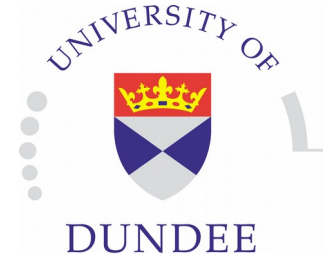
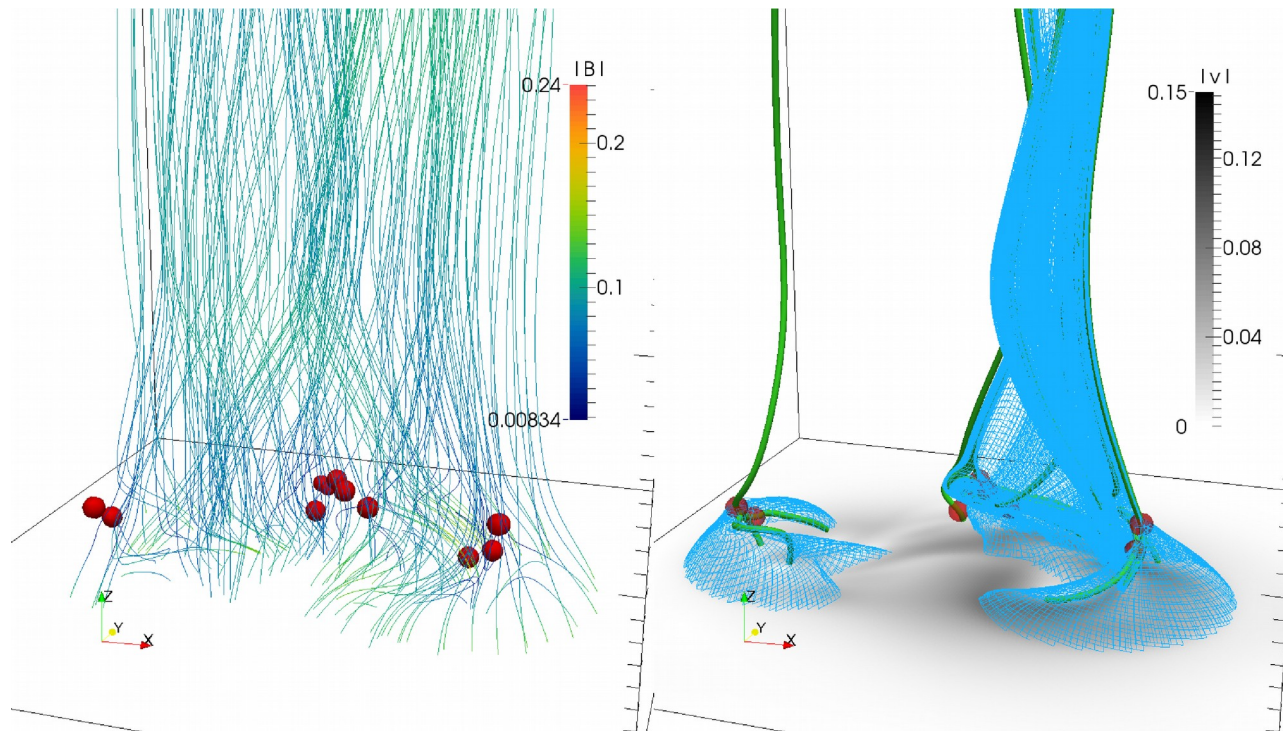


