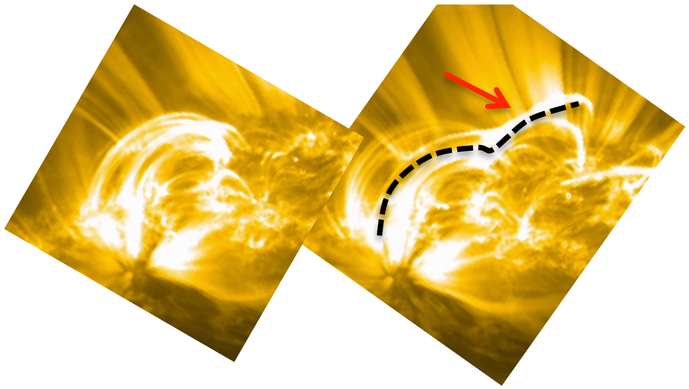
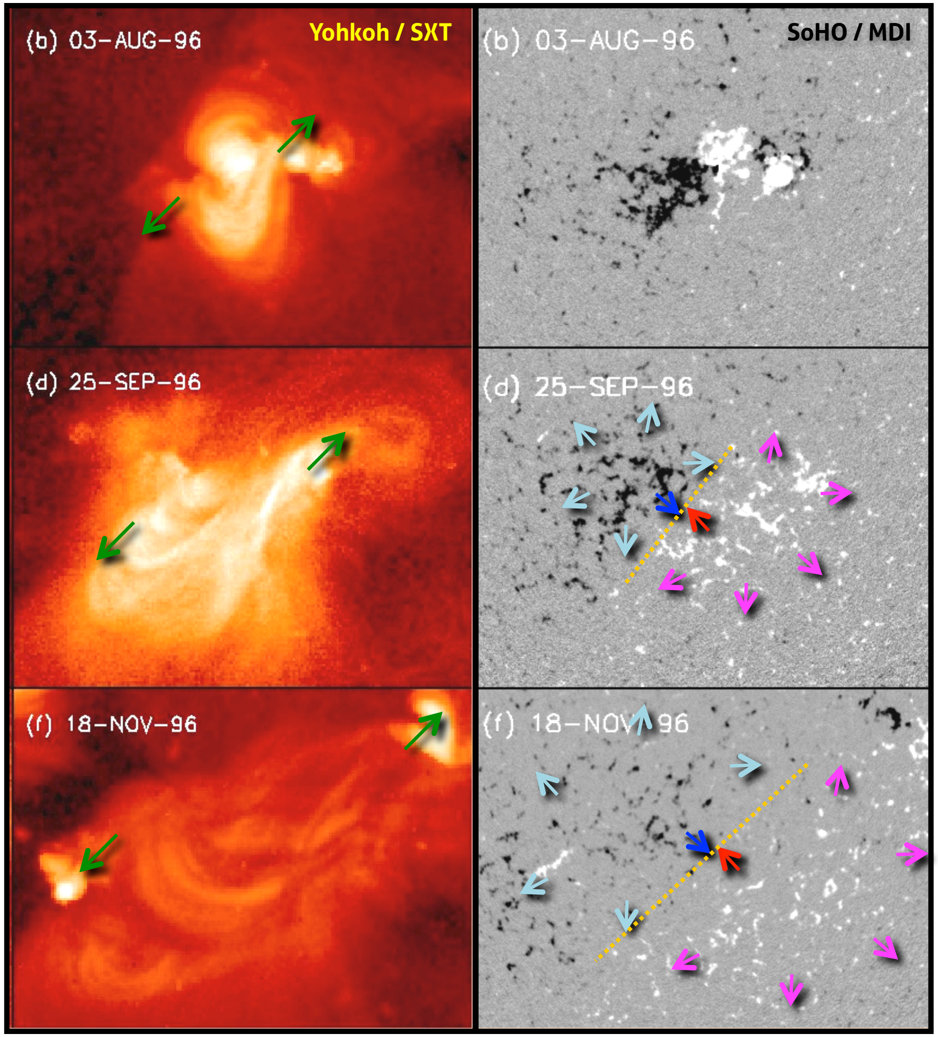
⟹ Reconnection in the corona

Masson et al. (2009)



LONG TERM EVOLUTION OF ACTIVE REGIONS

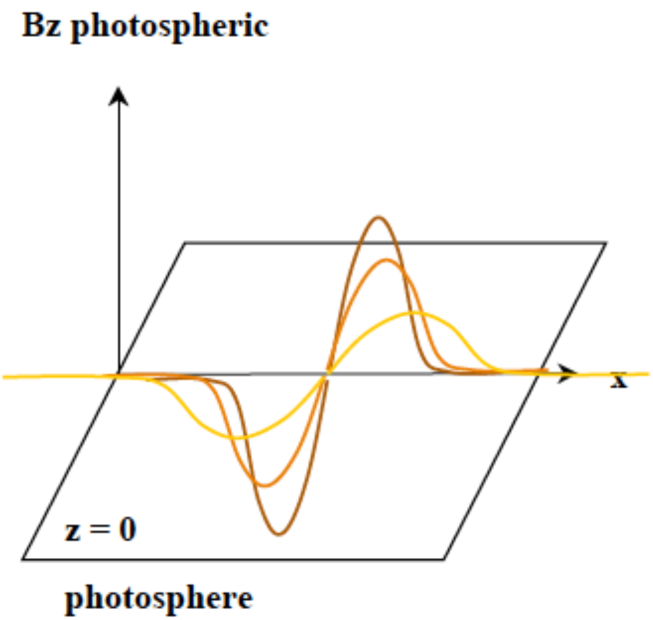


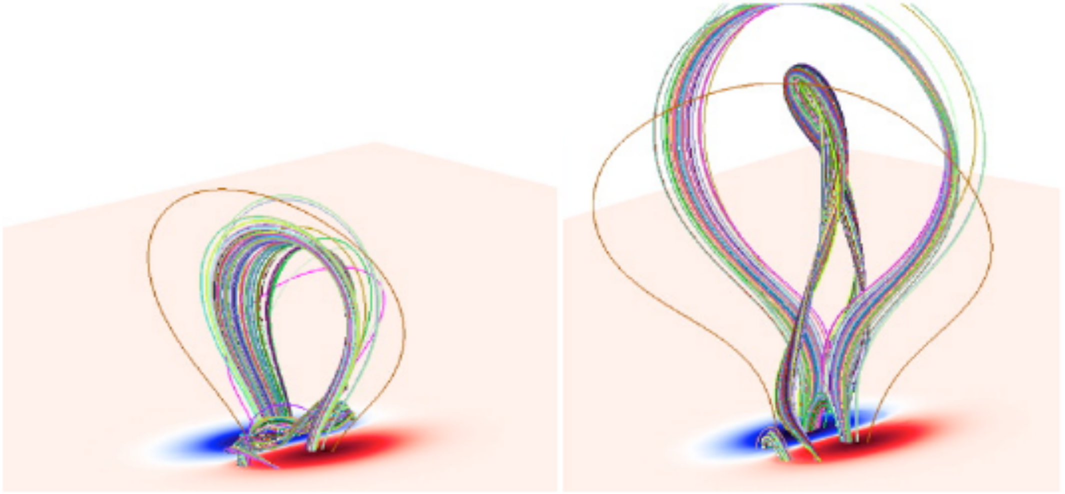
- Shearing coronal loops
- Converging motions at PIL
- Flux dispersal and B decrease
- Flux cancellation at PIL

Démoulin et al. (2002)
van Driel Gesztelyi et al. (2003)
Martin et al. (1985)
Schmieder et al. (2008)
Park et al. (2010)
Green et al. (2011) ...

CORONAL RESPONSE TO FLUX DISPERSION

- Magnetic flux density drops → coronal tension decreases
- B cancels at PIL → magnetic flux decrease in photosphere
  → flux rope formation in corona



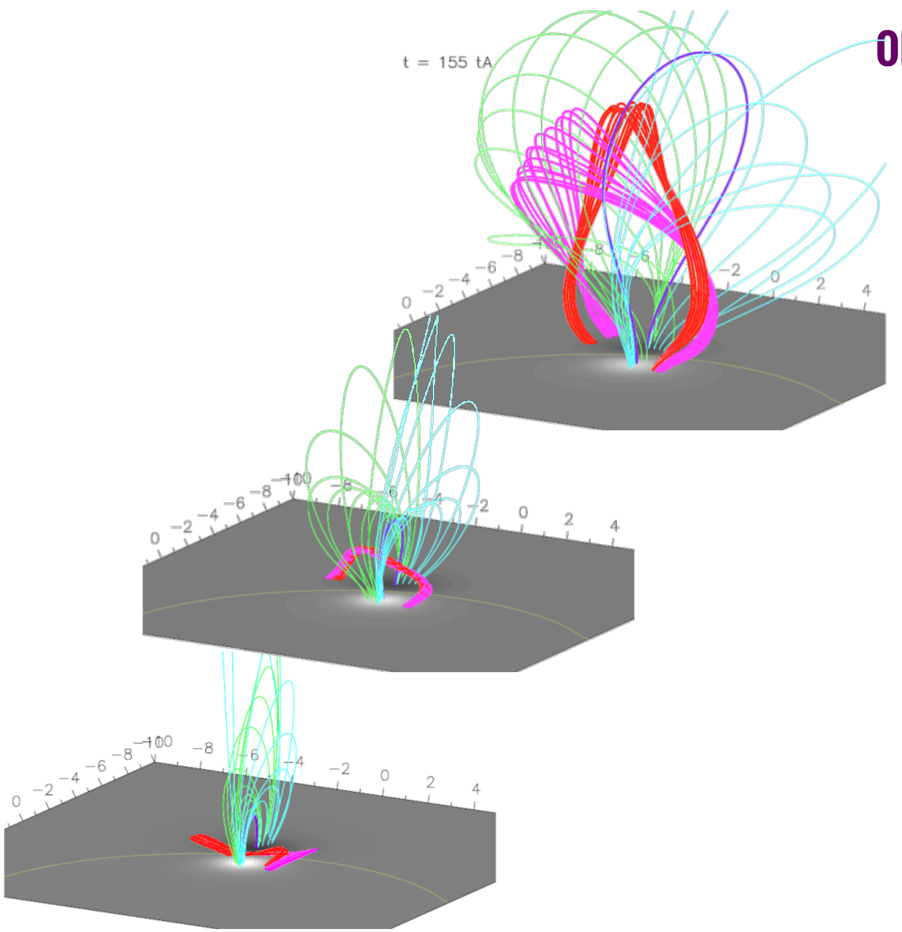


Amari et al. (2003,2011)
MacKay & van Ballegooijen (2006)
Yeates & MacKay (2009)

$\Longmapsto$ *Favorable conditions for triggering eruptions*

★ See Louis' talk (Tuesday)

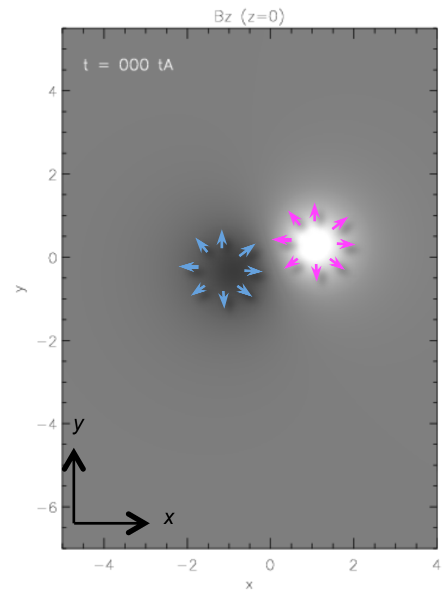
THRESHOLD FOR ERUPTIONS?



OHM code $\beta = g = 0$

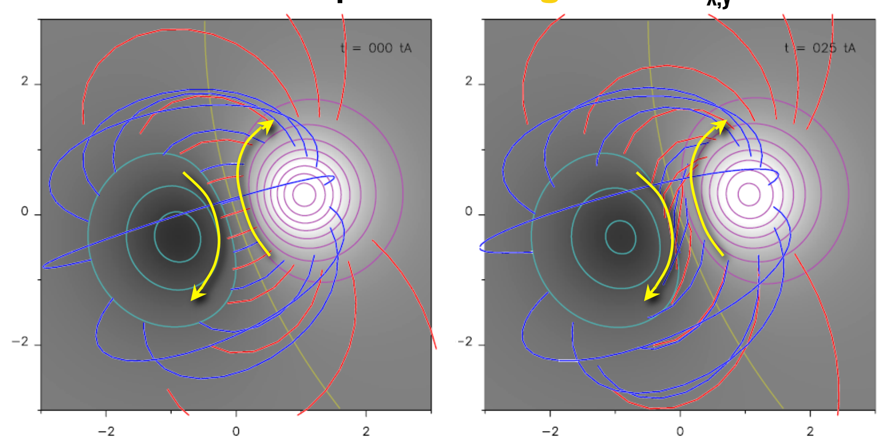
Aulanier, Török, Démoulin & DeLuca (2010)

- Photospheric magnetic diffusion of $B_{x,y,z}$



Aulanier, Török, Démoulin & DeLuca (2010)

