Gyrokinetic Simulations of Solar Wind Turbulence and its Dissipation: Importance of Nonlocal Effects on the Energy Cascade

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Gyrokinetics in Laboratory and Astrophysical Plasmas Programme
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The Center for Multi-scale Plasma Dynamics

Outline

- Turbulent Spectra in the Dissipation Range of the Solar Wind
  - Questions about the Dissipation Range
- Theoretical Models of Kinetic Plasma Turbulence
- Gyrokinetic Simulations of Kinetic Turbulence
- Improved Cascade Model and Implications
- Answers to Questions about the Dissipation Range
- Conclusions

Solar Wind Magnetic Energy Spectrum

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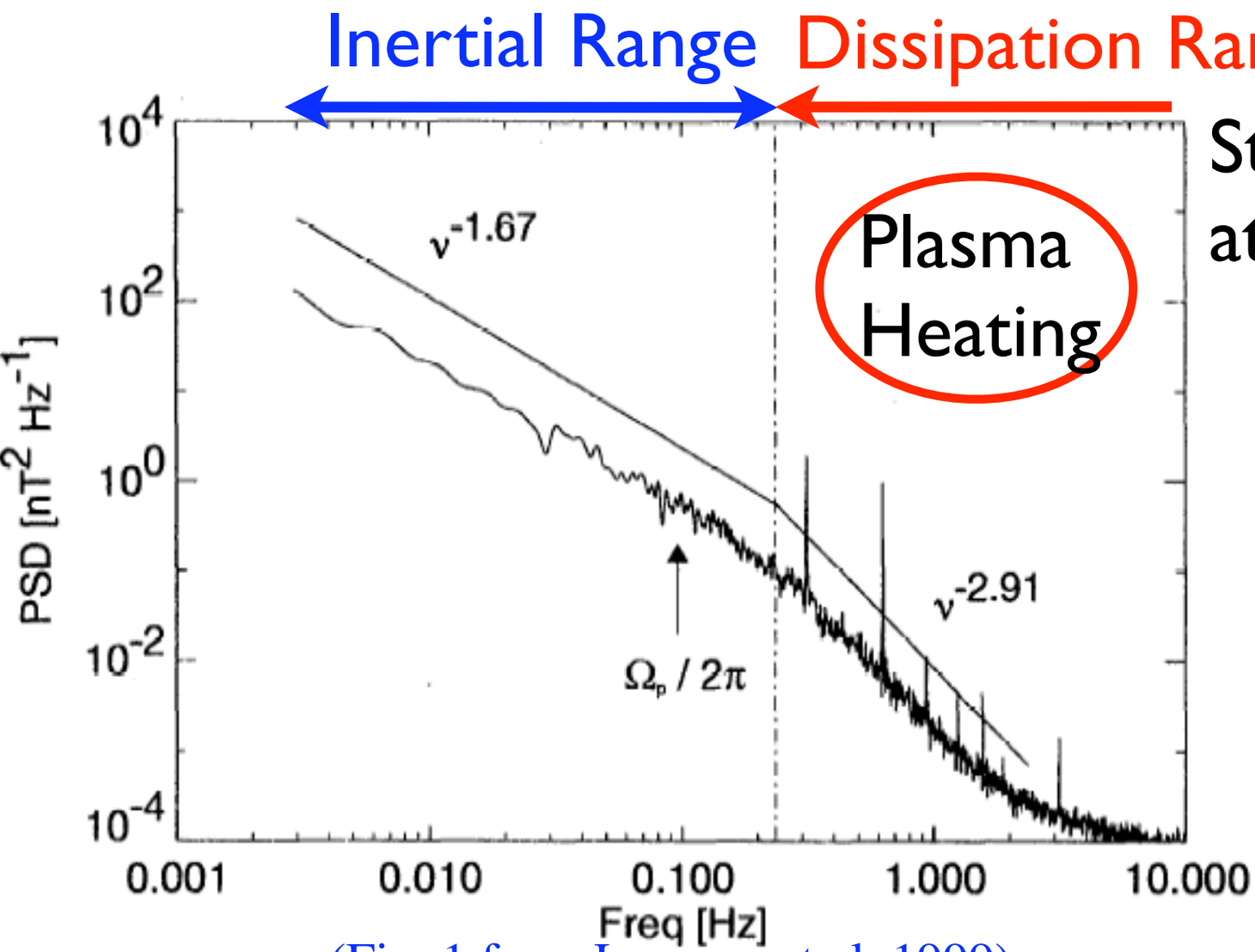
Early Observations



(Fig. 1 from Leamon et al. 1999)

Steeper Dissipation Range attributed to:

- Proton Cyclotron Damping
  (Goldstein, Roberts, & Fitch 1994, Leamon et al. 1998b, Gary 1999)
- Kinetic Alfven Wave Damping
  (Leamon et al. 1998a)
- Whistler Dispersion
  (Stawicki, Gary, & Li 2001)

Physics underlying the dissipation range is not well understood!

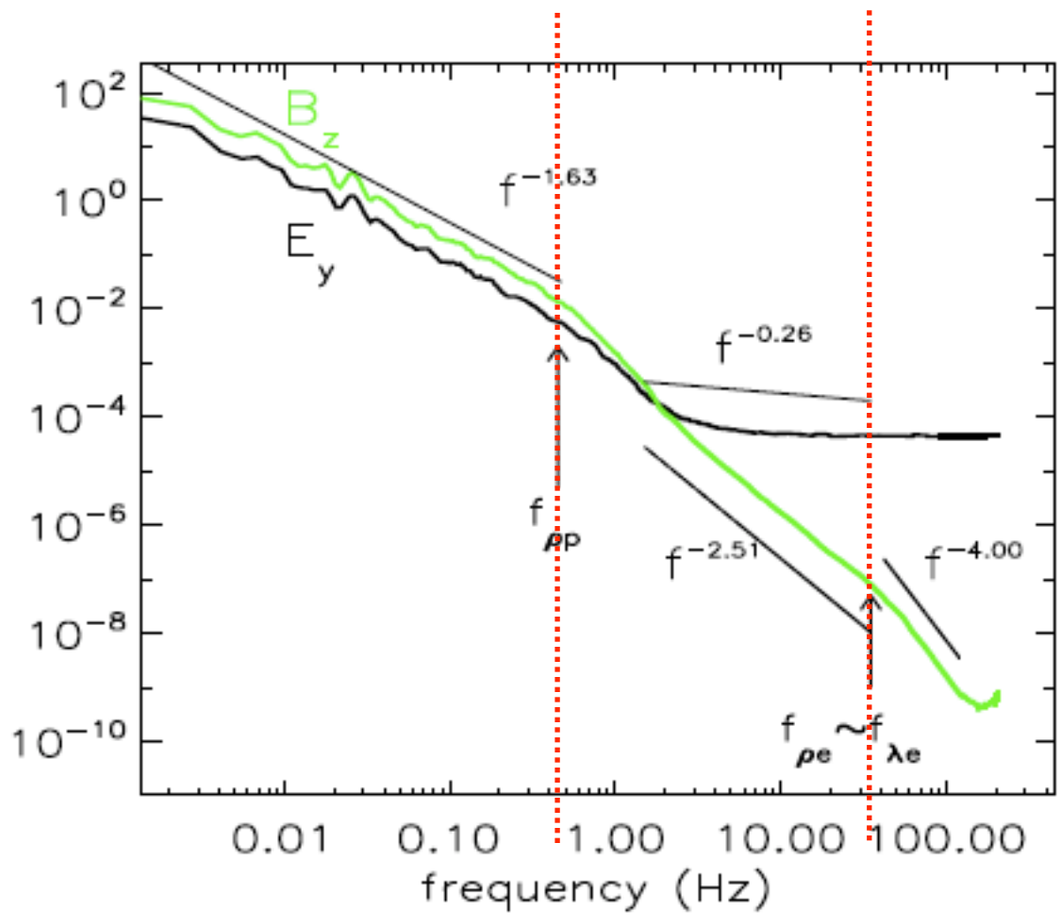
Turbulent plasma heating depends critically on this physics!

Dissipation Range Spectra

Recent Observations

Observations find nearly power-law behavior down to electron scales!

How do we interpret these observations?



(Sahraoui, Goldstein, Robert, Khotyaintsev 2009, PRL)

(see also Kiyani et al. 2009, PRL and Alexandrova et al. 2009 PRL)

1) Can theoretical models explain the observations?

2) What are the wave modes that comprise the dissipation range? KAW or whistler?

3) Is this a dissipation range or a dispersion range?

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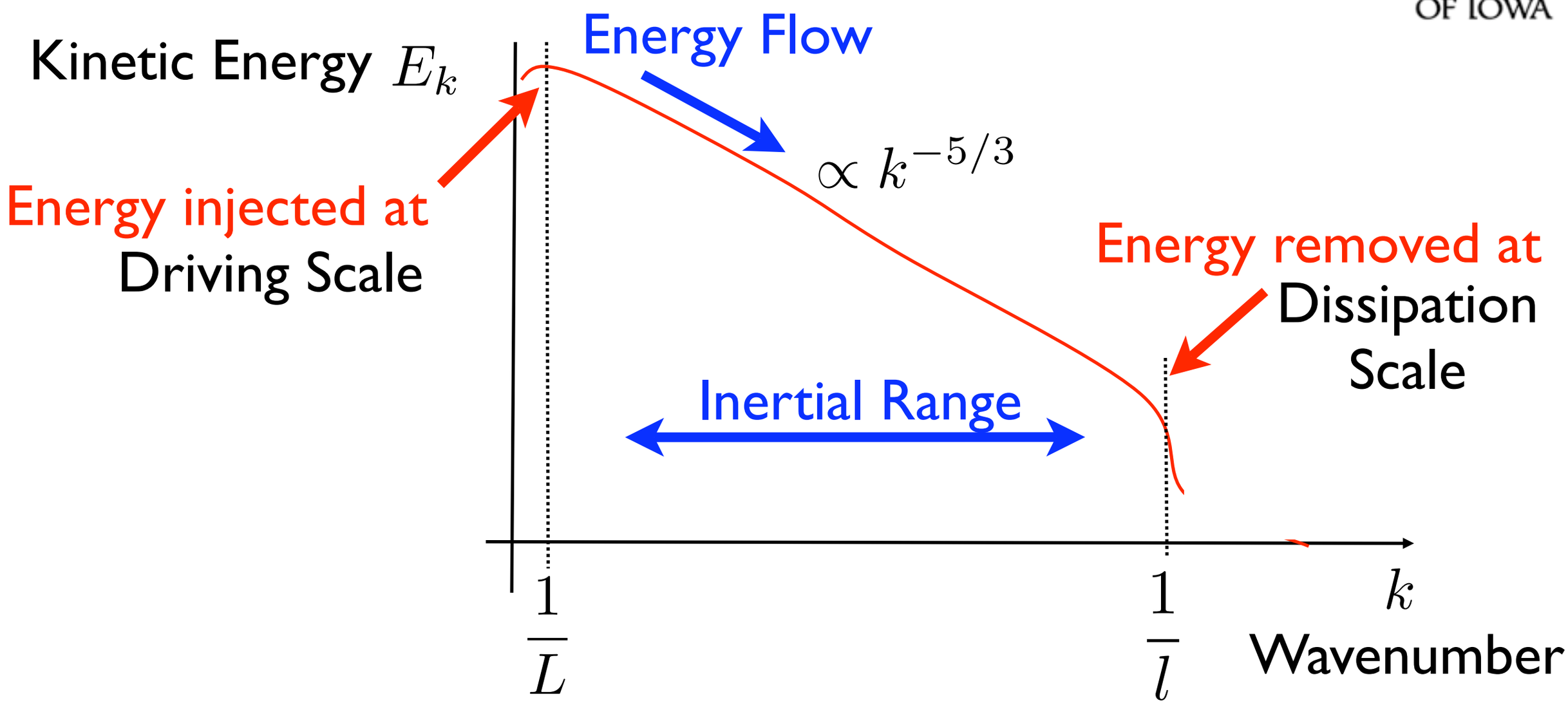
Kolmogorov Hydrodynamic Turbulence



- Astrophysical turbulence develops an Inertial Range
- Kolmogorov Hypothesis: (Kolmogorov, 1941)
  - Energy transfer occurs locally in wavenumber
  - Energy cascade rate in inertial range is constant

Modifications for Kinetic Turbulence

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Turbulence Theory in Kinetic Plasmas must incorporate:

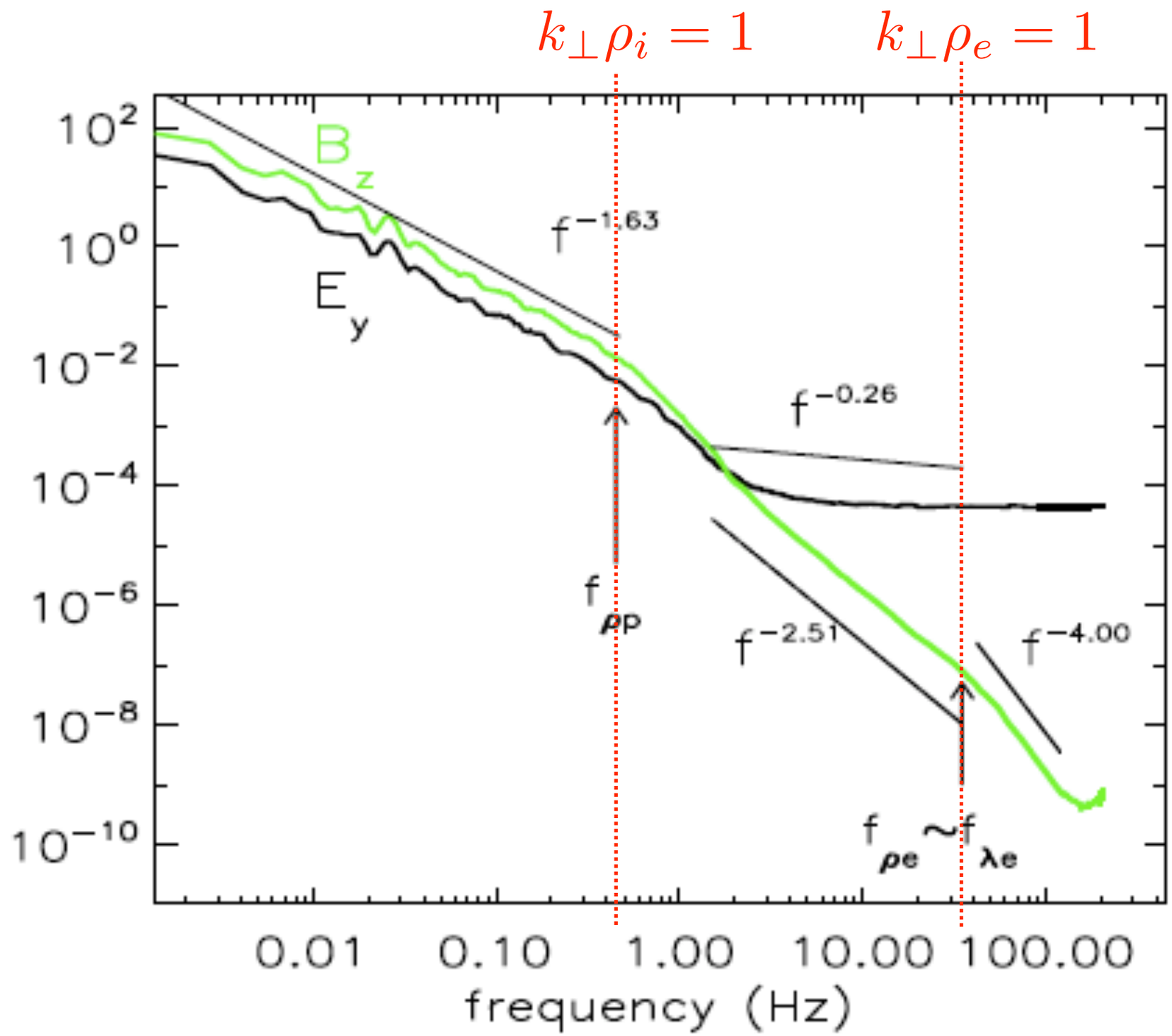
1) Inherent anisotropy of MHD turbulence

2) Weak collisionality at small scales

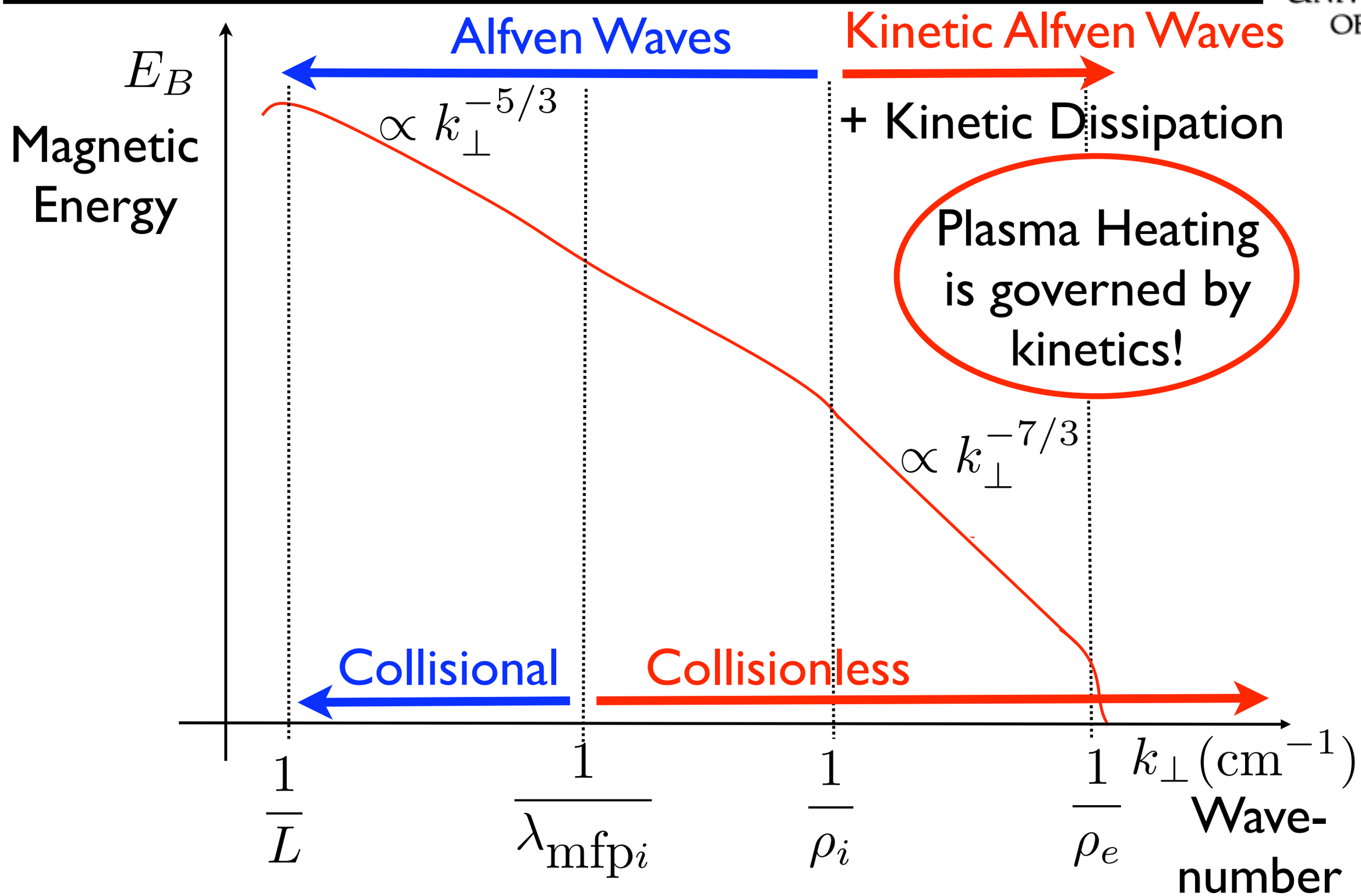
   a) Transition to Kinetic Alfven Waves at $k_\perp \rho_i \sim 1$

   b) Damping via Kinetic Mechanisms, e.g. Landau damping

Solar Wind Observations



Model of Kinetic Turbulent Cascade



(Schekochihin, Cowley, Dorland, Hammett, Howes, Quataert, & Tatsuno, ApJS 182, 310, 2009)

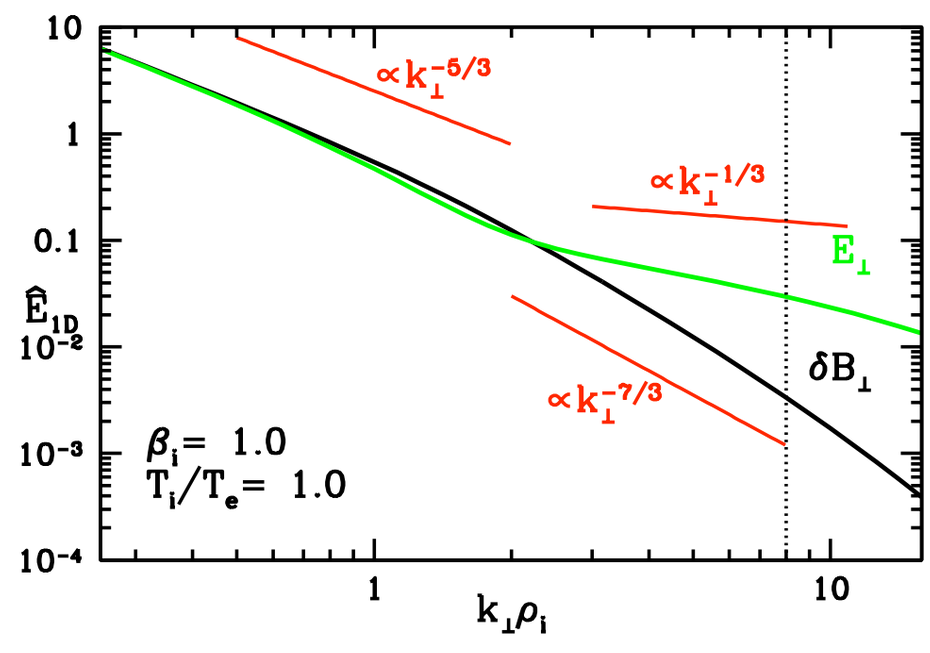
Cascade Model for Kinetic Turbulence

- Cascade Model based on three assumptions: (Howes et al., 2008b)
  1. Kolmogorov Hypothesis: Spectrally local nonlinear transfer
  2. Critical Balance of linear and nonlinear times
  3. Applicability of linear kinetic damping rates

$$\frac{\partial b_k^2}{\partial t} = -\frac{\partial}{\partial \ln k_\perp}\left(\frac{b_k^2 \omega_{nl}(k_\perp)}{C_1 C_2}\right) + \mathcal{S}(k_\perp) - 2\gamma(k_\perp) b_k^2$$

Nonlinear Transfer Source Dissipation

Predicted Magnetic Energy Spectrum



(see also Podesta, Borovsky, and Gary 2010)

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Gyrokinetics

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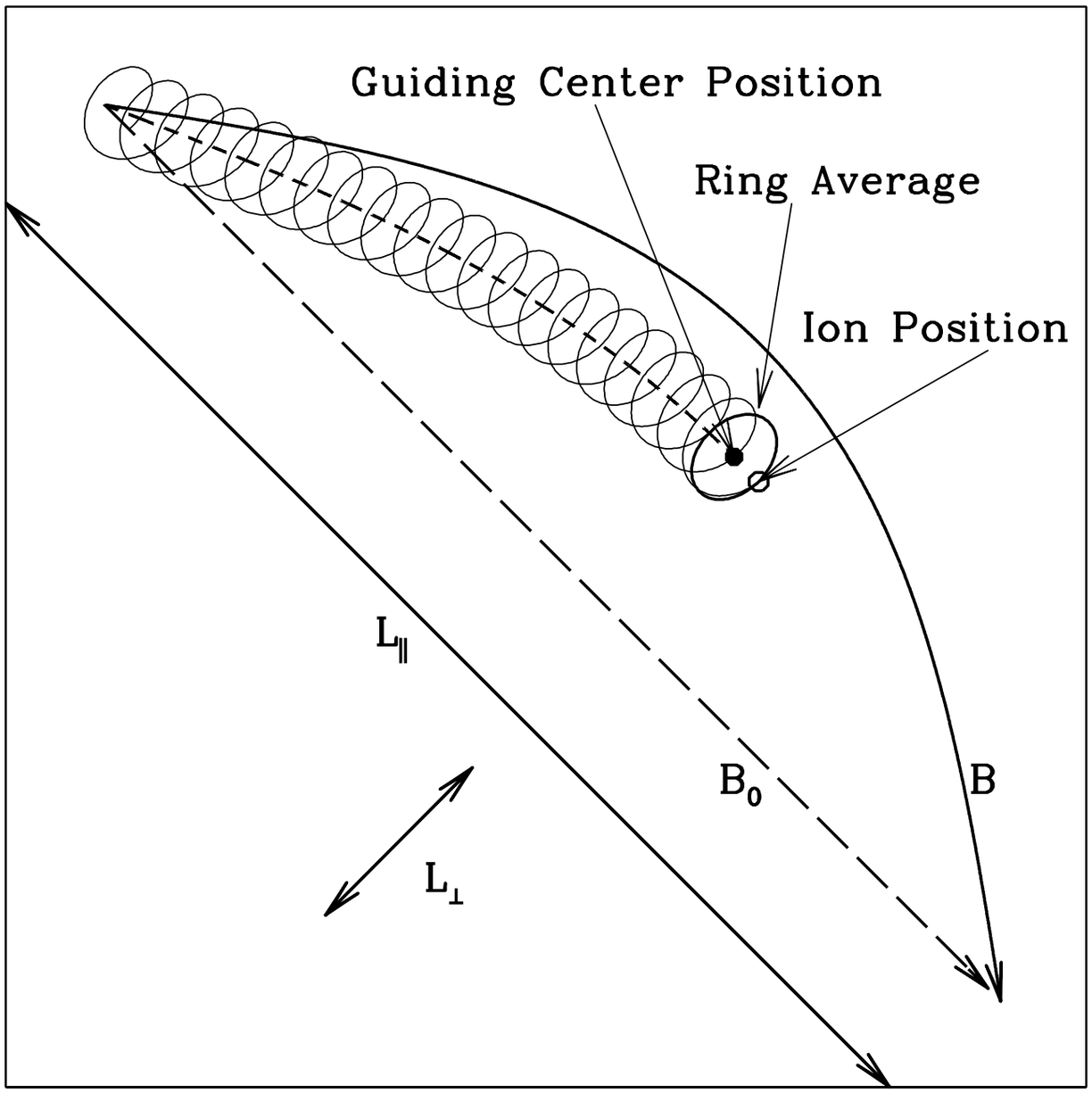
Gyrokinetics is kinetic theory averaged over the Larmor motion.

