Current Sheets and Landau Damping in Kinetic Plasma Turbulence

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Collaborators

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Department of Energy INCITE Program

Outline

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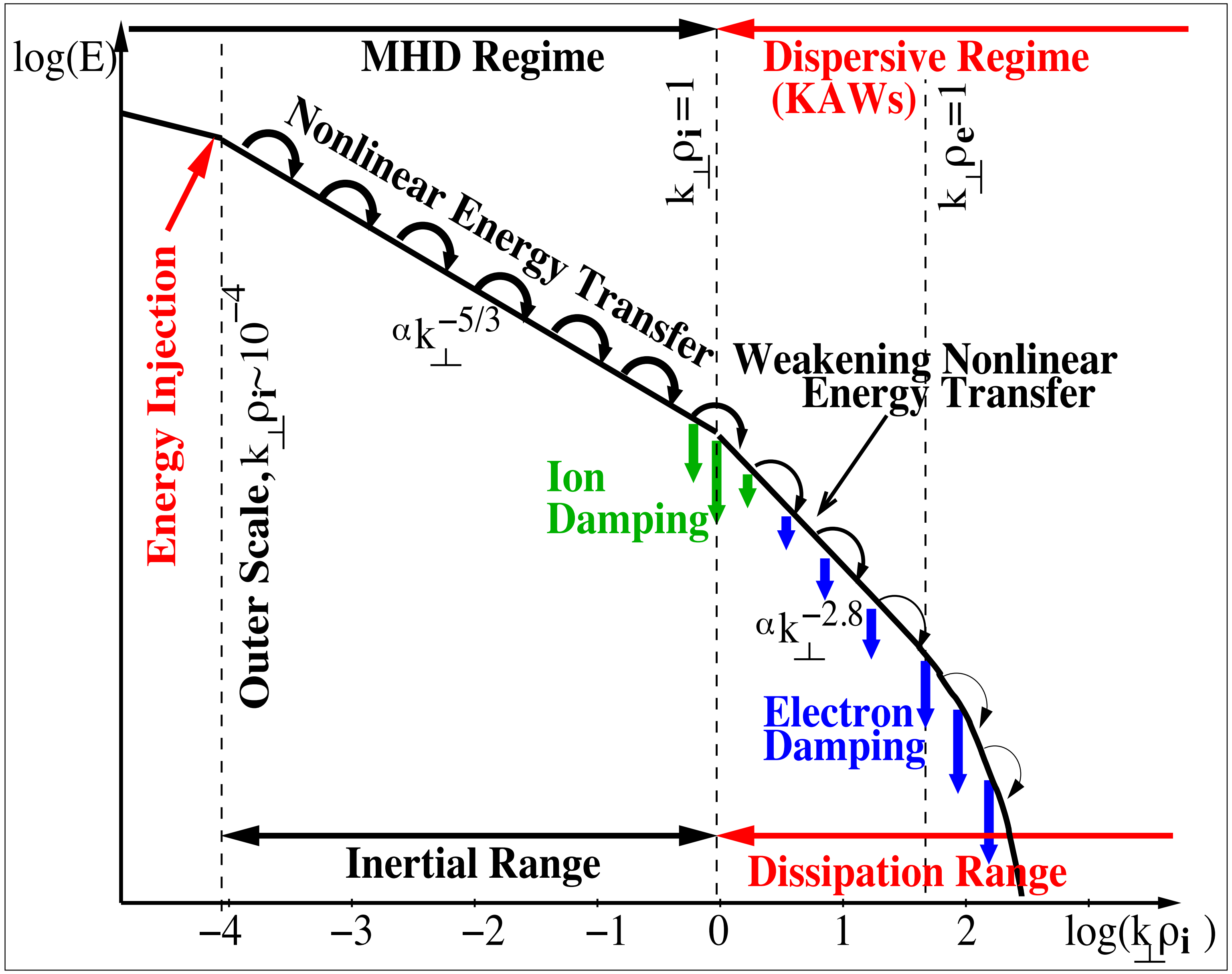
- Basic Picture of Plasma Turbulence
  - Key Questions about Plasma Turbulence
- Electron-scale Observations of Solar Wind Turbulence
- Proposed Dissipation Mechanisms for Kinetic Turbulence
- Simulations of Kinetic Alfven Wave Turbulence
  - Exponential Decay of Spectrum at Electron Scales
  - Collisionless Damping vs. Current Sheet Dissipation
- Reconciliation and Hypothesis
- Conclusions

Basic Picture of Plasma Turbulence



Key Properties:
1) Nonlinear Energy Transfer
2) Collisionless Damping and Dissipation
3) Coherent Structures

Key Questions about Plasma Turbulence

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Important Questions about the Properties of Plasma Turbulence

Q1) What is the nature of Nonlinear Energy Transfer?

a) In the MHD Regime $k_\perp \rho_i \ll 1$

b) In the Dispersive Regime $k_\perp \rho_i \gtrsim 1$

Q2) What physical mechanism governs the Dissipation of the Turbulence?

Q3) How do Coherent Structures arise from and/or affect both the nonlinear energy transfer and dissipation?

