Kinetic-Alfvén-wave turbulence --- Intermittency, electron heating, and role of reconnection

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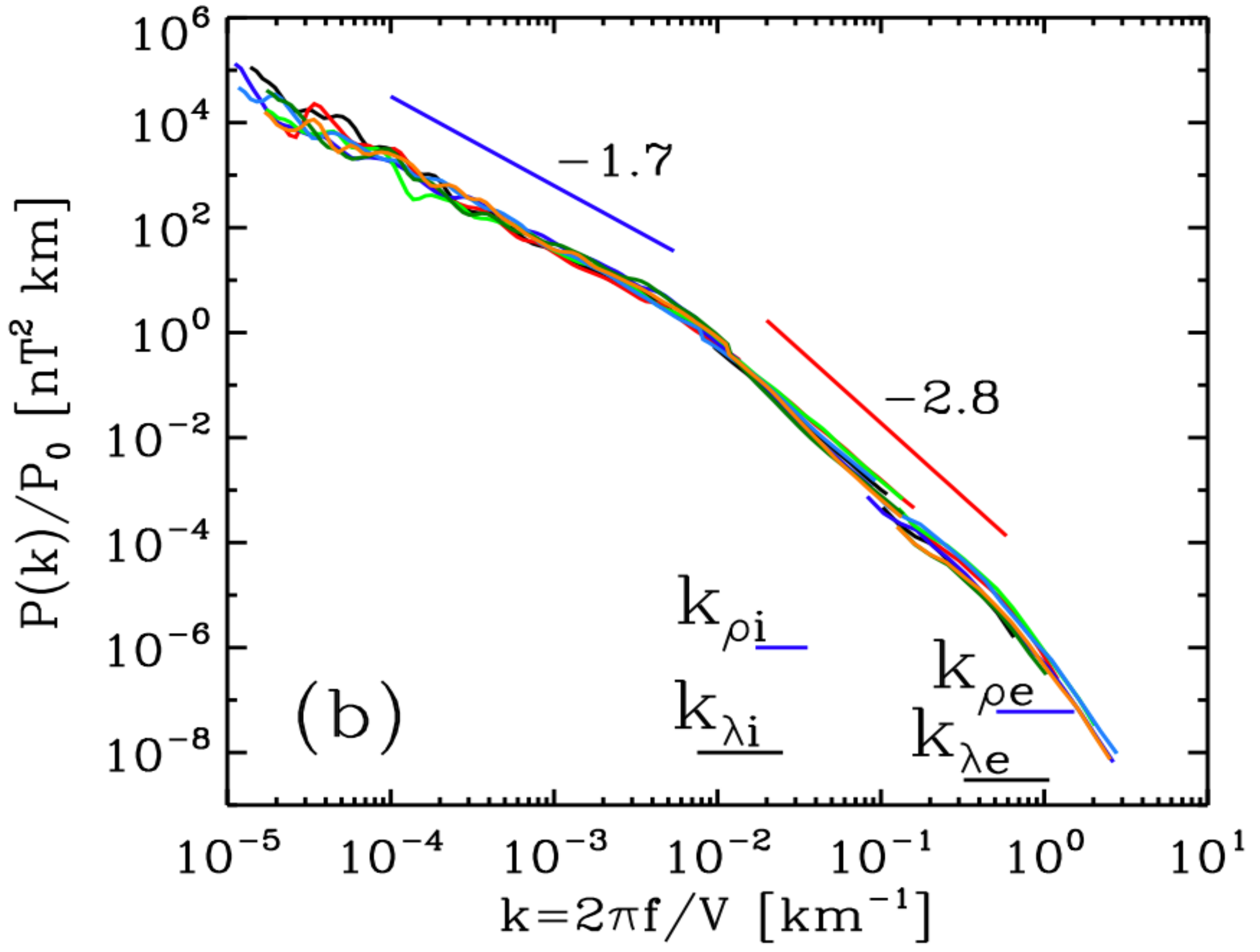
Plasma turbulence in the sub-ion-Larmor-radius range



Solar wind magnetic spectrum form
Cluster [Alexandrova+ 2019]

Main questions:

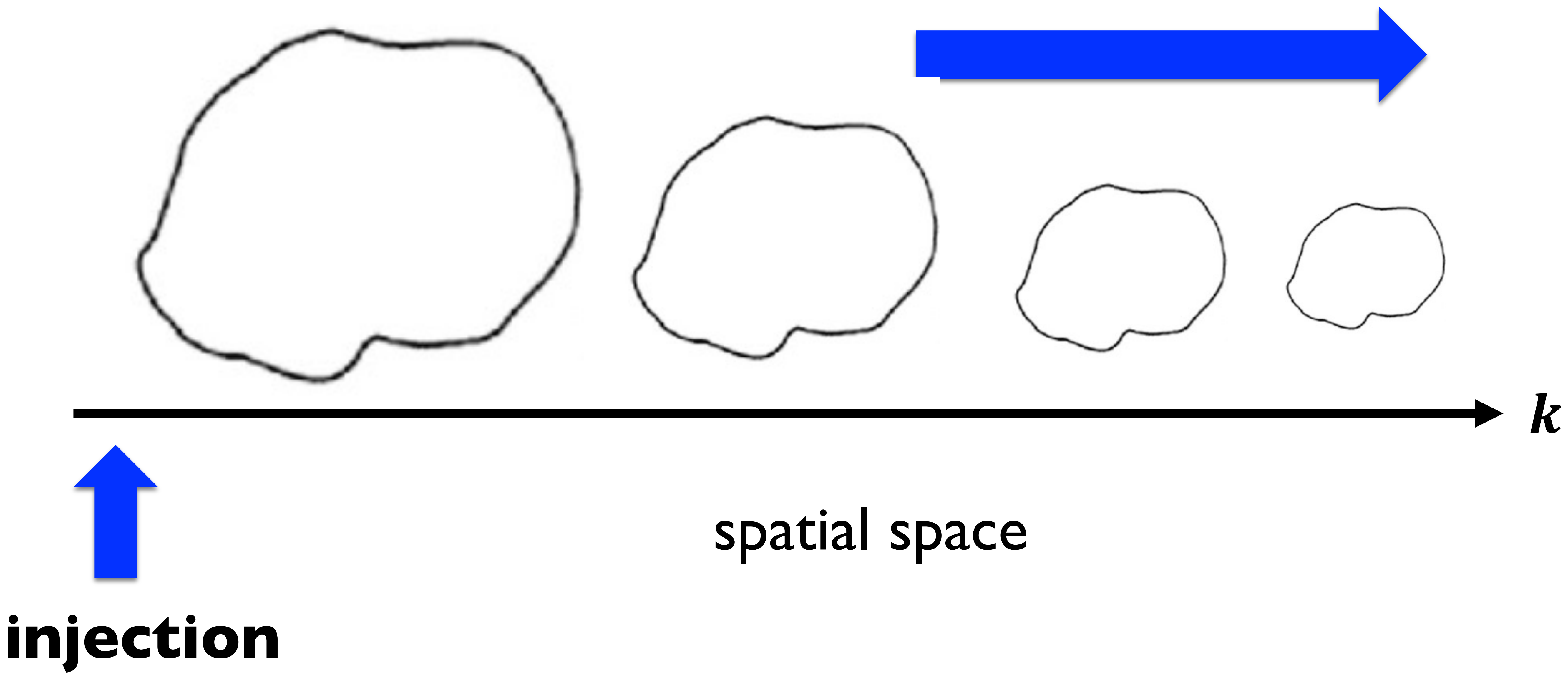
What are the spectra of fluctuations?

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?

Collisional plasma --- “fluid channel” of thermalisation

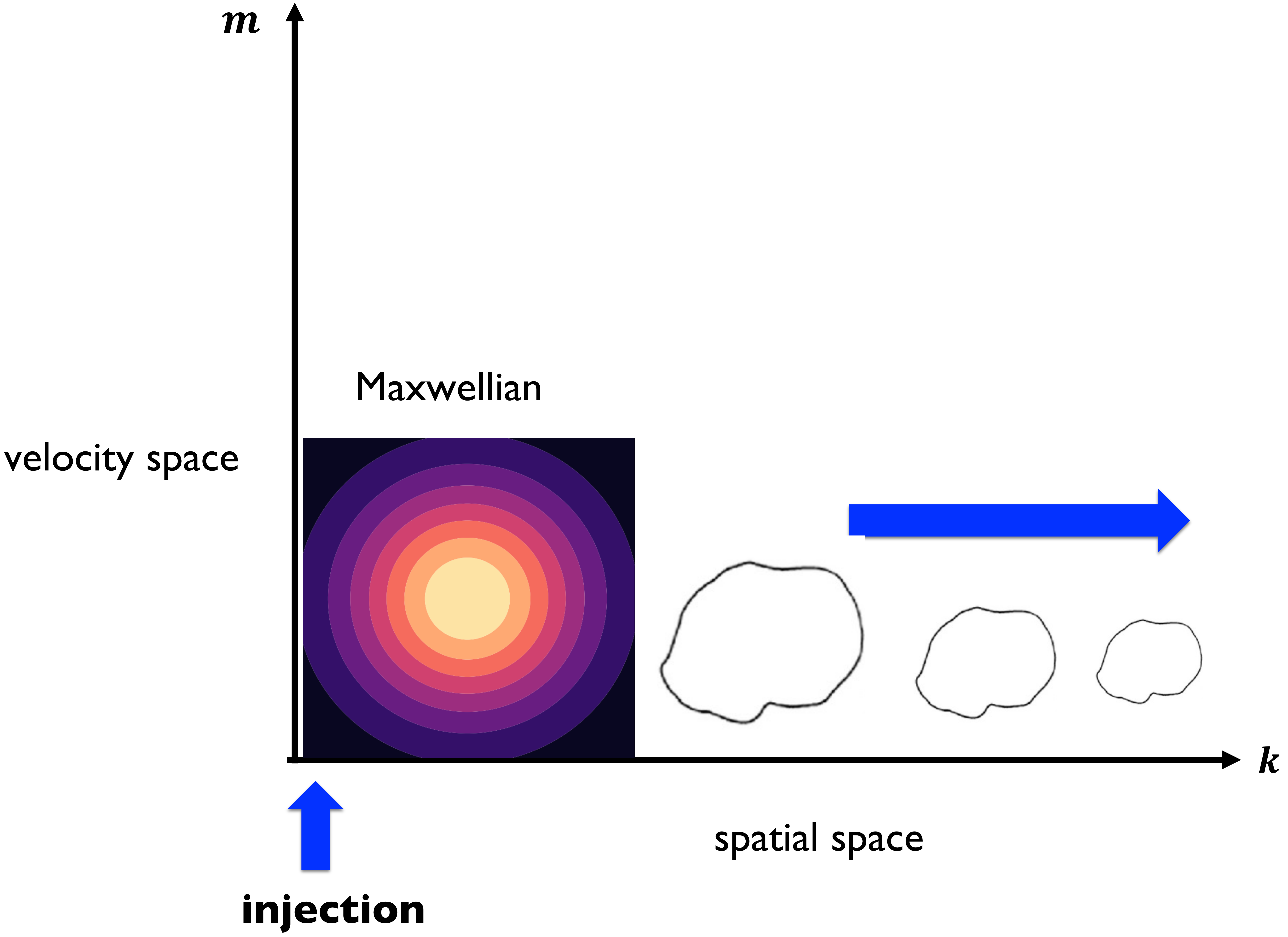


Nonlinear advection

“fluid-channel” of dissipation

at small spatial scales

How is energy thermalized in a collisionless plasma? Additional channels?

