Dissipation and Heating in MRI Turbulence

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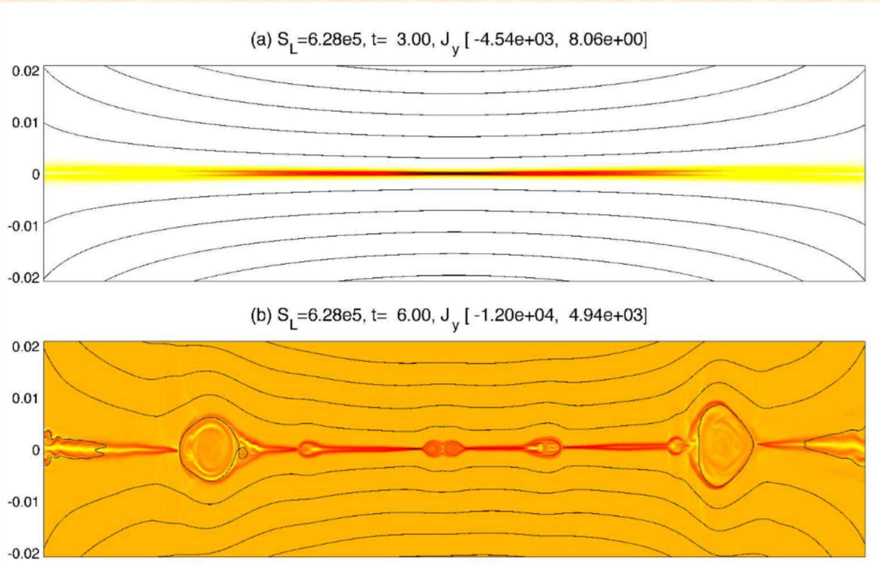
Work with Ji-Ming Shi (PU)

Dissipation and Heating

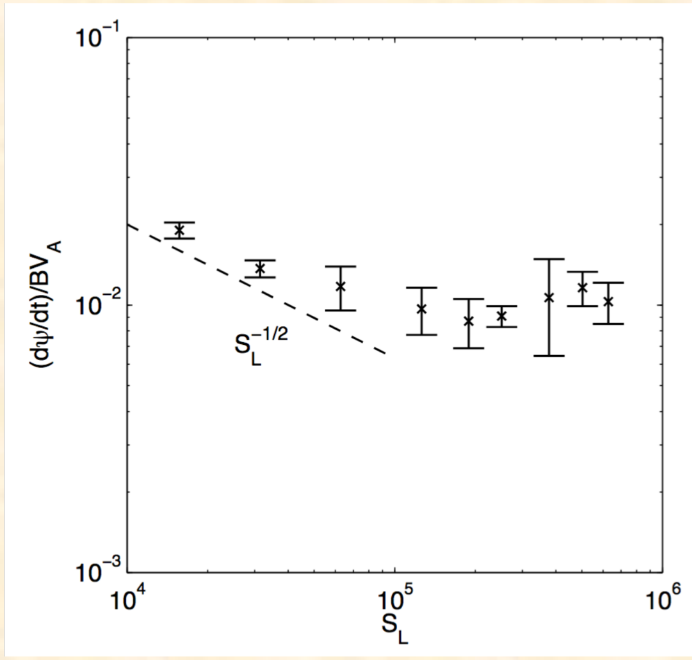
- Small-scale dissipation directly related to heating and disk emission. Therefore important to understand.
- Previous work has shown Ohmic resistivity can dominate dissipation mechanisms (e.g. Lesur & Longaretti 2007; Simon & Hawley 2009; Guan et al. 2009).
- Further work on reconnection in driven and MRI turbulence has studied statistics in incompressible regime (Zhdankin et al. 2017)
- Investigate role of different dissipation mechanisms (resistivity, viscosity, shocks) and intermittency/statistics of dissipation regions (Ross & Latter 2018).

Further motivation from recent studies of reconnection

Reconnection rate of idealized current sheets independent of Lundquist number due to plasmoid instability (Loureiro & Uzdensky 2016; Huang & Bhattacharjee 2016; Cerri & Califano 2017)



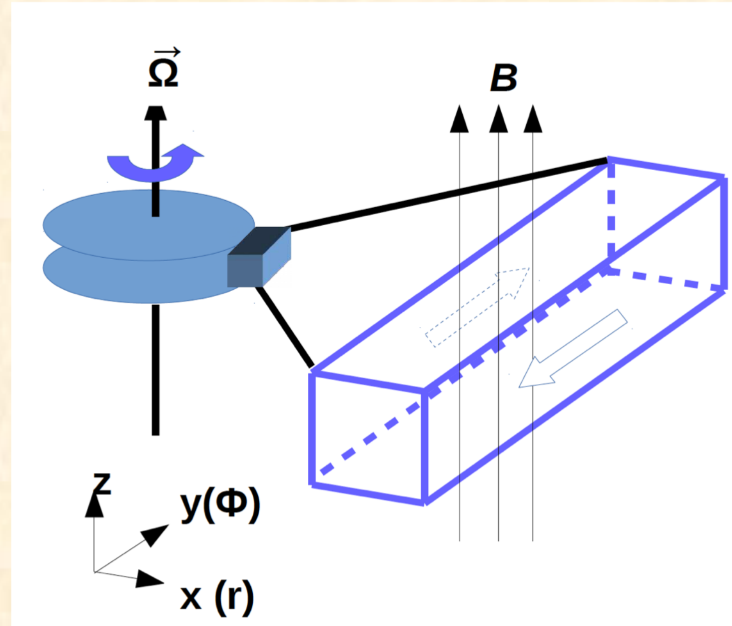
Disruption of Sweet-Parker reconnection layer by plasmoids

