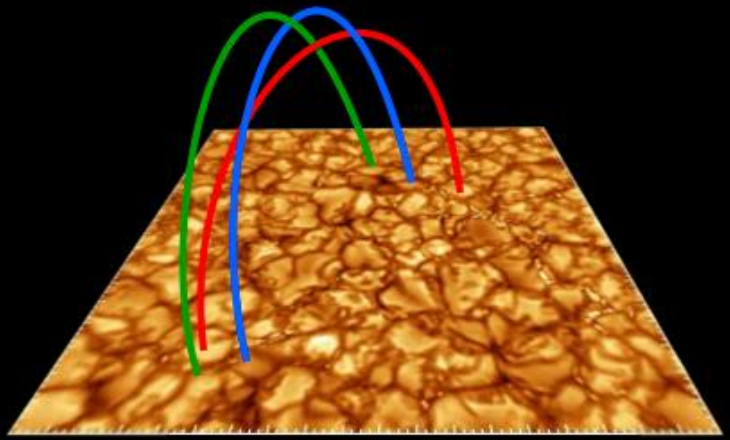
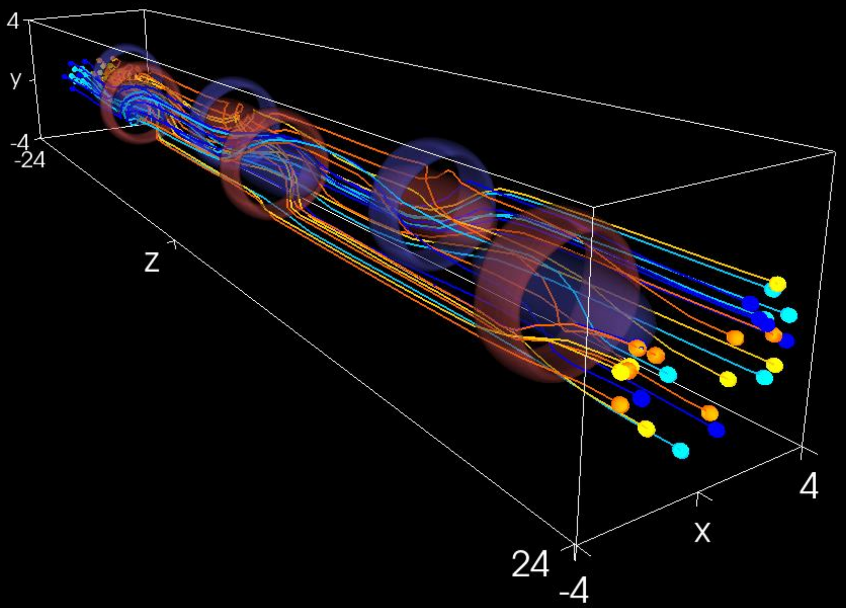
Heating of braided coronal loops by turbulent 3D reconnection





