SOLAR FLARES MODELLING AND IRIS OBSERVATIONS

FROM AN MHD STANDARD MODEL TO SMALL-SCALE PHYSICS

MIHO JANVIER

Institut d'Astrophysique Spatiale

Special thanks: UCL/MSSL group for the discussions

IRIS-9, Göttingen, 25-29 June 2018

Invited Talk

4. Eruptions in the solar atmosphere

Completing solar flare models with spectroscopic (IRIS) observations

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Solar flares are amongst the most energetic events in our solar system. Generally seen as intense brightenings in the UV and X-ray domains, they also inject solar energetic particles and coronal mass ejections (CMEs) into the interplanetary medium. Their effects on the space environment of planets are non-negligible, with the known consequences on human activities. A better understanding of the processes taking place during flares is needed in order to develop future prediction capacities.

In the last decades, the wealth of data from space and ground missions as well as developments of numerical models have provided a deeper knowledge of the behaviour of magnetic fields during solar flares. From flux ropes to flare loops, from electric currents to flare ribbons, we will see how both observations and modelling help bring together a generic 3D picture of the mechanisms taking place prior and during solar flares. The evolution of different magnetic structures, well reproduced with a magnetohydrodynamic (MHD) model, is dictated by magnetic reconnection, which converts magnetic energy stored in the Suns corona. In particular, consequences of magnetic reconnection can be seen in the different layers of the solar atmosphere, which allows us to go back to its intrinsic properties in 3D.

We will then show that while 3D MHD models are mostly focussed on the behaviour of the magnetic field due to the low-beta condition of the corona, spectroscopic observations can come in handy when completing the cartoon with the plasma behaviour. In particular, as IRIS reveals the dynamics of the chromosphere and the transition region, it brings new understandings on the exchange of energy via non-thermal particles and plasma flows prior and during solar flares. We will discuss how the observations of flaring regions (heating, kernel brightening, ribbons, plasma velocities) help us getting a better understanding of flares throughout the different layers of the Sun's atmosphere.

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A FOCUS ON ERUPTIVE FLARES

- Observations
- From observations to models

FLUX ROPE INSTABILITY

- Numerical models to address the trigger problem
- Spectroscopic observations

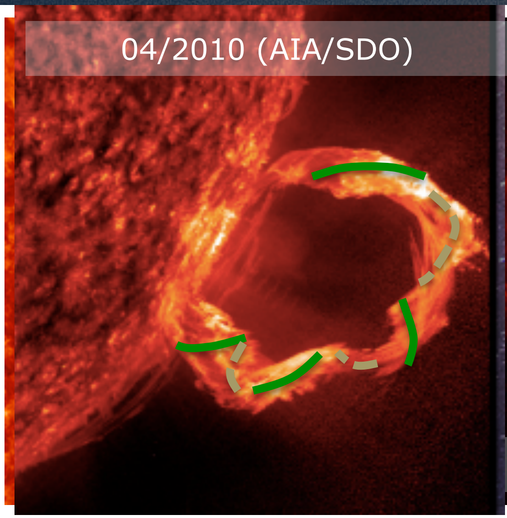
FROM MODELS TO OBSERVATIONS

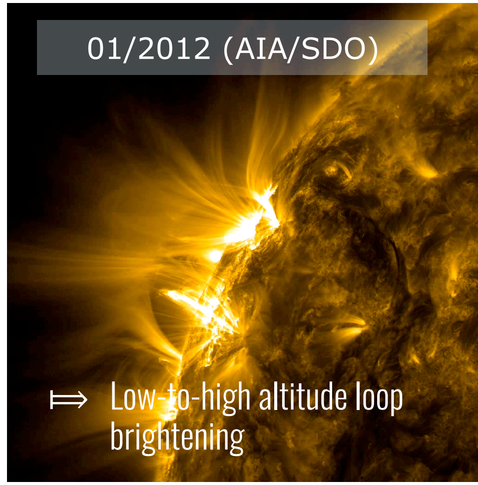
- Current ribbons
- Slipping reconnection

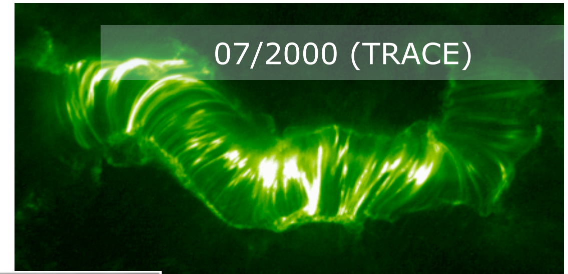
A BIGGER PICTURE?

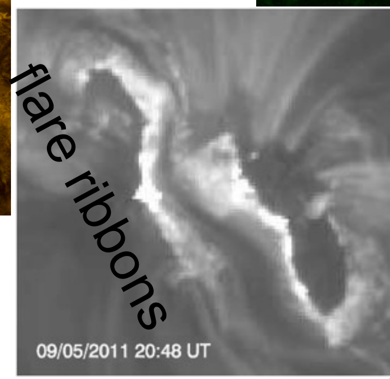
- What are the gaps to fill?
- Future observations

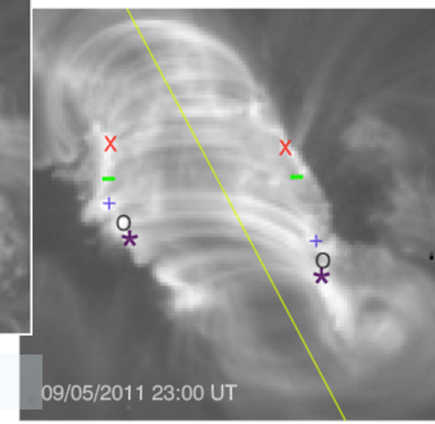
A FOCUS ON ERUPTIVE FLARES: RECURRENT OBSERVATIONAL CHARACTERISTICS











05/2011 (EUVI/STEREO)

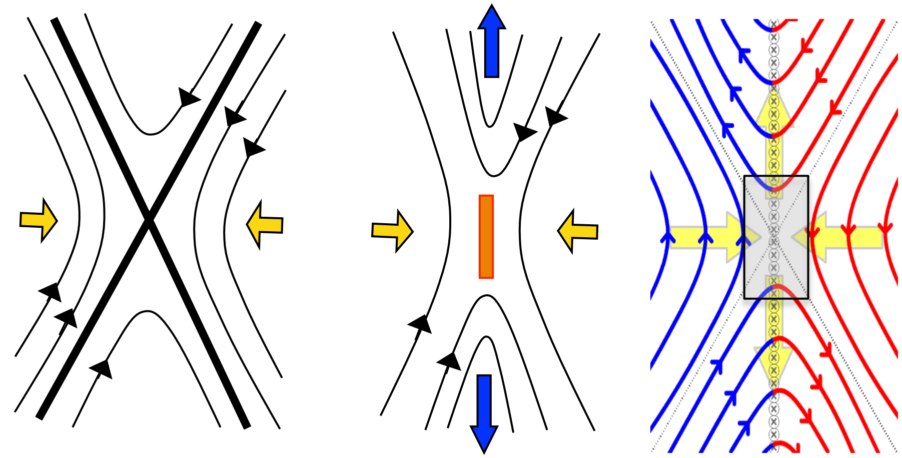
Schmieder et al. 1995, Moore et al. 1995, Asai et al. 2003, Fletcher et al. 2011, Zhang et al. 2011

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

MAGNETIC RECONNECTION

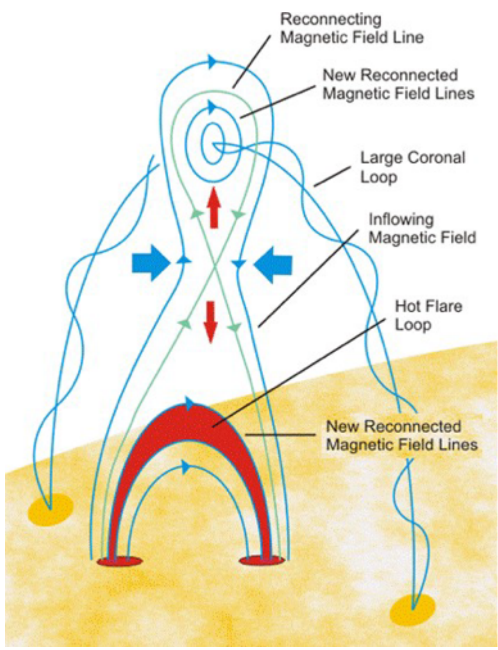
We needed a model:

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



60s: Sweet and Parker proposed:
magnetic reconnection

Creation of high **electric current density sheet**
→ dissipation of magnetic field (Ohm's law)



Standard 2D model of flare loop formation during flares
CSHKP Model

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

Forbes & Malherbe (1986)

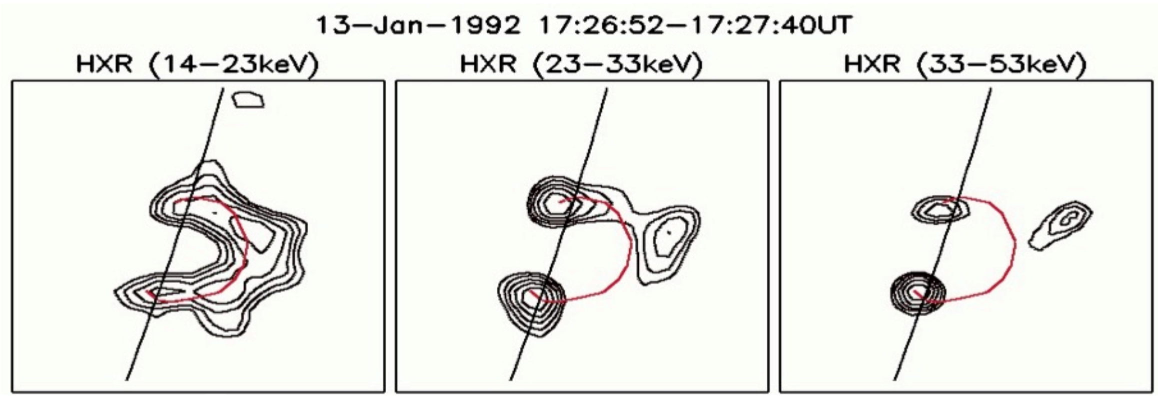
Magnetic reconnection leads to:
⇛ Flux rope + post-flare loops
⇛ Two flare ribbons

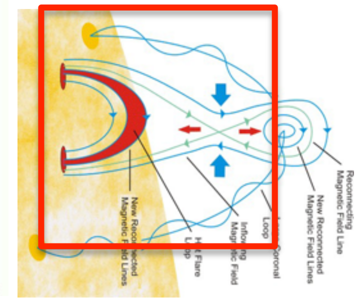
MAGNETIC RECONNECTION: OBSERVATIONAL EVIDENCES FROM SPECTROSCOPY

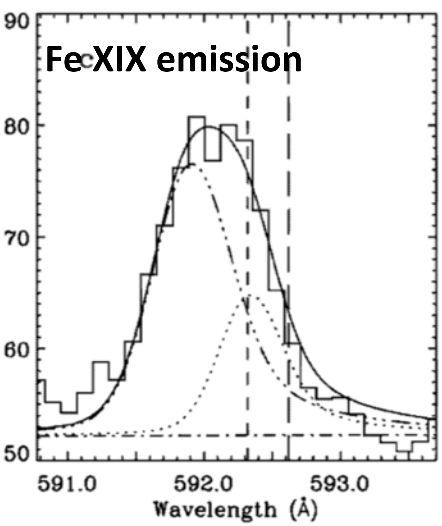
Hard X-ray source above the loop top:

particle acceleration at reconnection site

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







Milligan et al. (2006)

Co-temporal with upflows/downflows seen in spectroscopy

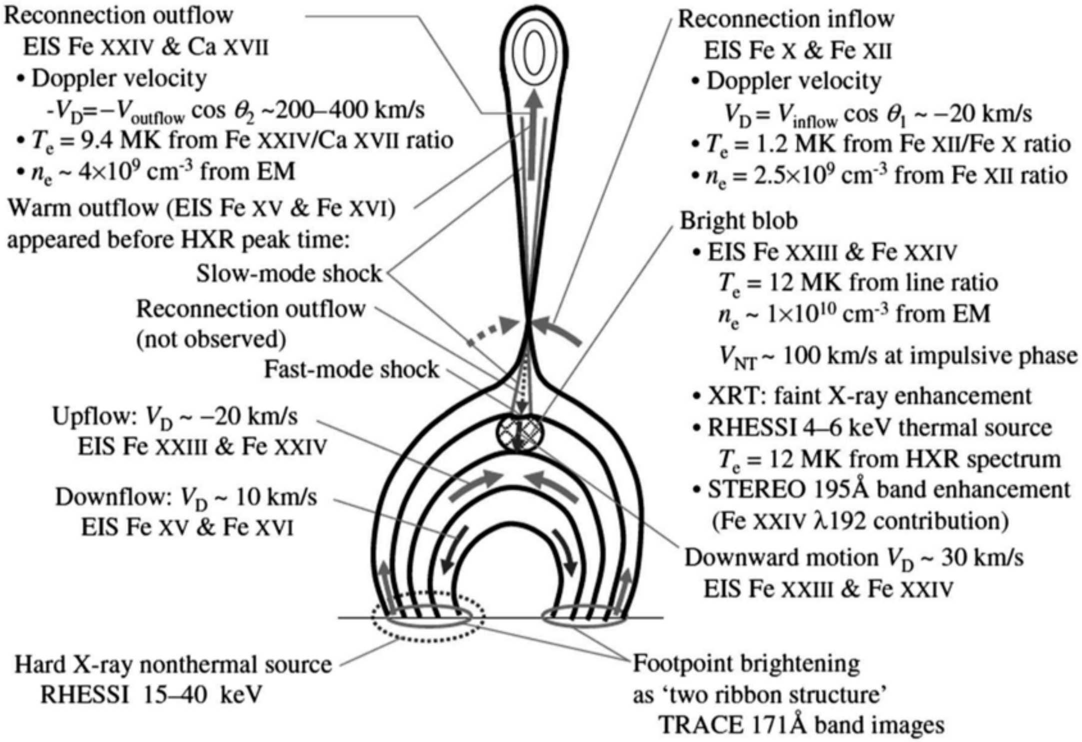
Chromospheric and loop response

Revealed high-temperature, high-velocity blueshift and cooler redshift emission compatible with models of chromospheric evaporation (SOHO/CDS, SSM)

(e.g. Antonucci et al. 1982; Teriaca et al. 2006; Young et al. 2013)

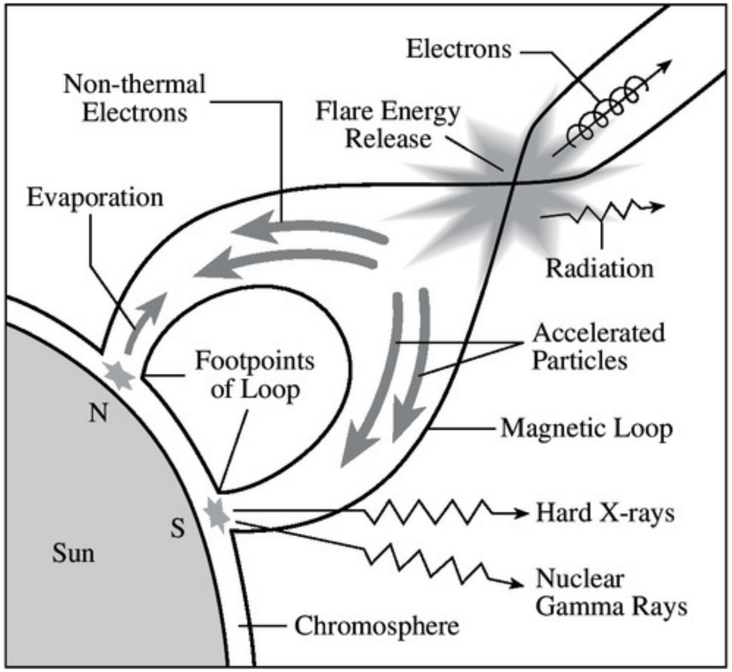
MAGNETIC RECONNECTION: OBSERVATIONAL EVIDENCES FROM SPECTROSCOPY

The picture before IRIS:



Hara et al. (2001)

MAGNETIC RECONNECTION: OBSERVATIONAL EVIDENCES FROM SPECTROSCOPY



The picture with IRIS:

Confirmation of blueshifts + large non-thermal broadening (Fe XXI line)

- Impulsive phase radiation **concentrated at chromospheric endpoints of the magnetic field**.