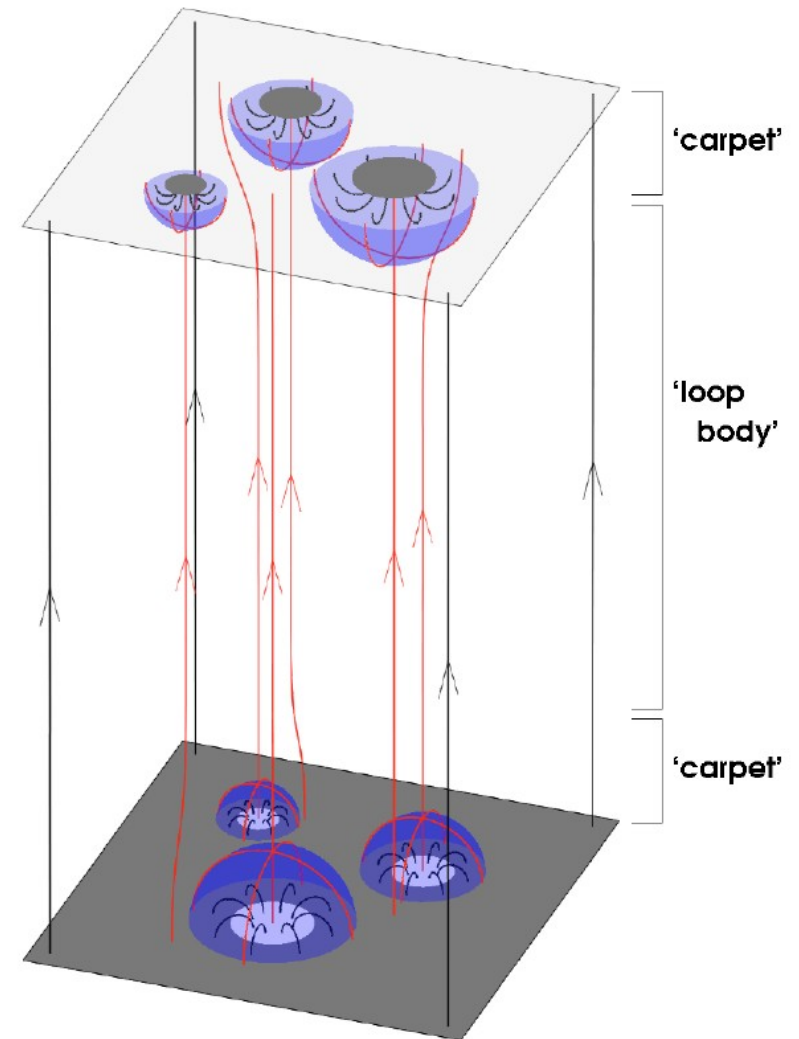
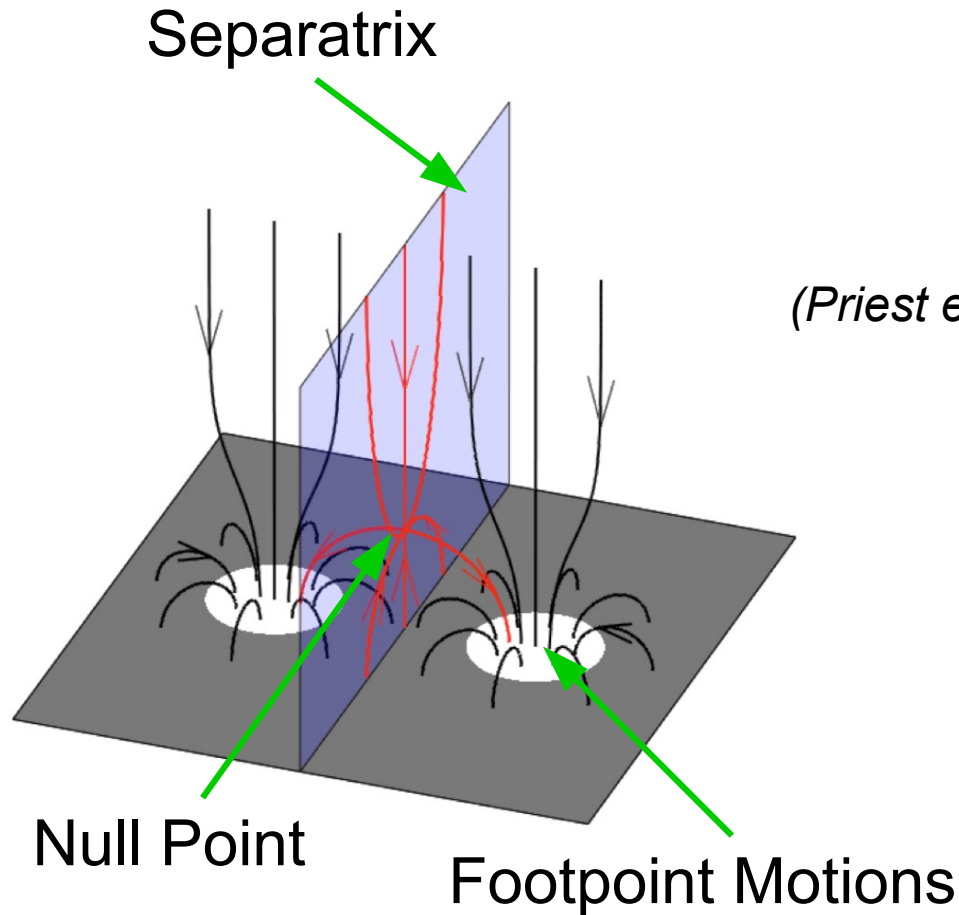
# Magnetic Field Line Topology and Energy Propagation in the Corona.



