Magnetic field topology and energy release sites

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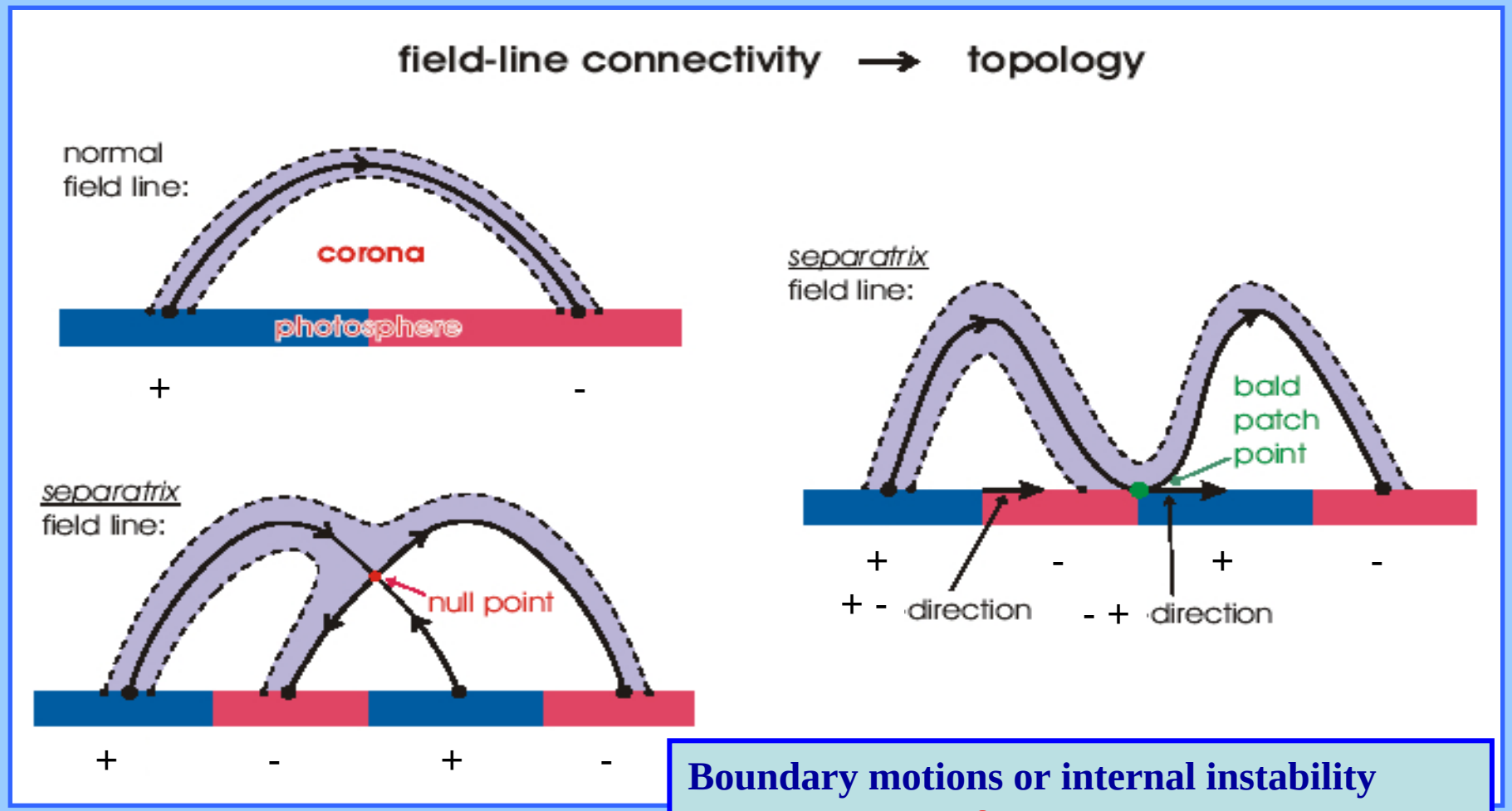
Basic configurations: 2D and 2.5D



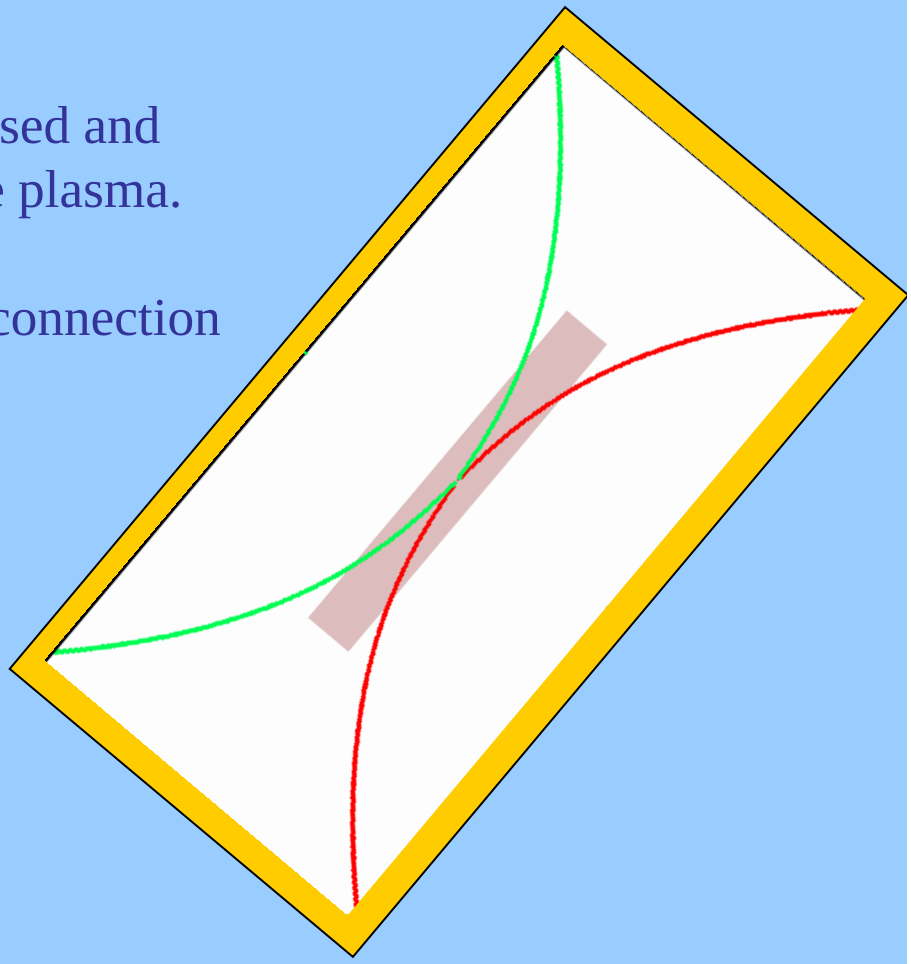
Boundary motions or internal instability
→ current sheet formation on the separatrices
→ magnetic reconnection

Energy release mechanism: **Magnetic reconnection**

Magnetic reconnection is a topological restructuring of the magnetic field caused by **change in the connectivity of its field lines.**

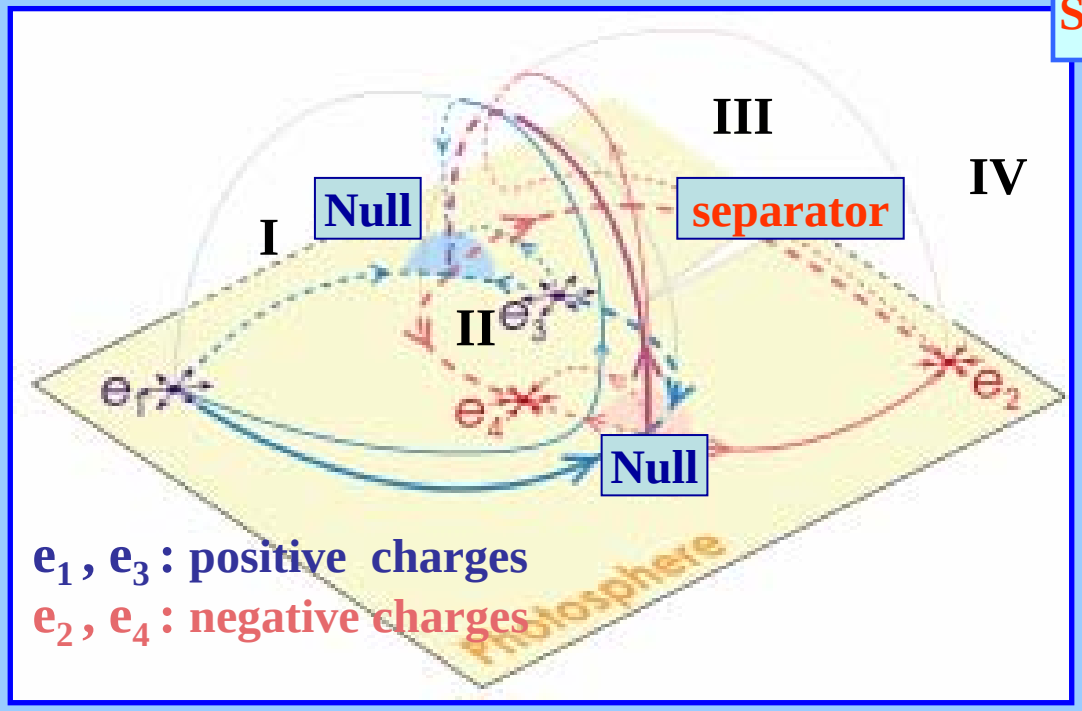
By this change free magnetic energy is released and converted into heat and kinetic energy of the plasma.

