Tearing, Reconnection, and Energy Dissipation in Plasma Turbulence

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Connecting Micro and Macro Scales: Acceleration, Reconnection, and Dissipation in Astrophysical Plasmas

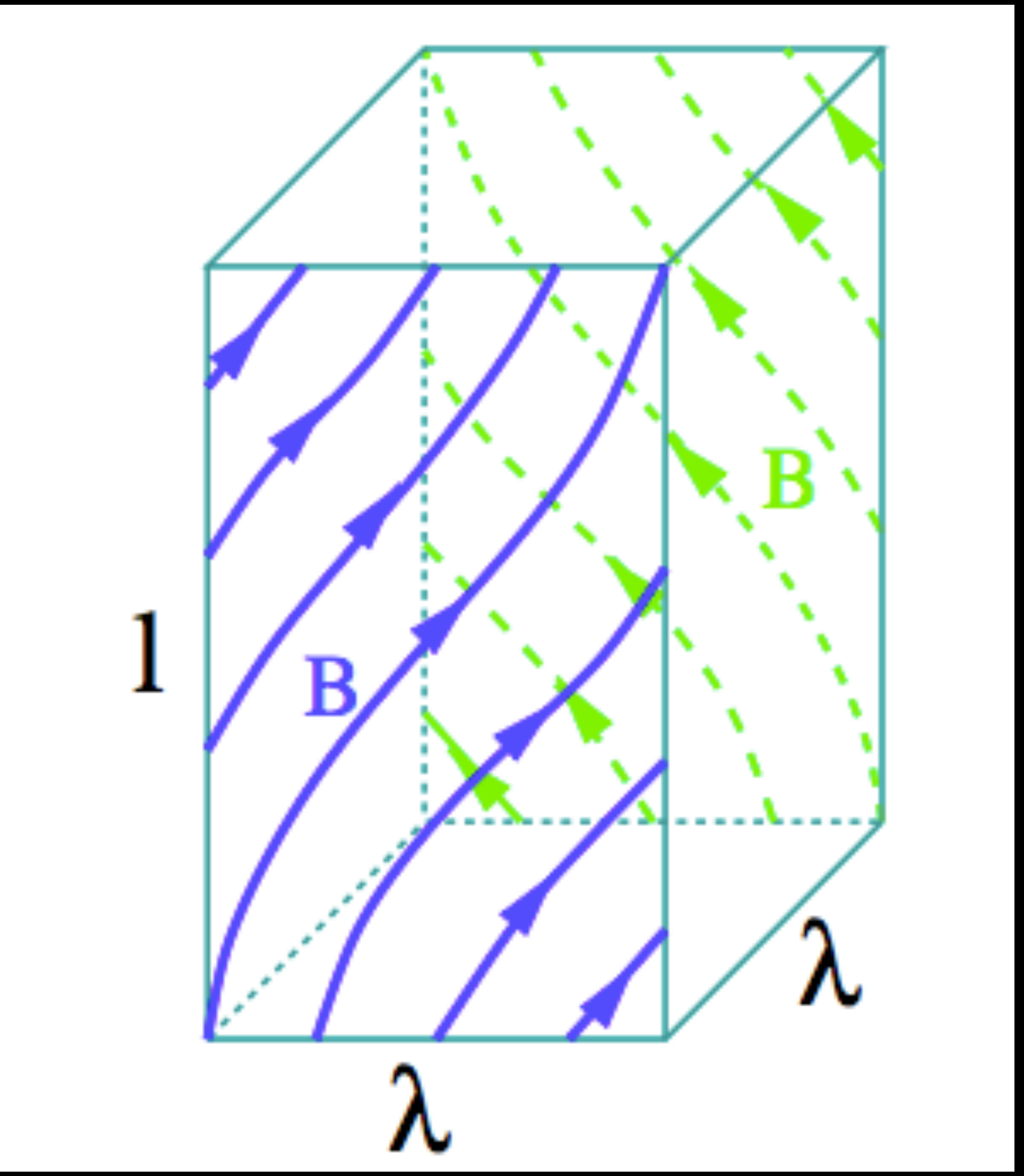
KITP, September 2019

Introduction

- Understanding of magnetic turbulence in plasmas has matured greatly over the last decade or so.
- A prominent unsolved question remains that of how energy dissipates in turbulence. This is essential to understanding observations.
- Magnetic reconnection has long been suggested to play an important role in turbulence.
- Reconnection is essentially an energy dissipation/conversion mechanism, so an assessment of whether indeed it is active in turbulence is critical.
- Goal of this talk is to examine this question analytically.
- Details in Loureiro & Boldyrev, arXiv:1907.09610

Models of MHD turbulence

MHD turbulent eddies are not isotropic



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

$E(k) \sim k^{-5/3}$

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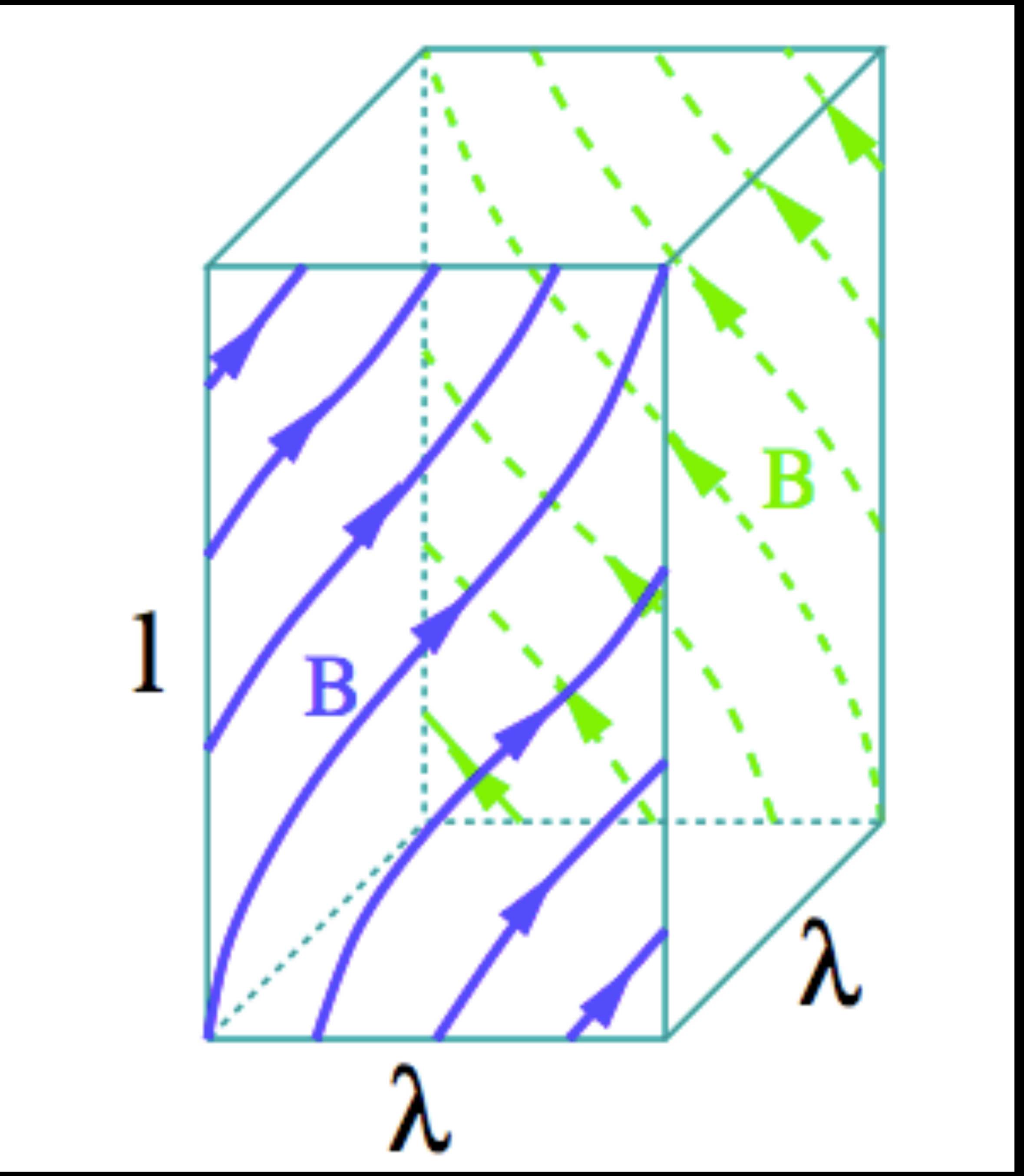

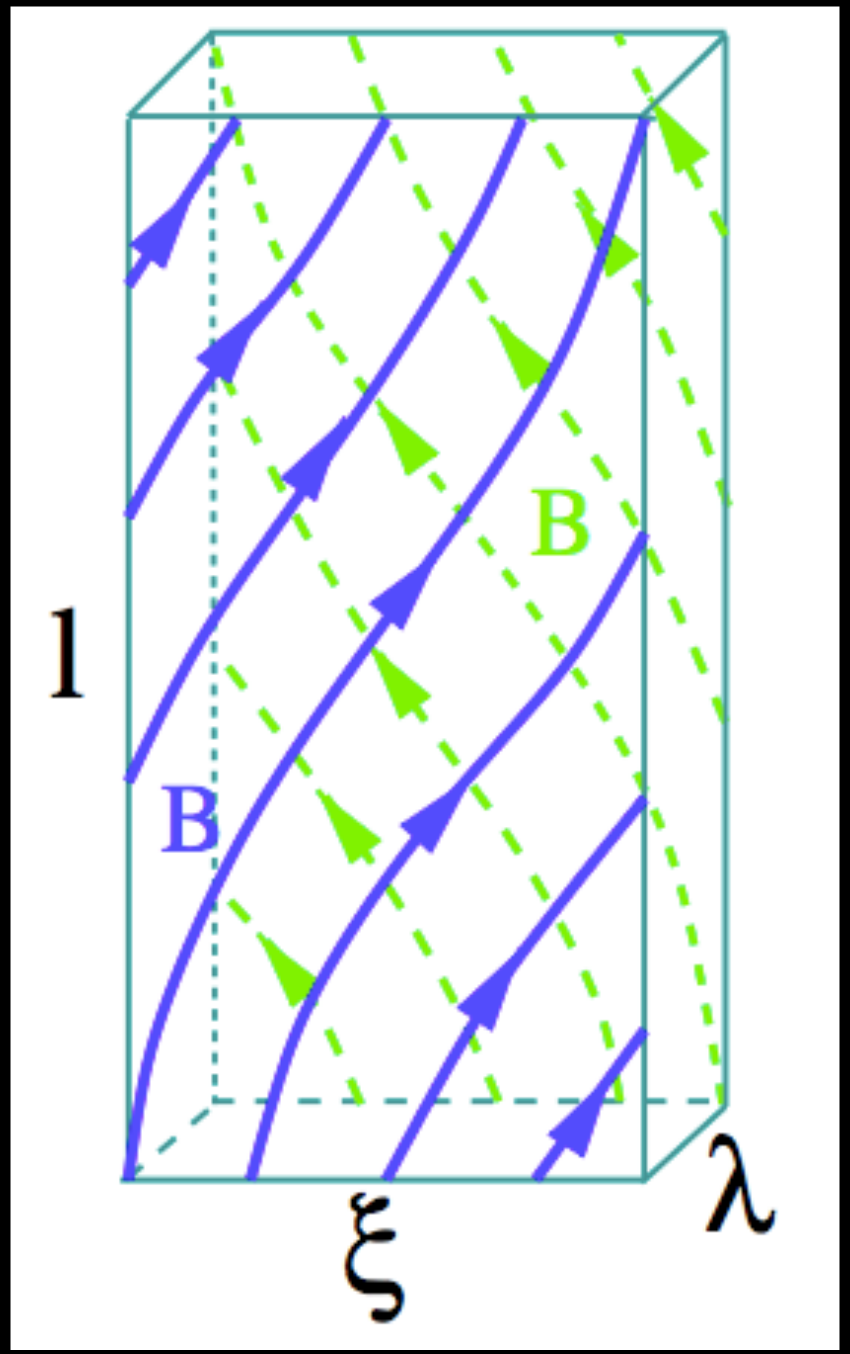

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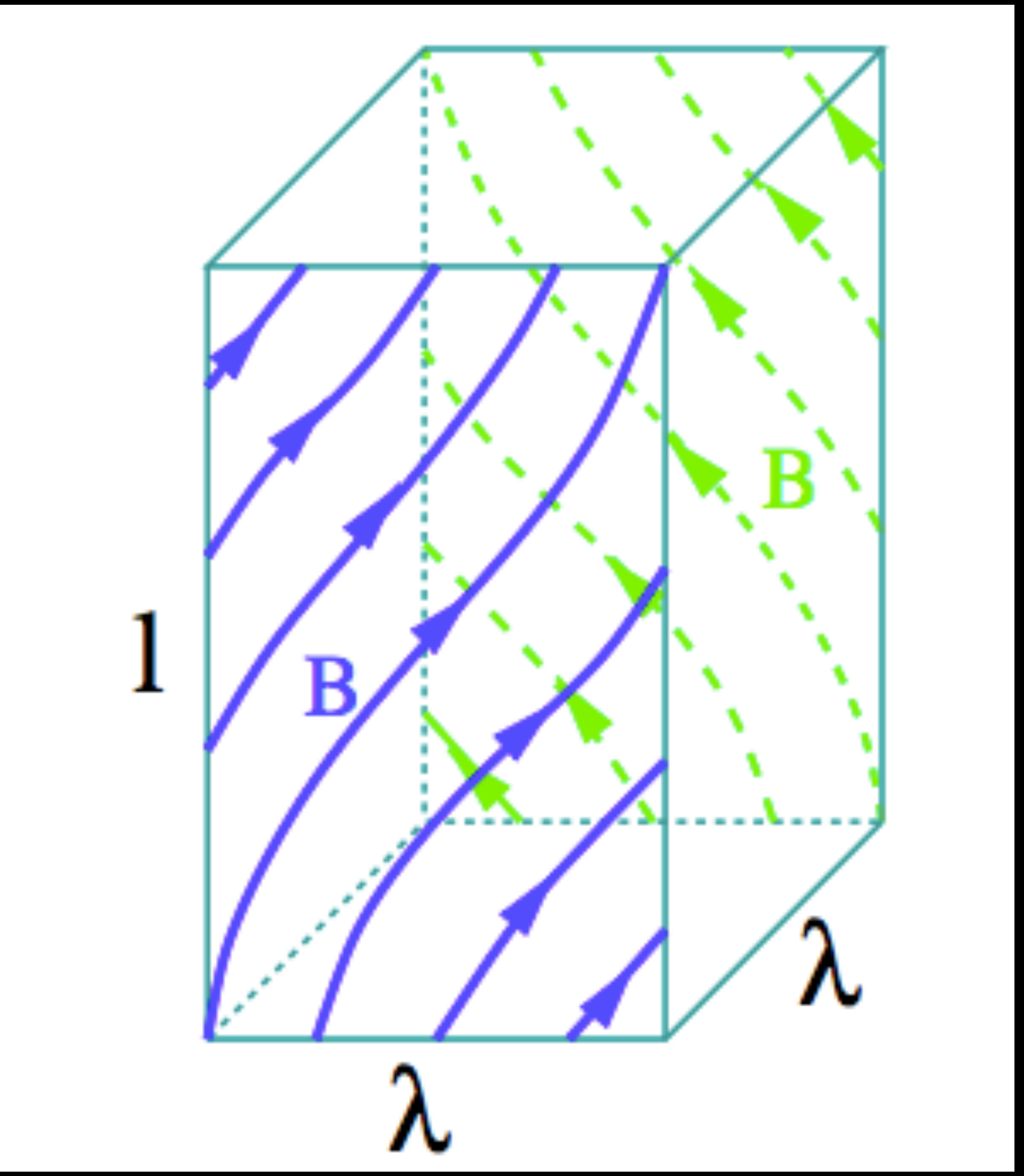

