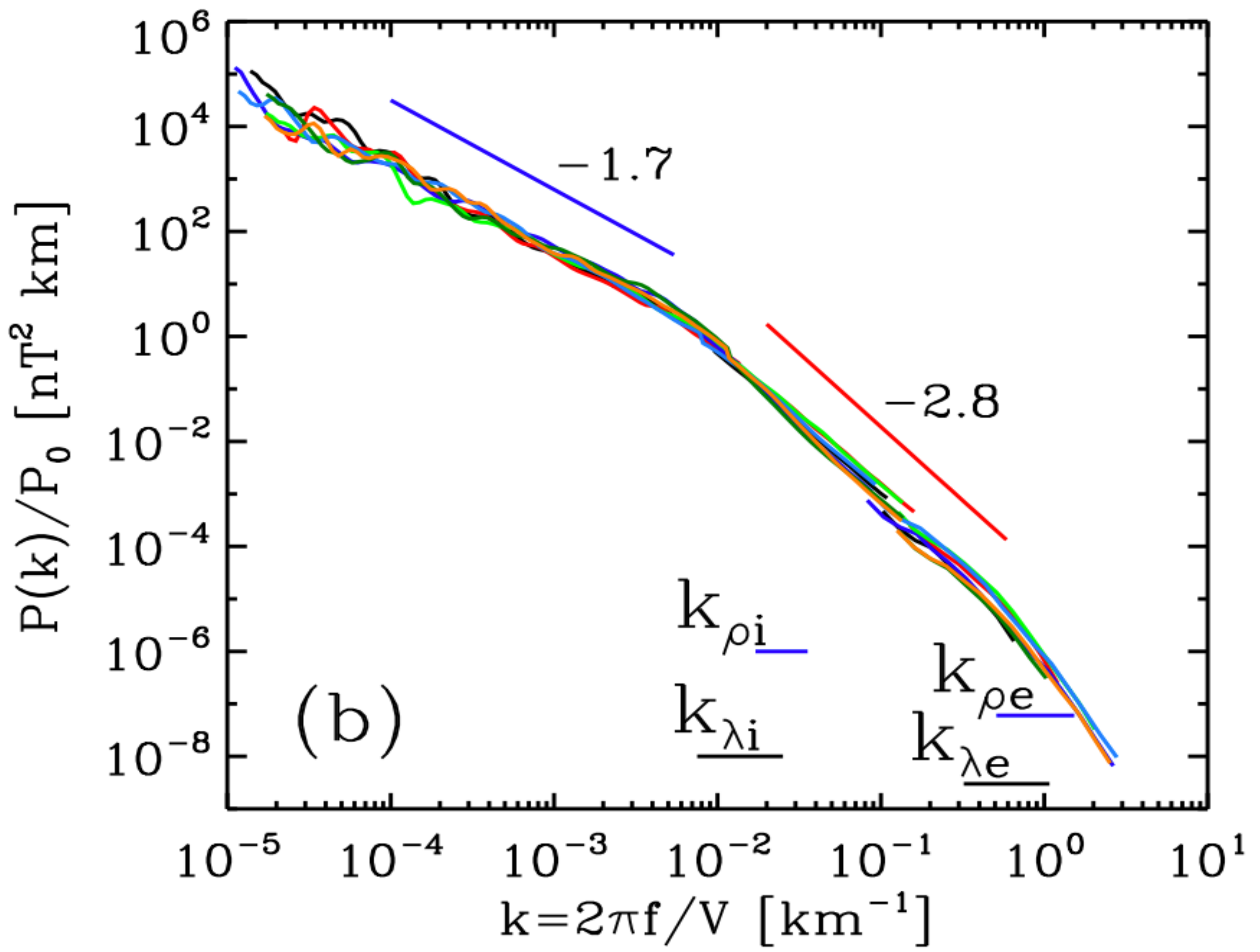
Intermittency and electron heating in kinetic-Alfvén-wave turbulence

Muni Zhou[1], Zhuo Liu[1], Nuno F. Loureiro[1]

[1]Massachusetts Institute of Technology

MIT Plasma Science & Fusion Center

Plasma turbulence in the sub-ion-Larmor-radius range



Solar wind magnetic spectrum form *Cluster* [Alexandrova+ 2019]

Main questions:

What are the spectra of fluctuations?

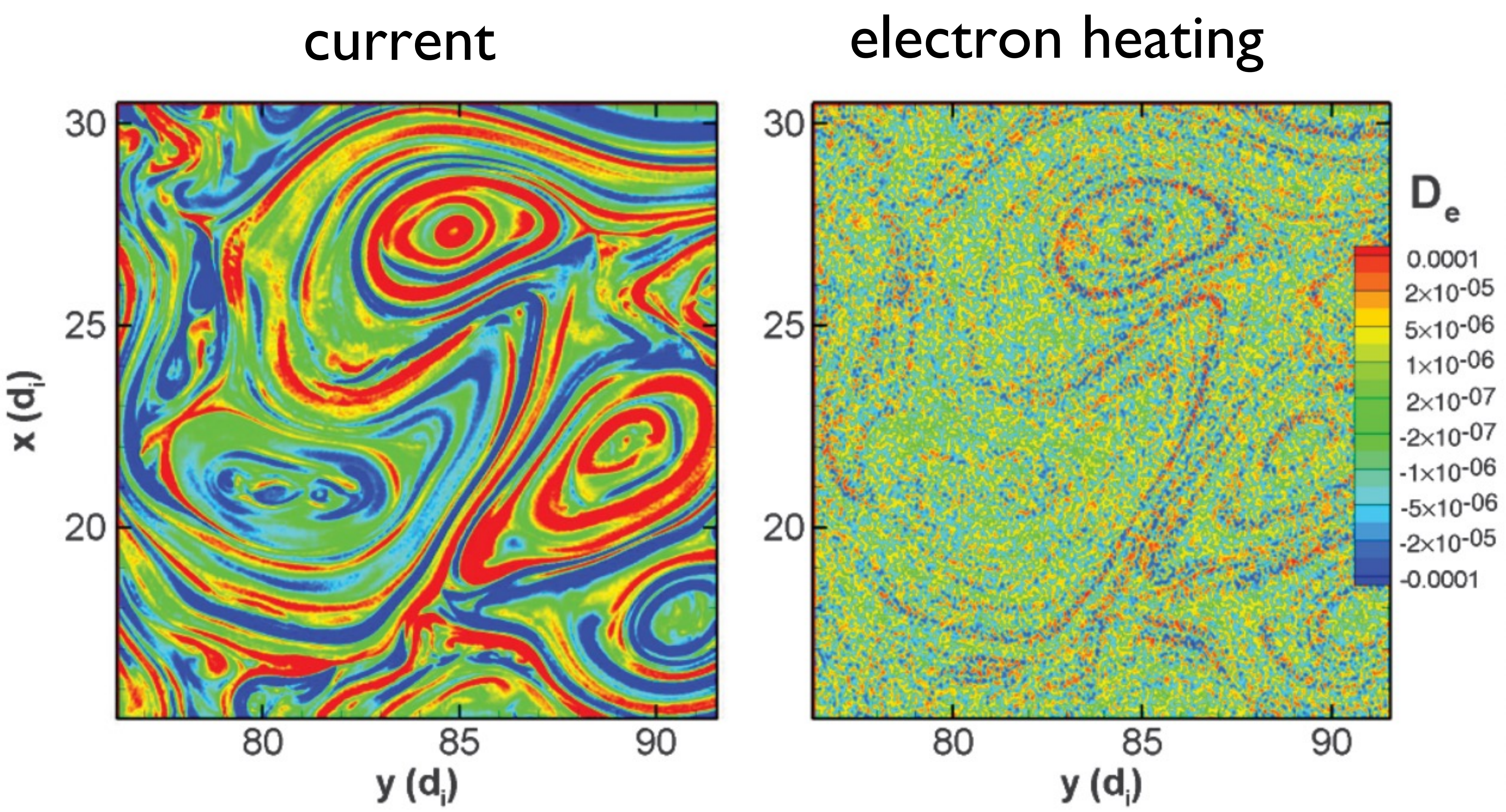
What is the mechanism causing the -2.8 magnetic spectrum measured in the solar wind?

What is the nature of the dissipative processes?

How are ions and electrons heated?

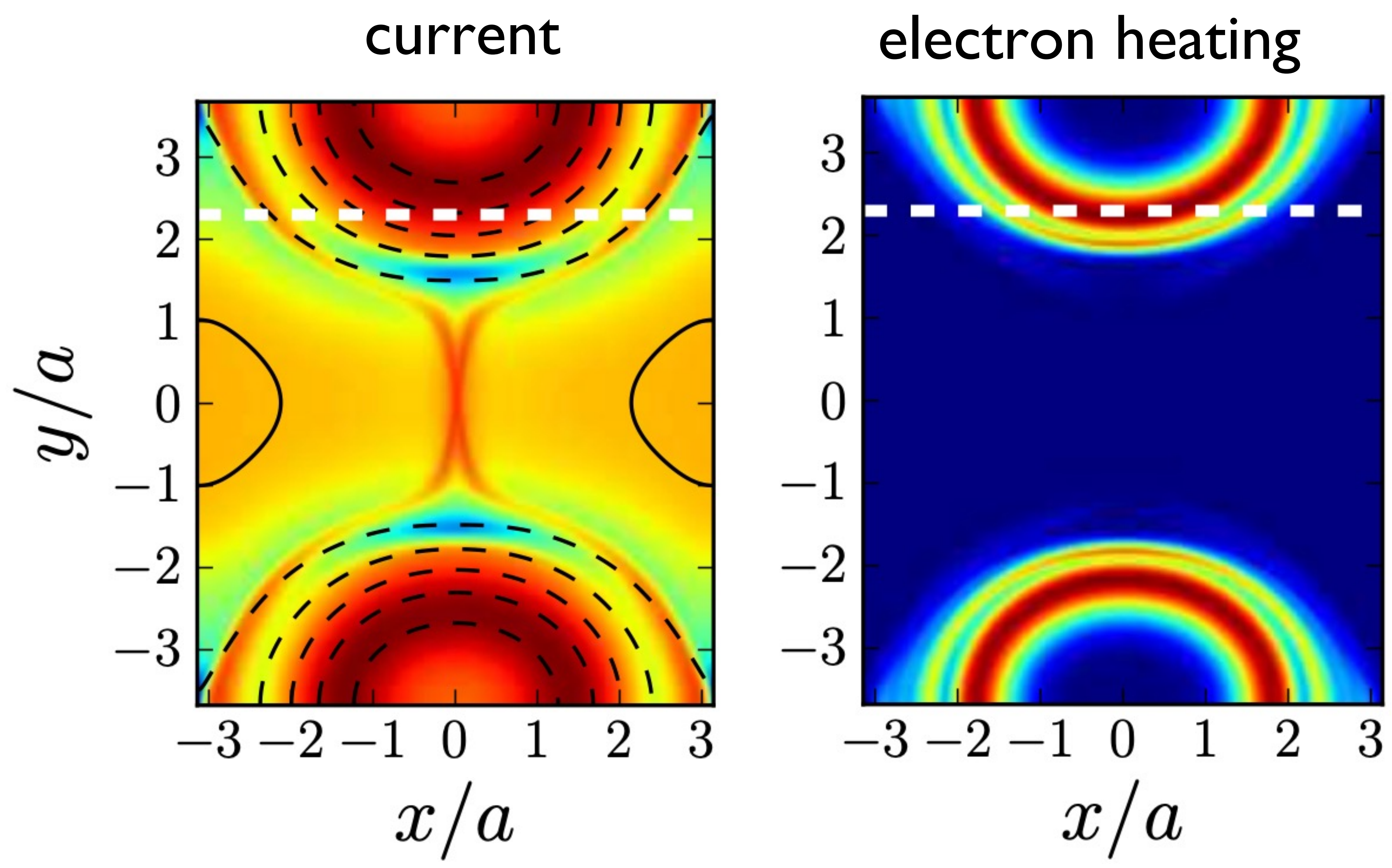
Electron heating

Efficient electron heating is observed in kinetic turbulence simulations around current sheets.



[Wan+ 2012, 2015]

Magnetic reconnection yields efficient electron heating



[Loureiro+ 2013]

Some long-standing discussion: relation between current sheets, reconnection, and heating

What can be the role of reconnection in kinetic turbulence? setting the spectra? facilitating heating?

Spectra and spectral anisotropy

Total magnetic fields $\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp$, correlation lengths of fluctuations: length $\ell \sim 1/k_\parallel$, thickness $\lambda \sim 1/k_\perp$, and width ξ

General arguments:

At scales $k_\perp\rho_i \gg 1$, equipartition b/w magnetic and density fluctuations gives $\varphi_\lambda \sim (\rho_i V_A/c)\delta B_{\perp\lambda}$

Linear time scale is set by propagation of KAWs $\gamma_l \sim \omega_{\mathrm{KAW}} \propto k_\perp\rho_s k_\parallel V_A \sim \rho_s V_A/(\ell\lambda)$

Dimensionally, the nonlinear eddy-turnover rate is $\gamma_{nl} \sim \varepsilon/(\rho_0 v_{A\lambda}^2/2) \sim \varepsilon/(\delta B_{\perp\lambda}^2/8\pi)$

Critical balance: $\gamma_l \sim \gamma_{nl}$

Kolmogorov-type cascade of KAW

Total magnetic fields $\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp$, correlation lengths of flu… …d width ξ

General arguments:

At scales $k_\perp\rho_i \gg 1$, equipartition b/w magnetic and density fluc…

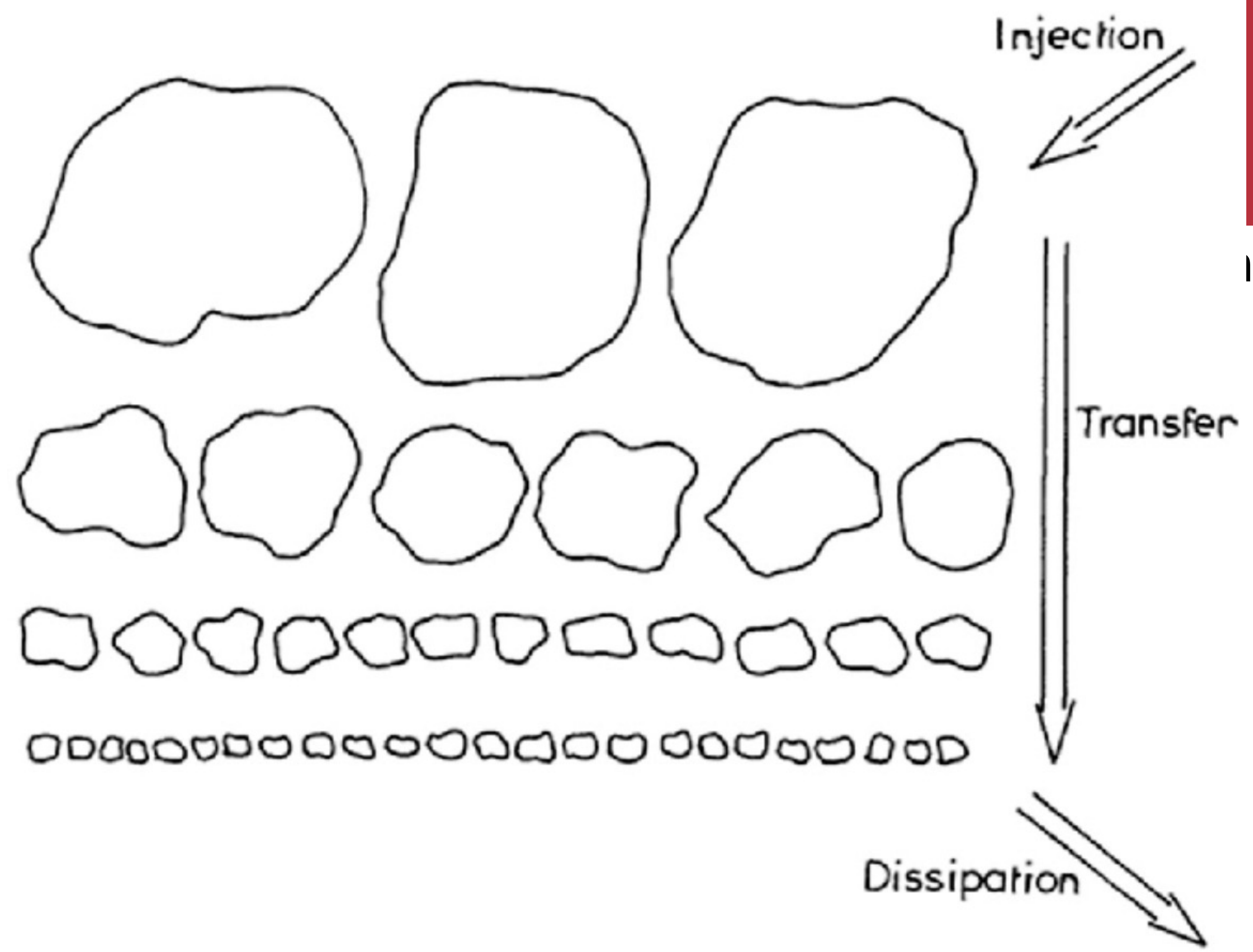
Linear time scale is set by propagation of KAWs $\gamma_l \sim \omega_{\mathrm{KAW}}$

Dimensionally, the nonlinear eddy-turnover rate is $\gamma_{nl} \sim \varepsilon/$

Critical balance: $\gamma_l \sim \gamma_{nl}$

Specify the nonlinear physics!

IF $\gamma_{nl} \sim u_\lambda/\lambda$, where $u_\lambda \sim (c/B_0)\varphi_\lambda/\lambda$



- Kolmogorov-type cascade of KAWs --- $k_\perp^{-7/3}$

[Cho&Lazarian 2004; Howes+ 2008; Schekochihin+ 2009]

Intermittency

Total magnetic fields $\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp$, correlation

General arguments:

At scales $k_\perp \rho_i \gg 1$, equipartition b/w magnetic an

Linear time scale is set by propagation of KAWs

Dimensionally, the nonlinear eddy-turnover rate i

Critical balance: $\gamma_l \sim \gamma_{nl}$

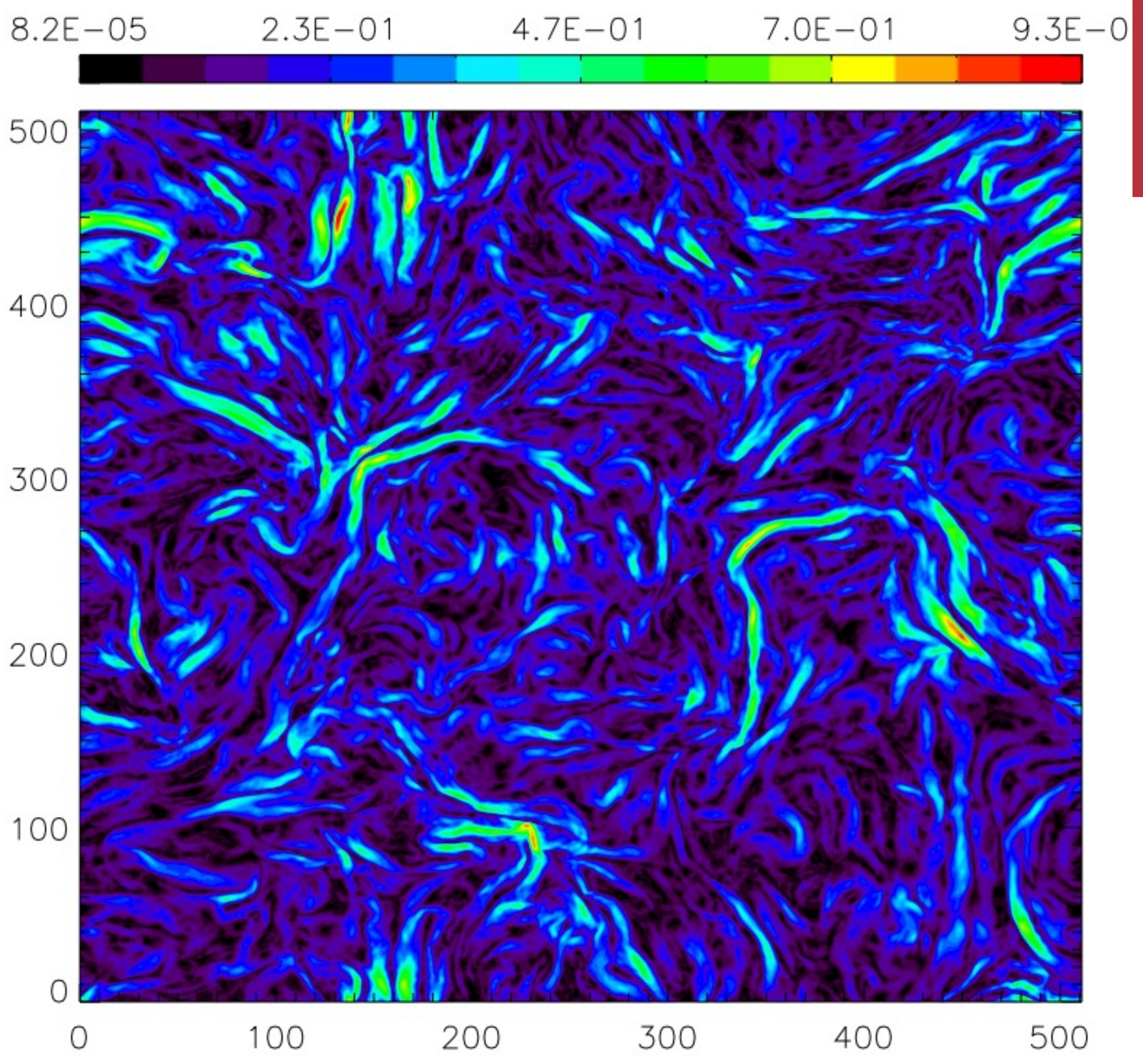
Specify the nonlinear physics!

