Magnetic Reconnection in the (3D) Solar Corona

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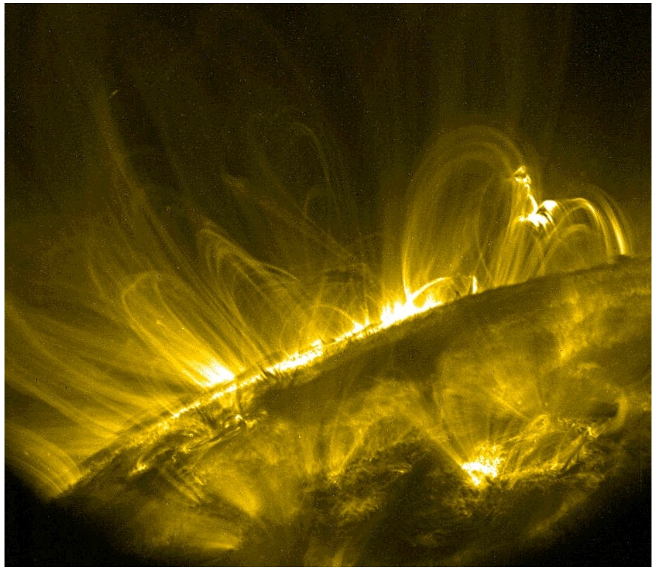
"If we knew what it was we were doing, it would not be called research, would it?"

-- Albert Einstein

Complex 3D magnetic fields

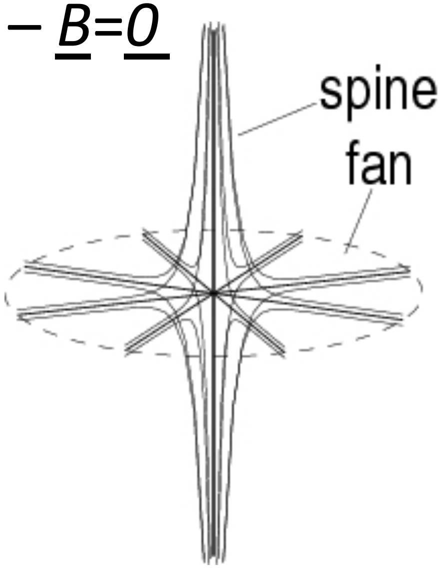


- Complex, ever-changing *B*
- Very low dissipation

- Where reconnection?

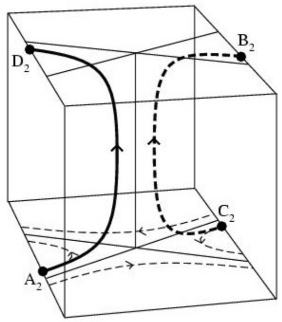
  ⟷ Where do *J* sheets form?

1 possibility: 3D nulls – *B*=*0*

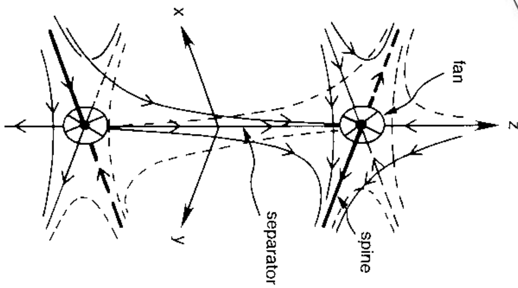


Also:

In absence of nulls



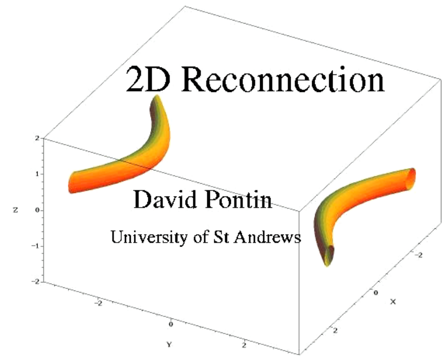
Separators

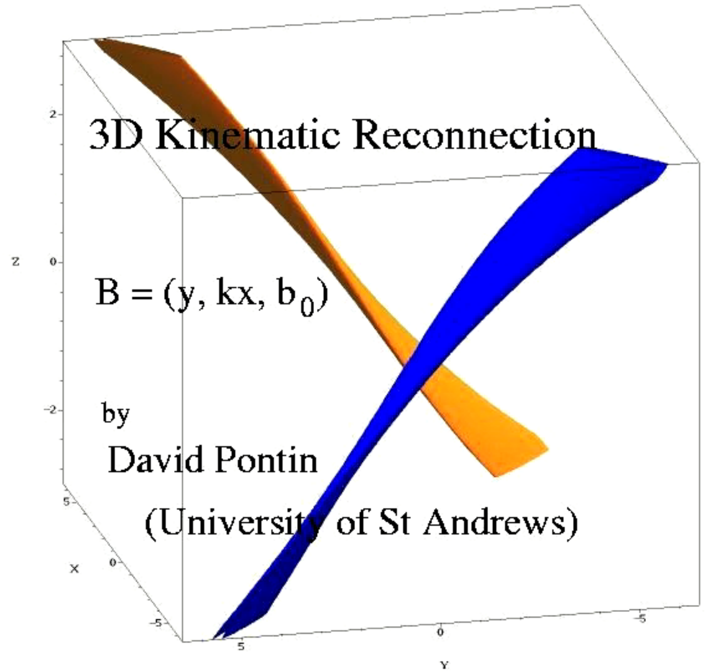


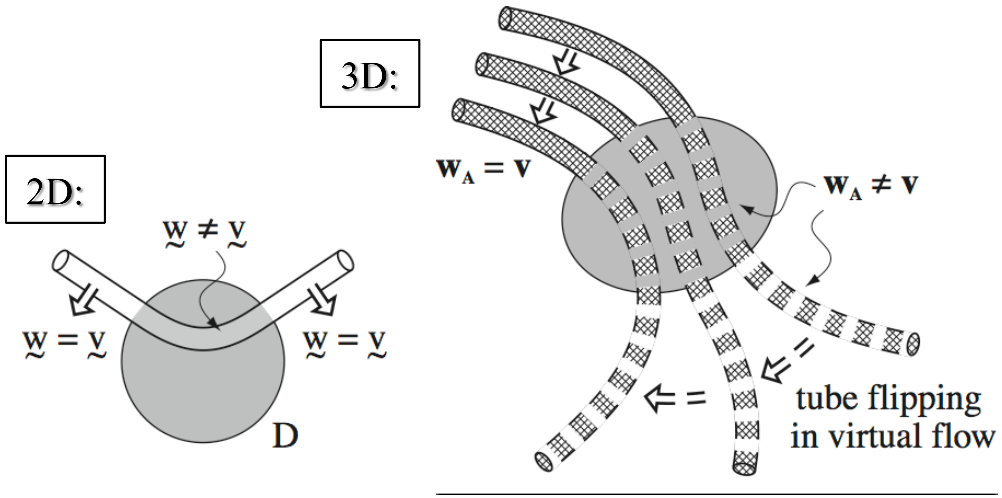
3D reconnection properties

(Priest et al '03)

- Rec occurs in many different B structures
- Field lines change connections continuously
- Mapping of field lines continuous ('flipping')
- No 1-to-1 rec of field lines





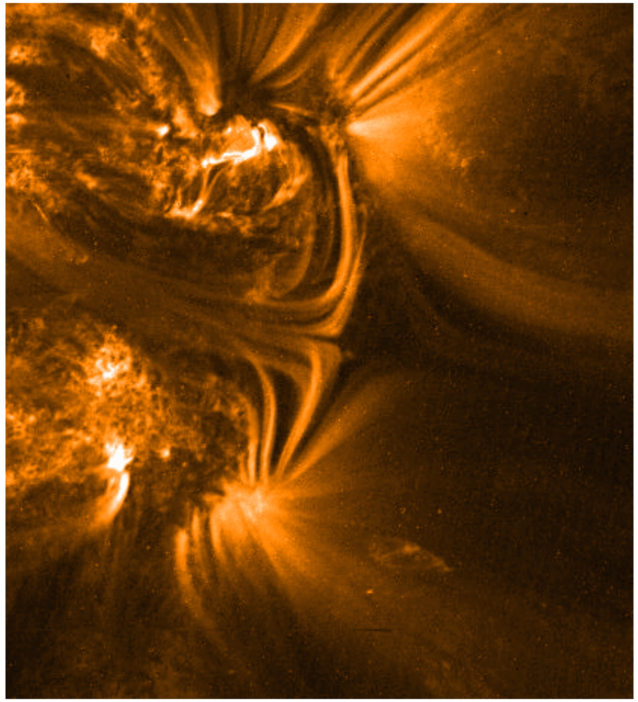


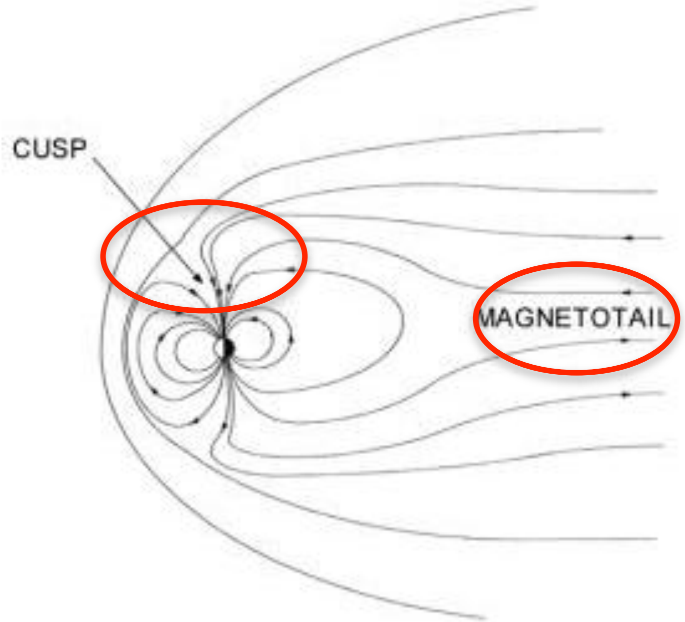
Reconnection at 3D nulls

3D nulls: where?

Solar corona: 7-15 coronal nulls for every 100 photospheric flux concentrations

(e.g. Longcope et al ‘03, Régnier et al ‘08, Longcope & Parnell ‘09)





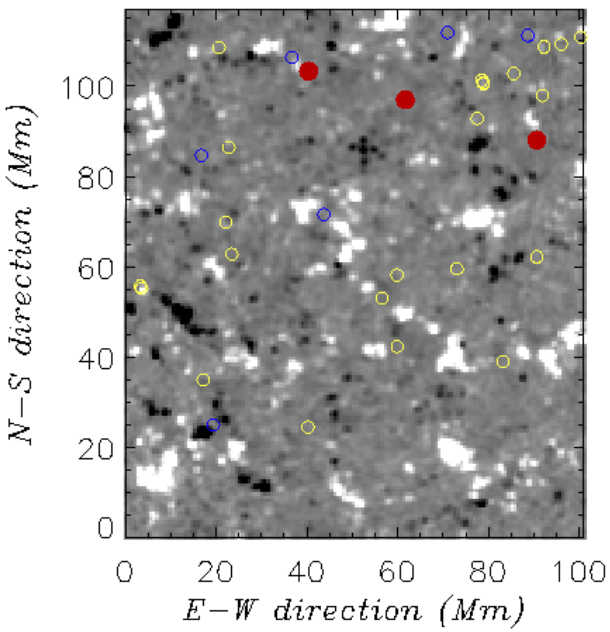
Magnetosphere

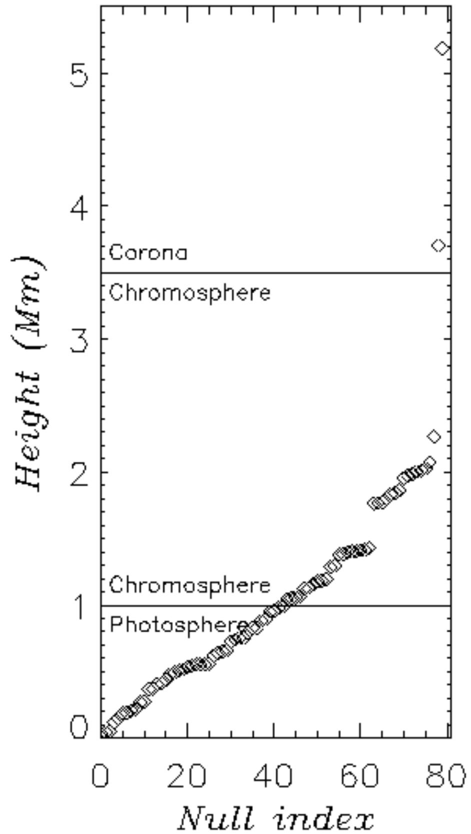
In situ observations in tail $\underline{J}$ sheet (e.g. Xiao *et al.* 06)

How common are 3D nulls?

(Régnier et al ‘08)

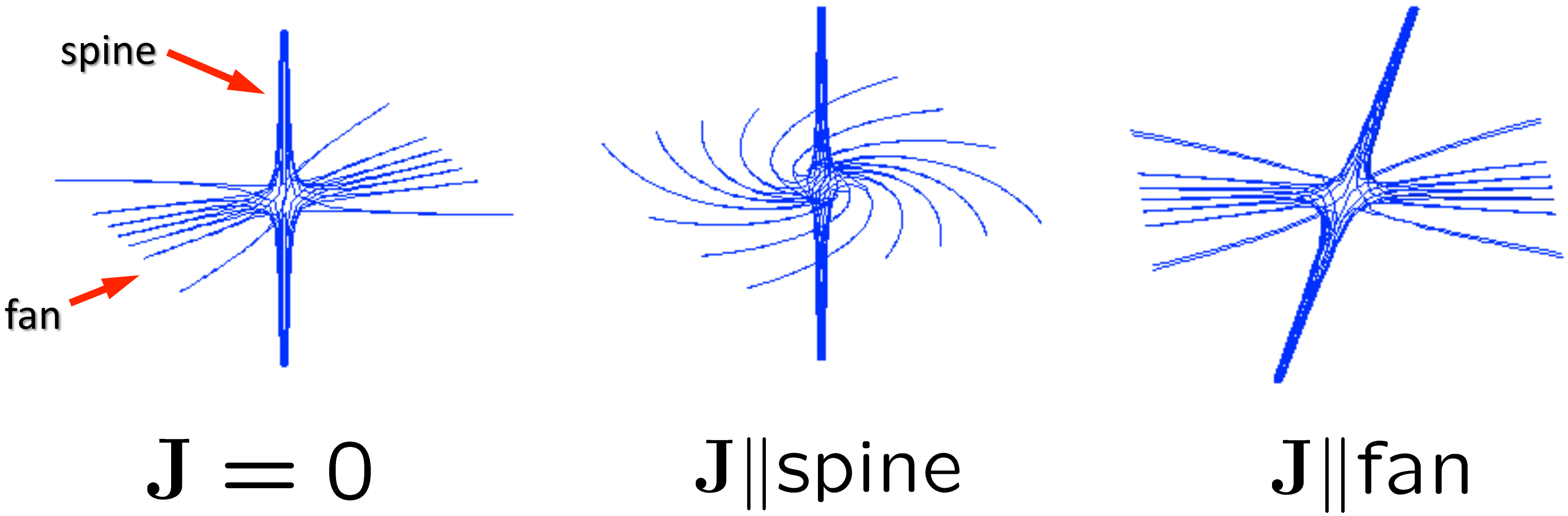
- Used Hinode SOT data as base boundary condition
- Extrapolated continuous potential field (i.e. no nulls on base)
- Used Tri-linear null finding method (Haynes & Parnell ‘08)
- 80 nulls identified in a single frame
- Exponential fall off with height





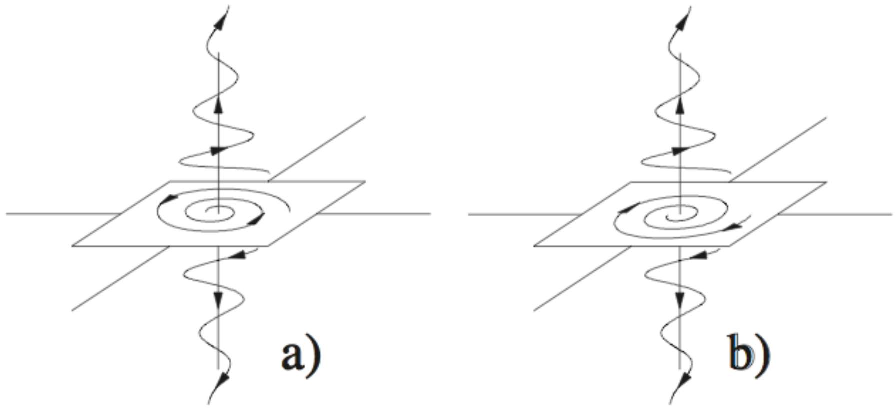
3D null structure

- Determine local structure by examining Jacobian $\nabla \mathbf{B}$
- Eigenvalues/eigenvectors determine spine/fan orientation

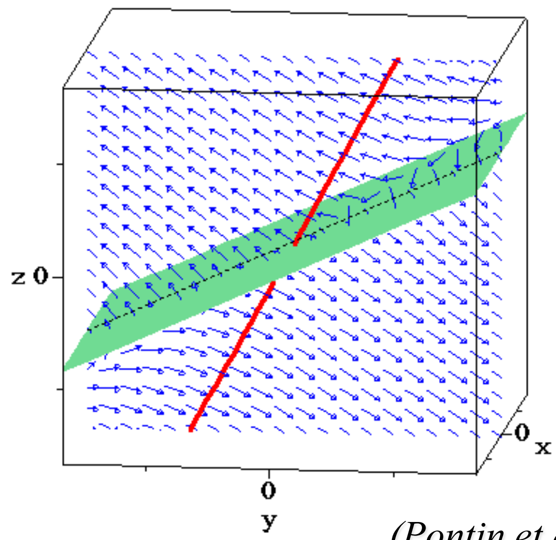


(Fukao *et al.* 1975; Parnell *et al.* 1996)

Why might reconnection occur at 3D nulls?



(Hornig & Schindler '96)



(Pontin et al '07)

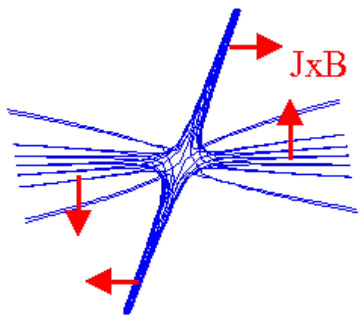
- No smooth continuous <u>*w*</u> exists satisfying $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{w} \times \mathbf{B})$

  i.e. these evolutions prohibited in ideal MHD

  For ideal evolution, ratio of eigenvalue pairs must be time-indep. (Hornig & Schindler '96)

- Lorentz force acts to collapse null just as in 2D.