- Photospheric shearing motions $u_{x,y}$



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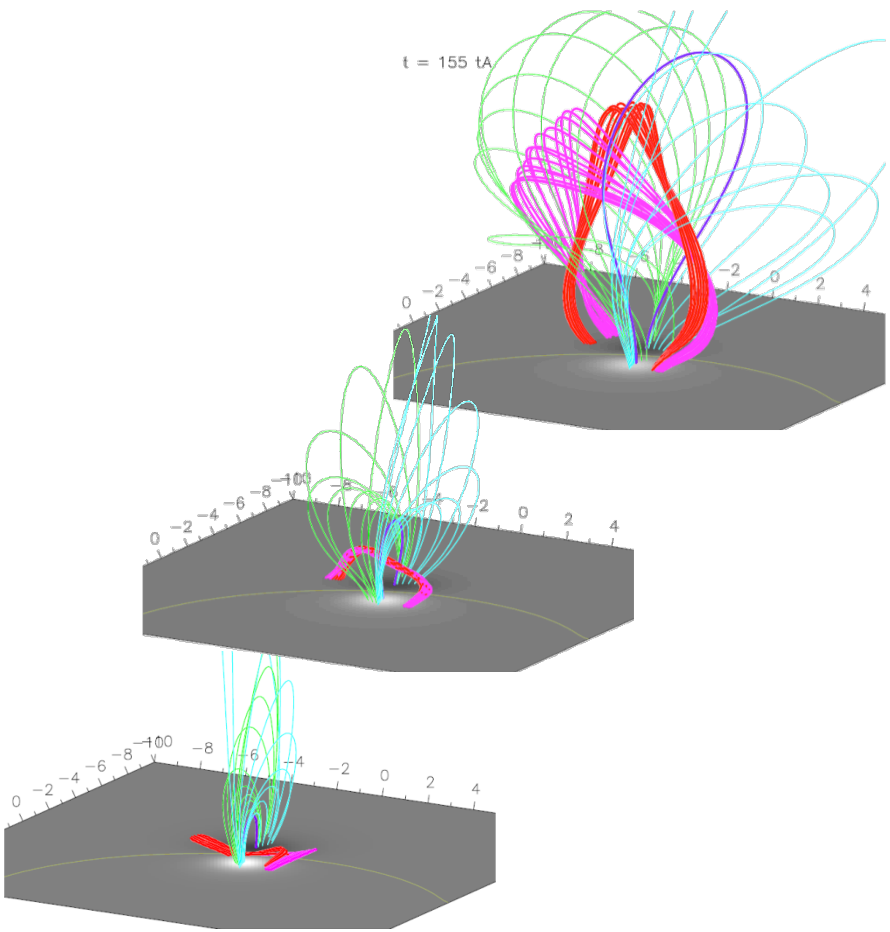

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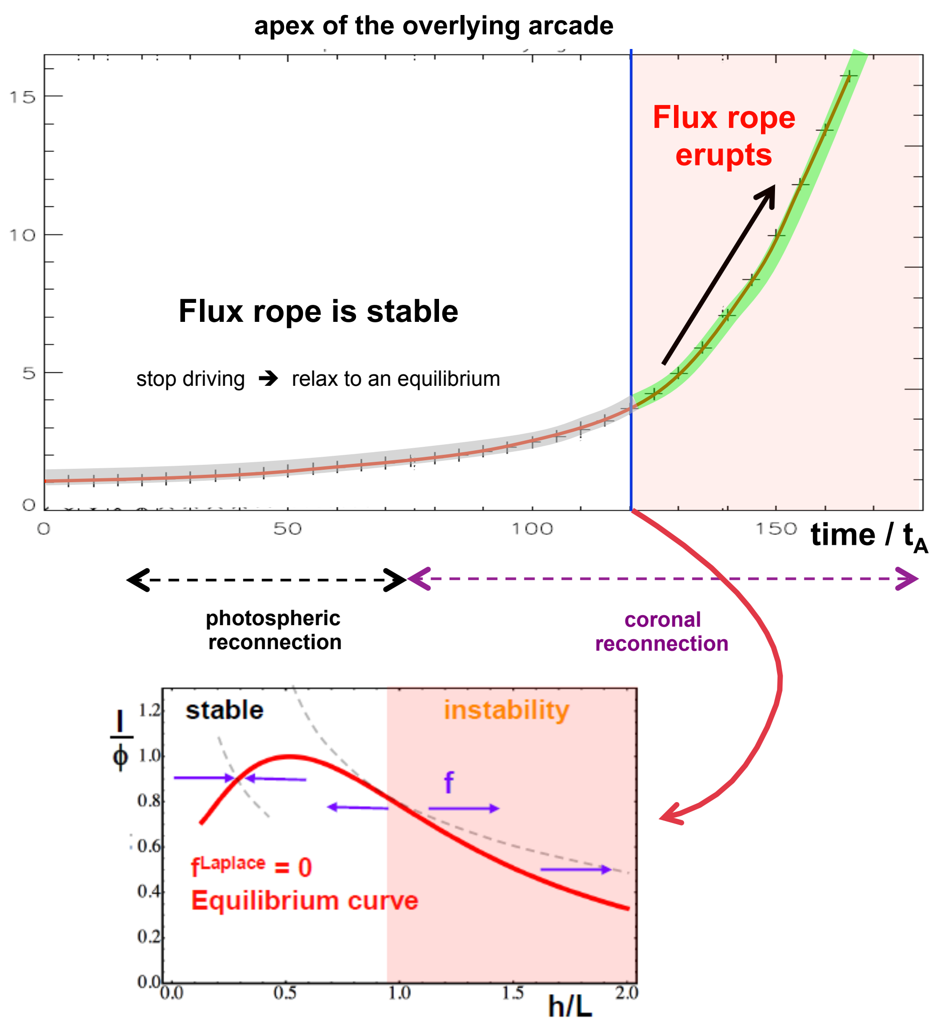
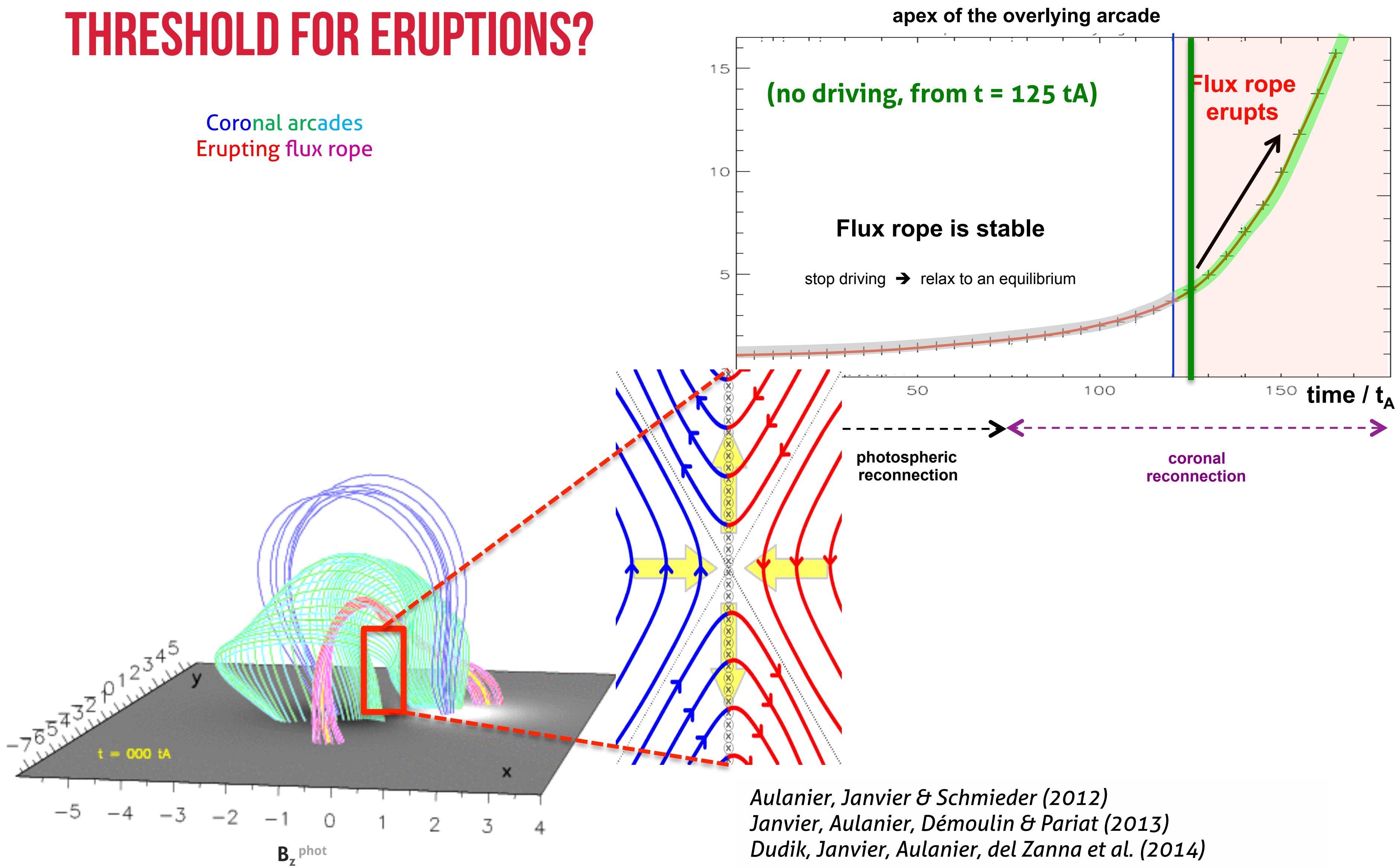


$\Longmapsto$ TORUS INSTABILITY

Démoulin & Aulanier (2010)

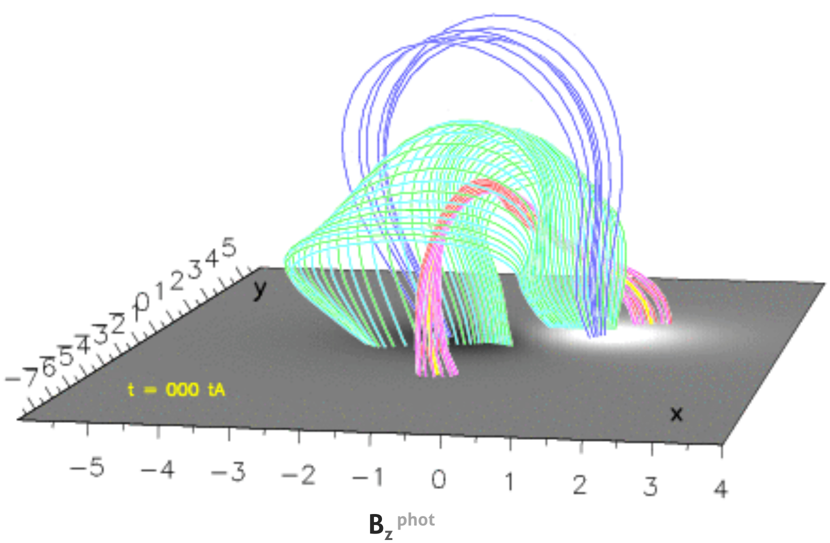
THRESHOLD FOR ERUPTIONS?



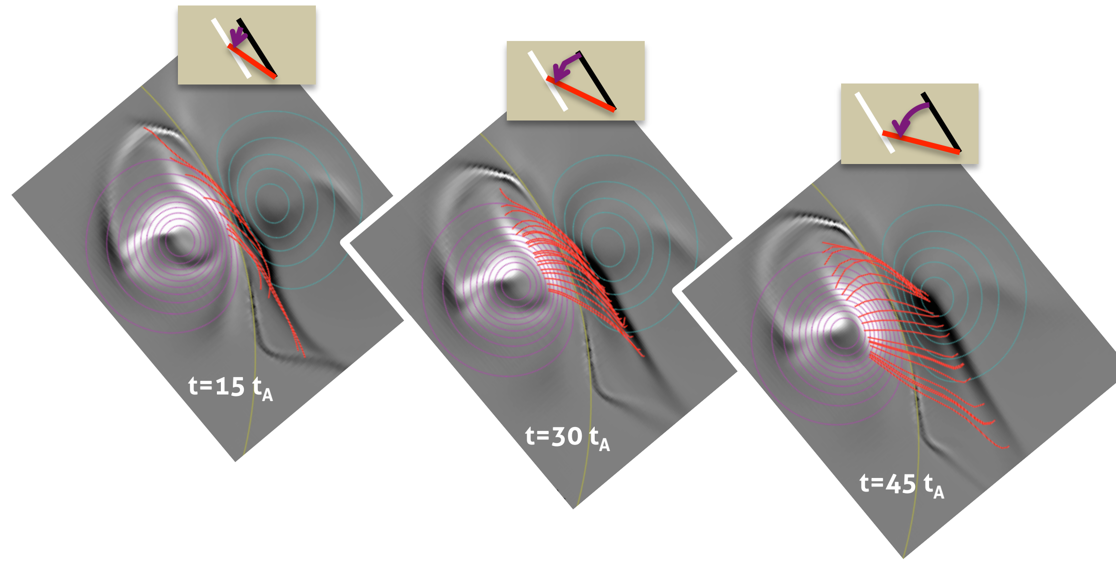
Aulanier, Janvier & Schmieder (2012)
Janvier, Aulanier, Démoulin & Pariat (2013)
Dudik, Janvier, Aulanier, del Zanna et al. (2014)

THRESHOLD FOR ERUPTIONS?

Coronal arcades
Erupting flux rope



❖ Shear transferred from pre-eruptive field lines via reconnection



❖ Formation of flare loops:

- strong-to-weak shear transition
- Low to high altitude formation

❖ Envelope formation of the flux rope

Aulanier, Janvier & Schmieder (2012)
Janvier, Aulanier, Démoulin & Pariat (2013)
Dudik, Janvier, Aulanier, del Zanna et al. (2014)

MECHANISMS FOR ERUPTIONS

Also in: Aulanier et al. (2014)

★ See Schmieder's talk (Thursday)

Torus instability (Loss of equilibrium)

Aulanier et al. (2010), Fan et al. (2010), Kliem et al. (2013)

$\Longmapsto$ MHD simulations (reproduce observations) + corresponds to <u>observations</u>

MECHANISMS FOR ERUPTIONS

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⟾MHD simulations (reproduce observations) + corresponds to observations

Breakout reconnection above flux rope *Antiochos et al. (1999), Karpen et al. (2012),…*

⟾Works *only if* not too much magnetic flux at high altitudes

MECHANISMS FOR ERUPTIONS

Also in: Aulanier et al. (2014)

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Antiochos et al. (1999), Karpen et al. (2012),…

⟹ Works *only if* not too much magnetic flux at high altitudes

Many processes that help, or lead to, one of the above:

- Flare reconnection from below → Tension transfer or accel' by recon' jet
- Purely converging or shearing motions → Building-up pressure below
- Twist emergence into B-free/weak corona → Mass drainage or additional shear flows
- Flux cancellation through B^{phot} diffusion → Decrease of arcade flux

OUTLINE

Flares (confined, eruptive): definition and observations

$\Longrightarrow$ *What happens?*

Confined/eruptive flares: difference in drivers

$\Longrightarrow$ *What drives flares?*

The topology of flares

$\Longrightarrow$ *Location of energy release?*

Prediction from models

$\Longrightarrow$ *What to look for?*

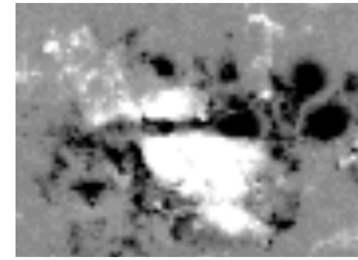
DOES ENERGY RELEASE OCCUR AT NULL POINTS / SEPARATRICES?