(Rutherford & Frieman 1968; Taylor & Hastie 1968; Frieman & Chen 1982; Howes et al. 2006)



- Low-frequency limit eliminates fast cyclotron timescale $\omega \ll \Omega_i$
- Anisotropic $k_\parallel \ll k_\perp$
- Captures: Finite Larmor radius, Landau resonance, and Collisions
- Excludes: Fast wave and cyclotron resonance

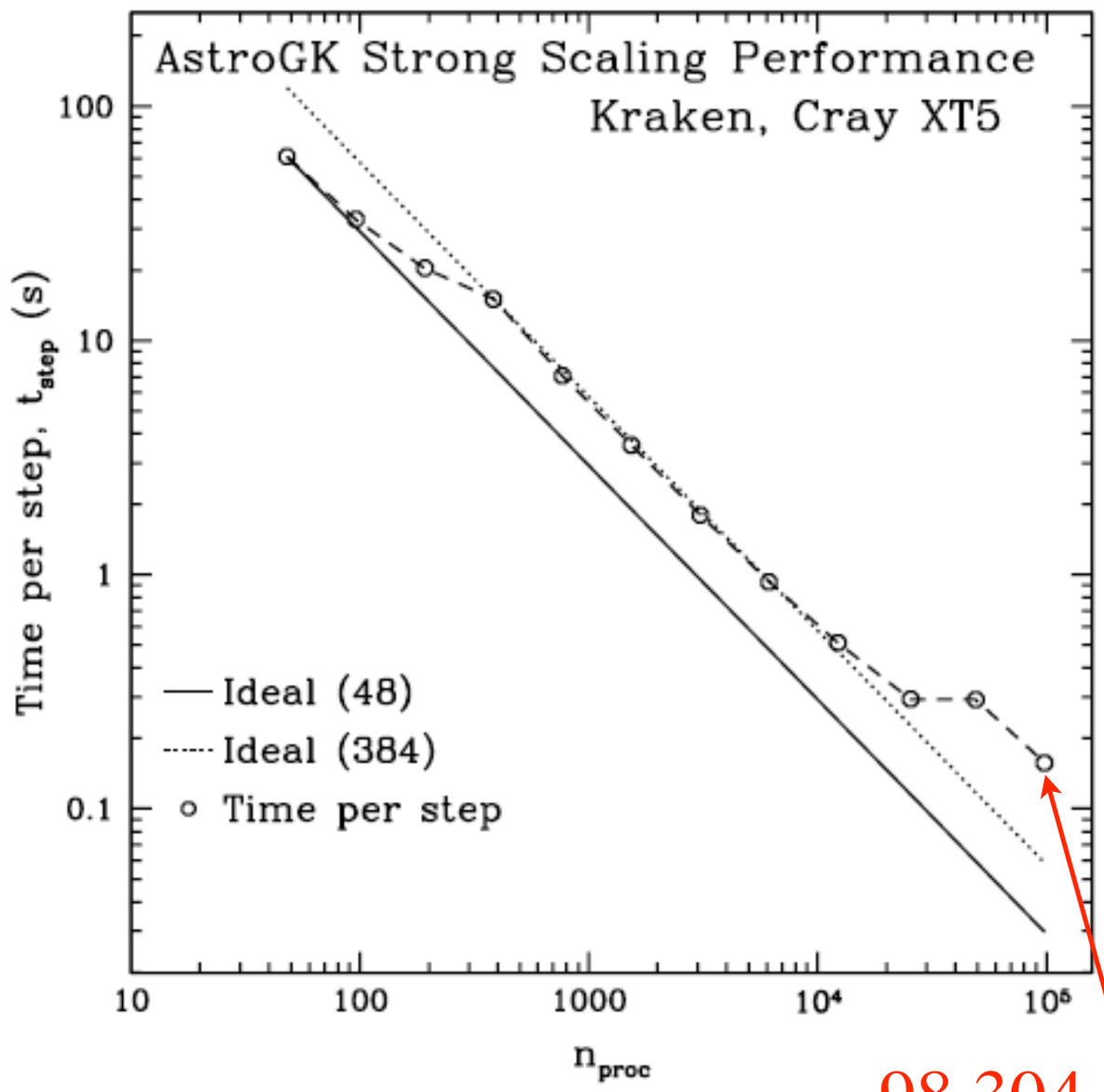
AstroGK Simulations

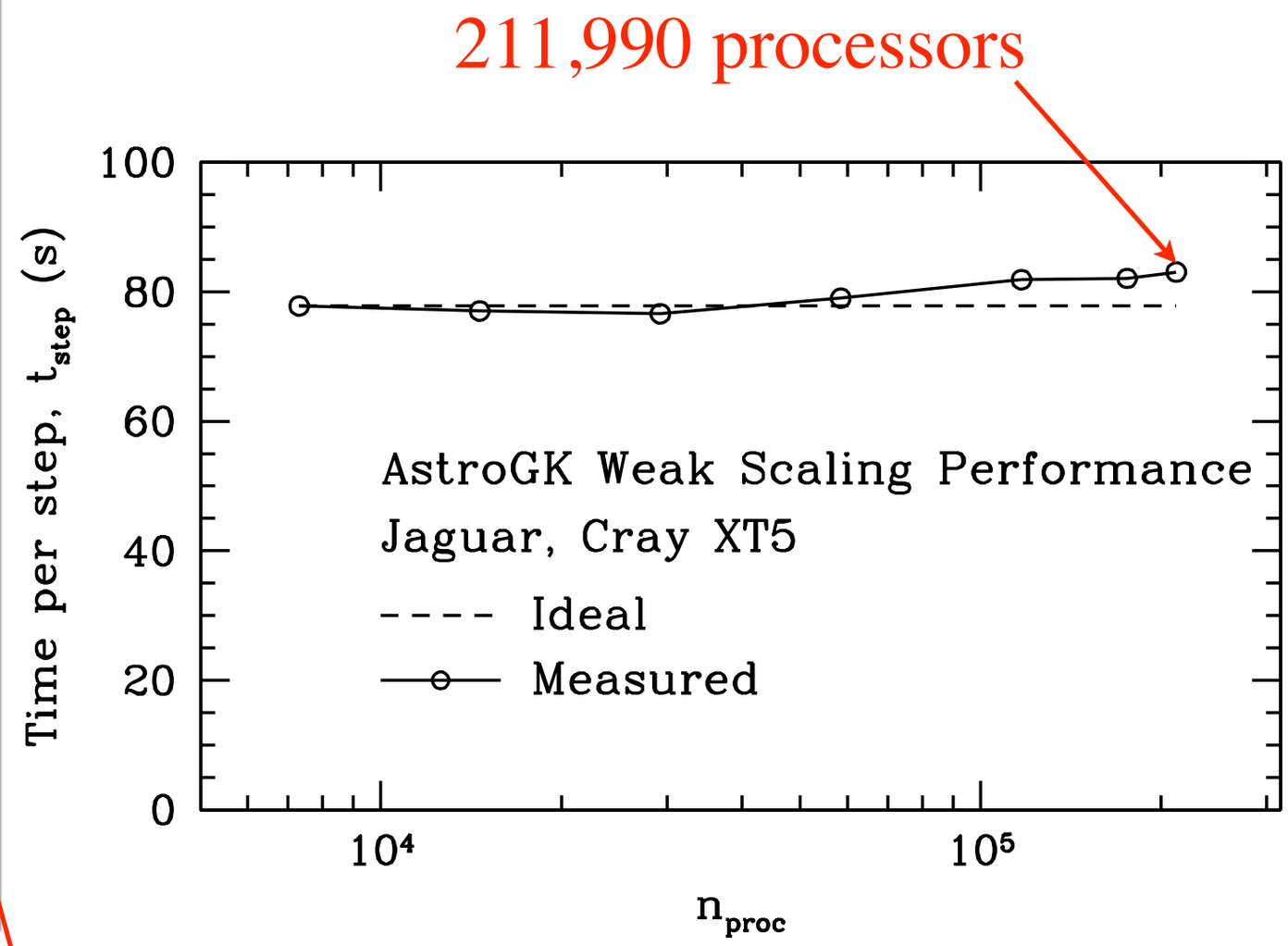
- 5-D Distribution Function, two species, fully electromagnetic
- Ion to Electron scale simulations require millions of CPU hours

AstroGK

The Astrophysical Gyrokinetics Code

(Numata, Howes, Tatsuno, Barnes, & Dorland, J. Comp. Phys., submitted 2010)

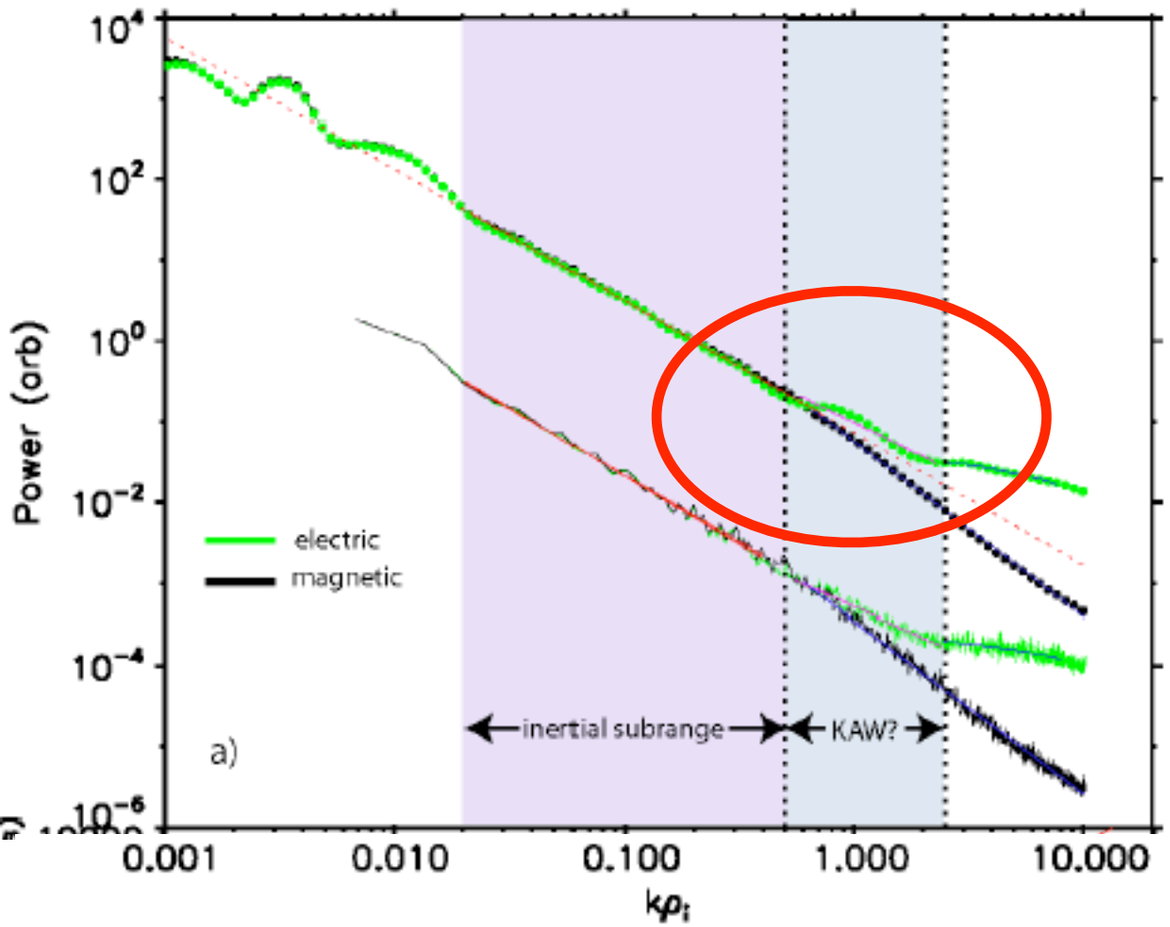




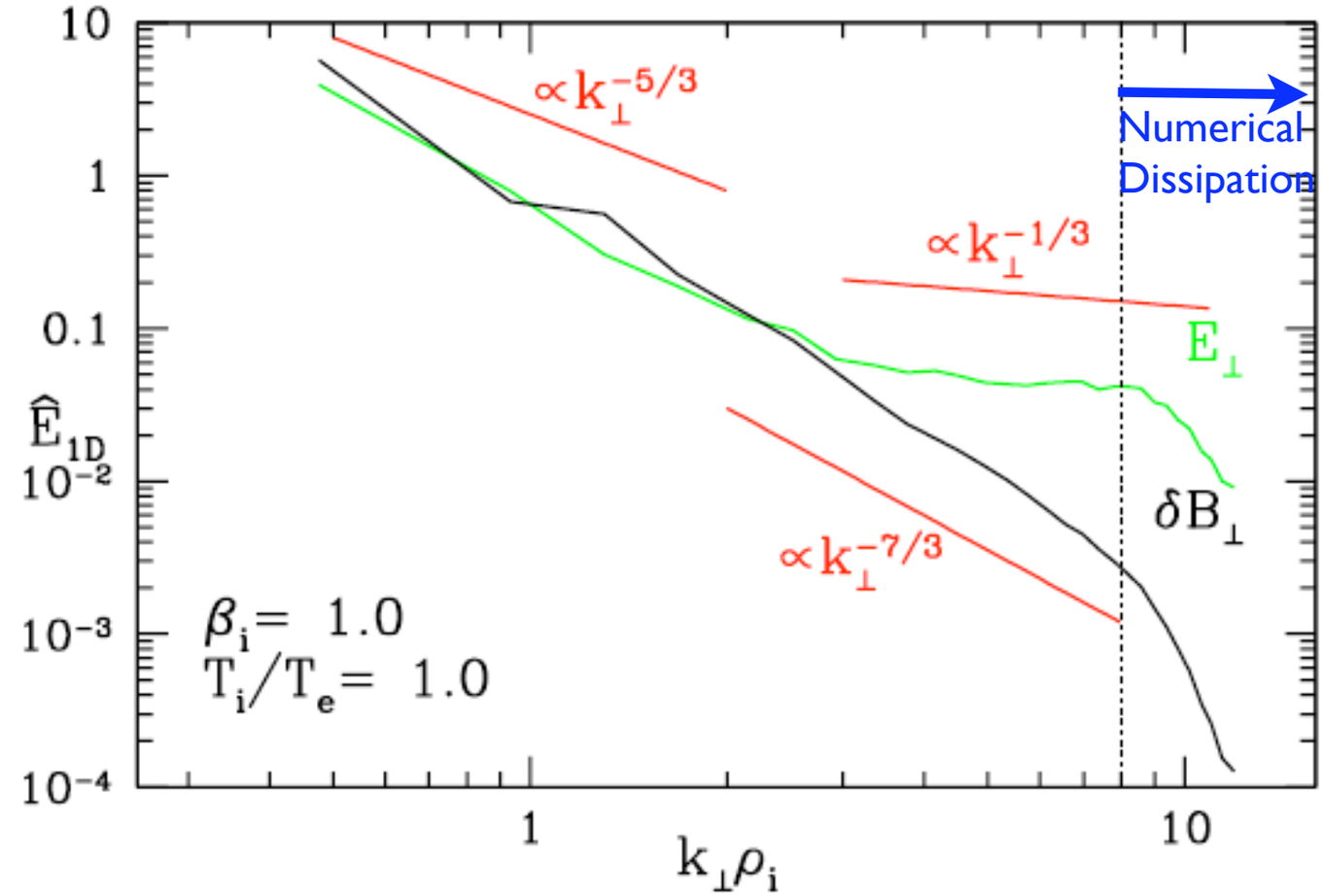
98,304 processors

Transition to Kinetic Alfven Wave Turbulence

(Fig. 3 from Bale et al. 2005)