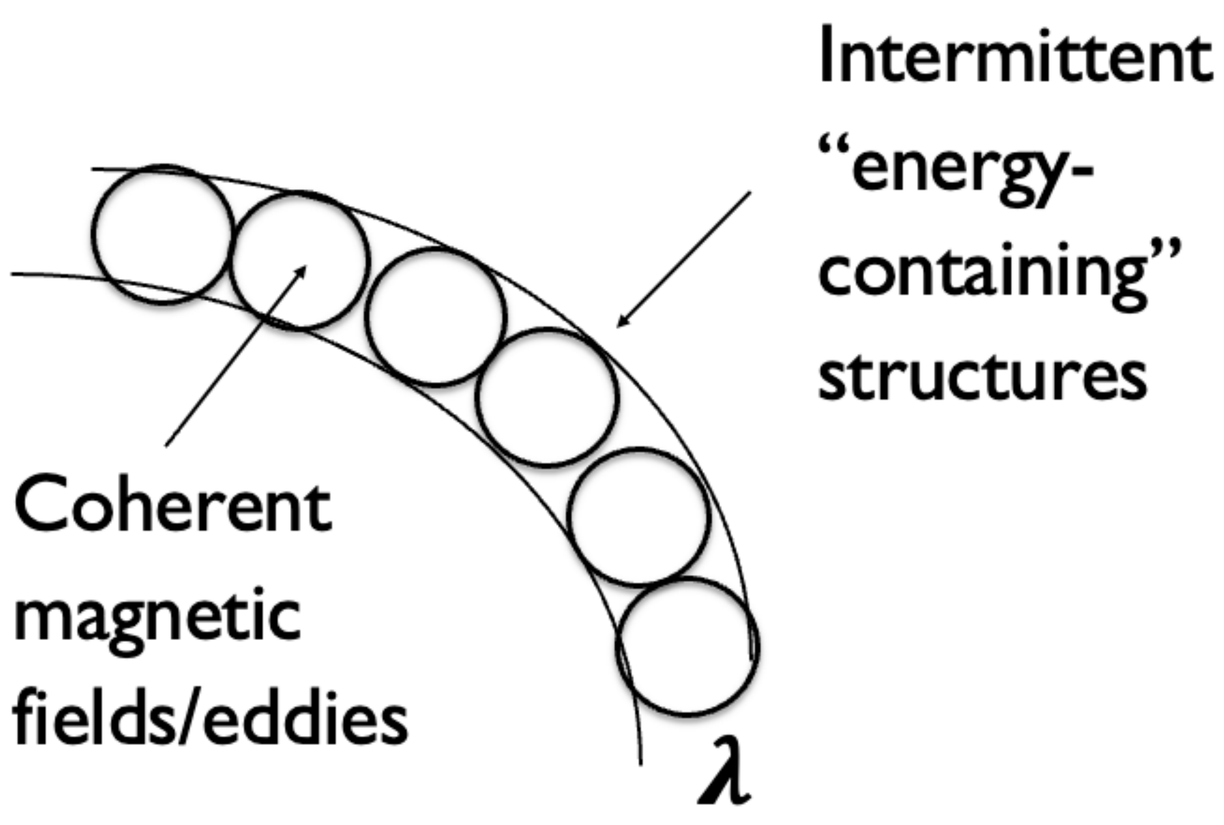
IF $\gamma_{nl} \sim u_\lambda/\lambda$, where $u_\lambda \sim (c/B_0)\varphi_\lambda/\lambda$

IF $\gamma_{\rm nl} \sim u_\lambda/\lambda$ $\gamma_{nl} \sim \varepsilon/(\delta B^2_{\perp\lambda}\, p_\lambda)$

Volume-filling factor $p_\lambda \propto \lambda$.

2D "energy containing" sheets





- Kolmogorov-type cascade of KAWs --- $k_\perp^{-7/3}$

  [Cho&Lazarian 2004; Howes+ 2008; Schekochihin+ 2009]

- Intermittency --- $k_\perp^{-8/3}$ and $k_\parallel^{-7/2}$

  [Boldyrev&Perez 2012]

Tearing mediation

Total magnetic fields $\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp$, correlation lengths of idth ξ

General arguments:

At scales $k_\perp \rho_i \gg 1$, equipartition b/w magnetic and density

Linear time scale is set by propagation of KAWs $\gamma_l \sim \omega_{\rm K}$

Dimensionally, the nonlinear eddy-turnover rate is $\gamma_{nl} \sim$

Critical balance: $\gamma_l \sim \gamma_{nl}$

Specify the nonlinear physics!

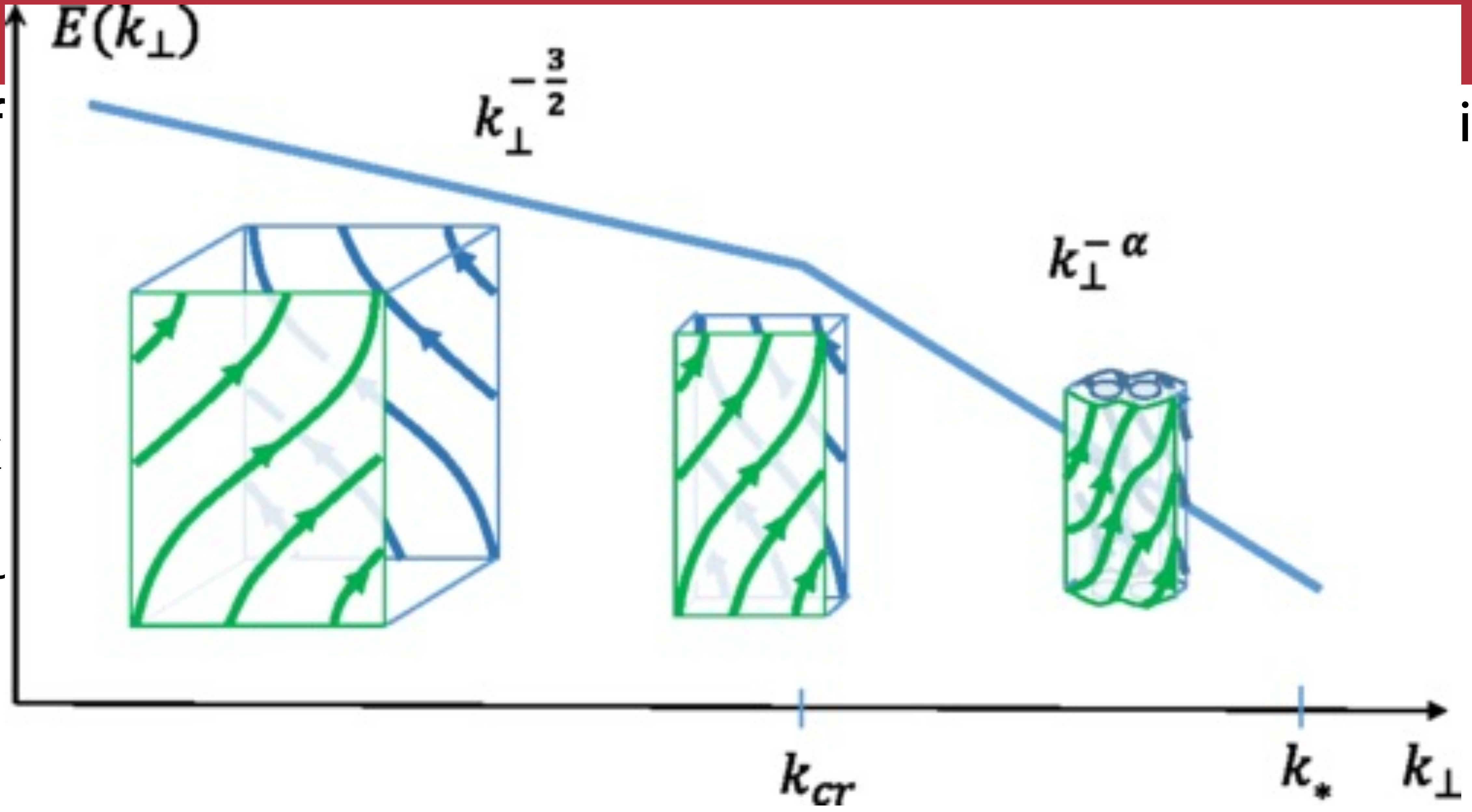
IF $\gamma_{nl} \sim u_\lambda/\lambda$, where $u_\lambda \sim (c/B_0)\varphi_\lambda/\lambda$

IF $\gamma_{\rm nl} \sim u_\lambda/\lambda$ $\quad \gamma_{nl} \sim \varepsilon/(\delta B^2_{\perp\lambda}\, p_\lambda)$

Volume-filling factor $p_\lambda \propto \lambda.$

2D "energy containing" sheets

IF $\gamma_{\rm nl} \sim \gamma_t \sim v_{A\lambda}\rho_i d_e^{1/2}\lambda^{-5/2}$



- Kolmogorov-type cascade of KAWs --- $k_\perp^{-7/3}$

  [Cho&Lazarian 2004; Howes+ 2008; Schekochihin+ 2009]

- Intermittency --- $k_\perp^{-8/3}$ and $k_\parallel^{-7/2}$

  [Boldyrev&Perez 2012]

- Tearing mediation --- $k_\perp^{-8/3}$ (or $k_\perp^{-3}$) and $k_\parallel^{-7/2}$

  [Loureiro&Boldyrev 2017] (the original MHD version of the theory: Loureiro&Boldyrev 2017; Mallet+ 2017)

Isothermal limit --- Spectra and spectral anisotropy

Total magnetic fields $\boldsymbol{B} = B_0\hat{\boldsymbol{z}} + \delta\boldsymbol{B}_\perp$, correlation lengths of fluctuations: length $\ell \sim 1/k_\parallel$, thickness $\lambda \sim 1/k_\perp$, and width ξ

General arguments:

At scales $k_\perp\rho_i \gg 1$, equipartition b/w magnetic and density fluctuations gives $\varphi_\lambda \sim (\rho_i V_A/c)\delta B_{\perp\lambda}$

Linear time scale is set by propagation of KAWs $\gamma_l \sim \omega_{\rm KAW} \propto k_\perp \rho_s k_\parallel V_A \sim \rho_s V_A/(\ell\lambda)$

Dimensionally, the nonlinear eddy-turnover rate is $\gamma_{nl} \sim \varepsilon/(\rho_0 v_{A\lambda}^2/2) \sim \varepsilon/(\delta B_{\perp\lambda}^2/8\pi)$

Critical balance: $\gamma_l \sim \gamma_{nl}$

Specify the nonlinear physics!

IF $\gamma_{nl} \sim u_\lambda/\lambda$, where $u_\lambda \sim (c/B_0)\varphi_\lambda/\lambda$

IF $\gamma_{\rm nl} \sim u_\lambda/\lambda$ $\quad \gamma_{nl} \sim \varepsilon/(\delta B_{\perp\lambda}^2\, p_\lambda)$

Volume-filling factor $p_\lambda \propto \lambda$.

2D "energy containing" sheets

IF $\gamma_{\rm nl} \sim \gamma_t \sim v_{A\lambda}\rho_i d_e^{1/2}\lambda^{-5/2}$

- Kolmogorov-type cascade of KAWs --- $k_\perp^{-7/3}$

  [Cho&Lazarian 2004; Howes+ 2008; Schekochihin+ 2009]

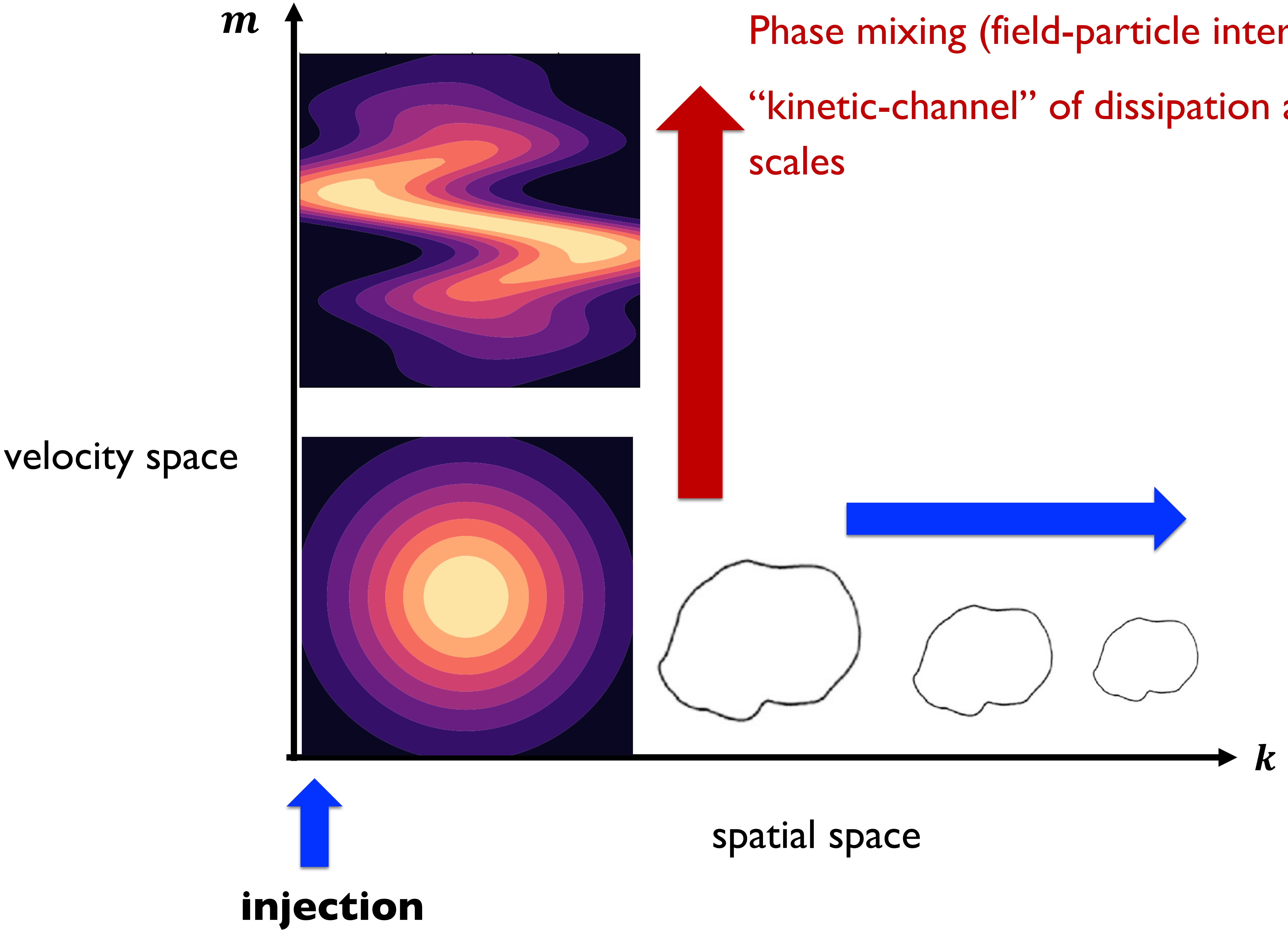
- Intermittency --- $k_\perp^{-8/3}$ and $k_\parallel^{-7/2}$

  [Boldyrev&Perez 2012]

- Tearing mediation --- $k_\perp^{-8/3}$ (or $k_\perp^{-3}$) and $k_\parallel^{-7/2}$

  [Loureiro&Boldyrev 2017] (the original MHD version of the theory: Loureiro&Boldyrev 2017; Mallet+ 2017)

Studying phase-space dynamics is crucial to understand particle heating



Phase mixing (field-particle interaction)