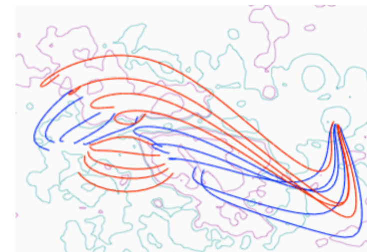
Method:

Input the photospheric magnetogram

Compute the coronal field

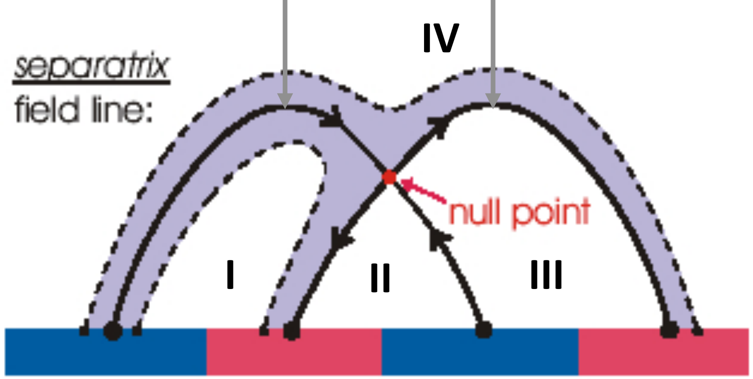
Compute magnetic null points & separatrices

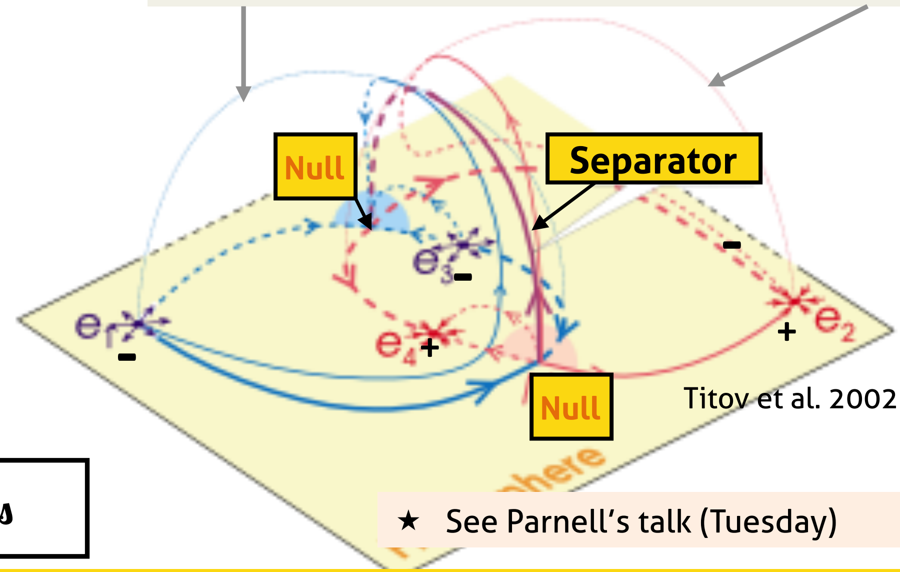




2D separatrices

3D separatrices: 2 intersecting cupola





4 connectivity domains

★ See Parnell's talk (Tuesday)

DOES ENERGY RELEASE OCCUR AT NULL POINTS / SEPARATRICES?

Method:

Input the photospheric magnetogram

↓

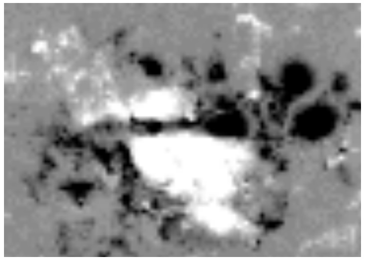
Compute the coronal field

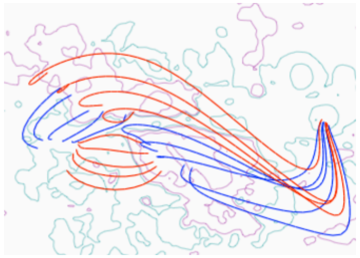
↓

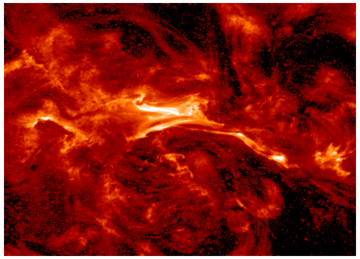
Compute magnetic null points & separatrices

↓

Comparison with observed energy release signatures



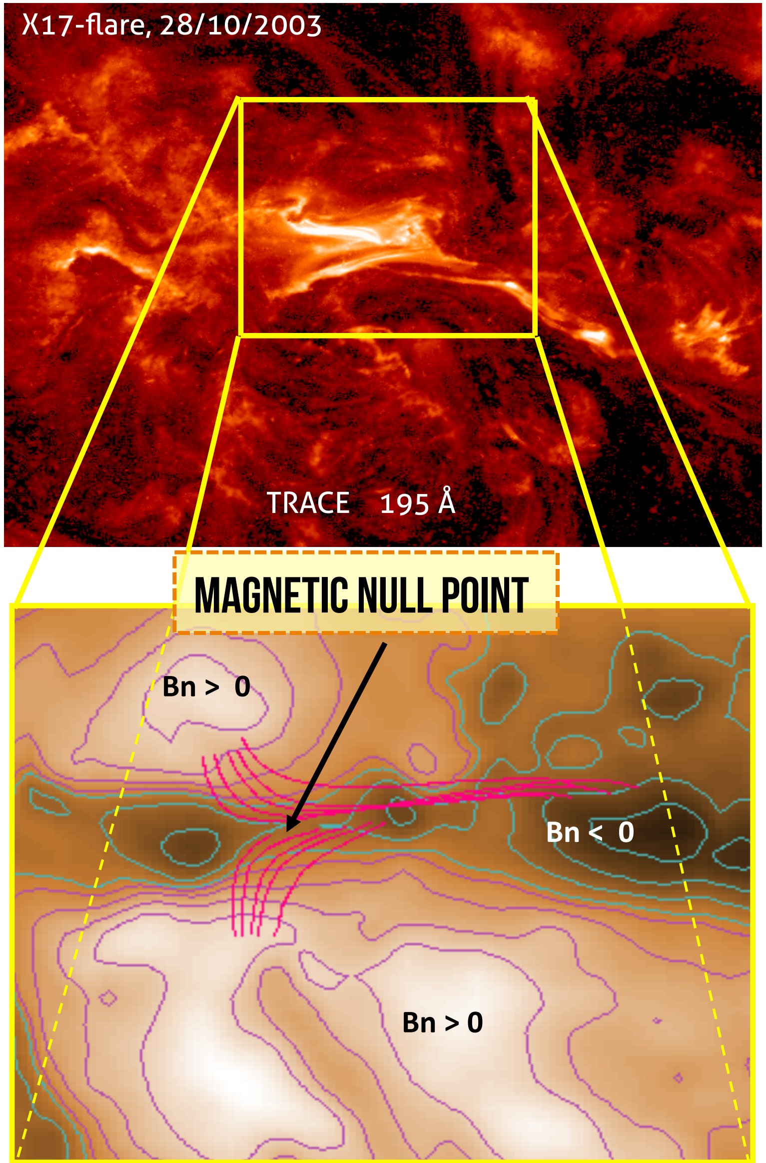




Various configurations analysed:

Gorbachev & Somov 1989, Mandrini et al. 1991, 1993, Démoulin et al. 1994,
Mandrini et al. 1996, 1997, Schmieder et al. 1997, Aulanier et al. 1998, Gaizauskas et al. 1999, Bagala et al. 2000, Fletcher et al. 2001, Mandrini et al. 2006, Cristiani et al. 2007, Savcheva et al. 2012, Mandrini et al. 2014, ...

DOES ENERGY RELEASE OCCUR AT NULL POINTS / SEPARATRICES?



MDI magnetogram → LFFF extrapolation

- Null point
- Field lines close to null point
(correspond to observed coronal loops!)

⟹ *Evidence of reco. at null point*

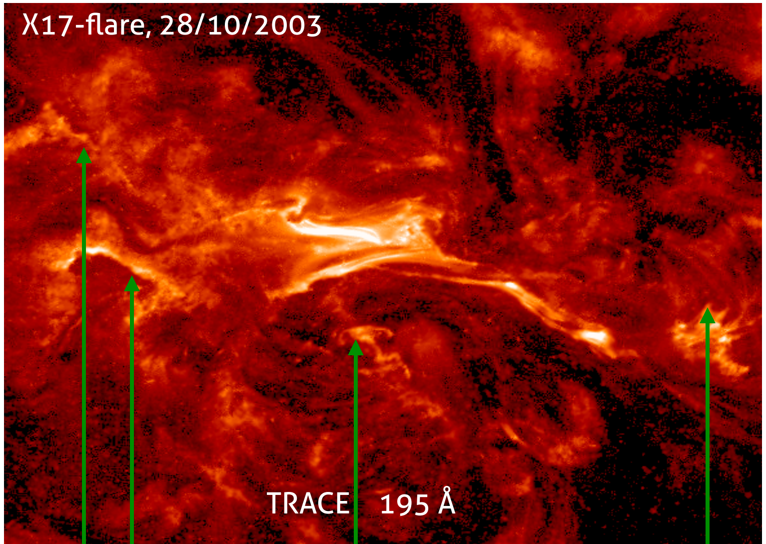
But **small scale event**

- Similar loops present from ~1 h **before** until **late decaying phase** of X17

⟹ *Event independent of X17 flare*

Mandrini et al. 2006

DOES ENERGY RELEASE OCCUR AT NULL POINTS / SEPARATRICES?

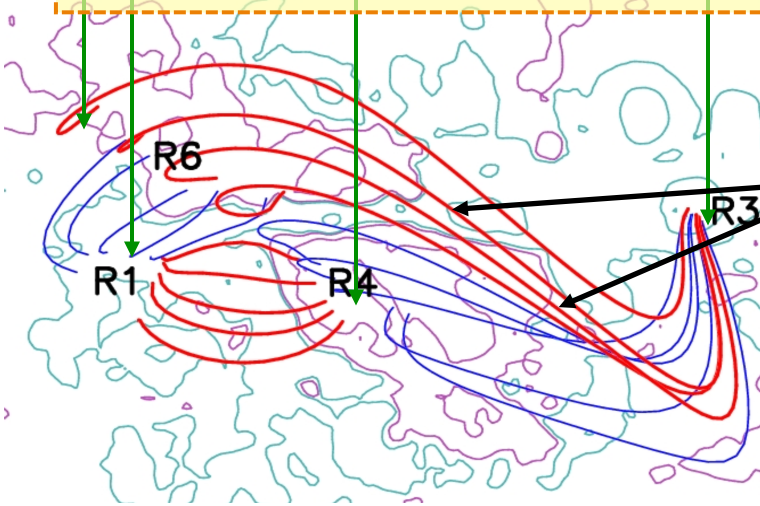


Large scale event

- Without magnetic null point
- Start from ~1 h before the X17 flare

⟹ *Precursor of the X17 flare:*
large scale quadrupolar reconnection

NO OTHER MAGNETIC NULL POINT, BUT QUADRUPOLAR CONFIGURATION
→ QUASI-SEPARATRIX LAYERS



Blue field lines reconnect ➔ red field lines

The X17 flare started below these f.l.

Mandrini et al. 2006

DEFINITION OF QUASI-SEPARATRIX LAYERS?

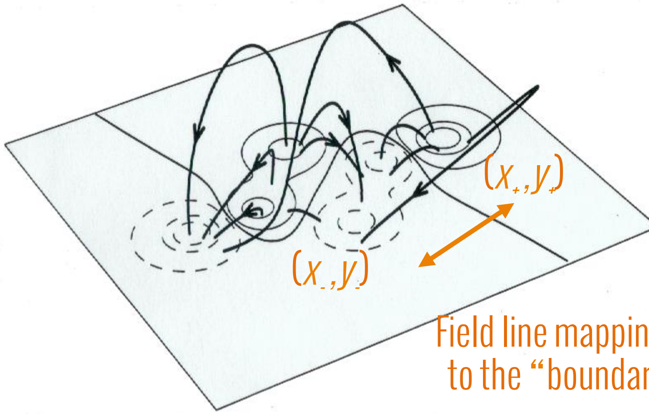
Localized, drastic change of magnetic connectivity (but continuous without null points)

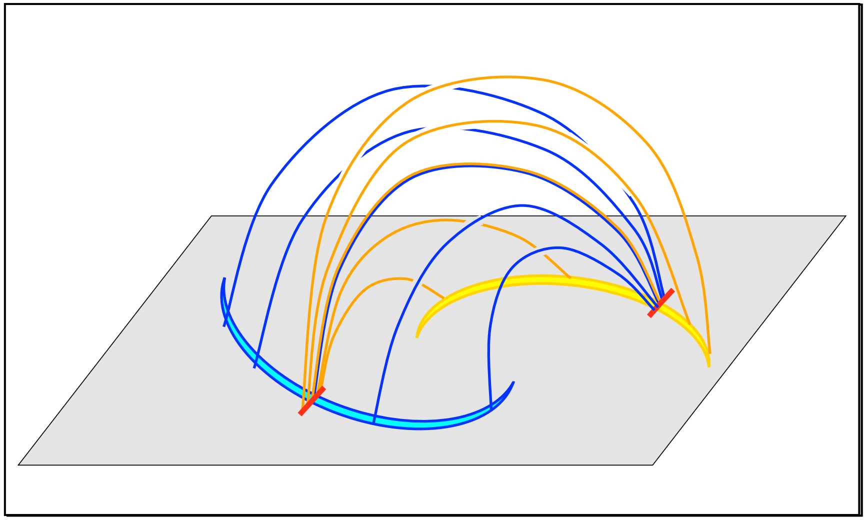
<u>QSL definition:</u> regions where

$$\boxed{Q \equiv \frac{\| F \|^2}{B_{n,+} / B_{n,-}} >> 1} \quad F = \begin{pmatrix} \partial x_- / \partial x_+ & \partial x_- / \partial y_+ \\ \partial y_- / \partial x_+ & \partial y_- / \partial y_+ \end{pmatrix}$$