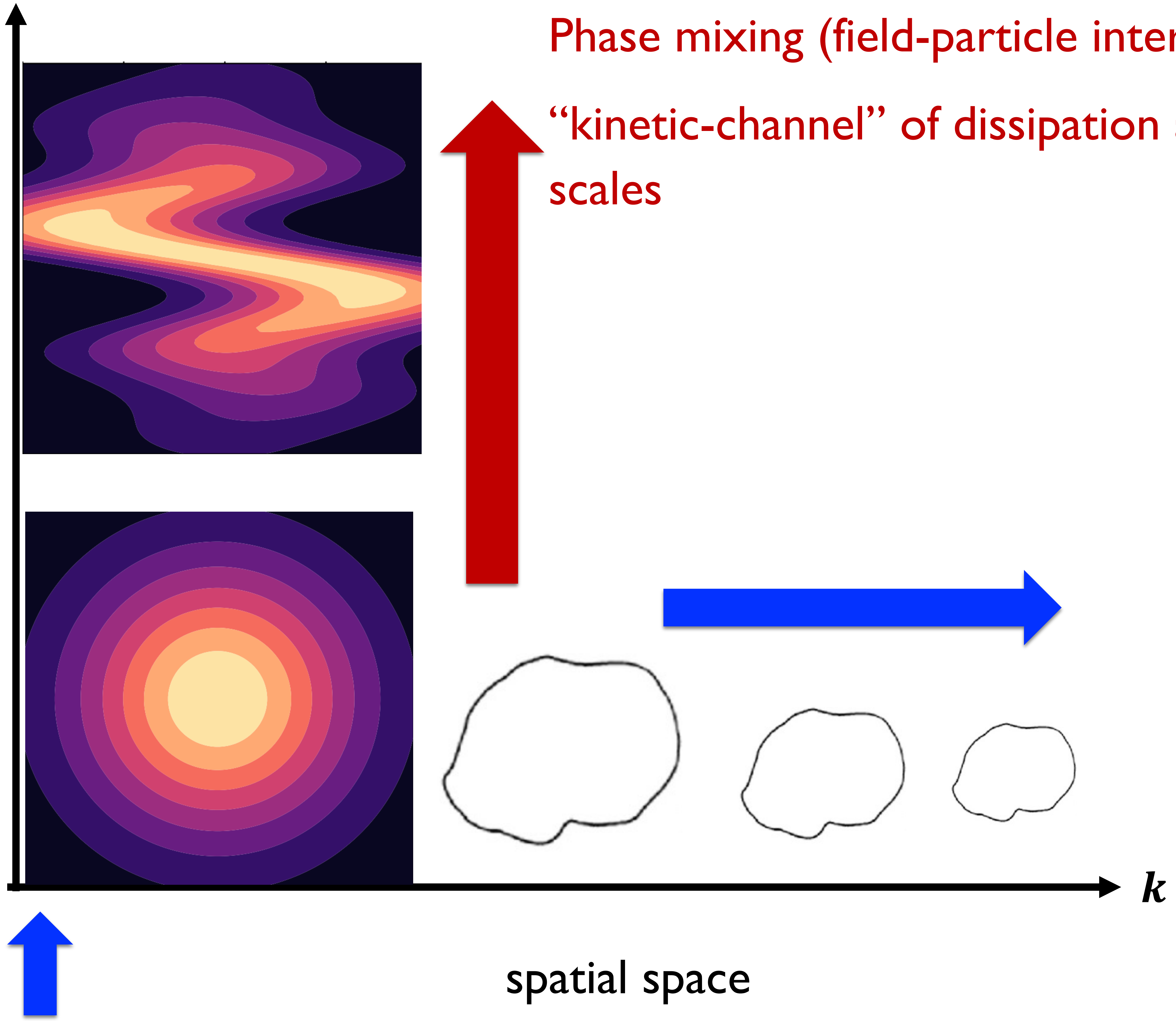


Nonlinear advection

“fluid-channel” of dissipation

at small spatial scales

The whole phase-space dynamics is crucial for particle heating



Phase mixing (field-particle interaction)

“kinetic-channel” of dissipation at small velocity-space scales

velocity space

Nonlinear advection

“fluid-channel” of dissipation

at small spatial scales

spatial space

injection

Kinetic Reduced Electron Heating Model (KREHM) framework

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

Ions become isothermal and electrostatic.

