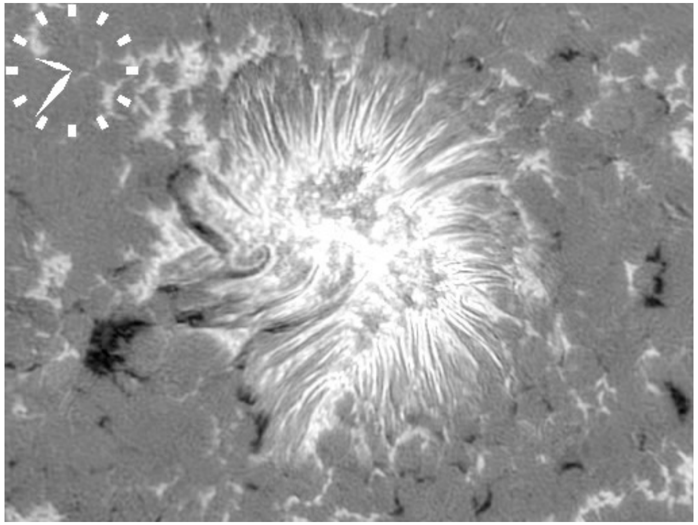
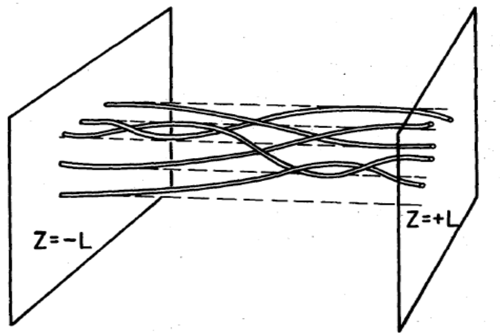
Reconnection and heating in braided coronal loops

D. Pontin, GSFC 5th March 2025

Braiding mechanism for 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 equilibrium except in certain non-generic cases.
- Consequence: tangential discontinuities, i.e. current sheets, form → reconnection and heating.





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

REVIEW ARTICLE

The Parker problem: existence of smooth force-free fields and coronal heating

David I. Pontin[1,2] · Gunnar Hornig[2]

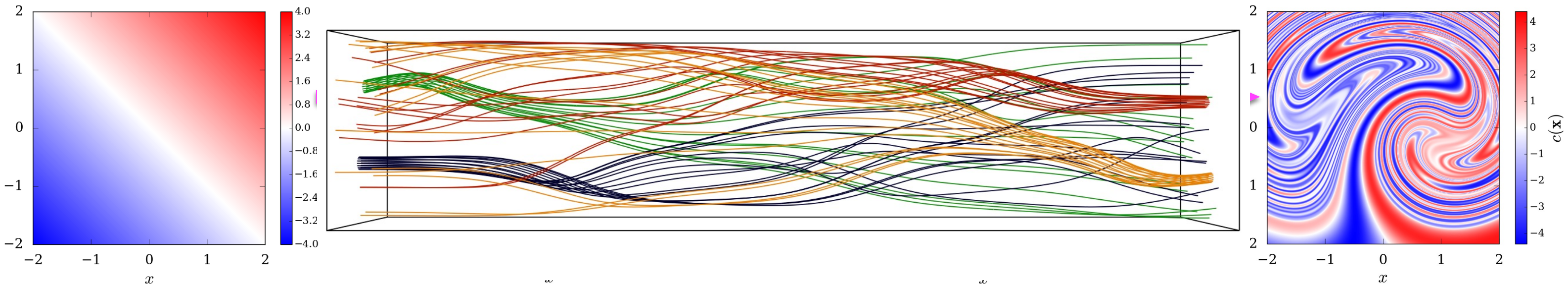
Living Reviews in Solar Physics (2020)17:5
https://doi.org/10.1007/s41116-020-00026-5

Parker's braiding mechanism

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

- Parker's claim is that no smooth equilibrium exists for braided fields → substantial debate without a consensus.
- No hard proof of current sheet (T.D.) formation in a geometry matching Parker's.
- But this does not matter….!
- Current sheets get progressively thinner as braid complexity increases (van Ballegooijen 1988, Mikić+ 1989, Pontin & Hornig 2015)
- **In solar corona continual braiding will inevitably lead to reconnection onset**

(Finite) current layers in equilibrium



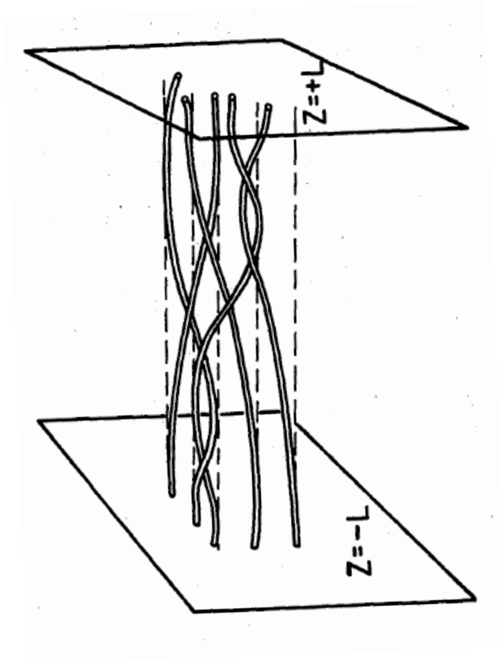
- Recall equilibrium satisfies $\mathbf{J}\times\mathbf{B} = (\nabla\times\mathbf{B})\times\mathbf{B} \approx 0$
- Suppose that $\nabla \times \mathbf{B} = \alpha \mathbf{B}$ so that $\mathbf{B} \cdot \nabla \alpha = 0$ and α const along B-lines
- Suppose α has distribution with length scale ℓ on (e.g.) 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

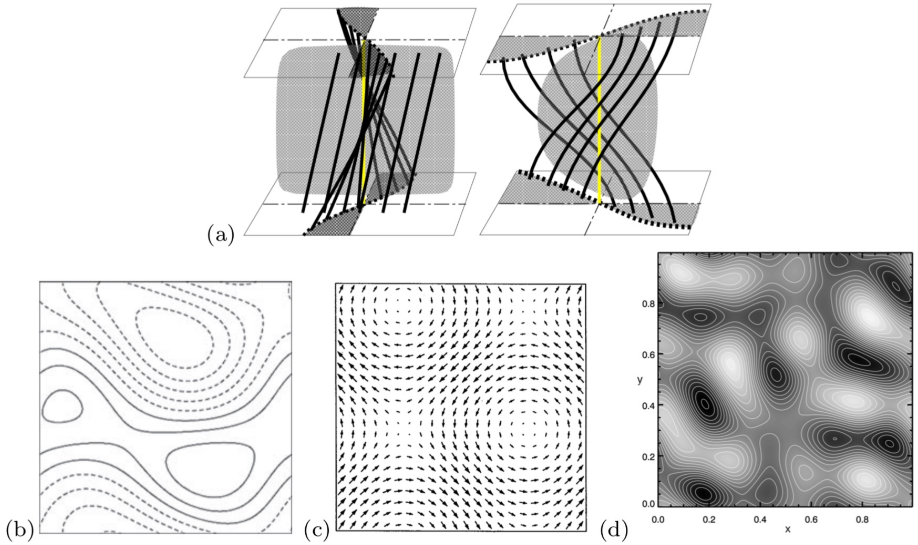
[Pontin & Hornig 2015, c.f. van Ballegooijen 1988]