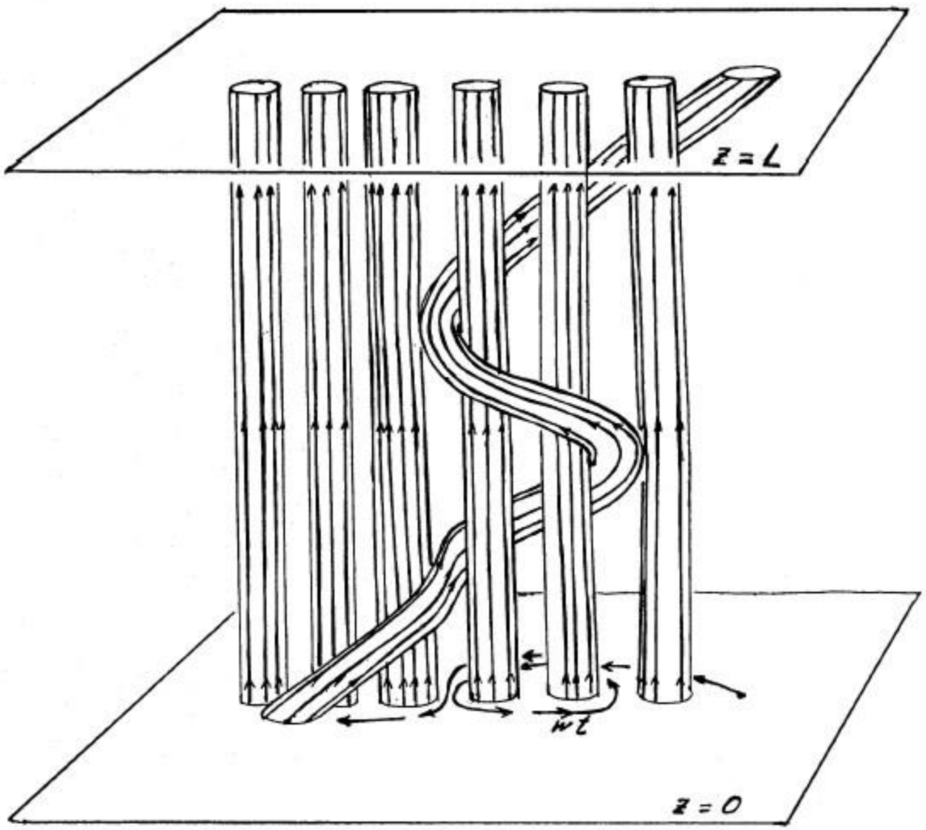
Alexander Russell

Mathematics, University of Dundee

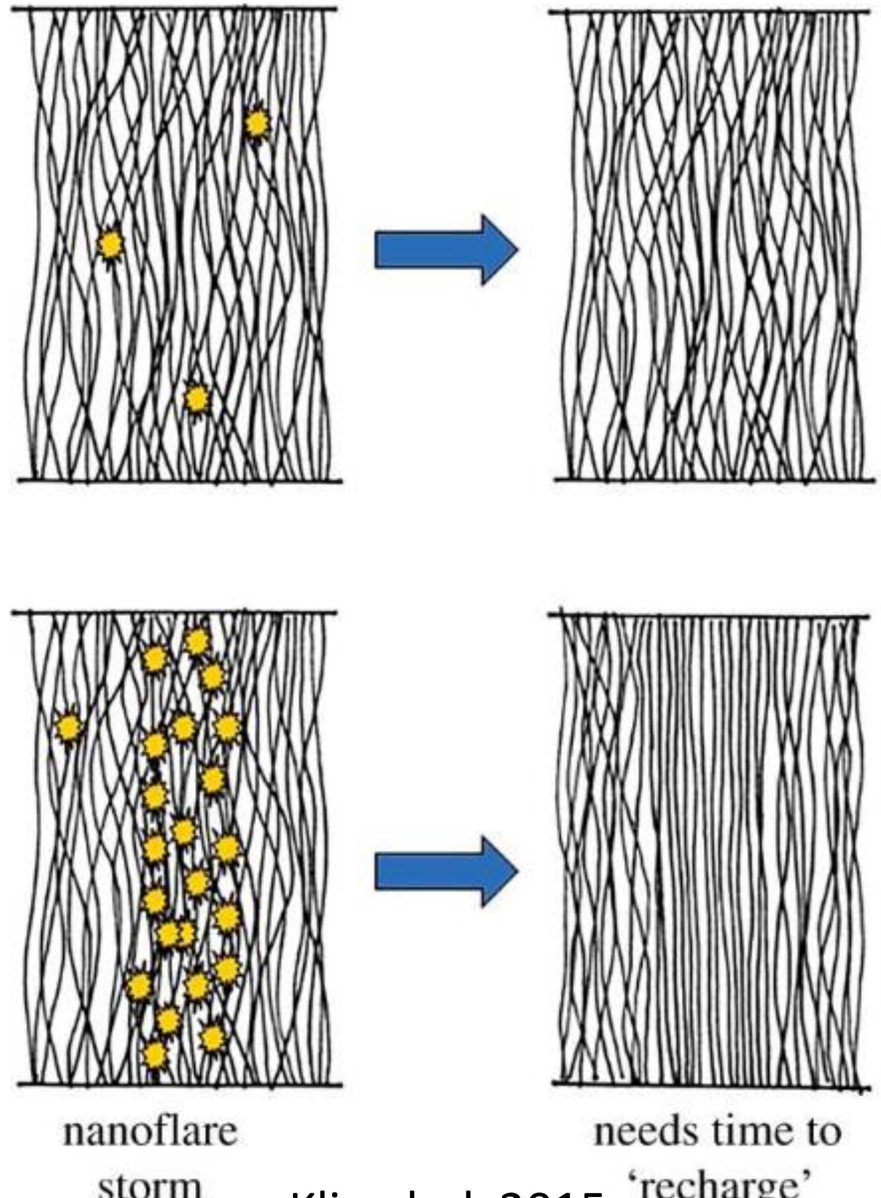
with

Gunnar Hornig (Dundee) and **Anthony Yeates** (Durham)

Braiding? Reconnection?