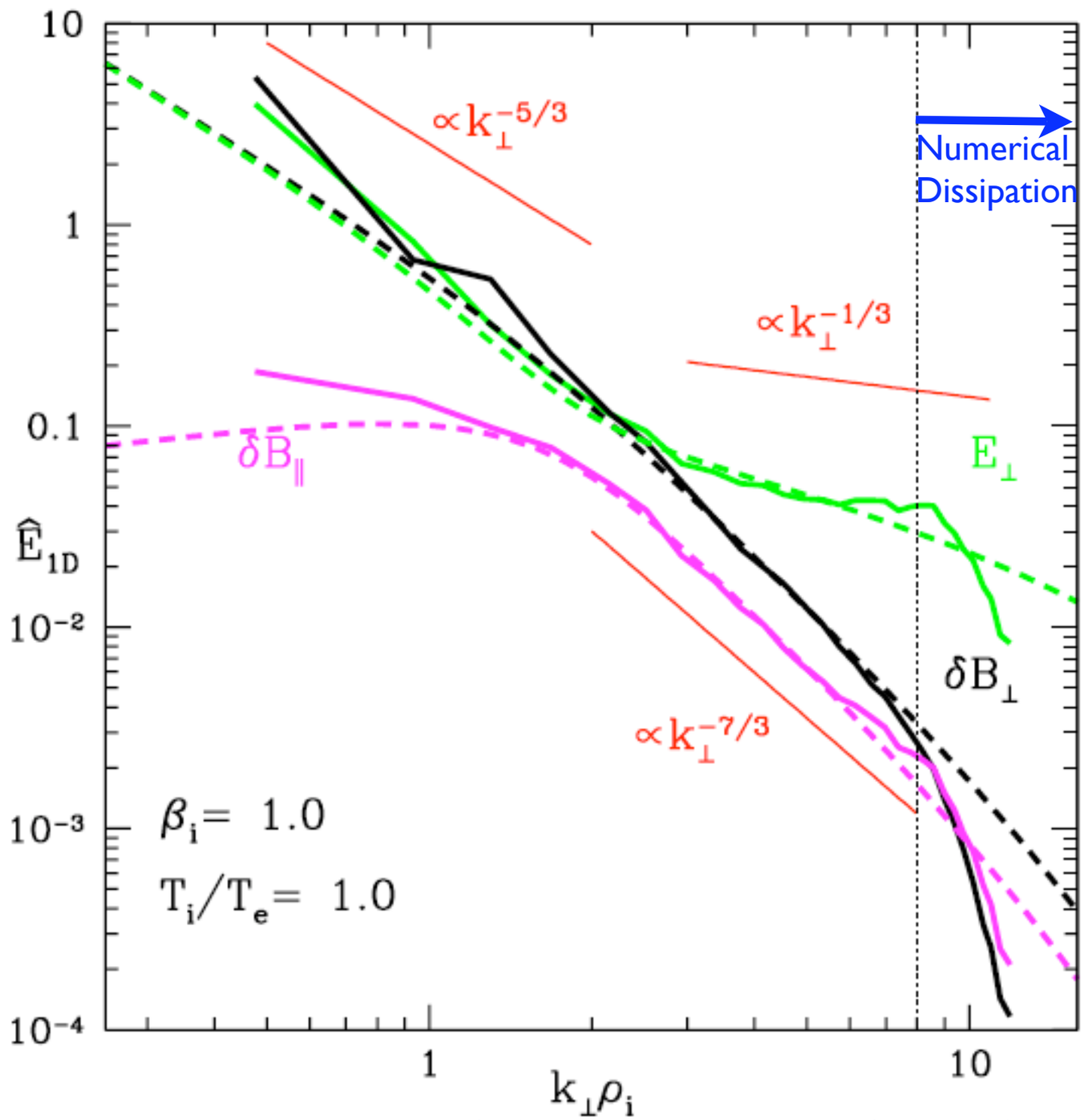
(Howes et al. 2008a)



Numerical results are strongly supportive of model of transition from MHD Alfven Waves to Kinetic Alfven Waves

- Supports the hypothesis that frequencies remain low, $\omega \ll \Omega_i$

Comparison to Cascade Model



(Howes et al. 2008a, Howes et al. 2008b)

- One fitted parameter
- Cascade model shows excellent agreement with numerical simulation
- Kinetic damping is weak for these plasma parameters
- Need more strongly damped case to better test model

First-Principles Calculation of Turbulence

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The use of Gyrokinetics enables direct numerical simulations of kinetic turbulence from first principles.

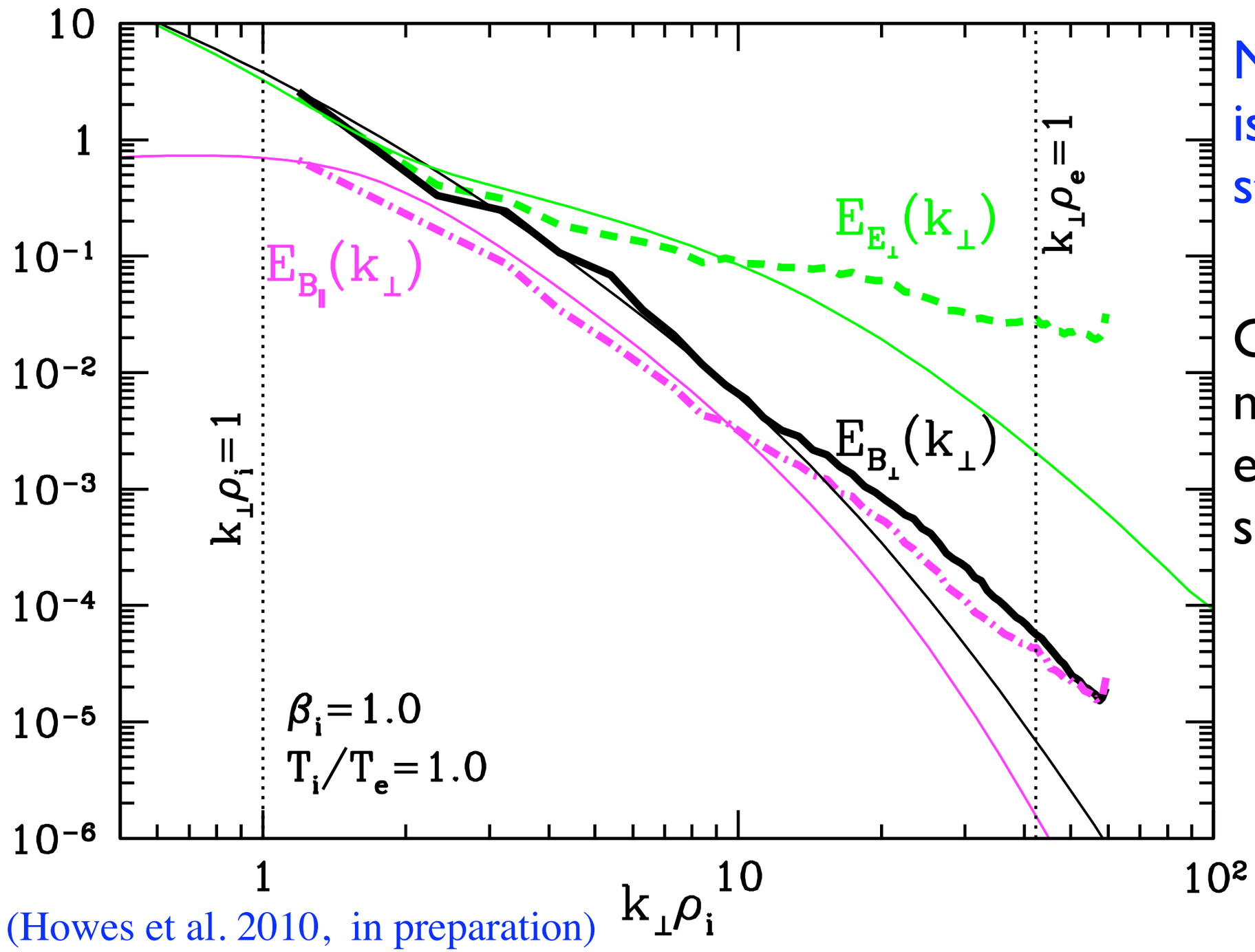
Using the nation's flagship supercomputing resources, today we can achieve turbulence simulations with the following properties:

- Three-dimensional:
  Important because turbulent interactions are inherently 3-D
- Employ a physical mass ratio $m_i/m_e = 1836$
- Resolve from the scale of the ion to the electron Larmor radius
  From $k_\perp \rho_i = 1$ to $k_\perp \rho_e = 1$
- Resolve sufficient kinetic damping to terminate the cascade without the need for artificial dissipation

These properties are necessary to make direct comparison to observations

Milestone Dissipation Range Simulation

Ion to Electron Scale Simulation



(Howes et al. 2010, in preparation)

No artificial dissipation is needed to achieve a steady-state

Original Cascade model predicted an exponential drop off in spectra

Key Finding:
Demonstrates that a Kinetic Alfven Wave cascade can reach electron scales

Direct Comparison to Observations

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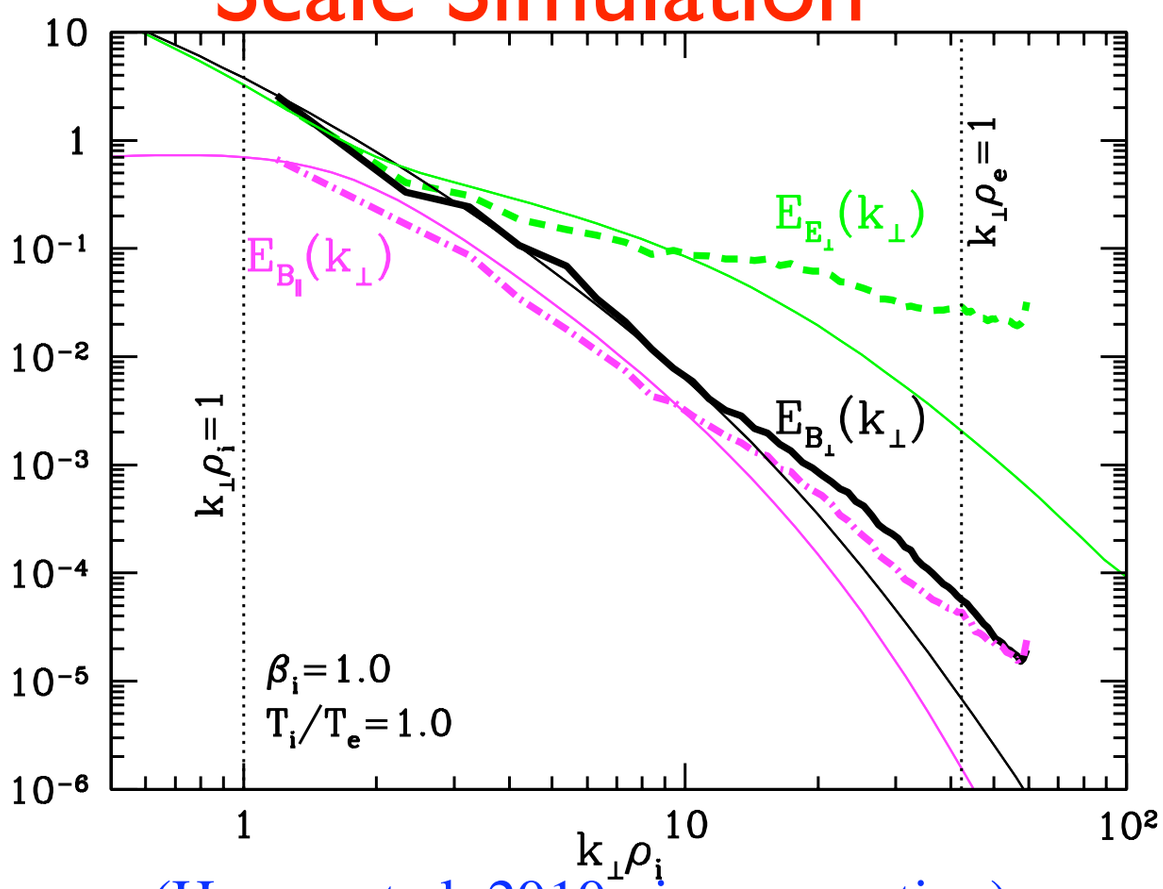
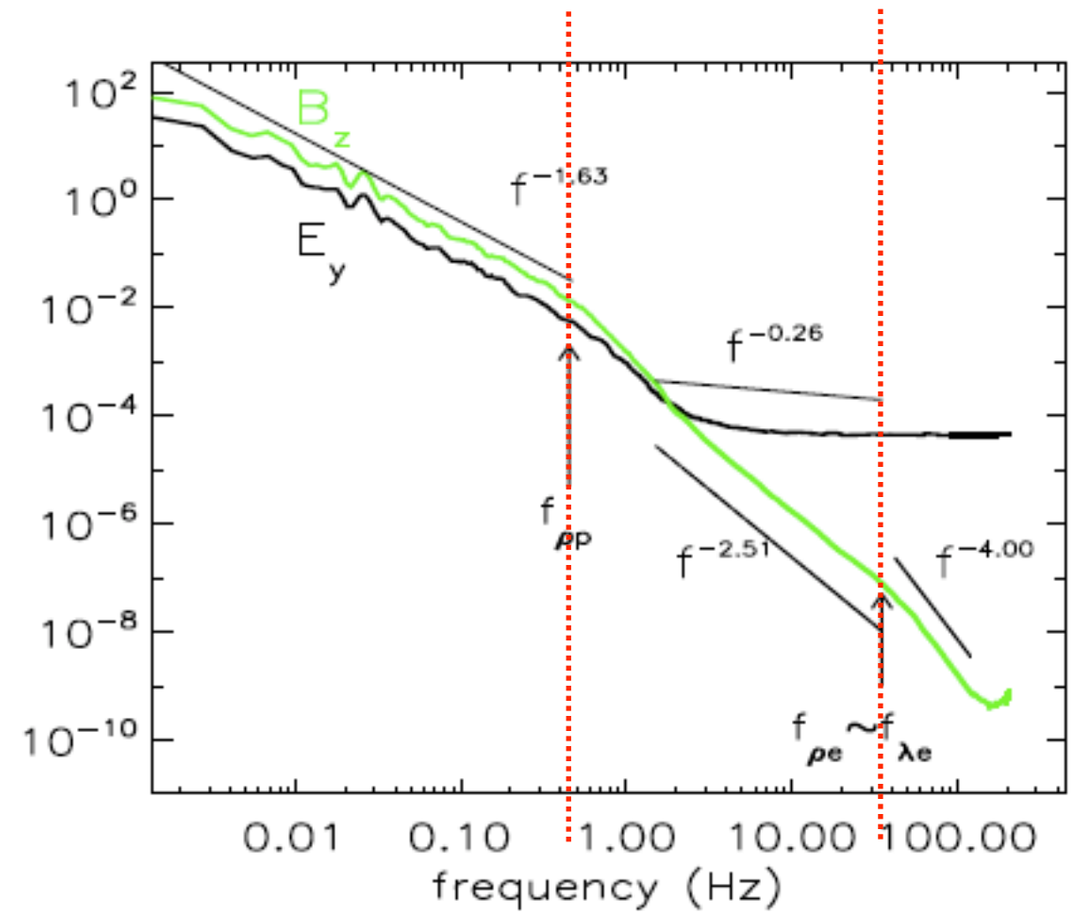
Ion to Electron Scale Simulation



