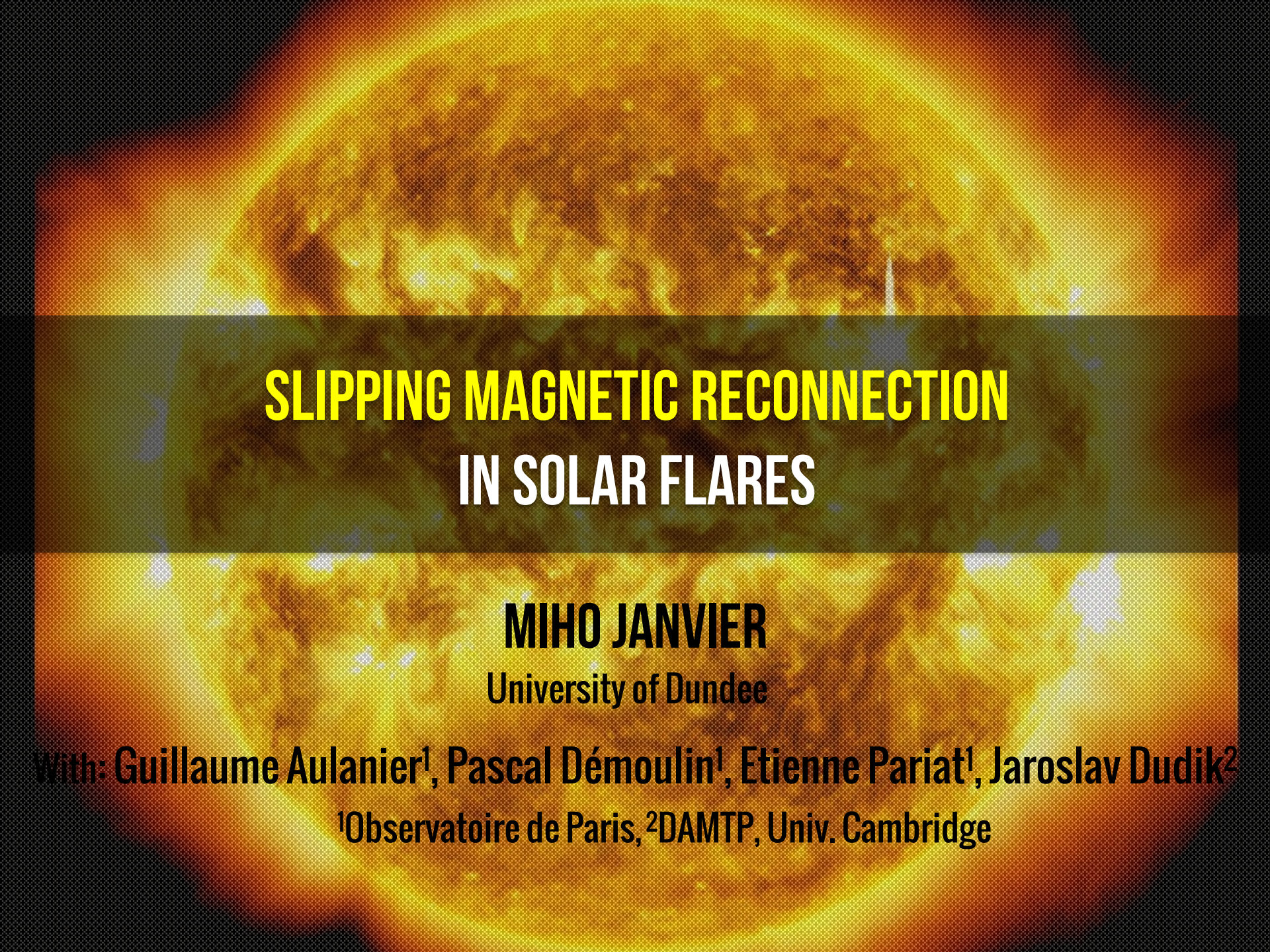


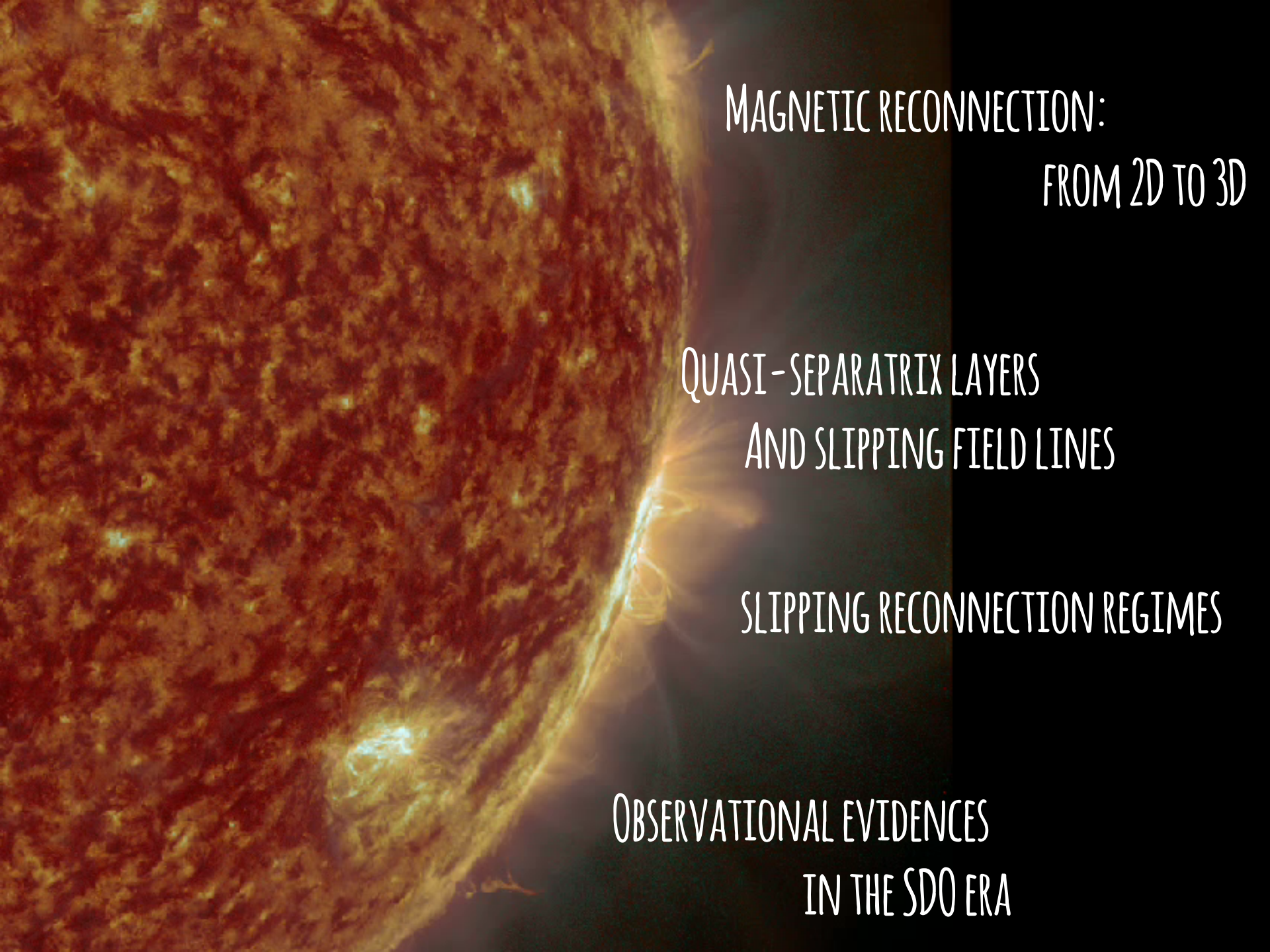
SLIPPING MAGNETIC RECONNECTION IN SOLAR FLARES

MIHO JANVIER

University of Dundee

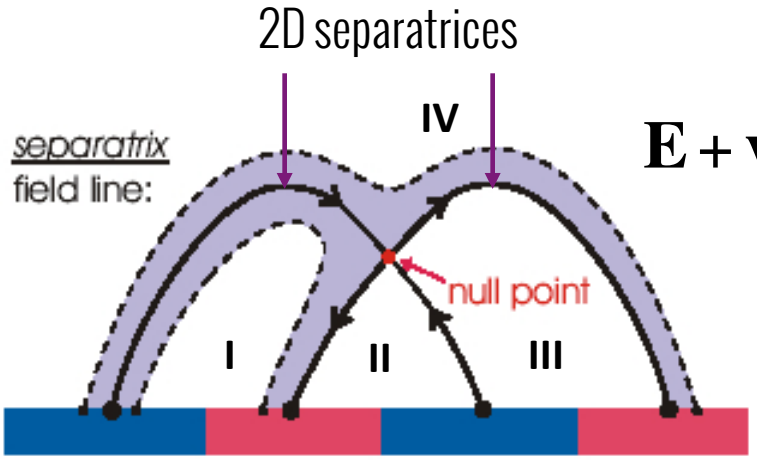
With: Guillaume Aulanier[1], Pascal Démoulin[1], Etienne Pariat[1], Jaroslav Dudik[2]

[1]Observatoire de Paris, [2]DAMTP, Univ. Cambridge


Magnetic reconnection:
from 2D to 3D
Quasi-separatrix layers
And slipping field lines
slipping reconnection regimes
Observational evidences
in the SDO era

SOLAR FLARES AND RECONNECTION: the 2D vision

Magnetic energy → heat + kinetic energy



$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J}$$

4 connectivity domains

See reviews: Zweibel & Yamada 2009, Yamada 2010

Idea of reconnection:
Dungey 1953

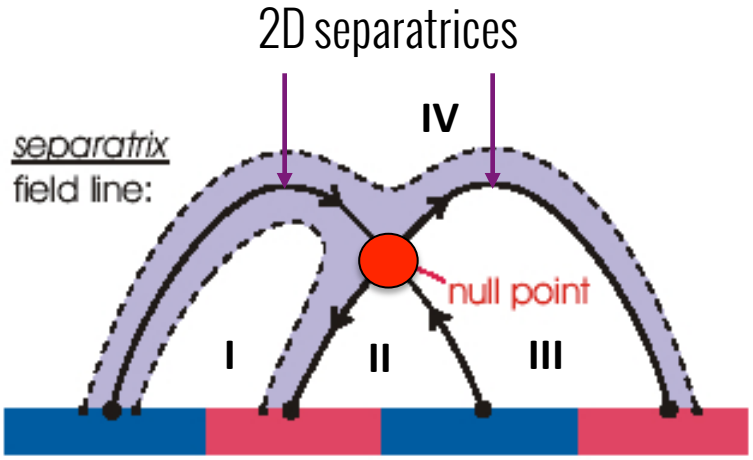
Field near neutral point is unstable
→ Produce current sheets

Sweet 1956
Parker 1957

Magnetic energy conversion
in current sheets **powers flares**

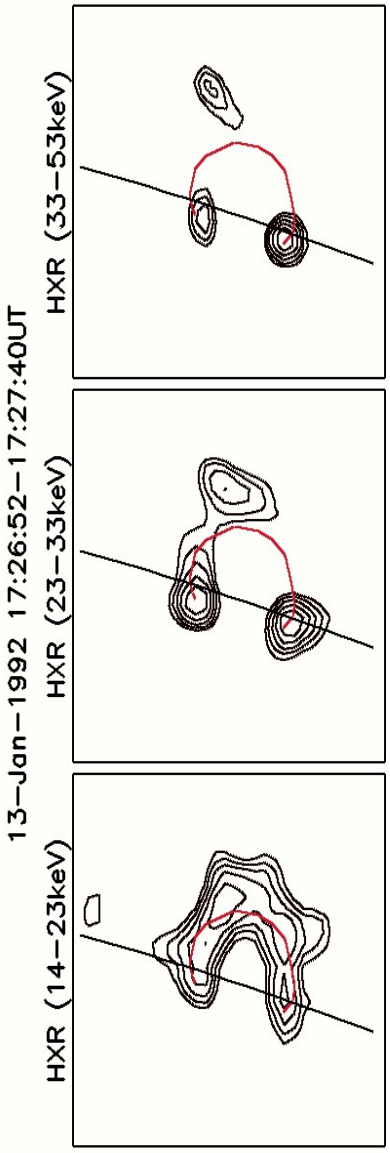
SOLAR FLARES AND RECONNECTION: the 2D vision

Magnetic energy → heat + kinetic energy



4 connectivity domains

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

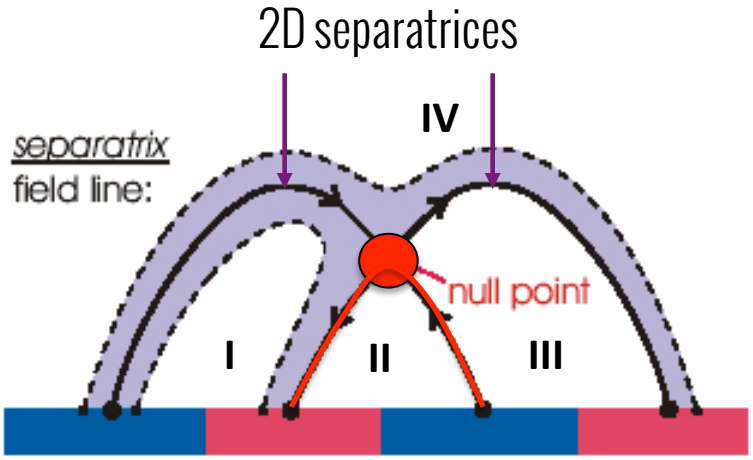


Hard X-ray source above the loop top:

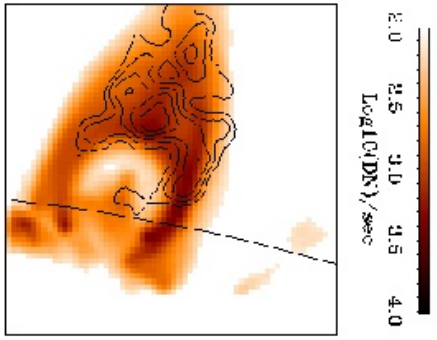
particle acceleration at reconnection site

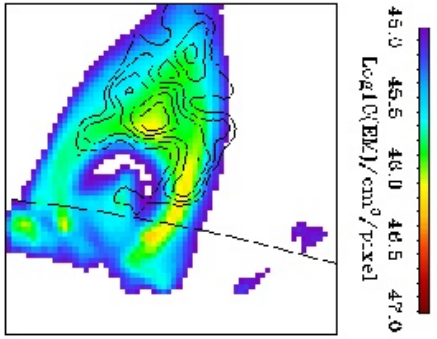
SOLAR FLARES AND RECONNECTION: the 2D vision

Magnetic energy → heat + kinetic energy



4 connectivity domains





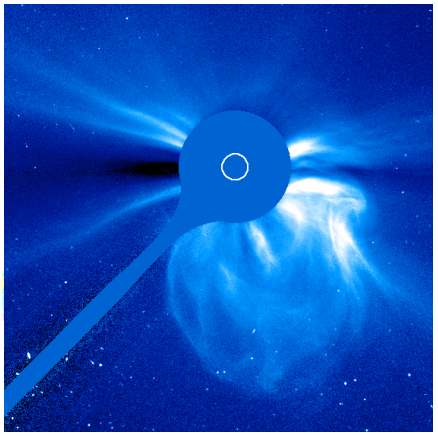
Tsuneta et al. (1996)
Yokoyama et al. (2001)

SXR high temperature ridges along outer or newly formed loops:

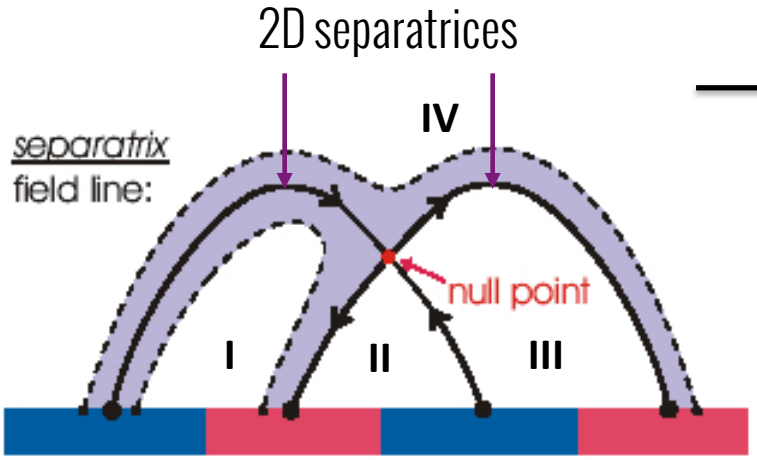
heating takes place

CME EJECTION

Transfer of kinetic energy



TOPOLOGY OF SOLAR FLARES: 3D extensions

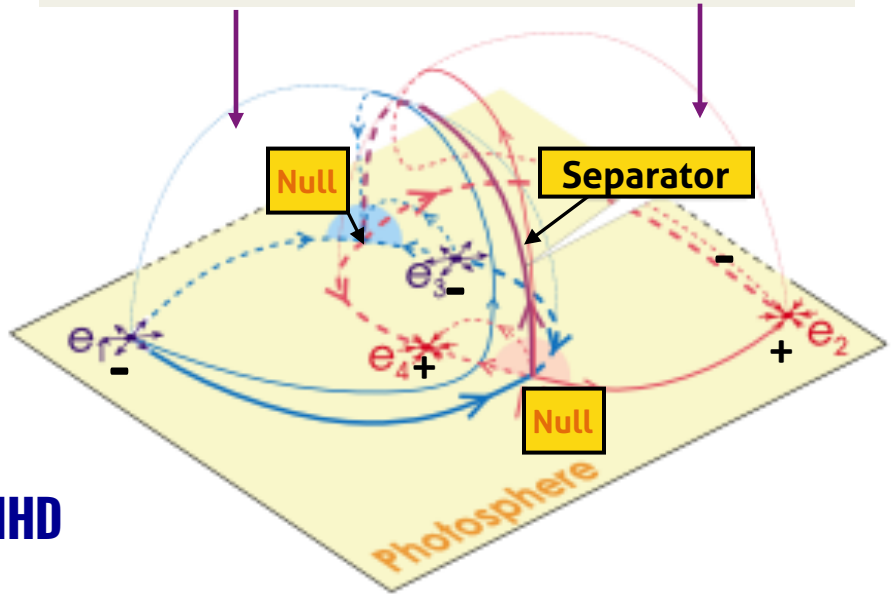


4 connectivity domains

Extensions from 2D to 3D

From 1995: See work by Longcope et al., Parnell et al., Pontin et al. Priest et al.

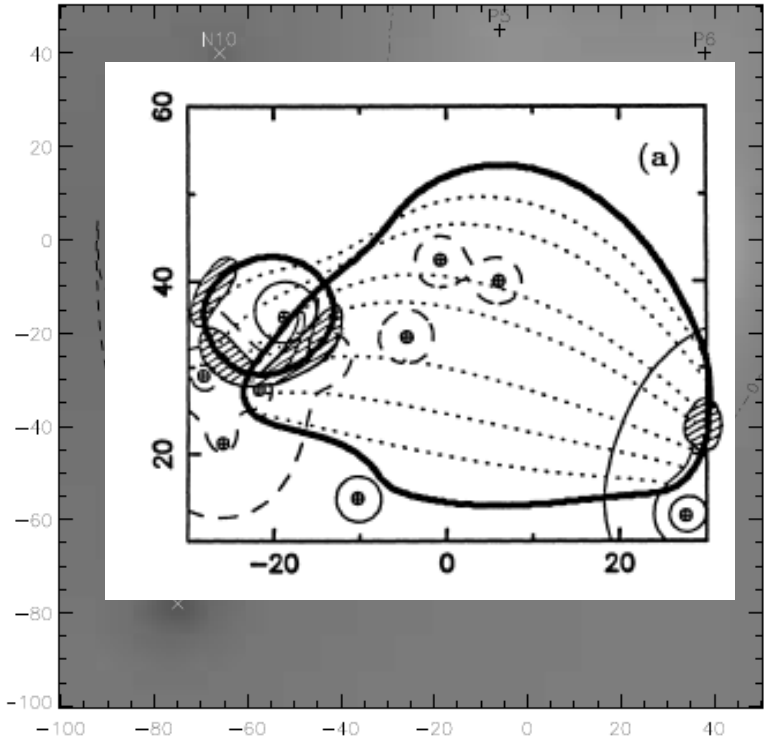
3D separatrices: 2 intersecting cupola



Lau & Finn 1990

Restrict reconnection to **phenomena arising in resistive MHD** associated with **boundary layers** and **isolated null points**

TOPOLOGY OF SOLAR FLARES: 3D extensions



Magnetic Charge Topology Models:

From 4 point charges...

Baum & Brathenal 1980, Gorbachev & Somov 1988, Lau 1993

...to multiple ones:

Mandrini et al. 1993, Démoulin et al. 1994a, Longcope 1996, Aulanier 1998

Démoulin et al. 1994b:

Photospheric mapping of the magnetic field:
Flares occur in regions where no null points are found

Schindler et al. 1988
Hesse & Schindler 1988

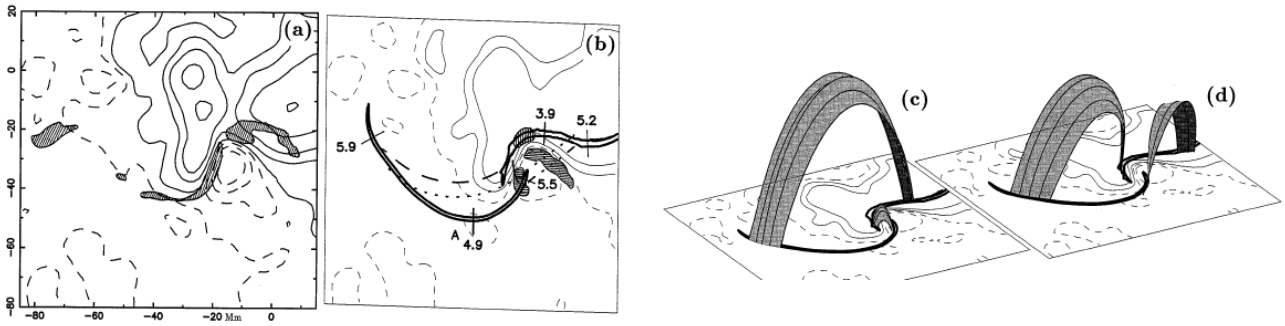
If no null points: mapping functions of field line footpoints from one boundary to another are continuous

→ Separatrices/Separators do not need to exist
→ « Reconnection » takes place where $E_{||}$ is important (« non-idealness »)

Also: Priest & Forbes 1989, 1992

FLARES IN 3D: no null point configuration

Priest & Démoulin 1995
Démoulin et al. 1996-1997

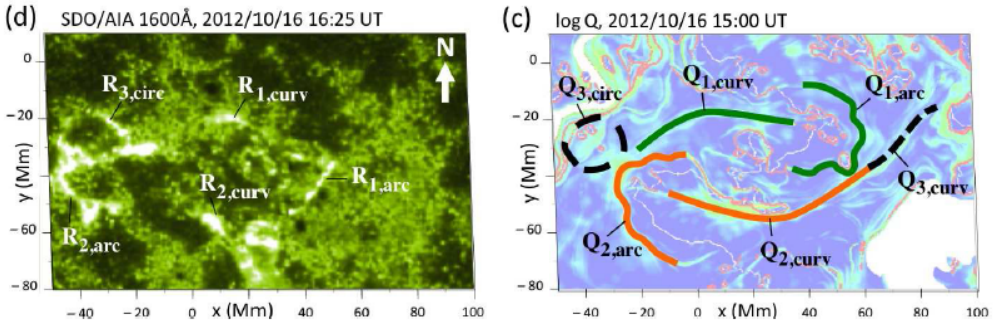


Idea of reconnection happening in **regions of strong magnetic field distorsion:**
« Quasi » separatrix layers

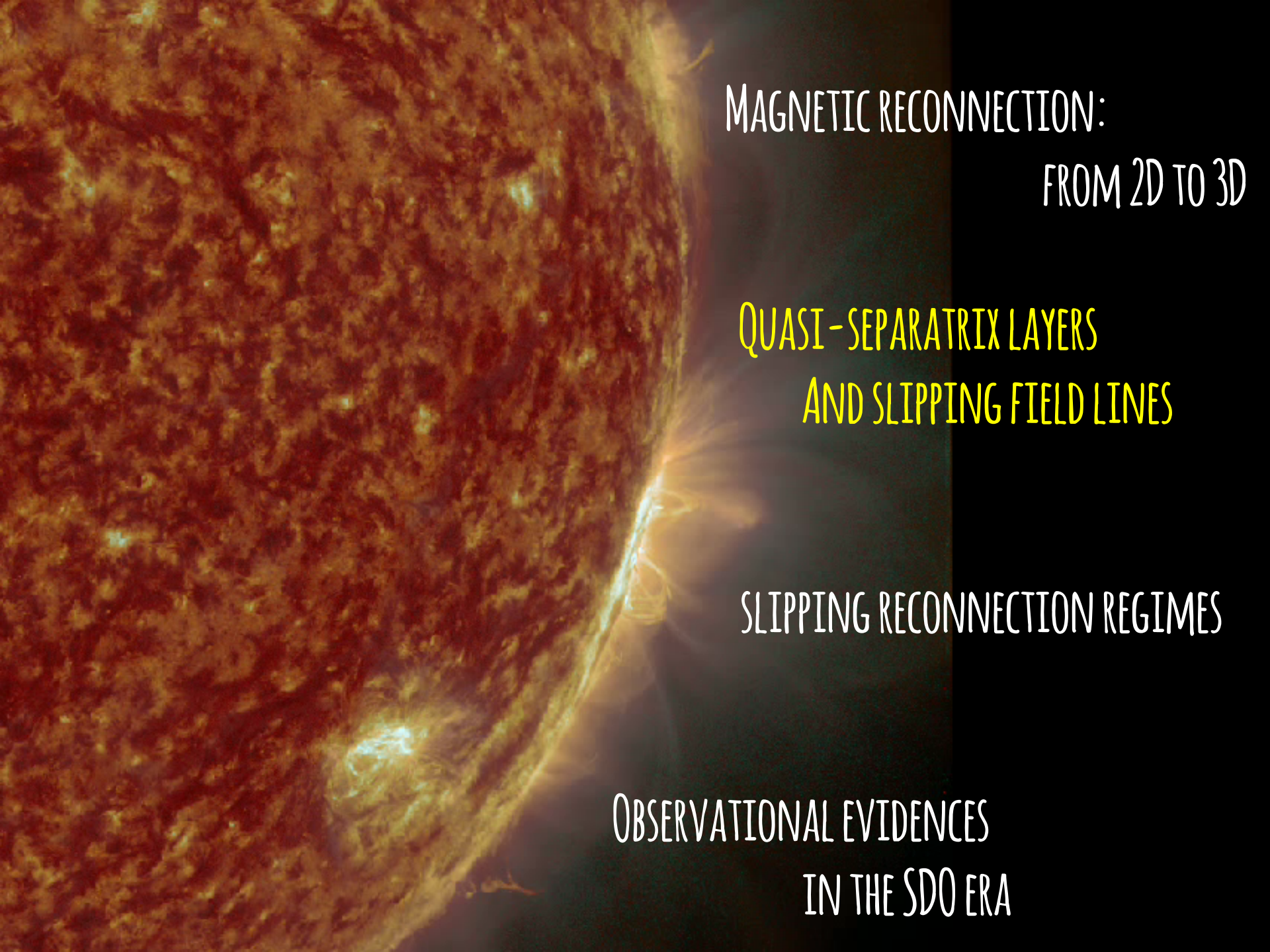
Reconnection can be (and is) defined **physically** as regions where ideal MHD breaks down

Since then: numerous evidences of flaring activity associated with quasi-separatrix layers:

Schmieder et al. 97, Démoulin et al. 97, Mandrini et al. 97, Bagala et al. 00, Wang et al. 00, Fletcher et al. 01, Mandrini et al. 06, Masson et al. 09, Chandra et al. 11, Savcheva et al. 12, Inoue et al. 13, Zhao et al. 14, Savcheva et al. 14, Dudik et al. 14



e.g. to explain « non-standard » flare: Dalmasse et al. (in press)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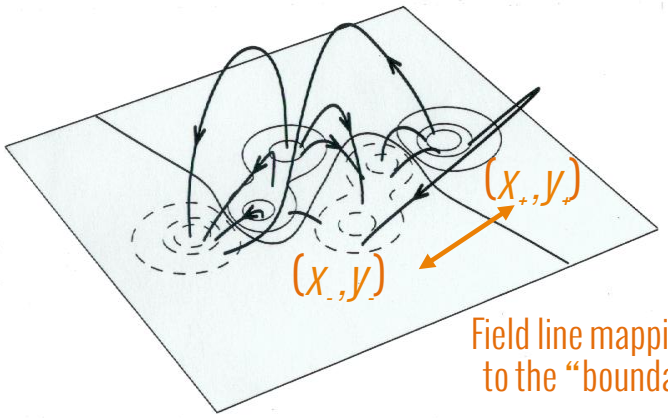
Quasi-separatrix layers

How to find the regions where there is a

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



Jacobi matrix:

MAPPING is key $F = \begin{pmatrix} \partial x_- / \partial x_+ & \partial x_- / \partial y_+ \\ \partial y_- / \partial x_+ & \partial y_- / \partial y_+ \end{pmatrix}$

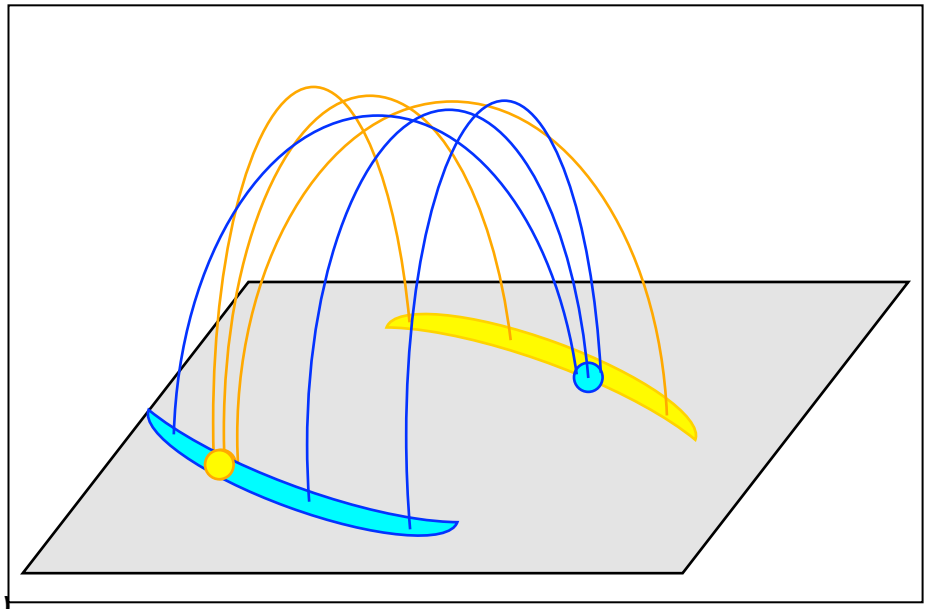
$$N \equiv \| F \|$$

"Field line mapping"

$$Q \equiv \frac{\| F \|^2}{B_{n,+} / B_{n,-}}$$

"Squashing degree"

