Magnetic topologies: where will reconnection occur ?

Magnetic reconnection :
an attractive mechanism for energy release in the corona (heating, flares, CMEs …)

How to quantify this in 3D configurations ?

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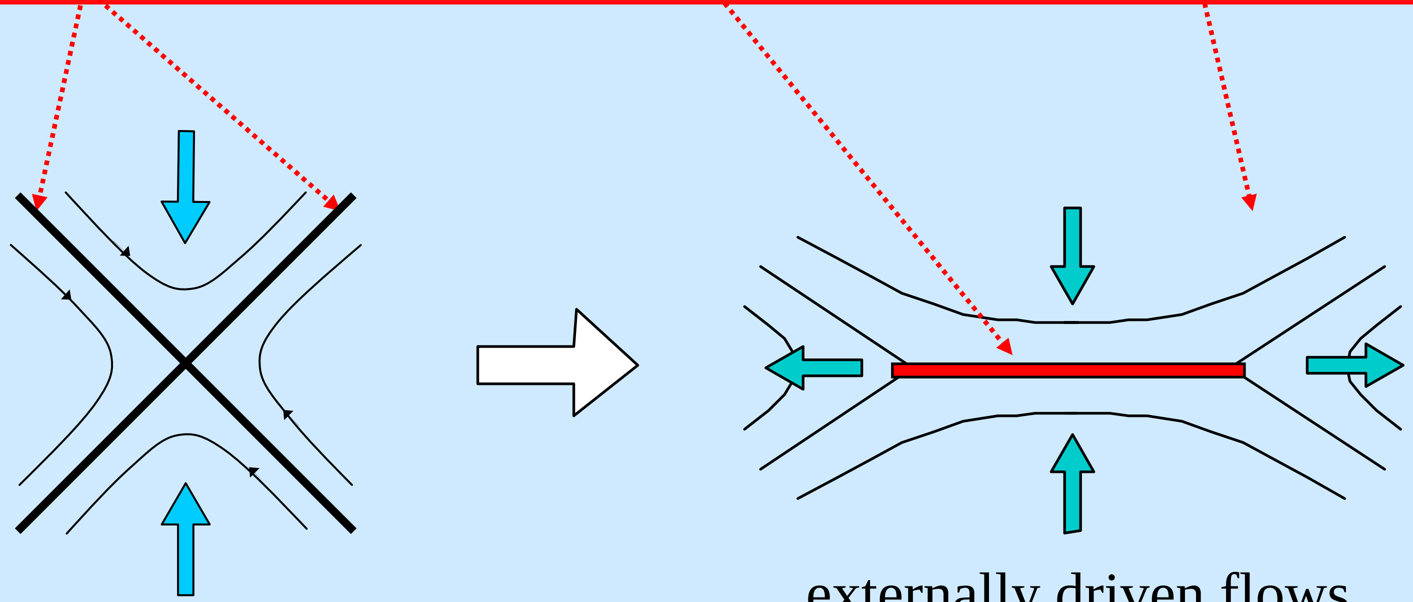
Separatrices in 2D => current sheet => reconnection

Magnetic null point



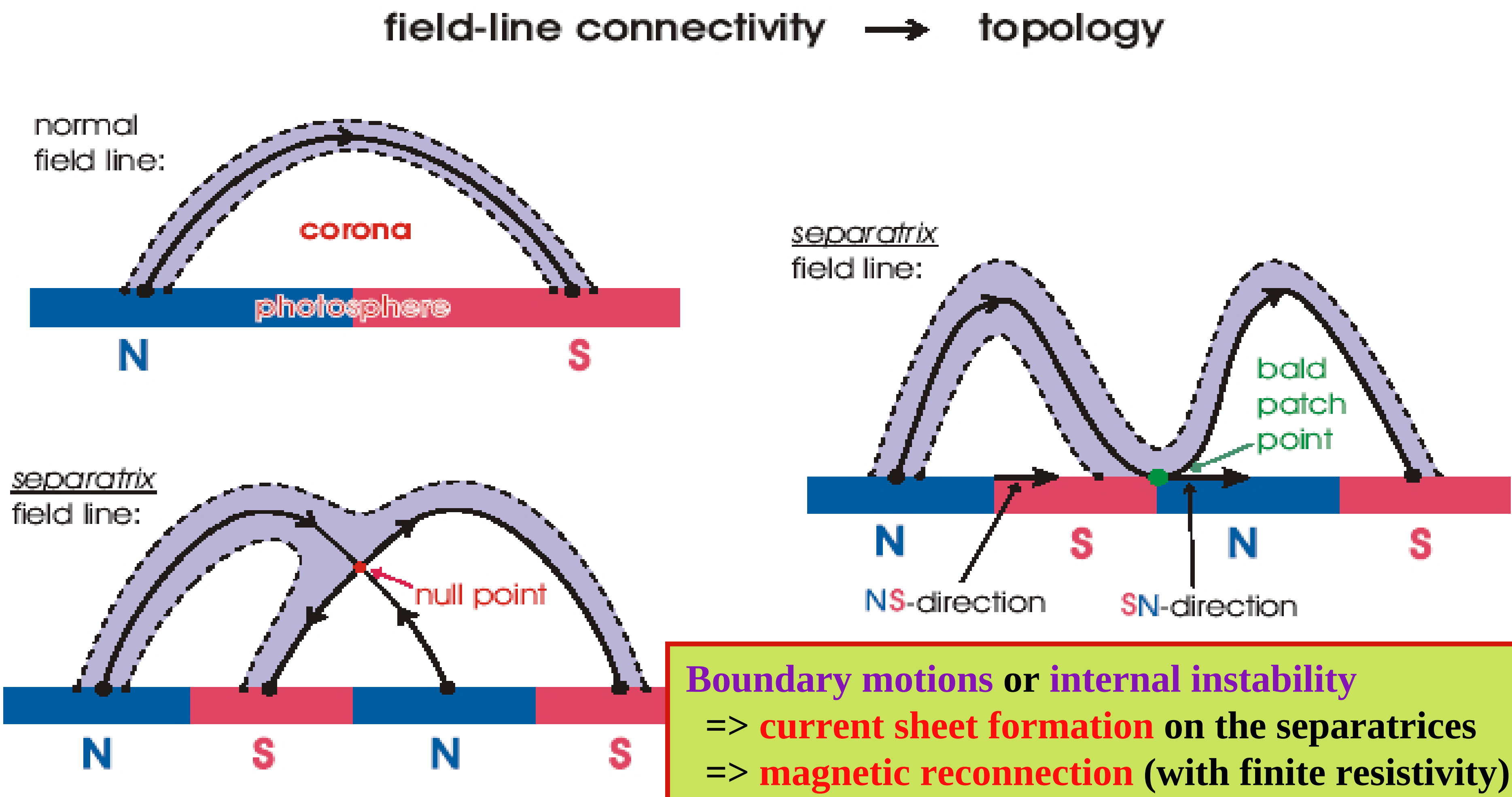
External forcing

externally driven flows

(Parker, Sonnerup, Sweet, Syrovatskii)

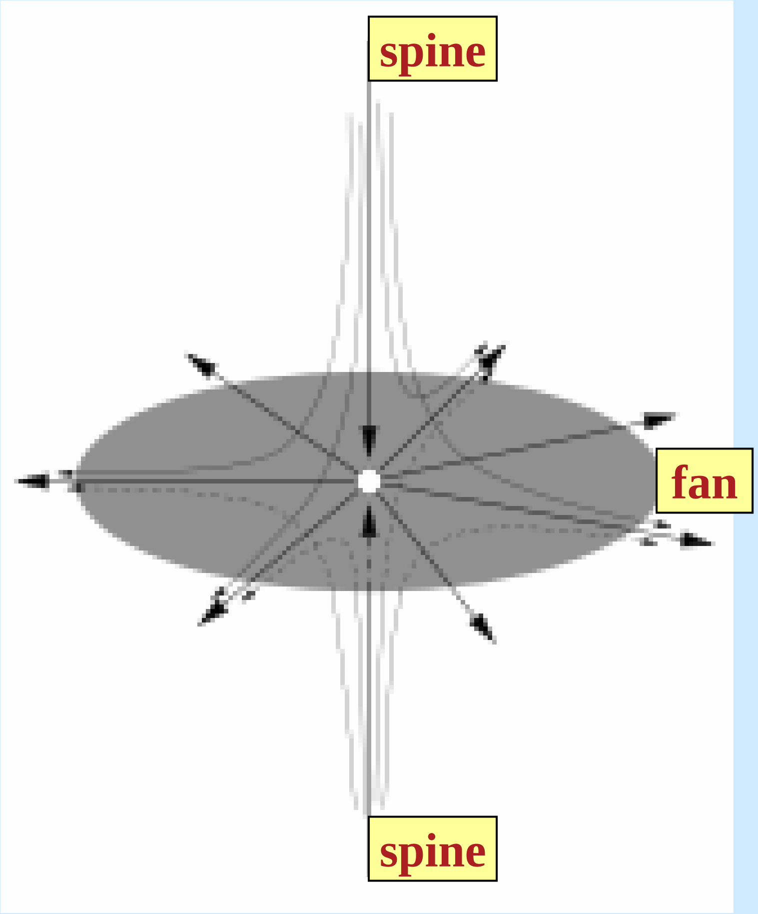
Separatrices in 2D and 2.5D cases => reconnection

