Secular Field-Particle Energy Transfer in a Turbulent, Gyrokinetic System

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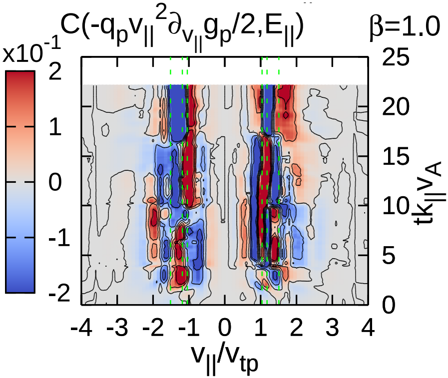

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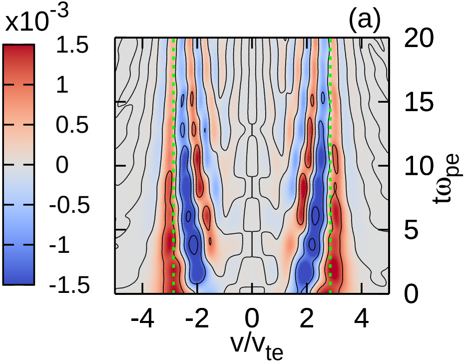
Correlations Measure Secular Transfer of Energy

$$\frac{\partial f_s}{\partial t} + v\frac{\partial f_s}{\partial x} - \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_s}{\partial v} = 0$$

$$\frac{\partial w_s}{\partial t} = -\frac{m_s v^3}{2}\frac{\partial \delta f_s}{\partial x} - \frac{q_s v^2}{2}\frac{\partial f_{s0}}{\partial v}E - \frac{q_s v^2}{2}\frac{\partial \delta f_s}{\partial v}E$$

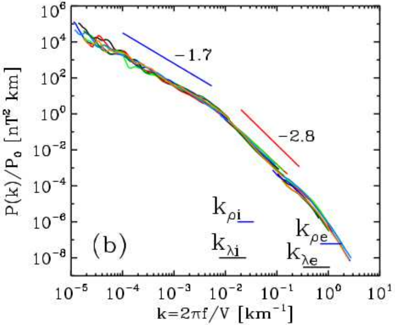
$$C_\tau\left(-\frac{q_s v^2}{2}\frac{\partial \delta f_{s0}}{\partial v}, E\right)$$



Can this method be applied to a fully turbulent system?

Are Correlations Applicable for Fully Turbulence Systems?

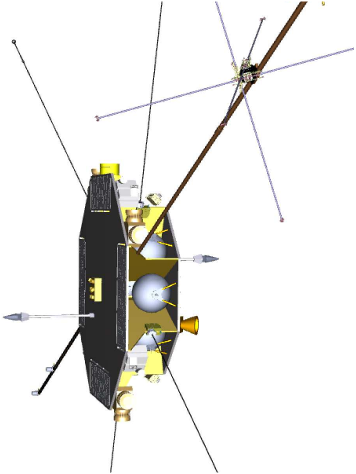
(Alexandrova et al. 2009)



- Turbulence is "Multiscale Disorder" (Schekochihin et al. 2008)
- Classify Damping Mechanisms as:
  - Coherent Wave-Particle
  - Incoherent Wave-Particle
  - Current Sheet Dissipation

Are Correlations Applicable for Fully Turbulence Systems?

http://thor.irfu.se/



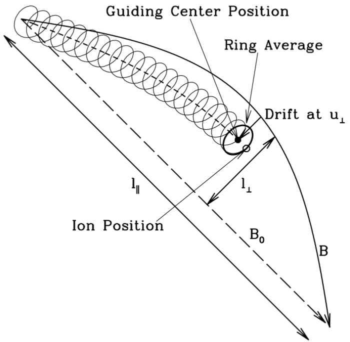
- Turbulence is “Multiscale Disorder” (Schekochihin et al. 2008)
- Classify Damping Mechanisms as:
  - Coherent Wave-Particle
  - Incoherent Wave-Particle
  - Current Sheet Dissipation
- Measurements of many real systems (solar wind turbulence) limited to single point observations

