RECONNECTION IN ALFVÉNIC TURBULENCE + MISCELLANEA

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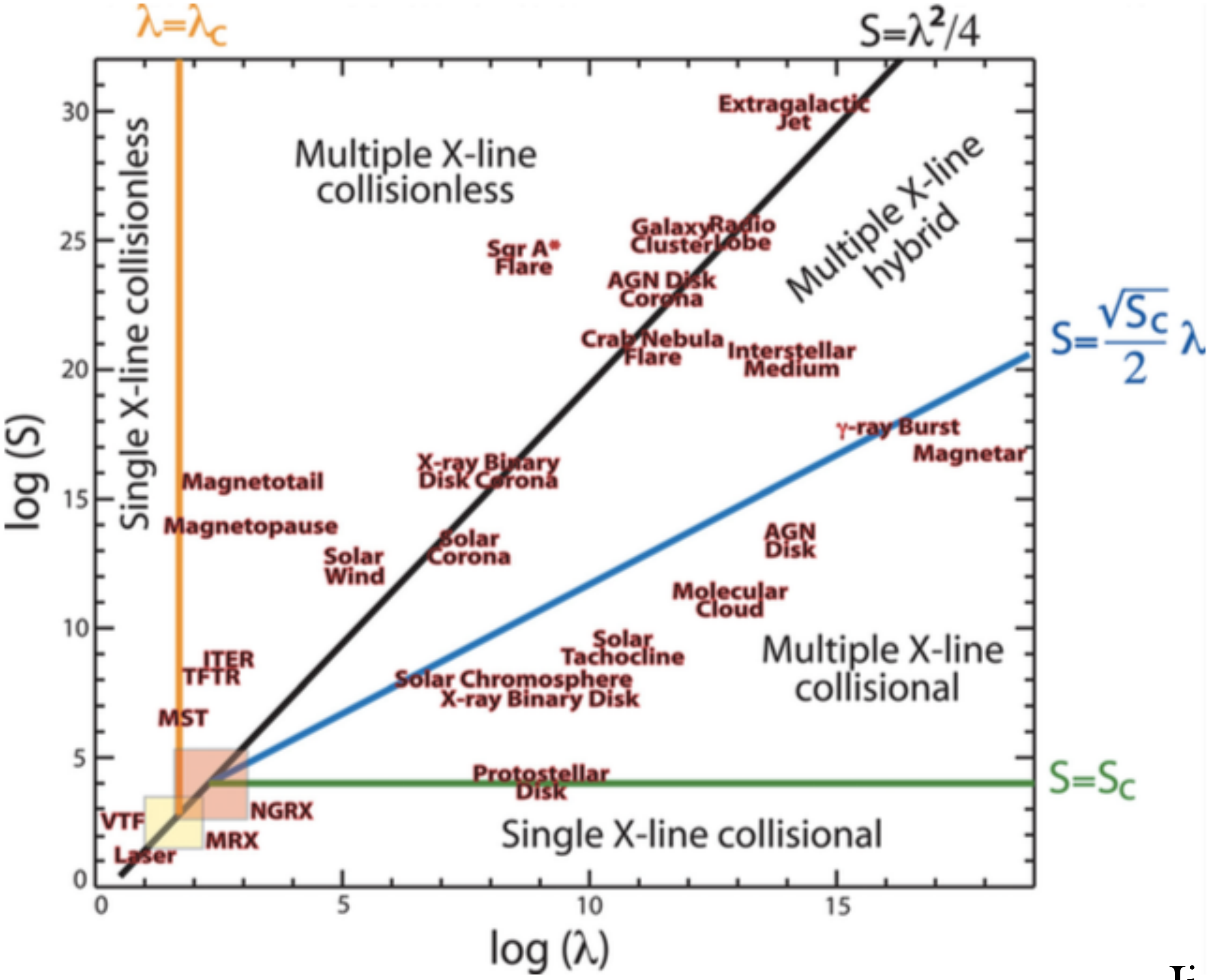
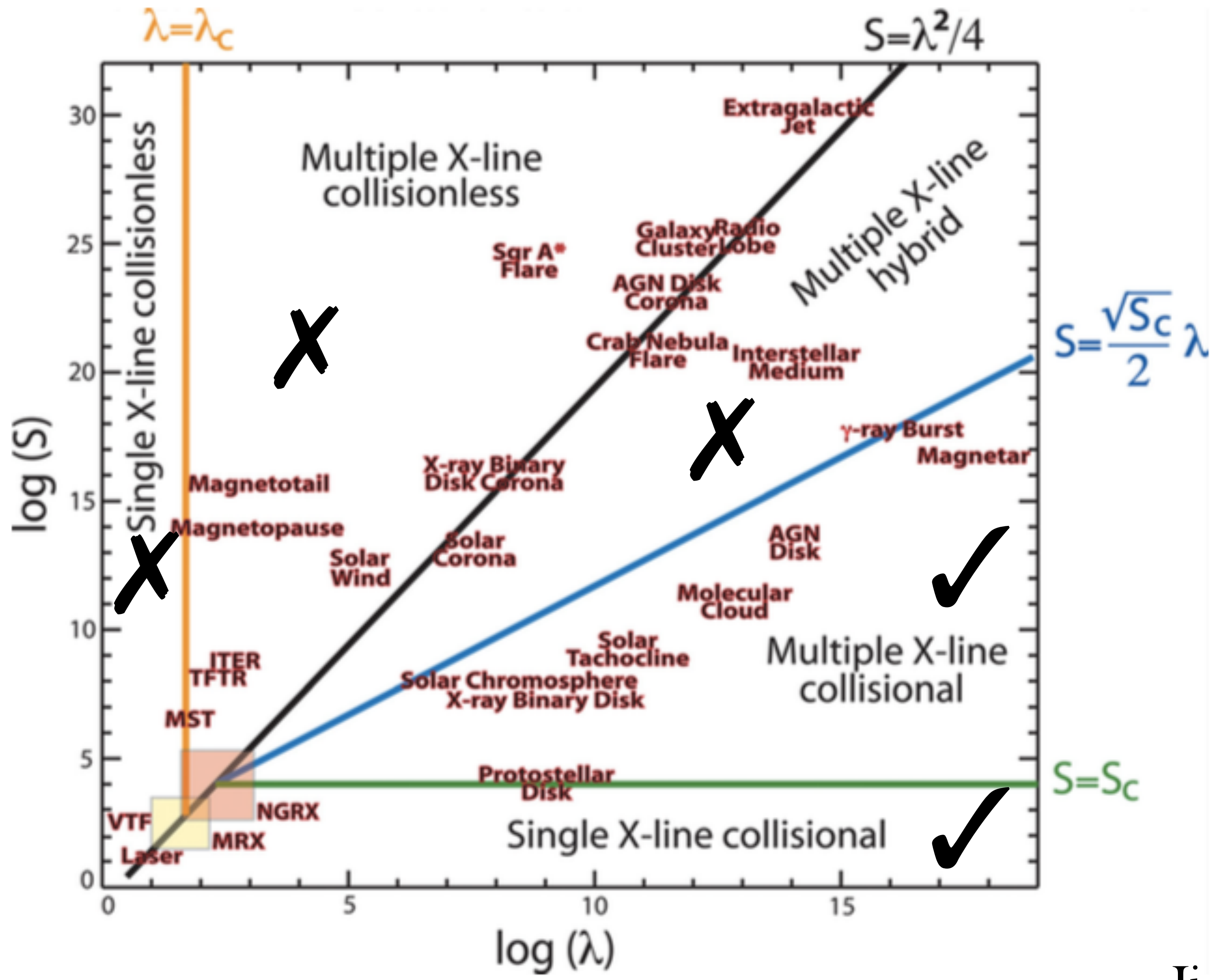
Some recent developments in reconnection