Basic magnetic topologies for $\vec{B}(x,y)$

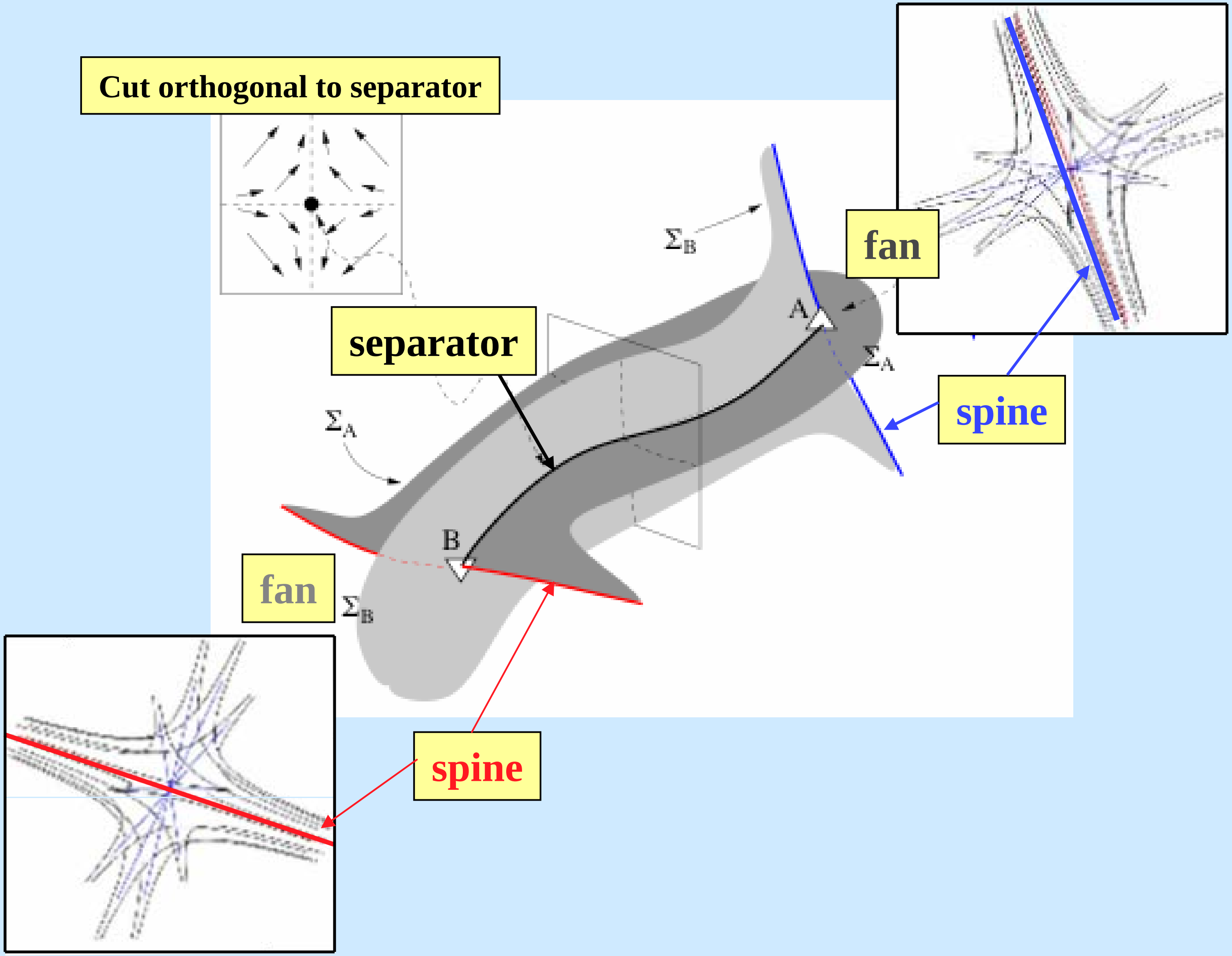


Boundary motions or internal instability
=> current sheet formation on the separatrices
=> magnetic reconnection (with finite resistivity)

Magnetic topology around a null point



Magnetic topology with 2 null points

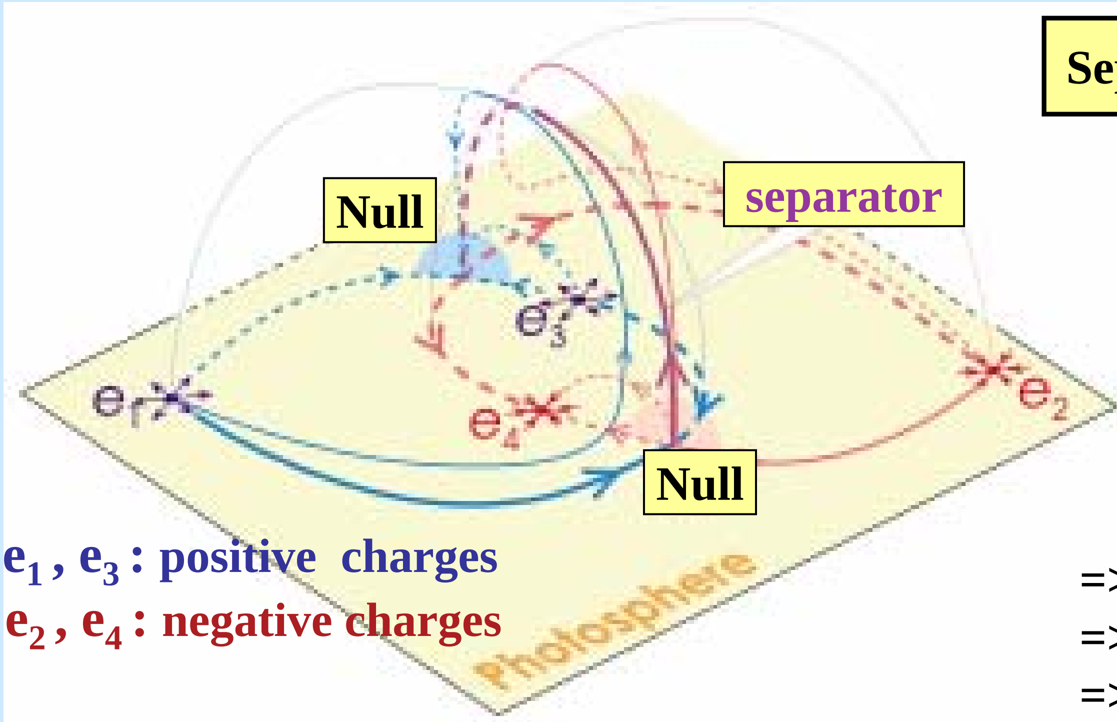


Next :

The magnetic field is described with photospheric magnetic charges

This models the concentration in very thin flux tubes

Configuration with 4 magnetic charges



Separatrices: 2 intersecting cupola

e_1 , e_3 : positive charges

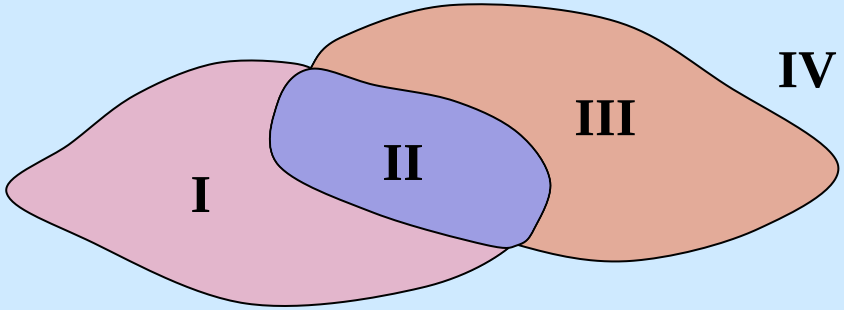
e_2 , e_4 : negative charges

Motion of the charges

=> Current sheet at separator

=> Reconnection (with $E_{//}$)

=> Flux exchange between domains



4 connectivity domains

(Sweet 1969, Baum & Brathenal 1980, Gorbachev & Somov 1988, Lau 1993)

Main properties

Skeleton :

Null points + spines + fans + separators
"summary of the magnetic topology"
(Molodenskii & Syrovatskii 1977, Priest et al. 1997, Welsch & Longcope 1999, Longcope & Klapper 2002)

Classification of possible skeletons (with 3 & 4 magnetic charges)

(Beveridge et al. 2002, Pontin et al. 2003, 1980, Gorbachev & Somov 1988, Lau 1993)

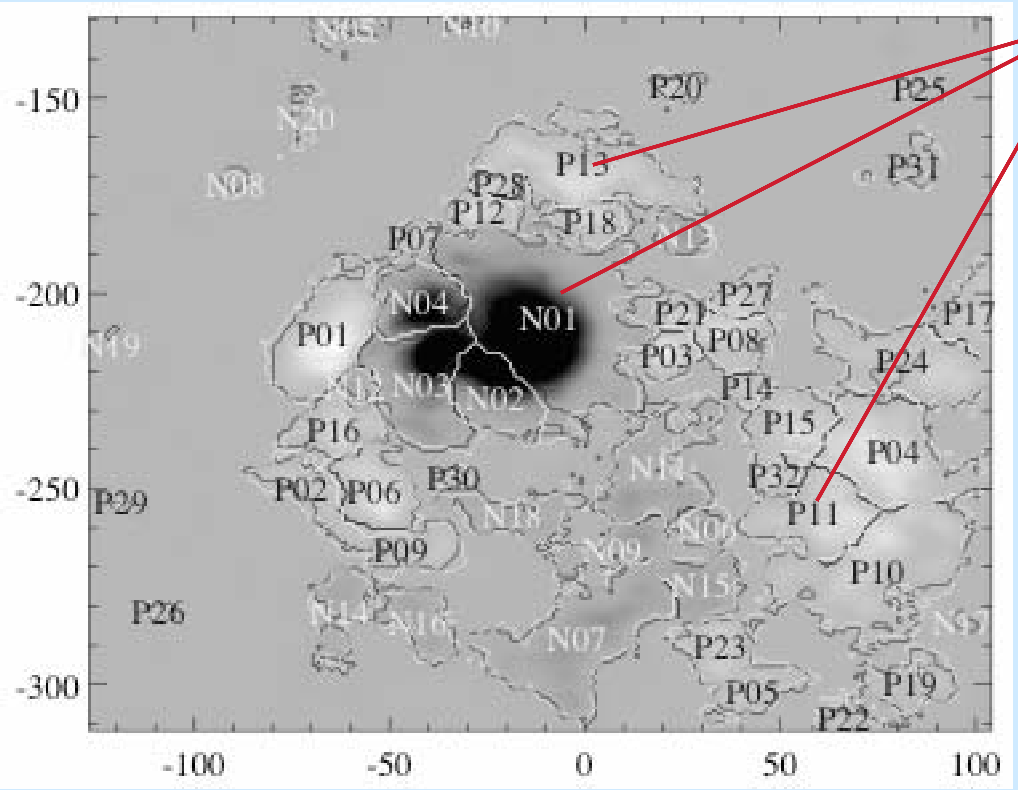
Global bifurcations :