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Recent Observations: Dissipation Range Spectra

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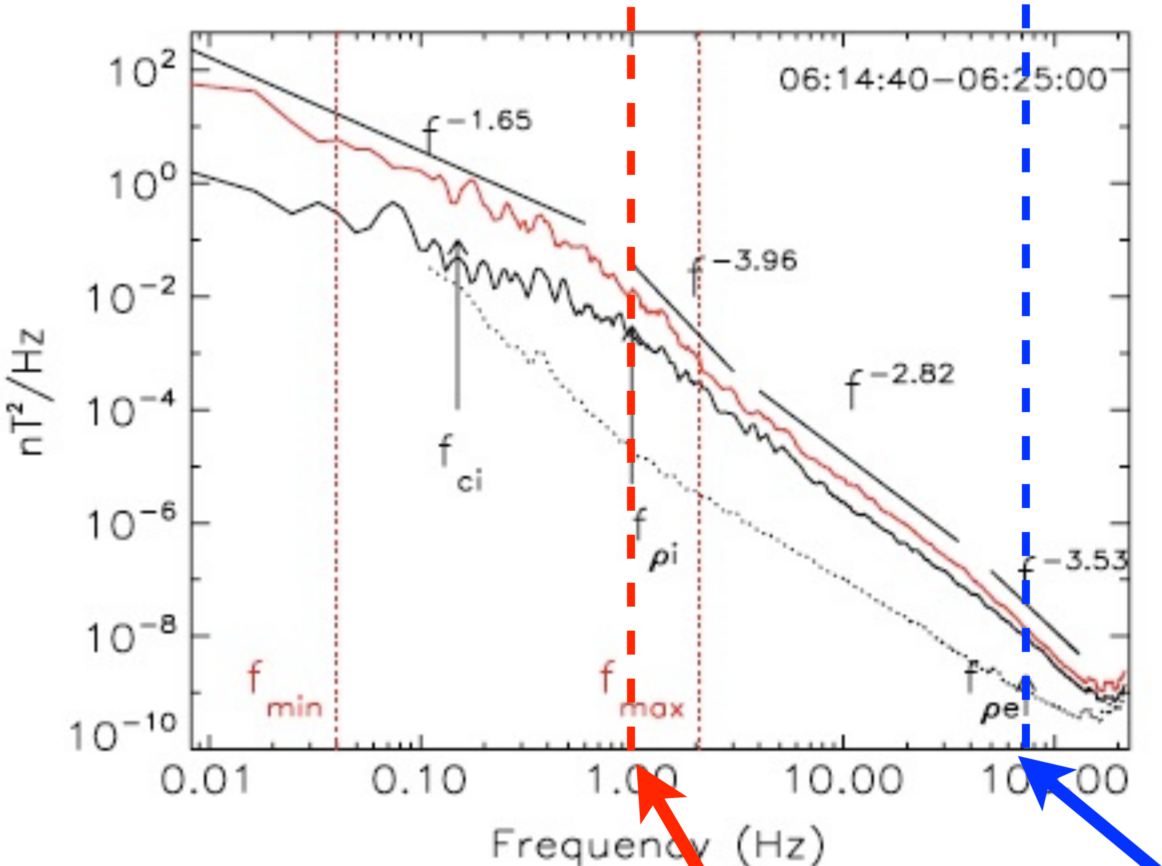
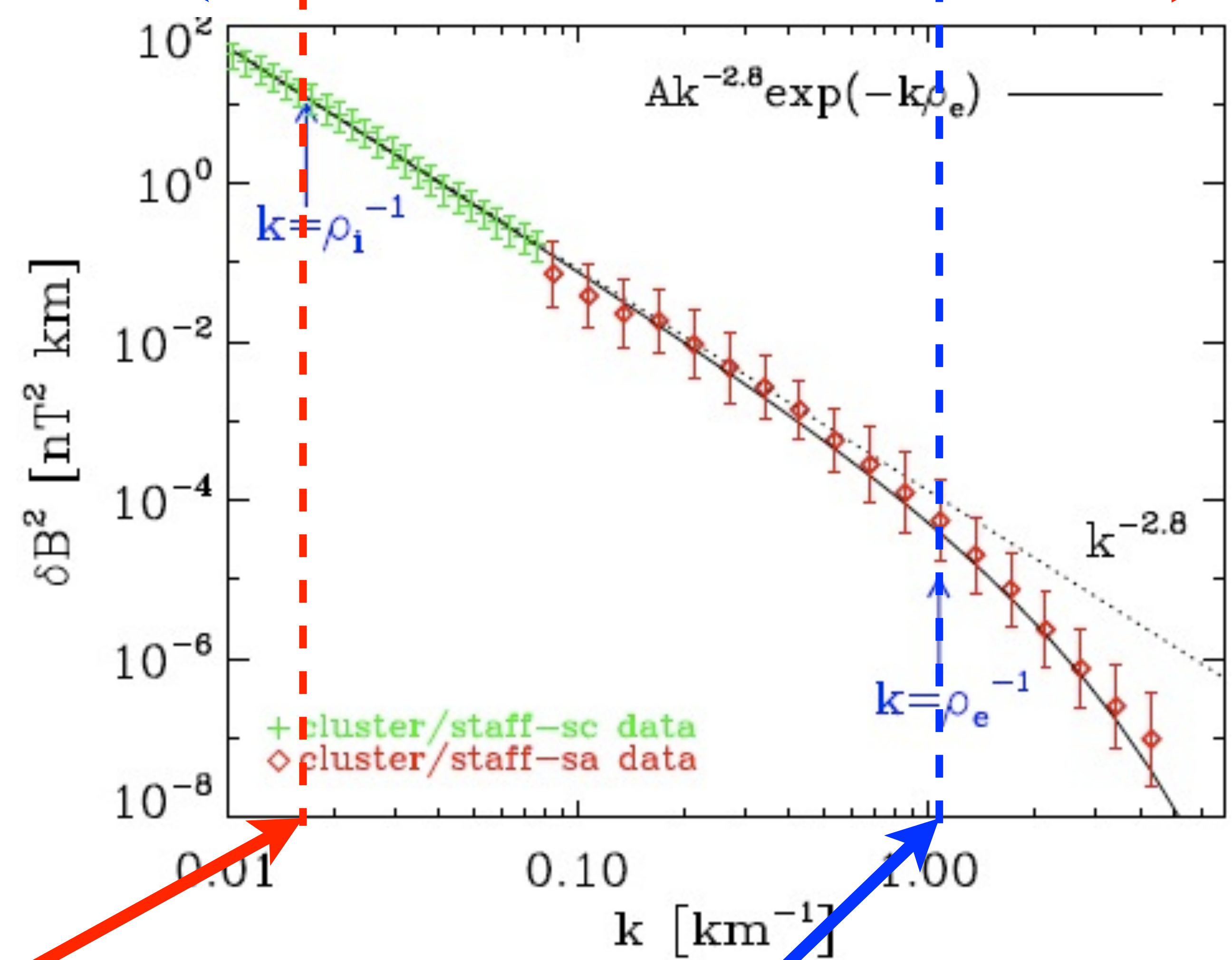
Inertial Range | Dissipation Range



