Using Field-Particle Correlations to Diagnose the Collisionless Damping of Plasma Turbulence

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Collaborators

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NASA and White House Office of Science and Technology Policy (PECASE)
National Science Foundation CAREER Award
National Science Foundation XSEDE Program
Department of Energy

Outline

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- Energy Transfer and Dissipation in Kinetic Plasma Turbulence
- Conservation of Energy in a Kinetic Plasma
- Diagnosing Energy Transfer from Fields to Particles
- Nonlinear Kinetic Simulations: 1D-1V Vlasov-Poisson System
  - Implementation
  - Evolution of the Distribution Function
- Field-Particle Correlations using Single-Point Measurements
  - Best Correlation for Numerical Simulations
  - Alternative Correlation for Spacecraft Observations
- Application to Strongly Turbulent Systems
- Conclusions

Why study dissipation of plasma turbulence?

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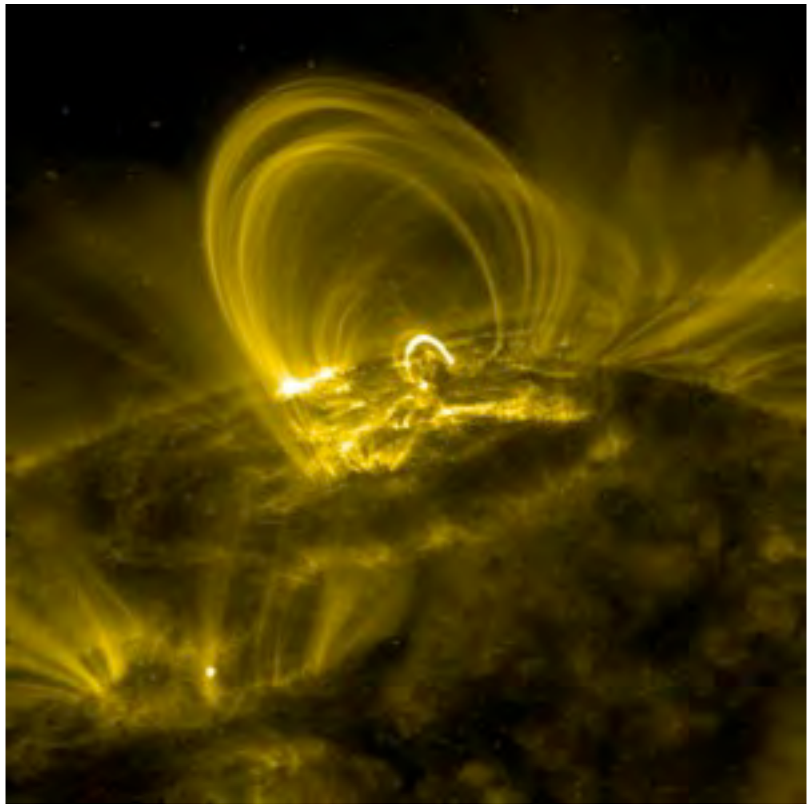
The plasma heating that occurs in space and astrophysical systems is caused by the dissipation of plasma turbulence

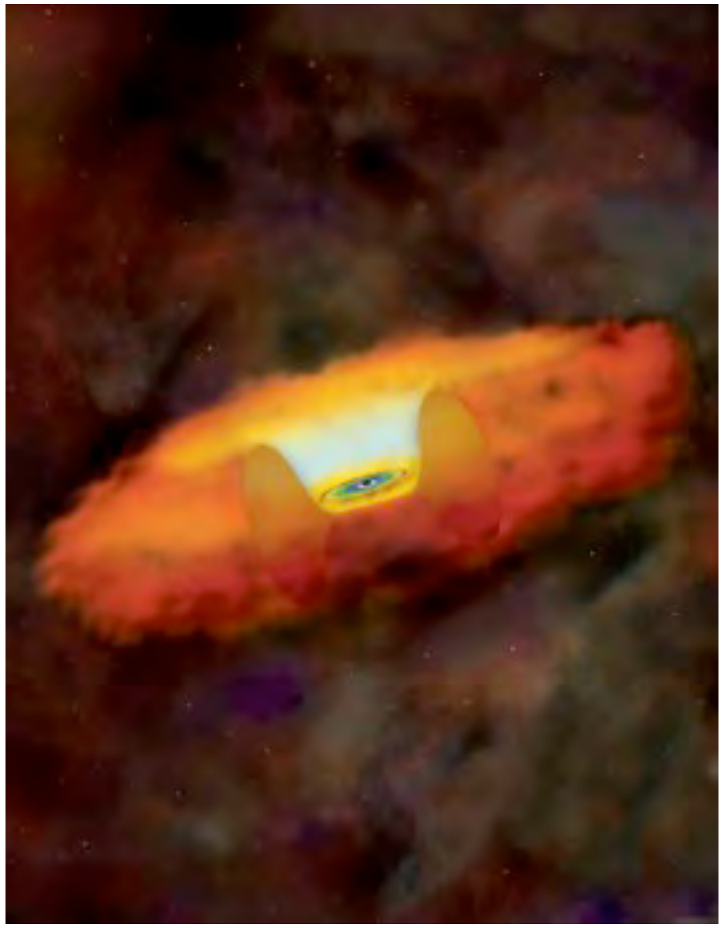
Explaining the plasma heating is crucial to understanding the evolution of many poorly understood astrophysical systems

- Heating of the Solar Corona
- Acceleration of the Solar Wind

- Interpreting observations of remote systems such as black hole accretion disks

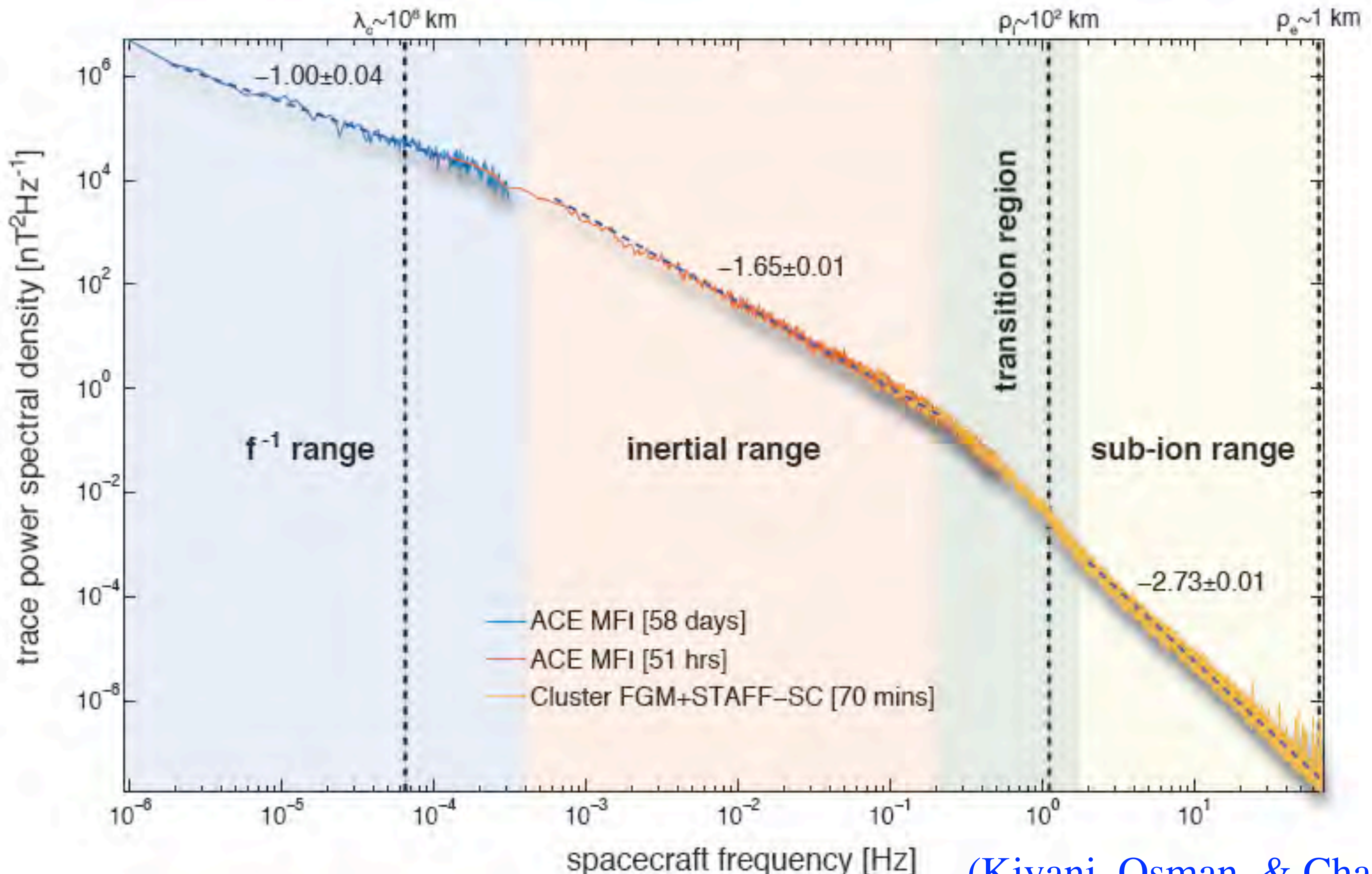


NASA/ TRACE Image



NASA/CXC/SAO -Artist's Conception

Solar Wind Turbulent Power Spectrum



(Kiyani, Osman, & Chapman, 2015)

Turbulence in the Near-Earth Solar Wind

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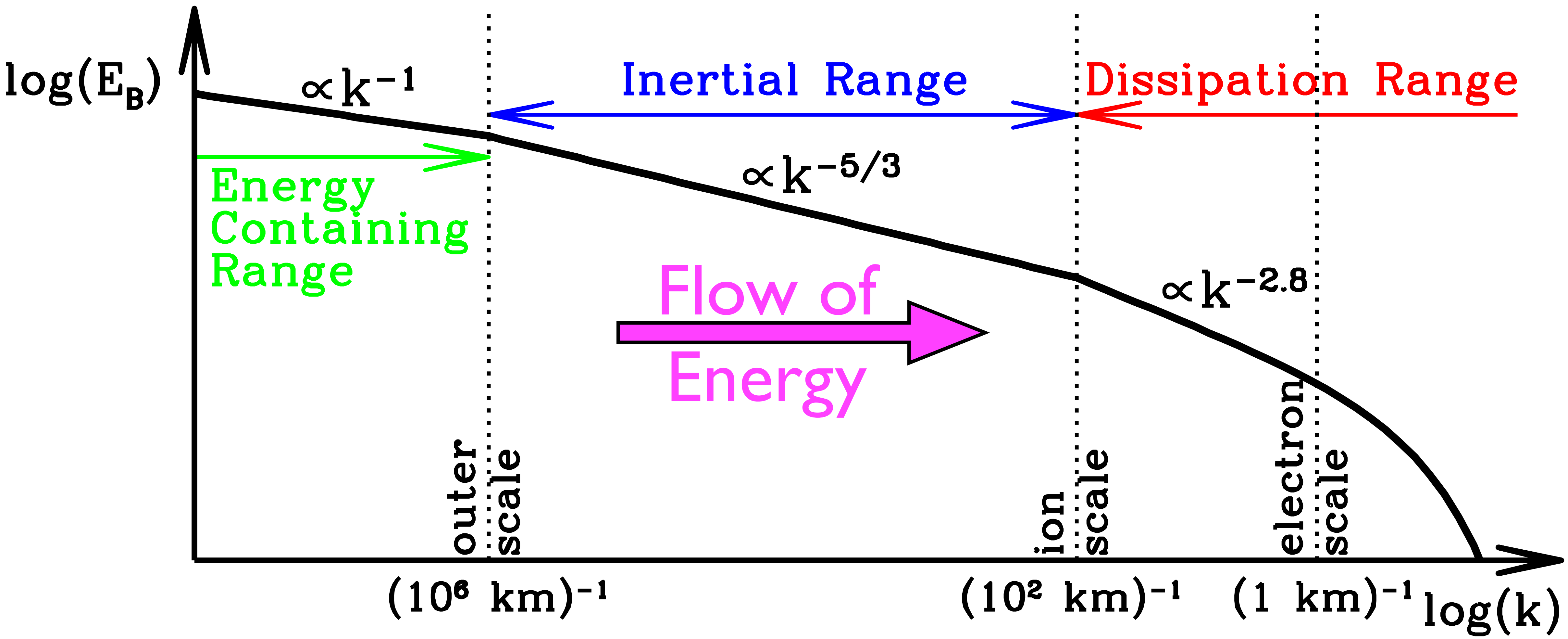

Ultimate Goal:

To understand the dynamics and energetics of the entire cascade

Flow of energy from large scale turbulent motions to plasma heat

THOR: Turbulence Heating ObserveR

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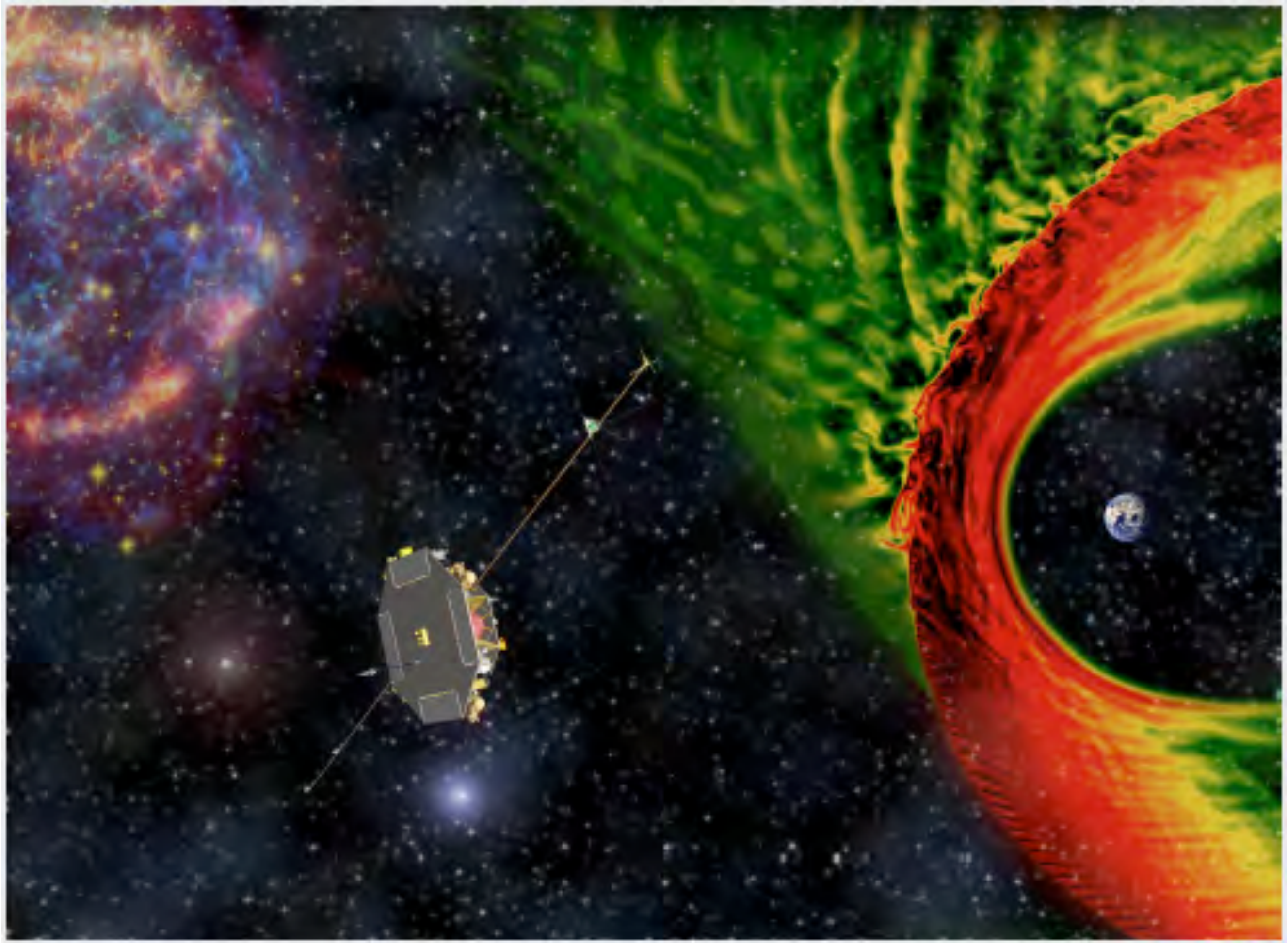
First spacecraft mission dedicated to plasma turbulence

The dissipation of turbulent fluctuations leads to continuous plasma heating and the acceleration of charged particles.



Mission:
Discover plasma heating and particle energization processes

But THOR is a single spacecraft mission, so developing techniques to identify and characterize the dissipation of turbulence using single-point measurements is of paramount importance

FIELD-PARTICLE CORRELATIONS

The Damping of Turbulent Fluctuations in the Solar Wind

- The collisional mean free path in the solar wind is about 1 AU

  ➡ The solar wind is a weakly collisional plasma

- To study the turbulent dynamics requires kinetic theory

6D (3D-3V) Distribution Functions

$$f_s(\mathbf{x}, \mathbf{v}, t)$$

3D Electromagnetic Fields

$$\mathbf{E}(\mathbf{x}, t) \qquad \mathbf{B}(\mathbf{x}, t)$$

- Damping of turbulent fluctuations requires collisonless interactions between the electromagnetic fields and the plasma particles

FIELD-PARTICLE CORRELATIONS

An innovative technique to measure and characterize the energy transfer associated with collisionless damping of plasma turbulence using single-point measurements

Maxwell-Boltzmann Equations of Kinetic Plasma Theory

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Boltzmann Equation

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s}\left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right] \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t}\right)_{\rm coll}$$

0

Lorentz Term responsible for interactions between fields and particles

Maxwell's Equations

$$\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{E} = 4\pi \rho_q$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \qquad \nabla \cdot \mathbf{B} = 0$$

But the Lorentz term not only describes collisionless damping, but also the oscillating energy transfer of undamped wave motion

Define: Key Challenge:

Secular Energy Transfer ← We want to measure this

Oscillating Energy Transfer ← But this is often much larger

Example: The Alfven Wave

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The Alfven Wave:

- Restoring force: Magnetic Tension
- Inertia: Transverse Plasma Motion

← Leads to oscillatory wave motion

- In the Ideal MHD limit, the wave is undamped:
  - All oscillating energy transfer, no secular energy transfer

- In a kinetic treatment under weakly collisional conditions, resonant wave-particle interactions can damp the wave
  - Electromagnetic wave energy is transferred to microscopic kinetic energy of the particles
  - For $k_\perp \rho_i \ll 1$,
    secular transfer is small relative to oscillating transfer
  - For $k_\perp \rho_i \gtrsim 1$,
    secular transfer increases in magnitude

    ➡ Collisionless damping of Alfven wave becomes strong

Physical Dissipation Mechanisms for Kinetic Turbulence

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In the weakly collisional solar wind,

Three mechanisms have been proposed:

(1) Coherent Wave-Particle Interactions (Landau damping, cyclotron damping)

(Barnes 1966; Coleman 1968; Denskat *et al*., 1983; Isenberg & Hollweg 1983; Goldstein *et al*. 1994; Quataert 1998; Leamon *et al*., 1998, 1999, 2000; Gary 1999; Quateart & Gruzinov, 1999; Isenberg *et al*. 2001; Hollweg & Isenberg 2002; Howes *et al*. 2008; Schekochihin *et al*. 2009; TenBarge & Howes 2013; Howes 2015; Li, Howes, Klein, & TenBarge 2016)

(2) Incoherent Wave-Particle Interactions (stochastic ion heating)

(Johnson & Cheng, 2001; Chen *et al*. 2001; White *et al*., 2002; Voitenko & Goosens, 2004; Bourouaine *et al*., 2008; Chandran *et al*. 2010; Chandran 2010, Chandran *et al*. 2011; Bourouaine & Chandran 2013)

(3) Dissipation in Current Sheets (collisionless magnetic reconnection)

(Dmitruk *et al*. 2004; Markovskii & Vasquez 2011; Matthaeus & Velli 2011; Osman *et al*. 2011; Servidio 2011; Osman *et al*. 2012a,b; Wan *et al*. 2012; Karimabadi *et al*.2013; Zhdankin *et al*. 2013; Osman *et al*. 2014a,b; Zhdankin *et al*. 2015a,b;)

Primary Aims of this Work

- The key challenge is to identify the secular energy transfer in the presence of a much larger oscillating energy transfer

- We want to achieve this using only single-point measurements

- We want to distinguish different collisionless damping mechanisms

The novel field-particle correlation technique
introduced here
achieves all of these goals.

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Maxwell-Boltzmann Equations

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Boltzmann Equation

$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s}\left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right] \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t}\right)_{\text{coll}}$$

0 0

Maxwell's Equations

$$\nabla \times \mathbf{E} = \frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \qquad \nabla \cdot \mathbf{E} = 4\pi\rho_q$$

$$\nabla \times \mathbf{B} = \frac{4\pi}{c}\mathbf{j} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \qquad \nabla \cdot \mathbf{B} = 0$$

0 0 0

⇒ Vlasov-Poisson Equations

1D-1V Vlasov-Poisson Equations

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Vlasov Equation

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

Poisson Equation

$$\frac{\partial^2 \phi}{\partial x^2} = -4\pi \sum_s \int_{-\infty}^{+\infty} dv \; q_s f_s$$

Distribution Function

$f_s(x, v, t)$

Electrostatic Potential

$\phi(x, t)$

Conservation of Energy

Electrostatic Limit of Poynting's Theorem

$$\frac{\partial}{\partial t}\left(\frac{E^2}{8\pi}\right) = -jE$$

Multiply Vlasov by $\frac{1}{2}m_s v^2$ and integrate $\int dx \int dv$

$$\frac{\partial}{\partial t}\int dx \int dv \frac{1}{2}m_s v^2 f_s + \int dx\, \frac{\partial}{\partial x}\left[\int dv \frac{1}{2}m_s v^3 f_s\right] - \int dx \frac{\partial \phi}{\partial x}\int dv \left(\frac{q_s v^2}{2}\right)\frac{\partial f_s}{\partial v} = 0$$

Perfect Differential → 0

Integrate third term by parts in v

$$\int dv \left(\frac{q_s v^2}{2}\right)\frac{\partial f_s}{\partial v} = \left[\frac{q_s v^2}{2} f_s\right]_{-\infty}^{\infty} - \int dv \;\; q_s v f_s \equiv -j_s$$

Conservation of Energy

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Combining Poynting's Thm and integrated Vlasov Equation:

$$\frac{\partial}{\partial t}\int_{-L}^{L} dx \left(\frac{E^2}{8\pi}\right) + \frac{\partial}{\partial t}\sum_s \int_{-L}^{L} dx \int_{-\infty}^{\infty} dv \; \frac{1}{2} m_s v^2 f_s = 0$$

Conserved Vlasov-Poisson Energy

$$W = \int_{-L}^{L} dx \; \frac{E^2}{8\pi} + \sum_s \int_{-L}^{L} dx \int_{-\infty}^{\infty} dv \frac{1}{2} m_s v^2 f_s$$

Electrostatic Field Energy

$$W_\phi \equiv \int_{-L}^{L} dx \; \frac{E^2}{8\pi}$$

Microscopic Kinetic Energy

$$W_s \equiv \int_{-L}^{L} dx \int_{-\infty}^{\infty} dv \; \frac{1}{2} m_s v^2 f_s$$

$$W = W_\phi + W_i + W_e$$

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Change of Particle Energy

Particles gain energy lost by the electric field

$$\sum_s \frac{\partial W_s}{\partial t} = -\frac{\partial W_\phi}{\partial t}$$

where the change in particle microscopic kinetic energy is

$$\frac{\partial W_s}{\partial t} = \int dx \int dv \, \frac{1}{2} m_s v^2 \frac{\partial f_s}{\partial t}$$

We want to measure the change in particle energy . . .

. . . using measurements of the change in the distribution function.

Change of Particle Energy

Closer look at $\frac{\partial W_s}{\partial t}$:

$$f_s(x,v,t) = f_{s0}(v) + \delta f_s(x,v,t)$$

Change of Particle Energy

$$\frac{\partial W_s}{\partial t} = \int dx \int dv\, \frac{1}{2} m_s v^2 \frac{\partial f_s}{\partial t}$$

Vlasov Equation

$$\frac{\partial \delta f_s}{\partial t} = -v\frac{\partial \delta f_s}{\partial x} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_{s0}}{\partial v} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial \delta f_s}{\partial v}$$

Ballistic Term — Linear Wave-Particle Term — Nonlinear Wave-Particle Term

$$\frac{\partial W_s}{\partial t} = \int dx \int dv \frac{1}{2} m_s v^2 \left[-v\frac{\partial \delta f_s}{\partial x} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_{s0}}{\partial v} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial \delta f_s}{\partial v}\right]$$

Change of Particle Energy

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$$f_s(x,v,t) = f_{s0}(v) + \delta f_s(x,v,t)$$

$$\frac{\partial W_s}{\partial t} = \int dx \int dv \frac{1}{2} m_s v^2 \left[-v \frac{\partial \delta f_s}{\partial x} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_{s0}}{\partial v} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial \delta f_s}{\partial v}\right]$$

0 0

Perfect Differential   Perfect Differential

Rate of Change of Particle Energy

$$\frac{\partial W_s}{\partial t} = -\int dx \int dv \; q_s \frac{v^2}{2}\frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

Change of Particle Energy in Phase Space

$$\frac{\partial W_s}{\partial t} = -\int dx \int dv \; q_s \frac{v^2}{2} \frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

But this is integrated over velocity and space.

Not observationally accessible!