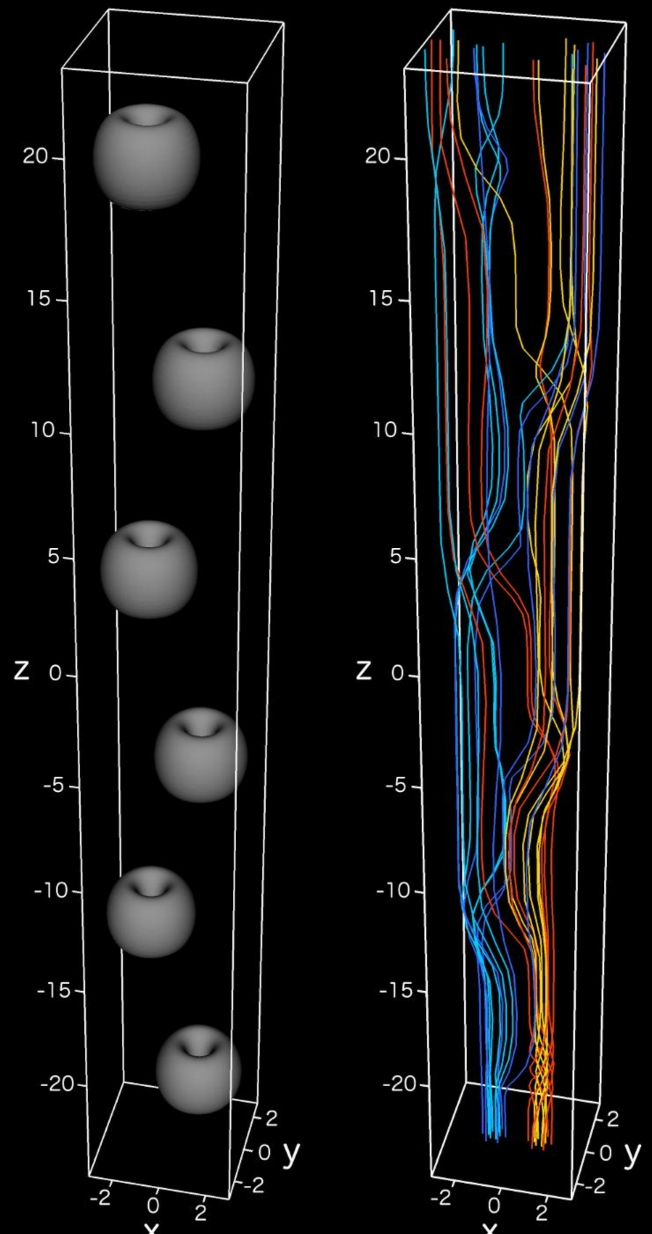


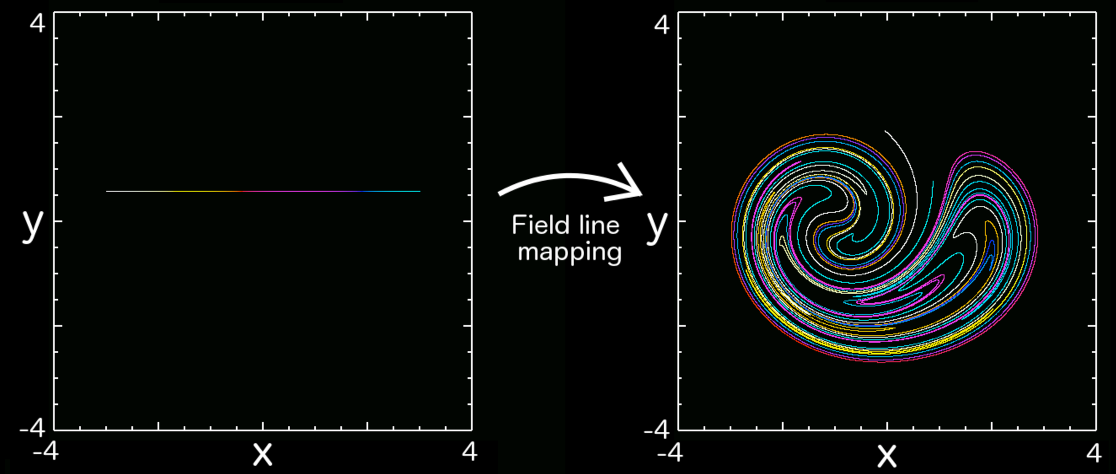
Parker 1983



Klimchuk 2015

Complexity in the field line mapping



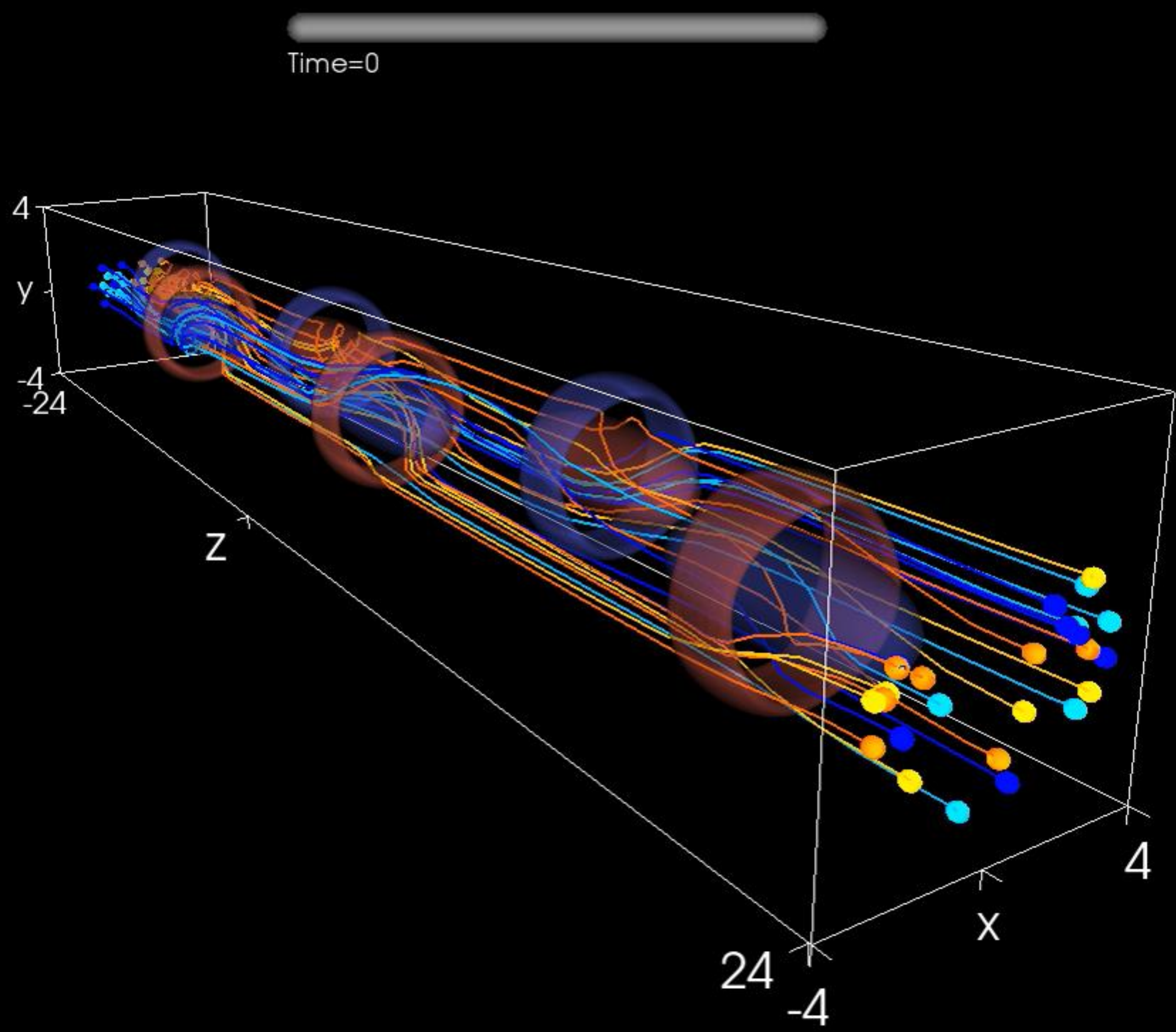


Consequences

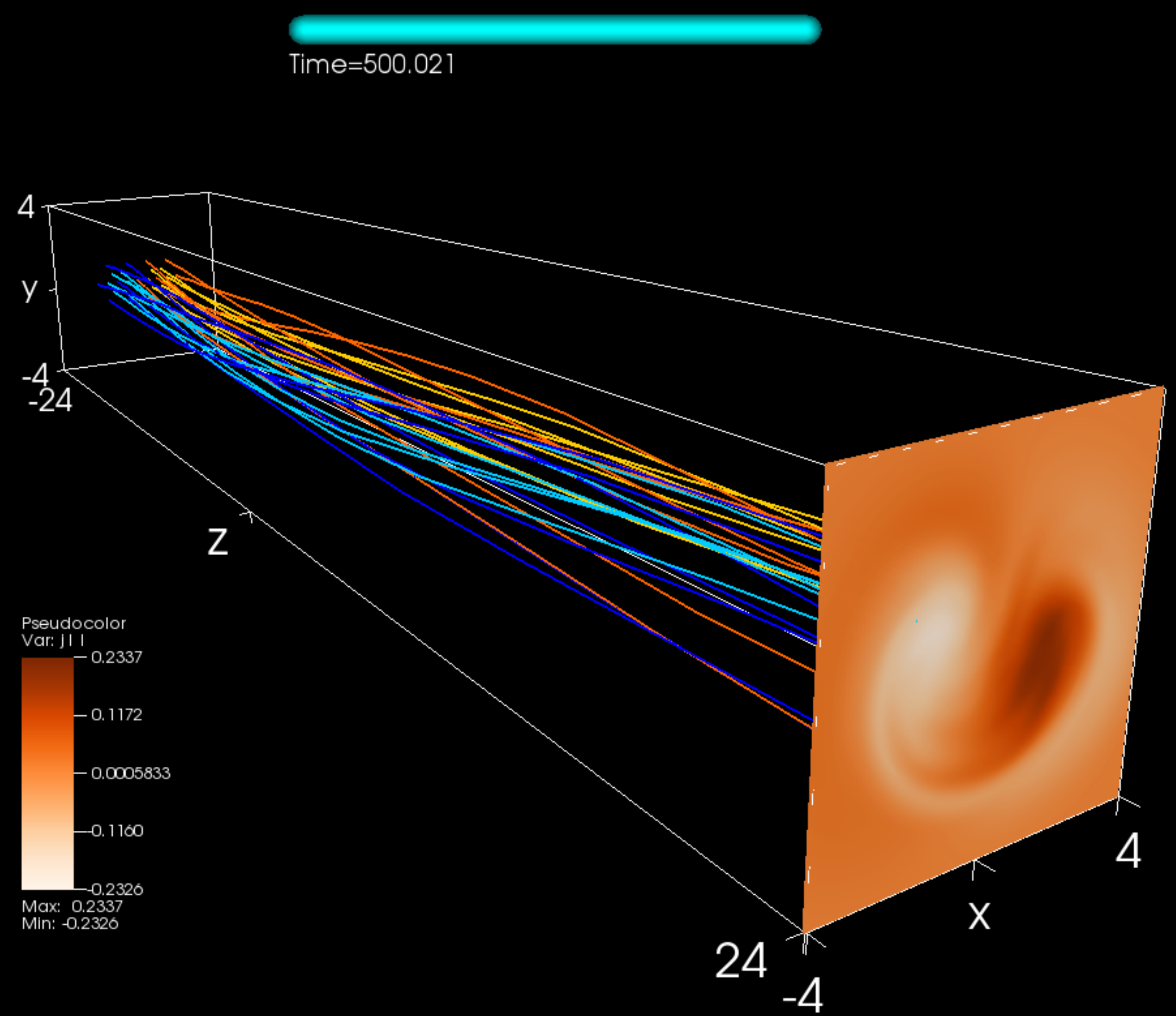
- Supercharged phase-mixing.
- 3D finite-B reconnection, from *voltage gradients*.
- Dynamics, topology, waves and reconnection are inseparable.