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

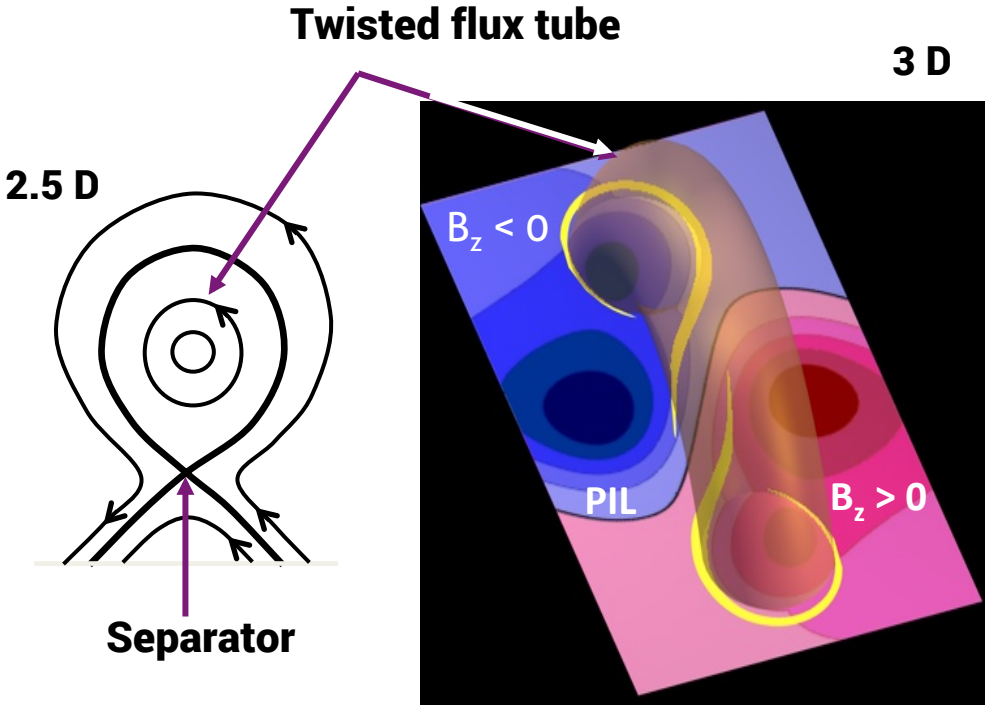


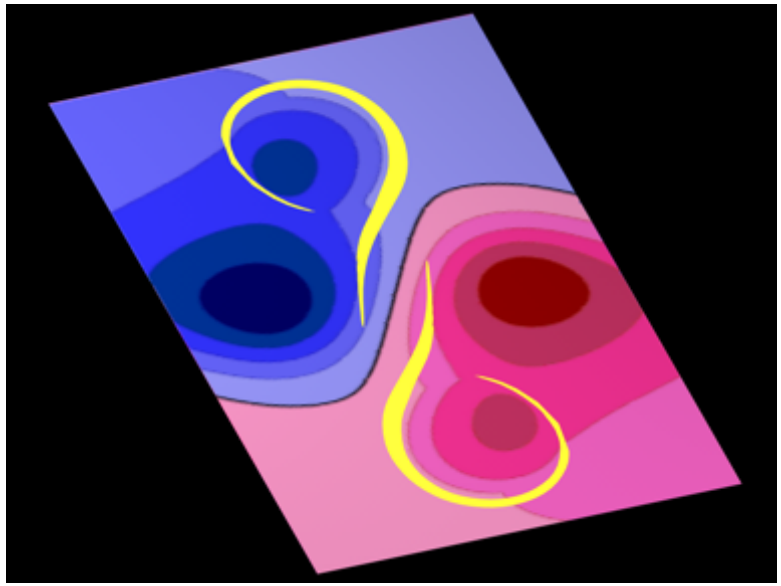
Same value of Q at both feet of a field line : $Q_+ = Q_-$

Quasi-separatrix layers - flux ropes

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

Quasi-separatrix layers are regions where: $Q >> 1$

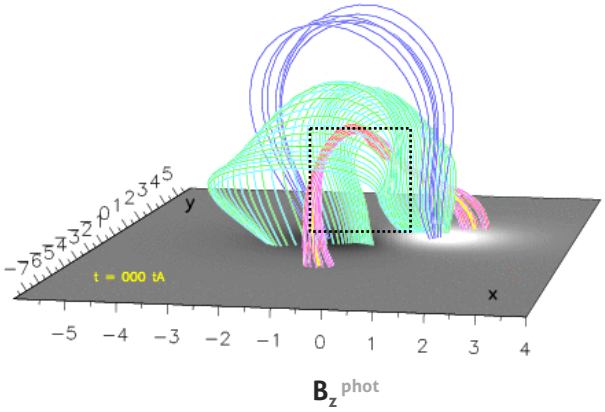




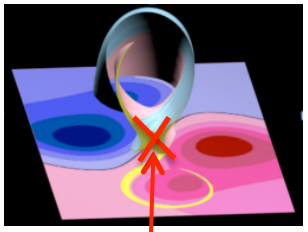
Démoulin et al. (1996), Titov (2007), Pariat et al. (2012)

QSLS: 3D MHD simulations

Coronal arcades
Erupting flux rope

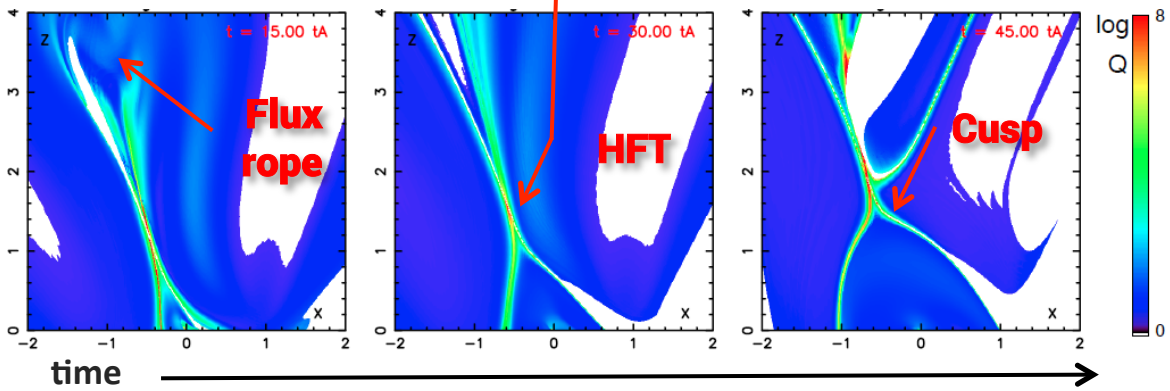


Vertical 2D cuts



Q = *squashing factor*

«gradient of field line connectivity»



Reconnection takes place (but no null points)

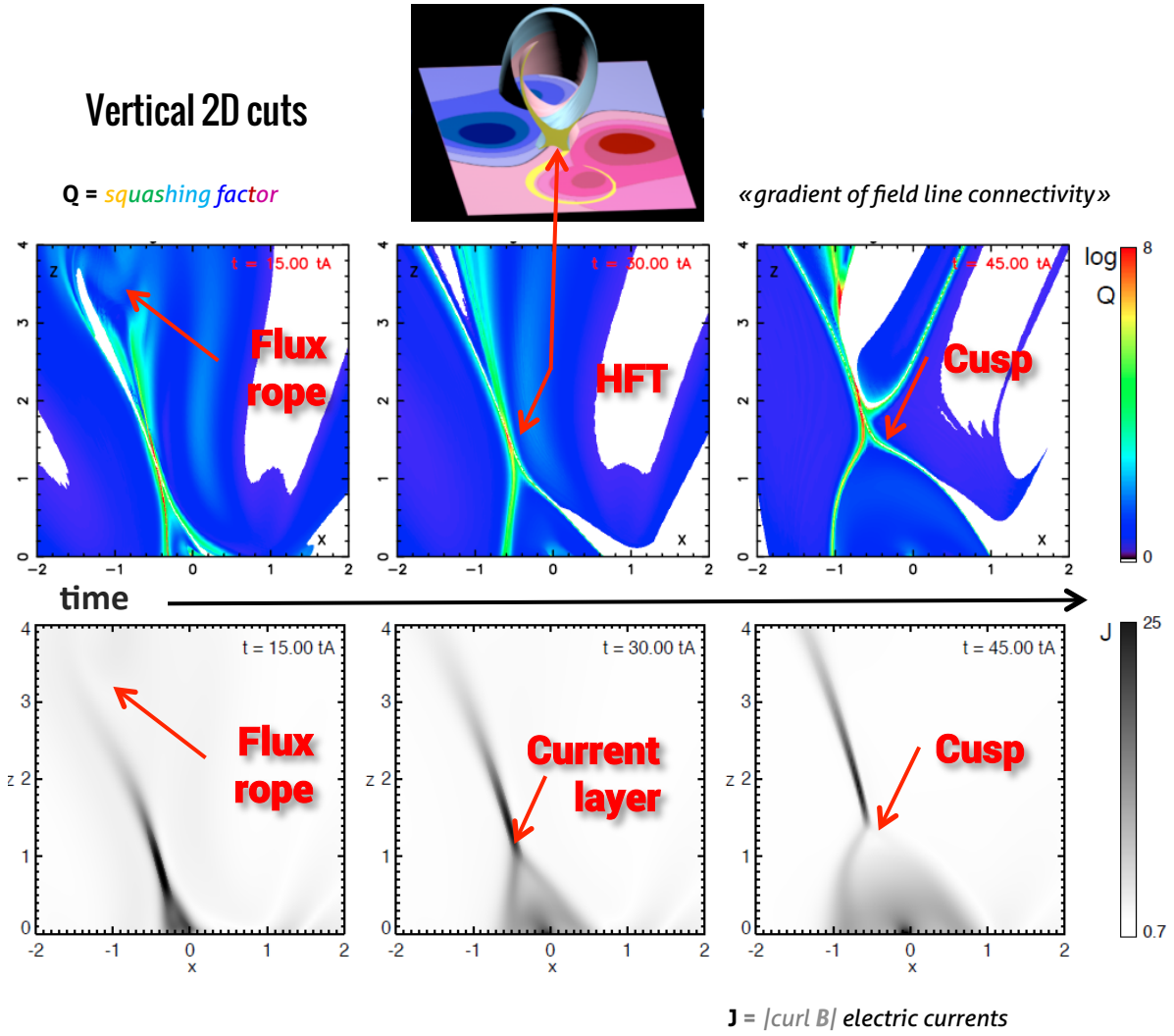
OHM code, β=0 simulation of eruptive flares

Janvier, Aulanier, Pariat & Démoulin (2013)

QSLS: 3D MHD simulations

QSLs: Preferential locations for electric current build-up

See also: Milano et al. 1999, Galsgaard et al. 00, 03, Pontin et al. 05, Aulanier et al. 05, 06, Pariat et al. 06, Büchner 06, Dreher et al. 08, Masson et al. 09...



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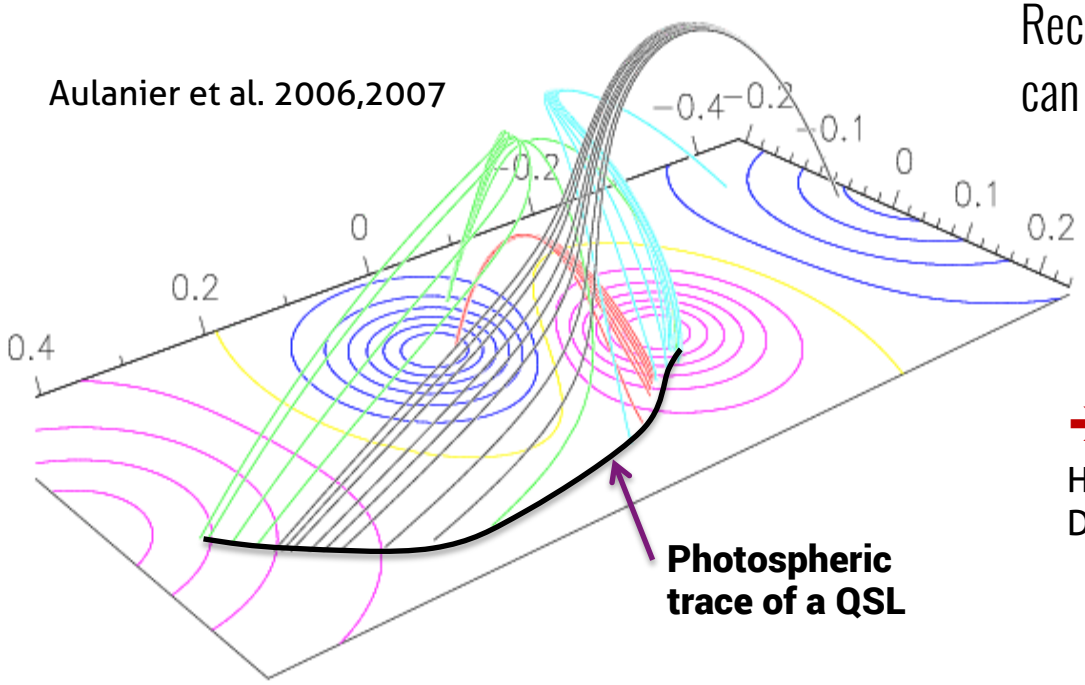
RECONNECTION IN QSLS: Slipping field lines



Reconnecting field lines within QSL:
can only "reconnect" with neighboring field lines