Small spatial scales should be present for reconnection to be efficient.

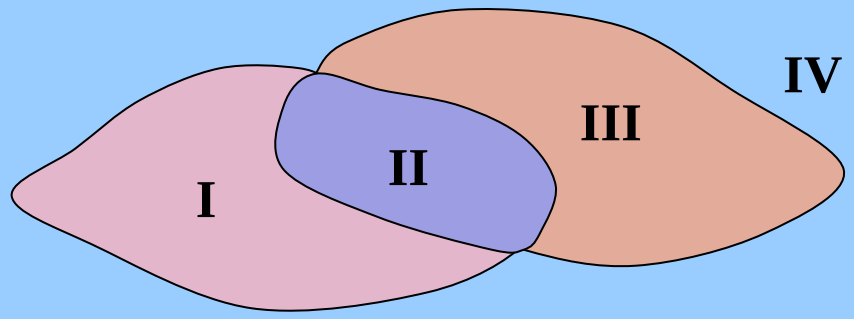


Configurations in 3D: **4 magnetic sources**

Separatrices: 2 intersecting surfaces



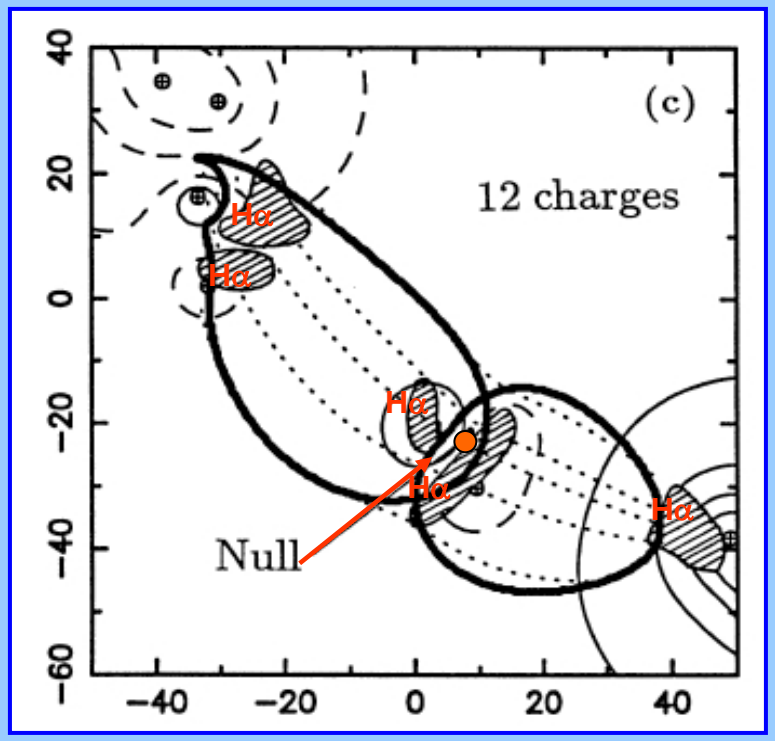
→ Current sheet at separator
→ Reconnection
→ Flux exchange between domains



(Baum & Brathenal 1980, Hénoux & Somov 1987, Gorbachev & Somov 1988, 1989, Lau 1993)

Topology: **magnetic sources and observations**

The magnetic field is described by charges { **below the photosphere** (topology given by: connectivity between sources)

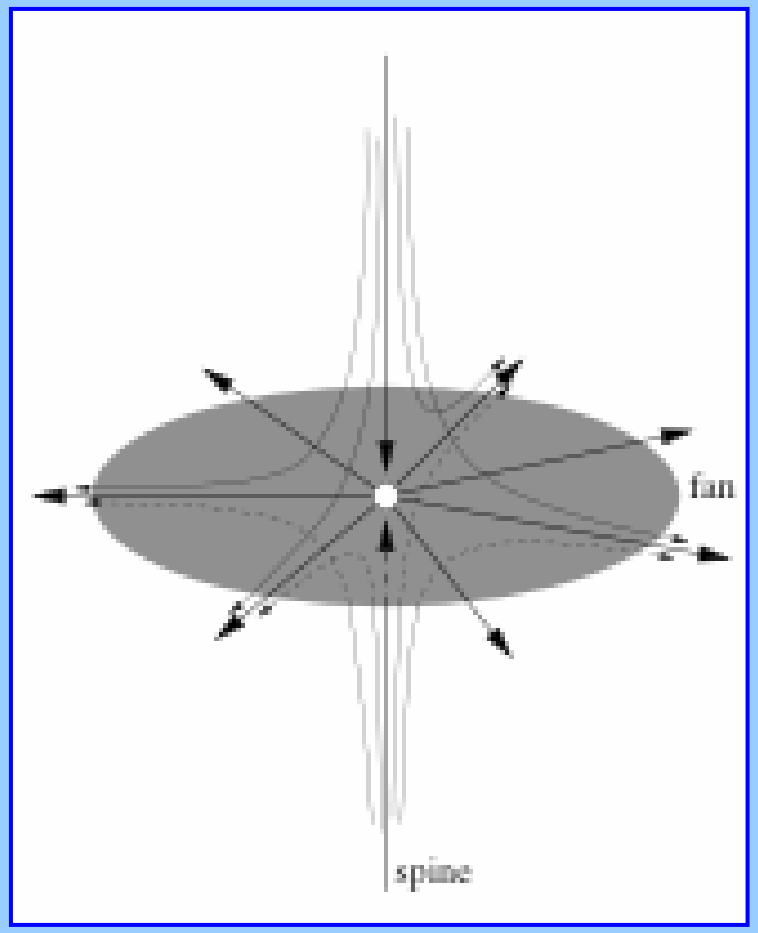


Choose **intensity and location** of charges by least-square fitting of the computed field to the observed field.

Hα and UV flare brightenings at intersection of separatrices with chromosphere → connected by lines expected to form by magnetic reconnection.

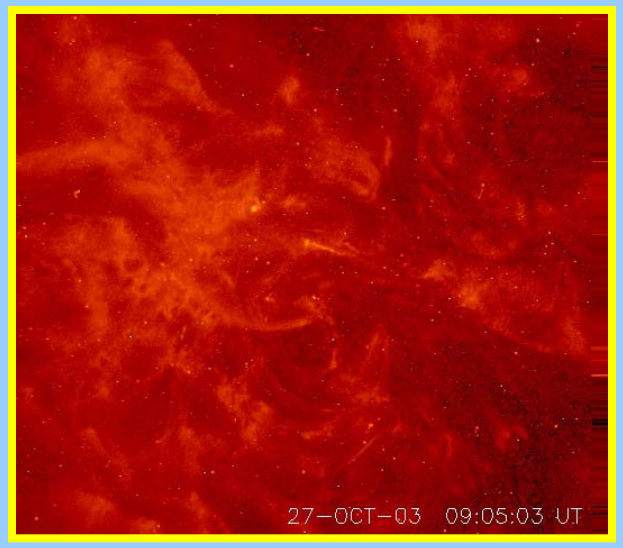
(Mandrini et al. 1991- coronal null, 1993, 1995, Démoulin et al 1993, 1994, van Driel-Gesztelyi et al. 1994, Bagalá et al. 1995, Gaizauskas et al 1998 - coronal null)

Topology around null points

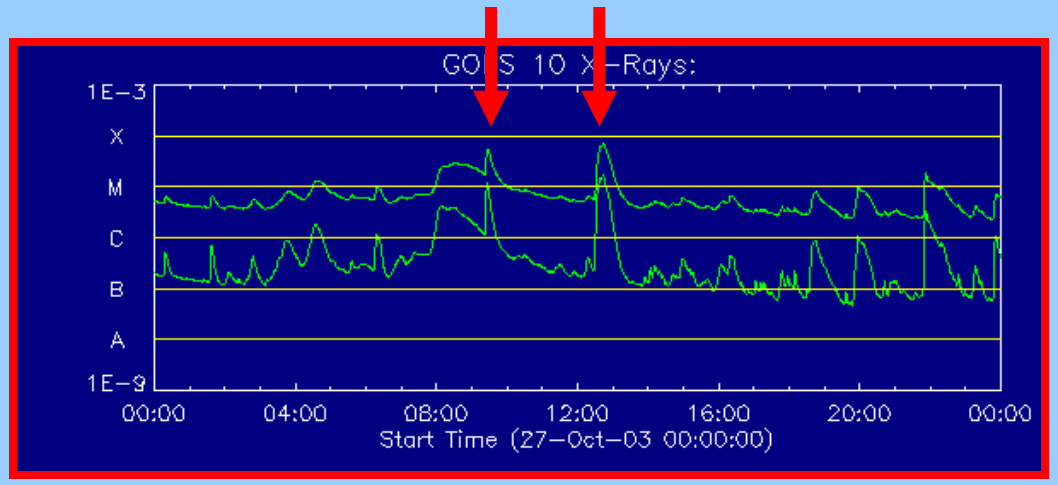


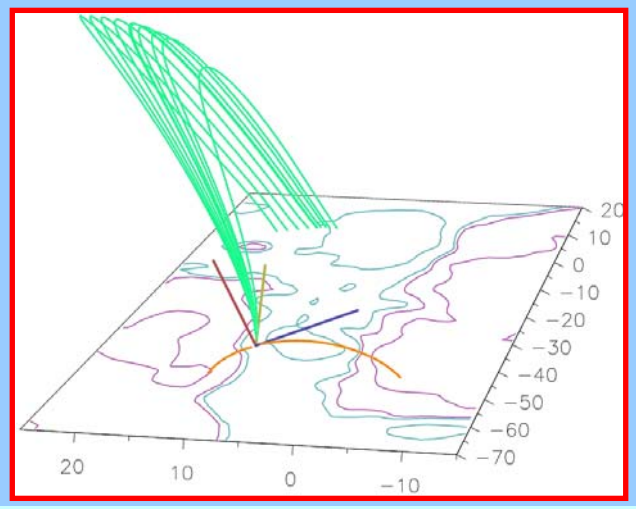
Topology without charges: **Coronal null points and observations**