**Simon Candelaresi, David Pontin, Gunnar Hornig**



# Magnetic Carpet

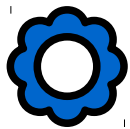
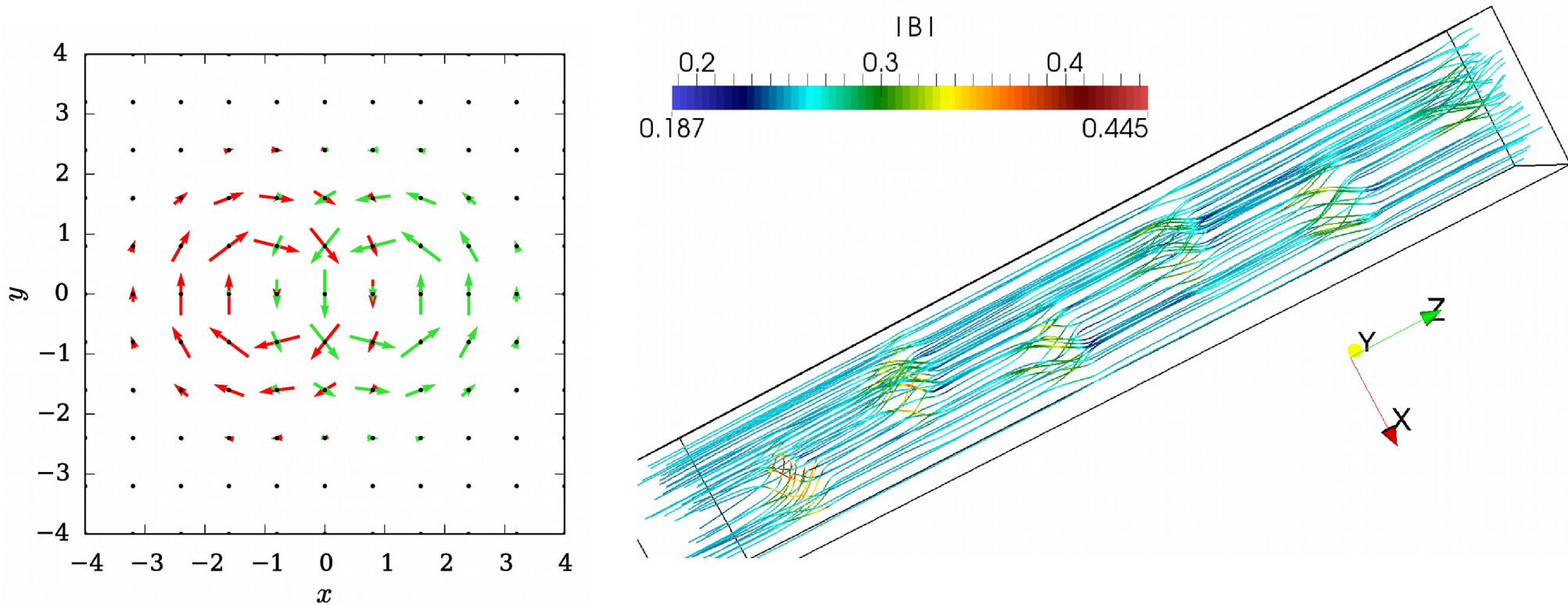


Questions: How do disturbances travel into the domain?  
Reconnection at null point?  
Propagation in presence of nulls?

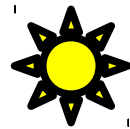
# E3 Experiments

Full resistive MHD simulations with the PencilCode.

Initially homogeneous field, E3 type boundary driving.