Also see van Ballegooijen 1988, Wilmot-Smith et al. 2009, Yeates et al. 2012, and Pontin & Hornig 2015.

Turbulent 3D reconnection



Robust end state

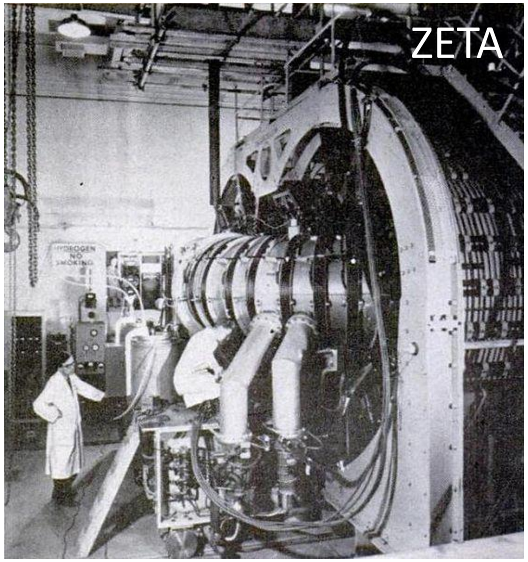


Taylor relaxation

- Taylor 1974 (also see 1986 and 2000 papers):

  “Some departure from perfect conductivity will bring about relaxation of the topological constraints … However [total helicity] will be almost unchanged.”