Reconnection phase diagram



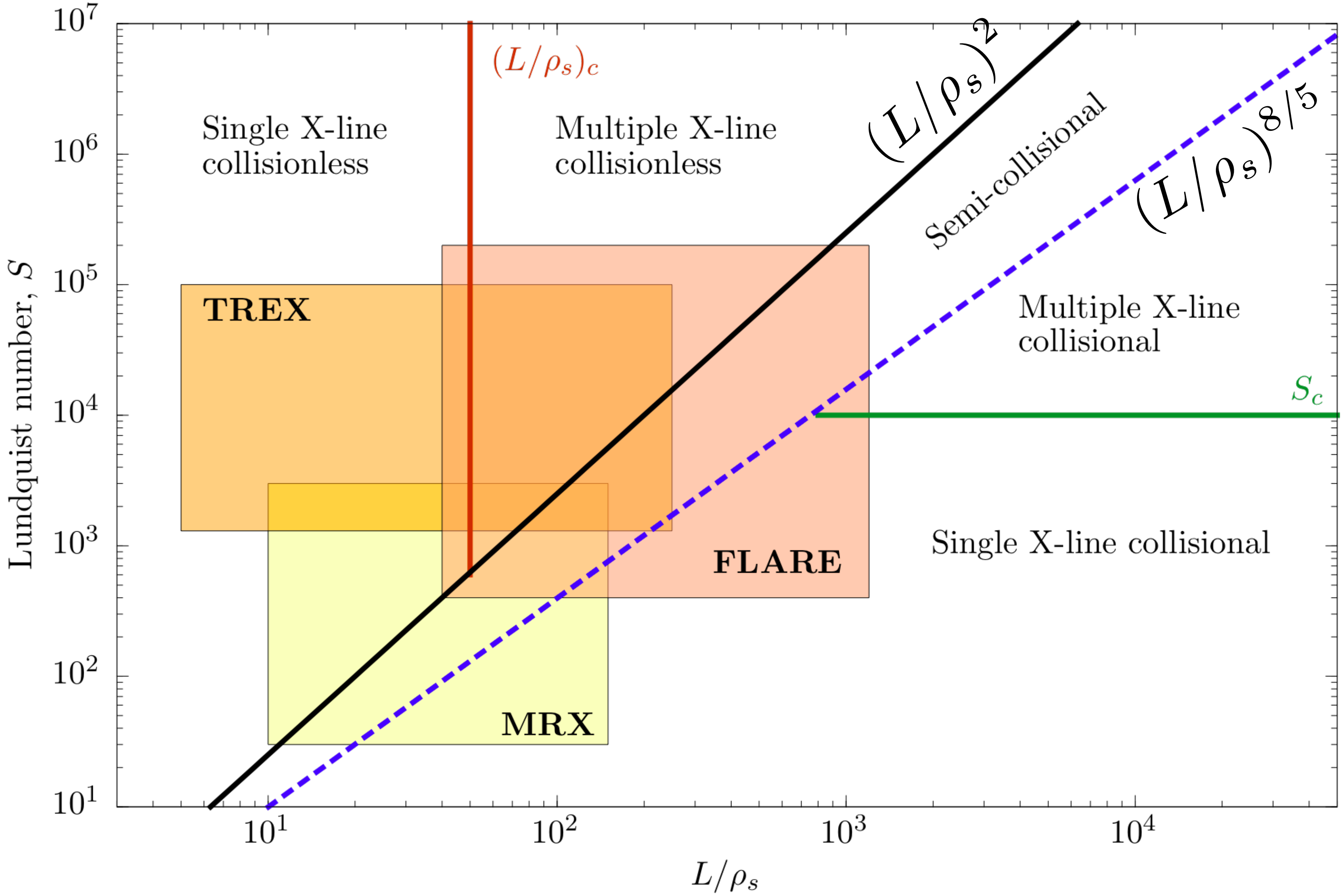
Ji & Daughton 2011

Reconnection phase diagram



Ji & Daughton 2011

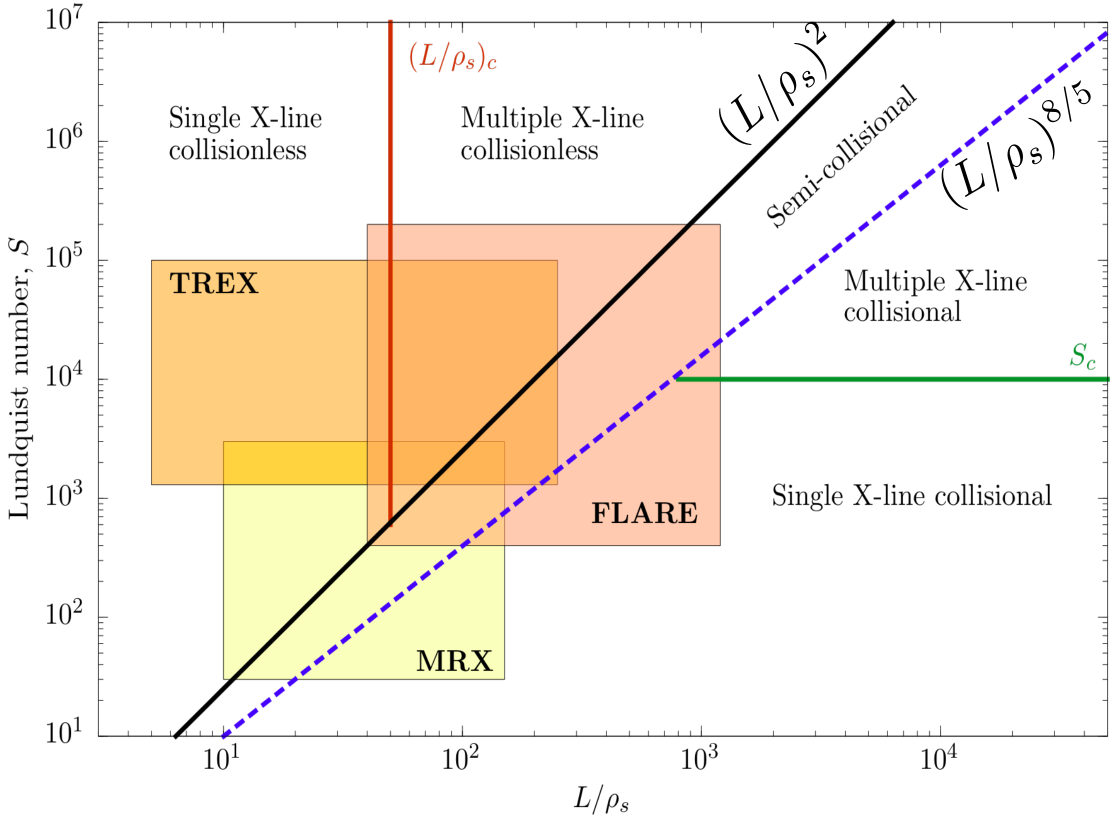
Reconnection phase diagram revisited



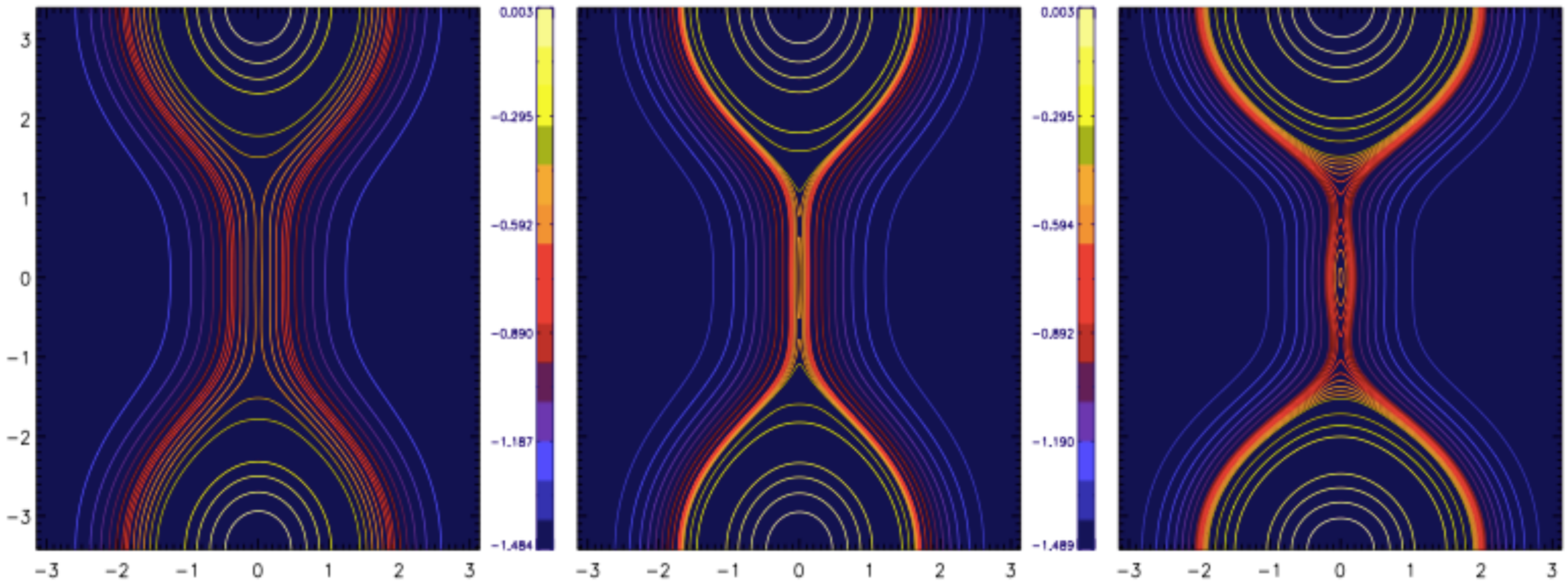
Baalrud *et al.* 2011; Loureiro & Uzdensky '16

Reconnection phase diagram revisited: some implications

- **No hard limit on minimum Lundquist number to access this regime!**
- Suggests easy accessibility in experiments and simulations.
- However, the theory is asymptotic: *strictly speaking, the scalings are valid if we are asymptotically far from the two bounding lines.*
- Does this really work at low S?