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

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

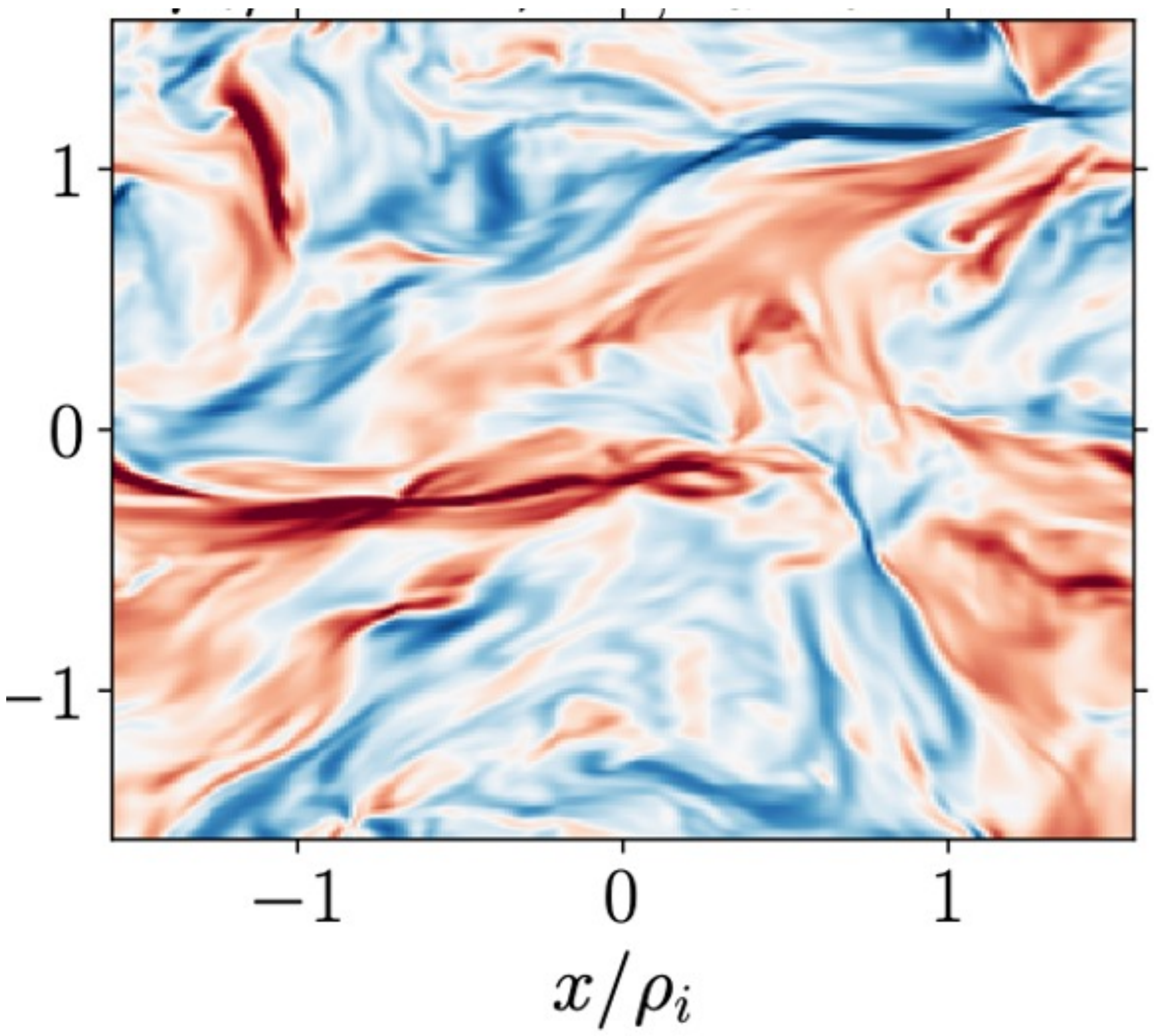
Ohm's law $$\frac{d}{dt}(A_\| - d_e^2\nabla_\perp^2 A_\|) = -c\frac{\partial\varphi}{\partial z} + \frac{cT_{e0}}{e}\hat{b}\cdot\nabla\left(\frac{\delta n_e}{n_{0e}} + \frac{\delta T_{\|e}}{T_{0e}}\right)$$