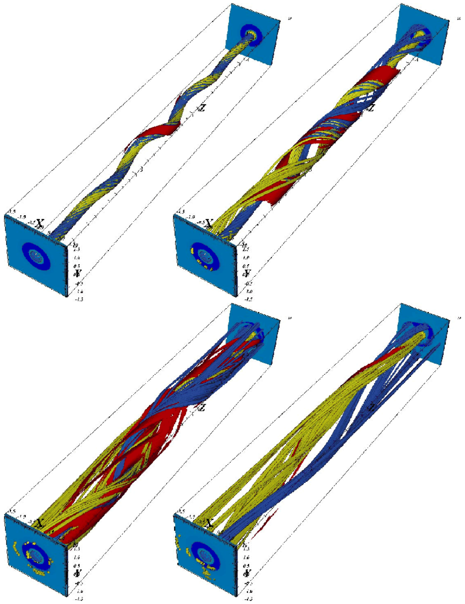
  “The final state of relaxation, therefore, will now be the state of minimum energy subject **only to the single invariant**.”



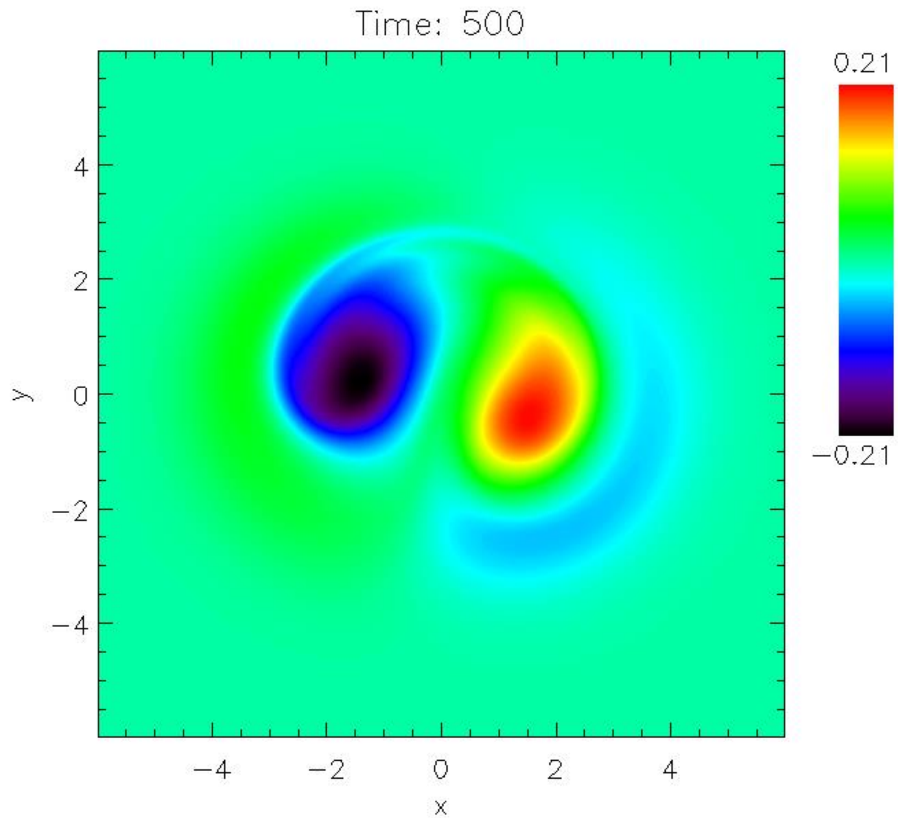
- Lowest energy $\mathbf{B}$ with a given total helicity is a linear force free field (Woltjer 1958):

  $\mathbf{J} = \lambda\mathbf{B}$ where λ is constant everywhere

- λ determined from the helicity.
- For application to twisted loops in the corona see Bareford, Hood & Browning 2013 and refs.



Beyond Taylor relaxation



$$\lambda = \left\langle \frac{\mathbf{j} \cdot \mathbf{B}}{B^2} \right\rangle$$

- Our braid relaxes to smooth field, following more reconnection than required to reach Taylor state (Pontin et al. 2011, A&A).
- But, L.F.F.F. would be uniform **B**. Don't get the Taylor state!
- Helicity has been conserved but there are additional constraints.

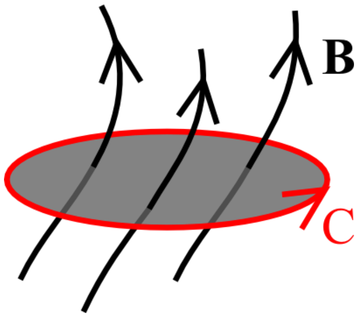
Field line helicity

In ideal MHD, every field line has its own helicity invariant:

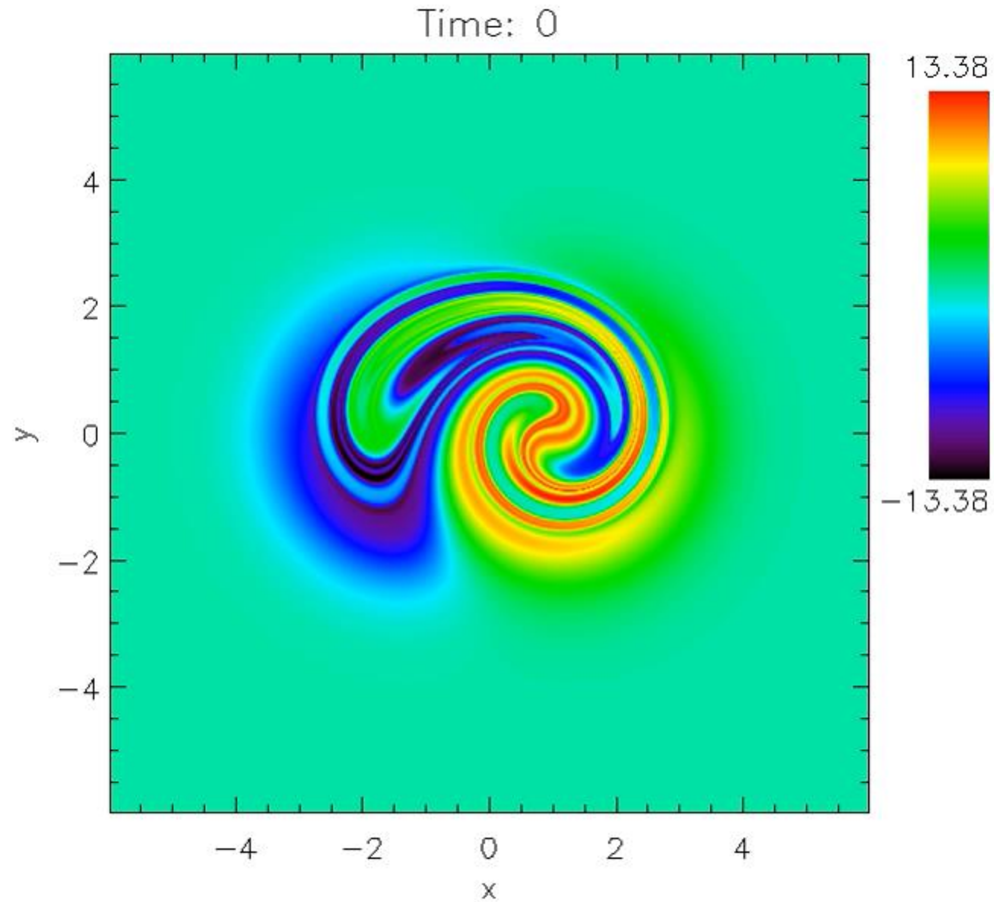
$$\mathcal{A} = \int_F \mathbf{A} \cdot d\mathbf{l}$$