Continuous change of connectivity between neighboring field lines

➔ **"apparent" slippage of the field lines**

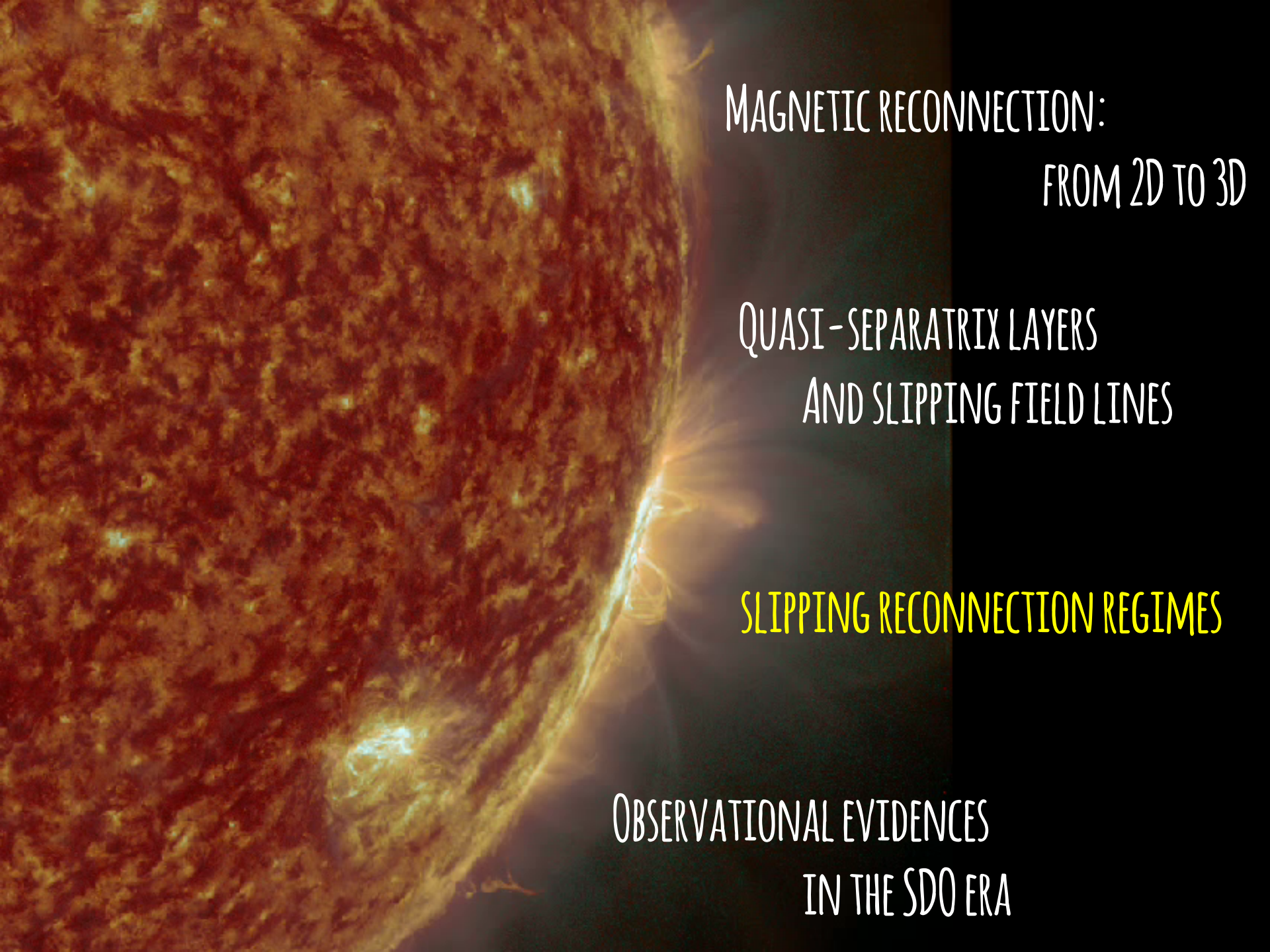
Hesse & Schindler 88, Priest & Forbes 92, Priest & Démoulin 95, Démoulin et al. 96

- Field lines plotted from fixed positions but:
- Two different time = two different field lines
- Field line motion is only apparent
- Only the connectivity change
- Similar slipping motion if other footpoint was chosen

Slipping reconnection

successive reconnection due to the continuous change of connectivity

Török et al. 2009, Masson et al. 2009,2011, Janvier et al. 2013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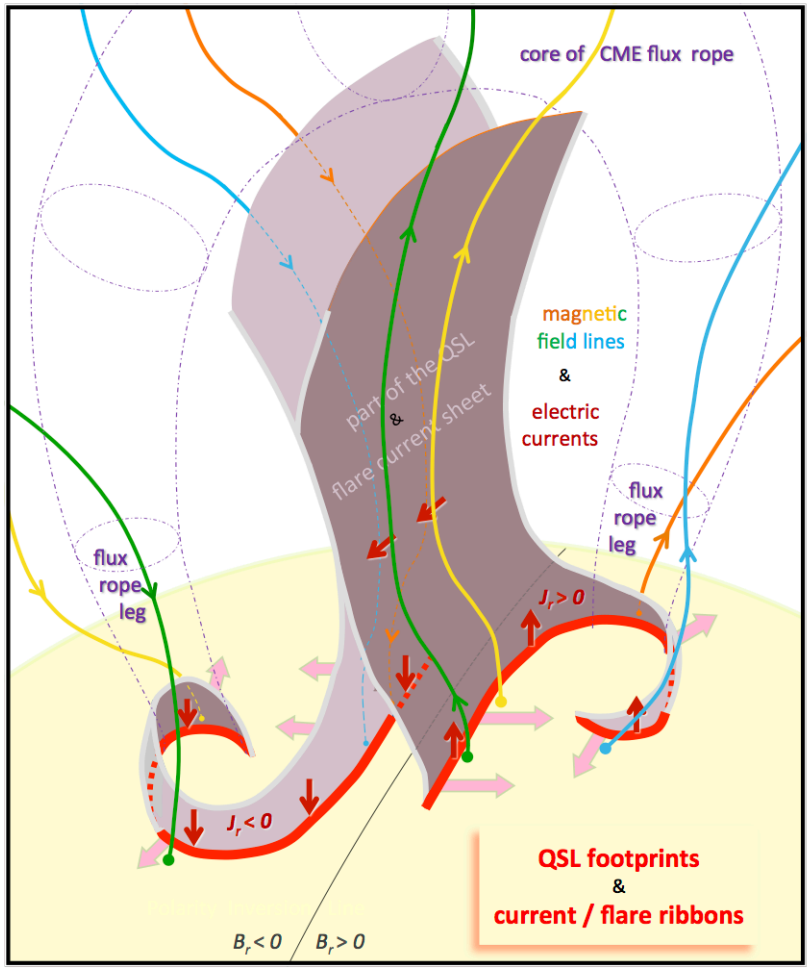
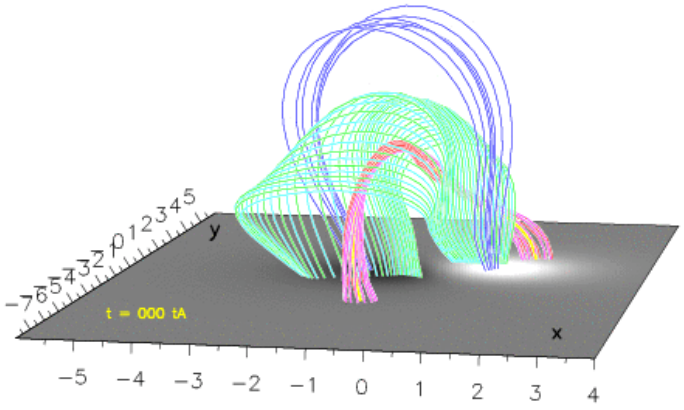
SLIPPING RECONNECTION: Eruptive flares

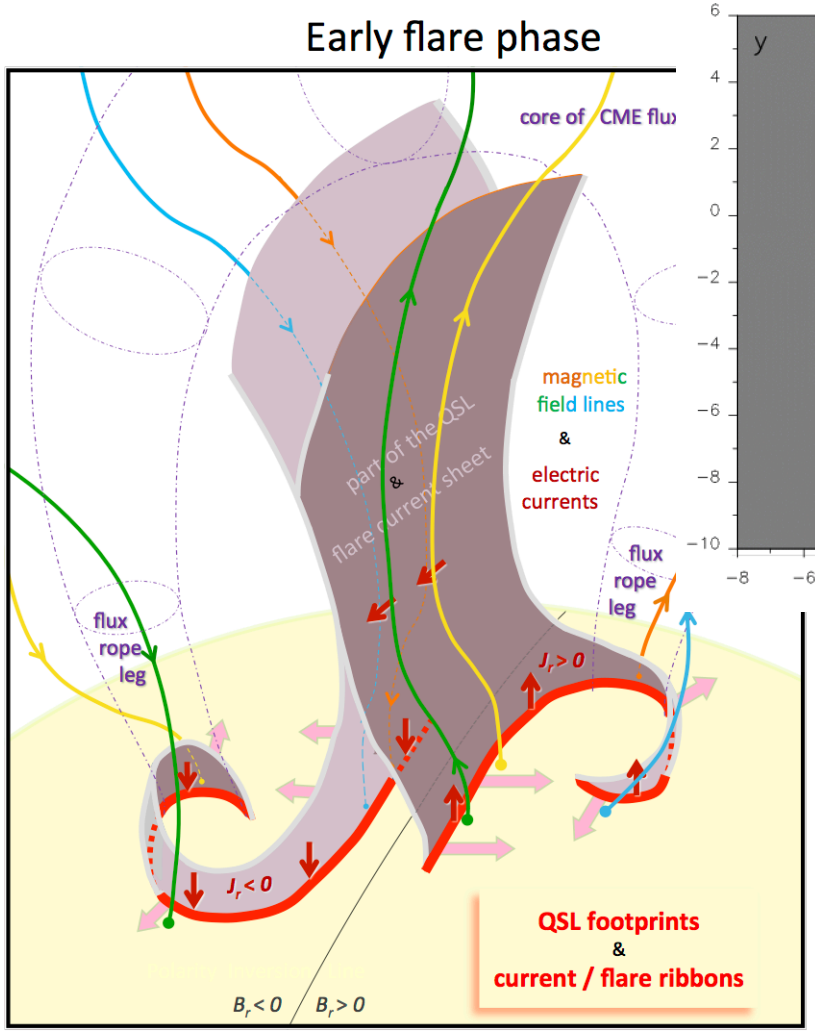
Early flare phase



Janvier et al. 2014



SLIPPING RECONNECTION: Eruptive flares



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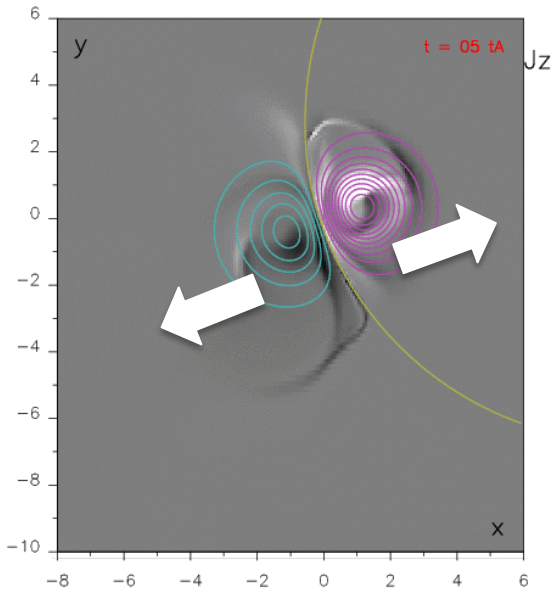

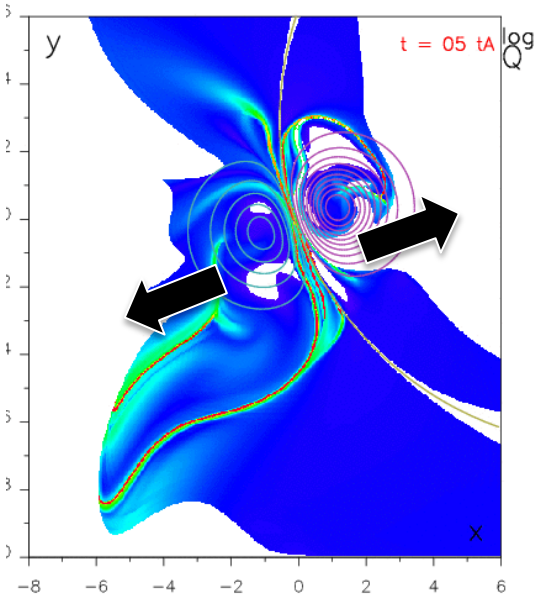

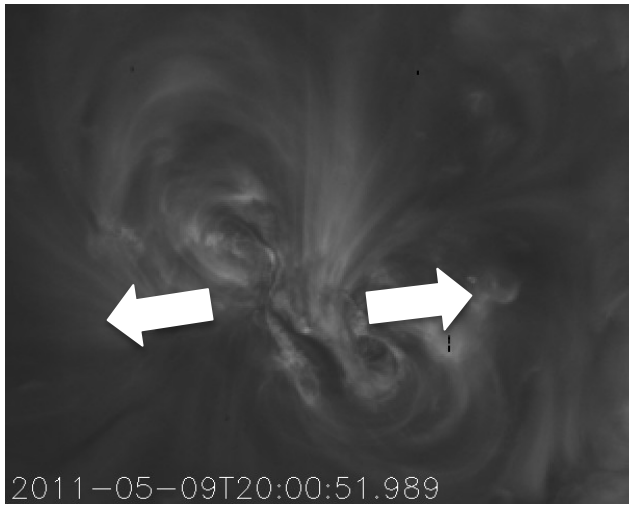

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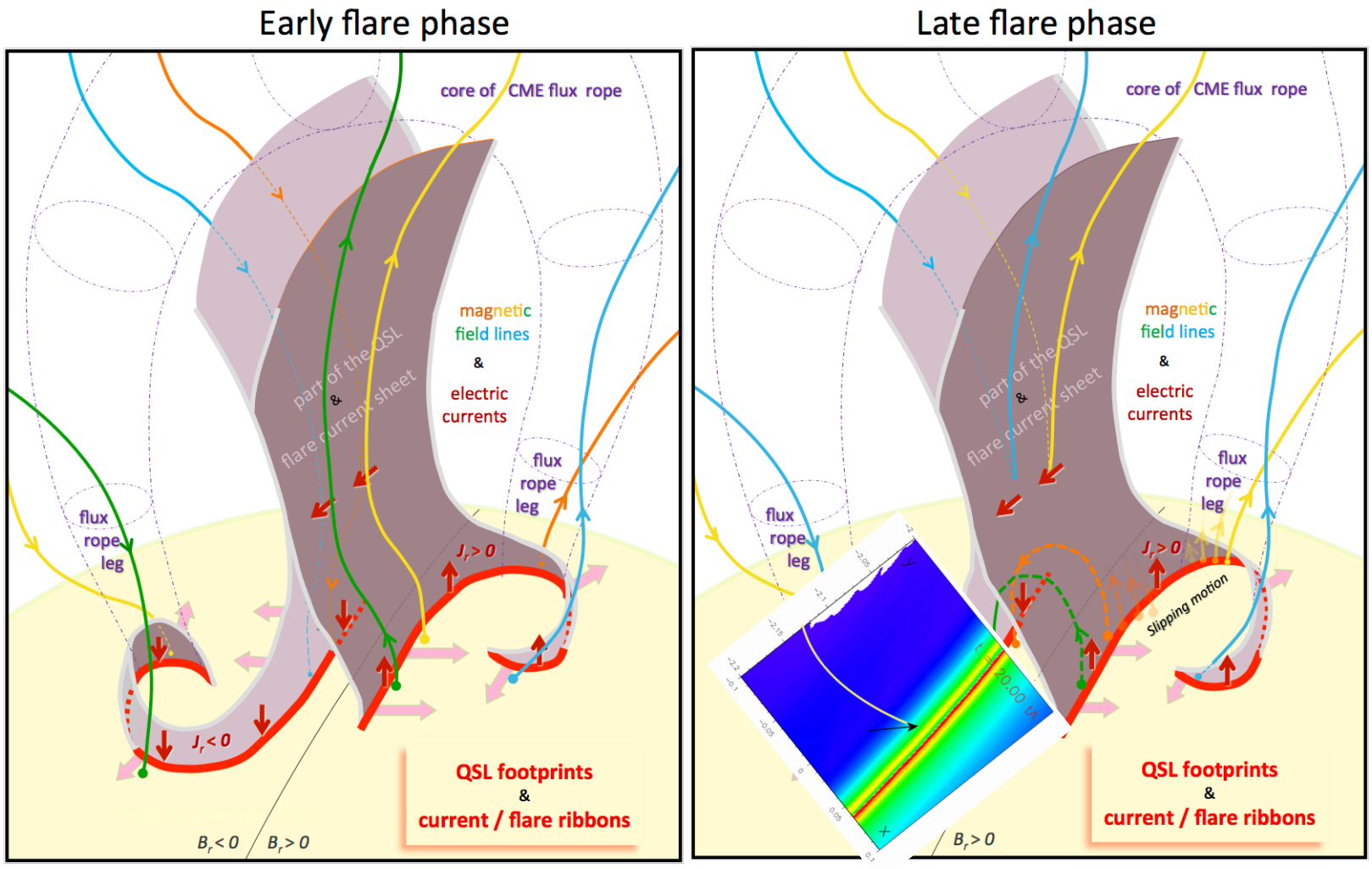