They modify the number of domains

- **separator bifurcation (2 fans meet)**
- **spine-fan bifurcation (fan + spine meet)**

(Gorbachev et al. 1988, Brown & Priest 1999, Maclean et al. 2004)

Magnetic charge topology for an AR (I)

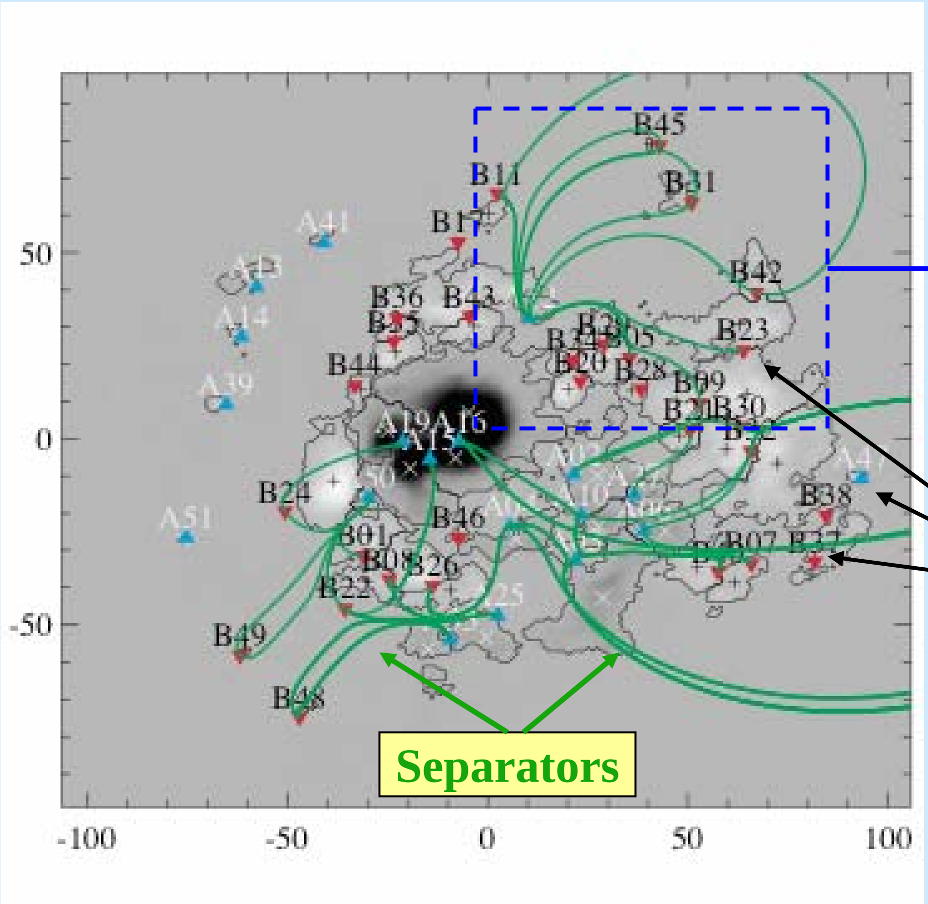


Partition of the magnetogram in flux regions

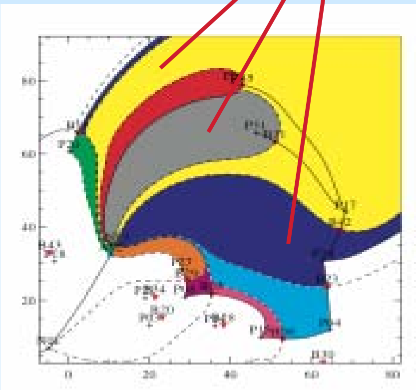
Then, **replace** the flux regions with magnetic charges with same flux

(Mandrini et al. 1991, 1993, Démoulin et al. 1992, 1994, Longcope & Silva 1998)

Magnetic charge topology for an AR (II)



Connectivity domains



Photospheric nulls ▲▼

Suppose no flux outside magnetic charges

(Barnes et al. 2005)

Charge evolution: build up of currents at separators (Longcope et al. 2001, 2005)

Next :

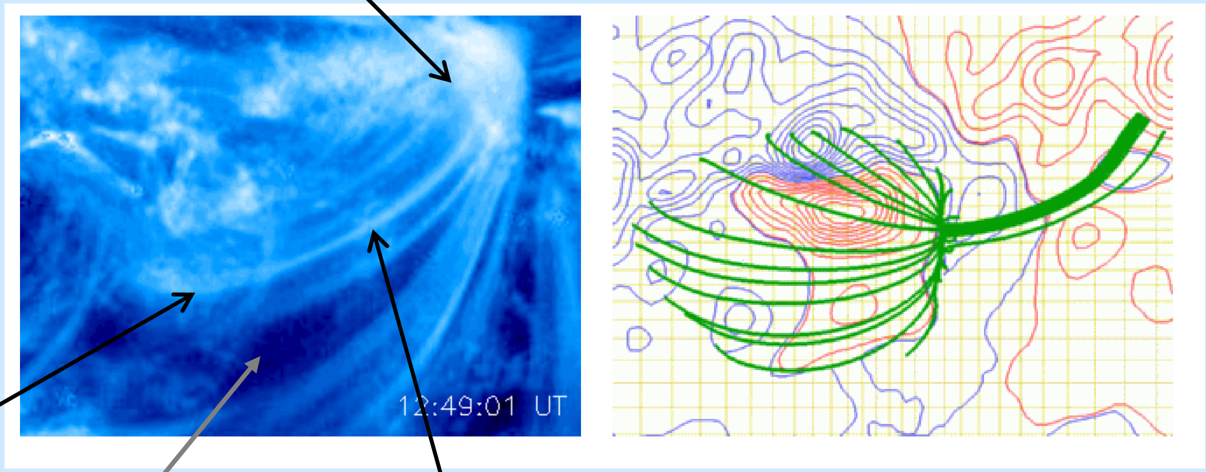
Magnetic topology properties which do not need a description of the magnetic field with magnetic charges (or large flux-free photospheric regions)

Coronal magnetic null points

Bastille day flare: **eruptive flare** within a complex magnetic topology: reconnection at the **coronal** null point triggers a CME

Spine ribbon

Fan + spine field lines



Bz < 0
Bz > 0

Null point location

Motions along the spine

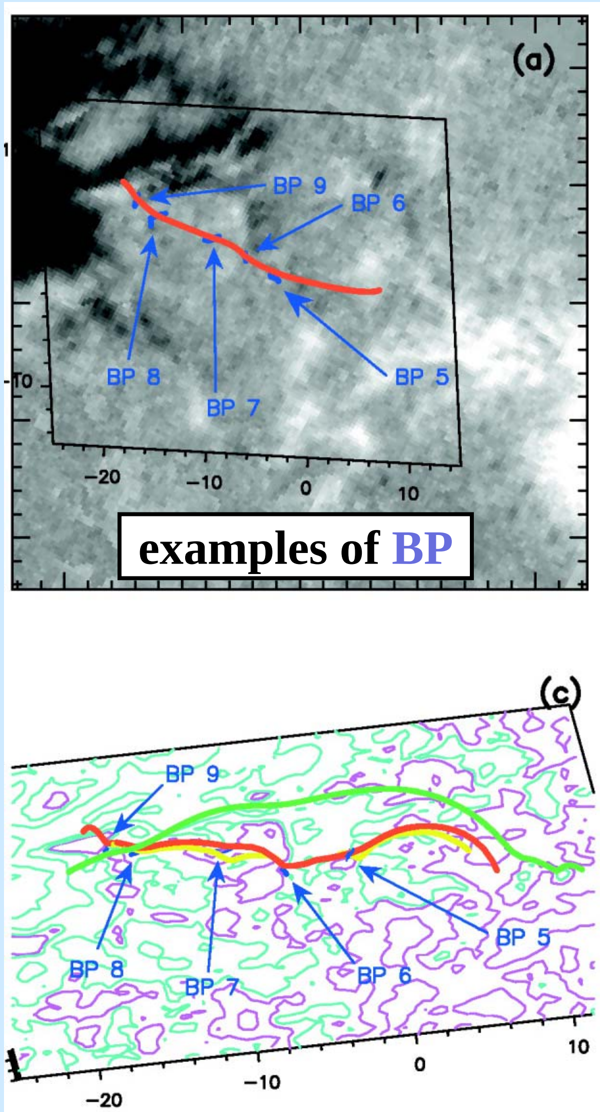
Artefact during flare (diffraction pattern)

Example of the breakout model

(Aulanier et al. 2000)

Magnetic bald patches (BP)

Magnetic dips at the photospheric level



Bz > 0
Bz < 0

Below the photosphere: Parker instability
- => undulatory flux tubes
- => **Dips** with **dense plasma** in the emerging flux tubes
- => **Flux tubes cannot emerge further**

Association: BP <-> Ellerman bomb

(signature of energy release)

Reconnection at BP separatrices needed for further emergence

(the dense dipped part is left behind)

(Pariat et al. 2005)

Coronal nulls & Bald Patches in observations

Coronal nulls :

Above mixed field: **rare** & density **decreases rapidly** with height (0.05 height $^{-3}$)

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

Associated with some flares

(Mandrini et al. 1991, Gaizauskas et al. 1999, Aulanier et al. 2000)

Bald Patches separatrices :

Associated with:

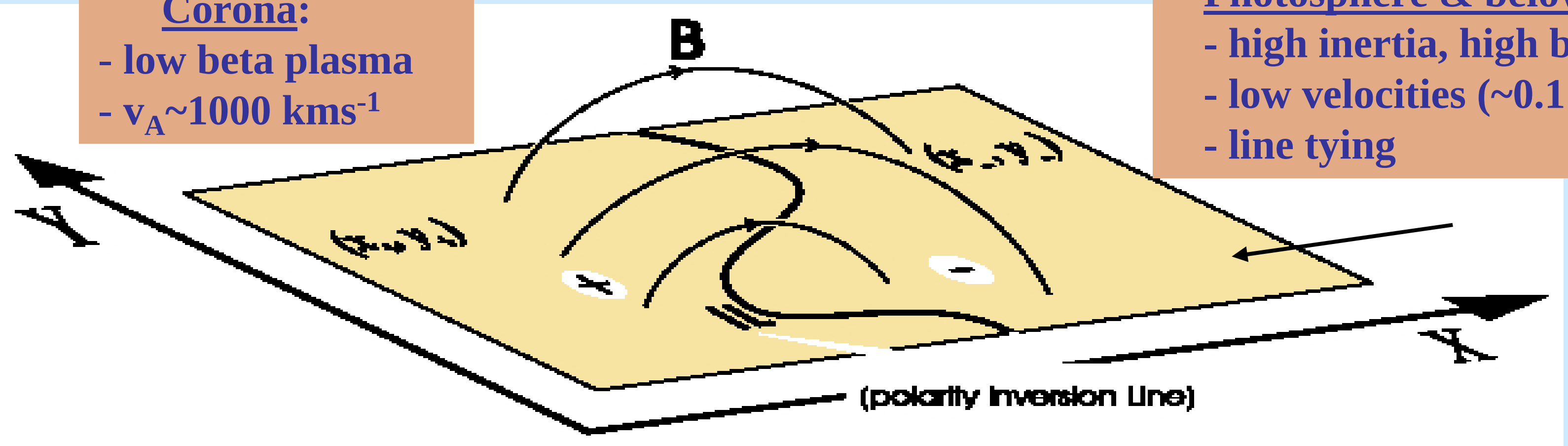
- some flares **(Aulanier et al. 1998)**
- some UV brightenings **(Fletcher et al. 2001)**
- some chromospheric events **(Mandrini et al. 2002,** Pariat **et al. 2005)**

BUT **many flare ribbons and loops are NOT related to Bald Patch and Null Points separatrices** **(Démoulin et al. 1994, …)**

=> Reconnection must occur in broader conditions

Definition of Quasi-Separatrix Layers

Corona:
- low beta plasma
- $v_A \sim 1000$ kms^{-1}



Photosphere & below:
- high inertia, high beta
- low velocities (~0.1 kms^{-1})
- line tying

Field line mapping to the "boundary" : $x_+, y_+ \rightarrow x_-, y_- : \quad x_-(x_+, y_+), y_-(x_+, y_+)$

Jacobi matrix :

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

Initial QSL definition : **regions where** $N \equiv \| F \| >> 1$ **(Démoulin et al. 1996)**

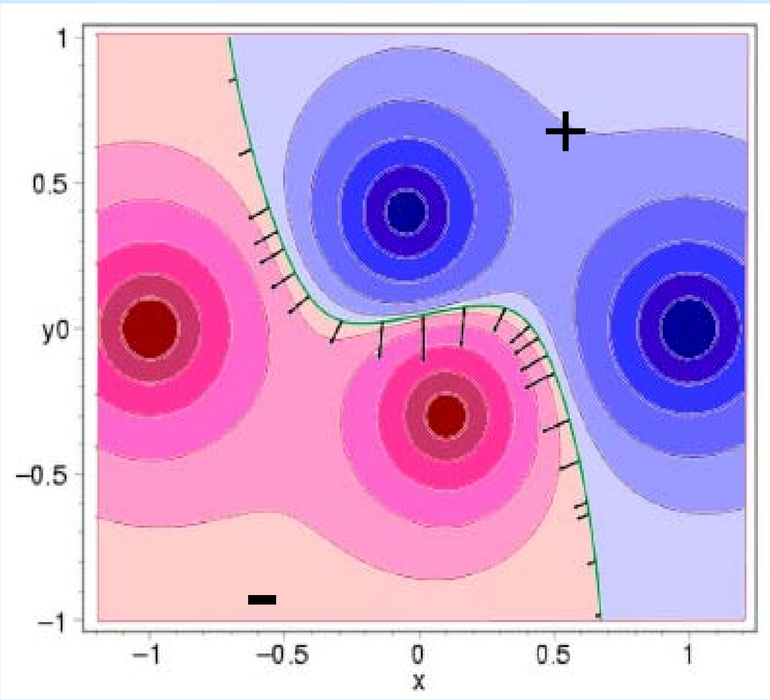
Better QSL definition : **regions where** $Q \equiv \dfrac{\| F \|^2}{B_{n,+} / B_{n,-}} >> 1$ **(Titov et al. 2002)**

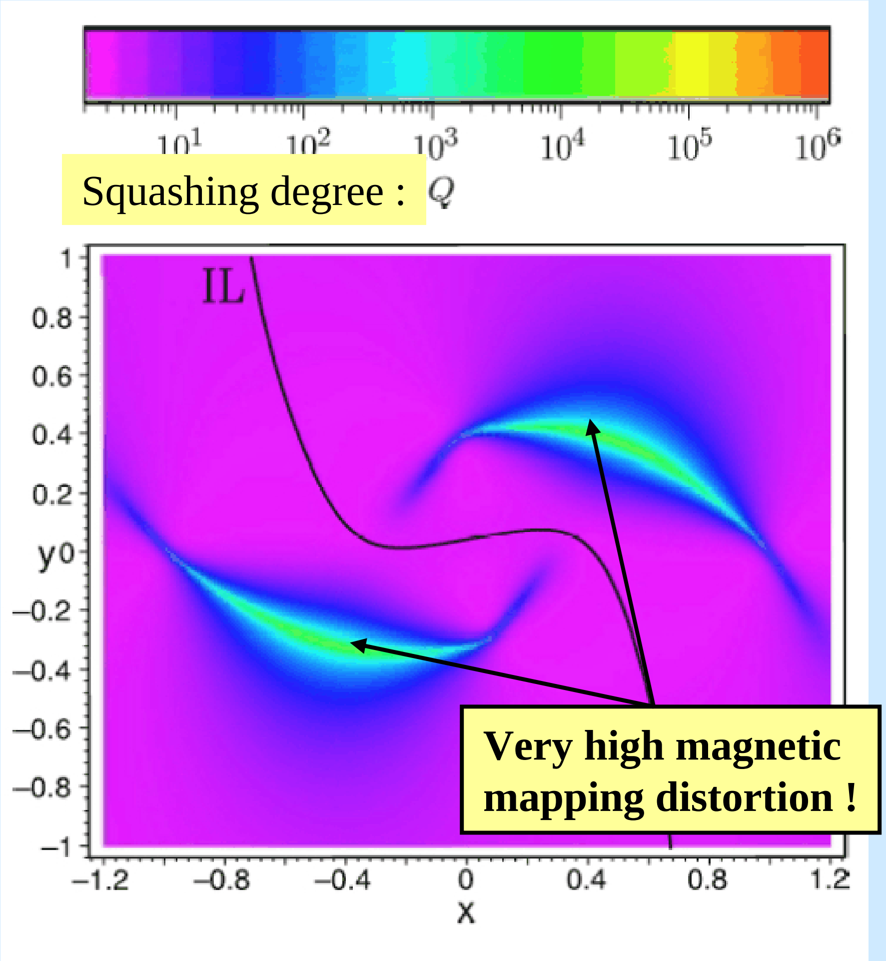
Squashing degree

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

A basic theoretical configuration

"magnetogram"
created with 4 magnetic concentrations



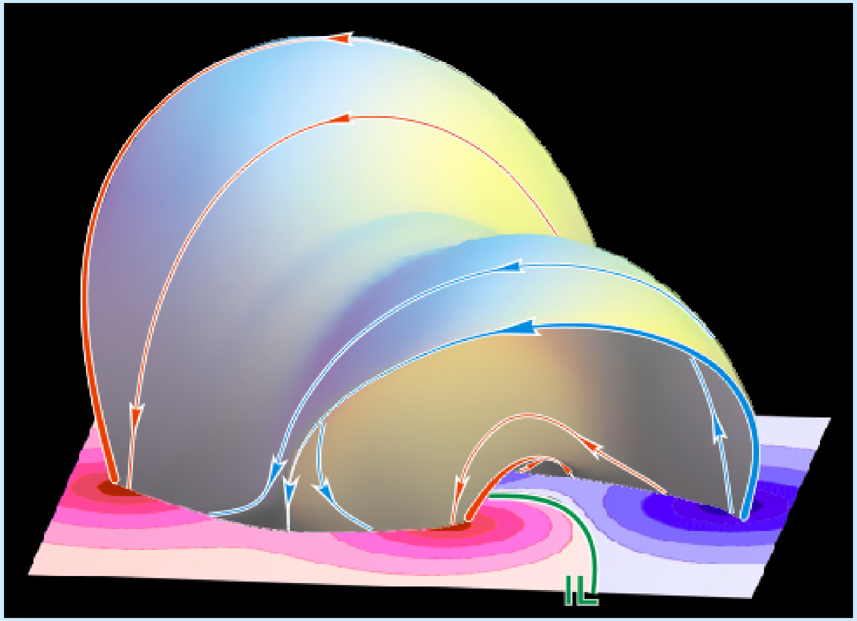


(Titov & Hornig 2002)

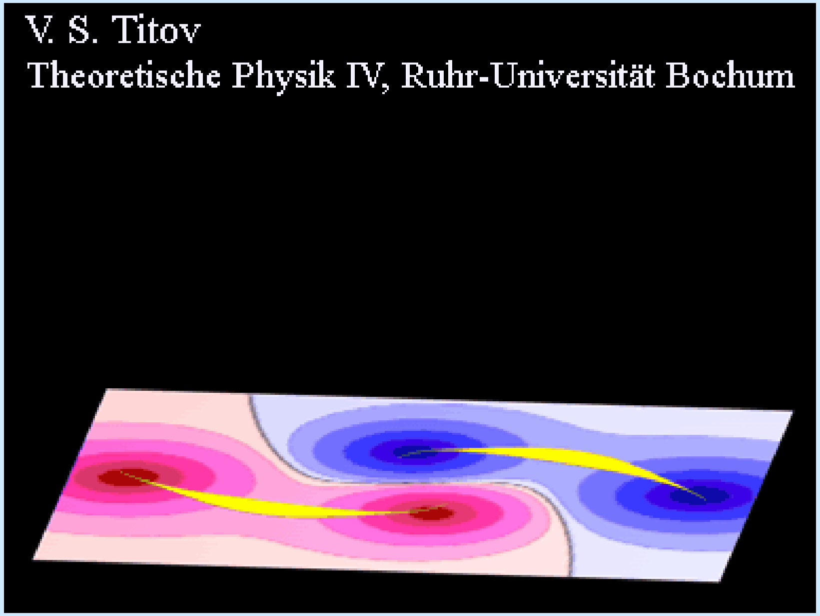
Above the magnetogram:
- No magnetic null
- No bald patch