Define:

Phase-space energy density $w_s(x,v,t) = \frac{1}{2} m_s v^2 f_s(x,v,t)$

Multiply Vlasov by $\frac{1}{2} m_s v^2$ but *do not integrate*

$$\frac{\partial w_s(x,v,t)}{\partial t} = -\frac{1}{2} m_s v^3 \frac{\partial \delta f_s}{\partial x} - q_s \frac{v^2}{2} \frac{\partial f_{s0}(v)}{\partial v} E(x,t) - q_s \frac{v^2}{2} \frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

This term is responsible for energy transfer

Change of Particle Energy in Phase Space

$$\frac{\partial w_s(x,v,t)}{\partial t} = -\frac{1}{2} m_s v^3 \frac{\partial \delta f_s}{\partial x} - q_s \frac{v^2}{2} \frac{\partial f_{s0}(v)}{\partial v} E(x,t) - q_s \frac{v^2}{2} \frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

How do we isolate the physics responsible for the energy transfer?

Take a correlation of $-q_s \frac{v^2}{2} \frac{\partial \delta f_s}{\partial v}$ and E

$$C_1(v,t,\tau) = C_\tau \left(-q_s \frac{v^2}{2} \frac{\partial \delta f_s(x_0,v,t)}{\partial v}, E(x_0,t) \right)$$

Field-Particle Correlations

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$$C_1(v,t,\tau) = C_\tau\left(-q_s\frac{v^2}{2}\frac{\partial \delta f_s(x_0,v,t)}{\partial v}, E(x_0,t)\right)$$

Benefits of this novel field-particle correlation technique:

1) Energy Transfer Calculation:

- Unnormalized correlation directly calculates energy transfer
- Can be used with single-point measurements

2) Velocity dependence of particle energization:

- Will highlight the resonant nature of mechanism
- Each mechanism will have a distinct velocity-space signature
    - Landau Damping, Transit Time Damping, Cyclotron Damping
    - Stochastic Ion Heating
    - Collisionless Magnetic Reconnection
- Properties of velocity-space signature can distinguish mechanism

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Numerical Implementation

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$$\frac{\partial \delta f_s}{\partial t} = -v\frac{\partial \delta f_s}{\partial x} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_{s0}}{\partial v} + \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial \delta f_s}{\partial v}$$

Separate Ballistic, Linear, and Nonlinear Wave-Particle Terms:

$$\delta f_s = \delta f_{sB} + \delta f_{sWl} + \delta f_{sWn}$$

Ballistic Term

$$\frac{\partial \delta f_{sB}}{\partial t} = -v\frac{\partial \delta f_s}{\partial x}$$

Linear Wave-Particle Term

$$\frac{\partial \delta f_{sWl}}{\partial t} = \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial f_{s0}}{\partial v}$$

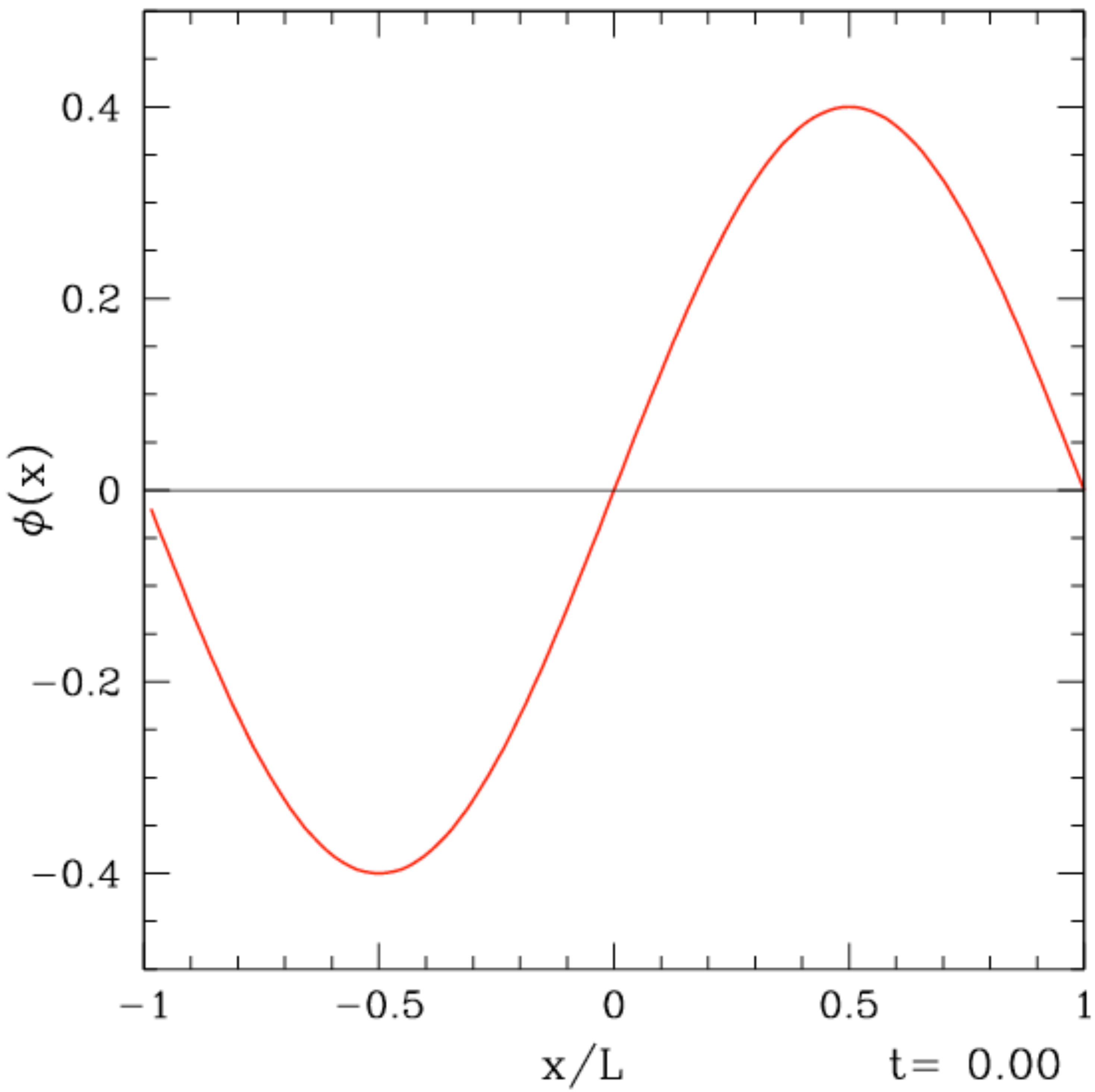
Nonlinear Wave-Particle Term

$$\frac{\partial \delta f_{sWn}}{\partial t} = \frac{q_s}{m_s}\frac{\partial \phi}{\partial x}\frac{\partial \delta f_s}{\partial v}$$

Simulation Setup

Sinusoidal Electron Density Perturbation

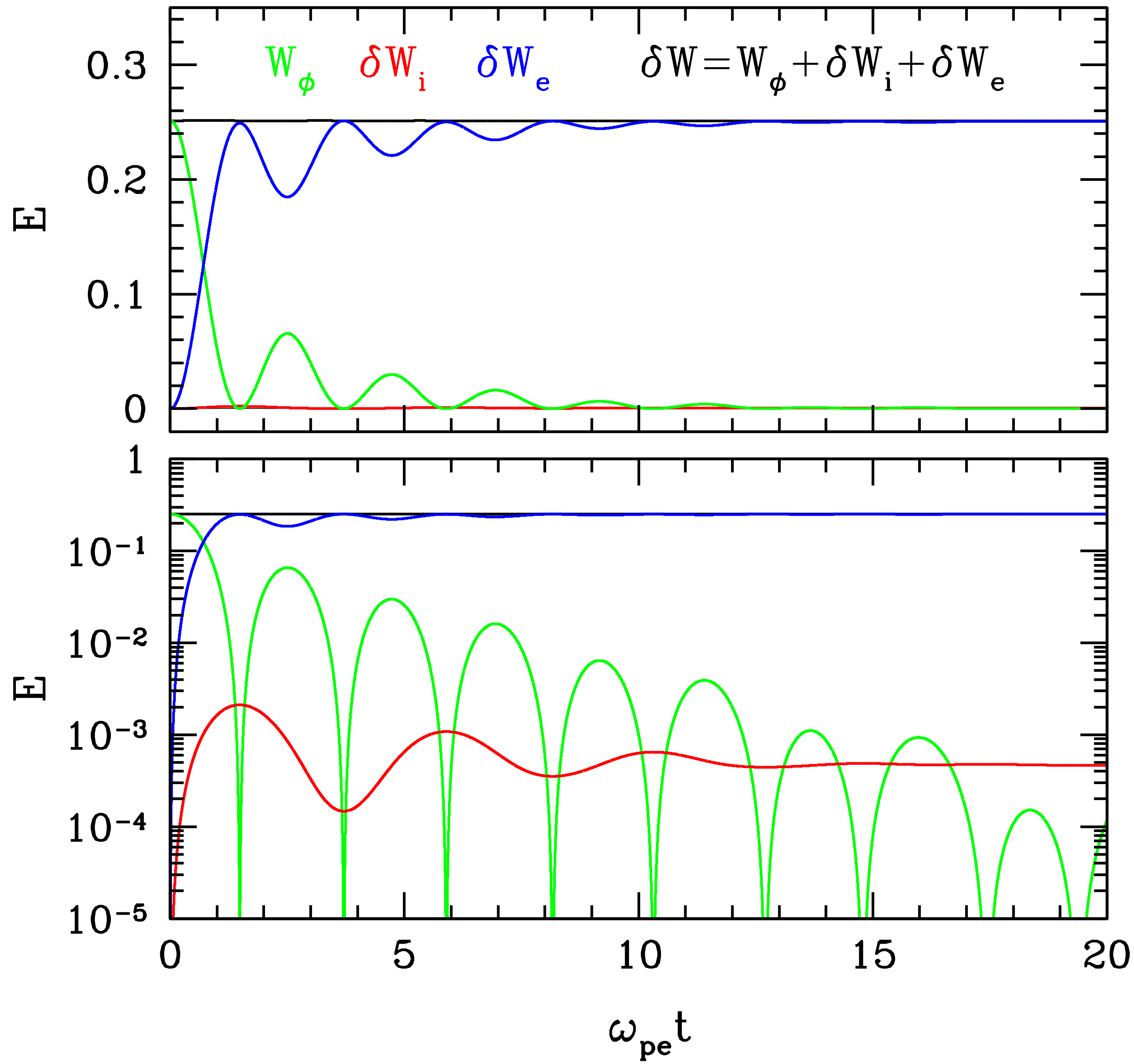
Generates a standing Langmuir wave pattern that damps in time



$$k\lambda_{de} = 0.5$$

$$\frac{m_i}{m_e} = 100$$

Evolution of Energy



Electrostatic Field Energy

$$\delta W_\phi = \int dx \frac{E^2}{8\pi}$$

is converted to

Microscopic electron kinetic energy

$$\delta W_e = \int dv \frac{1}{2} m_e v^2 \delta f_e$$

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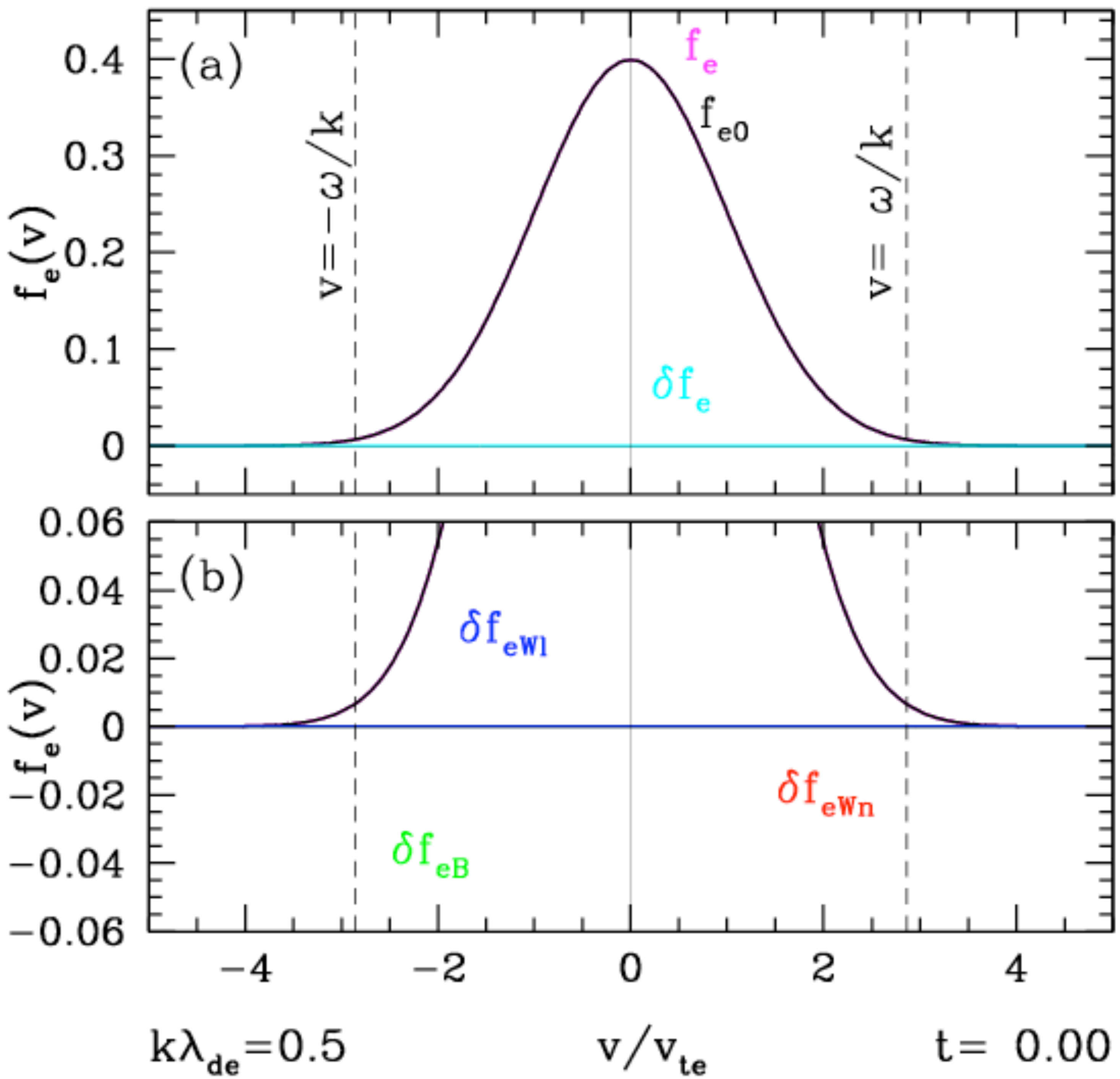
Time Evolution of $f_e(x_0, v, t)$