(Howes et al. 2010, in preparation)

Recent Observations



(Sahraoui, Goldstein, Robert, Khotyaintsev 2009, PRL)

Both Numerical Simulations and Observations find nearly power-law behavior down to electron scales!

Cascade Models by Howes et al. 2008 and Podesta et al. 2010:

- Predicted an exponential roll off of spectrum
- Appear not to be in agreement with observations or simulations
- Simulations point to necessary refinements in cascade model!

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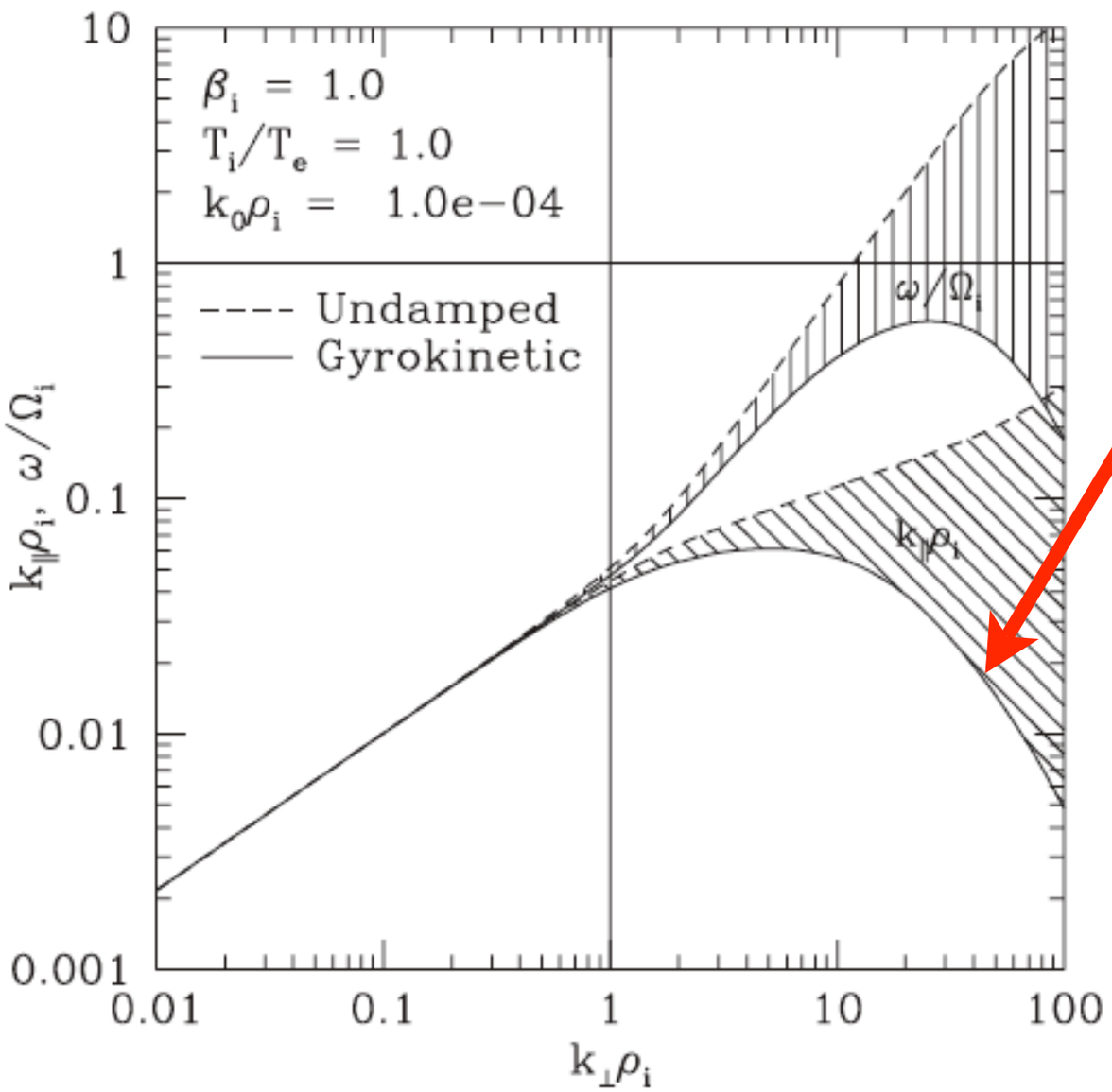
Improved Cascade Model

Problems with the original cascade model: (Howes et al., 2008b)

1. Apparent disagreement with simulations and observations

   Dissipation range slopes do not fall off exponentially

2. Assuming critical balance even when turbulence is dissipating



Parallel wavenumber decreases as perpendicular wavenumber increases

This behavior does not seem to make physical sense!

Improved Cascade Model

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Original Cascade Model: (Howes et al., 2008b)

1. Kolmogorov Hypothesis: Spectrally local nonlinear transfer
2. Critical Balance of linear and nonlinear times
3. Applicability of linear kinetic damping rates

Weakened Cascade Model:

1. Drop the assumption of Critical Balance

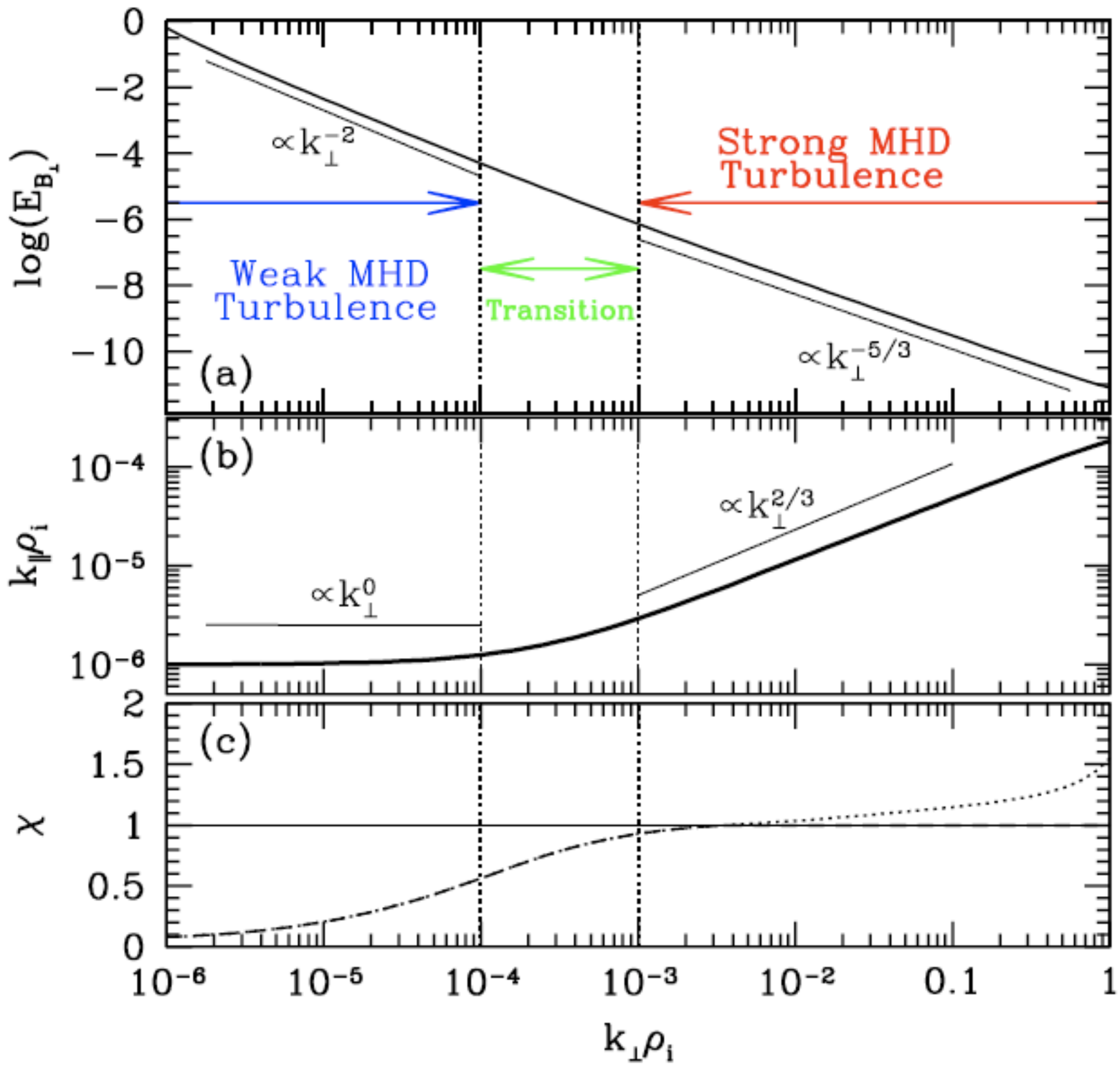
→ Model transition between weak and strong turbulence

2. Drop Kolmogorov's Locality Hypothesis

→ Account for effect of nonlocal fluctuations on cascade

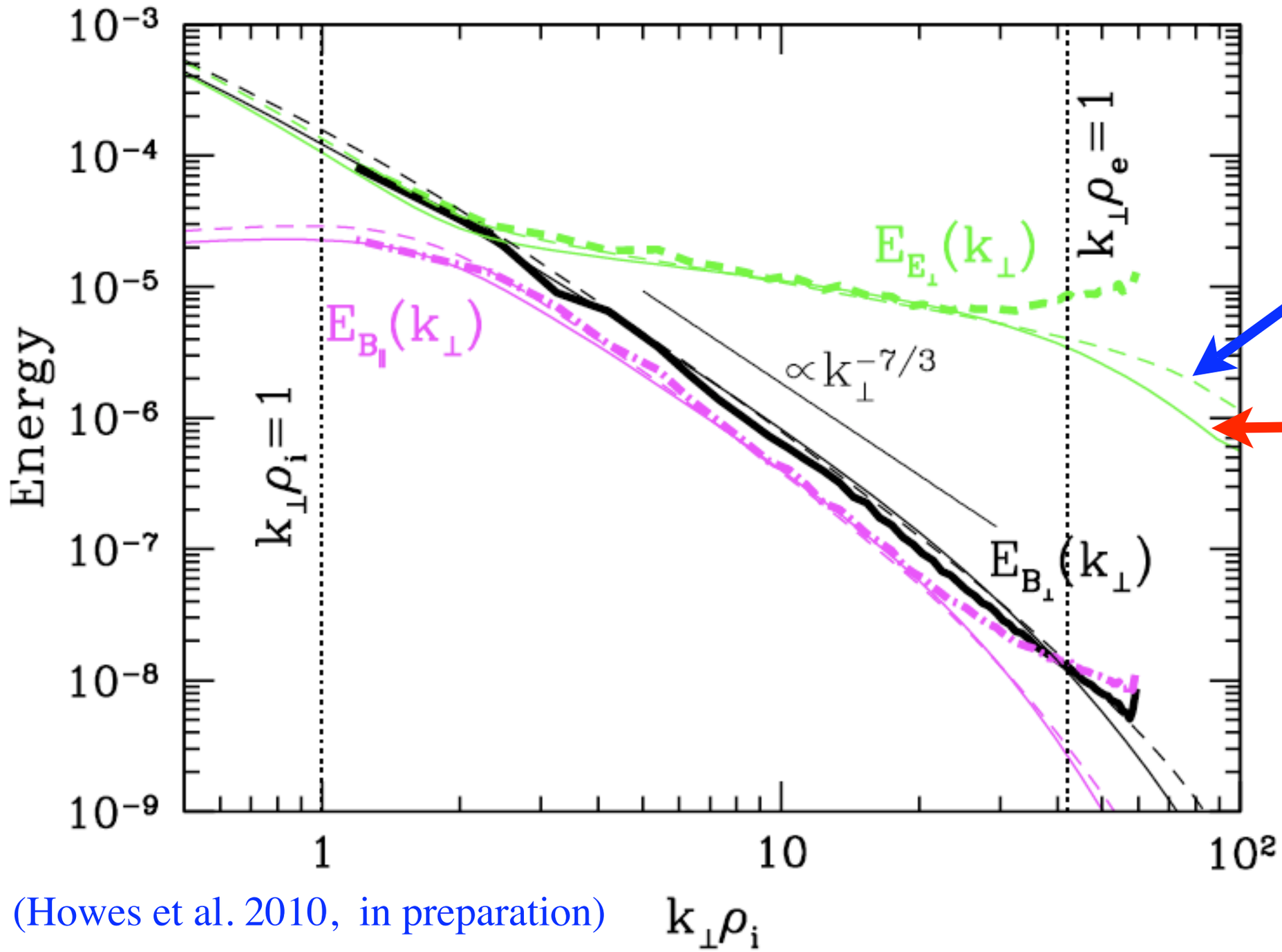
Weak to Strong Turbulence

Weakened Cascade Model



Nonlocal Interactions $\beta_i = 1$

For $\beta_i = 1$ plasma, *both* local and nonlocal models give similar results



Local Model (dashed)

