Magnetic Reconnection
in
Solar, Space and Laboratory Plasmas

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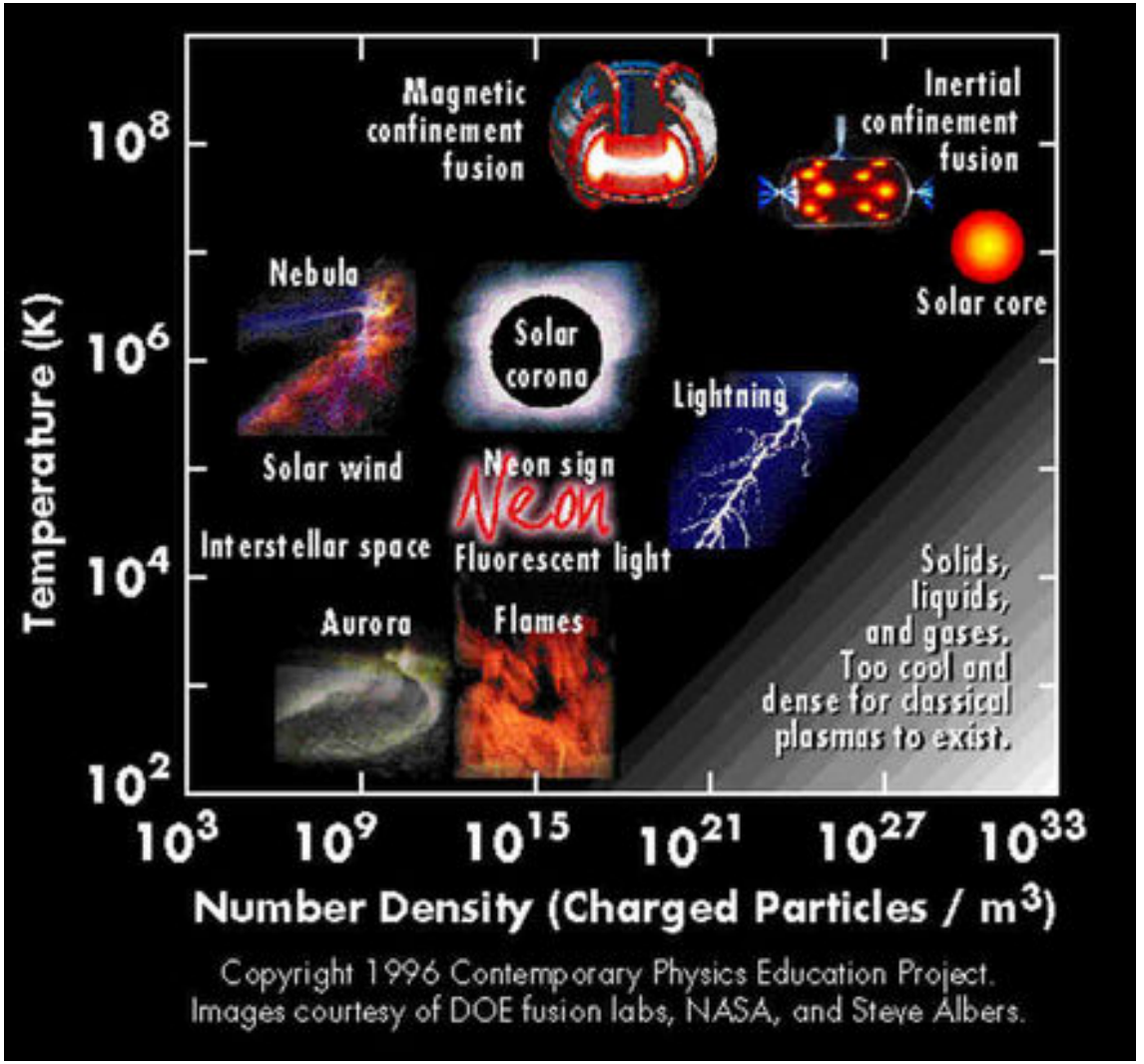
My Background

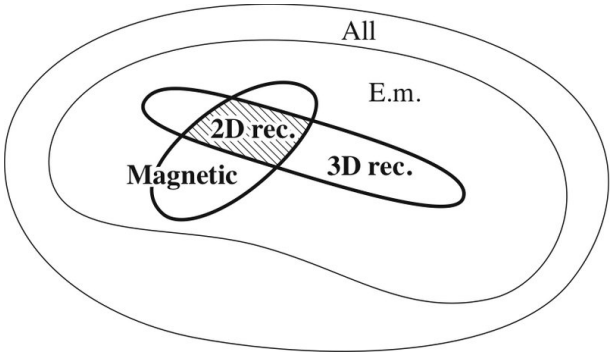
- Solar coronal physic related MHD problems since 1995
- Coronal heating
  - Fast magnetic energy release in complex 3D magnetic fields
- Magnetic flux emergence
  - Restructures the magnetic field in the corona through reconnection
- Magnetic reconnection in general
- Numerical 3D MHD experiments

What do we want to explorer?



Magnetic Reconnection

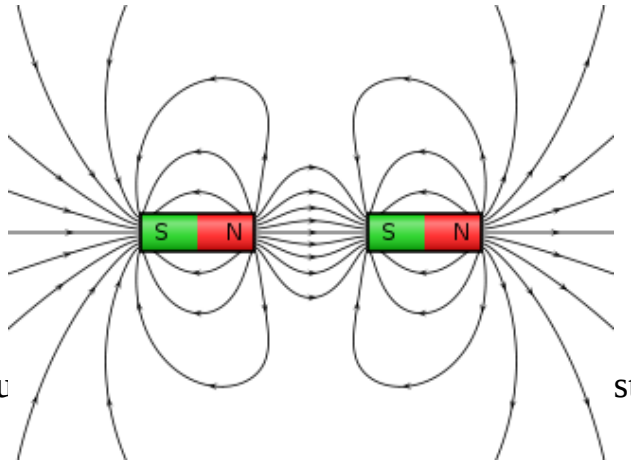
- What does MR do? What is it?
- Simplification of the magnetic field line structure on a “local scale” with global consequences
- Conversion of *free magnetic energy* in to other forms of energy
  - Kinetic energy (bulk motions)
  - Ohmic heating (localised in a given volume)
  - Particle acceleration (non-Maxwellian tail on the distribution function)

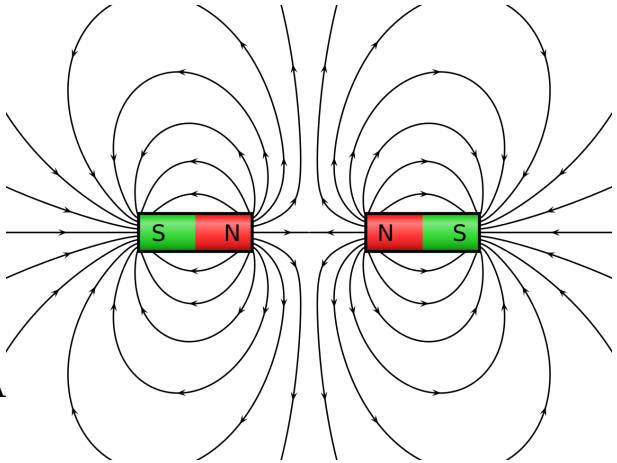


You have seen it!
without knowing!?

- Where do we see this?

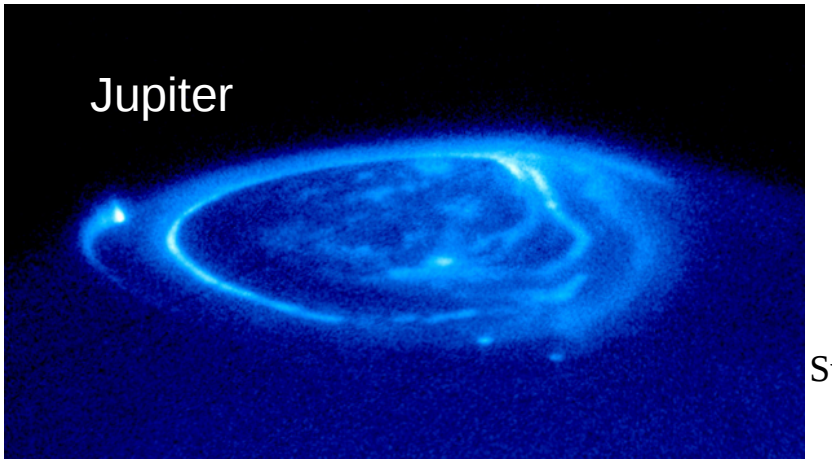
- You have most likely forced it yourself!
  - Two bar-magnets
    - Put them together as one long bar-magnet
    - Change the order of them or rotate one 360 degrees...

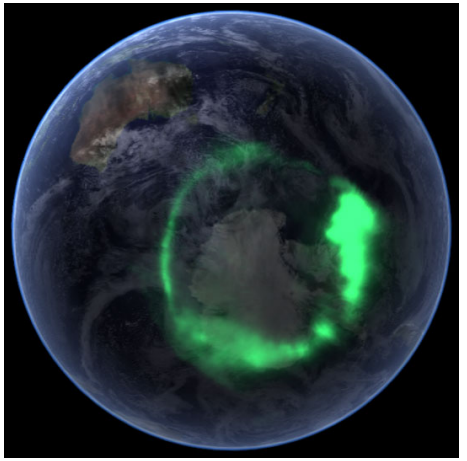


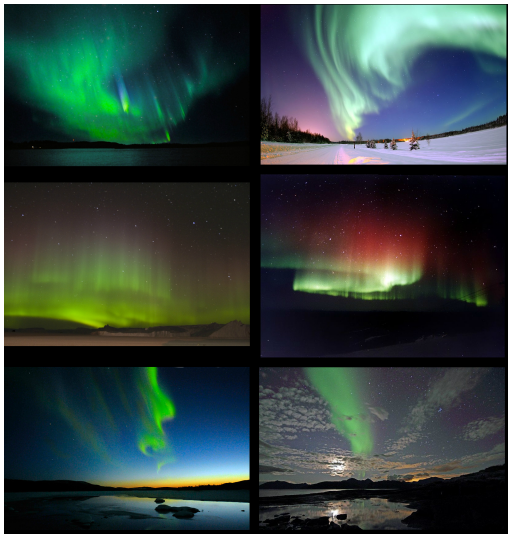


Earth Atmosphere

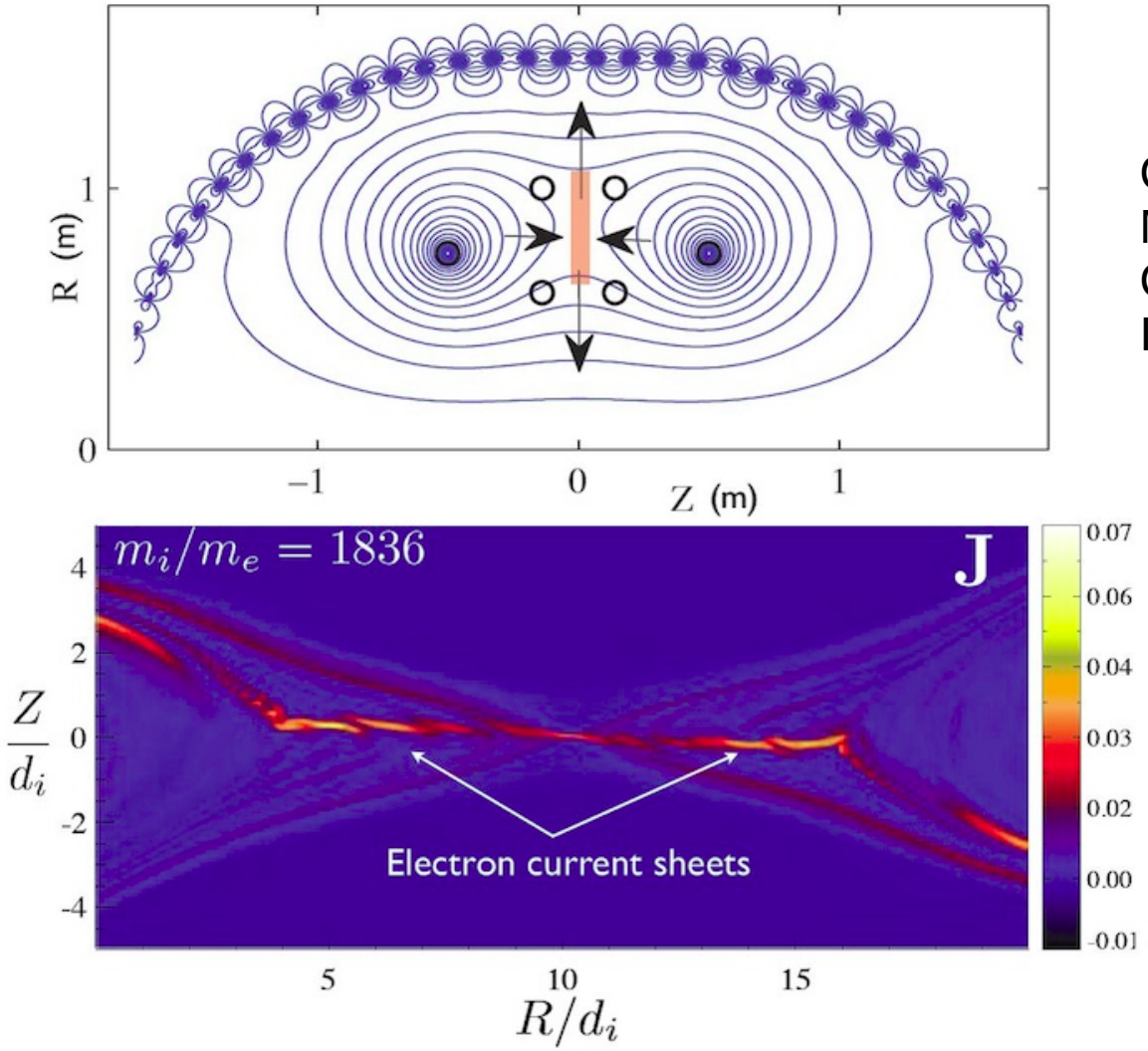
- Auroras are the signature of reconnection
  - Not the process itself
  - Indirect evidence of particle acceleration effects in the outer solar atmosphere
  - The “battle” between the earth magnetic field with the extended solar magnetic field + high load of particles....