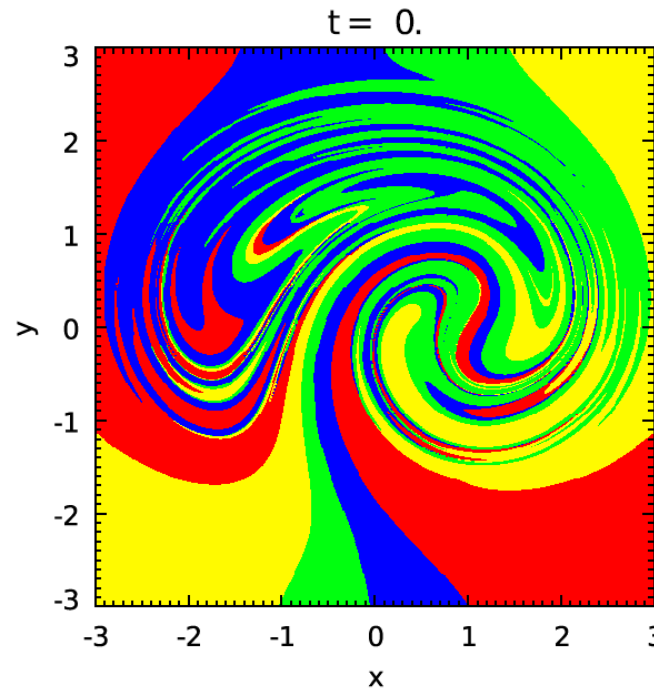
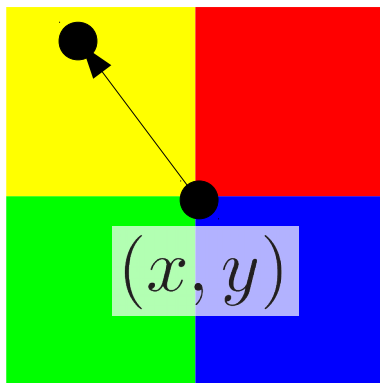
Blinking Vortex  
Footpoint Driving



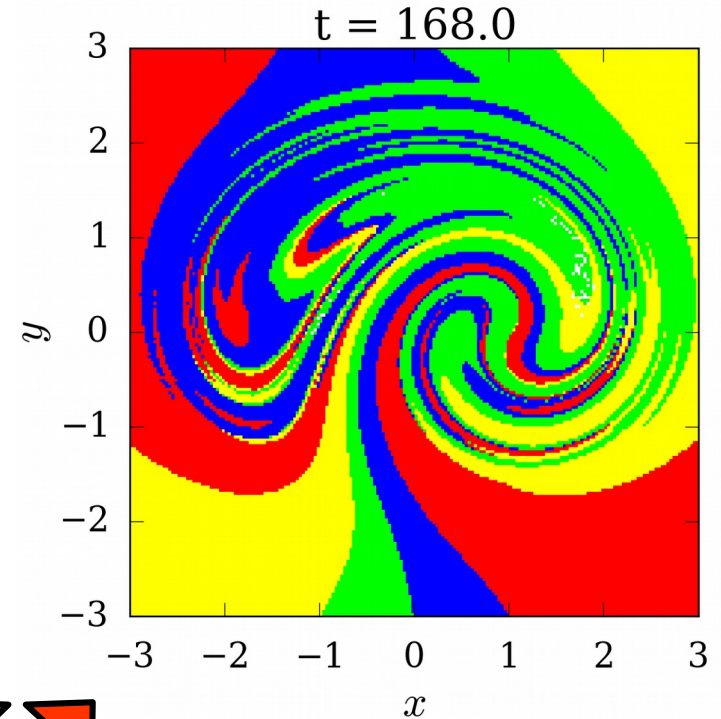
Braid propagates into domain.

# E3 Experiments

Field Line Mapping



(Yeates et al. 2010)