Flux braiding simulations

Continuous driving in a resistive plasma ("flux braiding")

- Many different approaches:
  - Driven vs relaxation
  - Full MHD vs Reduced MHD
  - Domain aspect ratios from 1:1 to 1:10
  - Different driving velocities (sequence of shears, superposition of vortices,…)





REVIEW ARTICLE

The Parker problem: existence of smooth force-free fields and coronal heating

David I. Pontin[1,2] · Gunnar Hornig[2]

Living Reviews in Solar Physics (2020)17:5
https://doi.org/10.1007/s41116-020-00026-5

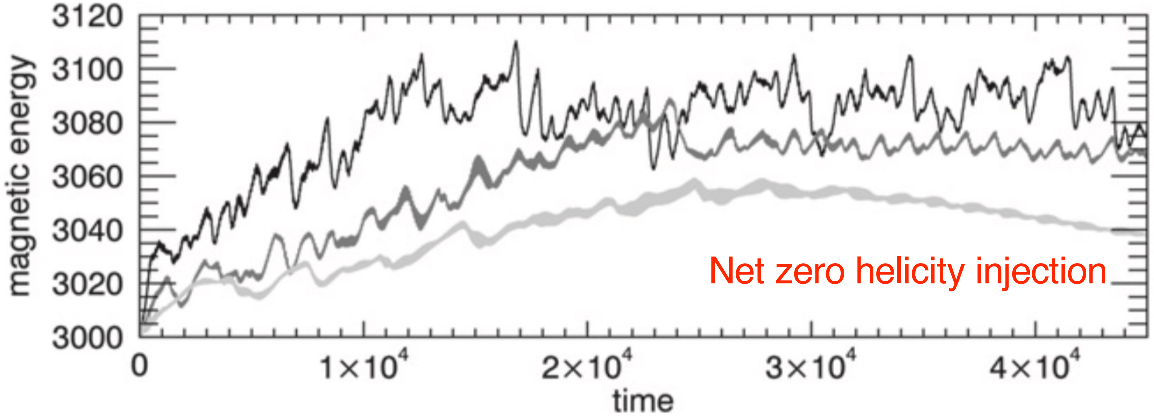
Main results of flux braiding experiments

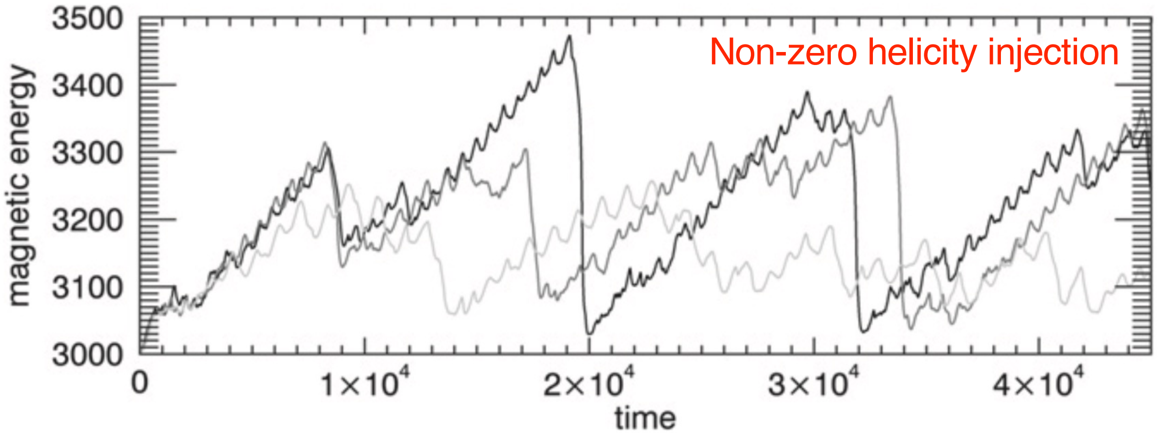
- Thin ribbons of current form, thickness decreases exponentially in time.
- Evolution resembles anisotropic turbulent cascade (either driven or decaying).
- Scaling exponents in stat. steady state depend on loop length, field strength…
- $E_m > E_k$ by a factor of 10 at least.
- E_m (equivalently $\langle B_\perp \rangle$) scales with driving speed v_0. Also scales with R_m, at least for $R_m \leq 10^3$.
- Geometry of driving has minimal importance, but helicity injection rate or correlation time may affect characteristics of energy release.

- Outstanding issues:
  - Most studies of scaling with R_m use RMHD: for large R_m, $B_\perp$ may grow sufficiently large to invalidate assumptions.
  - …and Poynting flux into volume depends on coronal state.
  - Coronal state is a function of R_m
  - Question of timescales: driving timescale vs energy release timescale
  - Effect of plasma/magnetic field structuring of chromosphere/carpet

Main results of flux braiding experiments

- Thin ribbons of current form, thickness decreases exponentially in time.
- Evolution resemb... ...ng).
- Scaling exponen... ...th…
- $E_m > E_k$ by a fact...
- E_m (equivalently ... ...least for $R_m \leq 10^3$.
- Geometry of driv... ...orrelation time may affect chara...





- Outstanding issu...
  - Most studies o... ...ficiently large to invalidate as...
  - …and Poynting...
  - Coronal state i...
  - Question of tim...
  - Effect of plasma/magnetic field structuring of chromosphere/carpet

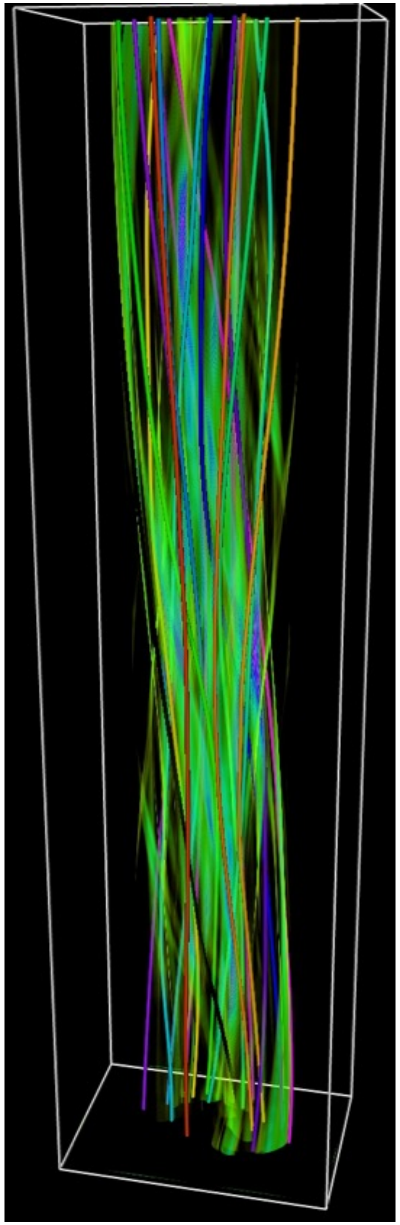
Main results of flux braiding experiments

- Thin ribbons of current form, thickness decreases exponentially in time.
- Evolution resembles anisotropic turbulent cascade (either driven or decaying).
- Scaling exponents in stat. steady state depend on loop length, field strength…
- $E_m > E_k$ by a factor of 10 at least.
- E_m (equivalently $\langle B_\perp \rangle$) scales with driving speed v_0. Also scales with R_m, at least for $R_m \leq 10^3$.
- Geometry of driving has minimal importance, but helicity injection rate or correlation time may affect characteristics of energy release.