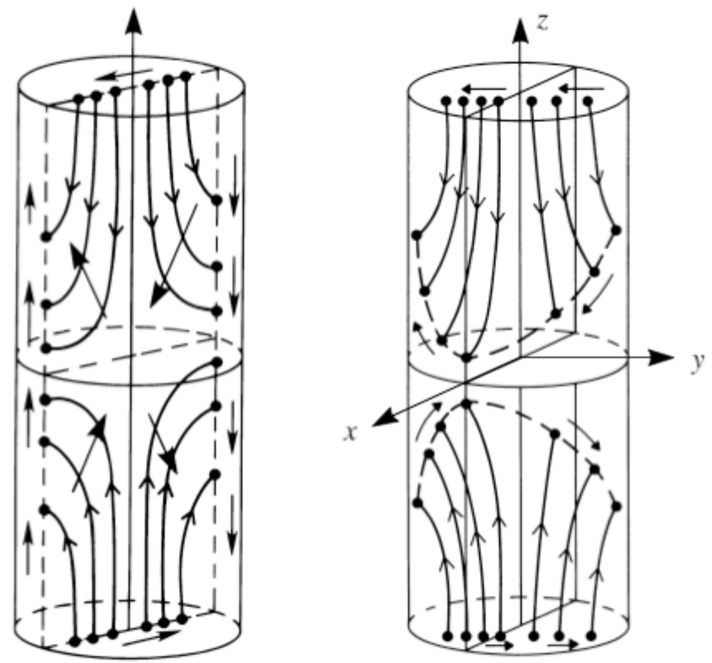
(Klapper et al '96, Parnell et al '97, Bulanov & Sakai '97, Mellor et al '03, Pontin & Craig '05)



Original models

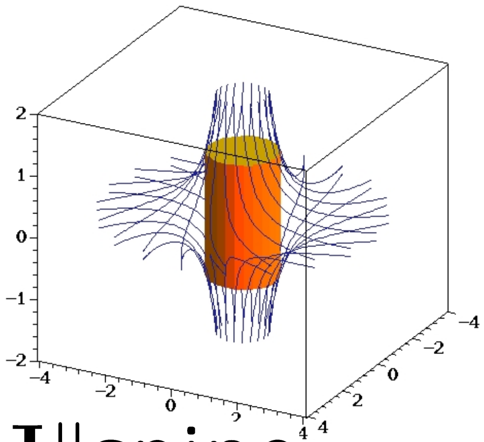
- Priest & Titov '96: kinematic *ideal* models: $\underline{J}=\underline{0}$, $\eta=0$
- "Spine rec":
  - imagine flow across fan
  - results in singular $\underline{E}$, $\underline{v}$ at spine
- "Fan rec":
  - imagine flow across spine
  - results in singular $\underline{E}$, $\underline{v}$ in fan

- Not realised (in general) in resistive MHD regime



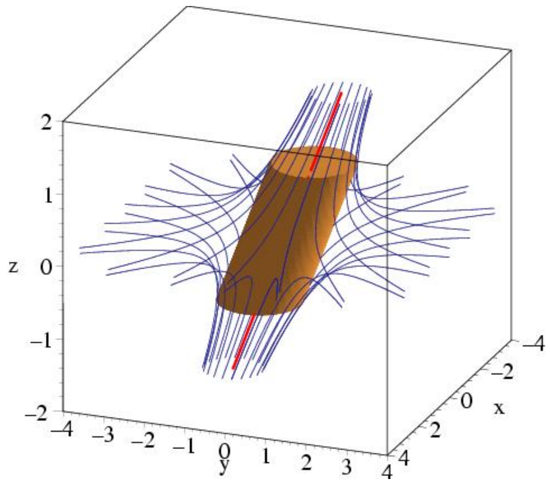
Modes of kinematic reconnection at 3D nulls

(Pontin, Hornig & Priest '04,'05)



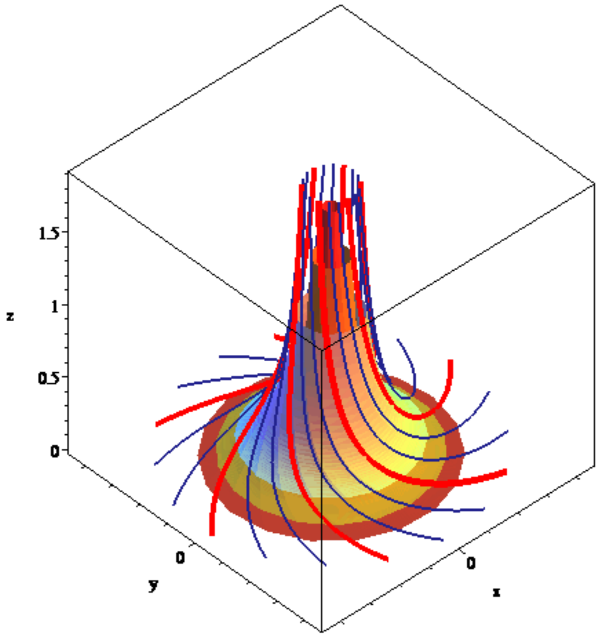
$\mathbf{J} \| $spine

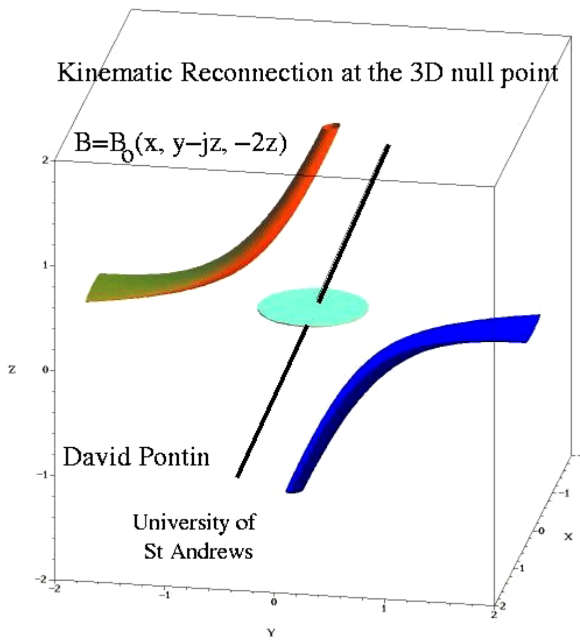
- kinematic
- steady-state
- localised η



$\mathbf{J} \| $fan

Rec rate $\int E_{\|} ds$ measures rate of rotational slippage

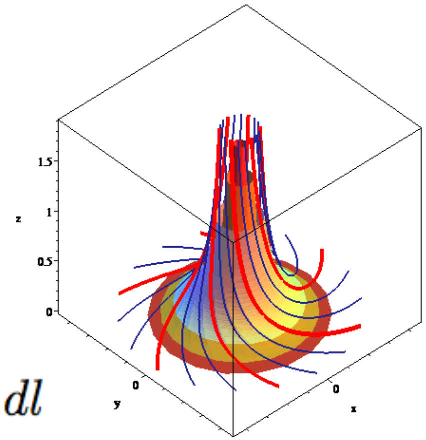




Rec rate measures flux transfer across separatrix (fan) surface

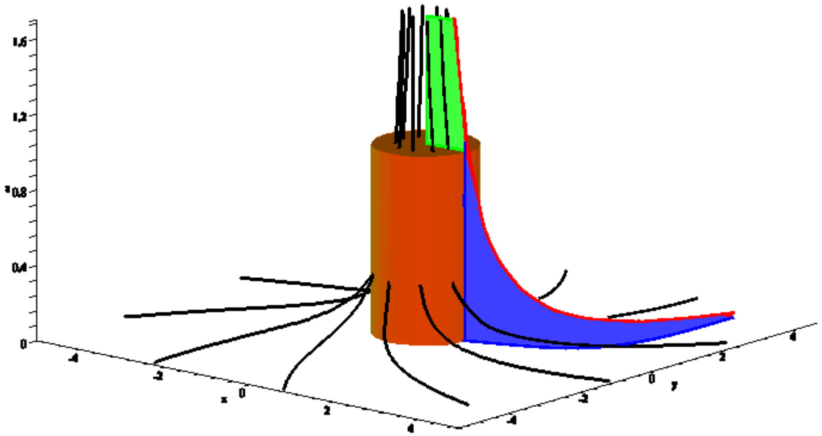
Rec rate: interpretation

$\mathbf{J}||$spine

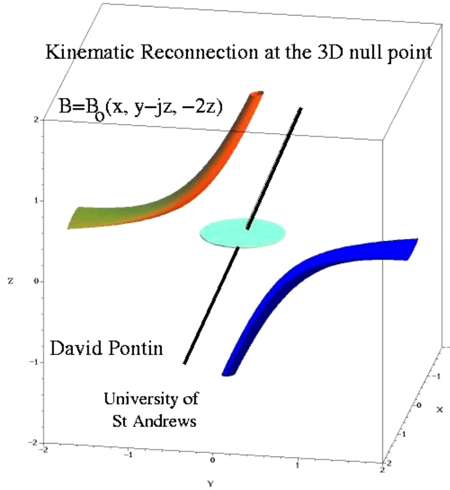


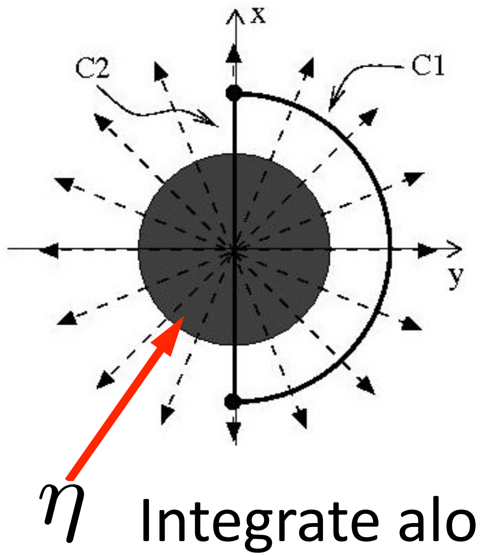
$$\psi = \int_{x=y=0} E_{||} dl$$

Measures rotational slippage



$\mathbf{J}||$fan





$$\Psi = -\int_{C1} \mathbf{v} \times \mathbf{B} \cdot \mathbf{dl}$$
$$= \int_{C1} \mathbf{E} \cdot \mathbf{dl}$$
$$= \int_{C2} E_{||} dl$$

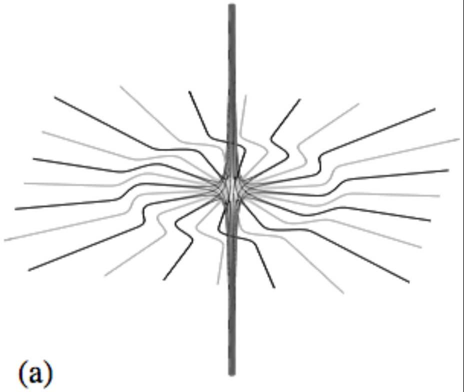
Integrate along fan || $\underline{J}$

Measures rate of flux transfer across separatrix (fan) surface

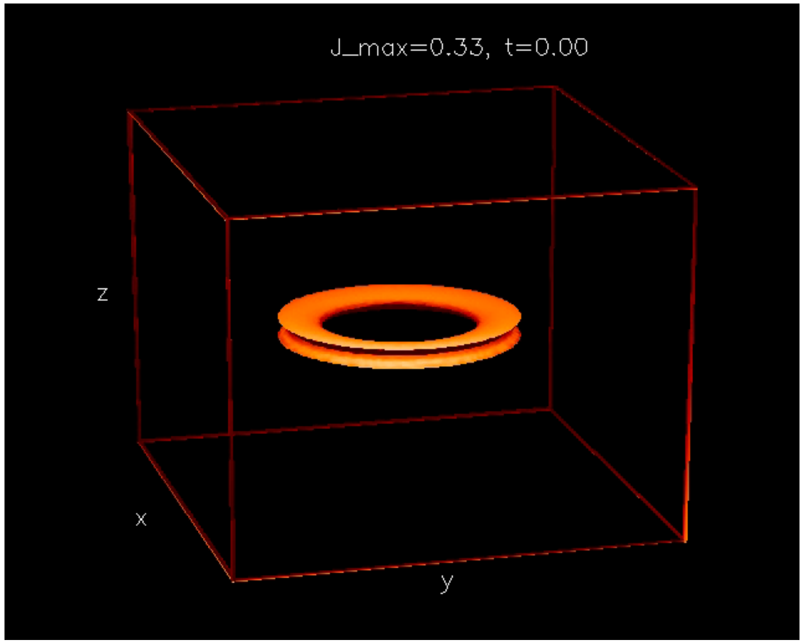
Formation of diffusion regions I

(Rickard & Titov '96, Galsgaard et al '03, Pontin & Galsgaard '07)

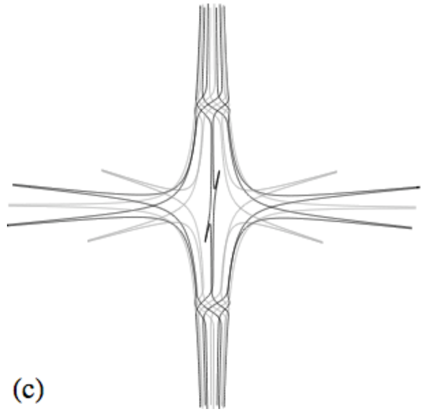
- Rotational pertub. in fan
- -> highly twisted J tube along spine



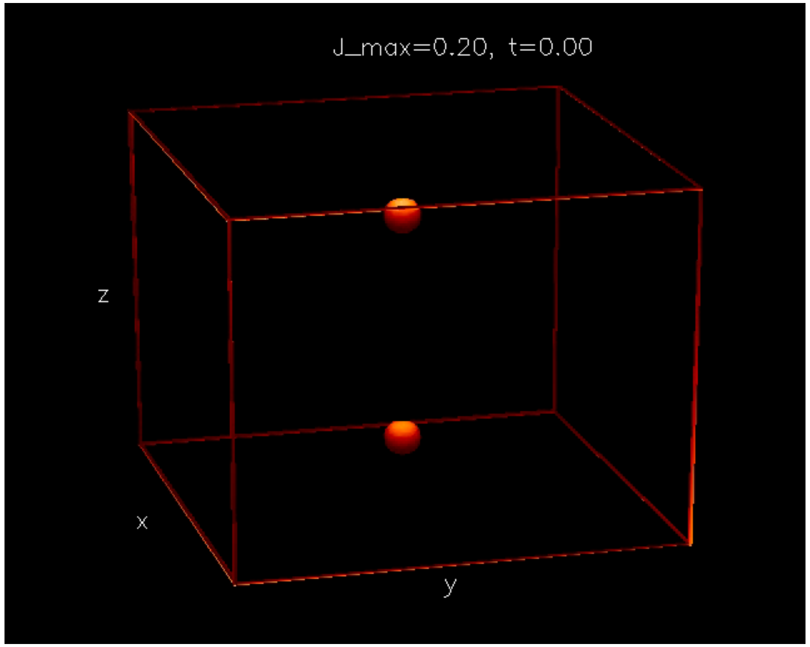
(a)



- Rotational pertub. of spine
- -> fan J sheet (associated with twisted B)



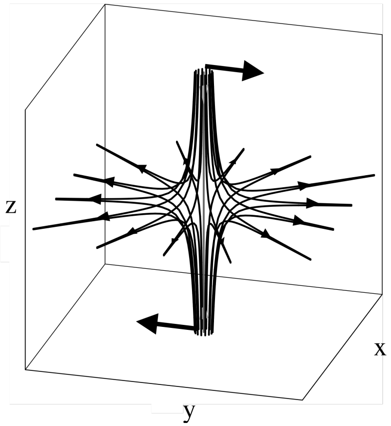
(c)

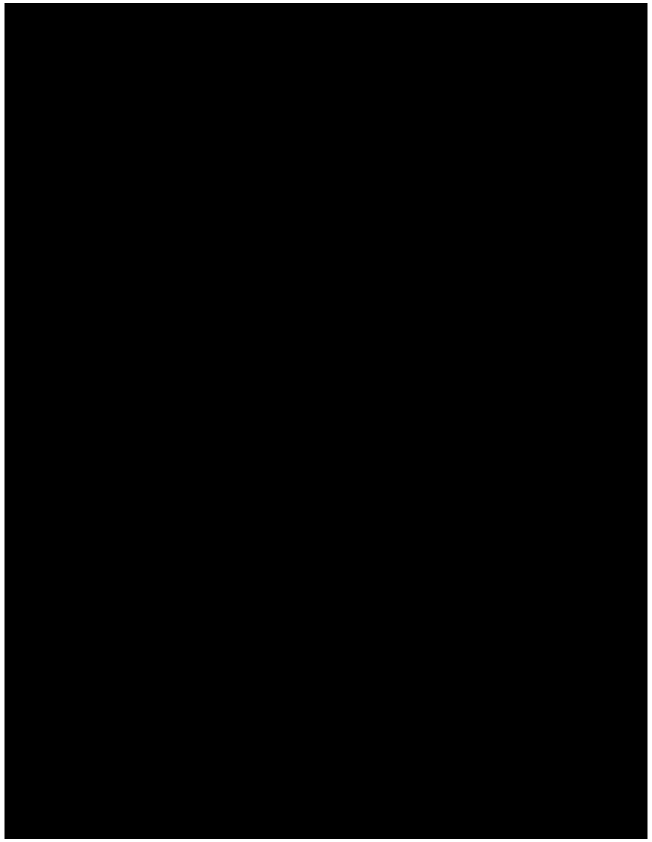


Formation of diffusion regions II

(Rickard & Titov '96, Pontin & Galsgaard '07, Pontin et al '07)

- Shear pertub. of spine OR fan focus at null itself
- E.g. By boundary driving:





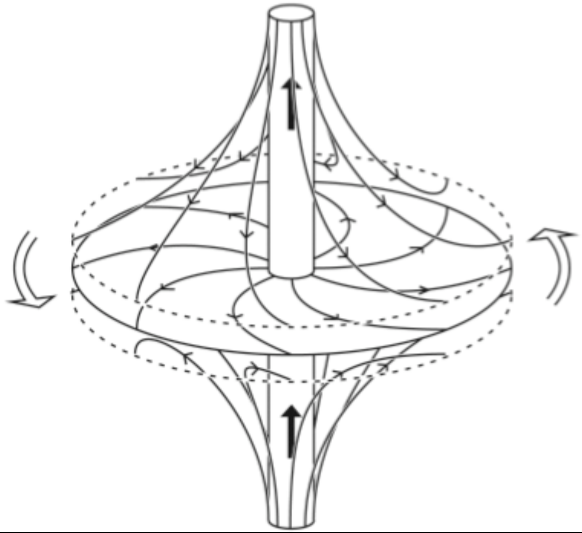
Proposed new nomenclature

(Priest & Pontin, Phys. Plasmas, in press)

- Old terminology `fan rec' and `spine rec' does <u>not</u> adequately describe 3D null rec regimes.
- Proposed new regimes:
  - "Torsional spine reconnection"
  - "Torsional fan reconnection"
  - "Spine-fan reconnection" (the most common in practice)

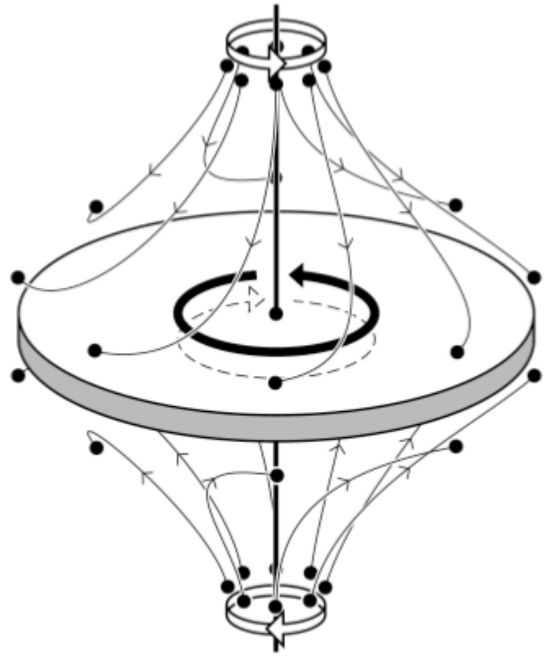
Torsional spine reconnection

- Rotational disturbance of fan
- Drives twisted $\underline{J}$ tube along length of spine
- $\underline{J}$ flows along spine
- Rotational $\underline{B}$-line slippage
- Expect steady state when tightening of twist and rot. slippage balance



Torsional fan reconnection

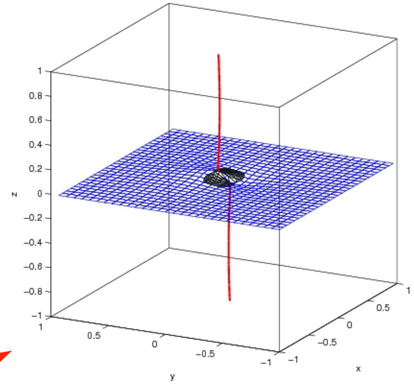
- Rotational disturbance about spine
- Drives planar <u>J</u> in entire fan plane (spine & fan orthogonal)
- <u>J</u> flows around fan. At null <u>J</u> flows || spine
- Rotational <u>B</u>-line slippage & rotational mismatching of <u>v</u> above/ below fan
- Expect steady state when twisting and rot. slippage balance

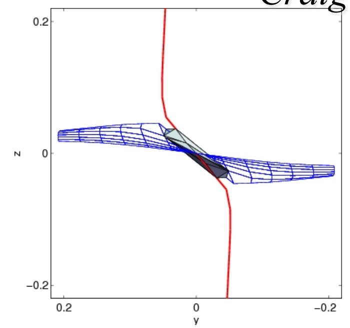


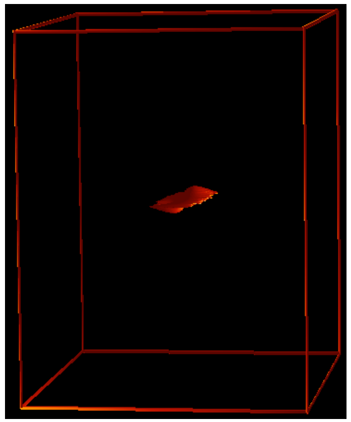
Spine-fan reconnection I

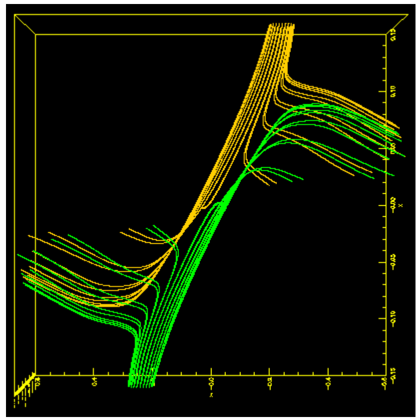
(Pontin & Craig '05)