We consider wave-particle correlations from single-point 'observations' of gyrokinetic turbulence simulations

Gyrokinetics, a rigorous kinetic limit

Gyrokinetics is a low-frequency ($\omega \ll \Omega_p$), anisotropic ($k_\parallel \ll k_\perp$) limit of the full six-dimensional kinetic plasma description. (Frieman & Chen 1982, Howes et al. 2006)

The particle's cyclotron motion is averaged out, reducing the velocity phase space from (v_x, v_y, v_x) to $(v_\perp, v_\parallel)$.

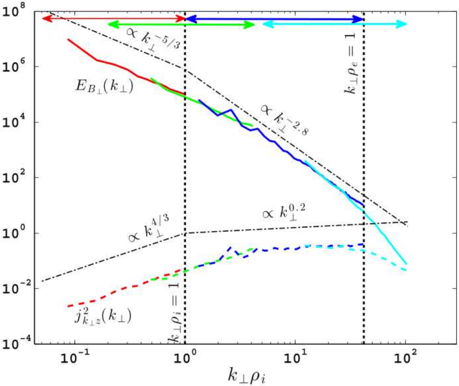


$$f_s(\mathbf{r}, \mathbf{v}, t) = F_{0s}(v)\left(1 - \frac{q_s\phi(\mathbf{r}, t)}{T_{0s}}\right) + h_s(\mathbf{R}_s, v_\perp, v_\parallel, t) + \delta f_{2s} + \ldots$$

The *Astrophysical Gyrokinetics* Code

AstroGK (Numata et al. 2010) is adapted from the code *GS2*

- Solves $h_s(\mathbf{R}_s, v_\perp, v_\parallel, t)$, $\phi(\mathbf{R}_s, t)$ $A_\parallel(\mathbf{R}_s, t)$, $\delta B_\parallel(\mathbf{R}_s, t)$ in an elongated triply periodic box with a uniform background magnetic field and no equilibrium gradients
- Can be driven via Langevin antennas (TenBarge et al. 2014) or initialized wave profiles (Nielson Thesis, 2012)



Linear and nonlinear simulations match expected damping and power spectra benchmarks, and has been used to examine a variety of turbulent phenomena (Howes et al. 2008, Howes 2011, TenBarge & Howes 2012, TenBarge et al. 2013, TenBarge & Howes 2013, Numata & Loureiro 2014)

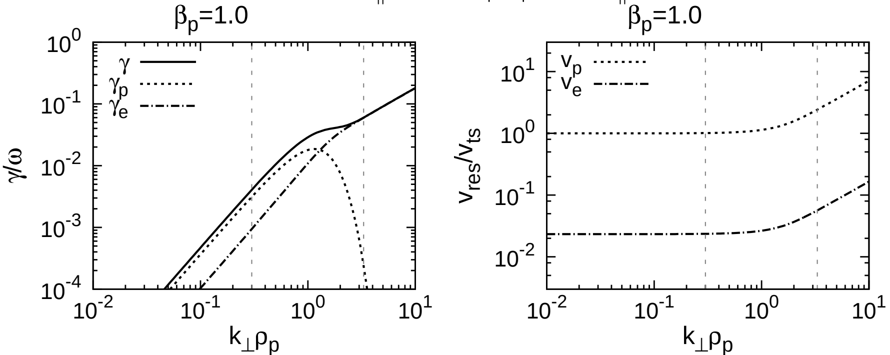
Coherent Damping Mechanisms

Coherent damping occurs for particles satisfying the resonance

$$\omega - k_\parallel v_\parallel - n\Omega = 0.$$

The $n = 0$ resonance corresponds to two physical mechanisms, Landau Damping (Landau 1946) , and Transit Time Damping. (Barnes 1966)

$$-q_s \frac{v_\parallel^2}{2} \frac{\partial \delta f_s}{\partial v_\parallel} E_\parallel; \quad \frac{m_s v_\perp^2}{2|B|} \frac{v_\parallel^2}{2} \frac{\partial \delta f_s}{\partial v_\parallel} \frac{\partial \delta B_\parallel}{\partial z}$$



