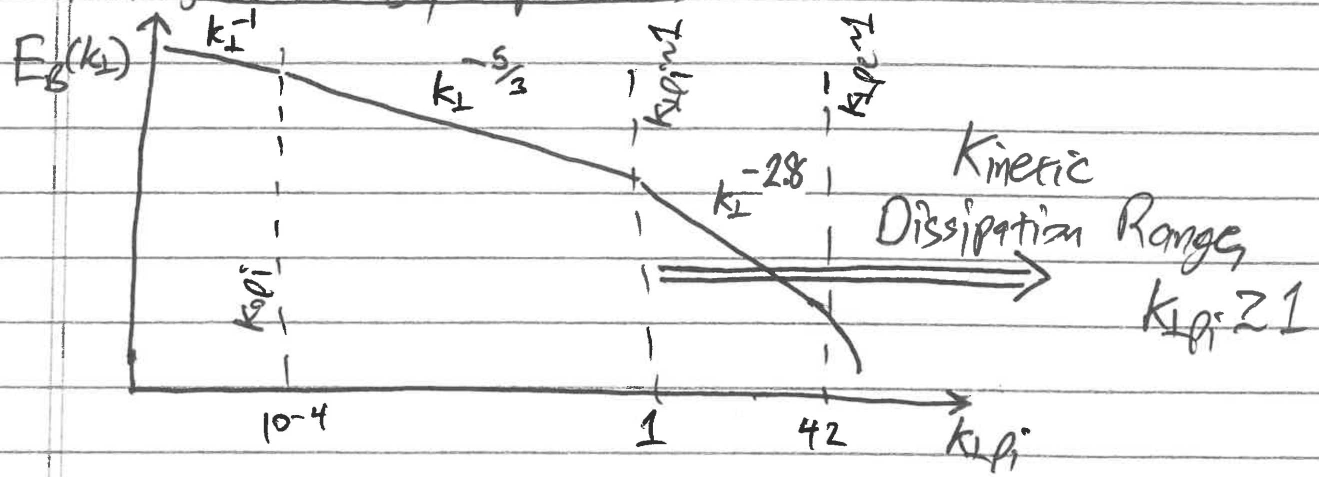
Lecture #14: Key Results on Kinetic Turbulence: Dissipation Range

I. The Dissipation Range of Kinetic Turbulence

A. Magnetic Energy Spectrum



1. Magnetic Energy Spectrum Steepens
2. Eventually turbulent cascade is terminated ⇒ plasma heating!

B. Key Questions

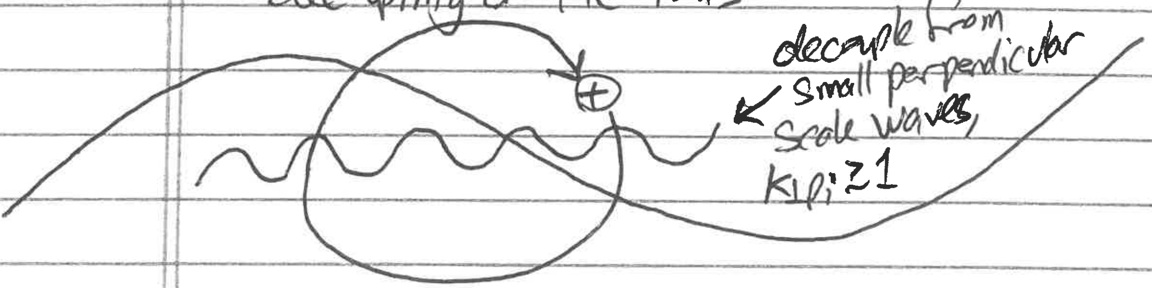
1. What controls the scale of the transition from the inertial to the dissipation range?
2. What is the nature of the fluctuations in the dissipation range?
3. What physical mechanisms damp the turbulent fluctuations?
4. How do coherent structures (current sheets) arise?

II. Key Features of Dissipation Range Turbulence

A. Transition Scale

1. MHD breaks down at ion kinetic scales $(k\rho_i \gtrsim 1)$.
   a. In the solar wind at 1 AU, the break is measured at a spacecraft frame frequency of $f \sim 0.4$ Hz. (Kiyani, et al. 2015)

2. Kinetic Physics
   a. Ion Finite Larmor Radius (FLR) effects lead to decoupling of the ions



   b. Linear wave modes become dispersive (phase and group velocities become dependent on $\underset{\sim}{k}$).

   c. Collisionless damping can become significant
      i) Ion damping peaks at $k\rho_i \sim 1$
      ii) Electron damping increases as $k\rho_i \gtrsim 1$ increases.

3. Many efforts in the literature to connect break to a characteristic scale
   a) Ion cyclotron frequency
   b) Doppler-shifted ion Larmor radius, $\rho_i = \frac{v_{ti}}{\Omega_i}$
   c) Doppler-shifted ion inertial length, $d_i = \frac{v_A}{\Omega_i} = \frac{c}{\omega_{pi}}$

Taylor's hypothesis $k \to f$ } b), c)

II. A. (Continued)

4. Contradictory Results have been found! Probably due to three competing effects at this scale: (Howes, 2015)
   a) Transition to dispersive waves (FLR)

   b) Peak in ion damping

   c) Possible role of energy injection by kinetic instabilities (Bale et al., 2009; Lion, et al., 2016)

5. "The Cone" suggests $k_\perp \rho_i \sim 1$ (Schekochihin et al., 2009)

B. Turbulent Fluctuations at the Transition Scale

1. Anisotropic Cascade: For $k_0 \rho_i \gg 1$, we expect $k_\perp \gg k_\parallel$ at $k_\perp \rho_i \sim 1$ (Howes, et al. 2008a,b; Schekochihin et al, 2009; Howes, et al. 2011)
   a. This is observationally supported by multispacecraft measurements (Sahraoui et al, 2010; Narita et al 2010; Roberts et al. 2013, 2015)