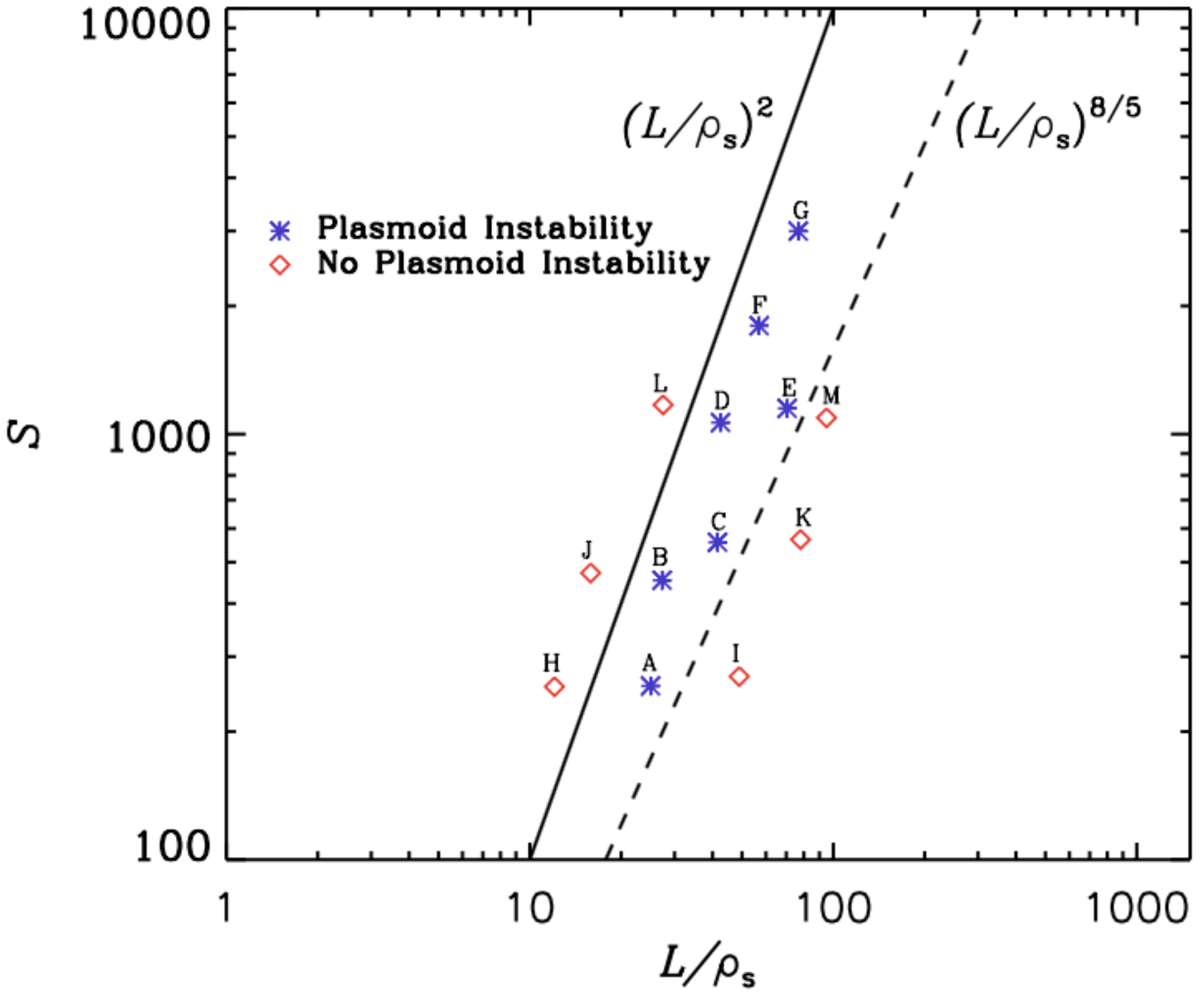
Semi-collisional plasmoids



Simulations in the **semi-collisional** regime. S =450, L/r_s=27.

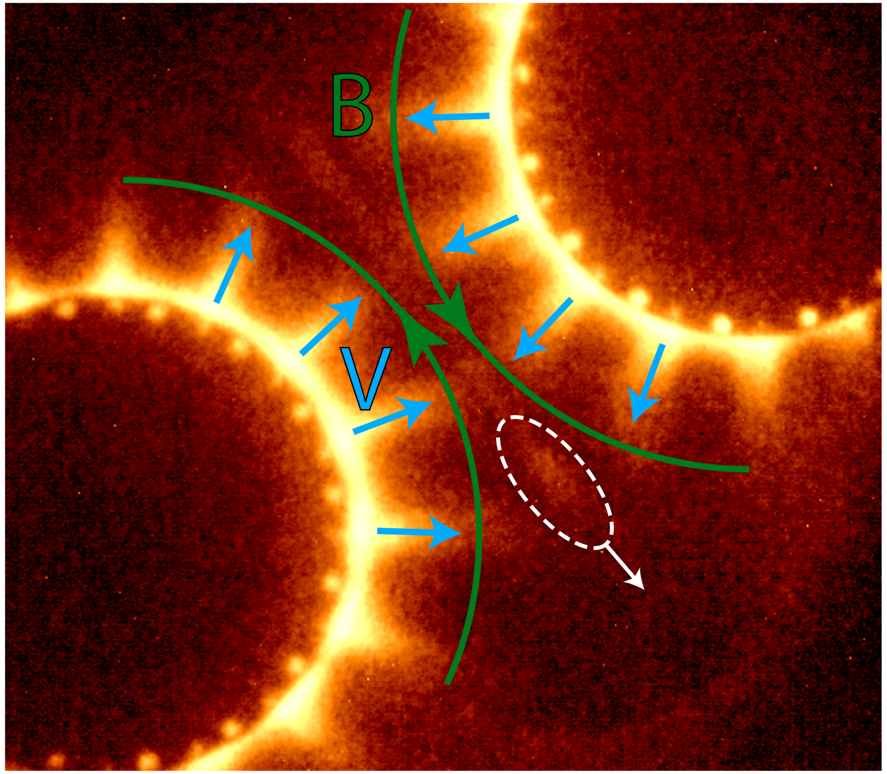
Bhat & Loureiro, 2017 (*in preparation)*

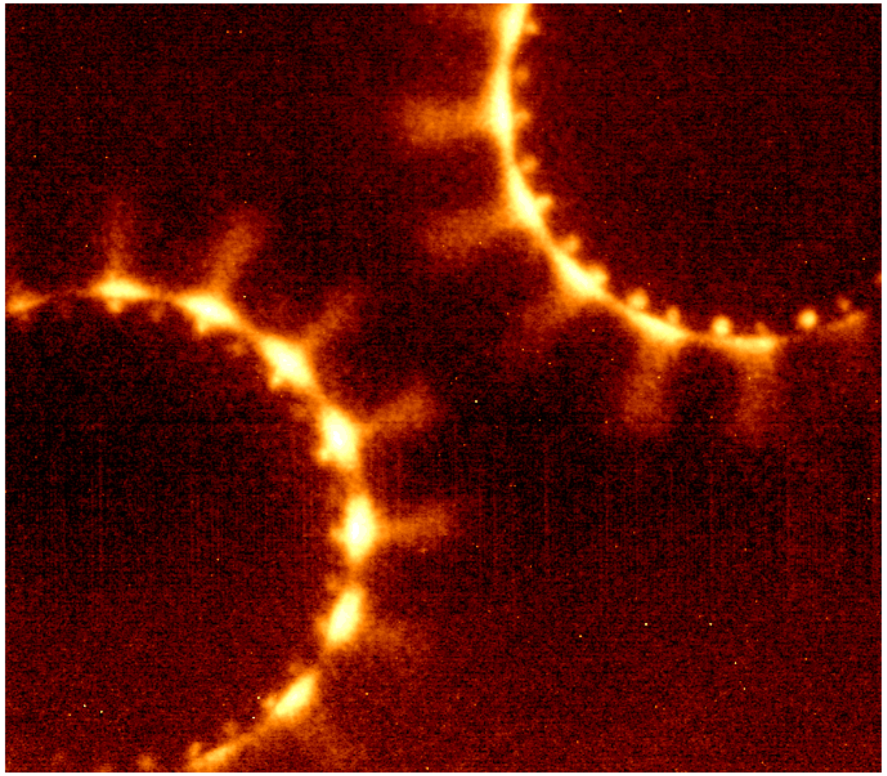
Semi-collisional plasmoid regime confirmed by numerical simulations