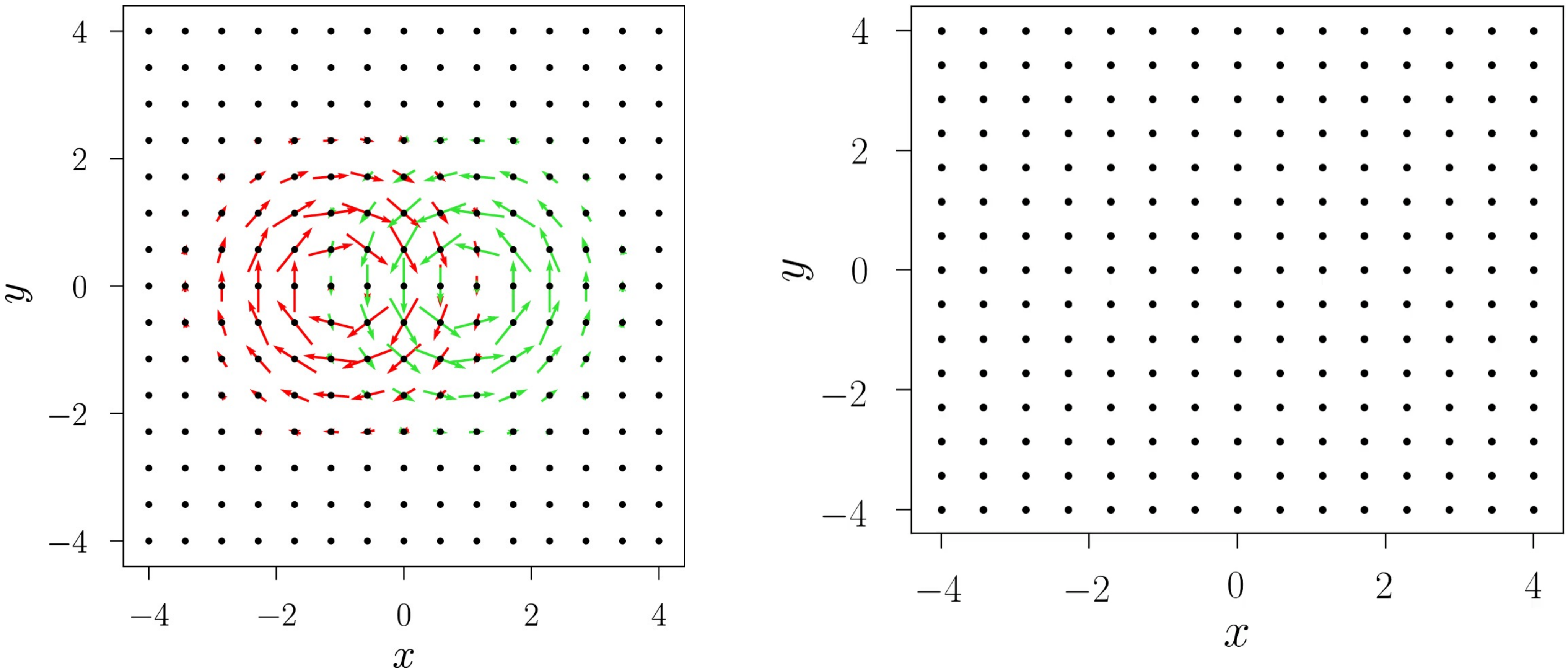
- Outstanding issues:
  - Most studies of scaling with R_m use RMHD: for large R_m, $B_\perp$ may grow sufficiently large to invalidate assumptions.
  - …and Poynting flux into volume depends on coronal state.
  - Coronal state is a function of R_m
  - Question of timescales: driving timescale vs energy release timescale
  - Effect of plasma/magnetic field structuring of chromosphere/carpet

MHD simulation – flux braiding

- Start from uniform magnetic field
- Apply driving continuously on line-tied boundaries
- Other boundaries periodic
- Solve resistive MHD equations (no thermal conduction, radiative losses). Hyper-resistivity/ viscosity
- 6x6x48 Mm
- Plasma-beta: 0.05
- 640x264x264;   1280x528x528;   1280x1056x1056
- Low and Med runs go to t~500 which is ~12 periods of driver. High run goes only until t~250