2. Alfven & Fast Wave modes (Howes, et al, 2014):
   a) For $k_\perp \rho_i \gtrsim 1$, and $k_\parallel \ll k_\perp$ $\Rightarrow$ KAWs. (Hasegawa & Sato; 1989; Stix, 1992)

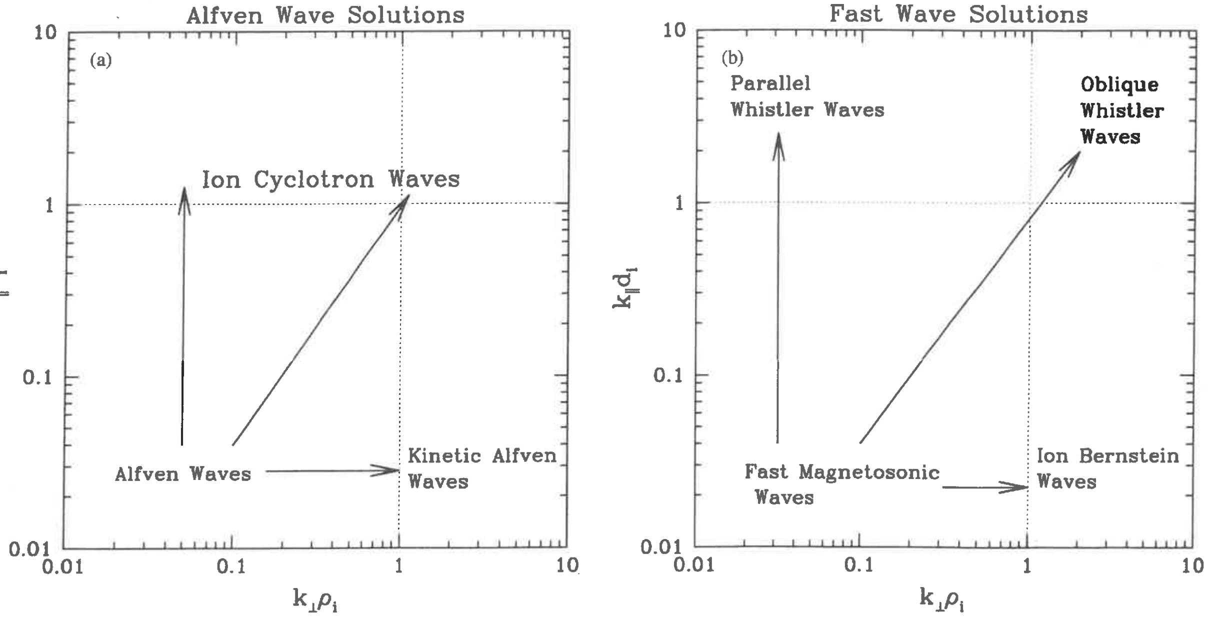


Figure 1. (a) Diagram of the region of $(k_\perp, k_\parallel)$ wavevector space inhabited by the linear wave modes of the Alfvén wave branch for a collisionless kinetic plasma governed by the Vlasov–Maxwell equations. (b) Same, for the fast wave branch.

II, B. 2. (Continued)

b) Since little fast wave energy in inertial range (Howes et al 2012), likely mostly Alfvenic.

c) Little energy expected to transition to fast modes:

(Howes, et al, 2014)

i) Alfven wave: $\omega_A \sim k_\parallel v_A$

ii) Fast wave: $\omega_F \sim k v_A \simeq k_\perp v_A$ when $k_\parallel \ll k_\perp$

iii) Thus $\frac{\omega_F}{\omega_A} \sim \frac{k_\perp \cancel{v_A}}{k_\parallel \cancel{v_A}} \sim \frac{k_\perp}{k_\parallel} \gg 1 \Rightarrow$ Frequency mismatch

$\Rightarrow$ Due to the frequency mismatch, little nonlinear transfer of Alfven wave energy to fast wave energy at $k_\perp \rho_i \sim 1$

(Howes et al, 2012)

3. Linear KAW Properties:

a) $$\omega = k_\parallel v_A \sqrt{1 + \frac{(k_\perp \rho_i)^2}{\beta_i + \frac{2}{1 + T_e/T_i}}}$$ (Howes et al. 2014)

b) KAW becomes compressible at $k_\perp \rho_i \gtrsim 1$

c) Strong collisionless damping by ions can occur at $k_\perp \rho_i \sim 1$.

4. Energy of Inertial Range Fluctuations:

a. 90-99% energy incompressible, 1-10% compressible (Bruno & Carbone, 2005; Alexandrova et al 2008)

b. Compressible is ~~all~~ slow waves in solar wind (Howes et al 2012)

$\Rightarrow$ 5. Turbulent energy expected to transfer to KAWs at $k \rho_i \gtrsim 1$ (Leamon et al, 1998, 1999; Gruzinov 1998; Quataert & Gruzinov 1999, Howes et al 2008a, TenBarge 2009)

II. (Continued)

C. Nature of Turbulent Fluctuations at Sub-Ion Scales

1. Early research focused on trying to identify the nature of turbulence in the dissipation range (at sub-ion scales):

   a. Mechanisms that dissipate the turbulence will depend strongly on the nature of these fluctuations.