Fluctuations of Distribution Function in time



Total $f_e(x_0, v, t)$

Perturbed $\delta f_e(x_0, v, t)$

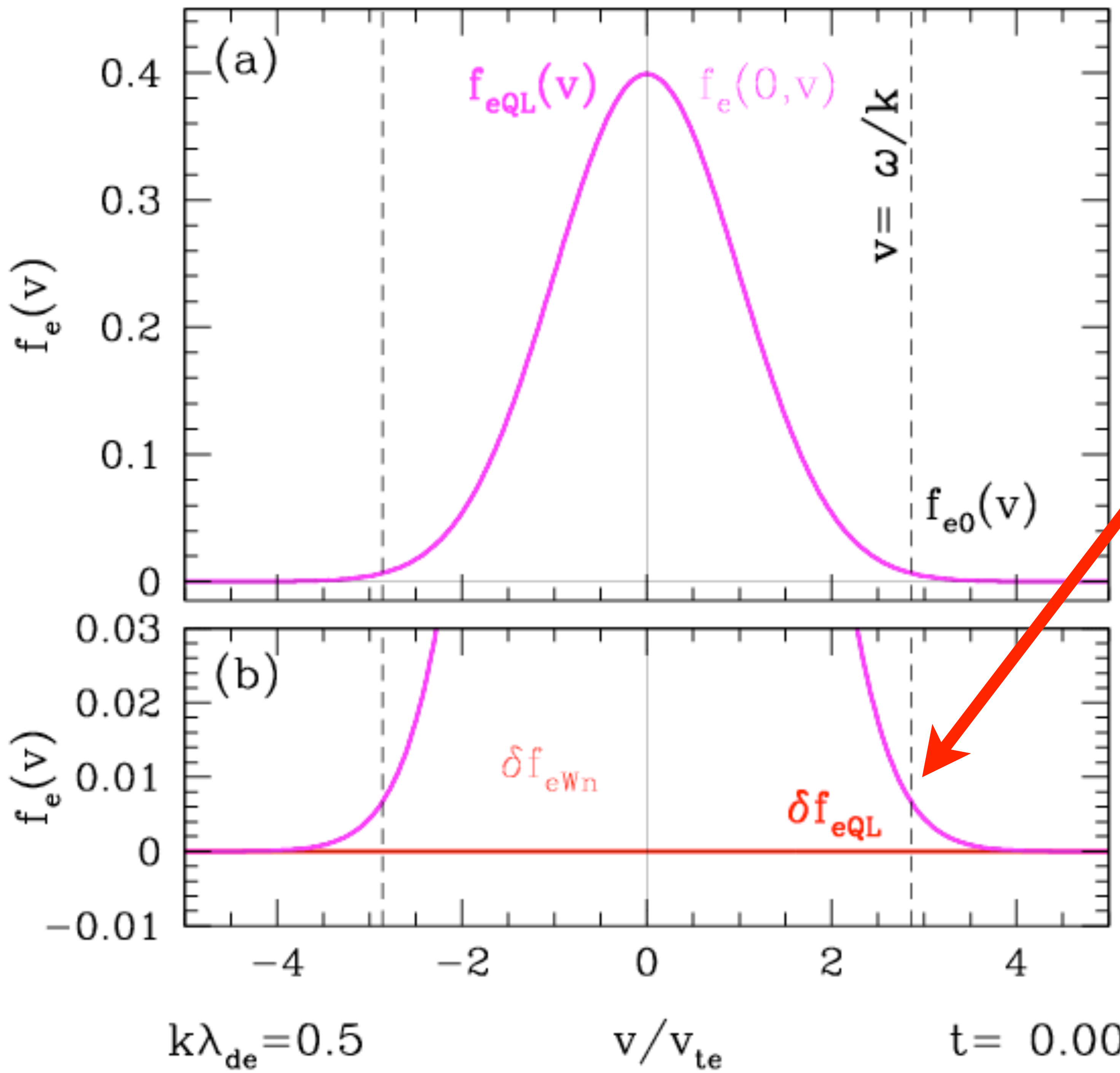
Ballistic Term $\delta f_{eB}(x_0, v, t)$

Linear Wave-Particle Term $\delta f_{eWl}(x_0, v, t)$

Nonlinear Wave-Particle Term $\delta f_{eWn}(x_0, v, t)$

Quasilinear Evolution

Integrating $\int dx$ yields quasilinear evolution of $f_{eQL}(v,t)$



Compare quasilinear $\delta f_{eQL}(v,t)$ with $\delta f_{eWn}(x_0,v,t)$

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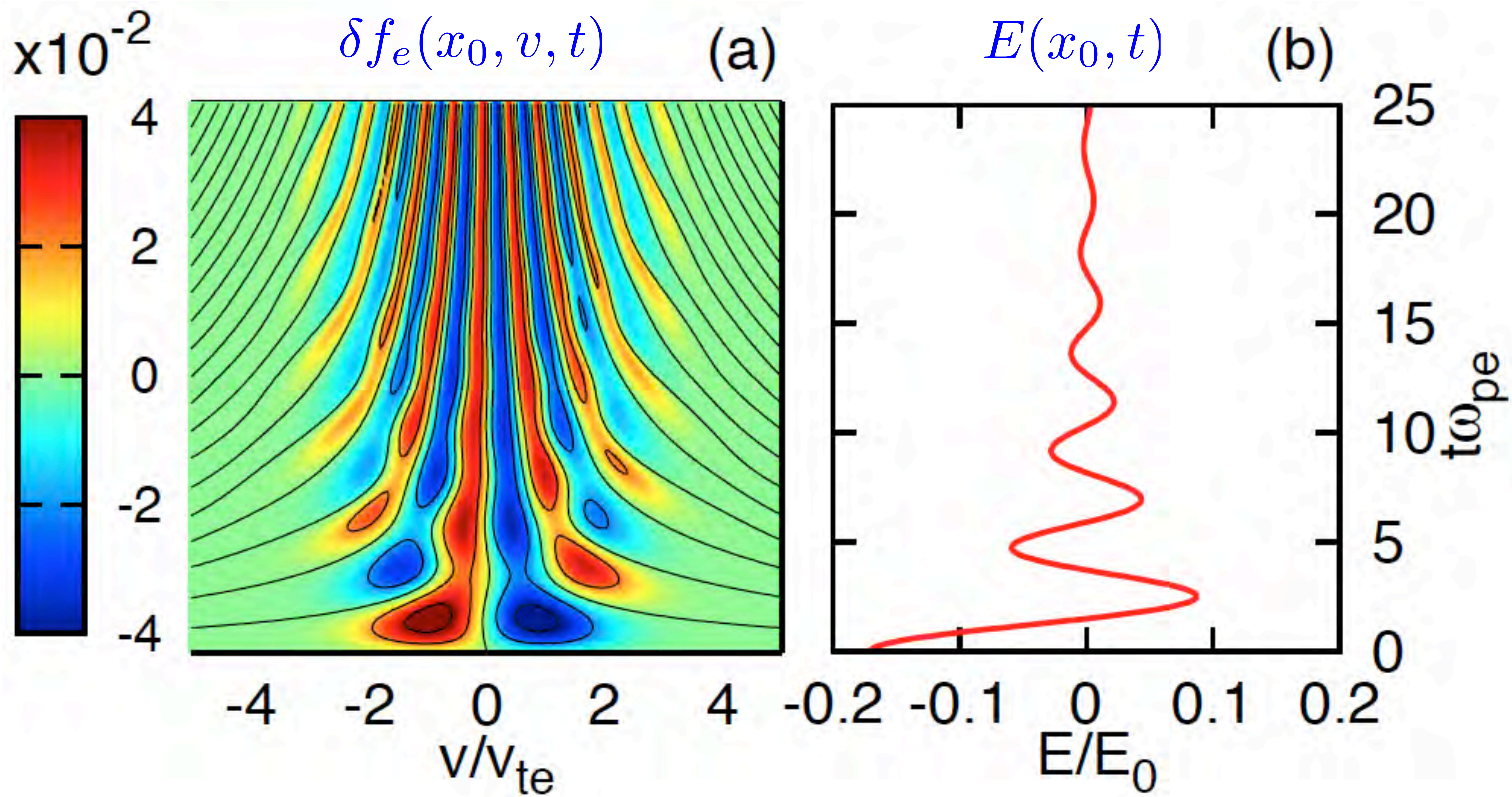
Observable Quantities

Single-point measurements of $\delta f_e(x_0, v, t)$ and $E(x_0, t)$



Goal: Determine Particle Energization

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- Using single-point measurements only, we want to devise a procedure to isolate the particle energization

- Determine particle energization as a function of velocity v

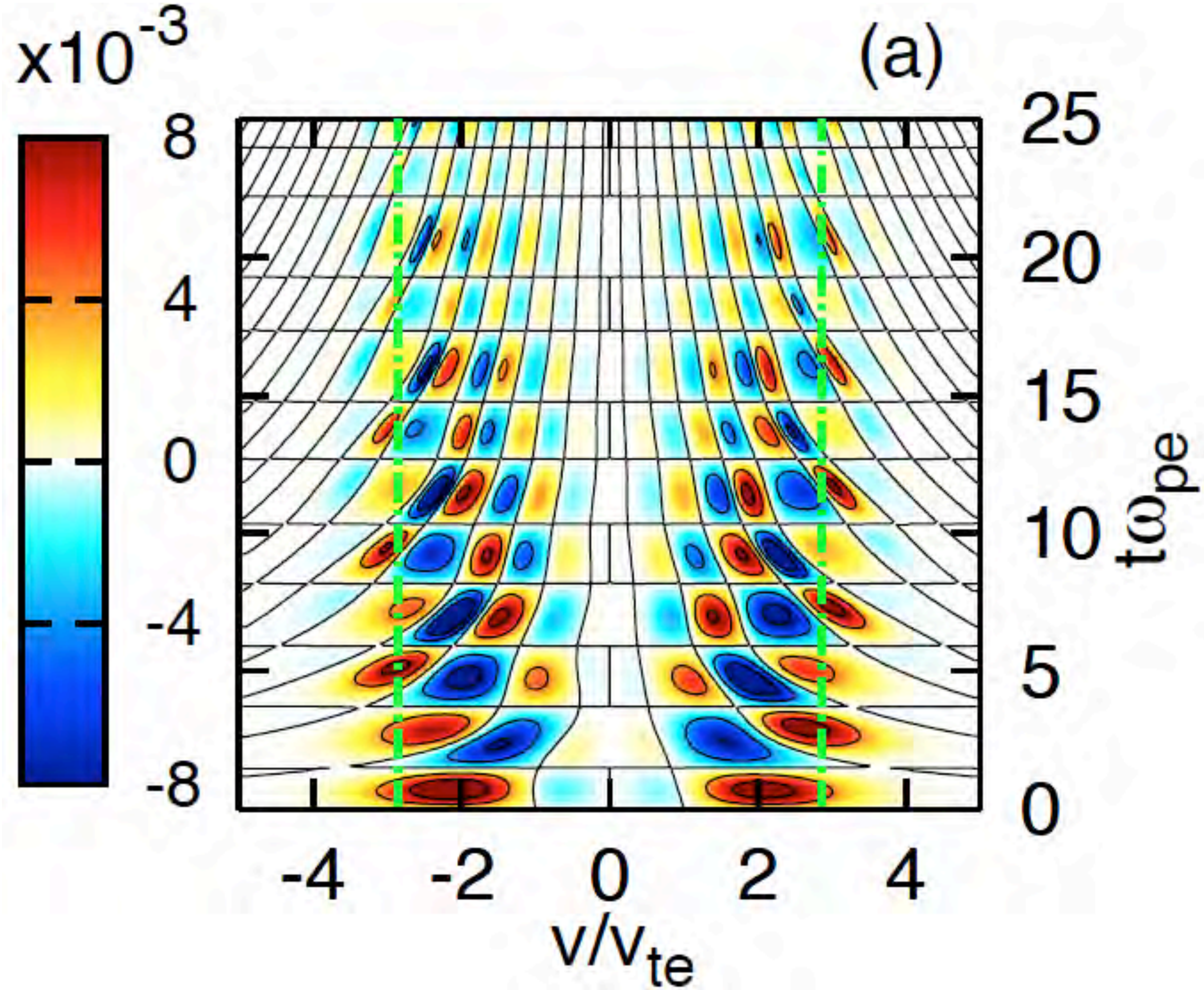
Energy transfer to particles in (x,v) phase space

$$\frac{\partial w_s(x,v,t)}{\partial t} = -\frac{1}{2} m_s v^3 \frac{\partial \delta f_s}{\partial x} - q_s \frac{v^2}{2} \frac{\partial f_{s0}(v)}{\partial v} E(x,t) - q_s \frac{v^2}{2} \frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

$$C_1(v,t,\tau) = C_\tau \left(-q_s \frac{v^2}{2} \frac{\partial \delta f_s(x_0,v,t)}{\partial v}, E(x_0,t) \right)$$