where $\mathbf{A}$ is the vector potential:

$$\mathbf{B} = \nabla \times \mathbf{A}.$$



$$\int_C \mathbf{A} \cdot \mathrm{d}\mathbf{l} = \int_S \mathbf{B} \cdot \mathrm{d}\mathbf{S}$$



Measures average winding of magnetic flux around the field line of interest (Berger 1988, Prior & Yeates 2014).

Distinguishes between fields with same total helicity (Yeates & Hornig 2014).

Dominant evolution in complex fields

- We have an evolution equation for $\mathcal{A}$ (Russell, Yeates & Hornig, PoP, 2015)
- Simplified Eulerian form:

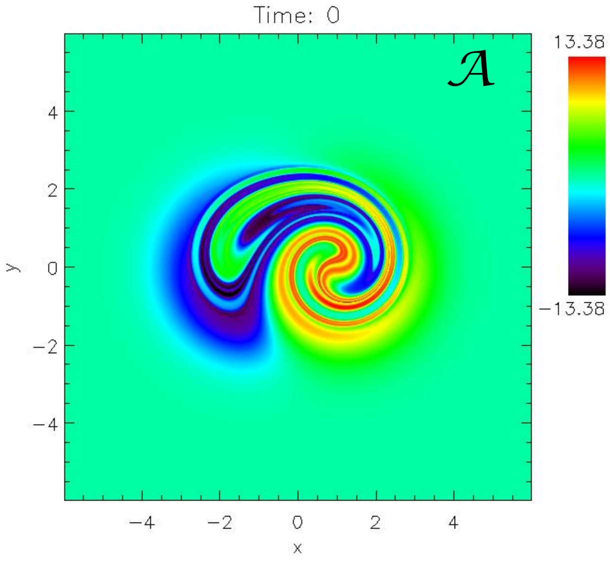
$$\frac{\partial \mathcal{A}}{\partial t} = -\mathbf{w} \cdot \nabla \mathcal{A} + [\mathbf{w} \cdot \mathbf{A}]_{\text{base}}^{\text{top}} - \Delta\psi - \Delta\phi$$

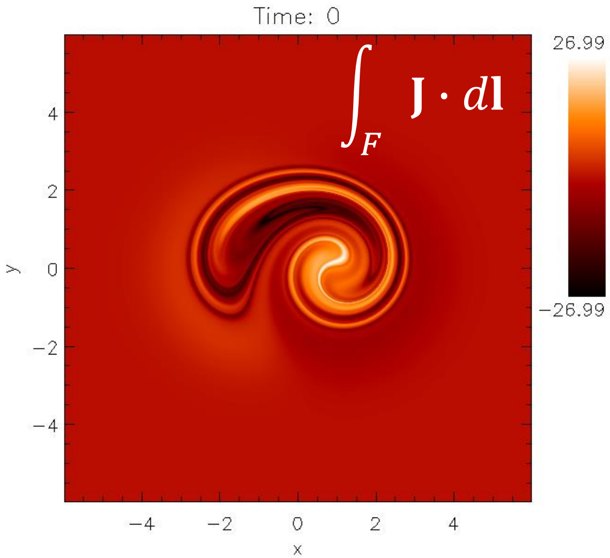
- Two length scales:
  - L, global scale of system.
  - l, perpendicular scale of quantities integrated through domain.
  - $l \ll L$ for complex field mappings.
- Scaling of terms:

$$\mathbf{w} \times \mathbf{B} = \nabla\psi - \mathbf{E} \;\; \Rightarrow \; w \sim (L/l)(\psi/A)$$