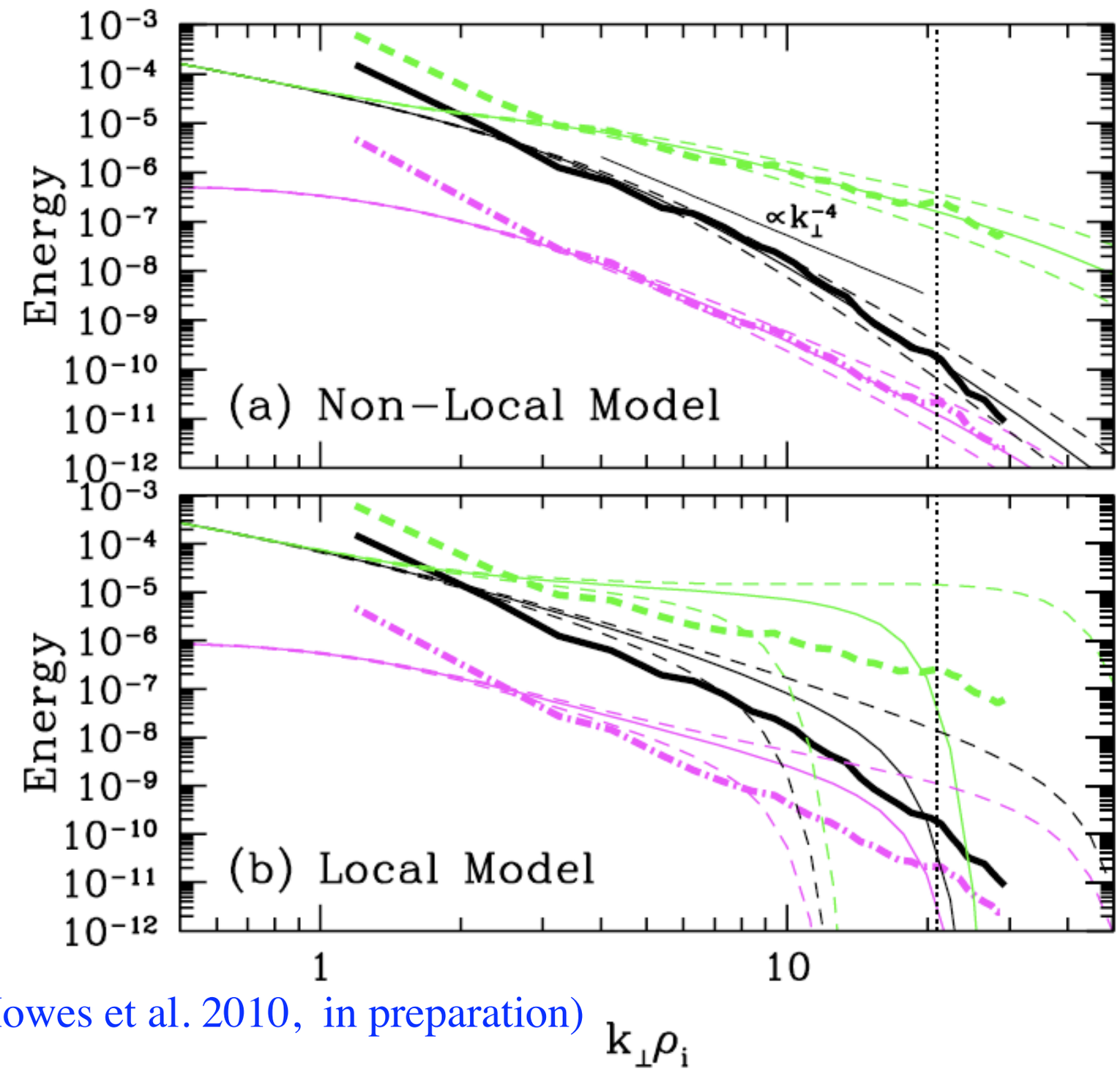
Nonlocal Model (solid)

Damping is relatively weak for $\beta_i = 1$

(Howes et al. 2010, in preparation)

Nonlocal Interactions $\beta_i = 0.01$

At $\beta_i = 0.01$, the kinetic damping is significantly stronger



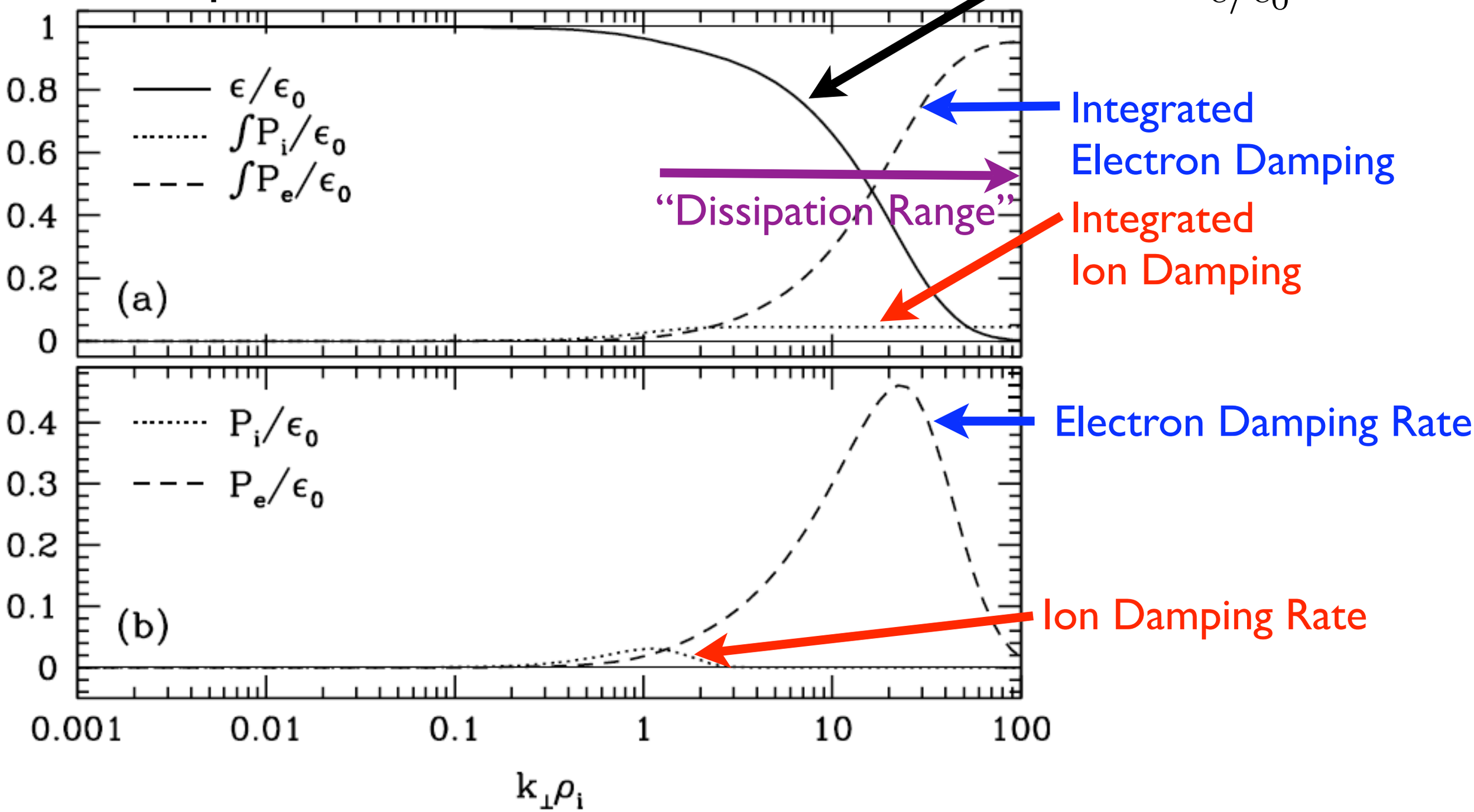
Nonlocal Model fits spectra well

Local Model is incapable of fitting spectra

(Howes et al. 2010, in preparation)