"kinetic-channel" of dissipation at small velocity-space scales

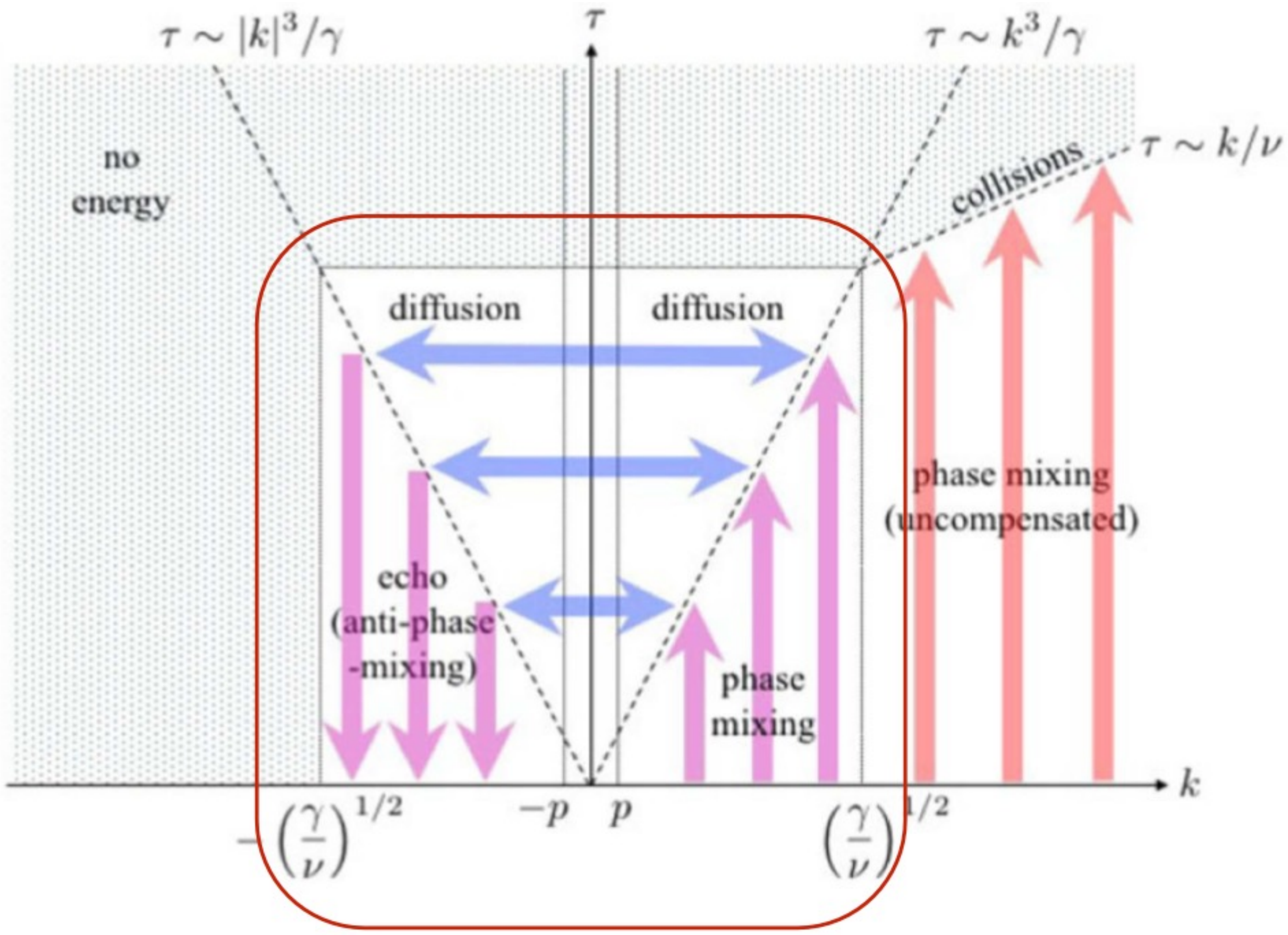
Nonlinear advection

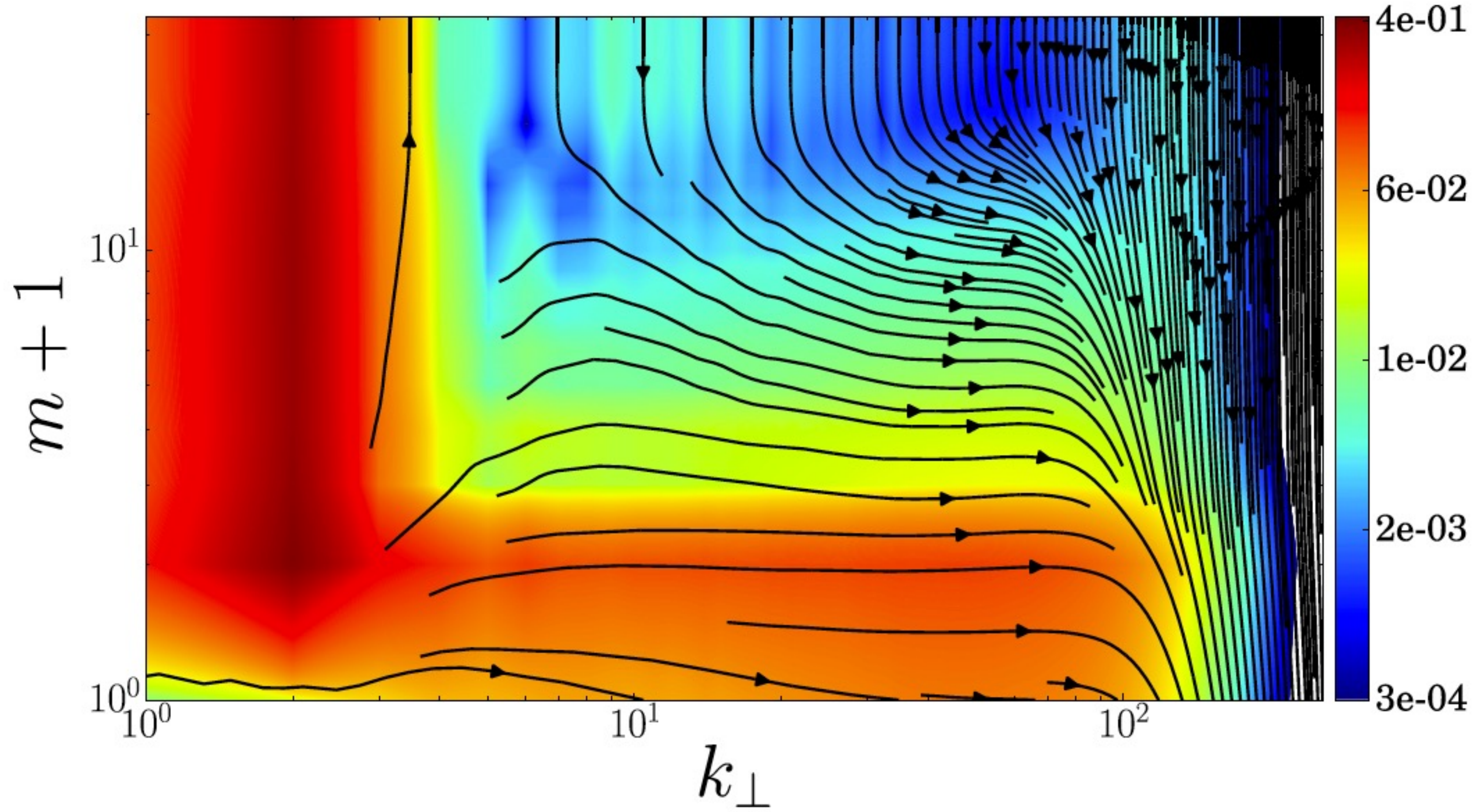
"fluid-channel" of dissipation

at small spatial scales

Anti-phase-mixing and plasma echoes

Schekochihin+ 2016; Adkins & Schekochihin 2018





Confirmed by simulations in the inertial range with compressive fluctuations [Meyrand+ 2018]

Q: is it obvious that echoes are expected in the sub-ρ_i range with electromagnetic fluctuations?

Kinetic Reduced Electron Heating Model (KREHM) framework

A rigorous asymptotic reduction of gyrokinetics (GK) valid in the limit of low electron plasma-beta $\beta_e \sim m_e/m_i$ [Zocco+ 2011]

Ions become isothermal.

GK Poisson's law containing FLR $\delta n_e/n_{0e} = 1/\tau(\hat{\Gamma}_0 - 1)e\varphi/T_{0e}$

Electrons are described by $\delta f_e = g_e + (\delta n_e/n_{0e} + 2v_\parallel u_{\parallel e}/v_{the}^2)F_{0e}$

Continuity: $$\frac{1}{n_{0e}}\frac{d\delta n_e}{dt} = -\hat{b}\cdot\nabla\frac{e}{cm_e}d_e^2\nabla_\perp^2 A_\parallel$$

Ohm's law $$\frac{d}{dt}(A_\parallel - d_e^2\nabla_\perp^2 A_\parallel) = -c\frac{\partial\varphi}{\partial z} + \frac{cT_{e0}}{e}\hat{b}\cdot\nabla\left(\frac{\delta n_e}{n_{0e}} + \frac{\delta T_{\parallel e}}{T_{0e}}\right)$$

Kinetic equation $$\frac{dg_e}{dt} + v_\parallel\hat{b}\cdot\nabla\left(g_e - \frac{\delta T_{\parallel e}}{T_{0e}}F_{0e}\right) = C[g_e] + \left(1 - \frac{v_\parallel^2}{v_{the}^2}\right)F_{0e}\hat{b}\cdot\nabla\frac{e}{cm_e}d_e^2\nabla_\perp^2 A_\parallel$$

Hermite expansion: $$g_e(r, v_\parallel, t) = \sum_{m=0}^{\infty} H_m(v_\parallel/v_{the})g_m(r,t)F_{0e}(v_\parallel)/\sqrt{2^m m!}$$

Kinetic Reduced Electron Heating Model (KREHM) framework

A rigorous asymptotic reduction of gyrokinetics (GK) valid in the limit of low electron plasma-beta $\beta_e \sim m_e/m_i$ [Zocco+ 2011]

Ions become isothermal.

GK Poisson's law containing FLR $\delta n_e/n_{0e} = 1/\tau(\hat{\Gamma}_0 - 1)e\varphi/T_{0e}$

Electrons are described by $\delta f_e = g_e + (\delta n_e/n_{0e} + 2v_\| u_{\|e}/v_{the}^2)F_{0e}$

Continuity: $$\frac{1}{n_{0e}}\frac{d\delta n_e}{dt} = -\hat{b}\cdot\nabla\frac{e}{cm_e}d_e^2\nabla_\perp^2 A_\|$$

Ohm's law $$\frac{d}{dt}(A_\| - d_e^2\nabla_\perp^2 A_\|) = -c\frac{\partial\varphi}{\partial z} + \frac{cT_{e0}}{e}\hat{b}\cdot\nabla\left(\frac{\delta n_e}{n_{0e}} + \frac{\delta T_{\|e}}{T_{0e}}\right)$$

Kinetic equation $$\frac{dg_m}{dt} = -v_{the}\hat{b}\cdot\nabla\left(\sqrt{\frac{m+1}{2}}g_{m+1} + \sqrt{\frac{m}{2}}g_{m-1} - \delta_{m,1}g_2\right) - \sqrt{2}\delta_{m,2}\hat{b}\cdot\nabla\frac{e}{cm_e}d_e^2\nabla_\perp^2 A_\|$$

g_m: Hermite moments of g_e

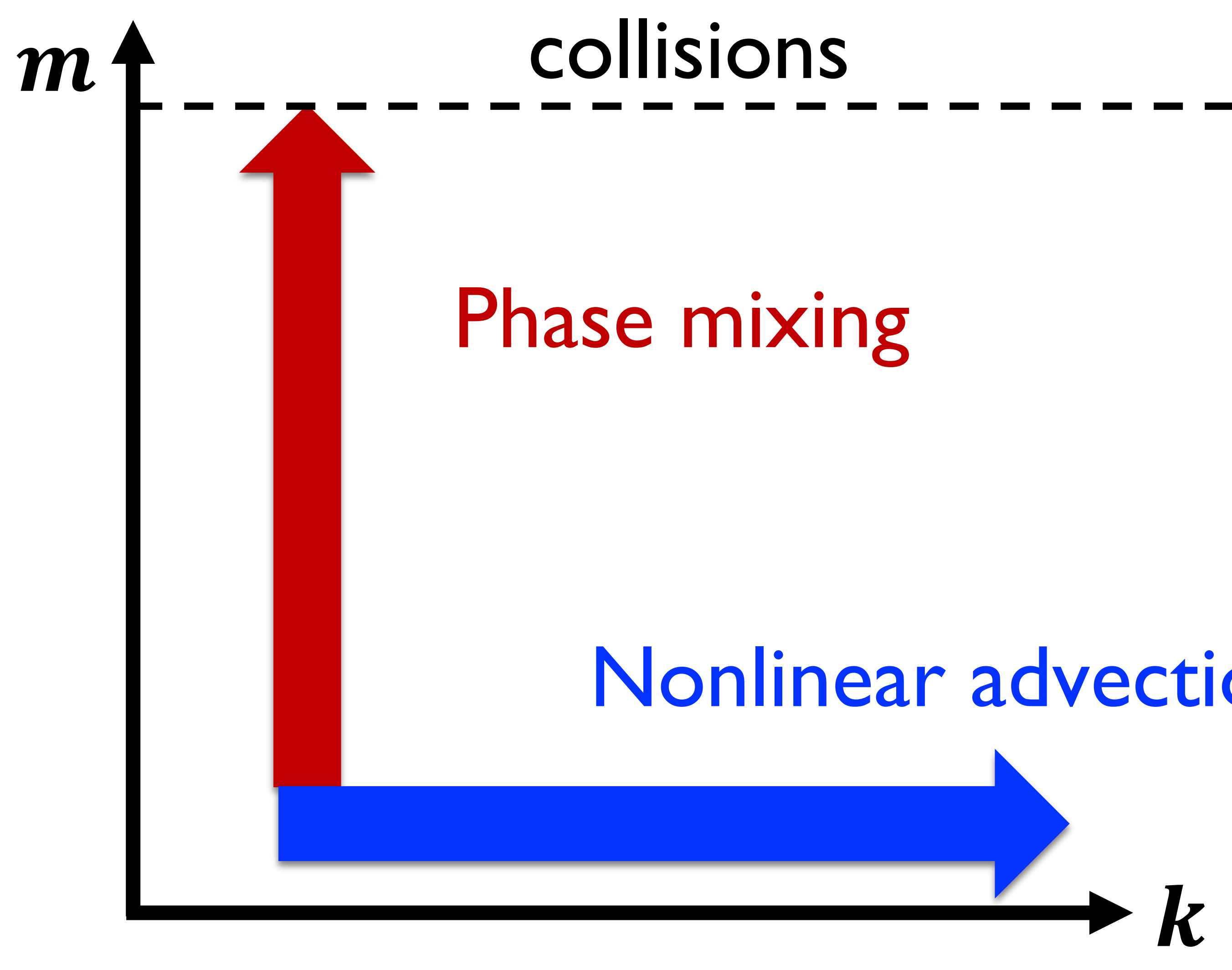
With kinetic electrons --- Phase space cascade and electron heating

$$\frac{dg_m}{dt} = \frac{\partial g_m}{\partial t} + \frac{c}{B_0}\{\varphi, g_m\}$$

Source of free energy in velocity space $\hat{b} \cdot \nabla J_\parallel$

$$\frac{dg_m}{dt} = -v_{\mathrm{the}} \hat{\mathbf{b}} \cdot \nabla \left(\sqrt{\frac{m+1}{2}} g_{m+1} + \sqrt{\frac{m}{2}} g_{m-1} - \delta_{m,1} g_2 \right) - \sqrt{2}\delta_{m,2} \hat{\mathbf{b}} \cdot \nabla J_\parallel$$

$$\approx k_\parallel v_{\mathrm{the}} g_m / \sqrt{m} \sim \frac{v_{\mathrm{the}}}{B_0} \{A_\parallel, g_m\} / \sqrt{m}$$



Critical Hermite moments and echos?

$$\frac{dg_m}{dt} = \frac{\partial g_m}{\partial t} + \frac{c}{B_0}\{\varphi, g_m\}$$

Source of free energy in velocity space $\hat{b} \cdot \nabla J_{\|}$

$$\frac{dg_m}{dt} = -v_{\rm the}\hat{\mathbf{b}} \cdot \nabla \left(\sqrt{\frac{m+1}{2}} g_{m+1} + \sqrt{\frac{m}{2}} g_{m-1} - \delta_{m,1} g_2 \right) - \sqrt{2}\delta_{m,2}\hat{\mathbf{b}} \cdot \nabla J_{\|}$$

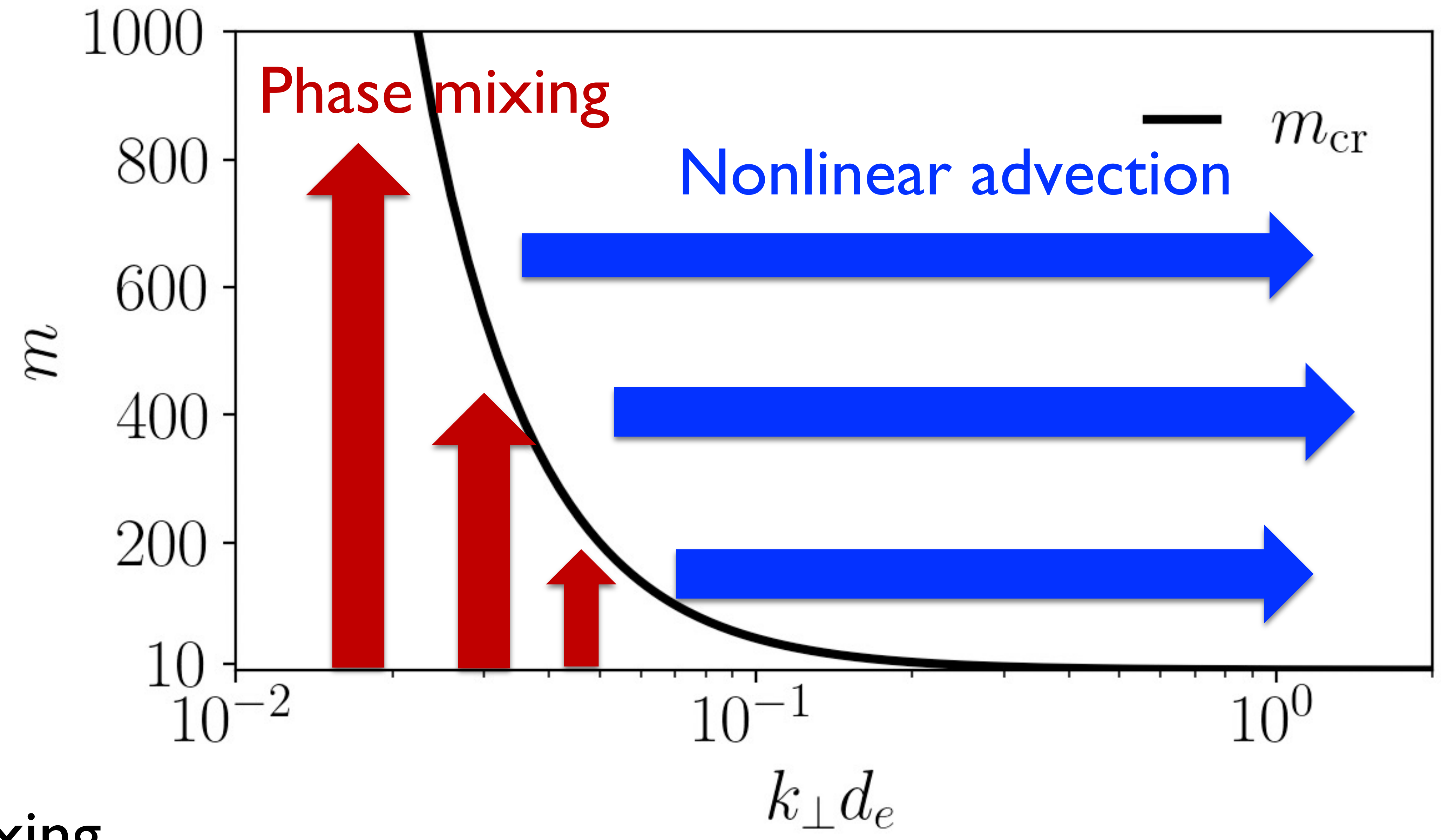
$$\approx k_{\|} v_{\rm the} g_m/\sqrt{m} \sim \frac{v_{\rm the}}{B_0}\{A_{\|}, g_m\}/\sqrt{m}$$

At each scale λ, there is a critical Hermite order m_{cr}:

nonlinear advection rate ~ Phase mixing rate

$$\frac{c}{B_0}\{\varphi, g_{m_{\rm cr}}\} \sim \frac{v_{\rm the}}{B_0}\{A_{\|}, g_{m_{\rm cr}}\}/\sqrt{m_{\rm cr}}$$

$$m_{\rm cr}(\lambda) \sim (\lambda/d_e)^2/(2\tau^2)$$



Above m_{cr} plasma echo is expected to happen and impede phase mixing

In weakly collisional plasmas, the collisional cut off $\gg m_{cr}$

Why is efficient electron heating observed in solar wind [Chen+ 2019] and in kinetic simulations[e.g. Howes+2016-2018]?

A zeroth-order solution of g_e in the velocity space and its Hermite spectrum

$$\frac{dg_m}{dt} = \frac{\partial g_m}{\partial t} + \frac{c}{B_0}\{\varphi, g_m\}$$

Source of free energy in velocity space $\hat{b}\cdot\nabla J_\|$

$$\frac{dg_m}{dt} = -v_{\mathrm{the}}\hat{\mathbf{b}}\cdot\nabla\left(\sqrt{\frac{m+1}{2}}g_{m+1} + \sqrt{\frac{m}{2}}g_{m-1} - \delta_{m,1}g_2\right) - \sqrt{2}\delta_{m,2}\hat{\mathbf{b}}\cdot\nabla J_\|$$

$$\approx k_\| v_{\mathrm{the}} g_m/\sqrt{m} \sim \frac{v_{\mathrm{the}}}{B_0}\{A_\|, g_m\}/\sqrt{m}$$

In the phase-mixing dominated regime, *l.h.s.* << *r.h.s.*

To the lowest order:

$$g_{m+1} = -\sqrt{m/(m+1)}\,g_{m-1} \qquad \text{for } m \geq 3, \text{ and}$$

$$g_3 = -\sqrt{2/3}\,(\rho_s/d_e)J_\|$$

The Hermite spectrum of g_e:

$$E_m \equiv \langle |g_m|^2/2\rangle \approx \langle |g_{m+1}||g_{m-1}|\rangle/2$$

$$E_{m+1}/E_{m-1} \approx g_{m+1}g_m/(g_{m-1}g_{m-2}) = \sqrt{(m-1)/(m+1)}$$

$$E_m \propto m^{-1/2}$$

Turbulence at scales below the electron skin depth

In the range $\lambda \ll d_e \lesssim \rho_i$, fluctuations become electrostatic.