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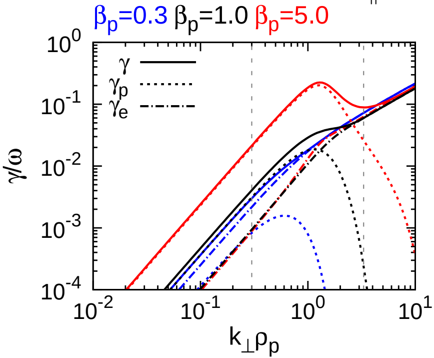

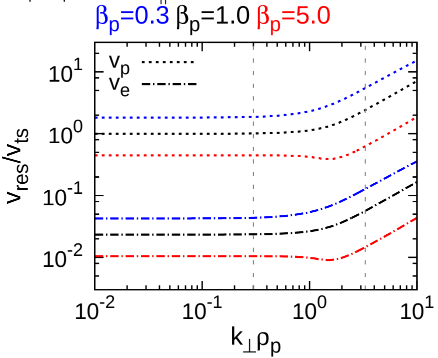

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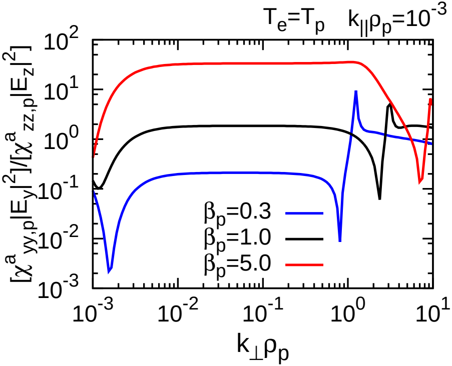
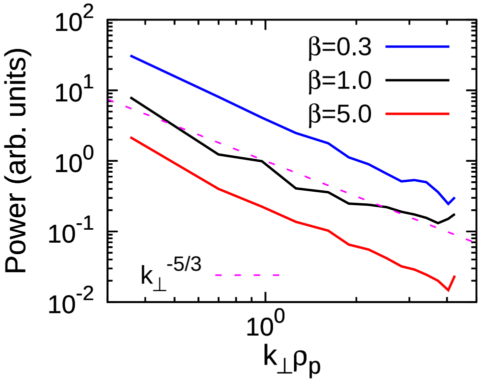


Collisionless Power Absorption can be expressed in terms of Anti-Hermitian Susceptibilities:

LD: $\propto \chi^a_{zz,s} |E_\parallel|^2$

TTD: $\propto \chi^a_{yy,s} |E_y|^2$

Preliminary Simulation Parameters



We perform three initial simulations, with the following parameters:

- $k_\perp \rho_p \in [0.3, 3.3]$
- $\beta_p = 0.3, 1.0, 5.0$
- $T_e = T_i$
- $\nu_s \approx 0.1 \gamma_s(k_{\perp,0})$

(Klein et al. 2016, in prep for submission to JPP)

At a discrete number of points in the simulation domain $\mathbf{x}_i$, we output at a fixed cadence $g_s(\mathbf{x}_i, \mathbf{v}, t)$, $E_\parallel(\mathbf{x}_i, t)$, & $\delta B_\parallel(\mathbf{x}_i, t)$.

"A Technical Step"