2. Two primary candidates:

   a) Whistler waves (Stawicki et al 2001; Gary et al 2010; Narita & Gary, 2010)

   b) Kinetic Alfven Waves (Leamon et al 1998, 1999; Gruzinov, 1998; Quataert & Gruzinov 1999, Howes et al. 2008a; Schekochihin et al 2009)

3. Other possibilities?
   a. Ion cyclotron waves (Jian et al, 2009)
   b. Ion Bernstein waves (Sahraoui et al. 2012)
   c. Pressure Balanced Structures (PBSs): non-propagating
   d. Inherently nonlinear structures or Current Sheets (Servidio et al, 2011)

4. Wave Mode Identification using Linear Wave Eigenfunctions

   a. Quasi-linear premise: Turbulence consists of largely linear wave modes that exchange energy nonlinearly

      i) Since amplitude $\frac{|\delta \underset{\sim}{B}|}{|\underset{\sim}{B}|} \ll 1$ at $k_\perp \rho_i \gtrsim 1$, fluctuations are expected to exhibit linear properties

II. C. 4. a. (Continued)

ii) Critical Balance:

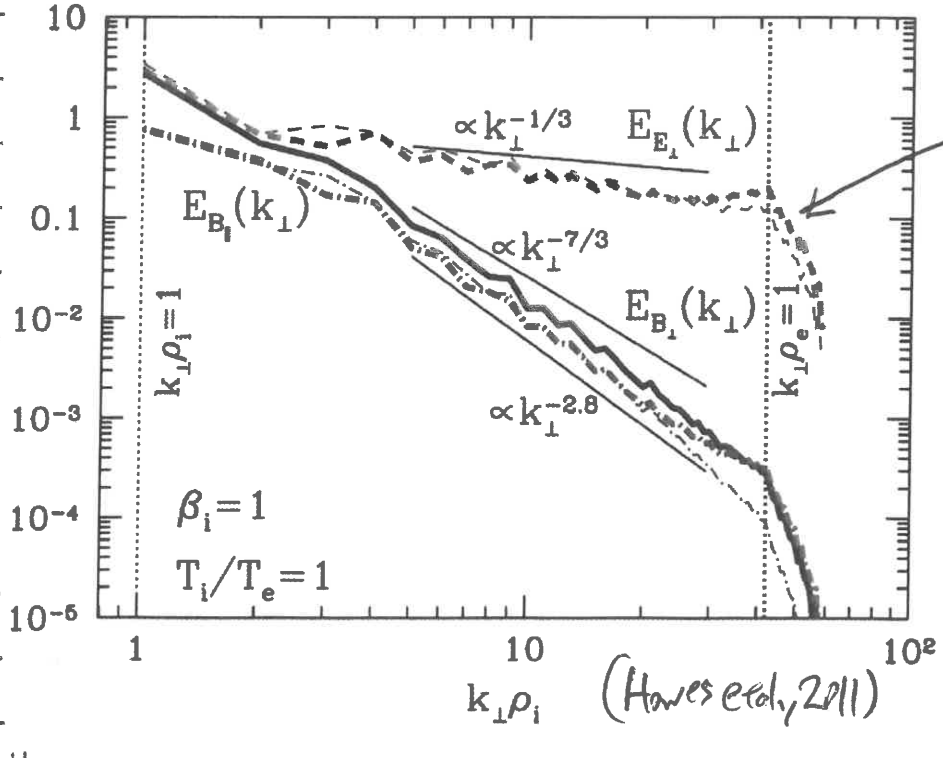
$$\frac{\partial z^\pm}{\partial t} \mp \underbrace{\underset{\sim}{v_A}\cdot\nabla \underset{\sim}{z}^\pm}_{\text{Linear}} = -\underbrace{\underset{\sim}{z}^\mp\cdot\nabla \underset{\sim}{z}^\pm}_{\text{Nonlinear}} - \frac{\nabla P}{\rho_0}$$

- Since $\chi \sim \frac{|\text{Nonlinear}|}{|\text{Linear}|} \sim 1 \rightarrow$ Linear term always contributes, even in Strong Turbulence

b. Can use relations between different components of the Wave Eigenmode (e.g. $\frac{\delta E_y}{\delta B_z}$, or $C(\delta n, \delta B_\parallel)$) to distinguish Alfven, fast, and Slow waves!

5. Numerical Results Supporting KAW Turbulence

a. Gyrokinetic Simulations: (Howes et al 2008b; Howes et al, 2011, TenBarge et al. 2013)



(Howes et al, 2011)

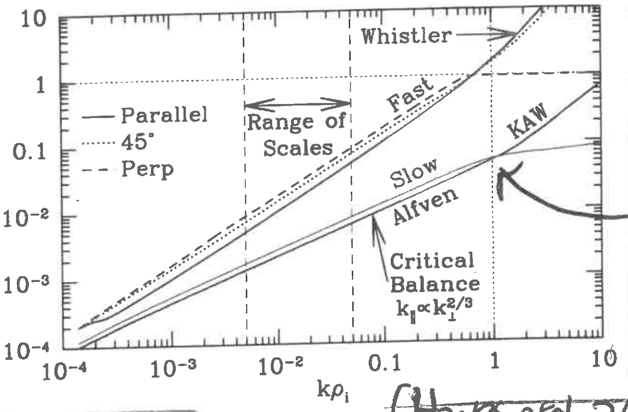
Prediction from Linear Eigenfunction (thin) matches Simulation result (thick)

i) Note: GK sim's. do not include fast/whistler wave physics.

II. C. 5 (Continued)

b. Fully Kinetic Particle-in-Cell (PIC) Simulations show transfer of energy dominantly to KAWs, even though whistlers are represented (Groselj et al. 2018)

c. Again, the mismatch of frequencies argues for little whistler energy



Frequencies at $k_\perp \rho_i \sim 1$ transition very different!