$$\mathbf{w} \cdot \mathbf{A} \sim (L/l)\psi$$

$$\mathbf{w} \cdot \nabla \mathcal{A} \sim (L/l)^2\psi$$



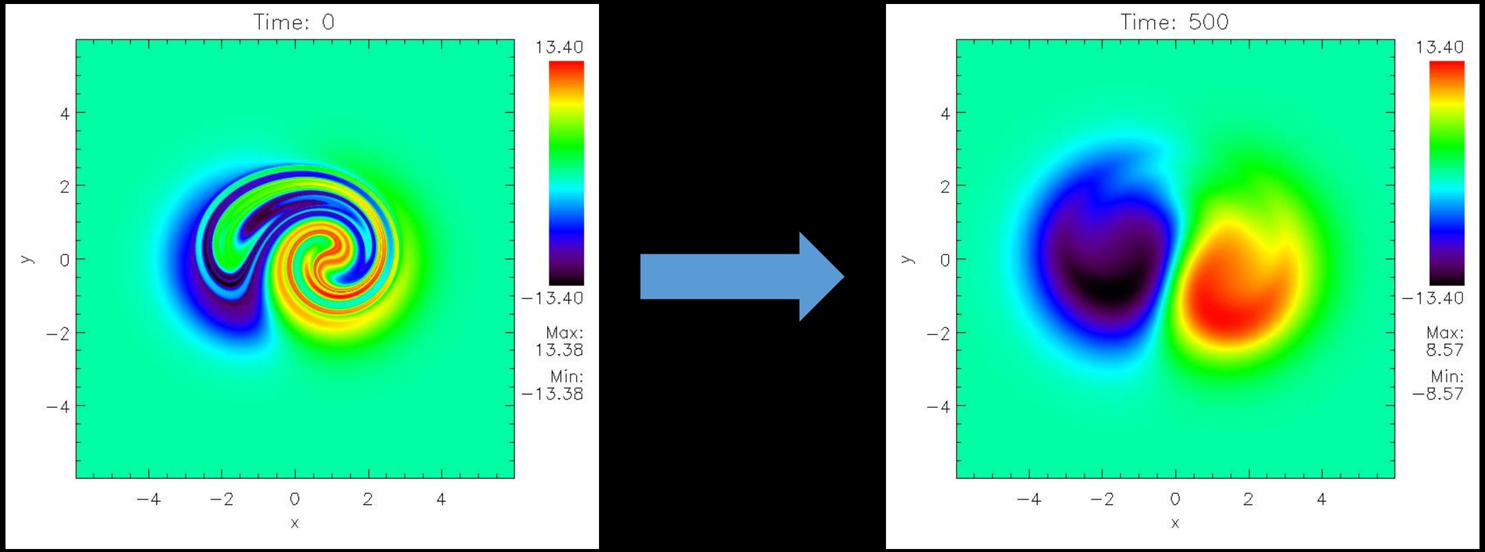


Dominant behaviour is advection

New relaxation hypothesis

The magnetic field relaxes to the lowest energy state consistent with rearrangement of field line helicity.

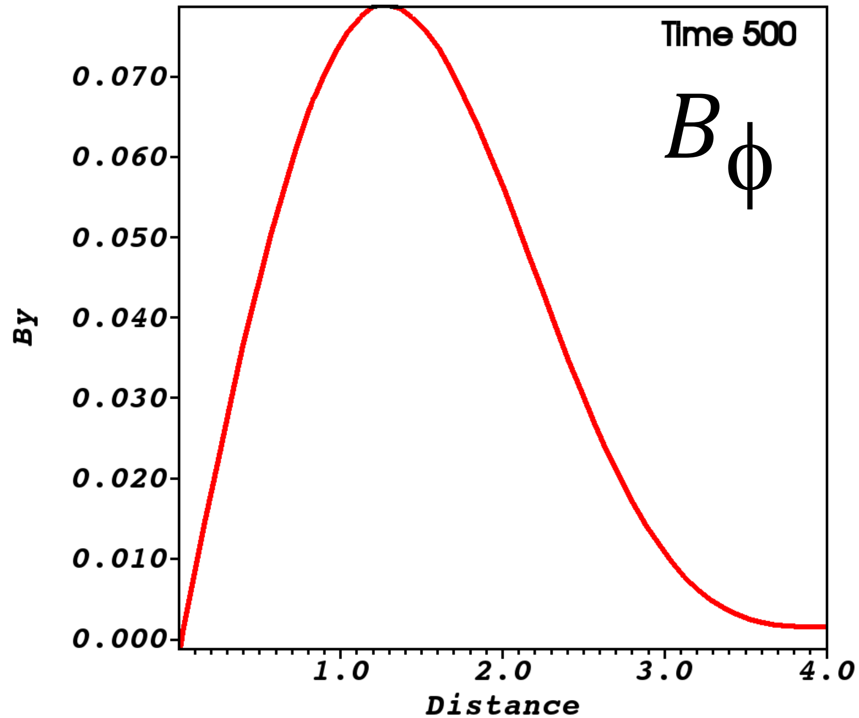
To first order, the magnetic fluxes of field line helicities are preserved. Second order effects come from the work-like $\mathbf{w} \cdot \mathbf{A}$ term and seem to reduce the extremes and make them more uniform.

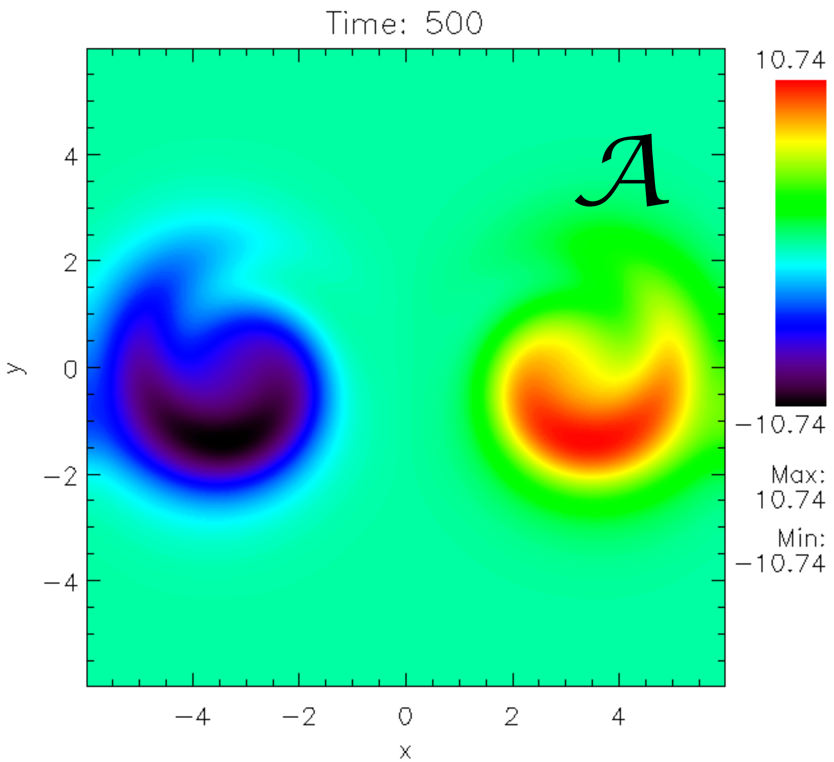


Predictive ability

- Two tubes expected from the topological degree (Yeates et al. 2015).
- Periodic end boundaries lead to two cylinder symmetric flux tubes.