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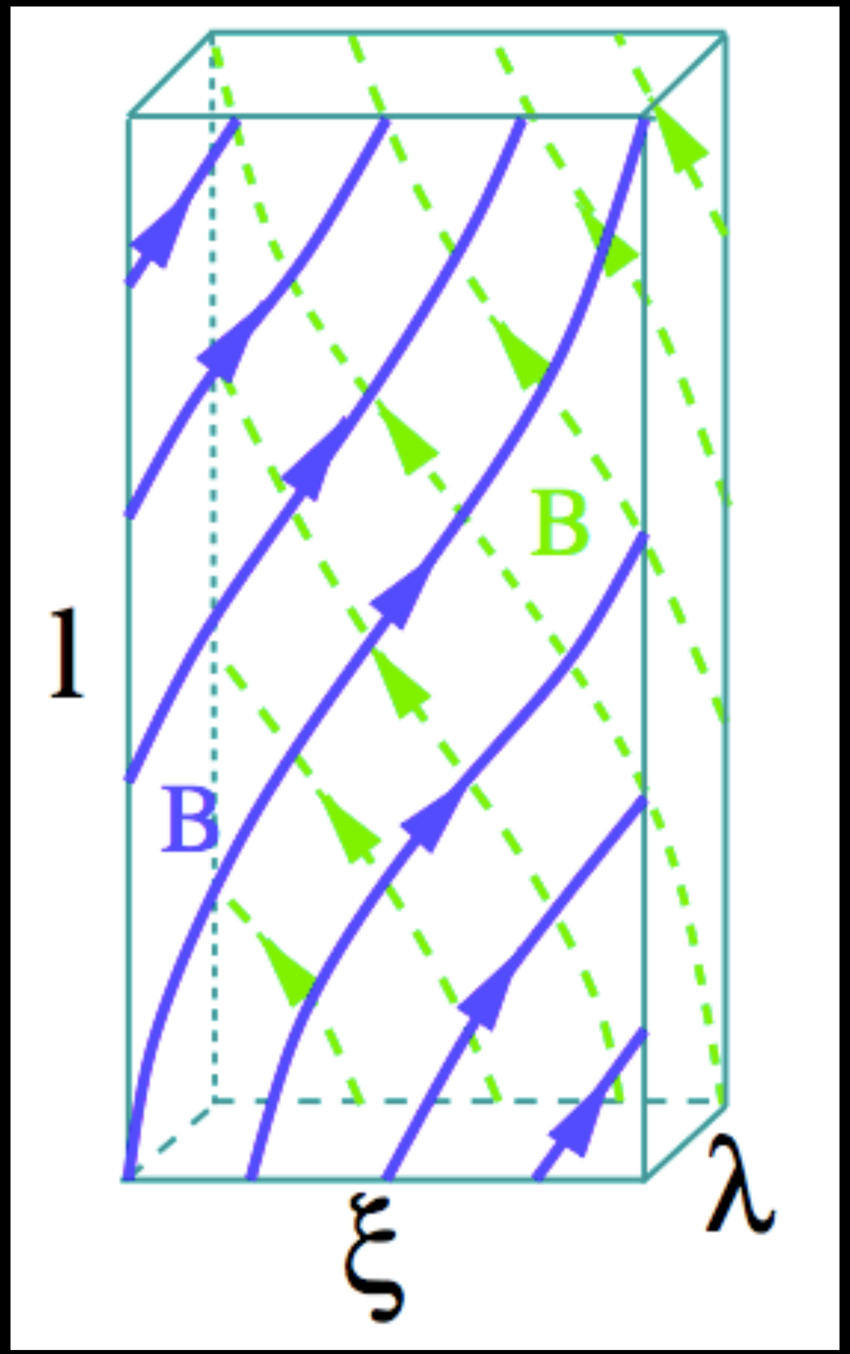

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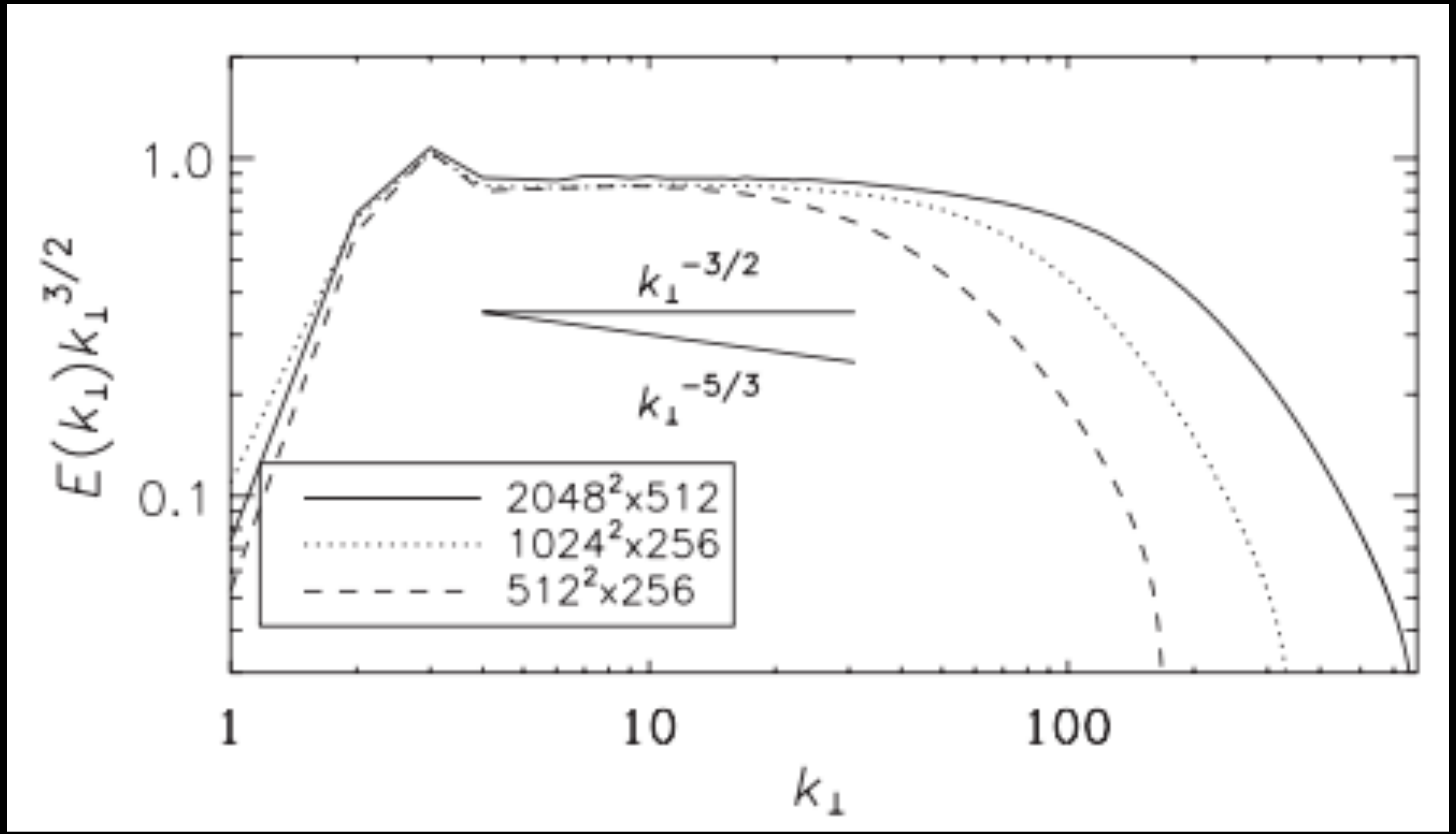

Magnetic energy spectrum. Perez *et al.*, PRX '12

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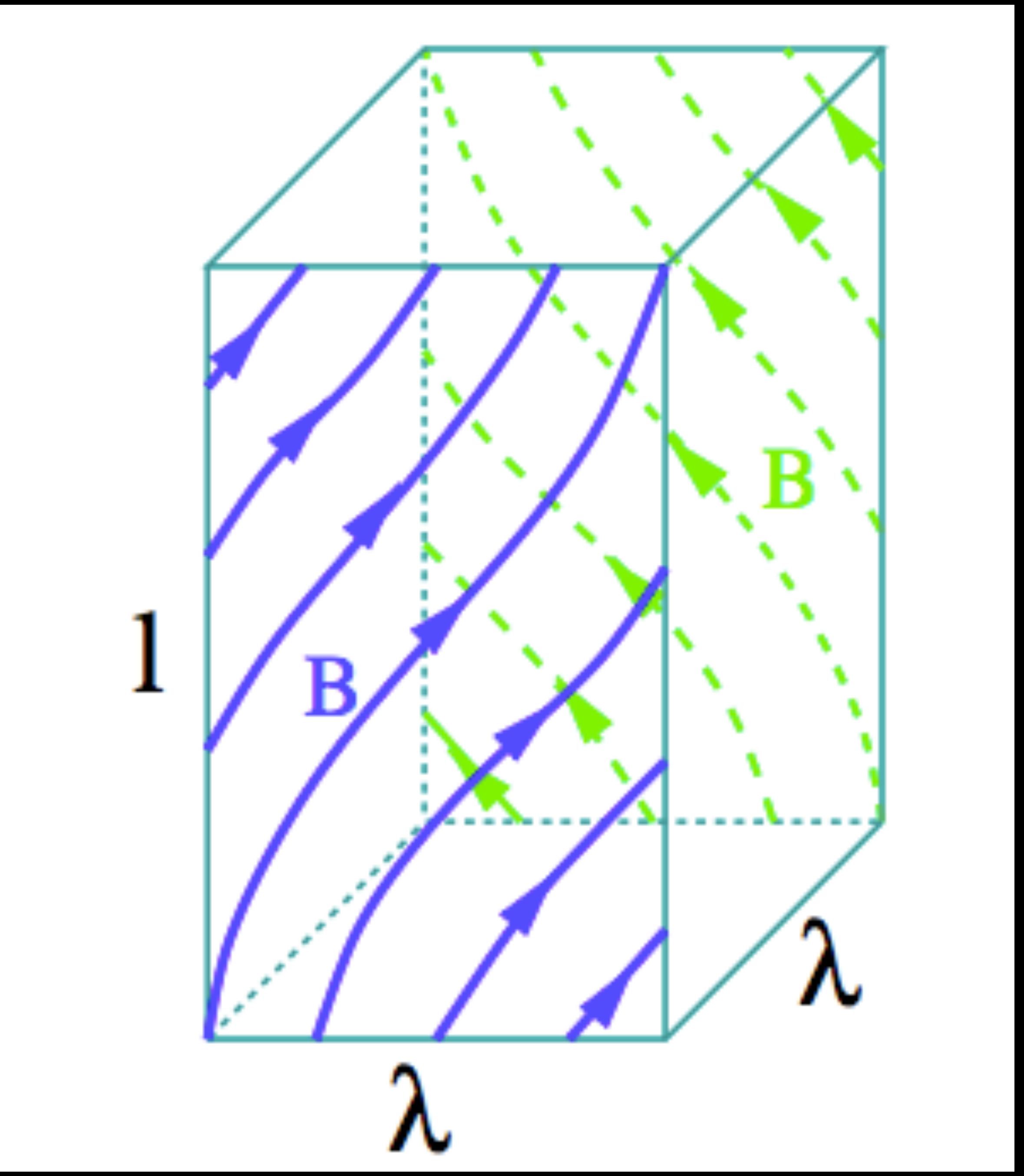

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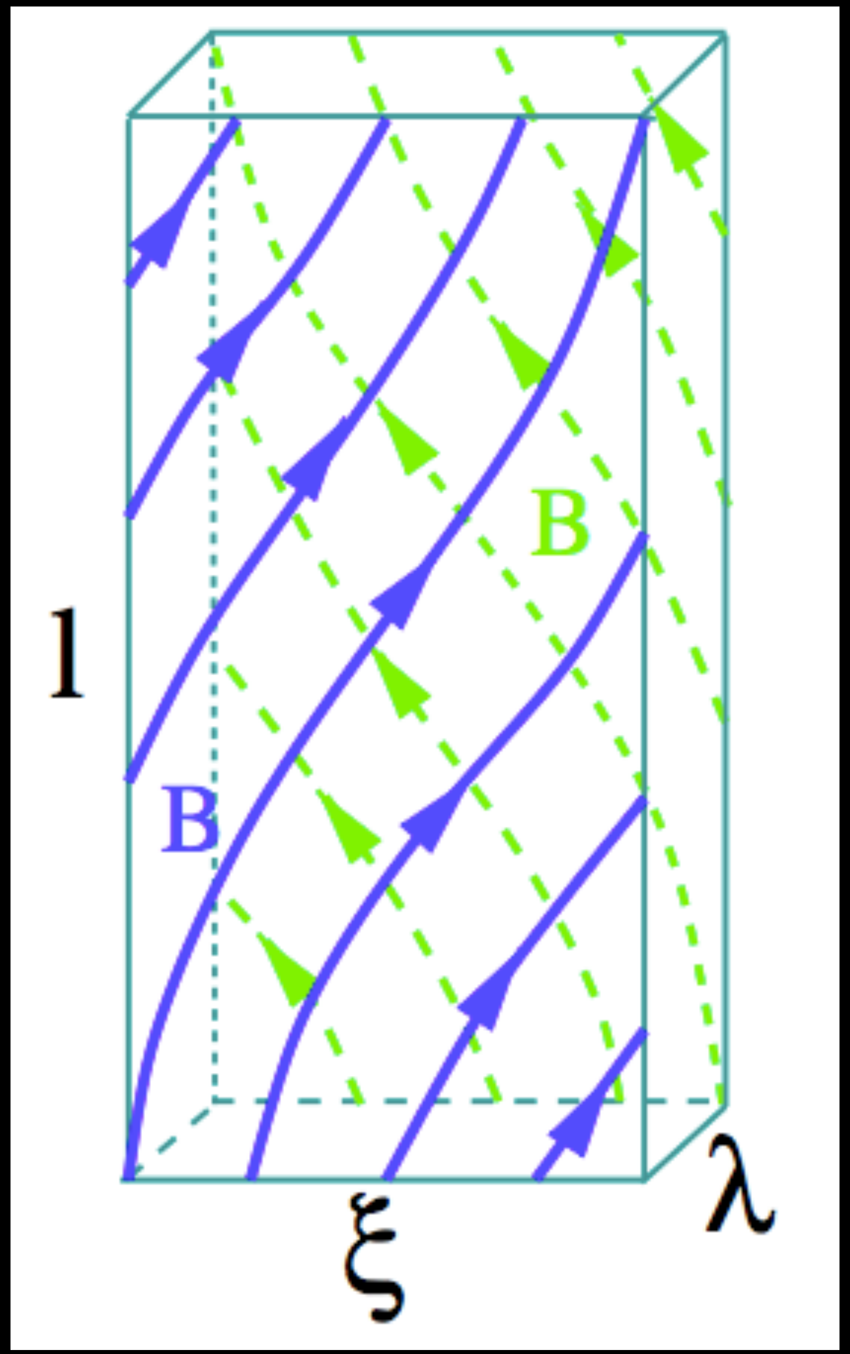