(Howes et al. 2012)

6. Observational Results Supporting KAW Turbulence

a. Observational plot of $\frac{\delta E_y}{\delta B_z}$ agrees with KAW dispersive increase of phase velocity (Bale et al. 2005)

b. Comparison of both $\frac{|\delta E|}{|\delta \mathbf{B}|}$ and $\frac{|\delta B_\parallel|}{|\delta \mathbf{B}|}$ shows the fluctuations are consistent with KAWs, but not whistlers (Salem et al. 2012)

c. Magnetic Helicity: $\sigma_m = \frac{k[i(B_y B_z^* - B_y^* B_z)]}{k_x |\mathbf{B}|^2}$ (Howes & Quataert, 2010)

i) Can be used to show dominantly KAW turbulence at $k_\perp \gg k_\parallel$, with a small contribution of whistler or ion cyclotron waves at $k_\parallel \gg k_\perp$ (He et al. 2011; Podesta & Gary 2011)

likely due to kinetic instabilities

II. C. G. (Continued)

d) Excellent Review of observational evidence for KAWs:
(Chen, 2016)

7. Note that if $\omega \to \Omega_i$, ion cyclotron damping may occur (Howes, 2011)

D. Kinetic Temperature Anisotropy Instabilities

1. Due to the spherical expansion of the outward flowing solar wind, a temperature anisotropy can develop that can trigger instability.

2. Ion temperature Anisotropy Instabilities

$\frac{T_\perp}{T_\parallel} < 1$

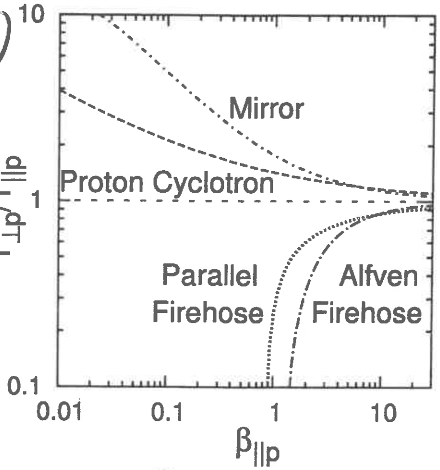
a) Parallel Firehose (Kennel 1966; Gary et al. 1976)

b) Alfven (Oblique) Firehose (Hellinger & Matsumoto, 2000)

$\frac{T_\perp}{T_\parallel} > 1$

c) Mirror Instability (Vedenov & Sagdeev, 1958; Tajiri 1967; Southwood & Kivelson, 1993)

d) Proton cyclotron (Gary et al. 1976)



(Klein & Howes, 2015)

3. Approximate marginal stability boundaries (Hellinger, et al. 2006)

TABLE I. Instability threshold parameters for $\gamma/\Omega_i|_{max} = 10^{-3}$ from Ref. 3.

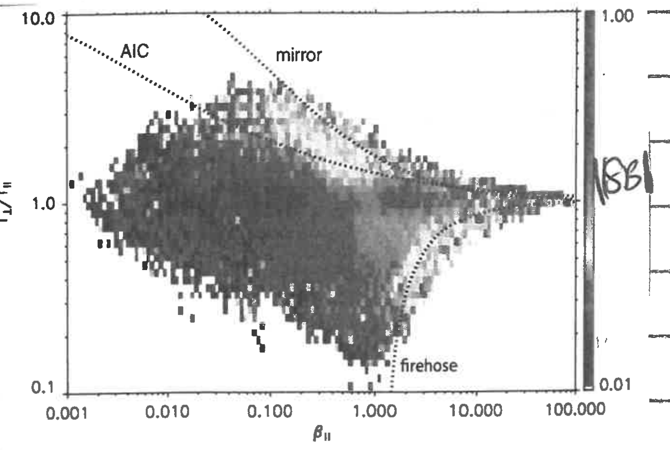
	a	b	β_0
Proton cyclotron	0.43	0.42	−0.0004
Parallel firehose	−0.47	0.53	0.59
Alfvén firehose	−1.4	1.0	−0.11
Mirror	0.77	0.76	−0.016

$$\boxed{\frac{T_\perp}{T_\parallel} = 1 + \frac{a}{(\beta_\parallel - \beta_0)^b}}$$

II. D. (Continued)

4. Wind spacecraft observations in Solar wind at 1 AU

a. 10 years of Wind data shows clear evidence of enhanced turbulent magnitudes $|\delta \underline{B}|$ near instability boundaries (Bale, etal. 2009)



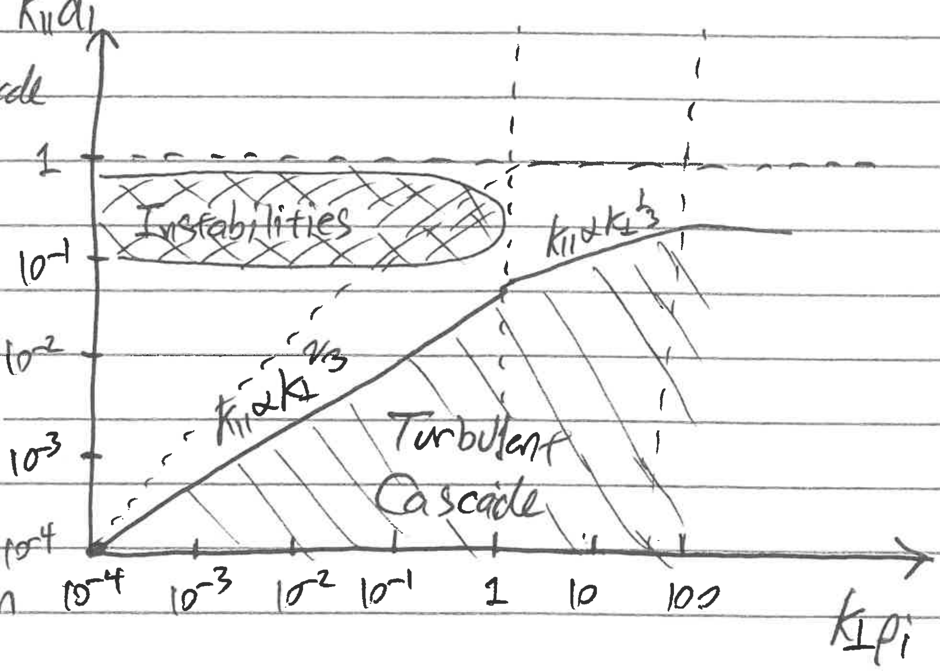
b. Thus instabilities contribute to turbulent fluctuations.