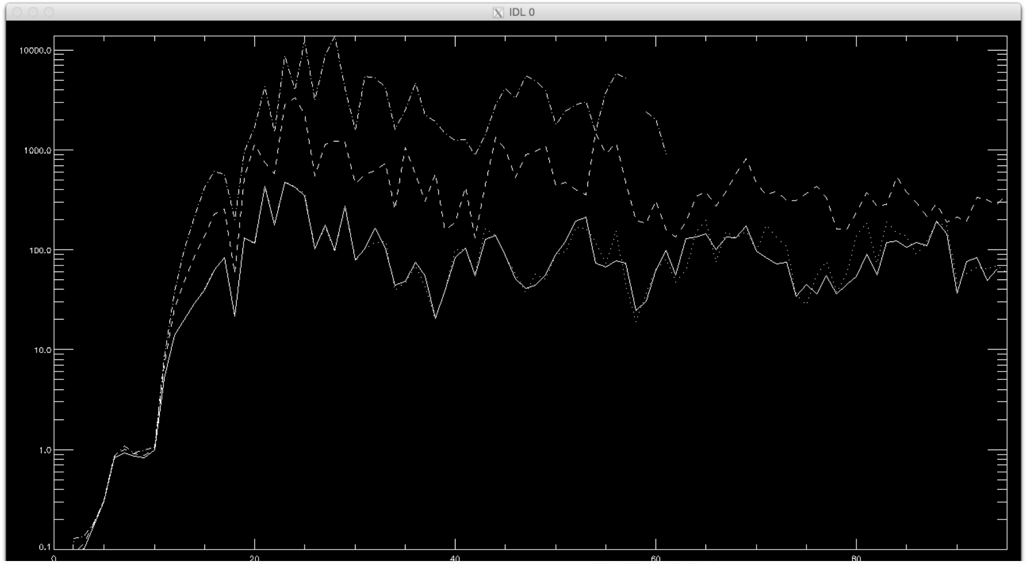


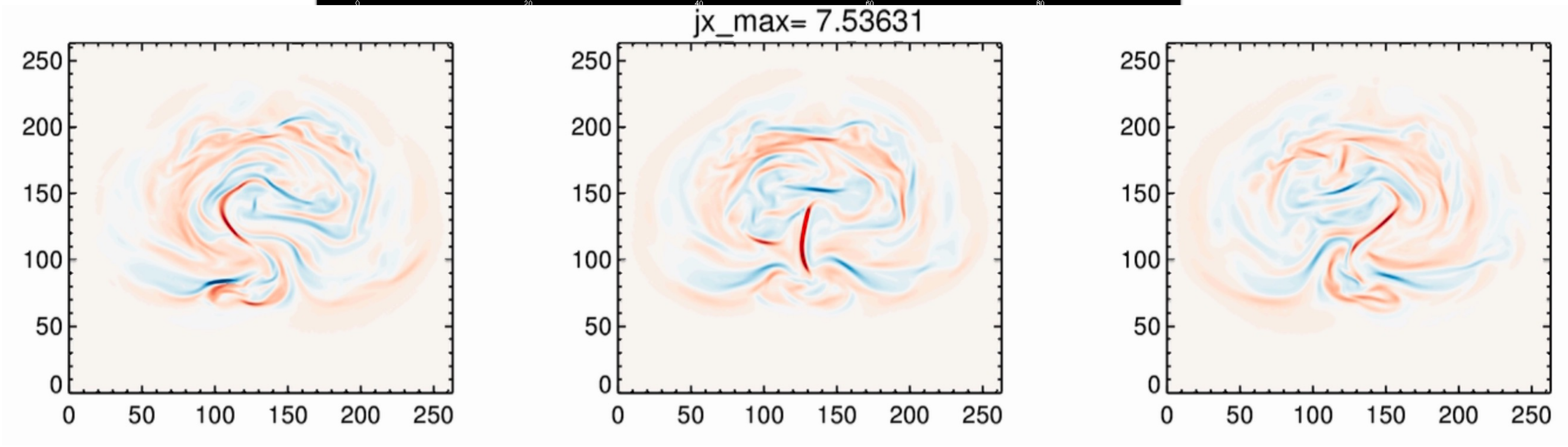
Boundary driving

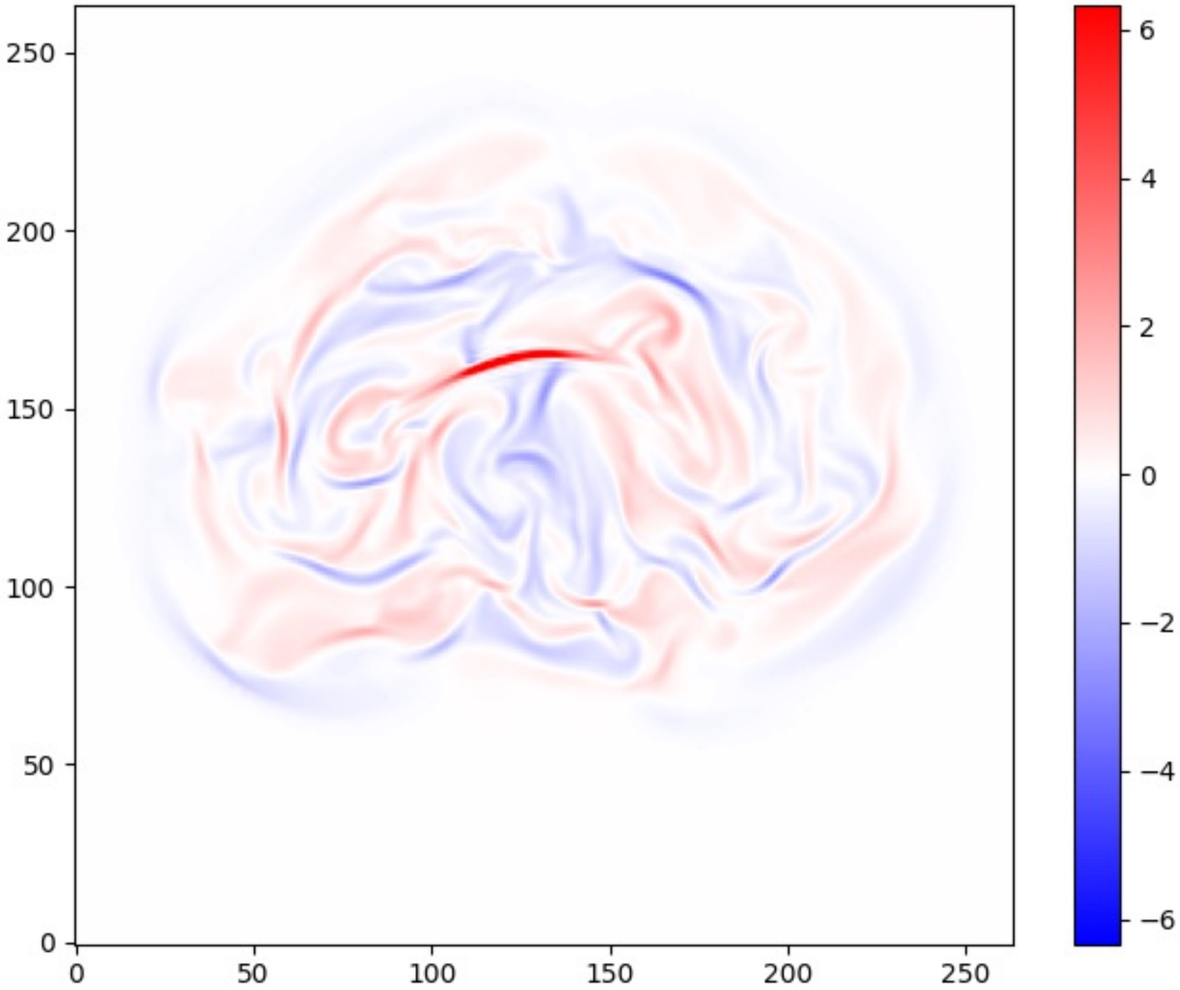


Evolution of axial current with time