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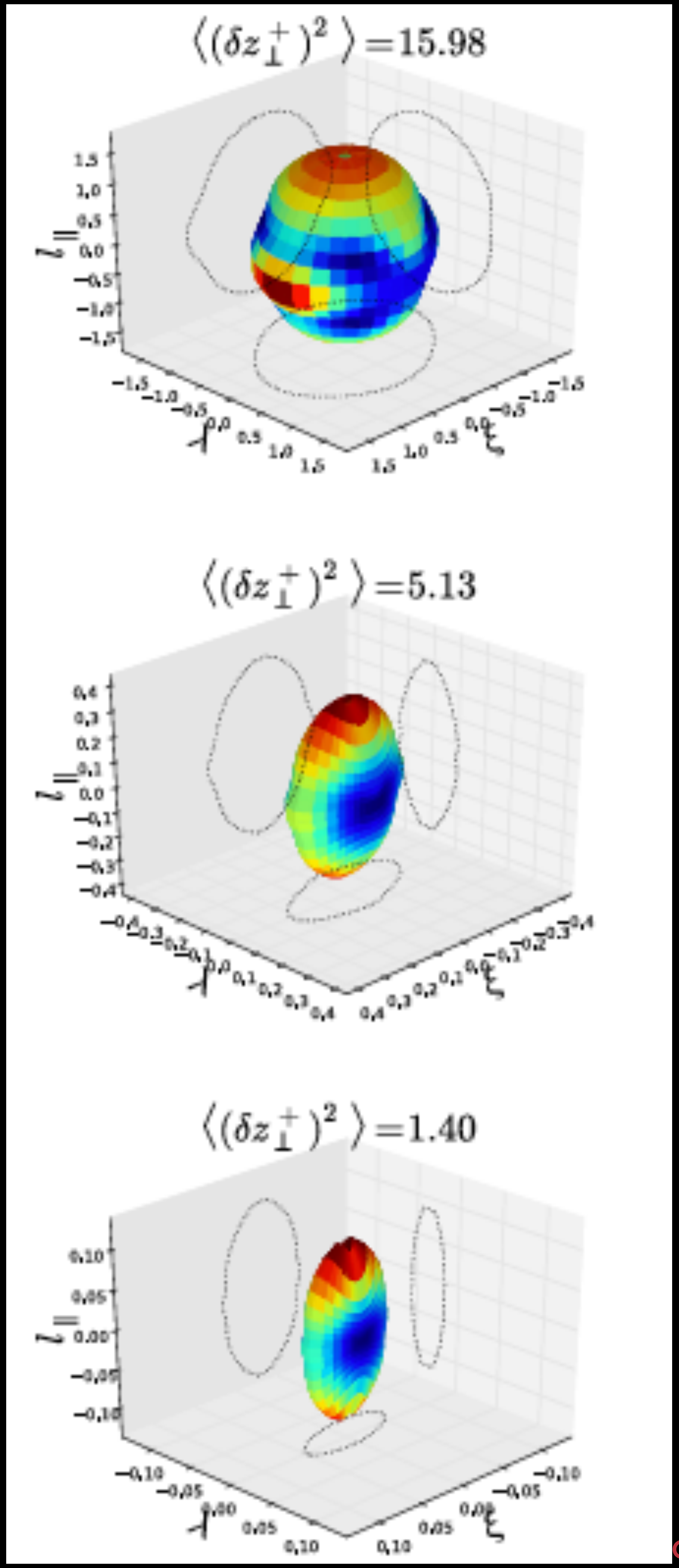
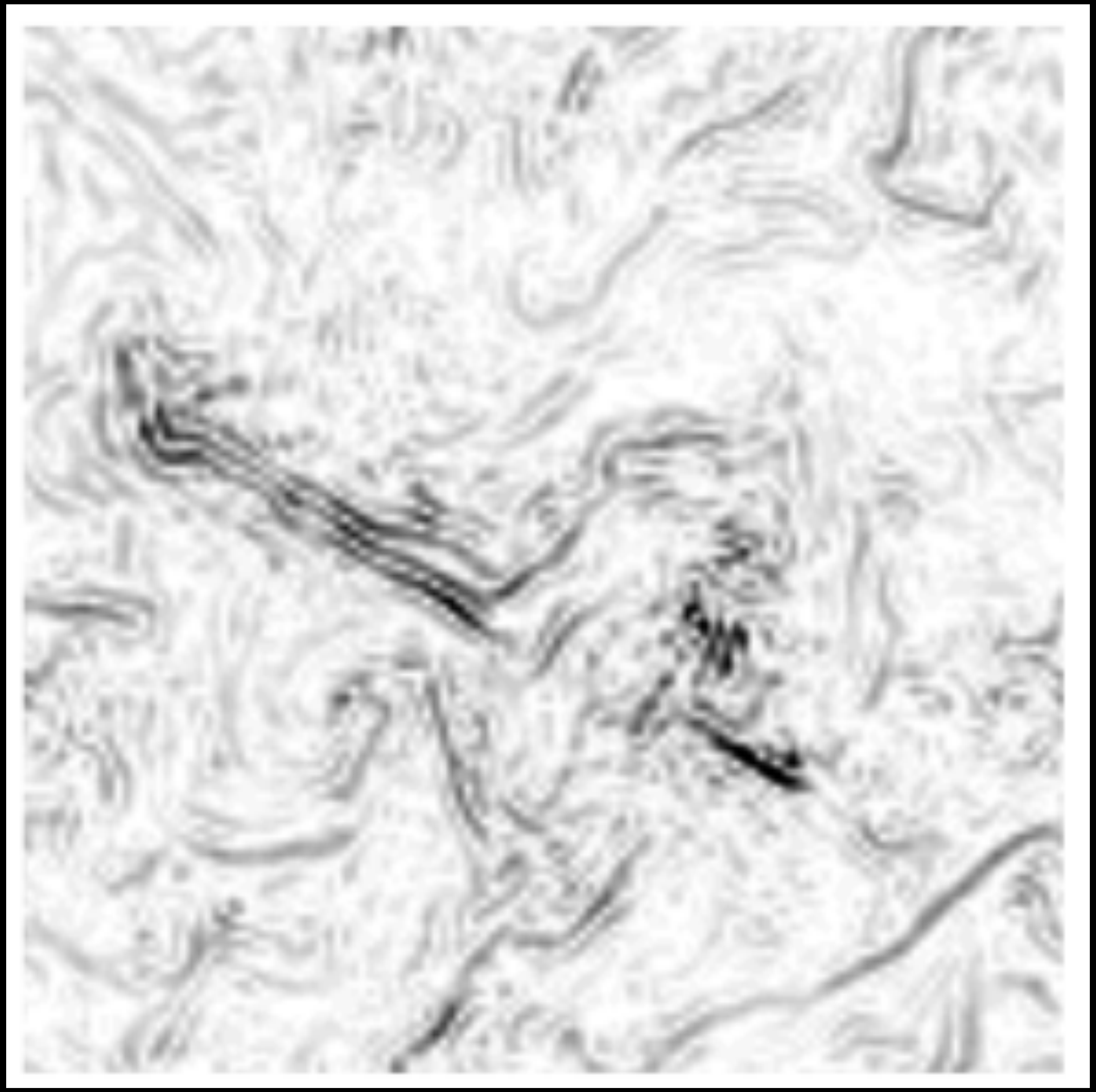


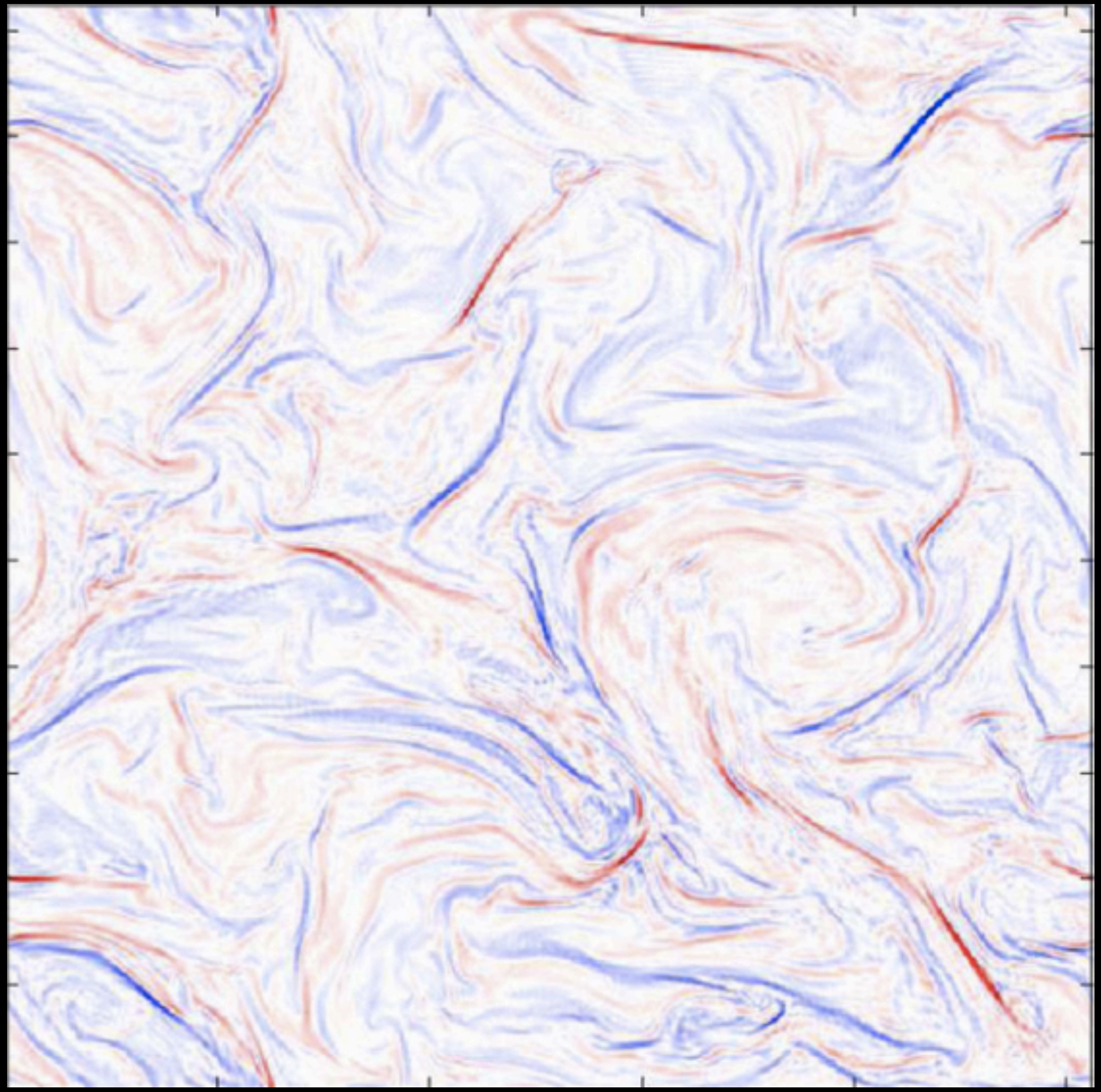
Mallet+ '16

Current sheet formation is predicted and observed

MHD turbulence simulations show abundant evidence for current sheet formation



Maron & Goldreich, ApJ ‘01

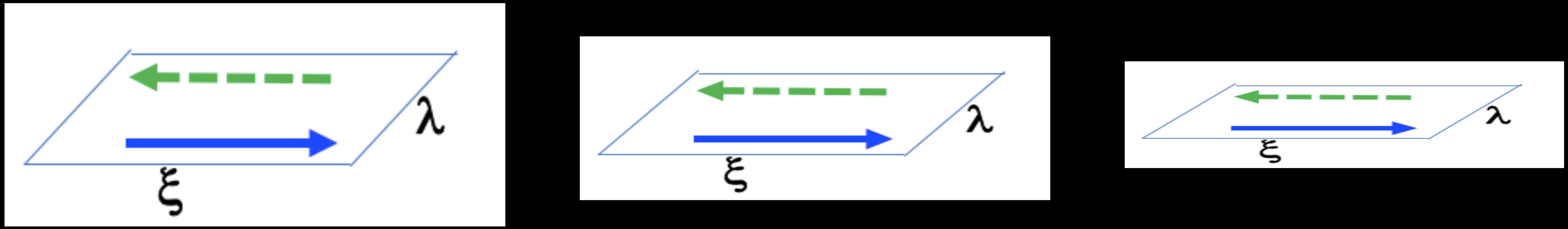


Zhdankin *et al.*, ApJ ‘13

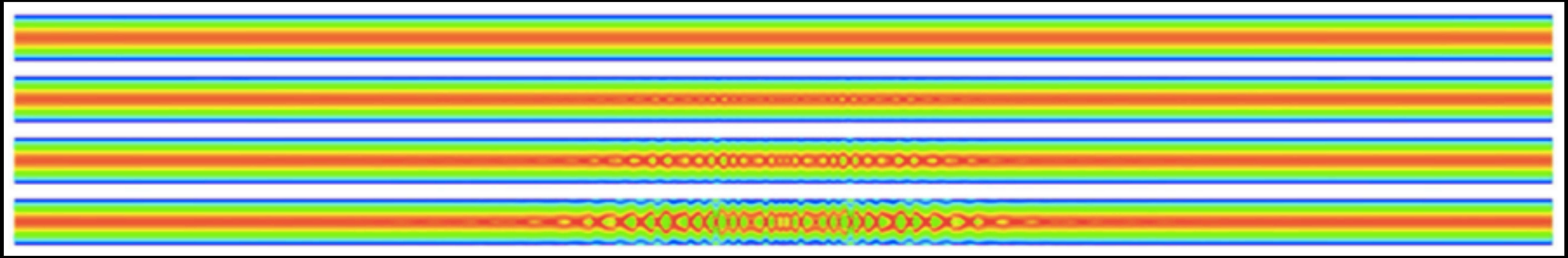
Strongly anisotropic current sheets are unstable

Current sheet anisotropy is limited by the tearing instability

- Eddy anisotropy in the field-perpendicular plane is predicted to increase as eddies get smaller



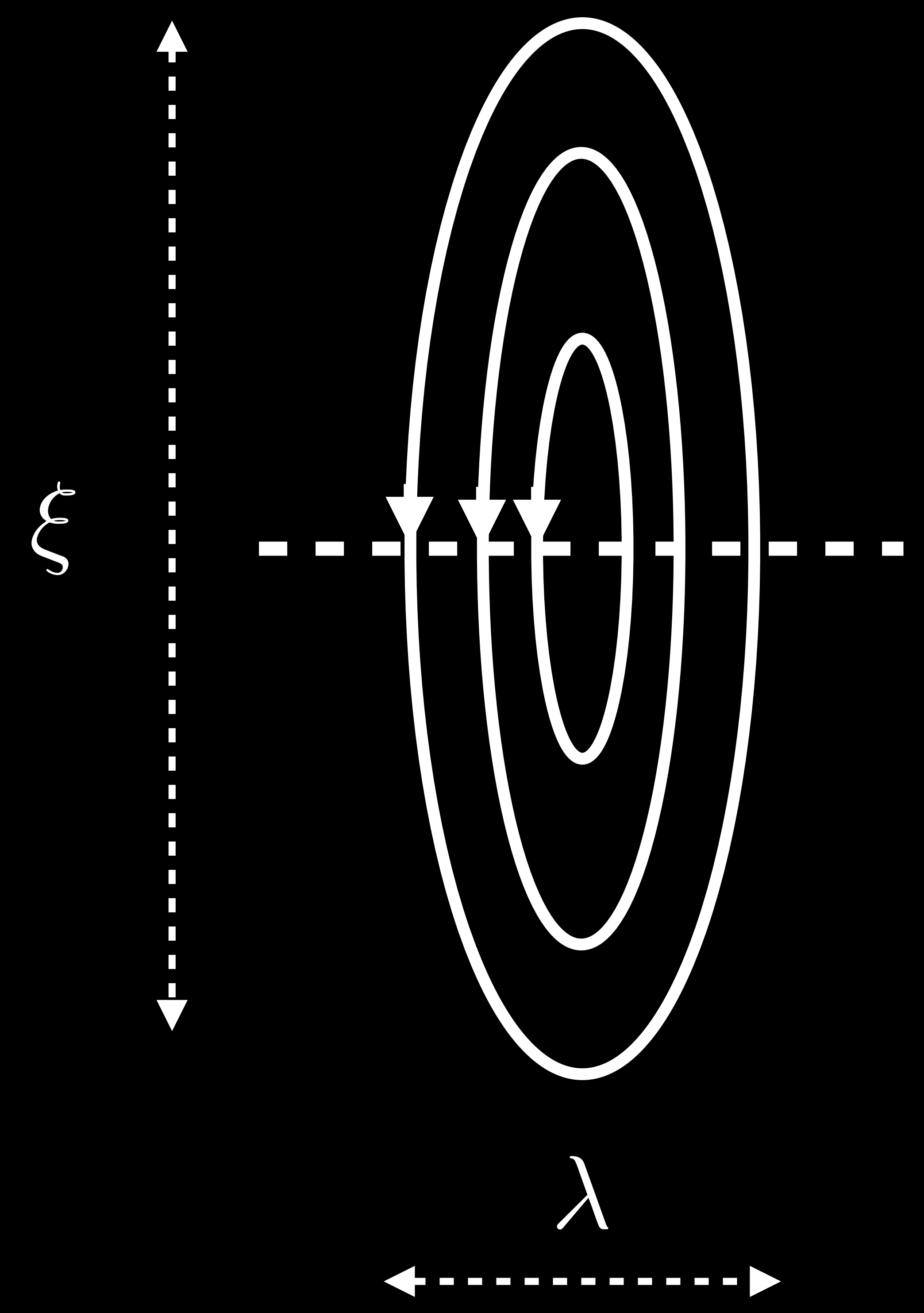
- At the dissipation scale, eddies' perpendicular aspect ratio would be the same as for a Sweet-Parker current sheet
- Cannot happen: Sweet-Parker sheets are super-Alfvénically unstable (Loureiro, Schekochihin & Cowley, 2007)