5. Instability-driven fluctuations are distinct from fluctuations associated with the turbulent cascade (Klein & Howes, 2015; Howes 2015; Kunz etal 2018)

a. Ion temperature anisotropy instability growth rates peak at scales $k_\parallel d_i \sim k_\parallel \rho_i \sim 1$ (Klein & Howes, 2015)

b. For a turbulent cascade driven at $k_0 \rho_i \ll 1$, fluctuations have $k_\parallel \ll k_\perp$

∴ Conjecture: Instability & turbulent fluctuations may persist side-by-side without significant interaction (Howes & Klein, 2015)



II. D. (Continued)

6. At higher values of $\beta_\parallel \gg 1$, the marginal stability boundaries converge to $\frac{T_\perp}{T_\parallel} \to 1^{\pm}$

   a. Thus, only a small range of $\frac{T_\perp}{T_\parallel}$ were fluctuations are stable

   b. In this case, instabilities can disrupt the turbulence altogether (Squire et al. 2016, 2017a,b)

7. In addition to ion instabilities driven modes with $k_\parallel d_i \sim 1$, electron instabilities can inject energy into fluctuations at smaller scales, $k d_i \gg 1$. (LaCombe et al. 2014)

E. Scaling of Turbulence Spectrum in Dissipation Range

1. From Lect #11, Sec II, A, predicted scaling for KAW turbulence is

   a. $E_B(k_\perp) \propto k_\perp^{-7/3}$

   b. Anisotropy: $k_\parallel \propto k_\perp^{1/3}$

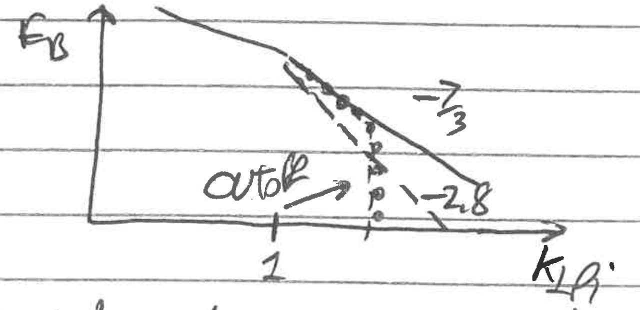
2. Observations show a scaling closer to about -2.8 rather than $-7/3 \simeq -2.3$ (Sahraoui et al. 2009, 2010; Kiyani et al 2010; Alexandrova et al. 2009, 2012; Chen et al. 2010)

   a. Perhaps this is not surprising since scale separation $\frac{\rho_i}{\rho_e} \simeq 42$.
   $\Rightarrow$ not "asymptotic" scale separation!

II. E. (Continued)

3. Why is the observed spectrum steeper than $-\frac{7}{3}$?

a. Collisionless damping was suggested. But early models predicted an exponential cutoff, rather than a steepened power law
(Howes et al. 2008;
Podesta et al. 2010)



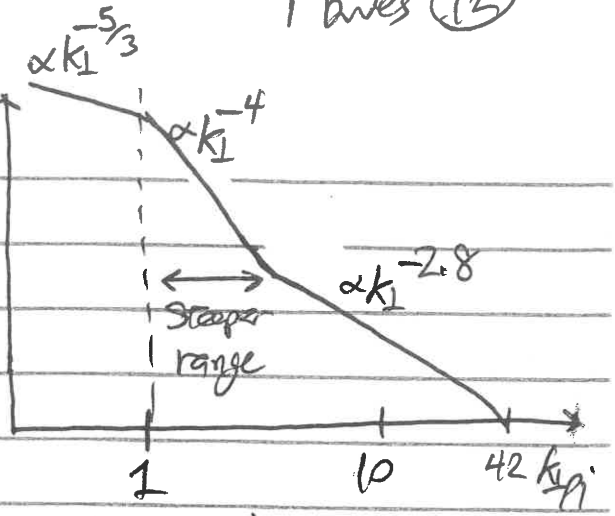
b. But numerical simulations showed an exponential cutoff does not occur! (Howes et al. 2011a)

c. A refined model, the "Weakened Cascade Model", taking into account collisionless damping and nonlocal energy transfer results in a further steepening of the power law beyond $-7/3$ at $k_\perp \rho_i \gtrsim 1$, and was able to reproduce a -2.8 spectrum
(Howes et al. 2011b)

d. More recent simulations have demonstrated that damping is active over the entire range $k_\perp \rho_i \gtrsim 1$, leading to a contribution from nonlocal energy transfer
(Told et al. 2015)

e. An alternative explanation, which does not require damping, is that intermittency of turbulent fluctuations at $k_\perp \rho_i \gtrsim 1$ can steepen the spectrum to $-8/3 \simeq -2.67$
(Boldyrev & Perez, 2012)

II. E. (Continued)



4. Steepening just below ion scales

a. Observations sometimes show a narrow range just below ion scales with a much steeper -4 spectrum (Sahraoui et al 2010, 2013; Bruno et al. 2014)

b. Faster solar wind with more turbulence power in inertial range has a steeper sub-ion spectrum (Bruno et al. 2014)

c. May be associated with an ion damping mechanism that is amplitude dependent.