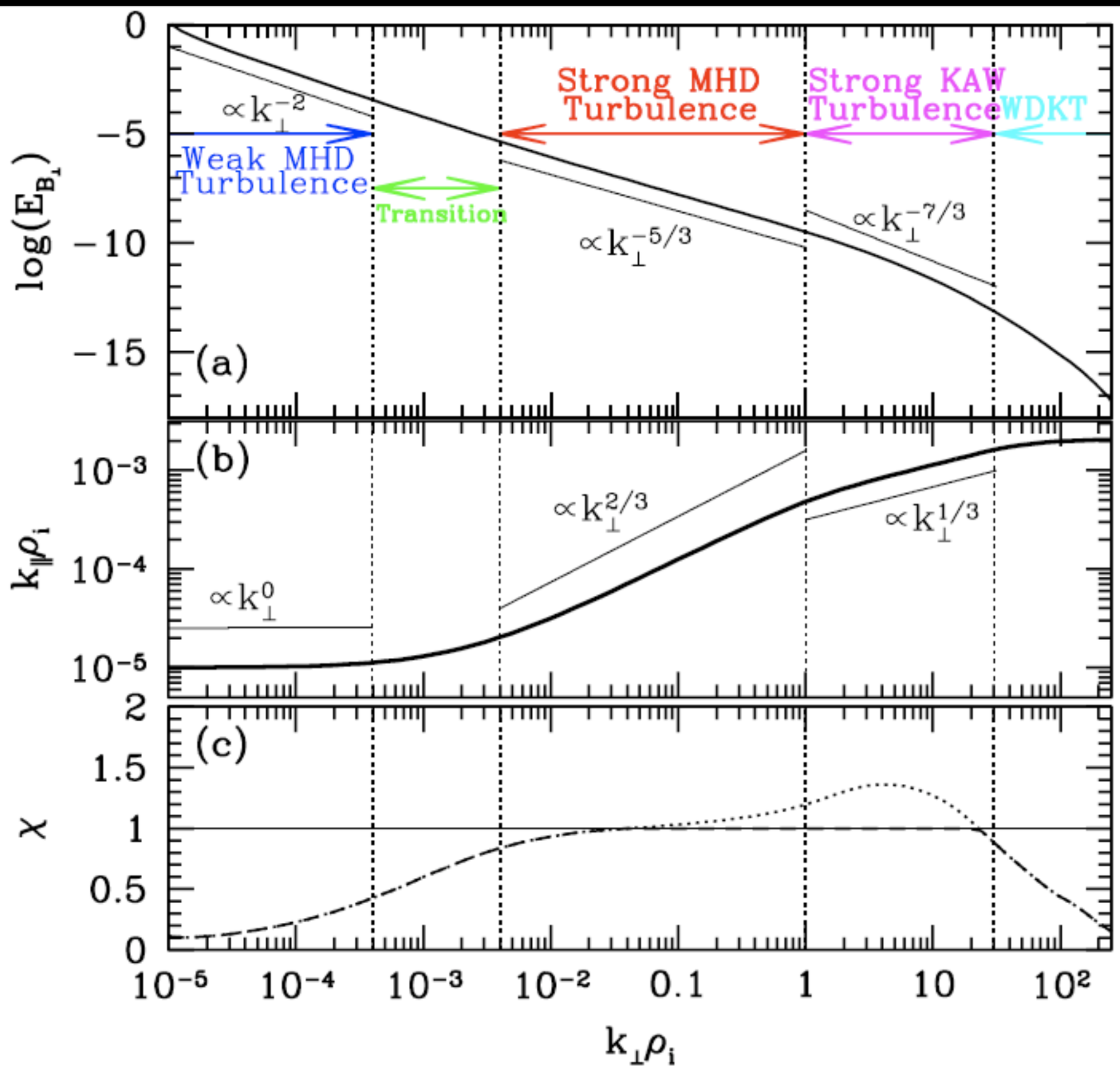
Energy Cascade and Kinetic Dissipation

Weakened Cascade Model is a useful tool for interpretation of numerical results



Future work will compare to ion/electron heating from simulations

Complete Kinetic Turbulence Spectrum



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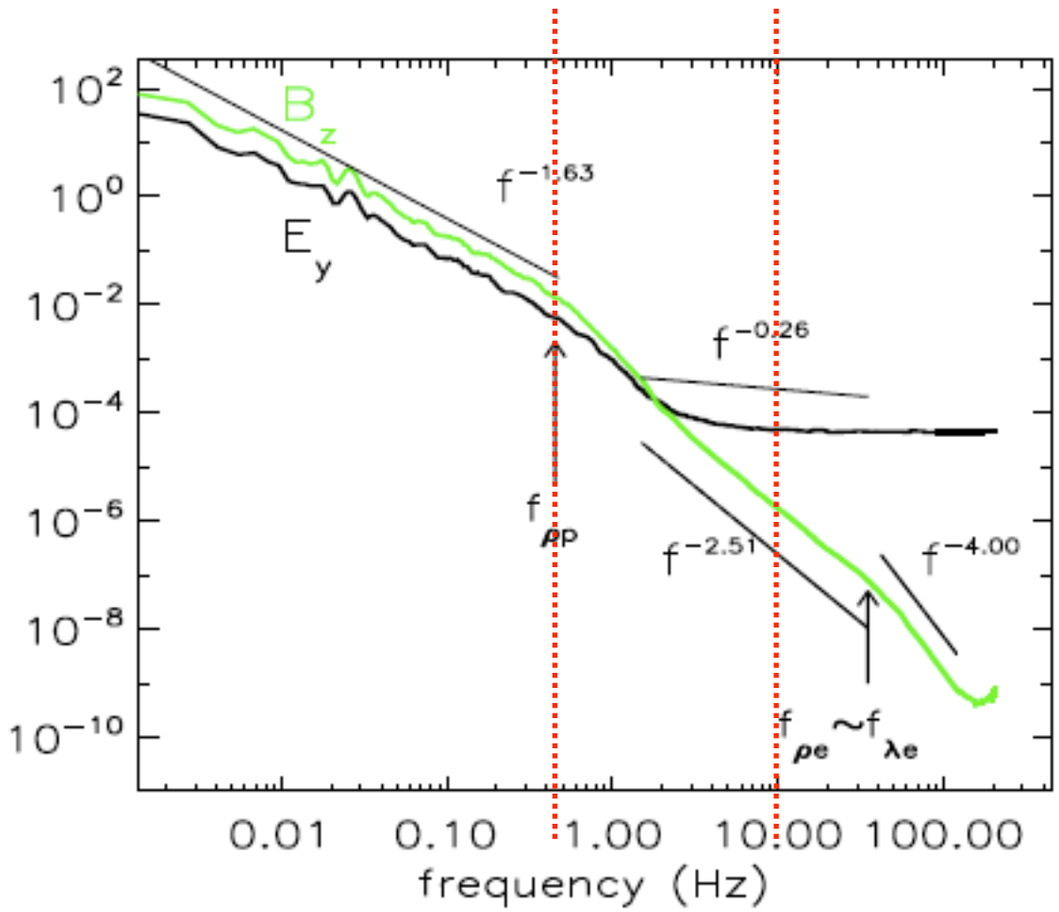
Question #1

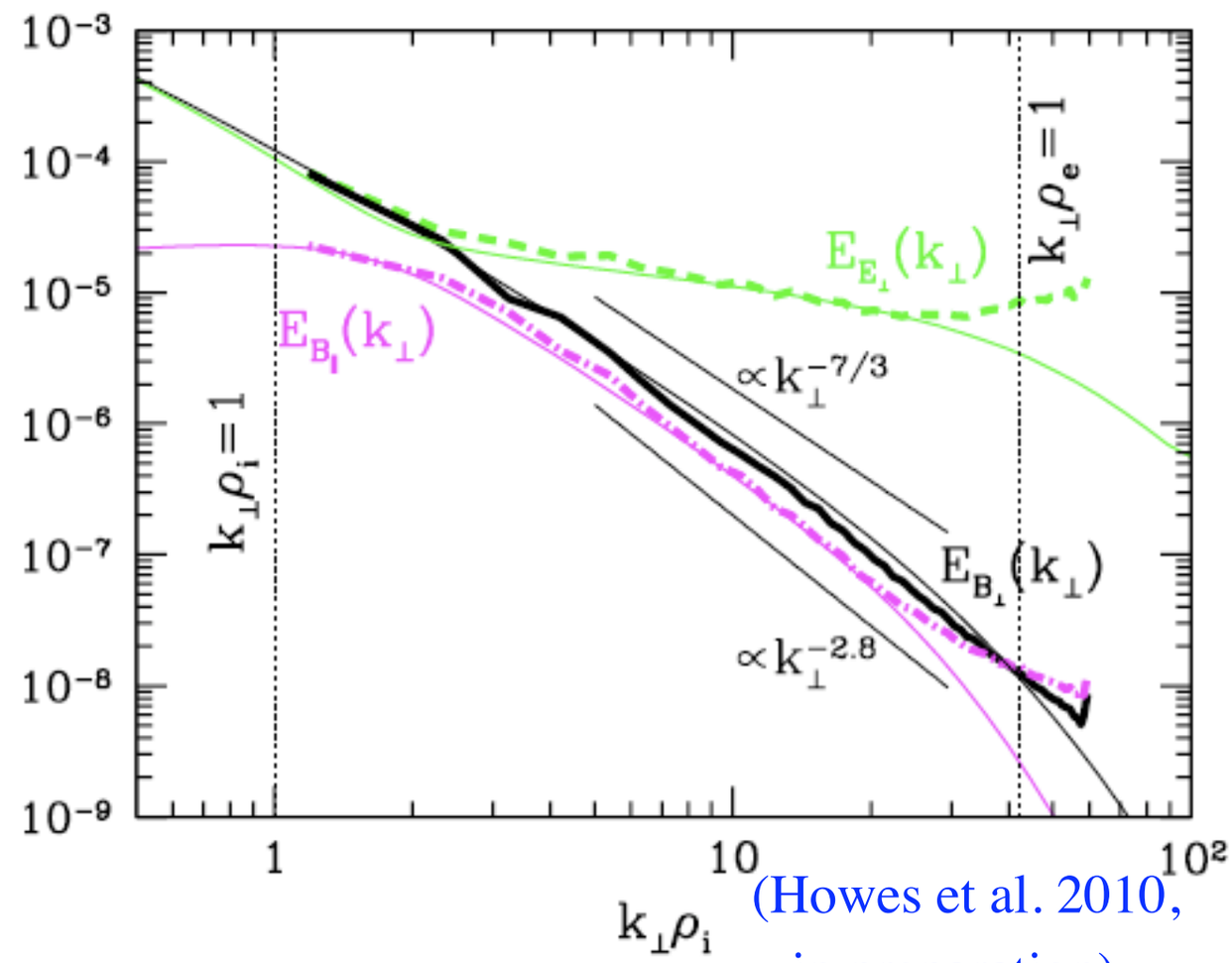
1) Can theoretical models explain the observations?

Solar Wind Observation



(Sahraoui, Goldstein, Robert, Khotyaintsev 2009, PRL)

AstroGK Simulation

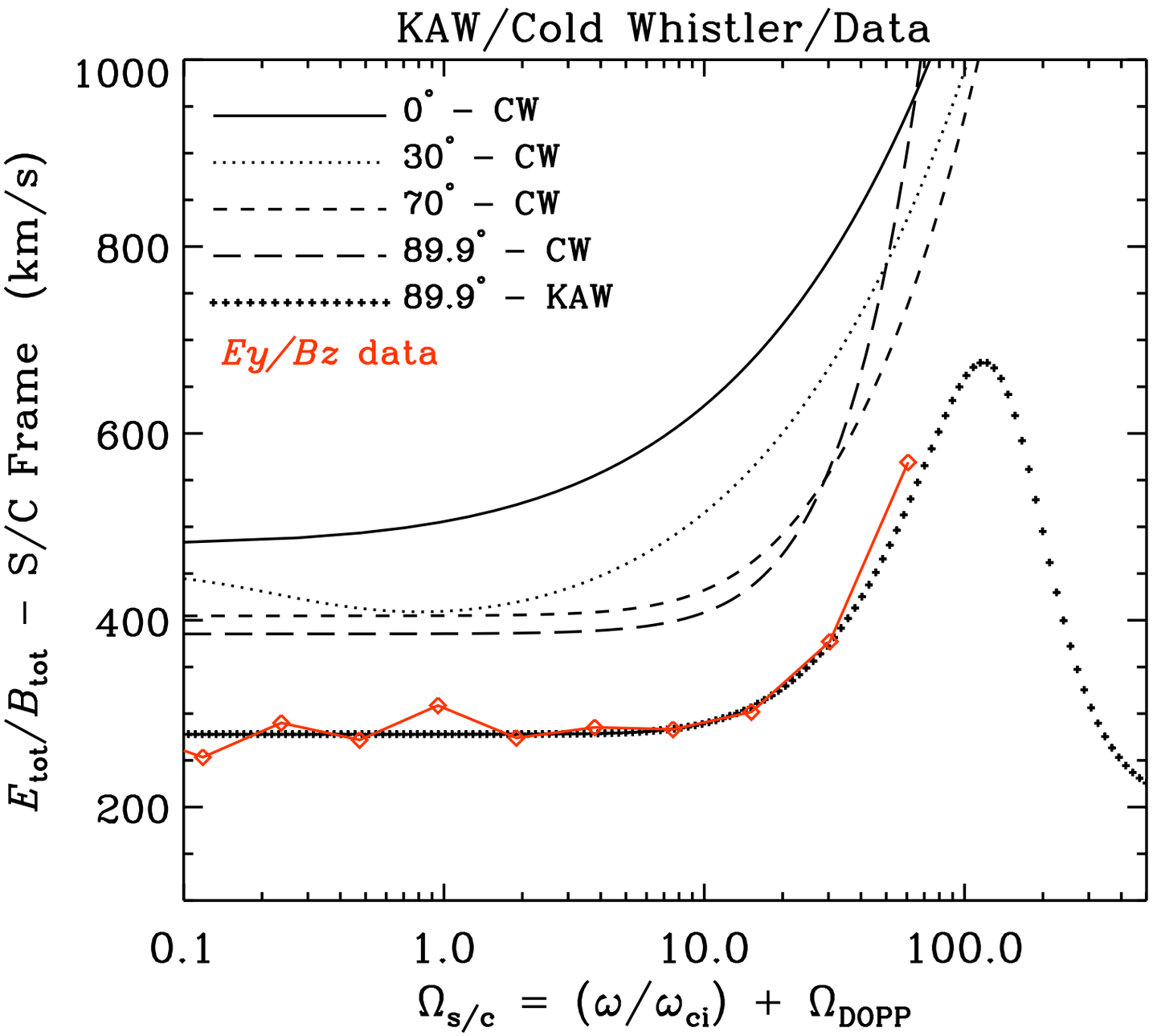


(Howes et al. 2010, in preparation)

- Cascade of Kinetic Alfven Waves reproduces observed behavior
- Interpretation using Weakened Cascade Model suggests importance of nonlocal effects on cascade on dissipation range spectrum
- This evidence supports our theoretical model of kinetic turbulence

Question #2

2) What are the wave modes that comprise the dissipation range?
KAW or whistler?

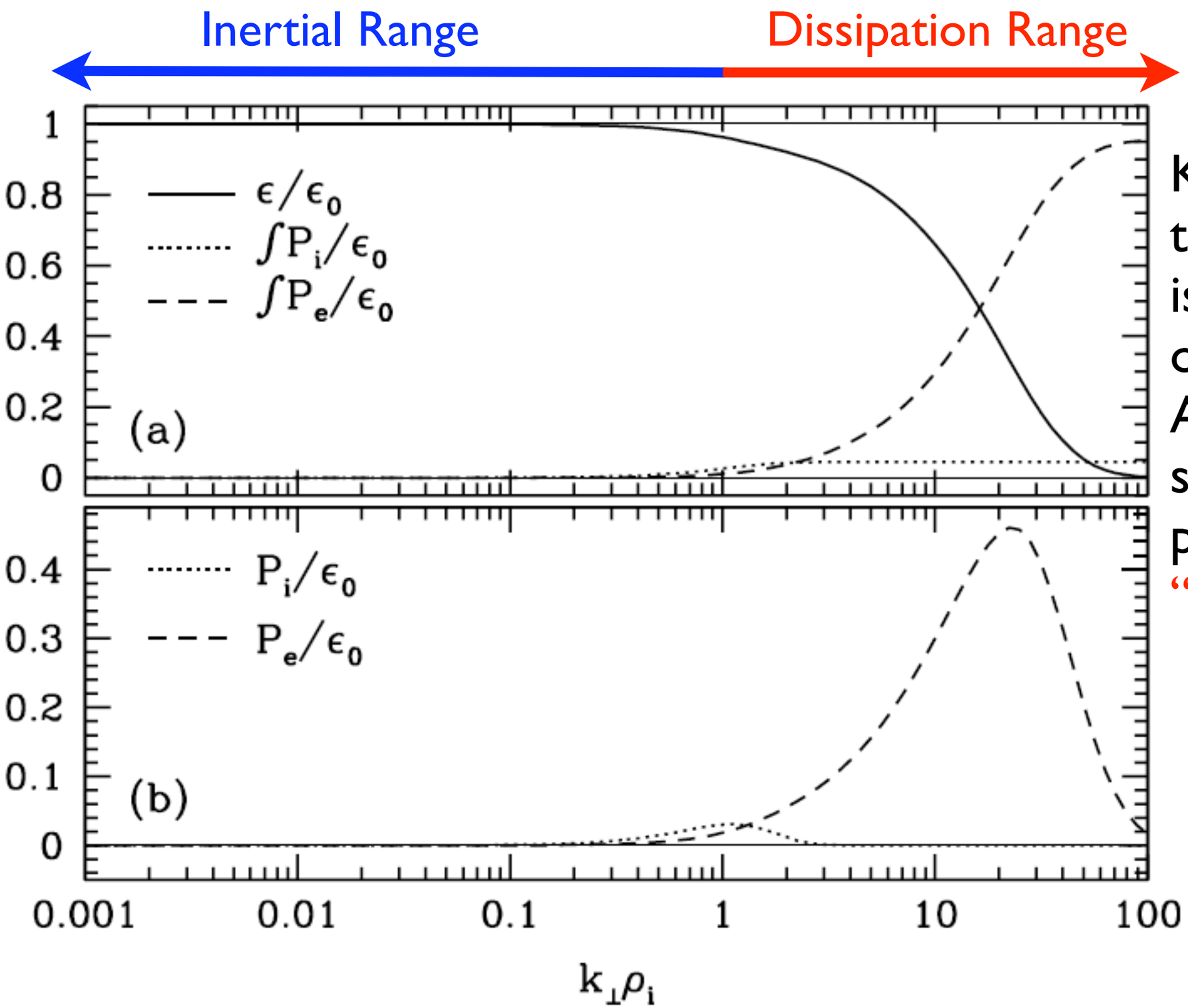


This excellent analysis demonstrates that the wave modes within the dissipation range are consistent only with Kinetic Alfven Waves

(Salem, Sundkvist, and Bale 2009, Solar Wind 12 Conference)

Question #3

3) Is this a "dissipation range" or a "dispersion range"?