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

g_m: Hermite moments of g_e

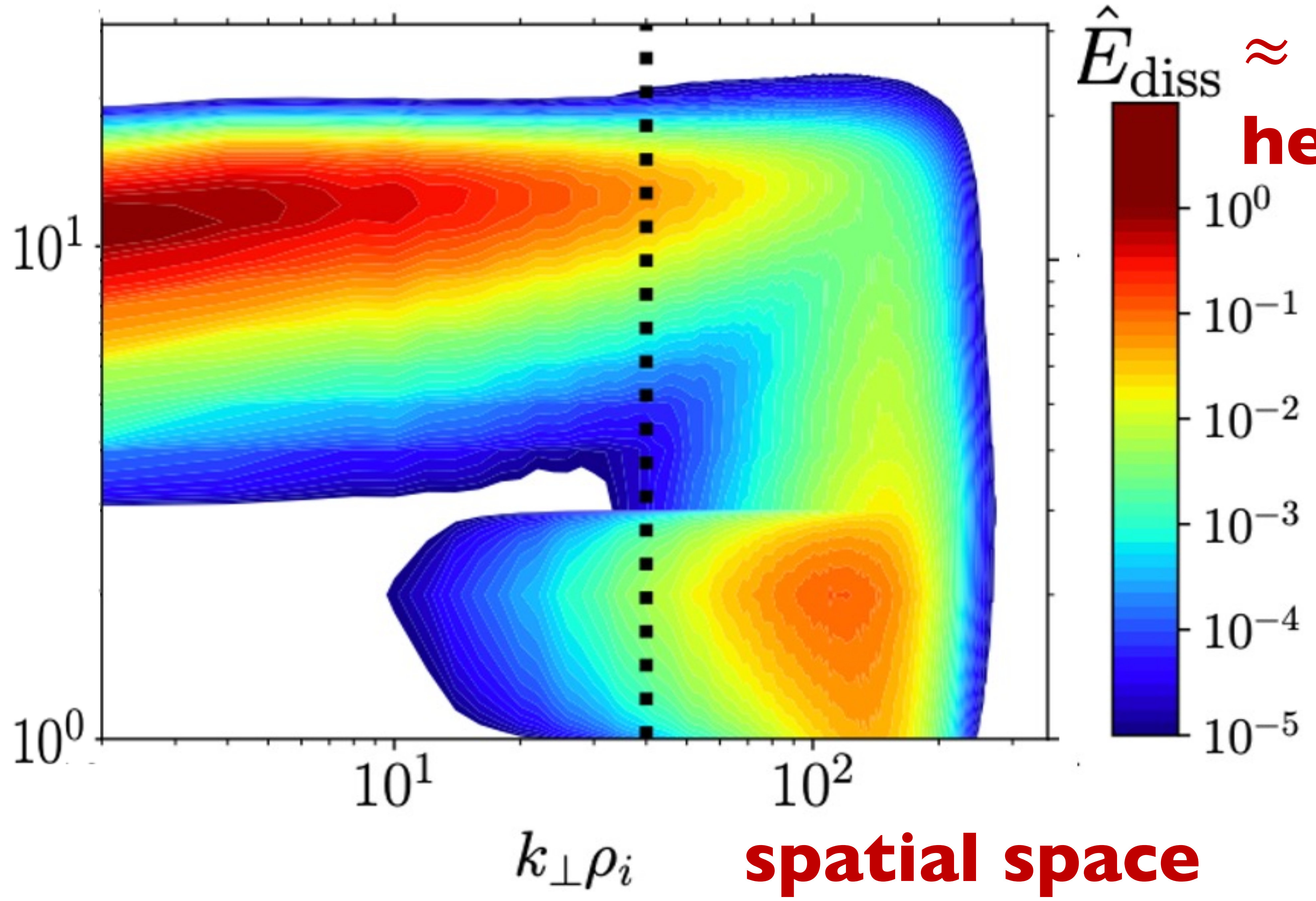
Simulations with kinetic electrons --- visualisation