Laboratory Experiments



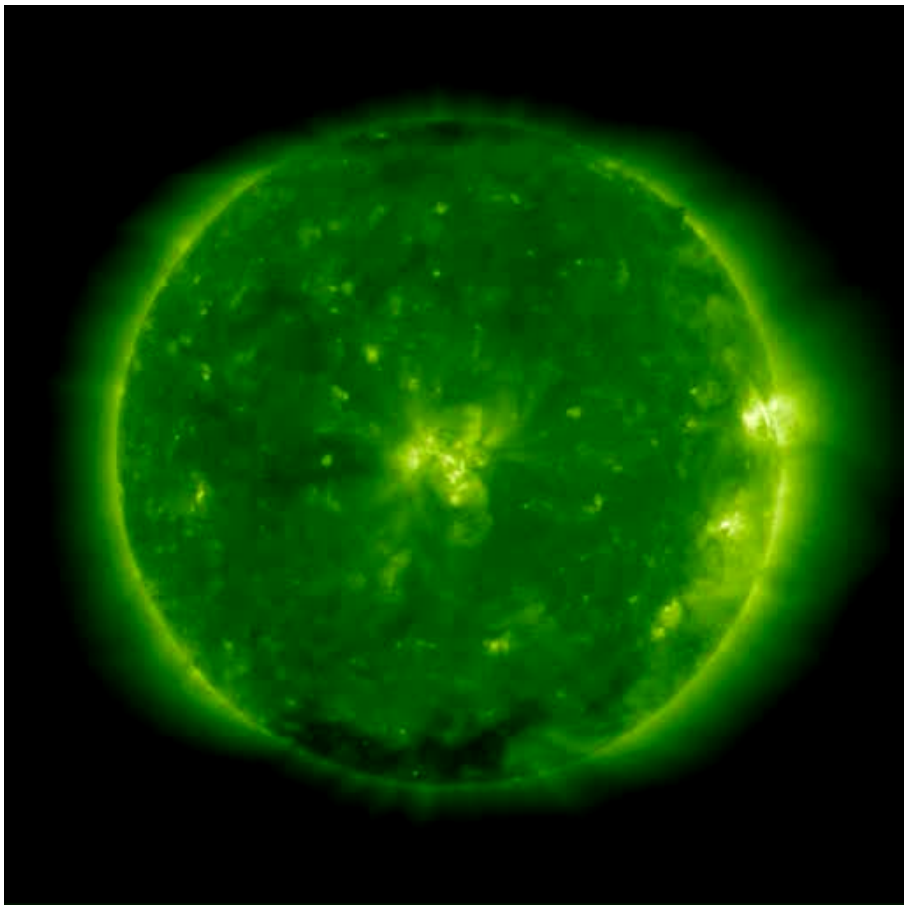
Cartoon of an instrument
Magnetic field lines
Current sheet
Inflow and outflow arrows

Comparison of current sheet from a *pic* simulation

Localised region around the current sheet

Figure 5: (top) Magnetic coil configuration for TREX implemented in the MPDX vacuum vessel. The bottom panel shows the current density for a 2D collisional VPIC simulation with mass ratio mi/me=1836 and collision frequency vee/wee = 0.001.

Solar reconnection



Showing the x-ray signature of the Sun over several years

Bright regions are associated with strong closed magnetic field

Most of the small scale blinking is assumed to be energy release events driven by reconnection

How about the different environments

- MRX experiments
  - Able within limits to change the parameters
    - Typically collision less environment
- Earth magnetosphere
  - Collision less environment
- Solar corona
  - Locally collision less environment
  - Not able to observationally resolve the small scales
  - Typically uses macroscopic approaches

How to treat it from a physical point of view

- Magnetised plasma
  - Collisional dominated or collision less?
    - Magneto hydro dynamics or particle investigations
      - *Macroscopic* or *microscopic* physics
  - Relevant length
    - Mean free path
    - Gyroradius
    - Debye length
    - Cyclotron frequency
    - Coulomb collision

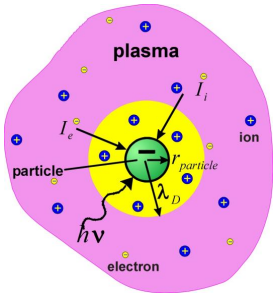
$$l = \frac{\mu}{p}\sqrt{\frac{\pi k_B T}{2m}}$$

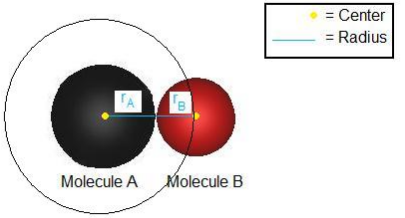
$$r_g = \frac{m v_\perp}{|q|B}$$

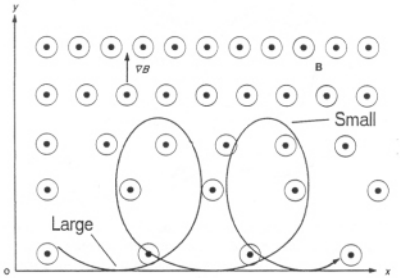
$$\lambda_D = \sqrt{\frac{\epsilon_0 k_B T}{n_e q_e^2}}$$

$$\omega_g = \frac{|q|B}{m}$$

$$r_0 = \frac{Ze^2}{4\pi\epsilon_0}\frac{1}{m_e v^2}$$







MHD approach

- Macroscopic description
  - Density, temperature/pressure, velocity, magnetic field
- 8 coupled partial differential equations
  - Induction eq
  - Mass conservation
  - Momentum conservation
  - Amperes law
  - Energy conservation – Adiabatic
  - Ohms law
  - Gas law

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \wedge \mathbf{E}$$

$$\frac{\partial \rho}{\partial t} + \nabla.(\rho \mathbf{v}) = 0$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla p + \mathbf{j} \times \mathbf{B}$$

$$\nabla \wedge \mathbf{B} = \mu_0 \mathbf{j}$$

$$\frac{d}{dt}\left(\frac{p}{\rho^{\gamma}}\right) = 0$$

$$\mathbf{E} + \mathbf{v} \wedge \mathbf{B} = 0$$

Induction Equation

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla \times \boldsymbol{E}$$

Ohms law: $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \eta j$ = Advection + diffusion
Ideal non-ideal

Magnetic Reynolds number $R_m = \frac{\boldsymbol{v} \times \boldsymbol{B}}{\eta J} = \frac{l_0 v_0}{\eta}$

Typical regimes for the induction eq depends on the R_m value

- >> 1: Advection – Ideal evolution
  - Magnetic field is *frozen* into the plasma
- << 1: Diffusion – Non-ideal evolution
  - Anihilation of magnetic field
- Order 1 : – Balance, near steady state B
  - Region where reconnection takes place

Diffusive time scale

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla x(\eta \boldsymbol{j})$$

Dimension analysis:

$$\frac{\boldsymbol{B}}{t} = \frac{\eta \boldsymbol{B}}{l^2} \rightarrow t = \frac{l^2}{\eta}$$

Solar values:

L = order 10-100 Mm

$\eta = 5.2\, x\, 10^{7} \ln \Lambda\, T^{-3/2}\, m^{2}\, s^{-1}$ Classical Spitzer resistivity

Where $\ln \Lambda$ is order 5-25 and T order 1 Mill K

$t = 10^{14}\, sec = 3.2\, Mill\ years$

Observe energy release events in radio obs with time structures of less than 1. sec

Implies *l=1 m*

Generalised Ohms law

$$\mathbf{E} + \mathbf{v} \times \mathbf{B} = \eta \mathbf{J} + \frac{1}{ne}\mathbf{J} \times \mathbf{B} - \frac{1}{ne}\nabla \mathbf{P} + \frac{m_e}{ne^2}\frac{\partial \mathbf{J}}{\partial t}$$

Resistive term
Hall term
Electron pressure term
Electron inertia term

Terms that can't be written as ?xB provide changes to the magnetic topology – ie reconnection

See for a more detailed description:

http://plasma.physics.swarthmore.edu/brownpapers/ohmnotes.pdf

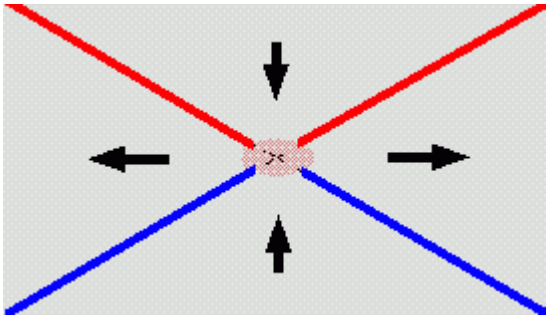
2D reconnection

Breaking of magnetic field lines

Takes place in locations where the B-field vanishes

X-point

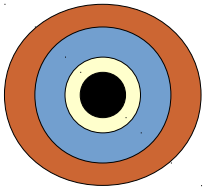
Opposite directed field brings into contact at one point in space. “Cut” and “glue” of field lines



O-point

Closed field lines around the null point

Pure diffusion process

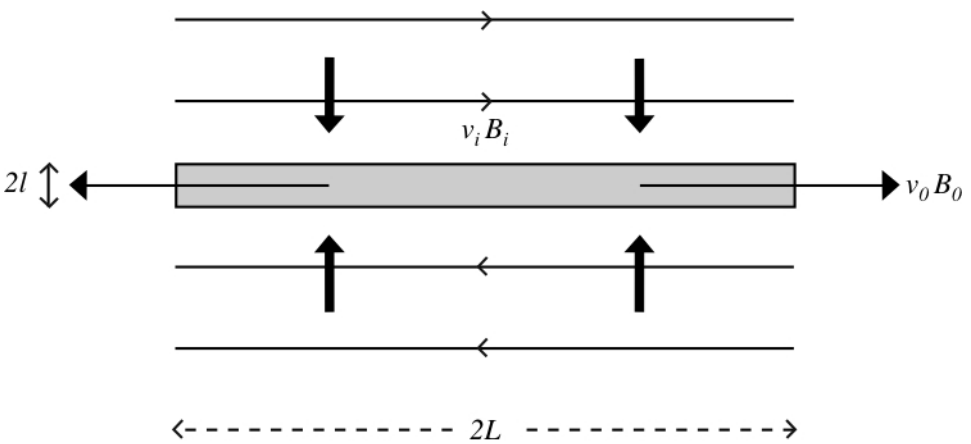


Sweet-Parker mechanism

Assumes a steady state situation

Induction equation on inflow region gives:

$$u_i = \frac{\eta}{l}$$



Mass conservation:

$$4\rho L v_i = 4\rho l v_o$$

Assuming the outflow speed is comparable to the inflow Alfven speed

$$v_i = \frac{v_{A_i}}{R_{mi}^{1/2}}$$

$$\frac{v_i}{v_{A_i}} = M_i = R_{mi}^{-1/2}$$

This mechanism is far to slow
In solar plasmas where R_m is order 10^{10}

Sweet 1958

Petschek's model

Near uniform field in the inflow region

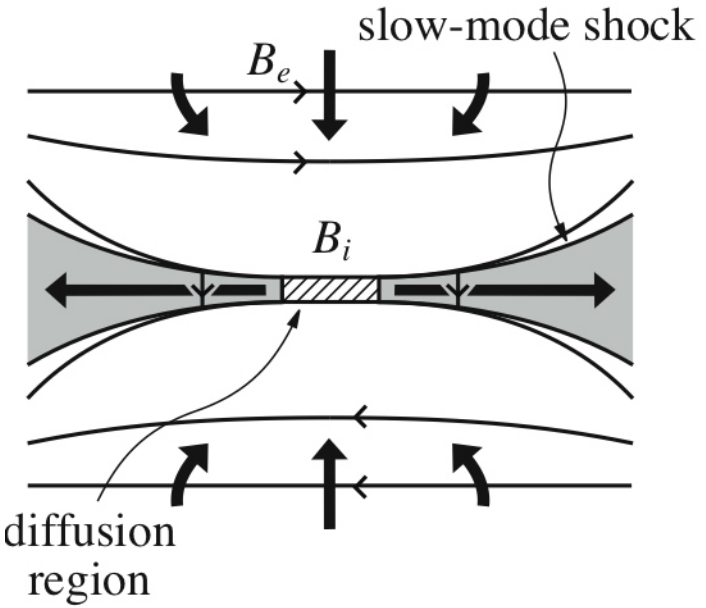
Small diffusion region
Smaller mass in the diffusion region

Conversion of energy also in the standing Slow-mode shocks

Various details....

Reconnection rate becomes:

$$M_e \approx \frac{\pi}{8 \log(R_{me})}$$



Much faster than *SP* and therefore uses as a limit for fast – slow reconnection speed

Petcheck 1964

A full parameter space of solutions

Linearise the problem
Use a single value to describe the solutions
Find a continuum of different solutions
Solve for steady state solutions

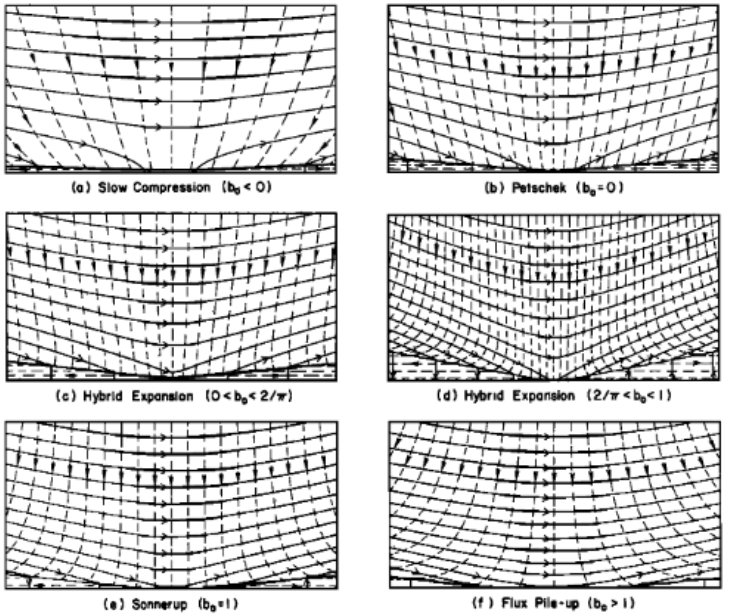
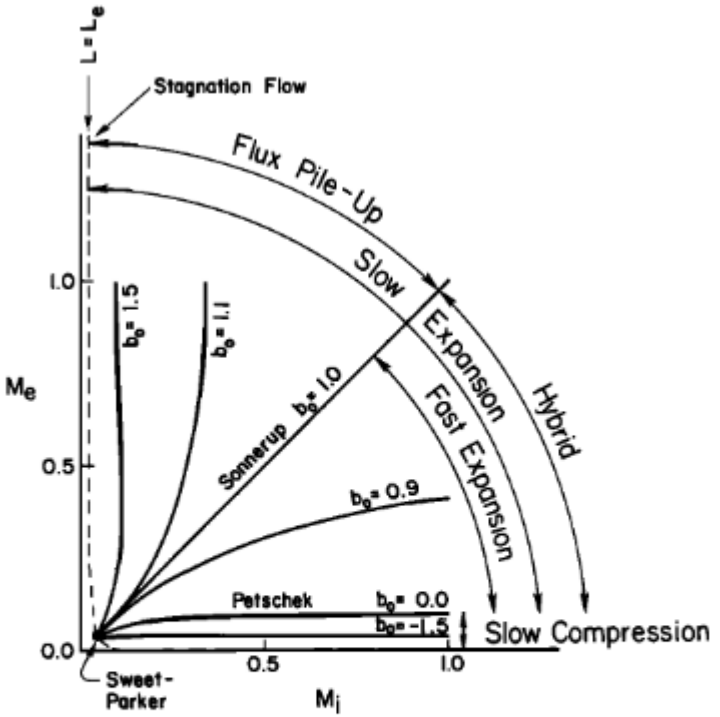


Fig. 6. Magnetic field lines (solid) and streamlines (dashed) for different classes of solution with $R_{me} = 500$ and the ends of the diffusion region indicated by dots: (*a*) $b_0 = -2.0$, $M_e = M_e^* = 0.043$, $M_i = 0.18$, $L/L_e = 0.127$; (*b*) $b_0 = 0$, $M_e = M_e^* = 0.091$, $M_i = 0.76$, $L/L_e = 0.010$; (*c*) $b_0 = 0.3$, $M_e = 0.100$, $M_i = 0.242$, $L/L_e = 0.053$; (*d*) $b_0 = 0.8$, $M_e = 0.200$, $M_i = 0.146$, $L/L_e = 0.080$; (*e*) $b_0 = 1.0$, $M_e = 0.100$, $M_i = 0.100$, $L/L_e = 0.200$; (*f*) $b_0 = 2.0$, $M_e = 0.100$, $M_i = 0.064$, $L/L_e = 0.392$. (Only every third streamline in the outflow jets is indicated.)

