Energy release in braided coronal loops

David I. Pontin
University of Dundee, UK

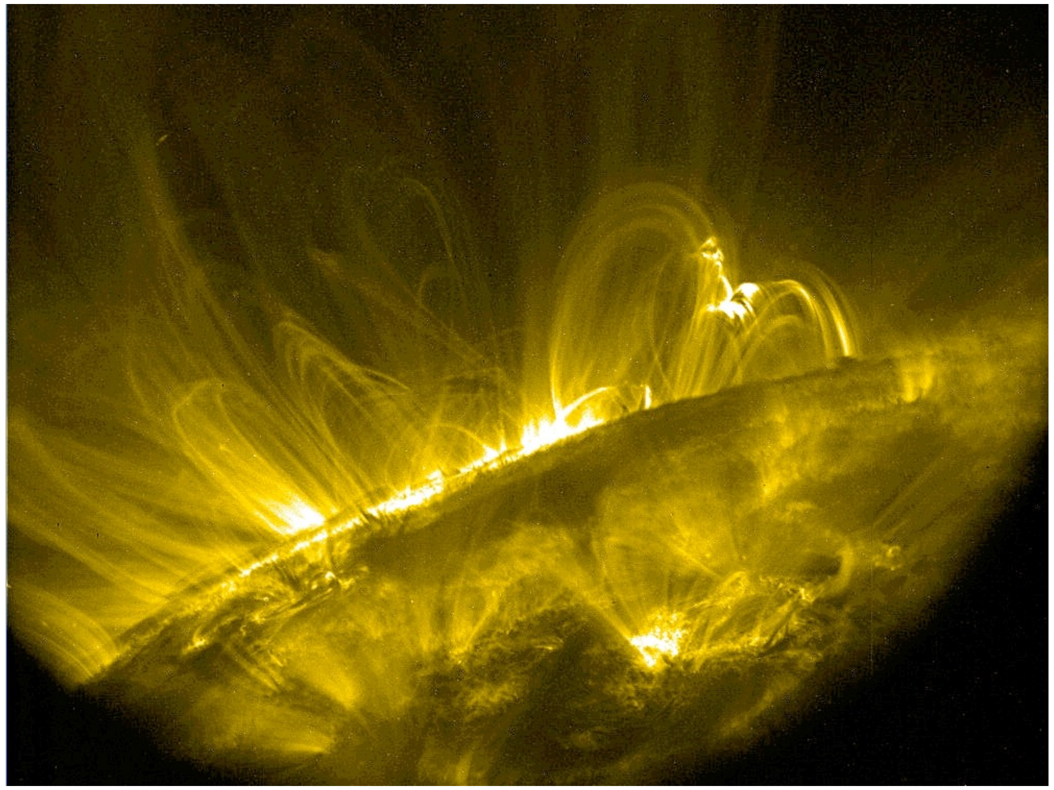
with: Klaus Galsgaard, Gunnar Hornig, Simon Candelaresi, Miho Janvier, Sanjiv Tiwari, Amy Winebarger

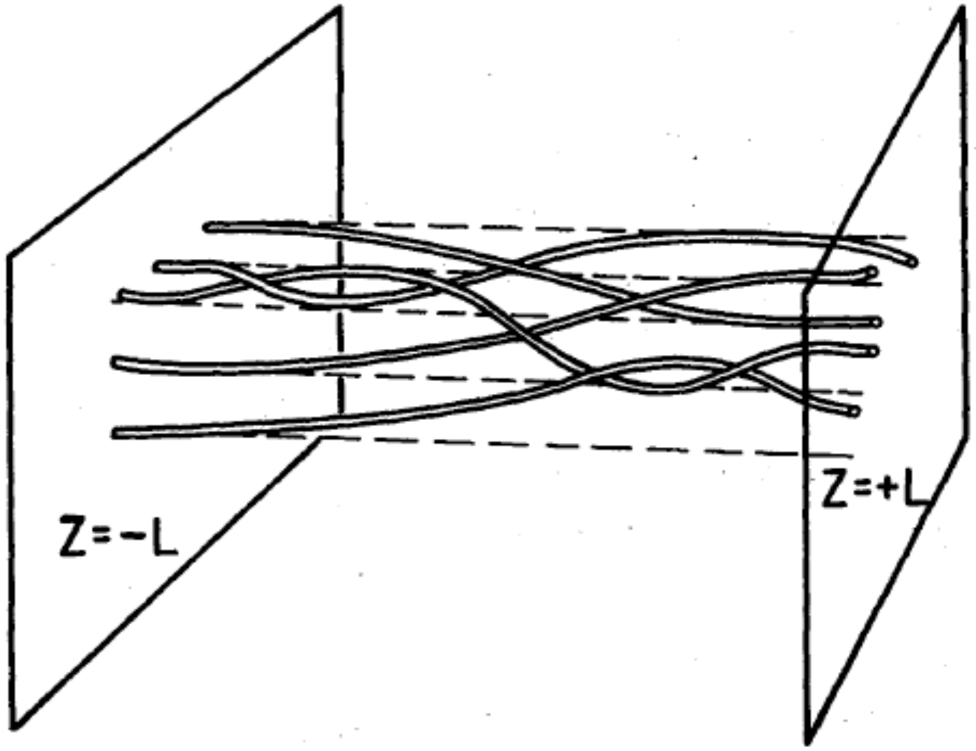
8th Coronal Loops Workshop, Palermo, 27th June 2017

"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' (I've found it!), but 'That's funny.....' "

Isaac Asimov

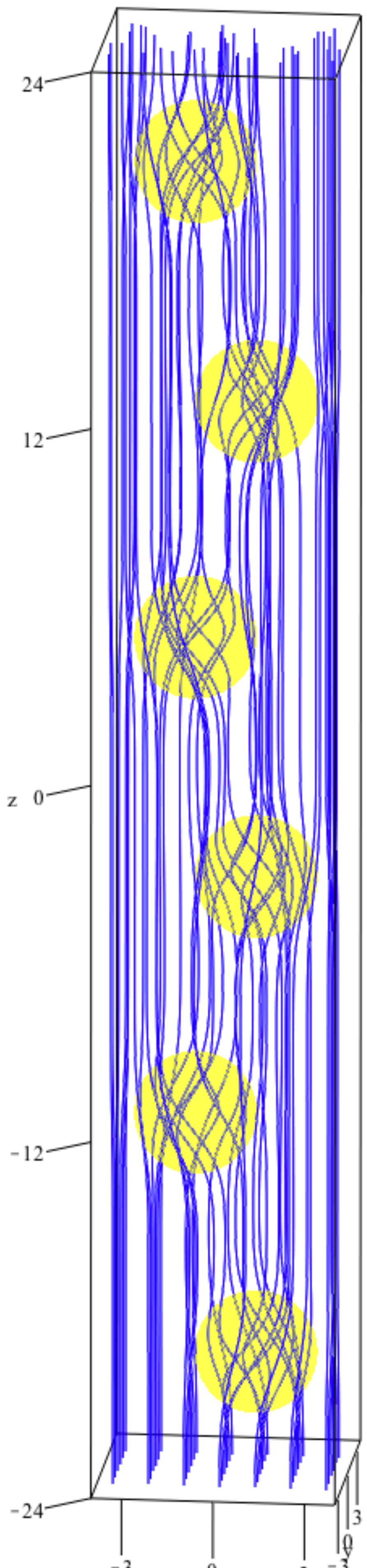
Motivation





Parker, E.N., ApJ, **174**, 499 (1972).