"Squashing degree"

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





Same value of Q at both feet of a field line : $Q_+ = Q_-$

DEFINITION OF **QUASI-SEPARATRIX LAYERS?**

Localized, drastic change of magnetic connectivity (but continuous without null points)

<u>**QSL definition**</u>: regions where

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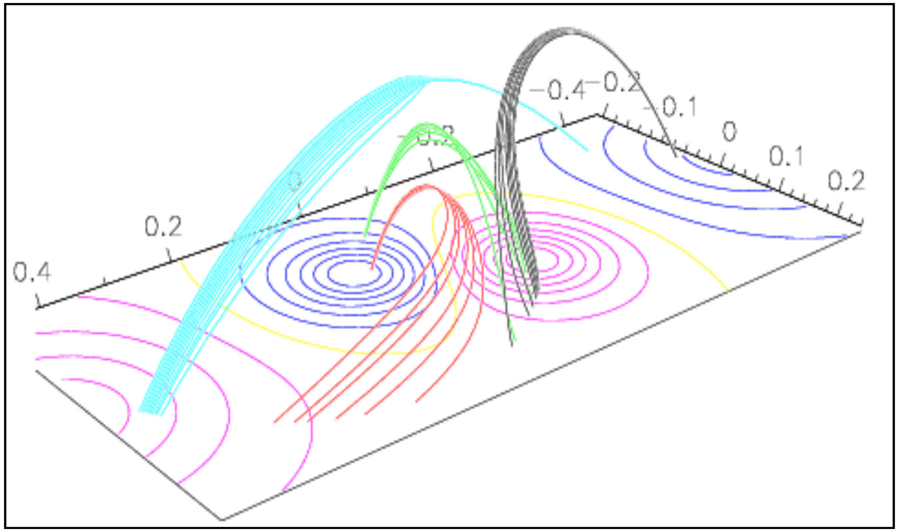
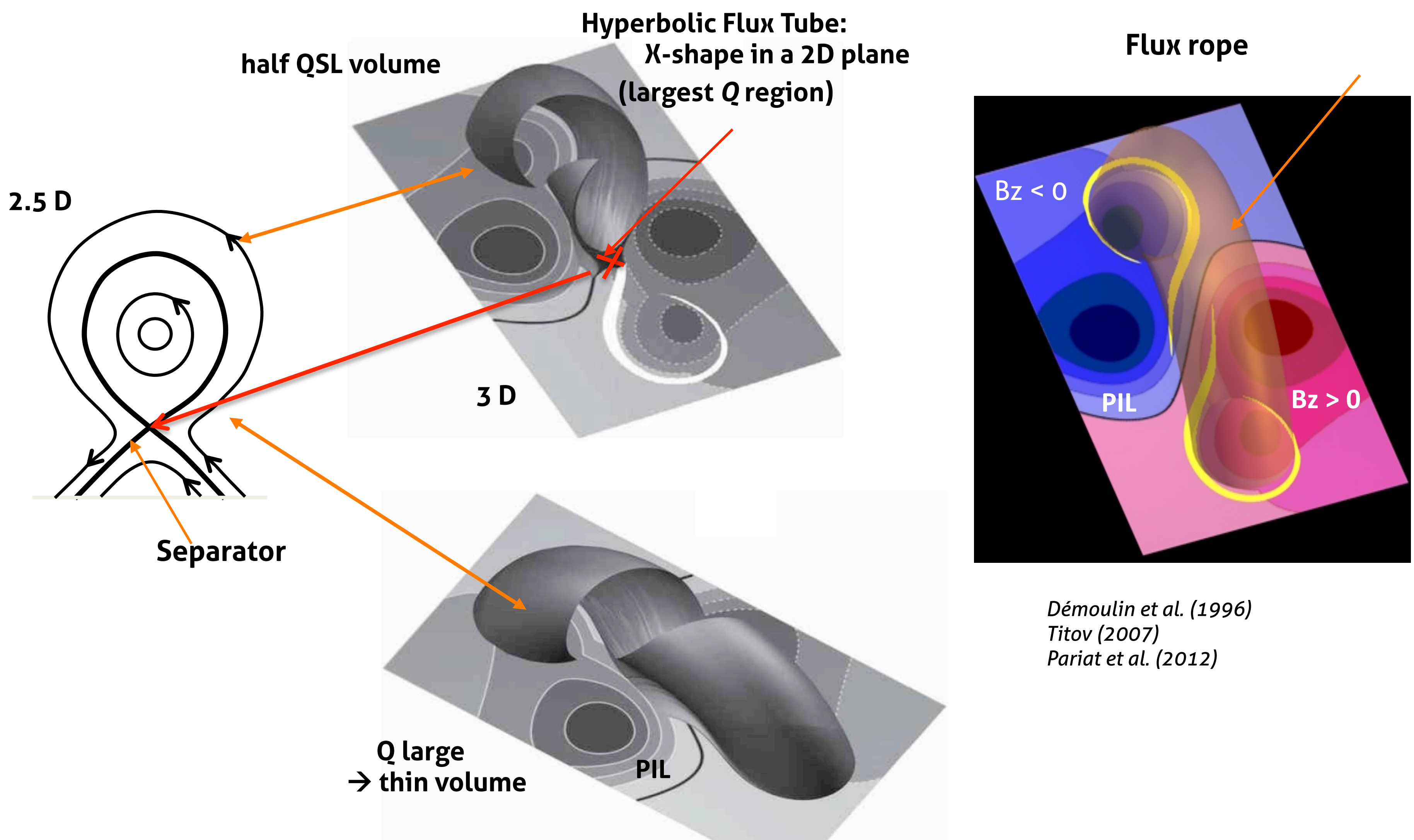


Leads to:

$\Longmapsto$ Slipping reconnection

successive reconnection due to the continuous change of connectivity

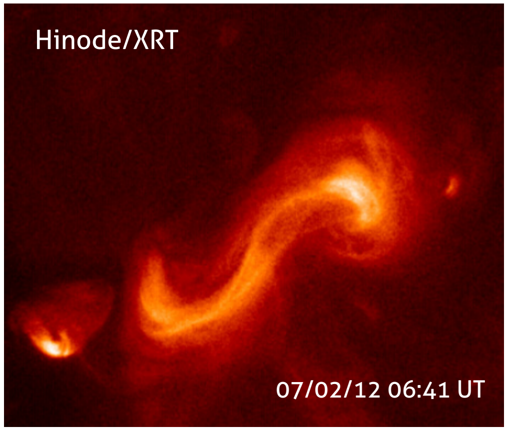
QSLS IN TWISTED CONFIGURATION

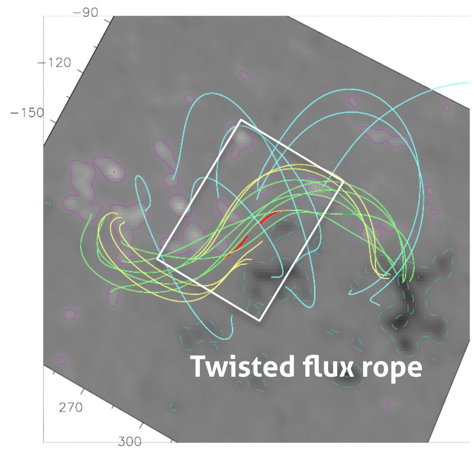


Démoulin et al. (1996)
Titov (2007)
Pariat et al. (2012)

QSLS IN ERUPTIVE FLARES: OBSERVATIONS – HFT

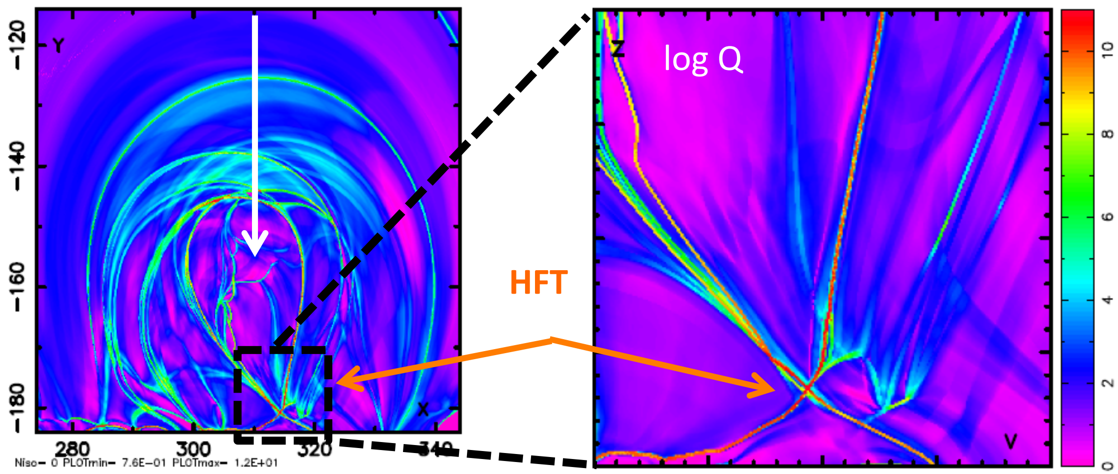
TOPOLOGY ANALYSIS WITH NLFFF EXTRAPOLATION





- 1st QSLs from a data-constrained NLFFF model
- More complex than previous analytical model but similarities in shape

Vertical cut

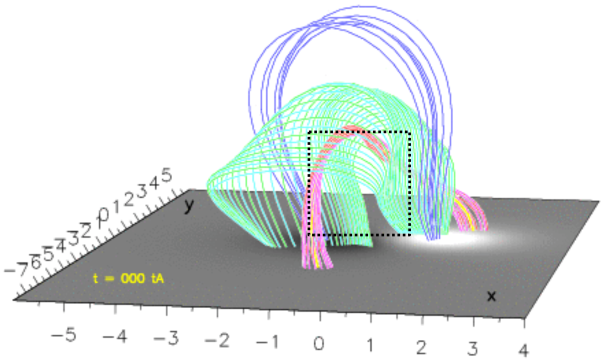


⟹ HFT are typical structures of sigmoid regions & Flux Ropes

Savcheva et al. (2012a,b)

QSLS IN ERUPTIVE FLARES: 3D MHD SIMULATION – HFT

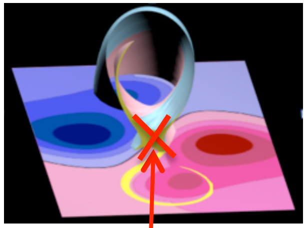
Coronal arcades
Erupting flux rope



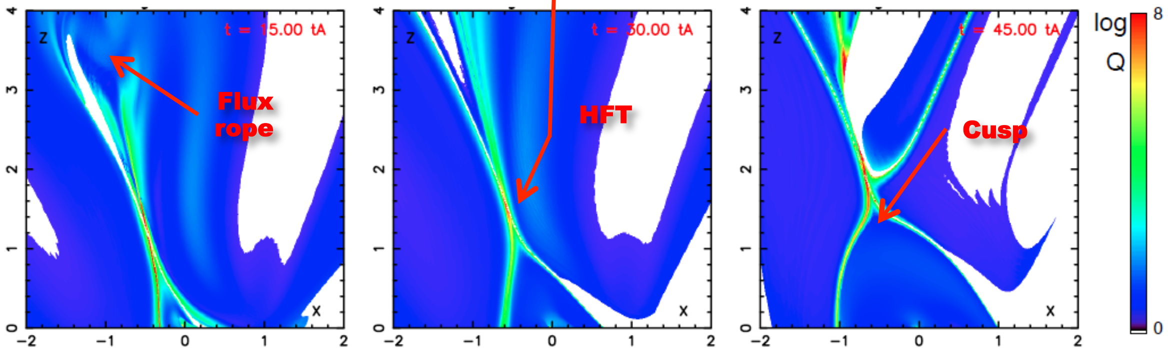
B_z^{phot}

Vertical cuts

Q = *squashing factor*



«gradient of field line connectivity»



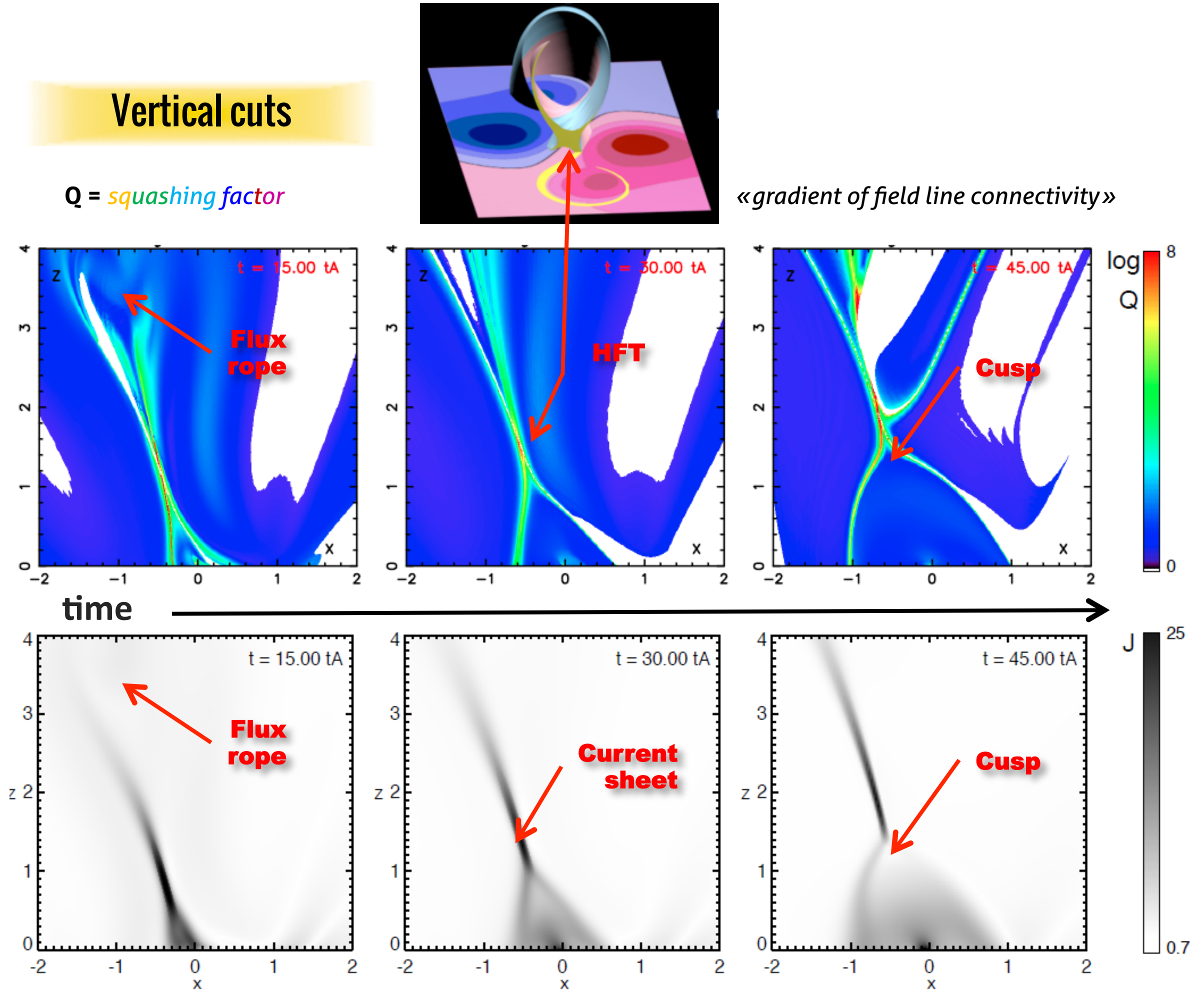
time

Janvier, Aulanier, Pariat & Démoulin (2013)