Samtaney *et al.*, 2009

Dynamic tearing onset in the inertial range

Matching the turbulence and tearing instability timescales



Loureiro & Boldyrev, PRL 2017

Boldyrev & Loureiro, ApJ 2017

Mallet *et al.*, MNRAS 2017

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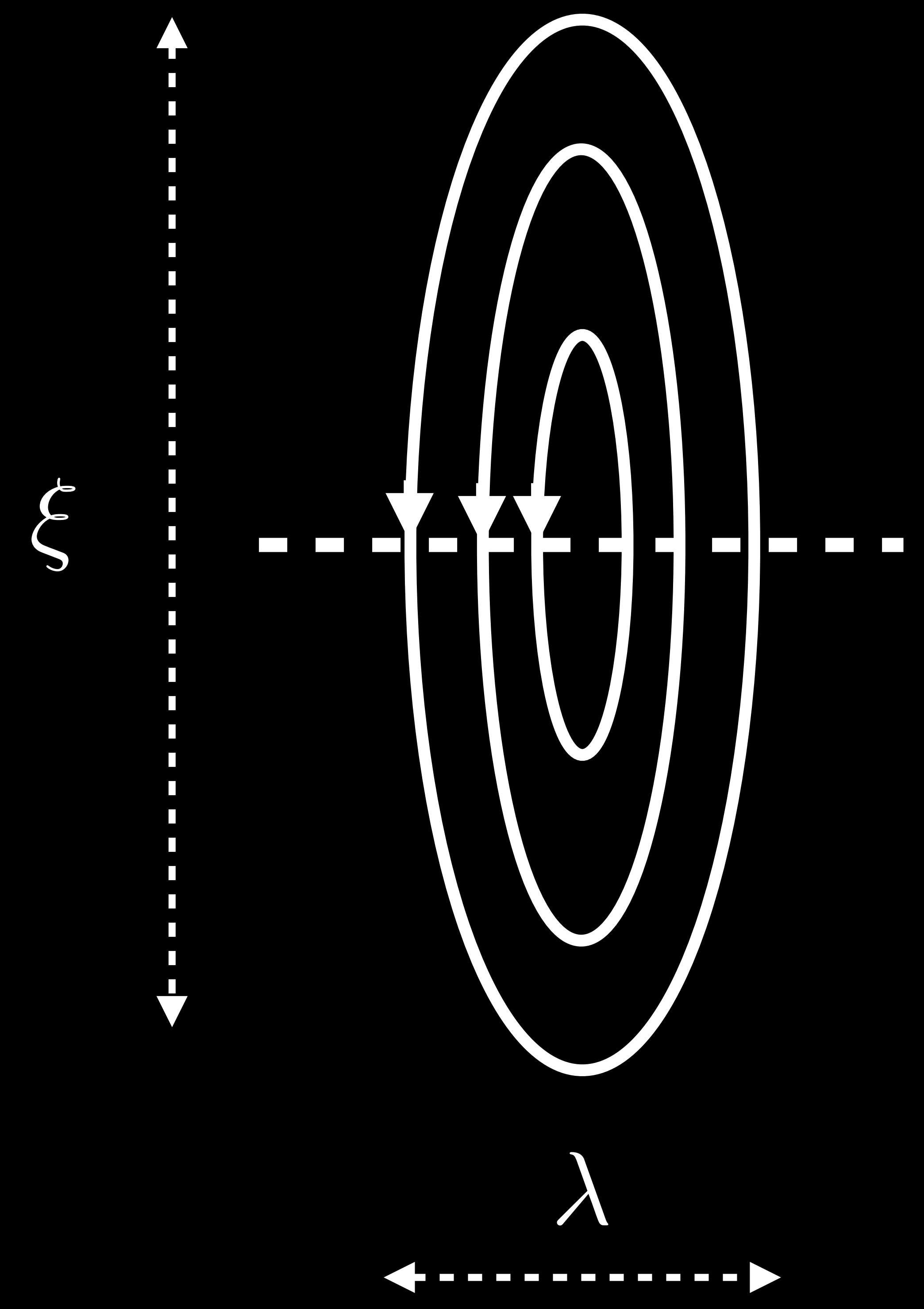

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$$\gamma_t(\lambda)\tau_{nl}(\lambda) \sim 1$$

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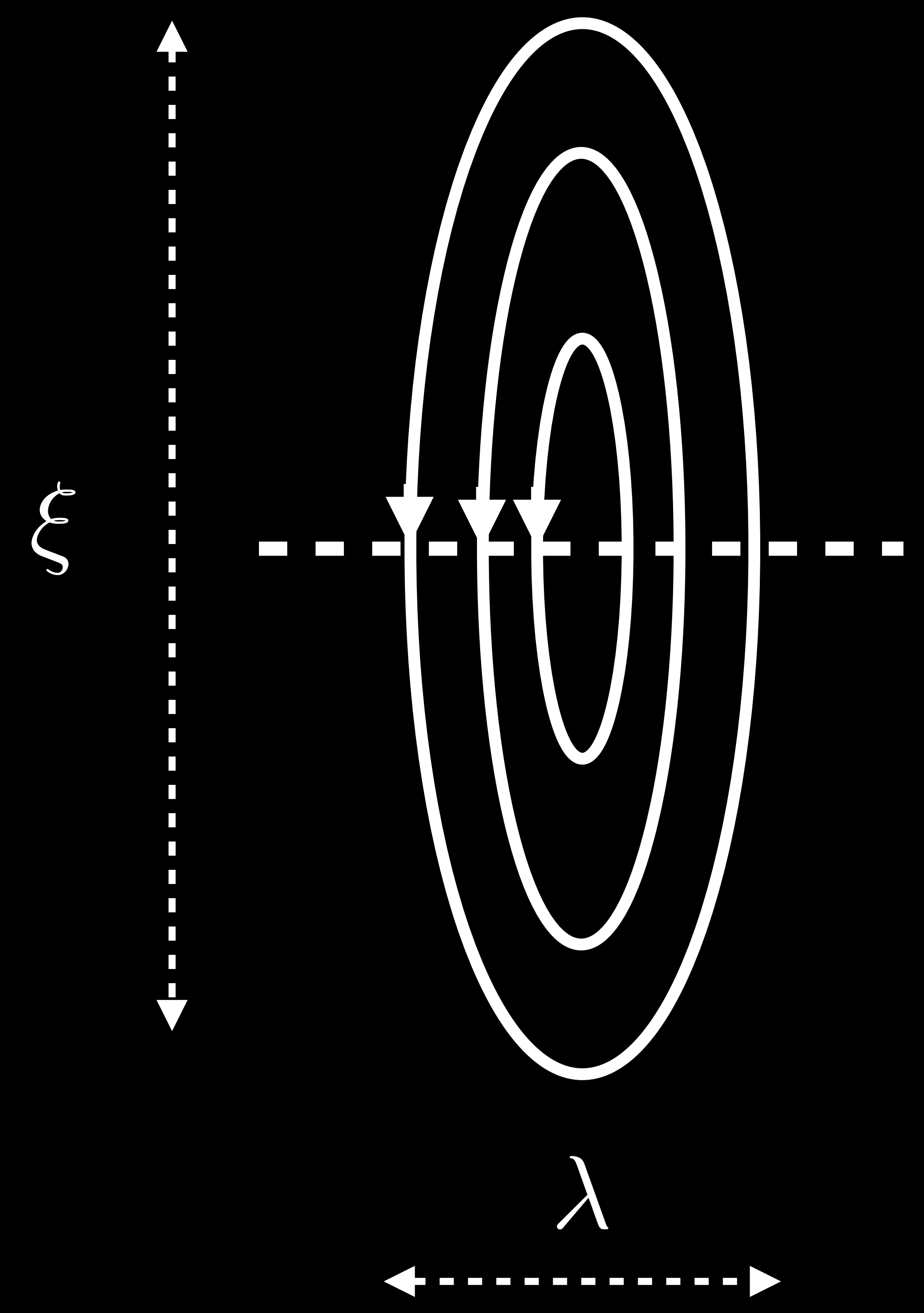

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$$\gamma_t(\lambda)\tau_{nl}(\lambda) \sim 1$$

- This leads to the prediction of a *critical scale* below which tearing is faster than turbulence:

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

Loureiro & Boldyrev, PRL 2017

Boldyrev & Loureiro, ApJ 2017

Mallet *et al.*, MNRAS 2017

Spectrum

Prediction of the existence of a new, sub-inertial range

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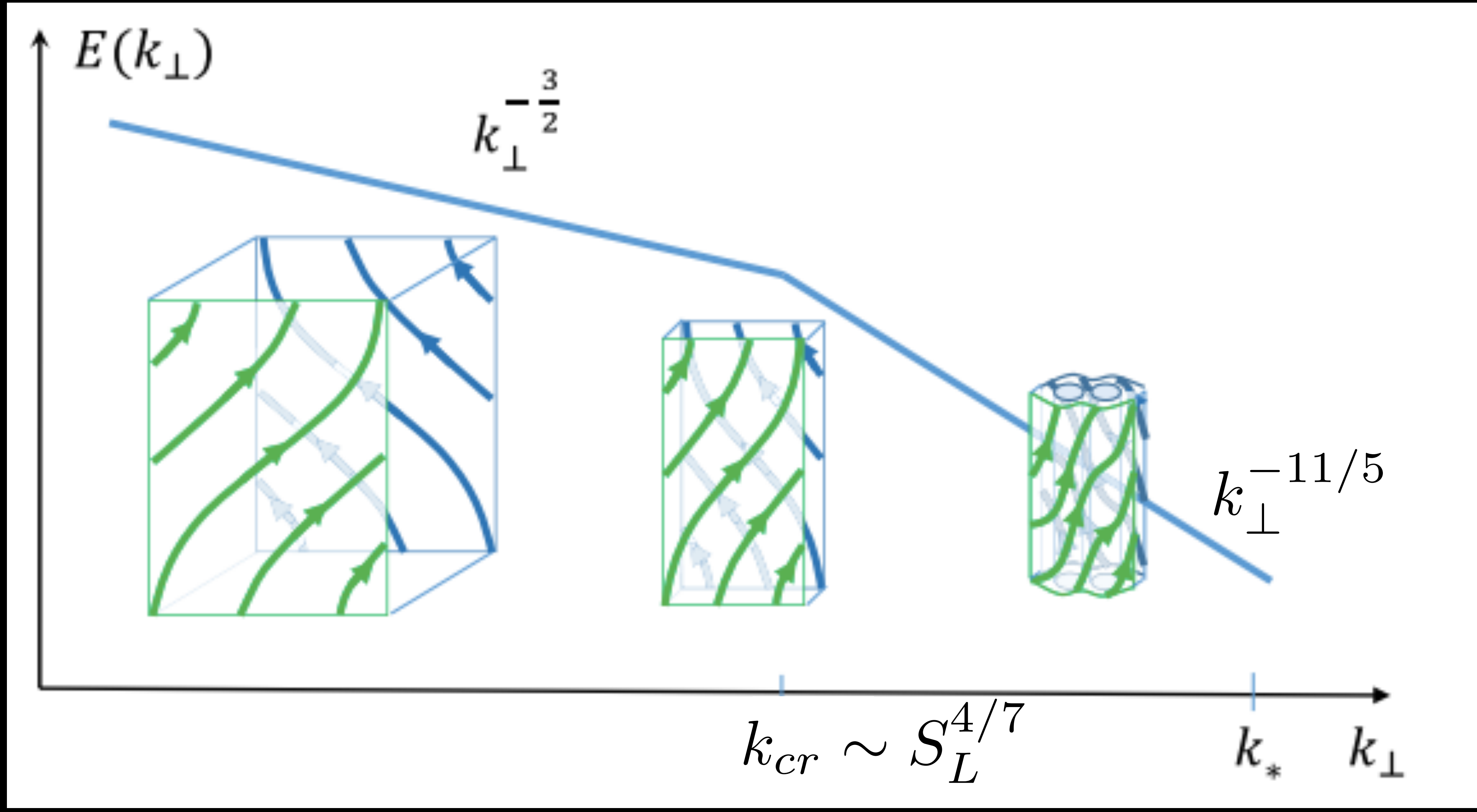
- Obtain:

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

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

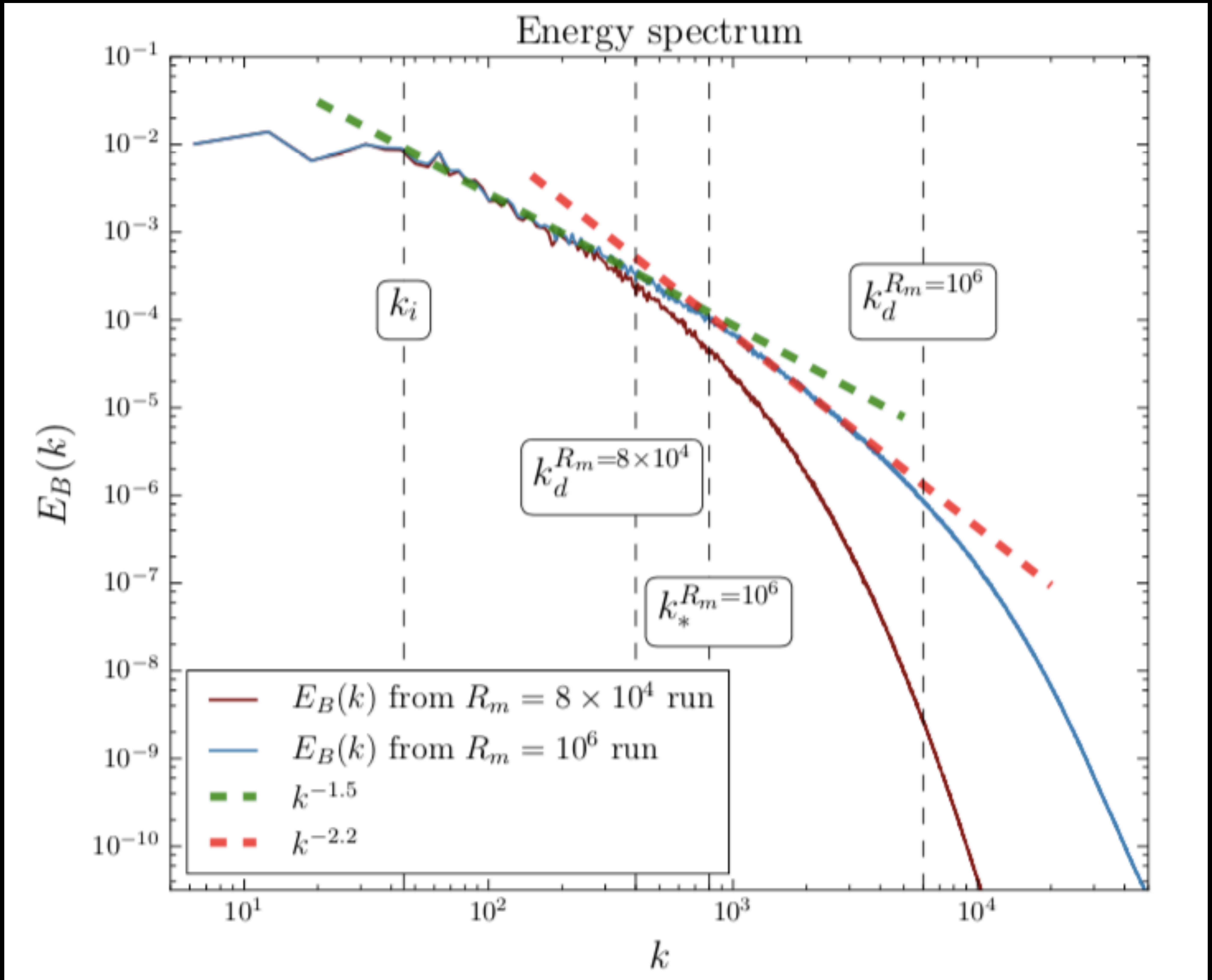
Boldyrev & Loureiro, ApJ 2017

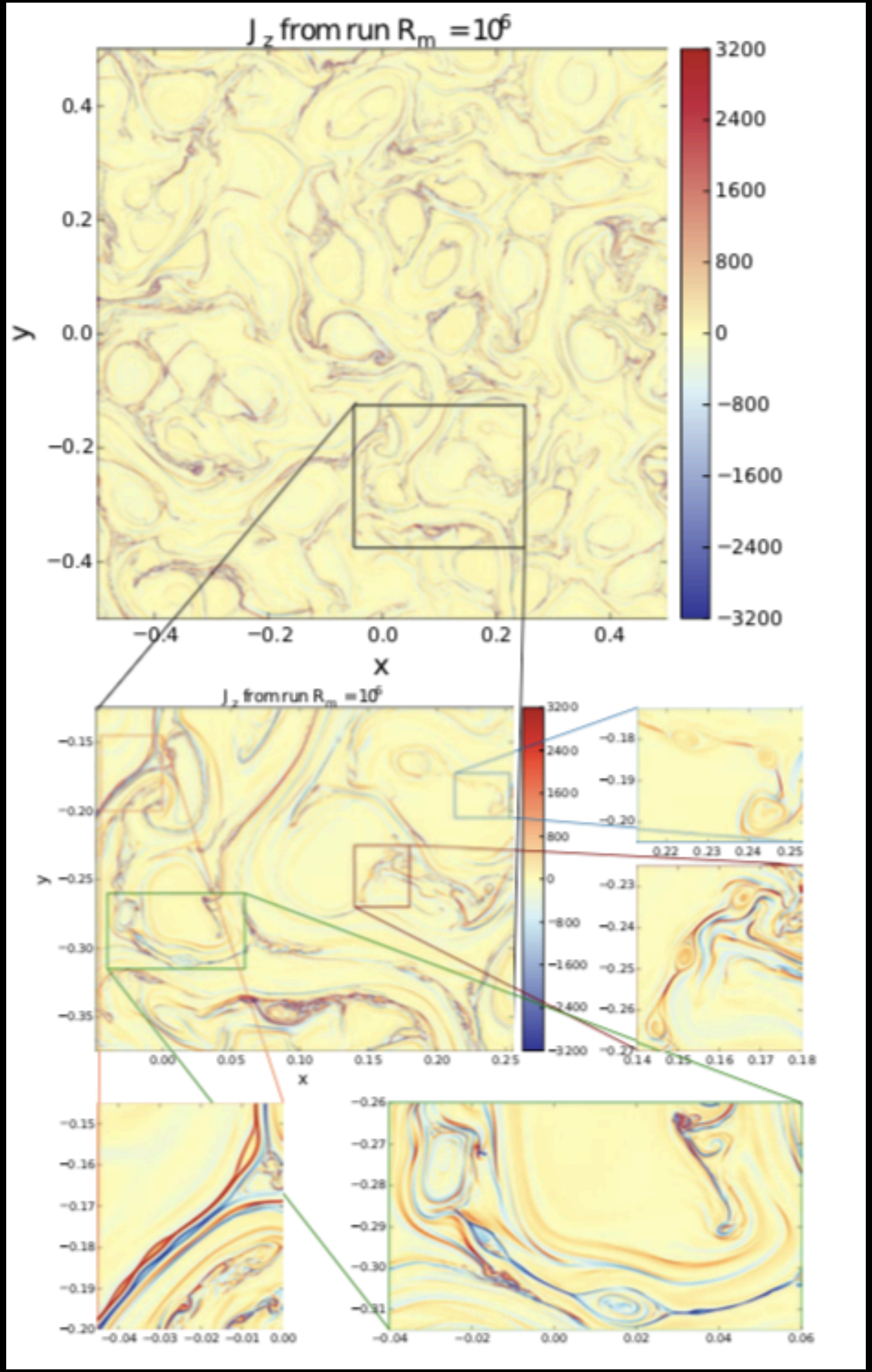
Mallet *et al.*, MNRAS 2017



Numerical support for tearing in MHD turbulence

Simulations seem consistent with these predictions





Dong *et al.* 2018

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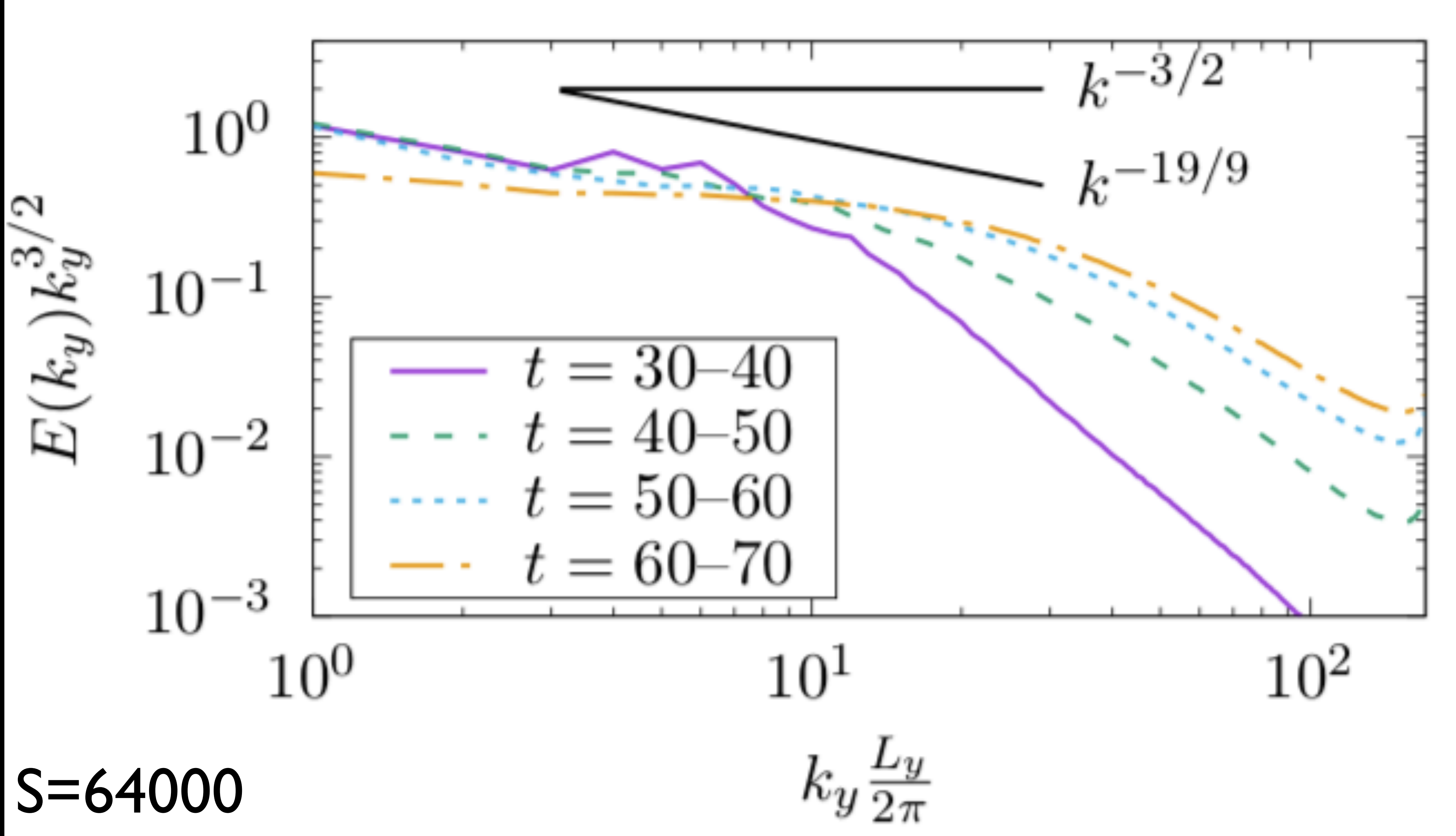

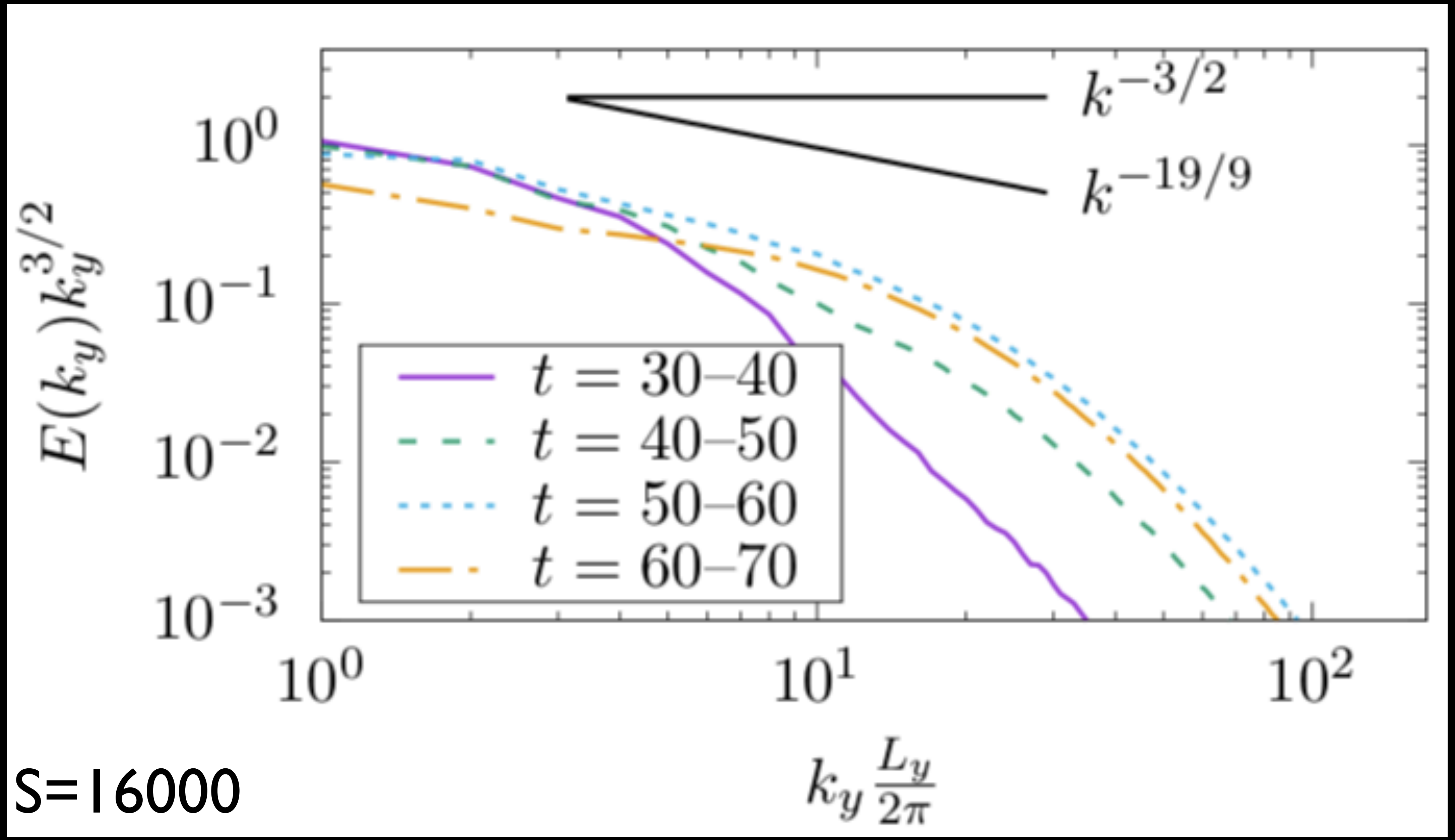

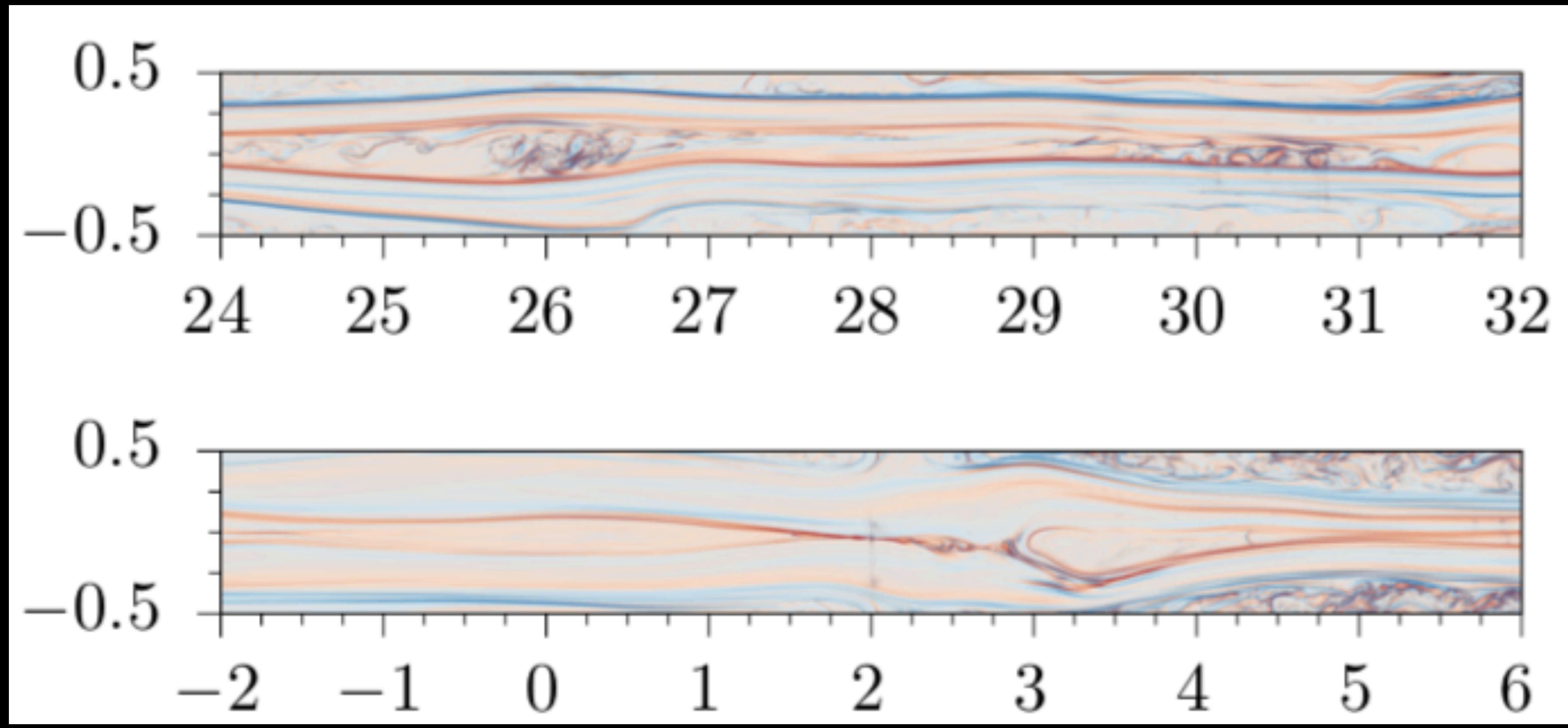

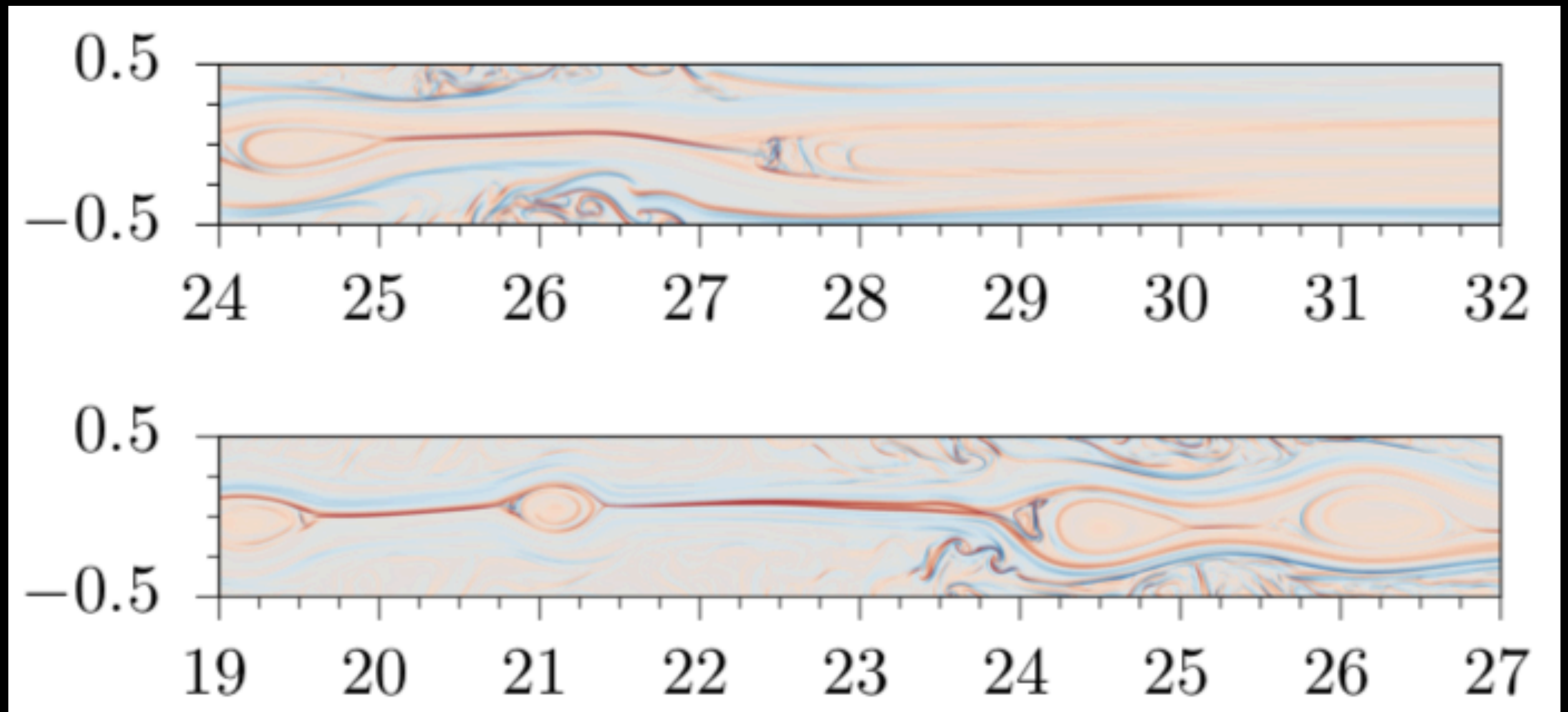

Walker *et al.*, PRE 2018

Extension to the kinetic regime

Collisionless tearing in MHD-scale eddies

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

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- Different cases can be analyzed, depending on electron beta.