Bhat & Loureiro, *in preparation*, 2017

Z-Pinch reconnection experiments





+ very interesting results on anomalous ion and electron heating

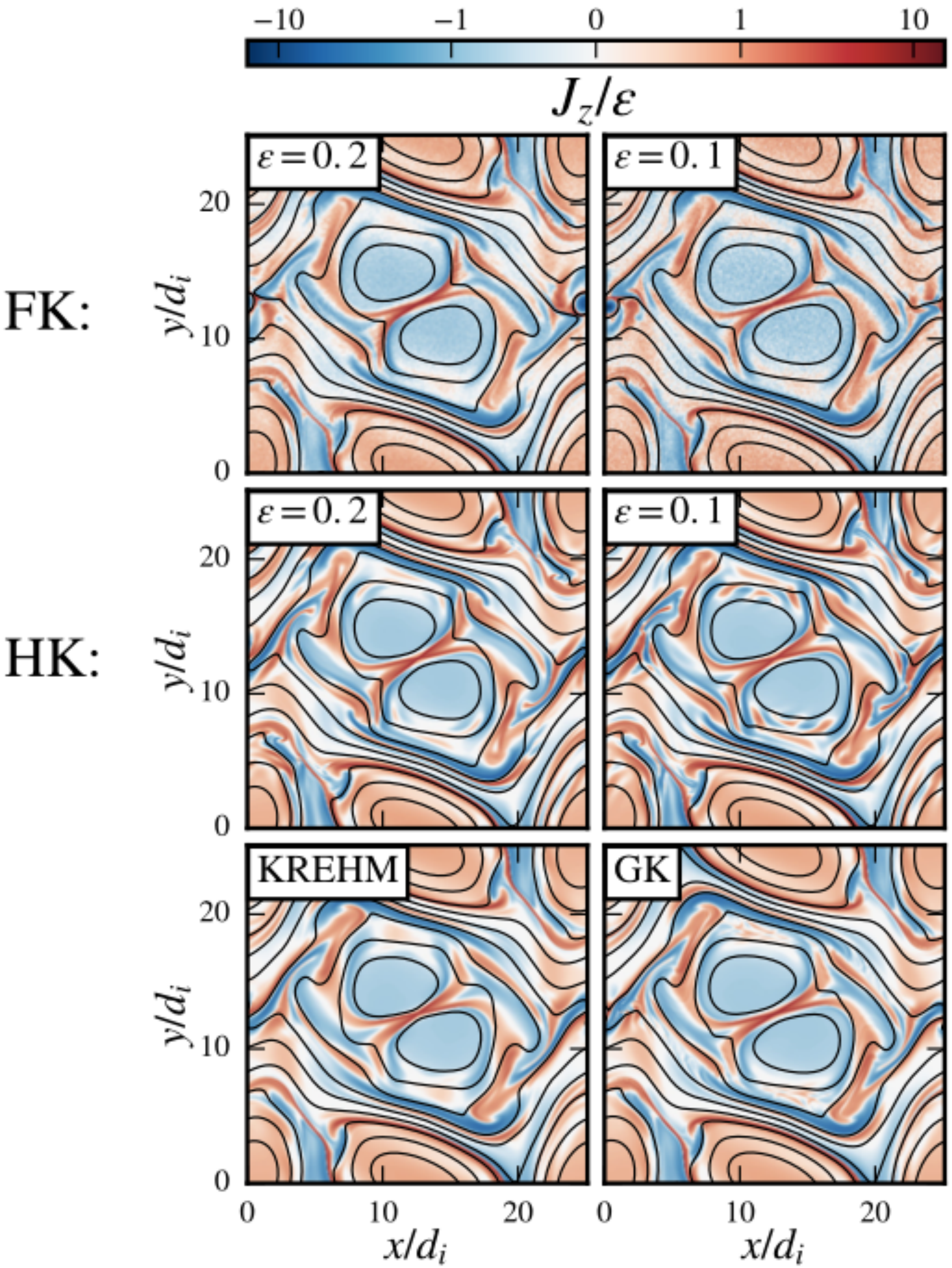
Hare et al, PRL 2017, arXiv:1705.10594

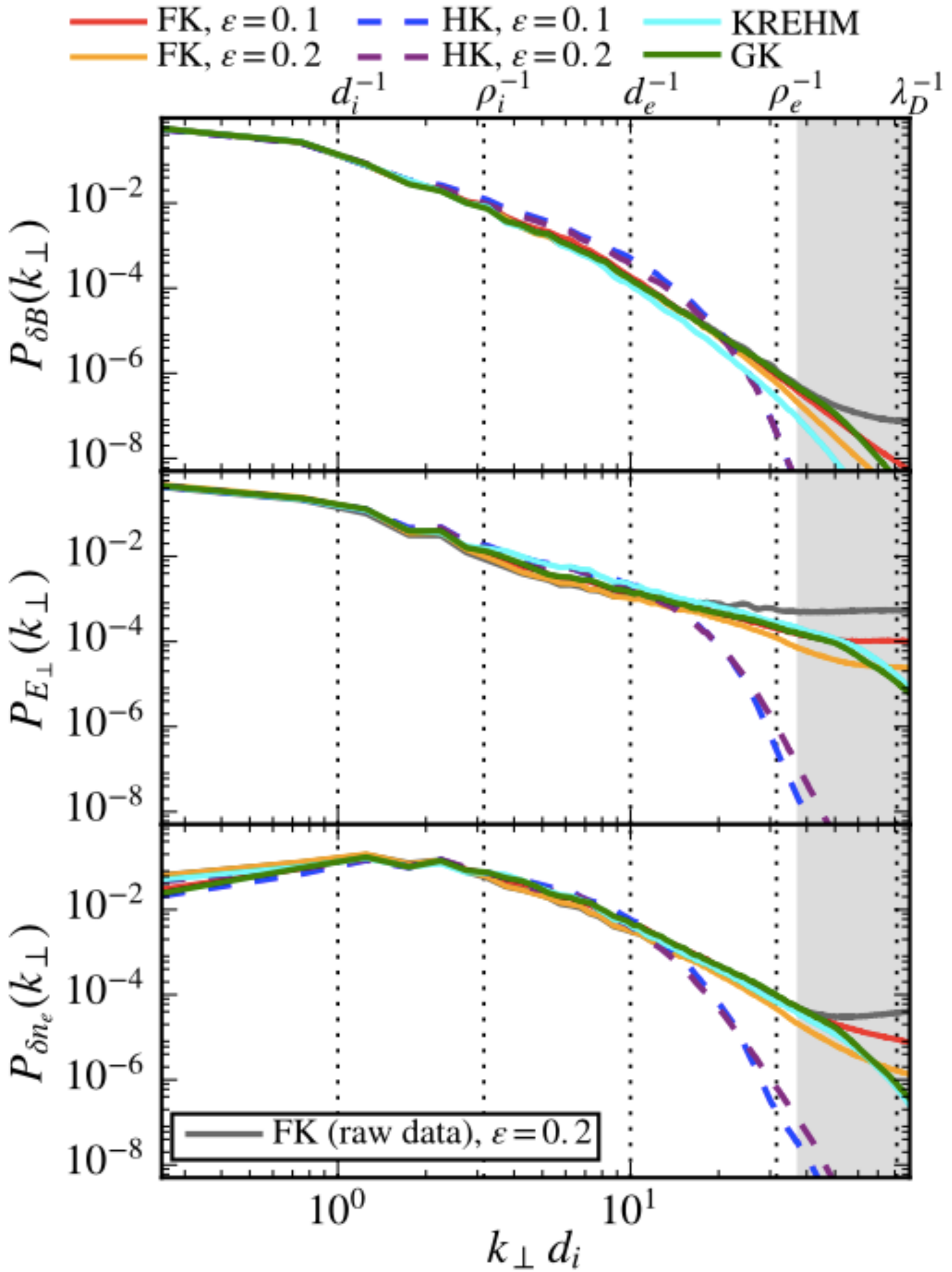
Kinetic simulations of decaying turbulence

Groselj *et al.,* arXiv:1706.02652

2D decaying turbulence

- FK= full kinetic (PIC; Osiris)
- HK= hybrid kinetic (full-f ion, fluid electrons+ electron inertia; HVM)
- GK=gyrokinetics (GENE)
- KREHM = reduced GK (valid when beta~m_e/m_i; Viriato)