No separatrices … but QSLs

3D QSL shape



Magnetic connectivities



Volume inside the surface Q = constant :
QSL shape

Summary :

(Titov et al. 2002)

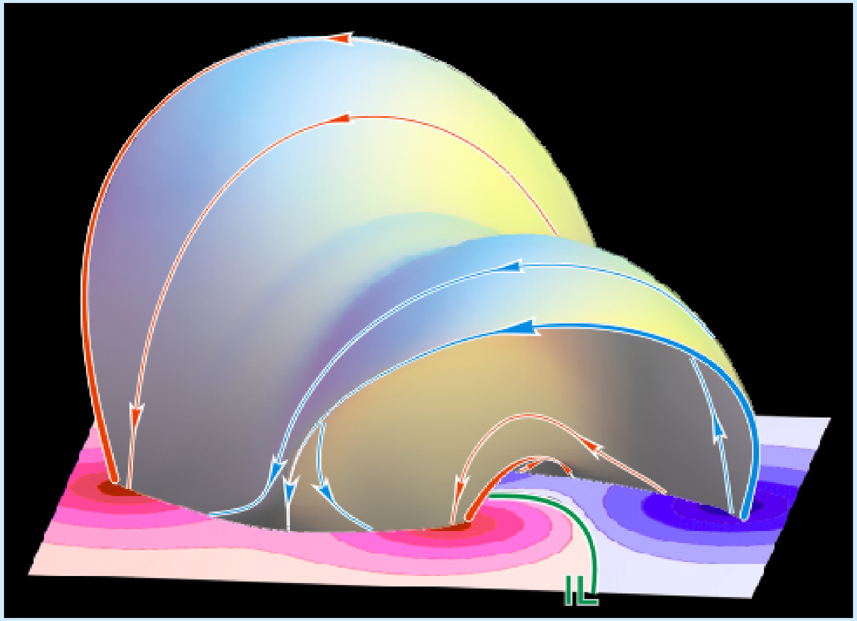
Boundary
$Bn < 0$

X shape

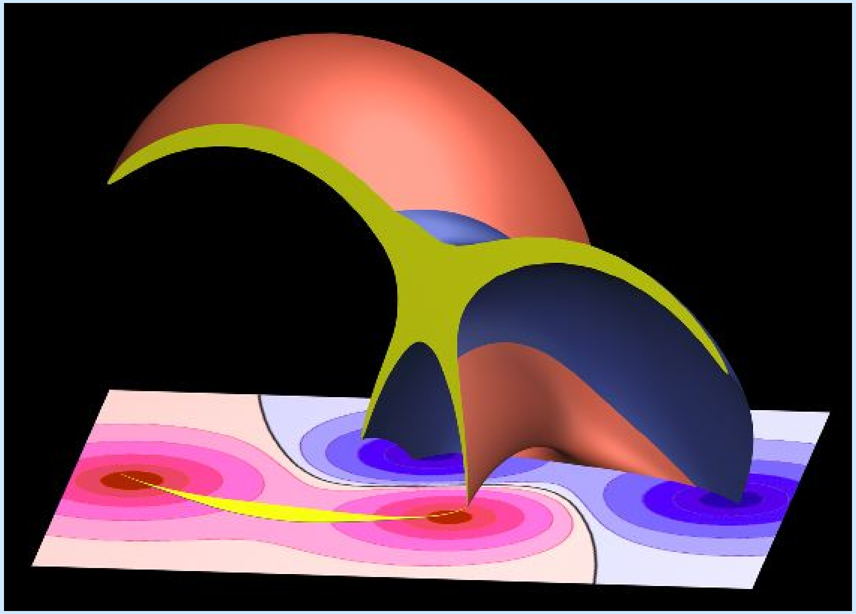
Boundary
$Bn > 0$

Hyperbolic Flux Tube

3D QSL shape



Magnetic connectivities



Volume inside the surface Q = constant :
QSL shape

Summary :

Boundary
Bn < 0

X shape

Boundary
Bn > 0

Hyperbolic Flux Tube

(Titov et al. 2002)

Does energy release occur at QSLs in solar flares ?

Input the photospheric magnetogram

↓

Compute the coronal field

↓

Compute QSLs

↓

Compare to observed flare signatures

Various flaring configurations analyzed

(Bagala et al. 2000, Démoulin et al. 1997, Gaizauskas et al. 1999, Mandrini et al. 1996, 1997, Schmieder et al. 1997)

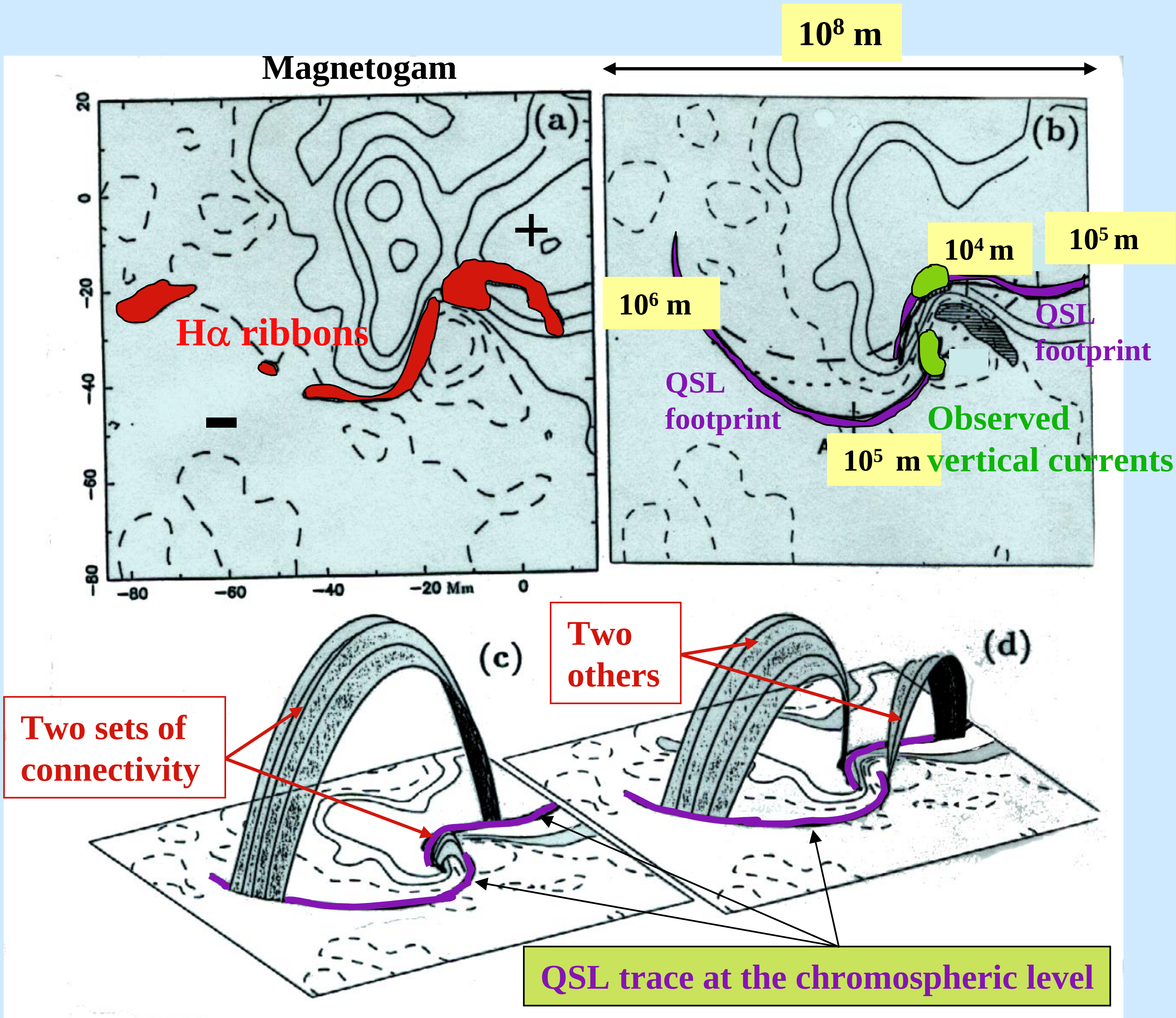
Example of flaring bipolar region

M4 flare
Nov. 5, 1980
AR 2776

Hα ribbons located on the QSL
(at chromospheric level)

NO magnetic null

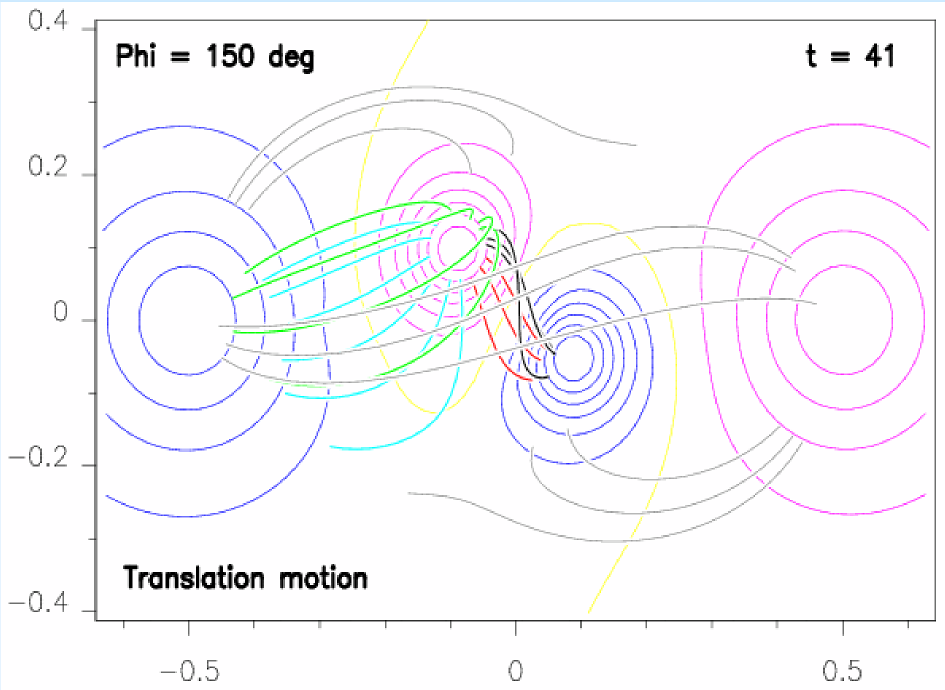
QSL thickness
~ 10^{-4} size AR
(lower if B
photospheric
more concentrated)