Kinetic damping, via the Landau resonance, is generally important over the entire Kinetic Alfven Wave cascade, so this should properly be called the "Dissipation Range"

Conclusions

We have proposed a model of the kinetic turbulent cascade

- First-principles calculations of the kinetic turbulent cascade using AstroGK are an invaluable tool to test this model

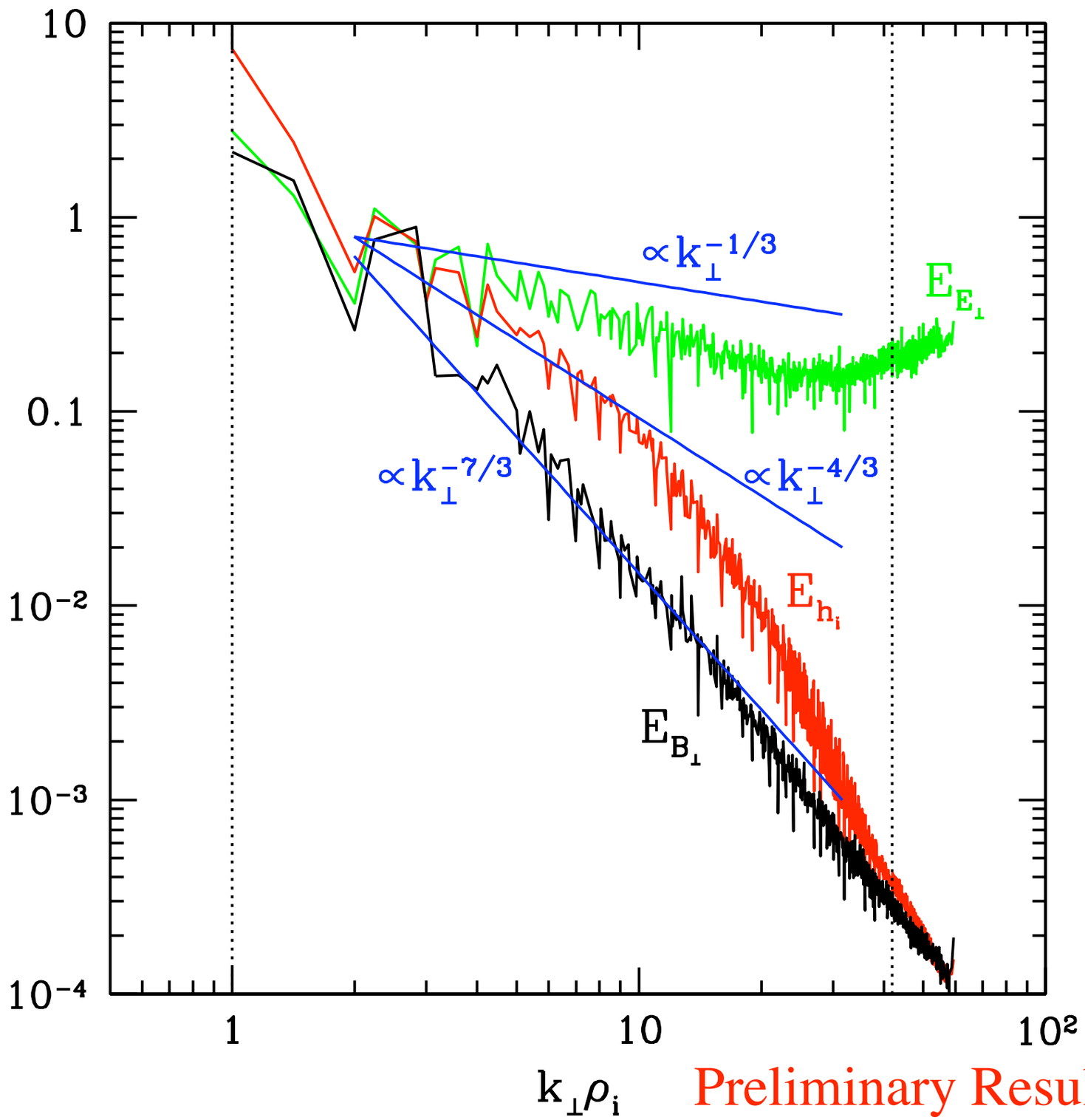
- 3-D calculations with physical mass ratio enable direct comparison to observations
  - Show that a Kinetic Alfven Wave cascade can reach $k_\perp \rho_e \sim 1$

- Ability to simulate a wide range of plasma parameters enables key testing of analytical models
  - Identify the need to account for nonlocal effects on cascade

We have just scratched the surface of questions we can answer with gyrokinetic simulations of kinetic turbulence

Current and Future Work

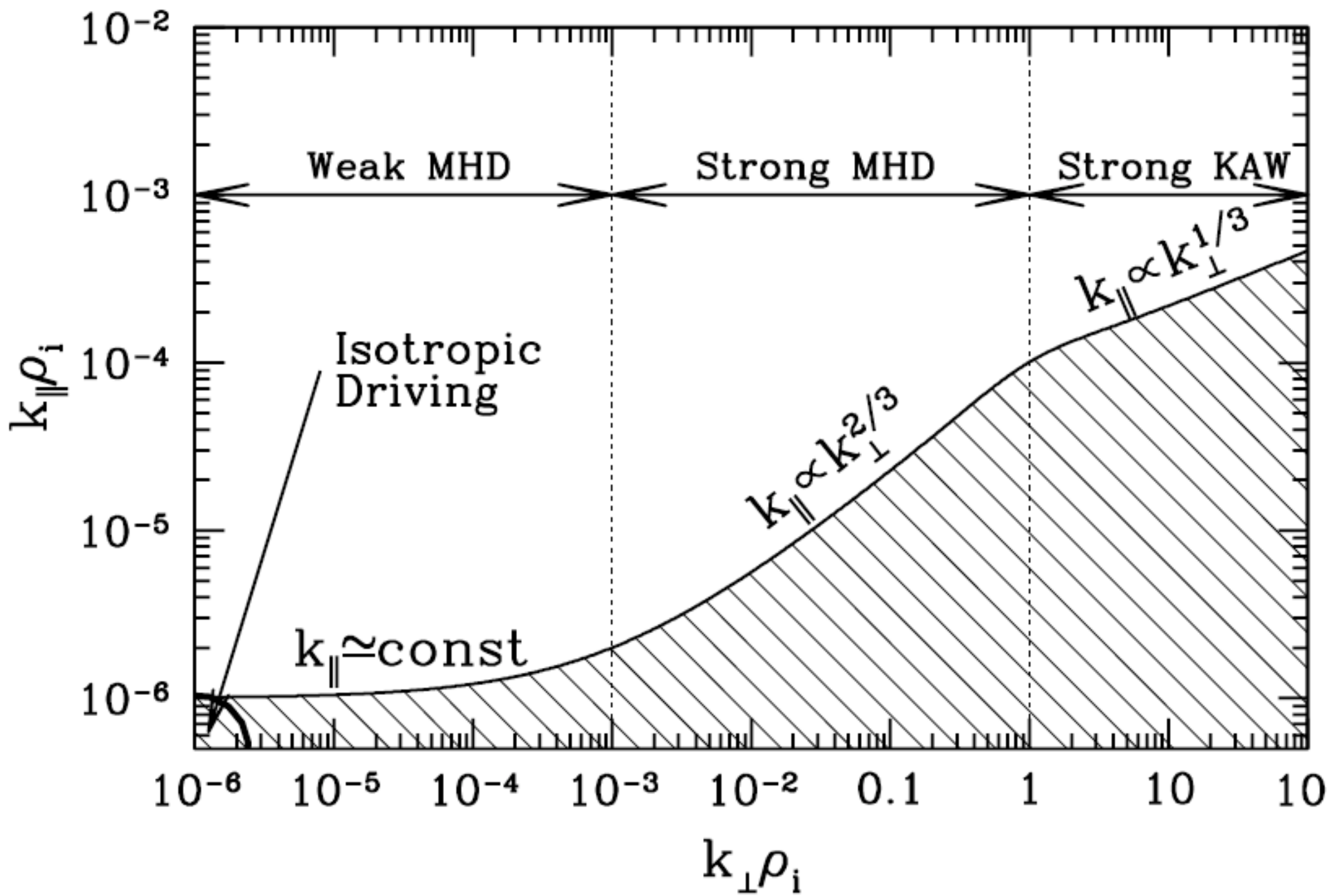
What is the role of entropy cascade in the turbulent dissipation and plasma heating?



Preliminary Results

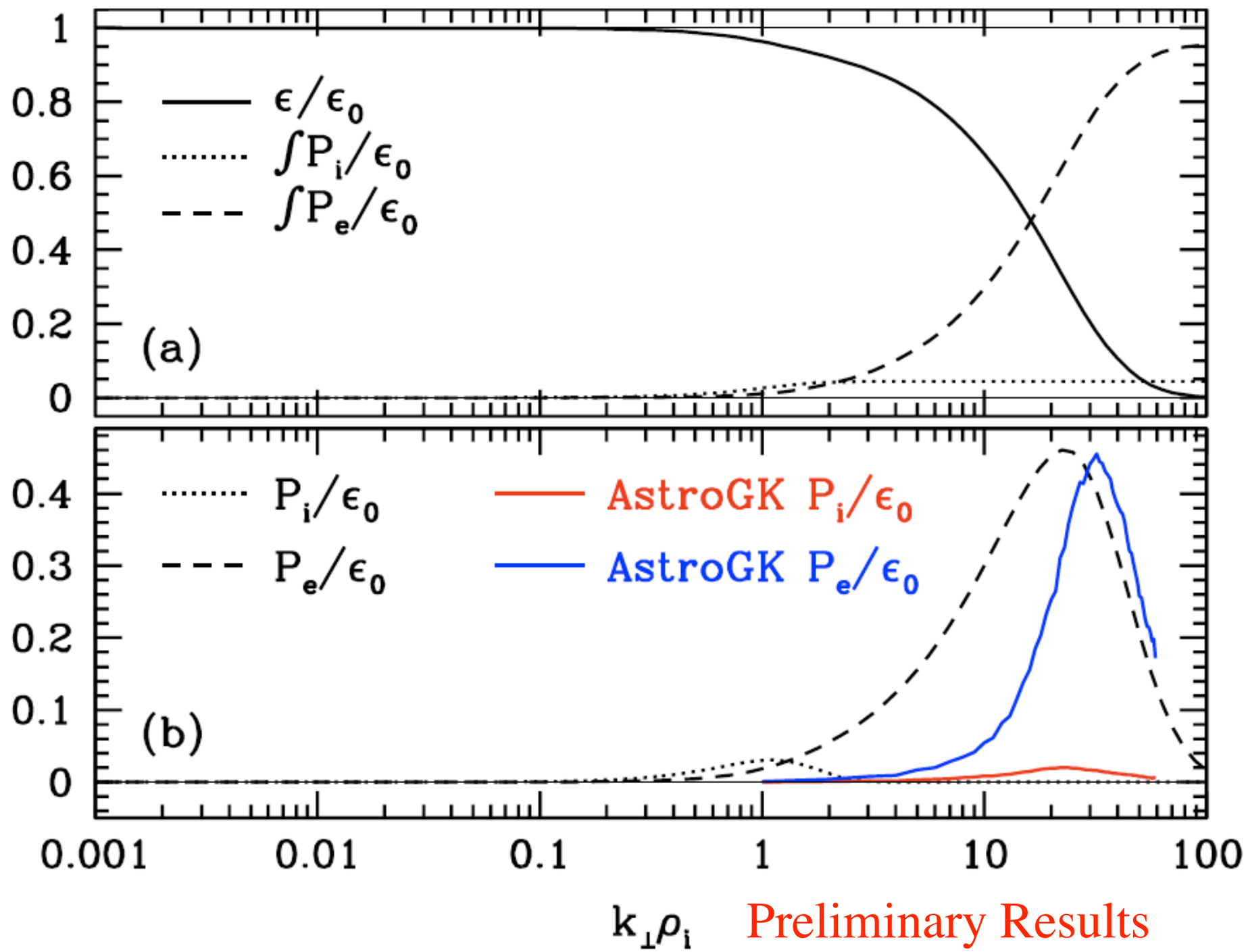
Current and Future Work

What anisotropy characterizes the distribution of power in wavevector space for KAW turbulence?



Current and Future Work

What determines the relative heating of ions, electrons, and minor ions?



Preliminary Results

THE END

Weakened Cascade Model

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Magnetic Energy Continuity

$$\frac{\partial b_k^2}{\partial t} = -k_\perp \frac{\partial \epsilon}{\partial k_\perp} + S - 2\overline{\gamma} k_\| v_A b_k^2$$

Nonlinear Energy Transfer

Linear Kinetic Damping

Energy Cascade Rate

$$\epsilon = C_1^{-3/2} \omega_{nl} b_k^2$$

Nonlinear Frequency

$$\omega_{nl}(k_\perp) = \int_{k_{\perp 0}}^{k_{\perp max}} d\ln k'_\perp \omega_{nl}^{(\mathrm{loc})}(k'_\perp) \times \left[\Theta(k_\perp - k'_\perp) + \frac{k_\perp^2}{k'^2_\perp}\Theta(k'_\perp - k_\perp)\right]$$

where $\omega_{nl}^{(\mathrm{loc})}(k'_\perp) = \chi(k'_\perp) k'_\perp b_k(k'_\perp) \overline{\omega}(k'_\perp)$

Parallel Cascade

$$\frac{d\ln k_\|}{d\ln k_\perp} = \left[\frac{2/3 + (1/3)(k_\perp \rho_i)^2}{1 + (k_\perp \rho_i)^2}\right] \chi^2$$

Nonlinearity Parameter

$$\chi = \frac{C_2 k_\perp b_k}{k_\| v_A}$$

Nonlocal Effects on Cascade