- Parker (1972) proposed braiding of magnetic field to explain coronal heating
- Field lines tangled by convective photospheric motions
- In corona $R_m \gg 1$ so evolution ‘ideal’ almost everywhere: topology preserved
- Parker argues that perturbed field can’t relax to smooth force-free equilibrium (**J**x**B**=**0**) except in certain non-generic cases.
- Consequence: tangential discontinuities, i.e. current sheets, form → reconnection and heating.



The model magnetic field

Braiding by motions

→ field relaxation forming current sheets?

→ reconnection and energy deposition

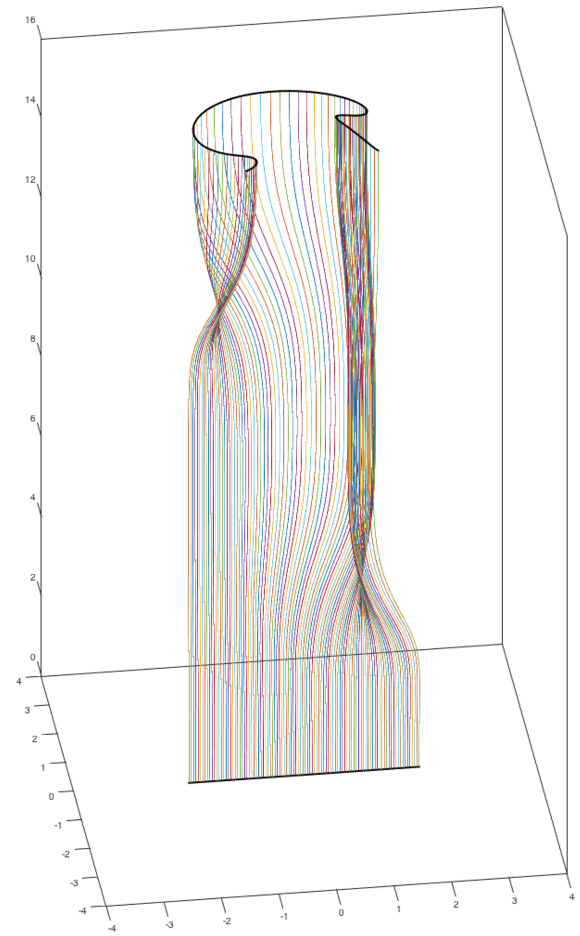
→ plasma response

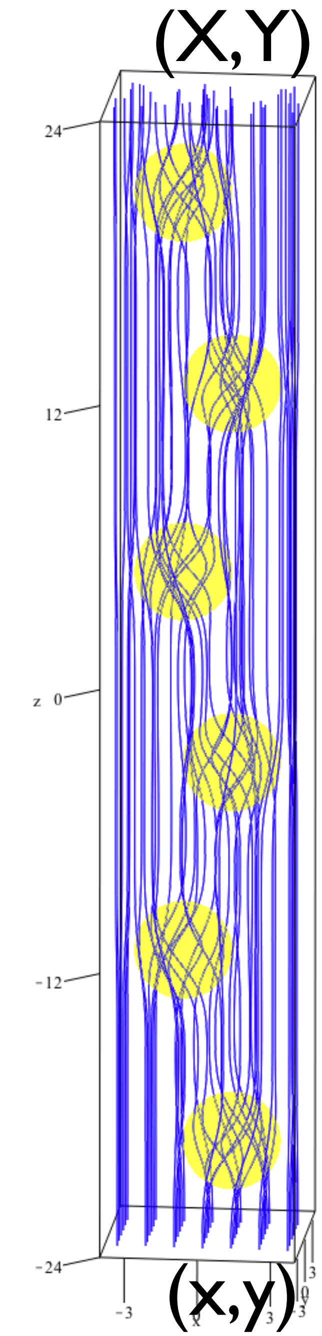
- Add six regions of twist to uniform **B**
- Subset of field lines in domain have pigtail braid linkage
- Net magnetic helicity (twist) is zero
- Could be generated by sequence of opposite-sense rotations at photosphere