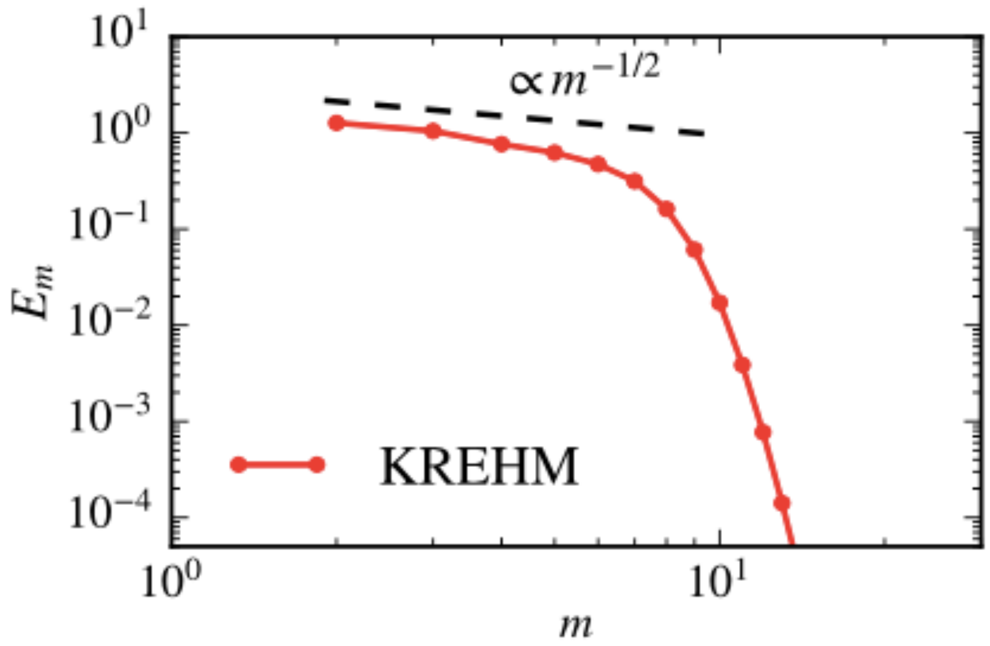


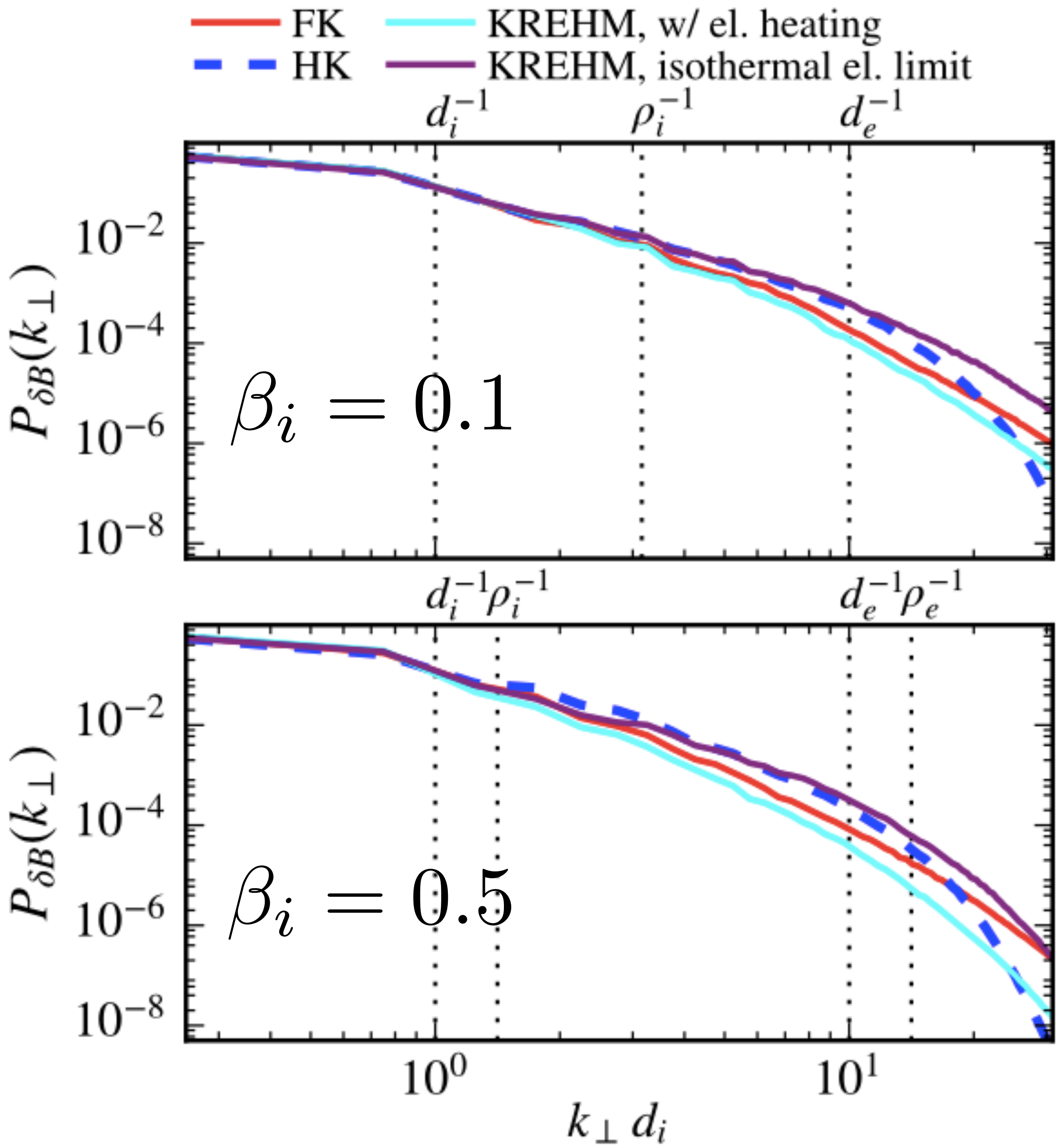


FK, $\varepsilon = 0.1$
FK, $\varepsilon = 0.2$
HK, $\varepsilon = 0.1$
HK, $\varepsilon = 0.2$
KREHM
GK
d_i^{-1}
ρ_i^{-1}
d_e^{-1}
ρ_e^{-1}
λ_D^{-1}
$P_{\delta B}(k_\perp)$
$P_{E_\perp}(k_\perp)$
$P_{\delta n_e}(k_\perp)$
10^{-2}
10^{-4}
10^{-6}
10^{-8}
FK (raw data), $\varepsilon = 0.2$
10^0
10^1
$k_\perp d_i$

Non-isothermal electrons matter (?)

Taking the isothermal limit of KREHM seems to provide a good agreement with the hybrid result (perhaps unsurprisingly)



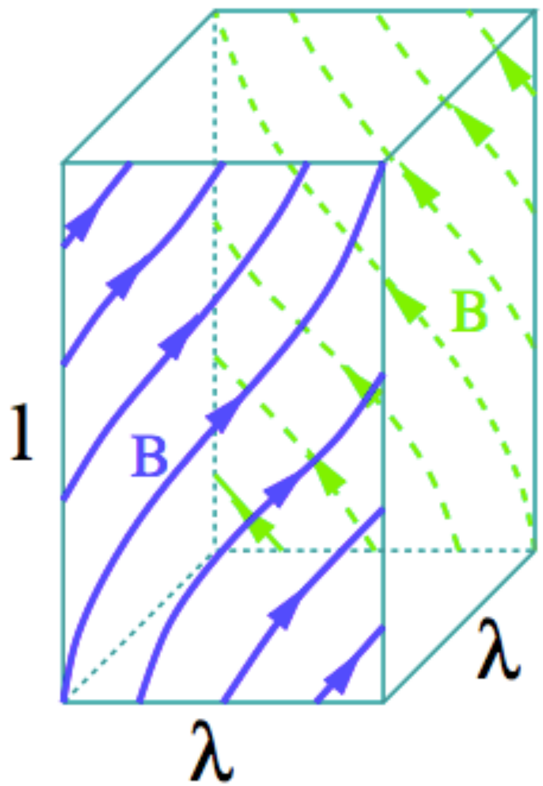


Reconnection in turbulence

Loureiro & Boldyrev, PRL 2017
Boldyrev & Loureiro, ApJ 2017 (arXiv:1706.07139)
Loureiro & Boldyrev, arXiv:1707.05899

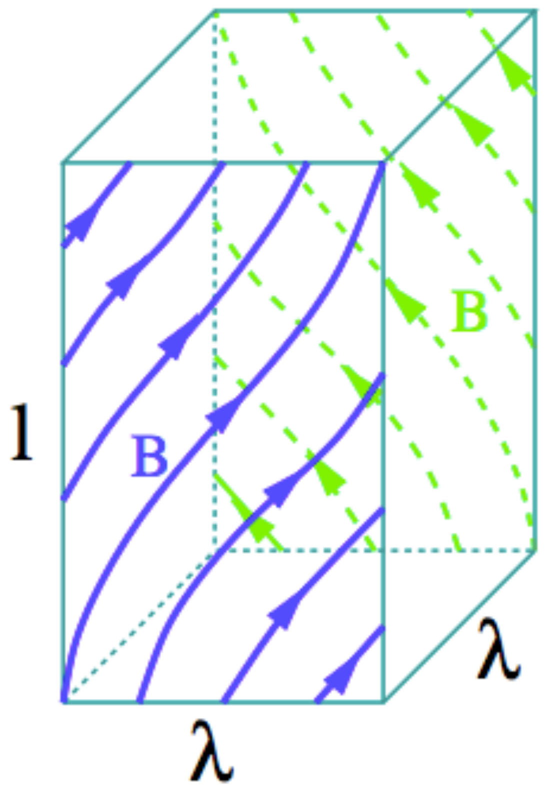
(Mallett, Schekochihin, Chandran, MNRAS 2017
Mallett, Schekochihin, Chandran, arXiv:1707.05907)

Anisotropic turbulent eddies

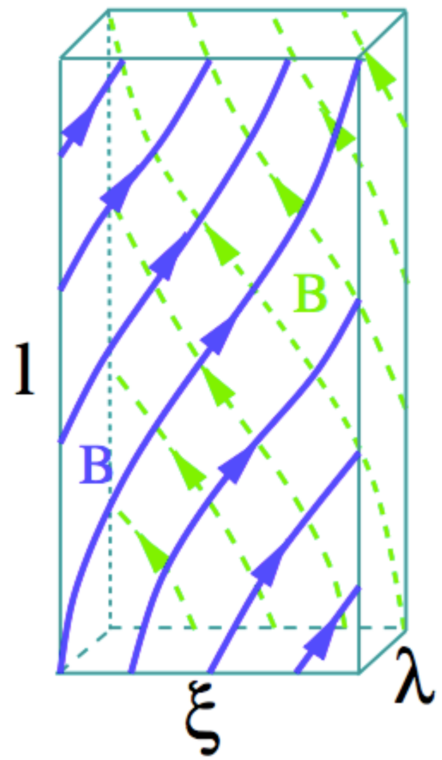


Goldreich-Sridhar (GS95): eddies' dimension perpendicular to the background field are comparable; become *filaments* at small scales.

Anisotropic turbulent eddies

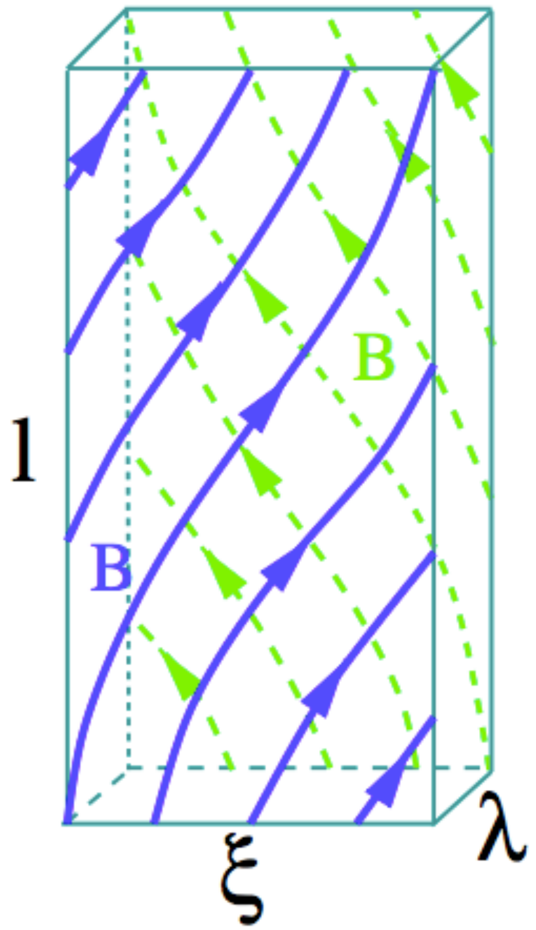


Goldreich-Sridhar (GS95): eddies' dimension perpendicular to the background field are comparable; become *filaments* at small scales. (key idea: *critical balance*)



Boldyrev 06: eddies fully anisotropic; ξ/λ >>1; become high-aspect ratio *current sheets* at small scales. (key idea: *critical balance* + *dynamic alignment*)

3D anisotropic eddies – scalings (Boldyrev '06)