Janvier et al. 2014

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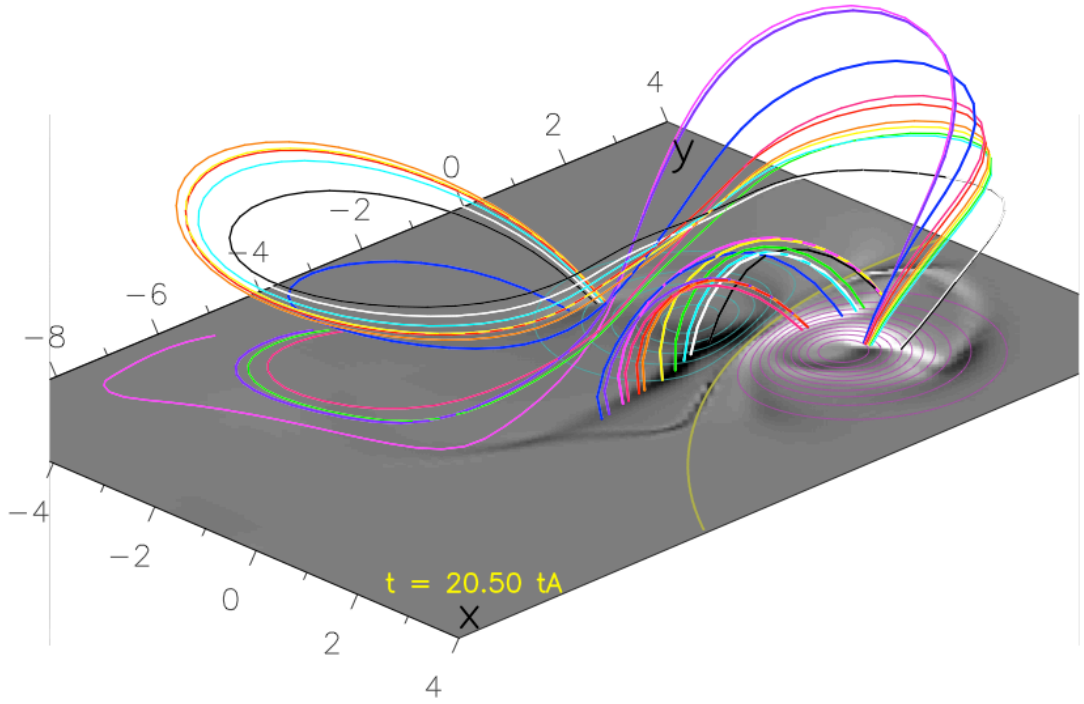
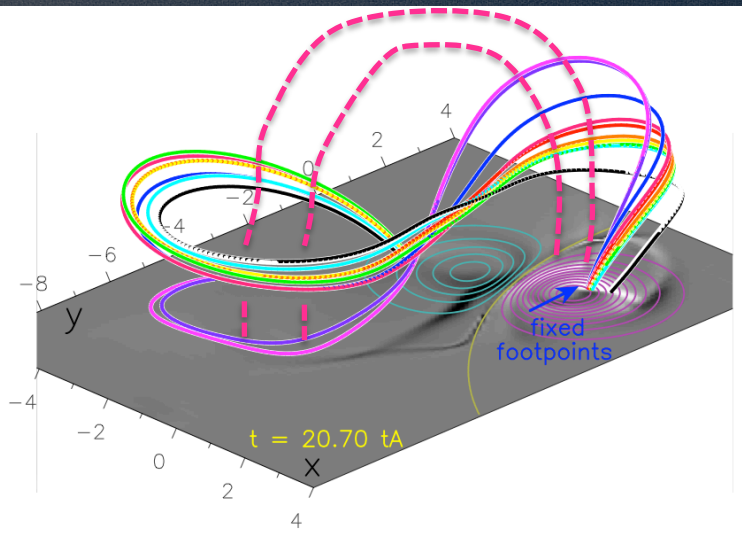
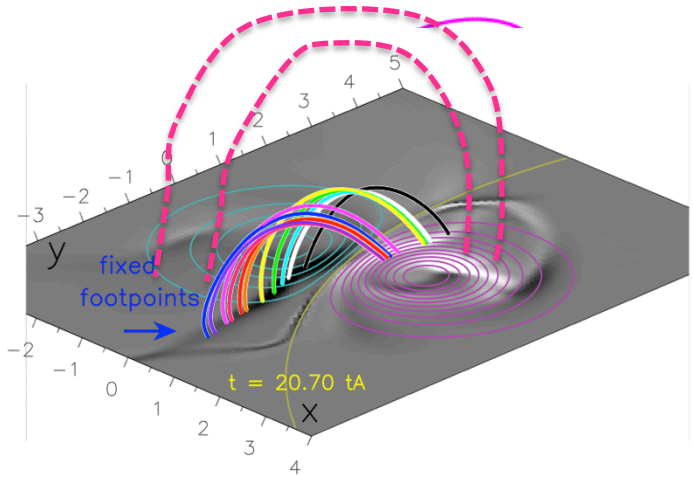
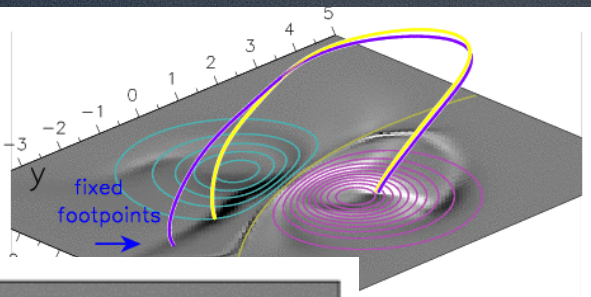