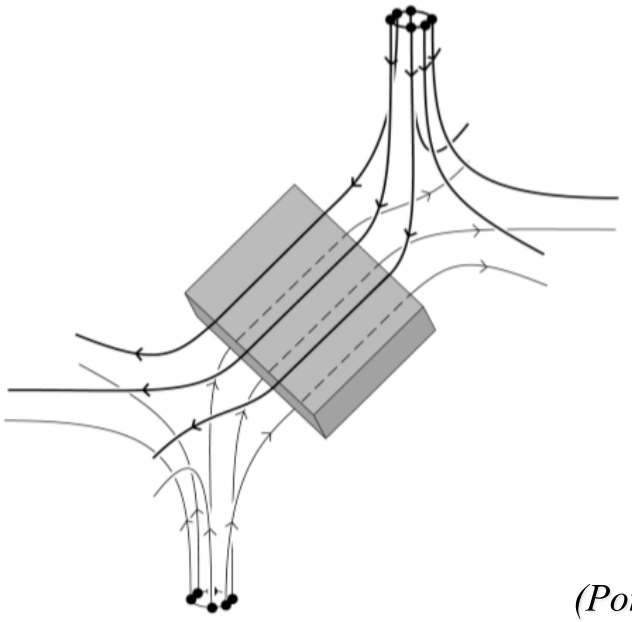
- Spine and fan collapse
- Distortion of B focussed in weak field region at null
- J sheet focussed at null
- Observed in ideal relaxation and resistive MHD dynamics

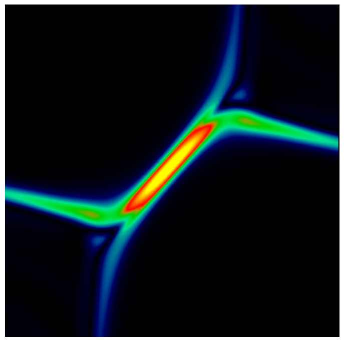


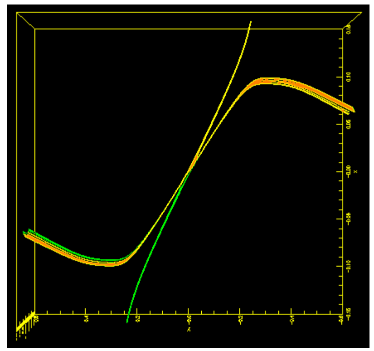








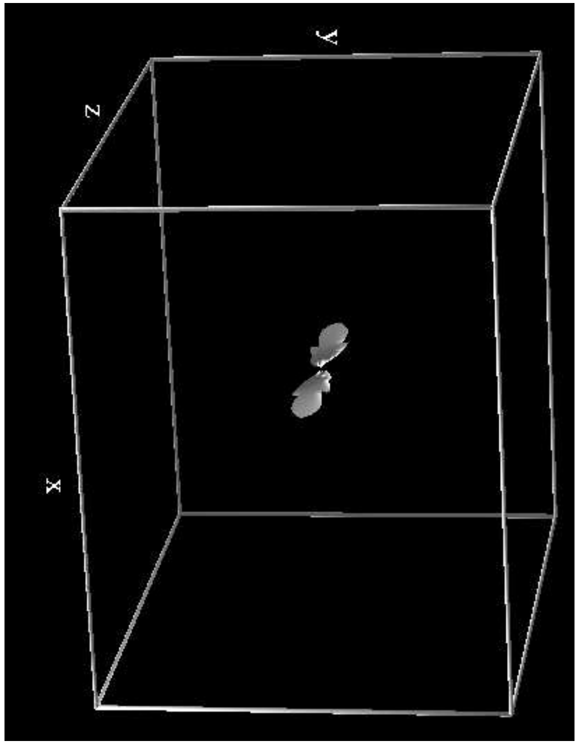




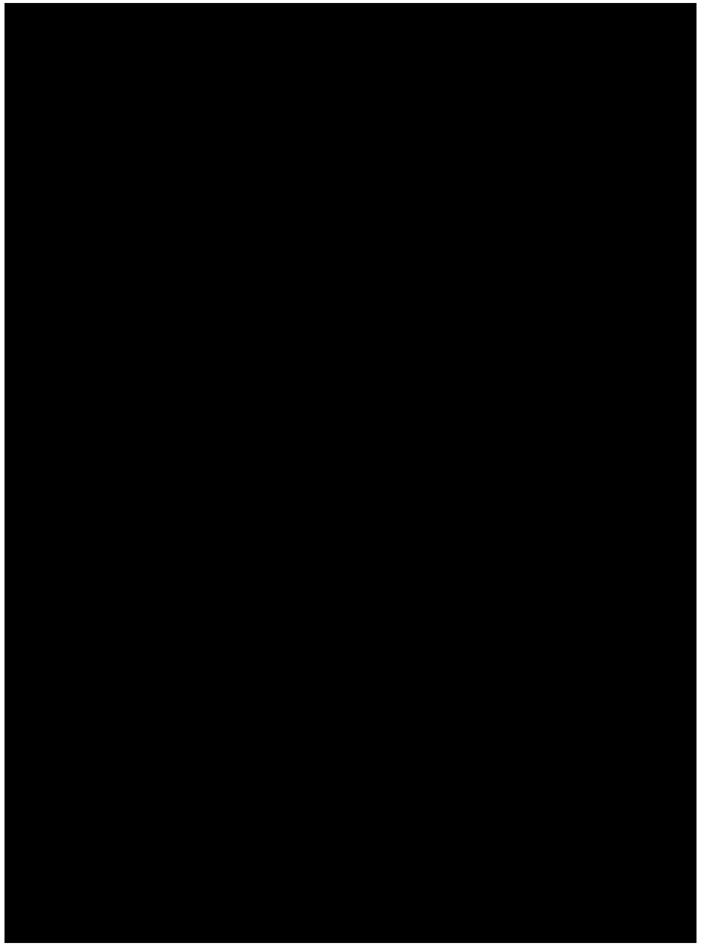
(Pontin et al '07)

$E_{||}$ and reconnection

- Localised $E_{||}$ concentration develops in fan, along <u>*B*</u>-line in direction of <u>*J*</u> flow

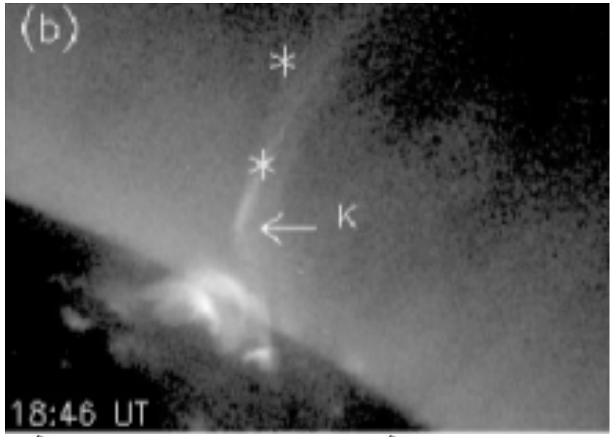


- Rec of <u>*B*</u>-lines through both spine and fan

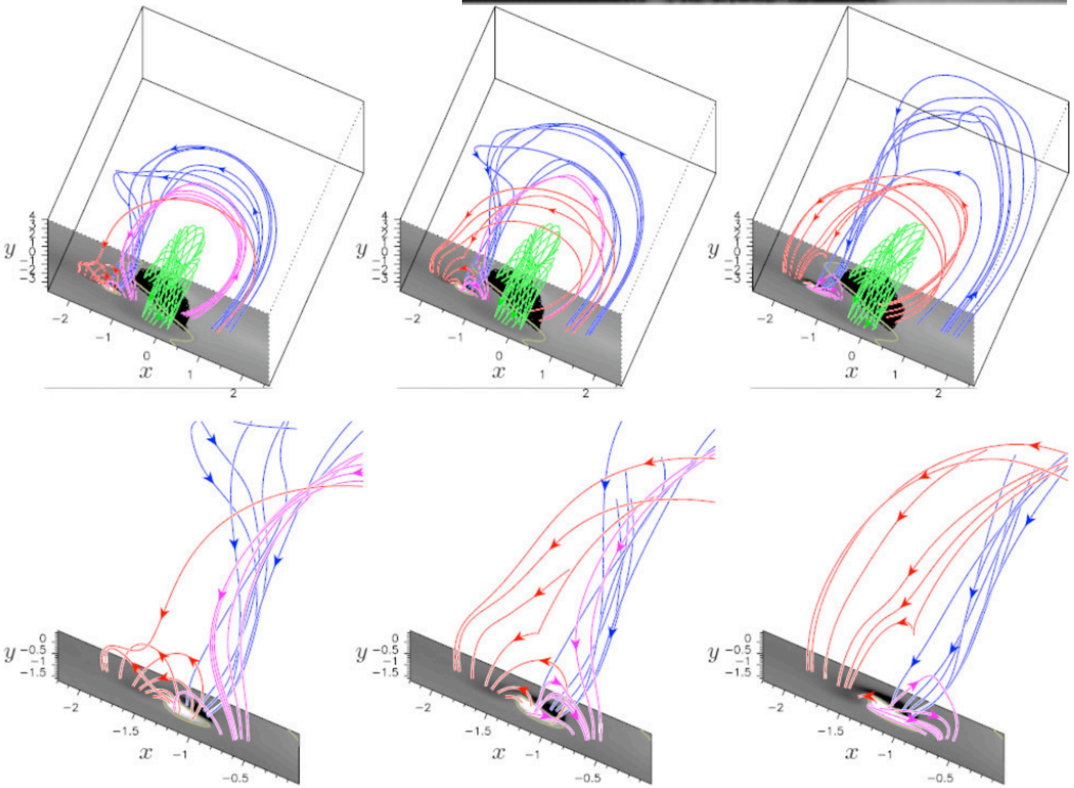


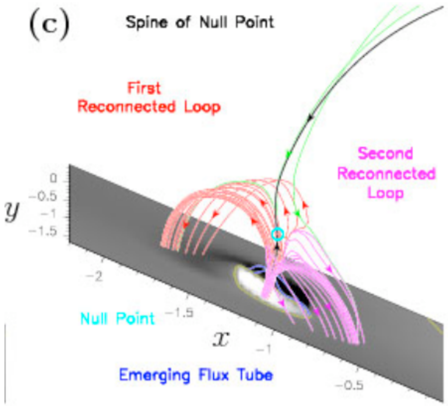
3D nulls in flux emergence simulation

(Torok et al., ApJ, 2009)



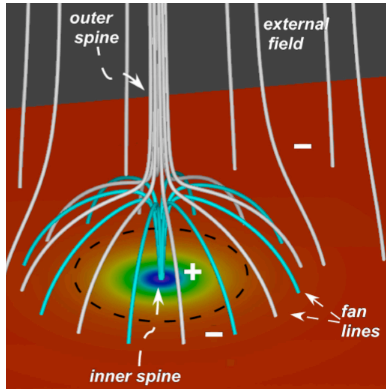
- Emergence of 1 flux rope in the vicinity of another modelled.
- 3D null point rises up into corona
- `Two-step' rec process identified: spine-fan
- `Anemone' structure formed.
- Model for coronal jets.



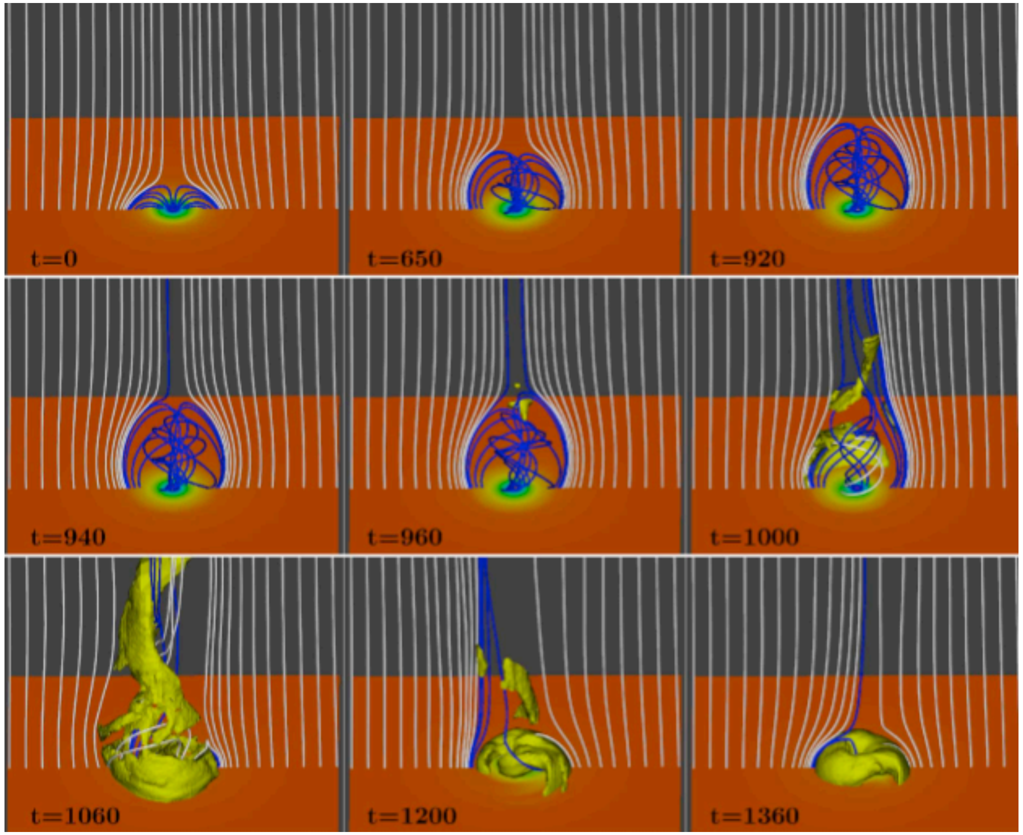


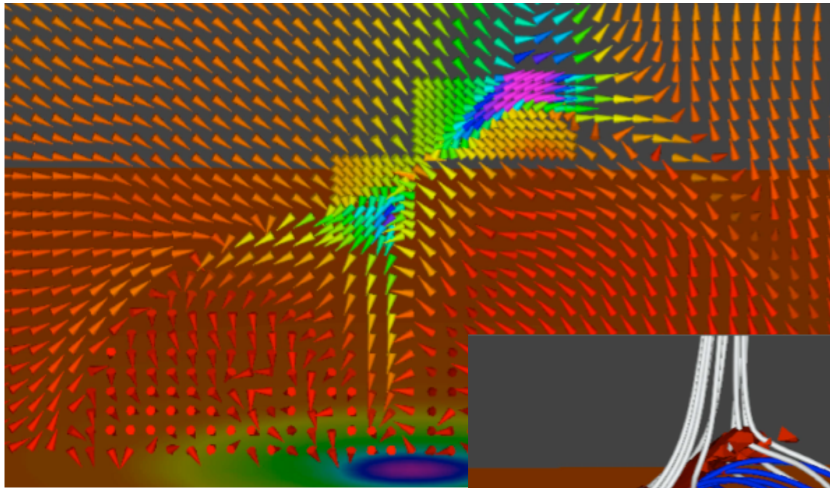
3D null rec as a model for jets

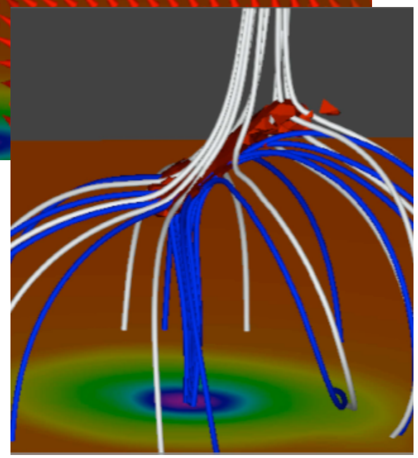
(Pariat et al '09)



- Twist B beneath fan dome – builds up free energy
- Instability -> rapid rec and ejection of twist along spine



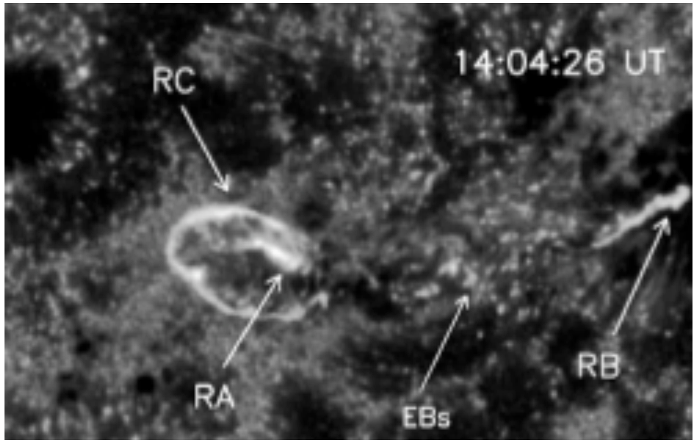


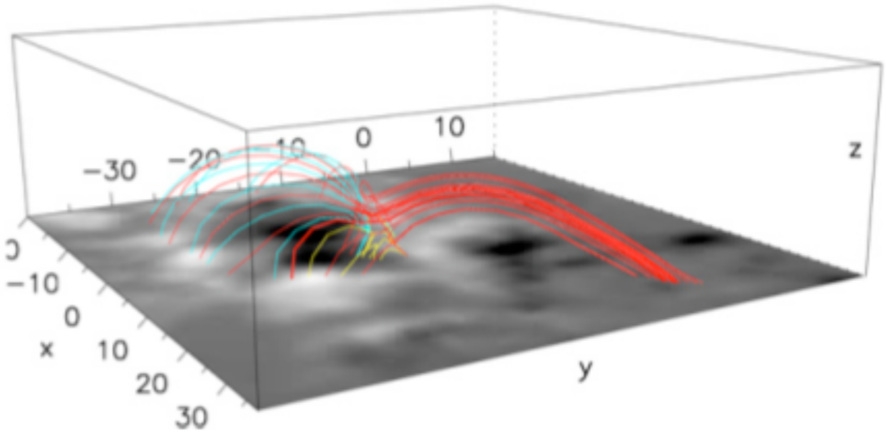


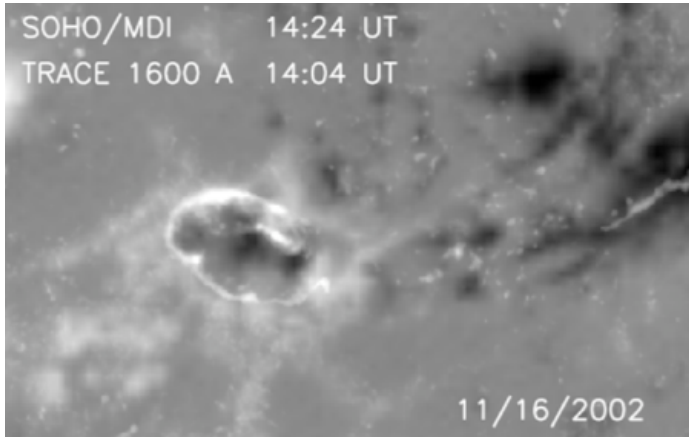
Null rec. and flare ribbons

(Masson et al., ApJ, 2009)

- Simulation for AR10191. Emergence of parasitic polarity -> C-class flare
- Closed flare ribbon associated with fan dome footprint & kernels at spine footpoints



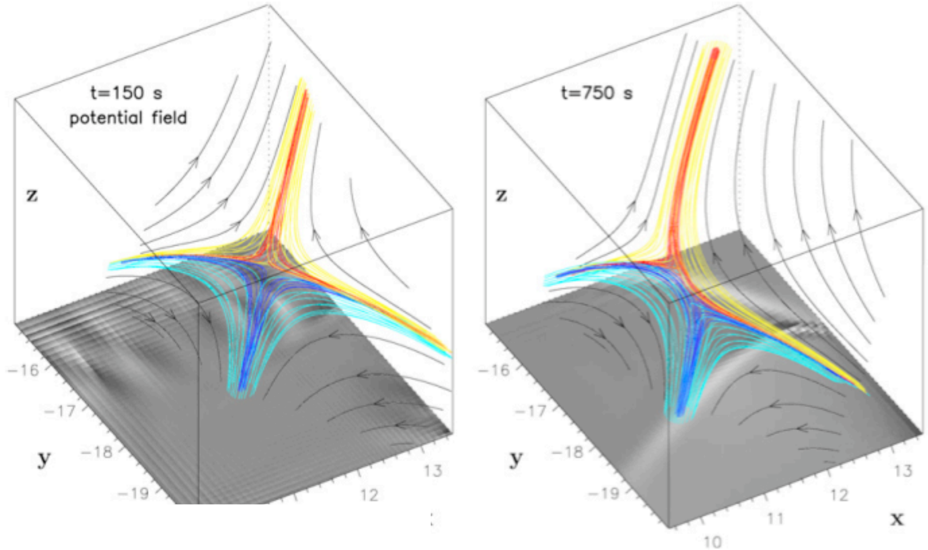


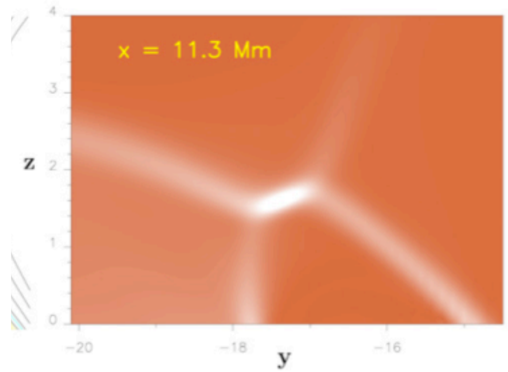


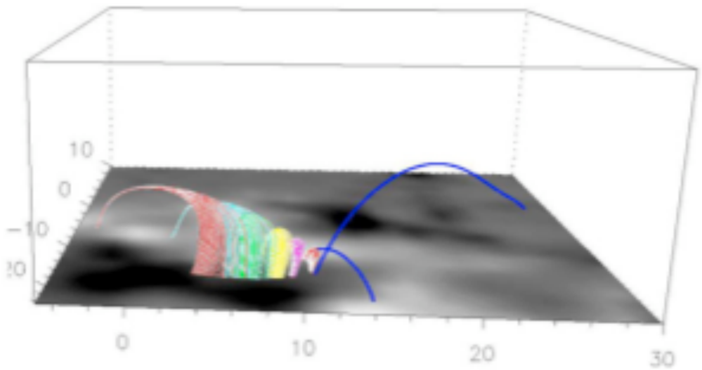
Null rec. and flare ribbons

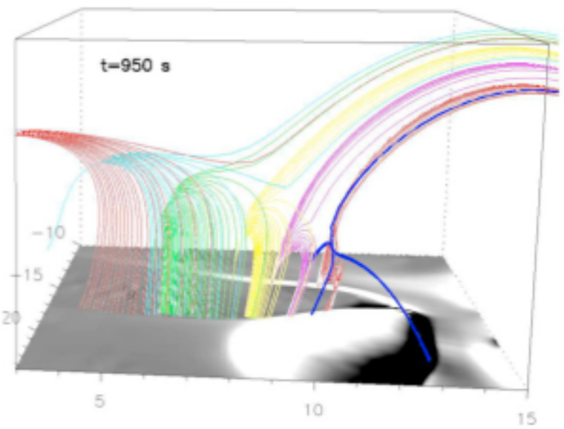
(Masson et al., ApJ, 2009)

- Null collapse -> thin current sheet and spine-fan rec.
- Facilitates flux transfer in/out of dome
- QSLs in vicinity of spine proposed to lead to slip-running rec. (torsional fan/ spine??)