MHD relaxation

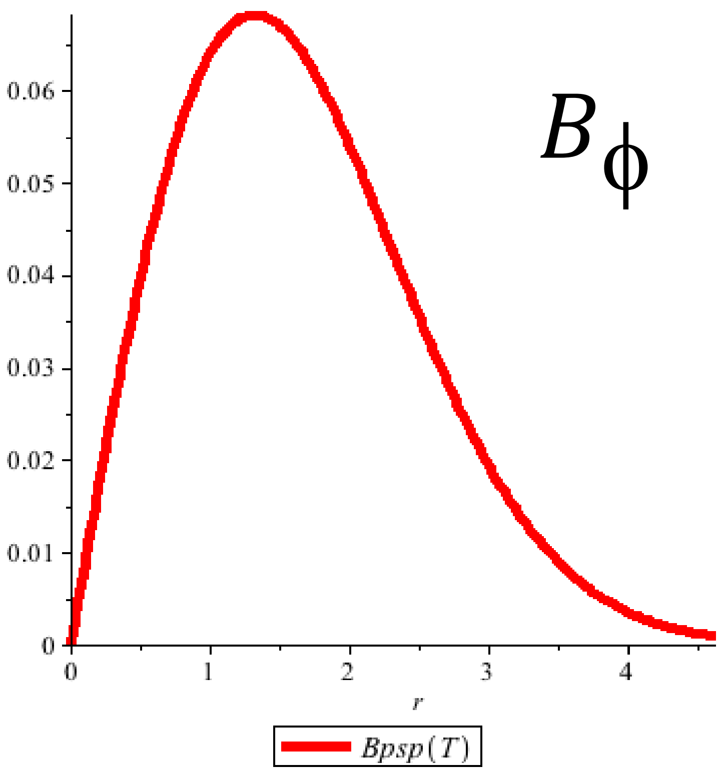


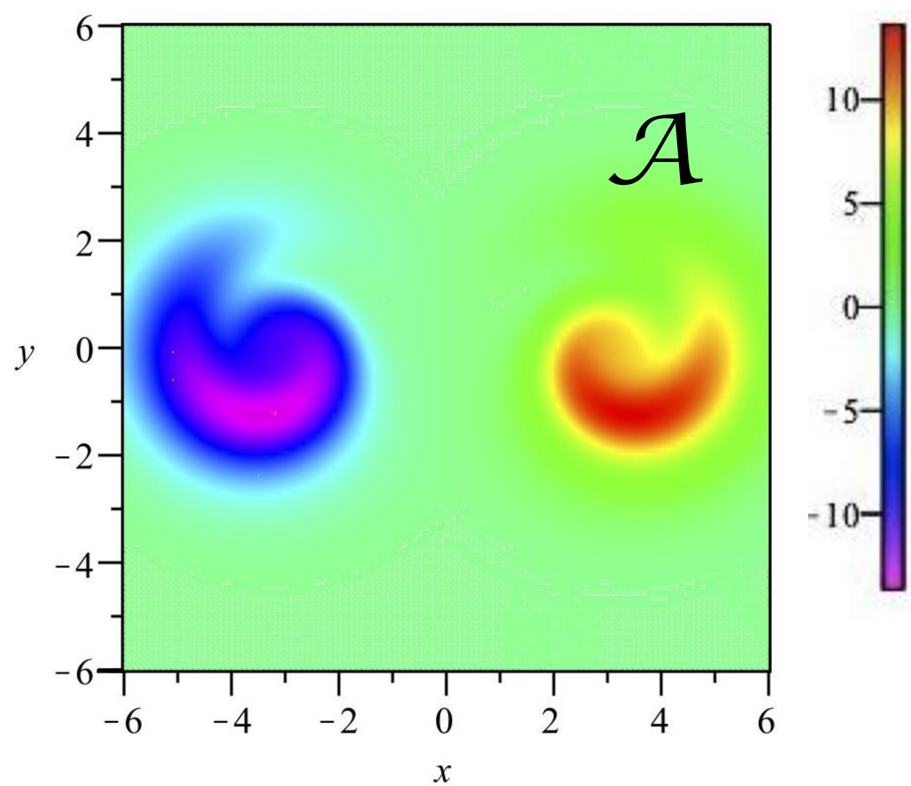


Predictive ability

- Two tubes expected from the topological degree (Yeates et al. 2015).
- Rearrange initial $\mathcal{A}$ into two tubes, then solve for steady state **B**:

Predicted





Summary

- Braiding's secret ingredient: extremely rapid growth of complexity & reduction of scales with composition of braiding.
- Reconnection: fully 3D, finite-B, typically turbulent.
- Surviving **B** & energy released determined by energy minimisation under fundamental constraints (relaxation).
- Progress by considering *field line helicity*, $\mathcal{A}$. To 1st approx, relaxation rearranges $\mathcal{A}$ while preserving its distribution.

http://www.maths.dundee.ac.uk/mhd/pubs.shtml

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Fully-funded STFC studentship available for PhD.

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