(Luoni et al. 2006)



M5.0 flare at 9:21 UT and
M6.7 at 12:27 UT
27 October, 2003 - AR10486





Fan along the lowest eigenvalue and spine – 27 October null point

Magnetic extrapolation of MDI magnetogram (lfff)

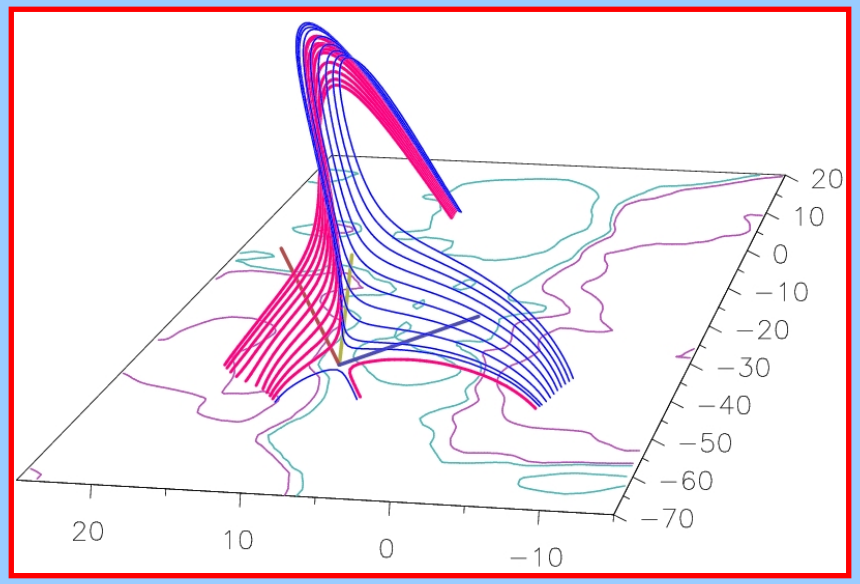
Null of type B: 2 positive eigenvalues (fan plane, $\lambda_{1,yellow}$ and $\lambda_{2,red}$), 1 negative (spine, $\lambda_{3,blue}$).

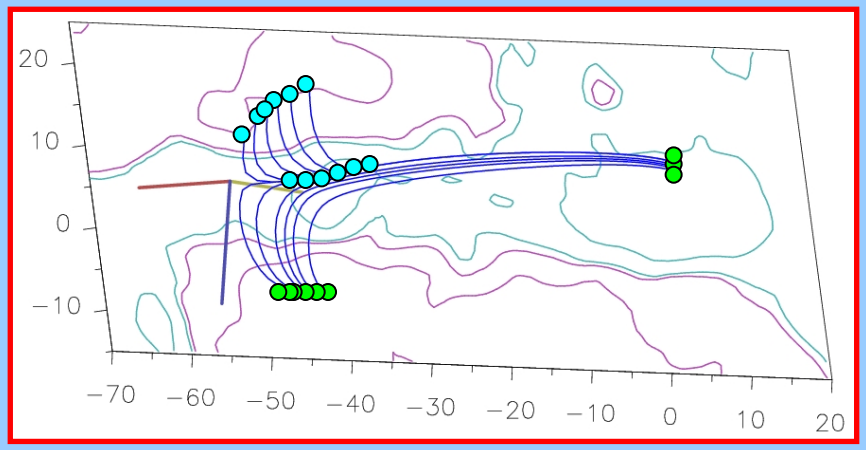
$\lambda_{1,yellow}$ 2 times lower $\lambda_{2,red}$

Coronal null points and observations

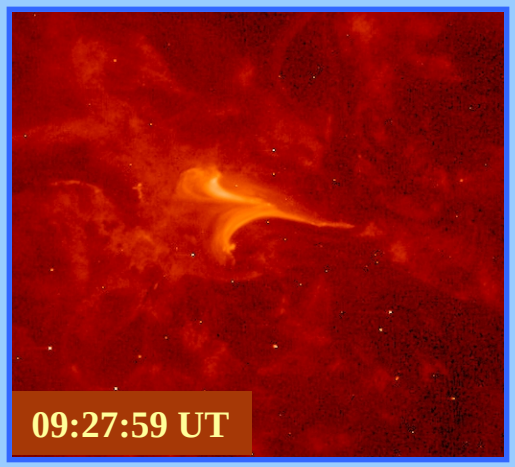
Field lines close to the null point correspond to the observed coronal loops

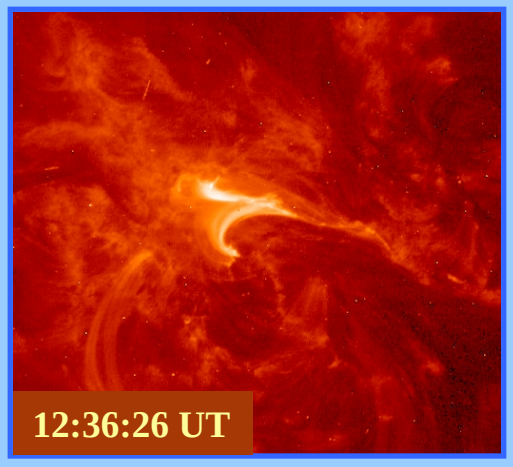
→ Evidence of reconnection at the null point

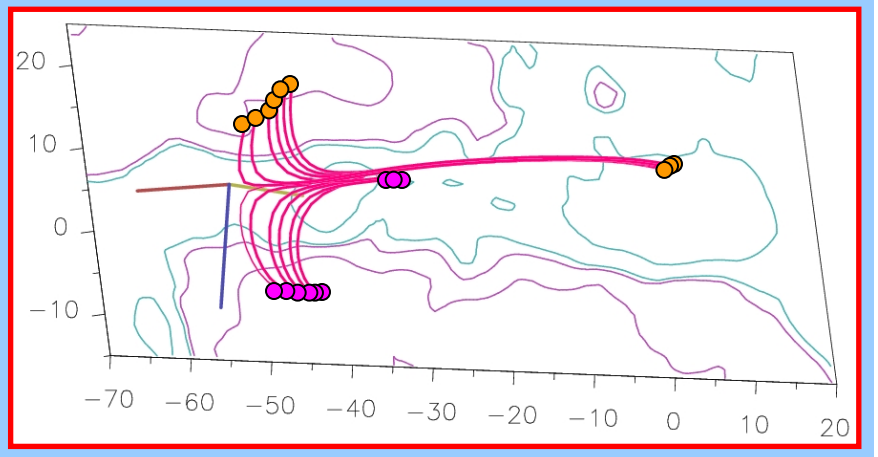




Before reconnection at the null





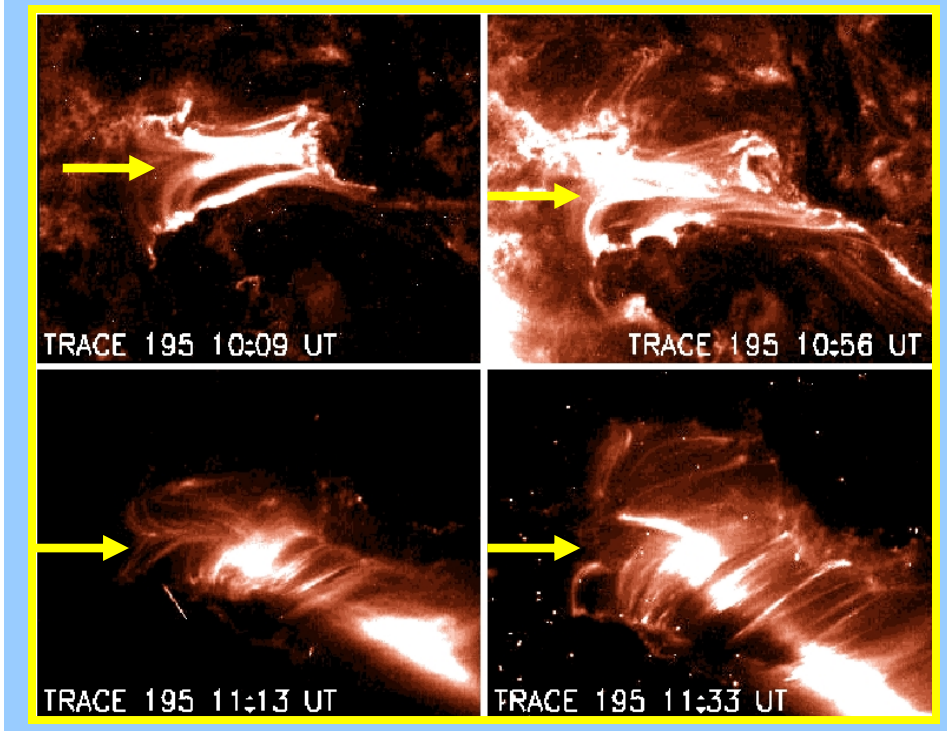


After reconnection at the null

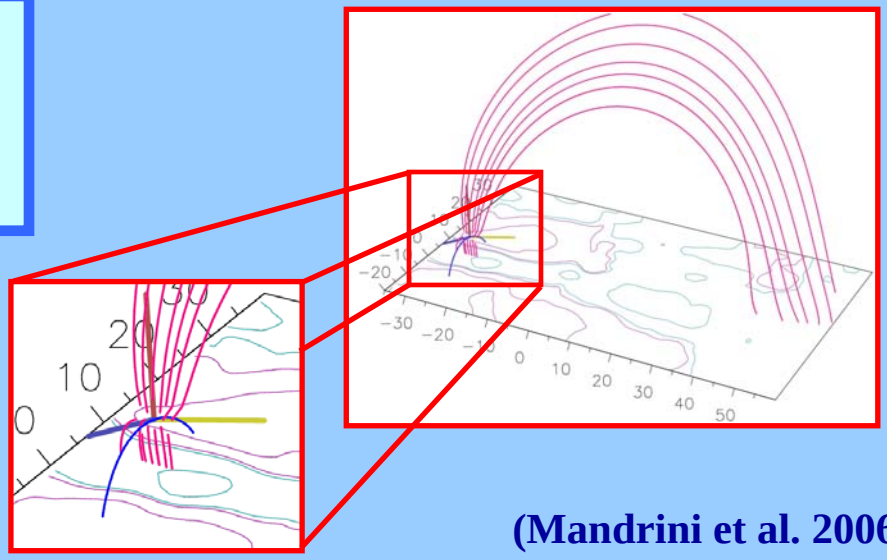
Two M flares on 27 October, 2003

(Luoni et al. 2006)