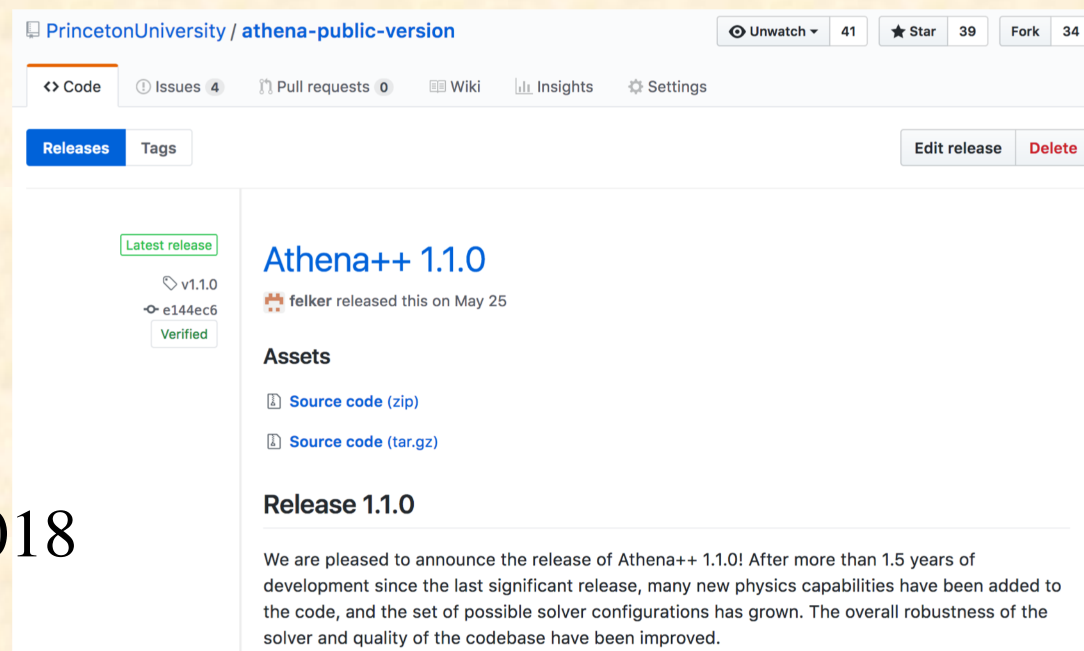


Reconnection rate constant for Lundquist number $S = V_A L/\eta > 3 \times 10^4$

Model setup and parameters

- Local unstratified shearing box
- Box size: 2 x 4 x 1 H
- High resolution: 512/H
- Weak vertical net field: $\beta \sim 1000$
- Explicit viscosity and resistivity: $P_m = 1$, $Re_M = 4000, 8000, 16000$



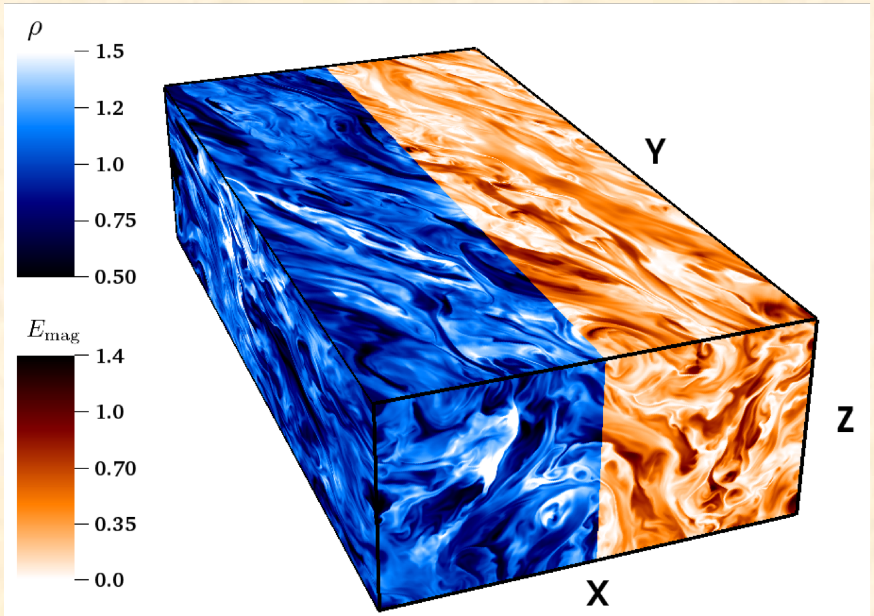


Simulations use Athena++
New public version: 25/5/2018

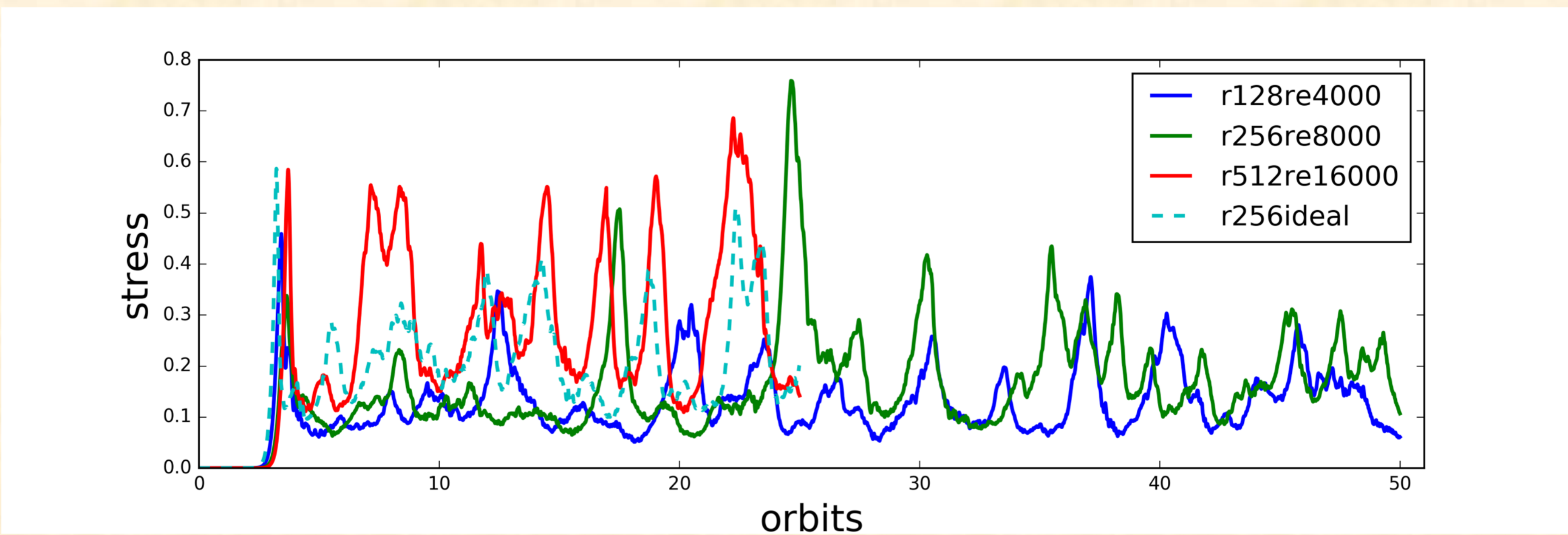
Converged results for different Re

Name[a]	$\Delta T(\Delta T_{\rm avg})^{(b)}$ (orbits)	$\alpha_{\rm M}{}^{(c)}$ $(\times 0.01)$	$\alpha_{\rm R}{}^{(c)}$ $(\times 0.01)$	$\alpha_{\rm tot}{}^{(c)}$ $(\times 0.01)$	$\frac{\mathcal{E}_\eta}{\mathcal{E}_\nu}\ ^{(d)}$
r64re4000	50 (25)	9.83	2.66	12.49	2.50
r128re4000	50 (25)	10.84	2.74	13.58	2.45
r256re4000	25 (10)	10.43	2.38	12.81	2.47
r512re4000	25 (10)	10.33	3.18	13.51	2.42
r256re8000	50 (25)	16.07	3.17	19.23	2.05
r512re8000	25 (10)	17.83	3.47	21.30	2.02
r256re8000adb	18(10)	15.96	2.54	18.50	2.59
r512re16000	25 (10)	26.24	4.61	30.85	1.70
r256ideal	25 (10)	18.76	3.38	22.14	$\cdots$