Priest & Forbes 1986, JGR 91, 5579



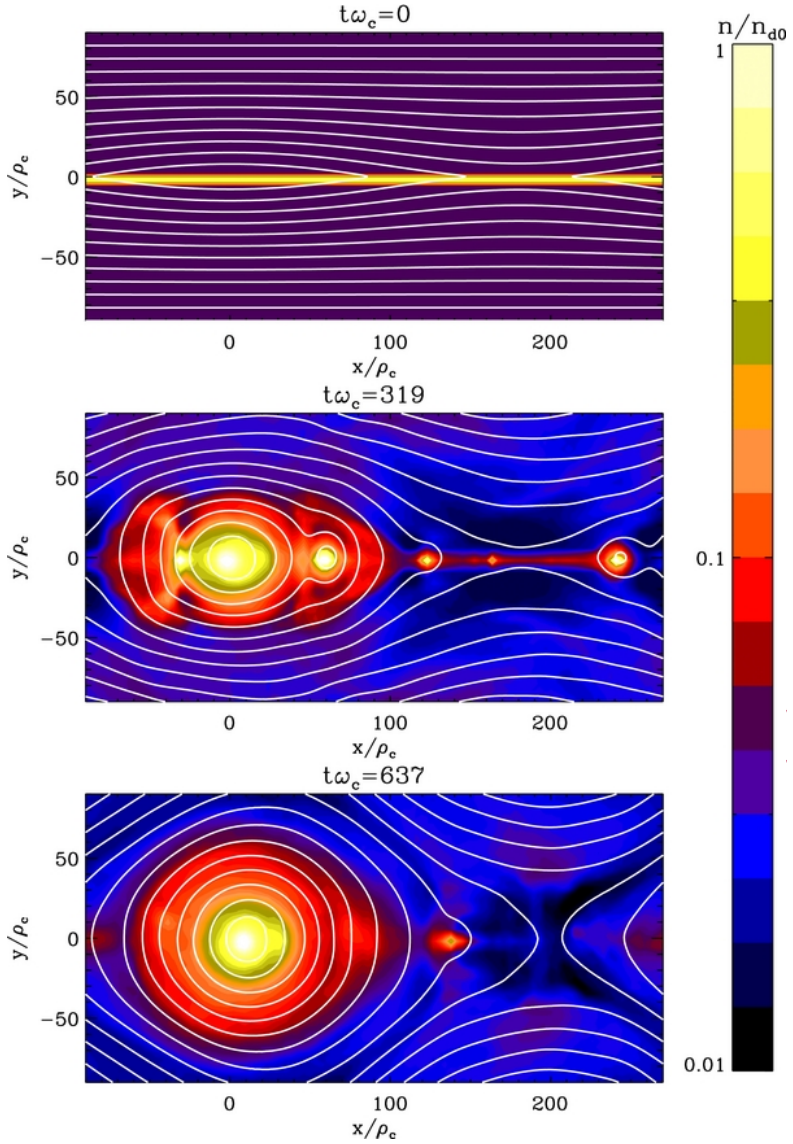
(b) $R_{me} = 500$

Fig. 9. The imposed Alfvén Mach number (M_e) at the inflow boundary as a function of the resulting Alfvén Mach number (M_i) at the entrance to the central diffusion region, for (*a*) $b_0 = 0$ (Petschek case) and several values of the magnetic Reynolds number (R_{me}) at the inflow boundary and (*b*) $R_{me} = 500$ and several values of b_0.

T

There is always a solution that is fast enough to suits you needs!!
Dynamical restructuring

Typical 2D evolution



Reconnection is a dynamical process

Where the creation of a current concentration is a reaction to an imbalance in the field.

First in a singular point, which then typically collapses onto a current sheet

Notice that the electric field in 2D is perp. to the plane of the paper and the magnetic field!

Numerical experiments show plasmoid formation and much more complex signatures

3D reconnection

Lots of what was leaned from 2D have to be almost completely reconsidered

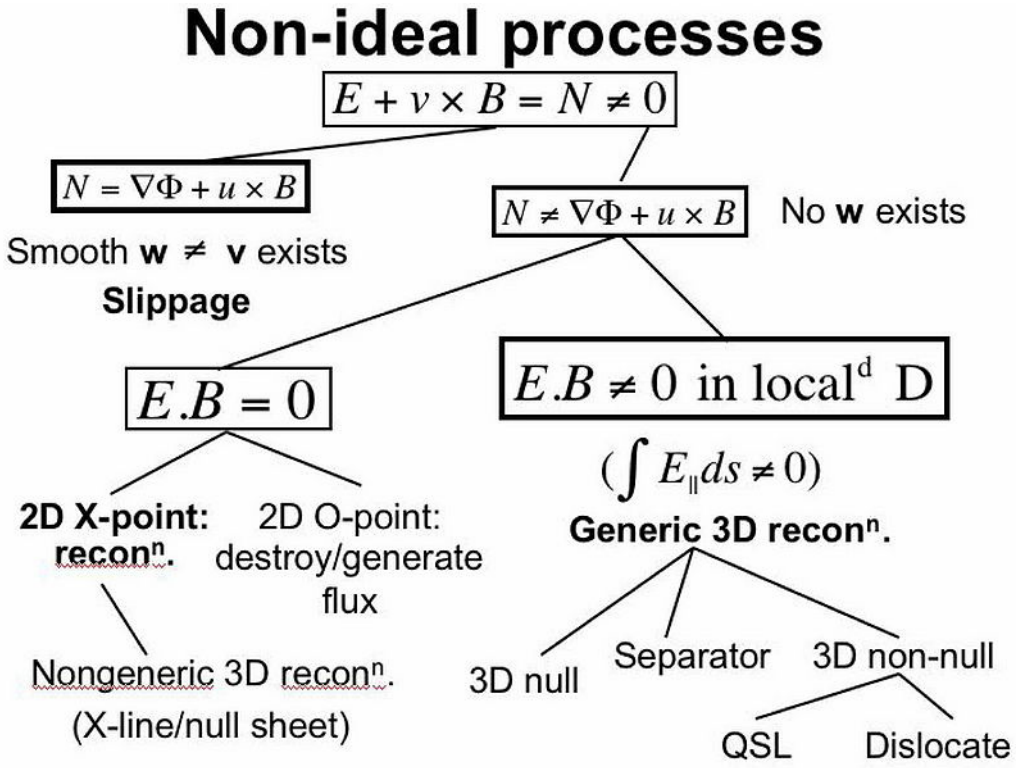
2D breaking of field lines in a single point in space

3D is different

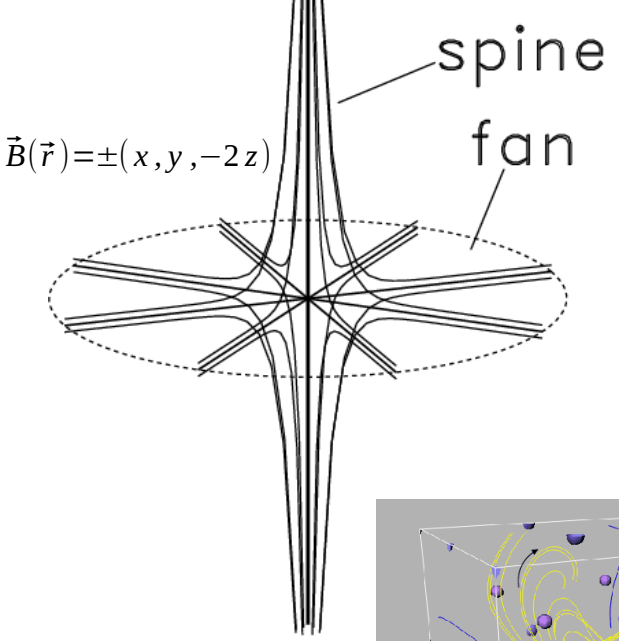
- At null locations
- At no null locations

The electric field parallel to the magnetic field is important

$$\int E_{par}\, ds \neq 0$$



Single Null Points



Locations in space where **B**=0

First order expansion of the magnetic field:

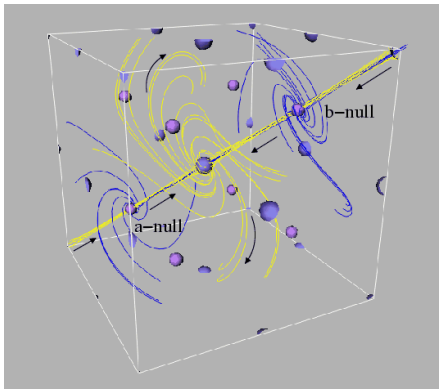
$$\vec{B}(\vec{r})=\bar{M}(\vec{r_0})(\vec{r}-\vec{r_0})$$

The eigenvalues and eigenvectors of the Jacobian matrix, M, determines the structure of the magnetic field

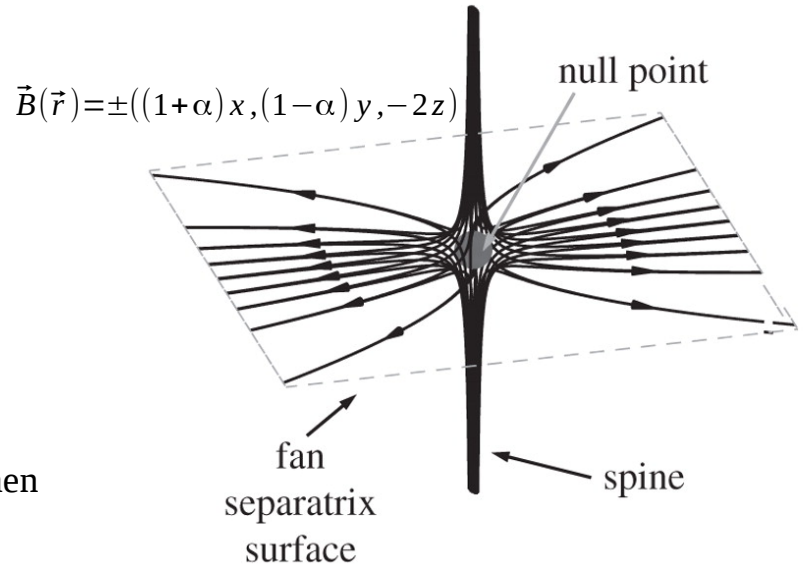
Trace of M is zero (Div(B)) → Sum of eigenvalues is zero

Two classes
- All real eigenvalues
- One real, to complex conjugated

Structure
- Spine axis (largest eigenvalue direction)
- Fan plane (divide space into independent flux regions



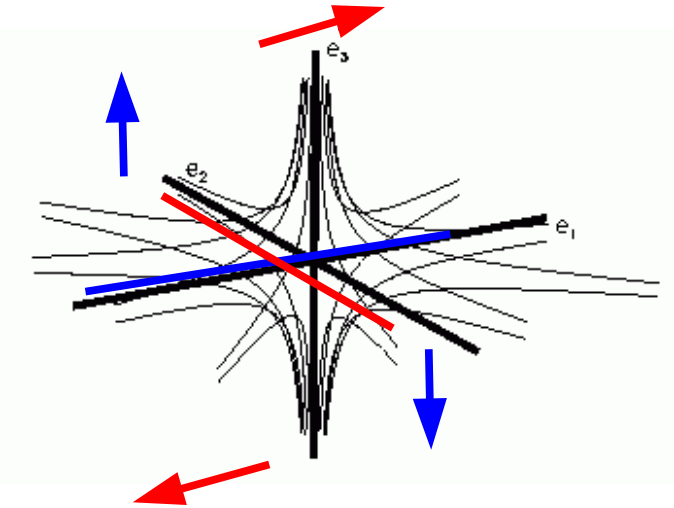
$\vec{B}(\vec{r})=\pm((1+\alpha)x-\beta y,(1-\alpha)y+\delta x,-2z)$



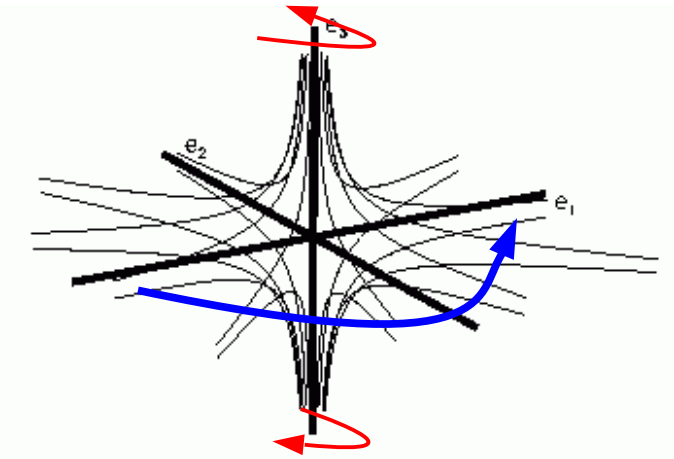
Single Null Perturbations

Two potential modes to perturb a single null

Shear motions
- Across spin axis
- Across the fan plane



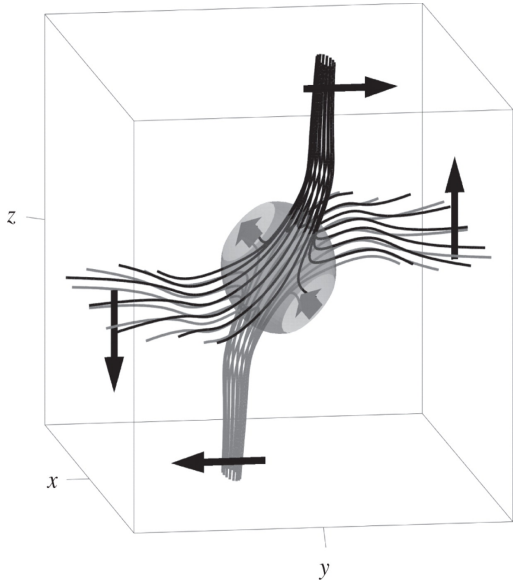
Rotation motions
- Around spine axis
- Sense of rotation is important