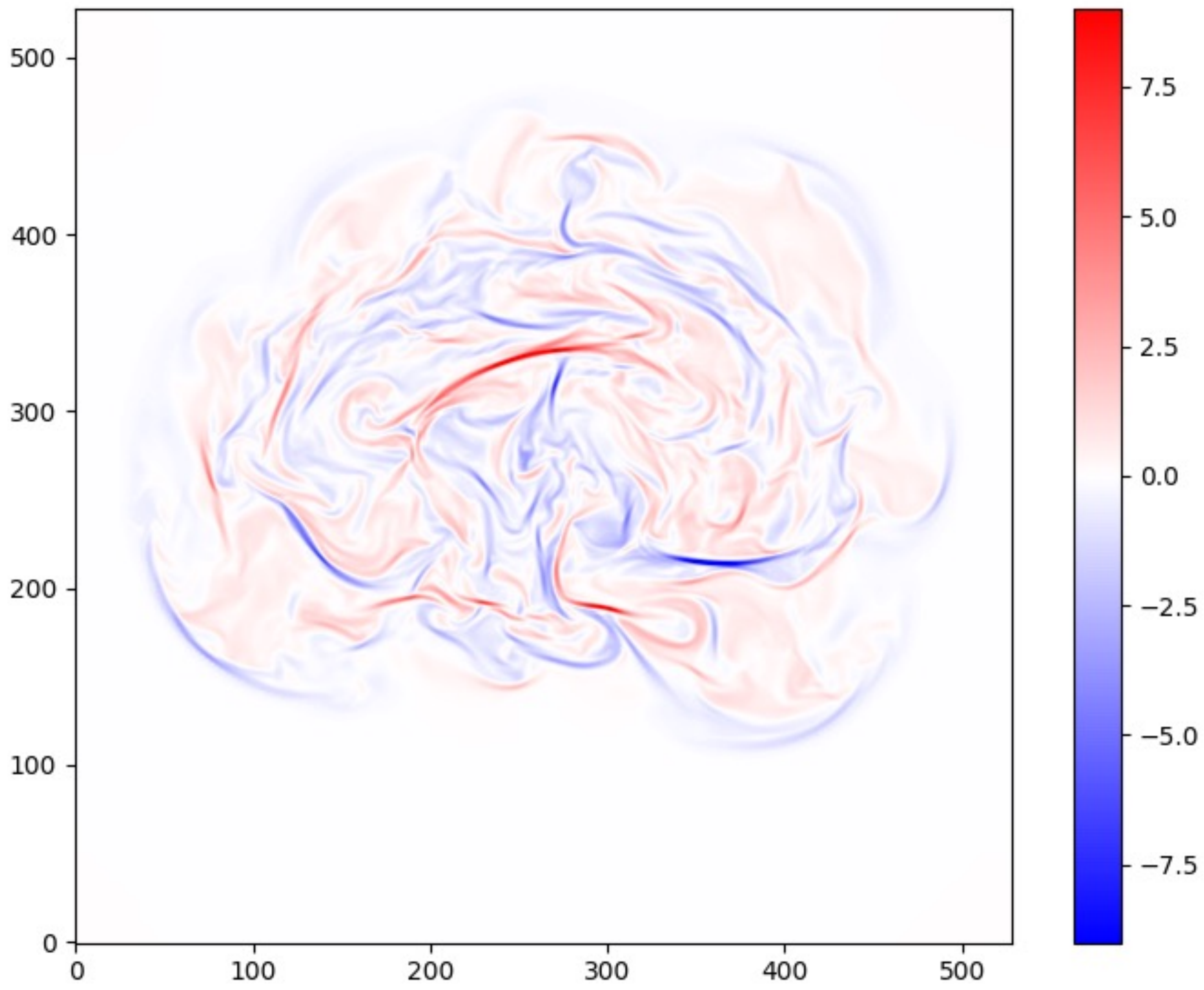
J_{max}



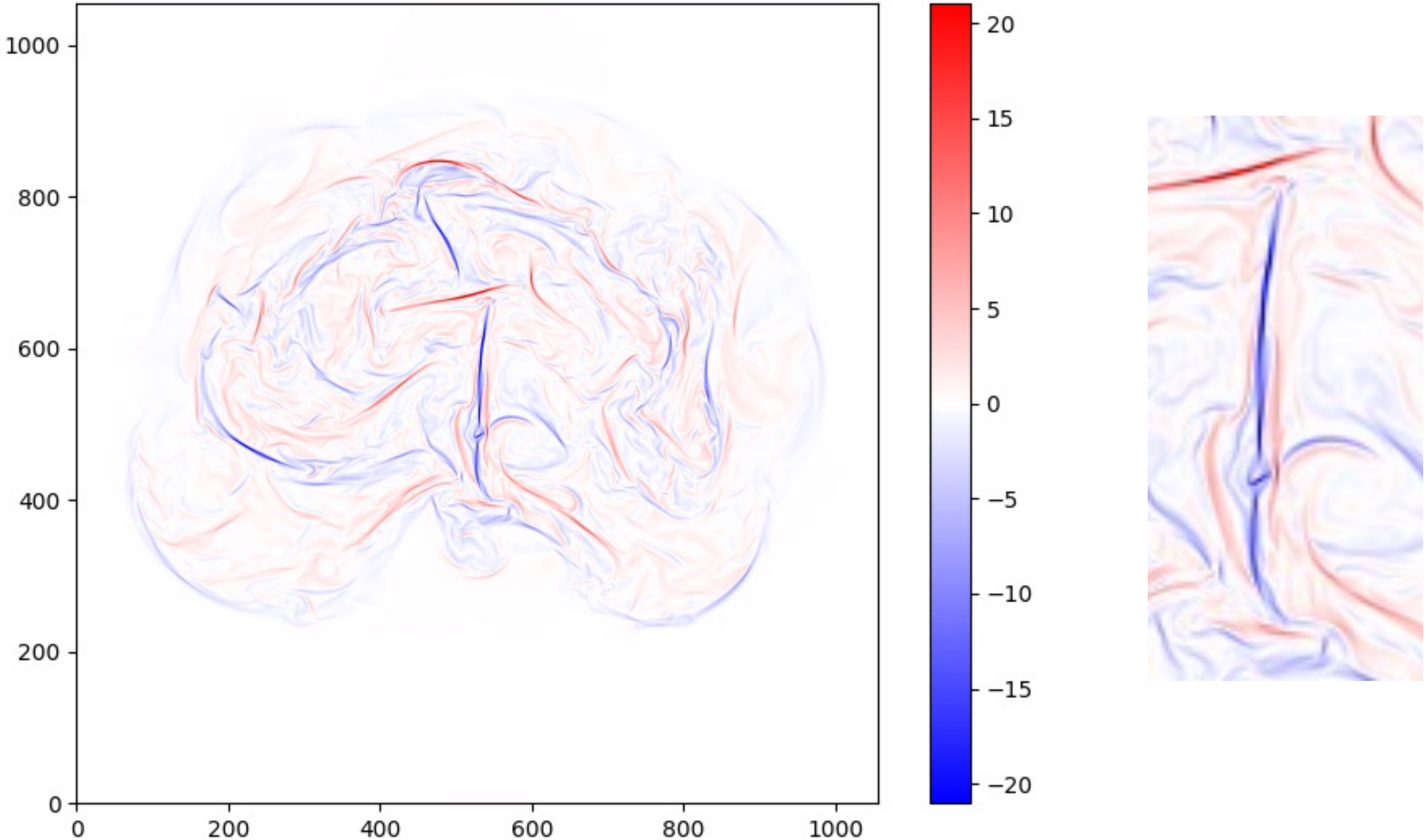




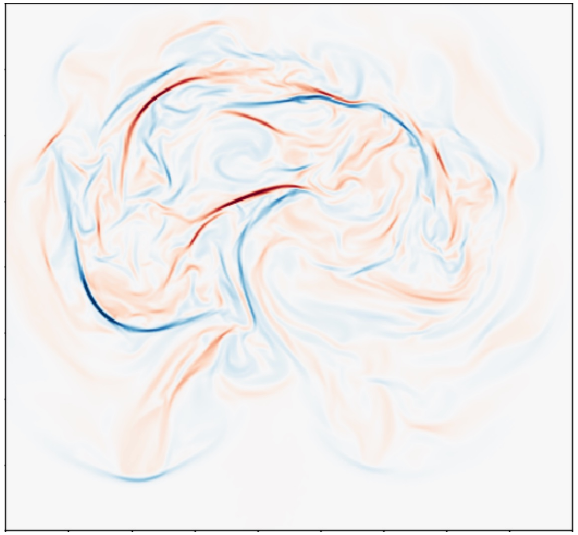
250
200
150
100
50
0
0
50
100
150
200
250
6
4
2
0
−2
−4
−6