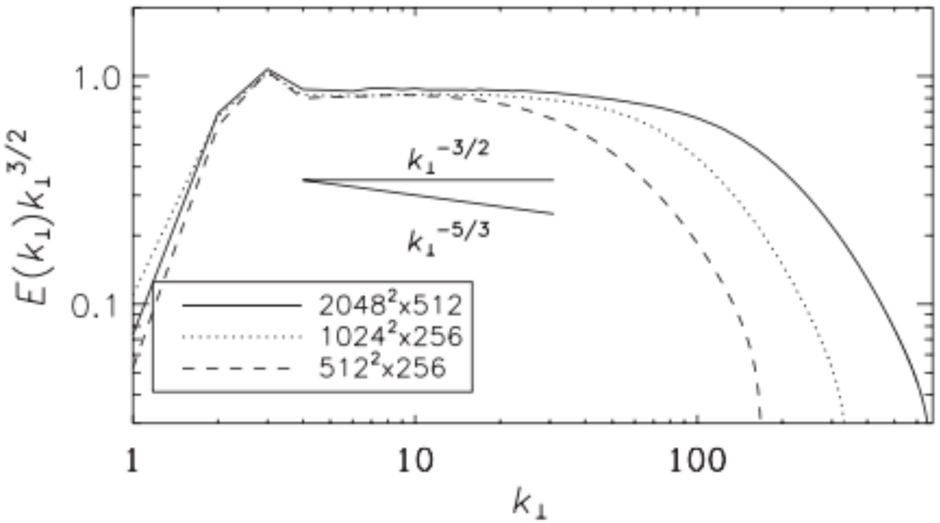


$$\xi \sim L(\lambda/L)^{3/4},$$
$$\ell \sim L(\lambda/L)^{1/2},$$
$$b \sim B_0(\lambda/L)^{1/4},$$
$$\tau \sim \ell/V_{A,0} \sim \lambda^{1/2}L^{1/2}/V_{A,0}$$

Spectrum:

$$E(k_\perp) \sim k_\perp^{-3/2}$$

Perez *et al.*, 2012



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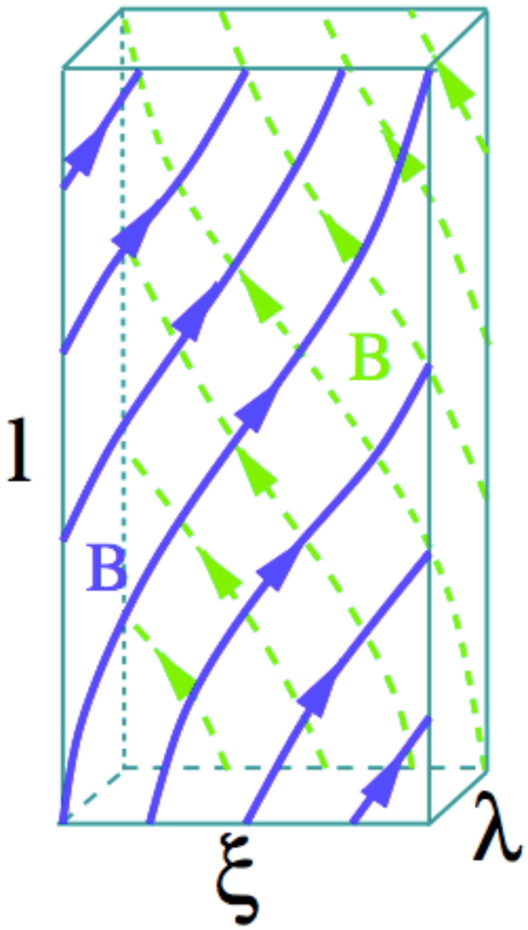

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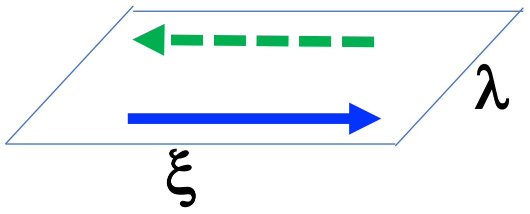
In the perpendicular plane, think of current sheets of length ξ, thickness λ



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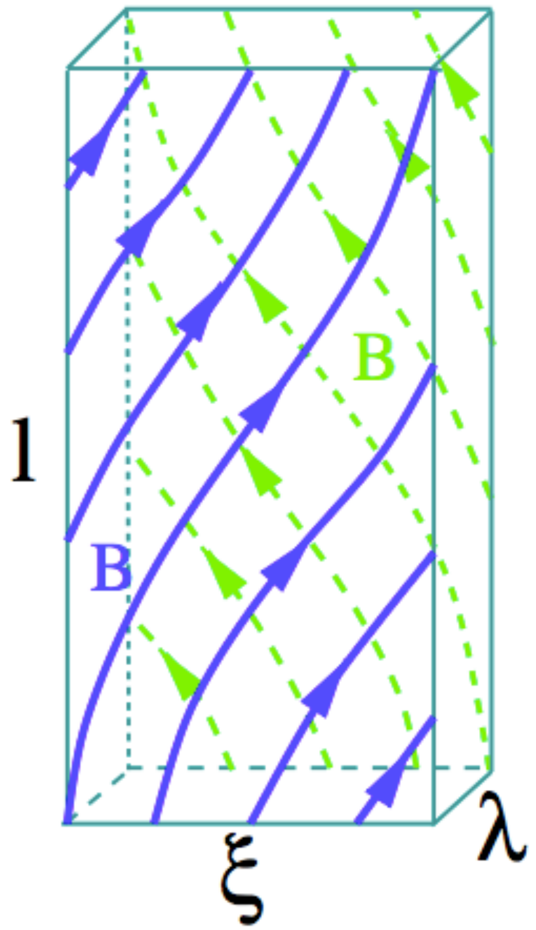

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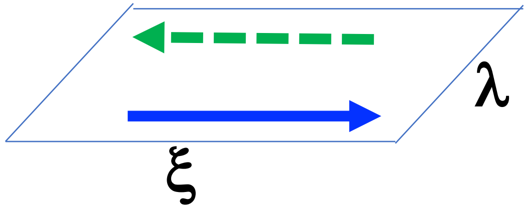
In the perpendicular plane, think of current sheets of length ξ, thickness λ; they last for a time interval τ, **unless they are first disrupted by reconnection**.



Onset of dissipation in turbulence

- Simplest (usual) estimate is to compare the eddy turn-over-time to the dissipation time:

$$\lambda^{1/2} L^{1/2} / V_{A,0} \sim \lambda^2 / \eta$$

- This leads to

$$\lambda / L \sim S_L^{-2/3} \sim R_m^{-2/3}$$

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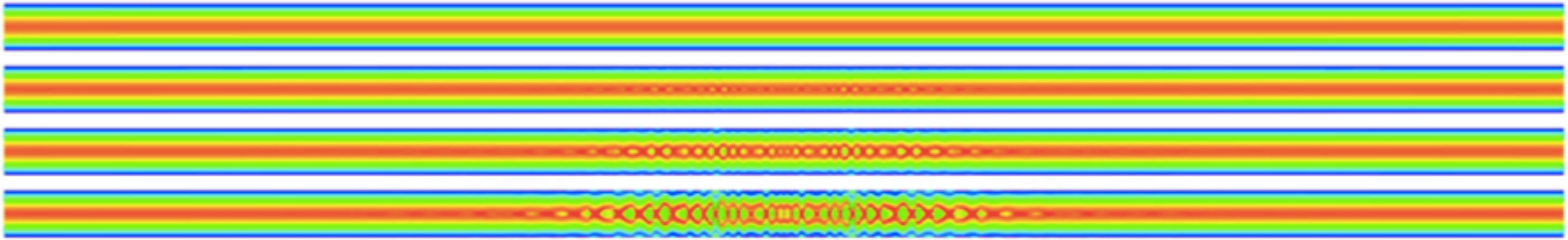
- *But this can't be right because of current sheet instability.*

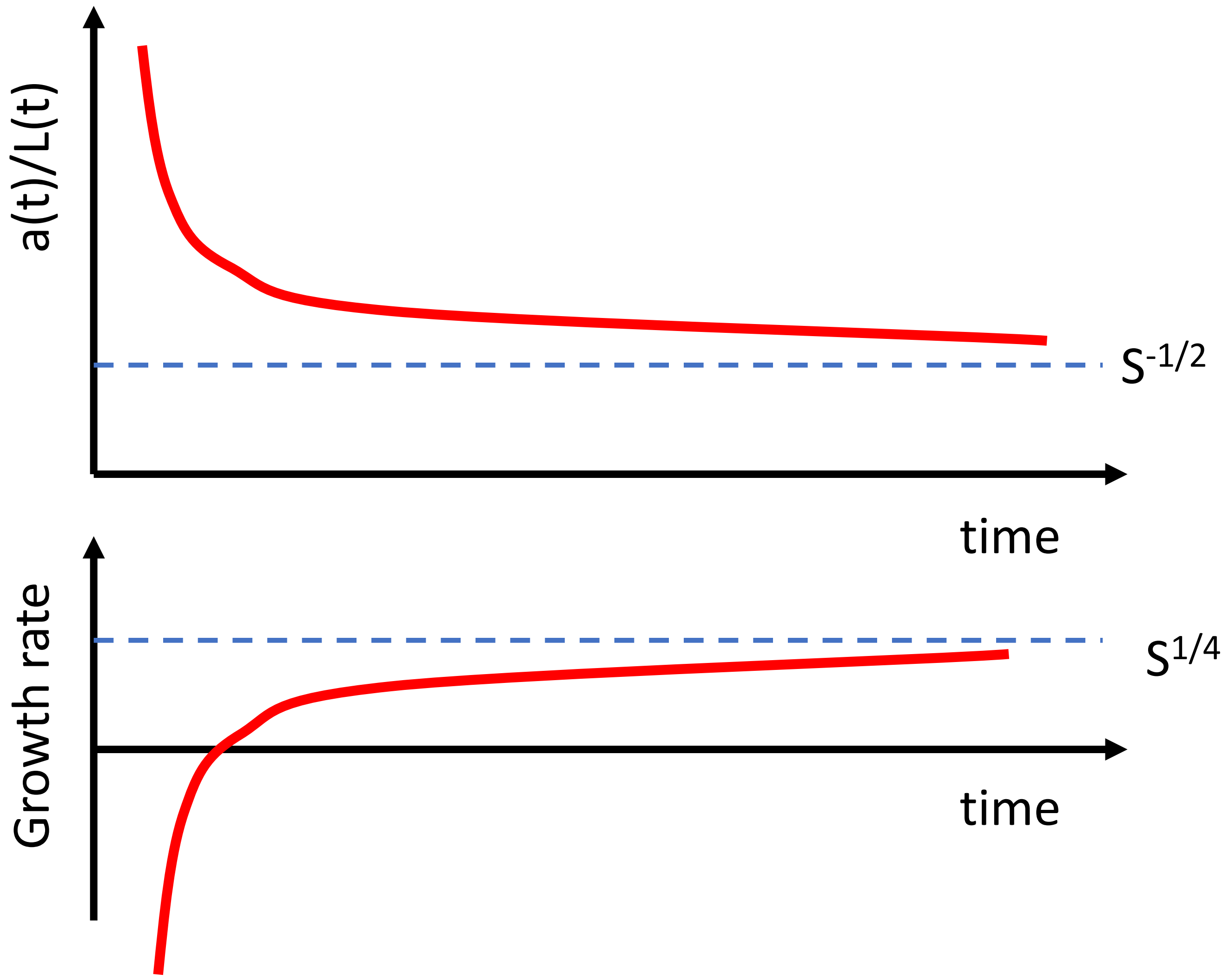
Current sheet instability

- Sweet-Parker current sheets are violently unstable to the plasmoid instability (Loureiro *et al.* ’07; see Loureiro & Uzdensky, PPCF ‘16 for a review)