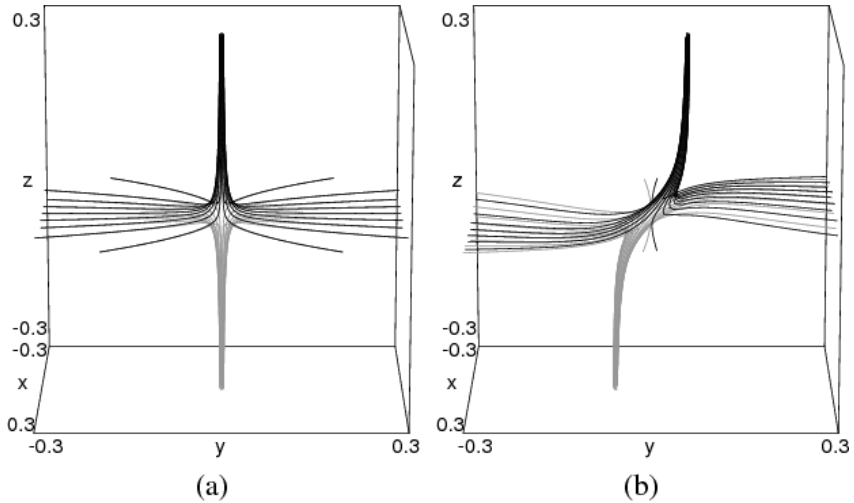


Shear driven collapse of a null

Two potential ways to perturb a single null

- Shear motion (the most generic)
  - Across the spine or fan plane
- Rotation
  - Spine or fan plane





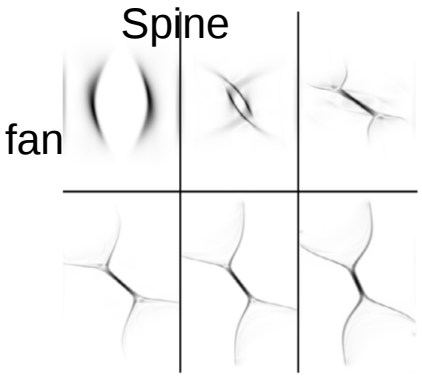
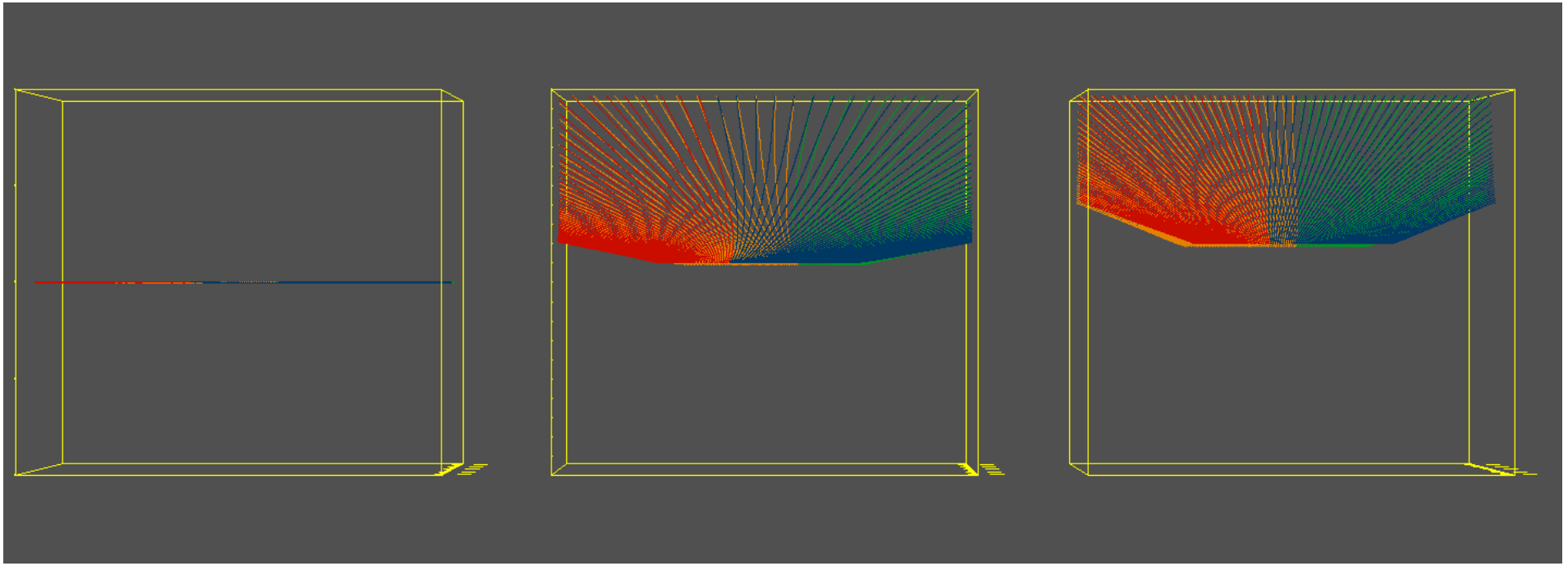


Fig. 4. Current amplitude at a number of characteristic instances in the dynamical evolution. The individual frames are scaled to their local dynamical range to enhance the visual appearance. The images represent the $z = 0$ plane for run "C3" at times $t = (0.4, 1.0, 2.2, 4.4, 9.2, 19.0)$.

(c)