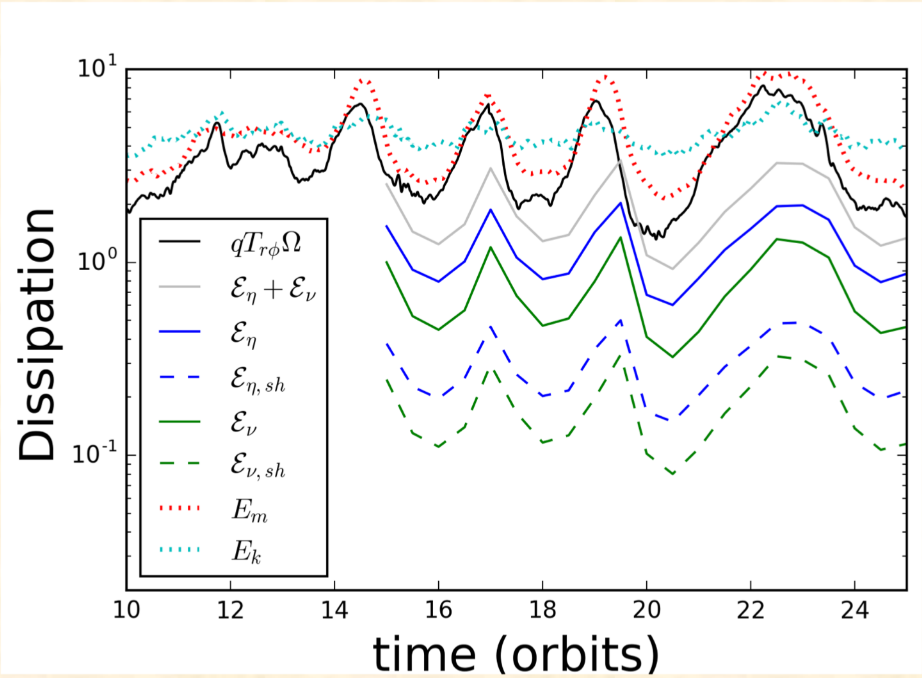
Non-linear saturation

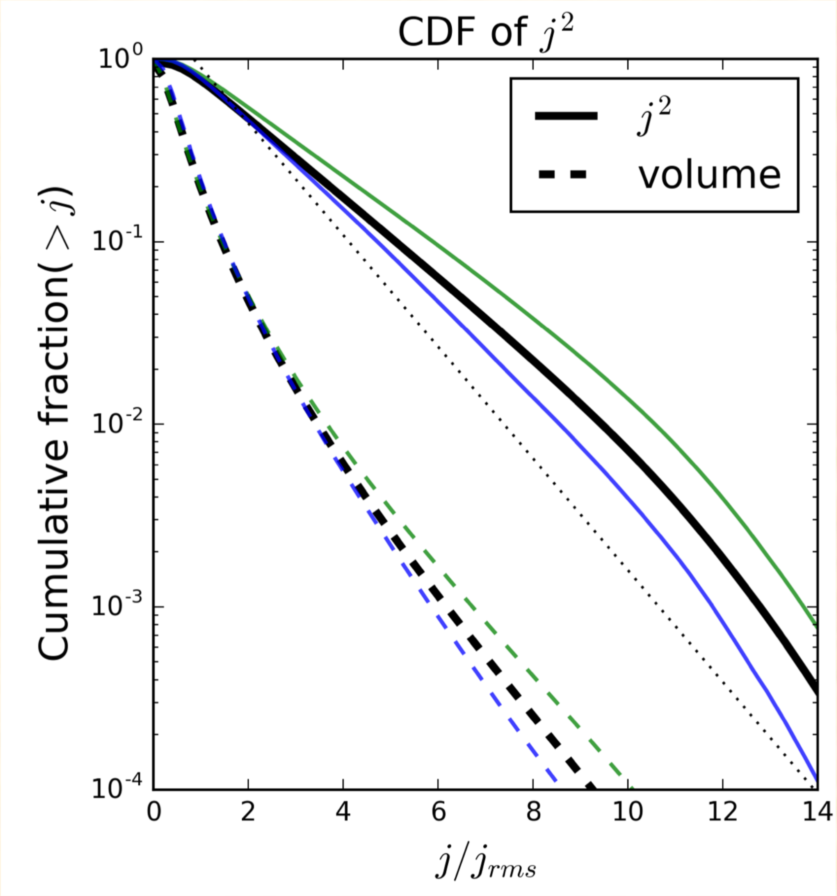


- Bursty behavior
- Channel modes
- $\alpha \sim Re_M^{1/2}$



Dissipation



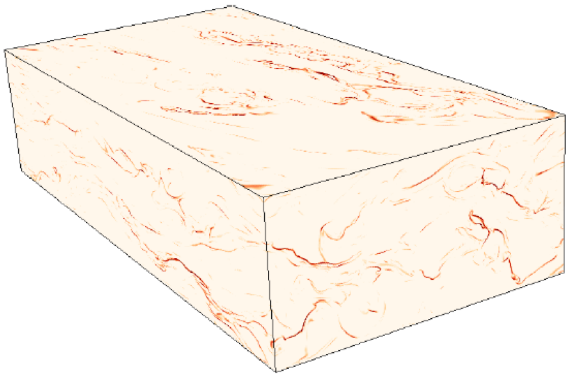


- Ohmic dissipation about 2x viscous dissipation.
- Compressional heating about 40% of total.