Evolution of Energy Transfer Rate

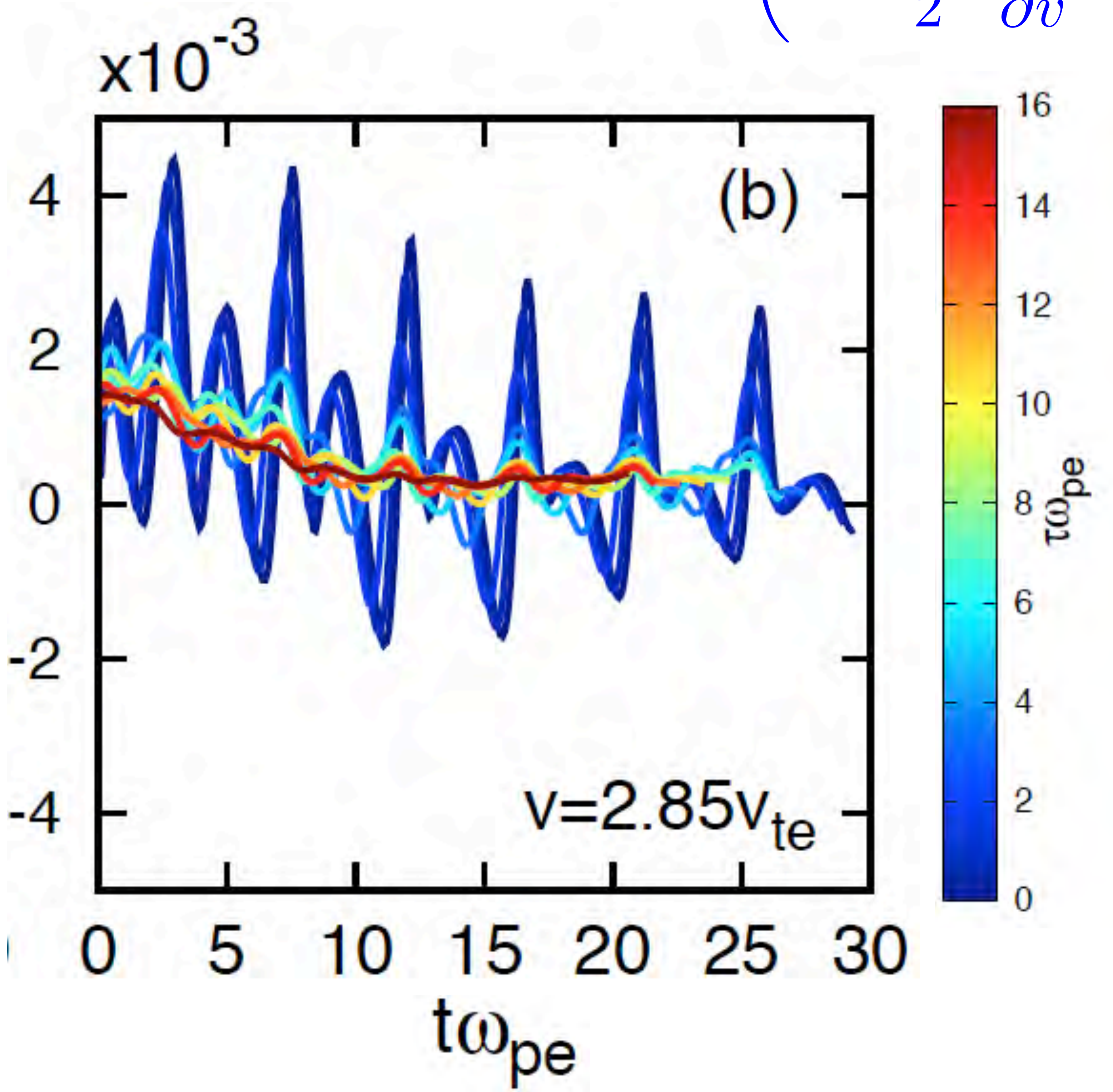
$$-q_s \frac{v^2}{2} \frac{\partial \delta f_s(x_0, v, t)}{\partial v} E(x_0, t)$$



Correlation Eliminates Oscillation

Increasing correlation time τ helps to eliminate oscillation

$$C_1(v,t,\tau) = C_\tau\left(-q_s\frac{v^2}{2}\frac{\partial \delta f_s}{\partial v}, E\right)$$