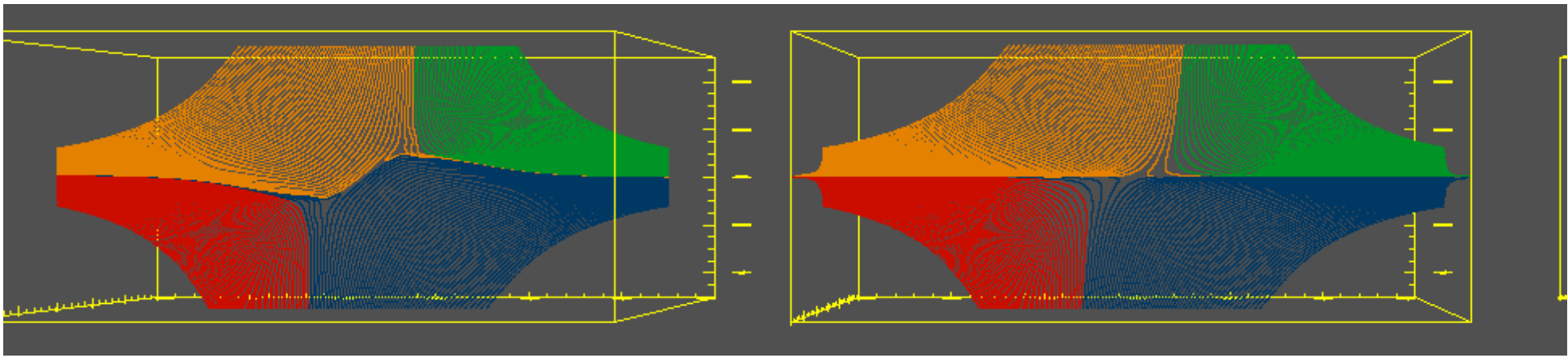
Field evolution

Top view

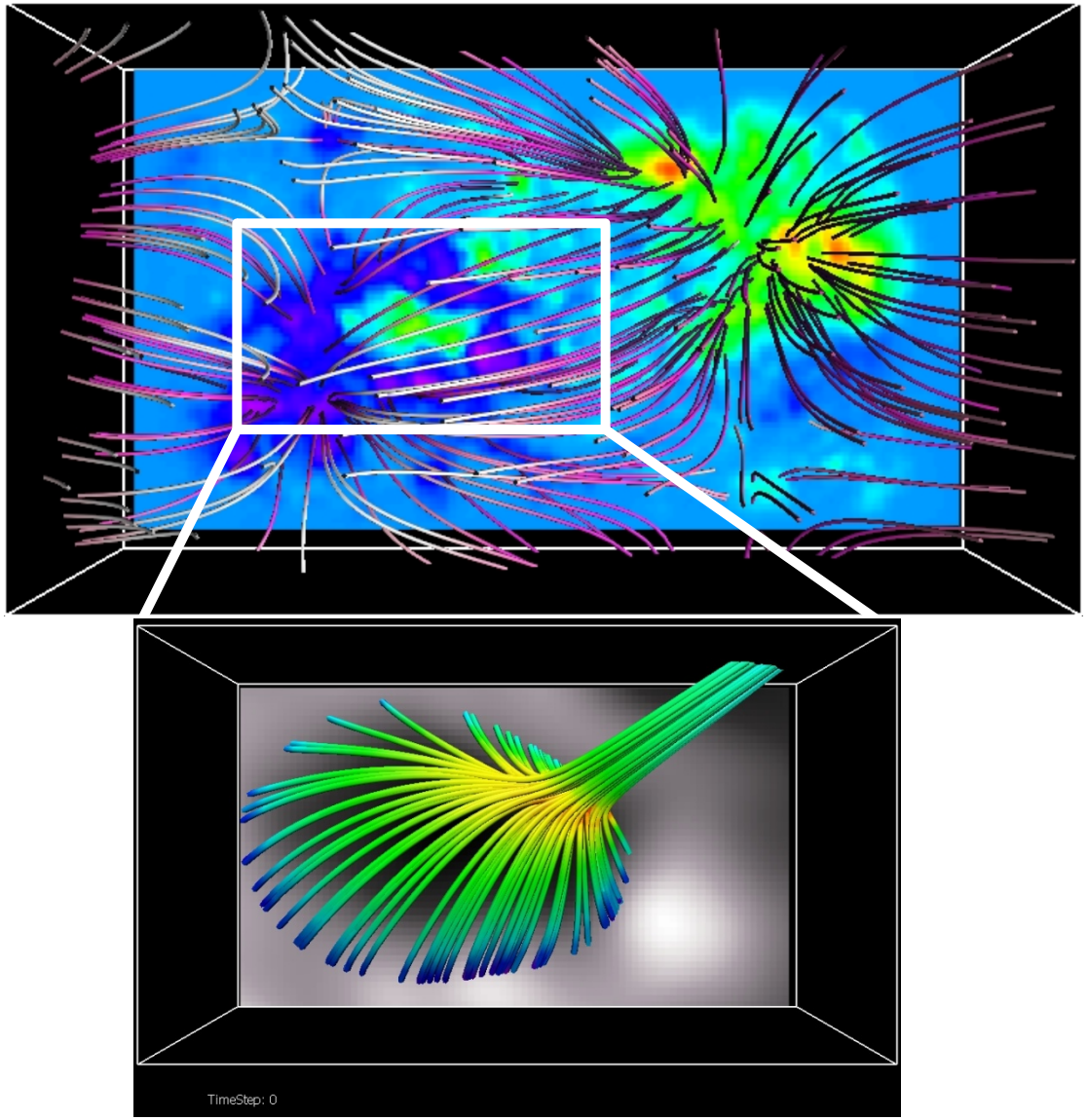


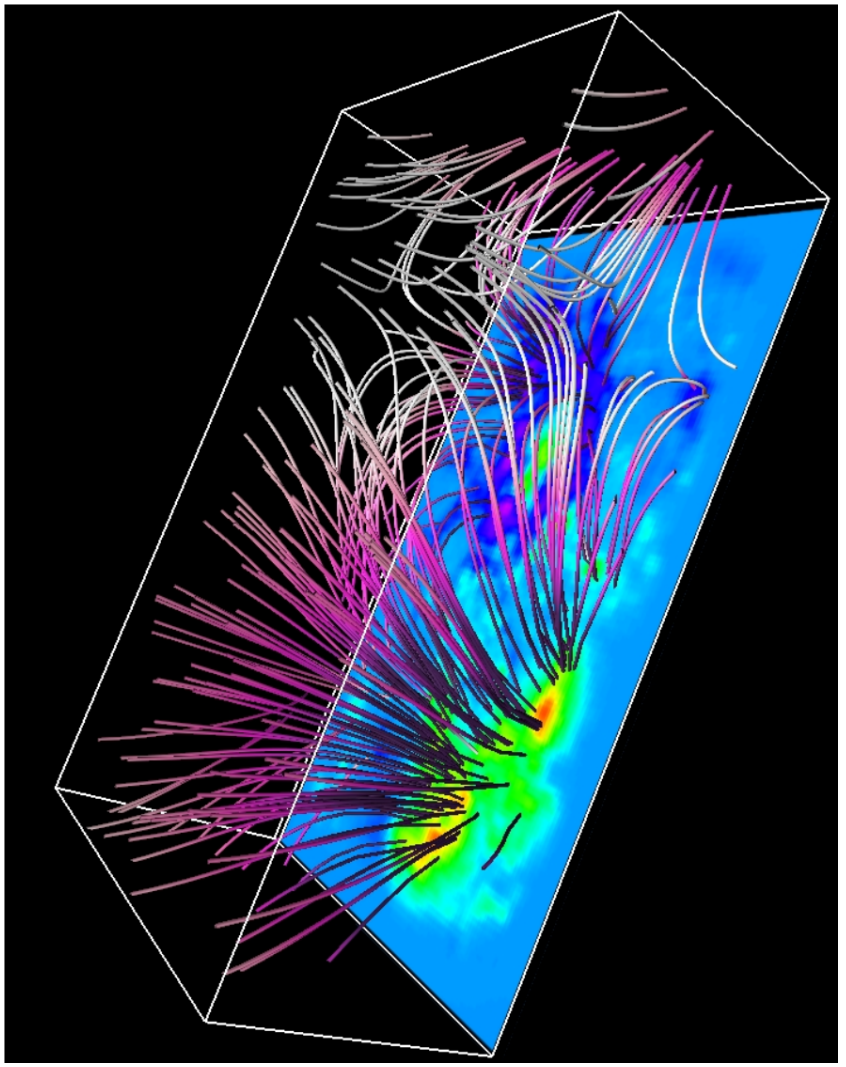
Field evolution

Side view



Solar example





Baumann et al. ApJ 2013

Current accumulation at the null

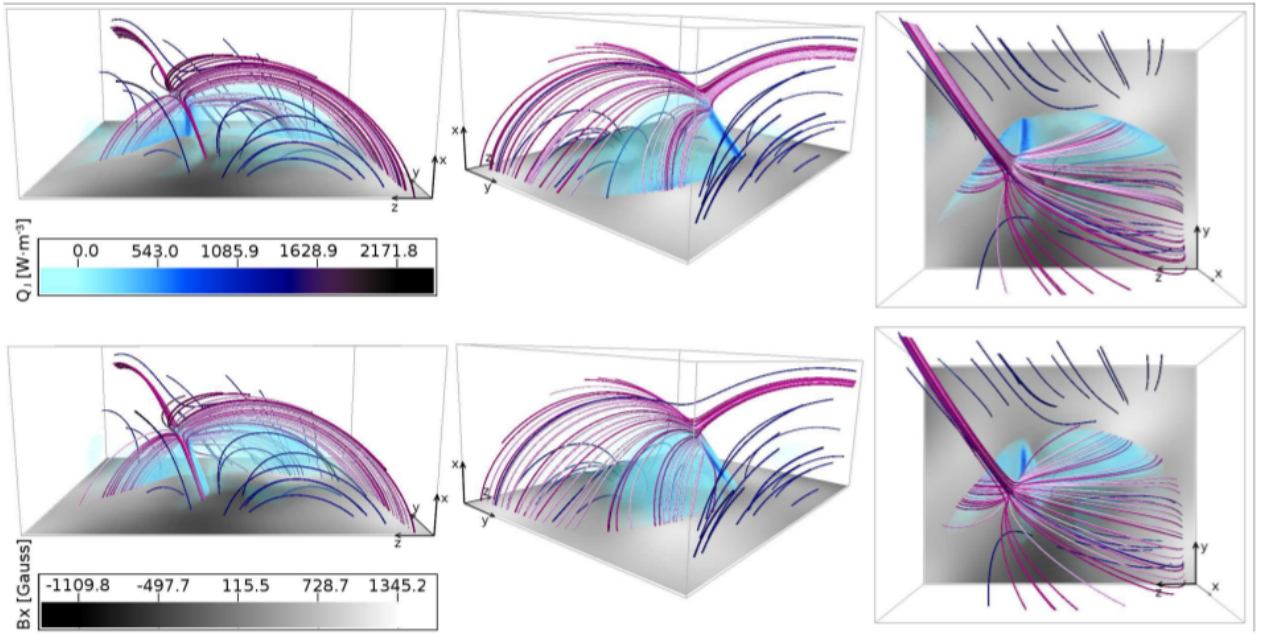


Figure 13. The highest joule dissipation of run 1 in the top row and run 1S in the lower row is shown as a semitransparent volume rendering at about D = 0.88 Mm. The box size is 10 × 16 × 22 Mm. The field lines represent magnetic field lines passing closest to the null point (purple), in the close surrounding of the null-point (magenta) and the overlying strong magnetic field (dark blue). The slice on the lower boundary shows the Bx magnetic field component.

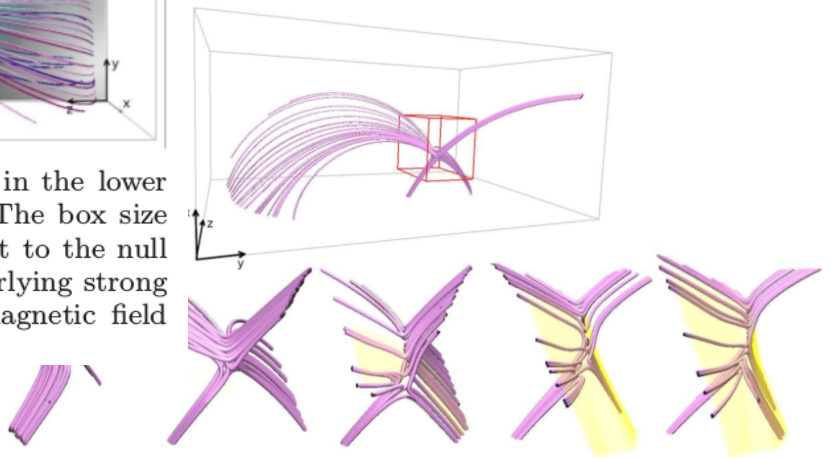


Figure 7. Relative motion of inner and outer spine for run 3. The top panel shows the cutout region for D = 0.03 Mm and the lower panel shows approximately the same selected region for D = 0.03, 0.55, 1.08, 1.62, 2.15 Mm. The yellow volume indicates the highest electric current density, which is located in the fan-plane.

Separators

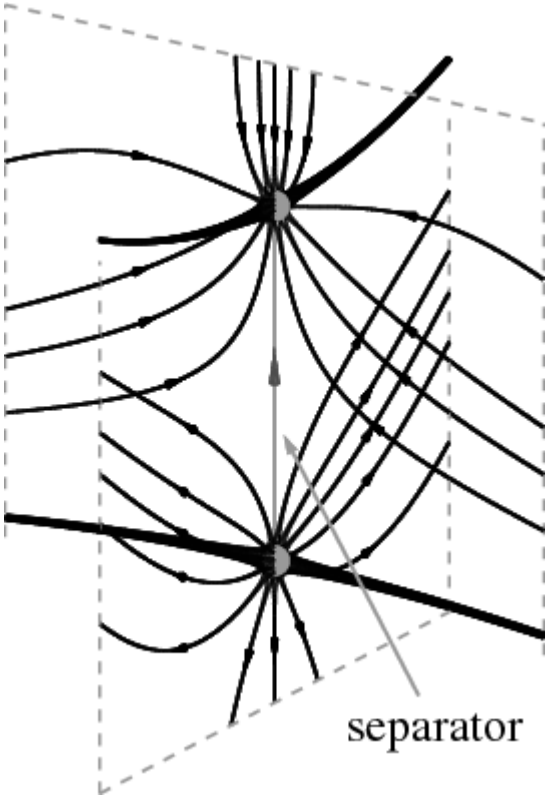
Null points are formed in a bifurcation process
    Formed in pairs

Connected through their weakest fan plane eigenvector

Spine axis are “orthogonal” to each other

Separator is defined as the intersection of the two nulls fan plane

Field perpendicular to the separator may either be
    An x-point structure (no or little current along it)
    An o-point structure (when current is strong enough)



Collapse of Separators
ABC field experiment

B defined by cos and sine functions
Constant alpha setup → J parallel to B

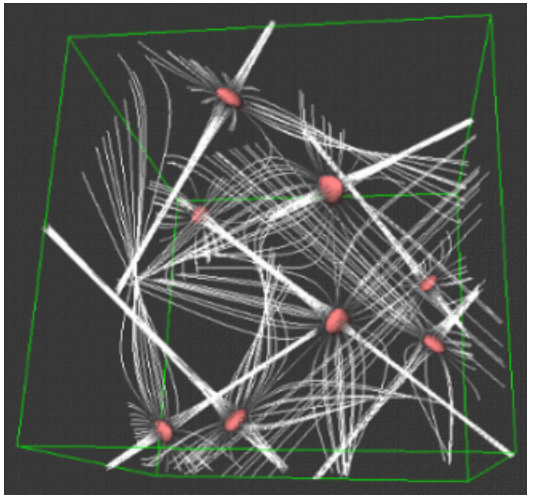
Stressed by boundary motions

Current accumulation along weak field separators

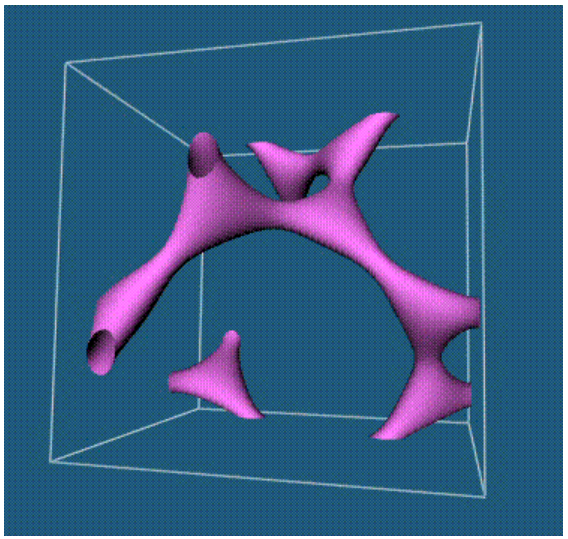
Collapse of the null region

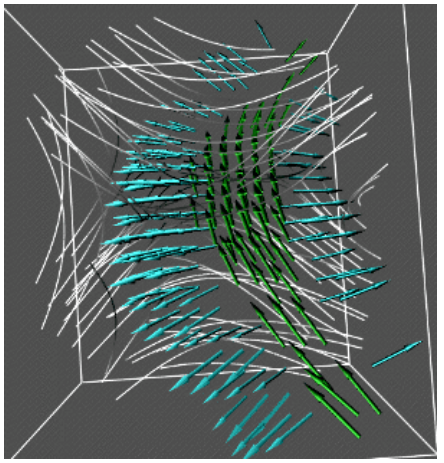
Reconnection → transferee of flux between domains

Looks like 2D reconnection with a non ignorable passive field component



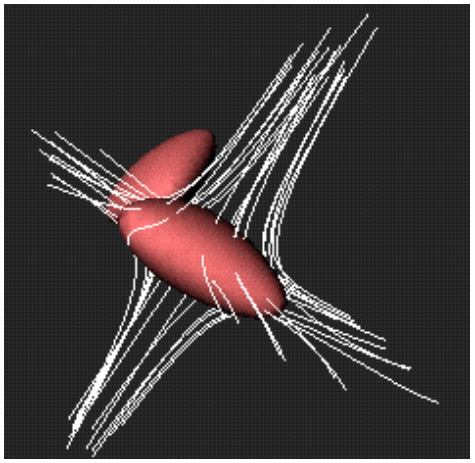
Driven ABS field – separator Rec.

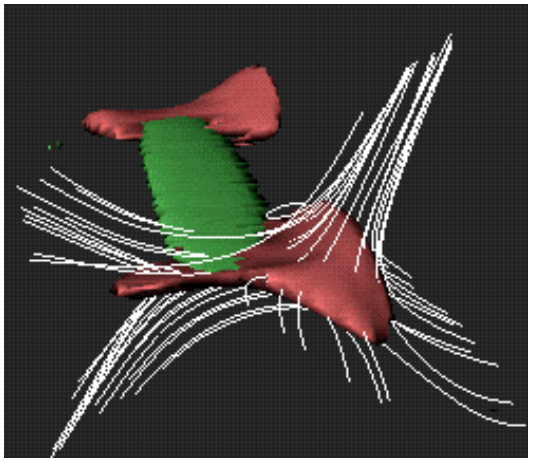


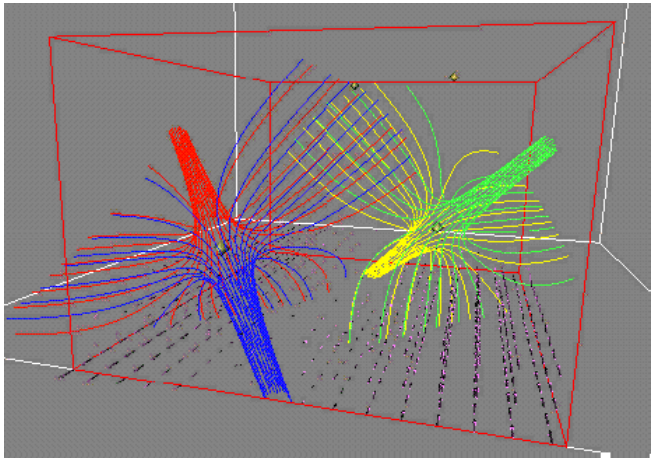


Galsgaard & Nordlund 97
Boundary stress forces the week field channels to collapse and form current sheets

Separator reconnection







Flyby setup

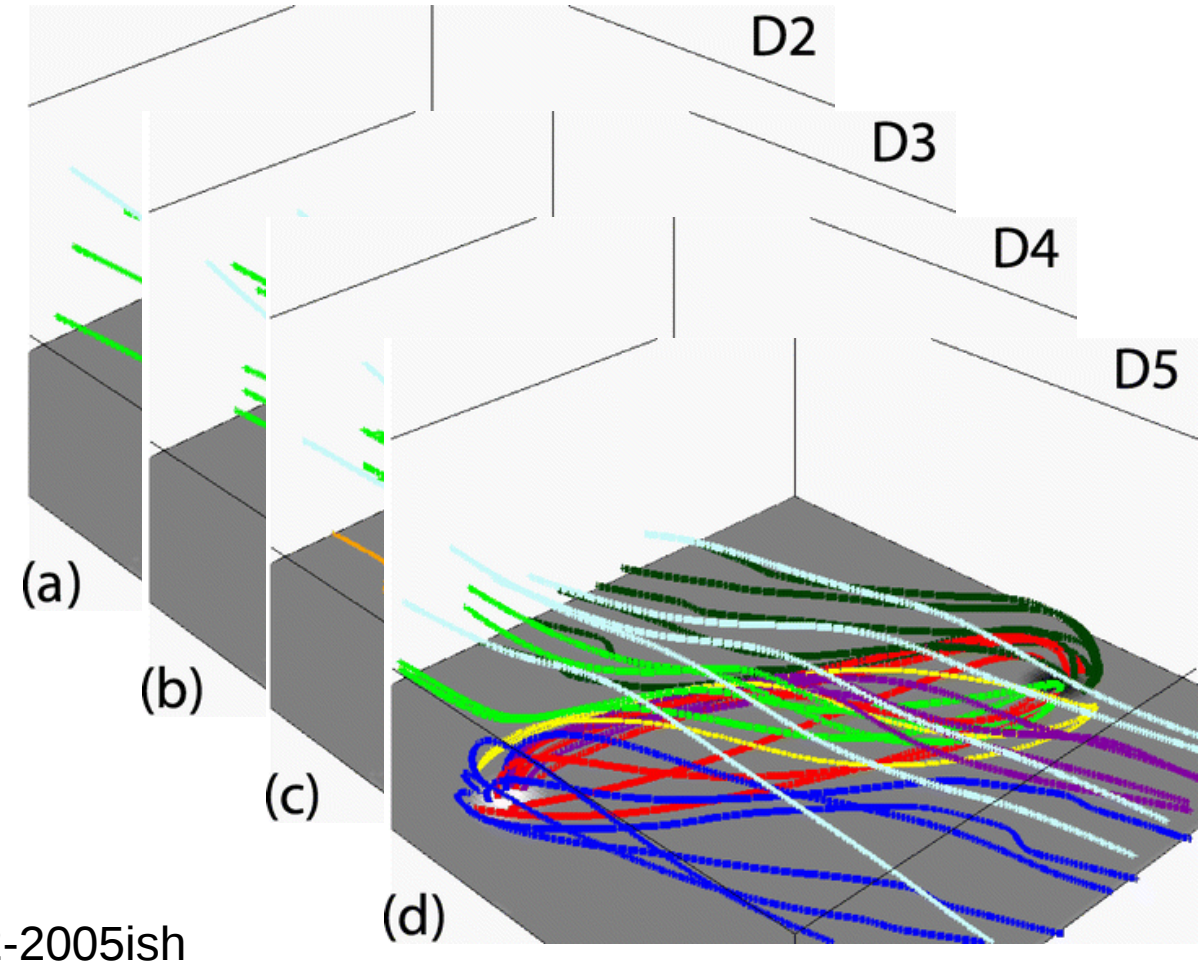
2 sources regions in a horizontal background field