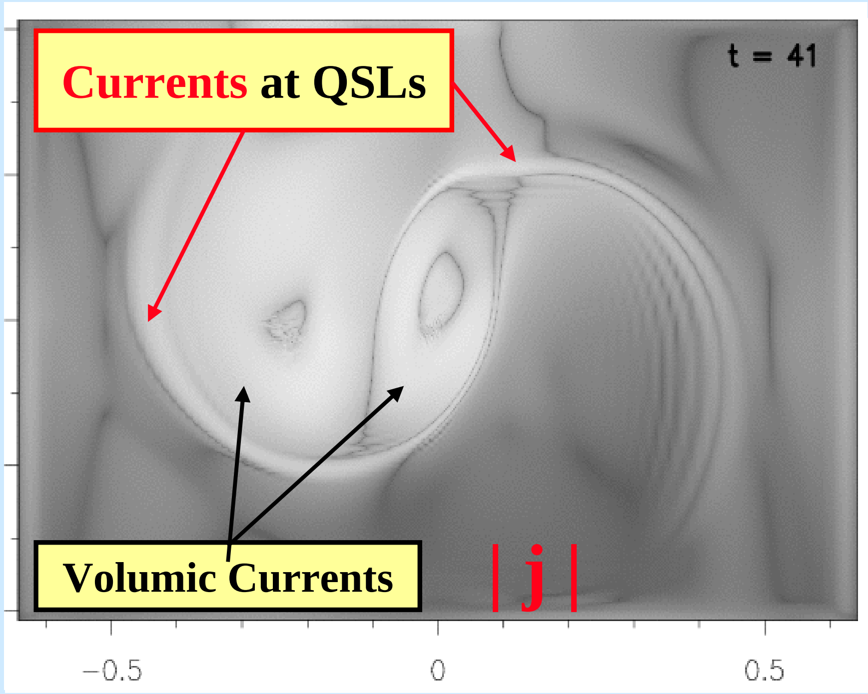


Formation of current at QSLs

- Expected theorically (Démoulin et al. 1997)
- Found in MHD simulations with stagnation type flows (Milano et al. 1999, Galsgaard et al. 2003)

New MHD simulations (initial configurations with thin QSLs) (Aulanier et al. 2005)





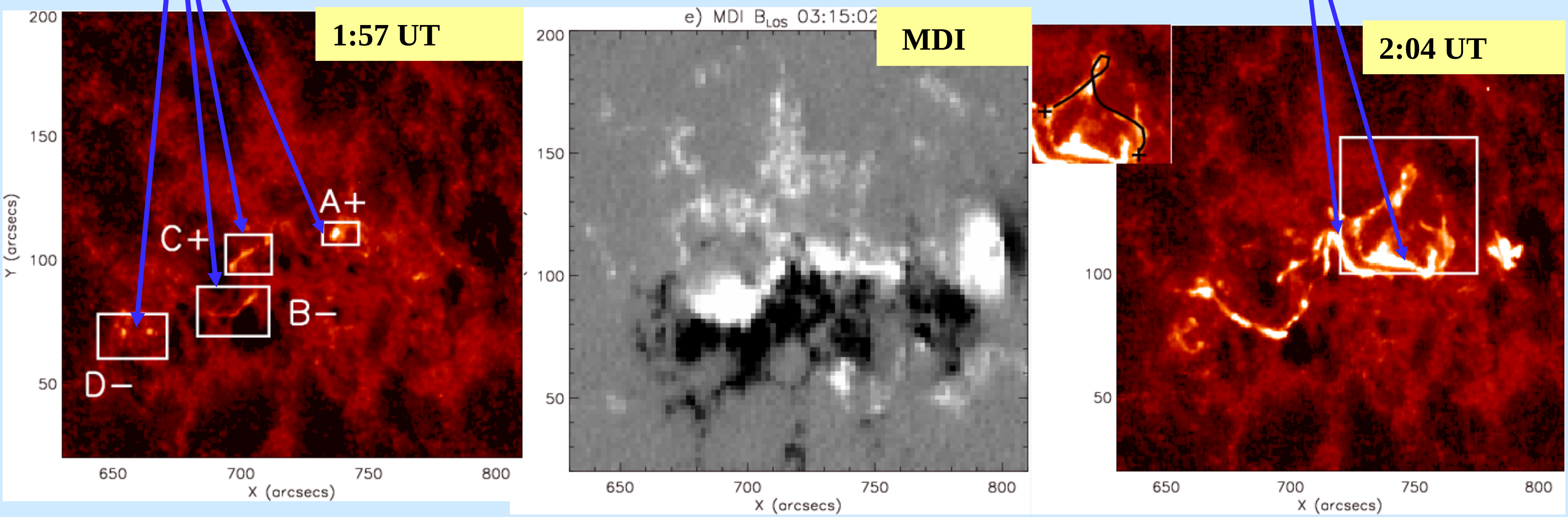
Do NOT need special motions

(opposite conclusion than Galsgaard et al. 2003)

Example of an eruption

quadrupolar reconnection (breakout)
4 ribbons

reconnection behind the twisted flux rope
(with kink instability)   2 J-shaped ribbons



(Williams et al. 2005)

Brief summary

Discret photospheric field :
(Model with magnetic charges)

--> **Photospheric null points** --> **Skeleton**

Separatrices → **Quasi-Separatrix Layers**

Separator → **Hyperbolic Flux Tube**

Generalisation to continuous field distribution :

Indeed, a little bit more complex…..

More still to come….

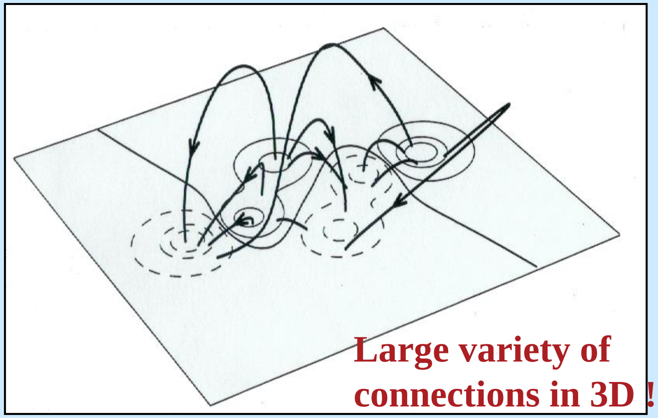
Where reconnection occurs in 3D ?

1. Generalization of 2D cases to 3D :

Bald Patch and Null Points separatrices

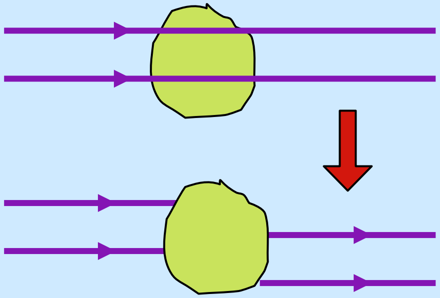
BUT many flare ribbons and loops NOT related to BP & NP separatrices

=> Reconnection must occur in broader conditions



(Démoulin et al. 1994)

2. One possibility: reconnection where resistivity is enhanced



"General magnetic reconnection" : $\int_{f.l.} \vec{E}.\frac{\vec{B}}{B}\,ds \neq 0$

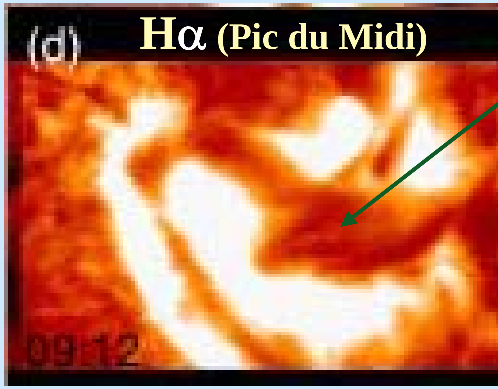
(Schindler et al. 1988
Birn et al. 1989
Hesse et al. 1990)

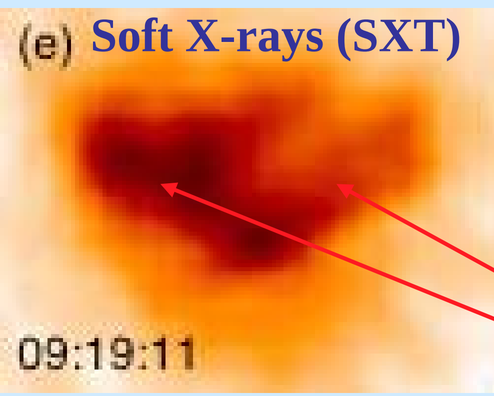
Why an increase of resistivity at some locations ?