(Fe XXI is observed to be entirely blueshifted → sites of evaporation are now likely to be resolved by IRIS)

(e.g., Graham & Cauzzi 2015; Polito et al. 2015, 2016; Tian et al. 2015, 2016; Young et al. 2015, Y. Li et al. (2015), Battaglia et al. (2015), D. Li et al. (2016), Brannon (2016), Mikula et al. (2017), Brosius & Inglis (2017), Tian & Chen (2018)

Fe XXI blueshifts co-temporal with HXR

C. Liu et al. (2015), Kleint et al. (2015), Tian et al. (2014), Tian et al. (2015), Warren et al. (2016)

Fe XXI blueshifts co-temporal with microwave

D. Li et al. (2018), Q. Zhang et al. (2016)

Confirms the energetic particles + « chromospheric evaporation » scenario (expansion and filling of coronal loops)

A FOCUS ON ERUPTIVE FLARES

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FLUX ROPE INSTABILITY

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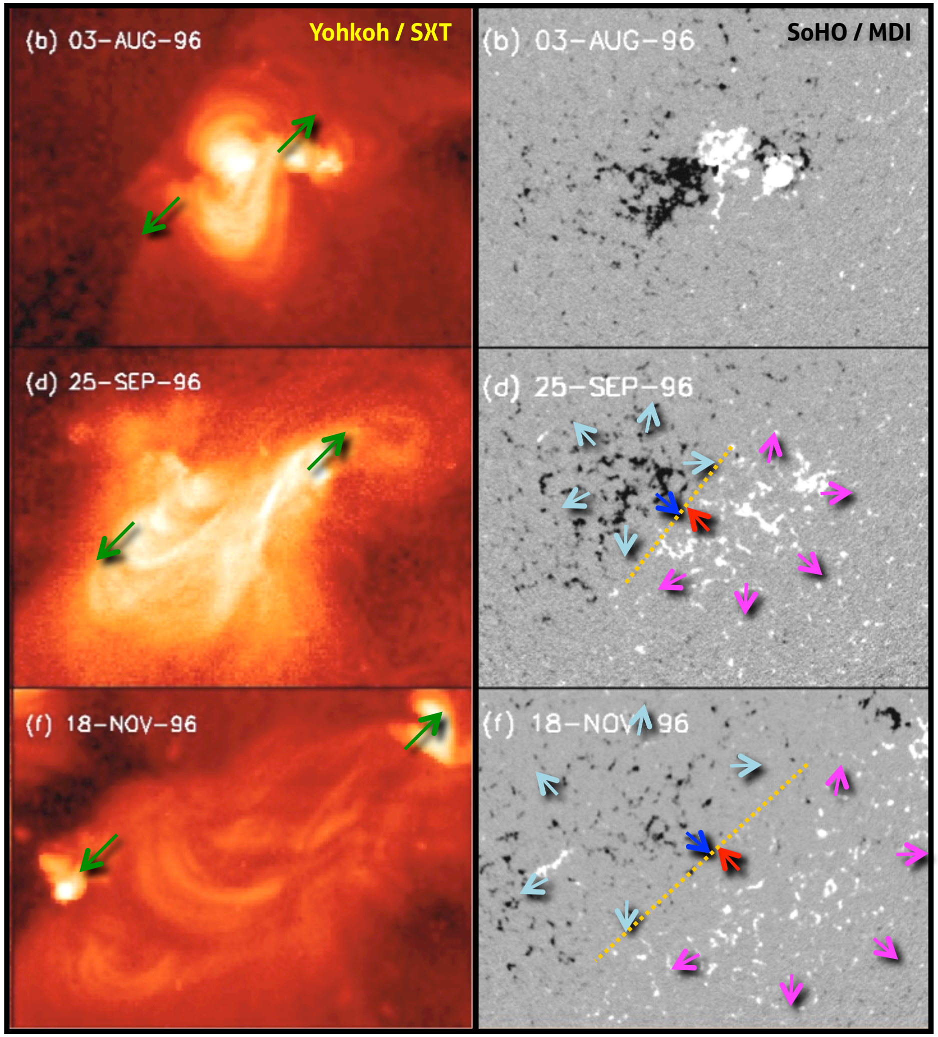
LONG TERM EVOLUTION OF ACTIVE REGIONS

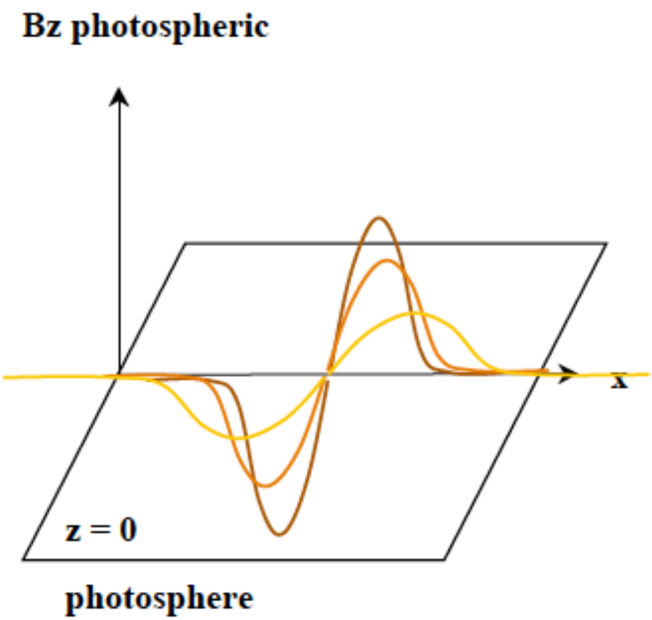


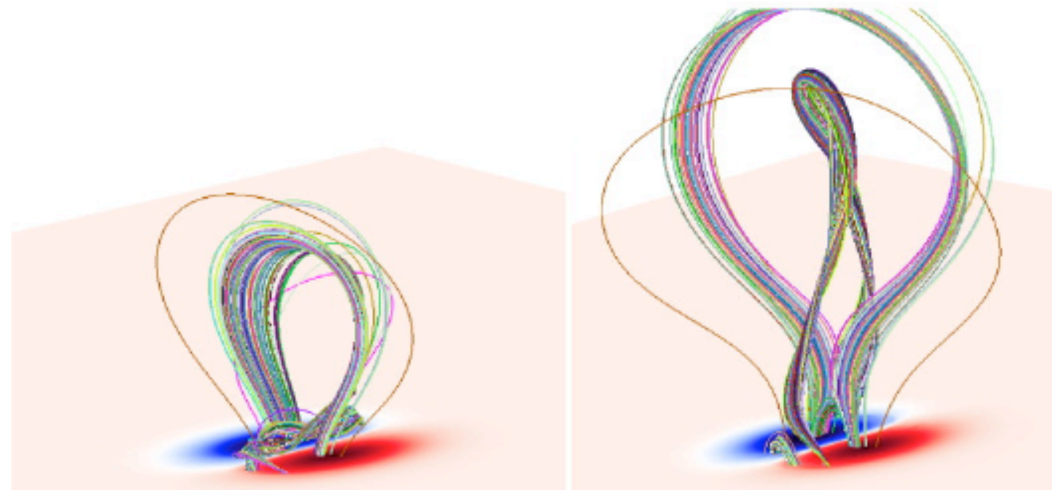
- Shearing coronal loops
- Converging motions at PIL
- Flux dispersal and B decrease
- Flux cancellation at PIL

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





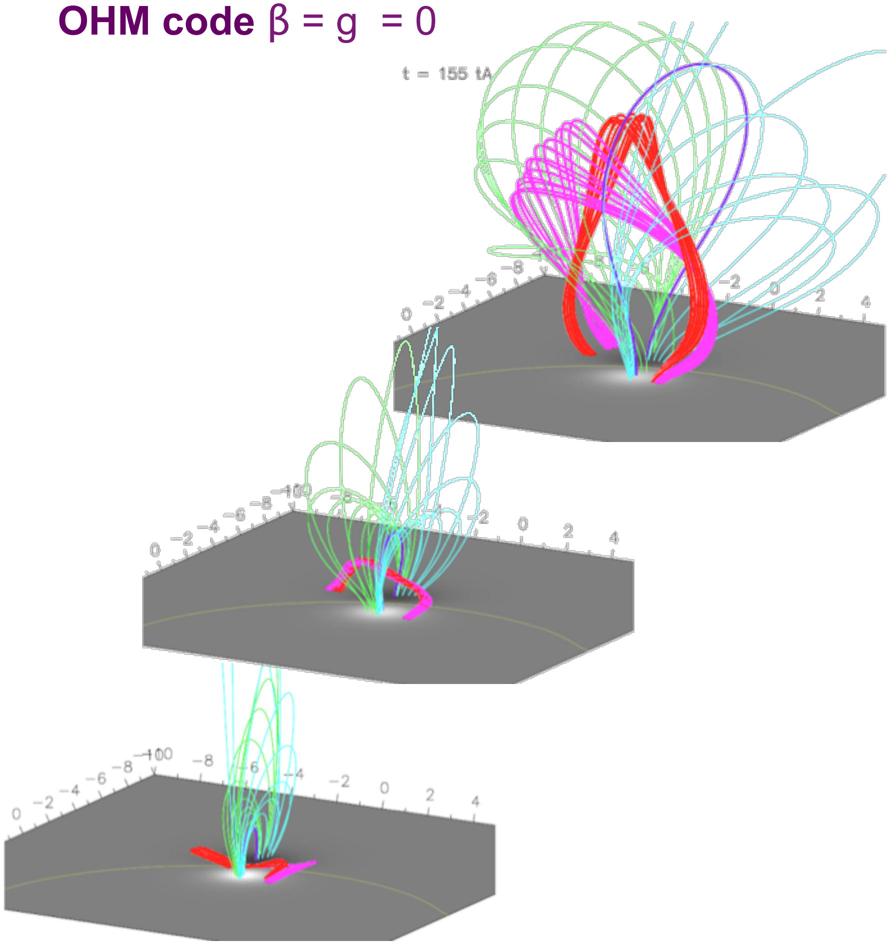
Amari et al. (2003,2011)
MacKay & van Ballegooijen (2006)
Yeates & MacKay (2009)

⟹ Favorable conditions for triggering eruptions

See review of Aulanier et al. (2014)

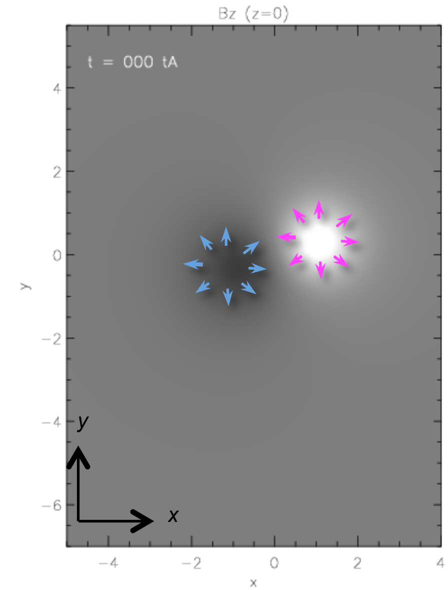
CONSTRUCTING A FLUX ROPE

OHM code β = g = 0

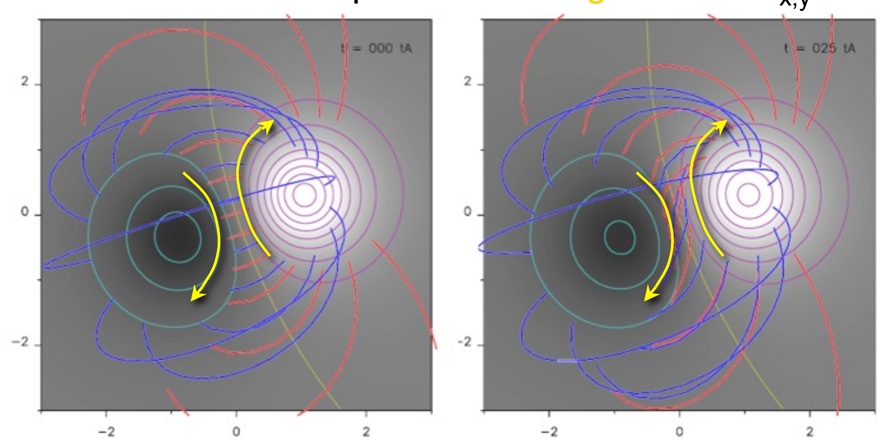


Aulanier, Török, Démoulin & DeLuca (2010)

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



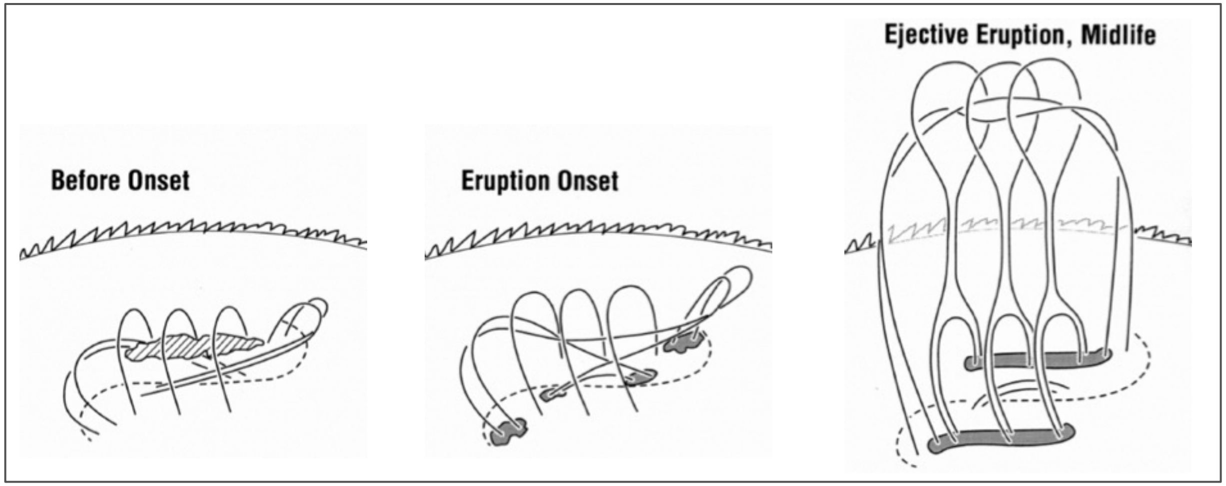
❖ Photospheric shearing motions $u_{x,y}$



THE FLUX ROPE INSTABILITY

Tether-cutting at the beginning of a flux rope formation

Sturrock (1989),
Moore & Roumeliotis (1992),
Moore,(2001),
Moore & Sterling (2006)

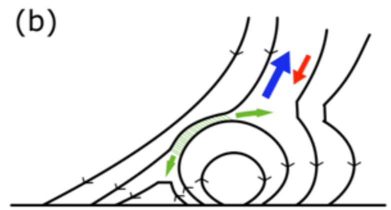


The picture with IRIS:

Blueshifts + non-thermal broadening (Fe XXI line) before flares have been reported

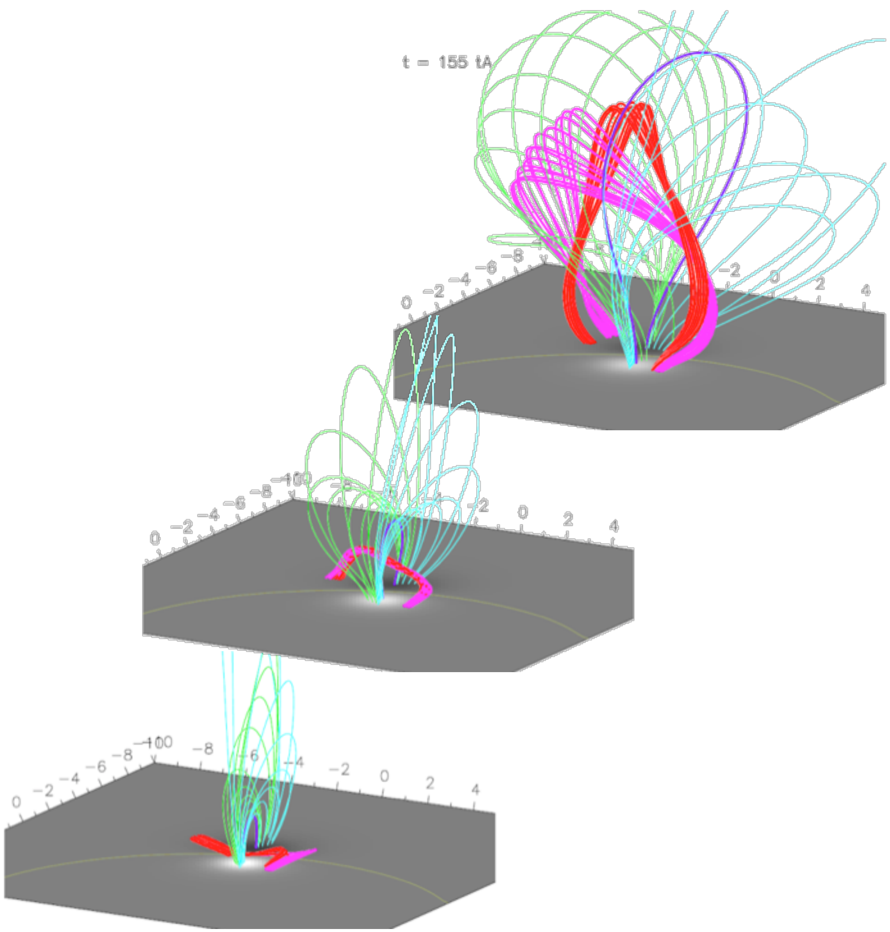
- When a filament is present, blueshifts ~15mn to ~40mn before flare
(Kleint et al. 2015, Woods et al. 2017, comparison with NLFFF modelling which reveals FR)

- Potential reconnection sites below prominences like in tether-cutting
(Reeves et al. 2015, Kumar et al. 2015, Chen et al. 2016)

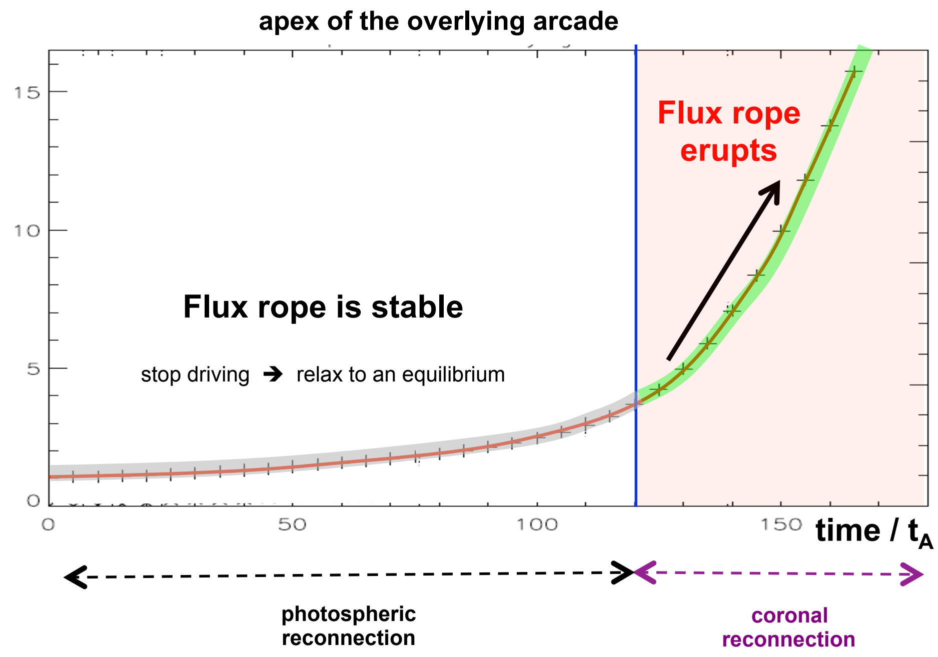


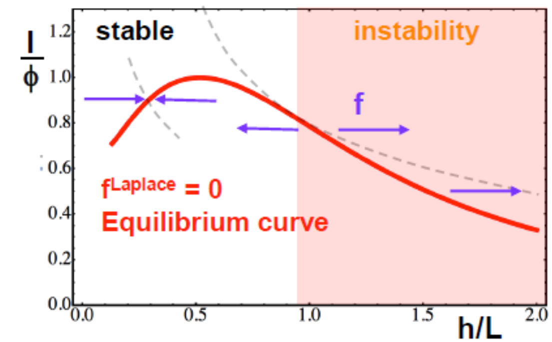
Other mechanisms:
- Kink mode? G. Zhou et al. (2016)
- Emergence, side reconnection as trigger? Bamba et al. (2017)

THRESHOLD FOR ERUPTIONS?