(Sahraoui *et al*. 2010, PRL)

Dissipation Range



(Alexandrova *et al*. 2012)

Typical Spectral Index in Dissipation Range is ~ -2.8

Ion Scale

Electron Scale

What are the physical mechanisms of dissipation?

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Physical Dissipation Mechanisms for Kinetic Turbulence

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The mean free path of plasma particles in the solar wind is $\sim 1\ \mathrm{AU}$

- Therefore, the dissipation mechanisms are described by kinetic theory

Three mechanisms have been proposed:

(1) Collisionless Wave-Particle Interactions (Landau damping)

(Howes *et al*. 2008, Schekochihin *et al*. 2009, TenBarge & Howes 2012)

(2) Stochastic Heating

(Chandran *et al*. 2010, Chandran 2010)

(3) Dissipation in Current Sheets

(Dmitruk *et al*. 2004, Markovskii & Vasquez 2011, Matthaeus & Velli 2011, Osman *et al*. 2012, Servidio 2011)

Current Sheets in Plasma Turbulence

For dissipation associated with current sheets, a natural question arises:

How do current sheets form in plasma turbulence?

From yesterday, it appears that current sheets arise naturally from the nonlinear interaction between counterpropagating Alfven waves

Alfven Wave Collisions!

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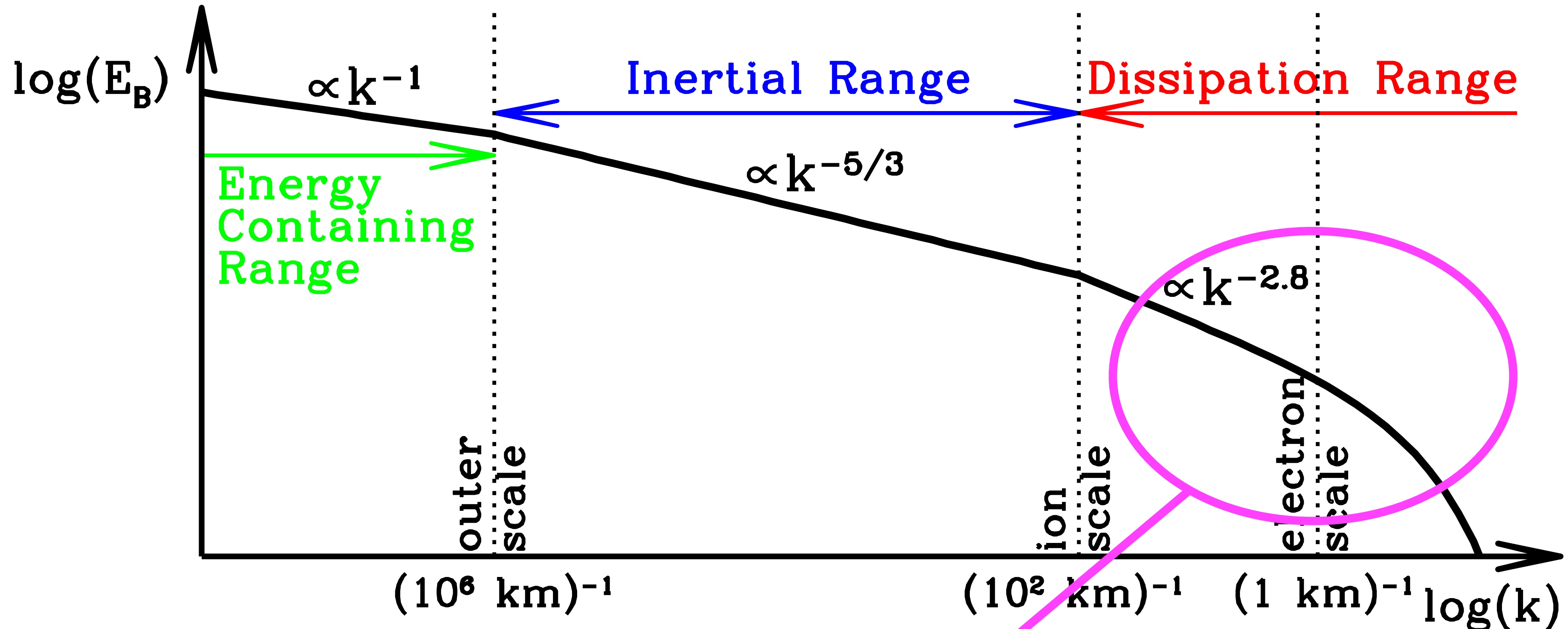
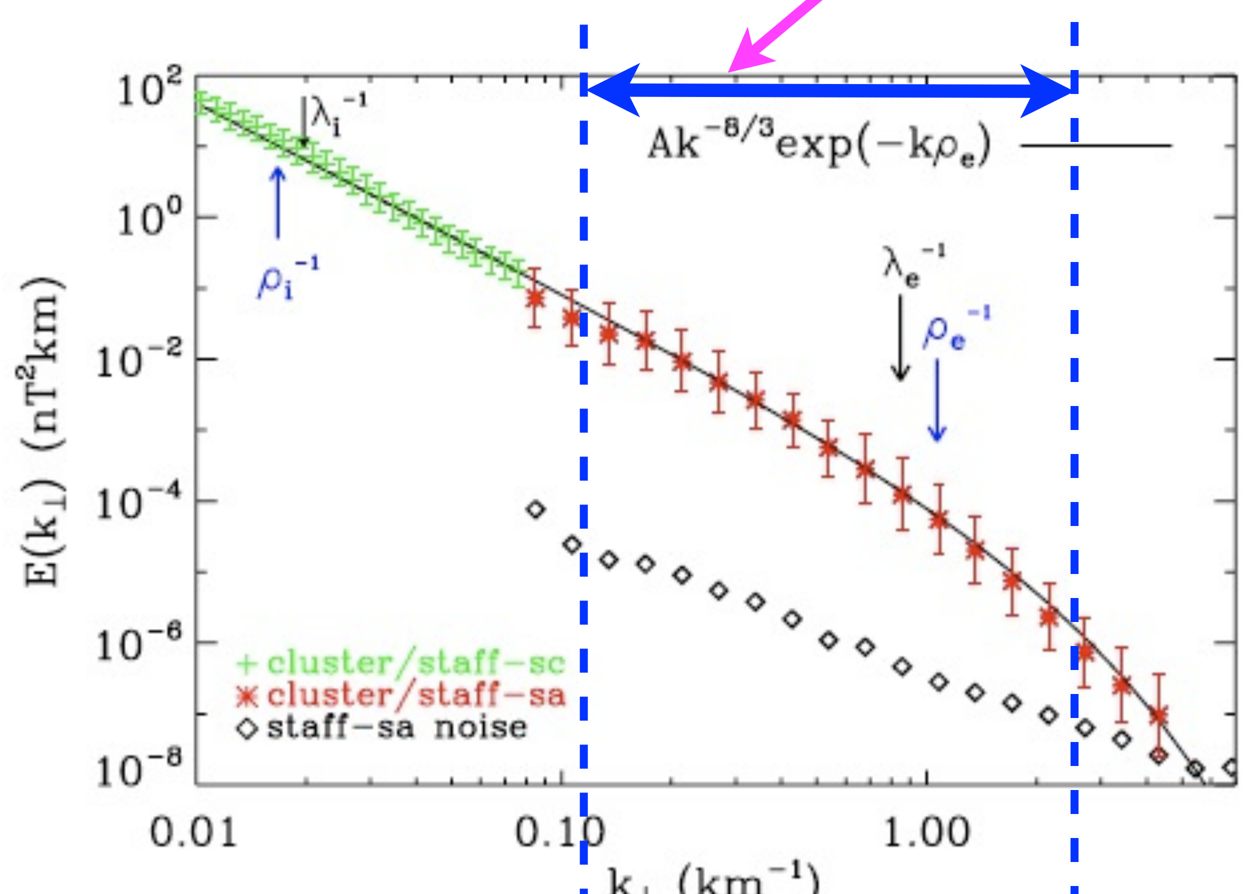
Simulation Parameters





(Alexandrova, LaComnbe, Mangeney, Grappin, & Maksimovic, 2012)