below ρ_i



Simulations with kinetic electrons --- energy dissipation at high m

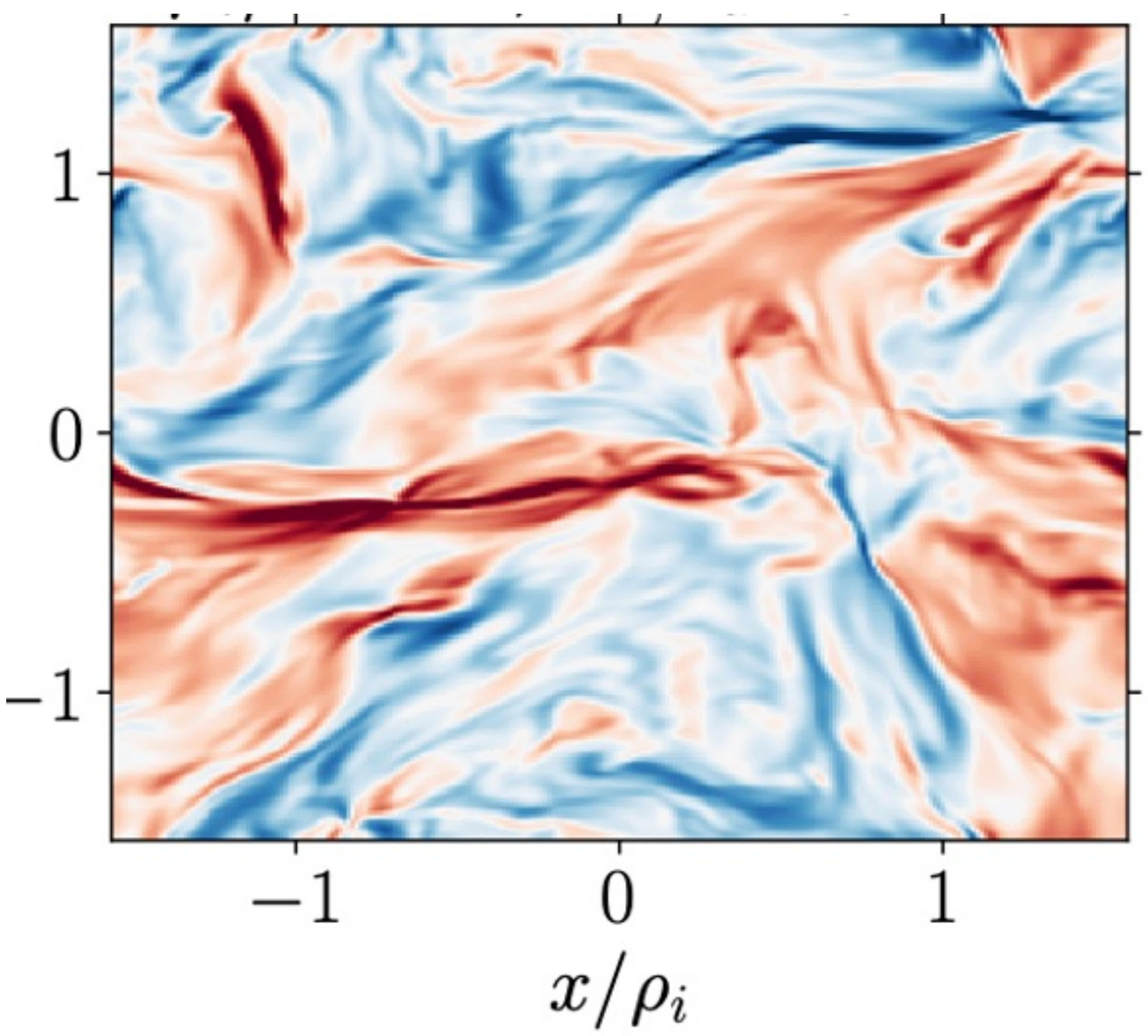
velocity space



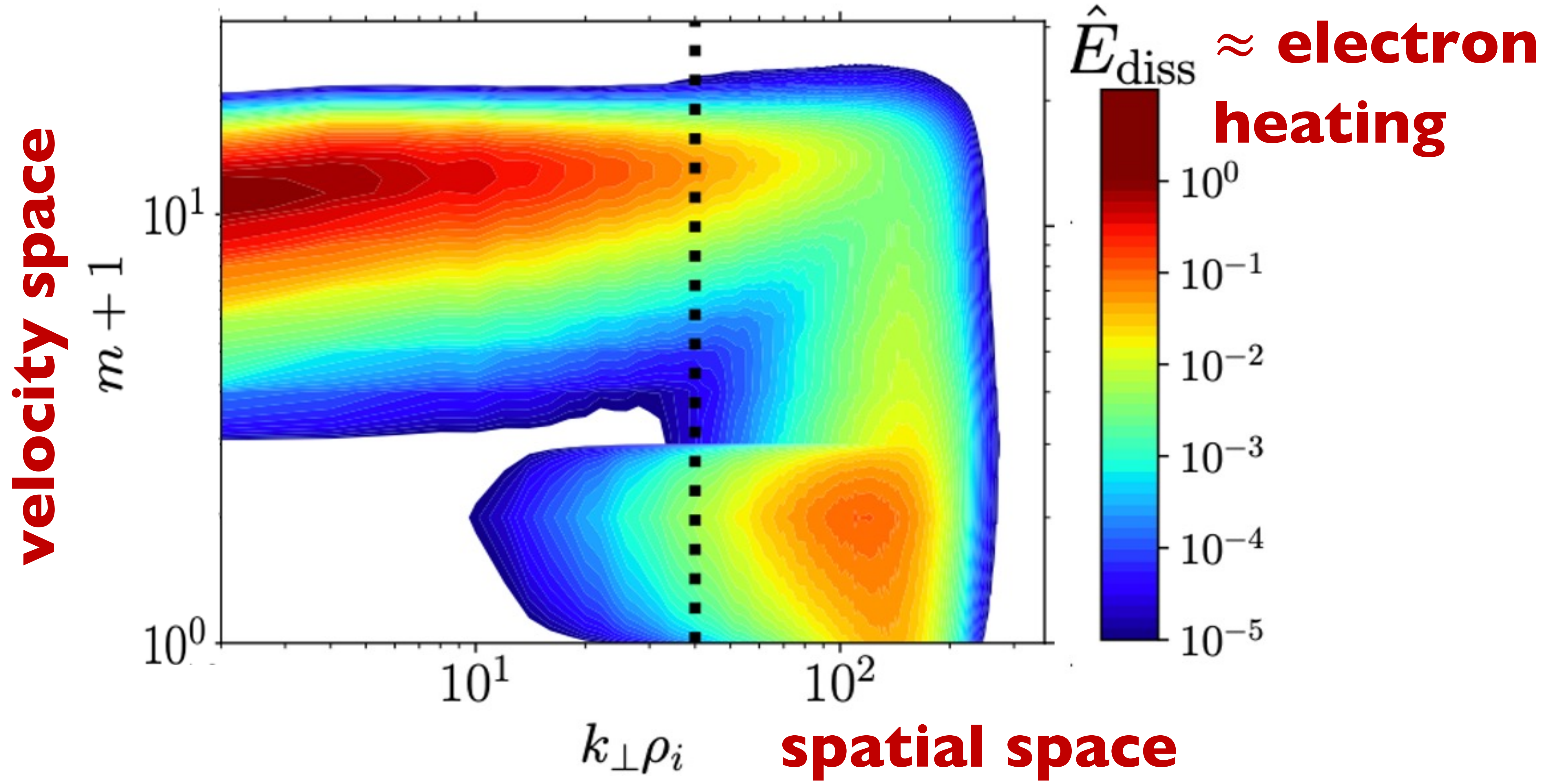
$\approx$ electron heating

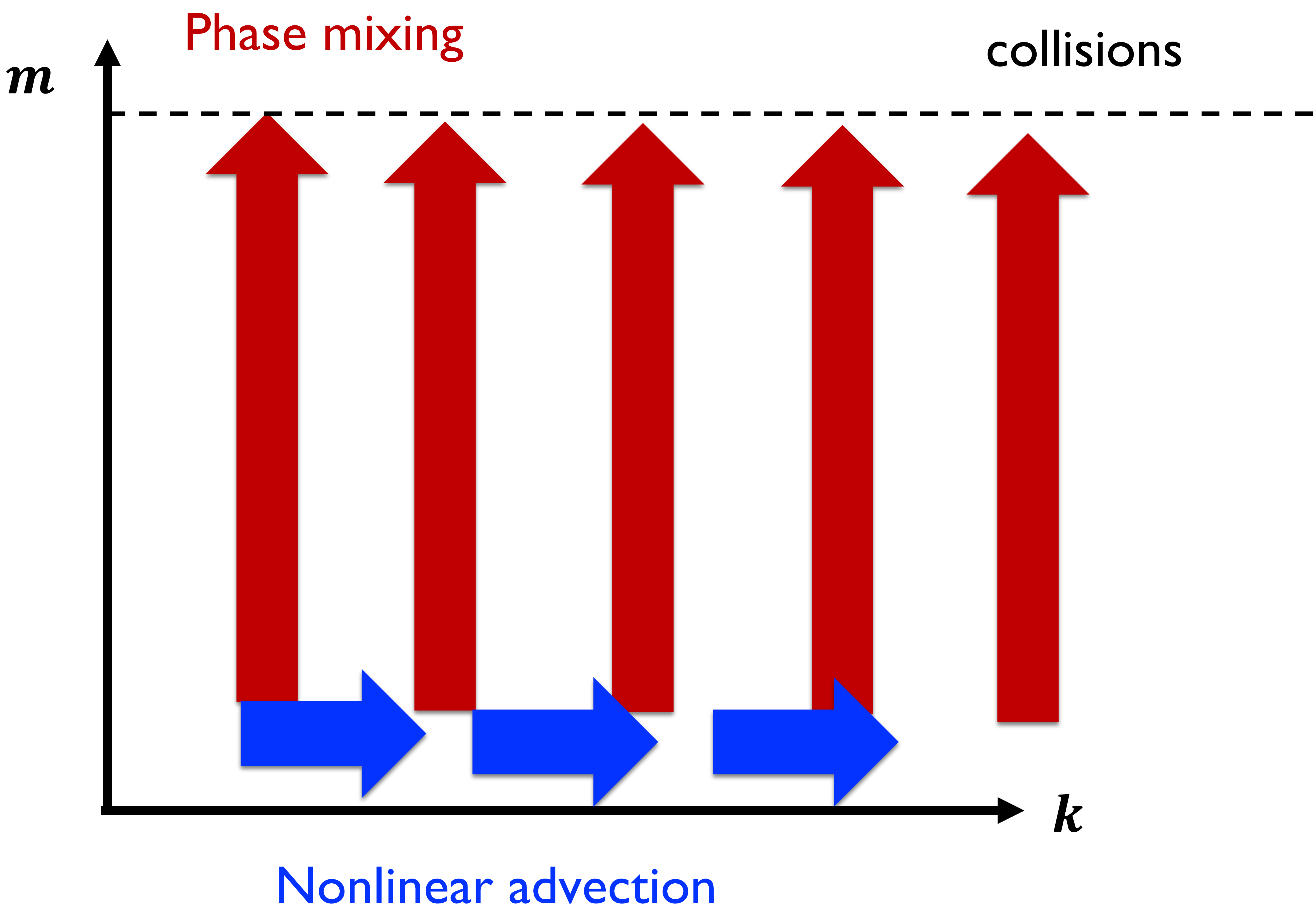