Summary I

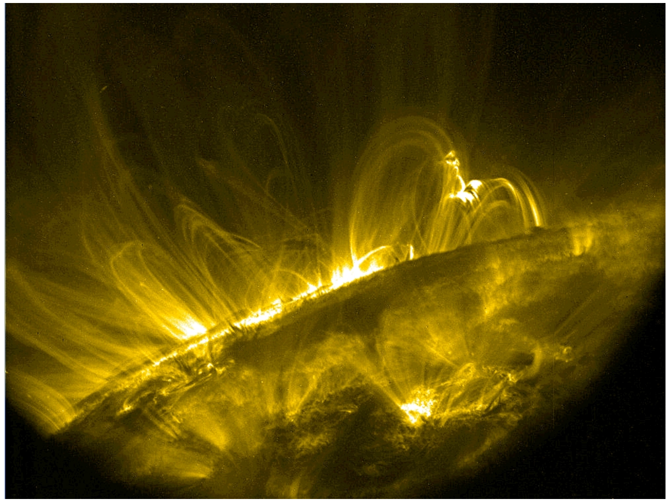
- 3D nulls occur frequently and are <u>one possible</u> site of rec.
- Different localised $\underline{J}$ structures / different rec regimes
  - "Torsional spine reconnection"
    - Rotational motion in fan drives strongly twisted $\underline{J}$ tube along spine
    - $\underline{J}$ || spine at null: $\int E_{\|} ds$ along spine measures rate of rot. slippage
  - "Torsional fan reconnection"
    - Rotational motion about spine drives planar $\underline{J}$ in entire fan plane
    - $\underline{J}$ || spine at null: $\int E_{\|} ds$ along spine measures rate of rot. slippage
  - "Spine-fan reconnection" (the most common)
    - Local collapse to form J sheet at null that locally spans spine and fan
    - Flux transfer through spine line and fan (separatrix surface)
- Old terminology `fan rec' and `spine rec' does <u>not</u> adequately describe 3D null rec regimes.
- 3D nulls may be important sites of rec in various solar phenomena: flares, CMEs, jets

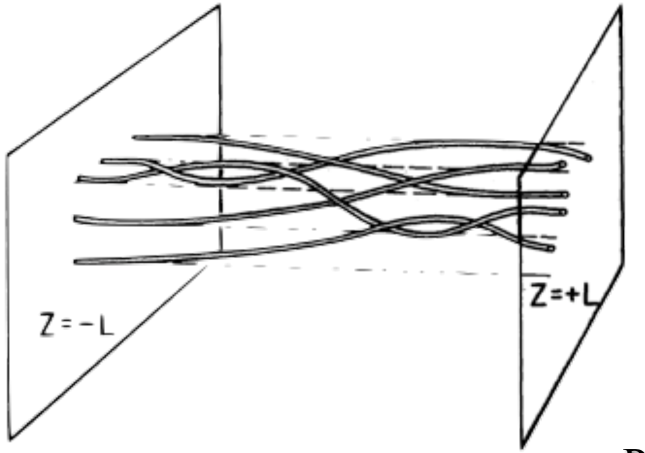
Reconnection in braided magnetic fields

(Wilmot-Smith et al. ‘09a,b

Pontin et al. ‘09)

‘Topologial Dissipation’





Parker, E.N.

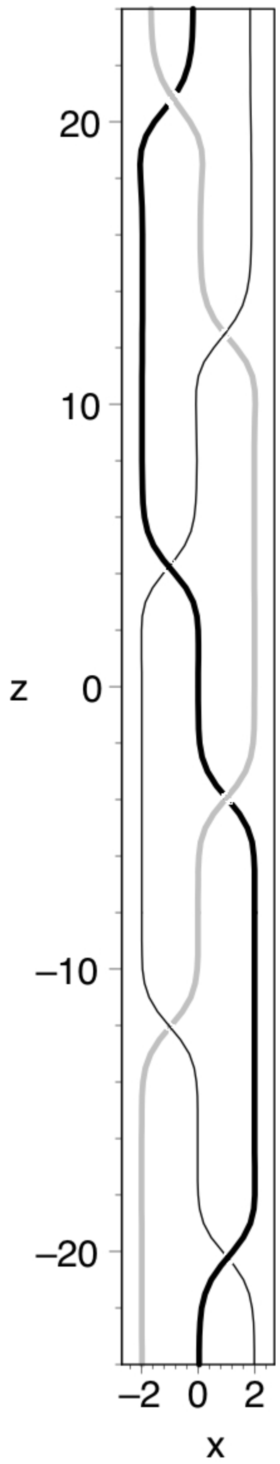
- Model solar loop as braided magnetic field between parallel plates.
- Argues that perturbed field can’t relax to smooth force-free equilibrium except in certain non-generic cases.
- Consequence - tangential discontinuities (current sheets) form => reconnection and heating.
- Many results for and against hypothesis

Method

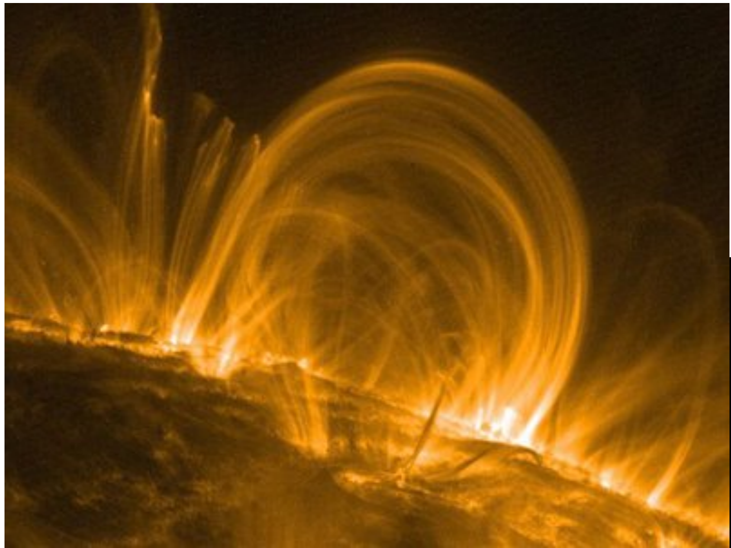
- Construct analytical braided magnetic field and use numerical relaxation to obtain a force-free equilibrium.
- To preserve the braid topology in the relaxation we use a Lagrangian magneto-frictional relaxation scheme.
- Do current sheets form?

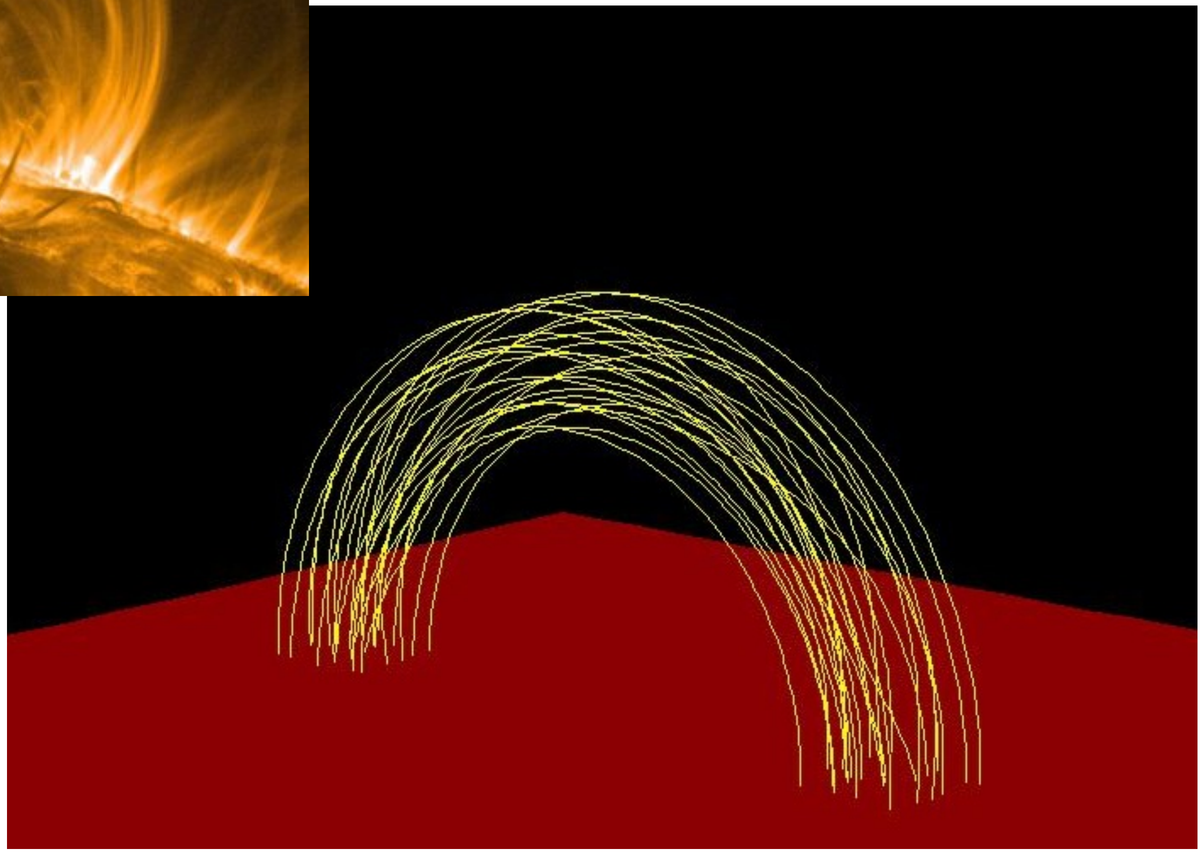
- Use this relaxed force-free state as an initial configuration for full MHD simulation: does rec occur, and if so where??

- Suppose photospheric motion occurs in random manner - take braid with no net twist.
- Model on pigtail braid.



Braid consistent with observed loops

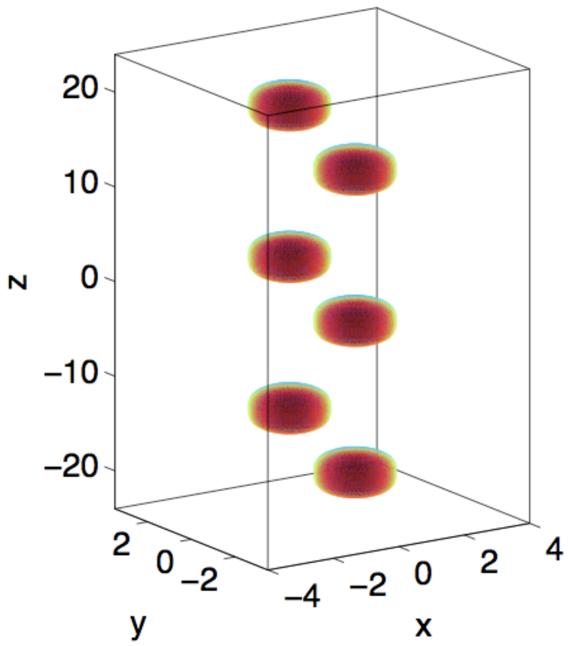




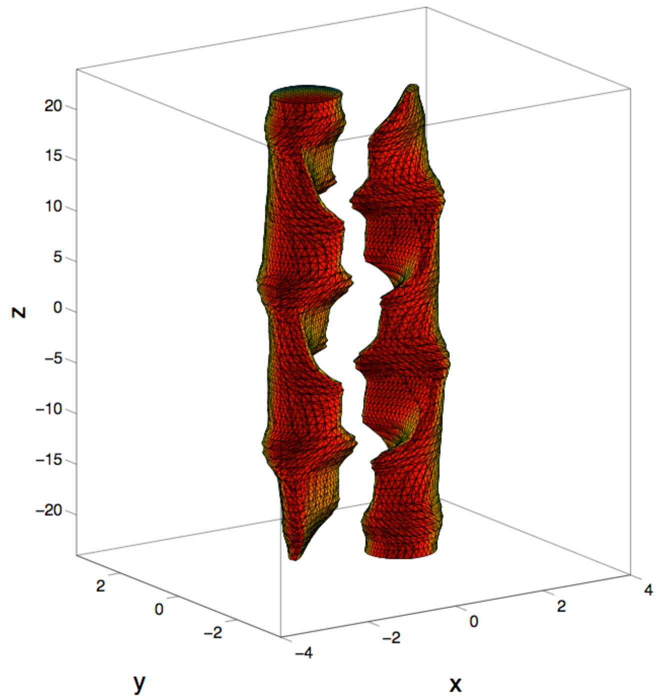
Numerical Method

- Code of Craig & Sneyd '86: 3D Lagrangian magneto-frictional relaxation scheme, implicit unconditionally stable ADI scheme.
- Relaxation preserves the topology of the braid
- Fictitious momentum equation -
  - parabolic system of equations, $\nu \mathbf{v} = \mathbf{j} \times \mathbf{B}$
  - monotonic decrease in magnetic energy
- Automatic conservation of $\nabla \cdot \mathbf{B}$.

Nature of relaxed state



Isosurface ($/j_{max}|/4$) of current in initial state .



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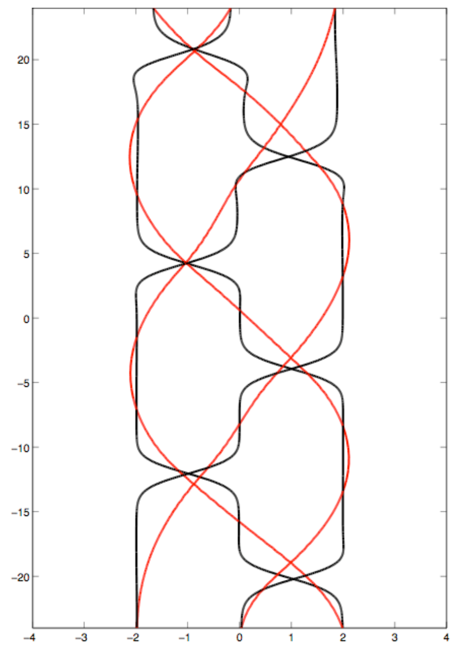
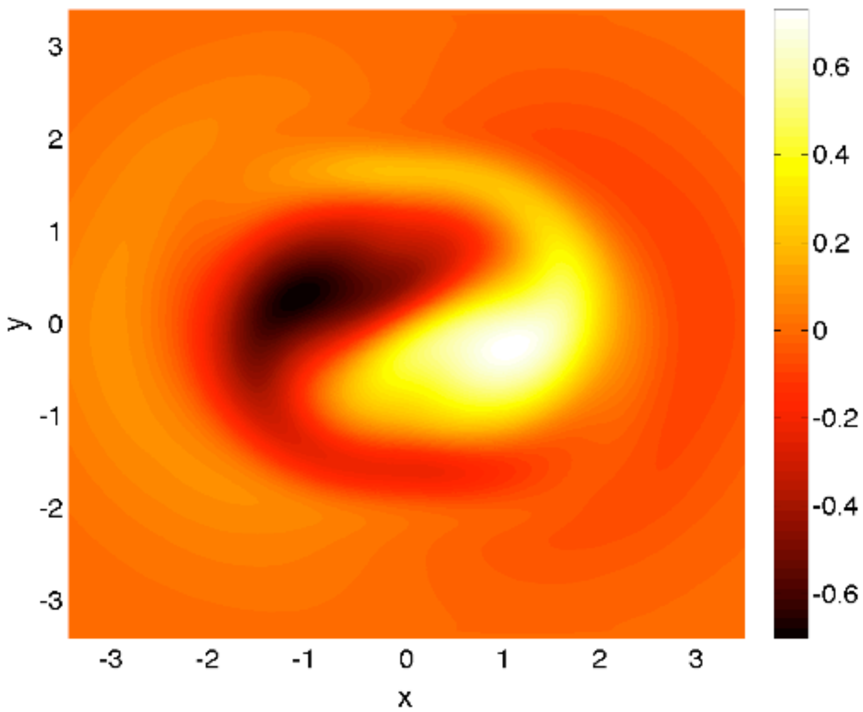


Field lines in initial and relaxed states.

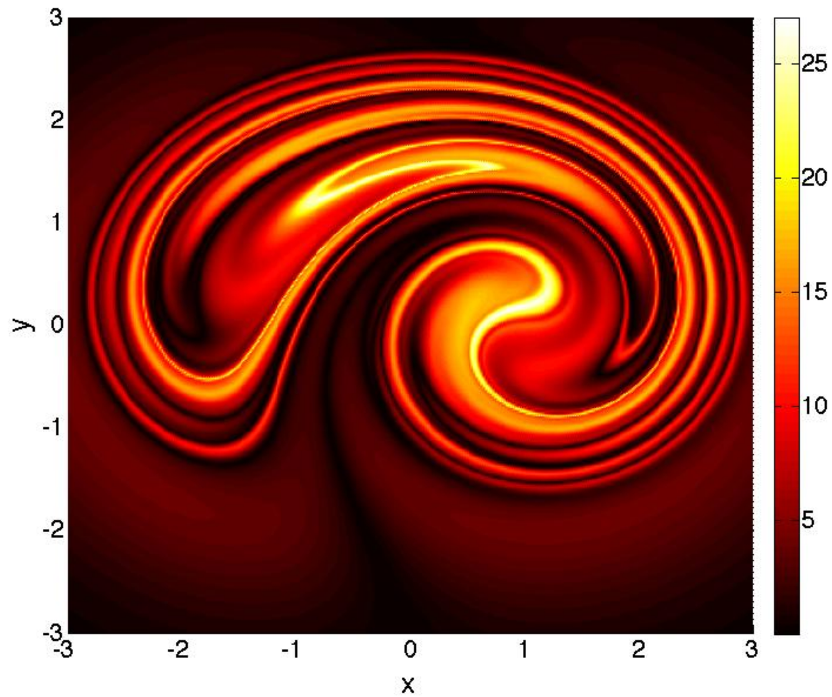
Nature of relaxed state

In contradiction to Parker's hypothesis,

no current sheets: smooth variation of *J*



However, $\left|\int j_{\|} \mathrm{d}l\right|$ does display small scales (in initial and final state)