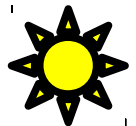
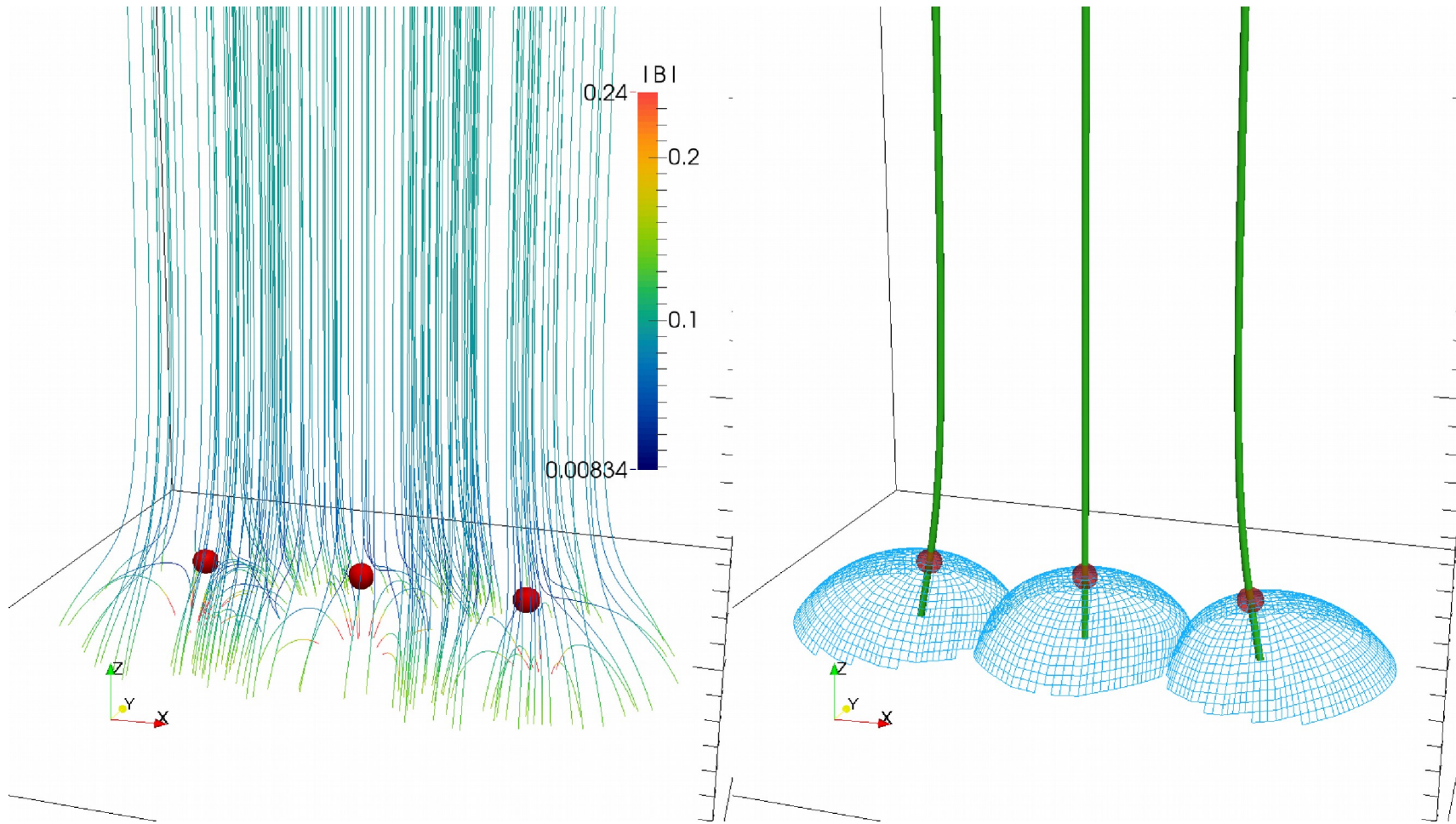


VS.

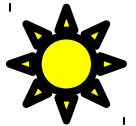


Controlled change of field line connectivity can be achieved through footpoint motions.

# Null Points



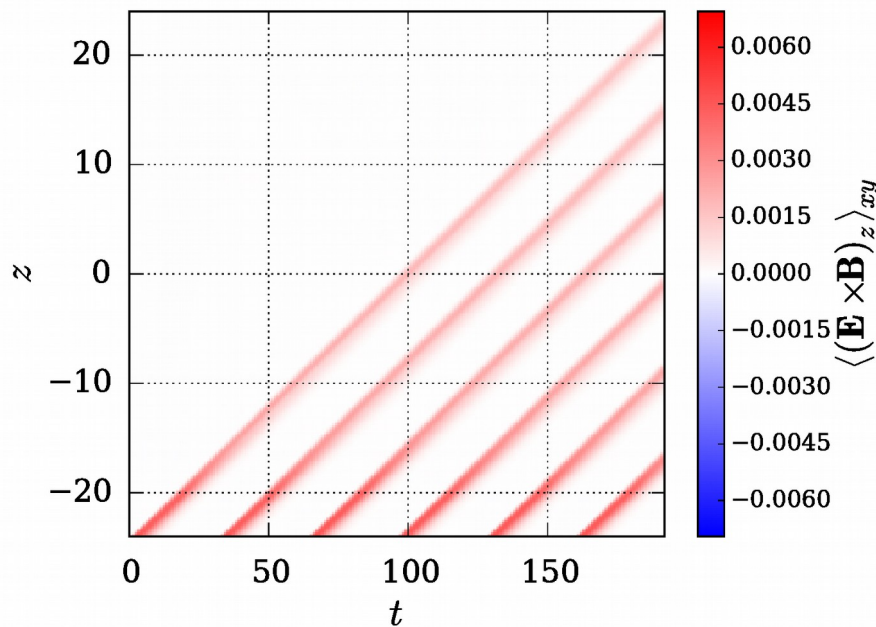
Null pair creation/annihilation.