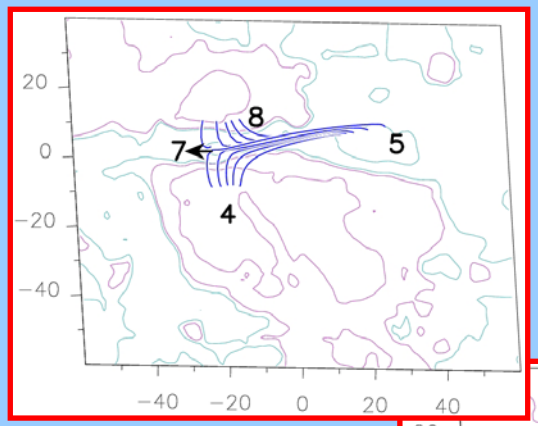
Coronal null points and observations



Images of the small event that accompanied the X17 flare on 28 October, 2003

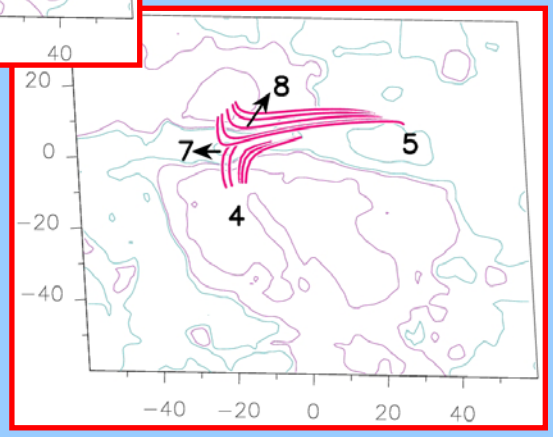


(Mandrini et al. 2006)



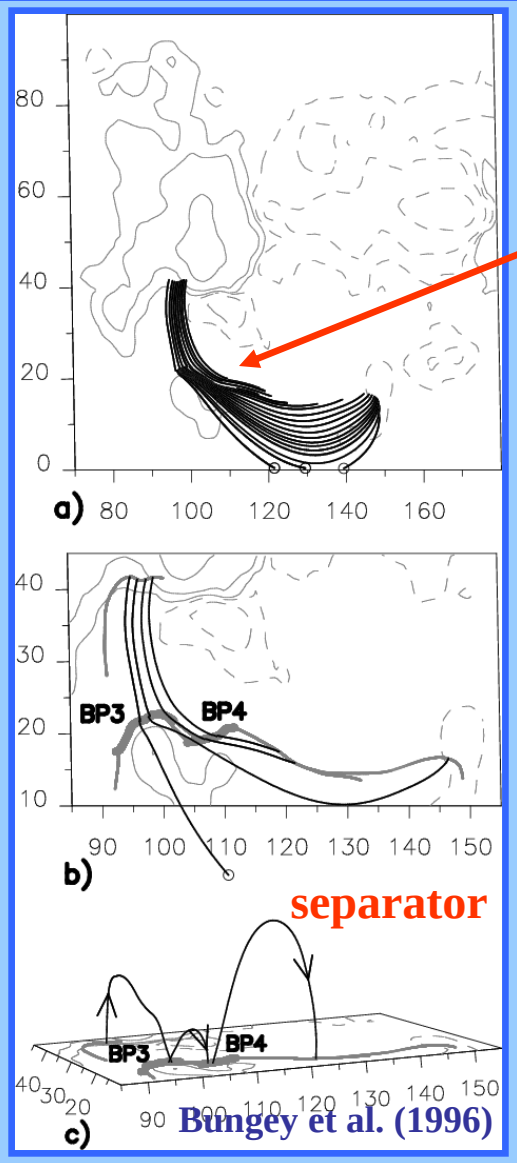
Before reconnection at the null

After reconnection at the null

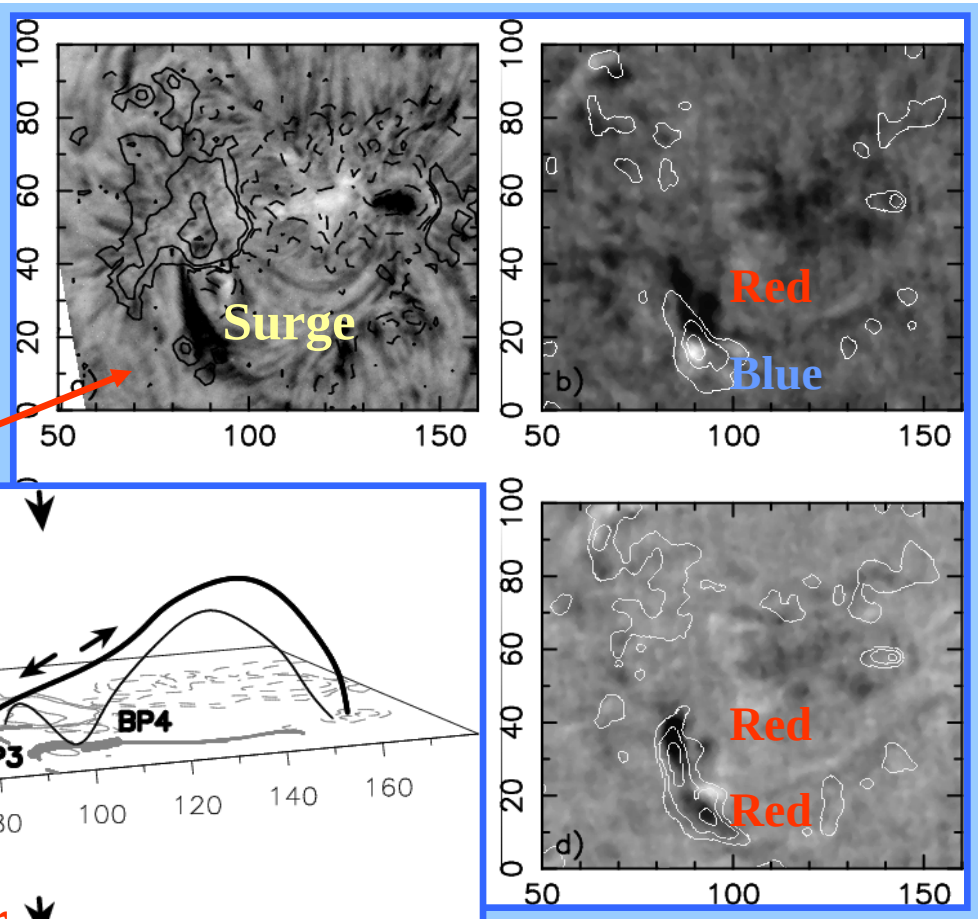


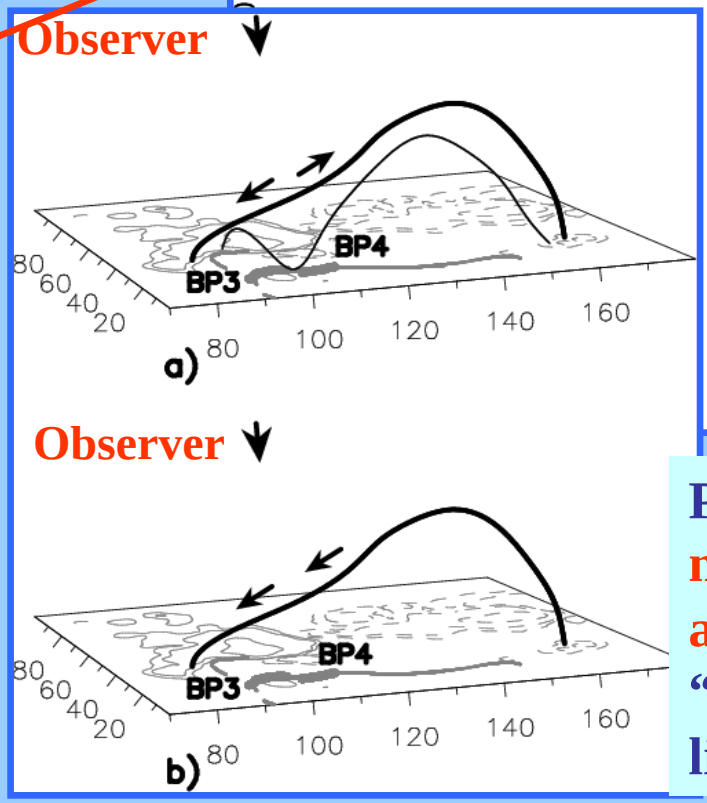
Field lines close to the null point correspond to the observed coronal loops
→ Evidence of reconnection at the null point

Bald patches and observations



Bungey et al. (1996)





Photospheric emergence → magnetic field reconnection at BPs separator → plasma "injected" in reconnected lines → surge

(Mandrini et al. 2002. Other examples: Aulanier et al. 1998, Fletcher et al. 2001, Pariat et al. 2005)

Coronal nulls and bald patches - Summary

Coronal nulls :

Associated with some flares:

(Mandrini et al. 1991, 2006, Gaizauskas et al. 1998, Aulanier et al. 2000, Luoni et al. 2006)

But are rare & number decreases rapidly with height.

