Diagnosing Plasma Heating and Particle Acceleration in Space and Astrophysical Plasmas

Gregory G. Howes
University of Iowa

Plasma Astrophysics and Extreme High Energies Mini-Workshop
UC Irvine
6 Feb 2017

This work is supported by the NASA PECASE Award NNX10AC91G, NSF/DOE Partnership in Plasma Physics Grant DE-SC0014599, NSF CAREER Award AGS-1054061, and the NSF XSEDE Program.

THE UNIVERSITY OF IOWA

Collaborators

The University of Iowa

Kris Klein (former grad student)	University of Michigan
Tak Chu Li (postdoc)	University of Iowa
Jim Schroeder (grad student)	University of Iowa
Andrew McCubbin (grad student)	University of Iowa
Jasper Halekas	University of Iowa
Francesco Valentini	University of Calabria
Ryusuke Numata	University of Hyogo
Nuno Loureiro	Massachusetts Institute of Technology
Matthew Kunz	Princeton University
Mike Stevens	Harvard-Smithsonian CfA
Justin Kasper	University of Michigan
Chris Chen	Imperial College

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

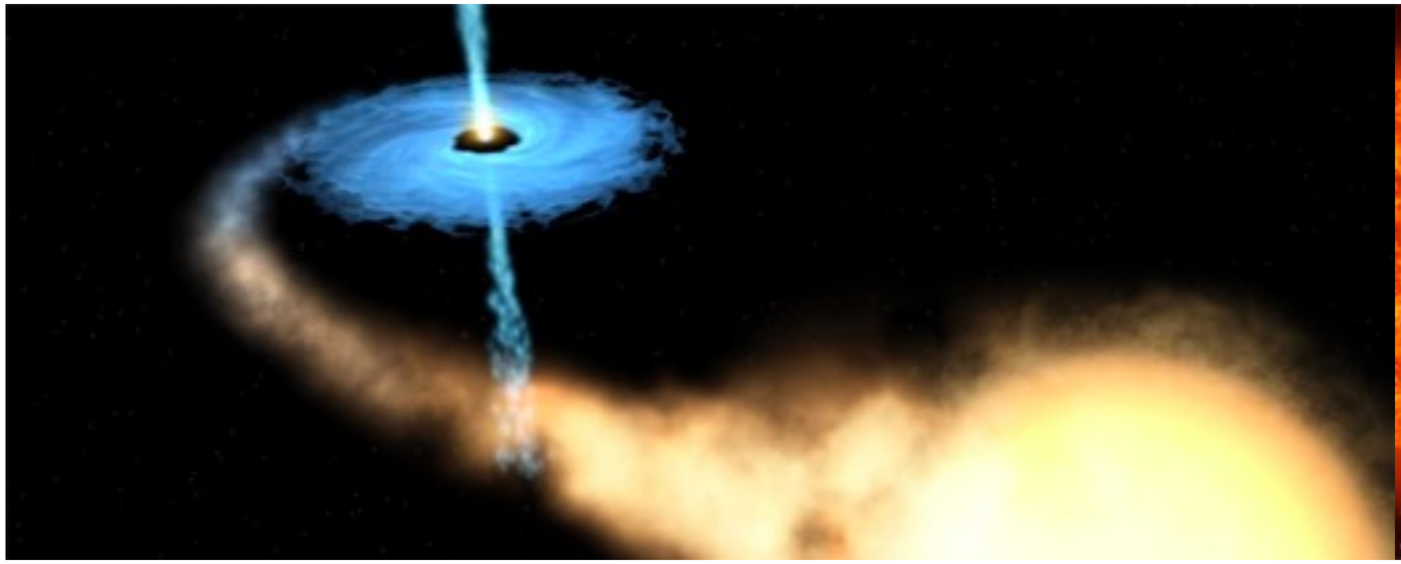
THE UNIVERSITY OF IOWA

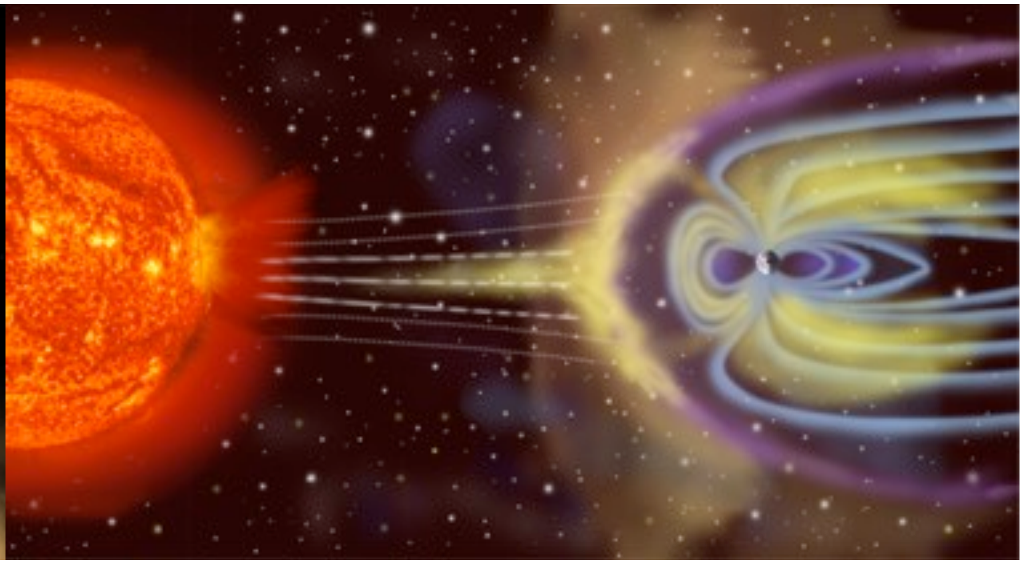
- Astrophysical Plasma Heating and Particle Acceleration
- Particle Energization in Weakly Collisional Plasmas
- Particle Energization in Kinetic Plasma Theory
- Numerical Demonstration of Field-Particle Correlation Technique
- Plasma Energization in Electromagnetic Plasma Turbulence
- Conclusions

Plasma Heating and Particle Energization

The University of Iowa

Astrophysical and heliospheric plasmas are magnetized and turbulent, and plasma turbulence almost certainly plays a key role in the heating of the plasma and the acceleration of particles

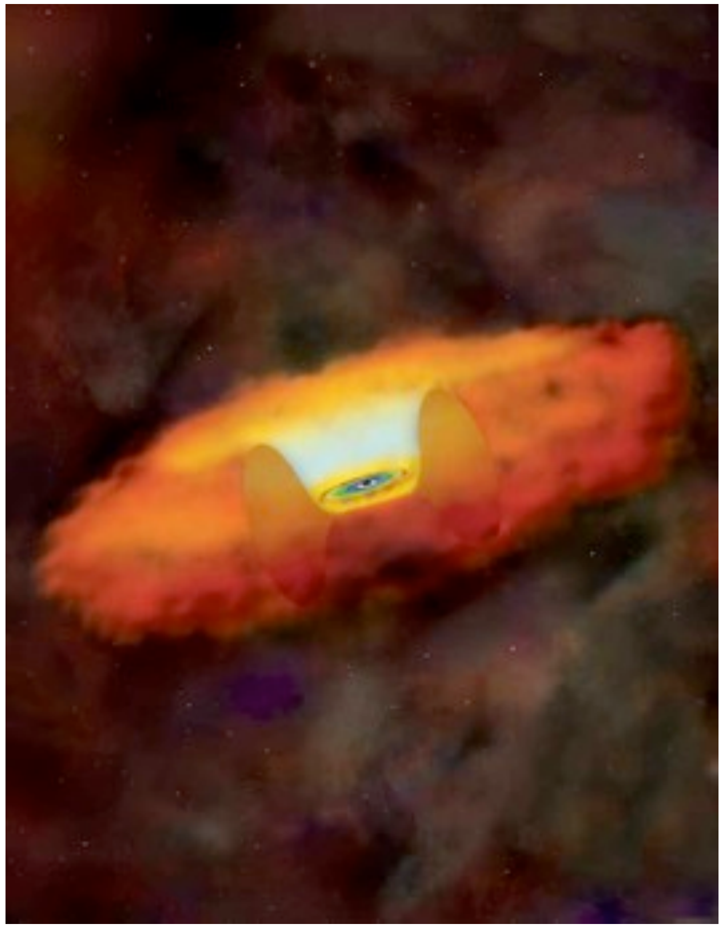




Explaining the plasma heating and particle acceleration is crucial to understanding the evolution of many poorly understood astrophysical systems