MHD evolution

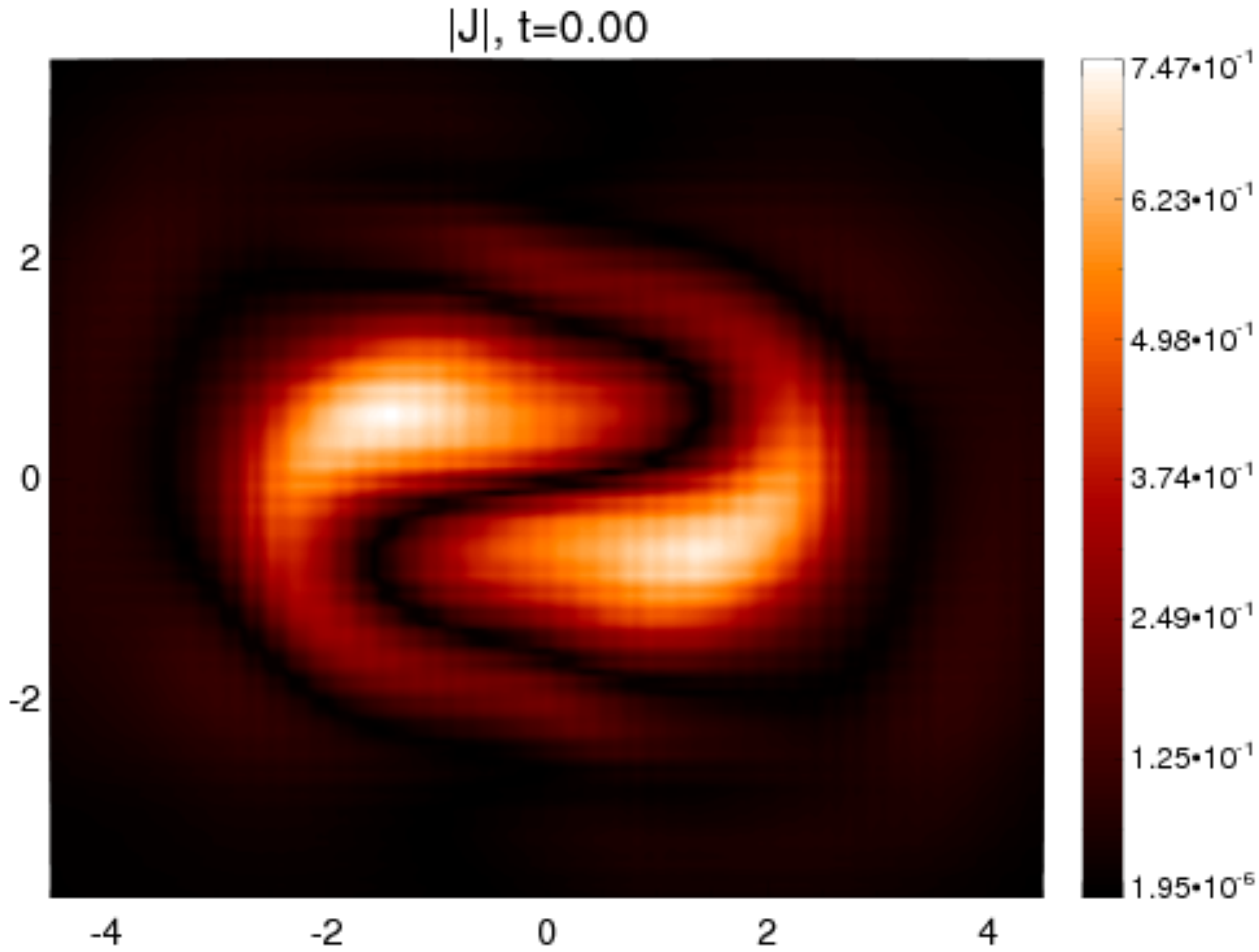
- Take final state from magnetic relaxation and insert into a resistive MHD code.

$$
\begin{aligned}
\frac{\partial \mathbf{B}}{\partial t} &= -\nabla \times \mathbf{E} \,, \\
\mathbf{E} &= -(\mathbf{v} \times \mathbf{B}) + \eta \mathbf{j} \,, \\
\mathbf{j} &= \nabla \times \mathbf{B} \,, \\
\frac{\partial \rho}{\partial t} &= -\nabla \cdot (\rho \mathbf{v}) \ , \\
\frac{\partial}{\partial t}(\rho \mathbf{v}) &= -\nabla \cdot \left(\rho \mathbf{v}\mathbf{v} + \underline{\underline{\tau}}\right) - \nabla P + \mathbf{j} \times \mathbf{B} \,, \\
\frac{\partial e}{\partial t} &= -\nabla \cdot (e \mathbf{v}) - P \nabla \cdot \mathbf{v} + Q_{visc} + Q_{Joule} \ ,
\end{aligned}
$$

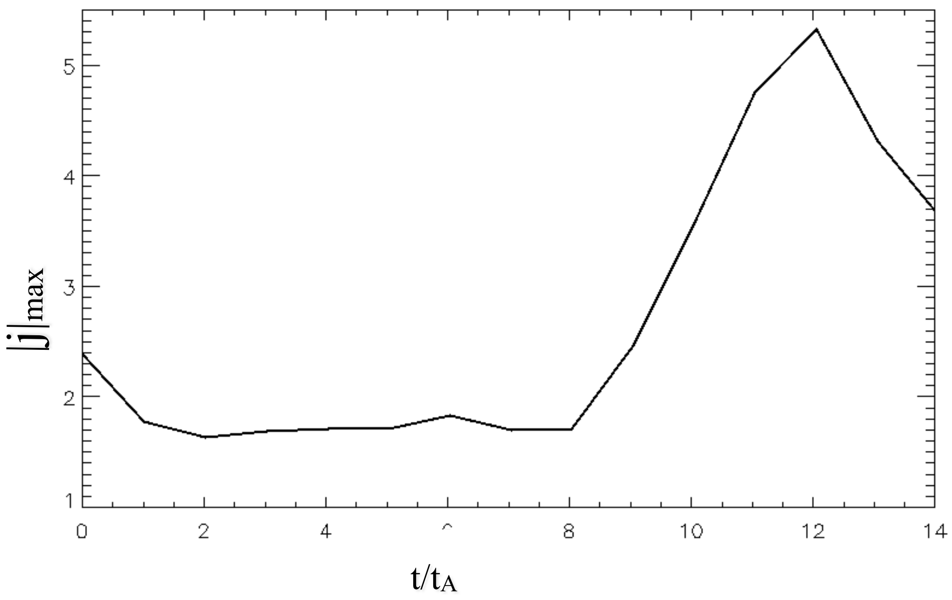
- Code, details at http://www.astro.du.dk/~kg
- Take uniform resistivity η.
- Line-tied boundary conditions.
- Time measured in units of Alfven travel time.
- Simulations: 128^3, 256^3, 320^3.

Current evolution

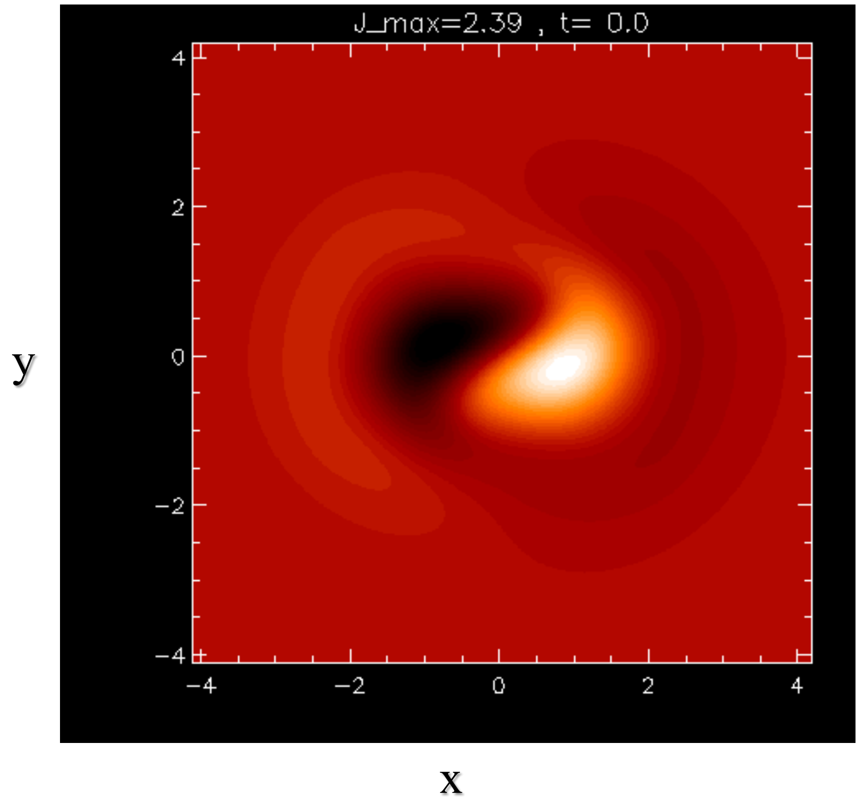
$\eta = \eta_h$



Current Evolution



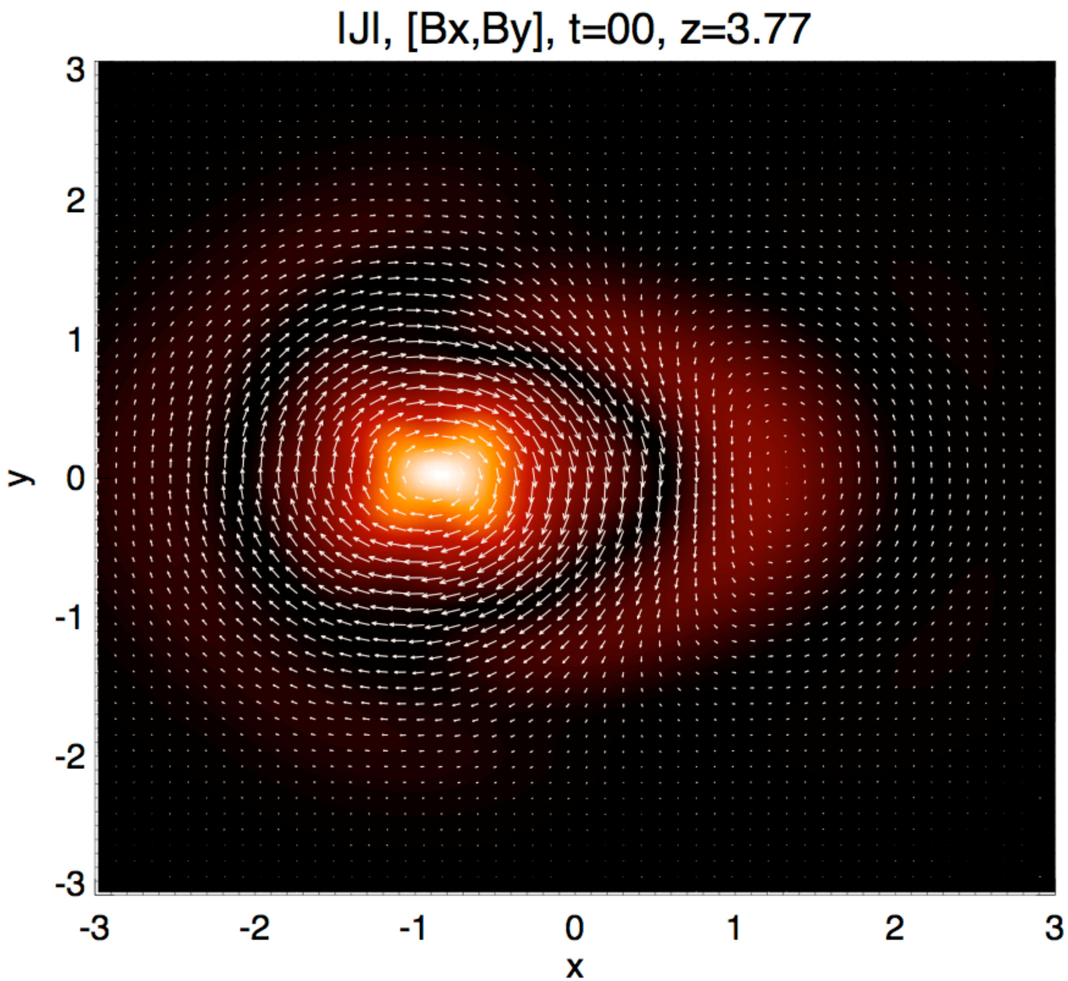
- Onset time for current growth cf. spacing of flux rings.
- Symmetric formation of two current sheets.



- j_z - white positive, black negative

(320^3 grid, η=0.001)

Magnetic field is not hyperbolic!



- *B* shows elliptic structure in region of *J* sheet formation.
- Structure consistent with high Q.
- Fundamental difference from 2D case – several 3D models of reconnection with elliptic field structure now exist (e.g. Hornig & Priest '03; De Moortel & Galsgaard '06a,b,; Wilmot-Smith & Priest '07; Parnell et al. '09).

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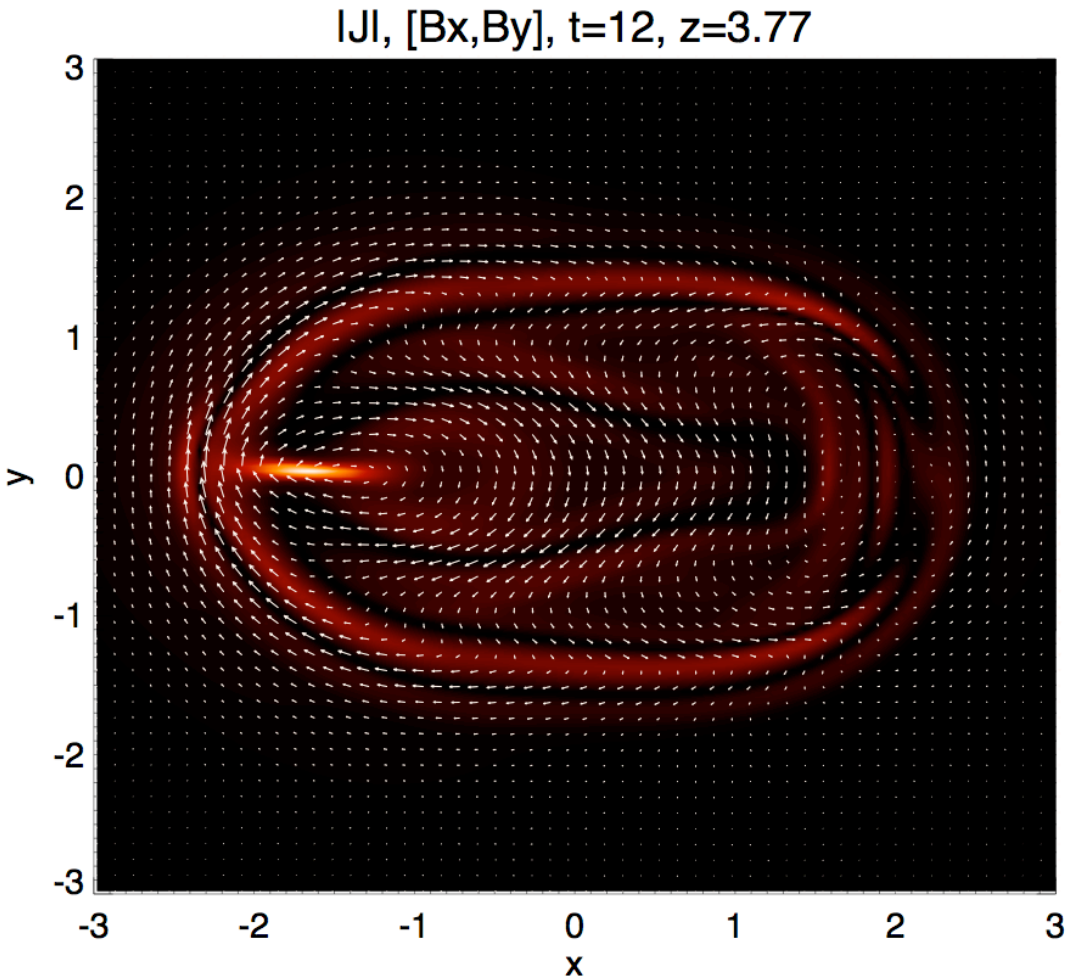

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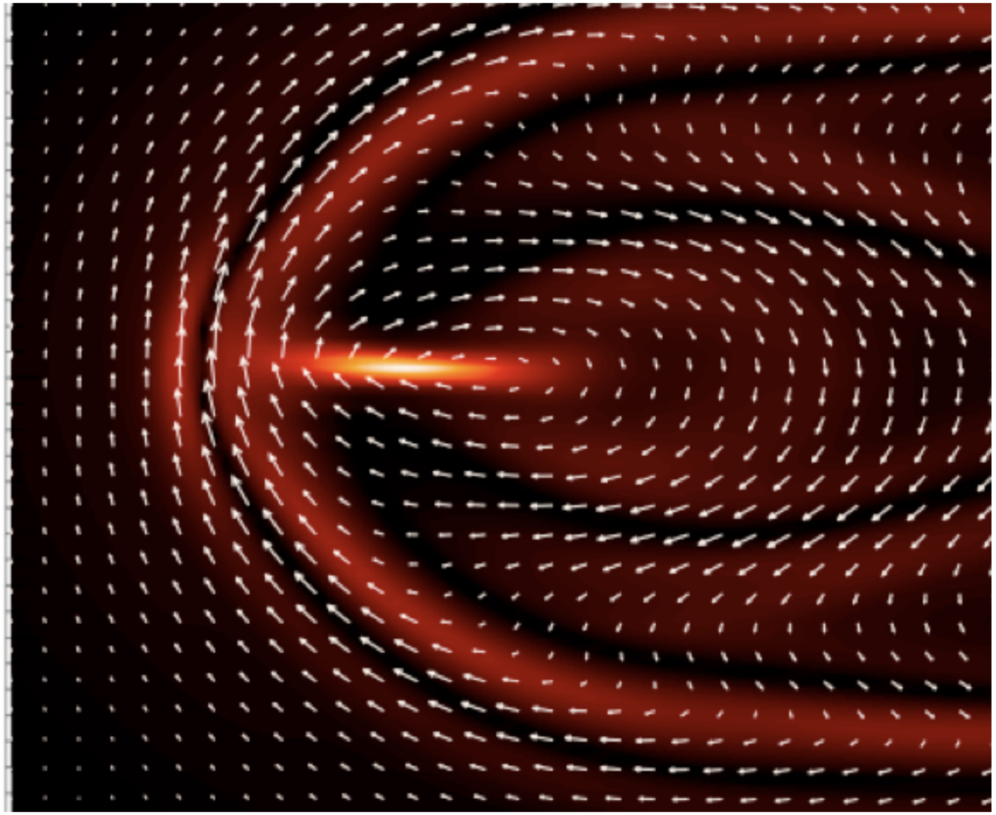

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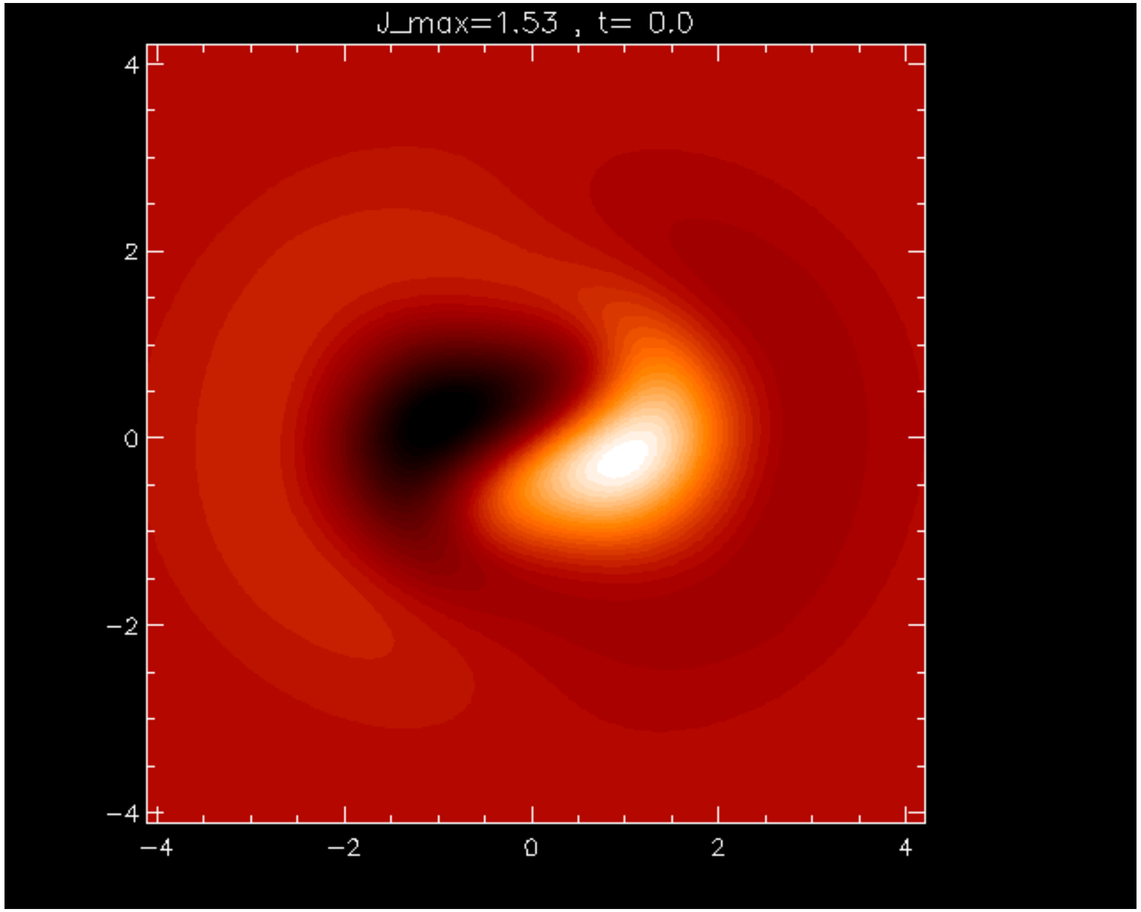
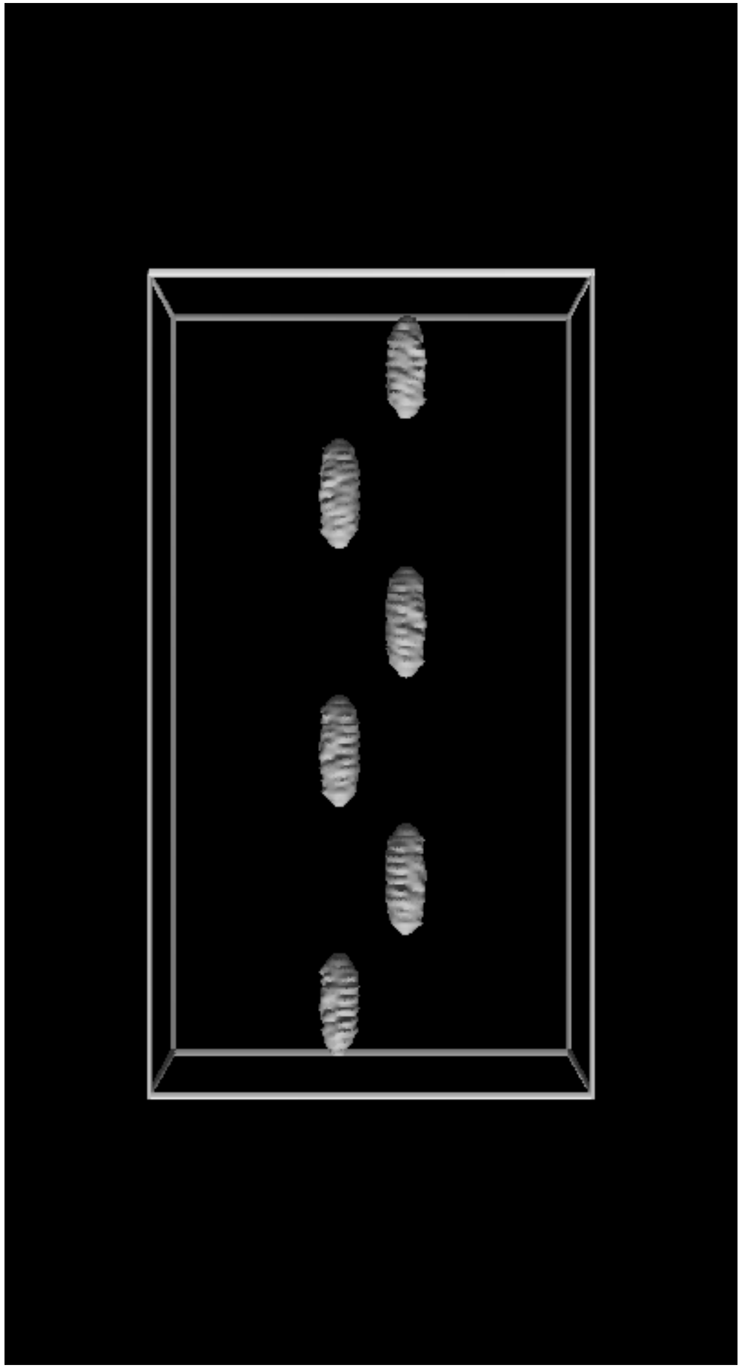
Long-time evolution