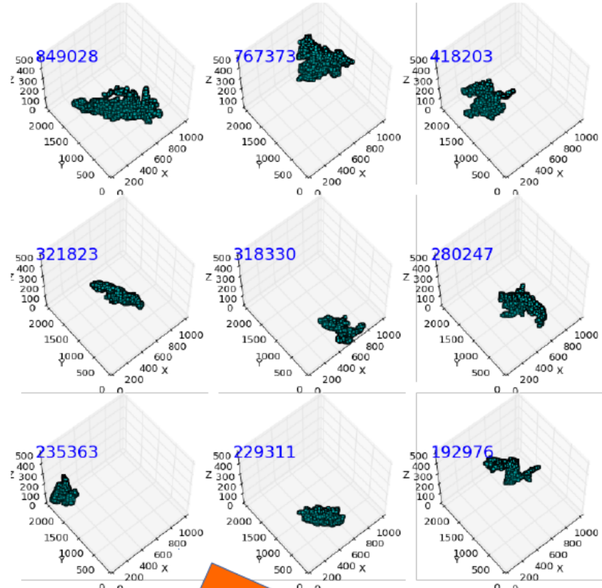
See also Ross & Latter (2018)

- Volume filling fraction of large Ohmic dissipation small.
- Blue/green lines show ranges during channel modes

Identifying current sheets

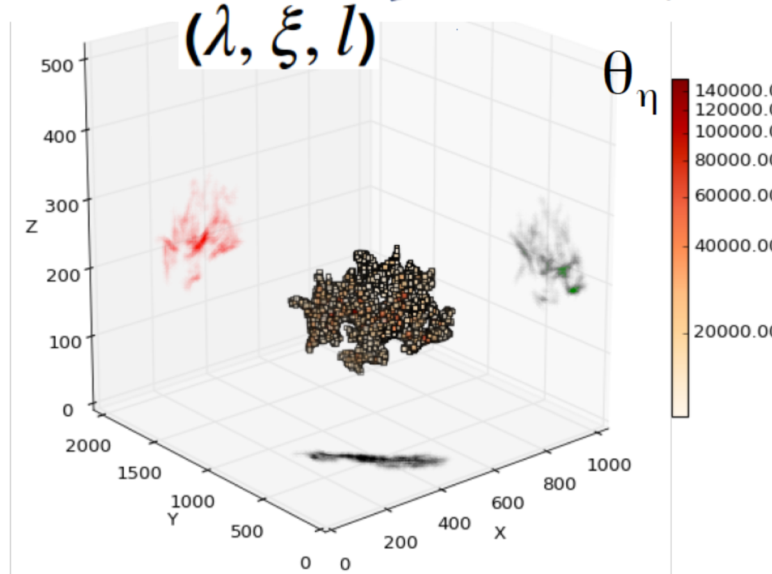


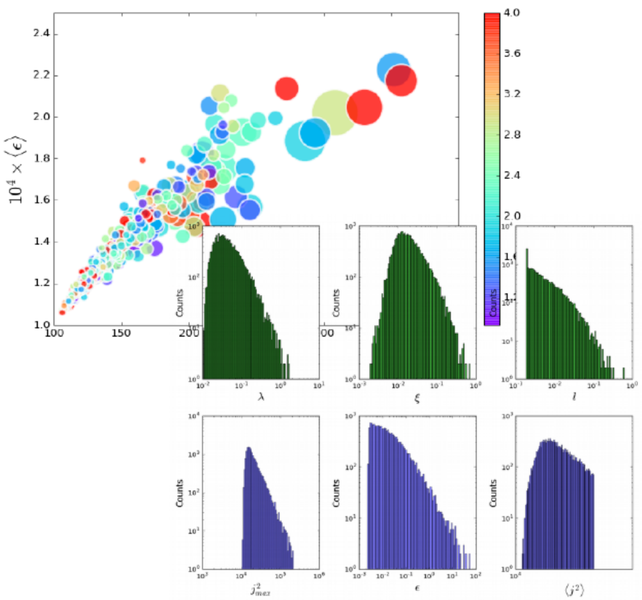
Connected component labeling algorithm `(scikit-image)`