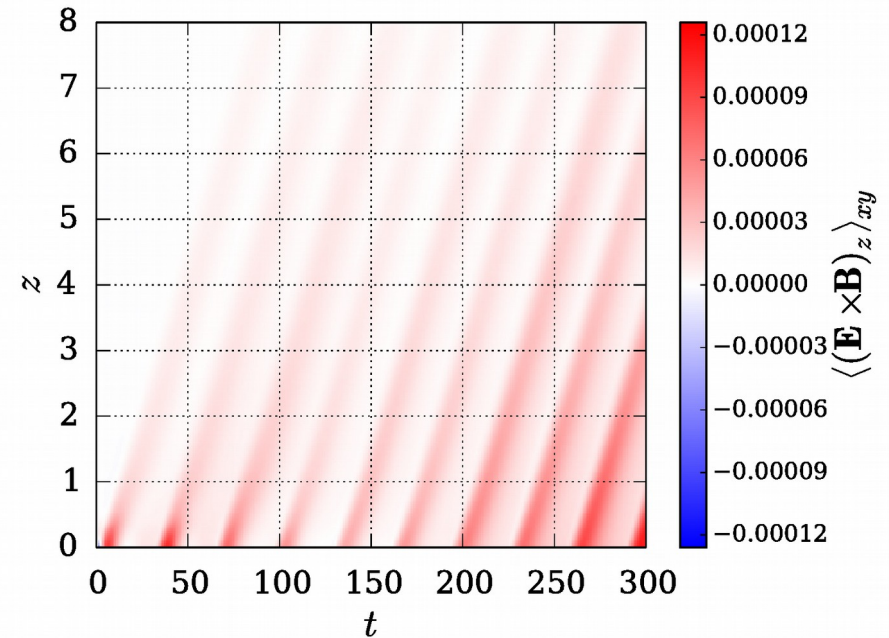
Footpoint motion can alter the field line topology.

# Energy Propagation

Homogeneous  $\mathbf{B}_0$



Magnetic Carpet  $\mathbf{B}_0$



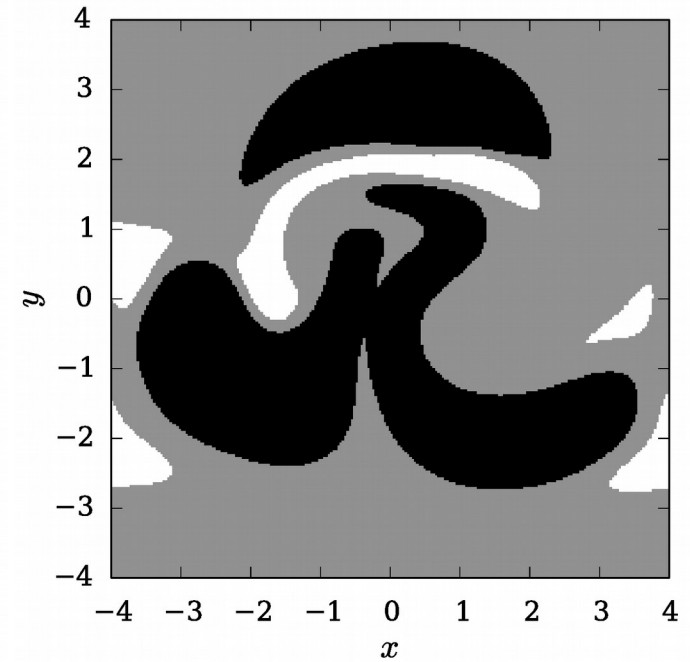
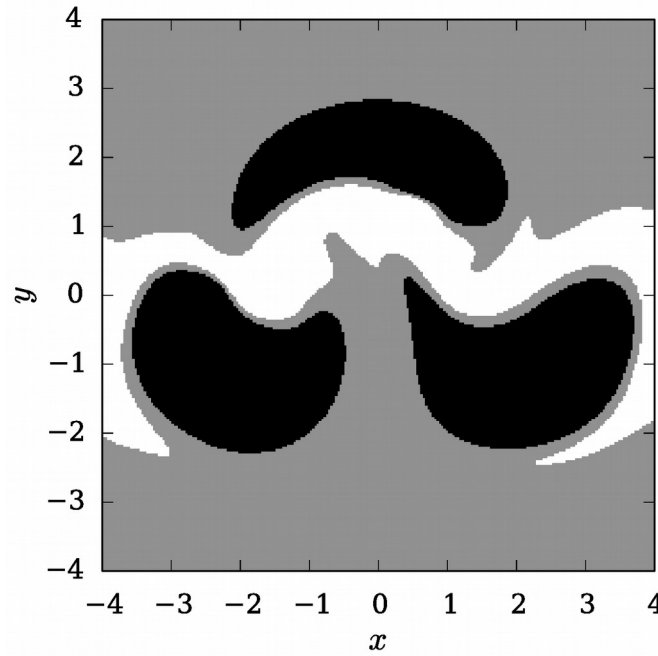
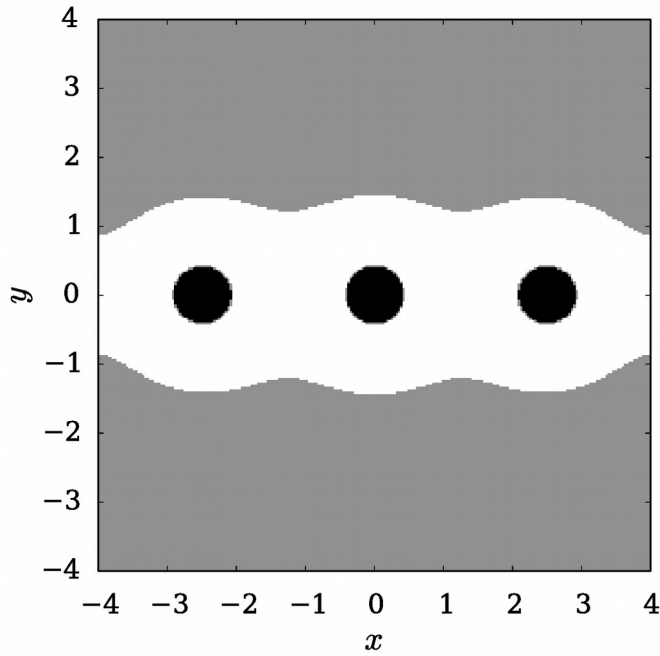
Topology efficiently inhibits energy propagation.