(Schrijver & Title 2002, Longcope et al. 2003)

Bald Patches separatrices :

Associated with:

- **a small flare** **(Aulanier et al. 1998)**
- **some UV brightenings** **(Fletcher et al. 2001)**
- **some chromospheric events** **(Mandrini et al. 2002, Pariat et al. 2005)**

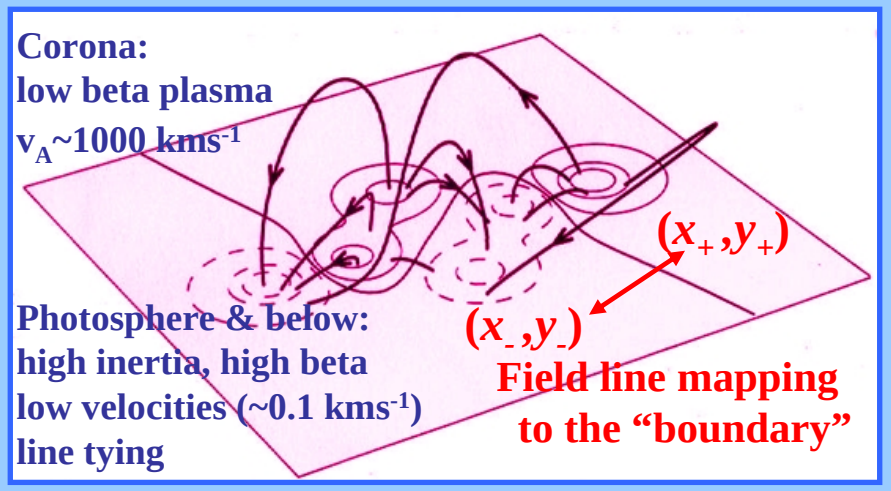
Many flare brightenings are not related to bald patch or null point separatrices

(Démoulin et al. 1994, …)

→ Reconnection should occur in more general situations

Magnetic reconnection: **QSLs**

The field line mapping is not discontinuous in general, but shows steep gradients at QSLs.



Field line mapping to the "boundary":

$$x_+, y_+ \rightarrow x_-, y_- : X_-(x_+, y_+), Y_-(x_+, y_+)$$

and the reverse.

Jacobian matrix:

$$F = \begin{pmatrix} \partial X_- / \partial x_+ & \partial X_- / \partial y_+ \\ \partial Y_- / \partial x_+ & \partial Y_- / \partial y_+ \end{pmatrix}$$

and the reverse.

Initial QSL definition: regions where $N \equiv \| F \| >> 1$

drastic change in connectivity

(Priest & Démoulin 1995, Démoulin et al. 1996)

Better QSL definition: regions where $Q \equiv \dfrac{\| F \|^2}{| B_{n,+} / B_{n,-} |} >> 1$

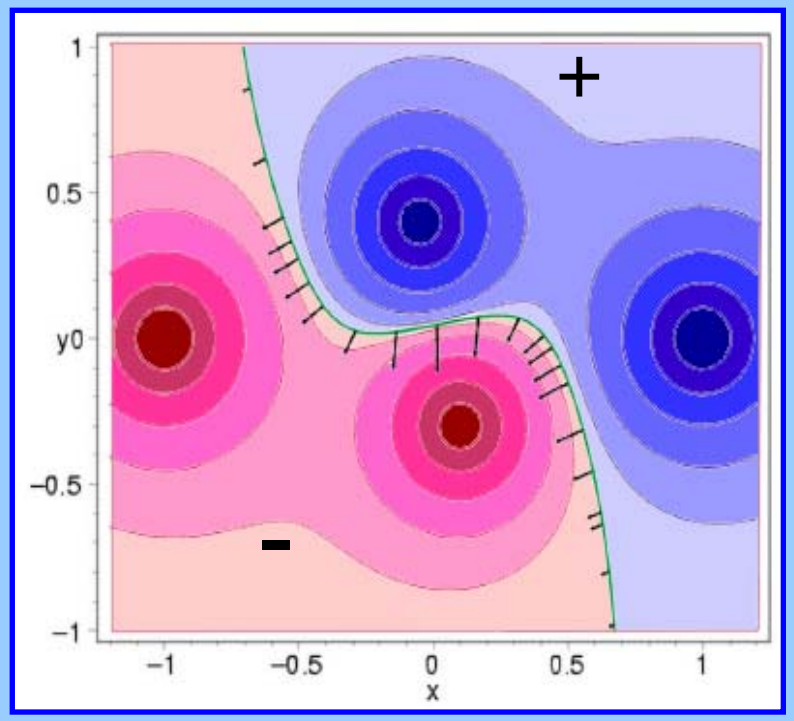
(Titov et al. 2002)

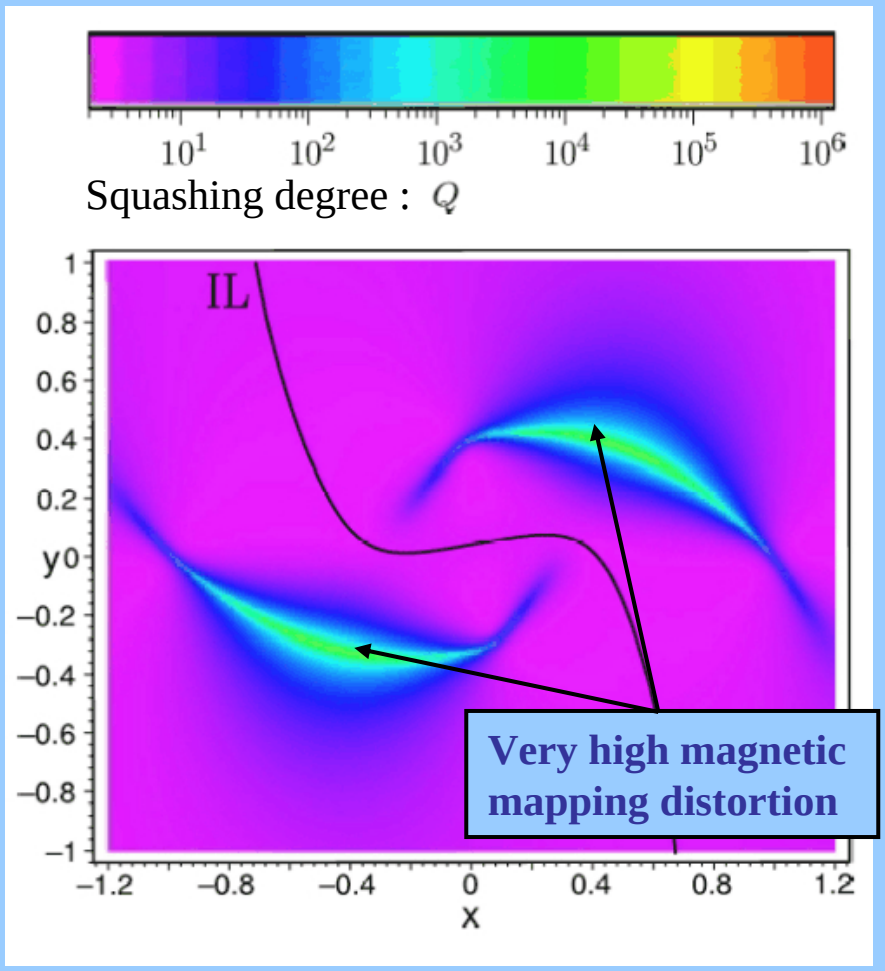
Squashing degree

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

QSLs: **Example of a simple configuration**

Magnetic configuration created by 4 magnetic sources
(potential magnetic field)