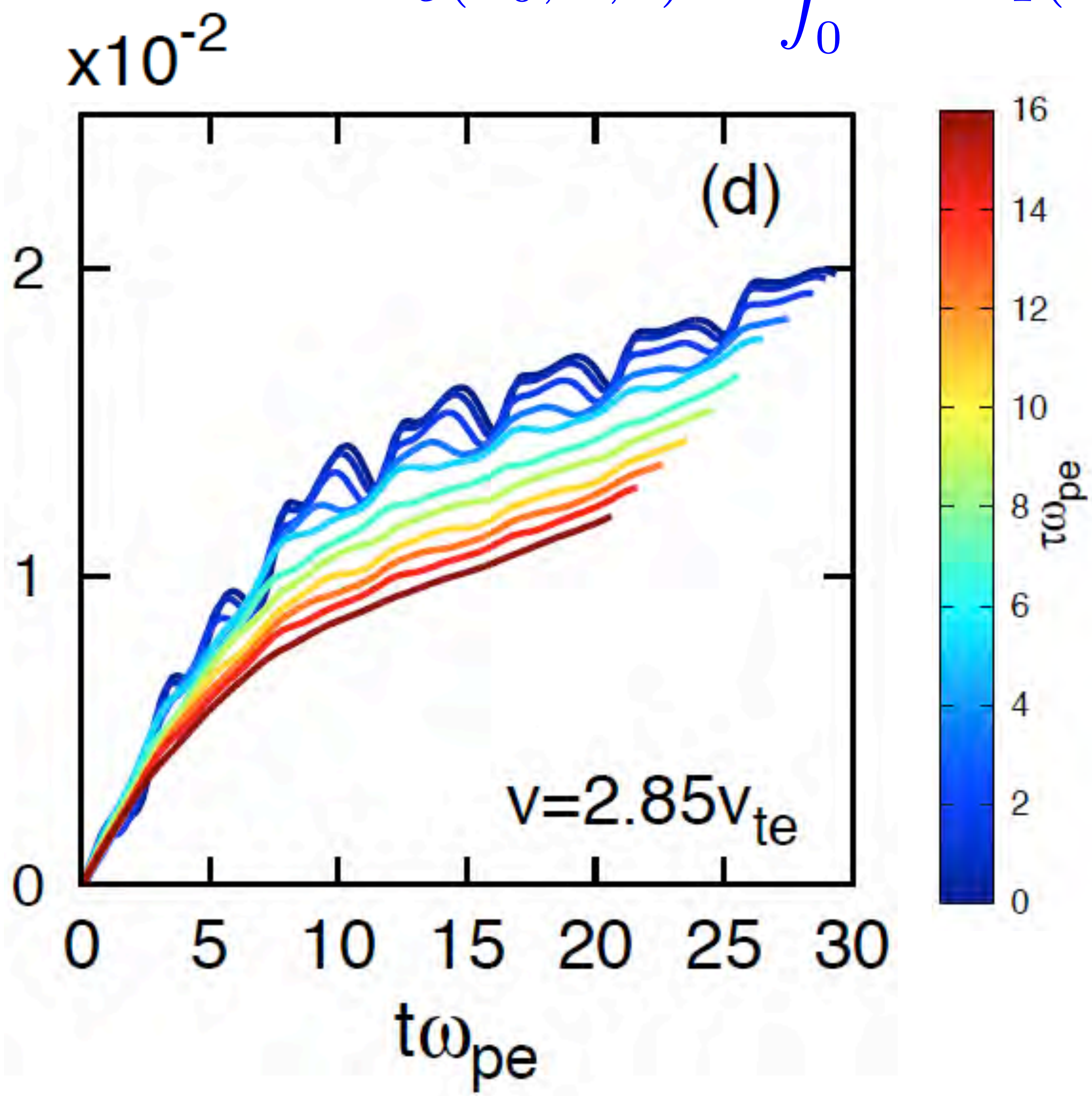
Wave Period

$T\omega_{pe} = 4.39$

Integration Yields Net Particle Energization

Integrating heating rate (from correlation) over time

$$\delta w_e(x_0, v, t) = \int_0^t dt' C_1(v, t', \tau)$$



Field-Particle Correlation Results

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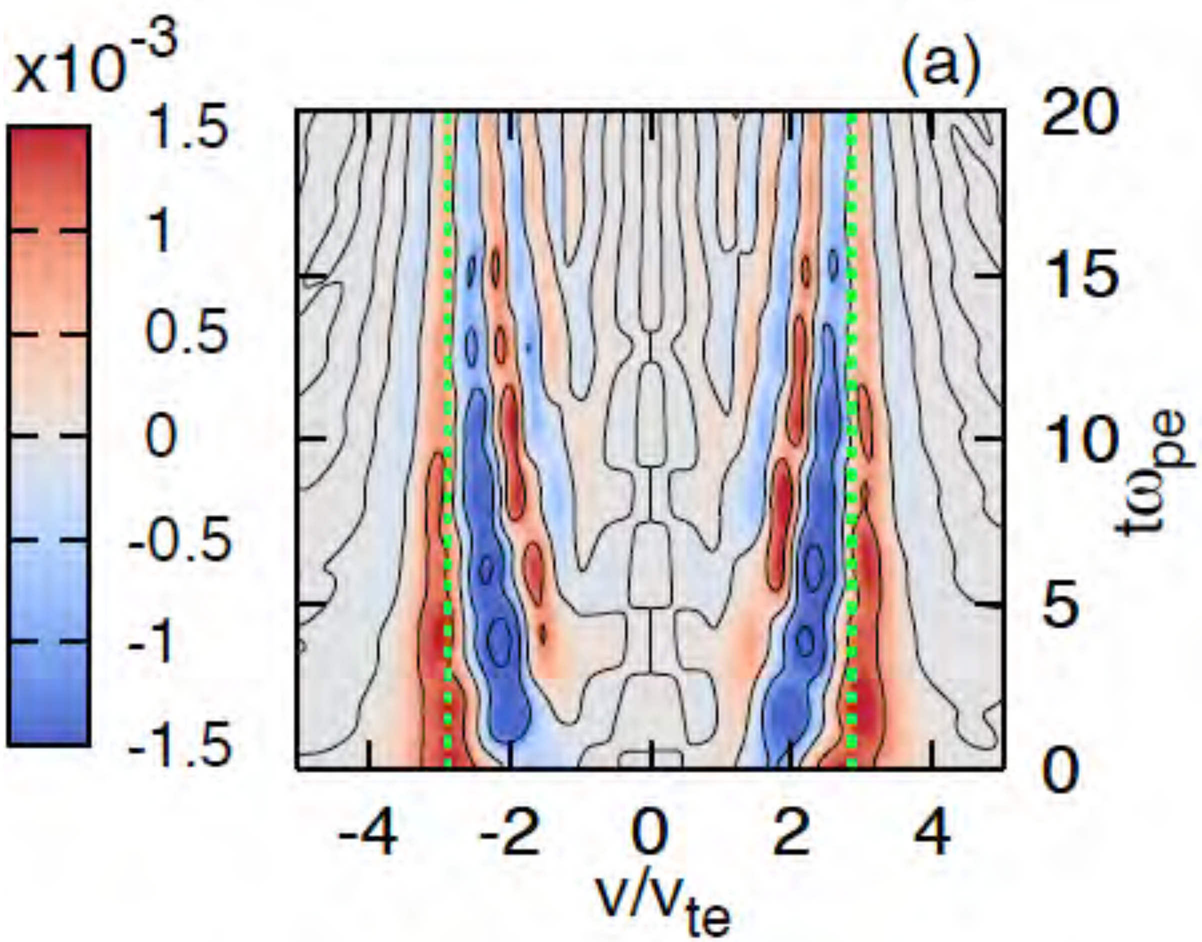
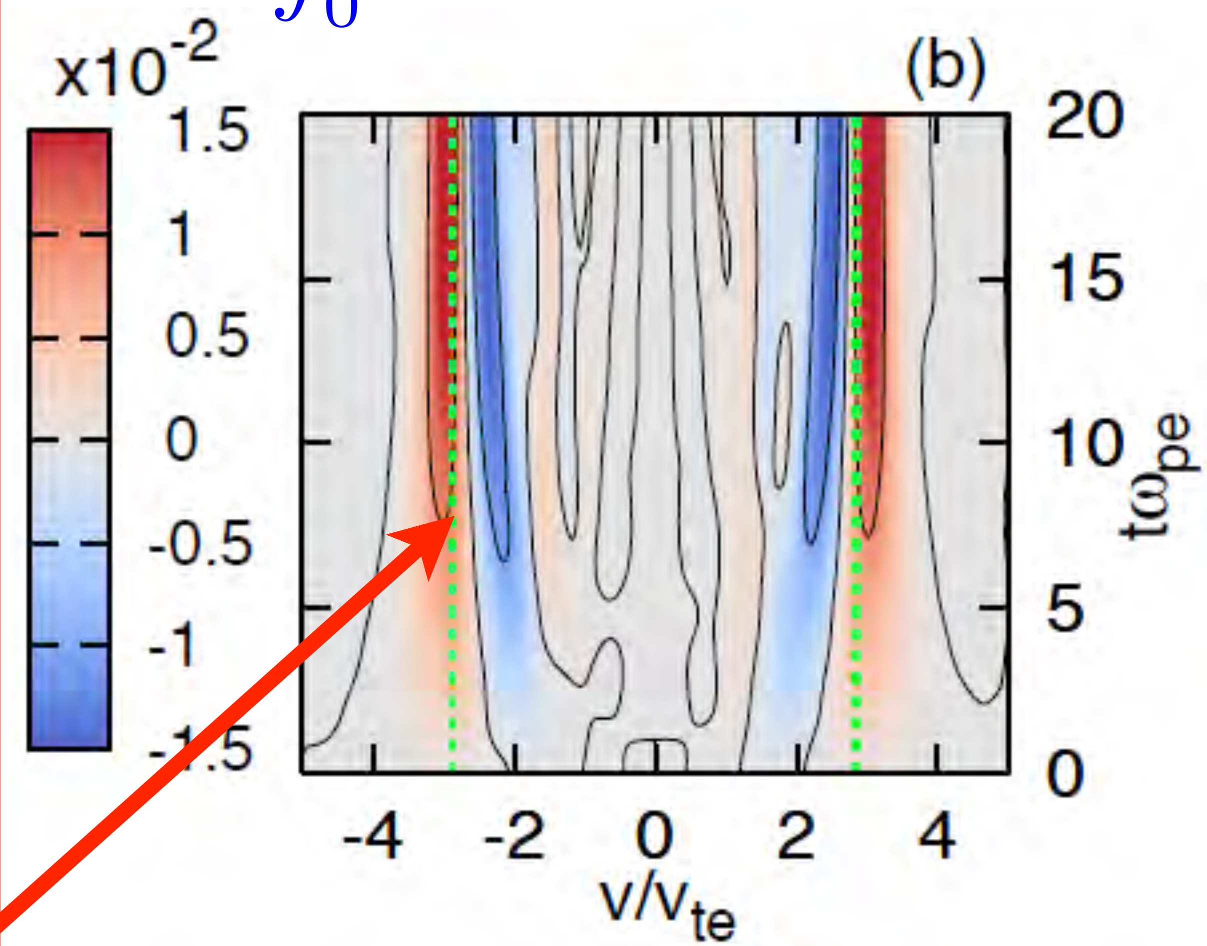
For a correlation time $\omega_{pe}\tau = 6.28$

$C_1(v,t,\tau)$



$\int_0^t dt' C_1(v,t',\tau)$



Key Result

Velocity-space signature of quasilinear flattening . . .

but from single-point measurements!

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Potential Difficulties

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$$\frac{\partial W_s}{\partial t} = -\int dx \int dv \; q_s \frac{v^2}{2} \frac{\partial \delta f_s(x,v,t)}{\partial v} E(x,t)$$

From low resolution, noisy measurements, derivative $\partial f_s / \partial v$ is very difficult to compute accurately

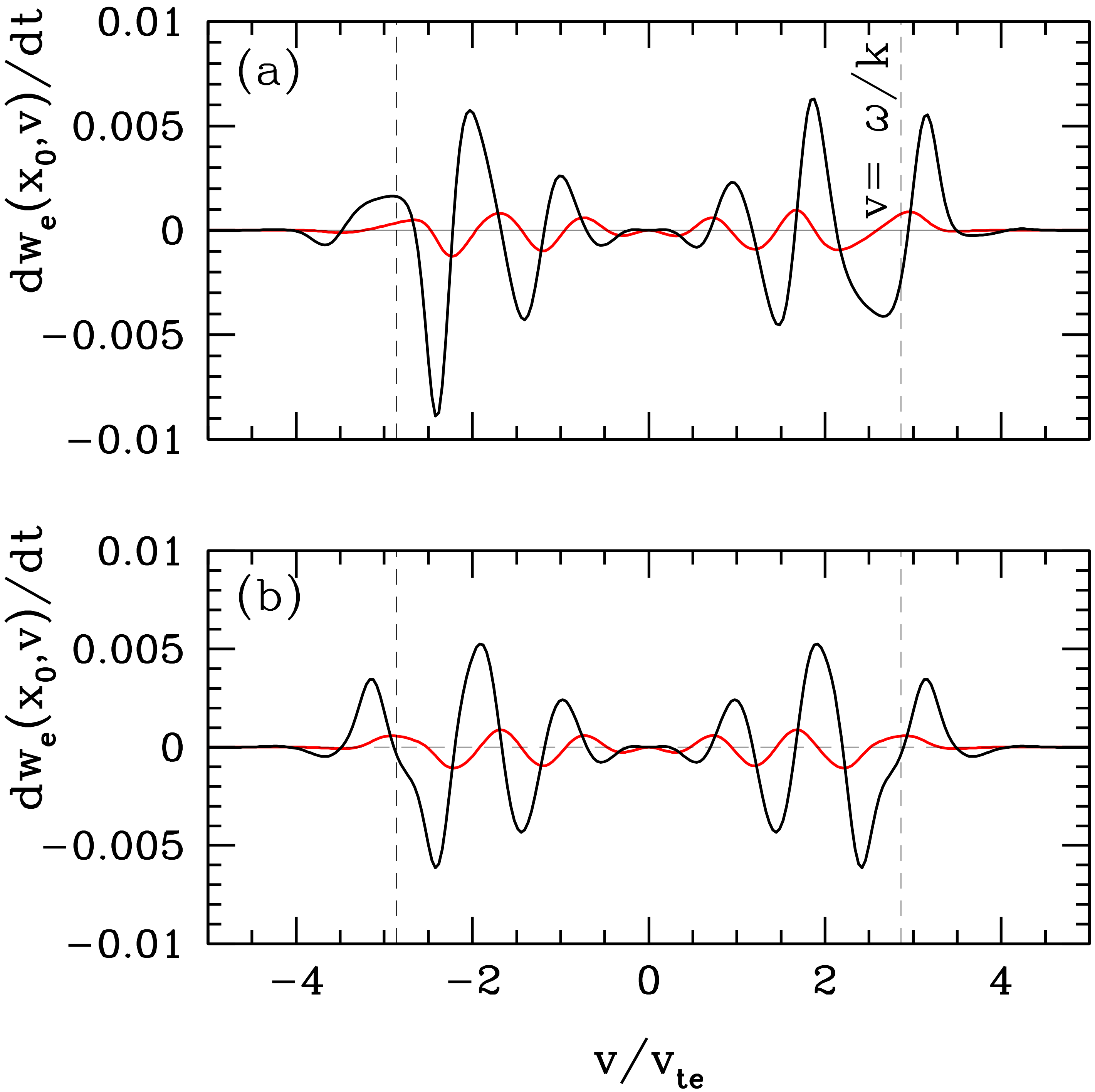
Integrate by parts $\int dv \left(\frac{q_s v^2}{2} \right) \frac{\partial f_s}{\partial v} = \left[\frac{q_s v^2}{2} f_s \right]_{-\infty}^{\infty} - \int dv \;\; q_s v f_s$

$$\frac{\partial W_s}{\partial t} = \int dx \int dv \; q_s v \delta f_s E$$

$$C_1(v,t,\tau) = C_\tau \left(-q_s \frac{v^2}{2} \frac{\partial \delta f_s}{\partial v}, E \right) \Rightarrow C_2(v,t,\tau) = C_\tau \left(q_s v \delta f_s, E \right)$$

Not exactly the energy transfer rate, but still may be useful to distinguish different energy transfer mechanisms

Alternative Correlation $C_2(v,t,\tau)$



$C_1(v,t,\tau)$

$$-q_s \frac{v^2}{2} \frac{\partial \delta f_s(x_0,v)}{\partial v} E(x_0)$$

$C_2(v,t,\tau)$

$$q_s v \delta f_s(x_0,v) E(x_0)$$

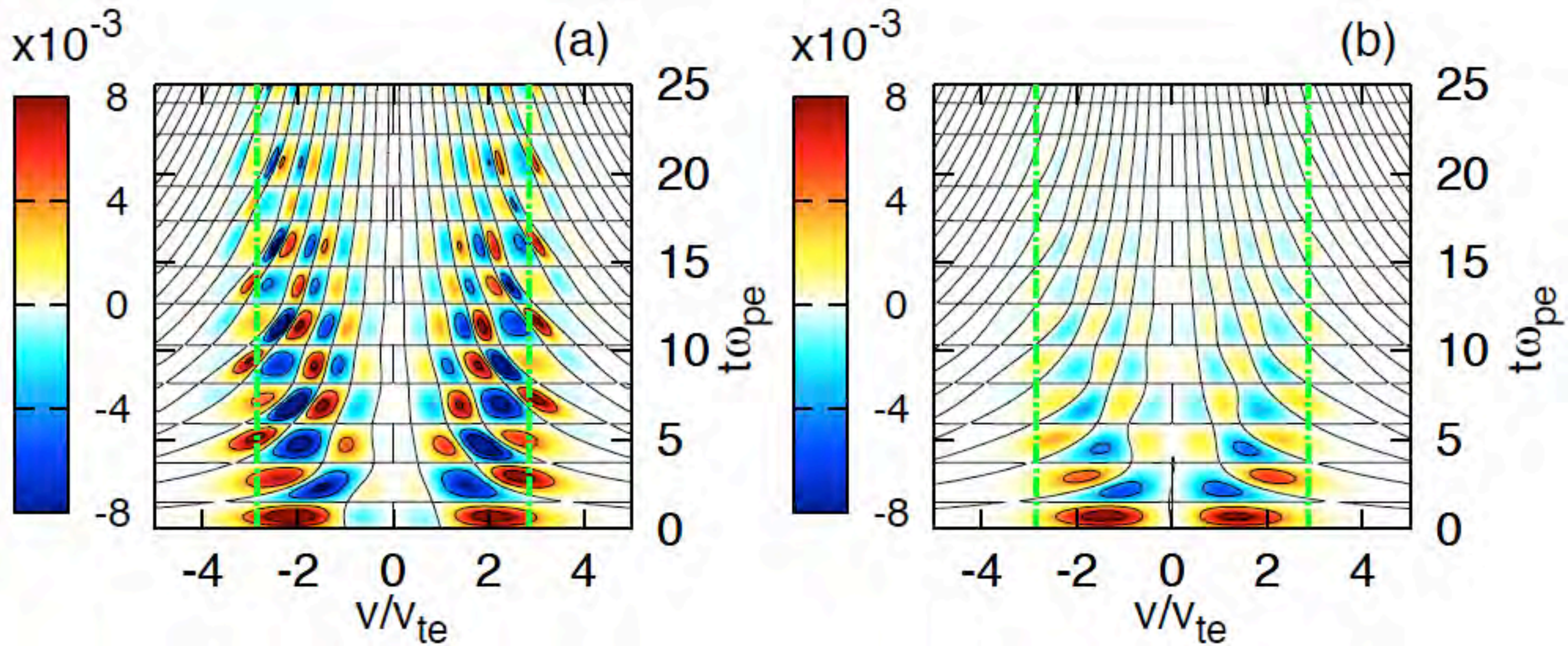
$C_2(v,t,\tau)$ is not exactly the energy transfer rate

But $C_2(v,t,\tau)$ still may be useful to distinguish different energy transfer mechanisms