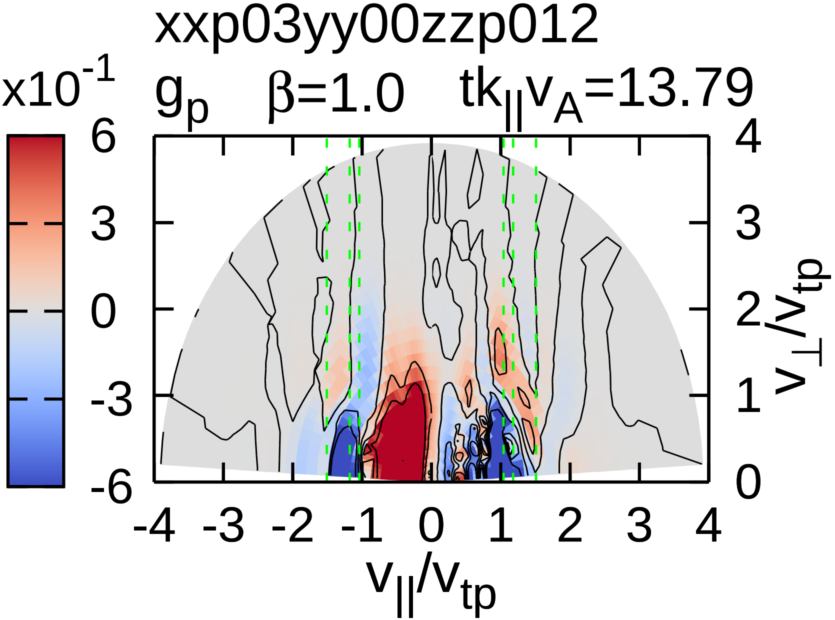
We transform to the complementary perturbed distribution: (Schekochihin et al 2009 ApJS, §5.1)

$$g_s(\mathbf{R}_s, v_\perp, v_\parallel) = h_s(\mathbf{R}_s, v_\perp, v_\parallel) - \frac{q_s F_{0s}}{T_{0s}} \left\langle \phi - \frac{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}{c} \right\rangle_{\mathbf{R}_s}$$

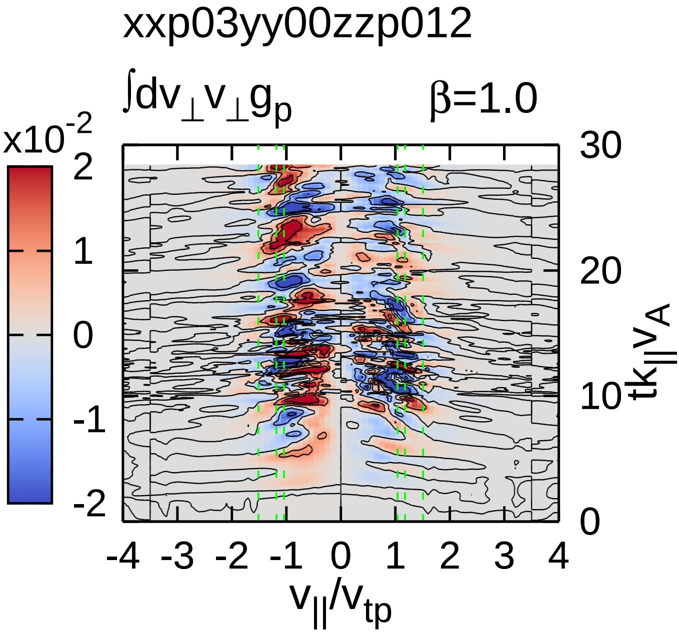
g_s describes perturbations to the Maxwellian velocity distribution in the frame moving with an Alfvén wave.

These perturbations are associated the compressive component of the turbulence and therefore the two collisionless damping mechanisms under consideration.

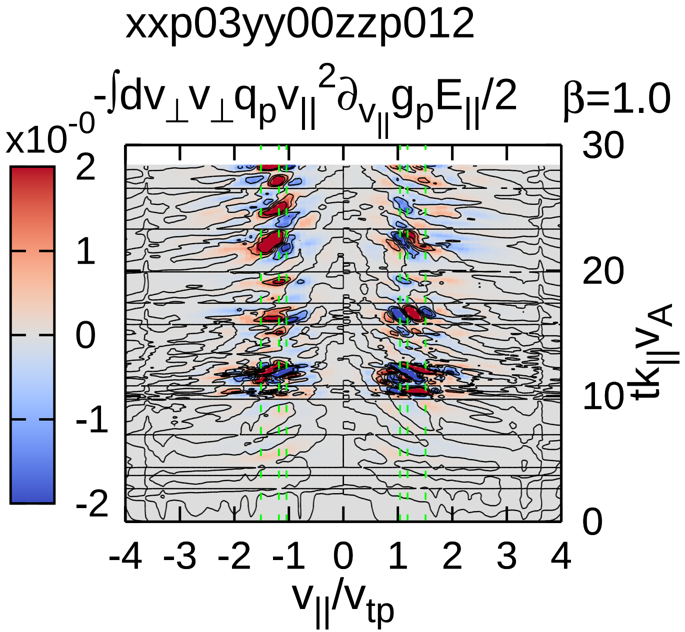
The Gyrotropic Perturbed Distribution is Messy