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- Different cases can be analyzed, depending on electron beta.
- Invariably, obtain spectra that scale as

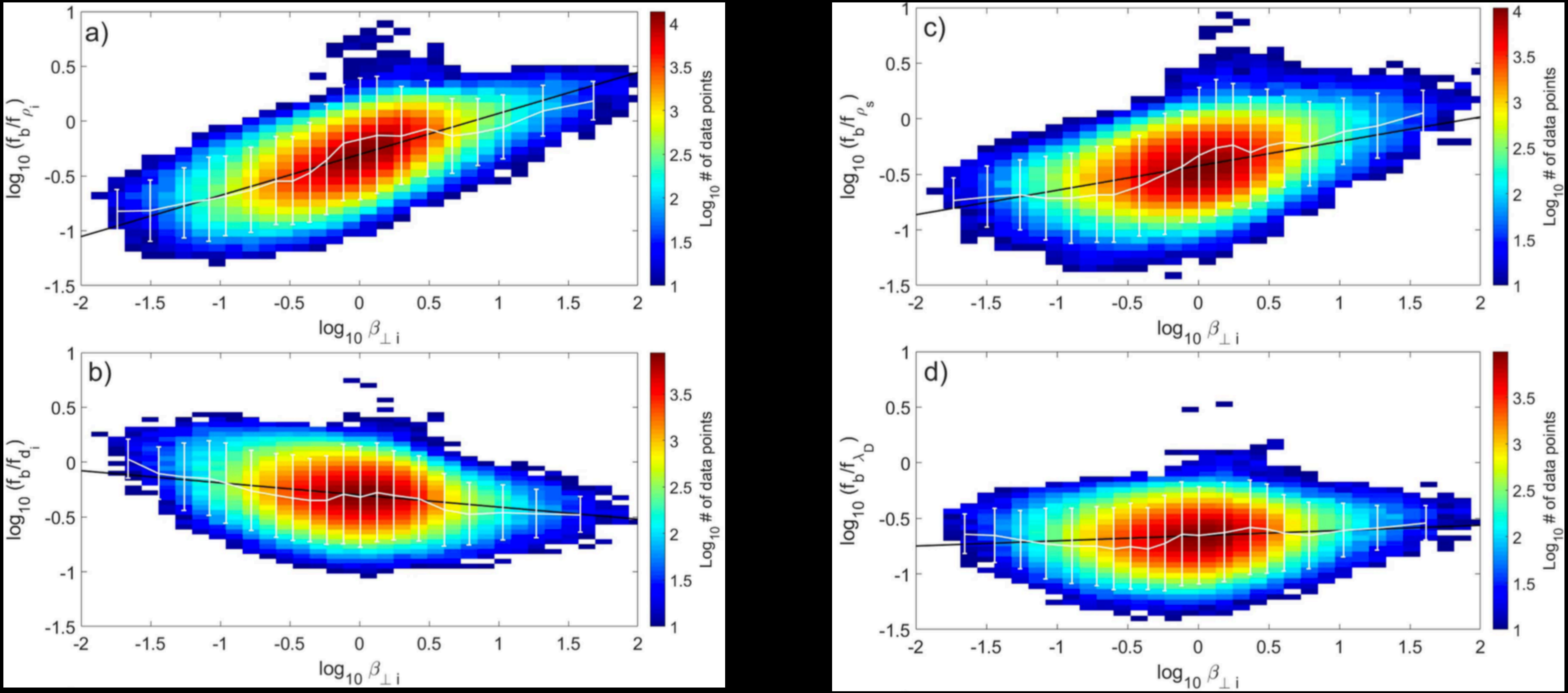
$$E(k_\perp) \propto k_\perp^{-3} \quad \text{or} \quad E(k_\perp) \propto k_\perp^{-8/3}$$

depending on what shape is assumed for the tearing magnetic field (tanh or sine).

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

Evidence for tearing onset in SW turbulence

Analysis of SW data shows evidence of a tearing-induced spectral break for low electron beta



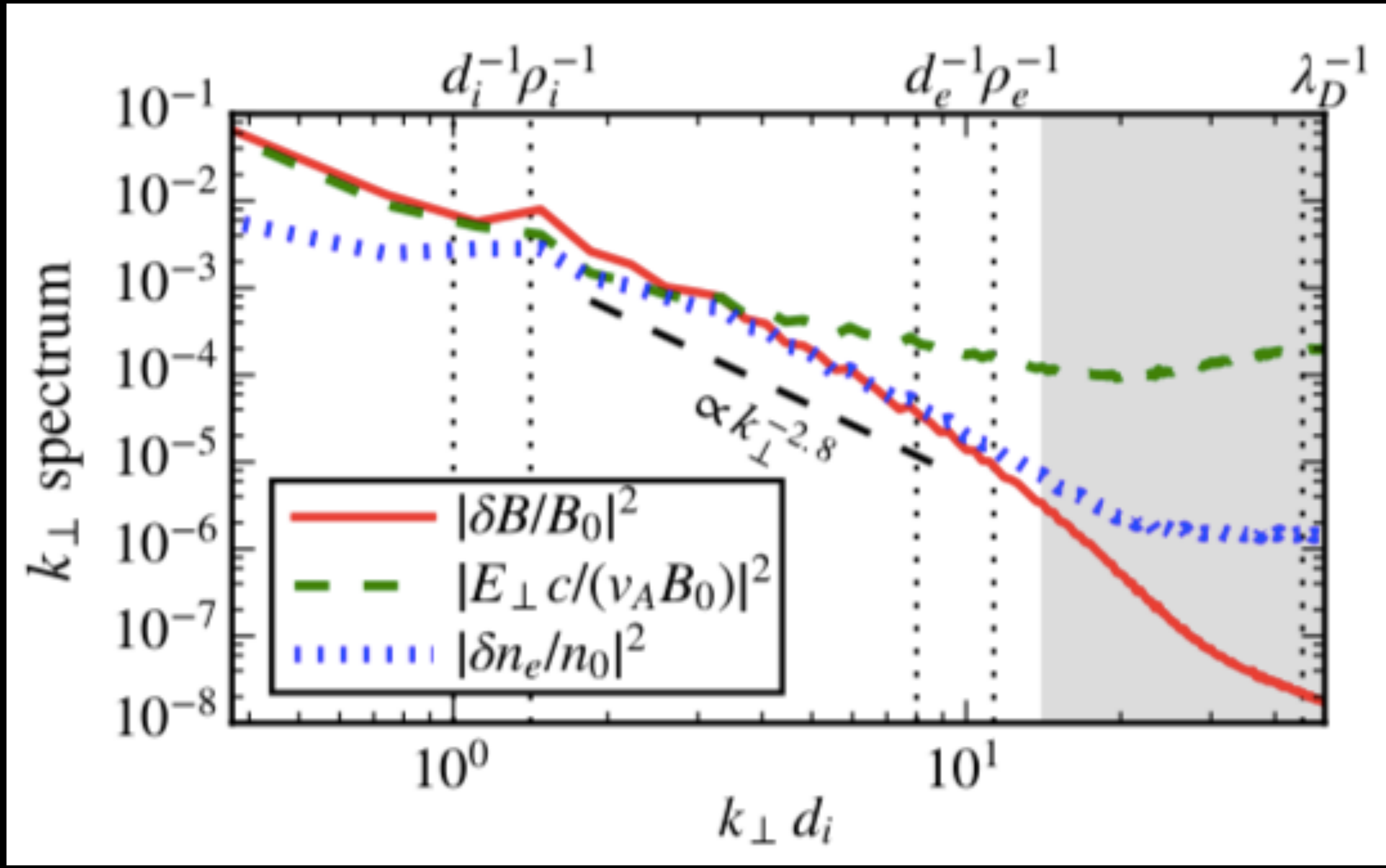
Vech *et al.*, ApJ 2018

Tearing in the kinetic turbulence range

Collisionless tearing at sub-Larmor radius scales

- Can we extend these ideas to the kinetic turbulent range, i.e.,

$$\lambda \ll \max(\rho_i, \rho_s)$$



D. Groselj *et al.*, PRL '18

Boldyrev & Loureiro, ApJ 2017

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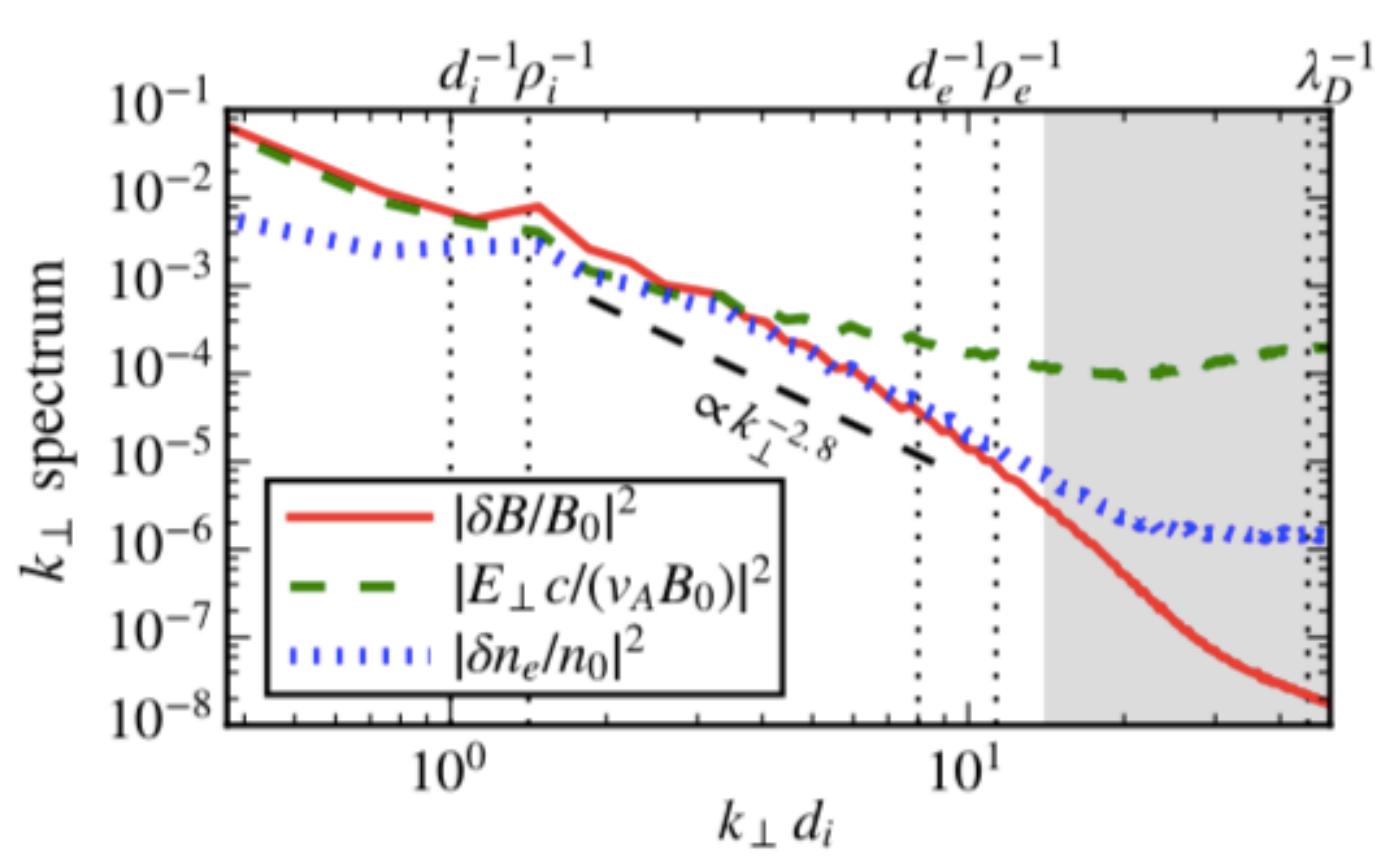
- Numerical simulations do suggest ubiquitous current sheet presence at these scales.
- Cannot estimate the critical scale for the transition to the tearing range – this requires knowing what the eddies look like.



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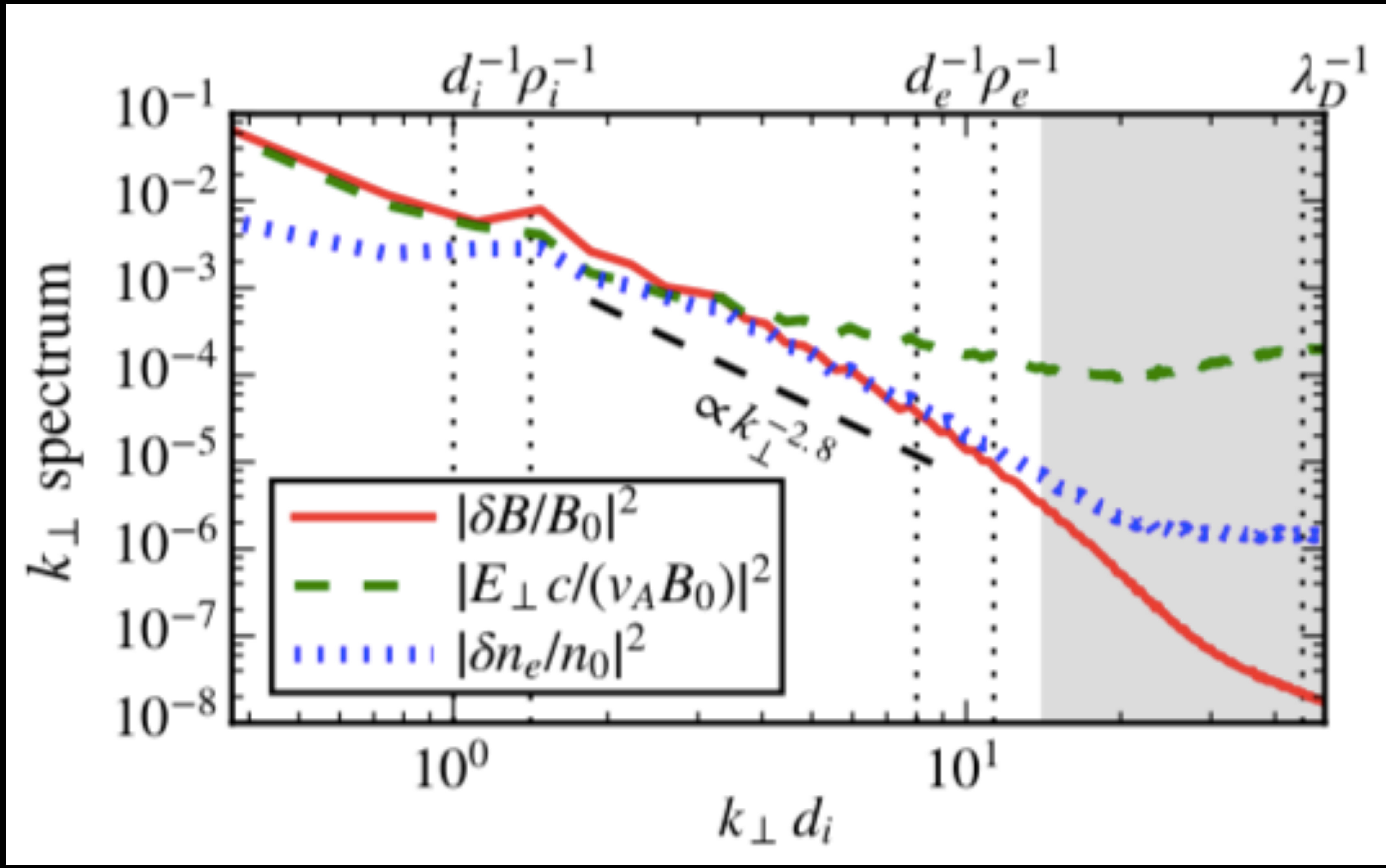