Fully Resolved Range of Simulation

$$5 \leq k_\perp \rho_i \leq 105$$

$$0.12 \leq k_\perp \rho_e \leq 2.5$$

Parameters

$$\beta_i = 1$$

$$T_i/T_e = 1$$

$$m_i/m_e = 1836$$

Magnetic Energy Spectrum of Simulation

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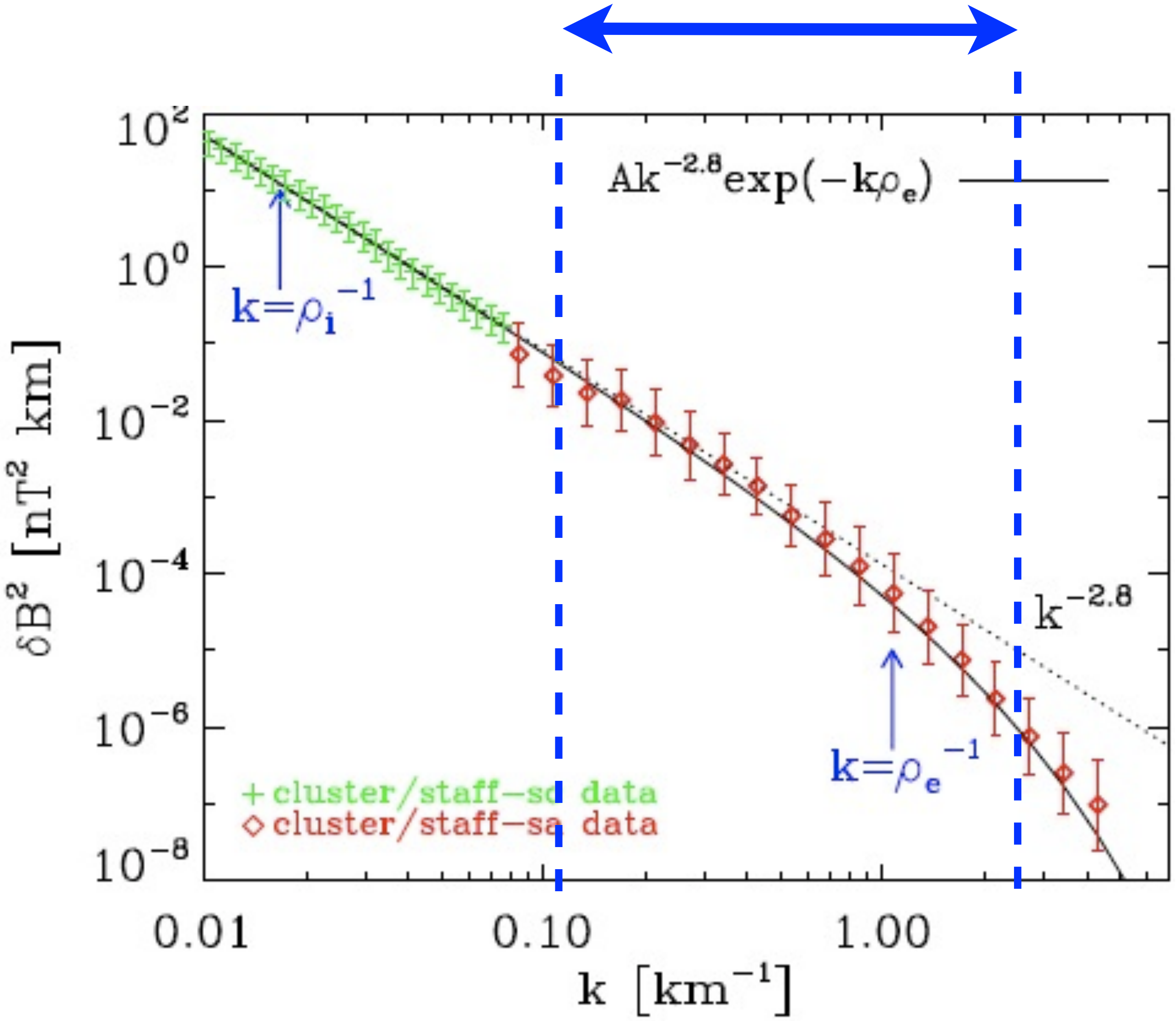
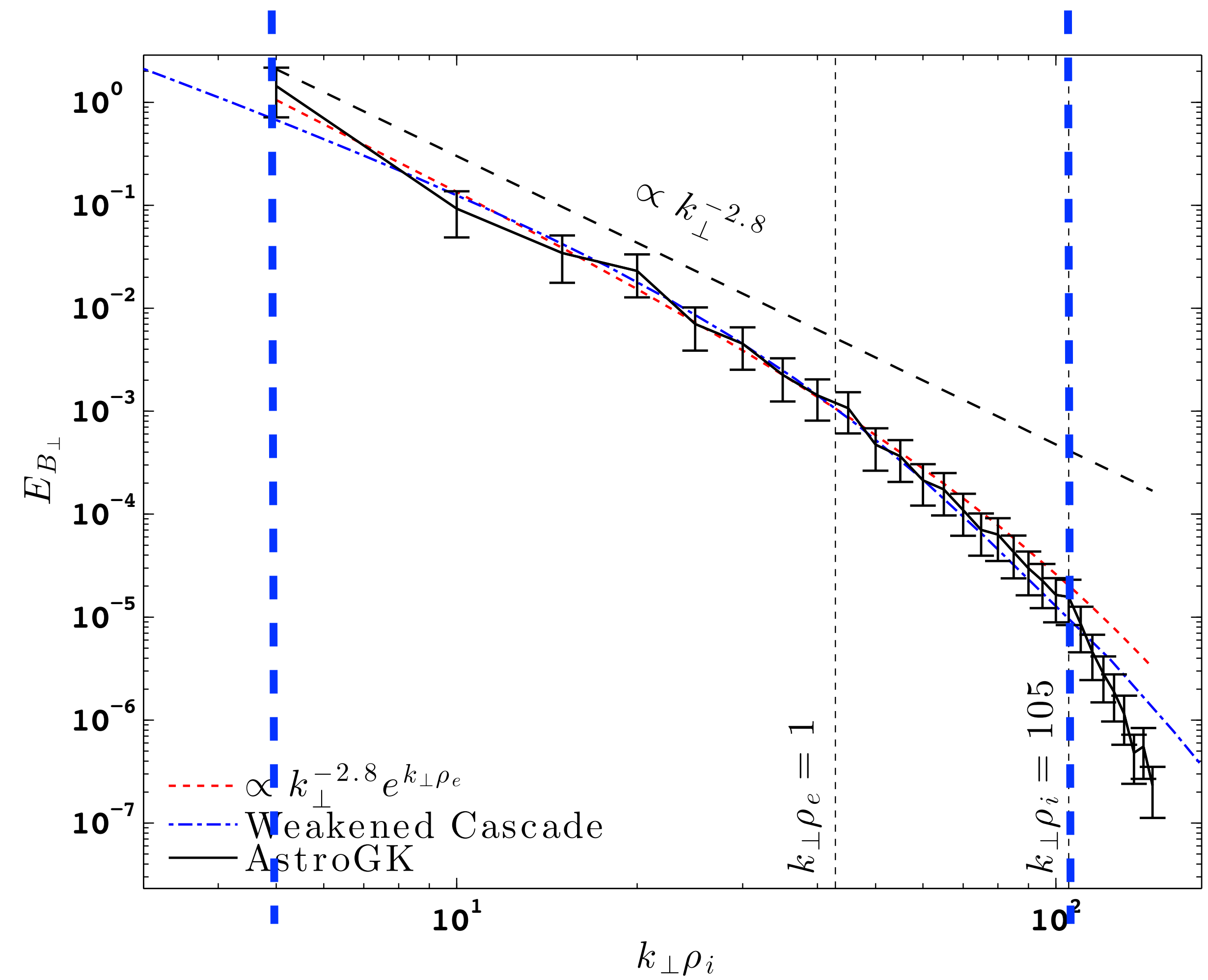
Fully Resolved Range of Simulation