500
400
300
200
100
0
0
100
200
300
400
500
7.5
5.0
2.5
0.0
−2.5
−5.0
−7.5

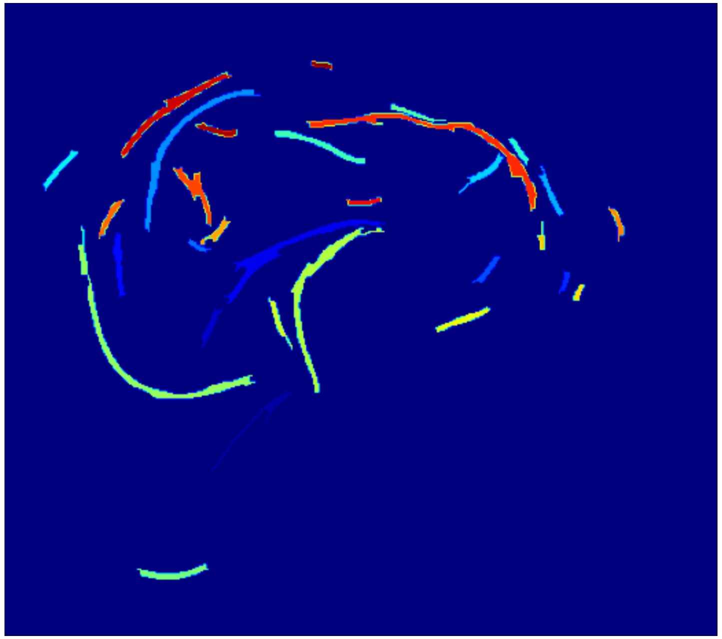


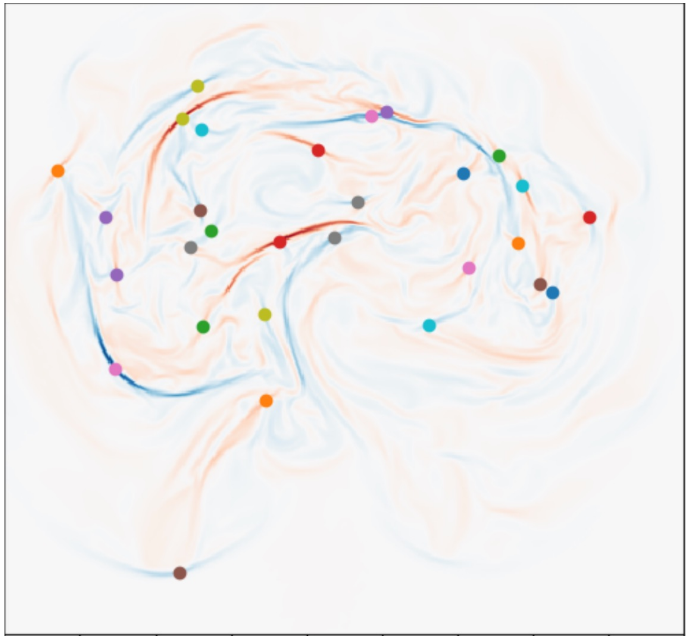
1000
800
600
400
200
0
0
200
400
600
800
1000
20
15
10
5
0
−5
−10
−15
−20



Identify rec regions

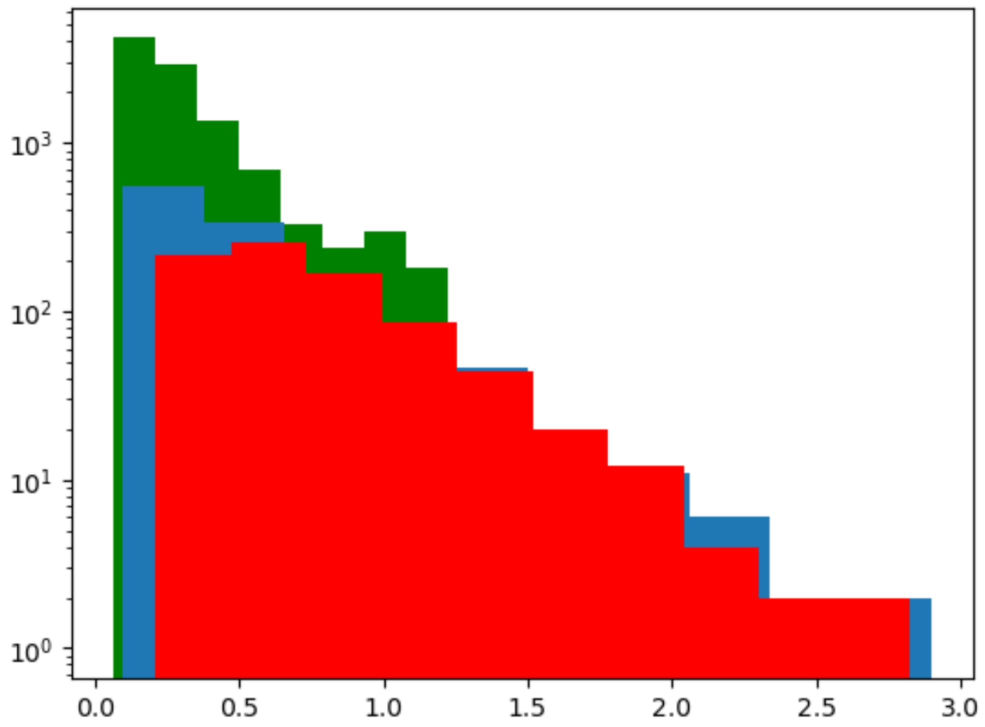
- “Canny” edge detection
- Separate $J_z>0$ and $J_z<0$
- Morphological closing
- Region labelling
- Identify end and centres of regions
- So far just in midplane