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- But can estimate the spectrum given expression for the tearing mode growth rate at those scales. Again, we obtain:

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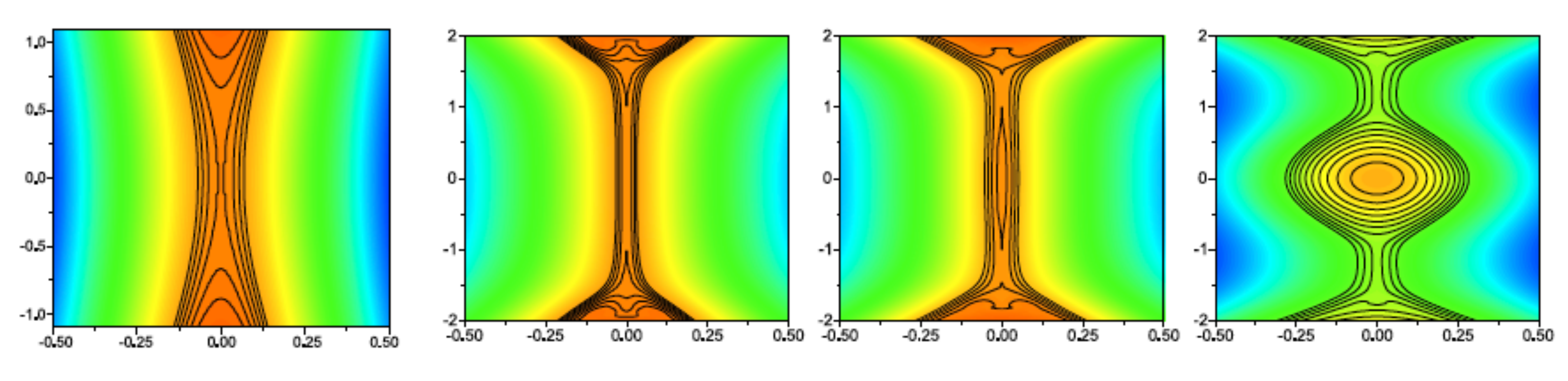
Boldyrev & Loureiro, ApJ 2017

Nonlinear Tearing-Mode Evolution

Recap of how MHD tearing proceeds in the absence of turbulence

- When the (most unstable) tearing mode becomes nonlinear, it continues to grow exponentially at the linear growth rate (the Waelbroeck collapse)
- *In the absence of background turbulence*, the collapse leads to the formation of a current sheet: of the Sweet-Parker (SP) kind, if $S < S_{cr} \sim 10^4$, or of the plasmoid-unstable kind, otherwise.
- If SP, the rate remains the same. If plasmoid-dominated, rate becomes $\sim S_{cr}^{-1/2} \sim 0.01$ (Uzdensky *et al.*, '10)



Loureiro *et al.* '05

- Collisionless tearing is similar, except rate becomes 0.1 (e.g., Comisso & Bhattacharjee '16, Cassak'17).

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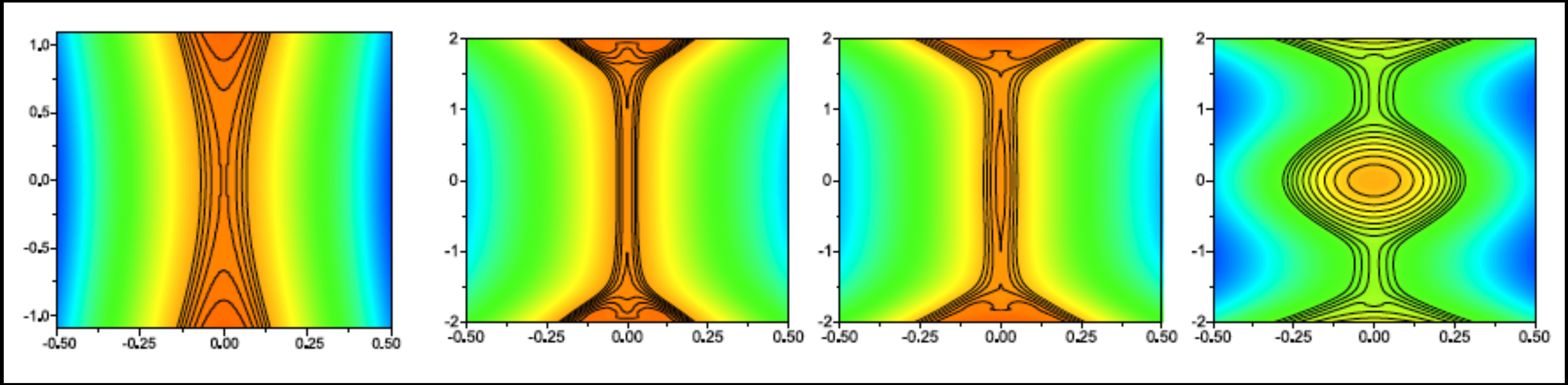

- What we usually call *reconnection* is the *advanced or the post-collapse stage*: more precisely, it is when the rate changes to 0.01 in the MHD plasmoid case, or 0.1 in the collisionless case.
- Crucially, **it is only in this (late nonlinear) stage of the tearing mode that significant amounts of flux are reconnected, and significant (~50%) amounts of energy are dissipated/converted.**

Tearing *vs.* Reconnection: enter turbulence

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- All we can say is that there is a finite (order 1) probability that the collapse will last long enough to transition to the reconnection stage proper (and an order 1 probability that it won't)

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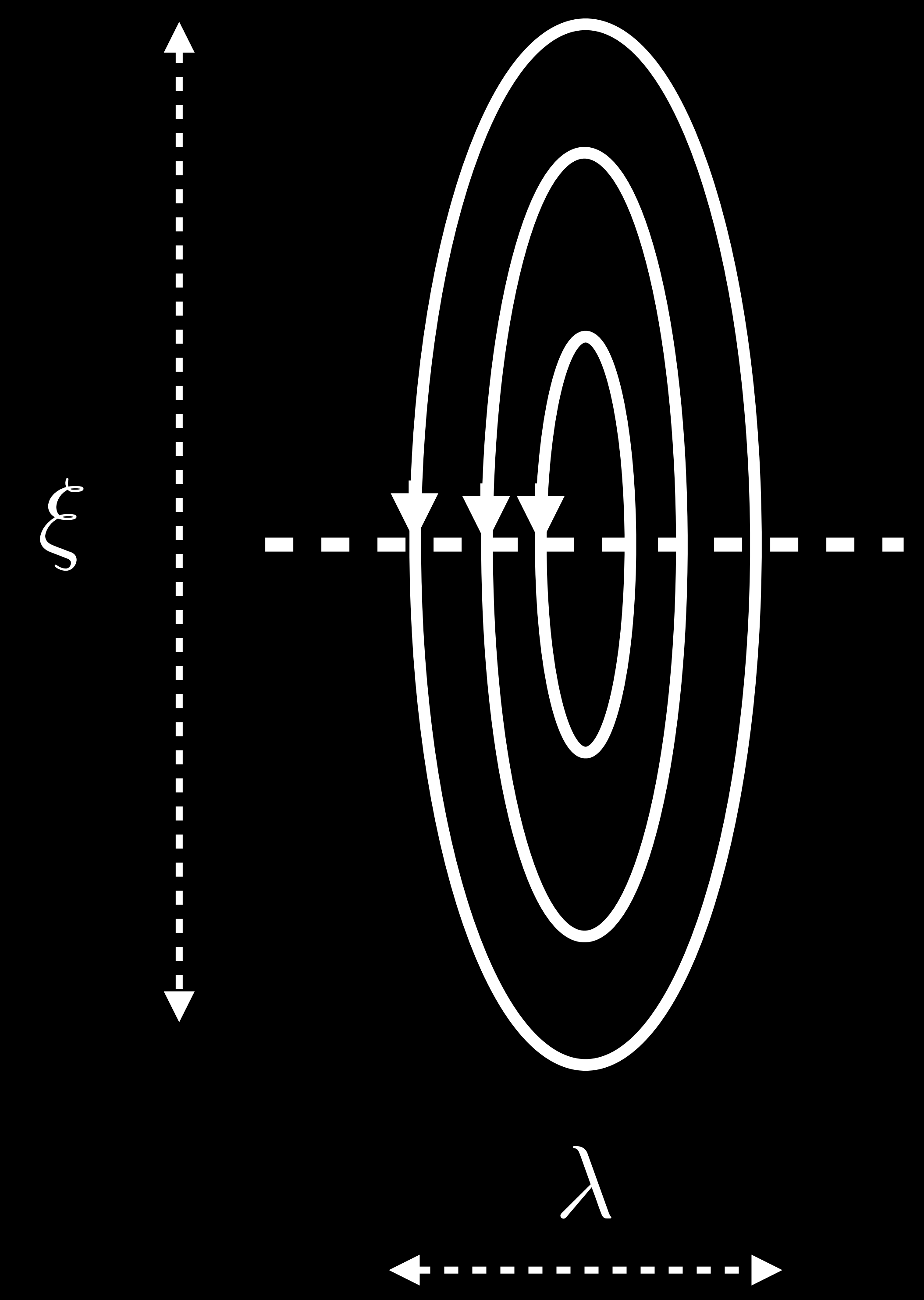
- **If it does transition to the reconnection stage, will there be time to reconnect significant amounts of flux (and dissipate significant amounts of energy) in the lifetime of the eddy?**

Reconnecting the flux in an eddy

How long does it take to reconnect the flux in an eddy?



$\psi_\lambda = B_\xi(\lambda)\lambda$ (reconnectable) flux contained in eddy.

$\tau_{rec} = \mathcal{R}^{-1}\tau_{A,\lambda}$ where $\tau_{A,\lambda} = \lambda/v_{A,\lambda}$

$\mathcal{R}$ is the (dimensionless) reconnection rate.

In MHD, $\mathcal{R} \sim S_\xi^{-1/2}$ if $S_\xi \lesssim S_{cr} \approx 10^4$

$\mathcal{R} \sim S_{cr}^{-1/2} \approx 0.01$ if $S_\xi > S_{cr}$ (the plasmoid regime)

In collisionless plasmas, $\mathcal{R} \sim 0.1$

Can full eddy reconnection happen?

Criterion for reconnection to have time to occur

- A typical eddy at scales $\lambda \ll \lambda_{cr}$ exists for a time of order γ_t^{-1}
- It has a finite probability of reaching the deep nonlinear stage, whereupon it may transition to the reconnection regime.
- *If*

$$\gamma_t \tau_{rec} \ll 1$$

then the *reconnection time is much shorter than the eddy turnover time*, and it is thus expected that full reconnection will occur. Observable consequence should be a steepening of the spectrum.

- *Otherwise, reconnection is slower*, and the eddy will cease to exist without significant reconnection having taken place.

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- Now need to work out this condition in the MHD and in the collisionless regimes.

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- Tearing becomes relevant below the scale $\lambda_{cr}/L \sim S_L^{-4/7}$

- The eddy turn over rate becomes the tearing mode rate $\gamma_t \sim \tau_{A,\lambda}^{-1}(\lambda v_{A,\lambda}/\eta)^{-1/2}$

  where $v_{A,\lambda} \sim \varepsilon^{2/5}\eta^{-1/5}\lambda^{3/5}$ with $\varepsilon = V_{A,0}^3/L$

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- So: $\gamma_t \tau_{rec} \ll 1 \quad \Rightarrow \quad \lambda/L \gg \mathcal{R}^{-5/4} S_L^{-3/4}$

- This is valid only if $\lambda_{cr} \gg \lambda \gg \lambda_{diss}$ where $\lambda_{diss} \sim S_L^{-3/4} L$

- The first inequality yields $S_L \gg \mathcal{R}^{-7} \sim S_{cr}^{7/2} \sim 10^{14}$

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- So: $\gamma_t \tau_{rec} \ll 1 \quad \Rightarrow \quad \boxed{\lambda/L \gg \mathcal{R}^{-5/4} S_L^{-3/4}}$
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- The first inequality yields $\boxed{S_L \gg \mathcal{R}^{-7} \sim S_{cr}^{7/2} \sim 10^{14}}$

Impossible to simulate.

Implication is that MHD simulations may be severely underestimating reconnection-driven dissipation.

Reconnection in collisionless turbulence

Reconnection in fluid-scale eddies

- Collisionless plasma: electron inertia (not resistivity) breaks the frozen flux. Now $\mathcal{R} \sim 0.1$
- Consider first the case when the tearing onset happens above the ion kinetic scales: $\lambda_{cr} > \rho_i, \rho_s, d_i$
- Low beta case as an example.
- Tearing mode onset scale is $\lambda_{cr}/L \sim (d_e/L)^{4/9}(\rho_s/L)^{4/9}$. Below that scale we have $\gamma_t \sim v_{A,\lambda} d_e \rho_s/\lambda^3$

In this case, we find: $\gamma_t \tau_{rec} \ll 1 \quad \Rightarrow \quad \lambda \gg \mathcal{R}^{-1/2}(d_e\rho_s)^{1/2}$

Valid if $\lambda_{cr} \gg \lambda \gg \rho_s \quad \Rightarrow \quad \mathcal{R} \ll \frac{d_e}{\rho_s} \ll \mathcal{R}^9 \left(\frac{L}{\rho_s}\right)^2$

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Reconnection at fluid scales

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- The left inequality may not hold in the pristine SW: it requires $\beta_e \ll 2(m_e/m_i)\mathcal{R}^{-2} \approx 0.1$ which may be too low.

- But the solar corona should observe both of these conditions (and fall in this case of collisionless reconnection at fluid scales).

- The right inequality places spectacular demands on computer simulations…

- Now consider the case when tearing onset is at sub-ion scales. As an example, take a plasma where $\beta_i \sim 1 \gg \beta_e$ (so-called inertial kinetic-Alfvén turbulence).

- From Boldyrev & Loureiro '19, we have $$\gamma_t \sim \frac{v_{Ae,\lambda}}{\lambda}\left(\frac{d_e}{\lambda}\right)^2$$

- Therefore, we find: $$\gamma_t \tau_{rec} \ll 1 \Rightarrow \frac{\lambda}{d_e} \gg \mathcal{R}^{-1/2} \sim 3$$

  – We don't know λ_{cr} for this case, so cannot compute the upper validity limit for this result.

  – The lower bound is that $\lambda/d_e \gg 1$, which is marginally satisfied.

  – Unlike previous cases, this condition may be easily satisfied in simulations.

- This is interestingly consistent with Phan *et al.* '18 observations of 'electron-only' reconnection events in the Earth's magnetosheath: reports of reconnection on current sheets ~4d_e wide.