Aulanier, Török, Démoulin & DeLuca (2010)





⟾ TORUS INSTABILITY (AND VARIATIONS)

Démoulin & Aulanier (2010),
«Double Arc» instability: Ishiguro & Kusano (2017)

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FROM MODELS TO OBSERVATIONS

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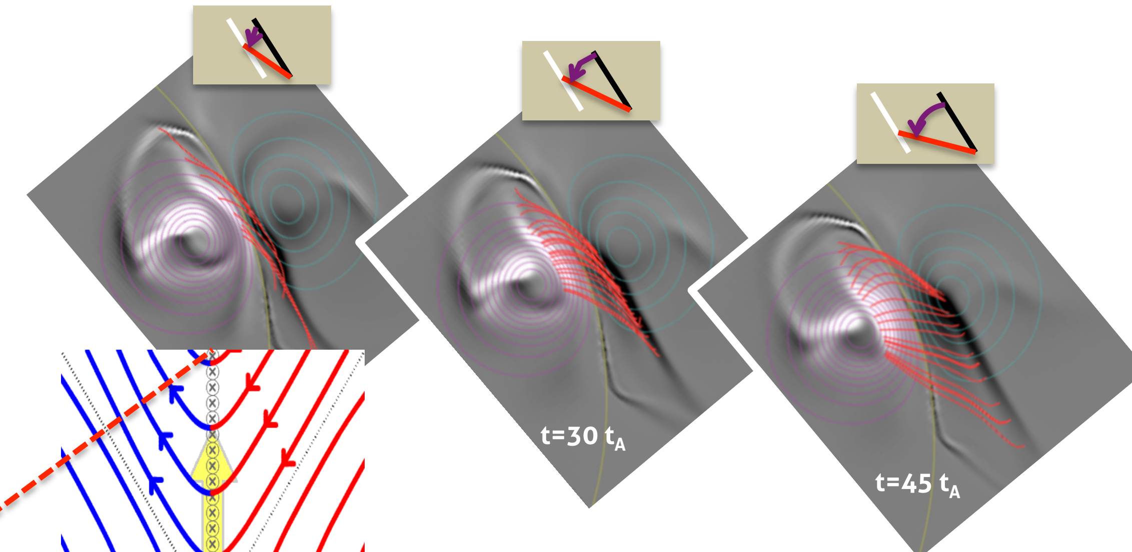
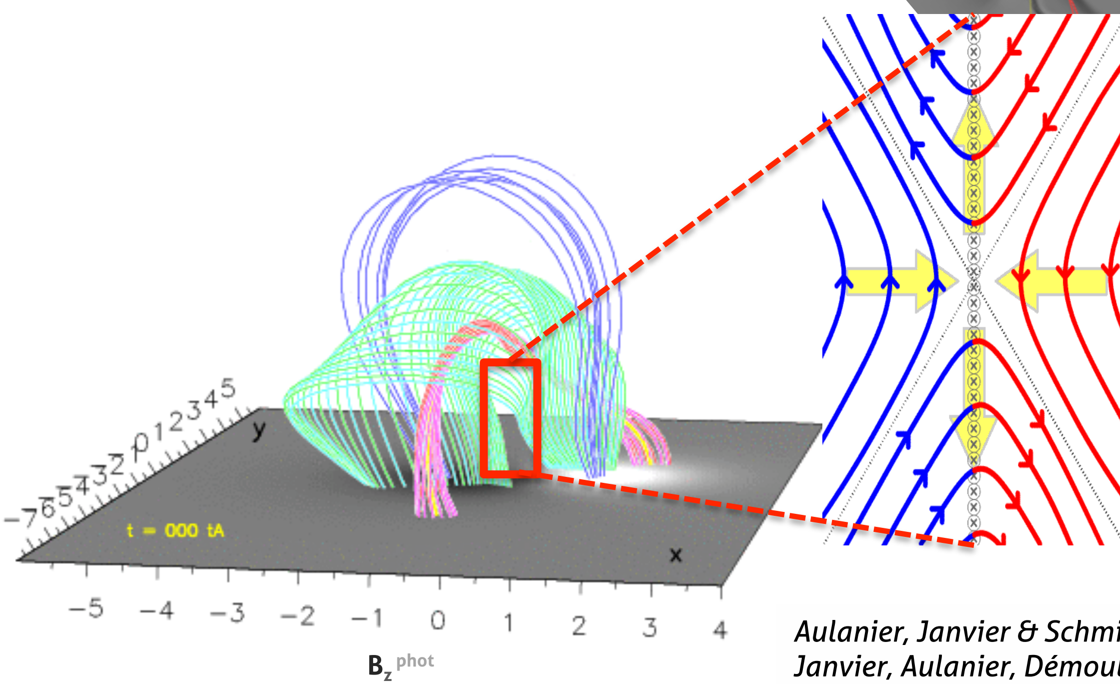
WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

THRESHOLD FOR ERUPTIONS?

- Shear transferred from pre-eruptive field lines via reconnection

Coronal arcades
Erupting flux rope



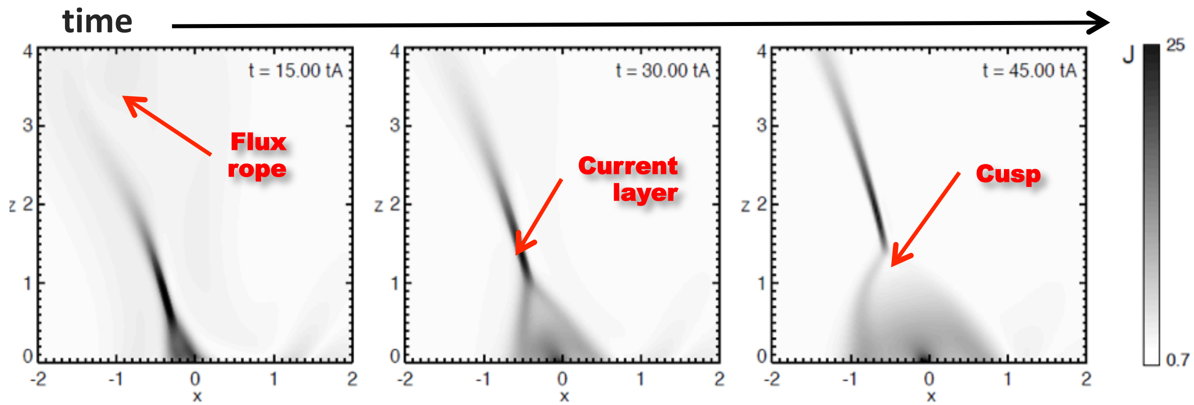


ation of flare loops:
to-weak shear transition
high altitude formation

lope formation of the flux rope

Aulanier, Janvier & Schmieder (2012)
Janvier, Aulanier, Démoulin & Pariat (2013)
Dudik, Janvier, Aulanier, del Zanna et al. (2014)
Dudik, Polito, Janvier, et al. (2016)

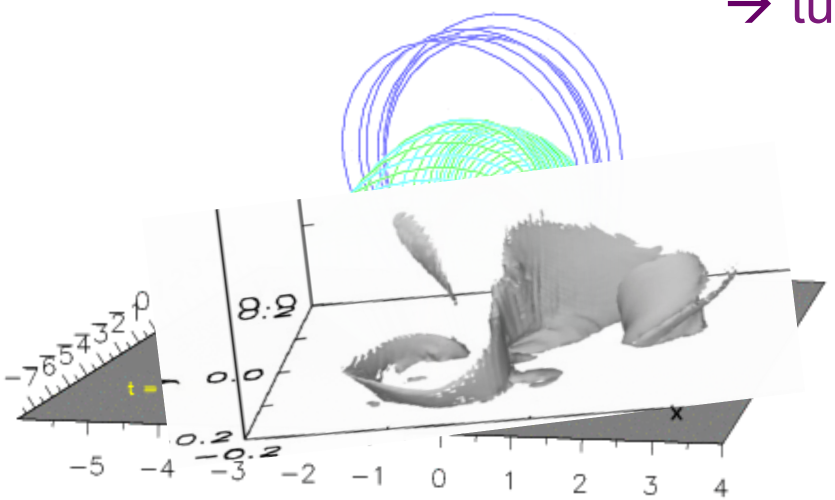
WHERE DOES RECONNECTION TAKE PLACE IN THE SIMULATION?

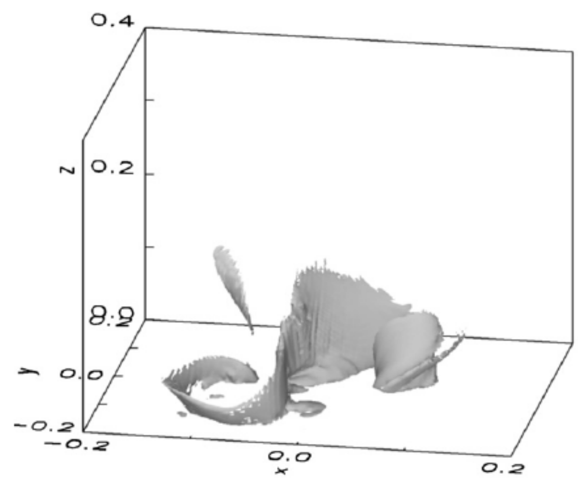


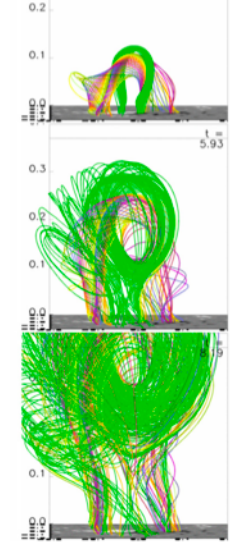
Janvier, Aulanier, Pariat & Démoulin (2013)

J = |curl **B**| *electric currents*

Collapse of the coronal current layer (=thinning)
→ turns on reconnection (J term in Ohm's law)







Kliem et al. (2013)

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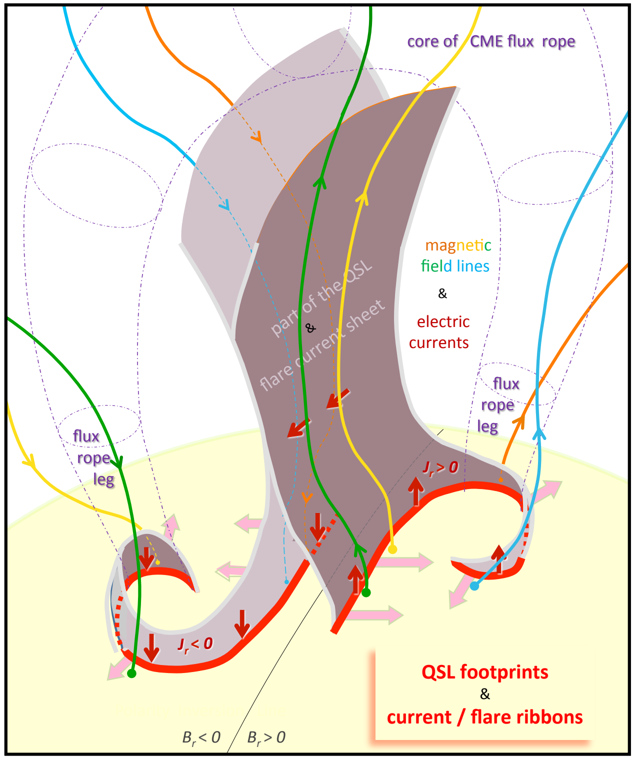

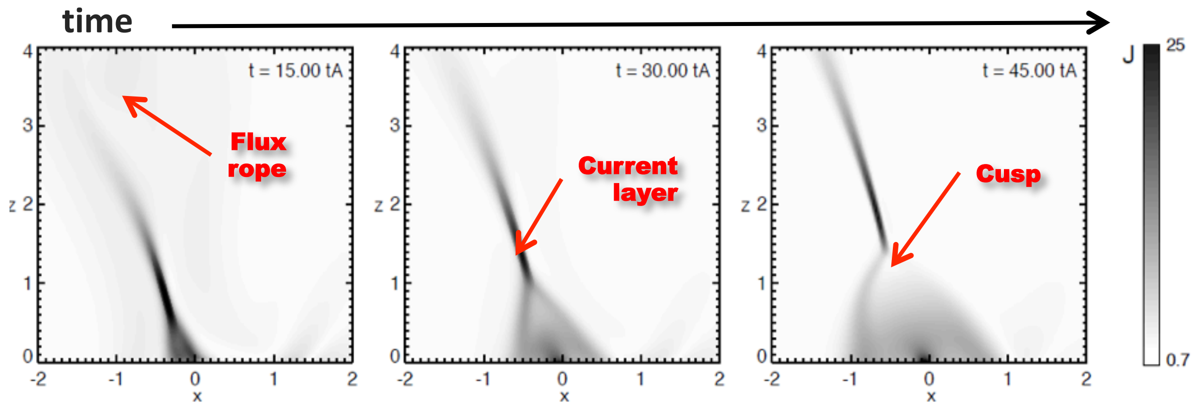

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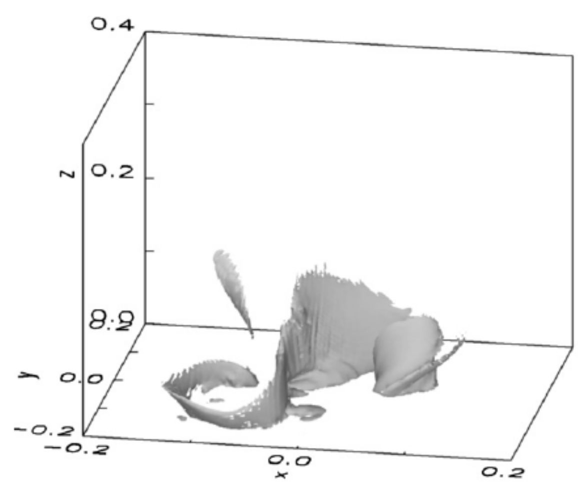
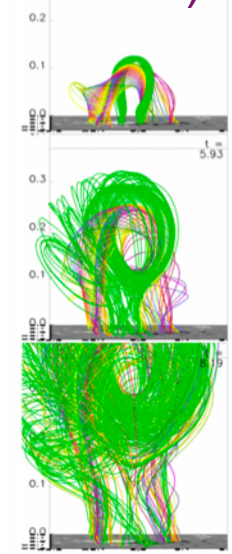
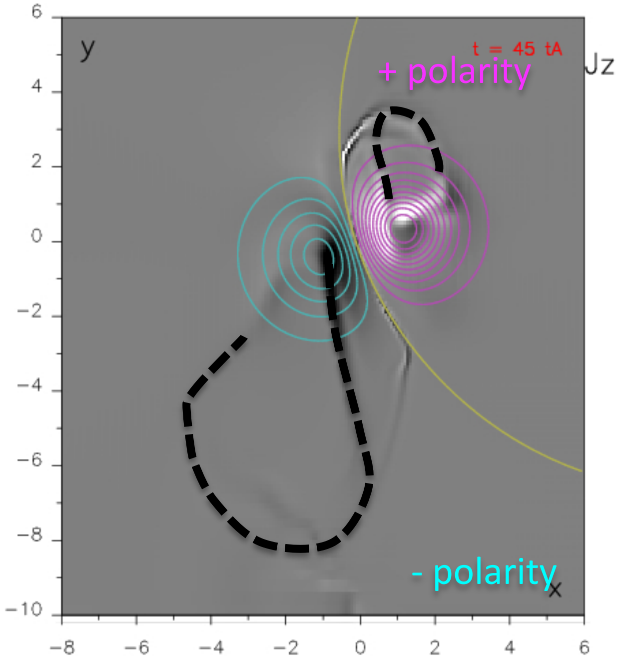




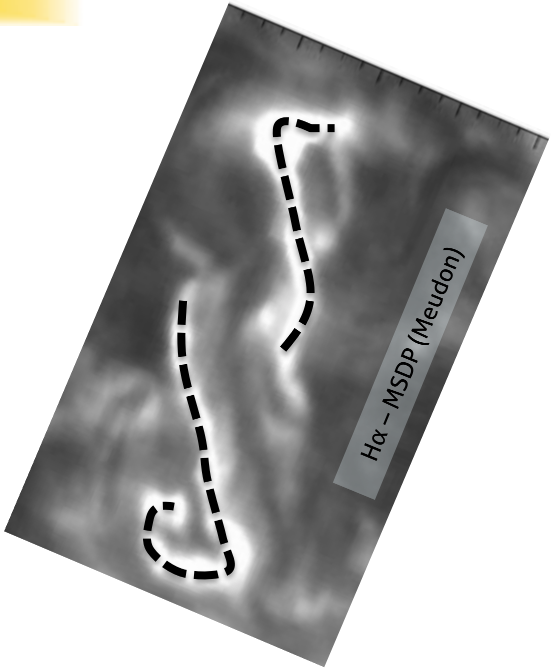
Kliem et al. (2013)