Equipartition between density fluctuations and kinetic energy of parallel electron flows:

$$(\delta n_e/n_{0e})^2 n_{0e} T_{0e} \sim d_e^2 |\nabla_\perp^2 A_z|^2/8\pi \longrightarrow \varphi_\lambda \sim (\rho_i V_A/c) d_e \delta B_{\perp\lambda}/\lambda$$

Assuming standard Kolmogorov-type cascade: $\varepsilon \sim \gamma_{\rm nl} e^2 n_{0e} \varphi^2/T_{0e}$ $\gamma_{\rm nl} \sim \varphi_\lambda/\lambda^2$

$$E_\varphi(k_\perp) \propto k_\perp^{-7/3}, \quad E_B(k_\perp) \propto k_\perp^{-13/3}.$$

Critical m_{cr} where phase-mixing rate balance nonlinear-advection rate:

$$m_{\rm cr} \sim (\lambda/d_e)^4/(2\tau^2)$$

At $k_\perp d_e \gg 1$, nonlinear advection is always faster than phase mixing --- fluid-channel of dissipation should dominate → steep Hermite spectrum

Numerical simulations

We perform simulations for turbulence in the kinetic range by solving KREHM equations

White-noise forcing added to the continuity equation (forcing density perturbation) at box scale

Balanced turbulence

Energy injection balanced by dissipation through hyper-collision at large m or through hyper-diffusion at large $k_\perp$

- Isothermal limit, i.e., $g_e = 0$: Energy spectra of fluctuations, spectral anisotropy, intermittency
- electron kinetic physics accounted for ($g_e \neq 0$): phase space dynamics, electron heating

Spectra and spectral anisotropy

Existing models:

- Kolmogorov-type cascade of KAWs --- $k_\perp^{-7/3}$. [Cho&Lazarian 2004; Howes+ 2008; Schekochihin+ 2009]
- Intermittency --- $k_\perp^{-8/3}$ and $k_\parallel^{-7/2}$ [Boldyrev&Perez 2012]
- Tearing mediation --- $k_\perp^{-8/3}$ (or $k_\perp^{-3}$) and $k_\parallel^{-7/2}$ [Loureiro&Boldyrev 2017]

(the original MHD version of the theory: Loureiro&Boldyrev 2017; Mallet+ 2017)

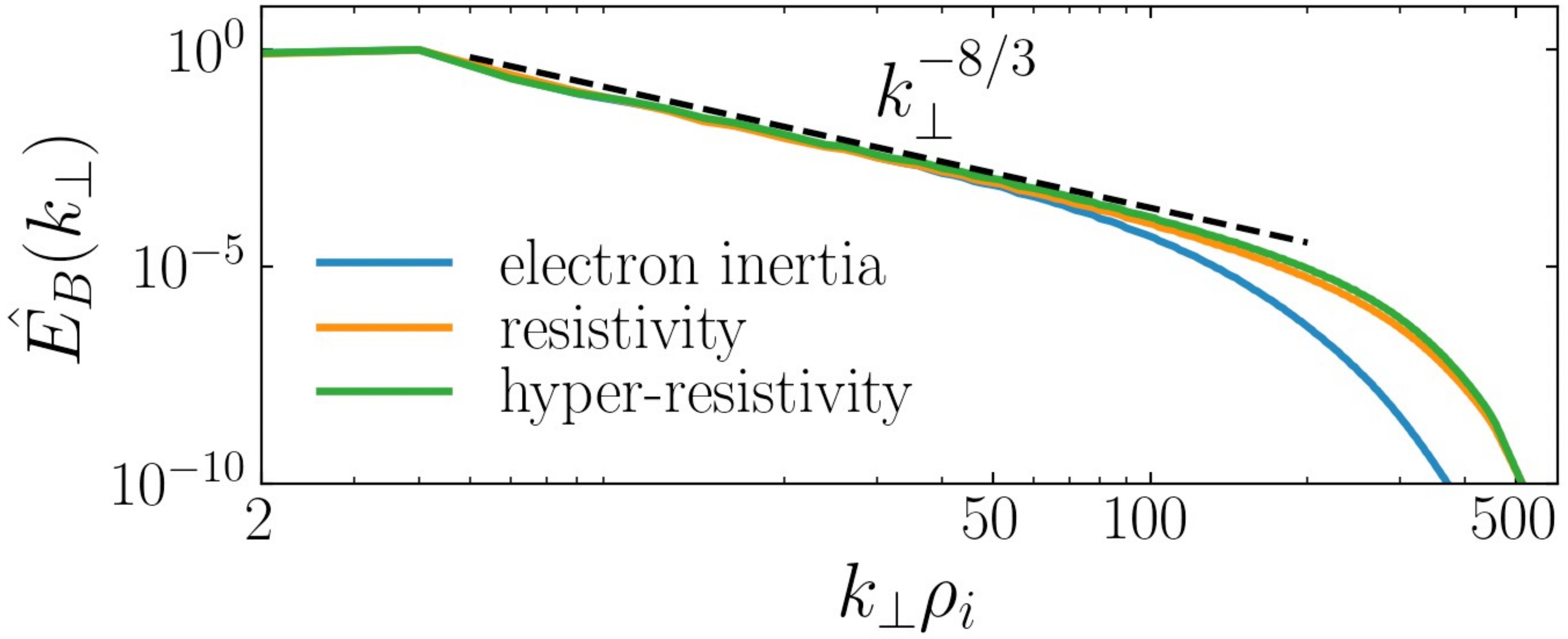
Our approach to distinguish the role of intermittency vs tearing mediation:

In numerical simulations, the frozen flux constraint can instead be broken by (hyper) resistivity $\eta_H \nabla_\perp^\alpha$:

$$E_B(k_\perp)dk_\perp \propto k_\perp^{-(7n\alpha+2\alpha+2)/(3n\alpha+2)} dk_\perp.$$

n is the parameter for the configuration of magnetic fields: n=1 Harris sheet; n=2 sinusoidal profile

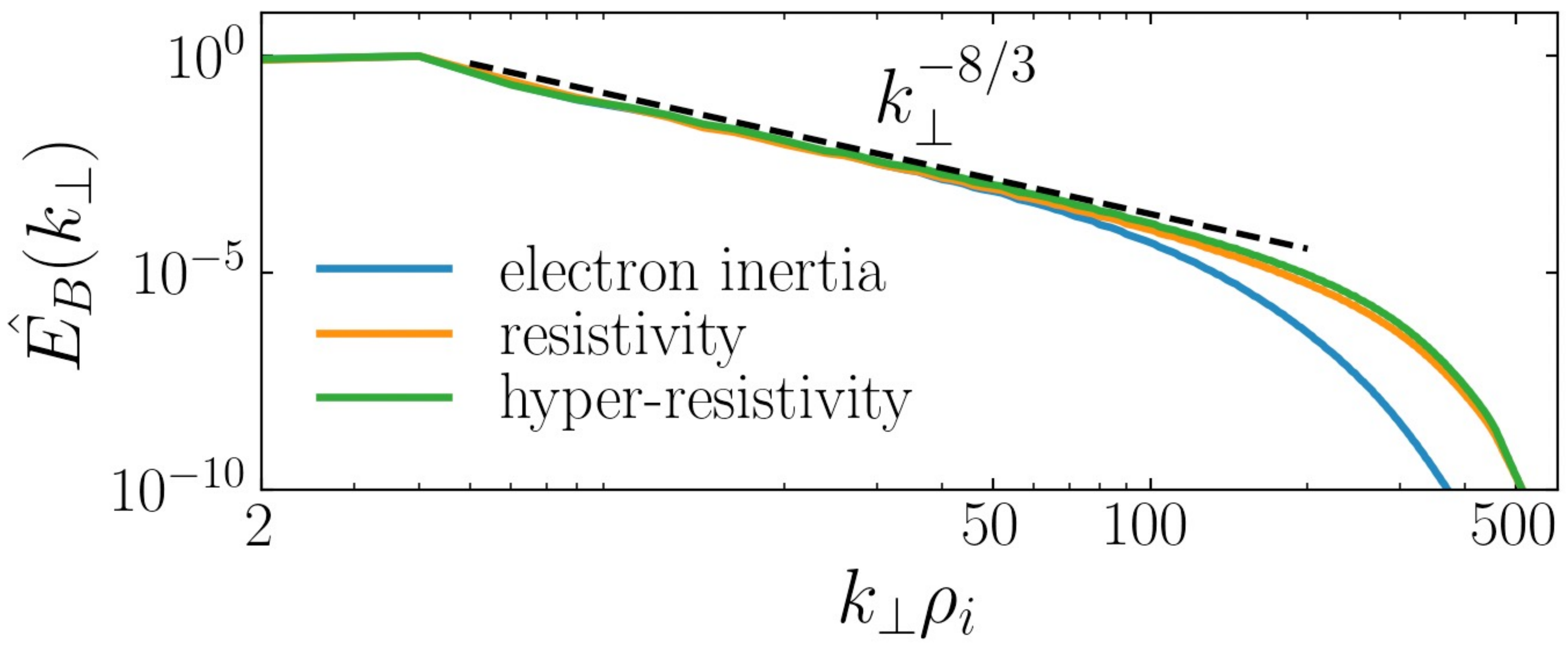
Isothermal simulations – Energy spectra



Simulations are performed in the sub-ρ_i range, with the flux-unfreezing mechanism being the main difference.

$\sim k_\perp^{-8/3}$ spectrum; predicted by the intermittency model and the tearing-mediation model

Energy spectra is not set by tearing mediation



Simulations are performed in the sub-ρ_i range, with the flux-unfreezing mechanism being the main difference.

If the spectra are set by the tearing mediation:

$$E_B(k_\perp)dk_\perp \propto k_\perp^{-(7\alpha+3)/(3\alpha+1)}$$

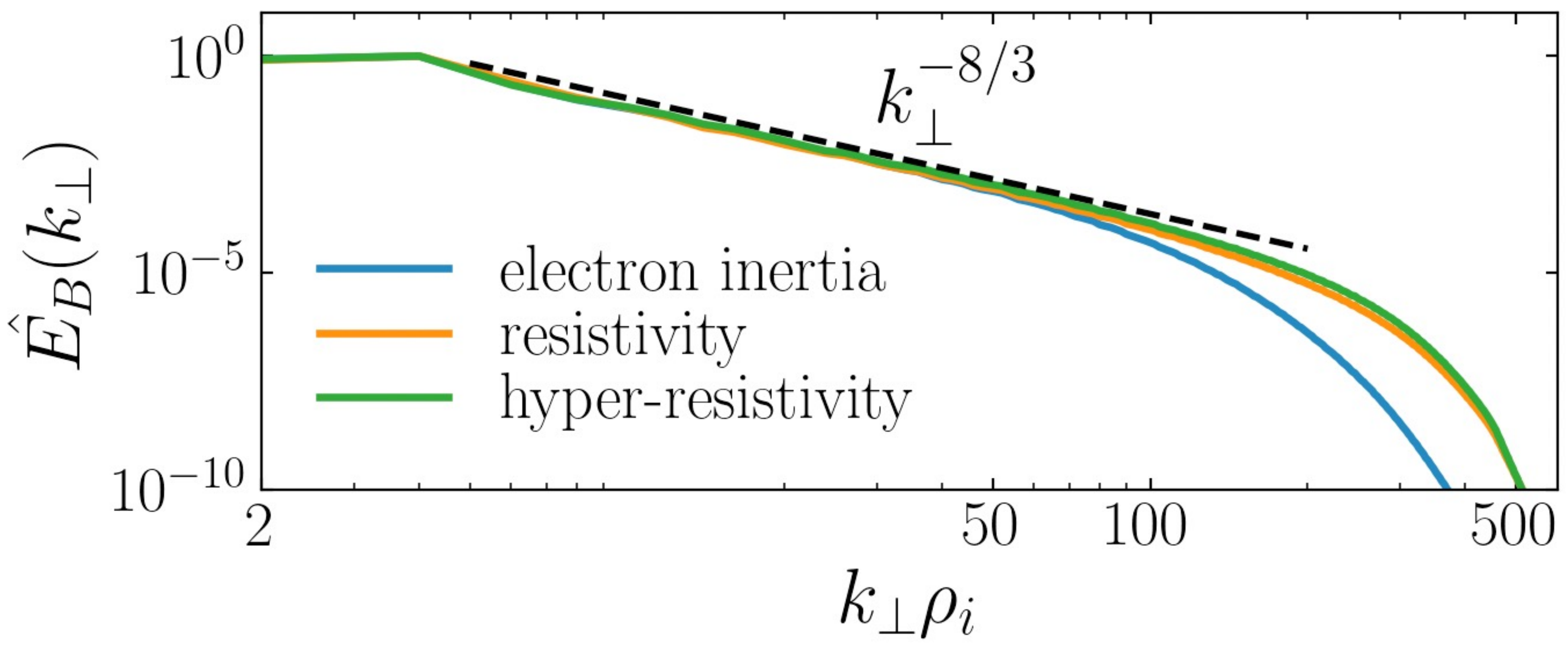
Electron inertia: -8/3

Resistivity: -2.4

Hyper-resistivity: -2.6

The overlap of the spectra rules out tearing-mediation as the physical mechanism underpinning the energy cascade.

Energy spectra is not set by tearing mediation



Simulations are performed in the sub-ρ_i range, with the flux-unfreezing mechanism being the main difference.

If the spectra are set by the tearing mediation:

$$E_B(k_\perp)dk_\perp \propto k_\perp^{-(7\alpha+3)/(3\alpha+1)}$$

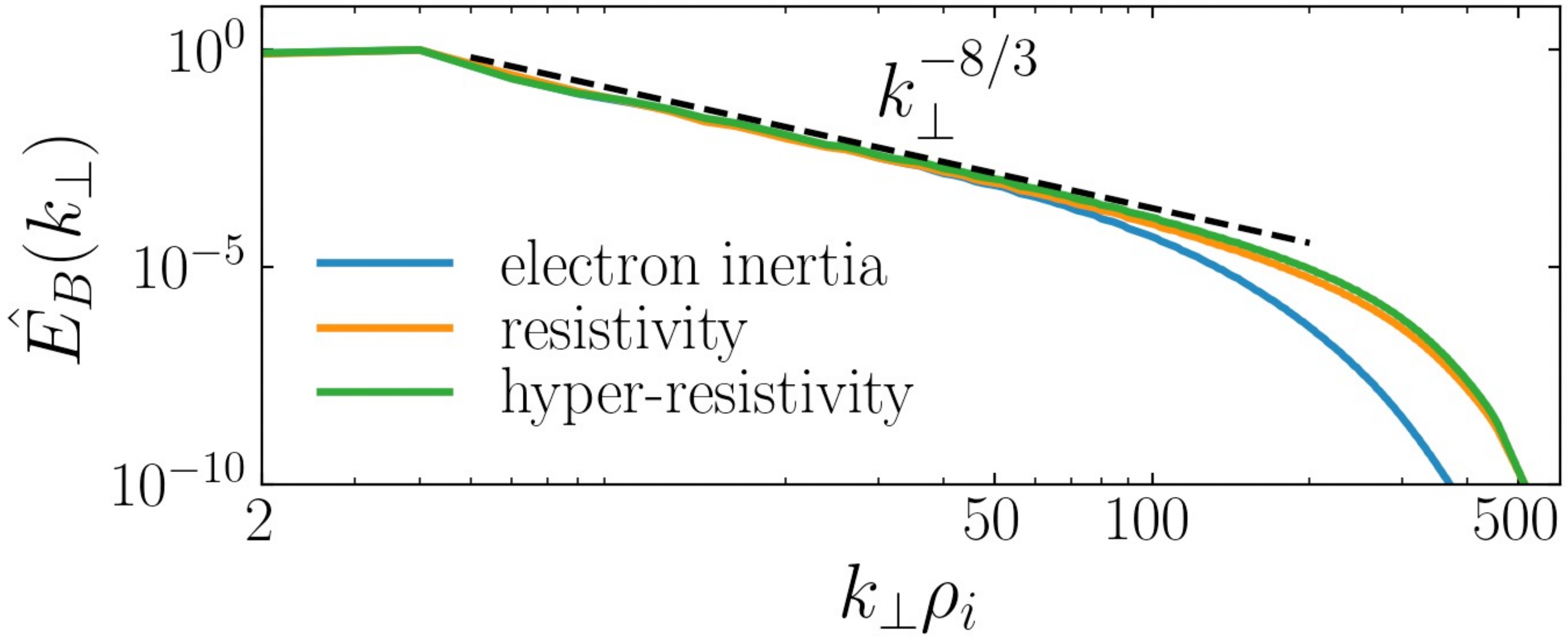
Electron inertia: -8/3

Resistivity: -2.4

Hyper-resistivity: -2.6

The overlap of the spectra rules out tearing-mediation as the physical mechanism underpinning the energy cascade.

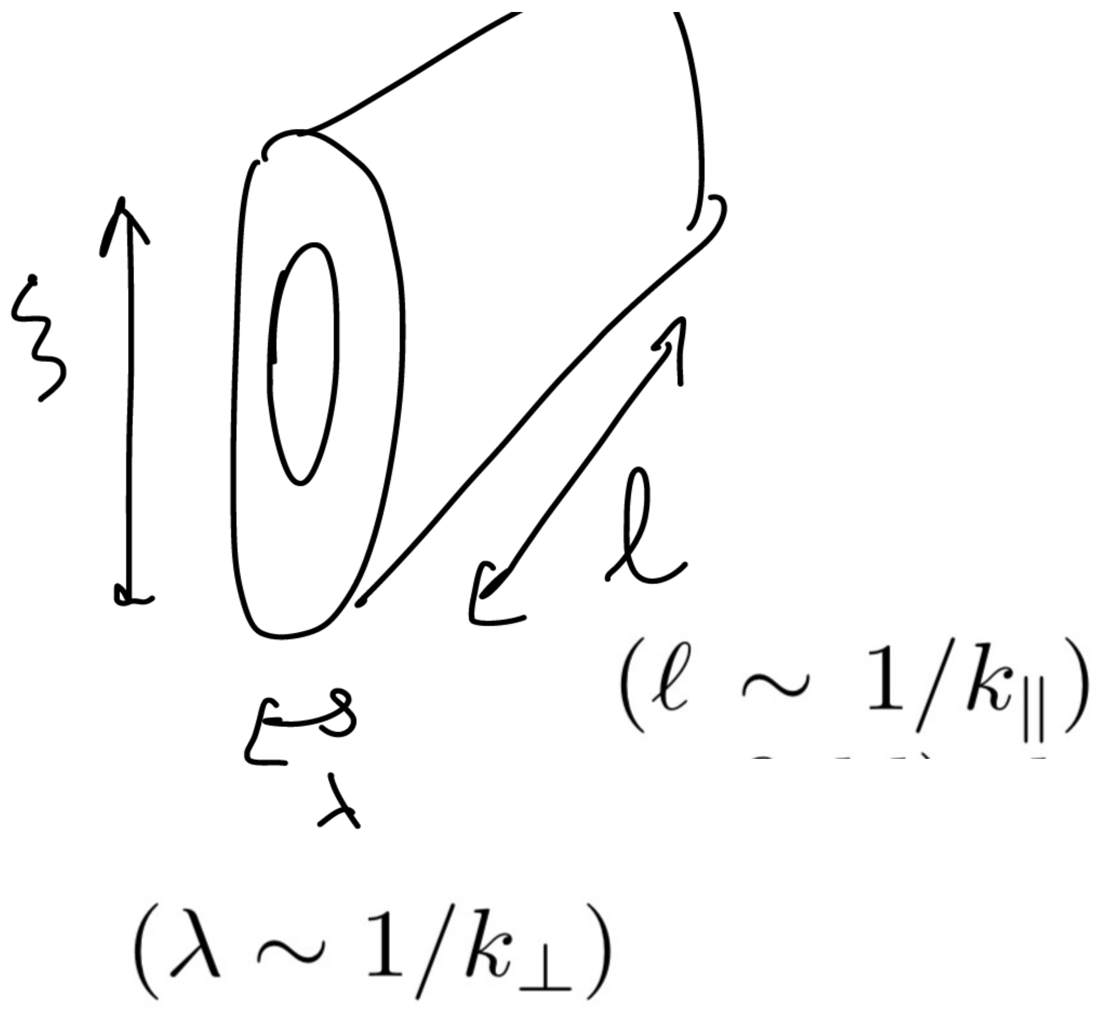
Spectral anisotropy shows no evidence of progressive alignment



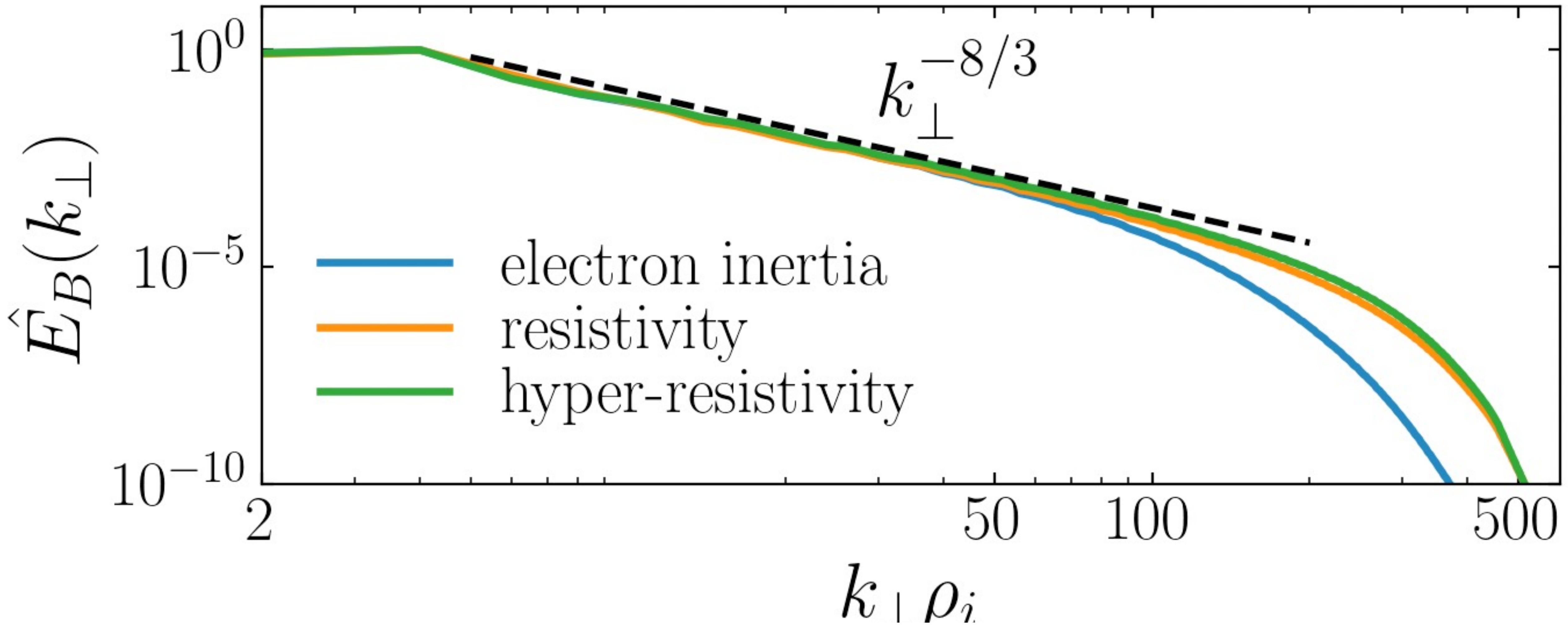
Why don't the turbulence eddies become tearing unstable?