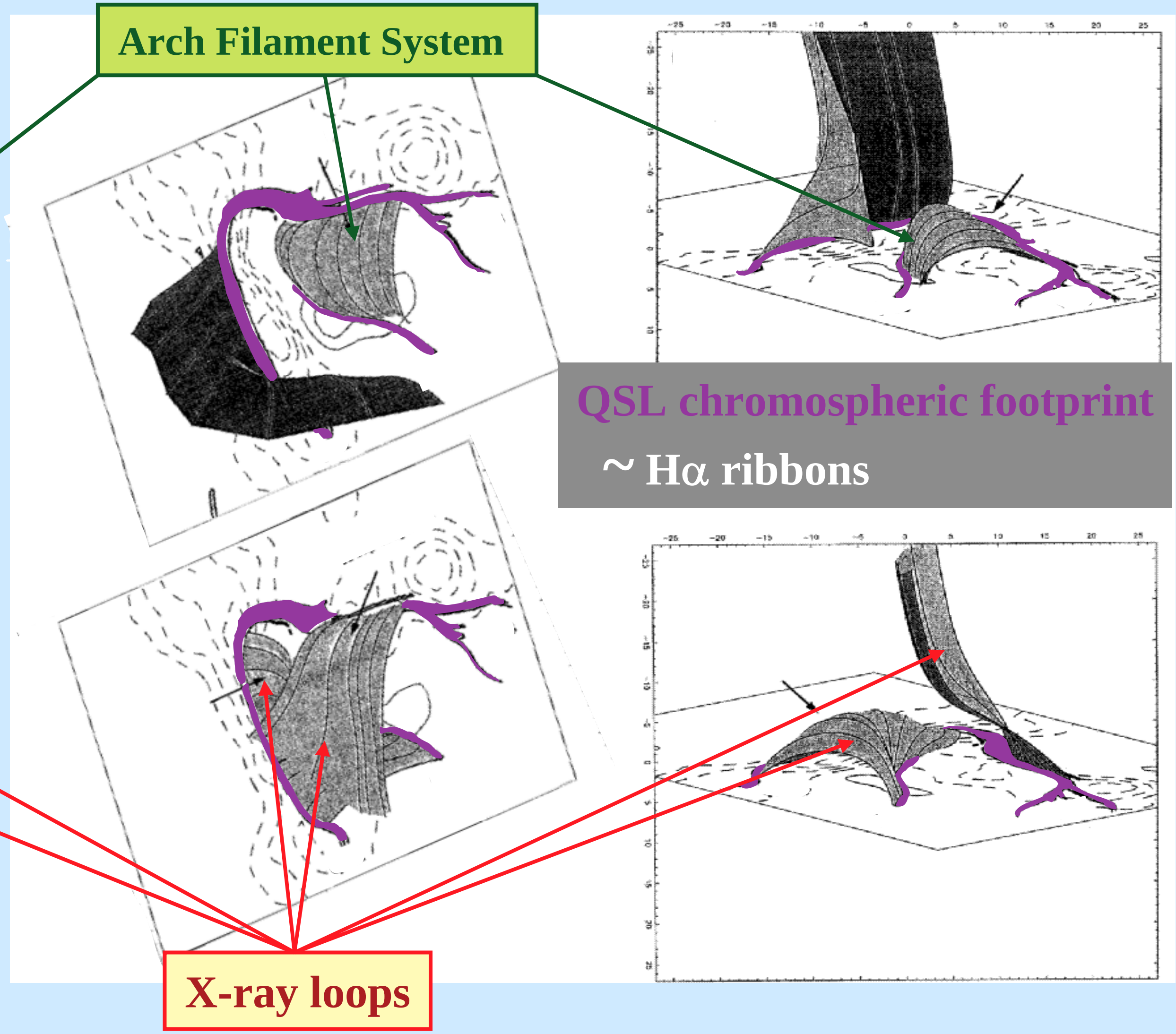
From flare studies, the reconnection is linked to the 3D organisation of magnetic field lines

Possibility of resistivity enhancement at separatrices…..+ QSLs !

A different type of flaring configuration





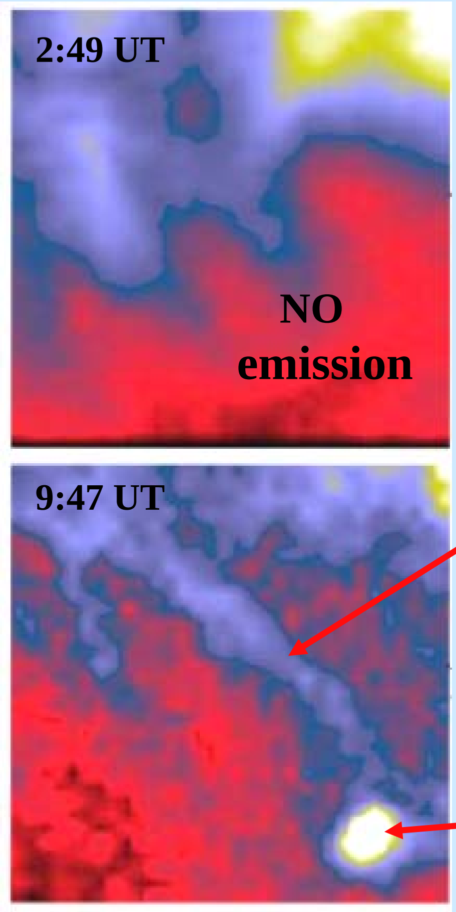


27 Oct. 1993

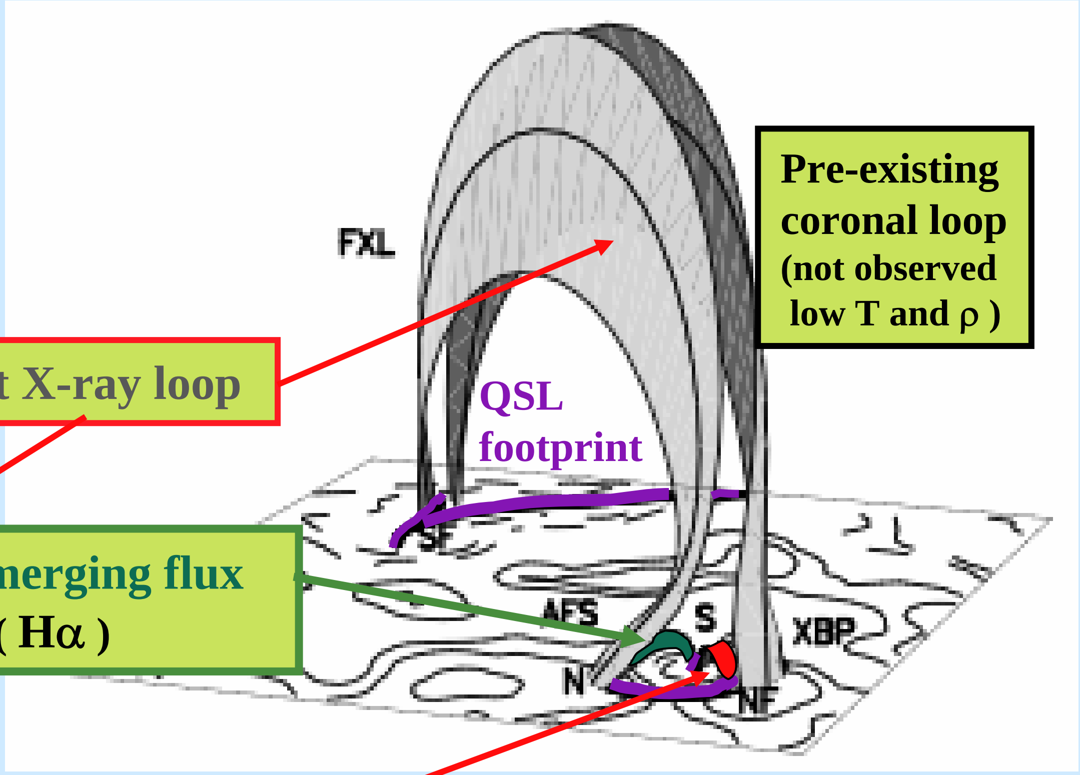
(Schmieder, Aulanier et al. 1997)

Reconnection at QSLs : X-ray bright point

Soft X-rays, May 1 1993
Yohkoh / SXT



Model from magnetic extrapolation



Faint X-ray loop

Emerging flux (Hα)

XBP

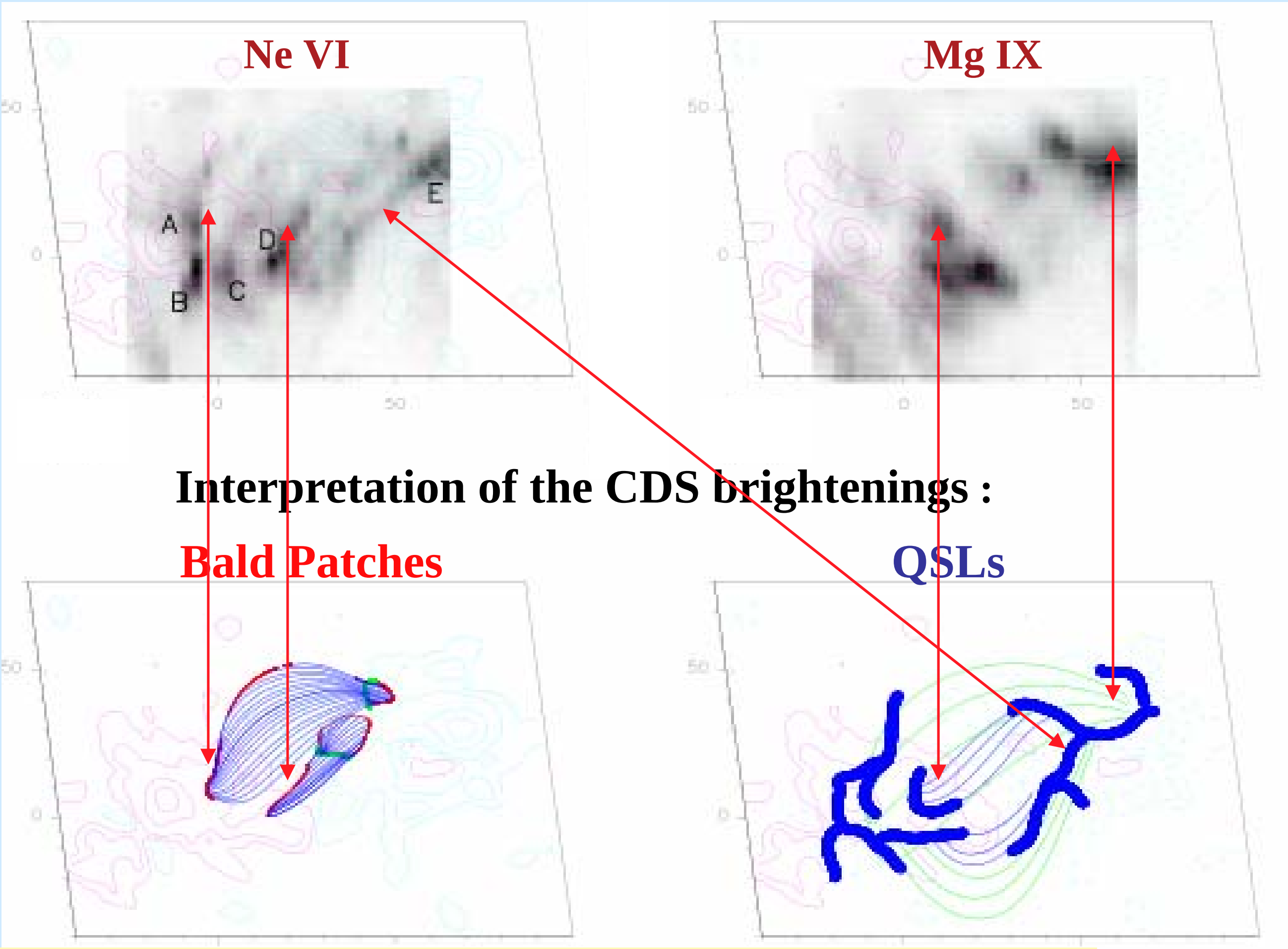
(Mandrini et al. 1996)