50% isosurface of |J|:

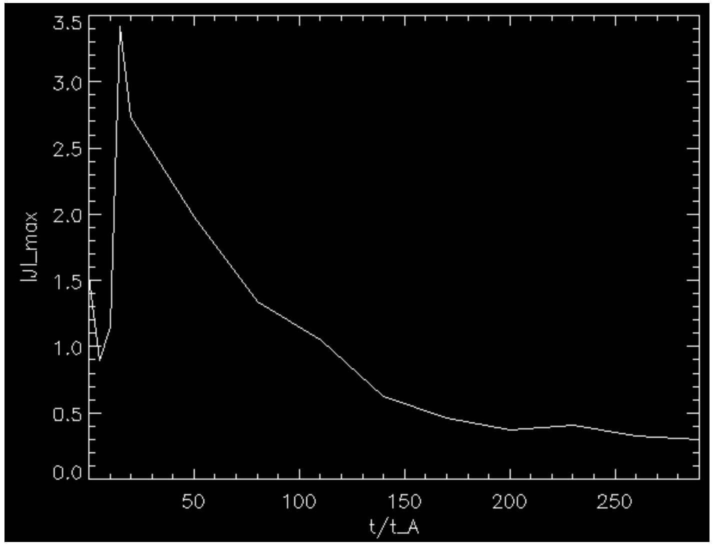
($\eta=10^{-3}$)

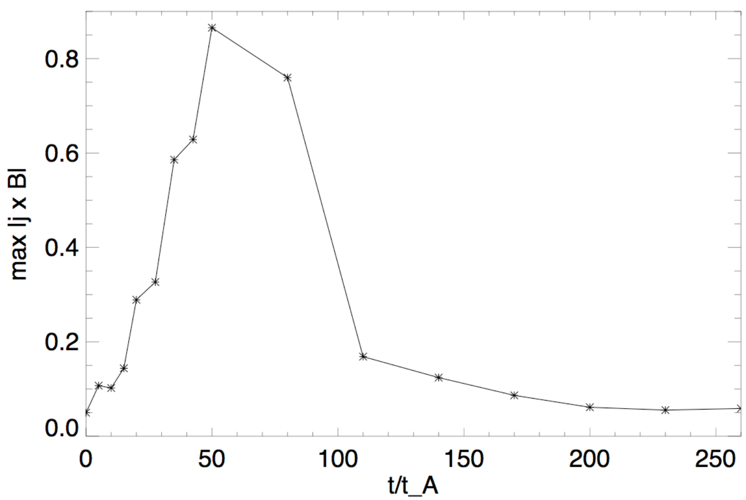
J_z at z=0:

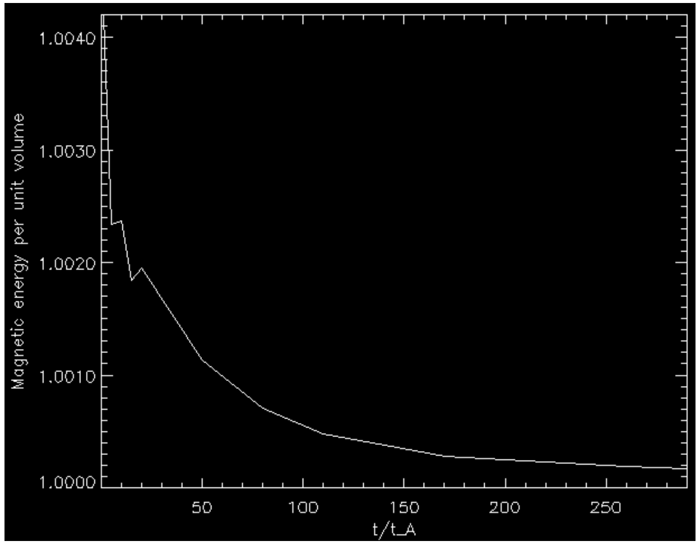




Turbulent relaxation



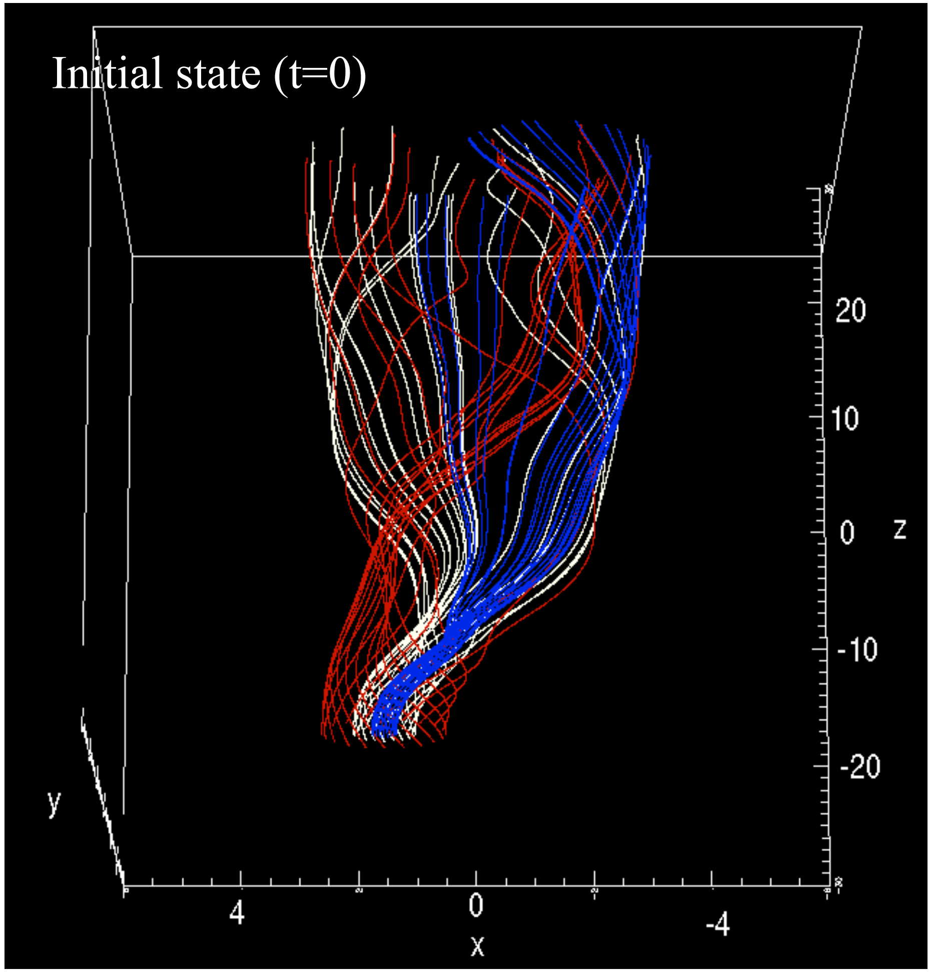


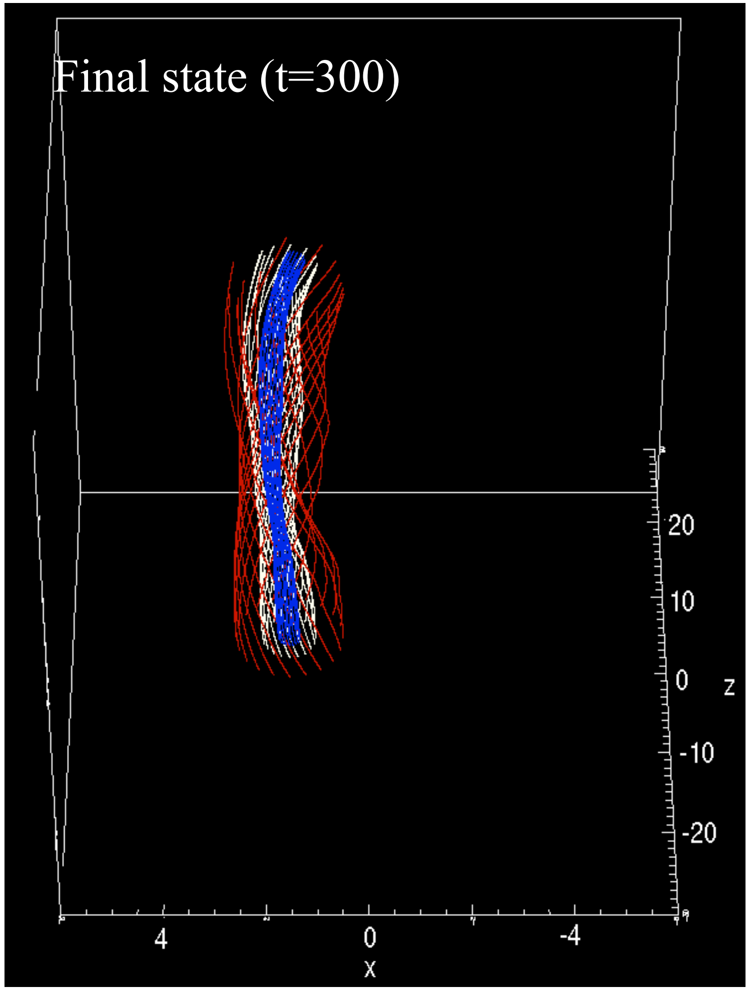


J_{max}, magnetic energy, $|JxB|_{max}$ all decay faster than resistive timescale

Separation of flux tubes

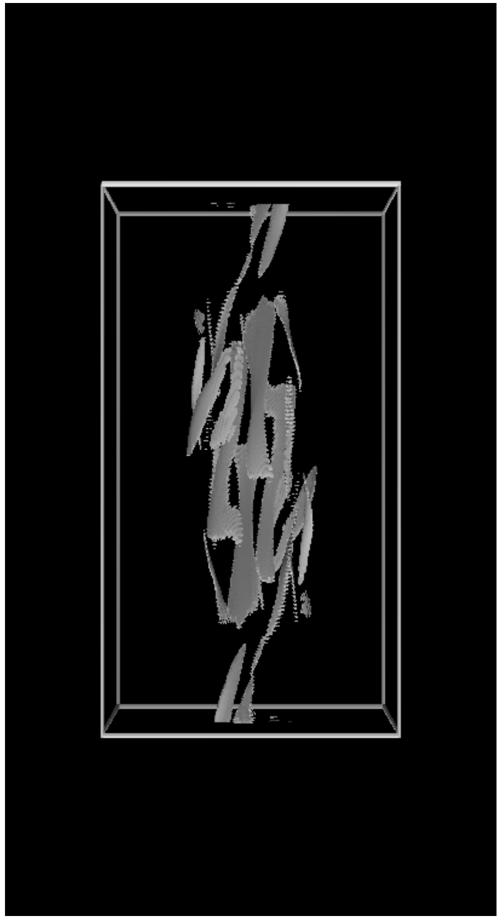
- Trace field lines from same locations on lower boundary (from ‘positive’ side of braid -- symmetric situation for ‘negative’ side of braid)
- Reconnection ‘unbraids’ magnetic field





Magnetic reconnection?

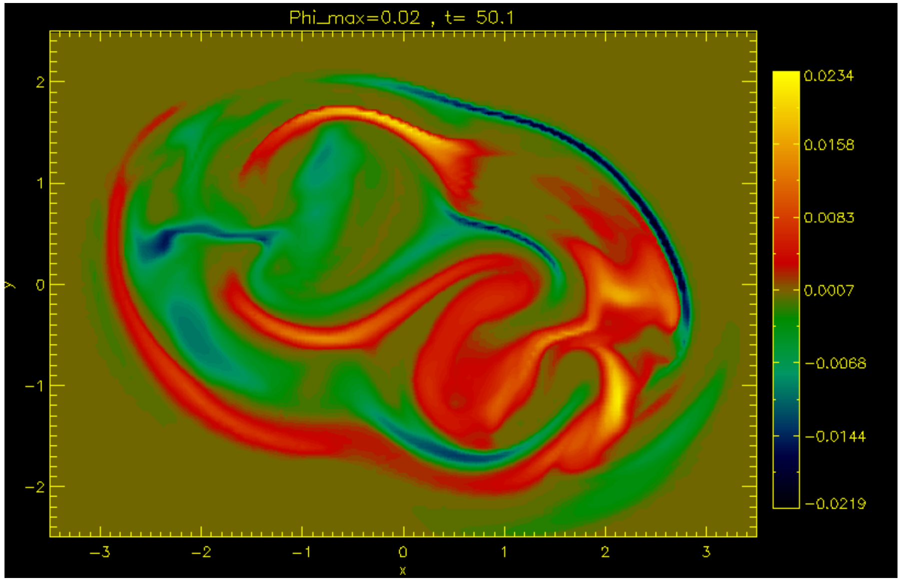
- Location of rec highly fragmented
- Level of fragmentation increases as eta decreased
- ‘Turbulent’ rec
- Note: no nulls, separators, etc!

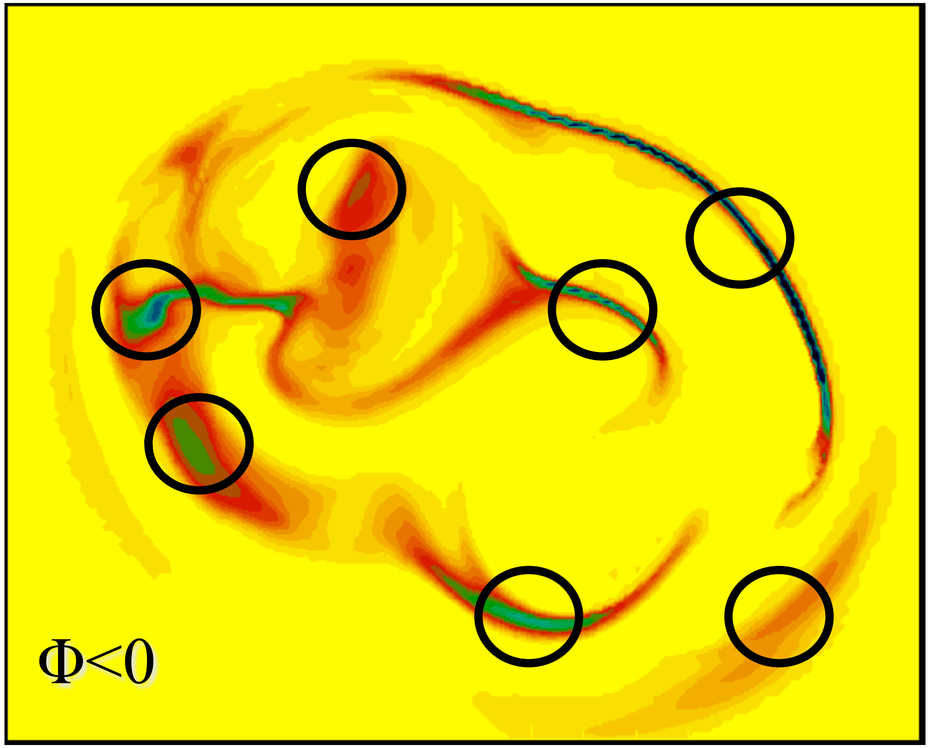


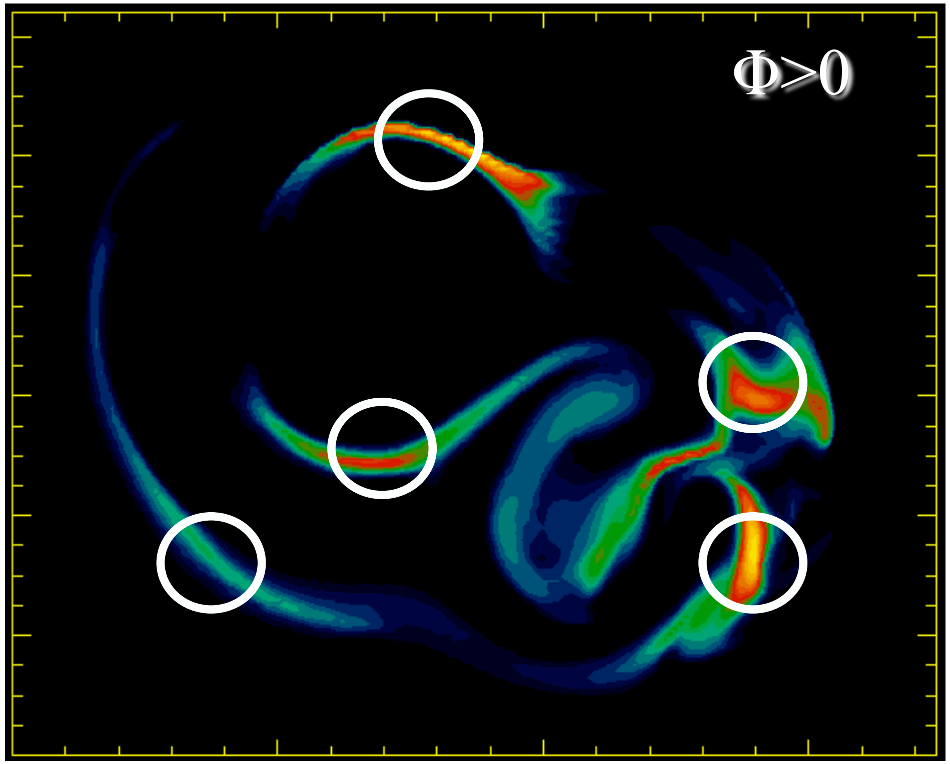
- Must measure rate in each regi $\int E_{||} ds$ arately
- Rec rate given by max value of along any B-line threading diffusion region

e.g. t=50

colourscale: $$\Phi = \int_{s:\ z=0}^{s:\ z=24} E_{\parallel} ds$$

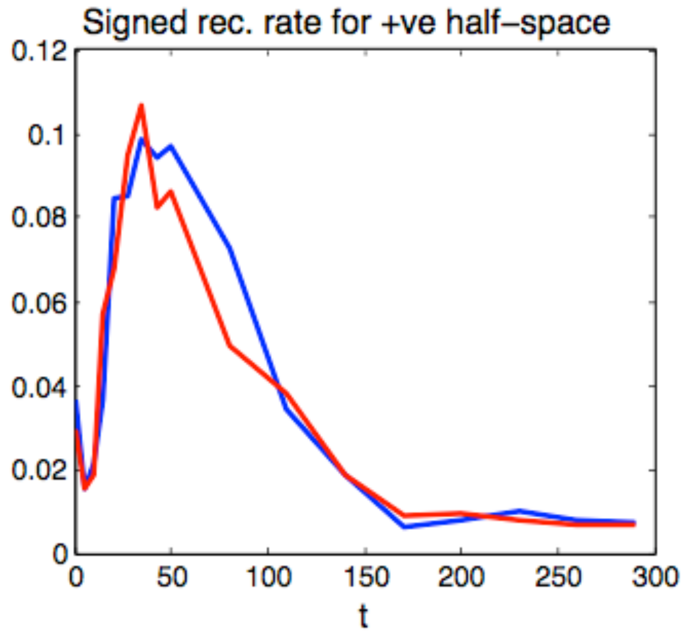






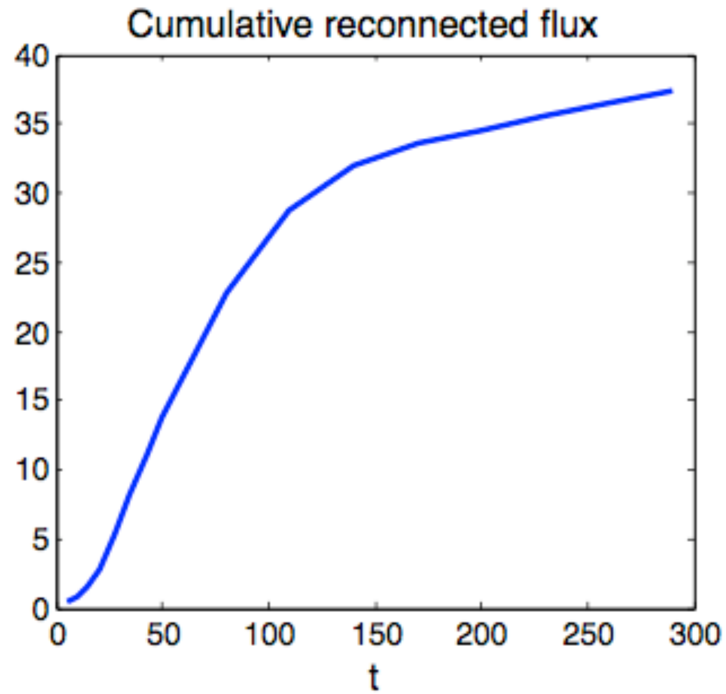
Reconnection rate

- Plot: signed rec rate for z>0: $\Sigma\Phi_{max}$, $\Sigma\Phi_{min}$
- Rec rate +ve/-ve approx equal
- Rec rate increase a result of splitting into multiple rec regions



t	0	10	20	35	50	80	110	170	230	290
$\Sigma\|\Phi_{max}\|$	0.066	0.040	0.153	0.206	0.183	0.122	0.072	0.015	0.018	0.014
$\|\Phi_{max}\|$	0.036	0.022	0.036	0.027	0.023	0.016	0.013	0.007	0.007	0.006
n	2	2	6	13	12	13	10	5	2	2