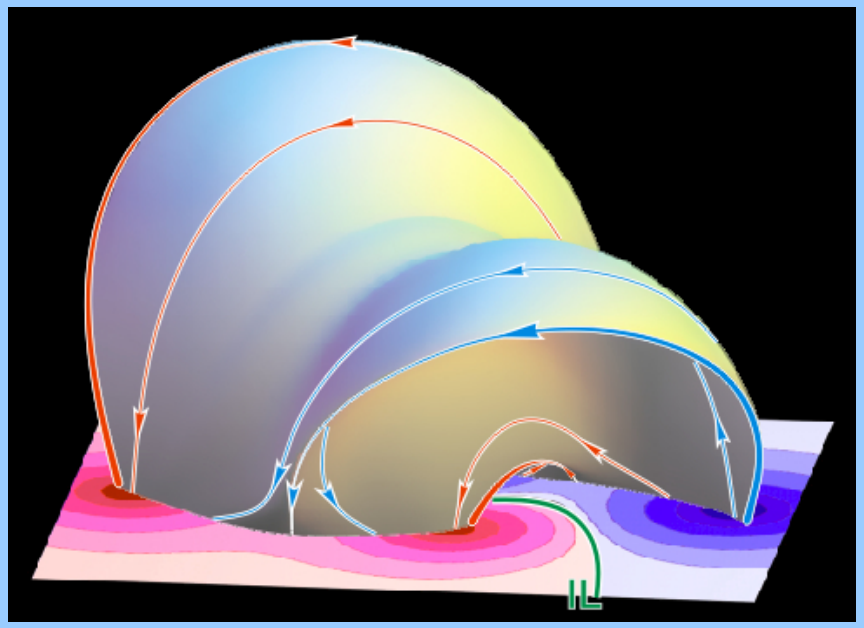


Above the configuration:
- No magnetic null
- No bald patch

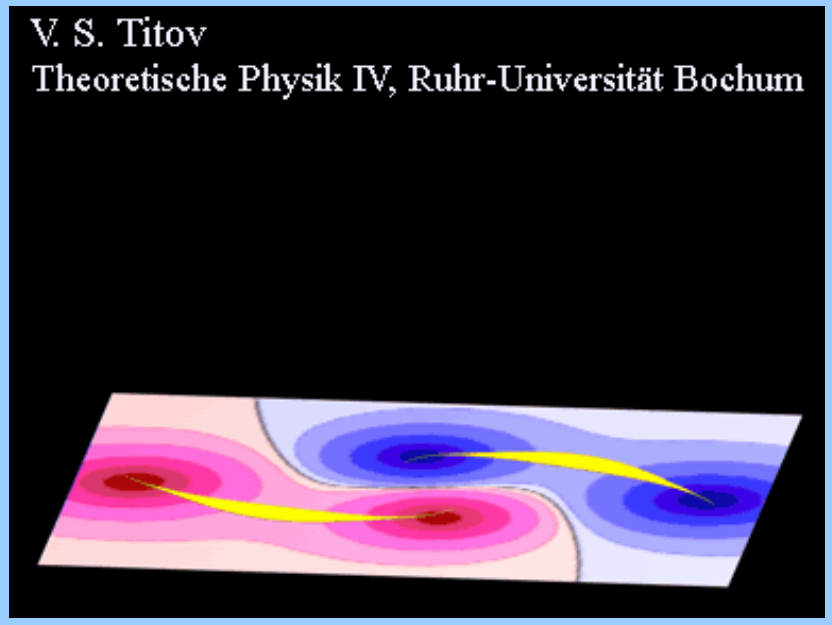
No separatrices ….but QSLs

(Titov & Hornig 2002)

QSLs: **3D shape**



Magnetic connectivities



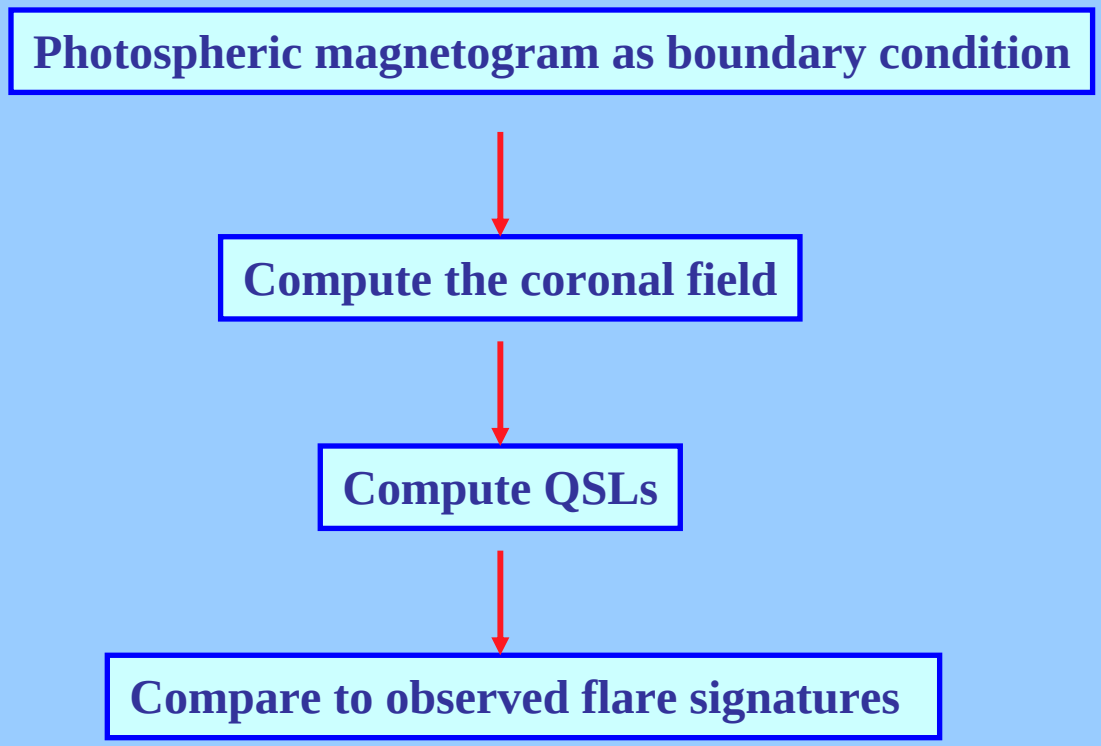
Volume inside the surface Q = constant
→ QSL shape

Boundary
Bn < 0

X shape
"QSLs crossing"
(can be compared to intersecting separatrices)

Boundary
Bn > 0

QSLs: **Observations**



Several flaring regions were analyzed: **Mandrini et al. 1996, 1997, 2006; Schmieder et al. 1997; Démoulin et al. 1997; Bagalá et al. 2000; Fletcher et al. 2001; Rudawy et al. 2001; Baker et al. 2009**

QSLs: **Observations**

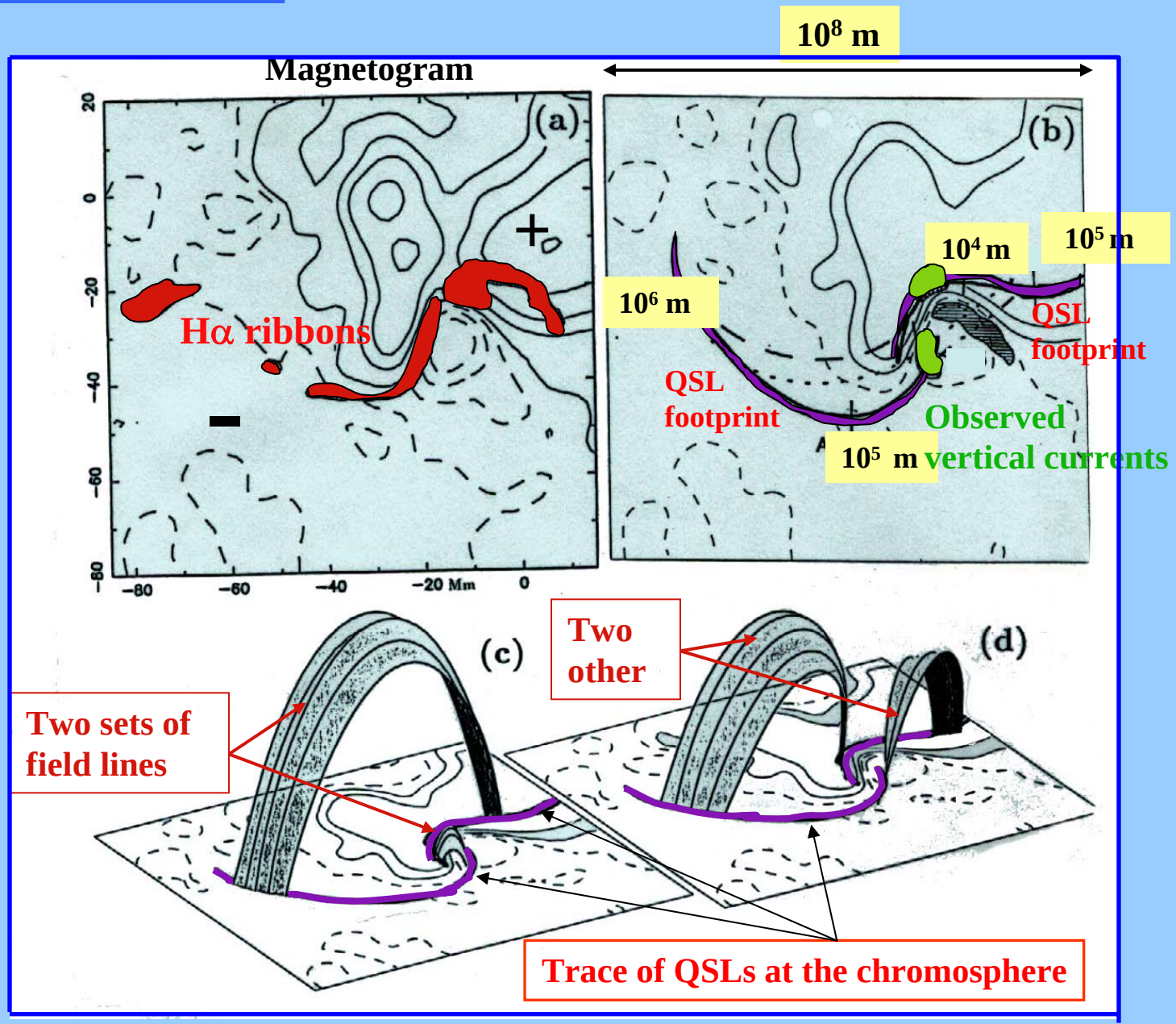
M4 flare
5 Nov., 1980
AR 2776

Hα ribbons located on the QSL (at chromospheric level)