Reconnection at kinetic scales in collisionless turbulence

Consistence with observations

Reconnection at kinetic scales in collisionless turbulence

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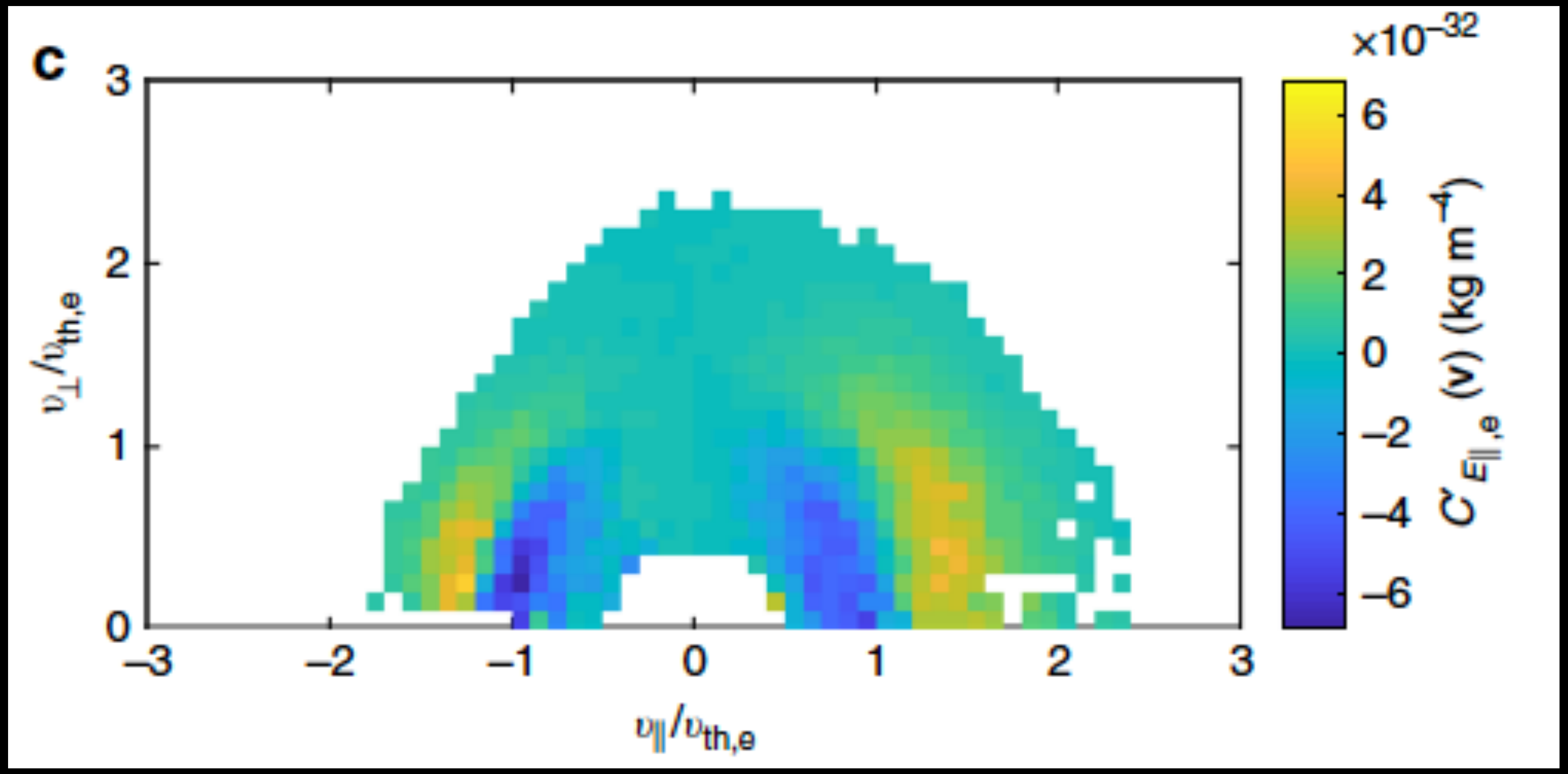

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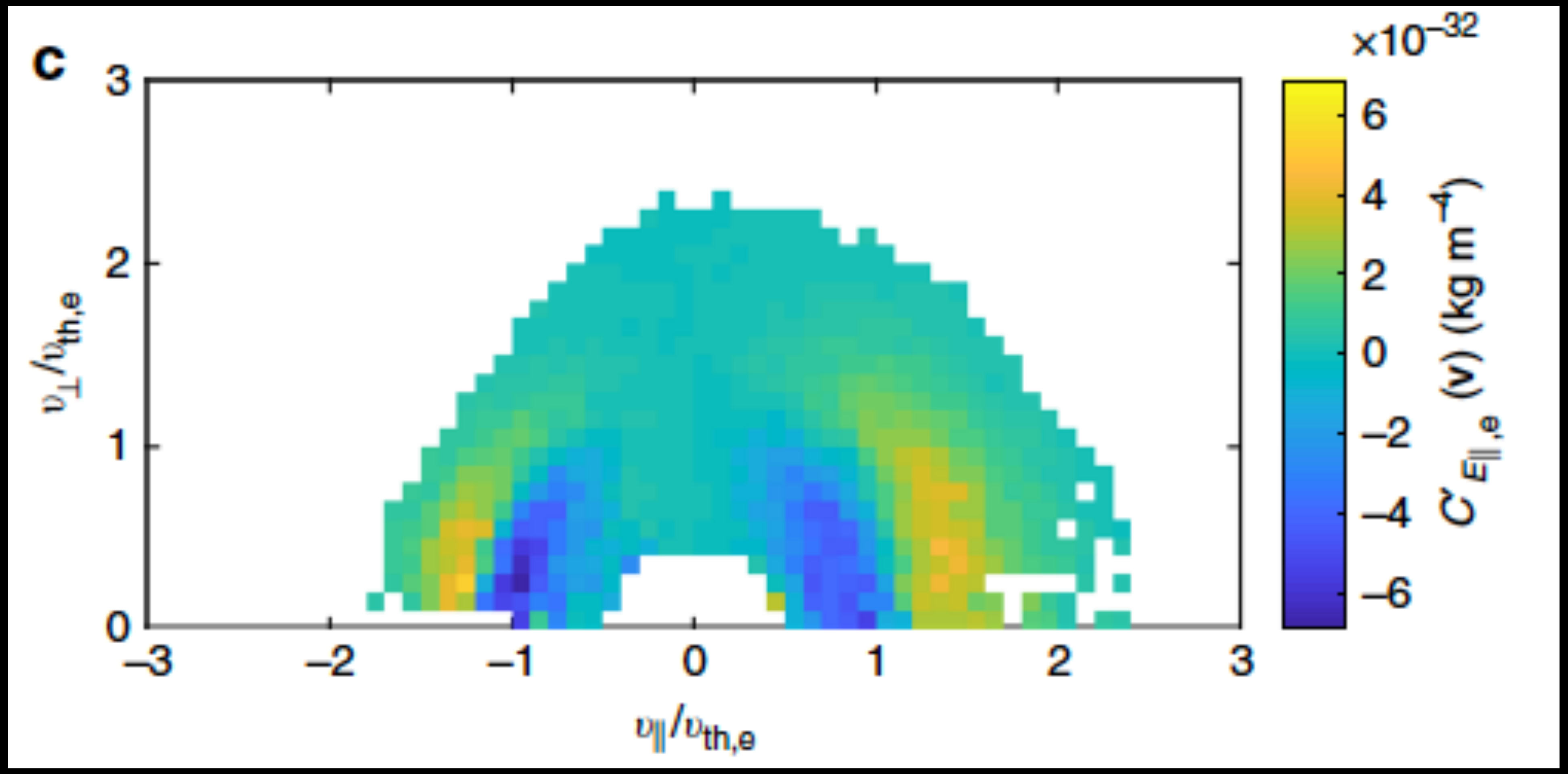

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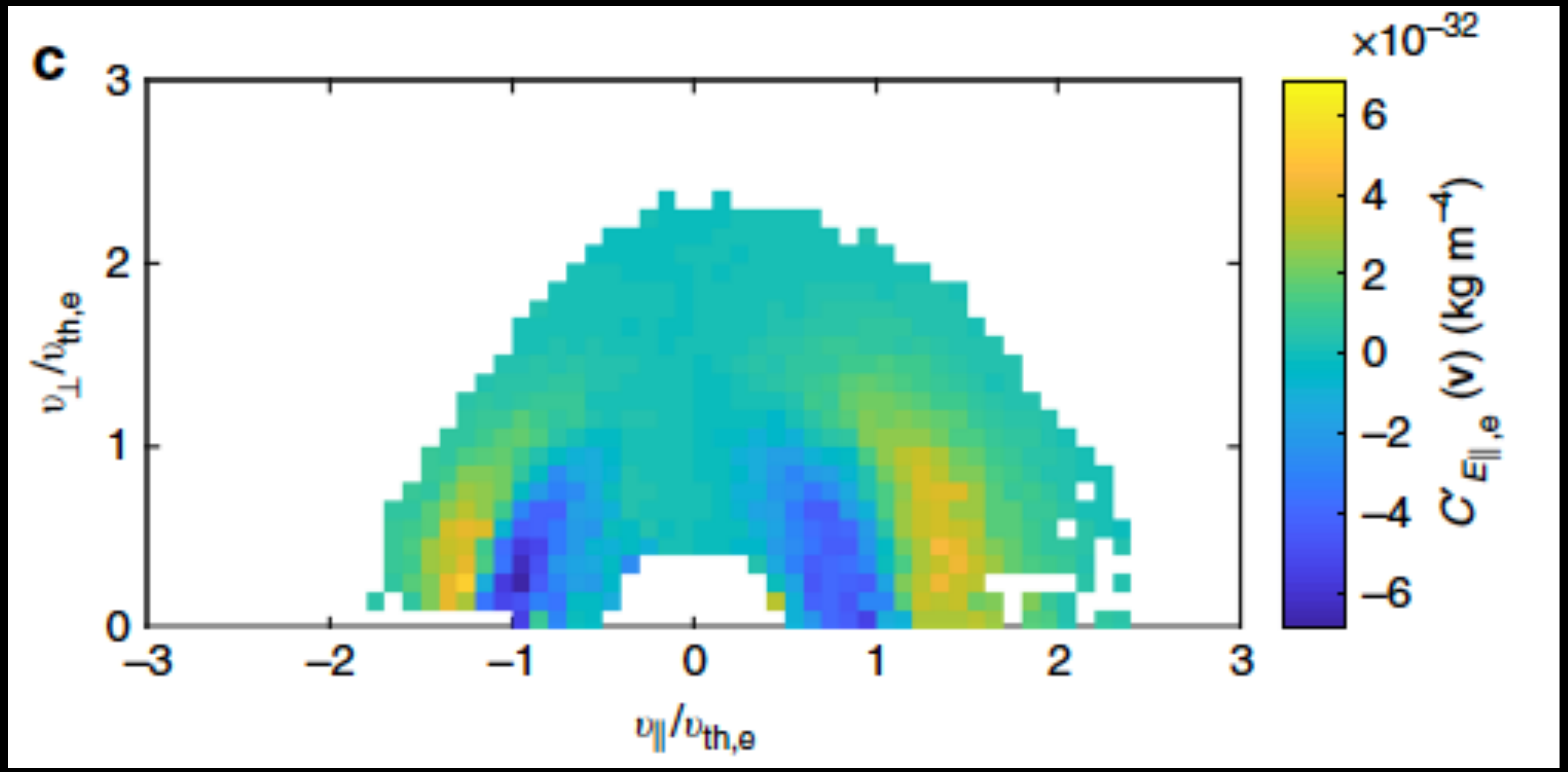

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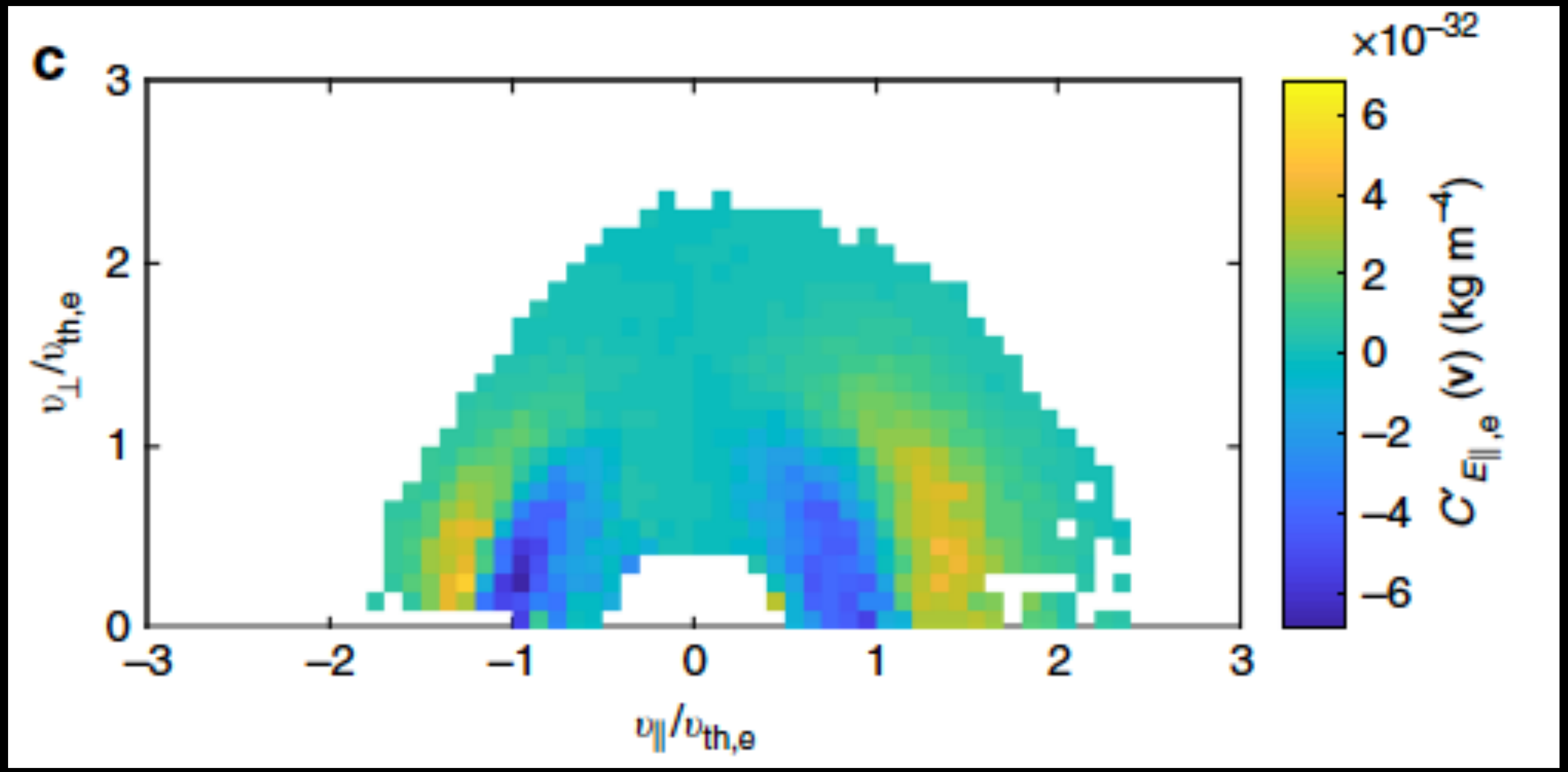

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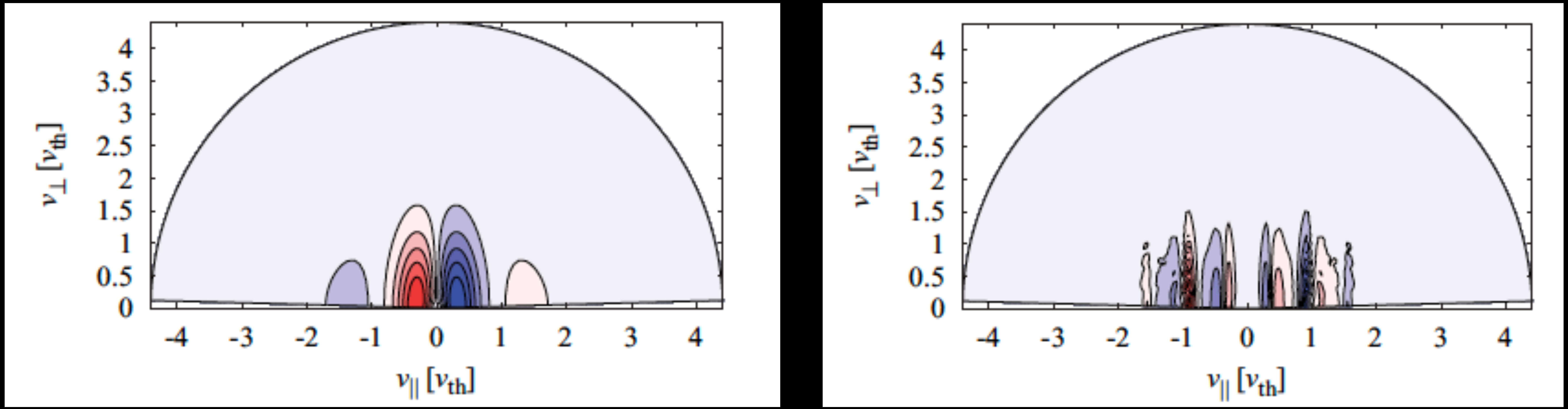

Numata & Loureiro 2015

Conclusions

1. If current understanding of MHD turbulence is correct, tearing mode 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. This marks the onset of a new, sub-inertial range whose spectrum is $k_\perp^{-11/5}$ or $k_\perp^{-19/9}$
- These ideas can be extended to the kinetic (collisionless) regime. In all cases, we obtain spectra that scale as $k_\perp^{-8/3}$ or $k_\perp^{-3}$ in good agreement with observations and simulations.

2. The onset of tearing <u>does not automatically guarantee</u> that the eddy will reconnect.

- Fundamentally, that's because the reconnection rate is different from the tearing rate; reconnection can only happen if it is *faster* than tearing.
- The conditions for reconnection to happen are *very demanding*
- *We may be significantly underestimating reconnection-driven energy dissipation/conversion in some simulations*

Details in
Loureiro & Boldyrev, arXiv:1907.09610

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