2 null points in the photosphere

Fan surfaces divides space into 3 domains

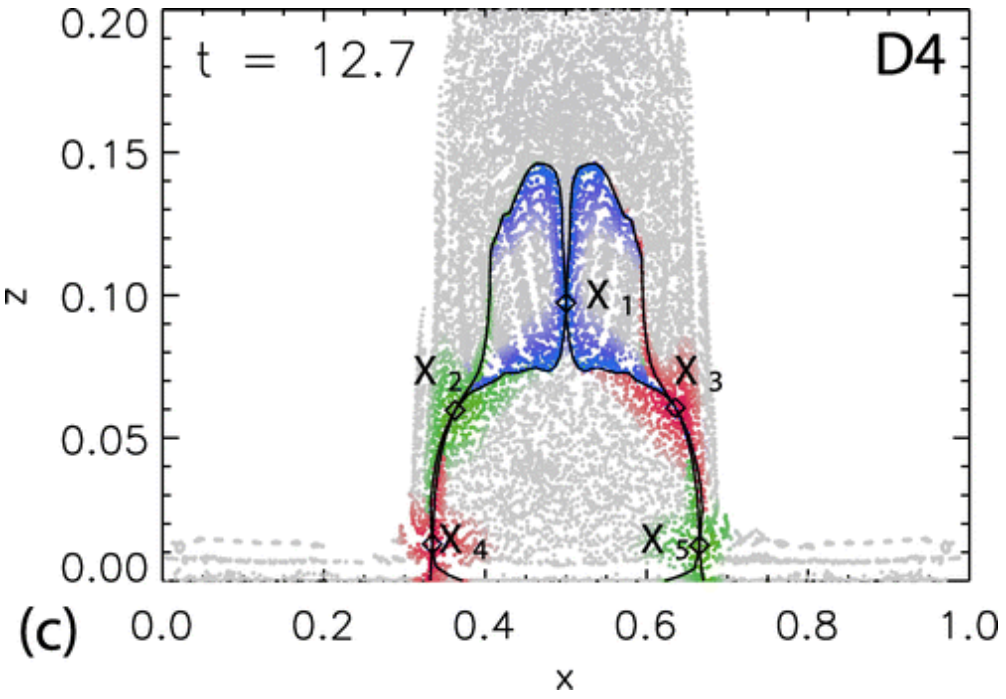
Forced to interact by boundary driving

Generates several separators



Series of papers by
Parnell, Galsgaard & Haynes 2002-2005ish

Recirculation of flux

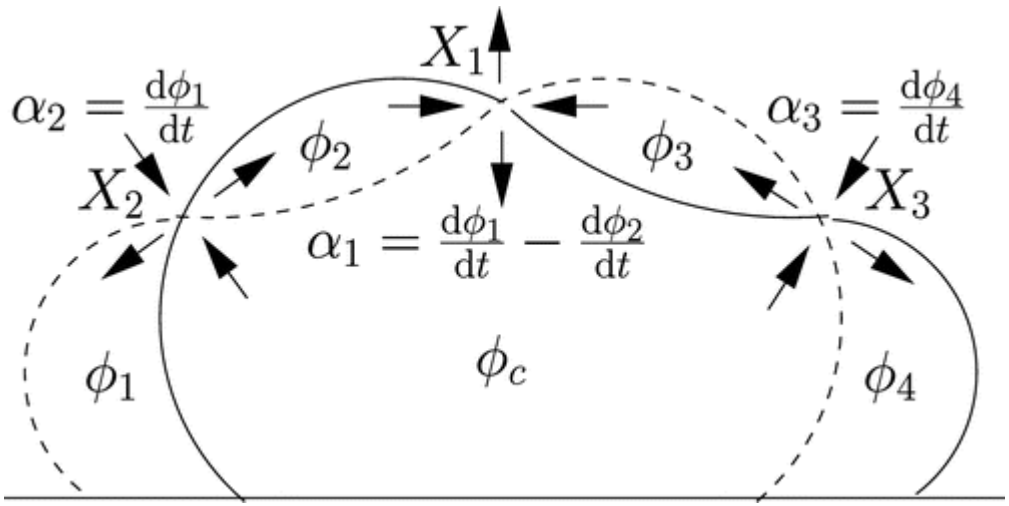


2D slice of the central plane
Field liens traces, colour coding of tracer particles that has changed connectivity.

X-points indicates locations of separators.

Recycling of flux → much more reconnection than a potential passage would indicate.

The total reconnection rate is the sum of all contributions.



Flux emergence
Nulls and separators

Flux emergence
Interaction between coronal flux and emerging flux

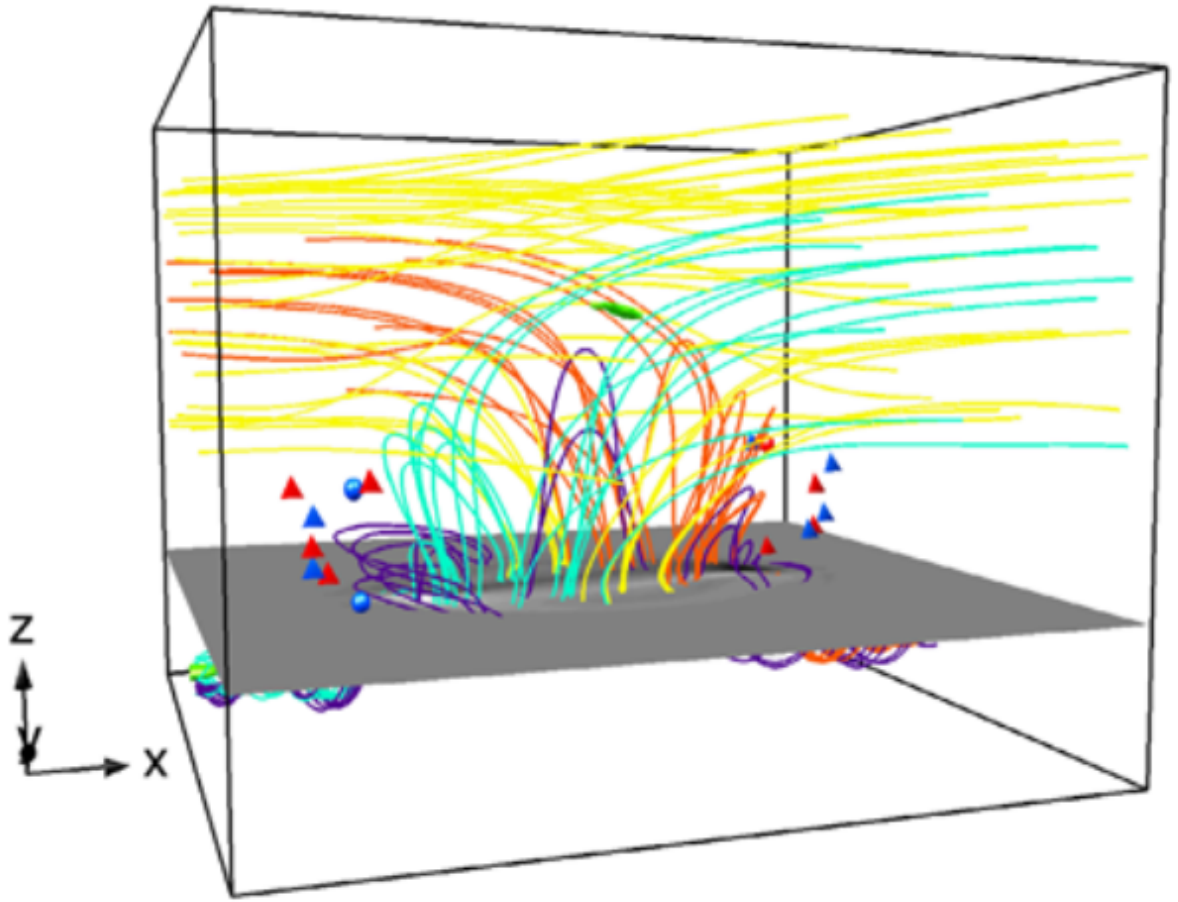
Null points formed in clusters

Many separators between the nulls

Twisted fan surfaces

Parallel electric field peaks at the separator lines

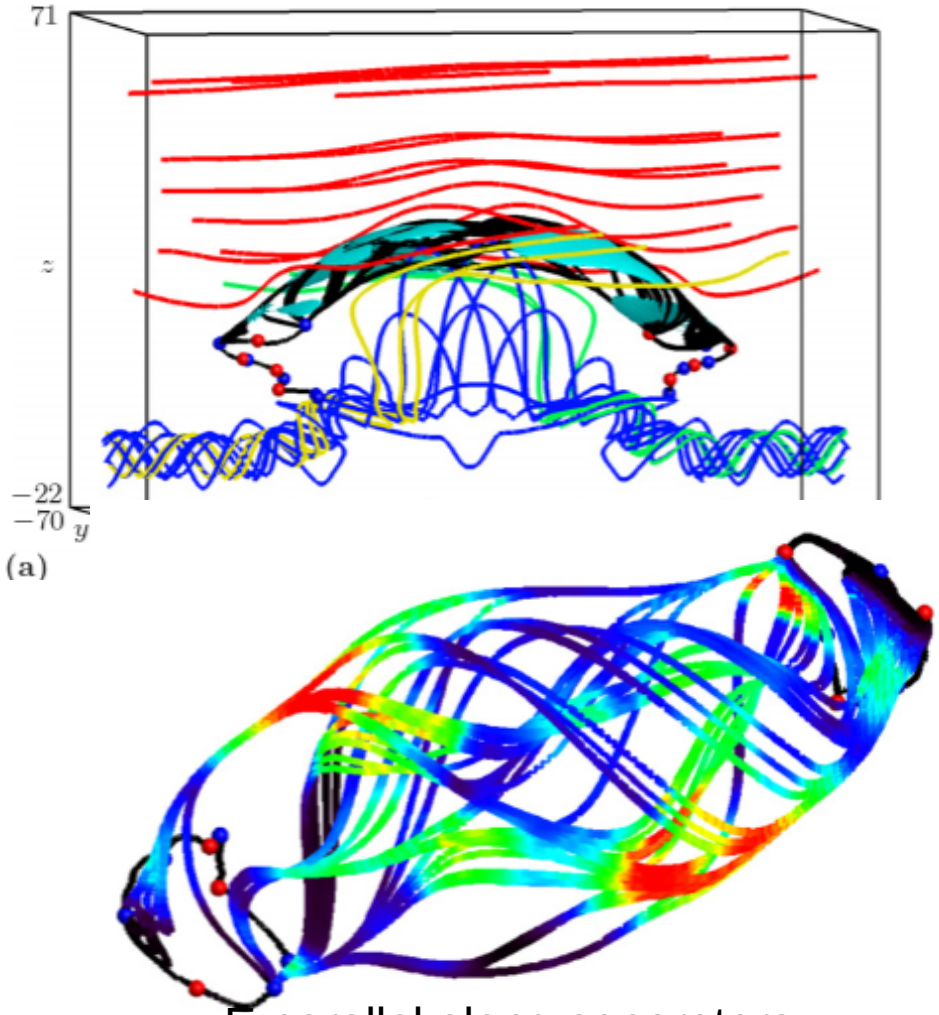
Not all separators are active in reconnection



Maclean et al.: SP 2009, 260, 299

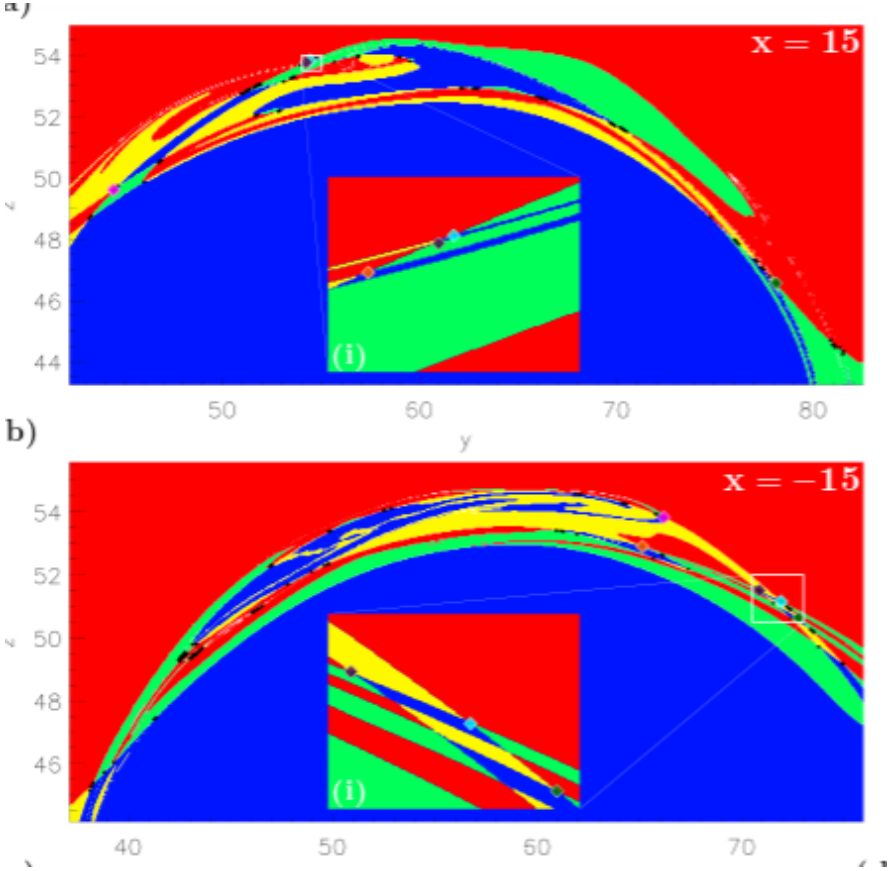
Flux emergence – Separators

Field lines,nulls and separators



E parallel along separators

Topological domain and separators



Parnell et al.: ApJ 2010, 725, L214

No-null reconnection in 3D QSL identification

No null reconnection potential locations can be identified using QSL methods

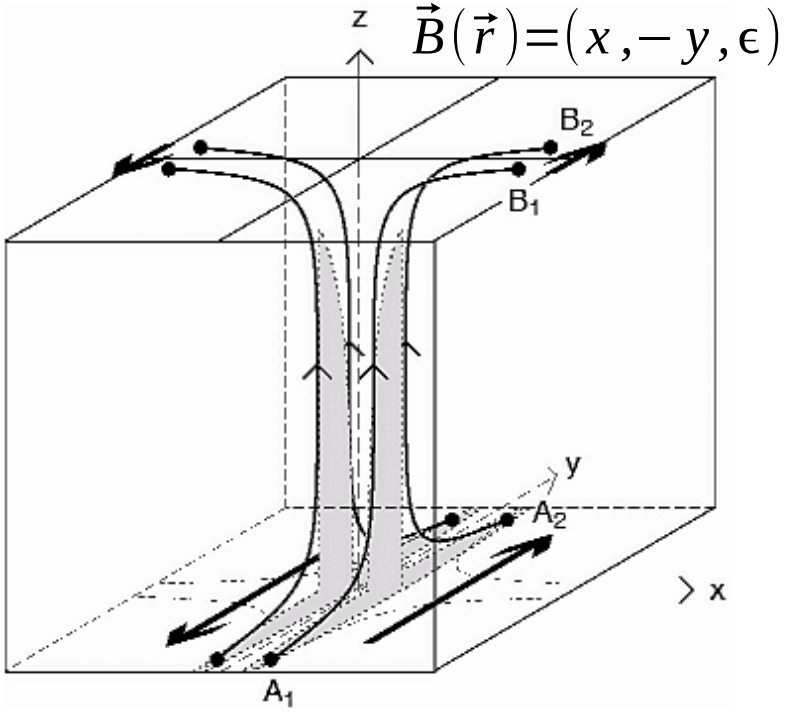
Looks for locations where the change in field line mapping is large (but continues!)