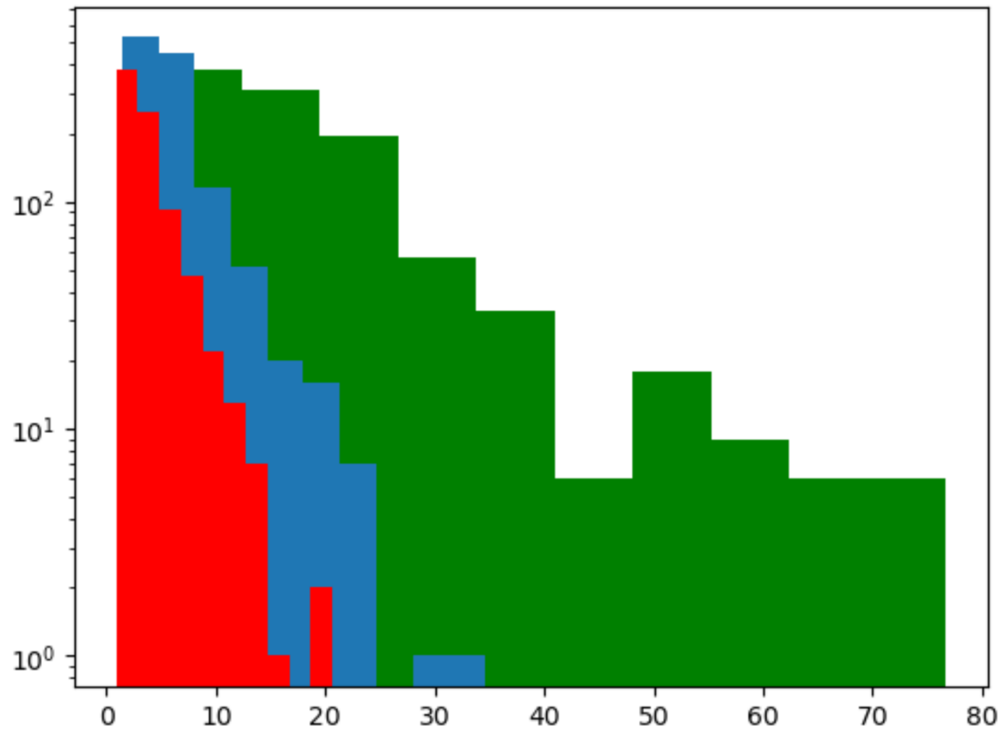


Distribution of current sheet lengths

Sheet lengths



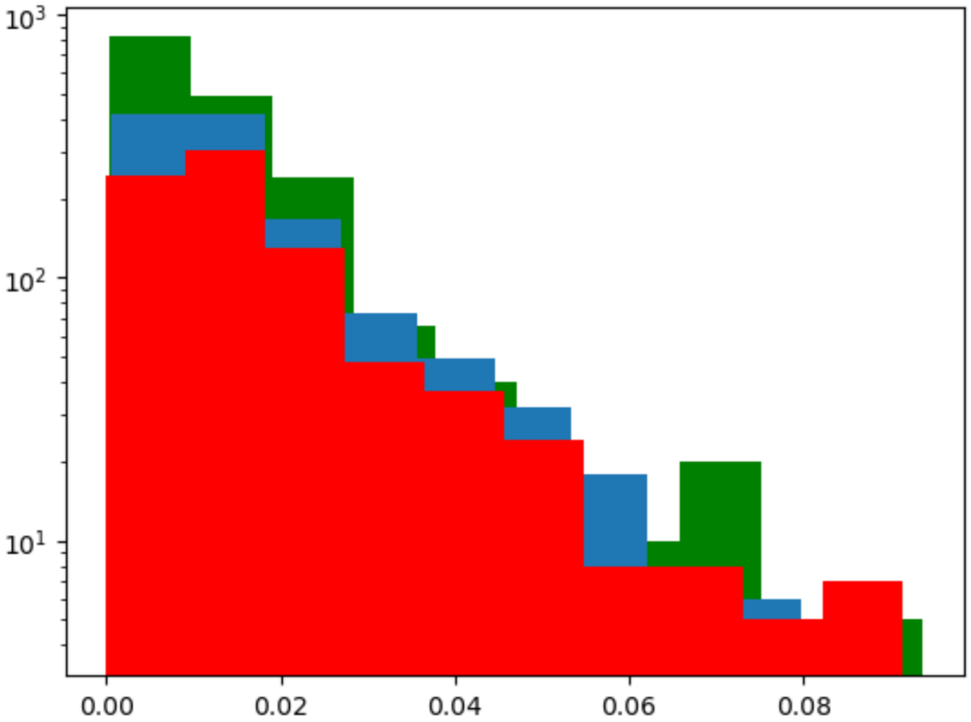
J_{max}



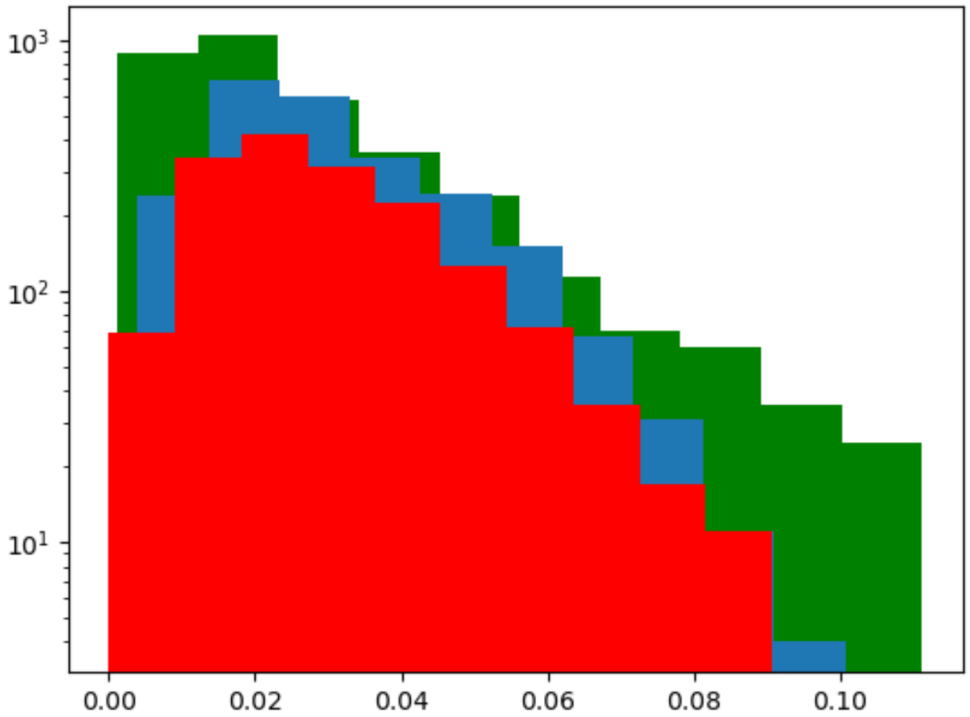
Note: normalisation of distributions is nonsense!

Distribution of current sheet in/outflows

v_{in}



v_{out}



Note: normalisation of distributions is nonsense!

An aside: non-thermal line-broadening in a flux braiding simulation

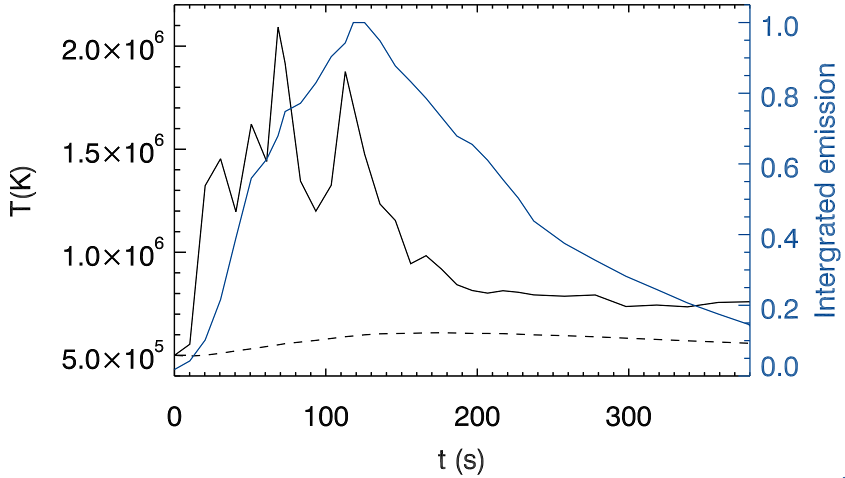
A&A 639, A21 (2020)
https://doi.org/10.1051/0004-6361/202037582

Astronomy & Astrophysics

Non-thermal line broadening due to braiding-induced turbulence in solar coronal loops

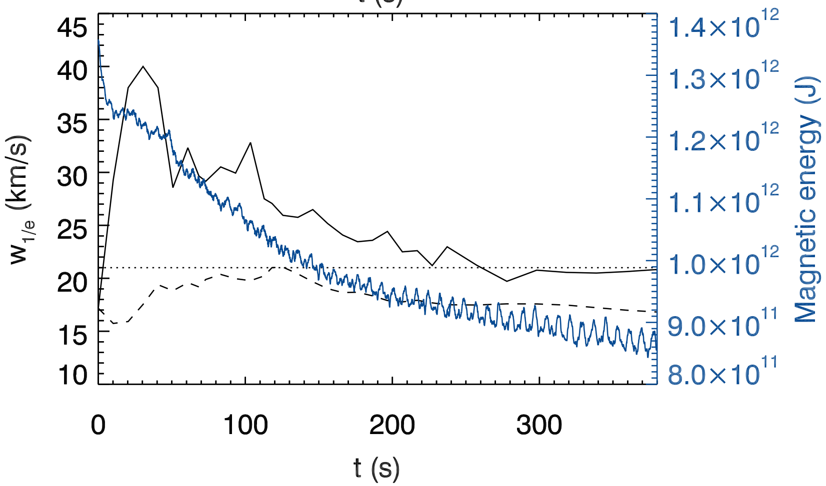
D. I. Pontin[1,2], H. Peter[3], and L. P. Chitta[3]