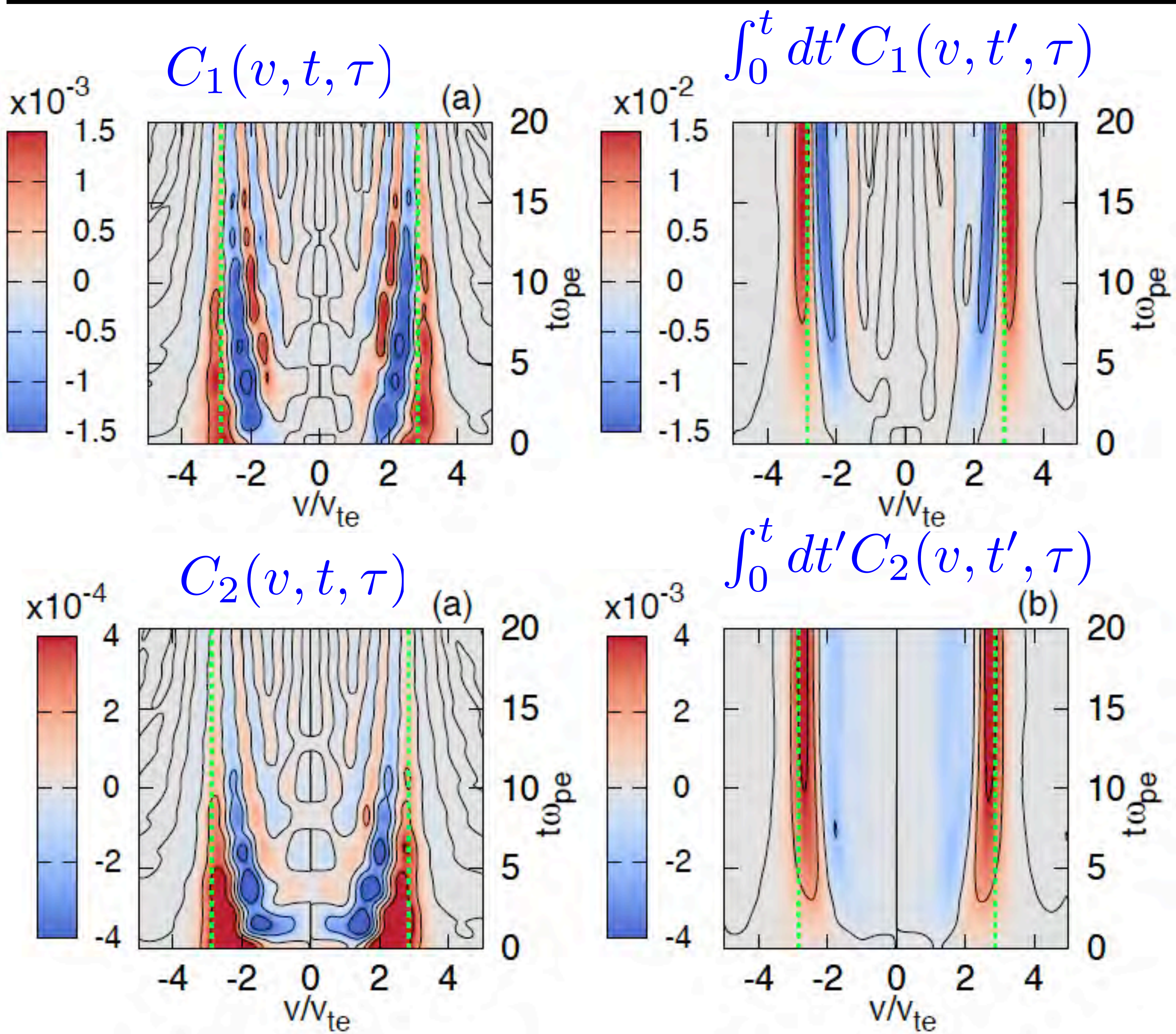
Comparison of $C_1(v,t,\tau)$ and $C_2(v,t,\tau)$

$$-q_s \frac{v^2}{2} \frac{\partial \delta f_s(x_0,v)}{\partial v} E(x_0)$$

$$q_s v \delta f_s(x_0,v) E(x_0)$$



Comparison of $C_1(v,t,\tau)$ and $C_2(v,t,\tau)$



Resonant Nature of Damping remains clear!

Weak Collisionless Damping

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$C_1(v,t,\tau)$ $\qquad\qquad$ $\int_0^t dt' C_1(v,t',\tau)$

Moderate Damping

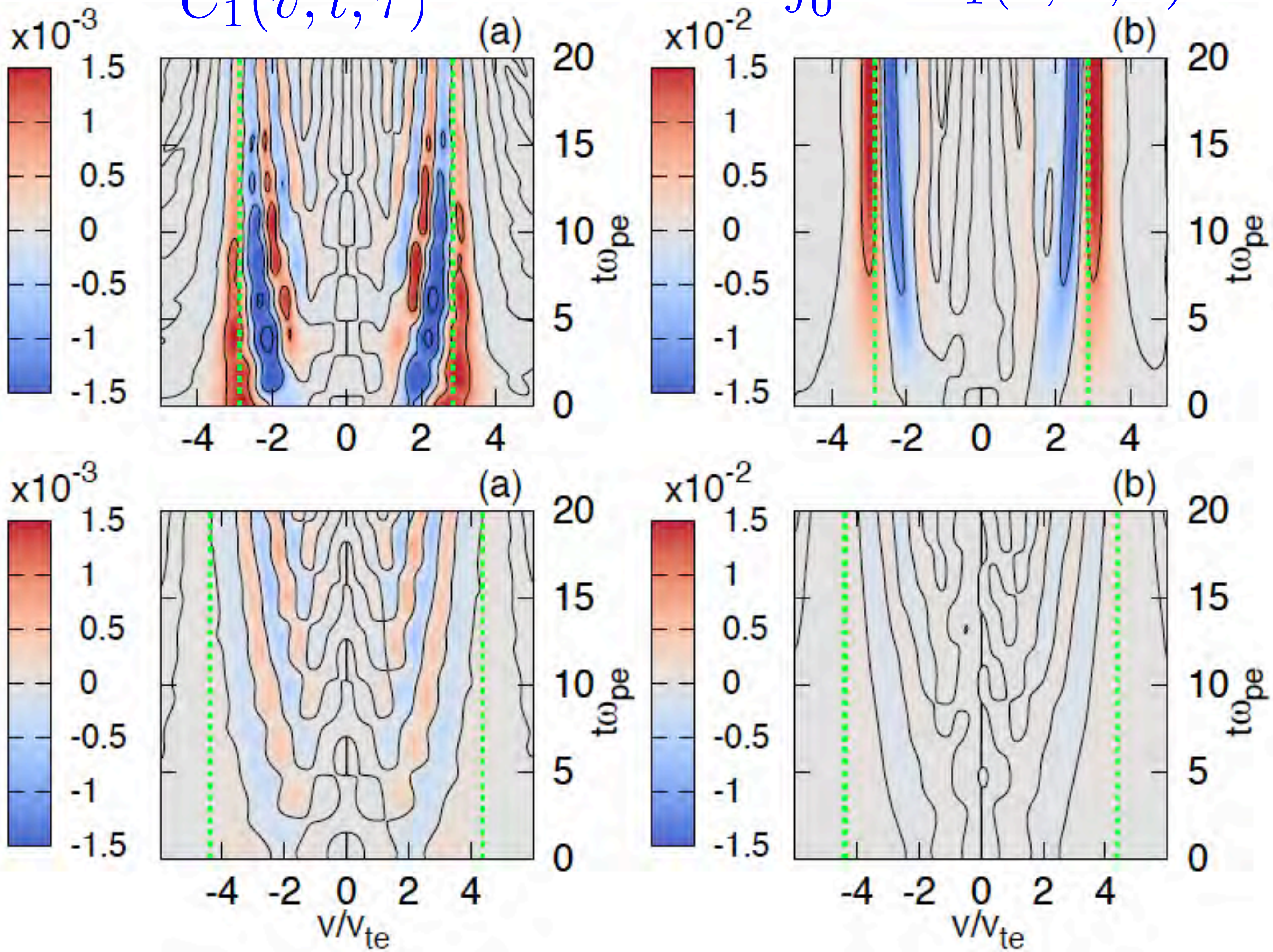
$k\lambda_{de} = 0.5$

$-\frac{\gamma}{\omega} = 0.11$

Weak Damping

$k\lambda_{de} = 0.25$

$-\frac{\gamma}{\omega} = 0.002$



NO FALSE POSITIVE SIGNATURE

Outline

- Energy Transfer and Dissipation in Kinetic Plasma Turbulence
- Conservation of Energy in a Kinetic Plasma
- Diagnosing Energy Transfer from Fields to Particles
- Nonlinear Kinetic Simulations: 1D-1V Vlasov-Poisson System
  - Implementation
  - Evolution of the Distribution Function
- Field-Particle Correlations using Single-Point Measurements
  - Best Correlation for Numerical Simulations
  - Alternative Correlation for Spacecraft Observations
- Application to Strongly Turbulent Systems
- Conclusions

Modifications for Solar Wind Turbulence

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- Field-particle correlations in 3V velocity space

$$C(v_{\perp 1}, v_{\perp 2}, v_{\|}, t, \tau) = C_\tau \left(\delta f_s(\mathbf{r}_0, v_{\perp 1}, v_{\perp 2}, v_{\|}, t), E_{\|}(\mathbf{r}_0, t) \right)$$

- Or can be used with reduced distribution functions,

$$C(v_{\|}, t, \tau) = C_\tau \left(\delta f_{\| s}(\mathbf{r}_0, v_{\|}, t), E_{\|}(\mathbf{r}_0, t) \right)$$

where $f_{\| s}(\mathbf{r}_0, v_{\|}, t) = \int v_\perp dv_\perp d\phi f_s(\mathbf{r}_0, v_{\perp 1}, v_{\perp 2}, v_{\|}, t)$

- For different damping mechanisms, form of correlation differs

Landau damping $C(v_{\|}, t, \tau) = C_\tau \left(\delta f_{\| s}(\mathbf{r}_0, v_{\|}, t), E_{\|}(\mathbf{r}_0, t) \right)$

Transit time damping $C(v_{\|}, t, \tau) = C_\tau \left(\delta f_{\| s}(\mathbf{r}_0, v_{\|}, t), \delta B_{\|}(\mathbf{r}_0, t) \right)$

Kinetic theory can be used to derive the appropriate forms

Applicability to Strongly Turbulent Systems

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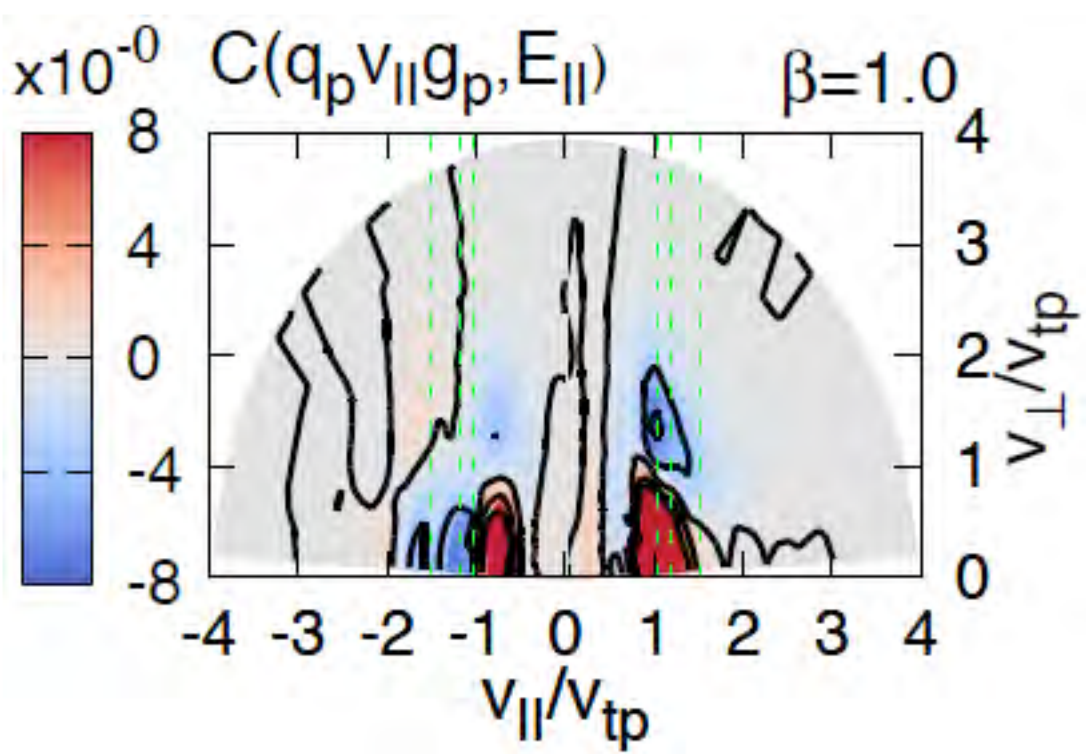
We have shown this correlation technique works for linear waves

But does it work for strongly turbulent systems?