Energy release occurred when the QSL thickness is lower than 100 m

Transition Region Brightenings

CDS / SoHO

Inversed contrast



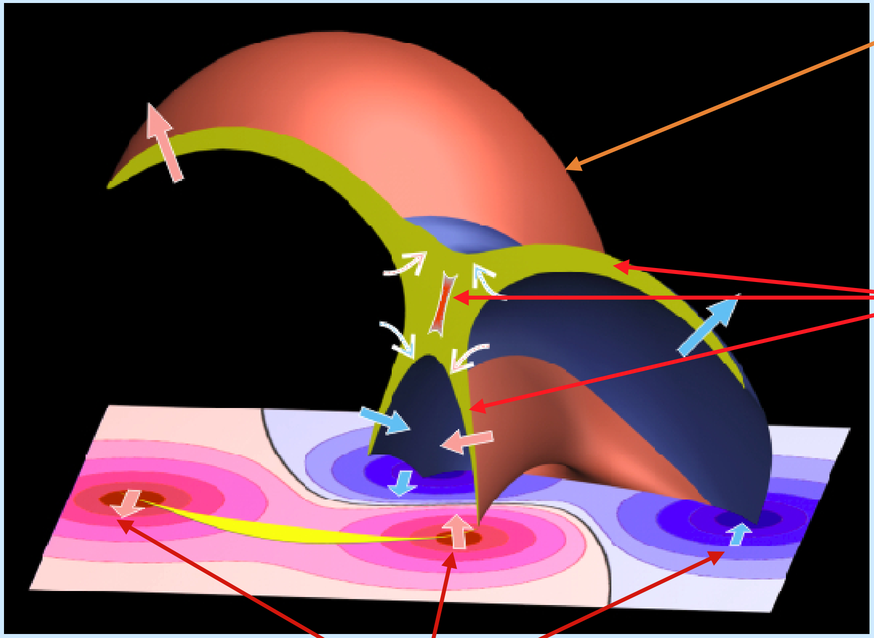
Mg / Ne abundances in CDS brightenings associated to :	compared to :
Bald Patches : [0.7, 1.7] QSLs : [2.0, 3.9]	photosphere: [0.2,0.3] corona: [1.4,2.0]

(Fletcher et al. 2001)

Formation of current layers at QSLs (1)

• Expected theoretically : - with almost any boundary motions
- with an internal instability

Using Euler potential representation: magnetic shear gradient across QSL (Démoulin et al. 1997)



Surface Q = constant (= 100)

Formation of current layers

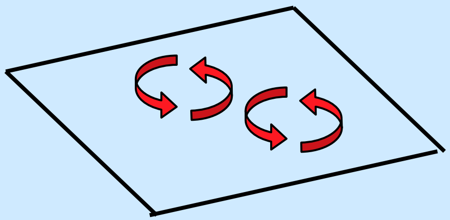
Example of boundary motions

(Titov, Galsgaard & Neukirch. 2003)

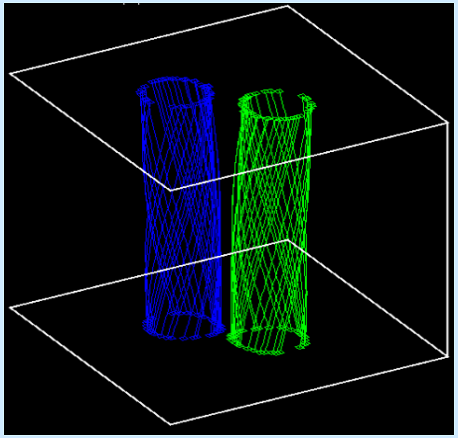
Formation of current layers at QSLs (2)

- **Found in MHD simulations**

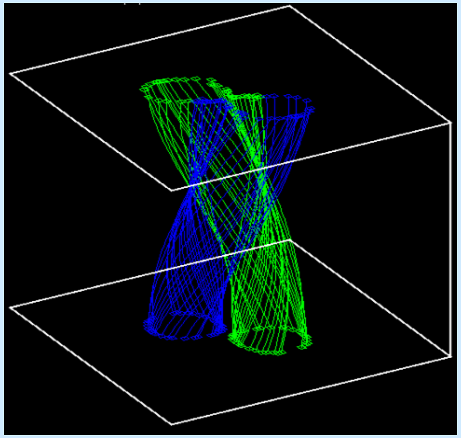
  - Start from a uniform B field
  - Apply twisting motions

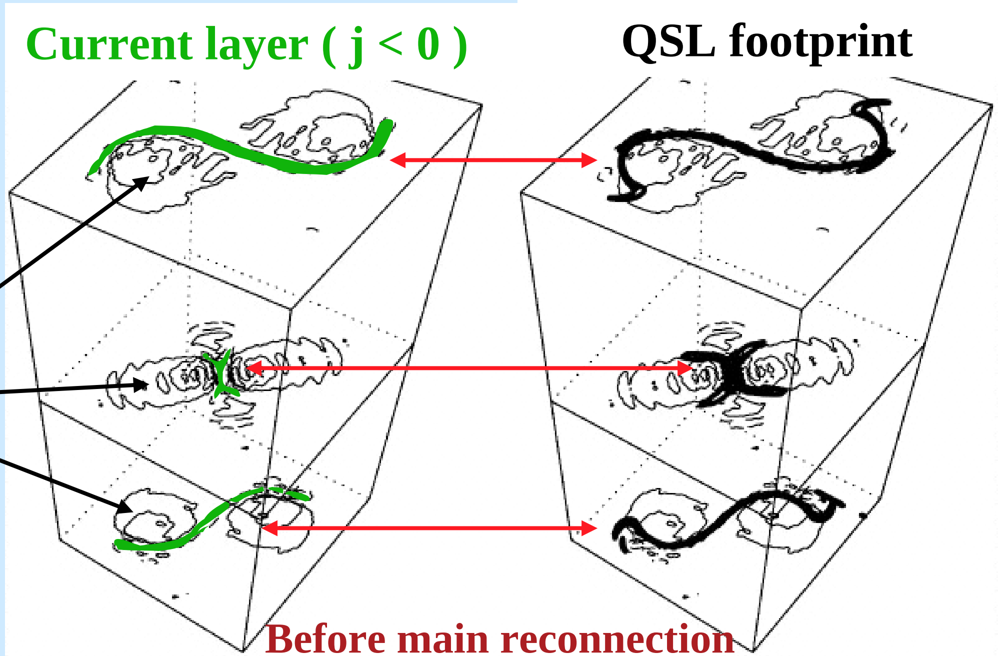


Two twisted flux tubes are formed



Then they reconnect



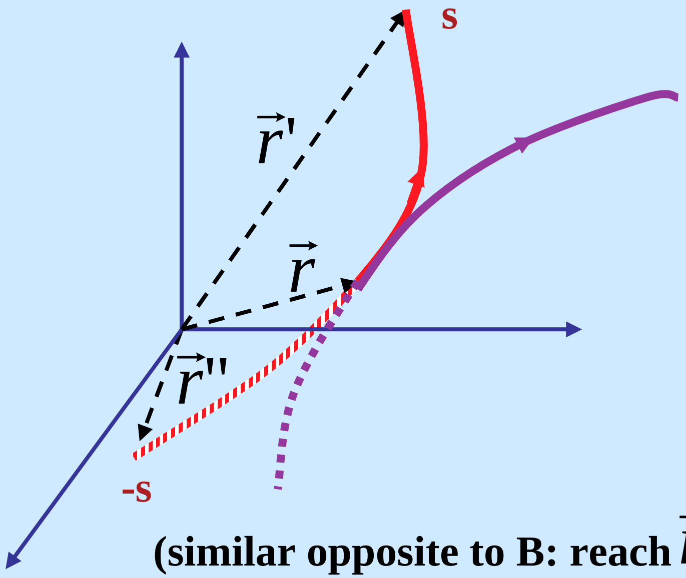


Twisted flux tube currents (j > 0)

(Milano et al. 1999)

How can we characterize 3D field-line linkage ?

Compute field line starting at $\vec{r}$
up to a curvilinear length s // to B: reach $\vec{r}\,'$



(similar opposite to B: reach $\vec{r}\,''$)

Field line mapping: $\vec{r} \to \vec{r}\,'$: $\quad \vec{r}\,'(\vec{r},s)$

Modify $\vec{r}$, how $\vec{r}\,'$ change ?

Jacobi matrix:

$$F_{(\vec{r},s)} \equiv \left(\partial\vec{r}\,'/\partial\vec{r} \right)_s$$

	$\vec{r}\,'(\vec{r},s)$	$\| F \|$
Most locations	Continuous	$\| F \| \approx 1$
Separatrix	Discontinuous	singular (delta function)
QSL	Drastic changes	$\| F \| >> 1$