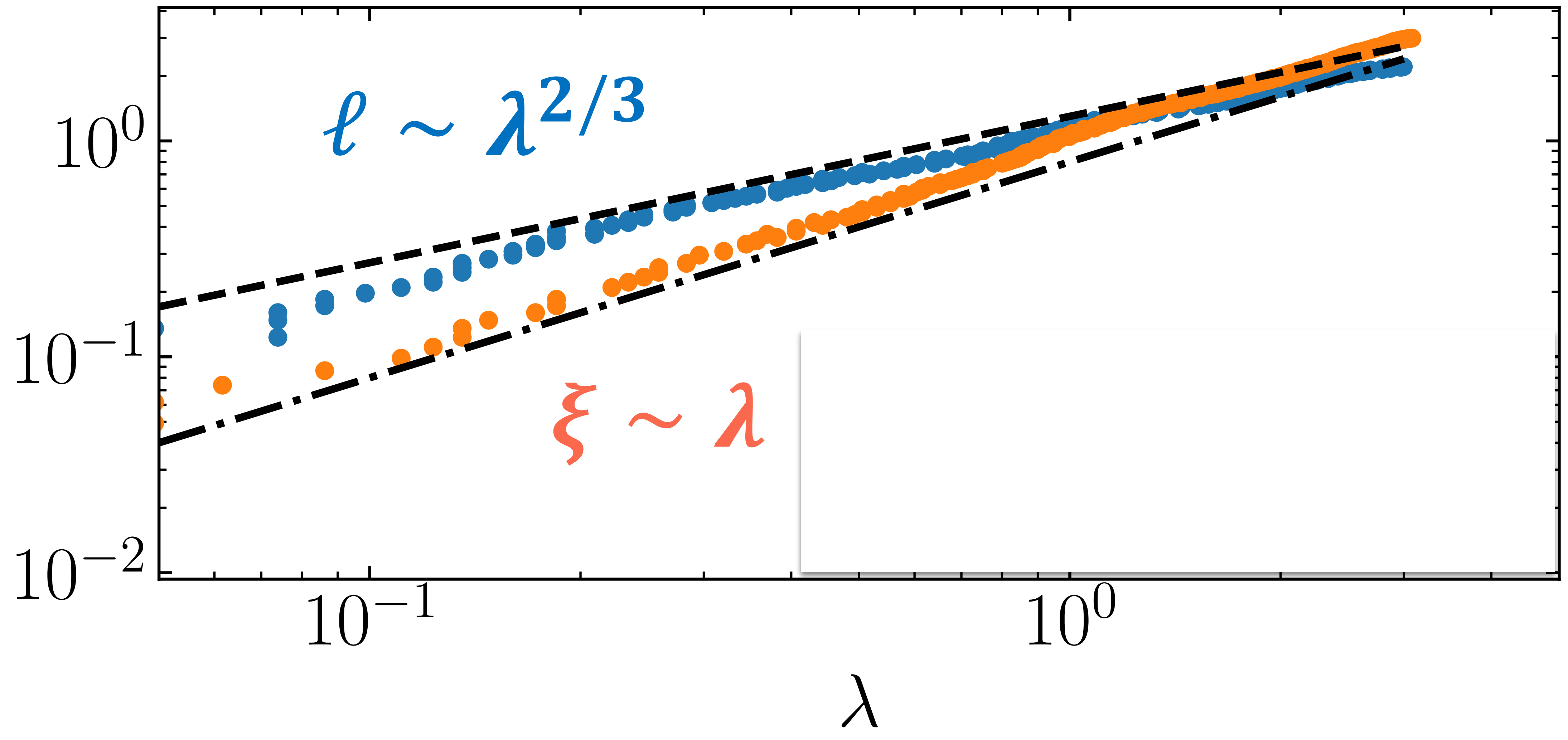
3D structure functions of the magnetic fields:

$$S_2(\delta\mathbf{r}) \equiv \langle|\Delta\mathbf{B}(\mathbf{r}, \delta\mathbf{r})|^2\rangle_\mathbf{r}$$



Spectral anisotropy shows no evidence of progressive alignment

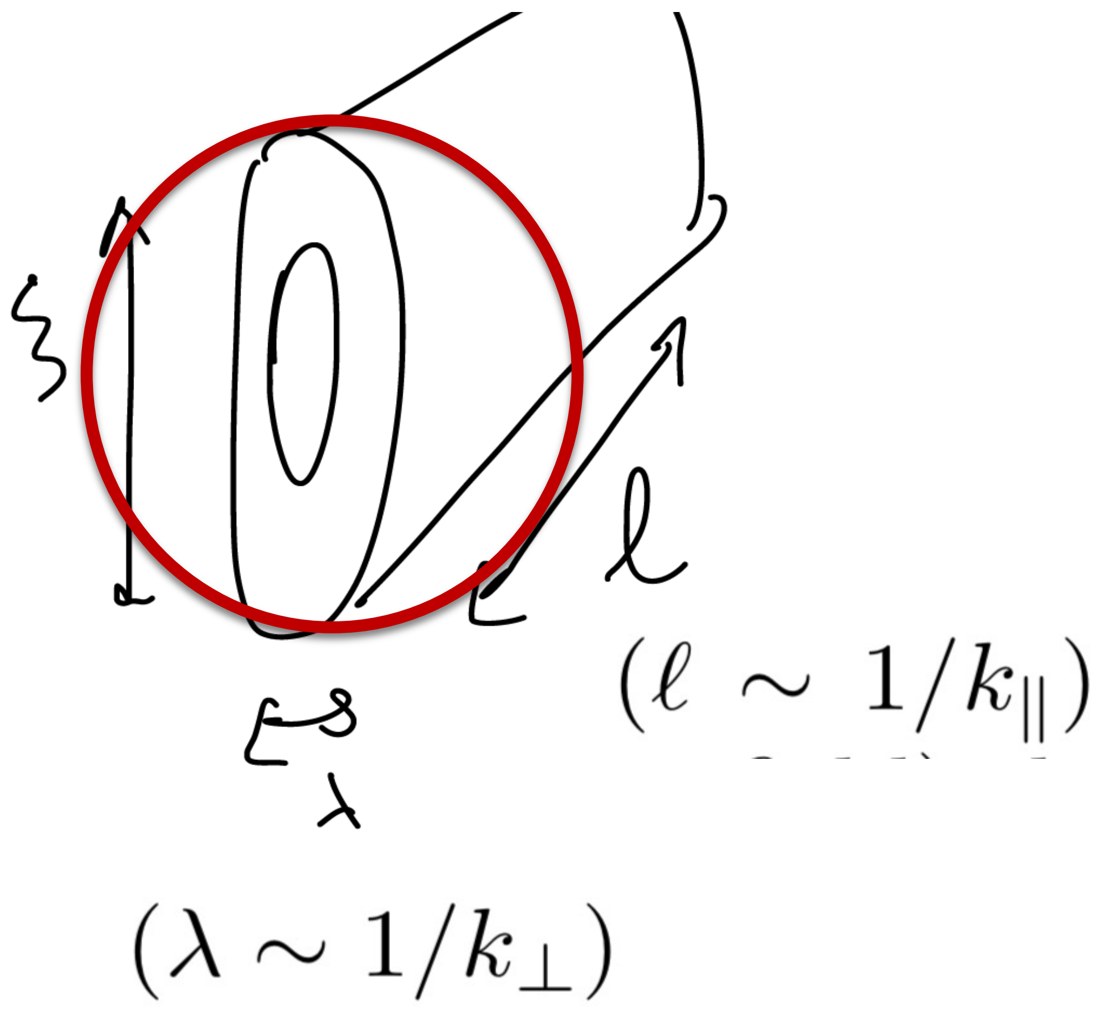




Why don't the turbulence eddies become tearing unstable?

3D structure functions of the magnetic fields:

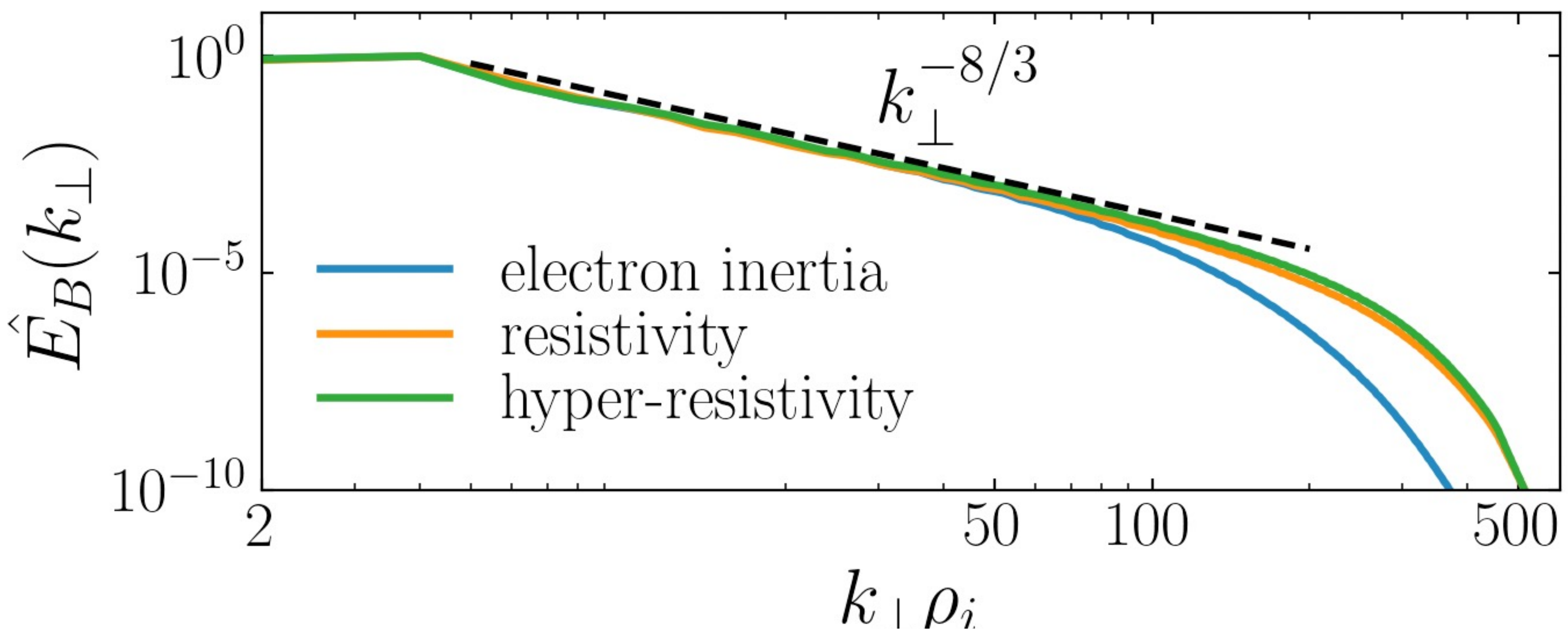
$$S_2(\delta \mathbf{r}) \equiv \langle |\Delta \mathbf{B}(\mathbf{r}, \delta \mathbf{r})|^2 \rangle_{\mathbf{r}}$$



Isotropic morphology of eddies in perpendicular planes

– *no progressive alignment for tearing mediation*

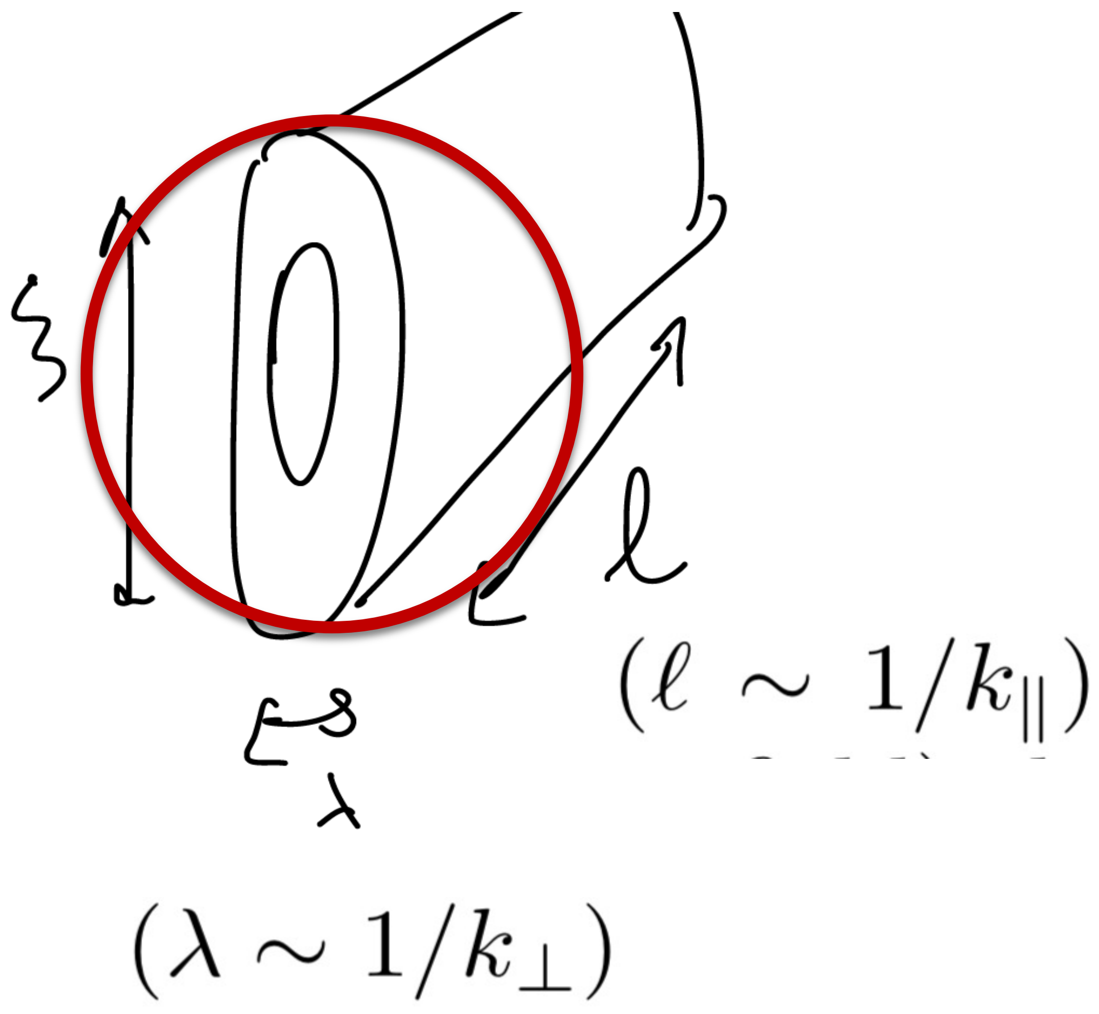
Spectral anisotropy shows no evidence of progressive alignment

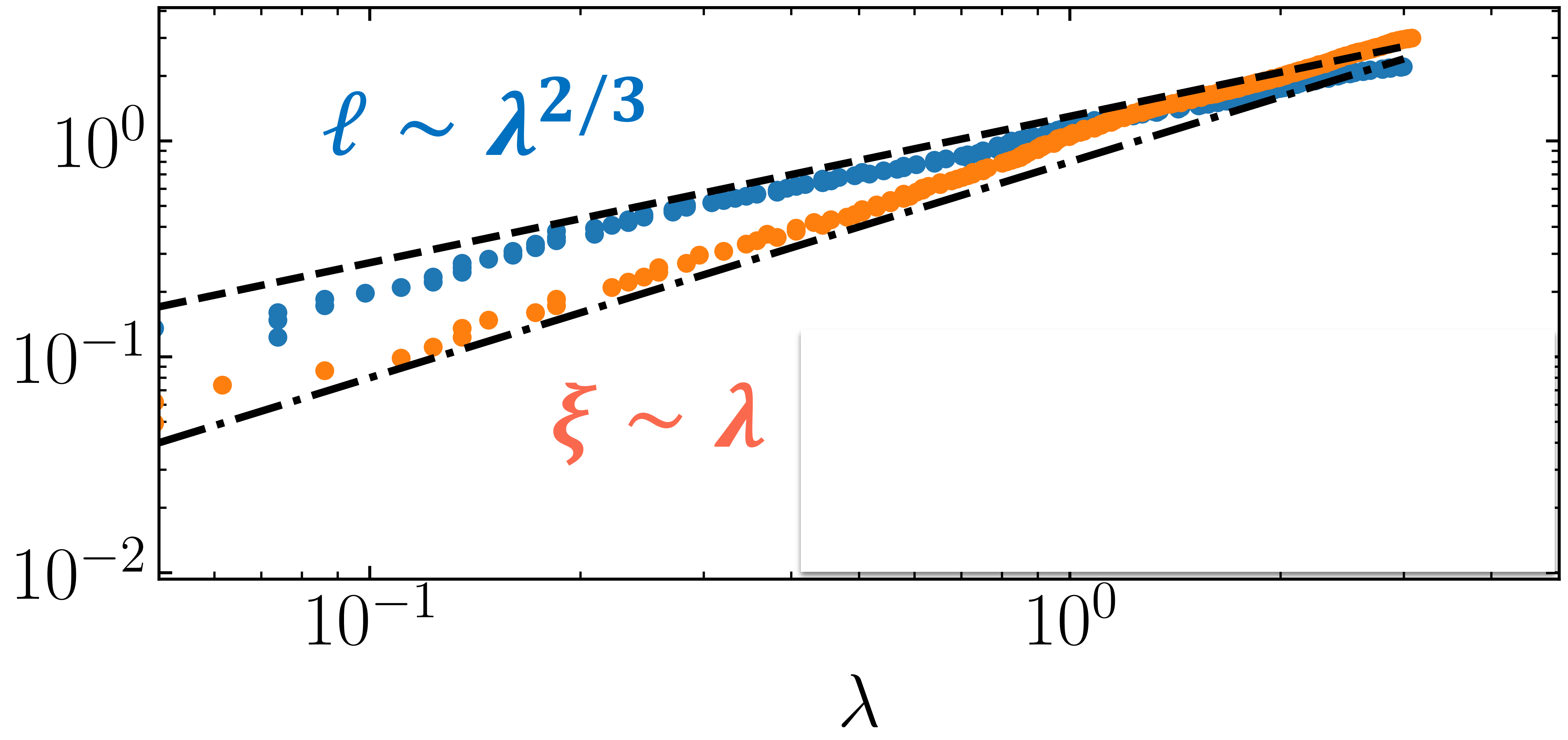


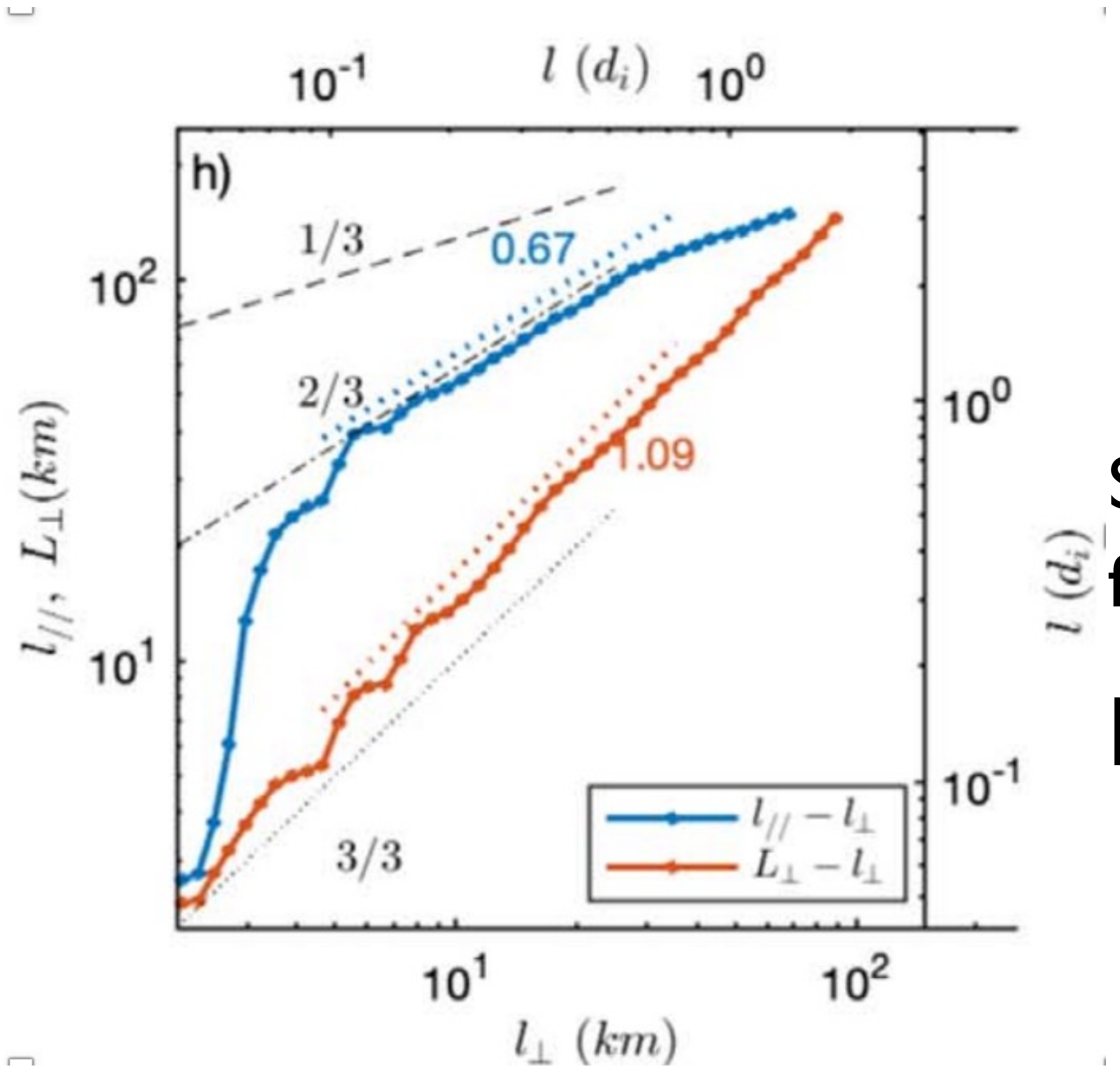
Why don't the turbulence eddies become tearing unstable?