(Alexandrova et al. 2012)

Gyrokinetic simulations of KAW turbulence lead to a spectrum in agreement with solar wind data



(TenBarge & Howes, 2013 ApJL)

This suggests our simulation is not missing essential physics

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Development of Current Sheets Down to Electron Scales

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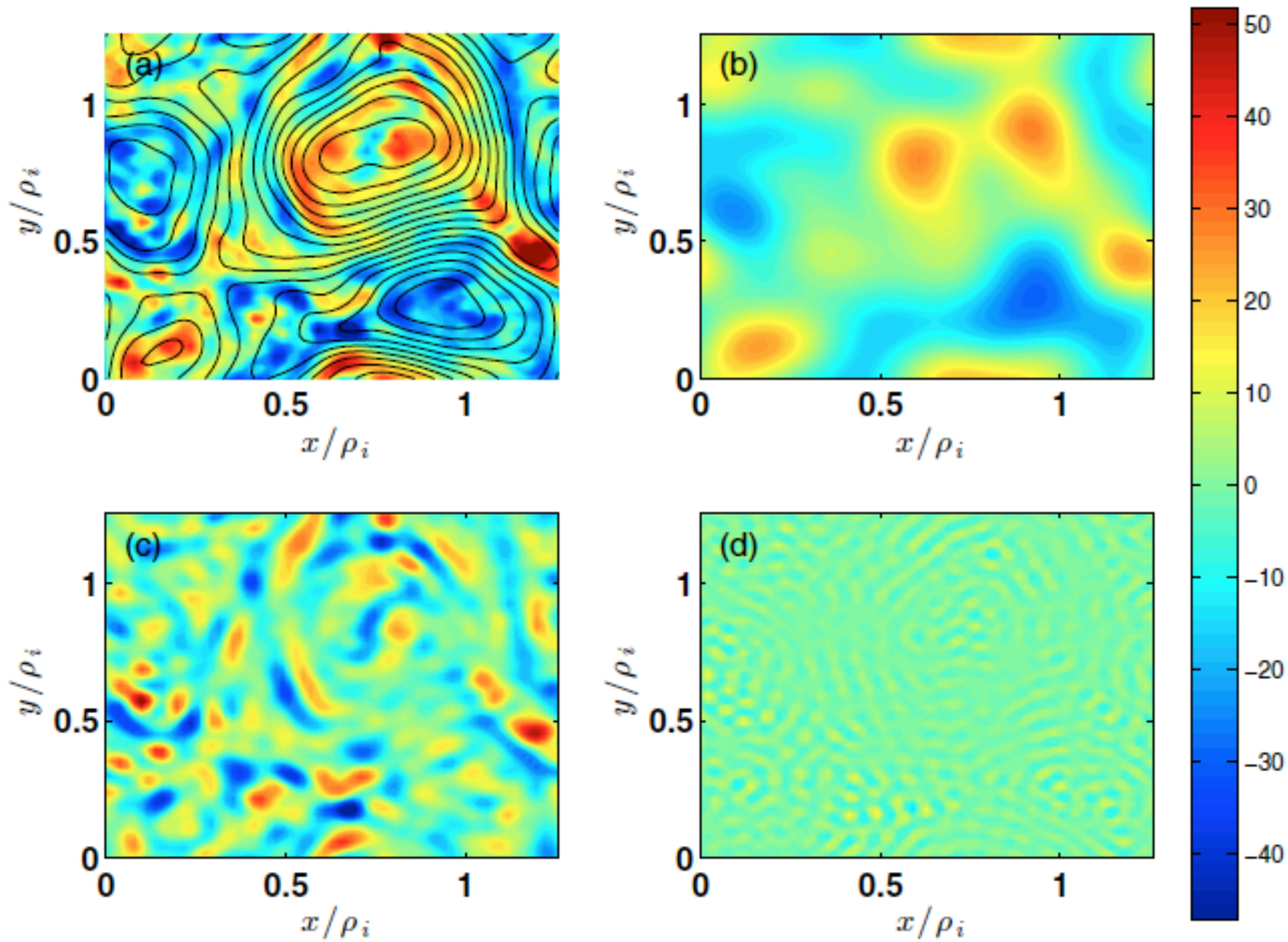
Parallel Current