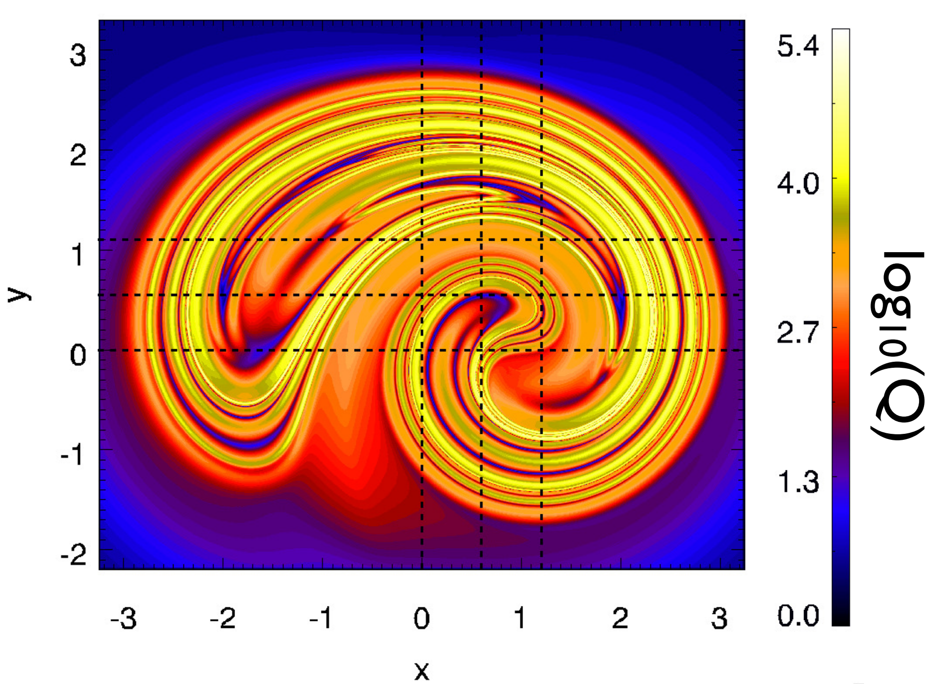
Field line tangling

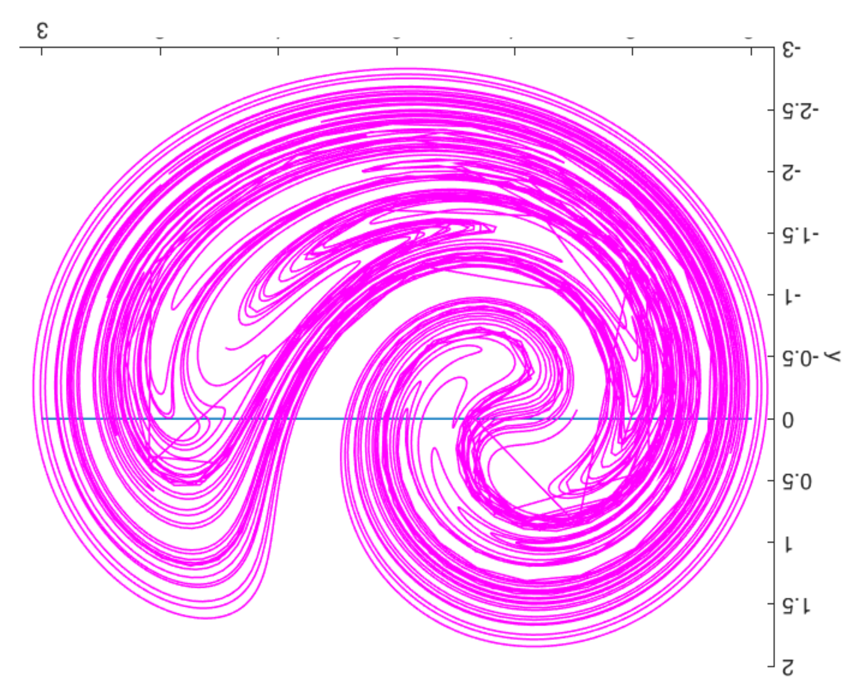
- Braiding of field lines induces strong gradients in field line mapping -> foliation of thin layers
- Increase in tangling -> increase in number of layers
- Tangling can be visualised using ‘squashing factor’

$$Q = \frac{\left(\frac{\partial X}{\partial x}\right)^2 + \left(\frac{\partial X}{\partial y}\right)^2 + \left(\frac{\partial Y}{\partial x}\right)^2 + \left(\frac{\partial Y}{\partial y}\right)^2}{\left| \frac{\partial X}{\partial x}\frac{\partial Y}{\partial y} - \frac{\partial X}{\partial y}\frac{\partial Y}{\partial x} \right|}$$







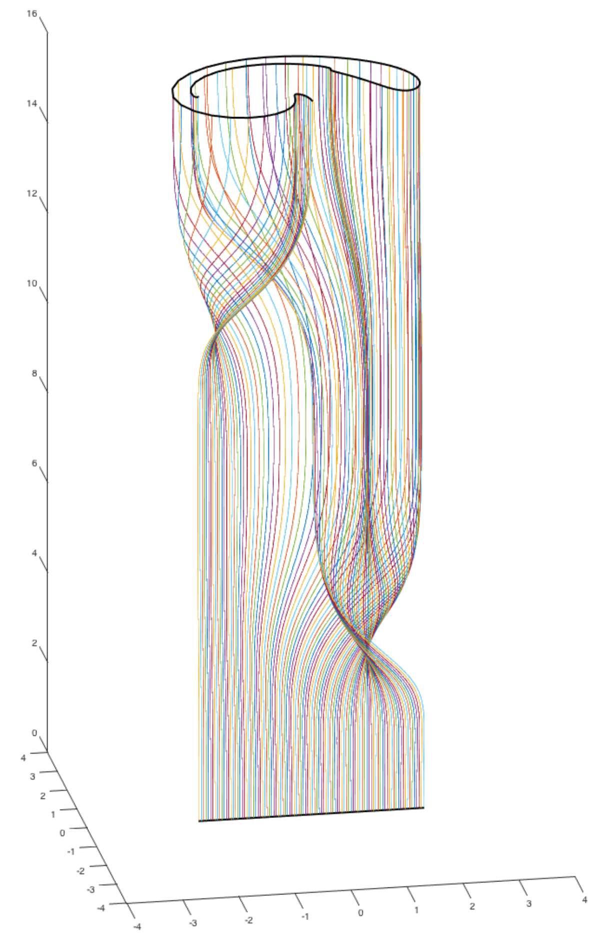


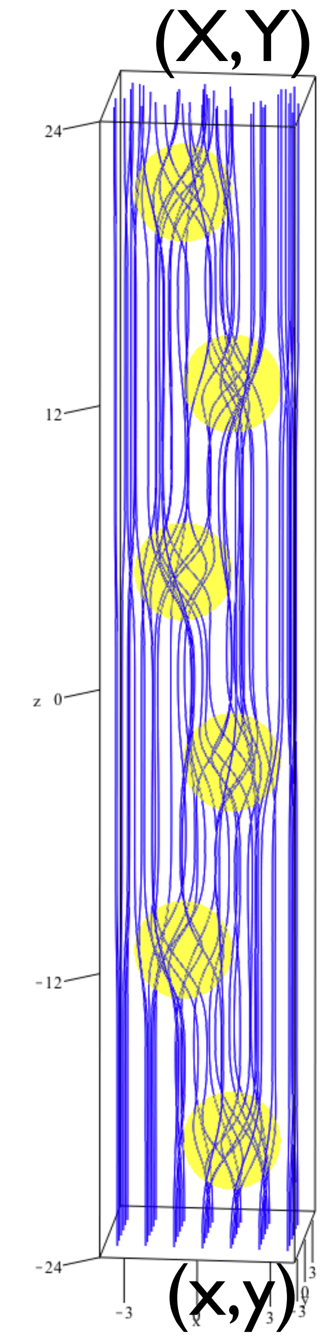
[Pontin & Hornig 2015]