- In fact, this instability means that Sweet-Parker current sheets can never really form: as one is trying to form, it is disrupted by its own instability along the way (Pucci & Velli ‘14, Uzdensky & Loureiro, ’16, Comisso et al. ‘16)

Reconnection onset in a forming sheet



- A forming current sheet **must** become unstable before attaining the Sweet-Parker aspect ratio $\sim S^{-1/2}$
- The important moment of time is when

$$\gamma[a(t), L(t)]\tau_{CS} \sim 1$$

Uzdensky & Loureiro, PRL '16

Dynamic reconnection onset

- ***At what scale does the eddy turnover time become comparable to the tearing mode growth time in the eddy?***

$$\gamma_{\rm tear}\tau \sim 1$$

- We find:

$$\lambda_{cr}^{\rm Coppi}/L \sim S_L^{-4/7}$$

Loureiro & Boldyrev, PRL '17
Mallet *et al.*, MNRAS '17
Boldyrev & Loureiro, ApJ '17

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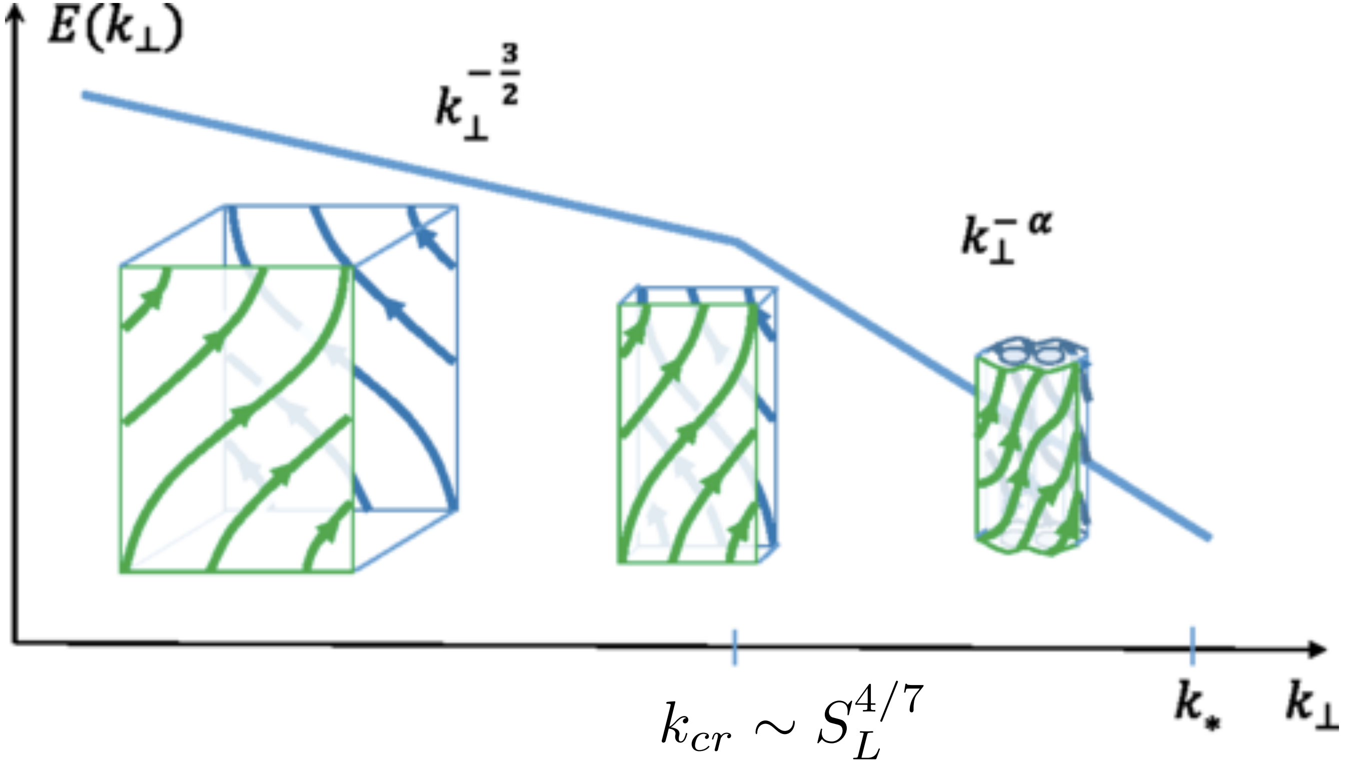


Loureiro & Boldyrev, PRL '17
Mallet *et al.*, MNRAS '17
Boldyrev & Loureiro, ApJ '17

Spectrum

- Spectrum can be computed from enforcing constant energy flux:

$$\gamma_{nl} v_{A\lambda}^2 = \epsilon$$

where $\epsilon \sim V_{A0}^3/L_0$ is the constant rate of energy cascade over scales.

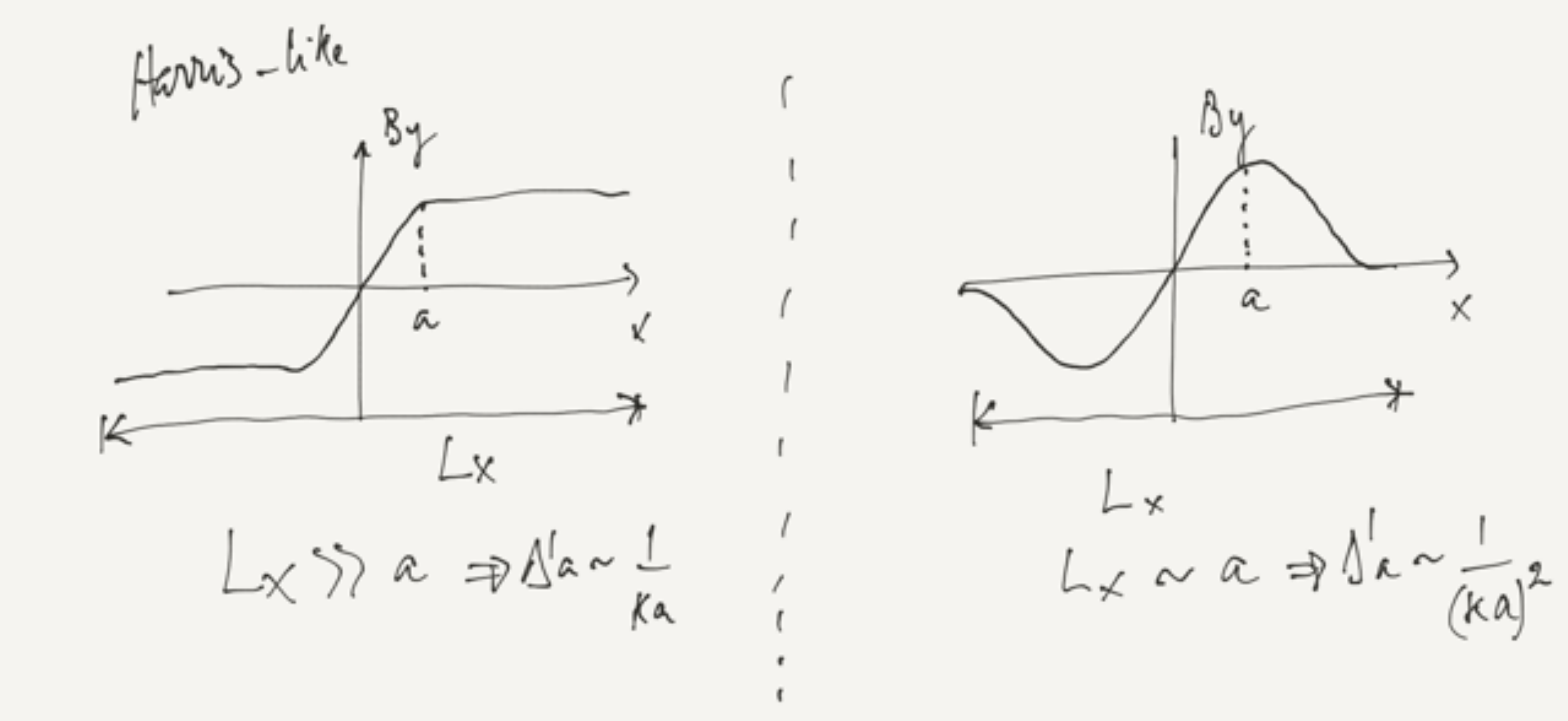
- We assume that when the tearing mode becomes nonlinear, the eddy adjusts its own timescale to become that of the mode:

$$\gamma_{nl} \sim \gamma_{tearing}$$

- Obtain: $$E(k_\perp)dk_\perp \sim \epsilon^{4/5} \eta^{-2/5} k_\perp^{-11/5} dk_\perp$$