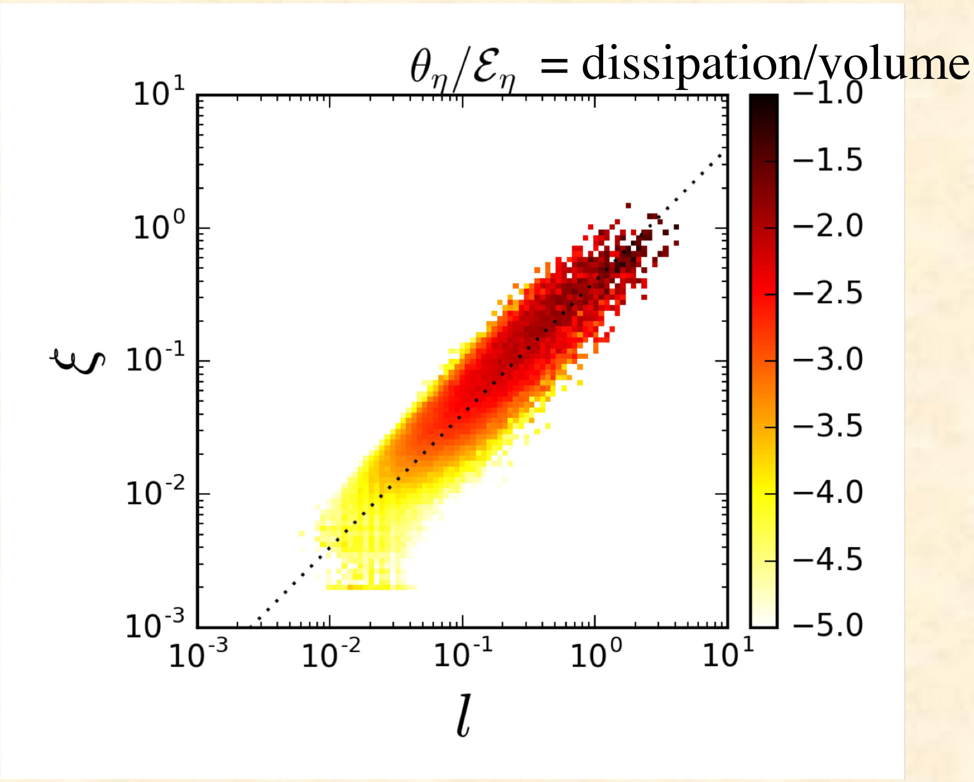
PCA `(sklearn)`

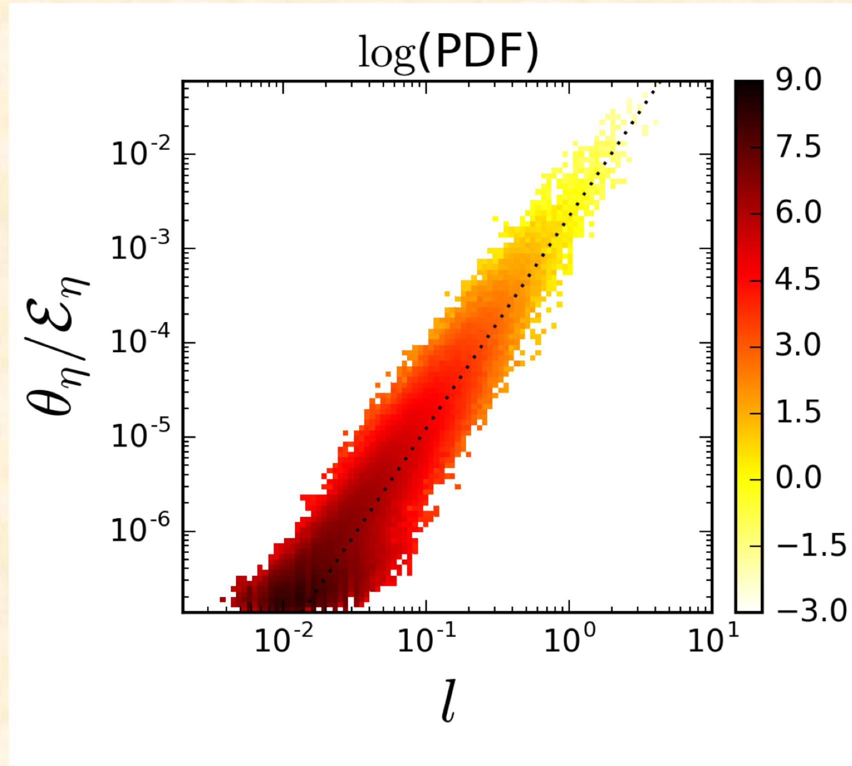
(λ, ξ, l)





Statistics of current sheets





- Length L ~ 3 Width
- Largest structures have largest dissipation

PDF results in equal contribution to dissipation at all scales (Zhdankin et al. 2014)

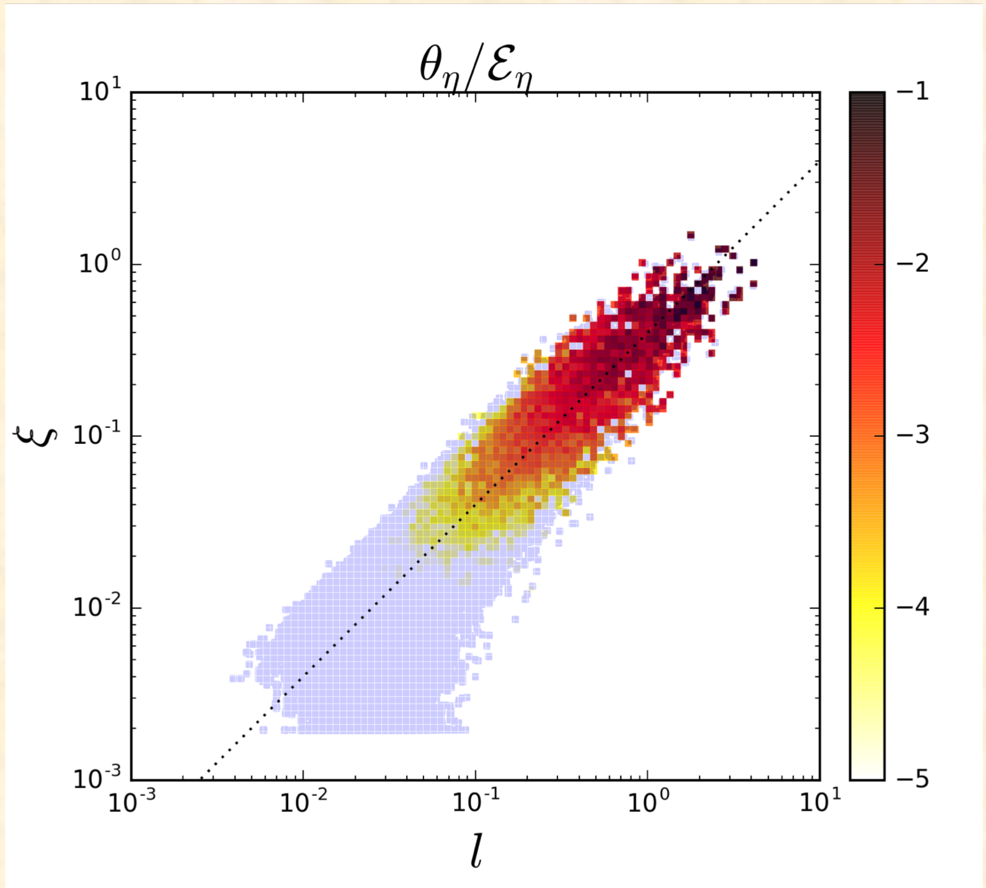
Overall very good agreement with previous studies (Zhdankin et al 2017)

Are current sheets produced by reconnection?

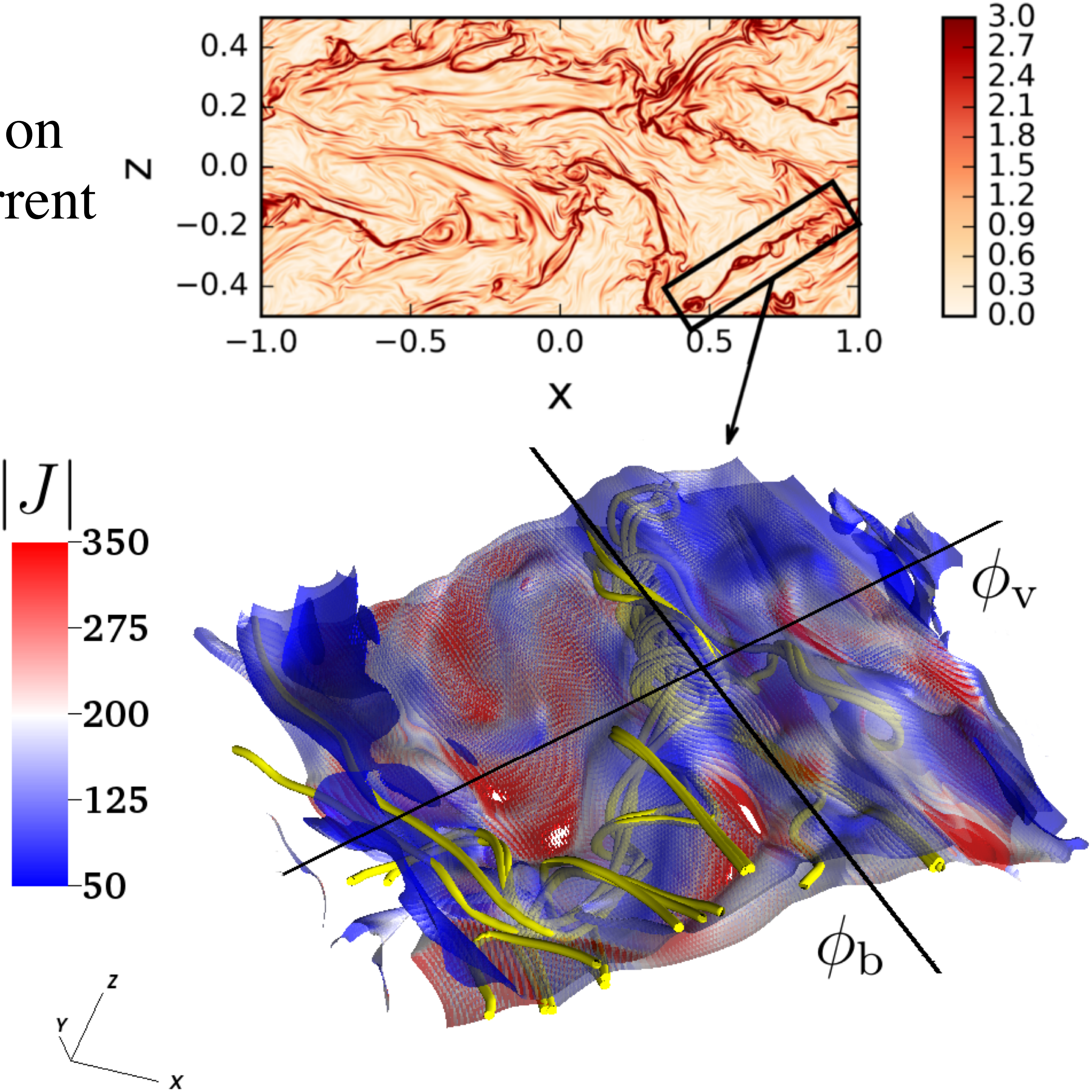
- Difficult to identify reconnection regions in 3D
- We require two components of B to vanish and the third to change sign to label a region as a reconnection site (Haynes & Parnell 2007)