SIMILARITIES BETWEEN QSLS, CURRENT RIBBONS & FLARE RIBBONS

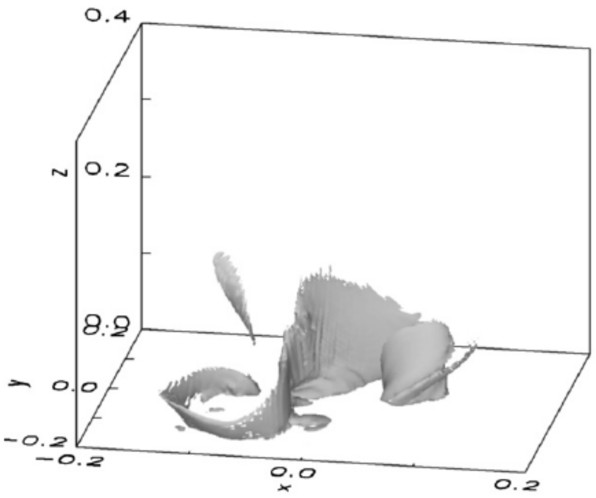
Top views



Janvier et al. (2013)



Chandra et al. (2009)



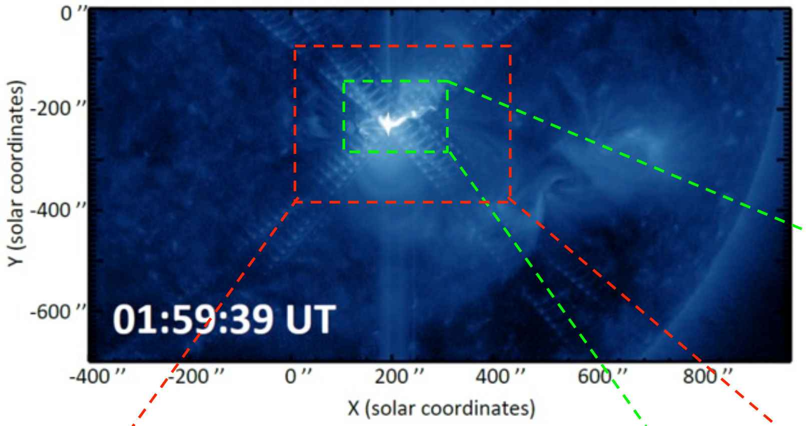
Kliem et al. (2013)

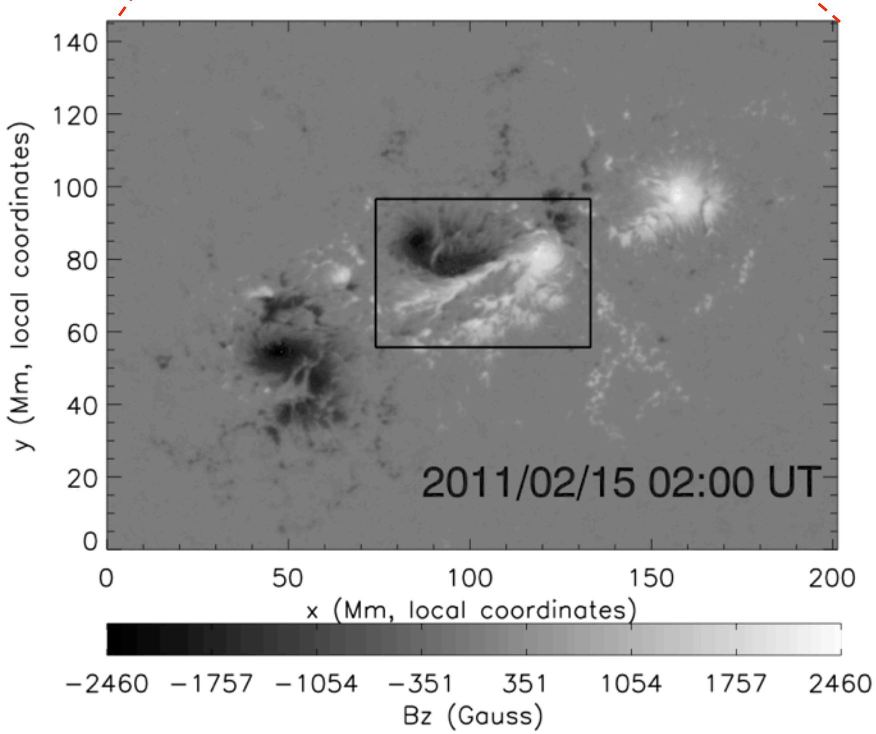
⟹Similar shape as flare ribbons

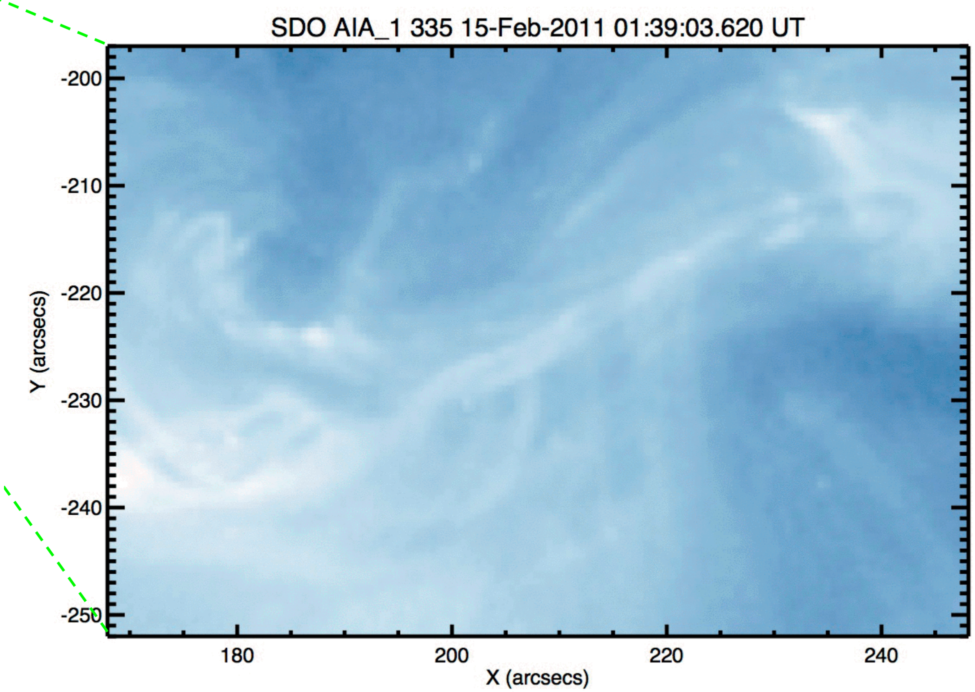
J-SHAPE STRUCTURE IS INDICATIVE OF THE PRESENCE OF A FLUX ROPE!

TEST CASE: AR 11158 (X2.2 CLASS FLARE)

X-class flare of Feb. 2011



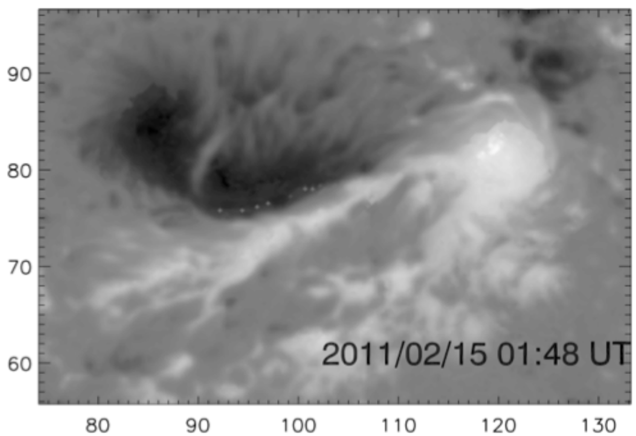


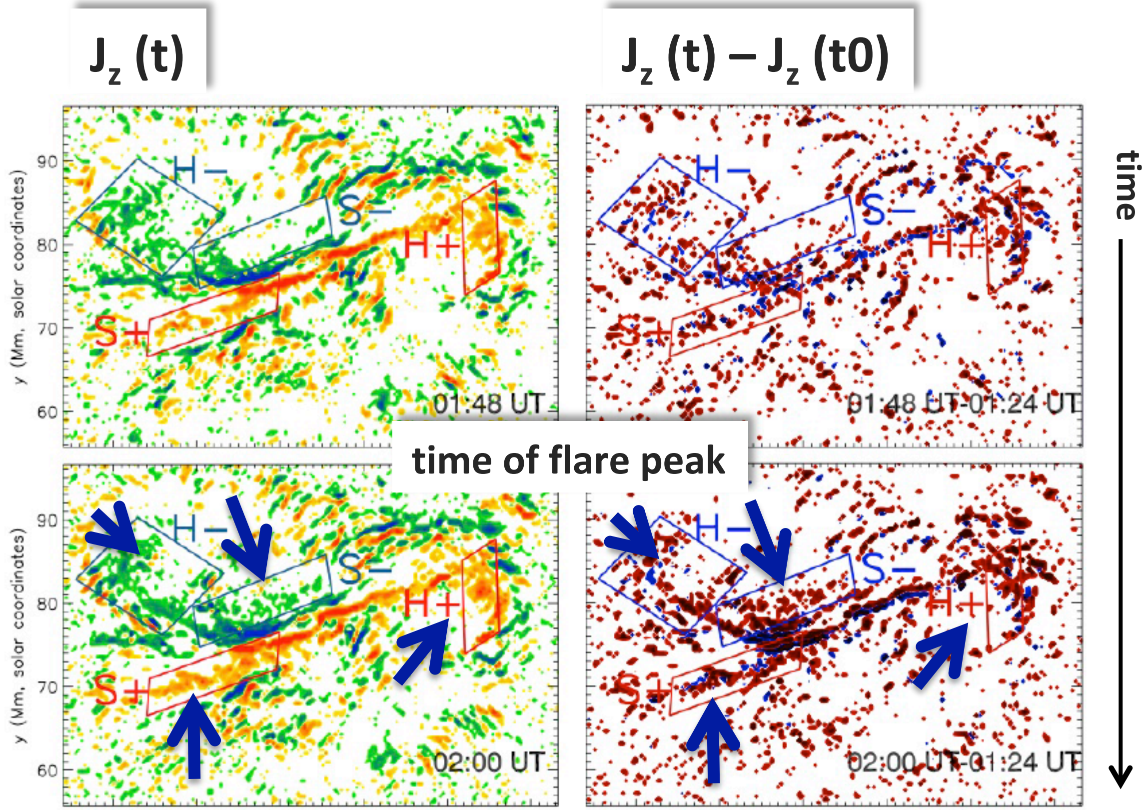


TEST CASE: DOES THE CURRENT DENSITY INCREASE?

Photospheric vertical currents = current ribbons

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





Inversion method: UNNOFIT Bommier et al. (2007)

⇛ **B**(x,y) ⇛ Current maps $J_z(x,y)$ ~ curl $|B|_z$ (12 min cadence w. HMI)

TEST CASE: DOES THE CURRENT DENSITY INCREASE?

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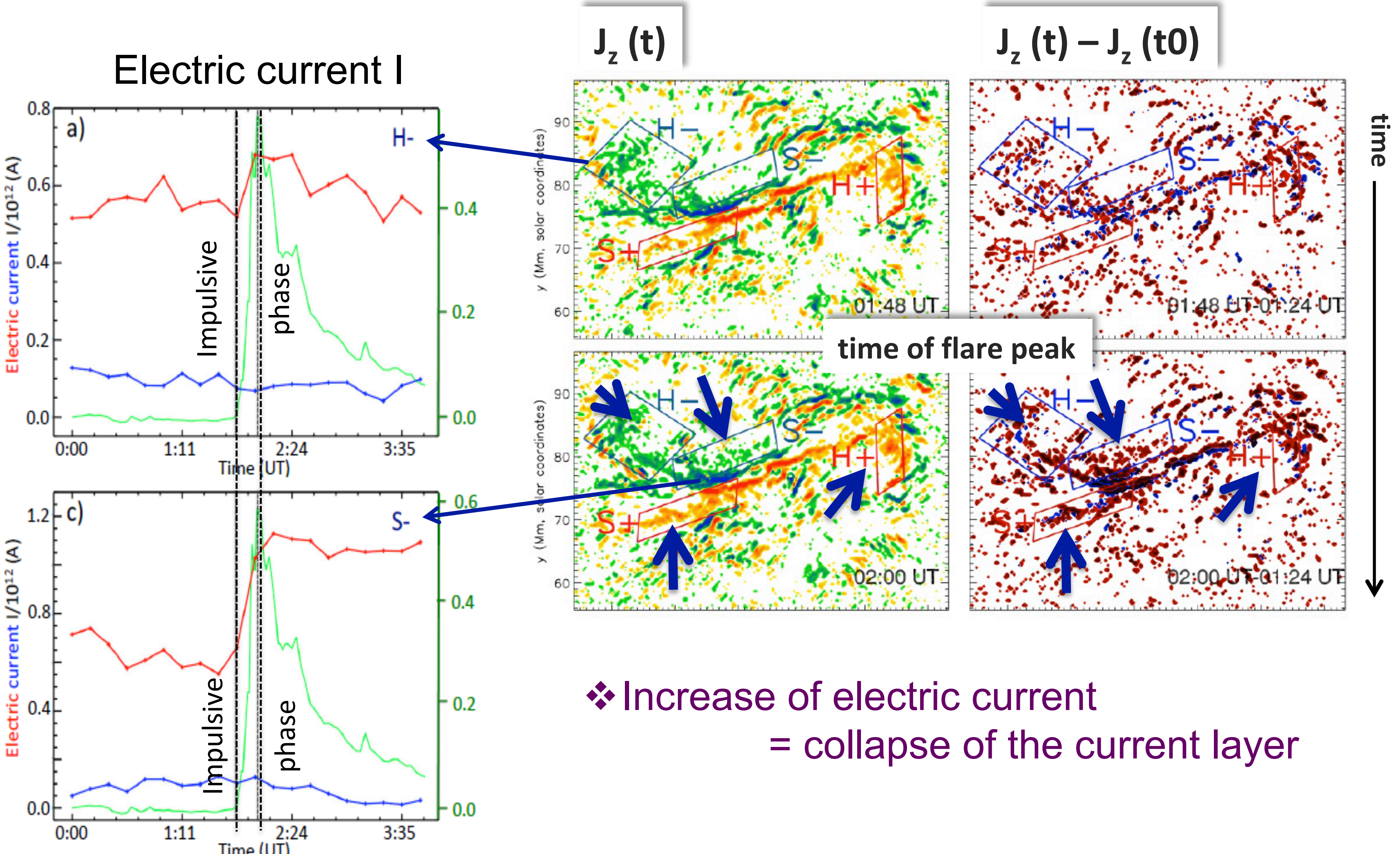

❖ Increase of electric current
= collapse of the current layer

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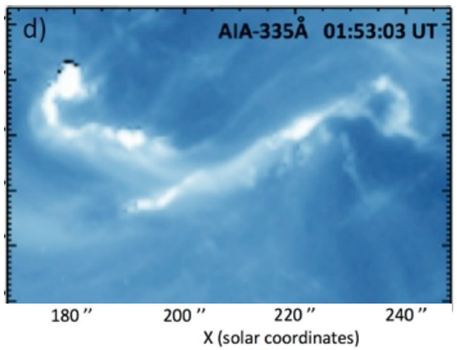
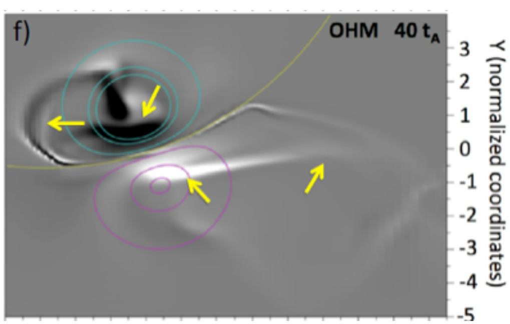
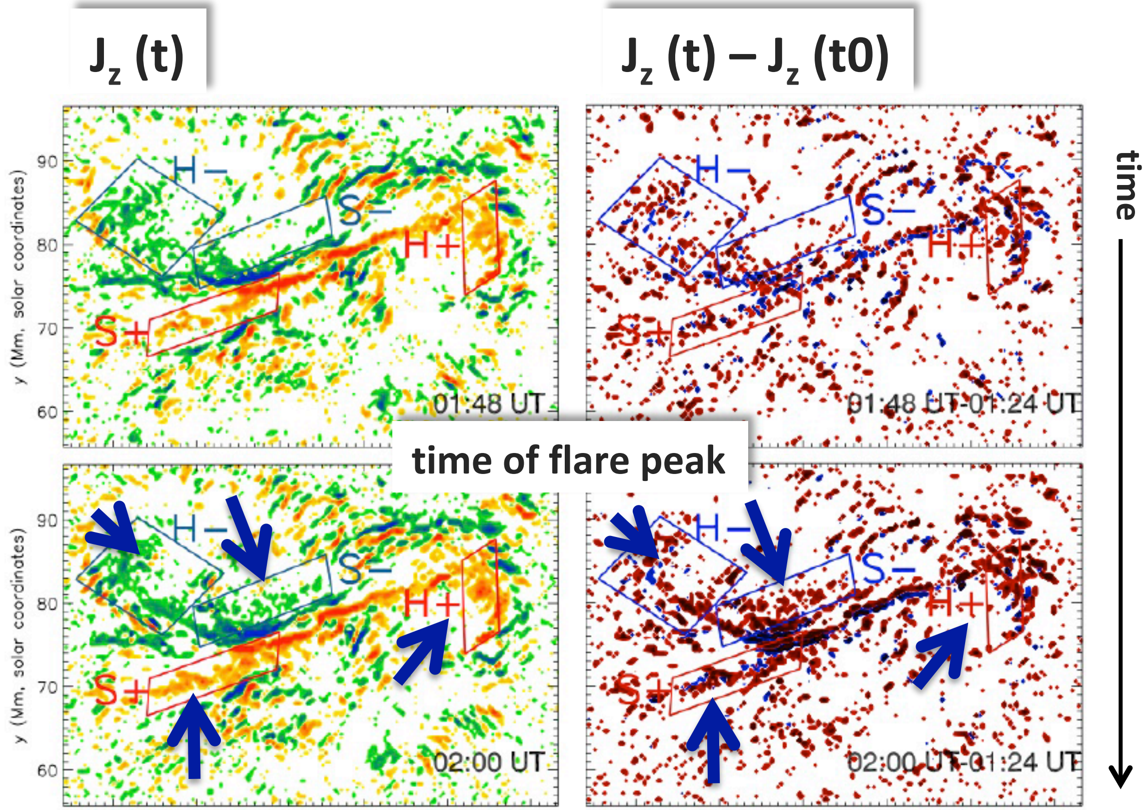