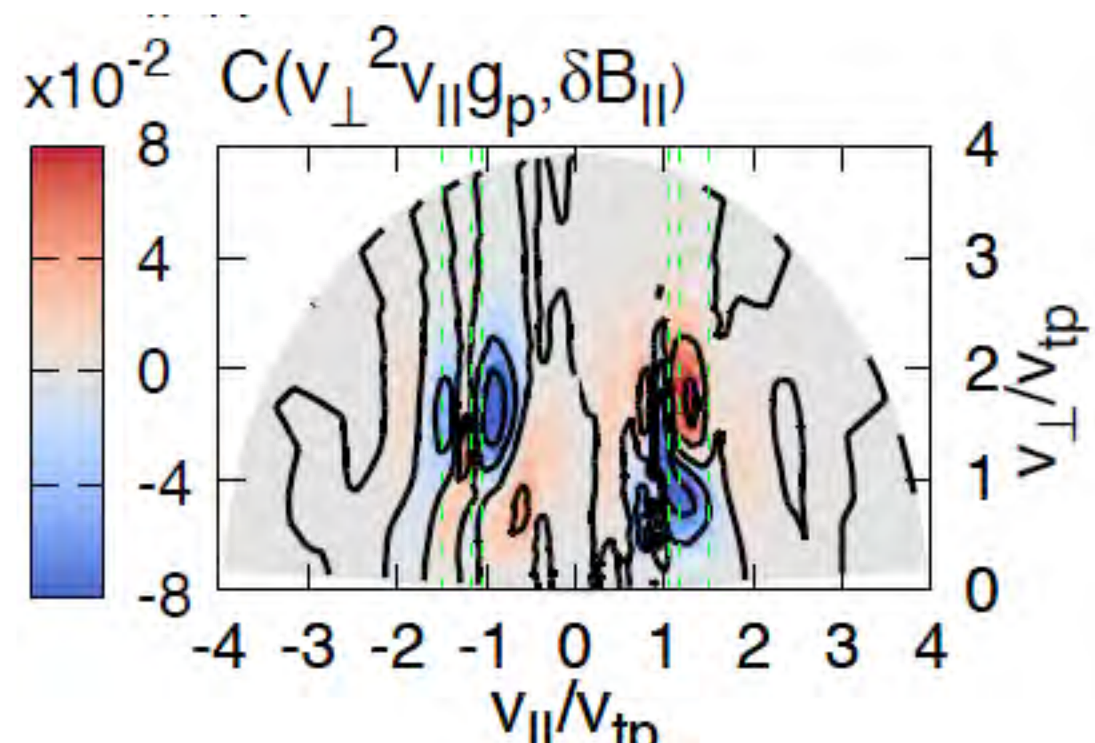
Yes!

NEXT TALK: Kris Klein

Secular Field-Particle Energy Transfer
in a Turbulent Gyrokinetic System



Landau Damping



Transit Time Damping

Solar Wind Turbulence

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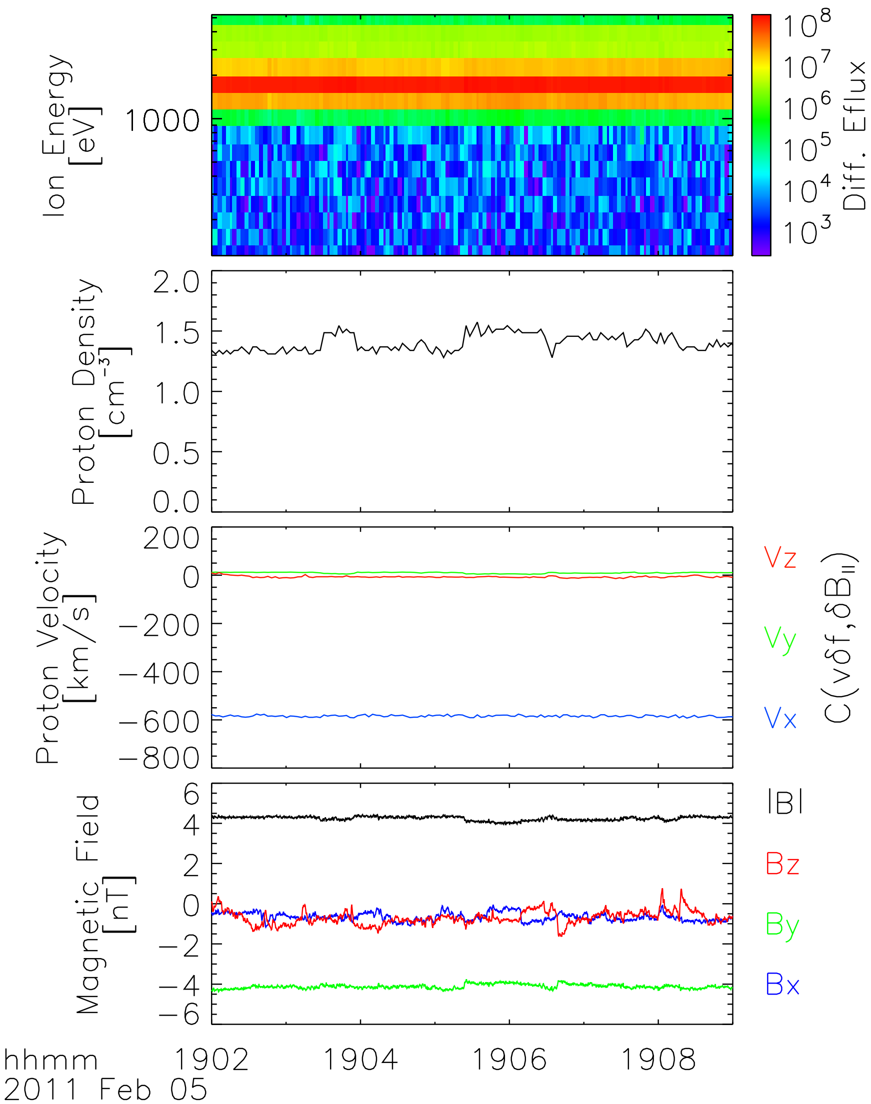
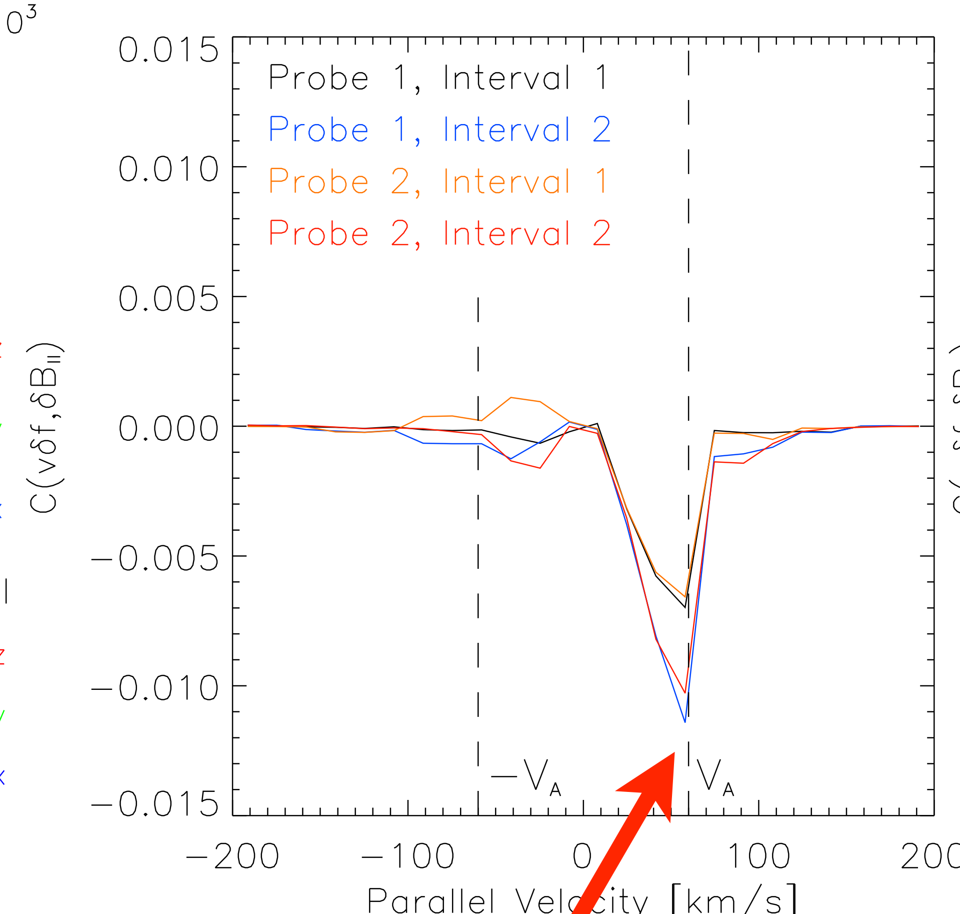
Preliminary work shows promising results in the solar wind

ARTEMIS data

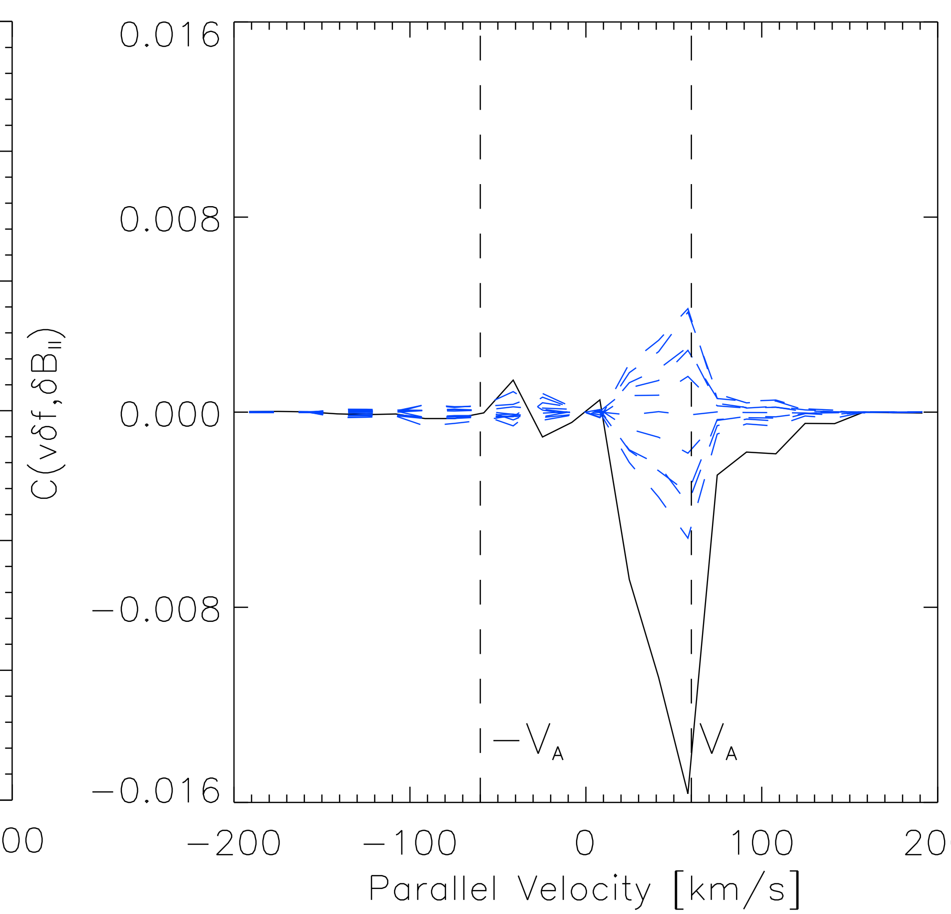


(Halekas & Howes, in prep, 2016)

$$C(v\delta f_i(v), \delta B_\parallel)$$



$$C(v\delta f_i(v), \delta B_\parallel)$$



ARTEMIS data shows a resonant velocity-space signature

Completely General Approach

- The development of this field-particle correlation technique did not depend on the existence of waves or turbulence

- Derived using the terms describing collisionless energy transfer in the nonlinear equations of kinetic theory

- The approach is completely general, and can be used to study any particle energization process, including
  - Collisionless magnetic reconnection
  - Particle acceleration

Conclusions

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- **Challenge**: Measure energy transfer and damping of turbulence in weakly collisional plasmas
  - Must isolate small secular transfer from large oscillating transfer
- Introduced an innovative Field-Particle Correlation Technique
  - Uses single-point measurements $\delta f_s(x_0, v, t)$ and $E(x_0, t)$
  - Provides a direct measure of energy transfer rate
- **Key Feature**: Particle energization as a function of velocity
  - Velocity-space signature of the collisionless damping mechanism
    - Landau damping, stochastic heating, collisionless reconnection
  - Can be used to distinguish different damping mechanisms
- Illustrated with Langmuir waves, but also works in magnetized turbulence: gyrokinetic simulations and solar wind turbulence

FIELD-PARTICLE CORRELATIONS

Powerful new technique to study

any particle energization process in the heliosphere

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END