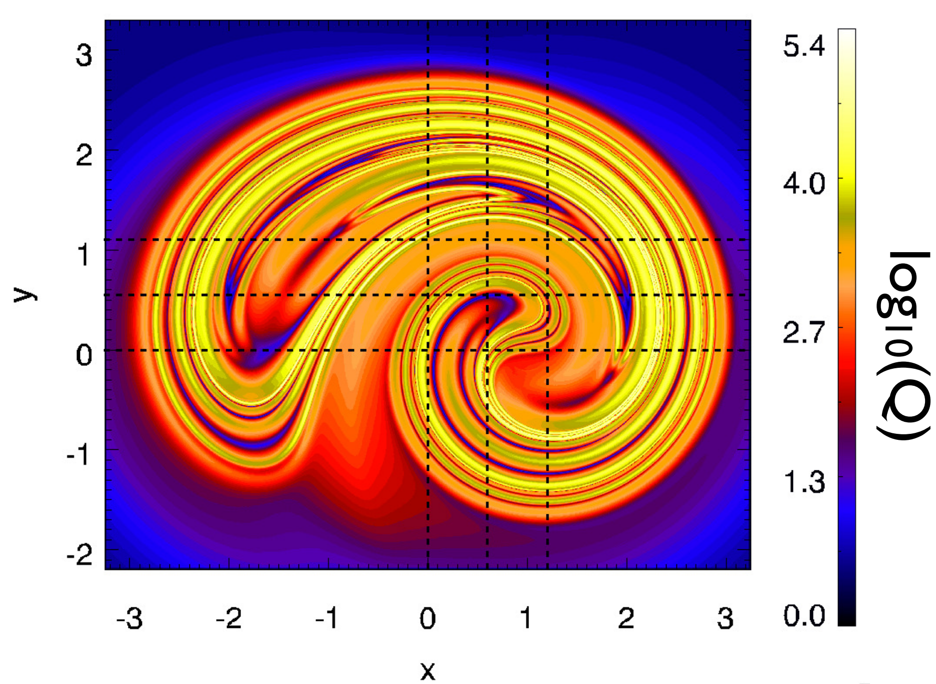
Field line tangling

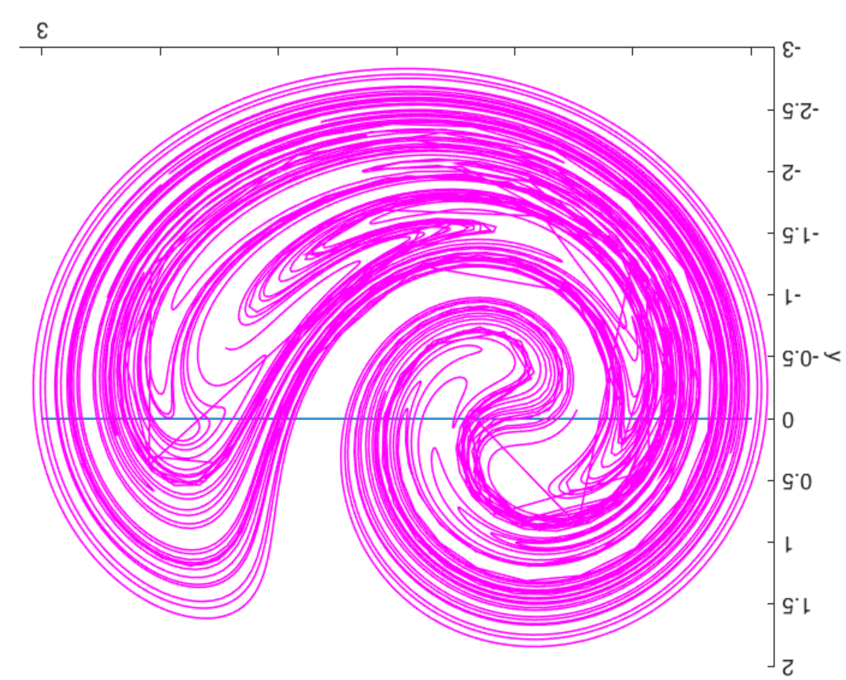
- Braiding of field lines induces strong gradients in field line mapping -> foliation of thin layers
- Increase in tangling -> increase in number of layers
- Tangling can be visualised using 'squashing factor'

$$Q = \frac{\left(\frac{\partial X}{\partial x}\right)^2 + \left(\frac{\partial X}{\partial y}\right)^2 + \left(\frac{\partial Y}{\partial x}\right)^2 + \left(\frac{\partial Y}{\partial y}\right)^2}{\left|\frac{\partial X}{\partial x}\frac{\partial Y}{\partial y} - \frac{\partial X}{\partial y}\frac{\partial Y}{\partial x}\right|}$$







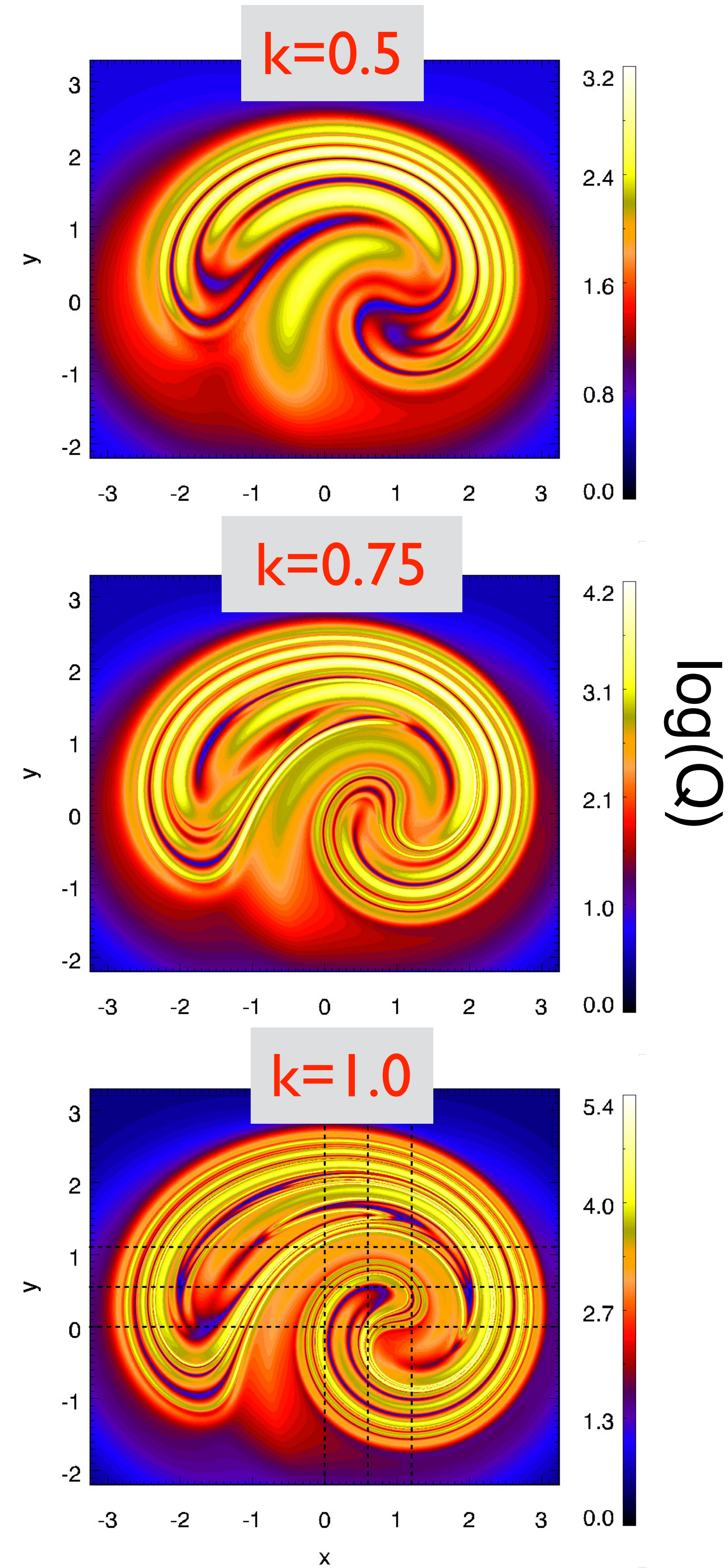


[Pontin & Hornig 2015]

Existence of equilibria

$$\mathbf{B} = B_0\mathbf{e}_z + \sum_{i=1}^{2n} k(-1)^i \exp\left(-\frac{(x-x_i)^2+y^2}{2} - \frac{(z-z_i)^2}{4}\right) \times(-y\,\mathbf{e}_x + (x-x_i)\,\mathbf{e}_y)$$

- We consider a sequence of braids of increasing complexity.
- For each braid in the sequence, perform an ideal relaxation (preserving topology, i.e. connectivity and tangling) towards a force-free equilibrium.
- Does this equilibrium contain thin (singular?) current layers?
- Computational ideal relaxation approach: Lagrangian mesh allows exact preservation of topology as equilibrium is approached. (https://github.com/SimonCan/glemur)