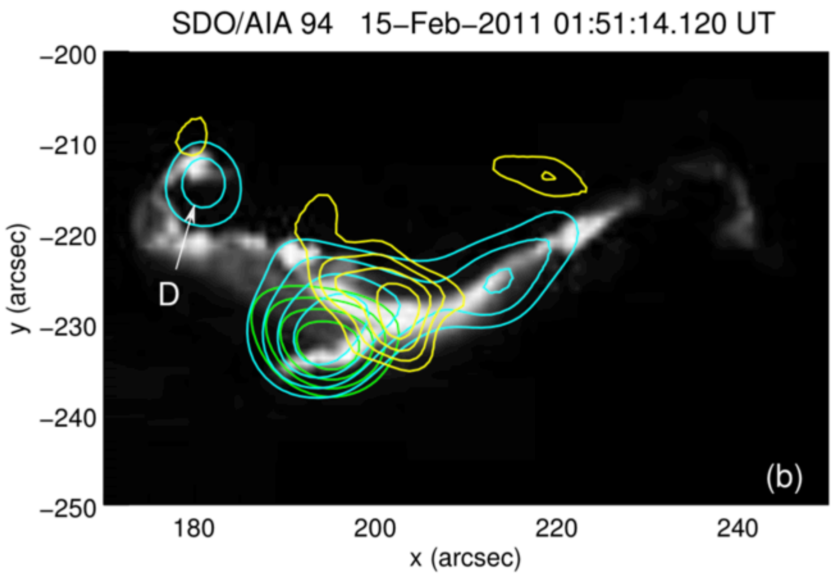


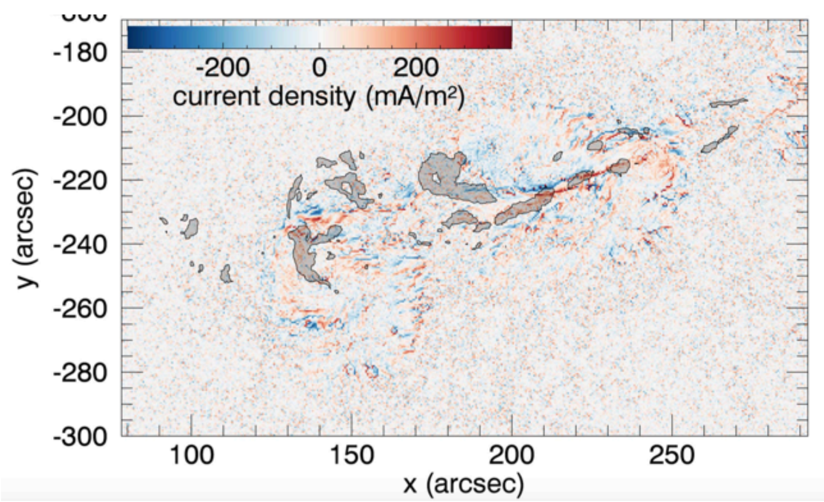


❖ Increase of electric current
= collapse of the current layer

See also Janvier et al. 2016 for a more complex event + comparison with magnetic topology (QSLs)

CURRENT DENSITY AND PARTICLES: CAN WE MAKE A LINK?

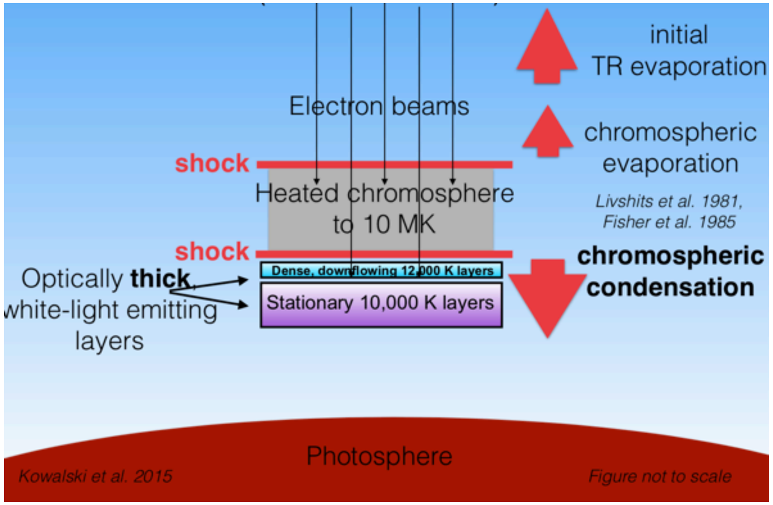




Same event: Musset et al. (2015) compared strong current density region with HXR emissions.

Haerendel 2017, Fleishman et al. 2018 discuss brigthness in EUV with locations of strong currents

How do (MHD) currents correlate with energy deposition?



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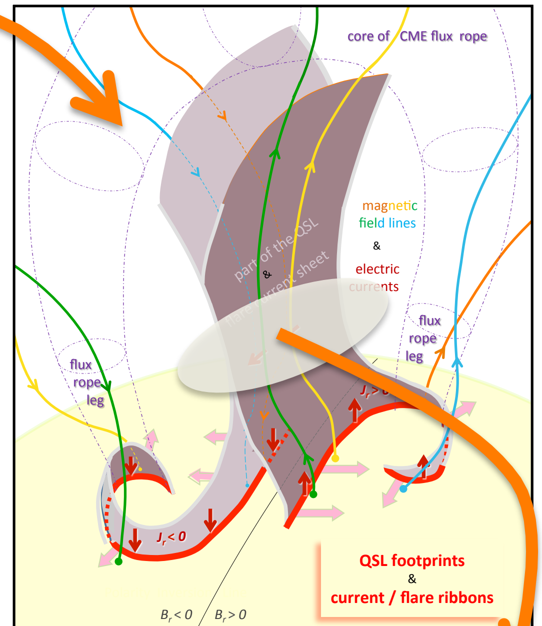
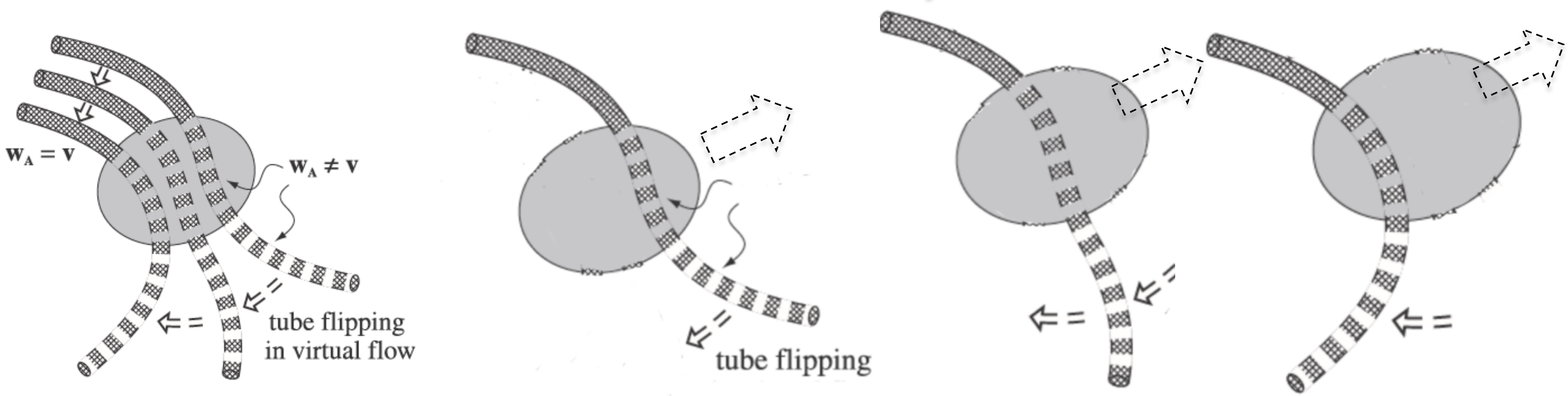
- Current ribbons
- Slipping reconnection

THE THEORY OF 3D RECONNECTION PREDICTS "SLIPPING "



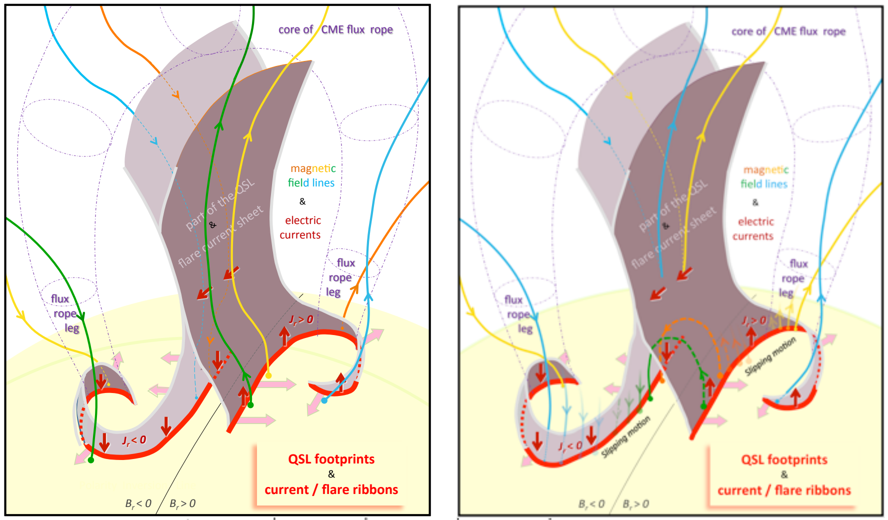
Finite volume of ***J***
→Reconnection is not
« cut and paste »
(no null points but QSLs)

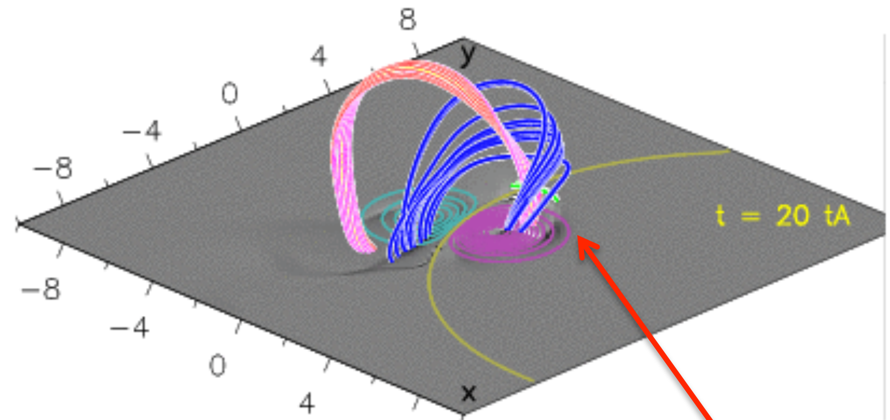


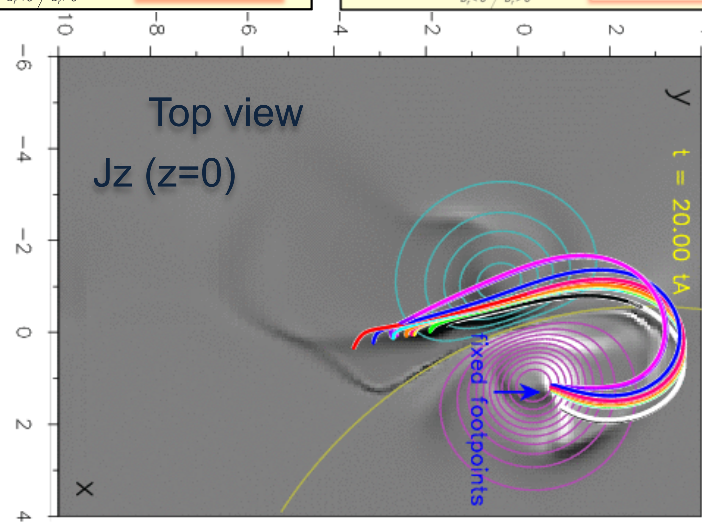
Priest & Forbes 1992, Demoulin et al. 1996,1997, Aulanier et al. 2005

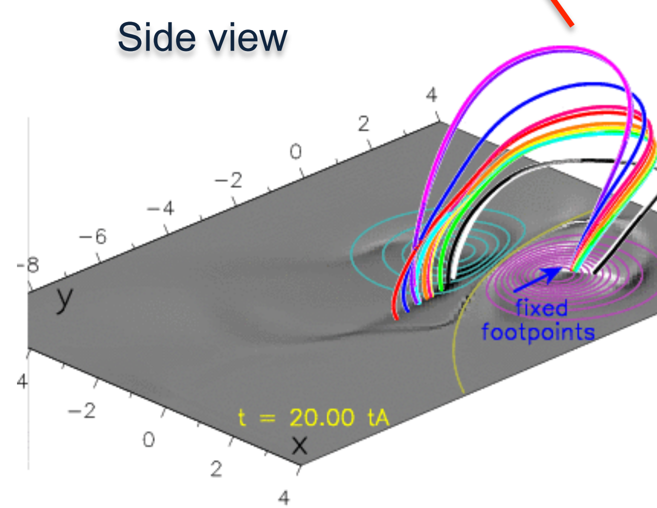
HOW FAST IS SLIPPING RECONNECTION?

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





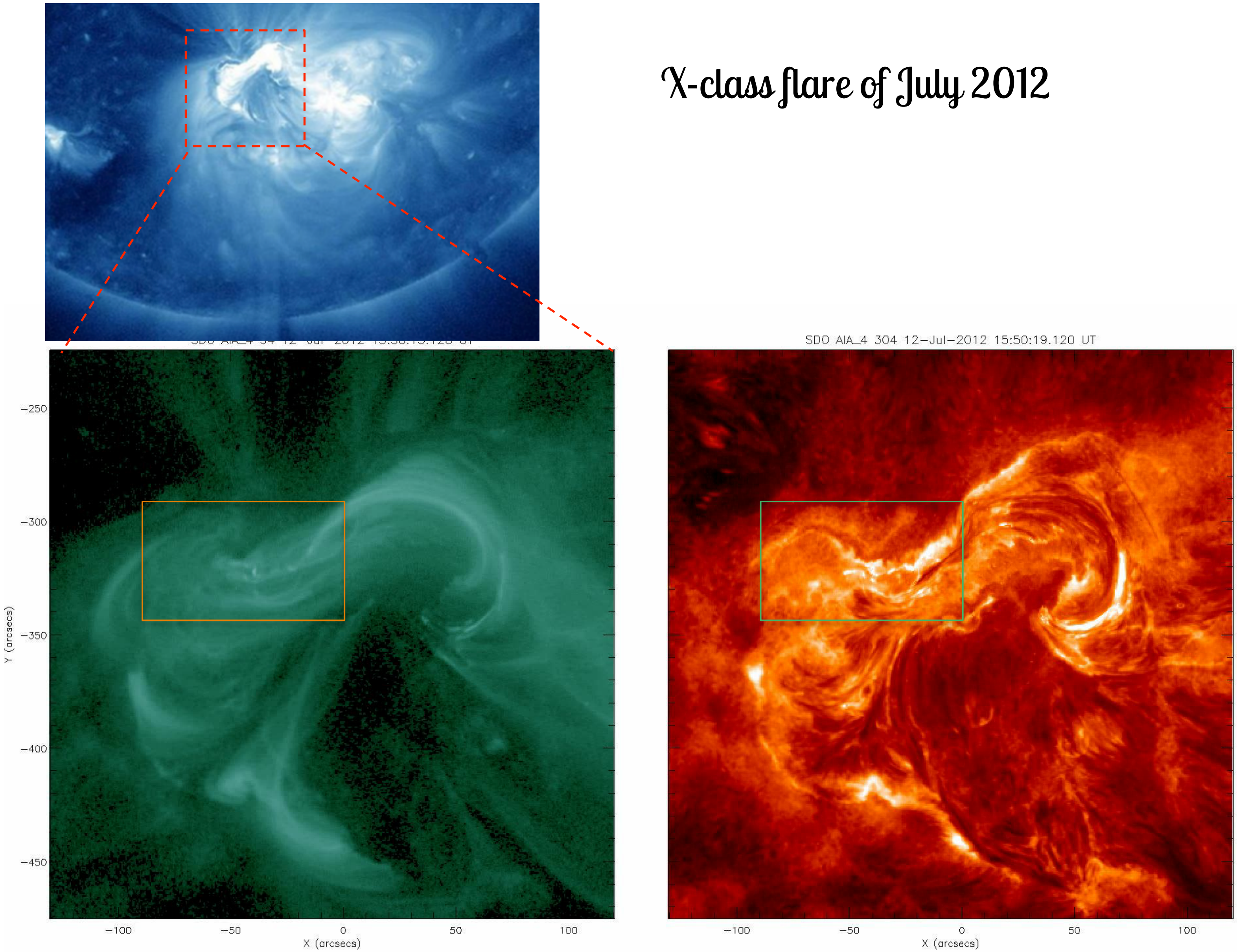




Janvier, Aulanier et al. (A&A 2013)

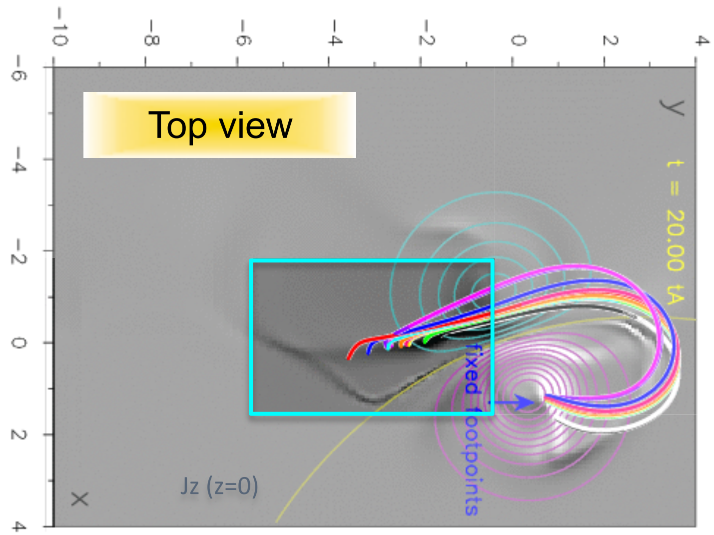
SO... DOES IT REALLY EXIST?