Reduction via Integration yields ...



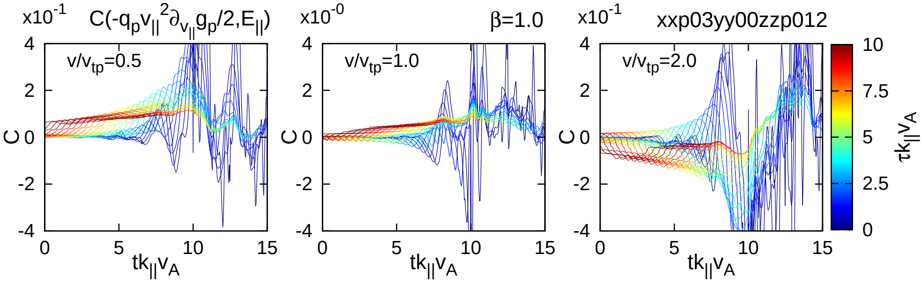
Instantaneous Energy Transfer: $-q_p v_\parallel^2 \partial_{v_\parallel} g_p / 2E_\parallel$



Choosing a Correlation Length

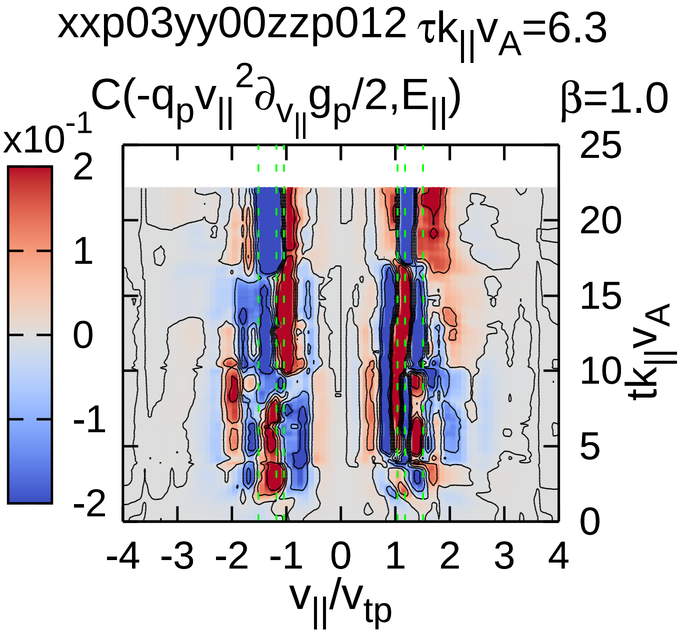
For discrete timeseries $E_{\|,j} \equiv E_\|(x_0, t_j)$ and $g_{sj}(v_\|) \equiv g_s(x_0, v_\|, t_j)$, we define the correlation over time $\tau = N\Delta t$ as

$$C_1(v_\|, t_i, \tau) \equiv \frac{1}{N} \sum_{j=i}^{i+N} -q_s \frac{v_\|^2}{2} \frac{\partial}{\partial v_\|} \left[\int dv_\perp v_\perp g_{sj}(v_\|) \right] E_{\|,j}$$