3D structure functions of the magnetic fields:

$$S_2(\delta\mathbf{r}) \equiv \langle |\Delta\mathbf{B}(\mathbf{r}, \delta\mathbf{r})|^2 \rangle_{\mathbf{r}}$$





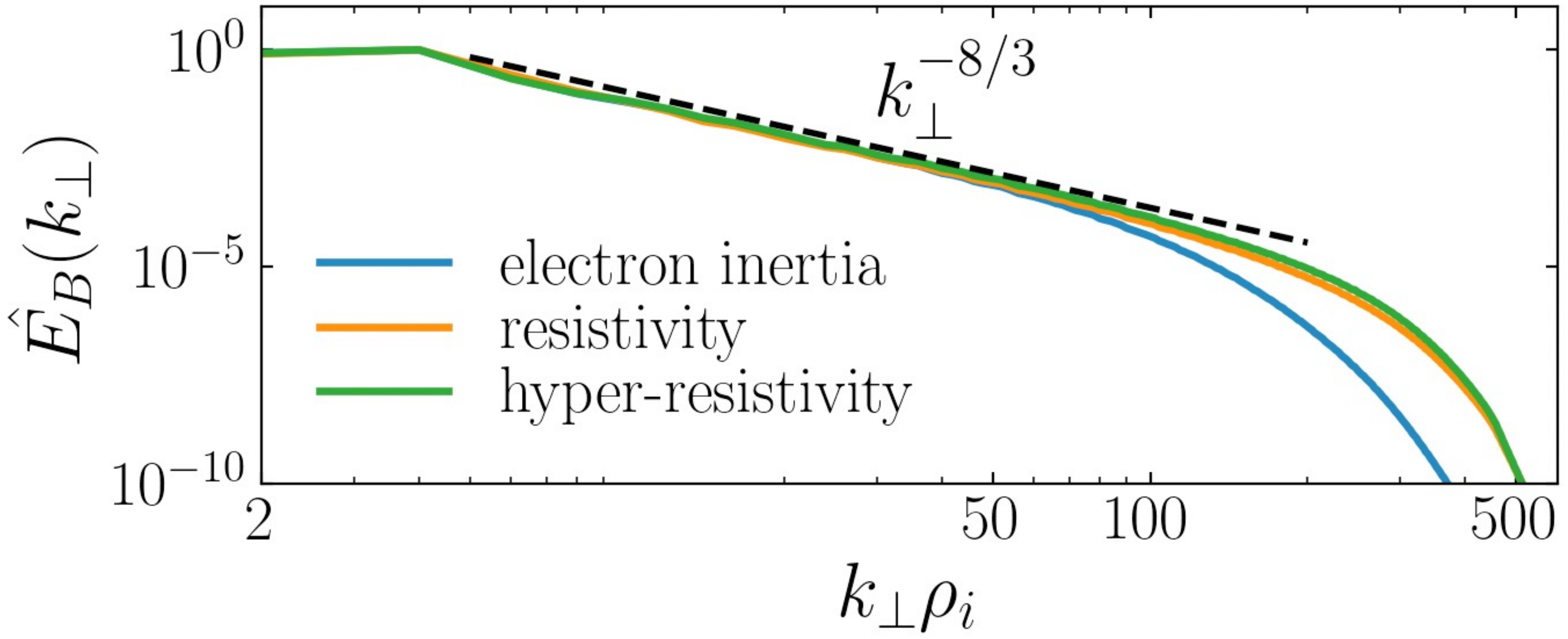


Solar wind measurements from MMS and PSP

[Wang+ 2020; Zhang+2022;]

Isotropic morphology of eddies in perpendicular planes – no progressive alignment for tearing mediation

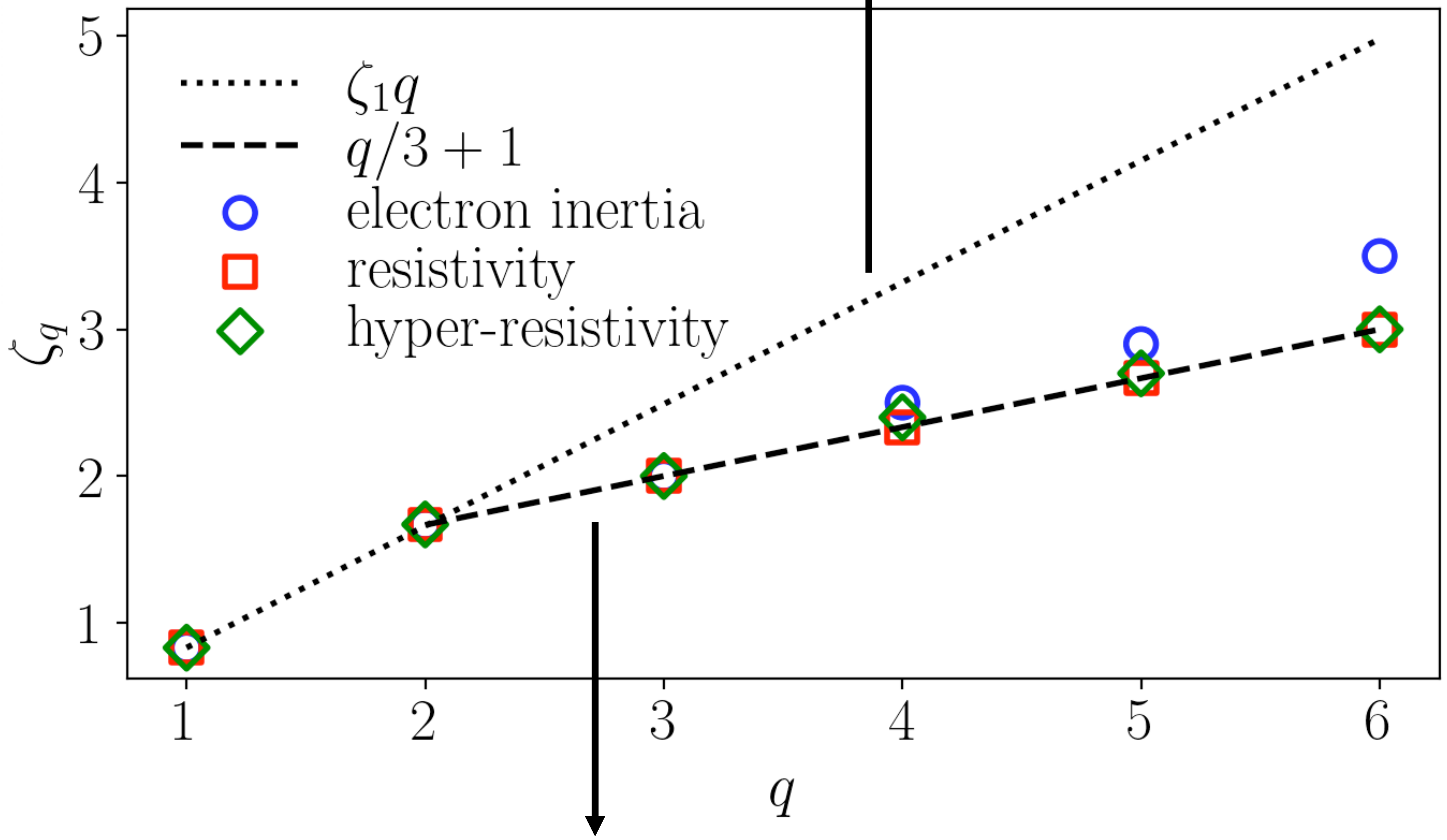
High-order structure function indicates 2D intermittent structures



Using higher order structure functions to quantify intermittency

$$S_q(\delta\mathbf{r}) \equiv \langle|\Delta\mathbf{B}(\mathbf{r},\delta\mathbf{r})|^q\rangle_{\mathbf{r}} \sim \delta\mathbf{r}^{\zeta_q}$$

Self-similar fluctuations, i.e., no intermittency



2D Intermittent structures;

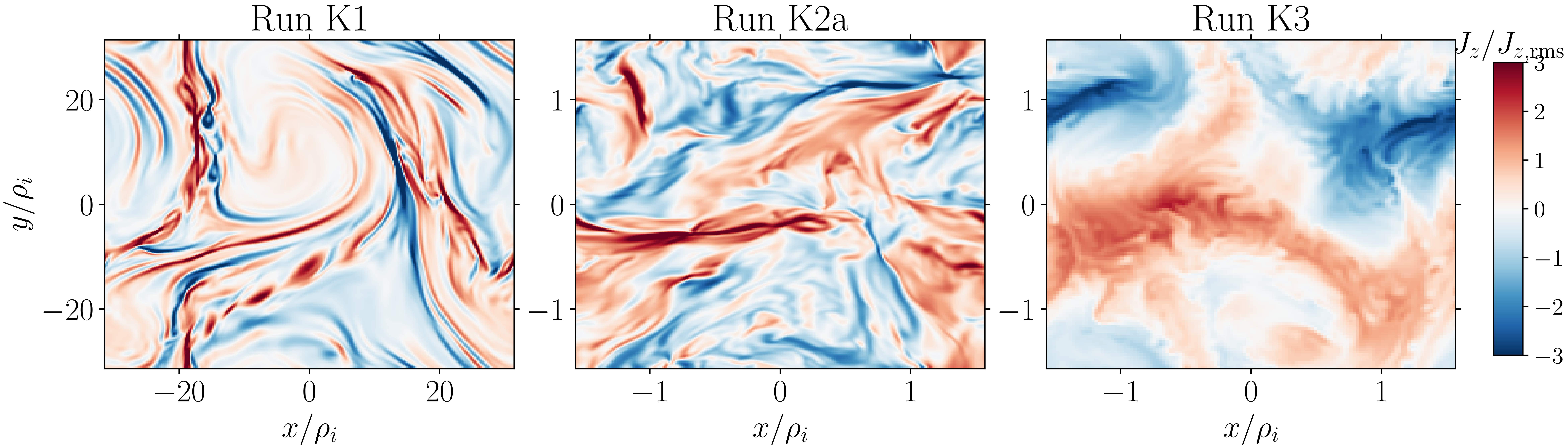
Main assumption to derive the -8/3 spectrum by Boldyrev&Perez 2012

Simulations with kinetic electrons

MHD transition to sub-ρ_i, d_e unresolved

sub-ρ_i, d_e resolved

sub-d_e

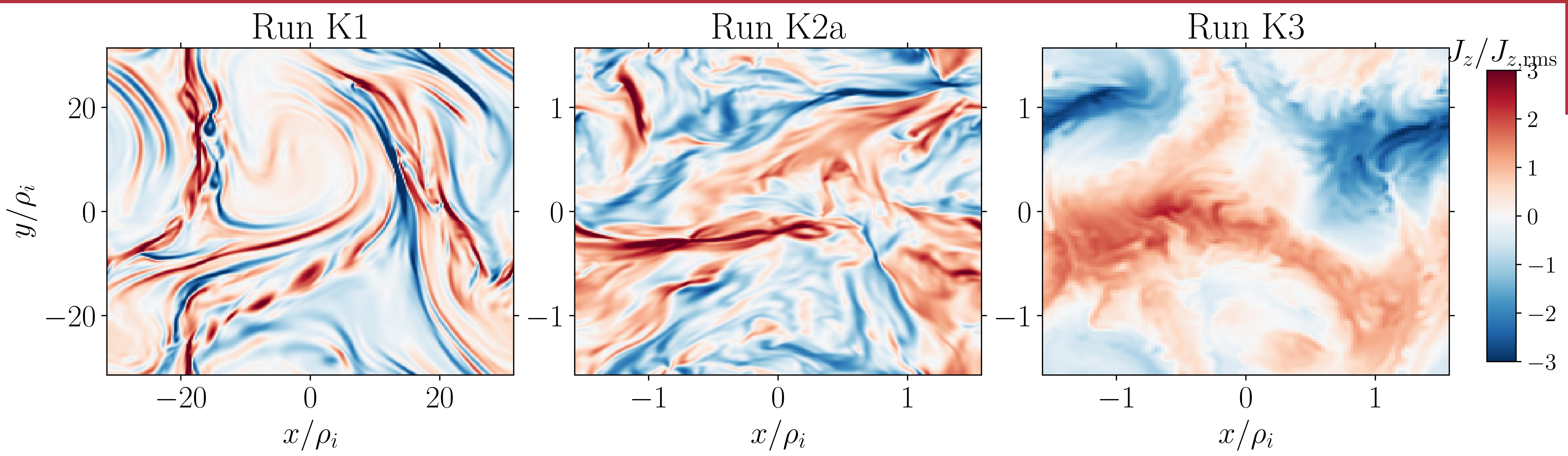


$\frac{\rho_i}{L} = 0.1;\ \ k_{\perp,max}d_e = 1$

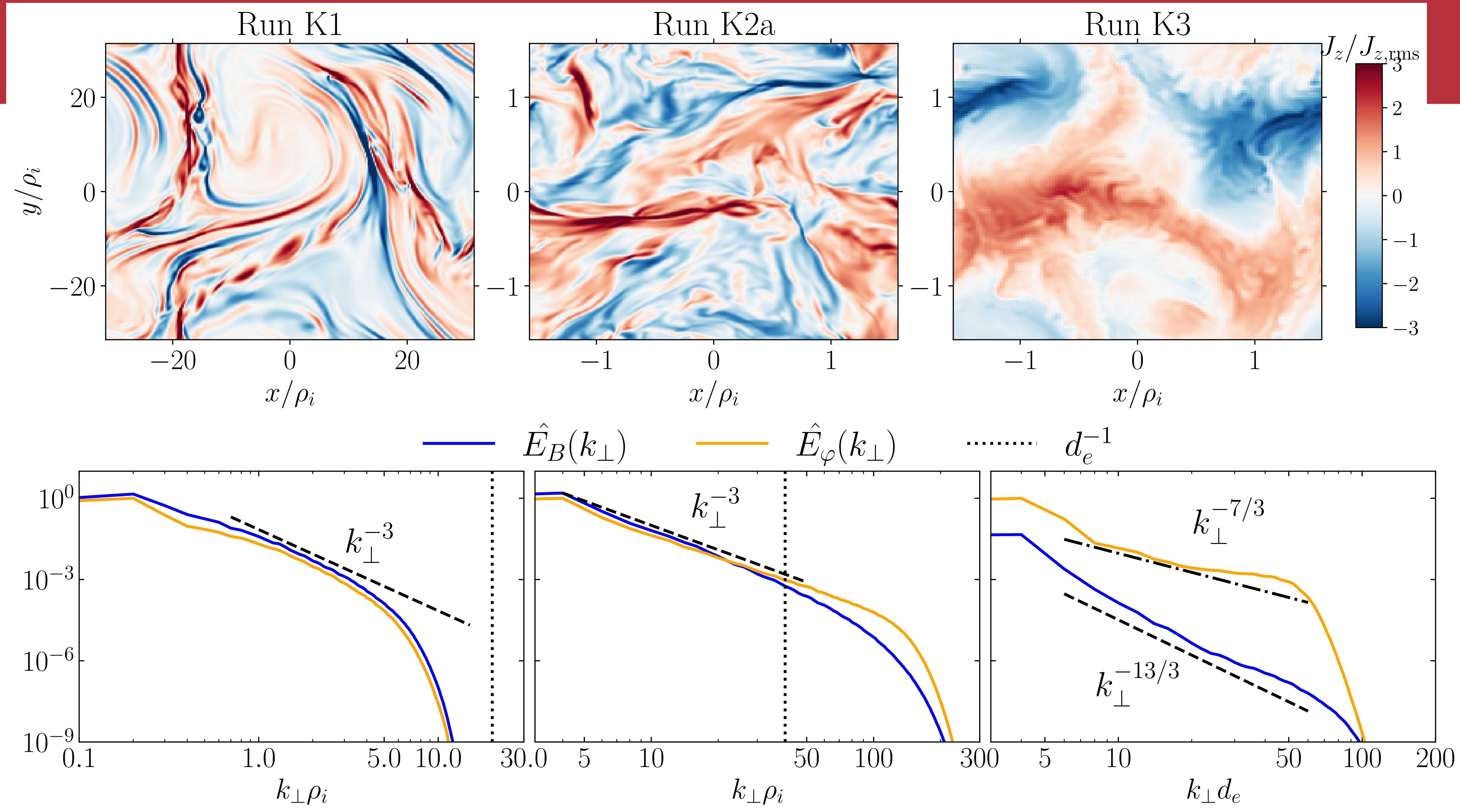
$\frac{\rho_i}{L} = 2;\ \ k_{\perp,max}d_e = 10$