spatial space

below ρ_i

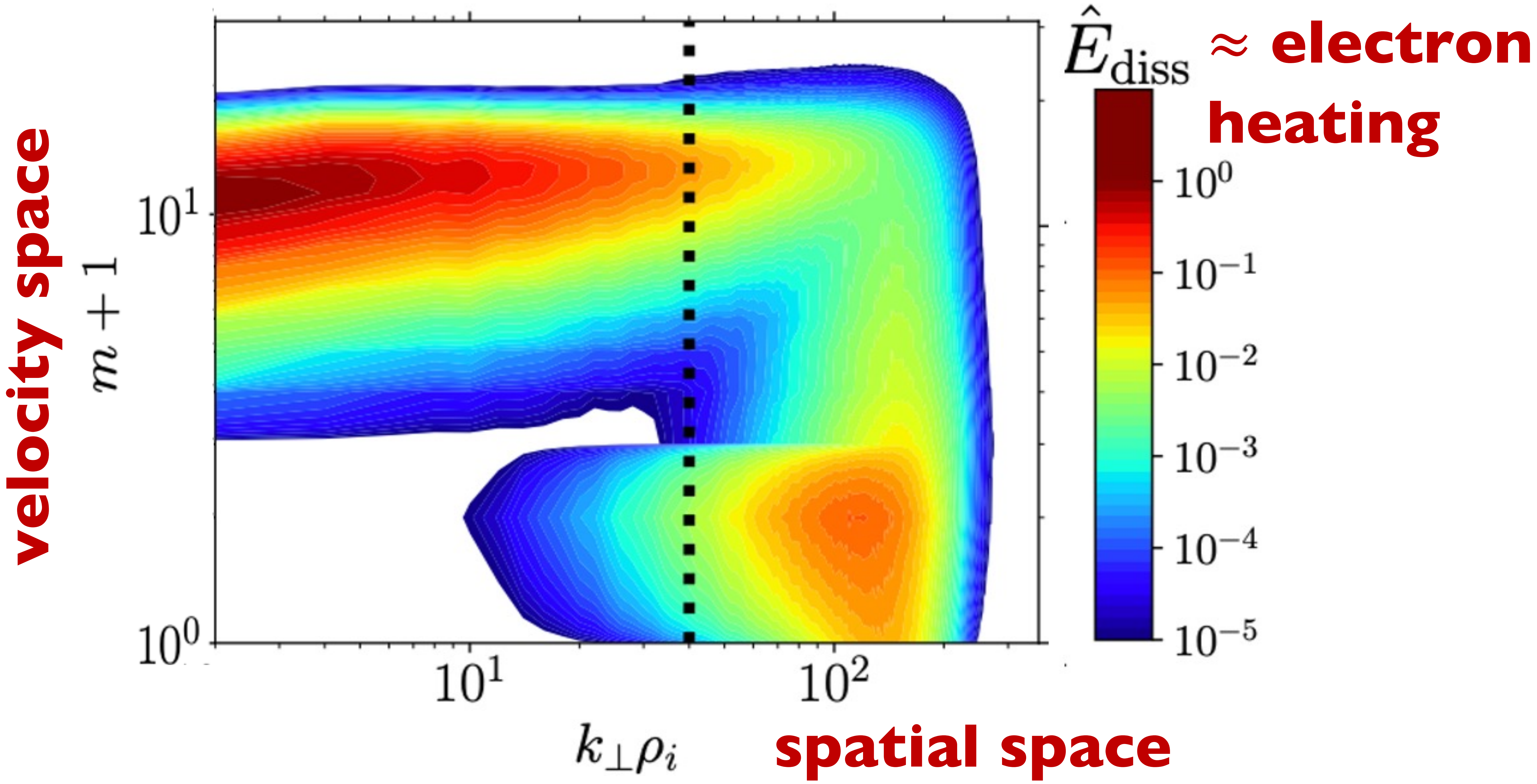


Phase mixing dominates nonlinear advection --- strong electron heating

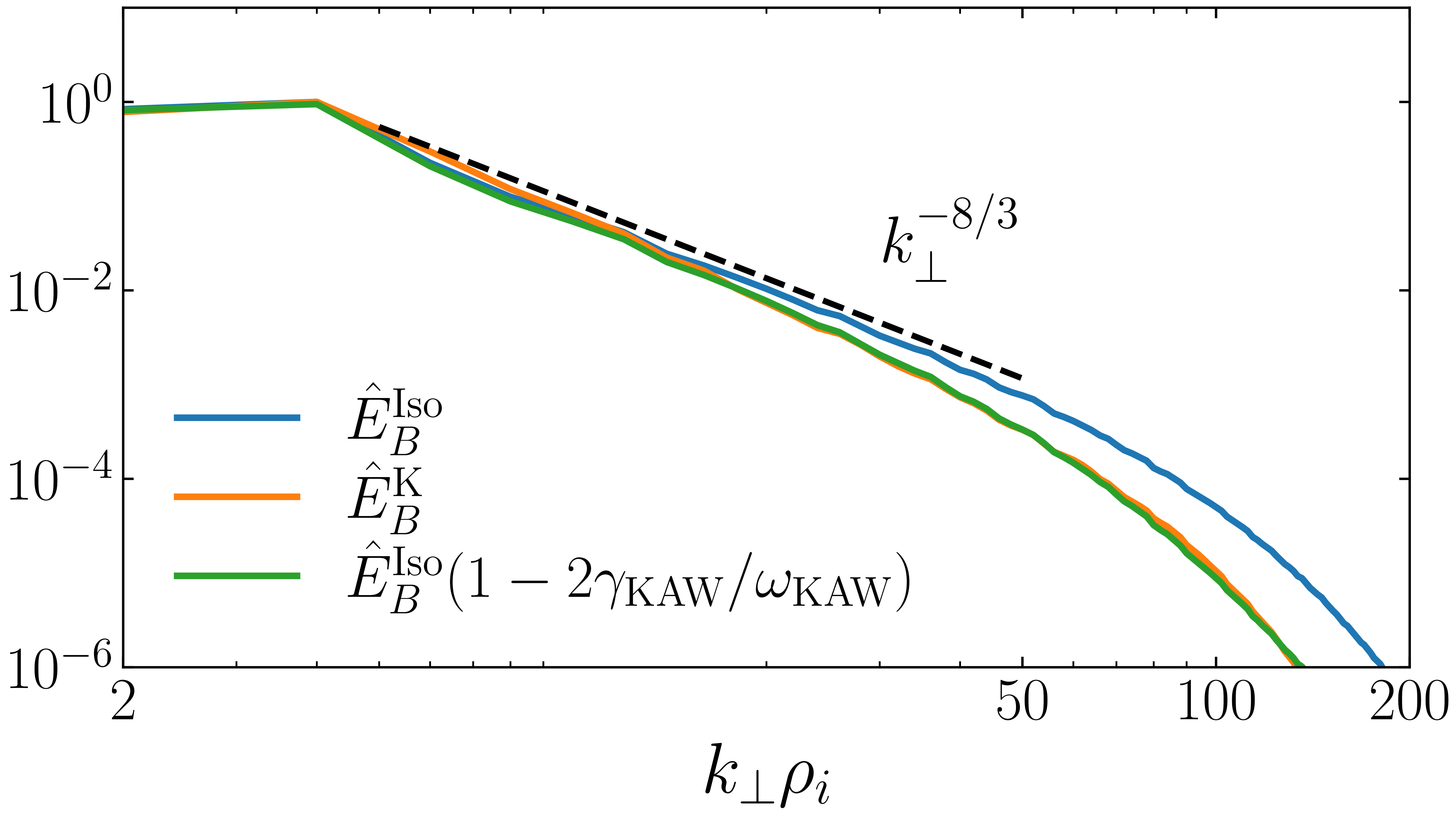




Landau damped EM energy matches electron heating



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



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

Conclusions

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

In this specific regime:

- 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.