5. Gyrokinetic simulations support the predicted scale dependent anisotropy $k_\parallel \propto k_\perp^{1/3}$ (TenBarge & Howes, 2013; TenBarge et al. 2013)

F. Mechanisms that Damp Turbulence in the Dissipation Range

1. Proposed Mechanisms for damping turbulent fluctuations fall into three general categories:

a) Resonant mechanisms: Landau damping, Transit-time damping, or ion cyclotron damping (Landau 1946; Barnes, 1966; Kennel, 1966; Coleman, 1968; Isenberg & Hollweg, 1983; Leamon et al 1998a, b; Quataert & Gruzinov 1999; Howes et al 2008a; Schekochihin et al 2009)

b) Non-resonant mechanisms: Stochastic ion heating (Chen et al. 2001; Johnson & Cheng, 2001; Chandran et al. 2010; Chandran 2010), or magnetic pumping by compressible fluctuations (Berger et al. 1958; Lichko et al. 2017)

c) Spatially localized mechanisms: Magnetic Reconnection at intermittent current sheets (Dmitruk et al. 2004; Matthaeus & Velli, 2011; Servidio et al. 2011b; Karimabadi et al. 2013; Zhdankin et al. 2013, 2015; Osman et al. 2014a,b; Loureiro & Boldyrev, 2017)

2. Collisionless damping (Howes et al. 2008a; Told et al. 2015)

a. ion damping peaks at $k_\perp \rho_i \sim 1$

b. electron damping increases monotonically at $k_\perp \rho_i \gtrsim 1$

3. Investigation of particle energization using the Field-Particle Correlation Technique (FPC) (Klein & Howes, 2016; Howes et al. 2017; Klein et al. 2017)

a. Kinetic numerical simulations showed ion Landau damping is effective in damping turbulence (Klein et al. 2017)

b. Current sheets are seen to arise from Alfvén & KAW turbulence (Howes, 2016; Verniero et al. 2018; Verniero & Howes, 2018). The FPC technique shows ion & electron Landau damping governs dissipation in these current sheets (Howes et al. 2018).

c. Higher frequency turbulence using a hybrid (kinetic ion & fluid electron) simulation shows a combination of ion Landau damping & ion cyclotron damping (Klein et al. 2020).

d. Application of the FPC technique to spacecraft measurements in the turbulent magnetosheath by the Magnetospheric Multiscale (MMS) mission shows that electron Landau damping is

  i) relatively ubiquitous (95% of 20 cases)
  ii) sometimes dominant (~30% of 20 cases)

(Chen et al. 2019; Afshari et al. 2021)

4. A nice, recent discussion contrasting the importance of waves vs. coherent structures in turbulent dissipation is presented in Groselj et al. (2019)

5. Determining the physical mechanisms of turbulent dissipation and plasma heating is currently an area of vigorous activity in heliophysics.

  a. This is a key goal of both the

    i) $1.5B NASA Parker Solar Probe mission (launched 2018)

    ii) $1.5B ESA Solar Orbiter mission (launched 2020)

II. (Continued)

G. Ion vs. Electron Heating

1. Major Long Term Goal in Heliophysics:

a. Develop a predictive theory of the turbulent dissipation and resulting plasma heating

b. A critical issue is how dissipated energy is partitioned between ions and electrons

2. Early theoretical prediction (Howes 2010)

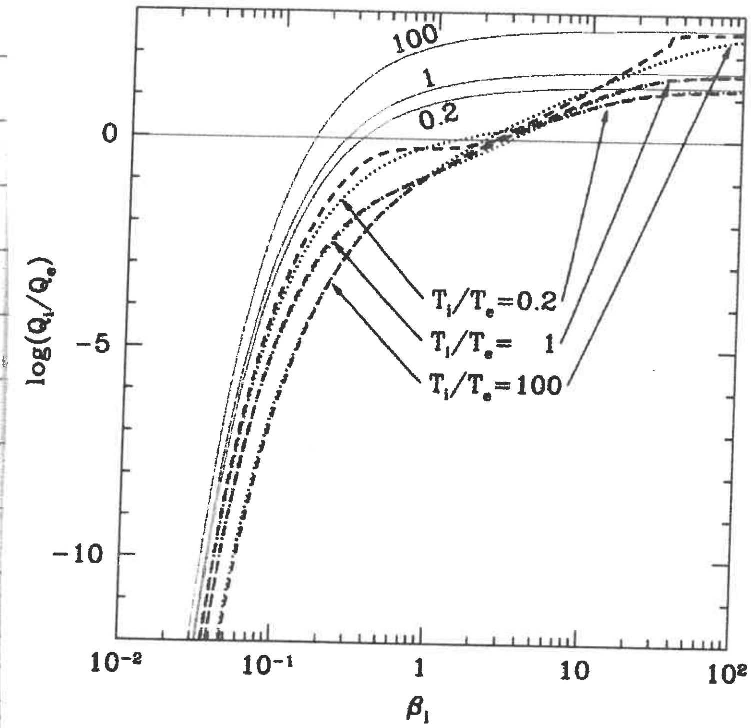


Figure 3. Calculations of $\log(Q_i/Q_e)$ versus β_i from the cascade model (dashed), the fitted heating prescription (equation 3; dotted) and equation (5) (solid) of Quataert (1998).

a) Use cascade model (See Lec #11 Sec II. B.) to predict ion-to-electron heating ratio Q_i/Q_e as a function of β_i & T_i/T_e

$$\frac{Q_i}{Q_e} = c_1 \frac{c_2^2 + \beta_i^p}{c_3^2 + \beta_i^p} \sqrt{\frac{m_i T_i}{m_e T_e}}\, e^{-1/\beta_i}$$

b) Has been widely used to interpret observations from the Event Horizon Telescope

c) Qualitative prediction corroborated by simulations (Kawazura et al. 2019)

II. G. (Continued)

3. In the low beta limit $\beta_i << 1$, analytical calculations predict (Schekochihin et al. 2019)

 a. Alfvénic fluctuations heat only electrons

 b. All ion heating is due to compressible fluctuations

 c. Since the incompressible Alfvénic fluctuations and the compressible fluctuations do not exchange energy in the inertial range, this means the ratio Q_i/Q_e is set at the large scales!