Reconnected flux



- Total poloidal (xy) flux at t=0 : ≈30 units
- at t=300: ≈ 15.3 units

(note: confirms all 'twist' is not cancelled)

- Total reconnected flux ≈ 37.4 units

- Flux is 'recursively reconnected'
- (lower bound)

Key points

- Complex field line mapping is consistent with existence of (approx) force-free field with large-scale *J*
- Small scales in integrated quantities
- Instability leads to formation of *J* sheets
- *B* is elliptic in plane perp. to guide field
- Multiple rec of magnetic flux

(Wilmot-Smith et al., ApJ, ’09a,b; Pontin et al. ApJ ’09
MHD evolution: papers in preparation)

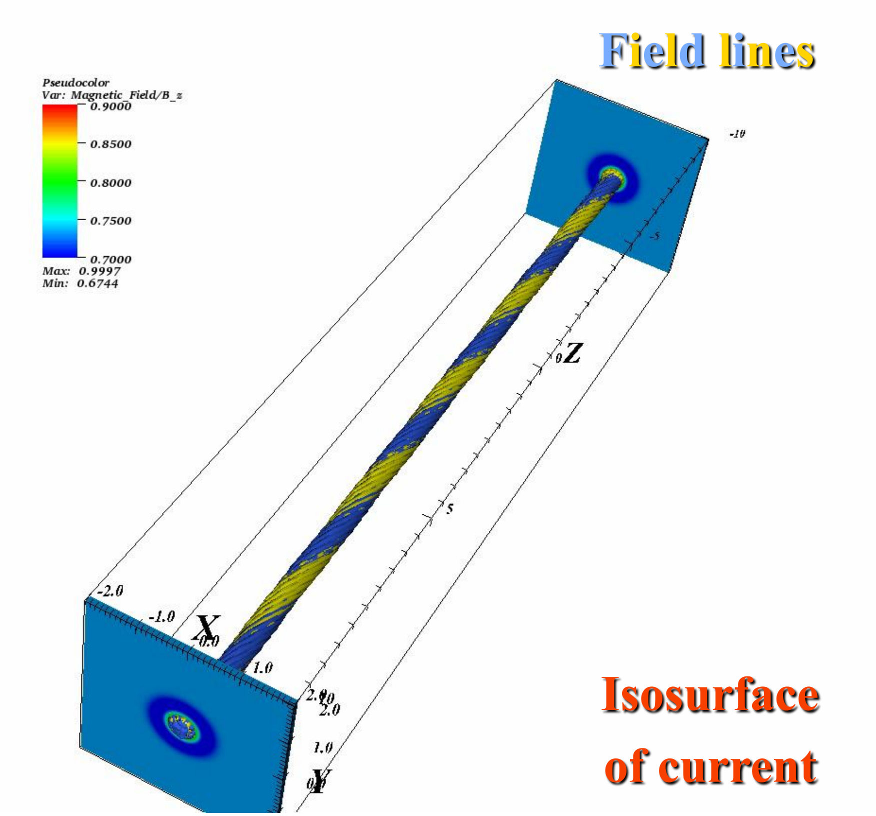
Following the theme: fragmentation of rec process in kink instability

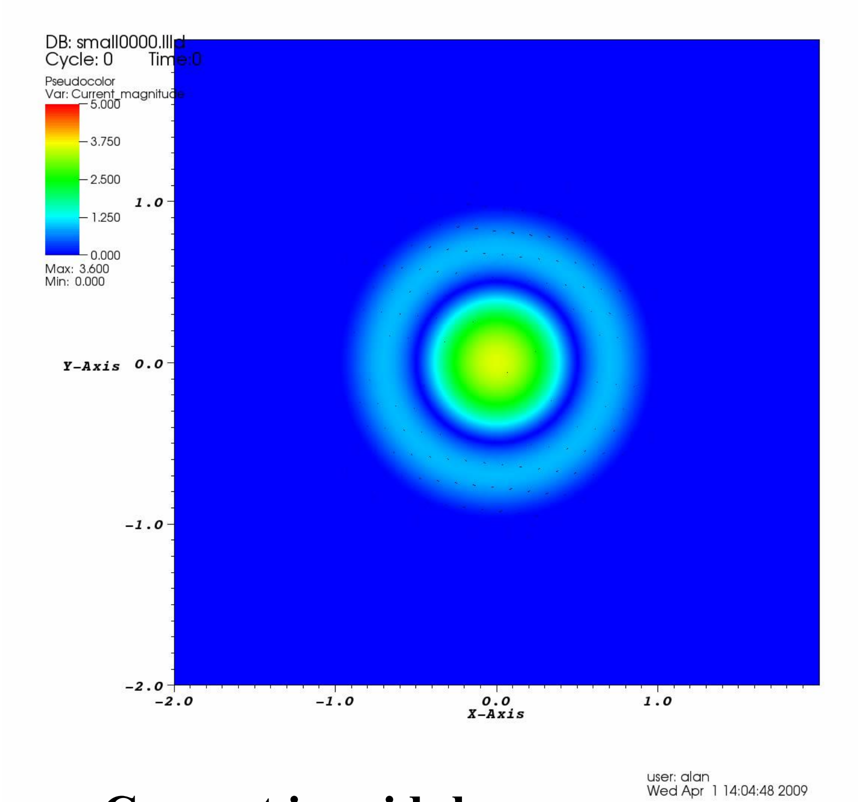
(Hood et al ‘09)

Fragmenting to Small-scales: Kink instability

(Hood et al, '09)

- Taylor Relaxation

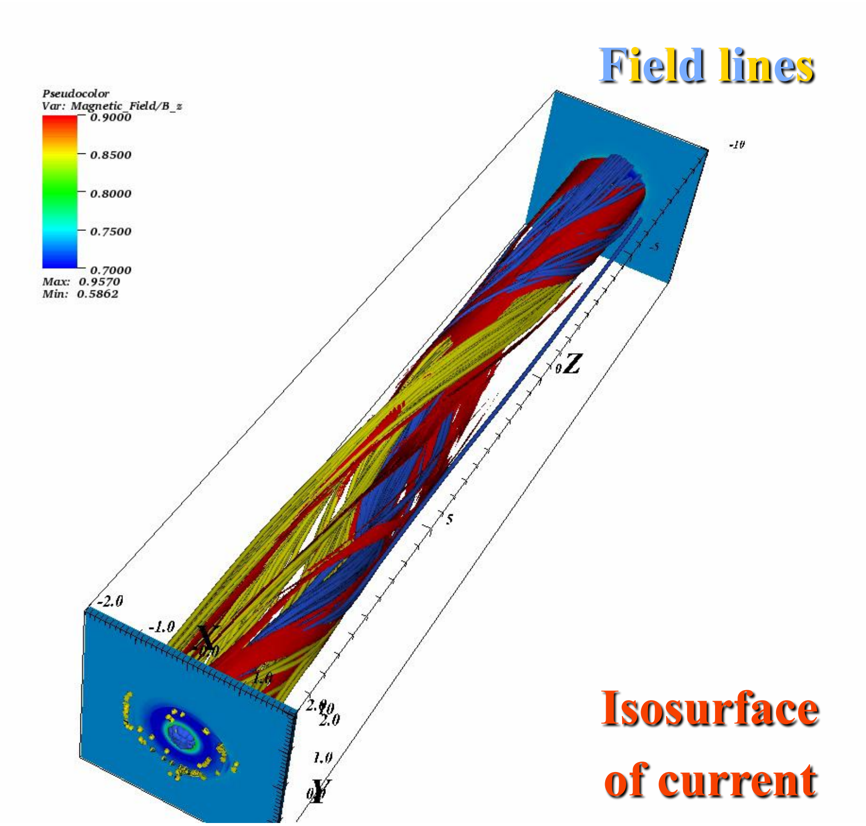


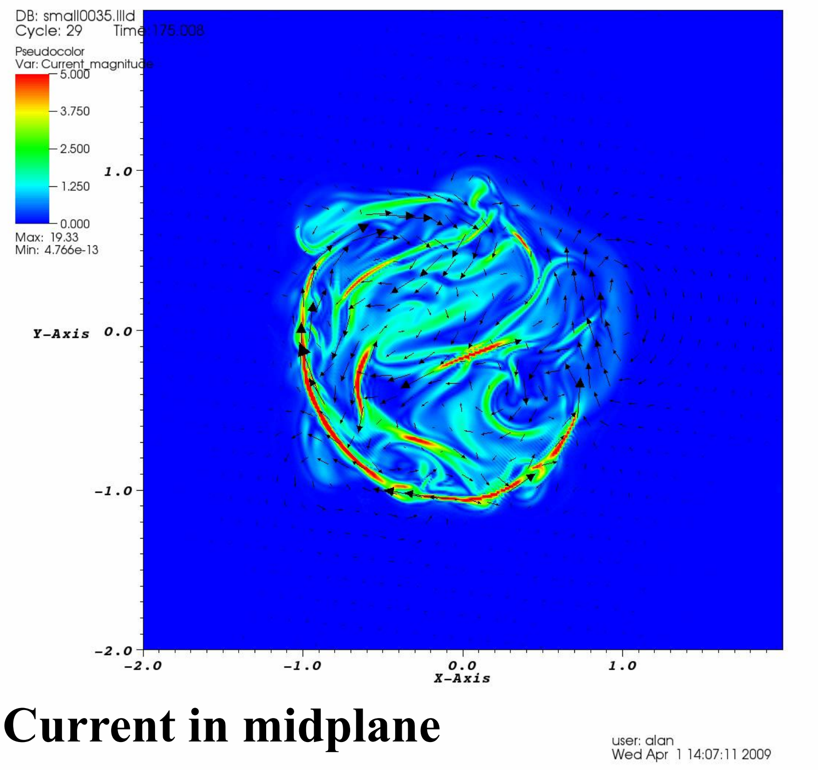


Current in midplane

Fragmenting to Small-scales: Kink instability

(Hood et al, '09)





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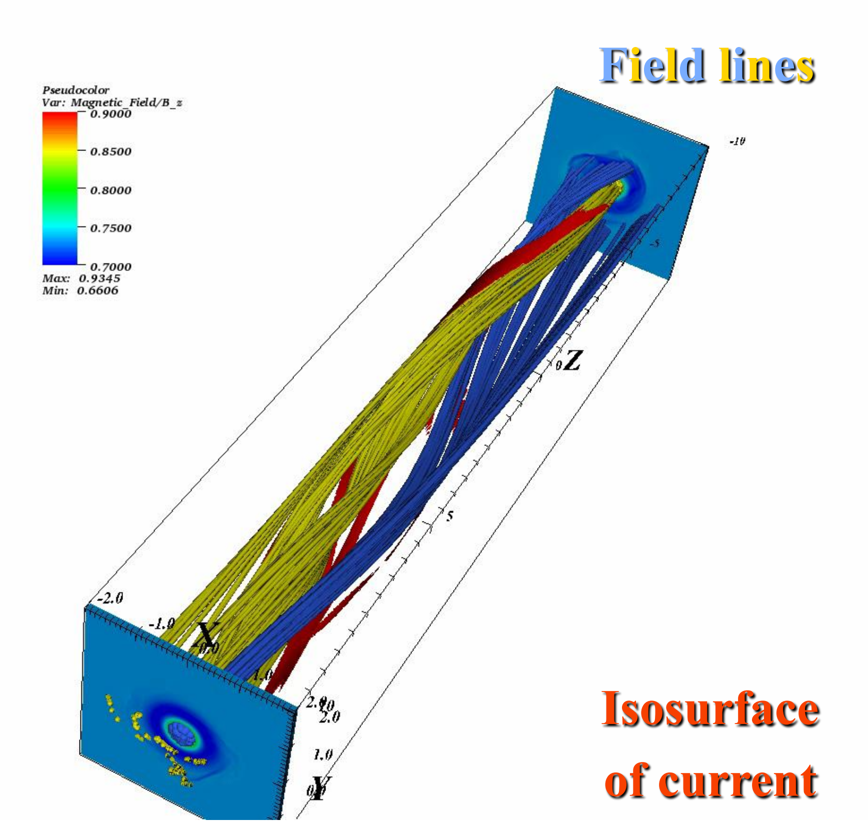
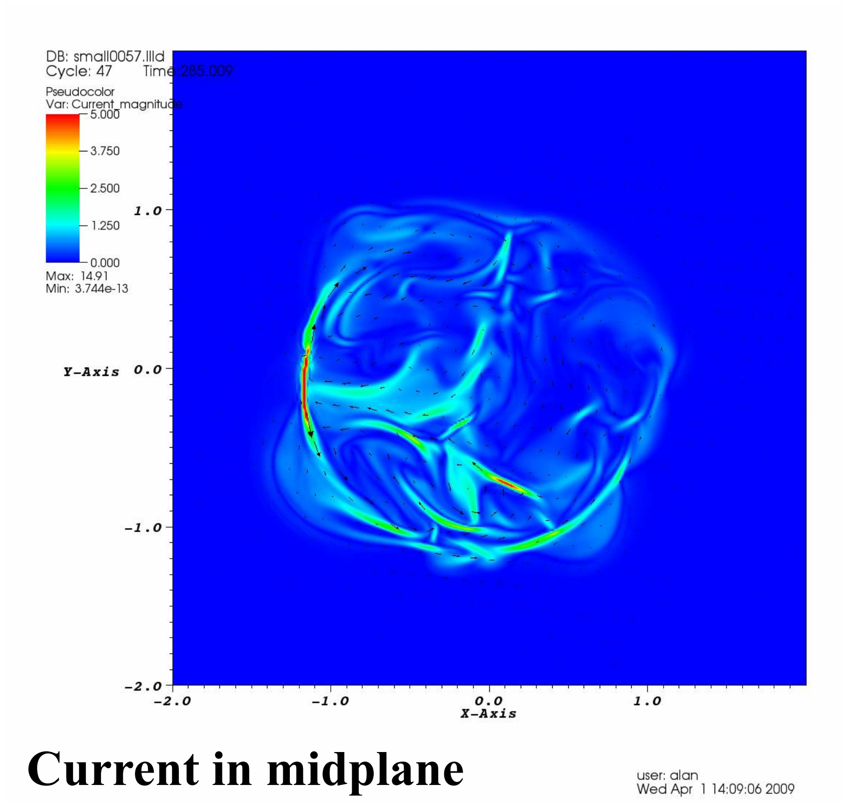




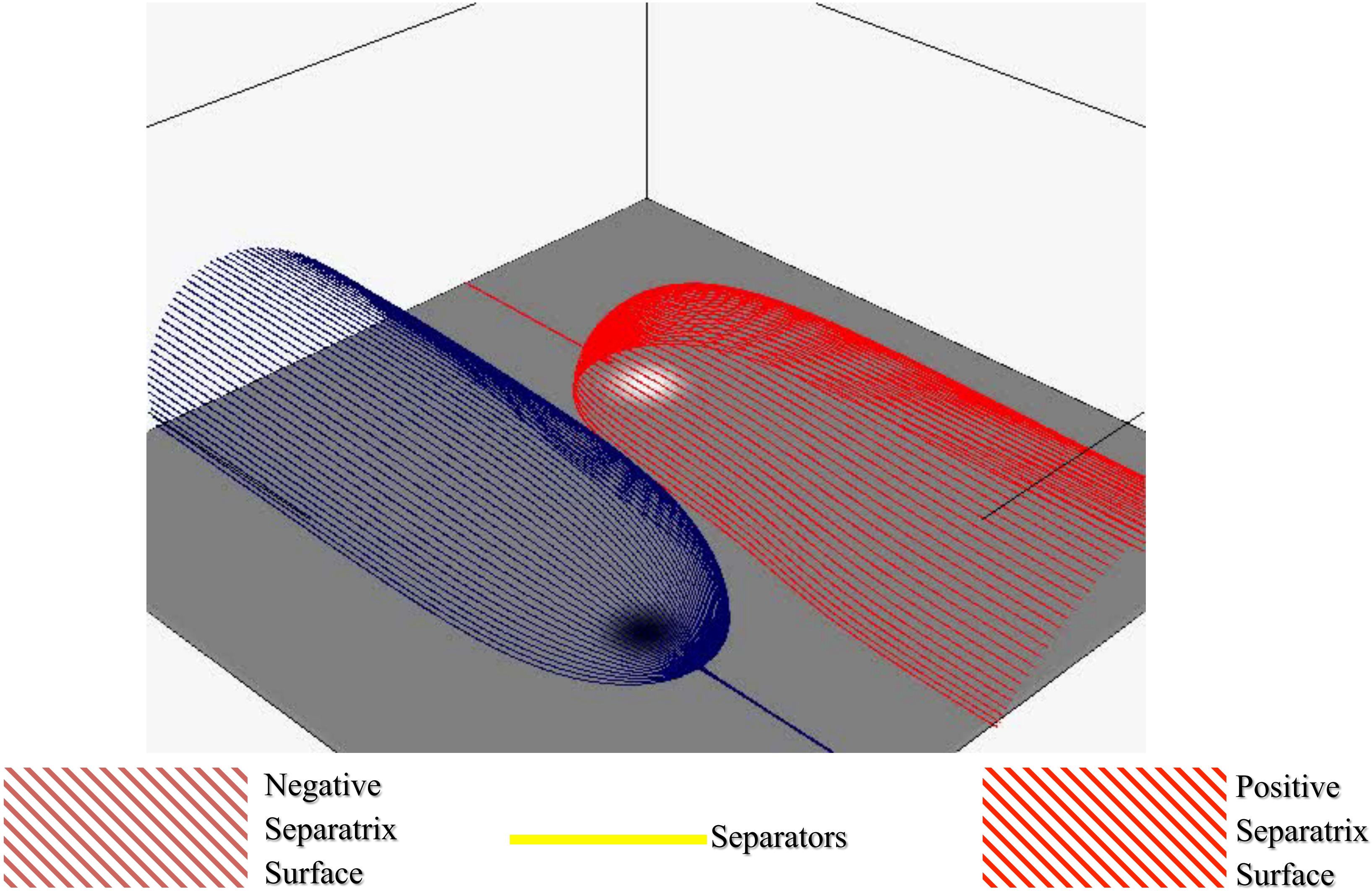
Following the theme: fragmentation of rec process and multiply-reconnected flux in ‘fly-by’

(Haynes et al., 2007; Parnell et al., 2008)

‘Fly-by’ of magnetic fragments

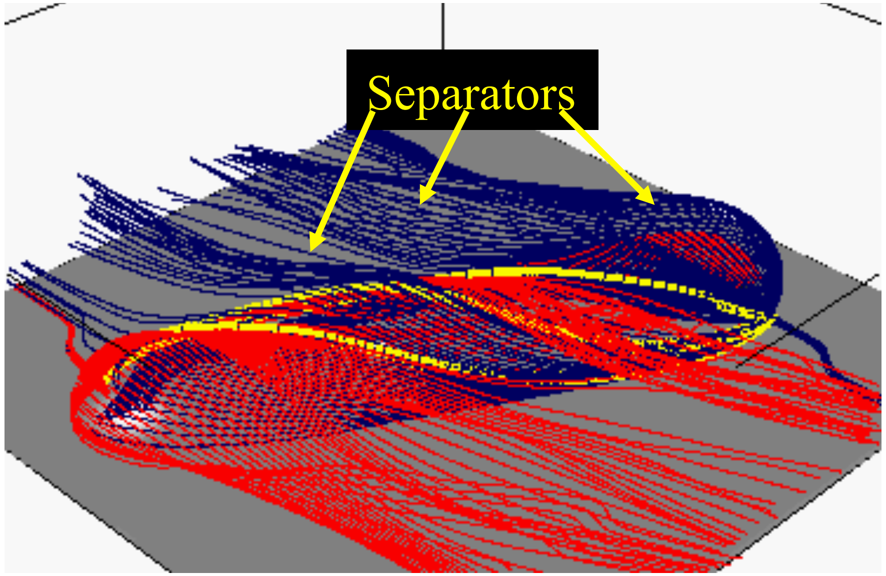
(Haynes et al., 2007; Parnell et al., 2008) .