Red/yellow points = reconnection
Blue points = no reconnection

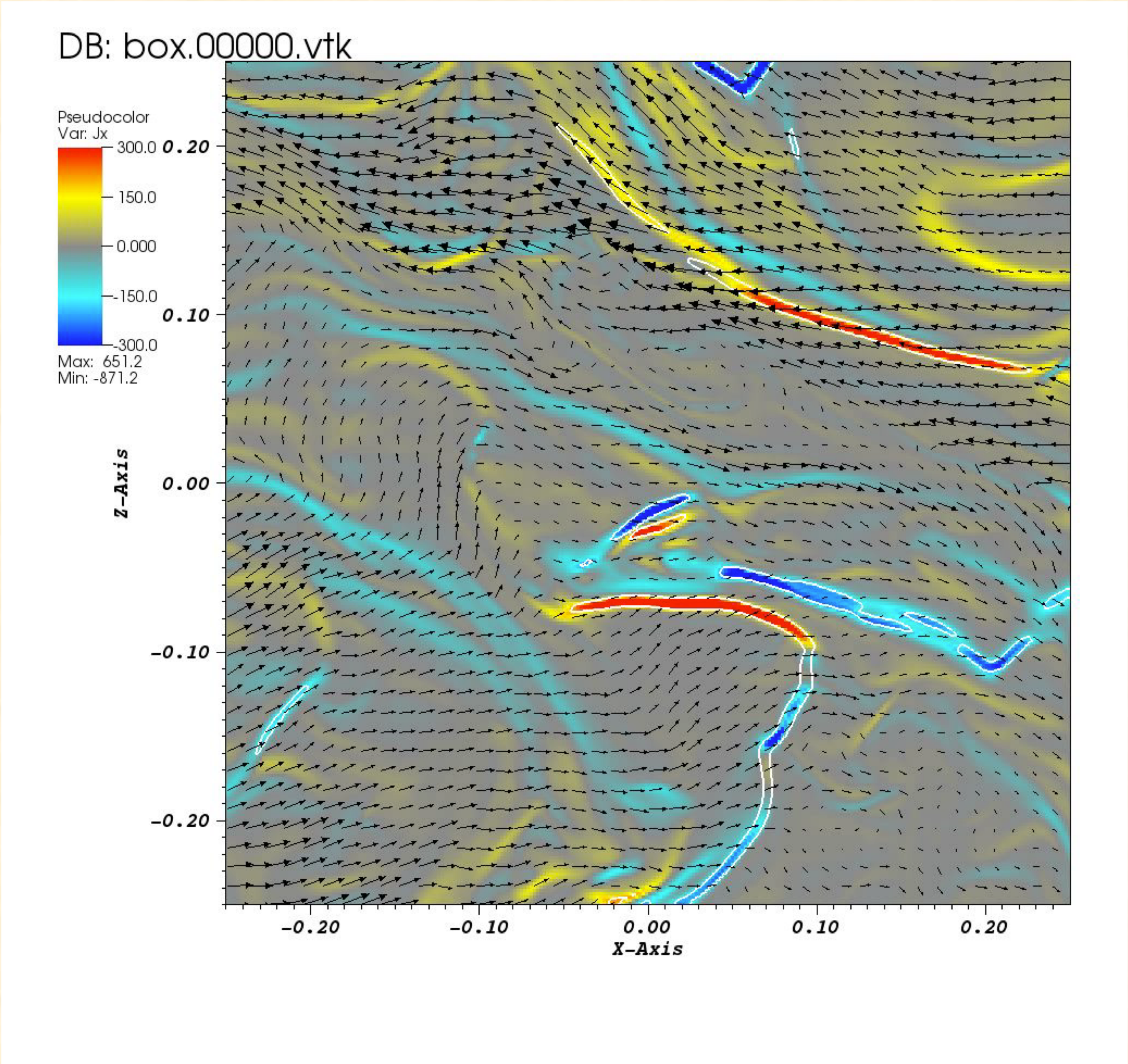
Most current sheets can be identified as reconnection sites.