X-class flare of July 2012



SLIPPING IN A FLARE

3D Slipping reconnection :
successive change of magnetic connectivity



Janvier, Aulanier, Pariat & Démoulin (2013)

Leads to:

❖ Apparent field line motion

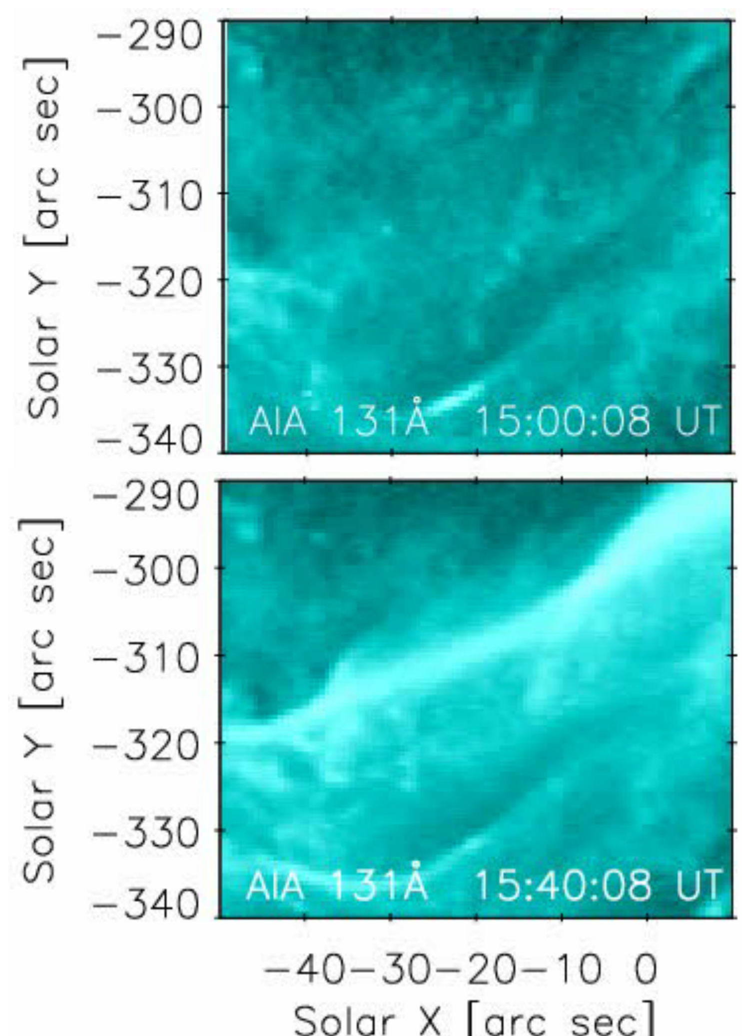
See also: Aulanier et al. (2007)

❖ Kernel motion

See also: Young et al. (2013)

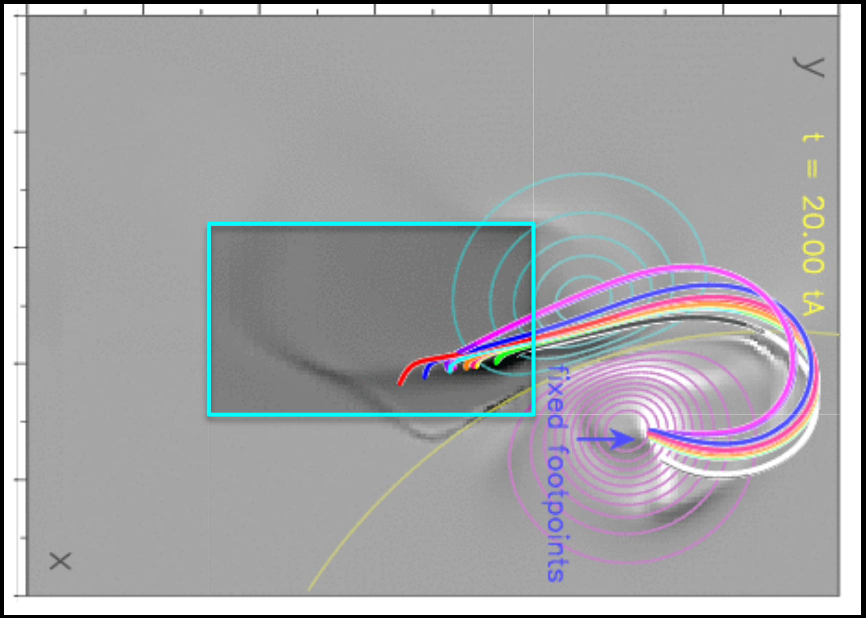
X-class flare of July 2012

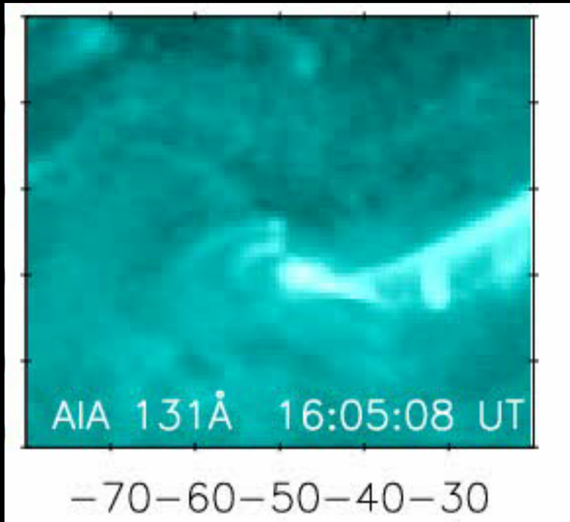
Dudik et al (2014)

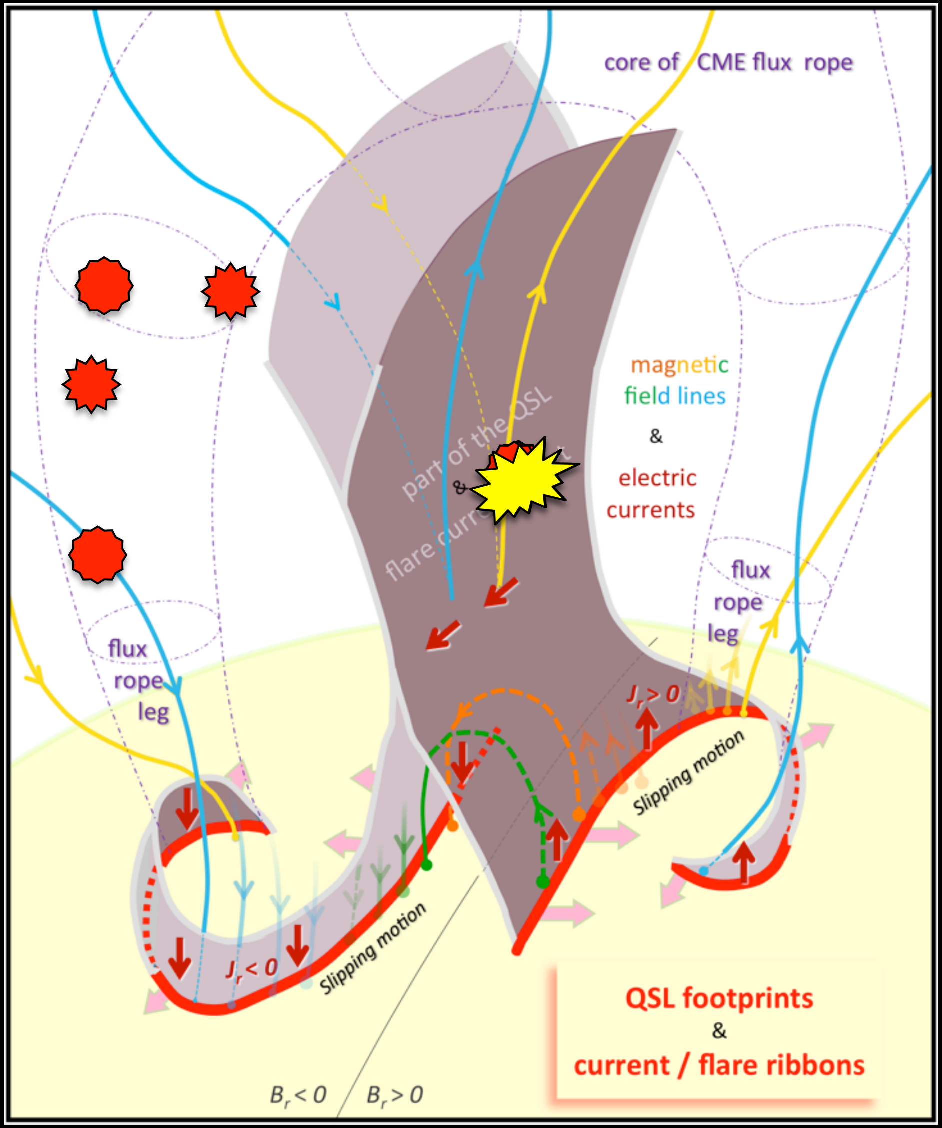


ERUPTIVE FLARES: SDO observations

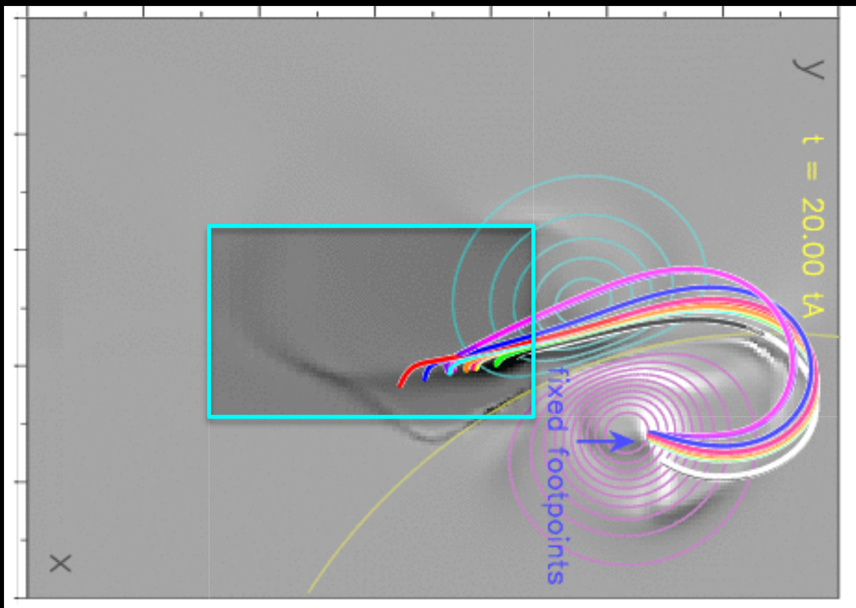
July 12 2012, X-class flare

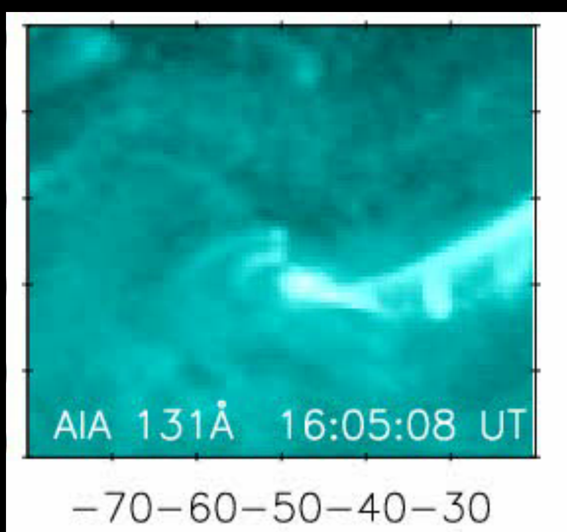




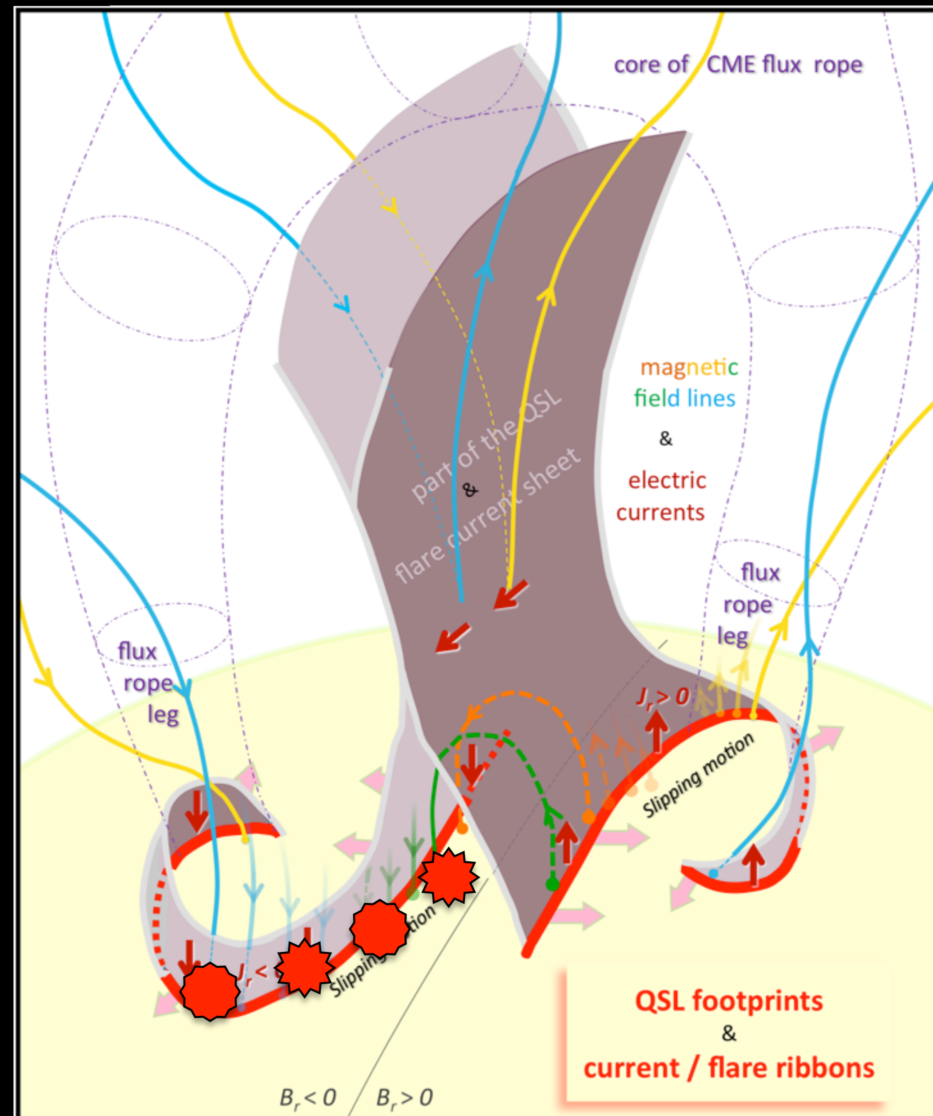


ERUPTIVE FLARES: SDO observations





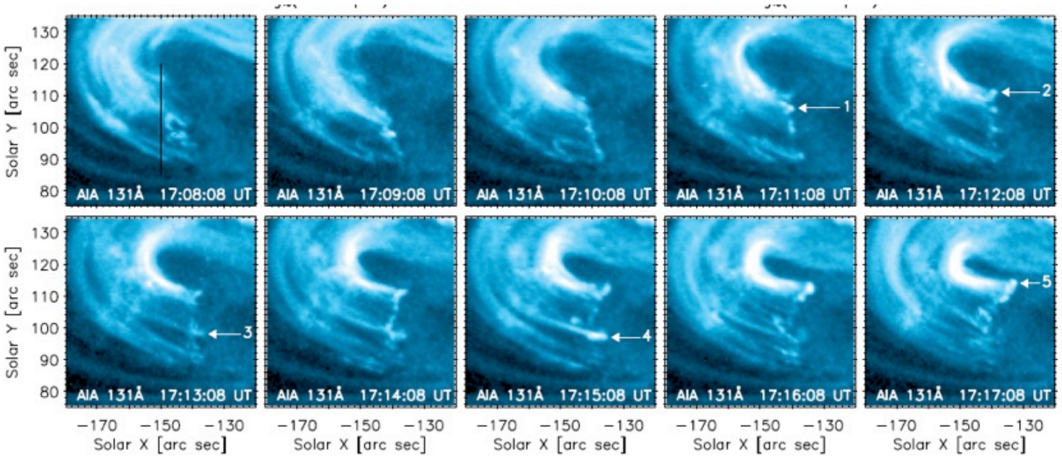
July 12 2012, X-class flare

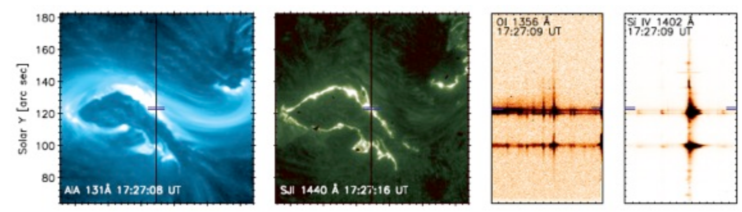


Further evidences + spectroscopic analysis

Now further evidences pointed out + detailed analysis

❖ Moving kernels (footpoints) + plasma upflows (spectroscopy diagnostics)