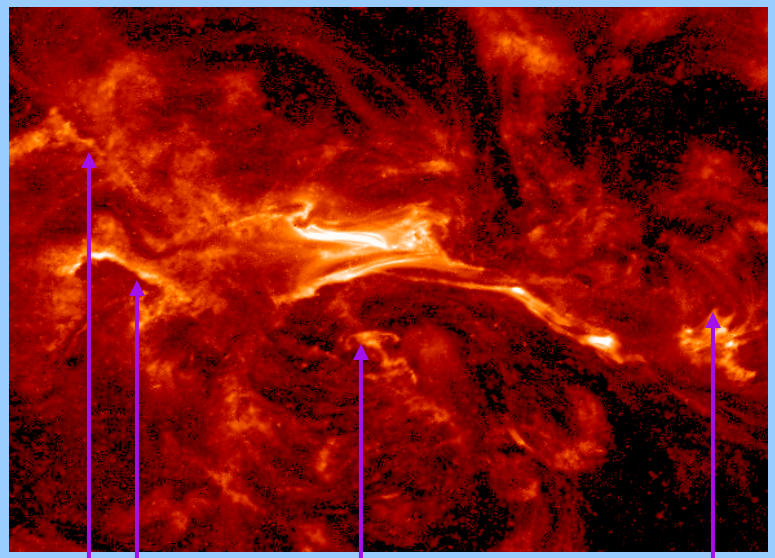
NO magnetic null

QSL thickness ~ 10^{-4} size AR (lower if B more concentrated at the photosphere)

(Démoulin et al. 1997)

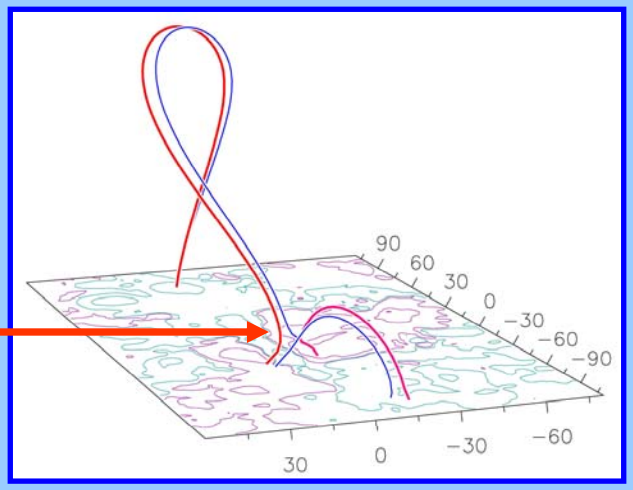


QSLs: **Observations**

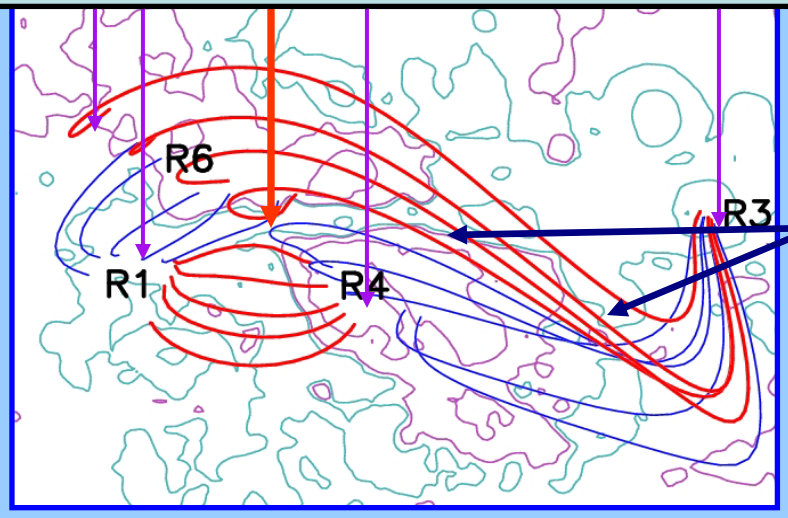


Large scale event on 28 October, 2003

Precursor of the X17 flare (~ 1.5 hr before) → large scale quadrupolar reconnection



No magnetic null point - 4 different connectivities → QSLs



blue lines reconnect → red lines

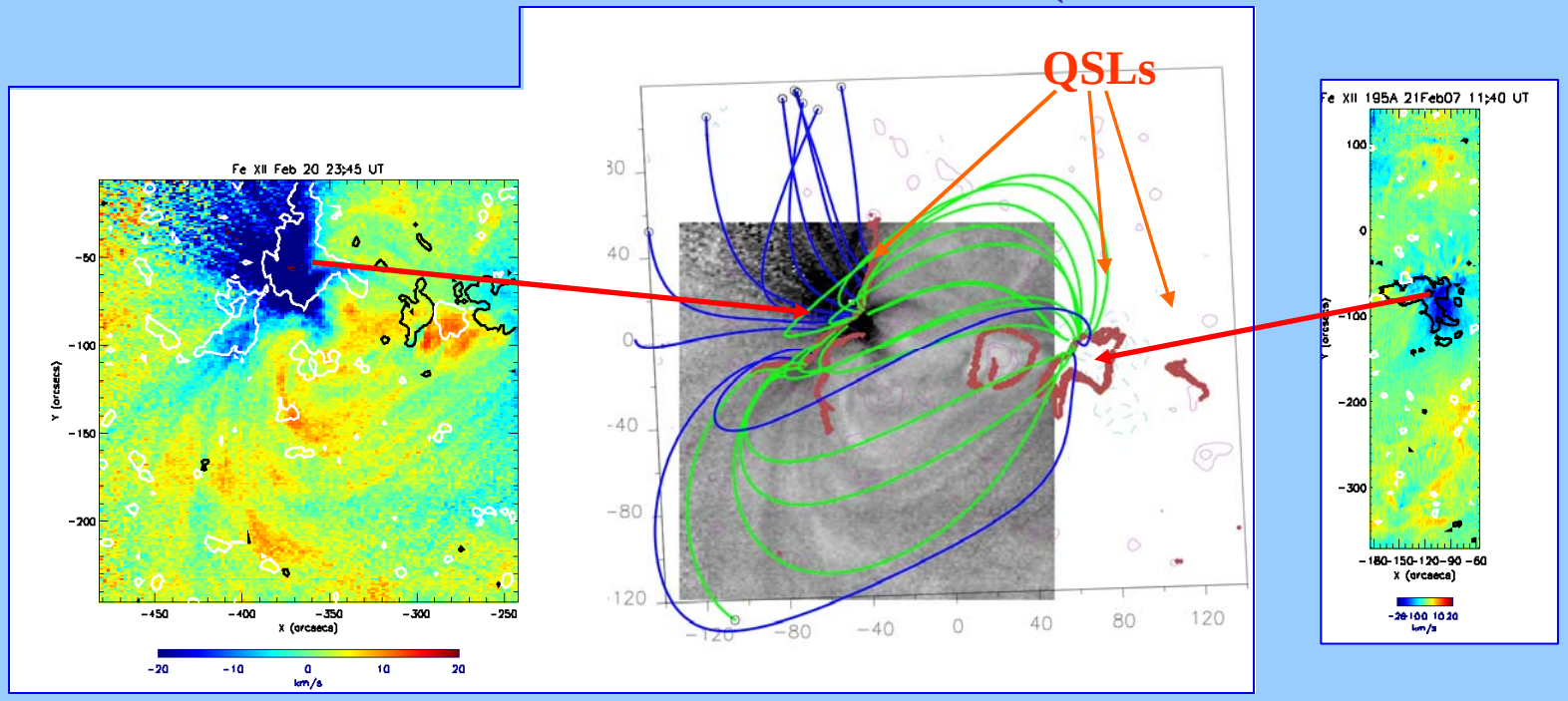
The X17 flare started "below" these field lines. Event "similar to a lateral breakout" (Antiochos et al. 1999) without a null point & separatrices.

(Mandrini et al. 2006)

QSLs: **Observations**

What is the driver of fast hot plasma streams originating at the periphery of solar active regions?

(Sakao et al., 2007; Harra et al., 2007)



(Baker et al. 2009)

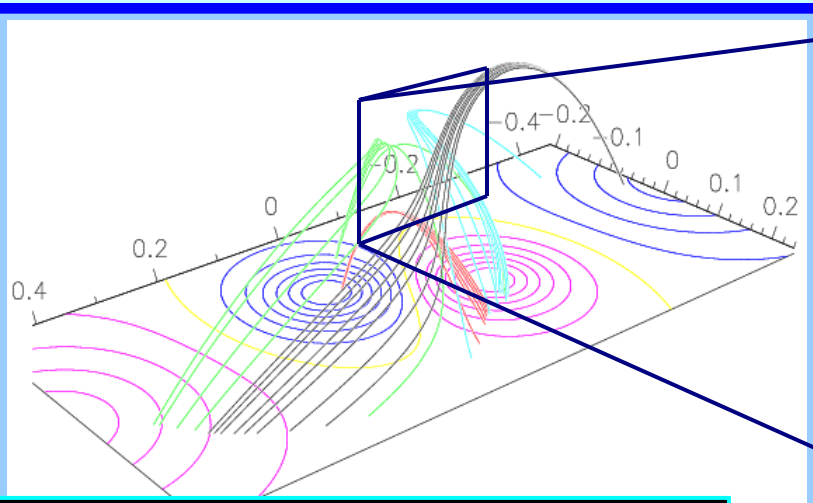
AR Outflows

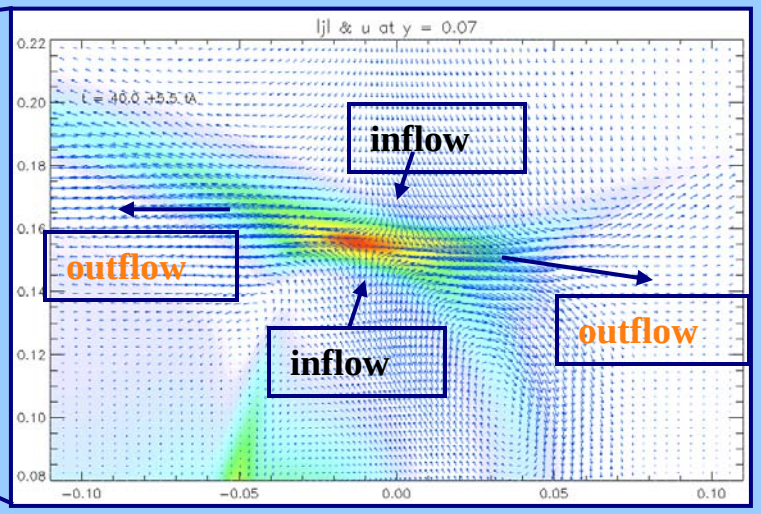
- Outflows of a few to 50 km/s **persist** for up to 3 days at nearly the **same location**.
- Outflows are located at the edges of ARs over **monopolar** regions where magnetic field lines of **drastically different connectivities** are rooted.