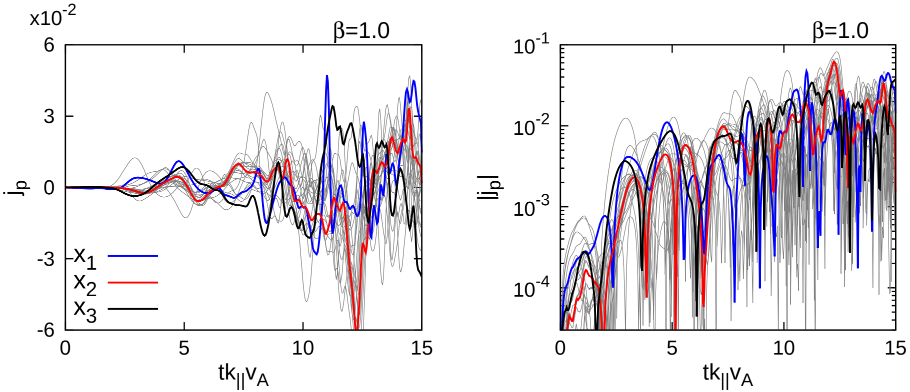


Lengthening τ removes the oscillatory contribution, leaving the secular transfer of energy.

Resonant Structure in Correlation



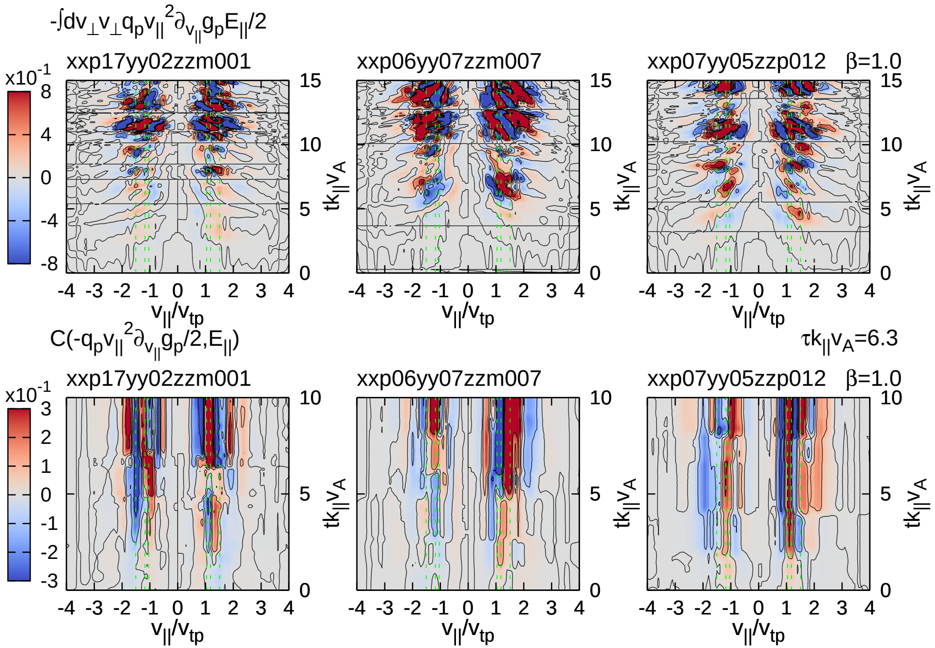
Turbulence is Intermittent...



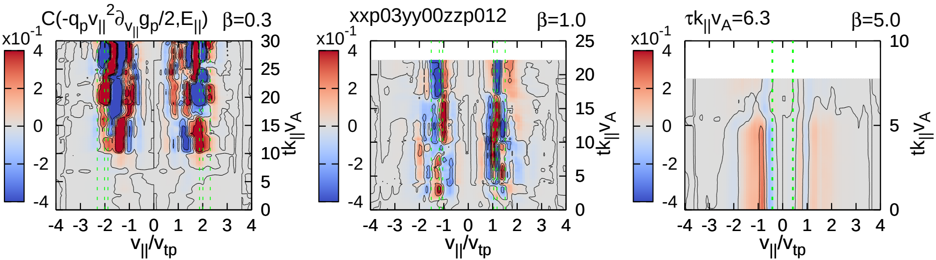
The current density $\int d\mathbf{v} v_{\|} g_s(\mathbf{x},\mathbf{v},t)$ is not homogeneous throughout the simulation.