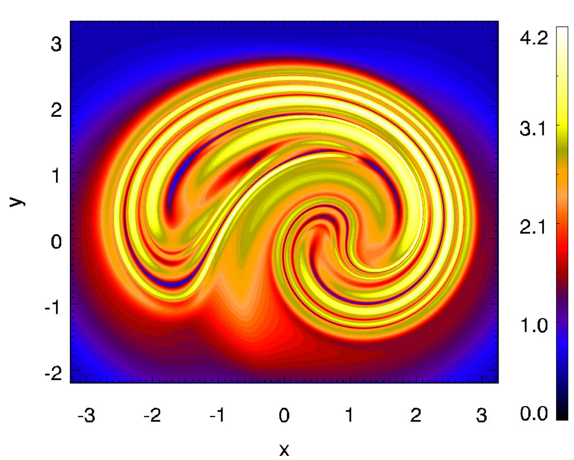


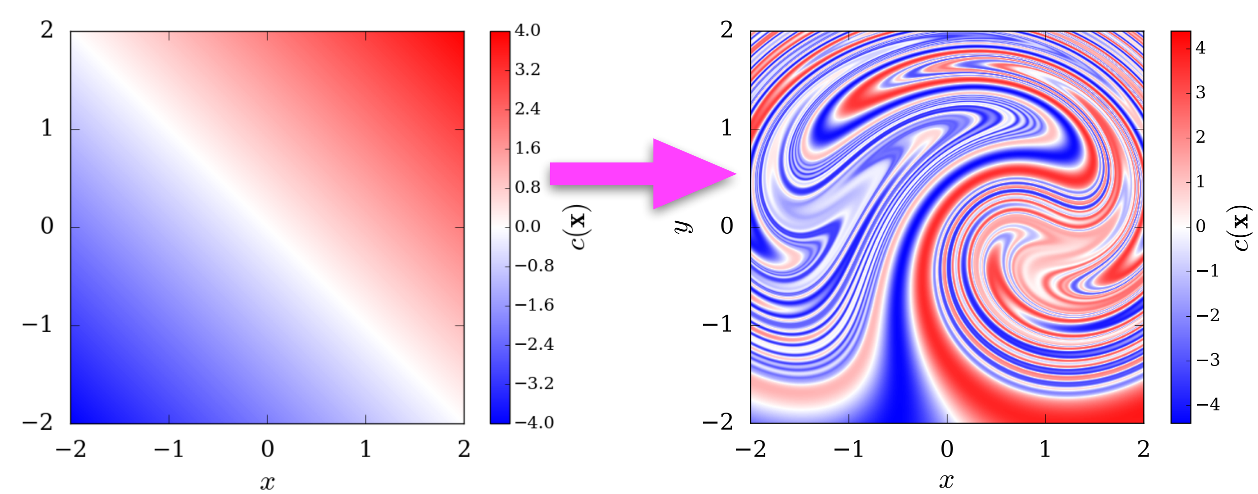
[Candelaresi, Pontin & Hornig 2014;
Pontin & Hornig 2015]

[Pontin & Hornig 2015]

(Finite) current layers in equilibrium

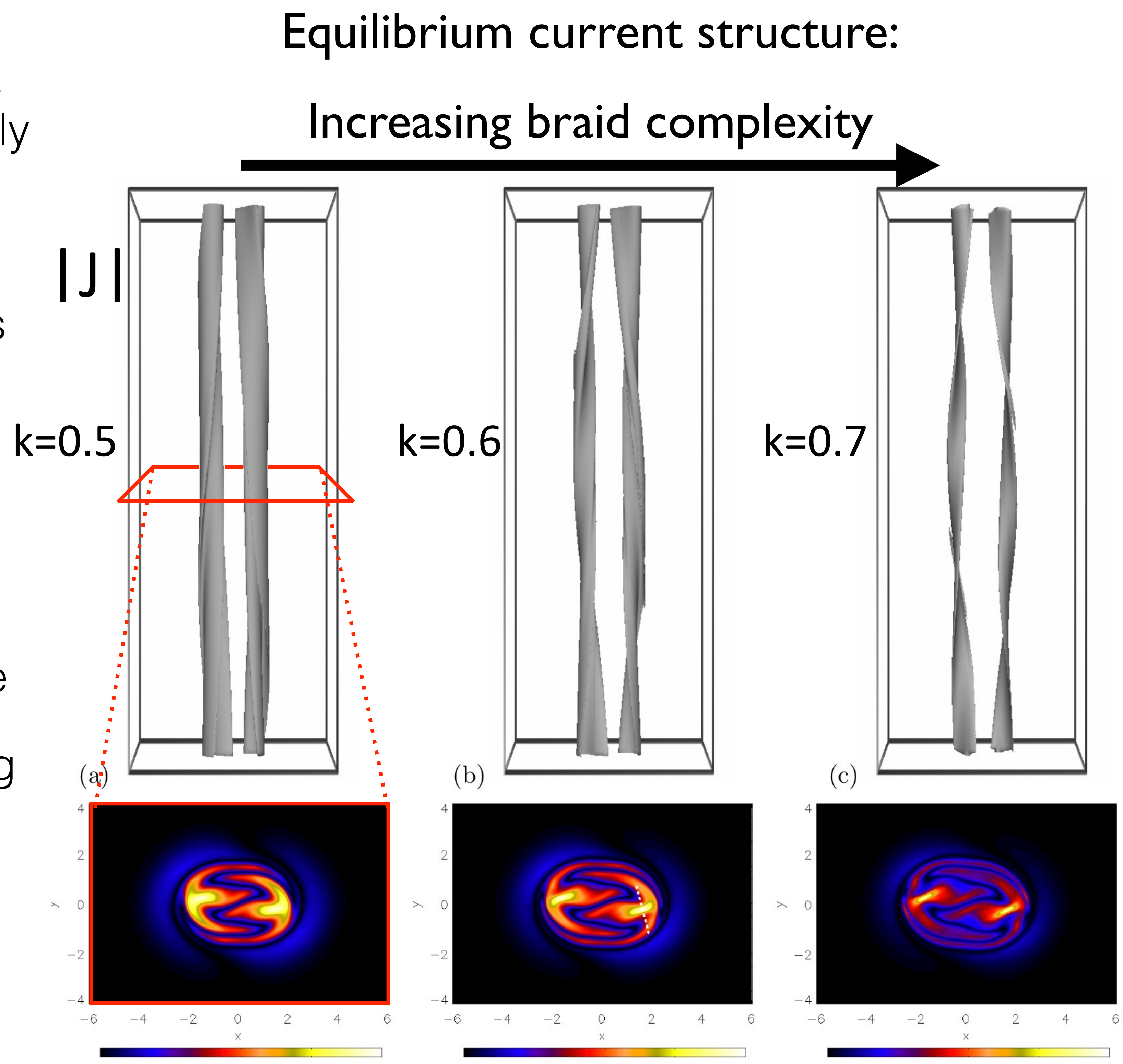
- Recall equilibrium satisfies $\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B} \approx \mathbf{0}$
- Suppose that $\nabla \times \mathbf{B} = \alpha \mathbf{B}$ so that $\mathbf{B} \cdot \nabla\alpha = 0$ and α = const along field lines.
- Suppose α has distribution with length scale ℓ on (e.g.) lower boundary
- Mapping along field lines, α naturally exhibits length scales on order of field line mapping on upper boundary: $\ell \times \lambda_{min}$ (λ_{min} smallest eigenvalue of mapping Jacobian DF)
- $\alpha = \mathbf{J}\cdot\mathbf{B}/B^2$, and so assuming $|\mathbf{B}| \sim O(1)$ then $J_{\parallel}$ also has length scales on order of $\ell \times \lambda_{min}$.
- Thus: if smooth force-free equilibrium exists, it must contain current layers at least as thin as layers in field line mapping