$\rho_i = d_e = 2L$

MHD to ρ_i **sub-ρ_i** **sub-d_e**



MHD to ρ_i **sub-ρ_i** **sub-d_e**

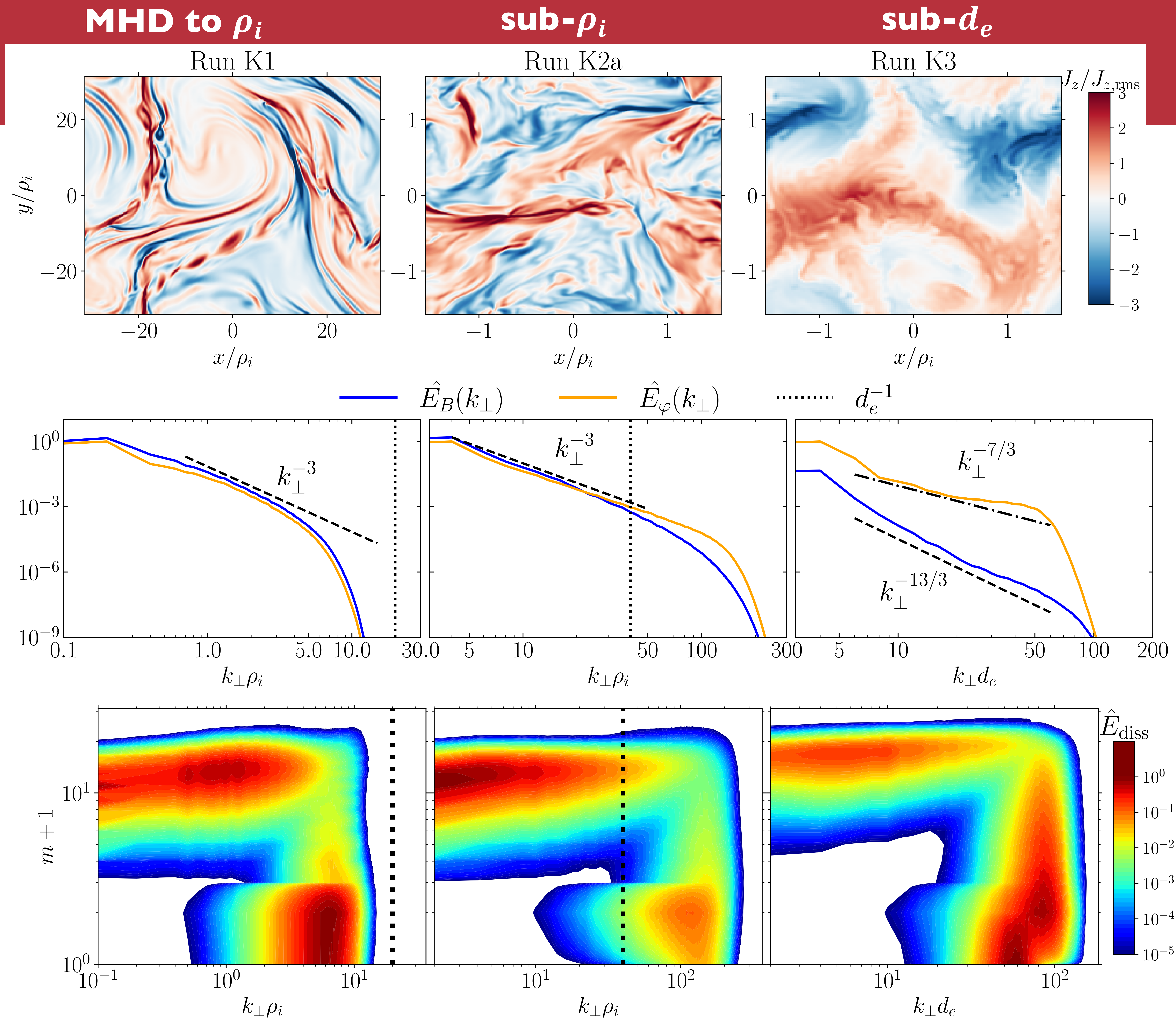


In the sub-ρ_i range:

spectra become steeper (than $k_\perp^{-8/3}$)

In the sub-d_e range:

$$E_\varphi(k_\perp) \propto k_\perp^{-7/3}, \quad E_B(k_\perp) \propto k_\perp^{-13/3}.$$



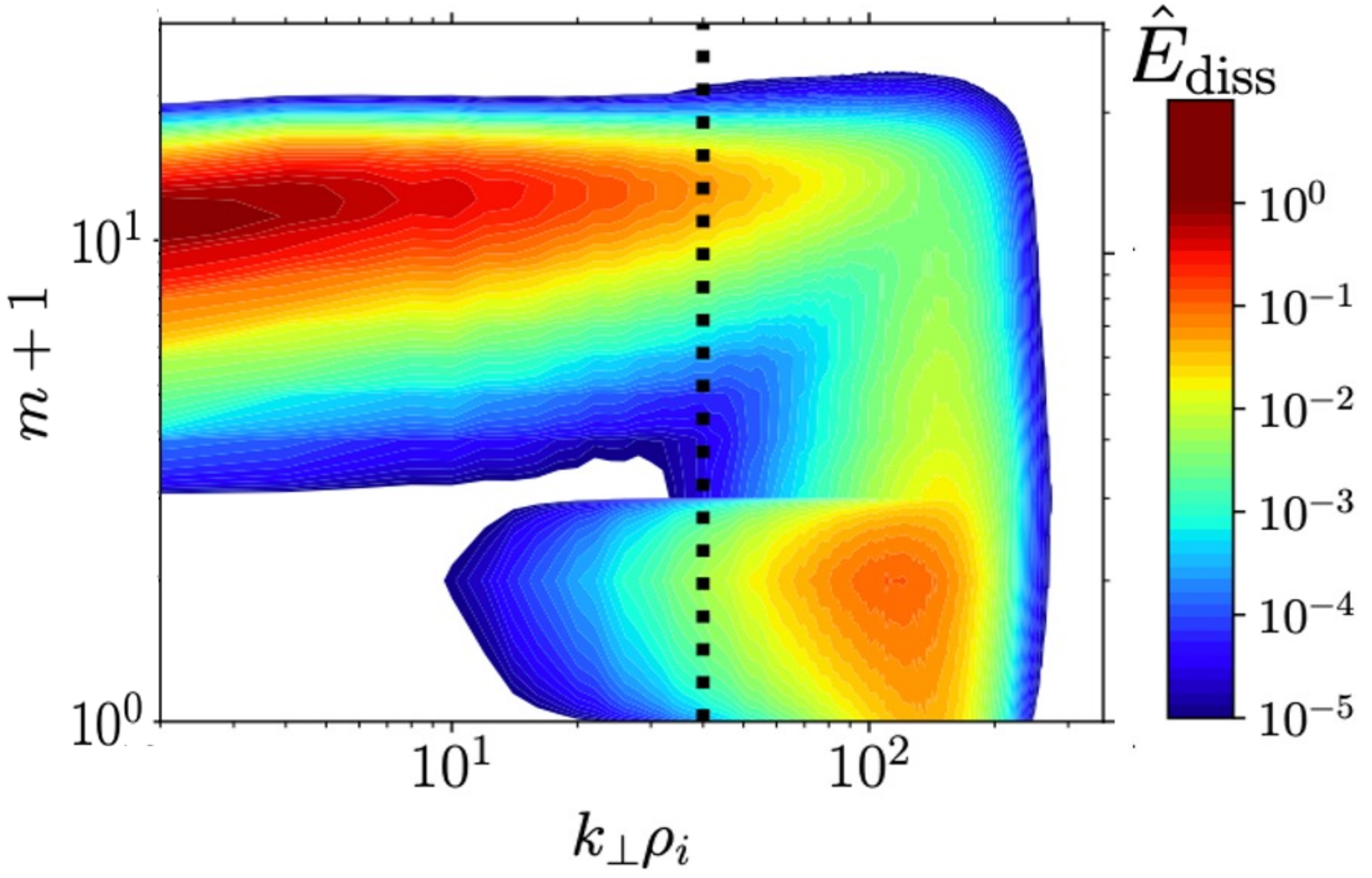
High-m dissipation turns on at ρ_i.

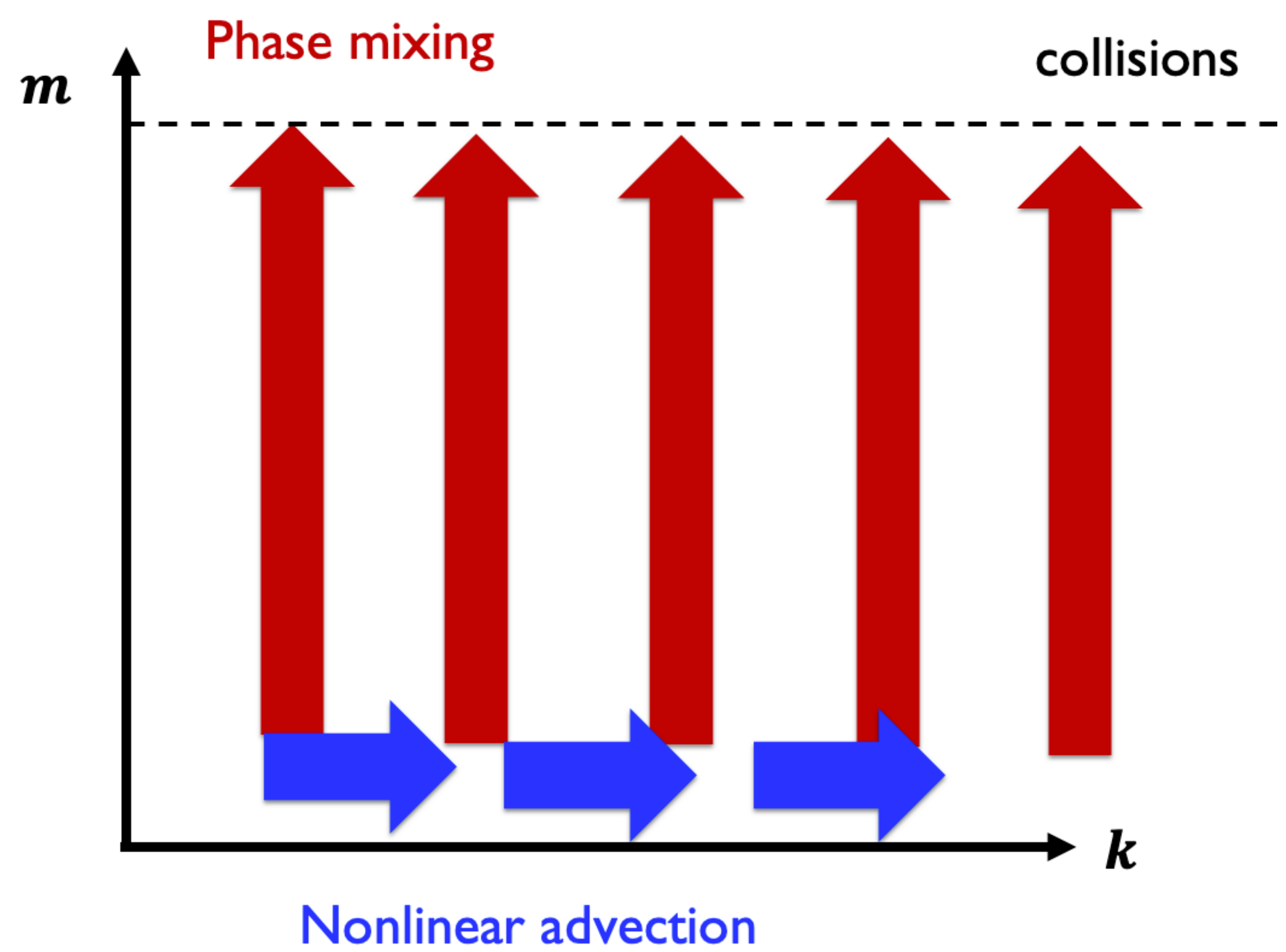
In the range $\rho_i < \lambda < d_e$, the “kinetic dissipation” dominates.

In the range $d_e > \lambda$, the “fluid dissipation” dominates.

Landau damped EM energy matches electron heating

sub-ρ_i turbulence

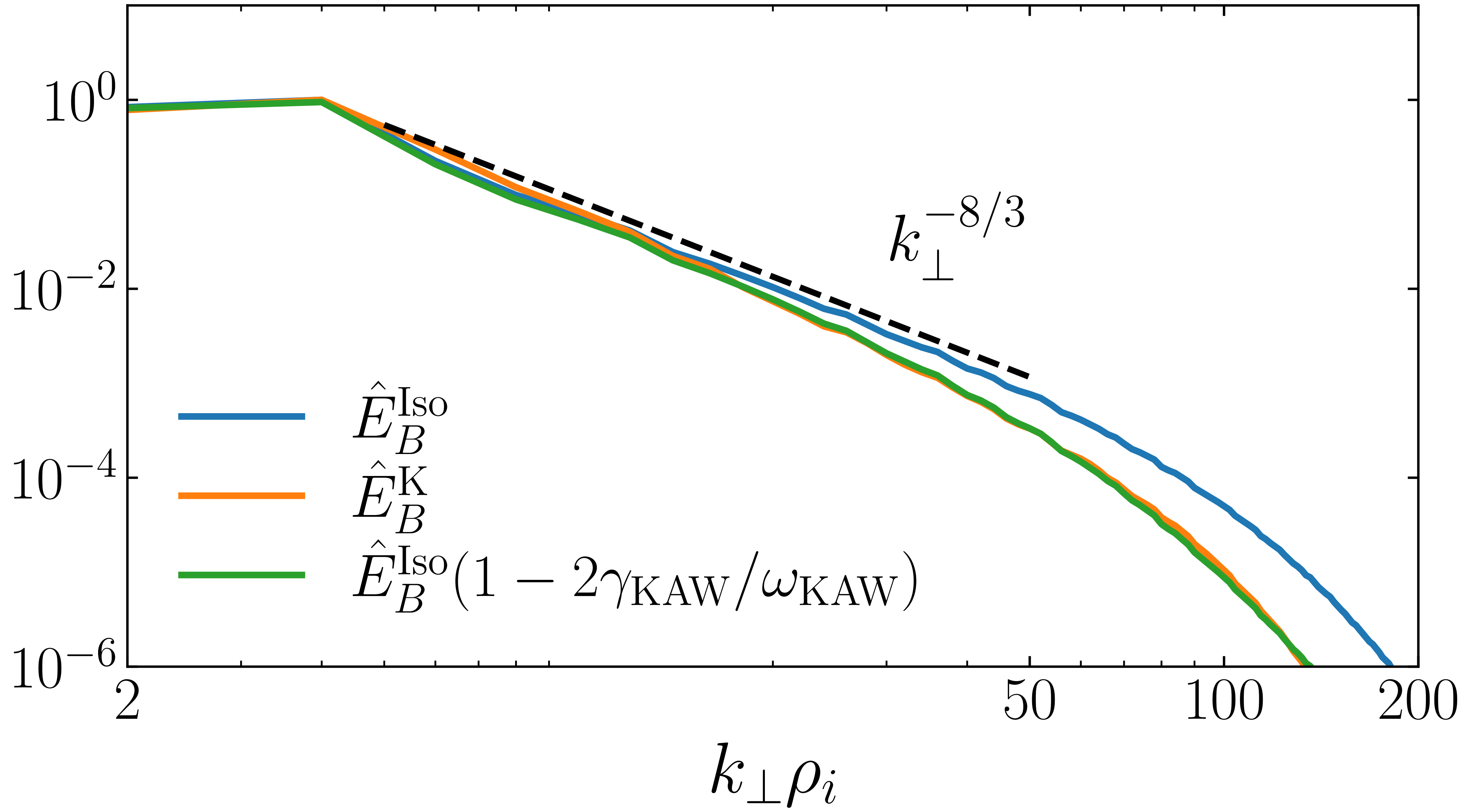




From the linear dispersion relation of KAWs: damping rate γ_{KAW} and frequency ω_{KAW}

$$\hat{E}_B^{\text{K}}(k_\perp) \approx \hat{E}_B^{\text{iso}}(k_\perp)(1 - 2\gamma_{\text{KAW}}/\omega_{\text{KAW}}).$$

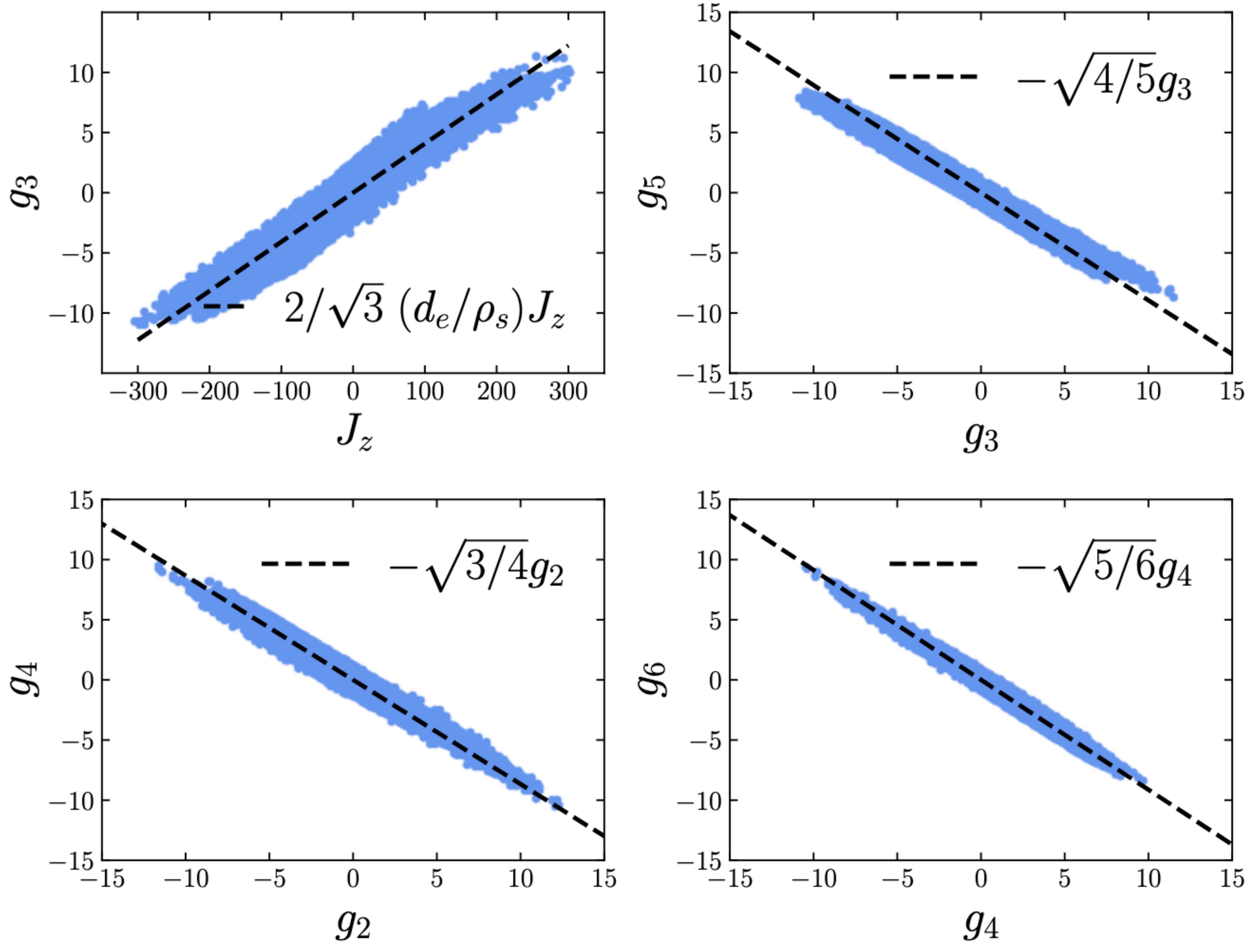
$\sim \gamma_{nl}$ (critical balance)



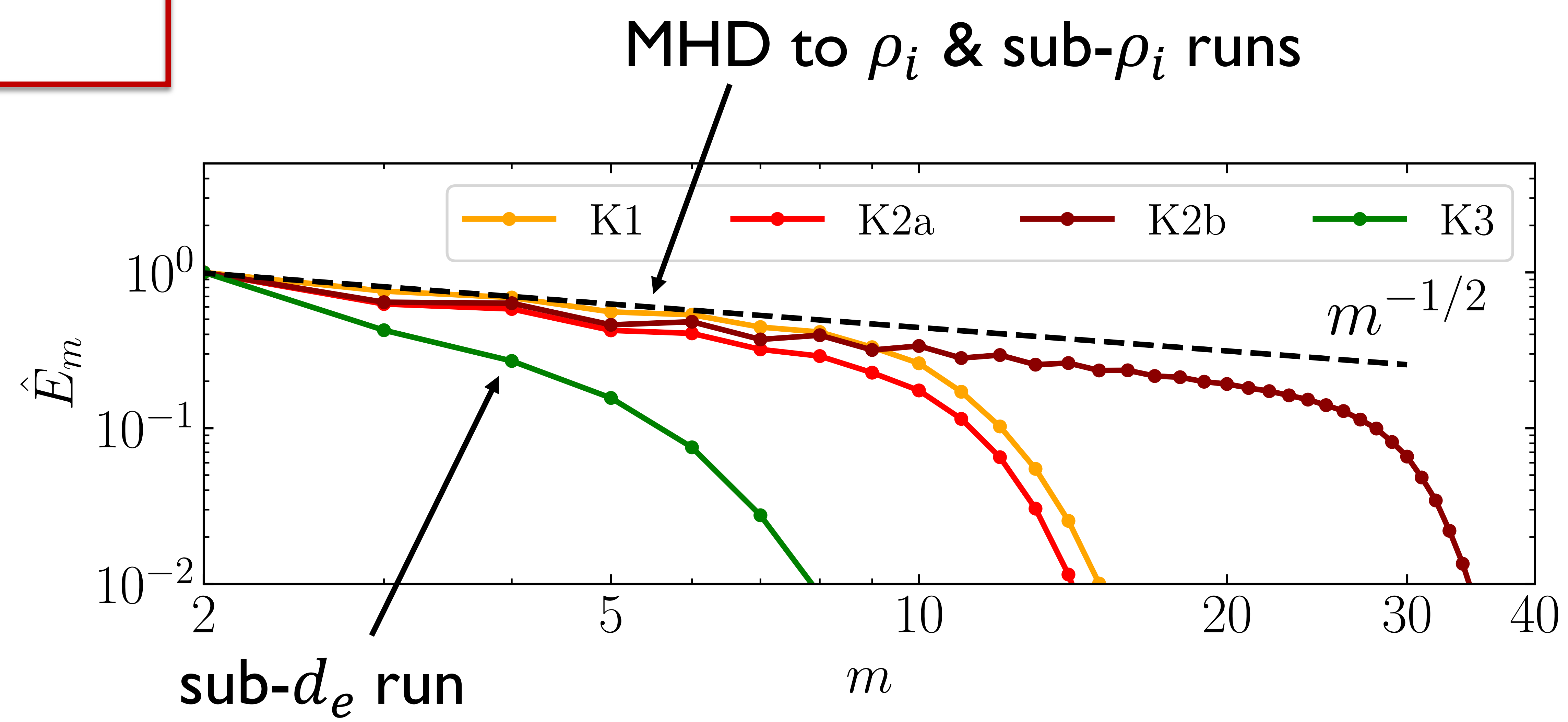
EM fluctuations are Landau-damped at each scale independently → phase mixing domination