It has been shown that regions of larger current are associated with stronger dissipation (Sundkvist et al. 2007, Greco et al. 2009, Osman et al. 2012, TenBarge & Howes 2013, Wan et al. 2016...)

...But the Damping Appears to be Resonant



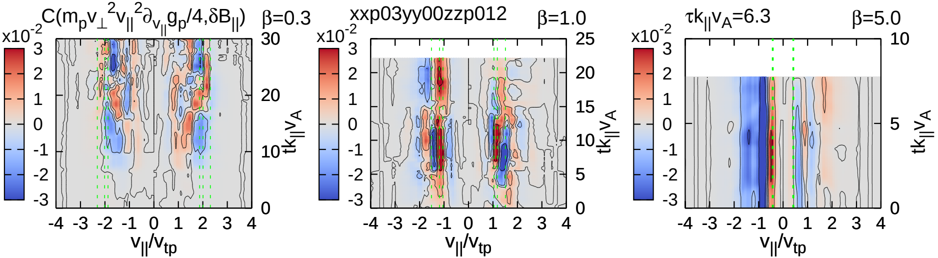
The Strength of Landau Damping Varies with β



- C_1 peaks near the appropriate resonant velocities.
- Landau Damping weakens for larger β_p.
- We next consider correlations for Transit Time Damping.

Considering Transit Time Damping

$$C_2(v_\parallel, t_i, \tau) \equiv \frac{1}{N}\sum_{j=i}^{i+N} \frac{v_\parallel^2}{2}\frac{\partial}{\partial v_\parallel}\left[\int dv_\perp v_\perp \frac{m_s v_\perp^2}{2|B|} g_{sj}(v_\parallel)\right]\delta B_{\parallel,j}$$

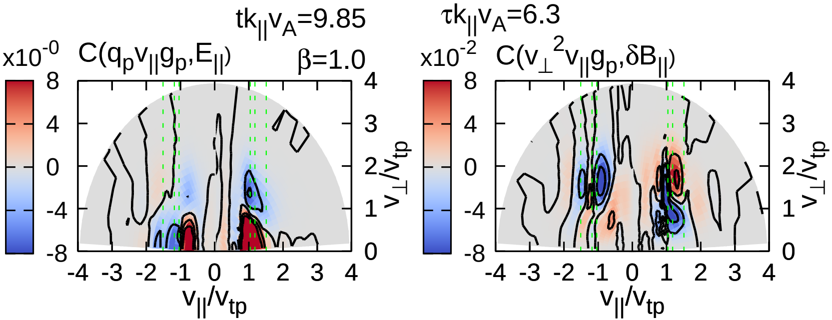


Distinguishing between LD and TTD

As the velocity derivative $\partial_{v_\parallel} g_s$ may be difficult to construct accurately for spacecraft data, we consider the related correlation:

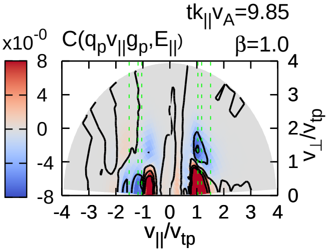
$$C_3(v_\parallel, v_\perp, t_i, \tau) \equiv \frac{1}{N} \sum_{j=i}^{i+N} -q_s v_\parallel g_{sj}(v_\parallel, v_\perp) E_{\parallel,j}$$

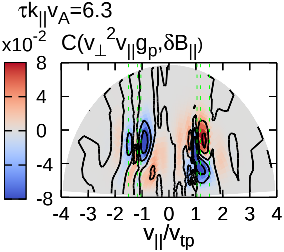
$$C_4(v_\parallel, v_\perp, t_i, \tau) \equiv \frac{1}{N} \sum_{j=i}^{i+N} m_s v_\parallel v_\perp^2 g_{sj}(v_\parallel, v_\perp) \delta B_{\parallel,j}$$