Can be created by dynamical changes of the B-field by boundary driving

$$Q(\mathbf{x}_+) = \frac{N_+^2}{|\det(\mathcal{D}_+)|}, \qquad Q(\mathbf{x}_-) = \frac{N_-^2}{|\det(\mathcal{D}_-)|},$$

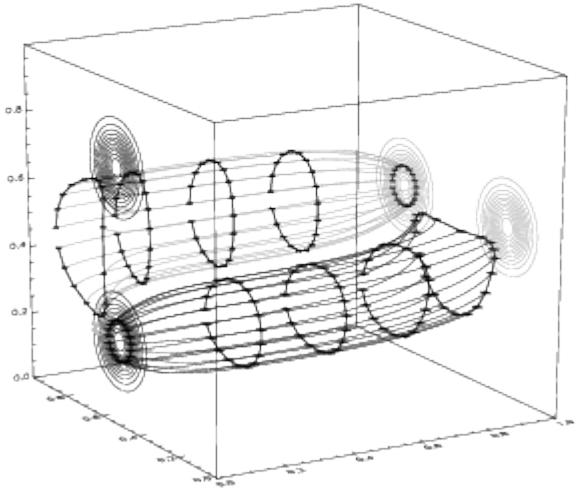
$$\mathcal{D}_+(\mathbf{x}_+) \equiv \begin{bmatrix} \frac{\partial X_-}{\partial x_+} & \frac{\partial X_-}{\partial y_+} \\ \frac{\partial Y_-}{\partial x_+} & \frac{\partial Y_-}{\partial y_+} \end{bmatrix}, \qquad \mathcal{D}_-(\mathbf{x}_-) \equiv \begin{bmatrix} \frac{\partial X_+}{\partial x_-} & \frac{\partial X_+}{\partial y_-} \\ \frac{\partial Y_+}{\partial x_-} & \frac{\partial Y_+}{\partial y_-} \end{bmatrix}.$$

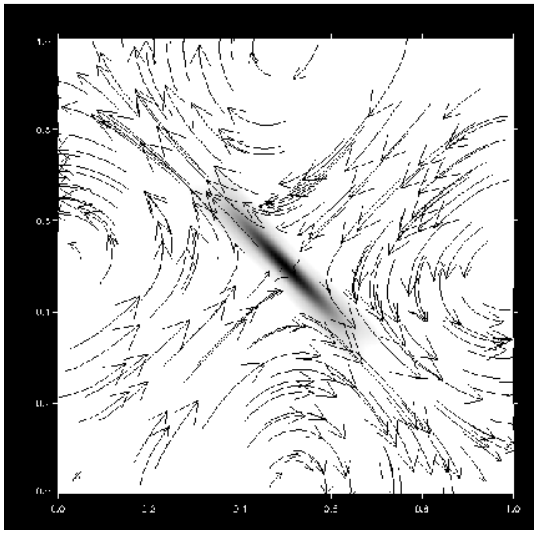
$$N_\pm(\mathbf{x}_\pm) = \left[\left(\frac{\partial X_\mp}{\partial x_\pm}\right)^2 + \left(\frac{\partial X_\mp}{\partial y_\pm}\right)^2 + \left(\frac{\partial Y_\mp}{\partial x_\pm}\right)^2 + \left(\frac{\partial Y_\mp}{\partial y_\pm}\right)^2 \right]^{1/2}.$$

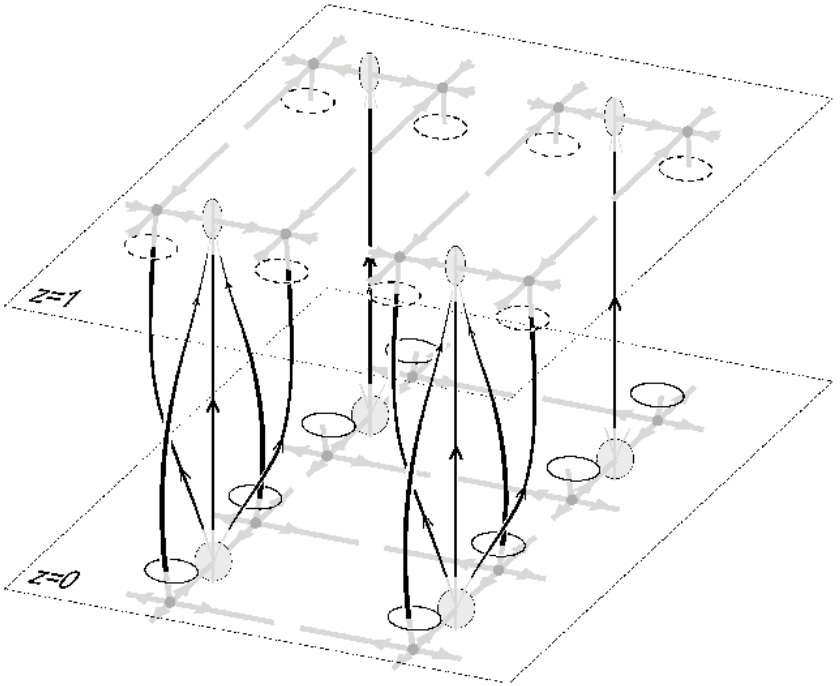


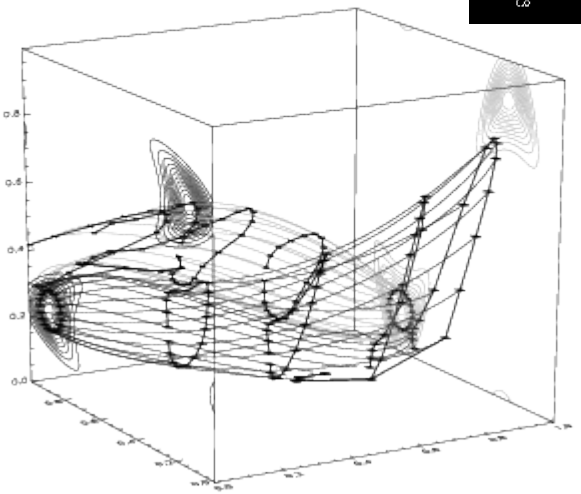
Priest & Demoulin 1995
Titov et al 2002

QSL experiment I







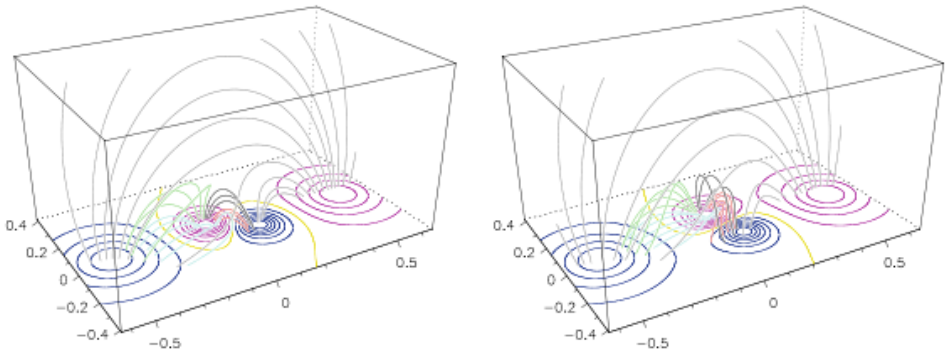


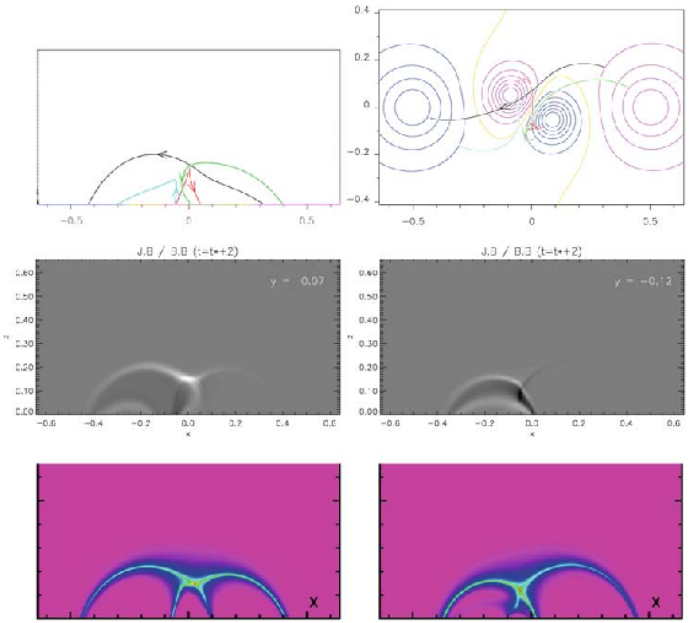
Hyperbolic flux tube

Boundary driving initiates a stagnation flow, but only when the driving is correct

Galsgaard et al. 2002

QSL experiment II



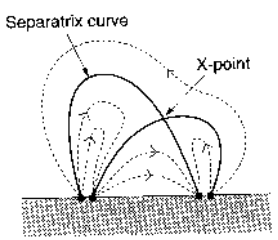


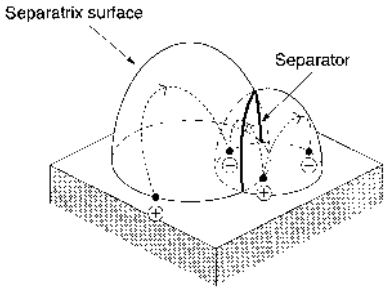
Like the previous experiment, but in a more Realistic setting

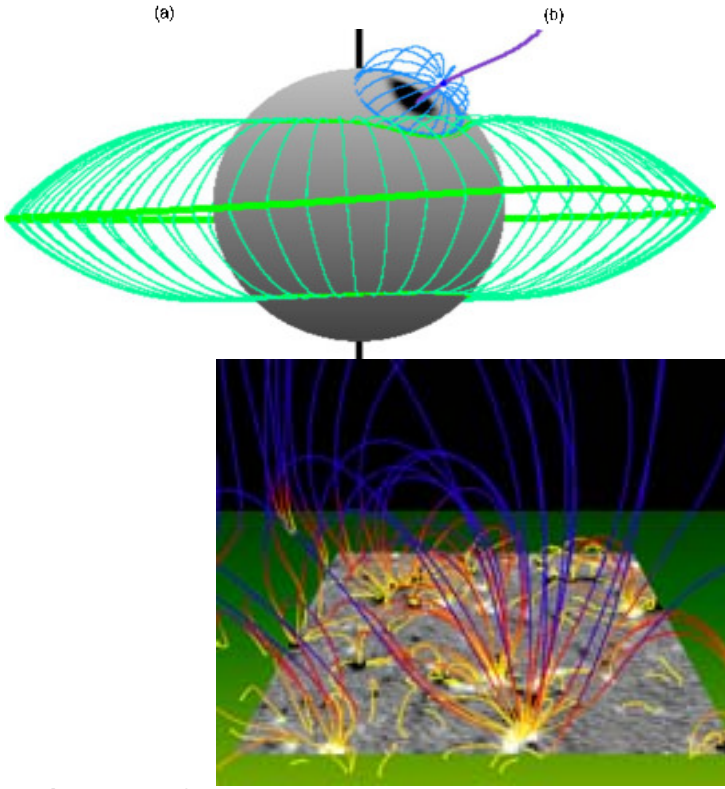
Aulanier et al. 2009

Figure 2. Magnetic field lines, electric currents and QSLs during the resistive relaxation of the configuration $\Phi = 150°$, at $t = t^{\star} + 2$, using $\eta = 15 \times 10^{-6}$. *Top row*: 3D projection views of four magnetic field lines, passing in the vicinity of the two narrowest current layers that are present in the QSLs at $y = 0.07$ and $y = -0.12$. Two projections are shown, along the y axis (*left panel*) and along the z axis, i.e. as viewed from above (*right panel*). The contours of $b_z(z = 0)$ are the same as in Figure 1. *Middle row*: 2D maps of $\alpha = \mathbf{j} \cdot \mathbf{b}/b^2$, drawn at $y = 0.07$ (*left panel*) and at $y = -0.12$ (*right panel*). The color coding is saturated, so that (*black; white*) stand for $\alpha = (-36; 36)$. *Bottom row*: 2D maps of the squashing degree Q in the QSLs in the same $y =$ constant planes. The (*red ; yellow; green; cyan; blue; pink*) colors stand for $Q = (10^8; 3\,10^6; 10^5; 5\,10^3; 50; 2)$. The central part of the HFT is thus drawn in *red*.

Identifications of potential Reconnection regions







How to identify potential regions for reconnection?