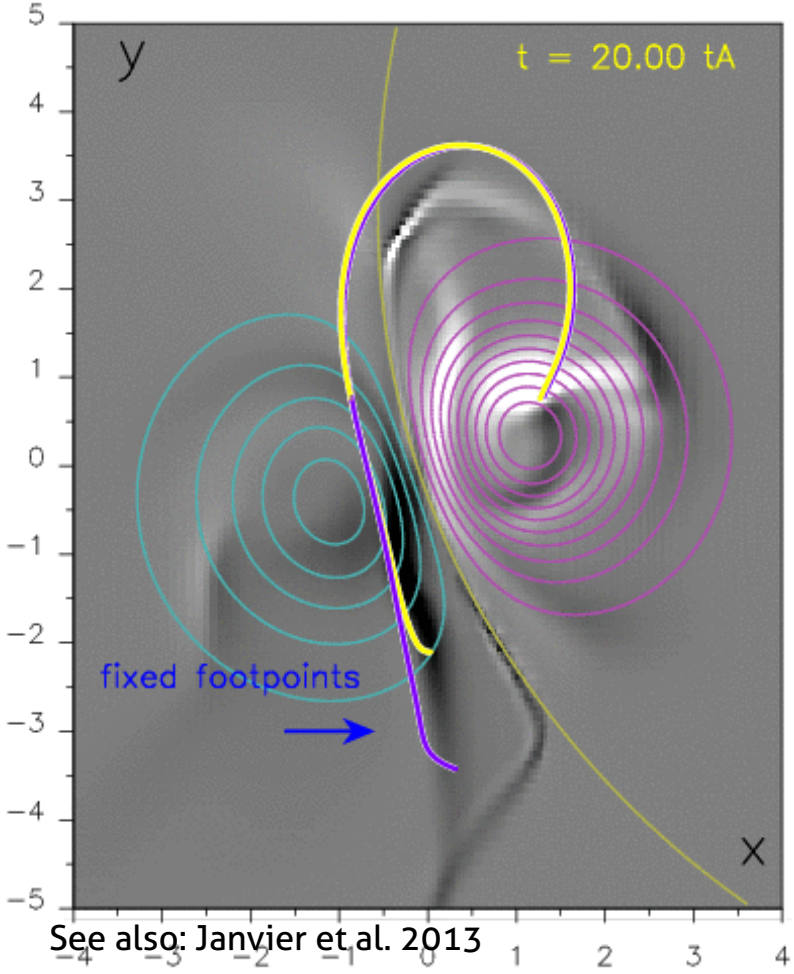


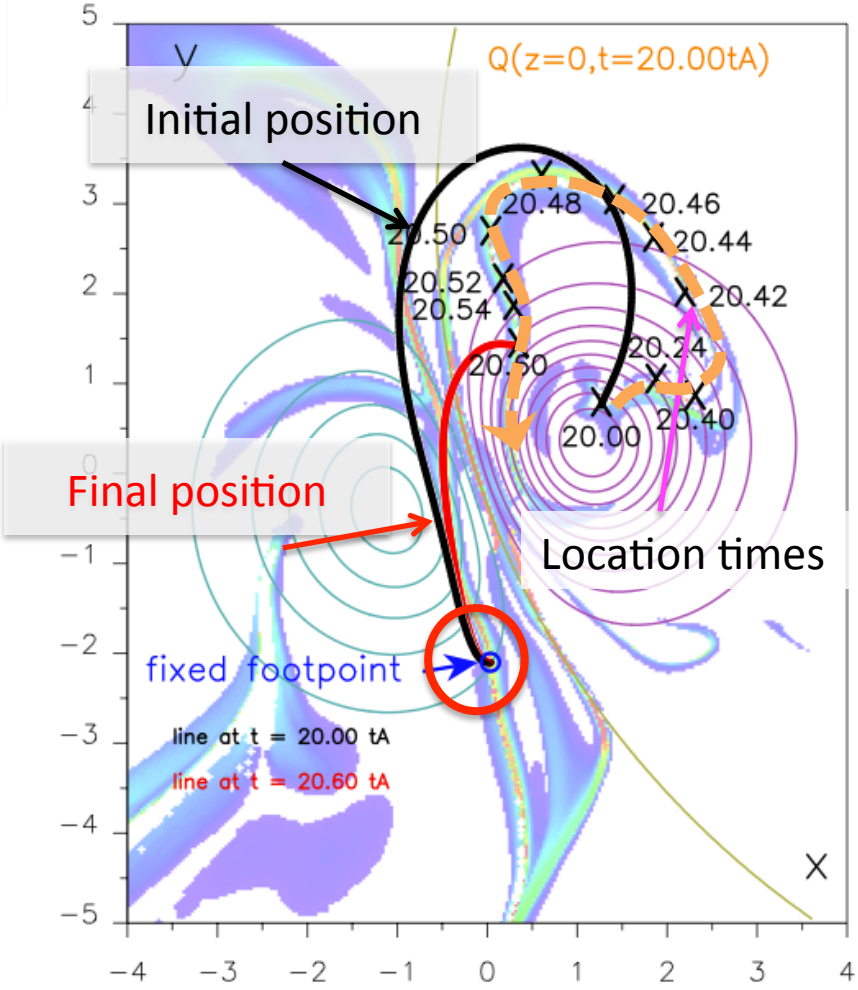


See also: Janvier et al. 2013

SLIPPING RECONNECTION: Eruptive flares



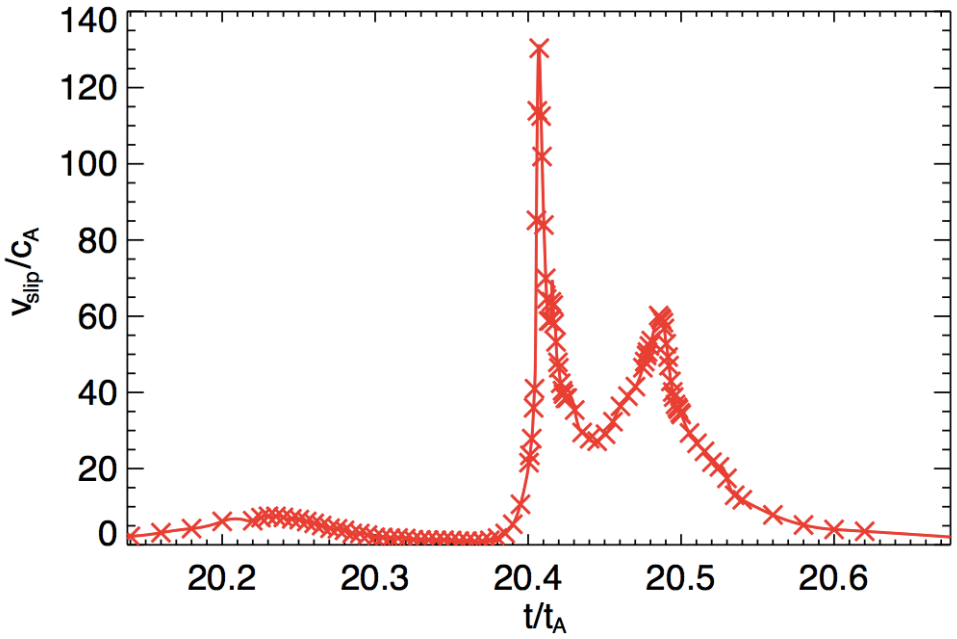


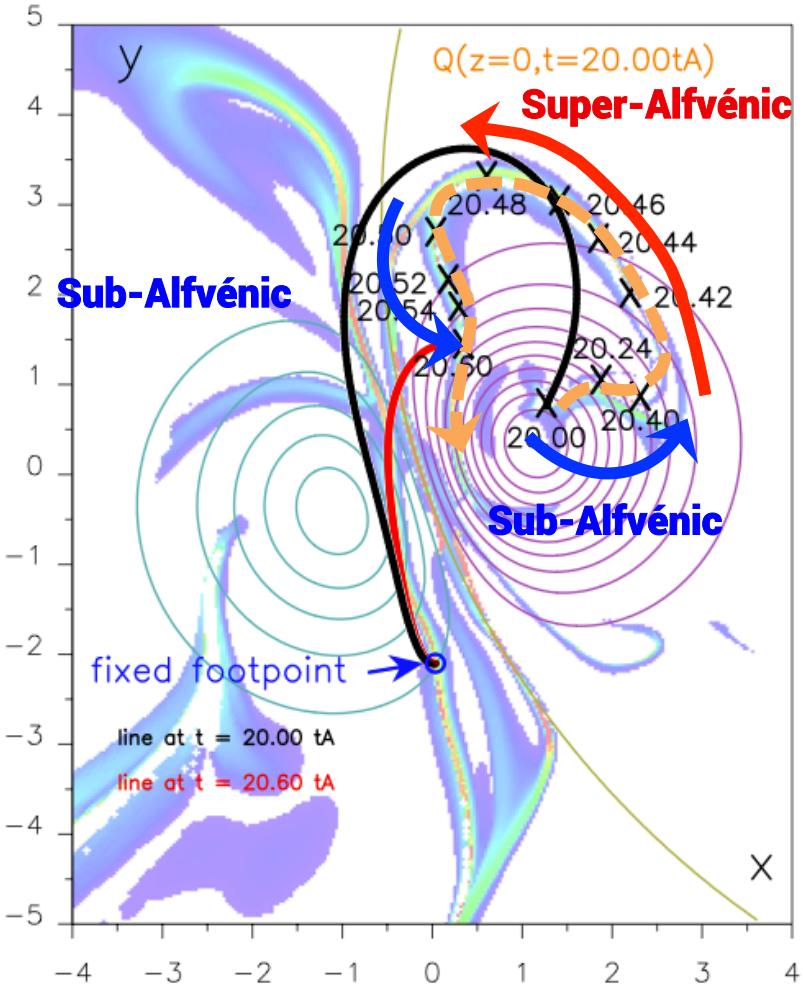


See also: Janvier et al. 2013

SLIPPING RECONNECTION: Eruptive flares

Slip-running speed profile





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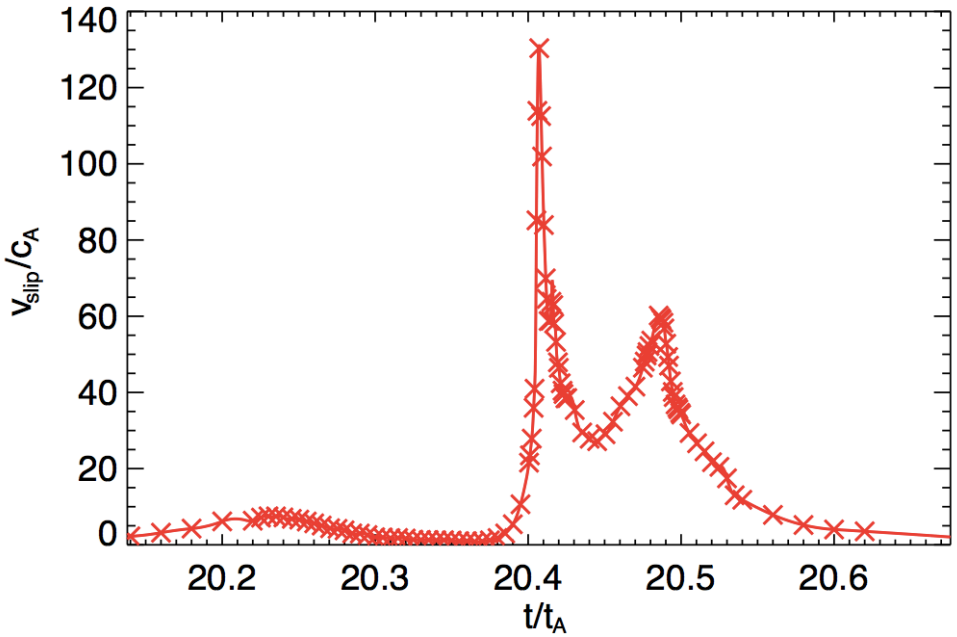
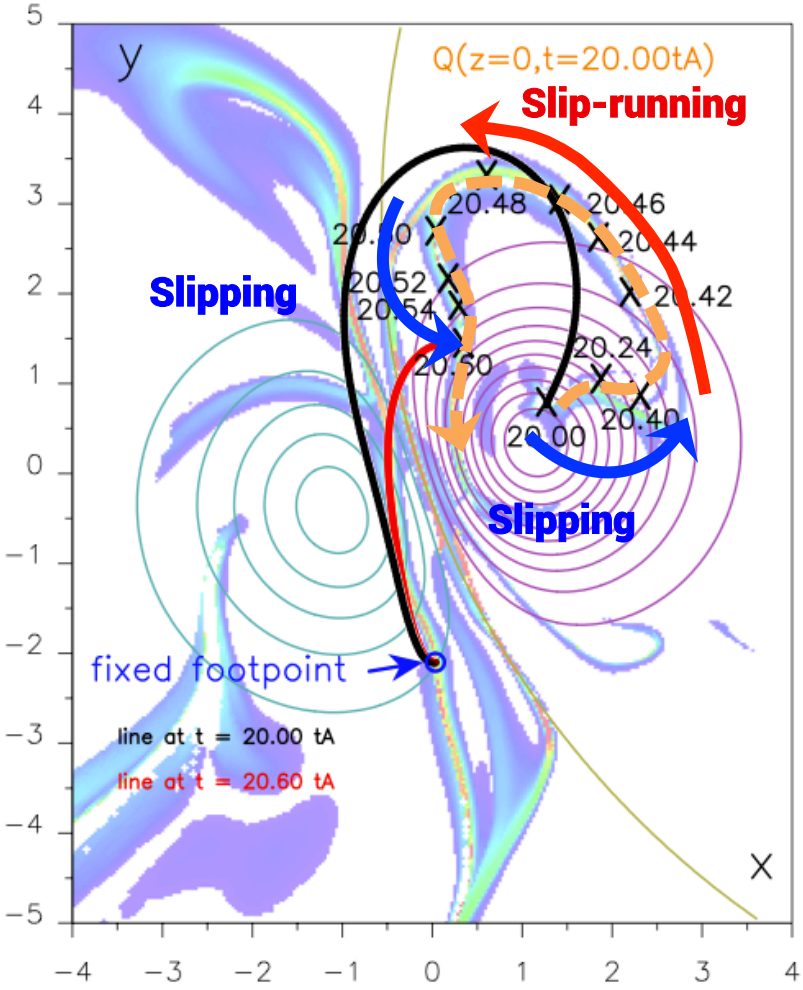


MHD paradigm: information « travels » at c_A:

➔ fixed footpoint does not « see » the change of connectivity

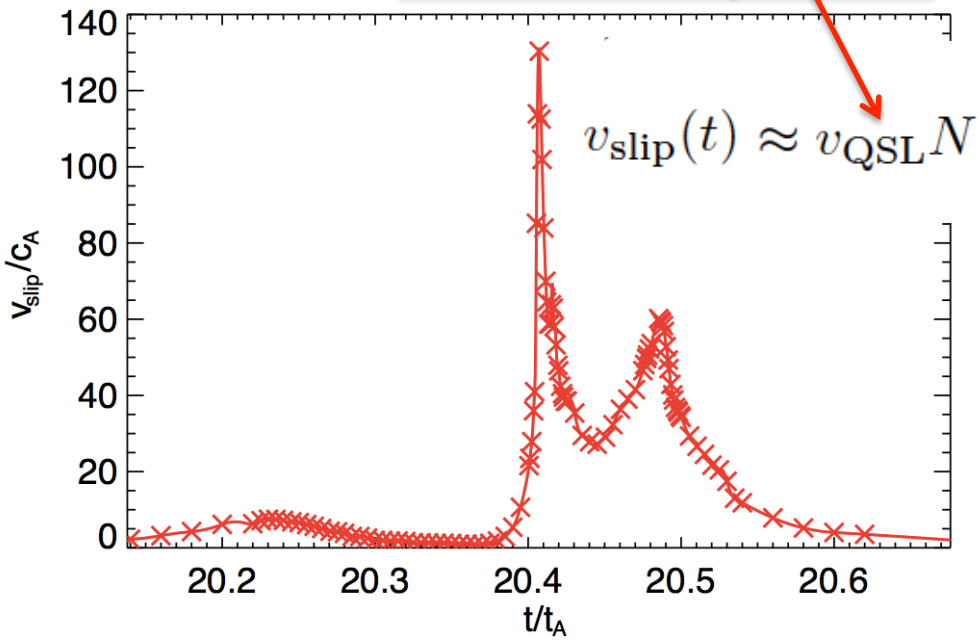
On MHD time-scales, at the scale of the whole system, slip-running field lines behave as if reconnected at separatrices.

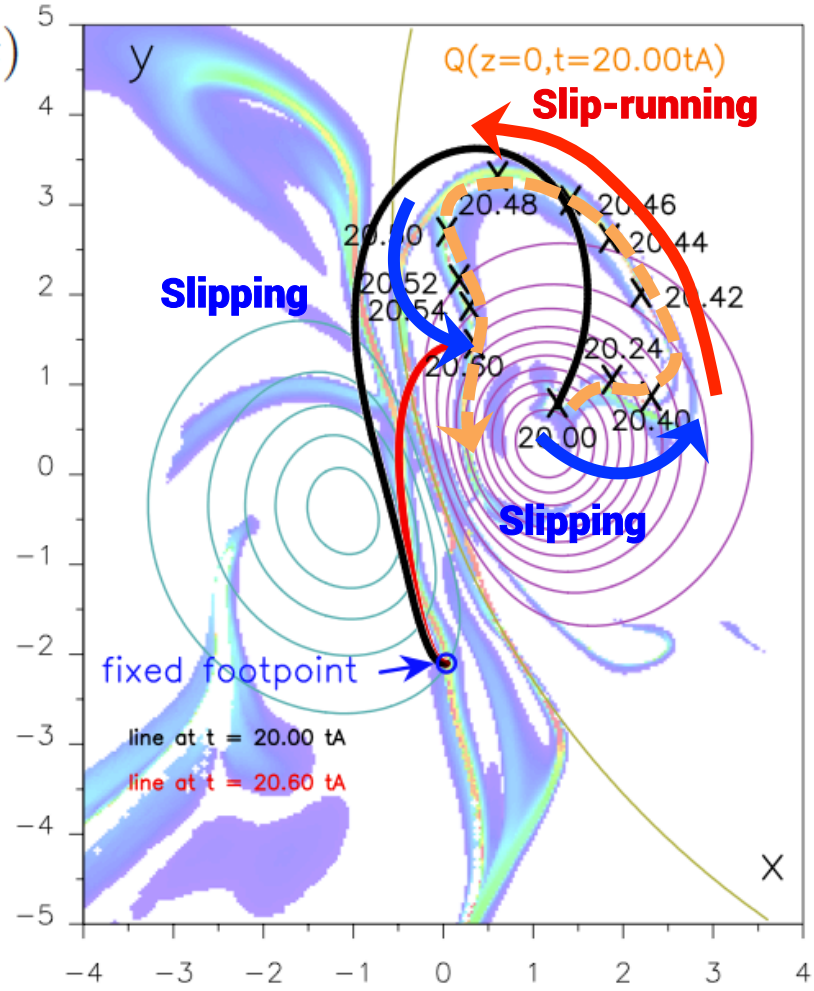


SLIPPING RECONNECTION: Eruptive flares

Reconnection physics (current layer)

Magnetic topology





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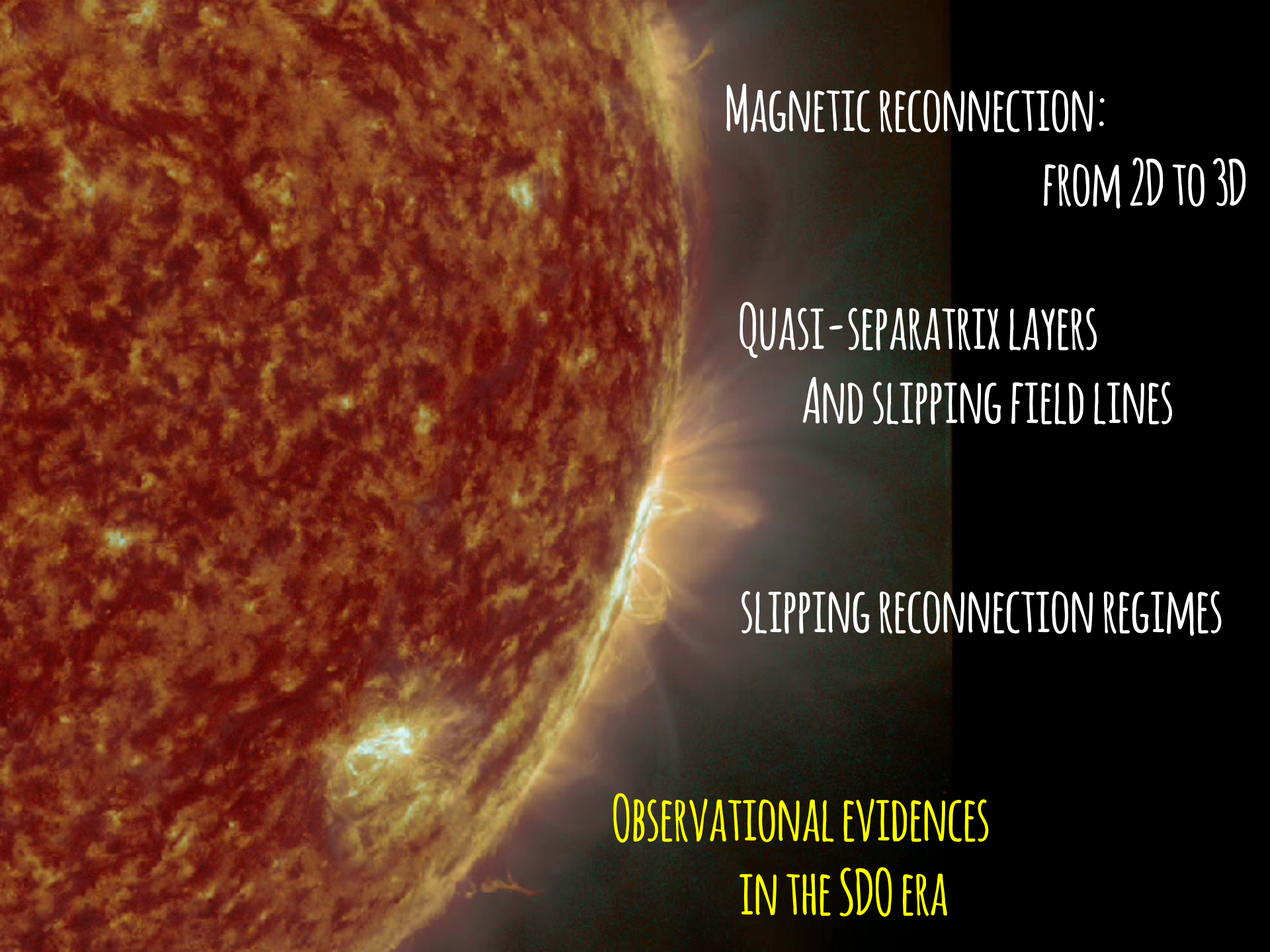
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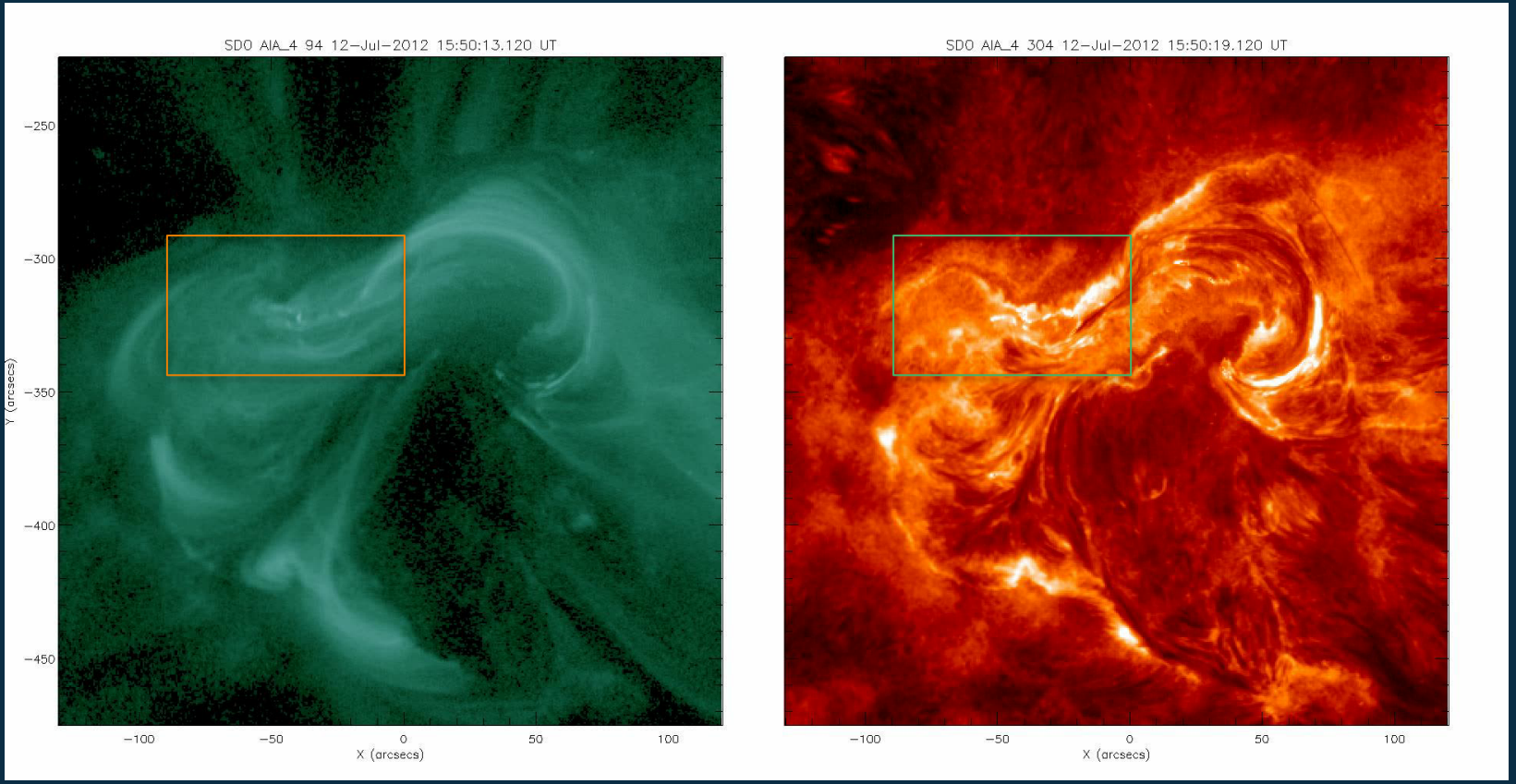
ERUPTIVE FLARES: SDO observations