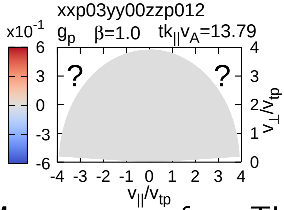
Looking Forward

A general technique for distinguishing damping mechanisms

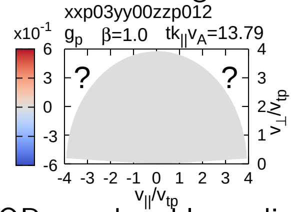




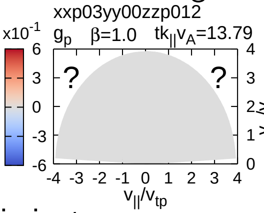
Reconnection



Cyclotron Heating



Stochastic Heating

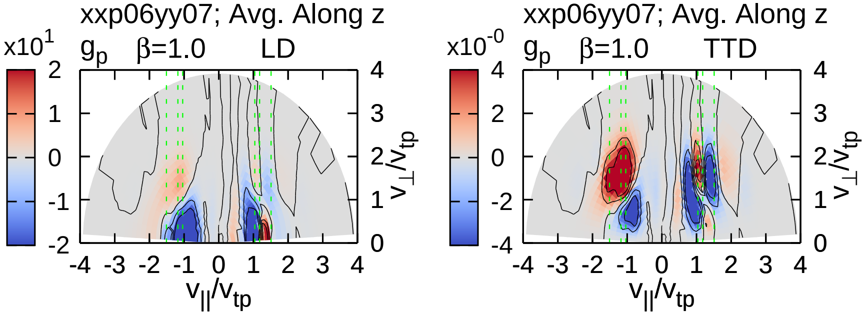


Measurements from THOR may be able to discriminate between these velocity space signatures.

Extra Slides

Equating Spatial and Temporal Averaging

In a low-frequency system with super-Alfvénic flow, an observer will sweep through a region more rapidly than the structure evolves (Taylor 1938, Fredricks & Coroniti 1976)



Single-point spacecraft observations will more closely resemble measurements of a frozen system along $\mathbf{x}(t) = -\mathbf{V}_{SW}t$.

Gyrokinetic Vlasov-Maxwell Equations

Linear, collisionless Vlasov equation:

$$\frac{\partial g_s}{\partial t} + v_\parallel \frac{\partial g_s}{\partial Z} + \frac{q_s F_{0s}}{T_{0s}} \frac{\partial}{\partial t} \left\langle \frac{v_\parallel A_\parallel}{c} \right\rangle_{\mathbf{R}_s} = v_\parallel \frac{q_s F_{0s}}{T_{0s}} \frac{\partial}{\partial Z} \left\langle \frac{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}{c} - \phi \right\rangle_{\mathbf{R}_s}$$

Quasi-Neutrality condition:

$$\sum_s \left[-\frac{q_s^2 n_{0s}}{T_{0s}} \phi + q_s \int d^3\mathbf{v} \left(\langle g_s \rangle_{\mathbf{r}} + \frac{q_s F_{0s}}{T_{0s}} \left\langle \left\langle \phi - \frac{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}{c} \right\rangle_{\mathbf{R}_s} \right\rangle_{\mathbf{r}} \right) \right] = 0$$

Parallel Ampere's law:

$$-\nabla_\perp^2 A_\parallel = \frac{4\pi}{c} \sum_s q_s \int d^3\mathbf{v} v_\parallel \langle g_s \rangle_{\mathbf{r}}$$

Perpendicular Ampere's law:

$$\nabla_\perp \delta B_\parallel = \frac{4\pi}{c} \sum_s q_s \int d^3\mathbf{v} \left\langle \hat{\mathbf{z}} \times \mathbf{v}_\perp \left(g_s + \frac{q_s F_{0s}}{T_{0s}} \left\langle \phi - \frac{\mathbf{v}_\perp \cdot \mathbf{A}_\perp}{c} \right\rangle_{\mathbf{R}_s} \right) \right\rangle_{\mathbf{r}}$$