Existence of equilibria: ideal relaxation simulations

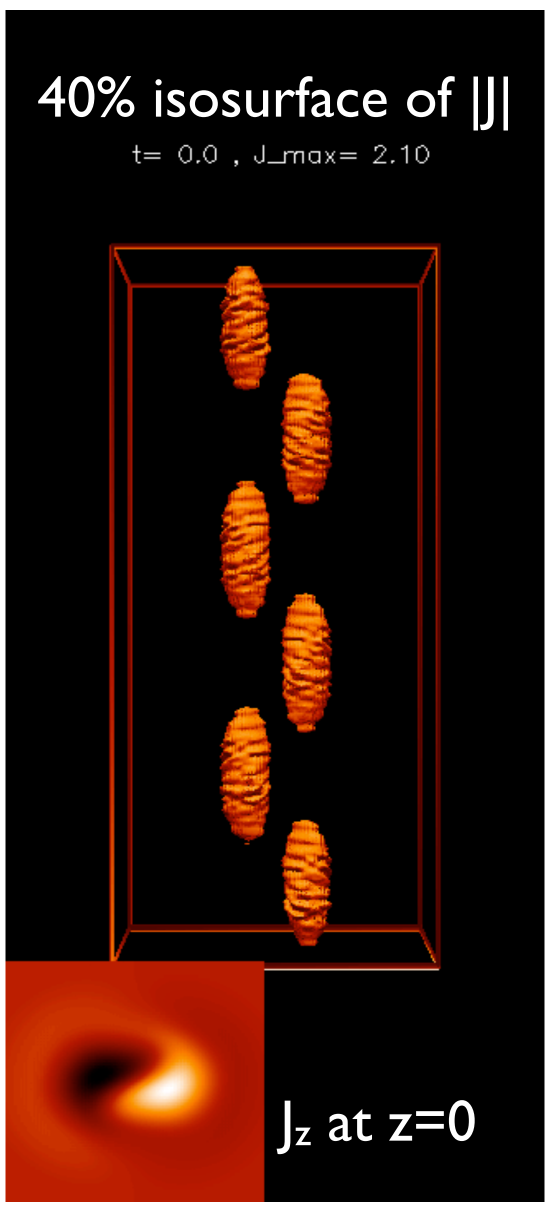
- For sequence of increasingly braided loops, equilibria obtained contain finite current layers.
- However, thickness of current layers decreases exponentially with braid complexity; |J| increases exponentially
- Identical scaling for thickness of layers of |**J**| and Q
- Scaling laws allow extrapolation beyond accessible range of tangling ➙ estimate critical braiding level to trigger energy release
- Implication: continual braiding will inevitably lead to reconnection onset, even for coronal magnetic Reynolds number

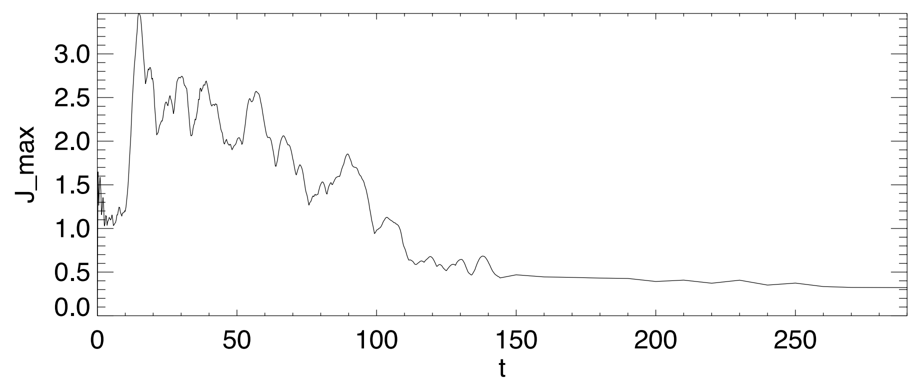


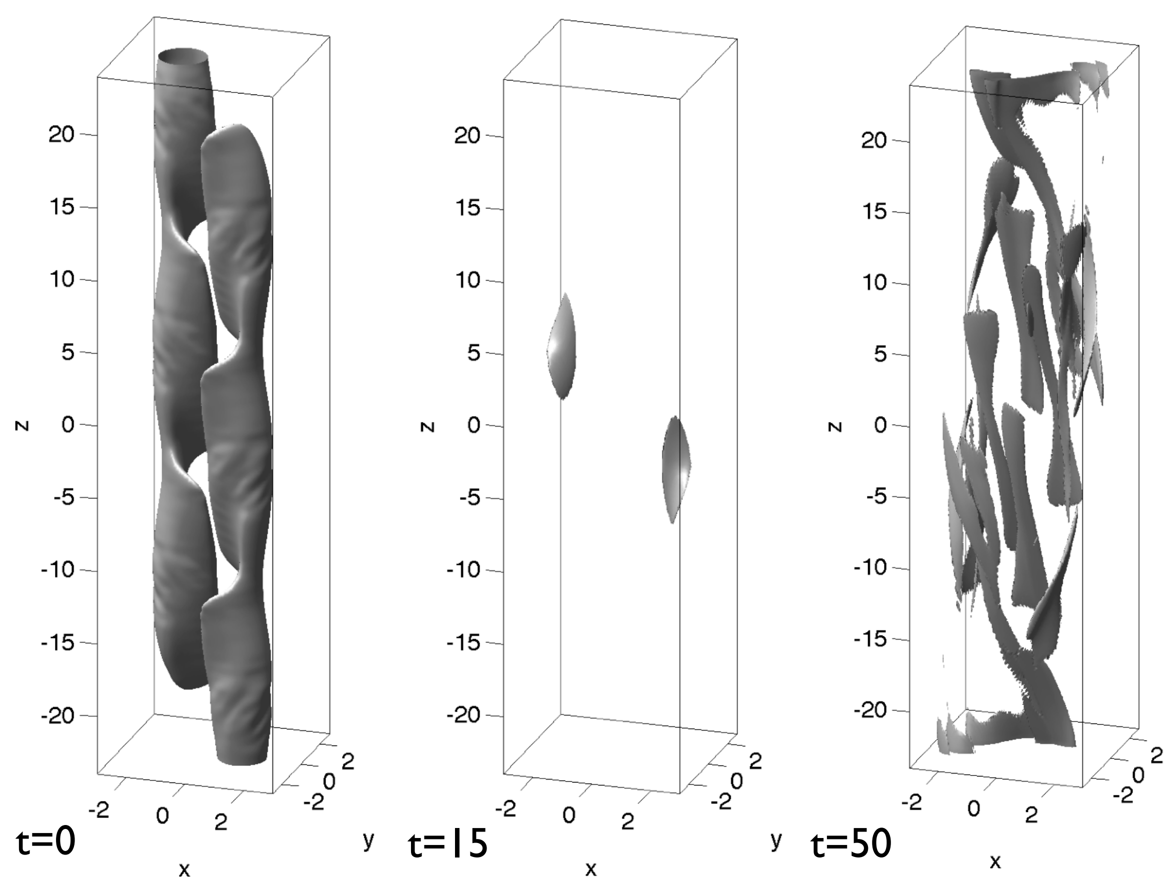
What happens when we turn on resistivity?