July 12 2012, X-class flare, Dudík, Janvier et al. (2014)



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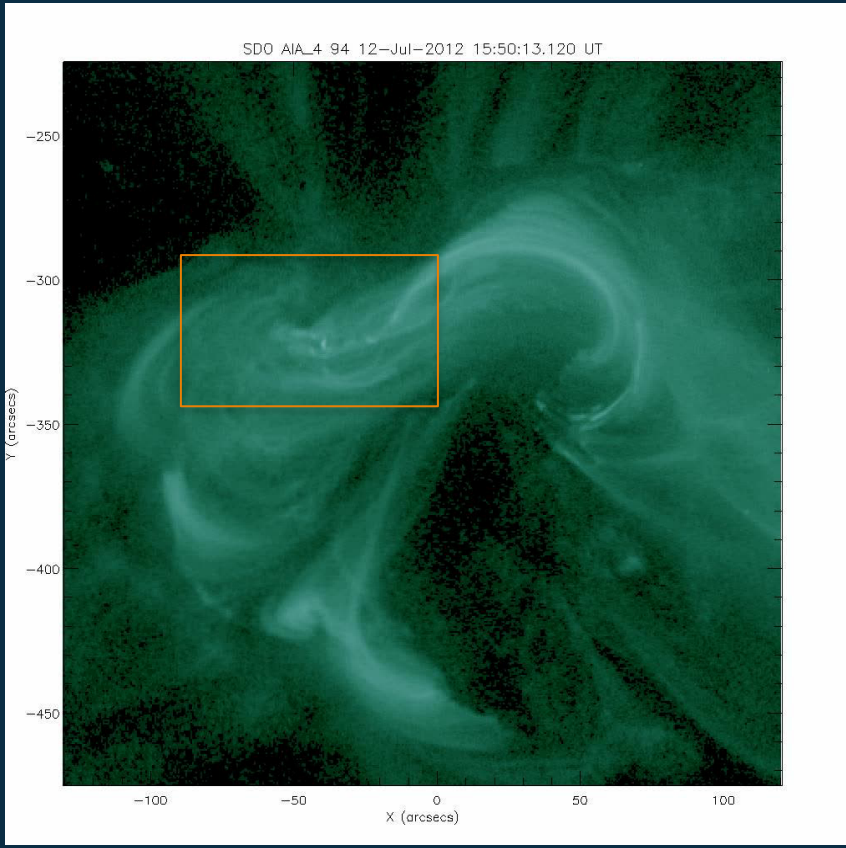

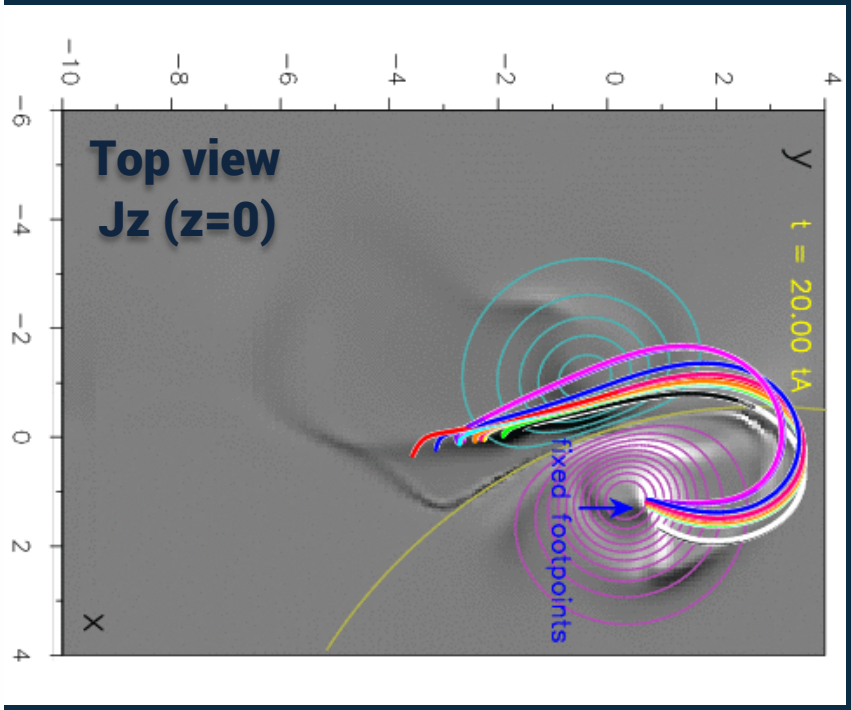

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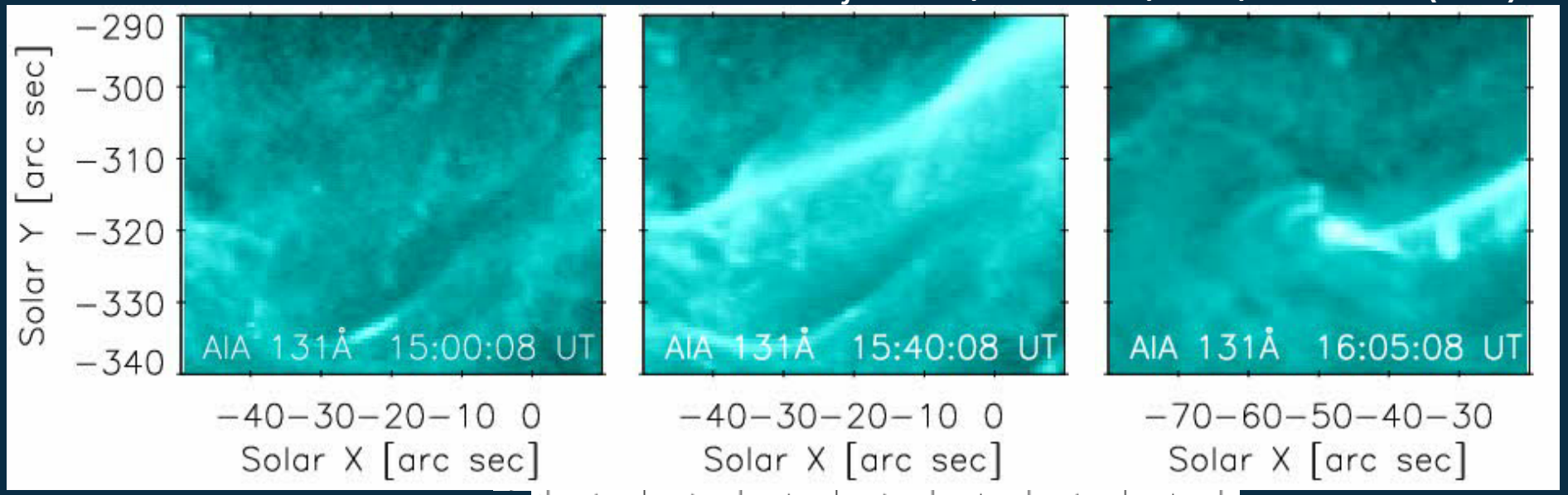

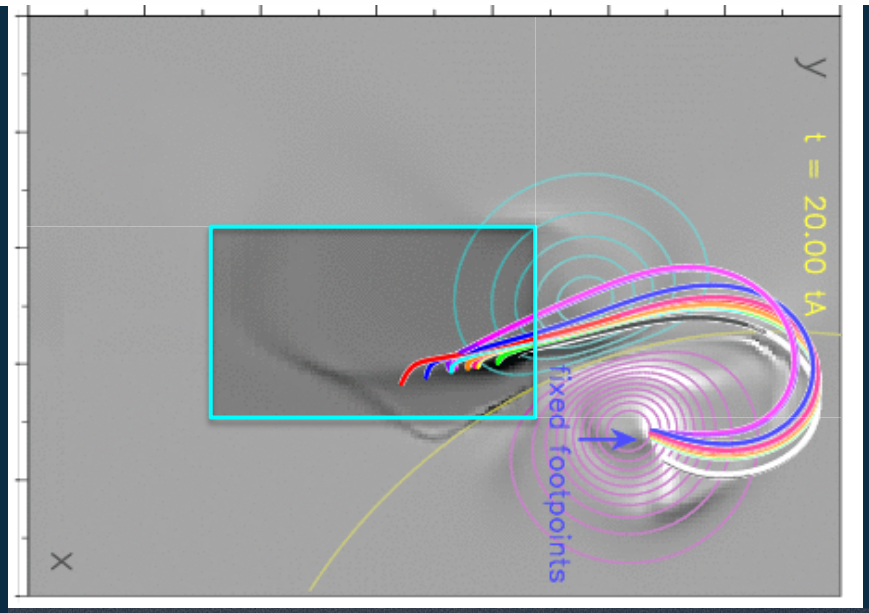

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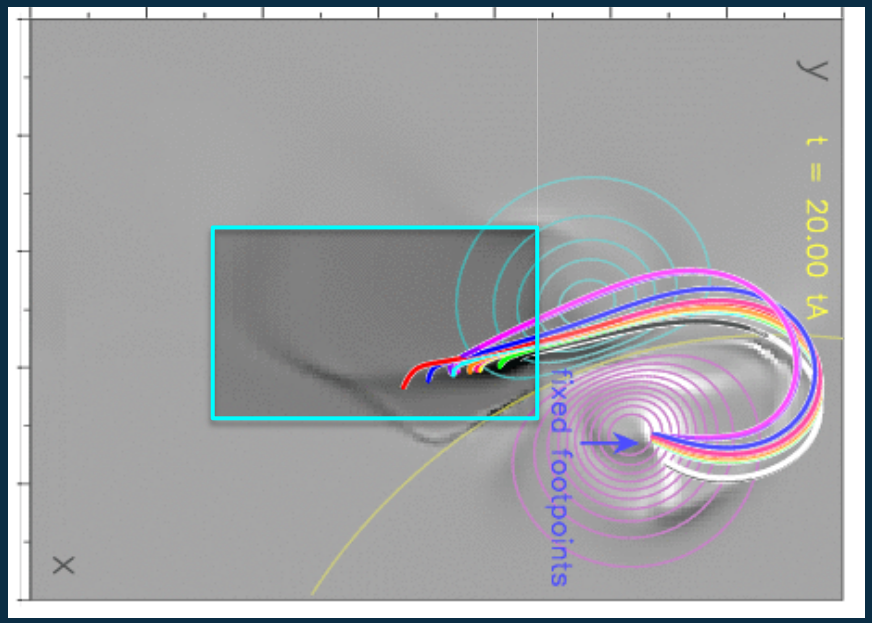
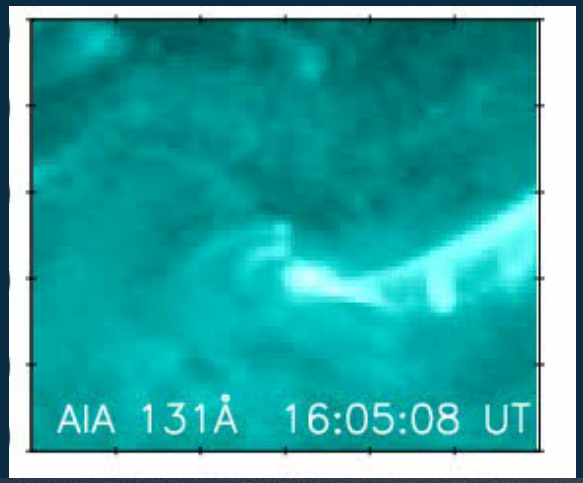
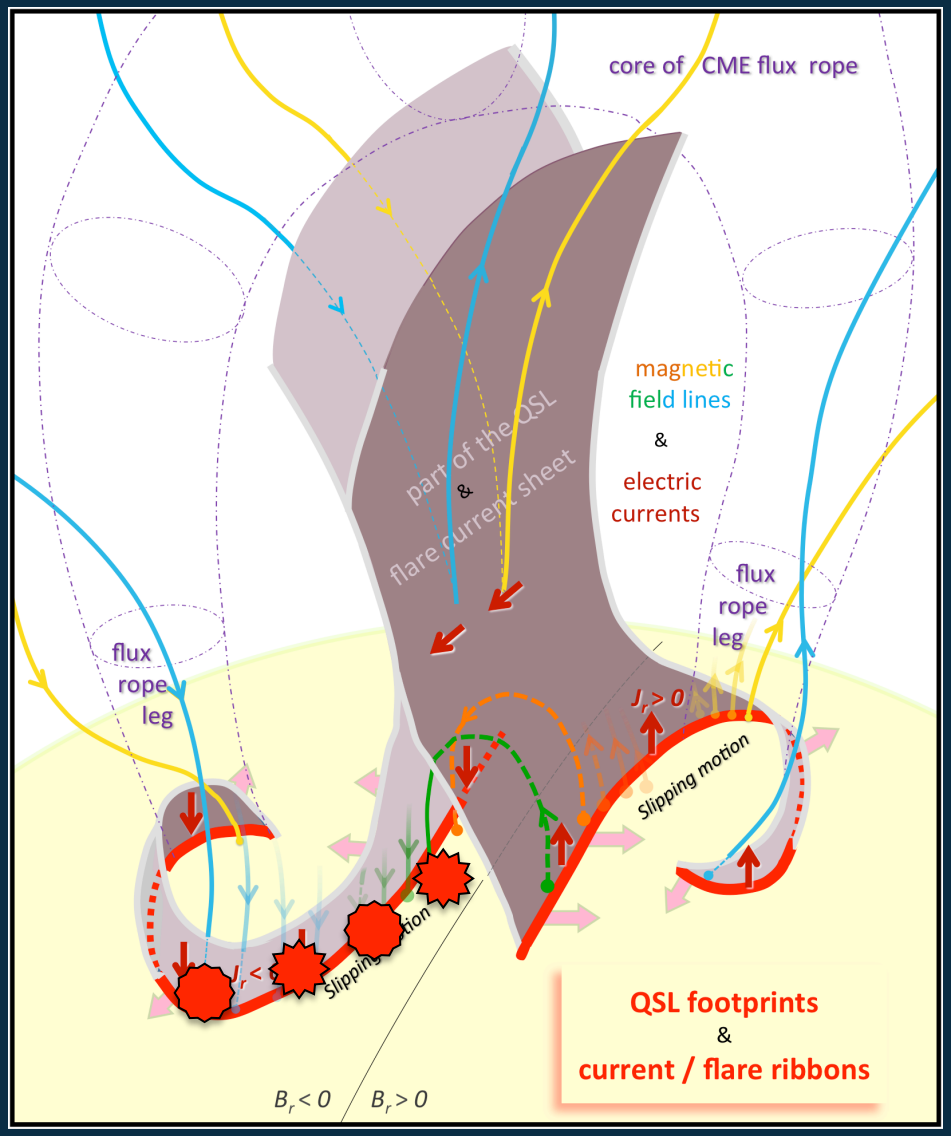