Vertical cuts

Q = *squashing factor*

«gradient of field line connectivity»



J = *|curl B| electric currents*

- **Current layers: Similar location as QSLs**

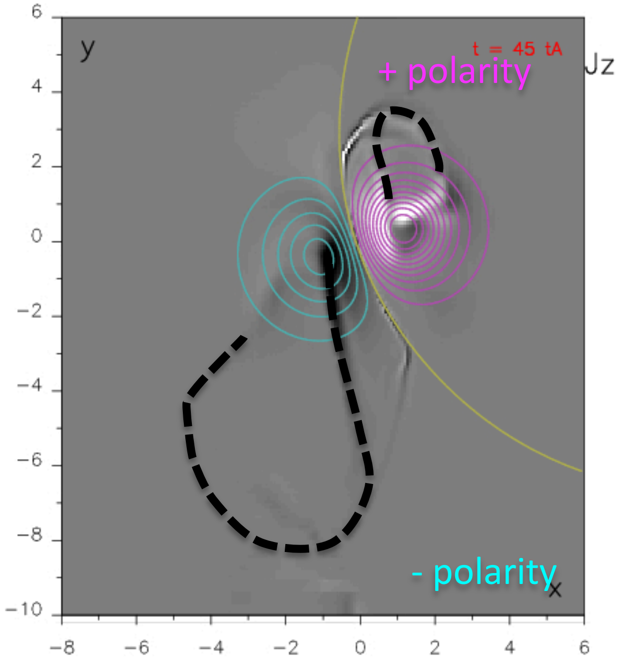
See also: (Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, …)

- **Collapse of the coronal current layer (=thinning)**

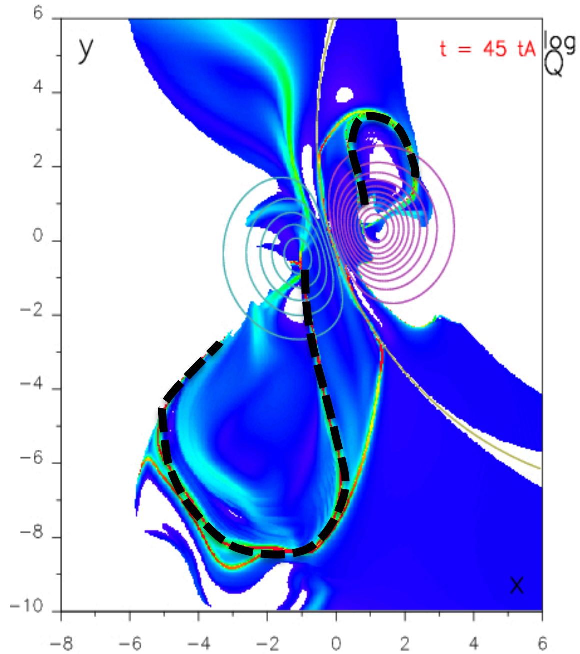
Prediction from the model (not yet observable)

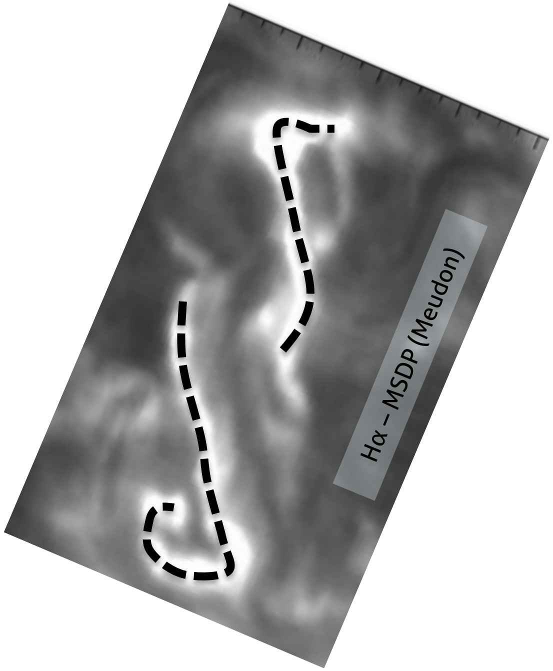
Janvier, Aulanier, Pariat & Démoulin (2013)

Top views



Janvier et al. (2013)

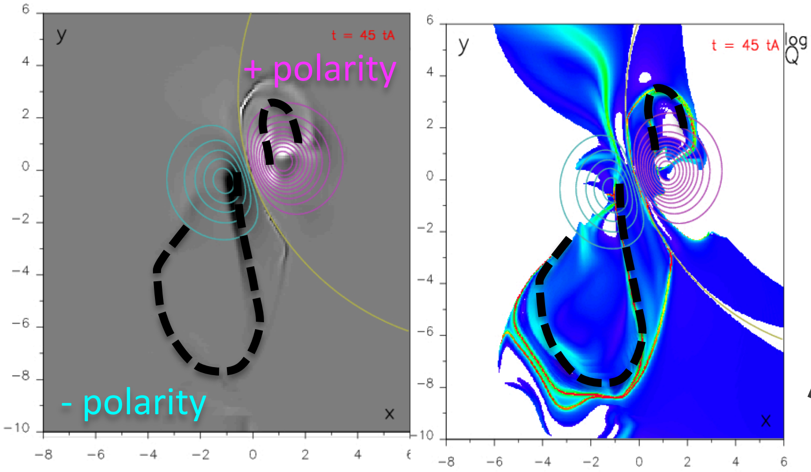




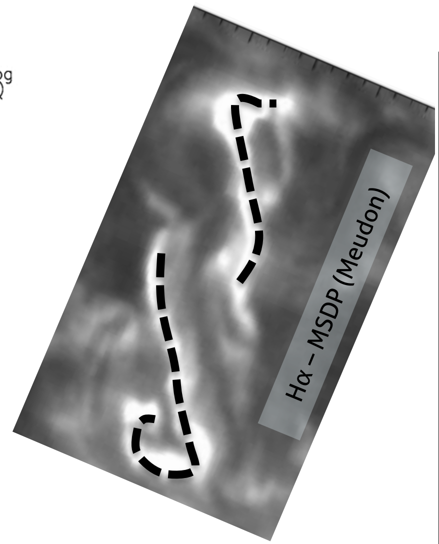
Chandra et al. (2009)

⟹Similar shape as flare ribbons

Top views

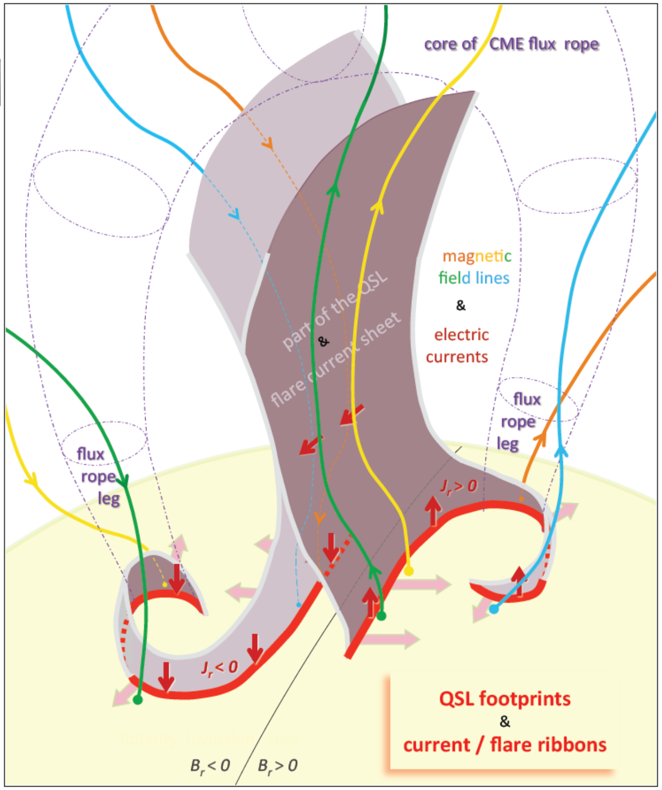


Janvier et al. (2013)



Chandra et al. (2009)

Standard flare model in 3D



⟹Photospheric currents: footprints of coronal current layer

⟹Flare ribbons: photospheric footprints of QSLs/HFT & currents

TOPOLOGY: TO PREDICT/UNDERSTAND WHERE RECONNECTION TAKES PLACE

OUTLINE

Flares (confined, eruptive): definition and observations

$\Longmapsto$ *What happens?*

Confined/eruptive flares: difference in drivers

$\Longmapsto$ *What drives flares?*

The topology of flares

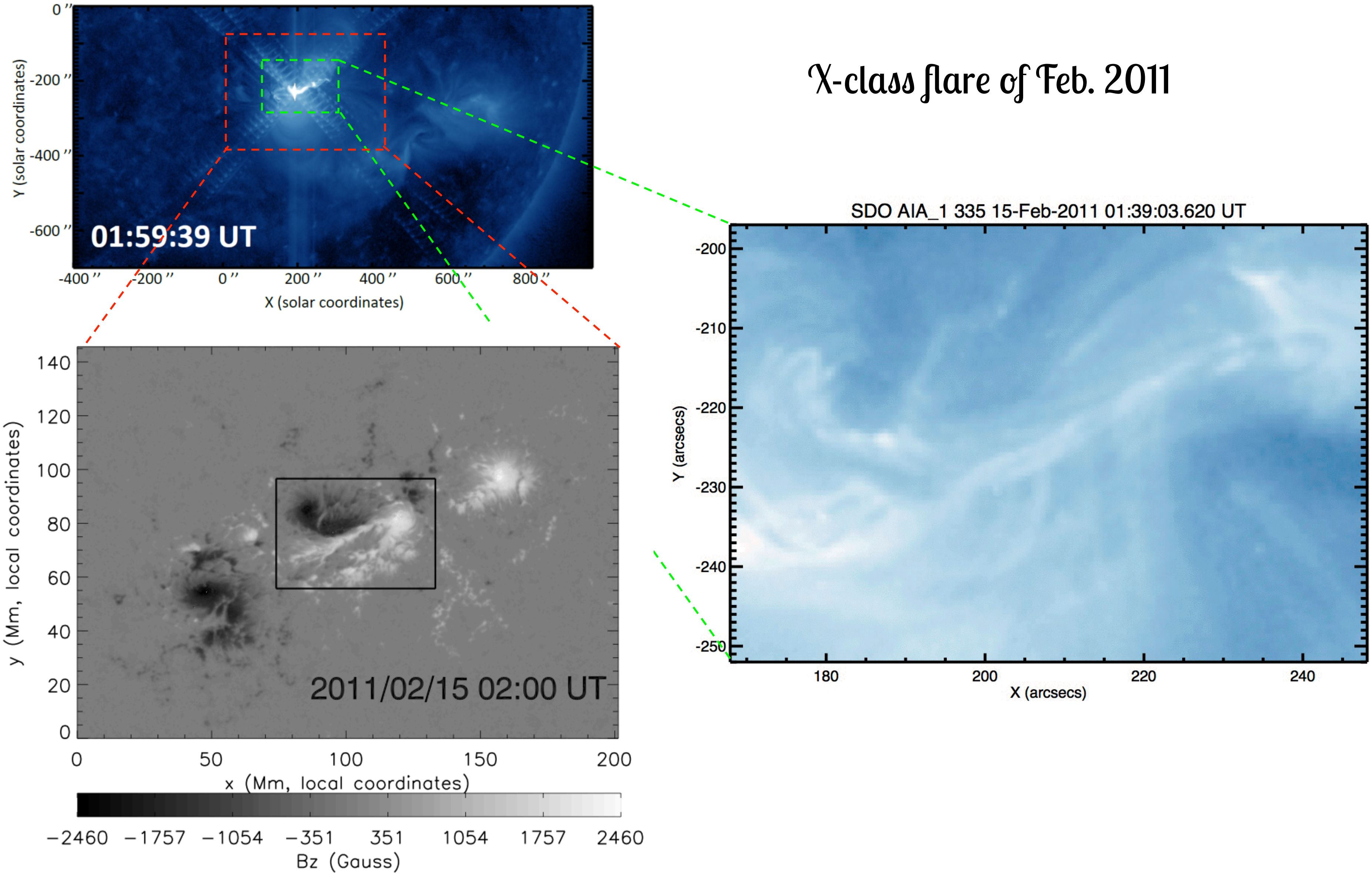
$\Longmapsto$ *Location of energy release?*