Results: line broadening



Maximum temperature

Emission integrated over loop



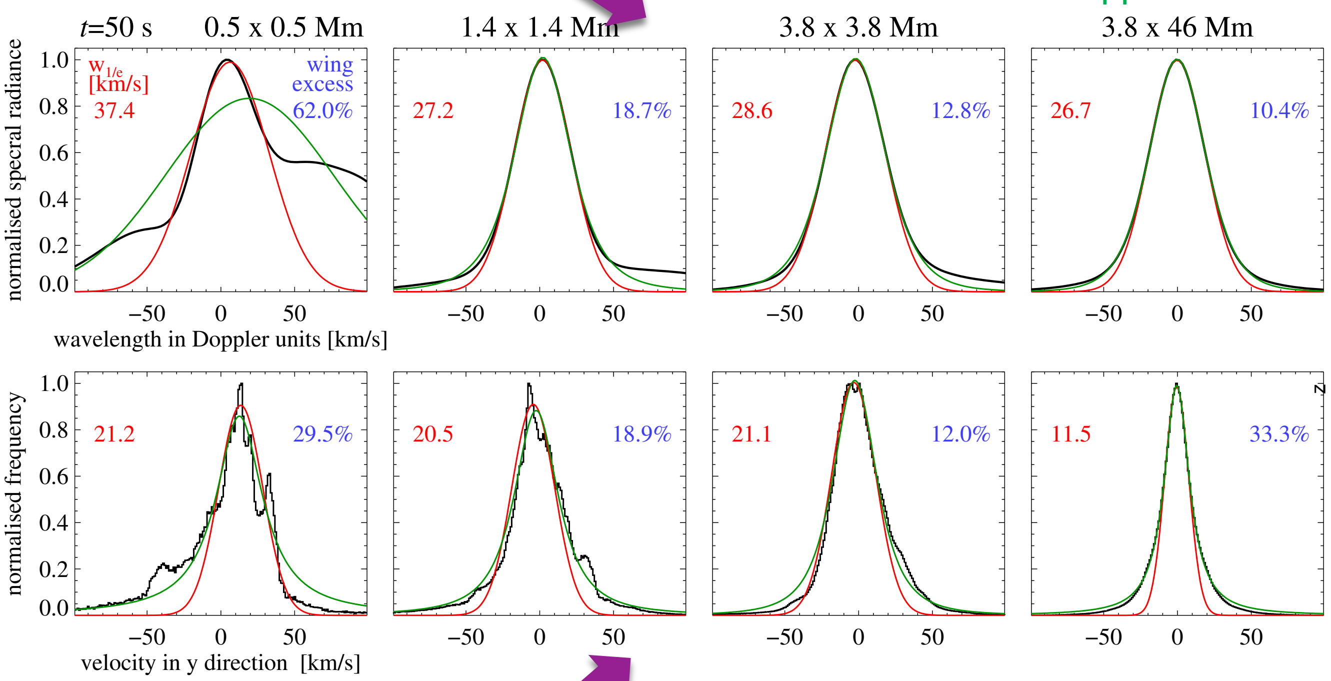
1/e-width of emission line

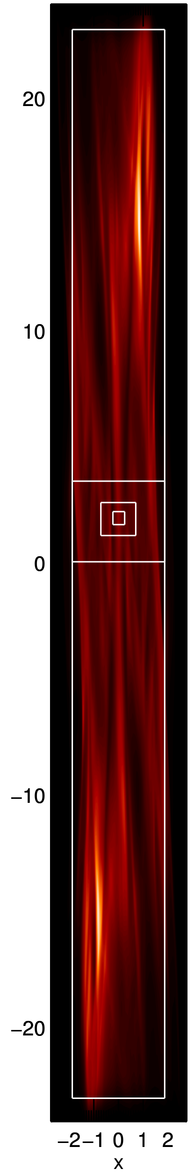
Magnetic energy

- When loop is brightest, $w_{1/e}$ ~ 25-30 km/s $\Longrightarrow$ w_{nth} ~ 14-21 km/s

Results: non-Gaussian spectra

Integrated emission (normalised)

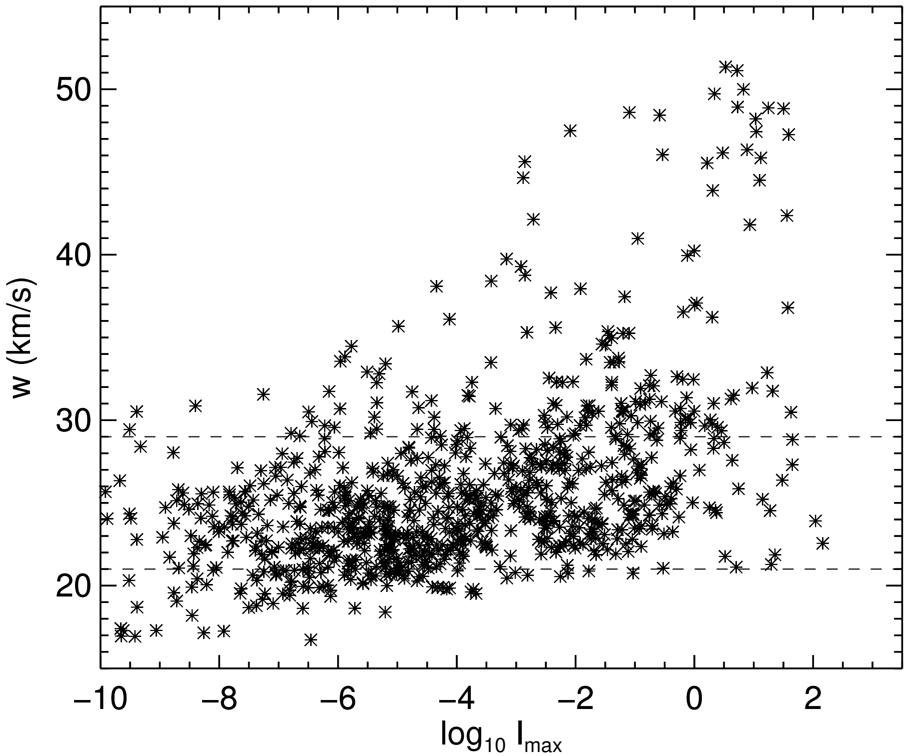




Line-of-sight velocity histograms

- Property (2): broadening ~indep of resolution
- Property (4): enhanced power in wings compared to Gaussian (~20%) – inherited from velocity distribution

Results: intensity vs line width



- Property 3: correlation between line width and intensity
- Speculate: strongest flows assoc with recently reconnected flux bundles

Conclusions (line broadening study)

- Recall: Coronal loop emission spectra (forming at around 1 to a few MK) exhibit the following properties:
  1) the non-thermal broadening is of the order of 15–30 km s^{-1}
  2) the broadening is approximately independent of instrument resolution (down to ~0.35′′),
  3) the correlation of line intensity and the non-thermal broadening
  4) the line profiles are non-Gaussian with enhanced power in the wings.
- These 4 properties reproduced self-consistently by loop heating through magnetic braiding.
- Wing enhancements are directly related to underlying velocity distribution, a signature of intermittency.