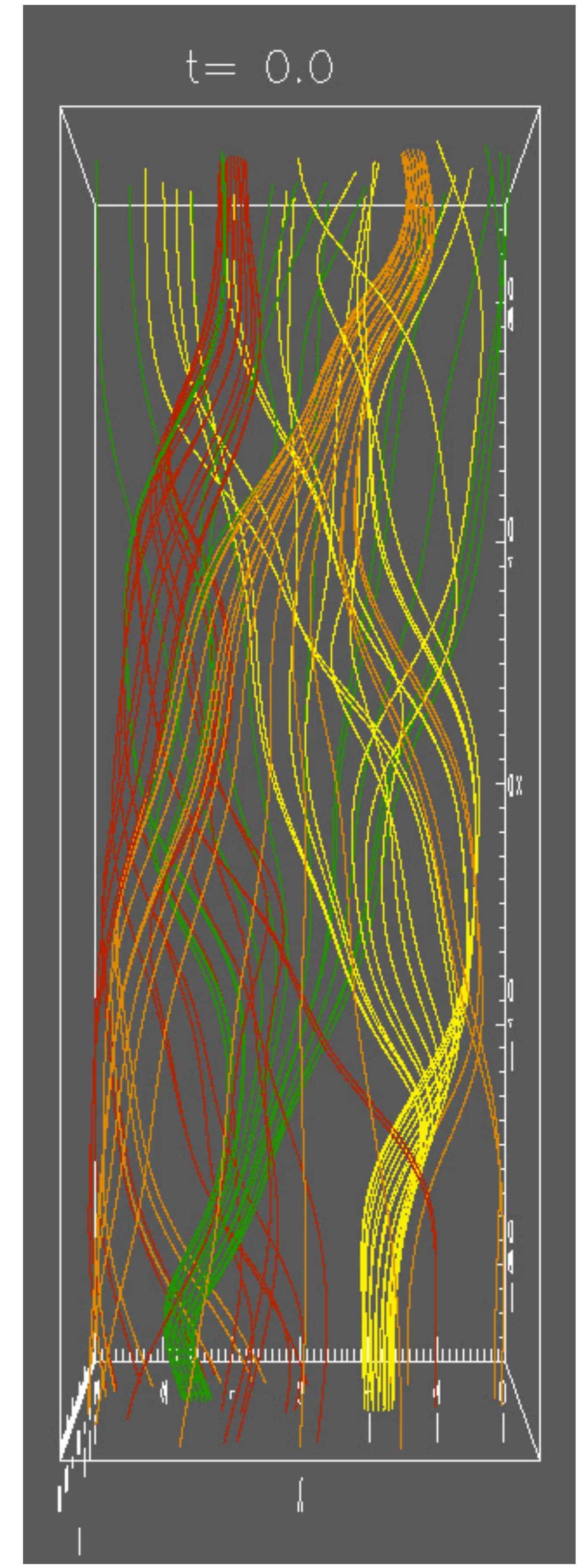
1) Braiding by surface flows
2) formation of current sheets
3) reconnection and energy deposition
4) plasma response

- High R_m numerical simulations.
- 'Line tied', v=0: no driving.
- Turbulent relaxation: rec. in cascade of current sheets -> lower energy state



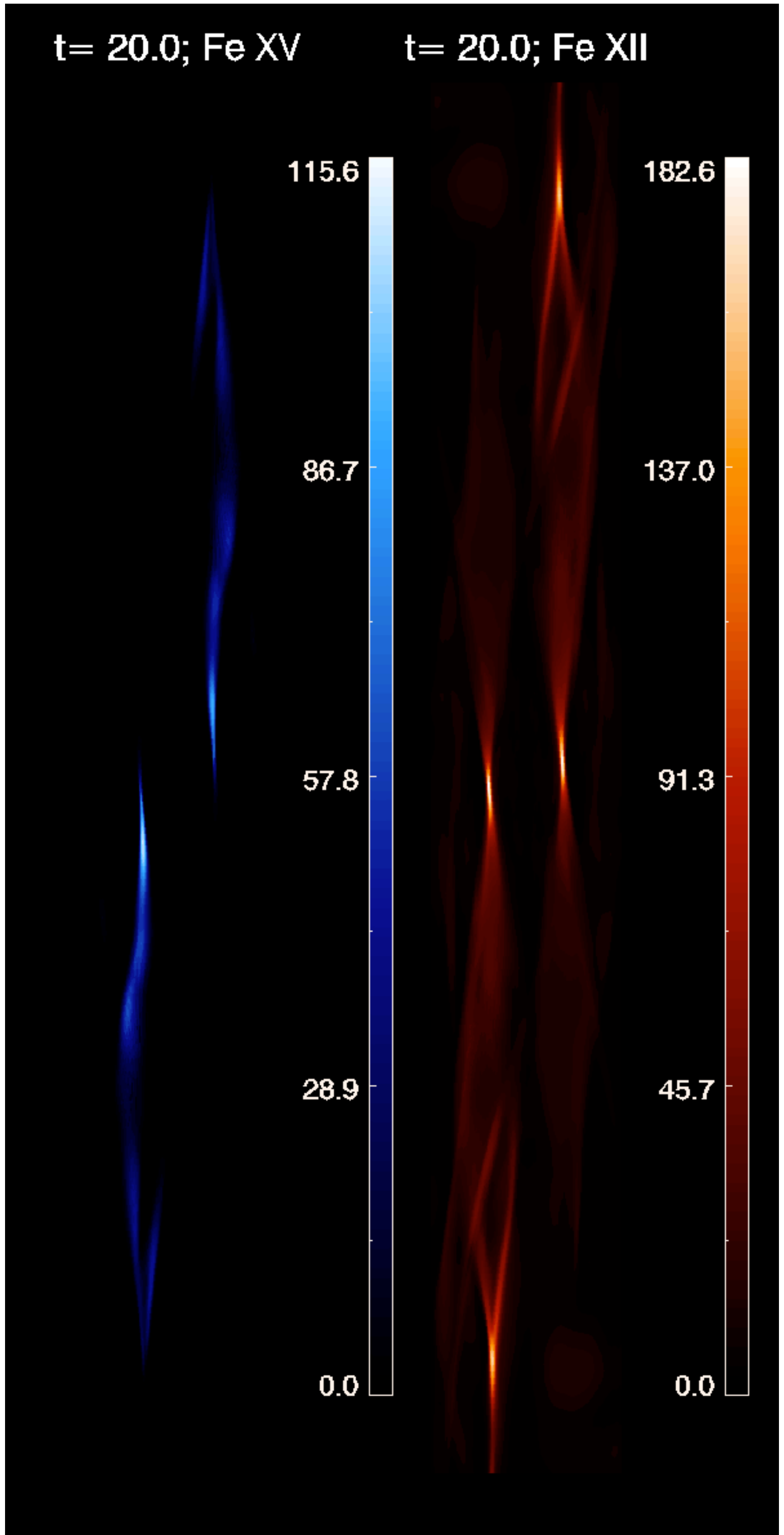






[Pontin et al 2011; Wilmot-Smith et al 2011]