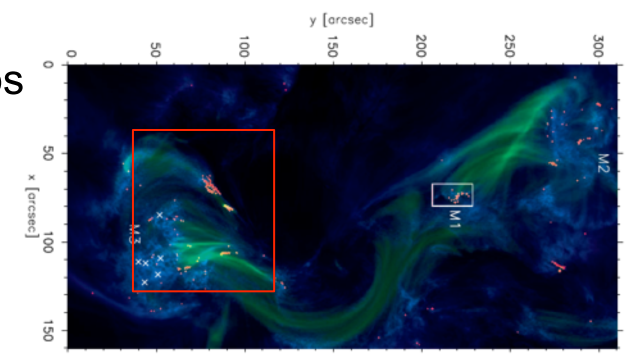




Dudik, et al (2016)

❖ To explain flickering at the end points of some coronal loops

Testa et al. (2013)

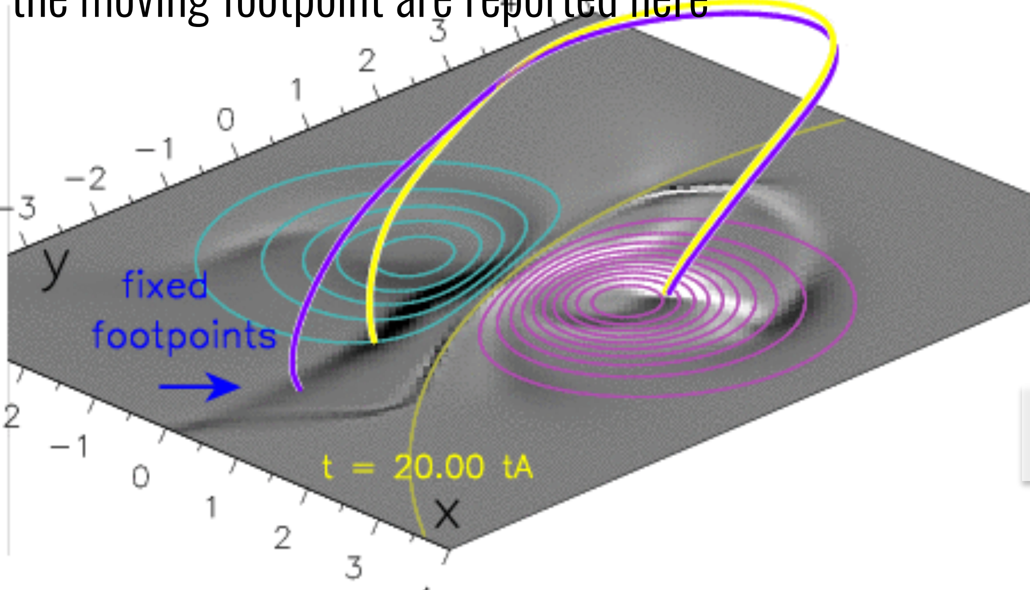


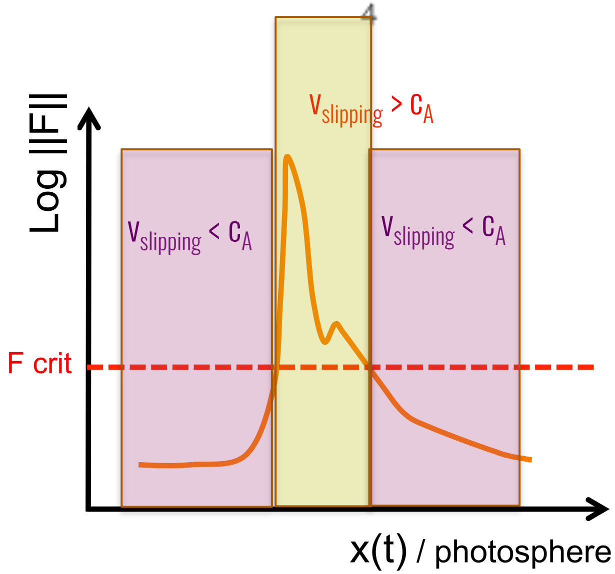
Direct observations:
2007: 1st observation (Hinode)
2013: 2 observations (Hi-C rocket + SDO/AIA)
2014: in 3 separate flaring regions
...

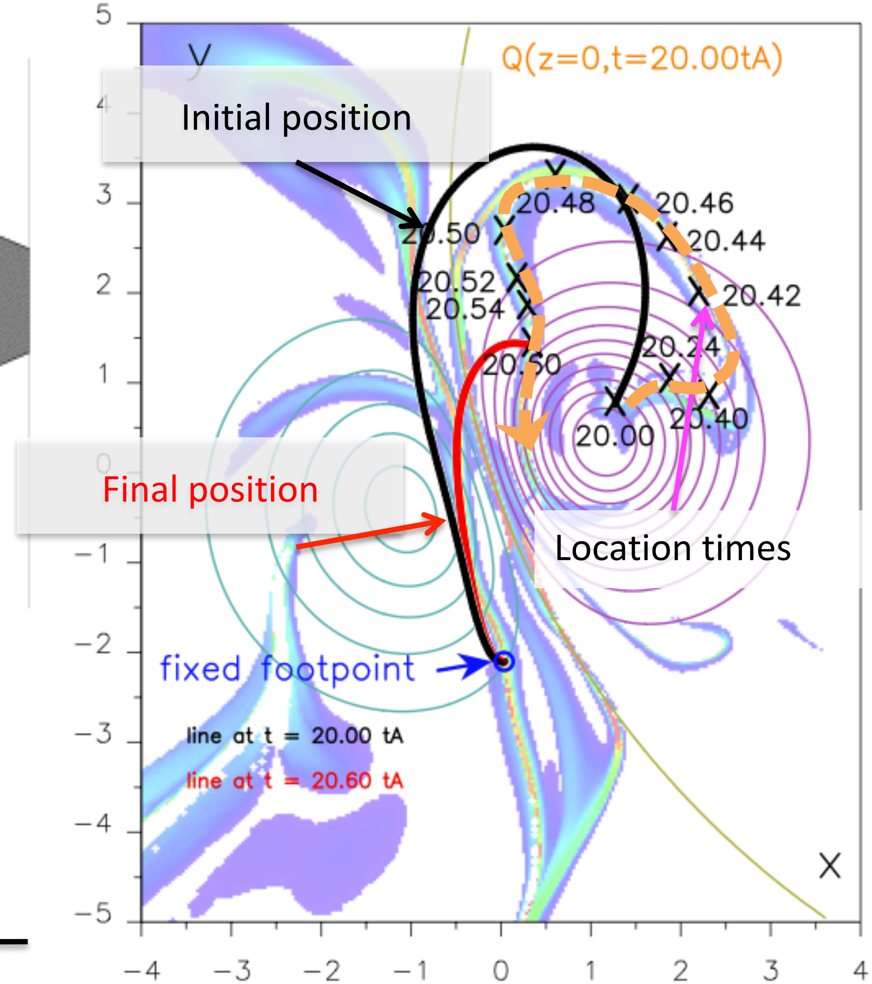
e.g. D. Li et al. (2015), T. Li et al. (2016)

HOW FAST IS SLIPPING RECONNECTION? DETAILED ANALYSIS

Slipping motion of the yellow field line: **locations** of the moving footpoint are reported here





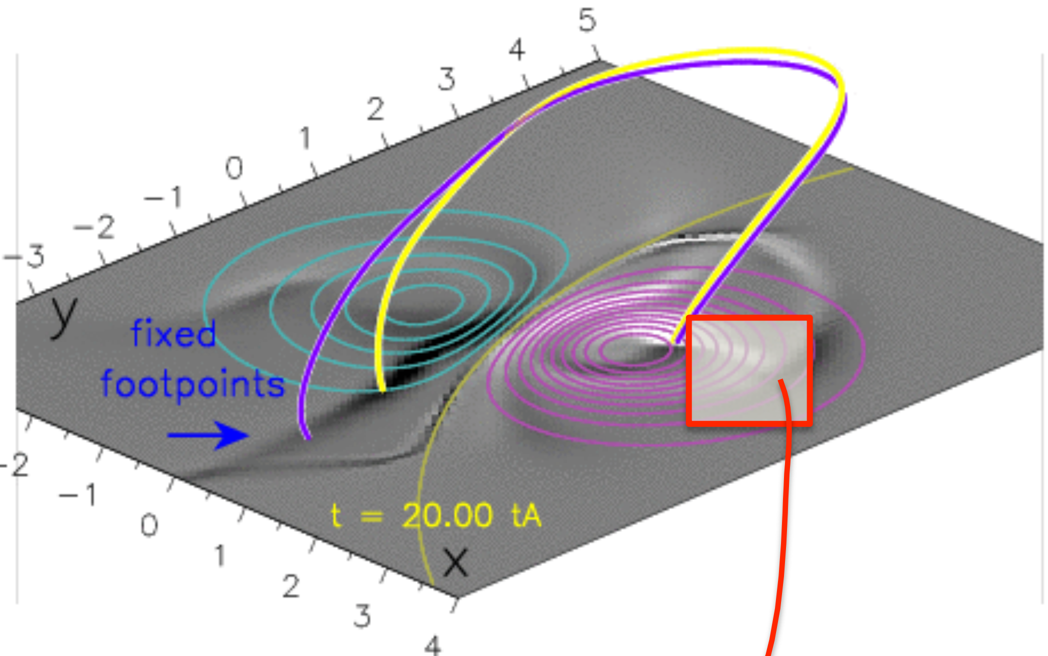


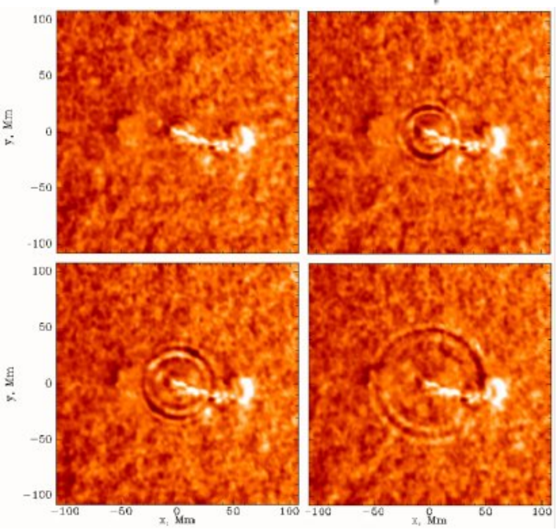
Q-map (magnetic topology)

+

locations of the footpoint

SLIPPING RECONNECTION AND ENERGY DEPOSITION





Could change of speed and energy deposition:

-Spatial place: gentle evaporation occurs at some locations vs explosive evaporation

-Sunquakes Matthews et al. (2015)

-Why some kernels appear and other not?

→ Topology: field line mapping dictates neighbouring F.L reconnecting with each other. Energy deposition larger if slipping is slower

→ Role of the current layer physics (turbulence? Plasmoids? Shocks? Waves?)

Sunquakes + HXR association

Kosovichev & Zharkova (1996), Zharkov (2013)

A FOCUS ON ERUPTIVE FLARES

- Observations
- From observations to models

FLUX ROPE INSTABILITY

- Numerical models to address the trigger problem
- Spectroscopic observations

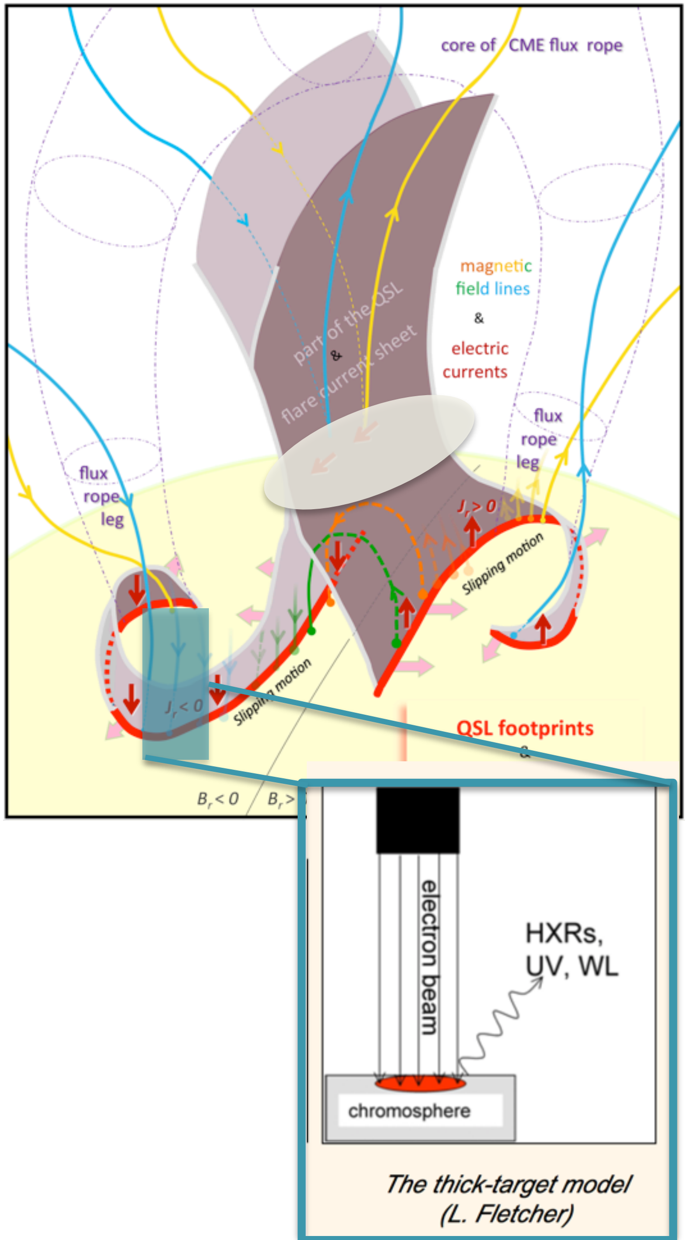
FROM MODELS TO OBSERVATIONS

- Current ribbons
- Slipping reconnection

A BIGGER PICTURE?

- What are the gaps to fill?
- Future observations

FROM MHD TO PARTICLE MODELS?



The thick-target model (L. Fletcher)

Macroscopic dynamics of magnetic fields

flux ropes, field distortion, current layers

+

instabilities, forcing (e.g. photospheric motions)

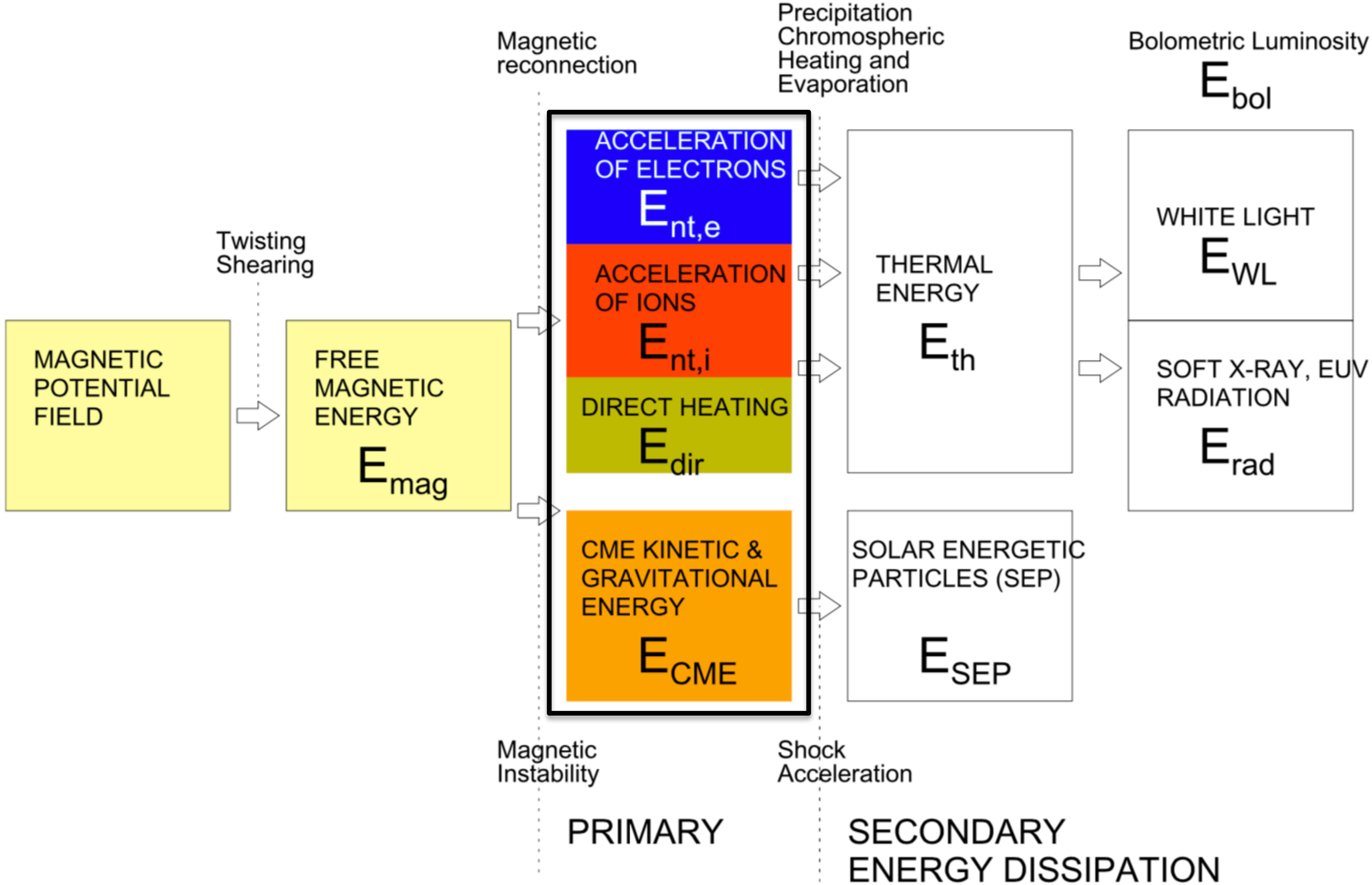
Current layer collapse, reconnection, large-scale morphology changes