4. Ultimately, we'd like to be able to predict Q_i/Q_e as a function of plasma parameters (β_i, T_i/T_e, etc.) and turbulence parameters ($k_0\rho_i$, compressible to incompressible ratio, χ, etc.)

H. Termination of the Turbulent Cascade

1. Simplified analytical treatment suggest, when dissipation becomes strong, spectrum should fall off exponentially

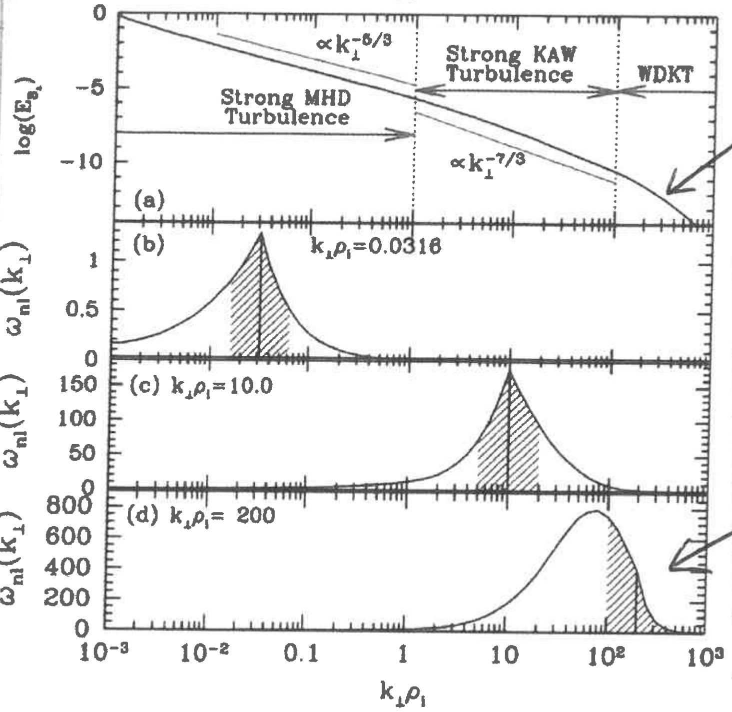
$$E_B \propto k_\perp^{-2.8} e^{-k_\perp\rho_e}$$

for dissipation strong at $k_\perp\rho_e \to 1$ (Terry et al. 2012)

II. H. (Continued)

Howes ⑰

2. Weak Dissipating KAW Turbulence (Howes et al. 2011b)



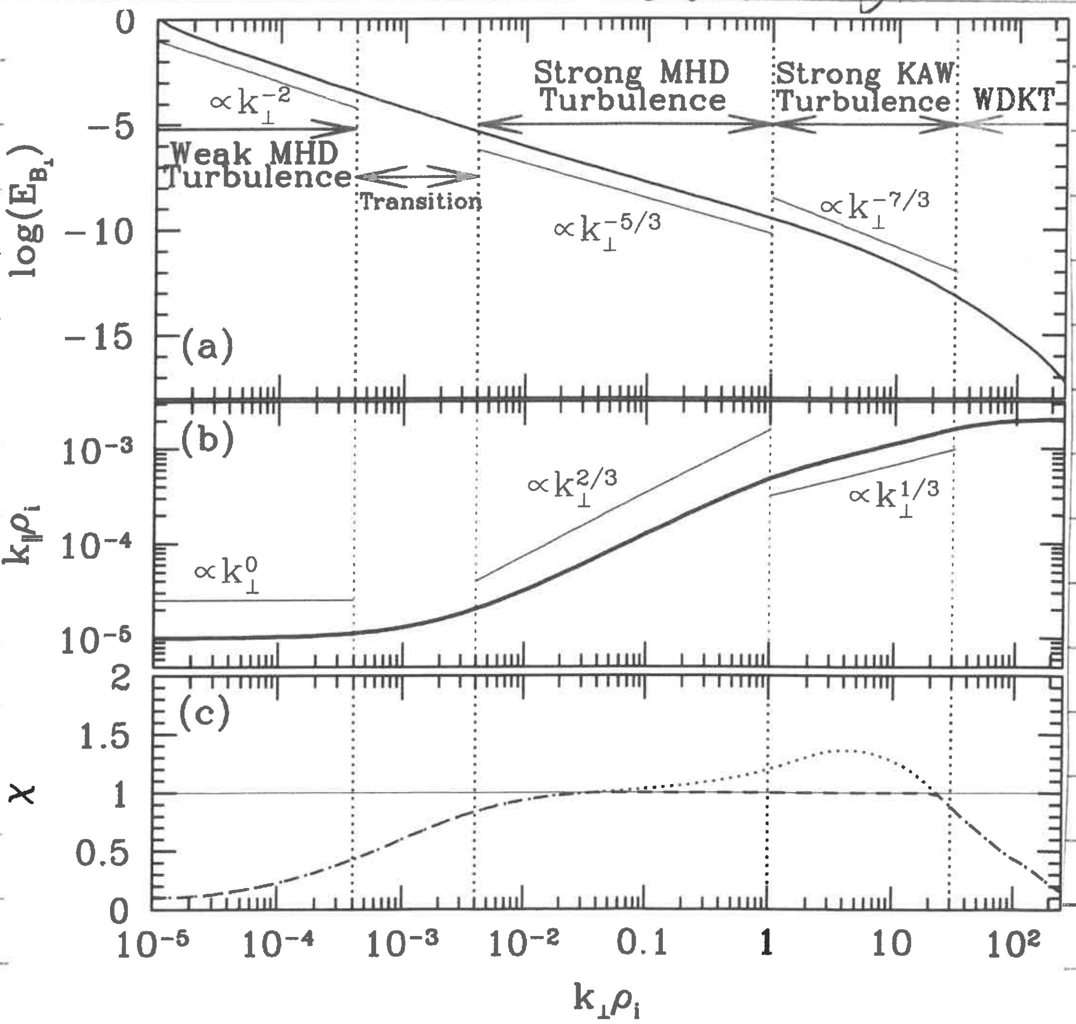
a) Collisionless Damping of fluctuations diminishes amplitude

b) Thus strong turbulence $\chi \sim 1$ transitions to weak turbulence $\chi \ll 1$.

c) Weak local nonlinear energy transfer becomes dominated by nonlocal energy transfer by large scale shearing.