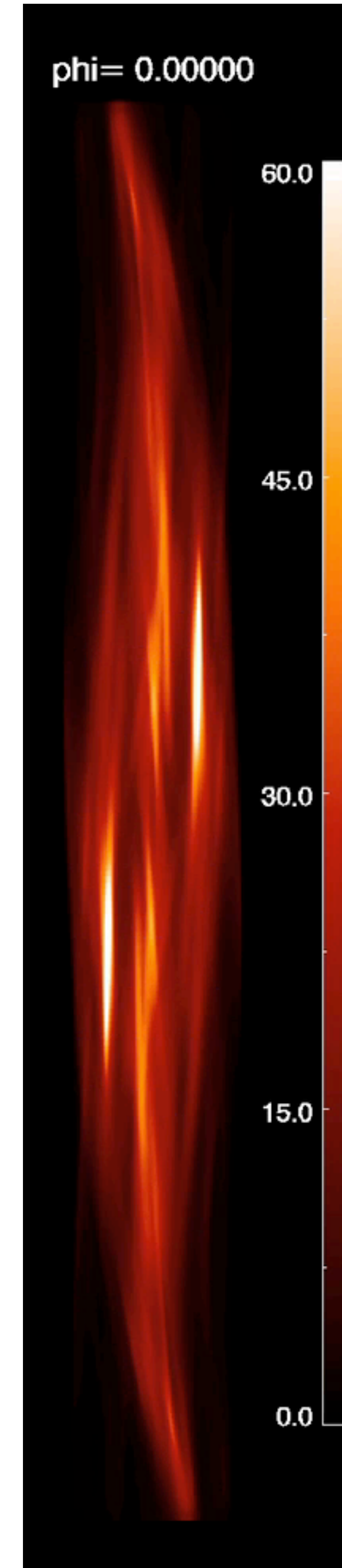
Observable signatures of energy release



[Pontin et al 2017]

Synthetic emission patterns generated for a simulation of a relaxing magnetic braid using FOMO

Dependence on line-of-sight at one fixed time



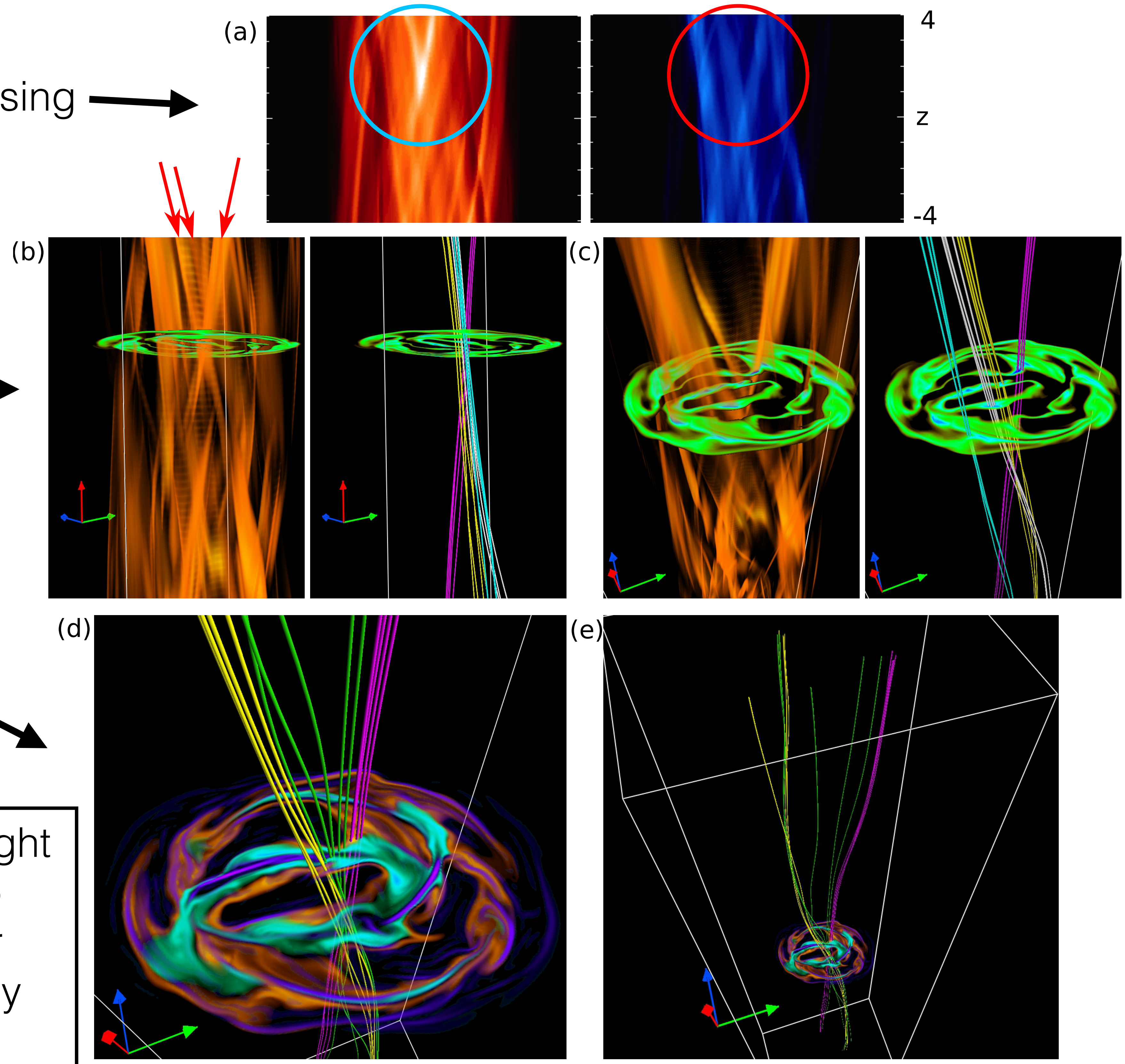
- Observational signatures highly dependent on:
  - viewing angle,
  - emission line,
  - degree of turbulence (here, resistivity),
  - existence of internal loop structure,
  - …
- Emission evolution always shows impulsive brightening of strands
- In many cases, no braided appearance ⇒ absence of crossing strands **does not** preclude field line tangling

Relating emission patterns to magnetic structure

Example ‘observed’ strand crossing

3D rendering of Fe XII emission + field lines traced from locations of enhancements

Orange: Fe XII emission
Cyan: Fe XV emission
Magenta: current density



Conclusion: in some cases, bright strand crossings correspond to ‘local braids’, but in many other cases not, and vice versa: many local braids do not appear as crossing strands

[Pontin et al 2017]

Summary

- Smooth braided equilibria do exist (at least in some cases). However, equilibria must contain current layers whose thickness scales inversely with the braid complexity

  $\Longrightarrow$ In solar corona continual braiding will inevitably lead to reconnection onset

- Critical braiding level in corona can provide onset threshold for ‘nanoflare' energy release
- Energy release is via a turbulent relaxation that lasts many crossing times
- Absence of braided appearance in emissions does not preclude braiding of field lines.

- Ongoing work: analyse timescale for field line tangling by boundary motions. Compare to timescale for energy release.

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