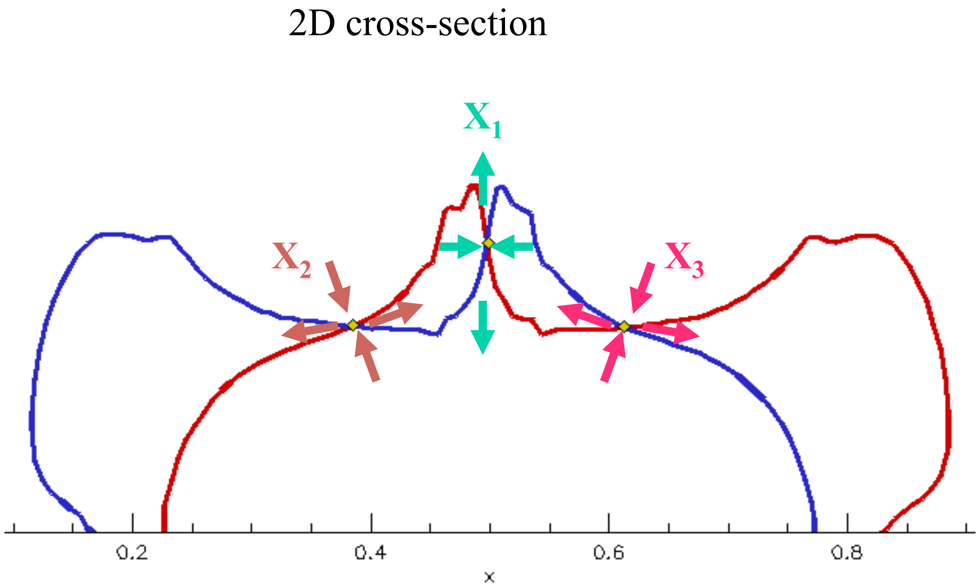
- 3D MHD Interaction: Evolution of magnetic skeleton



Multiply Reconnected Flux

- 3D MHD Interaction: Triple separator reconnection





Importance of topology:

- Topological structures can focus current
- Can identify recycling of flux via recursive reconnection

Multiply Reconnected Flux

- How much reconnection?
  - Potential field evolution:

    open $\longrightarrow$ closed $\longrightarrow$ reopened

    Total flux reconnected = R_T = $2\phi_0$ (ϕ_0 - source flux)

  - Resistive MHD evolution:

    open $\longrightarrow$ closed $\longrightarrow$ reopened

    > Recursively reconnected flux:

    Total flux reconnected = R_T = $3.6\phi_0$

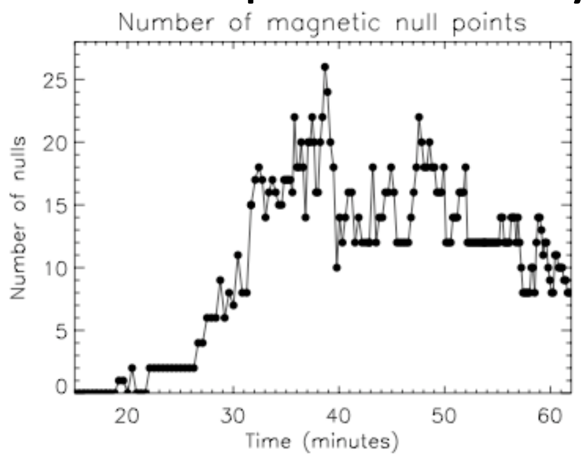
Complex topology of reconnection site in flux emergence

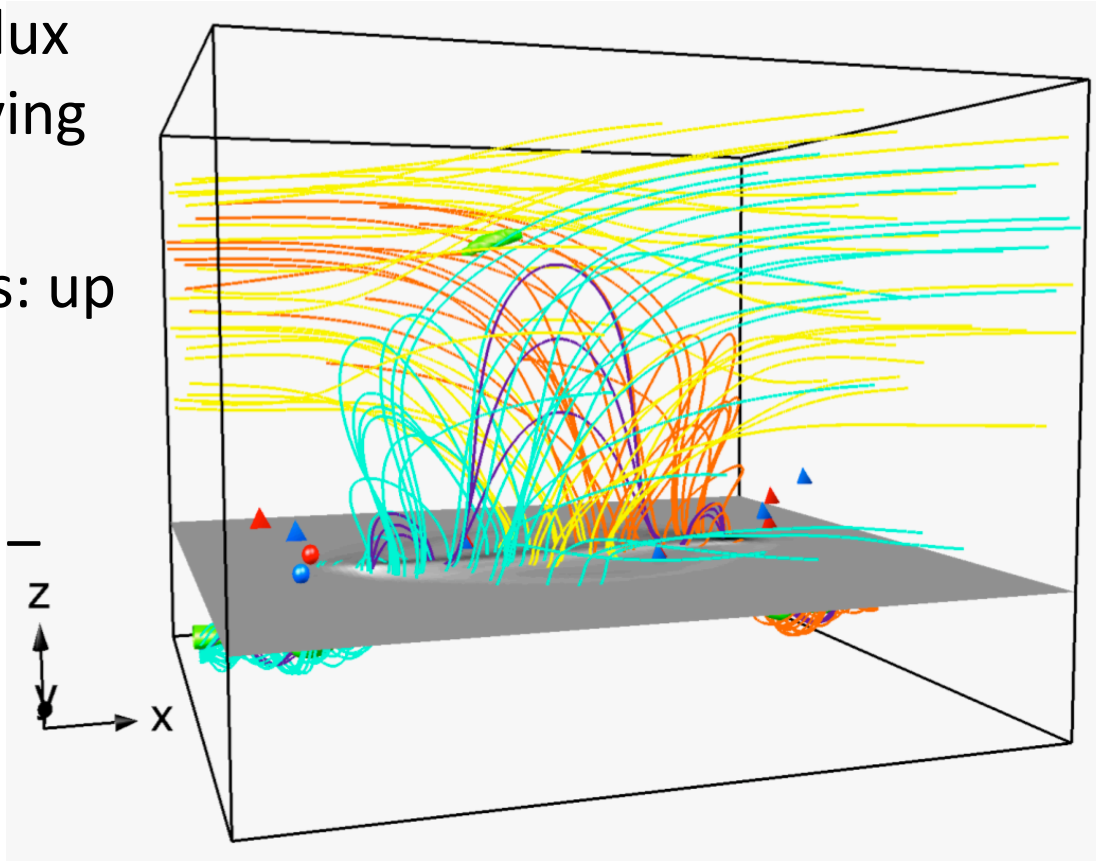
(MacLean et al., Sol Phys, in press.)

Nature of rec in flux emergence?

(MacLean et al., Sol Phys, in press.)

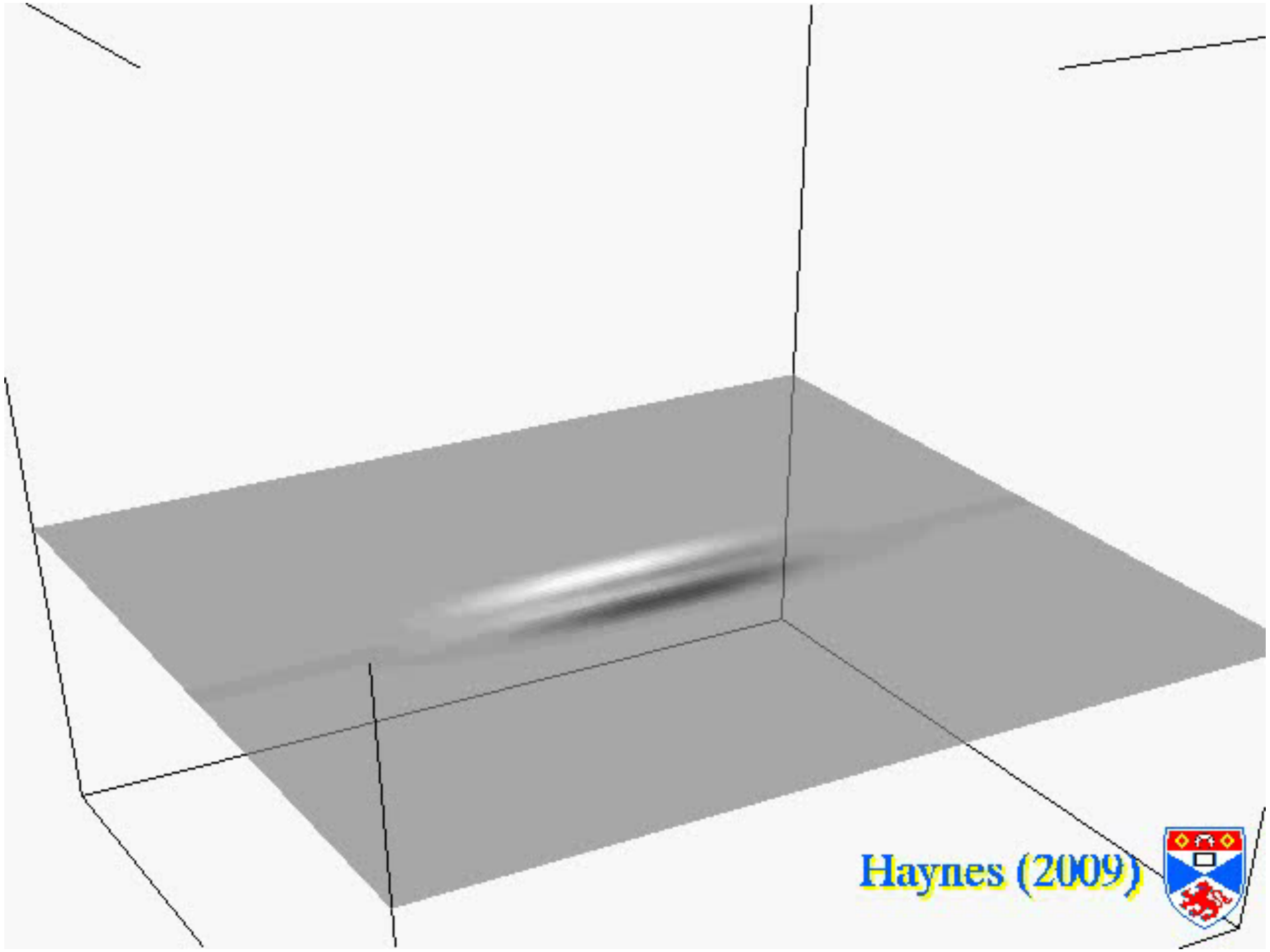
- Emergence of buoyant flux rope into uniform overlying field
- Clusters of nulls at flanks: up to 26 at any given time
- Nulls themselves not located in high J regions – but separators may be





- Highlights complexity and difficulty in interpretation for complex coronal *B*!

Importance of separators?



- Highly complex evolution of topology

In Summary

Rec (3D) in the corona

- Many different rec modes in 3D
- Topology/geometry of B crucial in determining where J sheets form
- Depending on B structure at J sheet, different rec modes with different properties
  - 3D nulls (torisonal spine, torsional fan, spine-fan modes)
  - Separators (null-null lines)
  - B with no nulls but complex mapping/geometry: quasi-separatrix layers, braided fields, ...

Recurring themes

- Rec of field lines does <u>not</u> happen in simple ‘cut-and-paste’ fashion as in 2D X-point models

- Complexity of the magnetic field structure is even greater than expected
- Fragmentation of rec region: cascade to small scales
- Multiple reconnection of the same flux
  - More rec -> more heating, particle acceleration, etc.

- There is still much left to understand about rec in 3D!

Interpretation of rec observations: observables

- Some features of 2D rec do carry over to 3D, e.g.
  - fast outflow jets
  - Heating and energisation of plasma -> ribbons
  - Downflows associated with retracting (relaxing) loops
  - Acceleration of particles -> hard X-ray sources
- BUT REMEMBER(!):

  3D rec fundamentally different from 2D -> interpreting solar observations in terms of 2D models can be highly misleading!
- The above properties will vary between rec. modes.
- Many different 'modes' of 3D rec. Important to understand the nature of the rec to understand the nature of heating and implications for dynamics.

Thanks for listening!

"There is a theory which states that if anyone ever discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another theory which states that this has already happened"

Douglas Adams, The Restaurant at the End of the Universe

For copies of papers see: http://www.maths.dundee.ac.uk/~dpontin/publications.html

References

- Longcope, D. W., Brown, D. S., and Priest, E. R. (2003). On the distribution of magnetic null points above the solar photosphere. Phys. Plasmas, 10:3321–3334.
- Longcope, D. W. and Parnell, C. E. (2009). The Number of Magnetic Null Points in the Quiet Sun Corona. Solar Phys. 254:51-75.
- Régnier, S.; Parnell, C. E.; Haynes, A. L. (2008). A new view of quiet-Sun topology from Hinode/SOT. Astron. Astrophys., 484:L47-L50.
- Haynes, A. L.; Parnell, C. E. (2007). A trilinear method for finding null points in a three-dimensional vector space, Phys. Plasmas, 14:082107.
- Xiao, C. J. et al (2006). In situ evidence for the structure of the magnetic null in a 3D reconnection event in the earth's magnetotail. Nature Physics, 2:478–483.
- Xiao, C. J. et al (2007). Satellite observations of separator-line geometry of three-dimensional magnetic reconnection. Nature Physics, 3:609-613.
- Lapenta, G. and Brackbill, J. U. (2000). 3D reconnection due to oblique modes: a simulation of Harris current sheets. Non-lin. Proc. Geophys., 7:151-158.
- Lapenta, G. and Knoll, D. A. (2003). Reconnection in the solar corona: role of the Kelvin-Helmholtz instability. Solar Phys., 214:107-129.
- Fukao, S., Ugai, M., and Tsuda, T. (1975). Topological study of magnetic field near a neutral point. Rep. Ion. Sp. Res. Japan, 29:133–139.
- Parnell, C. E., Smith, J. M., Neukirch, T., and Priest, E. R. (1996). The structure of three-dimensional magnetic neutral points. Phys. plasmas, 3(3):759–770.
- Hornig, G. and Schindler, K. (1996). Magnetic topology and the problem of its invariant definition. Phys. Plasmas, 3:781–791.
- Pontin, D. I., Bhattacharjee, A., and Galsgaard, K. (2007). Current sheet formation and non-ideal behaviour at three-dimensional magnetic null points. Phys. Plasmas, 14:052106.
- Klapper, I., Rado, A., and Tabor, M. (1996). A lagrangian study of dynamics and singularity formation at magnetic null points in ideal three-dimensional magnetohydrodynamics. Phys. Plasmas, 3(11):4281– 4283.
- Parnell, C. E., Neukirch, T., Smith, J. M., and Priest, E. R. (1997). Structure and collapse of three-dimensional magnetic neutral points. Geophys. Astrophys. Fluid Dynamics, 84:245–271.

- Bulanov, S. V. and Sakai, J. (1997). Magnetic collapse in incompressible plasma flows. J. Phys. Soc. Jpn., 66(11):3477–3483.
- Mellor, C., Titov, V. S., and Priest, E. R. (2003). Linear collapse of spatially linear 3D potential null points. Geophys. Astrophys. Fluid Dynamics, 97(6):489–505.
- Pontin, D. I. and Craig, I. J. D. (2005). Current singularities at finitely compressible three-dimensional magnetic null points. Phys. Plasmas, 12:072112.
- Priest, E. R. and Titov, V. S. (1996). Magnetic reconnection at three-dimensional null points. Phil. Trans. R. Soc. Lond. A, 354:2951–2992.
- Pontin, D. I., Hornig, G., and Priest, E. R. (2004). Kinematic reconnection at a magnetic null point: Spine-aligned current. Geophys. Astrophys. Fluid Dynamics, 98:407–428.
- Pontin, D. I., Hornig, G., and Priest, E. R. (2005). Kinematic reconnection at a magnetic null point: Fan-aligned current. Geophys. Astrophys. Fluid Dynamics, 99:77–93.
- Rickard, G. J. and Titov, V. S. (1996). Current accumulation at a three-dimensional magnetic null. Astrophys. J., 472:840–852.
- Galsgaard, K., E. R. Priest, and V. S. Titov (2003), Numerical experiments on wave propagation towards a 3D null point due to rotational motions, J. Geophys. Res., 108(A1), 1042.
- Pontin, D. I. and Galsgaard, K. (2007). Current amplification and magnetic reconnection at a 3d null point. physical characteristics. J. Geophys. Res., 112:A03103.
- Priest, E. R. and Pontin, D. I. 3D null point reconnection regimes. To be published in Phys. Plasmas. (arXiv:0910.3043)
- Al-Hachami, A. K. and Pontin, D. I. Magnetic reconnection at 3D null points: effect of magnetic field asymmetry, submitted to Astron. Astrophys. (arXiv:0908.4507)
- Török, T.; Aulanier, G.; Schmieder, B.; Reeves, K. K.; Golub, L. (2009). Fan–Spine Topology Formation Through Two-Step Reconnection Driven by Twisted Flux Emergence. Astrophys. J. 704:485-495.
- Maclean, R. C.; Parnell, C. E.; Galsgaard, K. Is null-point reconnection important for solar flux emergence? to be published in Solar Phys. (arXiv:0910.0368)
- Masson, S.; Pariat, E.; Aulanier, G.; Schrijver, C. J. (2009). The Nature of Flare Ribbons in Coronal Null-Point Topology. Astrophys. J. 700:559-578.
- Guo, J. et al. Is the 3-D magnetic null point with a convective electric field an efficient particle accelerator? submitted to Astron. Astrophys.
- Pariat, E.; Antiochos, S. K.; DeVore, C. R. (2009). A model for solar polar jets. Astrophys. J., 691:61-74.

- Craig, I.J.D., Sneyd, A.D. , ApJ. 311 451 (1986)
- Parker, E.N., ApJ, **174**, 499 (1972).
- Wilmot-Smith, A. L., Hornig, G. and Pontin, D. I., Magnetic braiding and quasi-separatrix layers, *Astrophys. J.*, **704**, 1288-1295, (2009).
- Pontin, D. I., Hornig, G., Wilmot-Smith, A. L. and Craig, I. J. D., Lagrangian relaxation schemes for calculating force-free magnetic fields, and their limitations, *Astrophys. J.*, 700, 1449-1455, (2009).
- Wilmot-Smith, A. L., Hornig, G. and Pontin, D. I., Magnetic braiding and parallel electric fields, *Astrophys. J.*, **696**, 1339-1347, (2009)
- G. Hornig and E. R. Priest, Phys. Plasmas 10, 2712 (2003).
- I. De Moortel and K. Galsgaard, Astron. Astrophys. 451:1101 (2006).
- I. De Moortel and K. Galsgaard, Astron. Astrophys. 459:627 (2006).
- Wilmot-Smith, A.W. and Priest, E.R., Flux tube disconnection: An example of three-dimensional reconnection, Phys. Plasmas, 14:102903 (2007)
- Hood, A. W.; Browning, P. K.; van der Linden, R. A. M., Coronal heating by magnetic reconnection in loops with zero net current, A&A, 516:913 (2009)
- Haynes, A.L., Parnell, C. E.; Galsgaard, K. and Priest, E.R., Magnetohydrodynamic evolution of magnetic skeletons, Proc. Roy. Soc. A., 463:1097-1115 (2007).
- Parnell, C. E.; Haynes, A. L.; Galsgaard, K., Recursive reconnection and magnetic skeletons, ApJ, 675:1656 (2008).