Prediction from models

$\Longmapsto$ *What to look for?*

ERUPTIVE FLARES: MODEL PREDICTION & OBSERVATIONAL CONFIRMATION

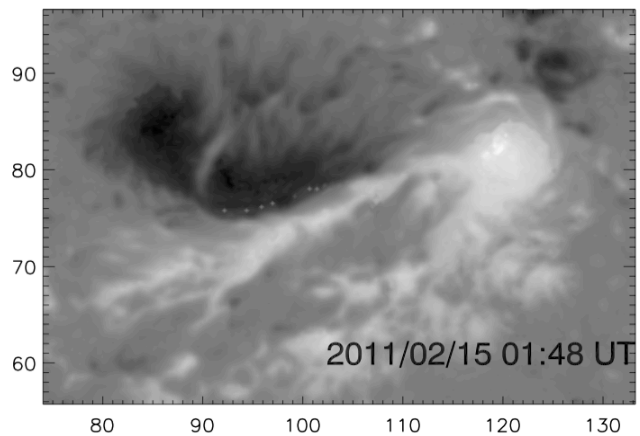
X-class flare of Feb. 2011

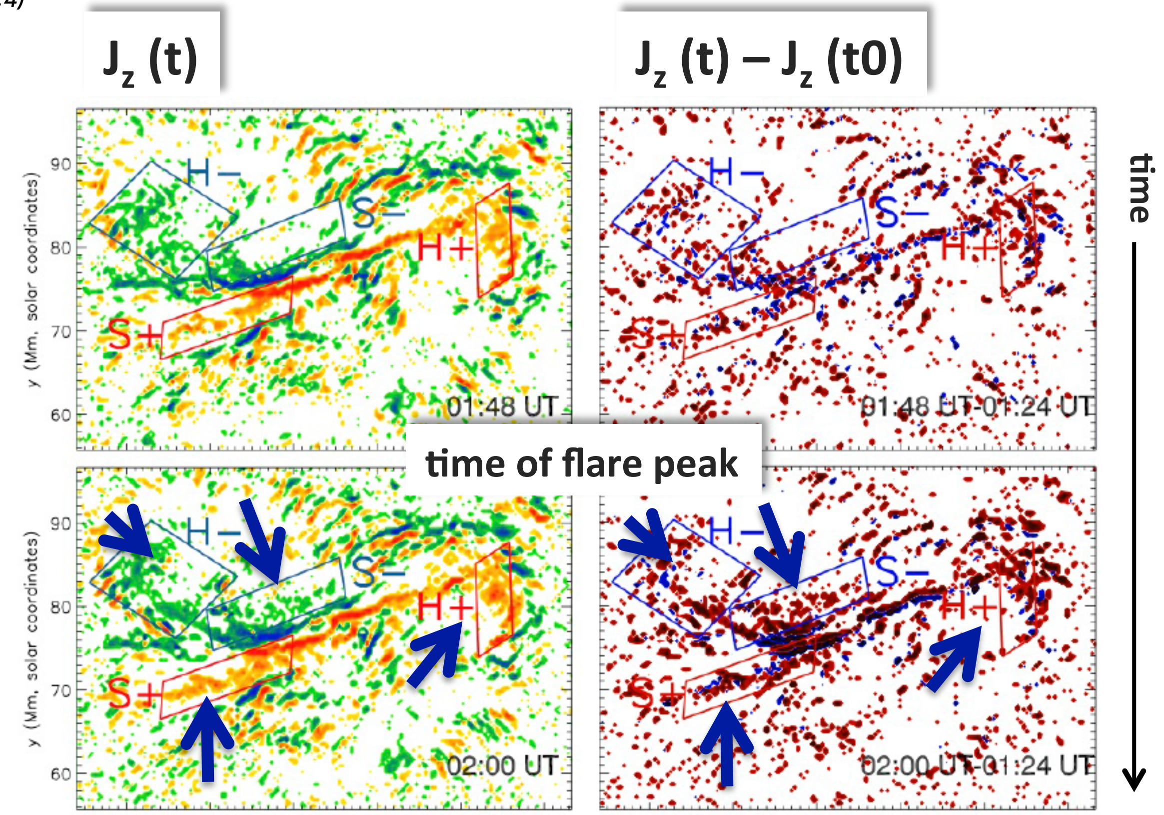


ERUPTIVE FLARES: MODEL PREDICTION & OBSERVATIONAL CONFIRMATION

Photospheric vertical currents = current ribbons

Janvier, Aulanier, Bommier, Schmieder, et al (2014)





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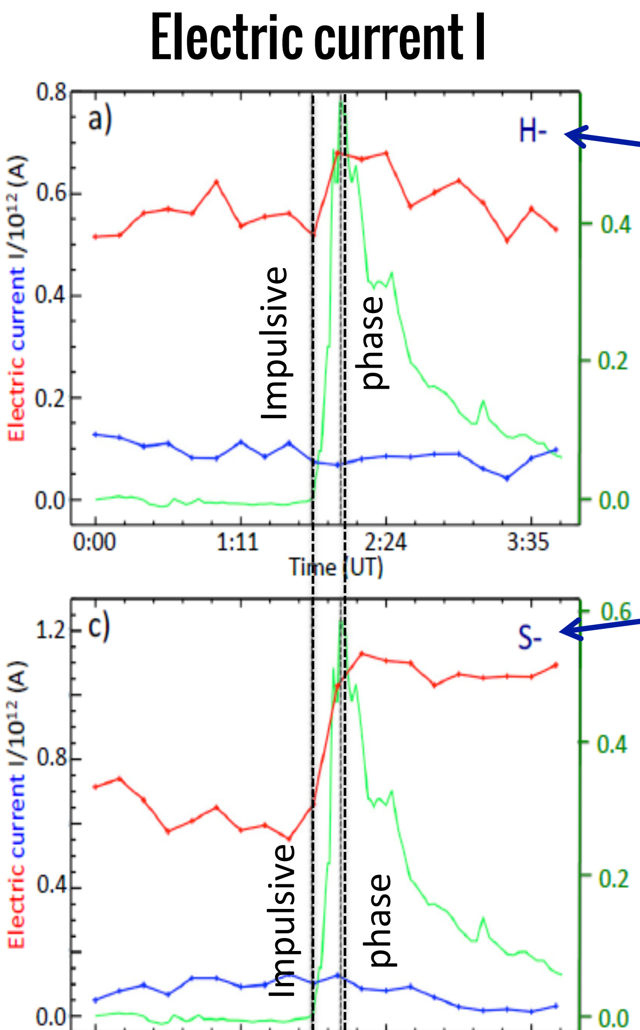
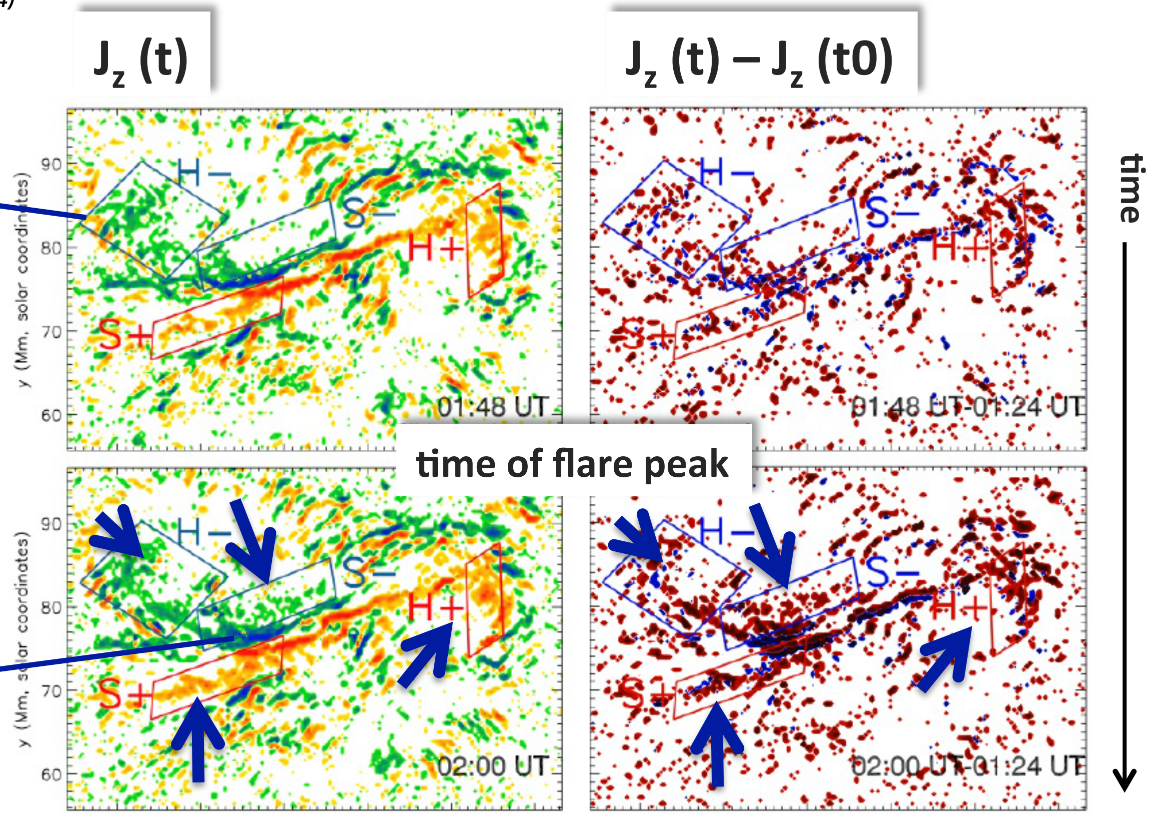
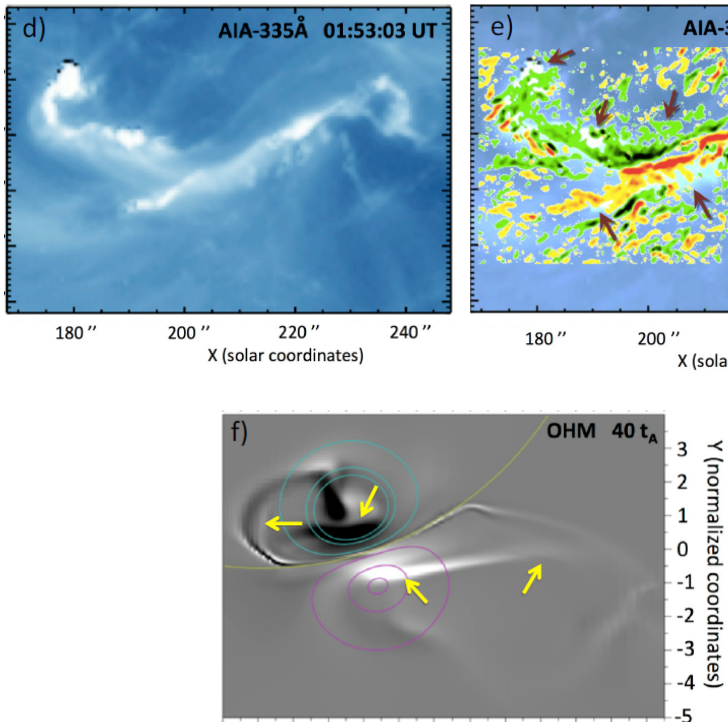




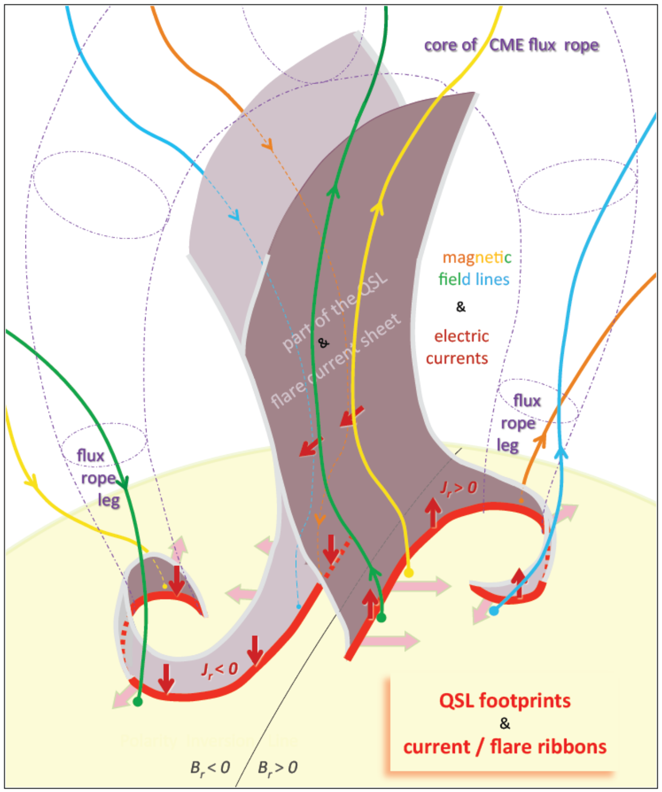
❖ **Increase of electric current**
= collapse of the current layer

ERUPTIVE FLARES: MODEL PREDICTION & OBSERVATIONAL CONFIRMATION

Views from Earth



Standard flare model in 3D



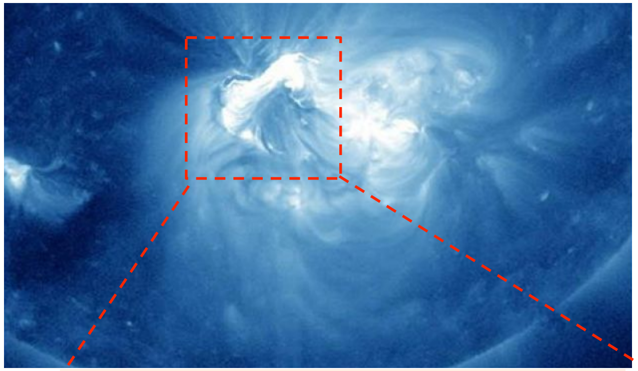
Observational evidences!