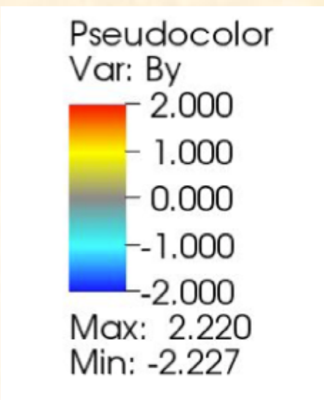
Zooming-in on individual current sheets

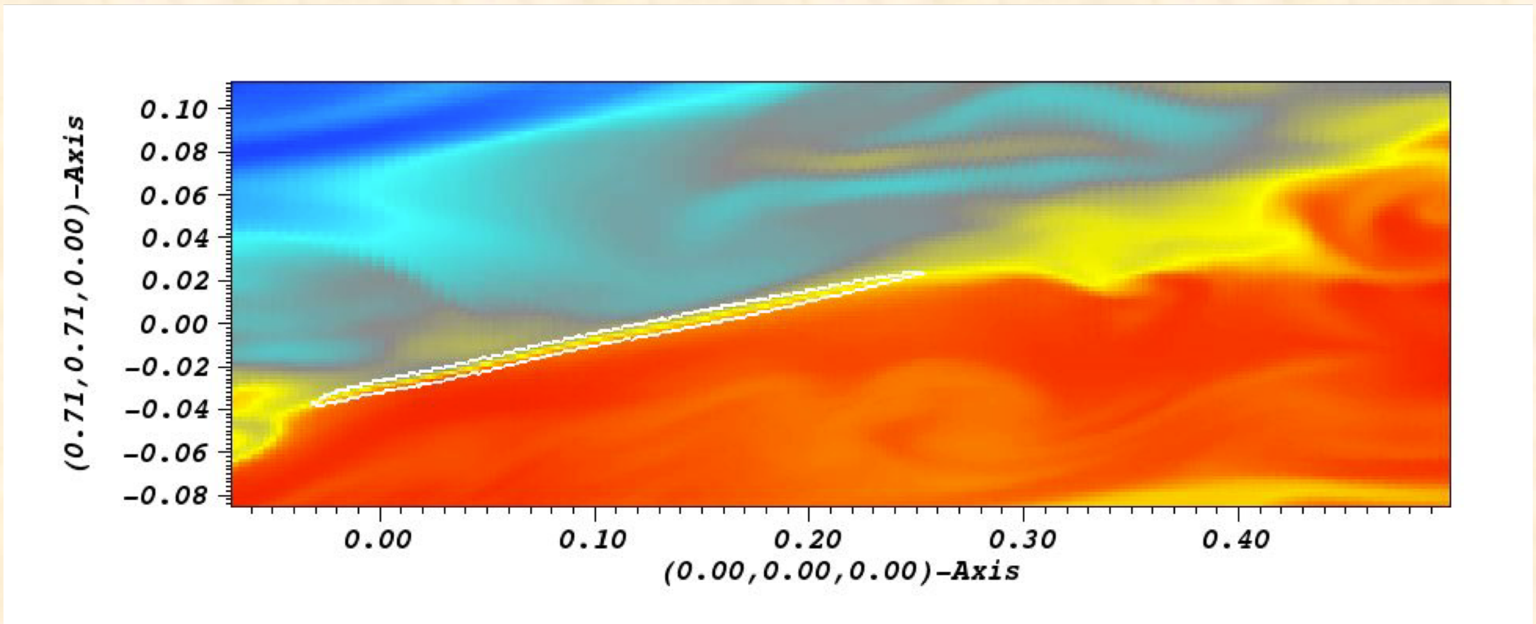


Current sheets destroyed by interactions.



K-H Instability destroys current sheets

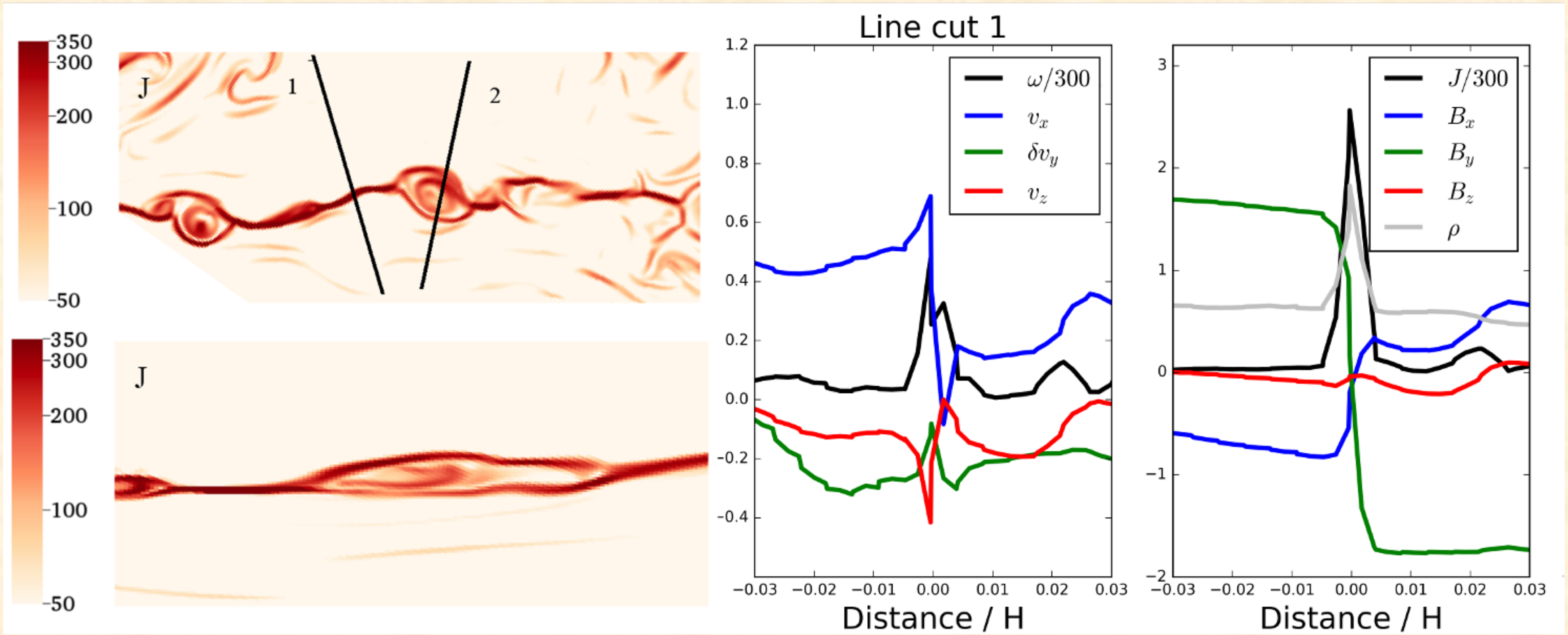




Typical lifetime of current sheet $\tau \sim 0.1\Omega^{-1}$

Comparing instability growth rates.