Need to know the magnetic skeleton defined by:

3D magnetic null points and separator lines

Identify all QSL regions

These are potential locations for Rec

Needs to have how the system is stressed to find the real locations..
It is a dynamical process!! and locations may be defined dynamically due to the stress of the field

Particle Reconnection

Lots of the real physics takes place on particle length scales

Needs also to treat reconnection from a particle point of view

Typically restricts us to investigate only very local phenomena
- Remember the length scales from first in the lecture

Need a different approach
- Analytical investigations is almost impossible
- Laboratory experiments
  - Limitations in resolution due to finite site probes
  - Limited parameter space, length scales, time scales, densities and temperatures
- Numerical experiments
  - Limited numerical resolution
  - Limited realism
    - Mass ratio, species, particle interaction
  - Distribution functions
  - Particle in cell simulations

Particle In Cell approach

- Grid equations:

$$\begin{aligned} \frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \\ \frac{\partial \mathbf{E}}{\partial t} &= \nabla \times \mathbf{B} - \mathbf{J} \end{aligned}$$

(Maxwell 1+2)

- Particle equation:

$$\frac{d(m_i \mathbf{v_i})}{dt} = q_i(\mathbf{E} + \mathbf{v_i} \times \mathbf{B}) + \mathbf{g}/m_i + \mathbf{f}_i$$

(Newton-Lorentz)

- Constraints on ICs:

$$\begin{aligned} \nabla \cdot \mathbf{B} &= 0 \\ \nabla \cdot \mathbf{E} &= 4\pi\rho_c \end{aligned}$$

(Maxwell 3+4)

PIC approach

- Grid equations:

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$
$$\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mathbf{J}$$

(Maxwell 1+2)

- Particle equations

$$\frac{d(m_i \mathbf{v_i})}{dt} = q_i(\mathbf{E} + \mathbf{v_i} \times \mathbf{B}) + \mathbf{g}/m_i + \mathbf{f}_i$$

(Newton-Lorentz)

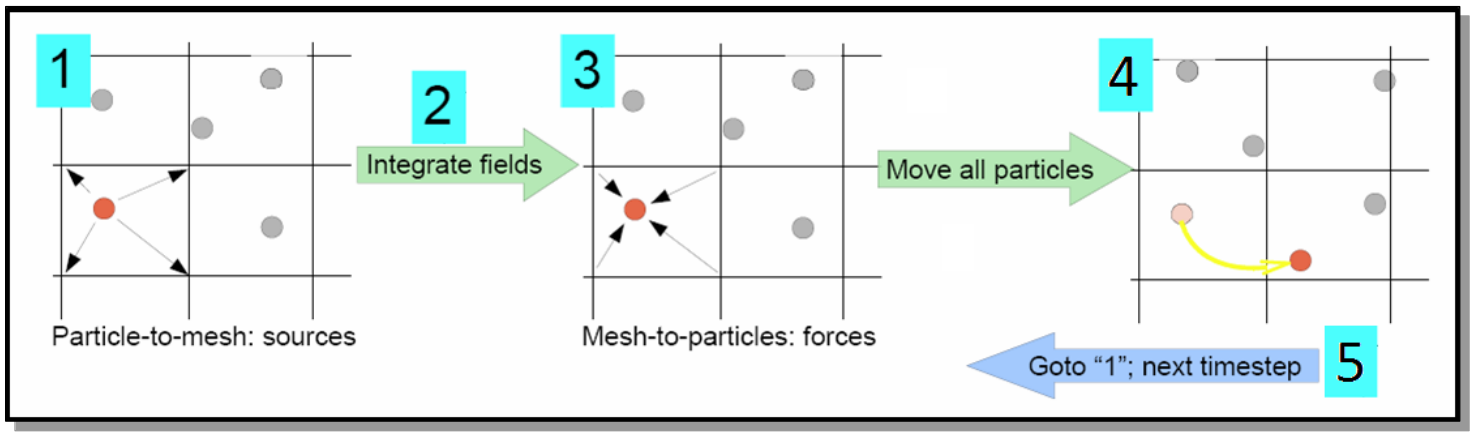
Very simple equations, but they need to be applied to a huge number of particles!

Step of sequence

1. Collect contributions of J from all (charged) particles
2. Advance B and E with the Maxwell equations
3. Interpolate B and E to (charged) particles
4. Move particles using B and E
5. Preform particle interactions (collisions, ionizations, radiation ….)

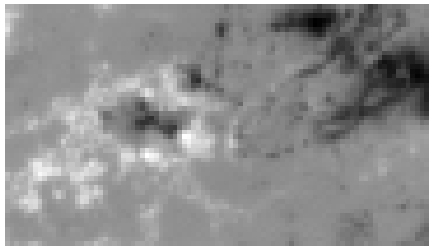
$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$
$$\frac{\partial \mathbf{E}}{\partial t} = \nabla \times \mathbf{B} - \mathbf{J}$$

$$\frac{d(m_i \mathbf{v_i})}{dt} = q_i(\mathbf{E} + \mathbf{v_i} \times \mathbf{B}) + \mathbf{g}/m_i + \mathbf{f}_i$$



From observations over MHD to PIC

Masson et al. 2009, Baumann et al. 2011
Observed C class flare

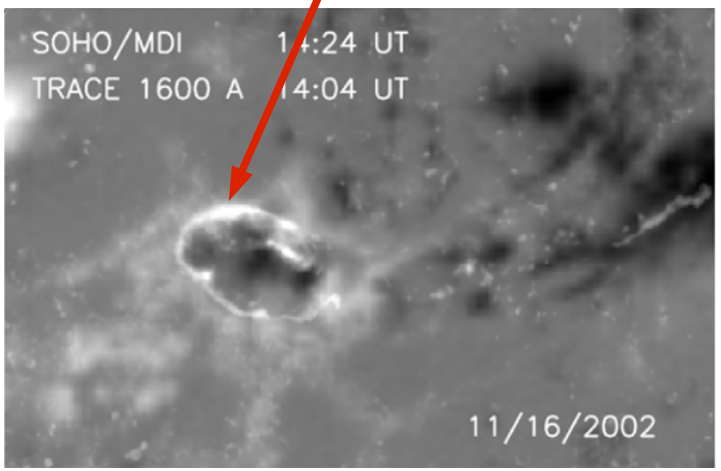


Initial conditions
B-field, driver

MHD simulation

MHD snapshot conversion

Flare ribbon

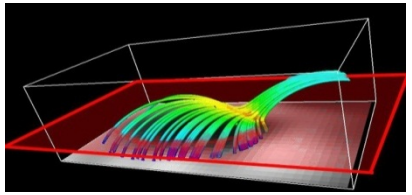


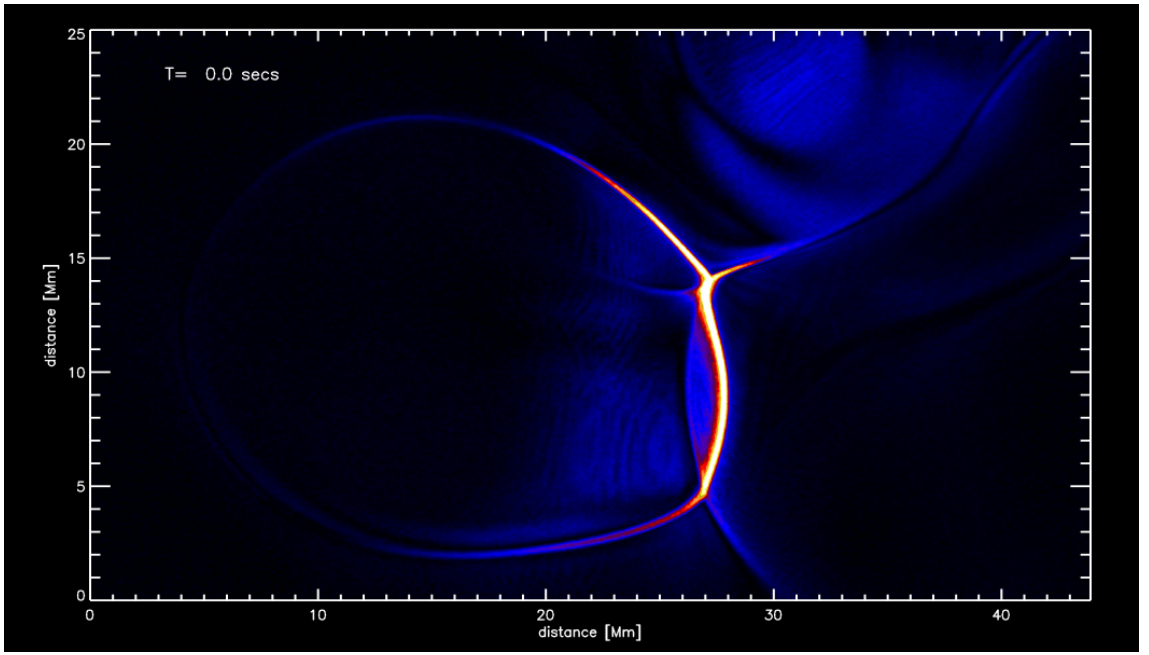
Comparison

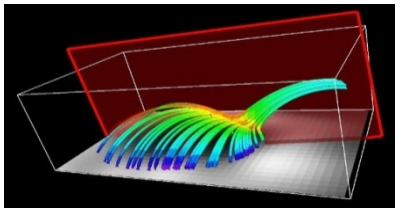
PIC simulation

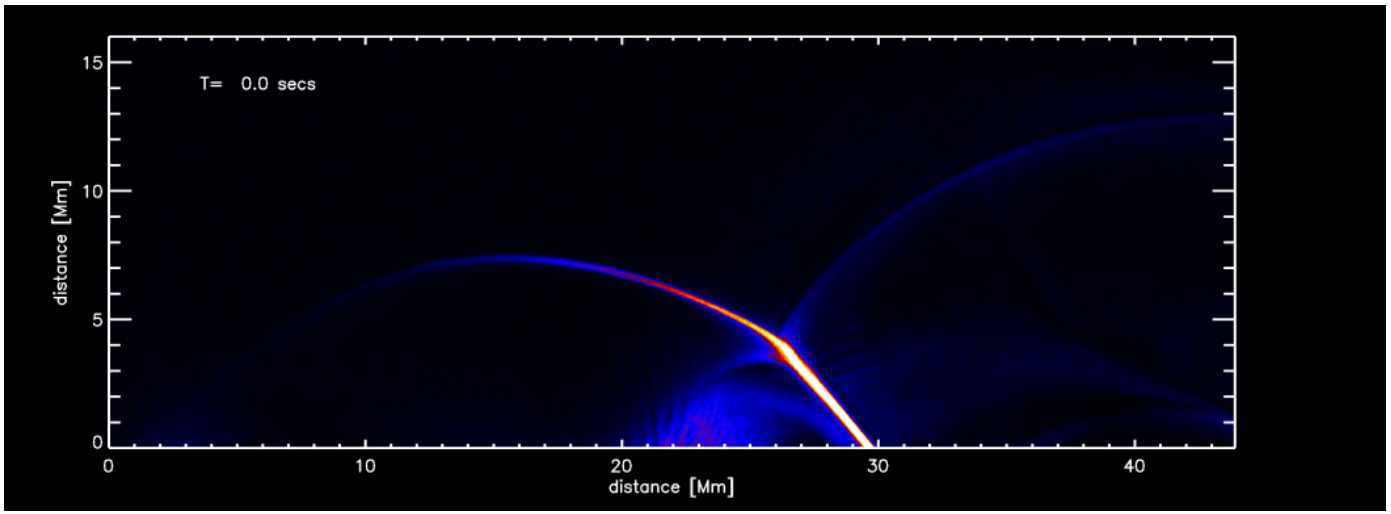
Baumann et al. 2013

PIC time evolution of current

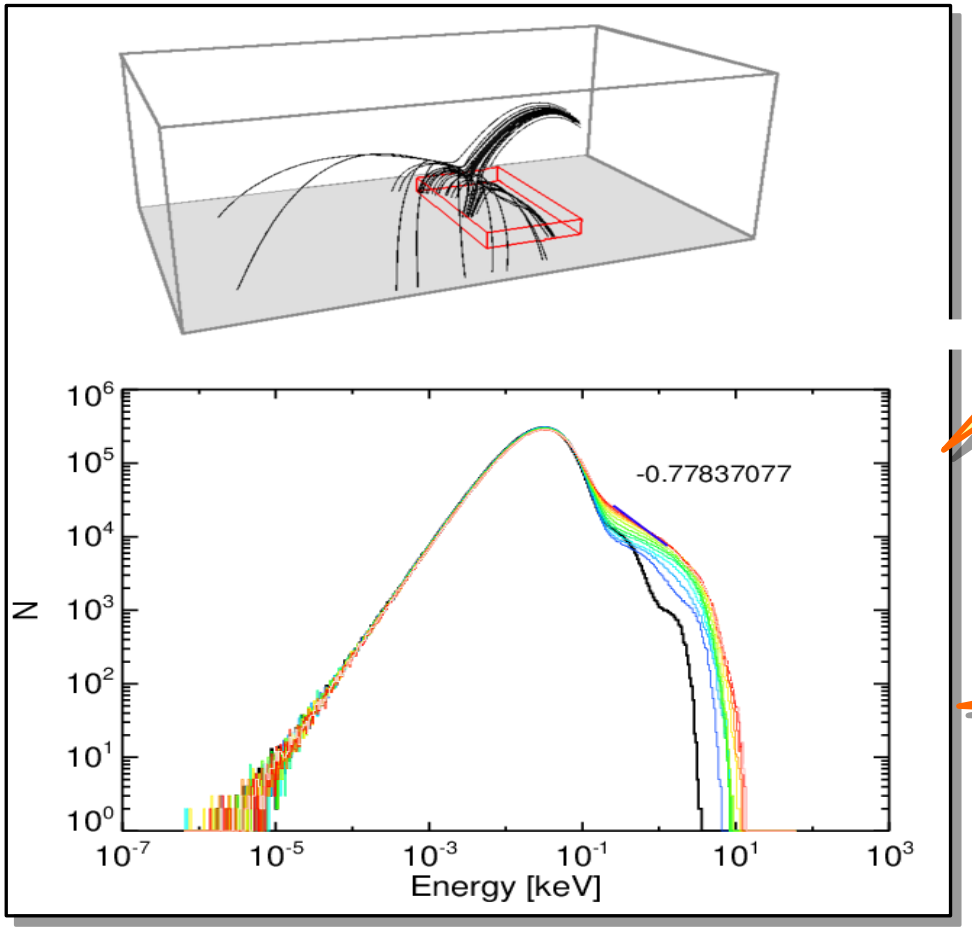








Power law distribution



Approximate dN/dln(E) slope (the disN/dE slope then -1.77)

10 sec time evolution

Clear evidence of particle acceleration

Summary

- Magnetic reconnection takes place in many forms in 3D
  - MHD approach
    - 3D null points
      - Spine, fan plane, separator lines
    - No nulls
      - QSL regions where the change in mapping is fast
- Requires a local component of the parallel electric field
  - Need to have a non-ideal component to Ohms law
  - The peak integral of E par through the diffusion region provides the rec rate
- Effect is a “slippage” of field lines though the diffusion region
  - Opposite directed rotation flows of field line motion is observed (an expected)
- The used approach has influence on the effects seen in the local rec region
  - MHD characteristic
    - Topology changes
    - Joule heating and kinetic energy
  - PIC characteristics
    - Separation of scales (ion, electrons)
      - More complicated diffusion region without clear shock fronts as in MHD
    - Non Maxwellian distribution functions
      - Solar obs indicate that ip to 50% can be put into this energy channel

Summary

- Important process for untangling the magnetic field
  - How complex can a field become before it breaks?
- Limitations to how much energy that may be released
  - Helicity conservation sets a lower limit....
  - At least on a given time scale....

- Only have the basic information on 3D reconnection today
  - Not clear what the requirements determine the speed
  - Not clear how the energy release is divided between the 3 types
  - Not clear which criteria determine the onset of rec
  - Only simple modes are investigated in detail using PIC
  - several of attempts to name “new” behaviour with new names

- Lots of work for some of you to continue with for the coming years!

- Is important for understanding many phenomena where magnetic fields are important in science