Transport of Energy

Particles acceleration, Waves

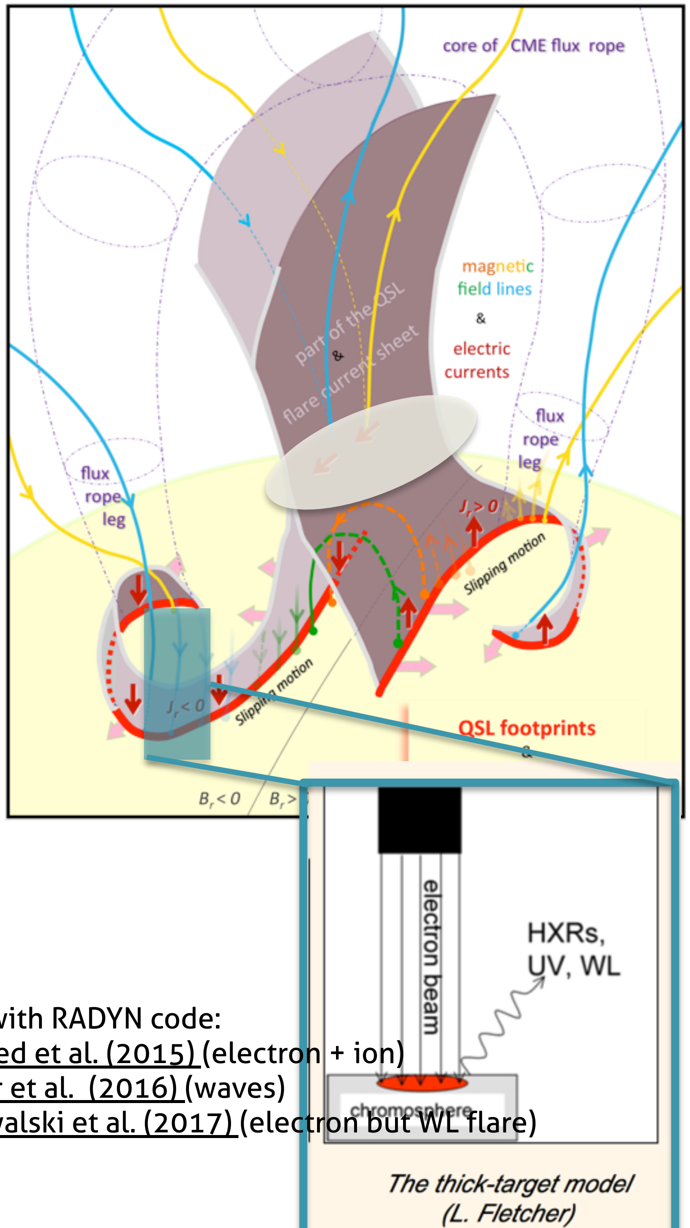
Chromospheric/Photospheric reaction (e.g. White-light flares),

FROM MHD TO PARTICLE MODELS? (ENERGETIC PERSPECTIVES)



Aschwanden et al. 2014-2017 (series of 5 papers treating flare energy, update from Emslie et al. 2012

FROM MHD TO PARTICLE MODELS?



Ex with RADYN code:
Allred et al. (2015) (electron + ion)
Kerr et al. (2016) (waves)
Kowalski et al. (2017) (electron but WL flare)

Macroscopic dynamics of magnetic fields

flux ropes, field distortion, current layers

+

instabilities, forcing (e.g. photospheric motions)

Current layer collapse, reconnection, large-scale morphology changes

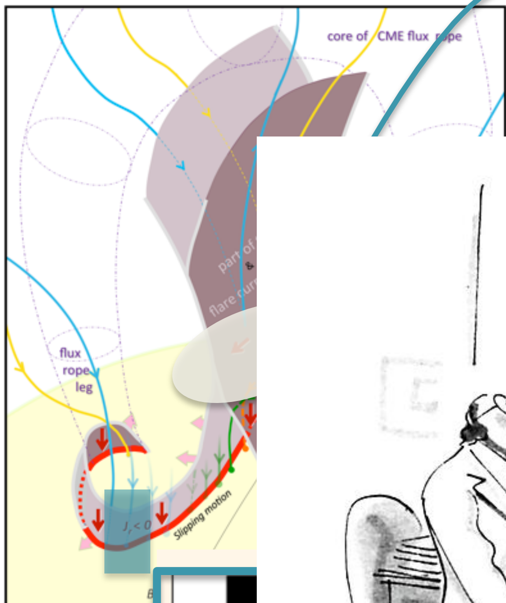
How is magnetic energy converted during reconnection?
Energetic partition between particles and waves?

Transport of Energy

Particles acceleration, Waves

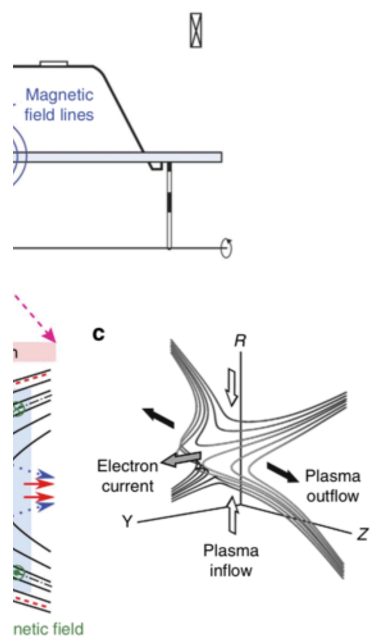
Chromospheric/Photospheric reaction (e.g. White-light flares),

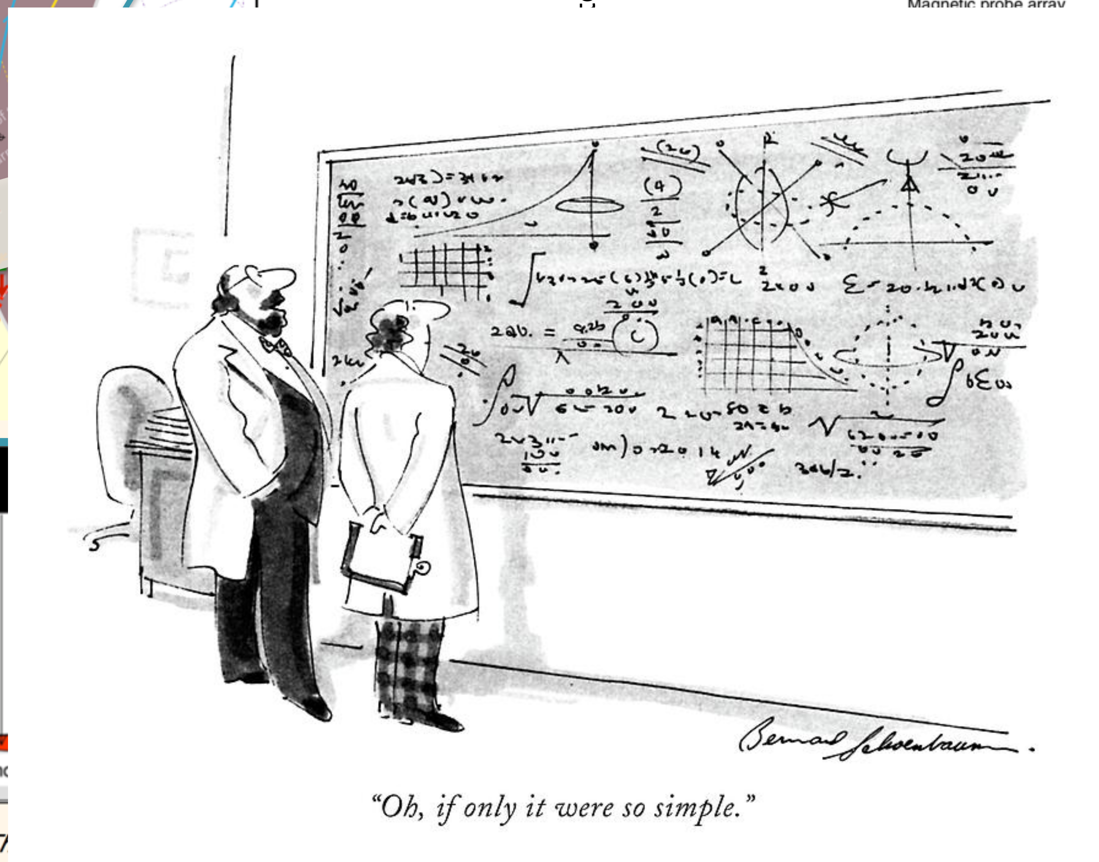
FROM MHD TO PARTICLE MODELS?



Allred et al. (2015),

Magnetic islands, turbulence, shocks, Alfvèn waves…





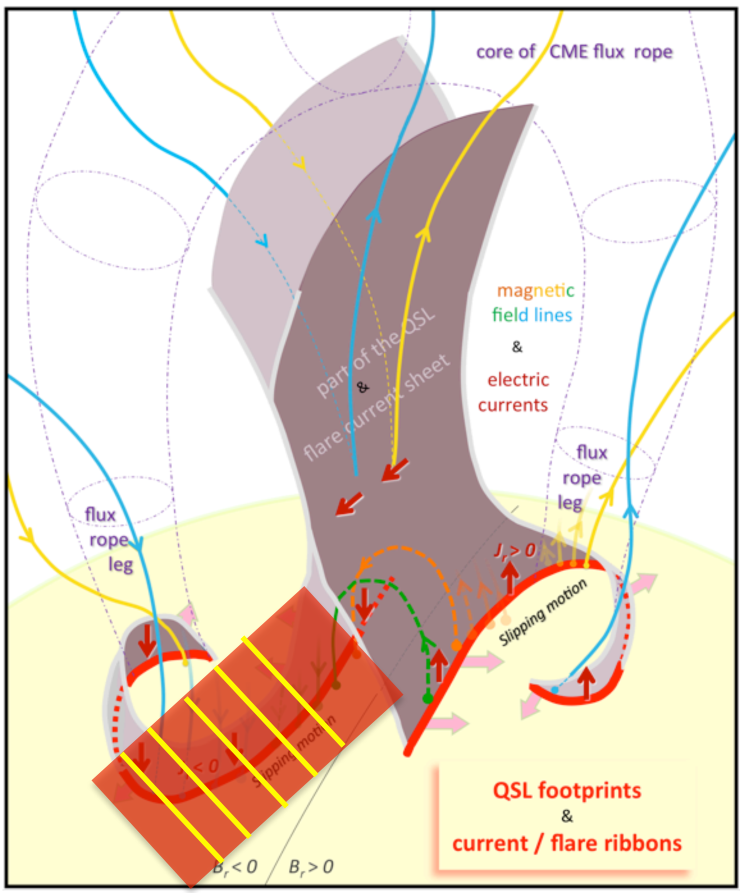
“Oh, if only it were so simple.”

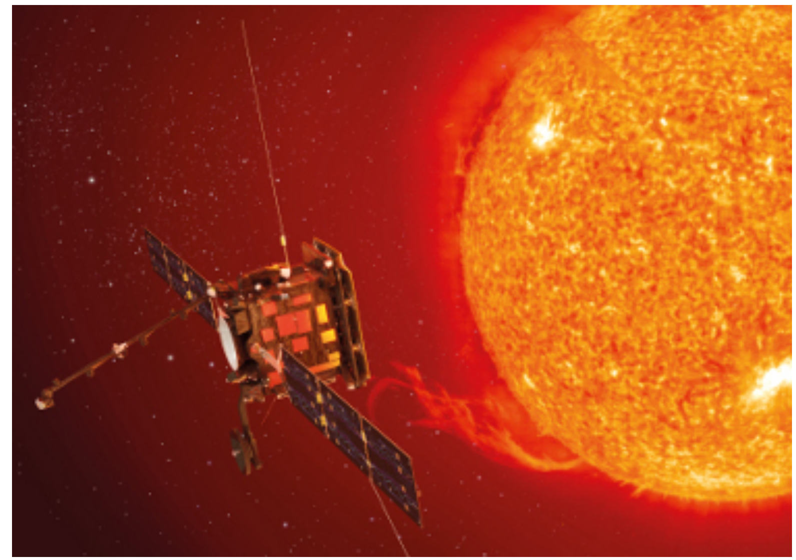
nt for ions and electrons

converted to particle energy, 2/3 of which transferred to ions and 1/3 to electrons. » → Also confirmed in MMS mission (see Toledo-Redondo et al. 2017)

FUTURE MISSIONS?

From 2020: SPICE has two EUV wavelength passbands, 70.0 – 79.2 nm and 97.0 – 105.3 nm.
From 10,000 to 10 million K: **SPICE will provide a complete temperature coverage from the low chromosphere to the flaring corona.**





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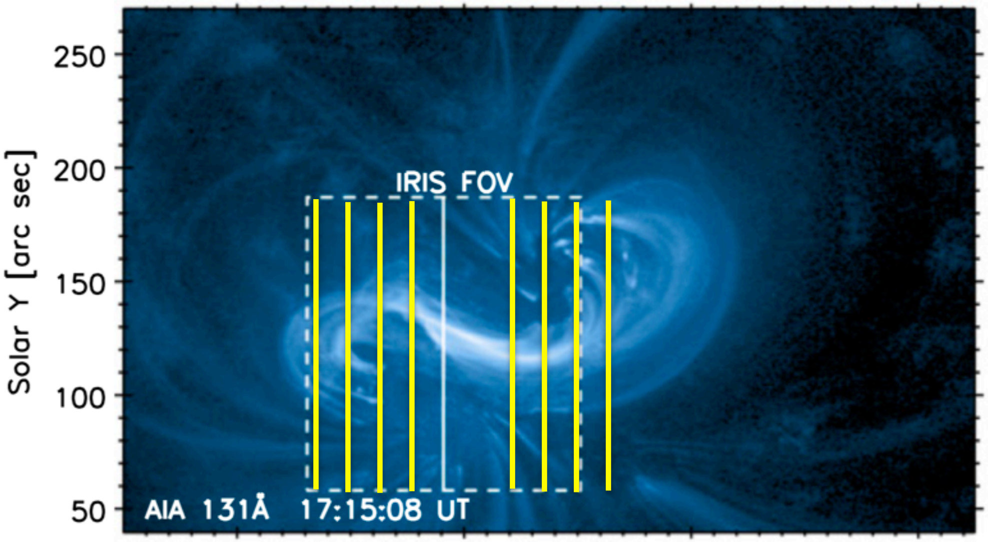

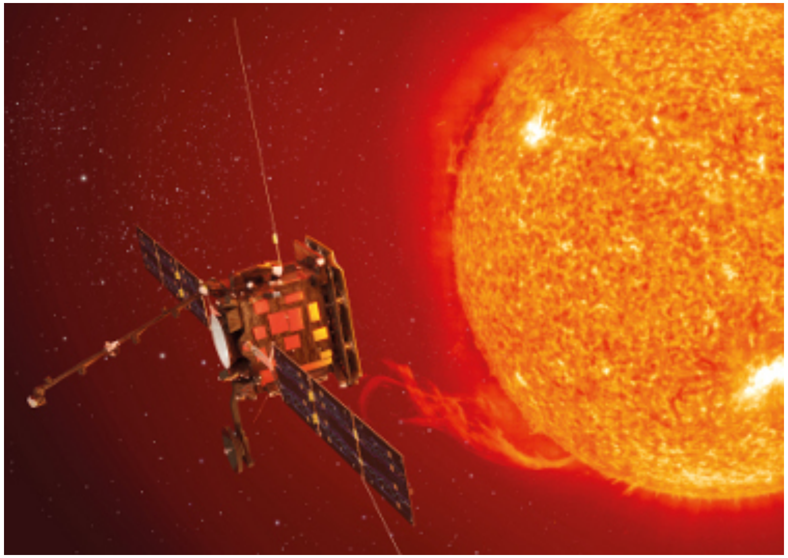

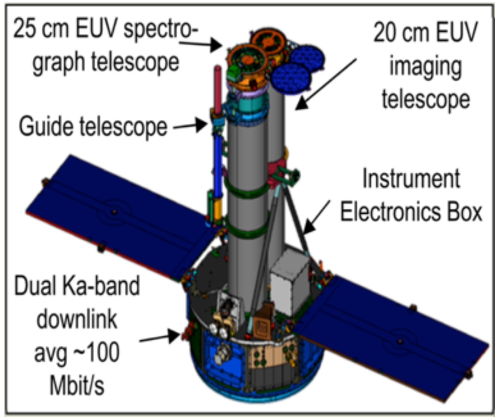

MUSE: "IRIS for the corona" with better spatial resolution than AIA and 100x faster than previous spectrographs, 35 slits. Launch in 2022?

Small Explorer based on heritage from IRIS, SDO, Hinode (PI: T. Tarbell)