ERUPTIVE FLARES: SDO observations

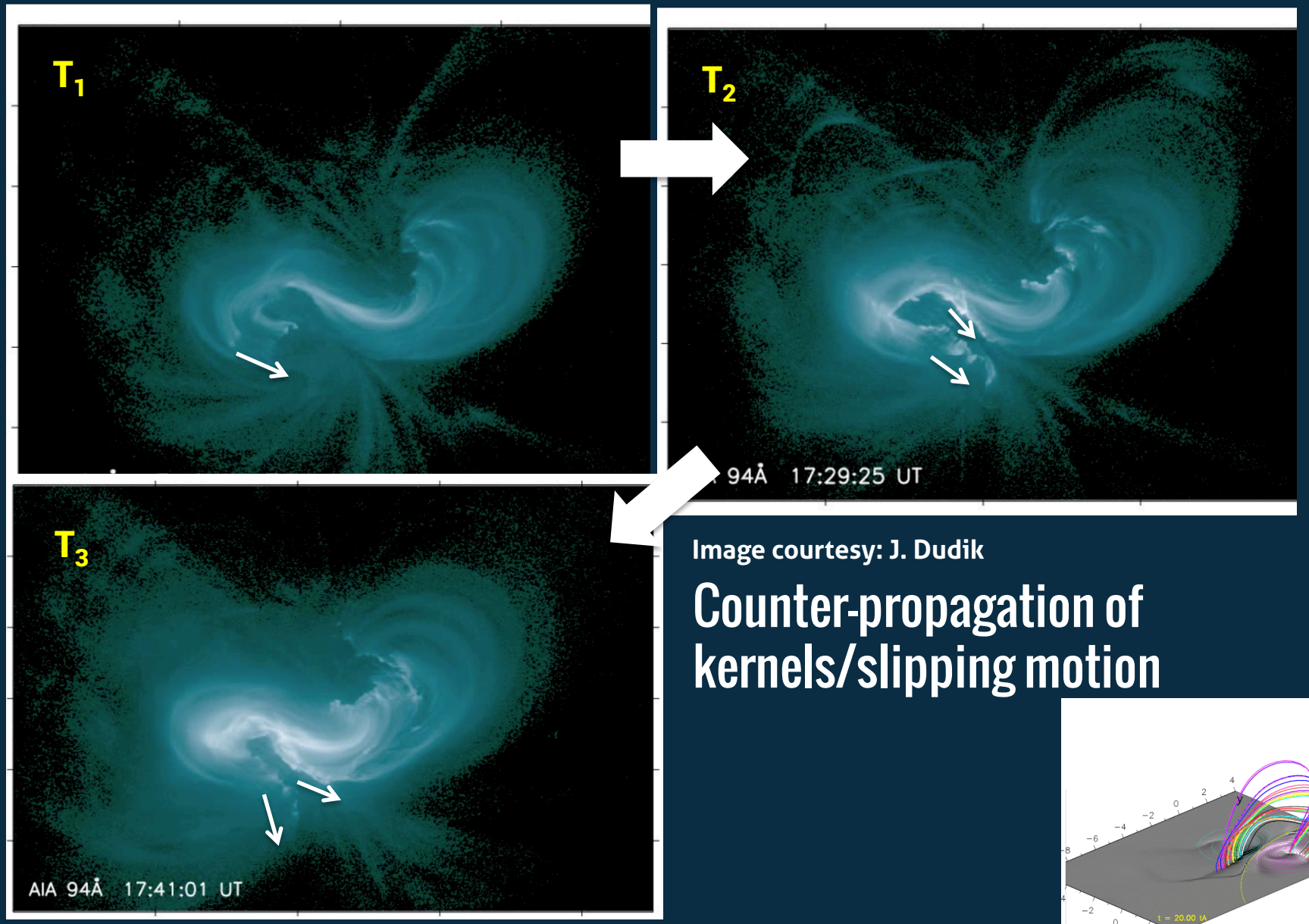
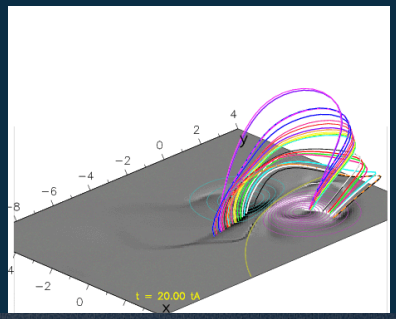


Image courtesy: J. Dudik

Counter-propagation of kernels/slipping motion



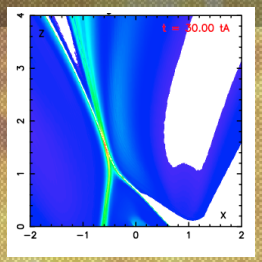
CONCLUSIONS

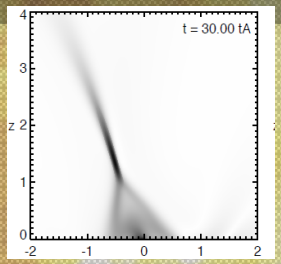
Flare configurations

- Null points + Separatrices
- Quasi-separatrix layers (dominant)

Definition of Quasi-Separatrix Layers

- QSLs extend the concept of separatrices
- QSLs: similar locations as currents

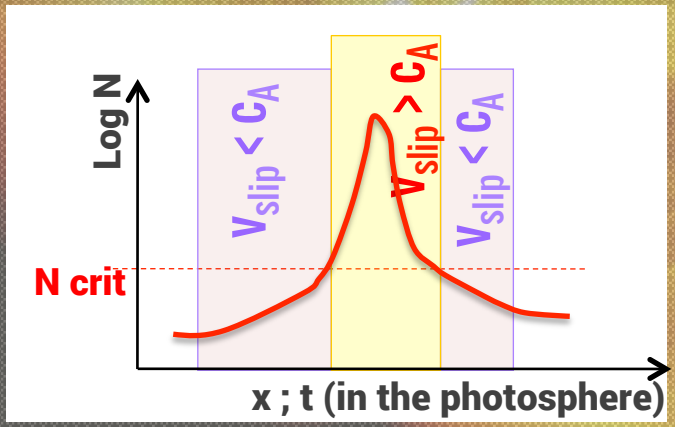




Slipping motion of field lines in QSLs

Slipping vs Slip-running

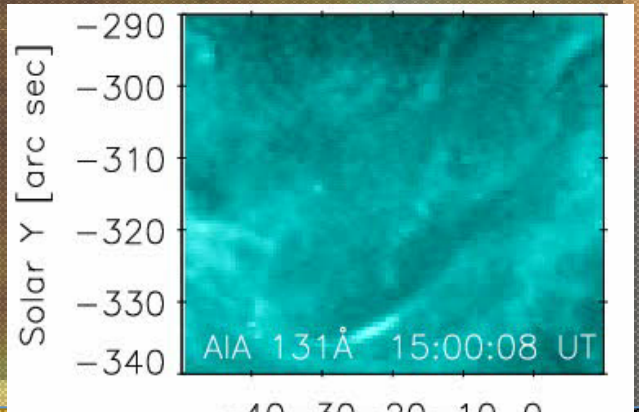
- Speed of change of connectivity linked with field line mapping
- Slipping vs « slip-running »



Model predictions vs Observations

Explains motion of kernels/loops

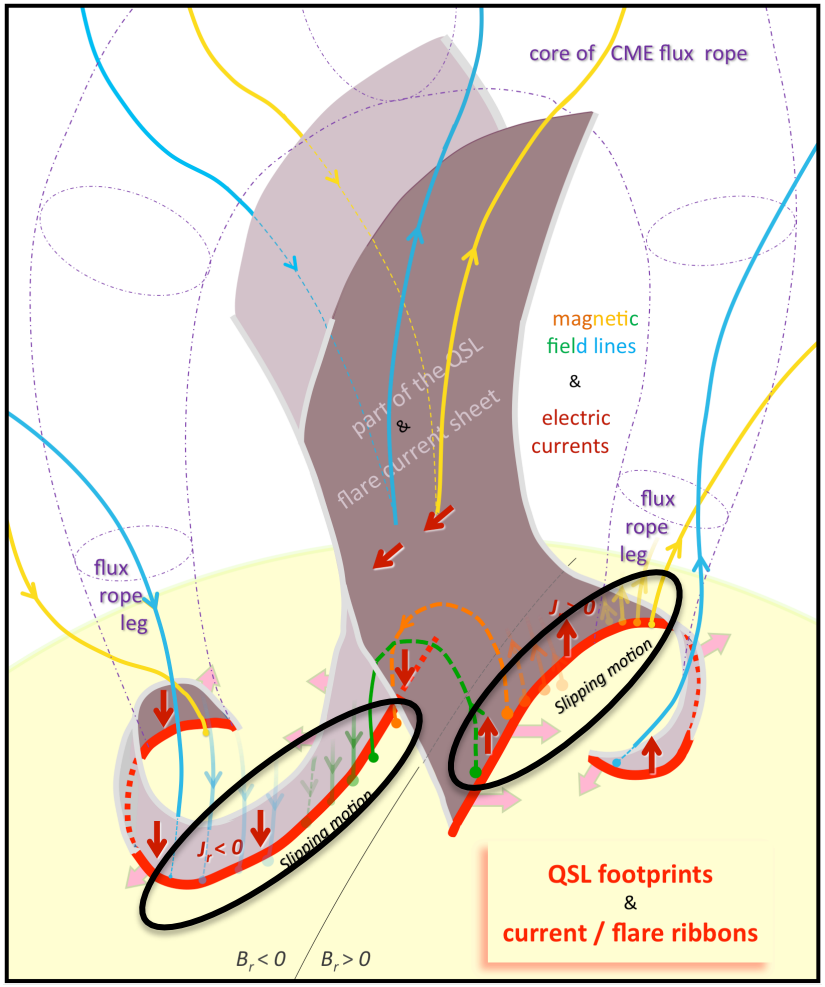
- High time cadence observations now show what models/ simulations predicted



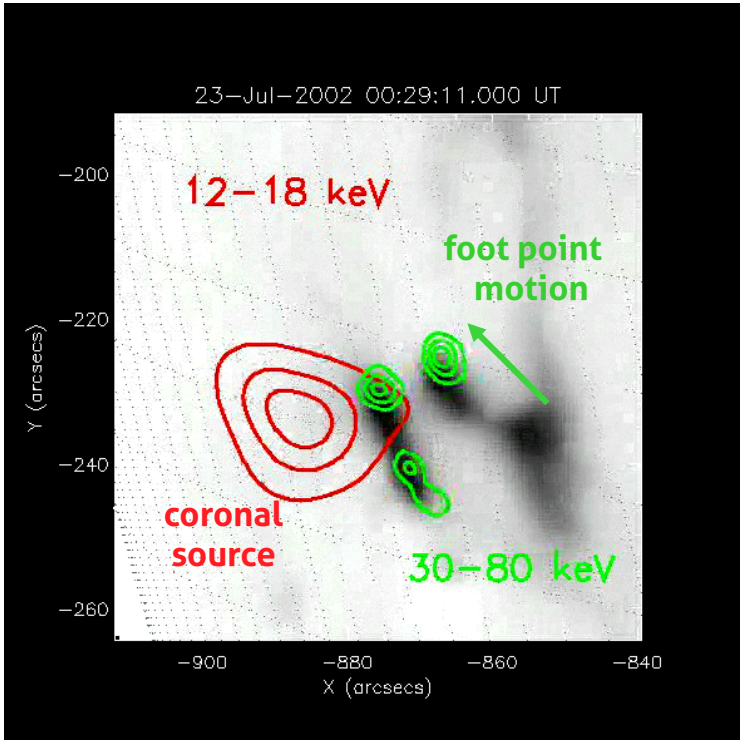
ERUPTIVE FLARES: MODEL PREDICTION & FUTUR CONFIRMATION?

QSL reconnection:

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



H_α & HXR sources



Krucker et al. (2003)

ERUPTIVE FLARES: MODEL PREDICTION & FUTUR CONFIRMATION?

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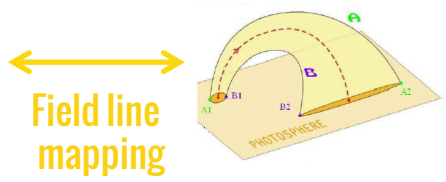
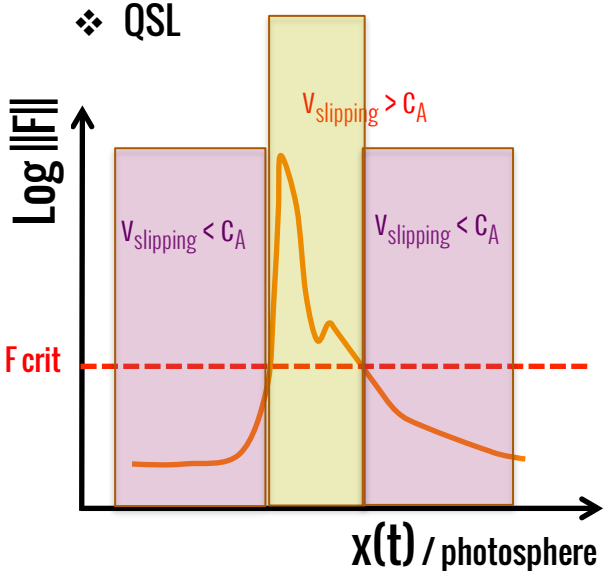
$$v_{slipping} = \alpha \, \| F \|$$



Janvier et al. (2013)

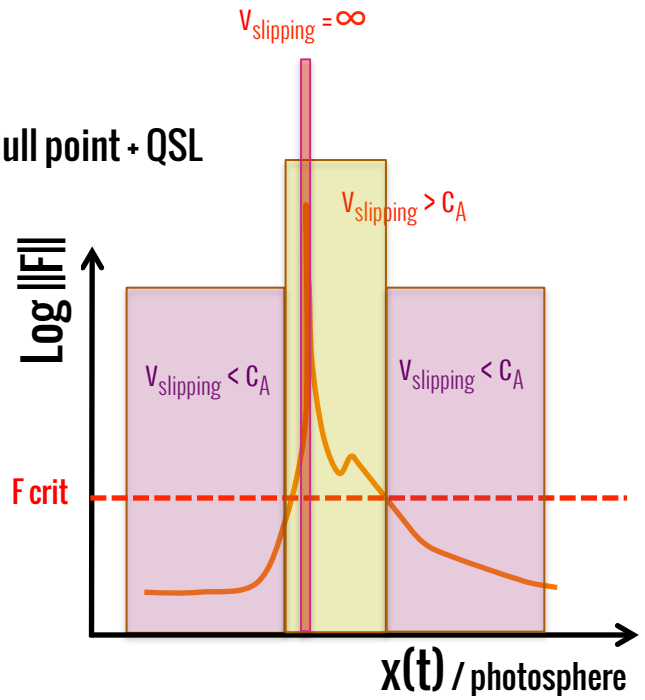
- QSL



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)