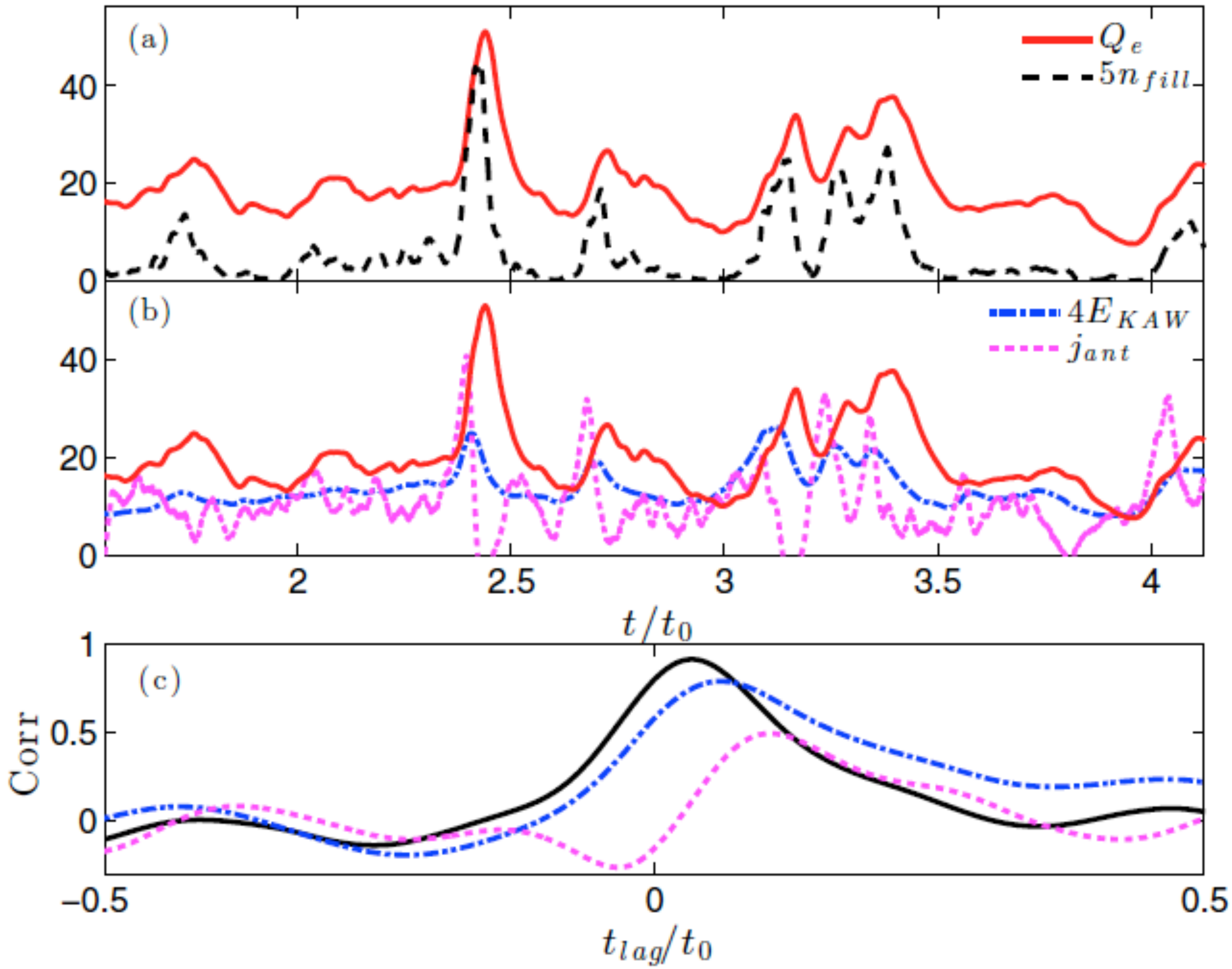
$0.12 \leq k_\perp \rho_e \leq 2.5$ $0.12 \leq k_\perp \rho_e \leq 0.5$



$0.5 \leq k_\perp \rho_e \leq 2.0$ $k_\perp \rho_e > 2.0$

Electron Heating Correlates with Current Sheets in Time

Heating Rate and Volume Fraction of Current



This seems to suggest that dissipation in current sheets is the dominant dissipation mechanism.