After change of topology  $\rightarrow$  efficient energy transport.

# Polarity Mixing

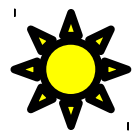
$t$



White:  $B < 0$

Gray:  $B \approx 0$

Black:  $B > 0$



Magnetic field polarities are efficiently mixed through footpoint motions.

# Conclusions

- Braiding through photospheric footpoint motion.
- Null point disruption through boundary motions.
- Energy propagation inhibited due to carpet structure.
- Efficient energy transport into corona after topology change.
- Polarity mixing on the photosphere.



# Recommendations

## Braided coronal loops: equilibria, heating, and observational signatures

David Pontin, G. Hornig and S. Canderarasi (University of Dundee, UK)

**Abstract**  
We examine coronal loops containing non-trivial magnetic field line braiding. We discuss the existence of braided force-free equilibria, and demonstrate that they must contain current layers whose thickness becomes increasingly small for increasing field complexity. Therefore if one considers a coronal loop that is driven by photospheric motions, the eventual onset of reconnection and energy release is inevitable. Once the initial reconnection event is triggered a turbulent relaxation ensues. We discuss the relation with Parker's braiding mechanism for coronal heating, and show expected observational signatures of energy release in such a braided coronal loop.

There are many steps for understanding/validating the braiding mechanism for coronal heating, as listed below. We focus on two of these.

- Braiding by convective motions
- Field relaxation forming current sheets(?) ← Section 1
- Reconnection and energy deposition
- Plasma response
- Observational signatures ← Section 2

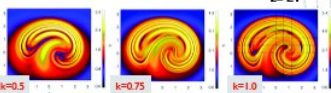
### 1. Existence/structure of braided force-free equilibria

#### 1(a). Model magnetic braid

We consider a loop that has already been braided. Our model loop consists of uniform field  $B_0$  plus six flux rings lying in the xy-plane. Flux rings placed as shown below (yellow), with alternating signs.

$$B = B_0 e_z + \sum_{i=1}^6 k_i (-1)^i \exp\left(-\frac{(x-x_i)^2 + y^2 + (z-z_i)^2}{\lambda^2}\right) \left( (-1)^i y e_x + (-1)^i x e_y + (z-z_i) e_z \right) \quad (*)$$

Increasing parameter  $k$  increases twist and thus complexity of field. This can be measured using the topological entropy or visualised by plotting the field line mapping for different  $k$ . Below: squashing factor  $Q$  plotted on the lower boundary for different  $k$ .