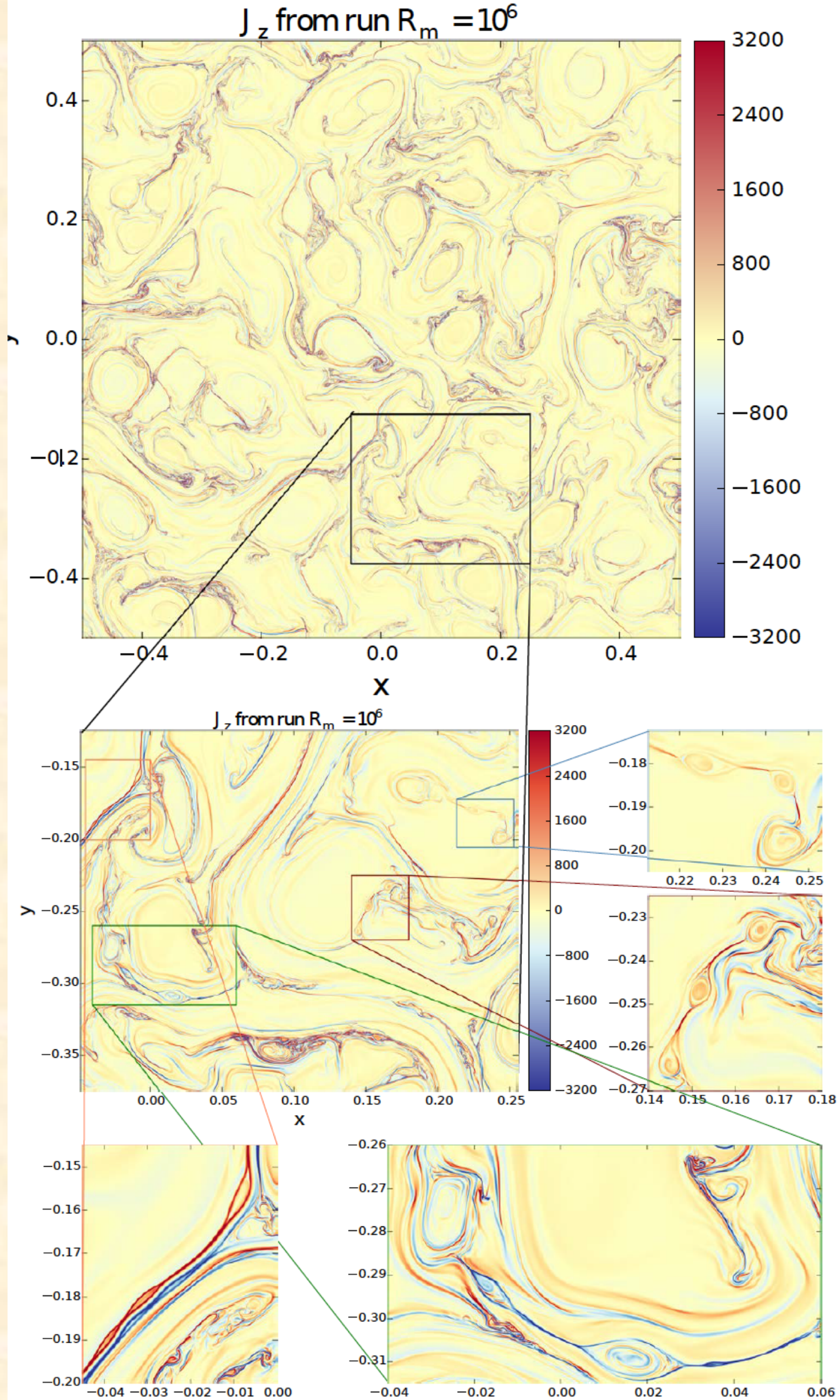
Measure jump in V and B along lines perpendicular to sheet



KHI growth rate: $\gamma_{KHI} \sim 10(k\xi)\Omega$

Tearing mode growth rate $\gamma_{TM} \sim 5(k\xi)^{-2/5}\Omega$

- KHI wins when perturbation smaller than thickness ($k\xi > 1$)
- KHI growth consistent with observed lifetime of current sheets



Compare to 64000^2 simulation of decaying MHD turbulence at $Re_M=10^6$ (Dong et al. 2018).

Why does TM dominate in this case?

- Higher Re_M, thinner sheets
- Less vigorous turbulence than MRI
- 2D versus 3D

Comparing ideal MHD and explicit dissipation

In ideal MHD, thickness of current sheets set by grid resolution Δx

- Compare ideal MHD simulations with fixed Re_M that gives same thickness:

Name[a]	l [b] (H)	ξ [b] (H)	λ_1 [b] (H)	λ_2 [b] (H)	N_{sh}[c] (>8)	N_0 [d]	$N_{sh,0}$ [e] (>8)	$N_{0,sh}$ [f]
r64re4000	1.48	0.41	0.18	0.030	$136^{\pm 29}$	$331^{\pm 55}$	$16^{\pm 4}$	$37^{\pm 9}$
r128re4000	1.27	0.38	0.17	0.019	$360^{\pm 96}$	$584^{\pm 105}$	$32^{\pm 9}$	$75^{\pm 19}$
r256re4000	1.11	0.35	0.15	0.014	$692^{\pm 139}$	$815^{\pm 88}$	$49^{\pm 10}$	$97^{\pm 22}$
r512re4000	1.07	0.35	0.15	0.012	$1109^{\pm 195}$	$949^{\pm 72}$	$55^{\pm 10}$	$128^{\pm 18}$
r256re8000	1.15	0.37	0.17	0.011	$1319^{\pm 223}$	$1370^{\pm 218}$	$89^{\pm 18}$	$253^{\pm 62}$
r512re8000	0.93	0.33	0.15	0.008	$2227^{\pm 454}$	$2077^{\pm 269}$	$137^{\pm 18}$	$343^{\pm 78}$
r256re8000adb	1.04	0.35	0.14	0.012	$1302^{\pm 175}$	$1514^{\pm 230}$	$83^{\pm 13}$	$186^{\pm 32}$
r512re16000	0.91	0.35	0.15	0.006	$4281^{\pm 760}$	$3103^{\pm 672}$	$209^{\pm 41}$	$772^{\pm 243}$
r256ideal	0.95	0.37	0.17	0.009	$2803^{\pm 457}$	$3326^{\pm 675}$	$183^{\pm 32}$	$833^{\pm 146}$

Name[a]	$\Delta T (\Delta T_{avg})$[b] (orbits)	α_M[c] ($\times 0.01$)	α_R[c] ($\times 0.01$)	α_{tot}[c] ($\times 0.01$)	$\frac{\mathcal{E}_\eta}{\mathcal{E}_\nu}$ [d]
r256re8000	50 (25)	16.07	3.17	19.23	2.05
r256ideal	25 (10)	18.76	3.38	22.14	…

- Overall statistics of current sheets extremely similar

Summary

- For $P_M = 1$, Ohmic dissipation and compressional heating dominate strong MRI-driven turbulence (with mean field).
- Properties of current sheets similar to previous studies
- Current sheets disrupted by mergers and KHI