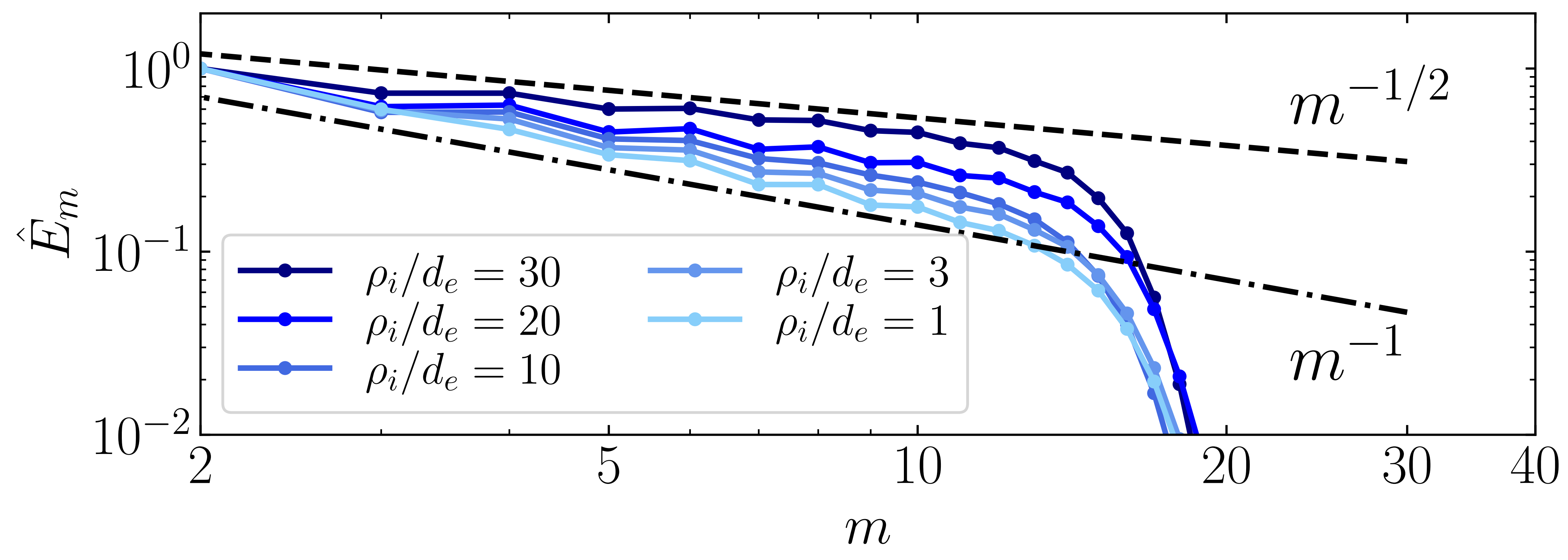
A zeroth-order solution of g_e in the velocity space and its Hermite spectrum

$$g_{m+1} = -\sqrt{m/(m+1)}\,g_{m-1} \qquad \text{for } m \geq 3, \text{ and}$$
$$g_3 = -\sqrt{2/3}\;(\rho_s/d_e)J_{\|}$$



Velocity-space spectrum:





With kinetic electrons --- Phase space cascade and electron heating

Assuming φ and $A_\parallel$ have the same configuration/gradients

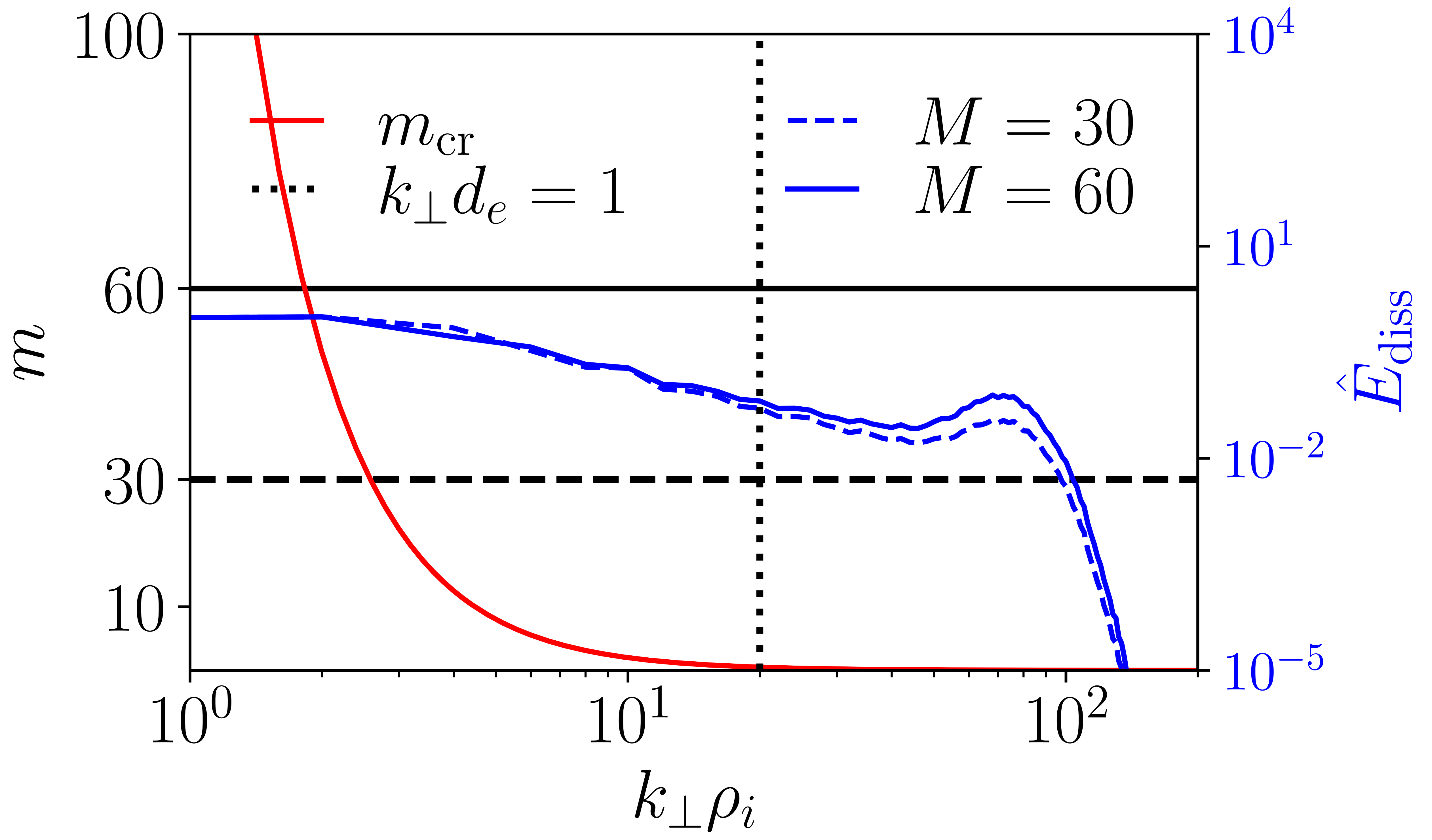
At each scale λ, there is a critical Hermite order m_{cr}:

Nonlinear advection rate~ Phase mixing rate

$$\frac{c}{B_0}\{\varphi, g_{m_{\rm cr}}\} \sim \frac{v_{\rm the}}{B_0}\{A_\parallel, g_{m_{\rm cr}}\}/\sqrt{m_{\rm cr}}$$

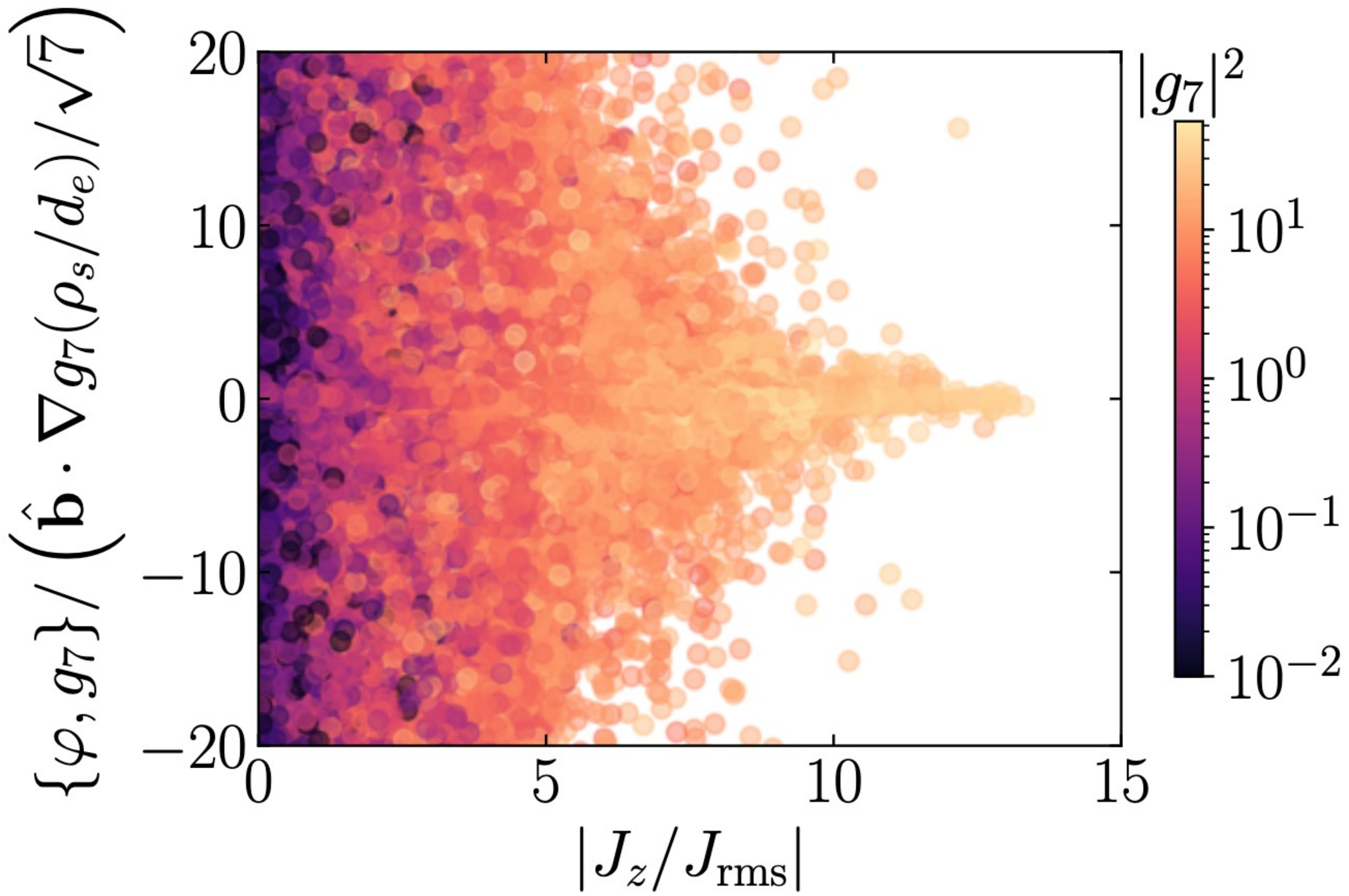
$$m_{\rm cr}(\lambda) \sim (\lambda/d_e)^2/(2\tau^2)$$

For both cases, there is a sufficiently wide dynamical range that echo could happen.



Local weakening of nonlinearity around current sheets enables strong phase mixing

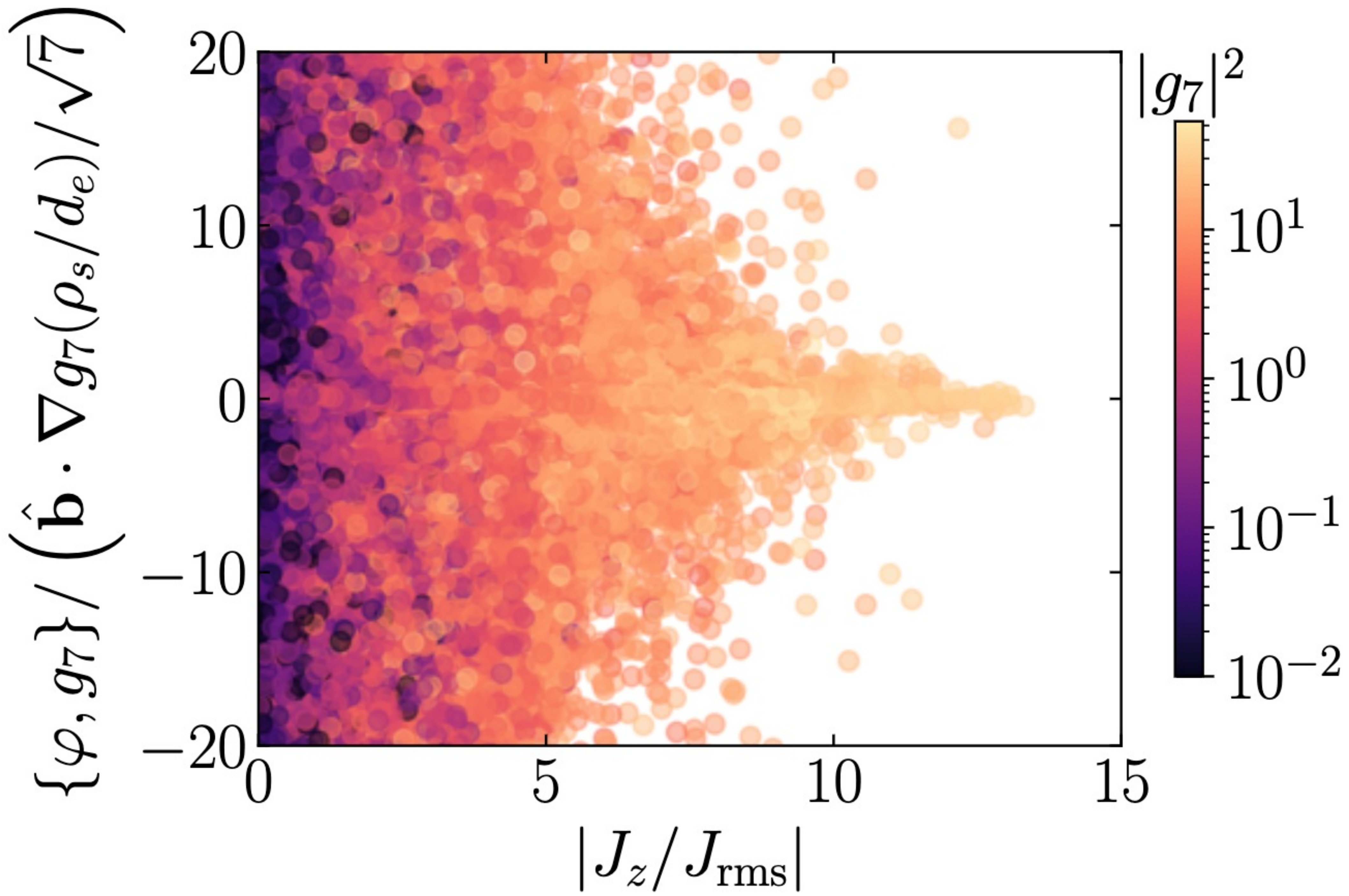
$$g_{m+1} = -\sqrt{m/(m+1)}\,g_{m-1} \qquad \text{for } m \geq 3, \text{ and}$$
$$g_3 = -\sqrt{2/3}\,(\rho_s/d_e)J_{\|}$$

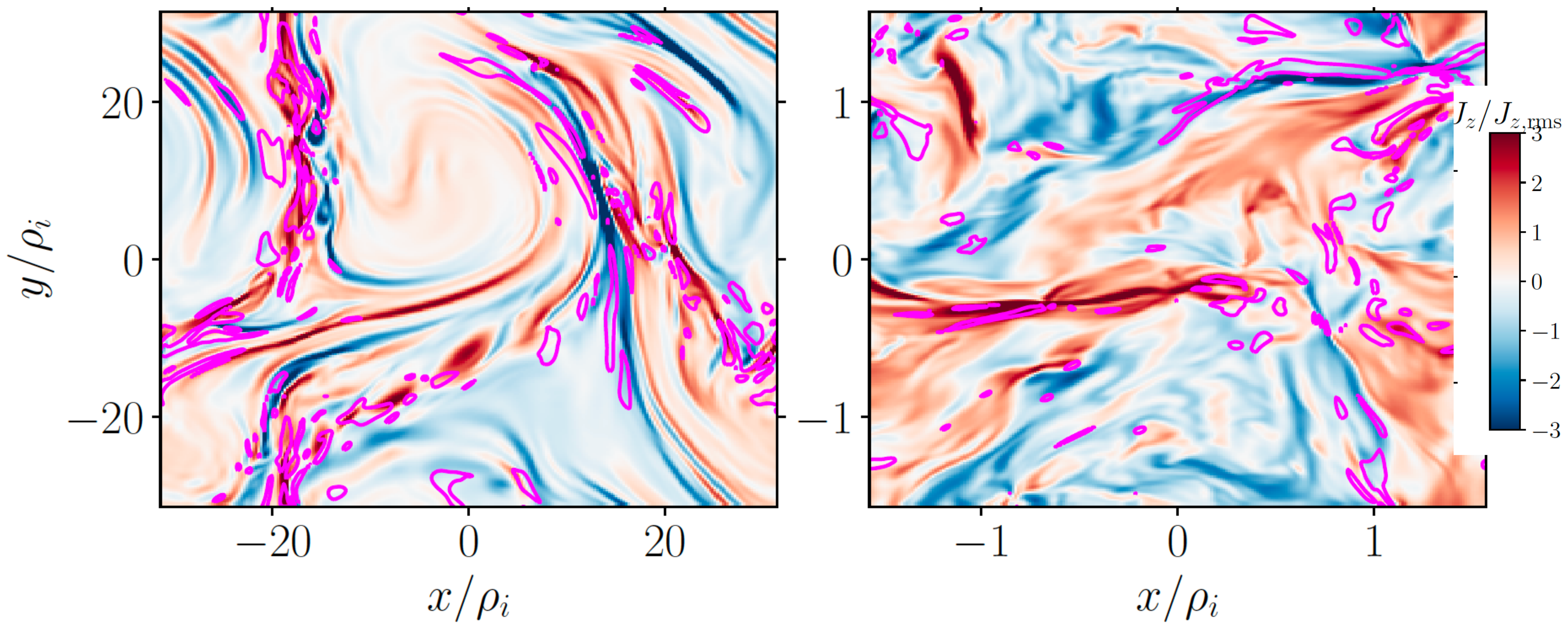


The ratio of the nonlinear-advection rate to phase-mixing rate as a function of normalized current density. The positions with large energy density of g_m (with strong current density) have locally weakened nonlinearity.

Heating occurs around current sheets

$$g_{m+1} = -\sqrt{m/(m+1)}\, g_{m-1} \qquad \text{for } m \geq 3, \text{ and}$$
$$g_3 = -\sqrt{2/3}\ (\rho_s/d_e) J_\parallel$$





The ratio of the nonlinear-advection rate to phase-mixing rate as a function of normalized current density. The positions with large energy density of g_m (with strong current density) have locally weakened nonlinearity.

Magenta contours indicates regions with strong collisional dissipation.

Conclusions

We study the kinetic turbulence in the low-β limit, composed of KAWs.

In this specific regime:

- The magnetic and density energy spectra in kinetic turbulence is set by intermittency.
- The kinetic channel (via phase mixing) of energy dissipates dominates the fluid channel, energy dissipated at small scales in velocity space.
- Electron heating is caused by Landau damping of KAWs in this regime.
- Energy dissipation/electron heating occurs mostly around current sheets, due to the local weakening of nonlinearity.