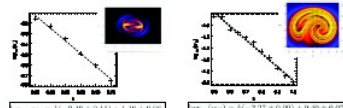
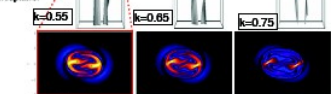
#### 1(b). Conditions for equilibrium structure

- Suppose that a force-free equilibrium exists for a given magnetic braid. Can we characterise its structure? In such an equilibrium we have  $\nabla \times B = \alpha B$  and  $B \cdot \nabla \alpha = 0$ , with  $\alpha$  constant along field lines.
- Suppose  $\alpha$  has distribution with length scale  $l$  on (e.g.) lower boundary
- Mapping along field lines,  $\alpha$  naturally exhibits thin layers (see above) with length scales on order of field line mapping on upper boundary:  $l \propto \lambda_{\text{map}}$  (being the smallest eigenvalue of the mapping Jacobian  $DP$ )
- But  $\alpha \propto \omega \cdot B e^{\int \alpha ds}$ , and so assuming  $|B| \sim O(1)$  then it also has length scales on order of  $l \propto \lambda_{\text{map}}$ .
- Thus: if smooth force-free equilibrium exists, it must contain current layers at least as thin as layers in field line mapping

#### 1(c). Ideal relaxation and equilibrium structures

We perform ideal relaxation simulations with  $B$  line-tied (and  $w=0$ ) on boundaries. We run a series of relaxations for different values of  $k$  in Eq (\*):  $0.5 < k < 1$ .

In equilibrium, current is localised in ribbons extending length of domain. Show: localisation of LI and intensity plot of LI in midplane.



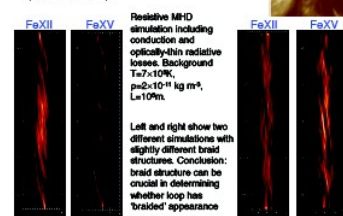
- Current layer thickness ( $w$ ) and thickness of  $Q$  layers in mapping ( $w_Q$ ) exhibit the same scaling, within error bars.
- Supports theory that scales in mapping control  $J$  layer scales in equilibrium.
- Implication: continual braiding will increase complexity until field is sufficiently tangled that thin enough current layers form, i.e. continual braiding will inevitably lead to reconnection onset
- Estimating  $J$  layer thickness required for fast reconnection, can extrapolate to find  $k$  value at onset. Free energy at this  $k$  consistent with nanoflare models.

#### 2a. Reconnection onset and turbulent relaxation

- If we turn resistivity on in the simulations, we get a turbulent relaxation involving myriad current layers, through which the field unbraids (Pontin et al. A&A, 2017).
- In corona, we expect a balance between tangling by boundary motions and this relaxation: field should exist in a marginally stable state close to critical degree of braiding.

#### 2b. Observational signatures of energy release

Use FOMO package to simulate emission during turbulent relaxation of initially-braided field (https://gitlab.com/isaiahbo/fomo). Compare with observations from Hi-C rocket (Cirtain et al. 2013).



#### Conclusions

- Smooth equilibria do exist for magnetic braids (at least in some cases)
- Equilibria must contain current layers whose thickness scales inversely with the braid complexity
- $\Rightarrow$  In corona continual braiding will inevitably lead to reconnection onset
- Results allow extrapolation to estimate critical braiding level in corona: could provide onset threshold for nanoflares
- After reconnection onset, turbulent relaxation 'unbraids' the field
- In corona expect a marginally-stable state in which field line tangling and energy release processes balance.
- Depending on braiding length scales and structure, tangling of field lines may be observable in coronal emission

#### References

- Cirtain, J. W. et al., 2013. Energy release in the solar corona from spatially resolved magnetic braids. *Nature* 501, 516-519.
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- Pontin, D. I. and Hornig, G., 2015. The structure of current layers and degree of field line tangling in coronal loops. *Astrophys. J.*, 805, 67.
- Pontin, D. I., Canderarasi, S., Pontin, A. J. B. and Hornig, G., 2016. Braided magnetic fields: equilibria, relaxation and heating. *Plasma Phys. Control. Fusion*, 58, 044004.

Postdoctoral research position available in Solar Magnetohydrodynamics at the University of Dundee (UK)

3 years

Closing date: 5<sup>th</sup> June.

<http://www.maths.dundee.ac.uk/mhd>

David Pontin (P 10.10)