Outflows and field lines starting from QSLs are spatially coincident ⇒ Magnetic reconnection and consequent energy release **drives plasma outflows at QSLs.**

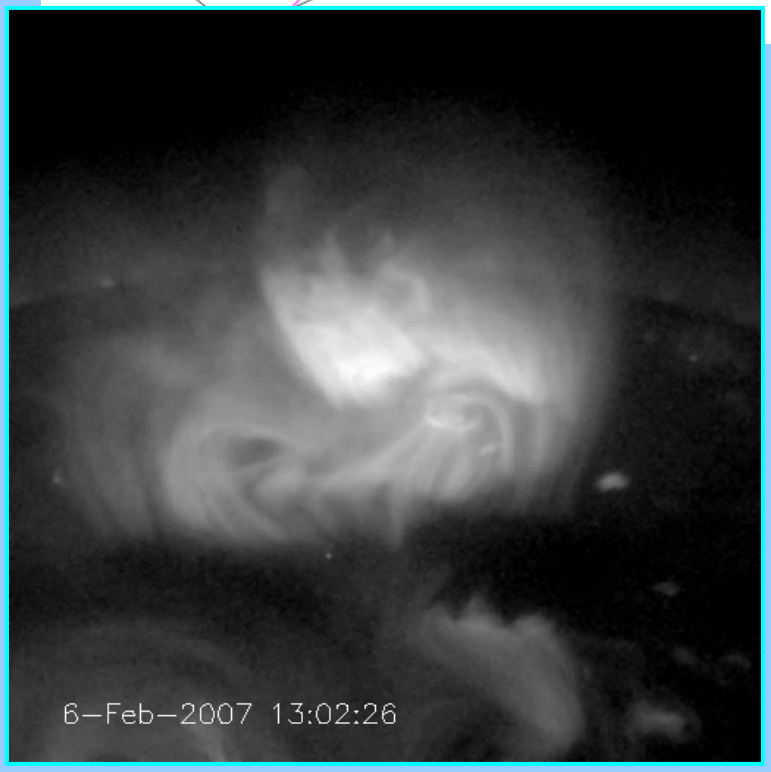
QSLs: **MHD simulations**

(Aulanier et al. 2006)





Similar to reconnection at a null point

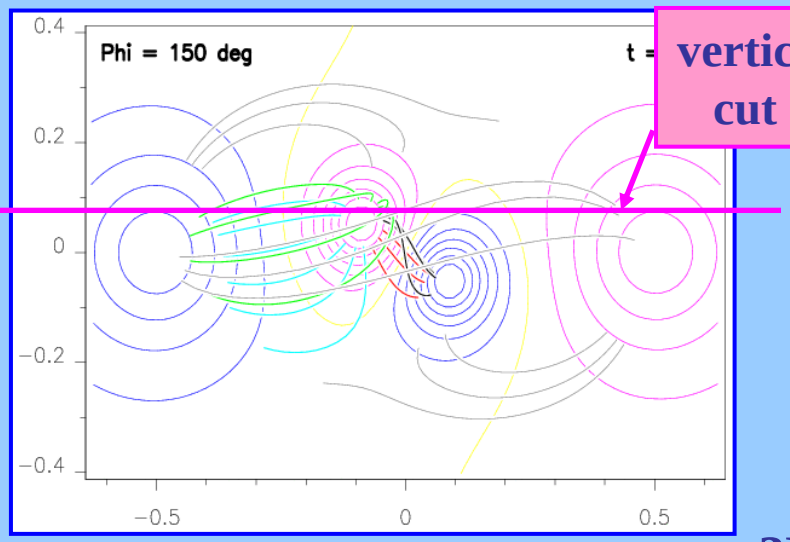


Fast footpoint slippage (slip-running reconnection) → Shift of the connectivity along the ribbon (different kind of motion as compared to 2D or null point reconnection)

A case for slip-running reconnection observed with Hinode/XRT **(Aulanier et al. 2007) (also Masson et al. 2009)**

Current formation at QSLs - 2.5 MHD simulation **(Milano et al. 1999)**

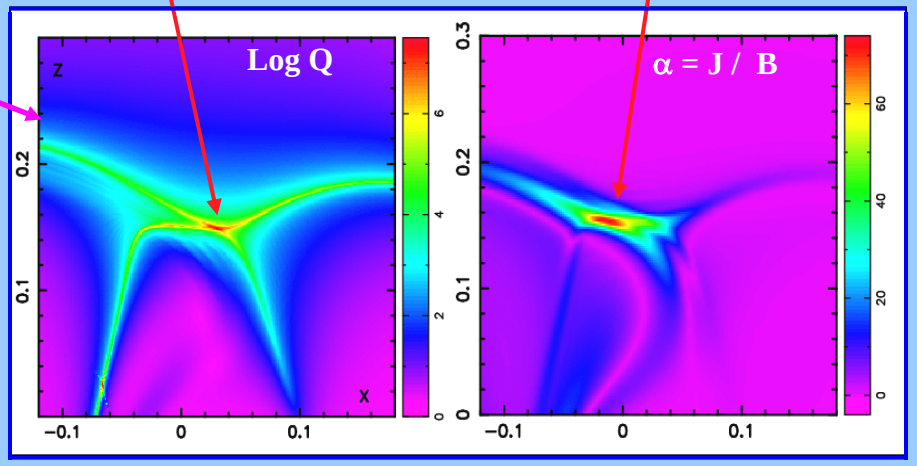
QSLs: **MHD simulations**

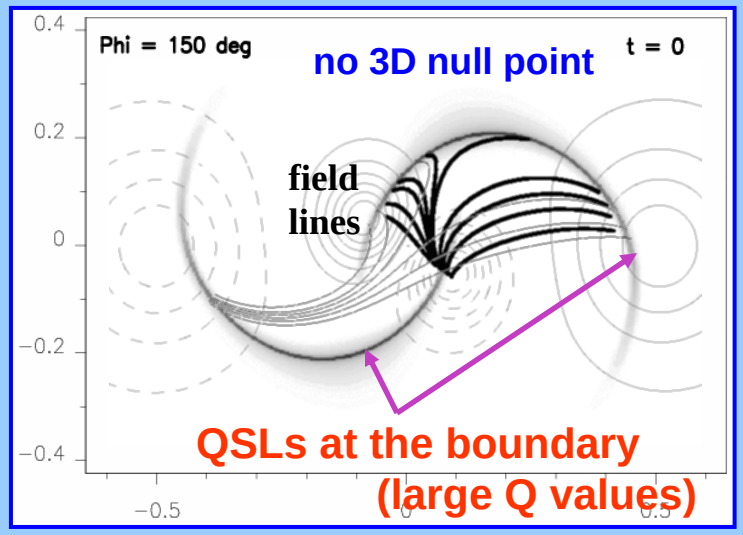


vertical cut

thinnest QSL part

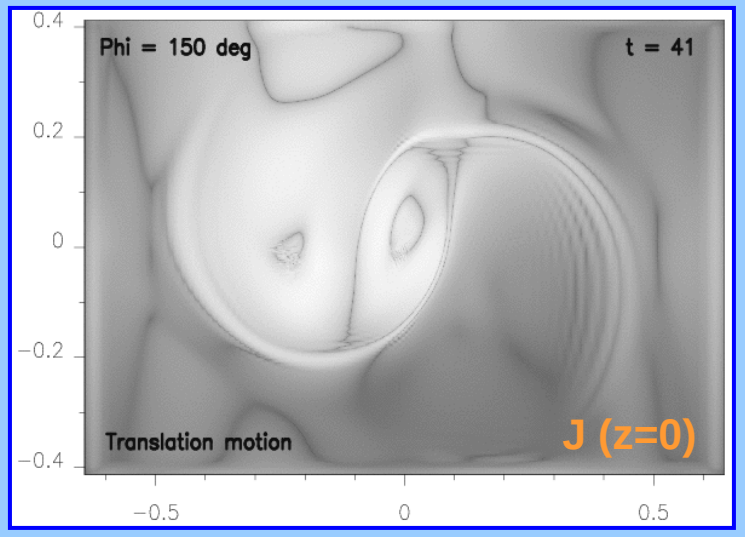
strongest J/B





(Aulanier et al. 2005)

3D MHD simulation



Current layers:

- Along the pre-existing QSLs
- Thickness decreases with time

Summary

Magnetic energy release occurs at QSLs .

Generalization

Separatrices → **Quasi-Separatrix Layers**

Separator → **Hyperbolic Flux Tube**

Magnetic configuration evolution → formation of thin current layers at QSLs
At some point of the evolution → magnetic reconnection

But still several open questions:
- When (where) does reconnection precisely start in QSLs?
- Is reconnection fast enough to explain the observed energy release rate?