Boldyrev & Loureiro ApJ 2017

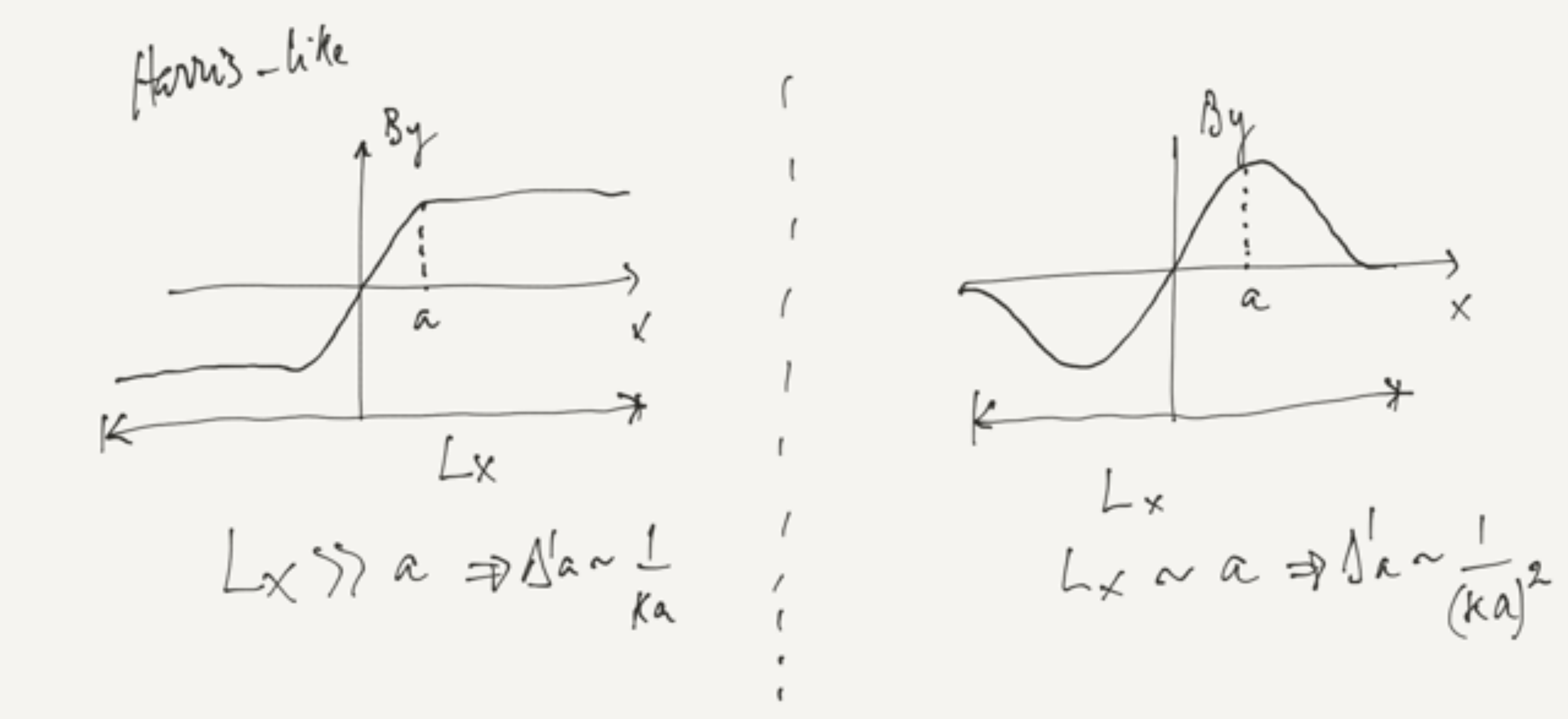
A boring (but important?) technical point



(n=1)

(n=2)

A boring (but important?) technical point



$$\lambda_{cr}^{(1)}/L \sim S_L^{-4/7},$$

$$E^{(2)}(k_\perp) \sim k_\perp^{-11/5}.$$

$$\lambda_{cr}^{(2)}/L \sim S_L^{-6/11},$$

$$E^{(2)}(k_\perp) \sim k_\perp^{-19/9}.$$

Extension to the kinetic reconnection regime

- In many realistic plasmas, collisions are so weak that reconnection in an **MHD-scale eddy** will trigger kinetic effects:

$$\lambda \gg \rho_i > \delta \sim d_e$$

- This can be handled with kinetic tearing mode theory (reconnection is caused by electron inertia, instead of collisions)
- Loureiro & Boldyrev, arXiv:1707.05899
- Mallett, Schekochihin, and Chandran, arXiv:1707.05907

Extension to the kinetic reconnection regime

n=1 case

$$\lambda_{cr}/L \sim (d_e/L)^{4/9}(\rho_s/L)^{4/9}$$

Valid if $\lambda_{cr} > \rho_s$:

$$\rho_s/L \ll (m_e/m_i)^2 \beta_e^{-2}$$

Spectrum:

$$E(k_\perp)dk_\perp \sim \epsilon^{2/3} d_e^{2/3} \rho_s^{2/3} k_\perp^{-3} dk_\perp$$

n=2 case

$$\lambda_{cr}^{(2)}/L \sim (d_e/L)^{8/21}(\rho_s/L)^{10/21}$$

Valid if $\lambda_{cr} > \rho_s$:

$$\rho_s/L \ll (m_e/m_i)^{4/3} \beta_e^{-4/3}$$

Spectrum:

$$E(k_\perp)dk_\perp \sim \epsilon^{2/3} d_e^{-4/9} \rho_s^{-5/9} k_\perp^{-8/3} dk_\perp$$

Kinetic reconnection regime, cont'd

- **Ultralow beta limit** (β_e<<m_e/m_i, e.g. Earth's magnetosphere)

$$\lambda_{cr}^{(1)}/L \sim (d_e/L)^{8/9}$$ or $$\lambda_{cr}^{(2)}/L \sim (d_e/L)^{6/7}.$$

Spectra:

$$E^{(1)}(k_\perp)dk_\perp \sim \epsilon^{2/3} d_e^{4/3} k_\perp^{-3} dk_\perp,$$
$$E^{(2)}(k_\perp)dk_\perp \sim \epsilon^{2/3} d_e^{-1} k_\perp^{-8/3} dk_\perp.$$

Kinetic reconnection regime, cont'd

- **High beta limit** (β_e~1; but cold ions)

$$\lambda_{cr}^{(1)}/L \sim (d_e/L)^{4/9}(d_i/L)^{4/9}, \quad \text{or} \quad \lambda_{cr}^{(2)}/L \sim (d_e/L)^{2/5}(d_i/L)^{16/35},$$

Valid if:

$$d_i/L \ll (m_e/m_i)^2; \qquad d_i/L \ll (m_e/m_i)^{7/3}.$$

Spectra:

$$E^{(1)}(k_\perp)dk_\perp \sim \epsilon^{2/3}d_e^{-2/3}d_i^{-2/3}k_\perp^{-3}dk_\perp,$$
$$E^{(2)}(k_\perp)dk_\perp \sim \epsilon^{2/3}d_e^{-7/15}d_i^{-8/15}k_\perp^{-8/3}dk_\perp.$$

But the validity conditions are very stringent; may imply that in the solar wind, for example, this transition to the reconnection range **cannot happen** in the MHD-scale interval.

Reconnection in the kinetic turbulence range

- Can we extend these ideas to the kinetic range, i.e., $\lambda < \max(\rho_i, \rho_s)$?
- Uncertain: no theory to describe eddy aspect ratio, etc…
- Numerical simulations do suggest current sheet presence.
- Cannot estimate the critical scale for transition to the reconnection range (this requires knowing what the eddies look like). But can estimate the spectrum given expression for the tearing mode growth rate.

$$E^{(1)}(k_\perp)dk_\perp \sim \epsilon^{2/3}(m_i/m_e)^{-1/3} d_e^{-4/3} k_\perp^{-3}$$
$$E^{(2)}(k_\perp)dk_\perp \sim \epsilon^{2/3}(m_i/m_e)^{-1/3} d_e^{-1} k_\perp^{-8/3}$$

for $\beta_i \sim 1 >> \beta_e$.
(if $\beta_i << 1$, there's a prefactor of $\beta_i^{-1/3}$)

Conclusions

- If our current understanding of MHD turbulence is correct (Boldyrev '06), reconnection has to become important:
  - Eddies become current sheets of progressively larger aspect ratios at small scales
  - Therefore, they are progressively more unstable to the tearing mode
- Can compute the scale at which reconnection becomes important by comparing the timescales of the turbulence and of the tearing mode.
- Can compute the spectrum in this new *reconnection range*
- These ideas can be extended to the kinetic regime. We obtain spectra that scale as $k_\perp^{-8/3} - k_\perp^{-3}$, in good agreement with observations and simulations.

Loureiro & Boldyrev PRL 2017, Boldyrev & Loureiro ApJ 2017, Loureiro & Boldyrev, arXiv:1707.05899

Extra slides

Angular distortion due to tearing

In Boldyrev's 06 phenomenology:

$$\theta \sim \lambda/\xi \sim (\lambda/L_0)^{1/4} \qquad \gamma_{nl} \sim v_{A\lambda}\theta/\lambda$$

The nonlinear tearing mode affects the evolution of the eddy by distorting the alignment angle of the magnetic lines:

$$\theta_t \sim \delta/\zeta$$

Requiring that $\gamma_{nl} \sim \gamma_{tearing}$

leads to $\theta \sim \theta_t$