Janvier, Aulanier, Bommier, Schmieder, et al (2014)

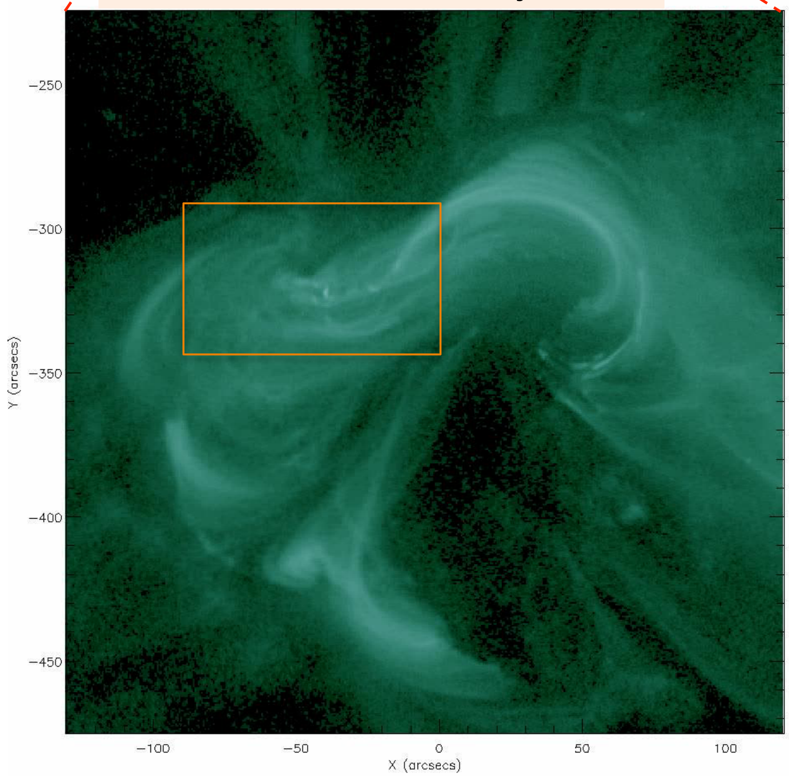
❖ Increase of electric current

= collapse of the current layer

ERUPTIVE FLARES: MODEL PREDICTION & OBSERVATIONAL CONFIRMATION

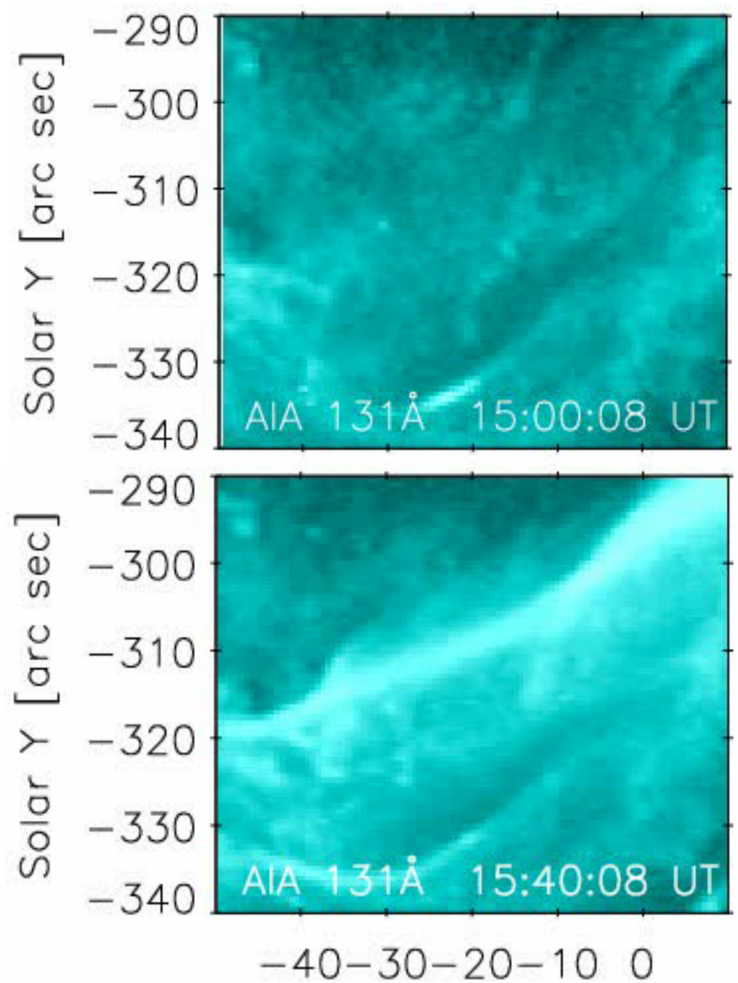


★ See Dudik's talk (Tuesday)



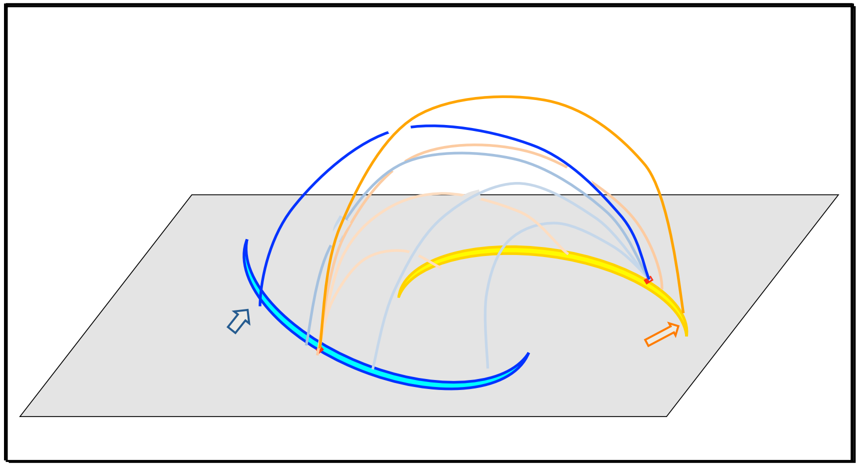
X-class flare of July 2012

Dudik, Janvier, Aulanier, Del Zanna, et al (2014)



ERUPTIVE FLARES: MODEL PREDICTION & OBSERVATIONAL CONFIRMATION

Slipping reconnection with QSLs:
successive change of magnetic connectivity



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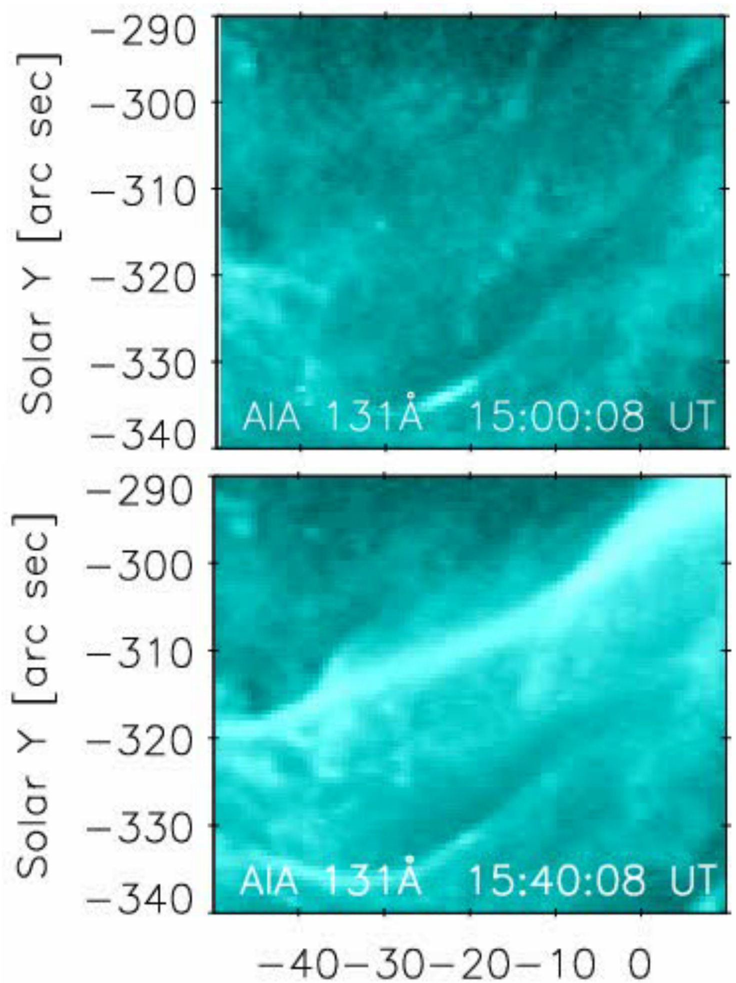


Leads to:

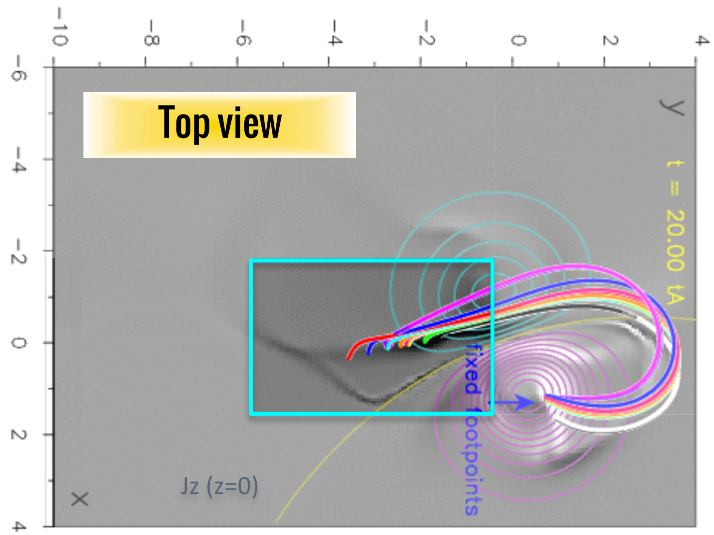
- ❖ **Apparent field line motion**

  See also: Aulanier et al. (2007)

- ❖ **Kernel motion**

  See also: Young et al. (2013)

Slipping reconnection with QSLs:
successive change of magnetic connectivity



Janvier, Aulanier, Pariat & Démoulin (2013)

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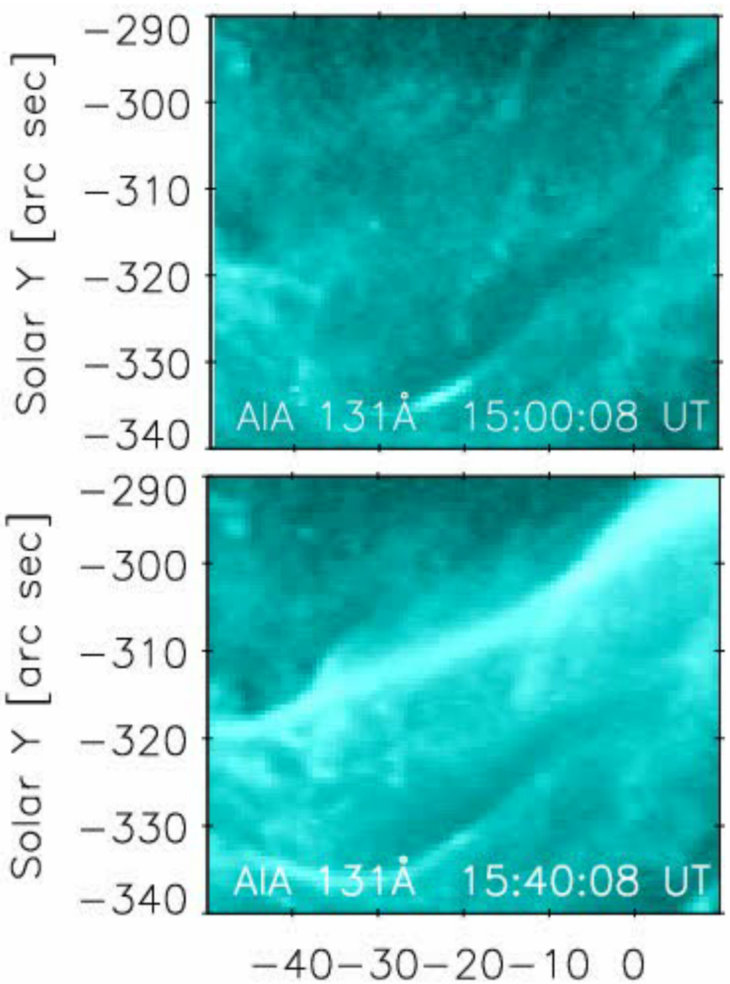
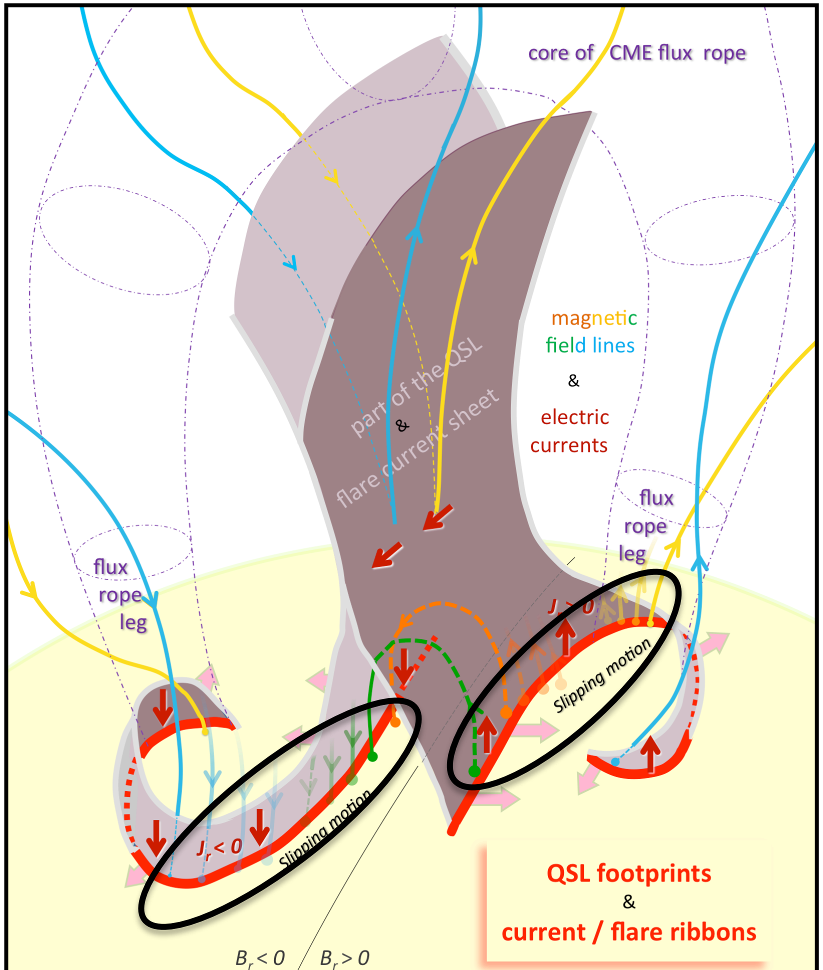
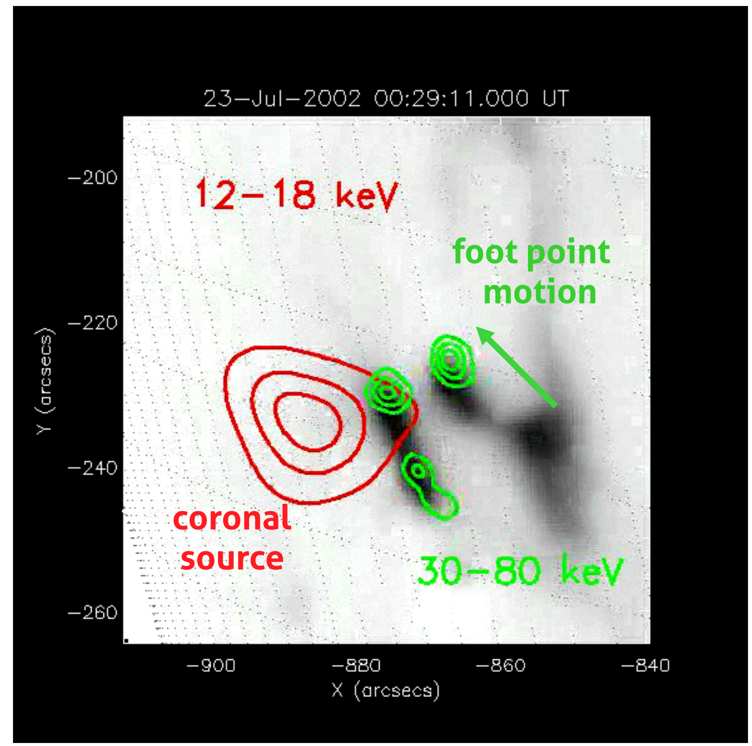