Electron Heating as a Function of Wavenumber

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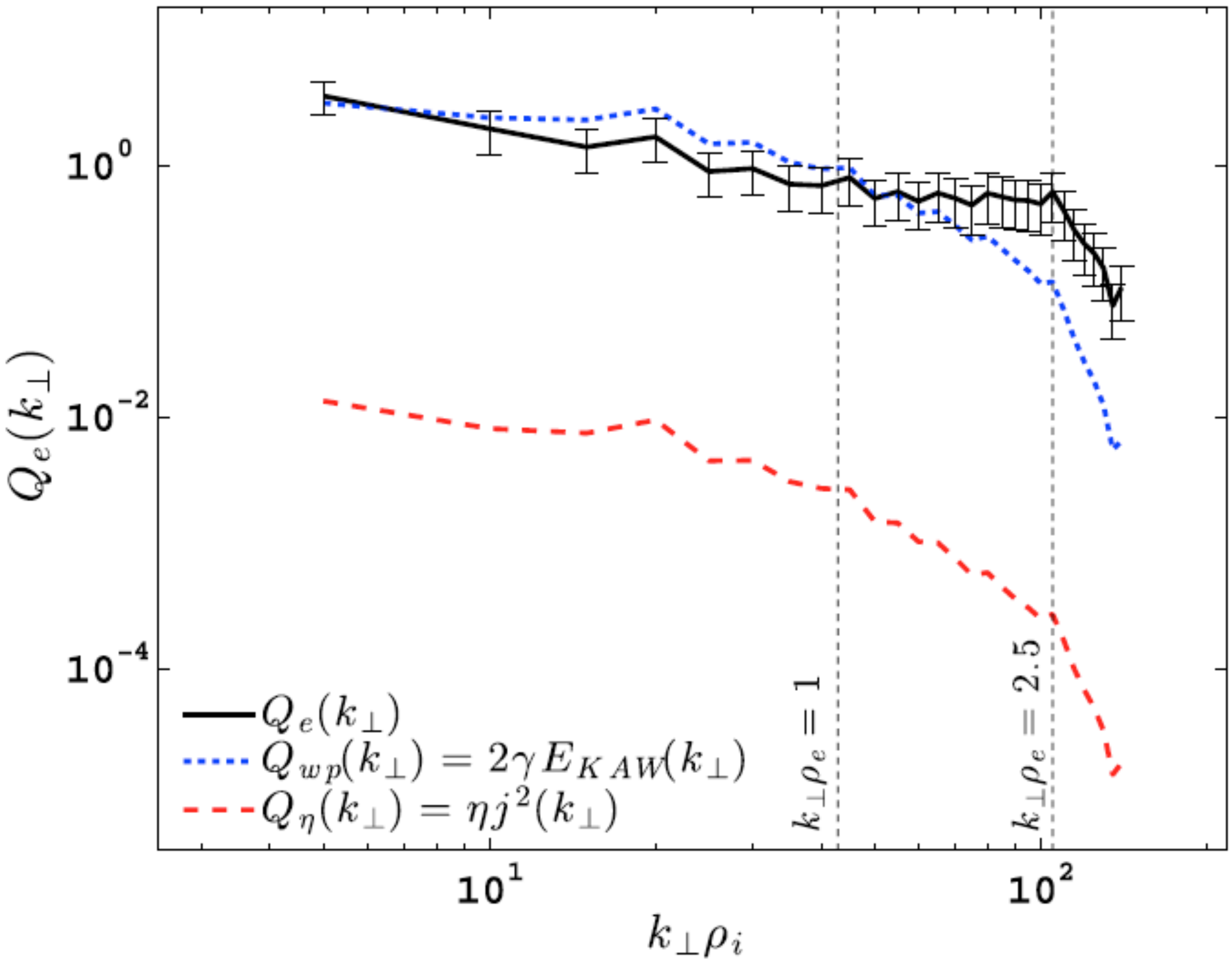
Landau Damping vs. Ohmic Heating



Landau Damping can account for all measured electron heating!

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Reconciliation

How does one reconcile the fact that Landau damping can entirely explain the measured electron heating with the clear correlation between current sheet formation and electron heating?

- Current density $j \propto kB$, so regions of strong current are also regions of enhanced small scale structure

- Landau damping rate increases with wavenumber

- Regions of strong current are also regions of more energy at small scales, and therefore are expected to also be regions of enhanced Landau damping

Hypothesis

- Current sheets form self-consistently through nonlinear interactions between kinetic Alfven waves

- Each of the Fourier wave modes that comprise this "coherent structure" damps at its linear Landau damping rate

- Therefore, we propose the hypothesis:
  - Current sheet formation and dissipation is dominated by evolution of Alfvenic turbulence
  - Current sheets correspond to regions of enhanced Landau damping, and consequently also enhanced heating

Criticisms of Hypothesis

- Current sheets are not moving, and so therefore do not damp via wave-particle interactions associated with the Landau resonance.
  - In fact, standing waves comprised of two counterpropagating Alfven waves do indeed damp at the Landau rate

- Current sheets are large-scale, long-lived structures in plasma turbulence simulations, not wave-like structures
  - Alfven wave collisions generate just such structures, having current sheets lengths (perpendicular to B_0) at the scale of the parent Alfven waves.
  - But, these current sheets merely consist of the sum of a number of Alfven waves with particular phase and amplitude relationships, as determined by the nonlinear interaction

Conclusions

- Gyrokinetic simulations reproduce the observed energy spectrum
  - Dissipation range is a turbulent cascade of kinetic Alfven waves
- Current sheets form self-consistently at the electron scale in simulations driven at large scale by waves
  - Consistent with the hypothesis that a sum of nonlinearly generated Alfven waves leads to intermittent current sheets

- Electron heating is well-correlated with presence of strong current sheets
- But, Landau damping can entirely account for measured heating

- Hypothesis:
  - Current sheet formation and dissipation is dominated by evolution of Alfvenic turbulence
  - Current sheets correspond to regions of enhanced Landau damping, and consequently also enhanced heating

THE END