3. Full picture of turbulent cascade.

Weak
→ Strong MHD
→ Strong KAW
→ Weak Dissipating KAW Turbulence (WDKT)



4. The contribution of nonlocal interactions to energy cascade in dissipation range when fluctuations experience damping is confirmed using numerical simulations (Told et al. 2015)

5. Observations indeed show an exponential cutoff at $k_\perp \rho_e \sim 1$,

$$E_B \propto k_\perp^{\alpha} e^{-k_\perp \rho_e} \quad \text{where} \quad -2.8 \le \alpha \le -2.5$$

(Alexandrova et al. 2012)

6. Numerical simulations over the range $0.12 \le k_\perp \rho_e \le 2.5$ indeed yield an energy spectrum fitting $E_B \propto k_\perp^{-2.8} e^{-k_\perp \rho_e}$ (TenBarge et al. 2013).

Haves (19)

III. Summary

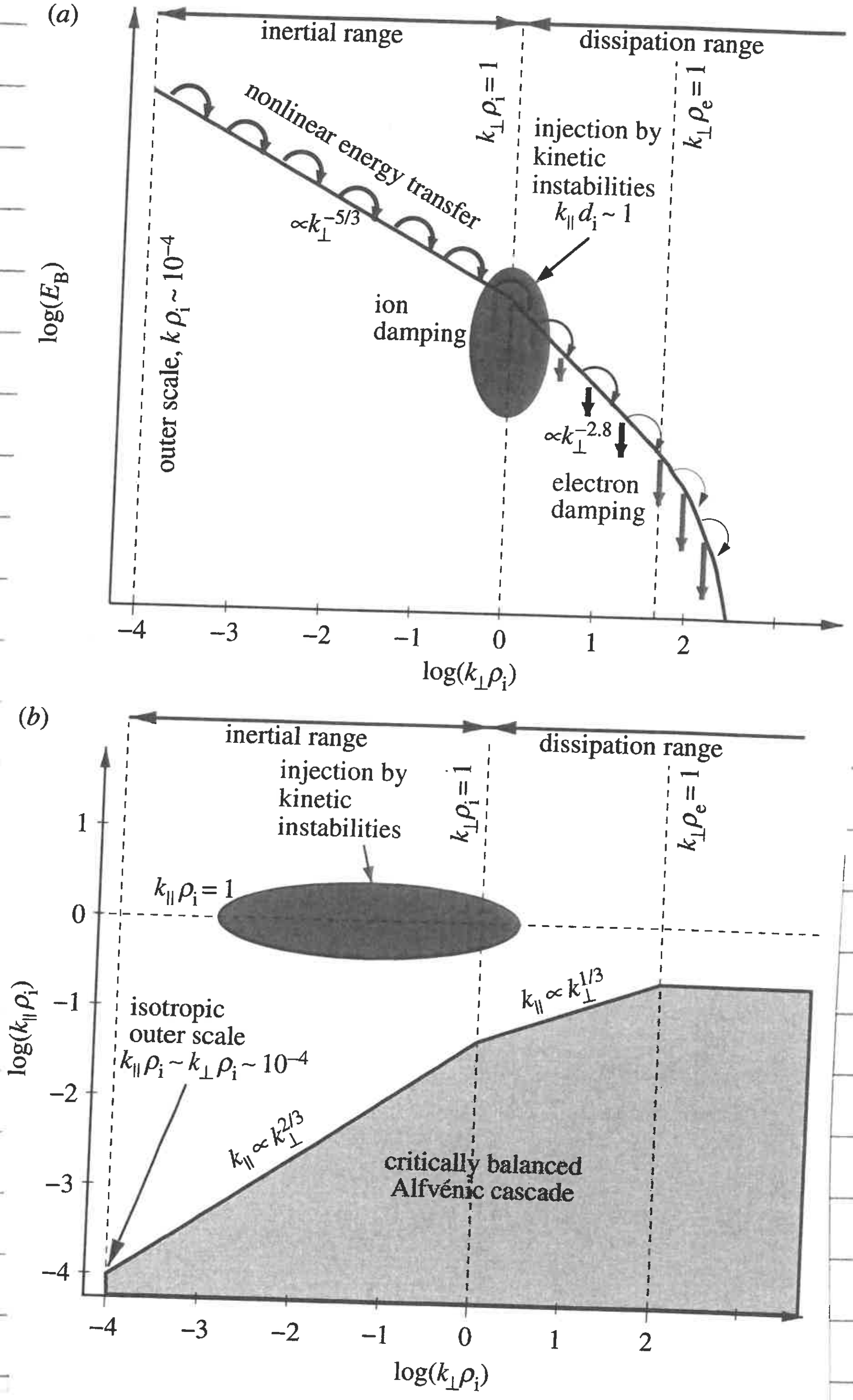


Figure 2. (*a*) Diagram of the magnetic energy spectrum in plasma turbulence, including the injection of energy by kinetic instabilities. (*b*) Anisotropic distribution of power in ($k_\perp$, $k_\parallel$) wavevector space due to both the cascade of energy from large scales (shaded) and the injection of energy by kinetic instabilities (ellipse). (Online version in colour.)

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