QSL reconnection:

- Change the particle-beam paths
- Motion of HXR source along flare ribbons



H_α & HXR sources



Krucker et al. (2003)

CONCLUSIONS

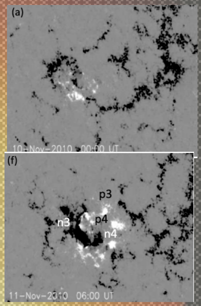
2 types of flares

- Confined flare (localised)
- Eruptive flare (with CME)

Driver of confined flares:

Large flux emergence

- New polarities emerging in older region



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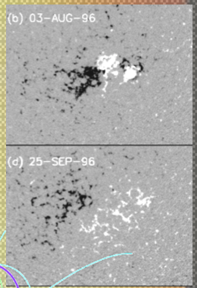
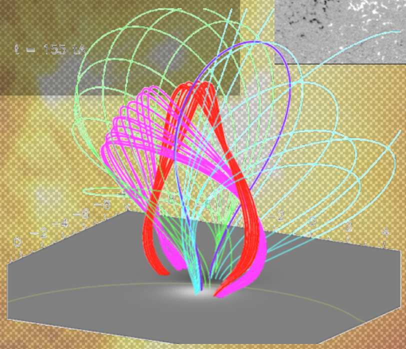
Driver of eruptive flares:

Large flux dispersal

- Coronal tension ↘ + Flux rope formation
- Torus unstable flux rope





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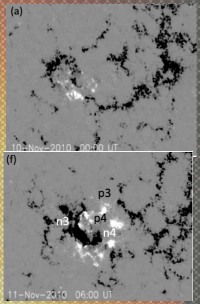

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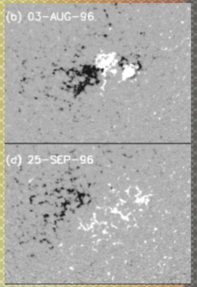
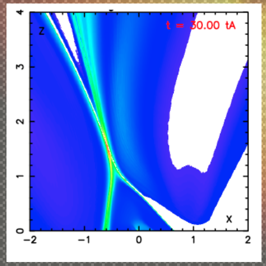
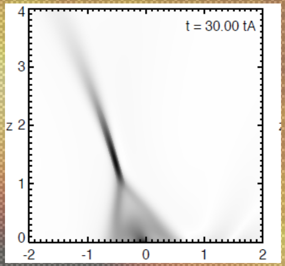


Topology of flares

Null points and QSLs

- QSLs extend the concept of separatrices
- QSLs: similar locations as currents
- Reconnection at QSLs: slipping reconnection (apparent motion of F.Ls)





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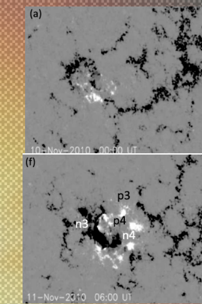

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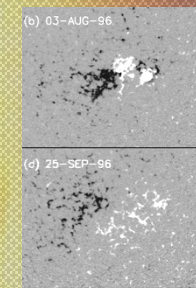

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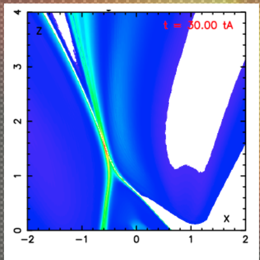
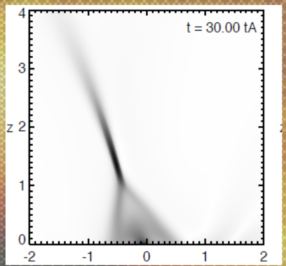
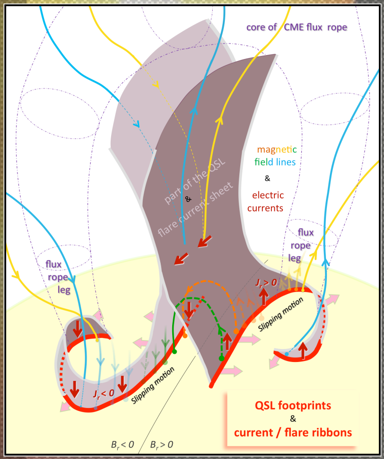




Model predictions

Standard flare model in 3D

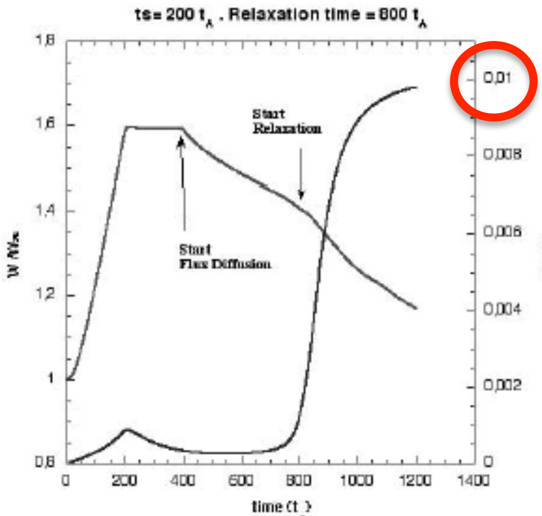
- Flare ribbons = footprint of the coronal current layer/HFT
- Slipping reconnection forms flare loops/flux rope envelope

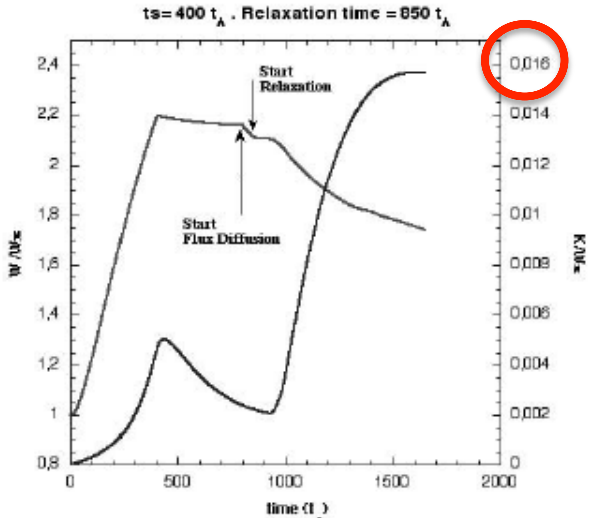


ERUPTIVE FLARES: MODEL PREDICTION & DISCREPANCIES

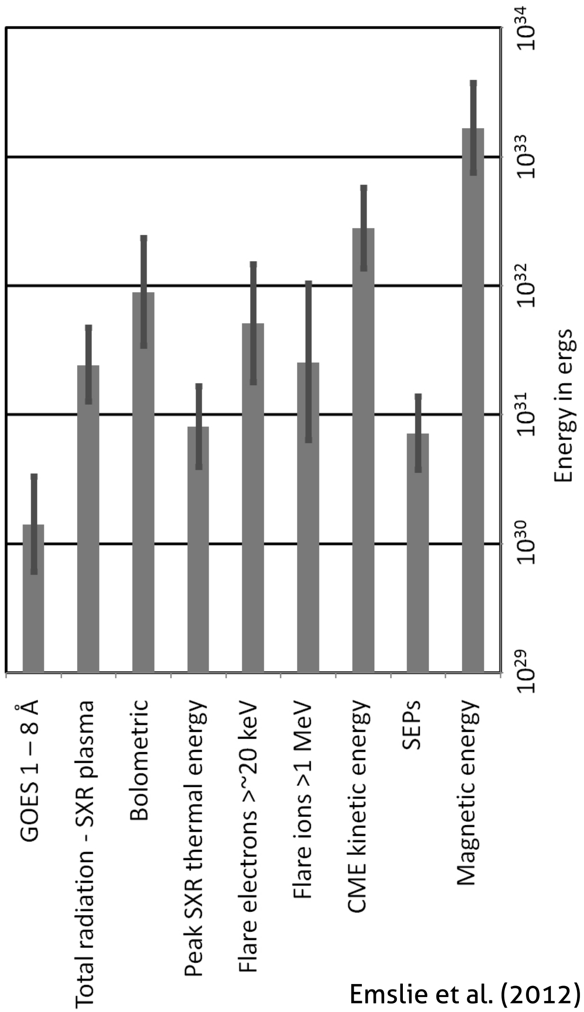
Energetics of flares (CME kinetic energy)

- Model prediction: kinetic enercy ~ 5-10% of flare energy
- Emslie: kinetic energy ~ same or 3x bolometric energy





Amari et al. (2003), also: Jacobs et al. 2006; Lynch et al. 2008; Reeves et al. 2010, Aulanier et al. 2012



Emslie et al. (2012)

Why such discrepancies?

- Observational biases?
- Numerical problems in ALL codes?

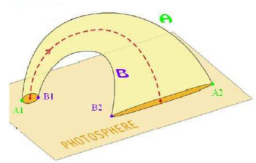
ERUPTIVE FLARES: MODEL PREDICTION & FUTUR CONFIRMATION?

QSL reconnection:

- Change the particle-beam paths
- Motion of HXR source along flare ribbons

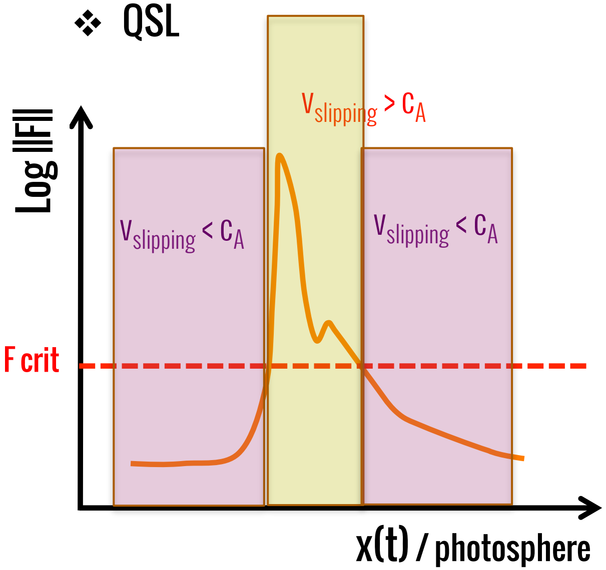
$$v_{slipping} = \alpha \, || F ||$$

Field line mapping



Janvier et al. (2013)

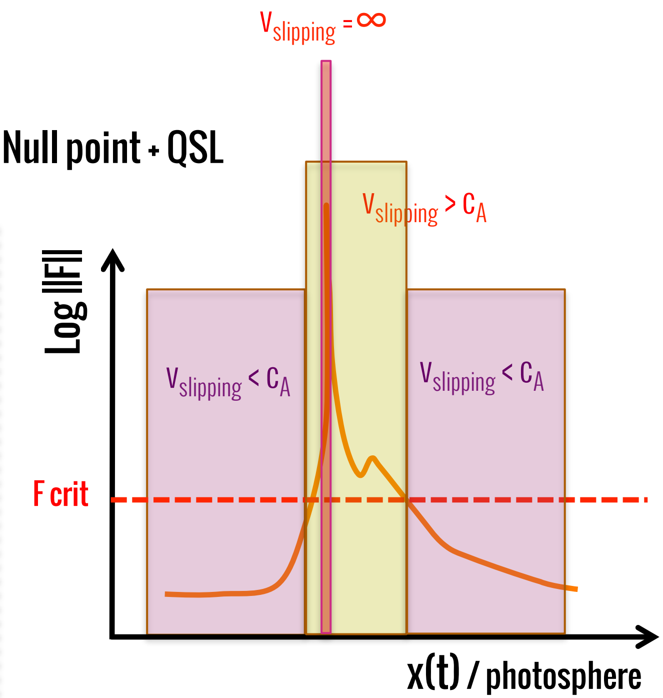
- QSL



Aulanier et al. (2006)
Fletcher & Hudson (2002)?
Janvier et al. (2013)
Dudik et al. (2014)

- **Slipping reconnection**
  → slow HXR motion
- **Slip-running reconnection**
  → fast HXR motion
- **Null-point/Separator reco.**
  → jump of HXR footpoint position

- Null point + QSL



Masson et al. (2009)