Black Hole Accretion Disks

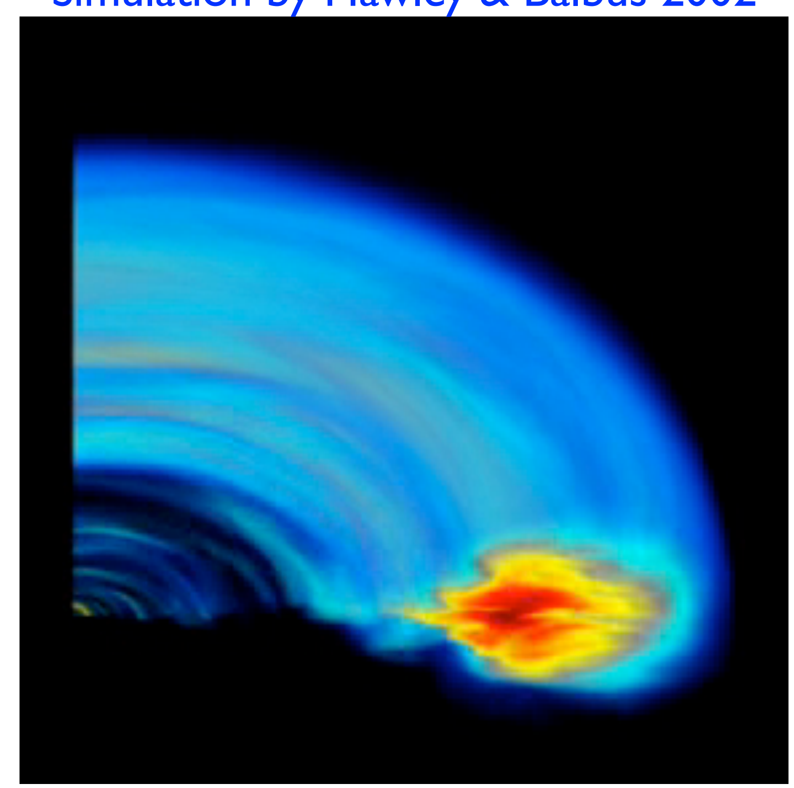
THE UNIVERSITY OF IOWA



NASA/CXC/SAO -Artist's Conception

- Matter spirals into the black hole, converting a tremendous amount of gravitational potential energy into heat
- This occurs via several processes:
  - Magnetorotational Instability (MRI) drives turbulence
  - Turbulence cascades nonlinearly to small scales
  - Kinetic mechanisms damp turbulence and lead to plasma heating

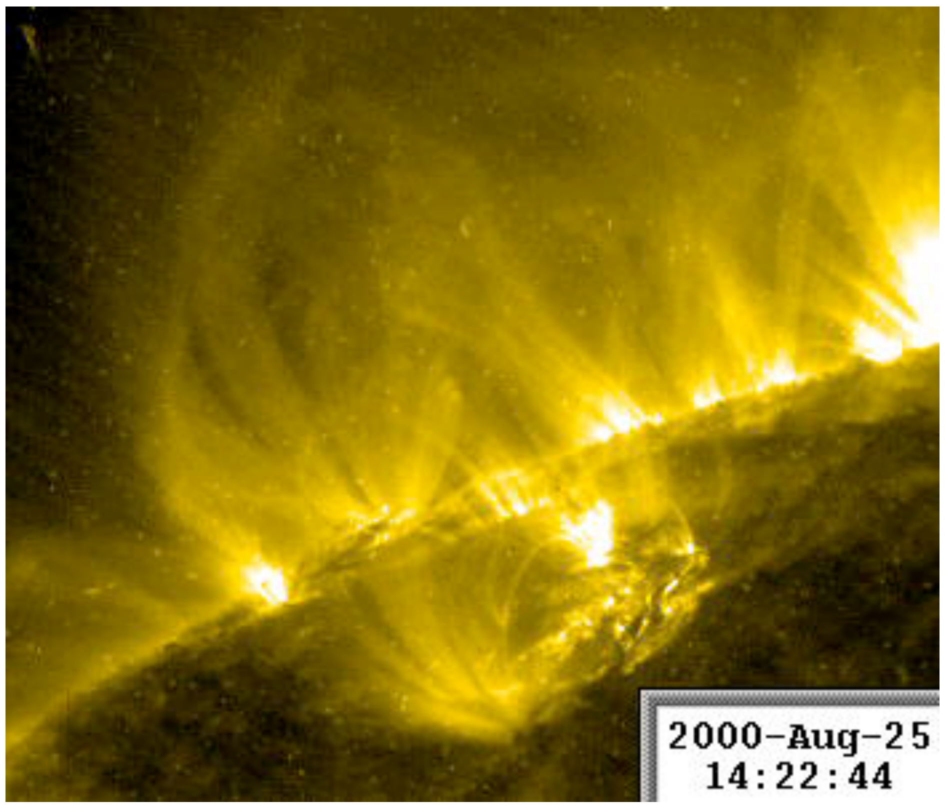
Simulation by Hawley & Balbus 2002



- Radiation emitted is function of plasma heating
- Interpretation of X-ray observations requires understanding of kinetic plasma turbulence and resulting plasma heating

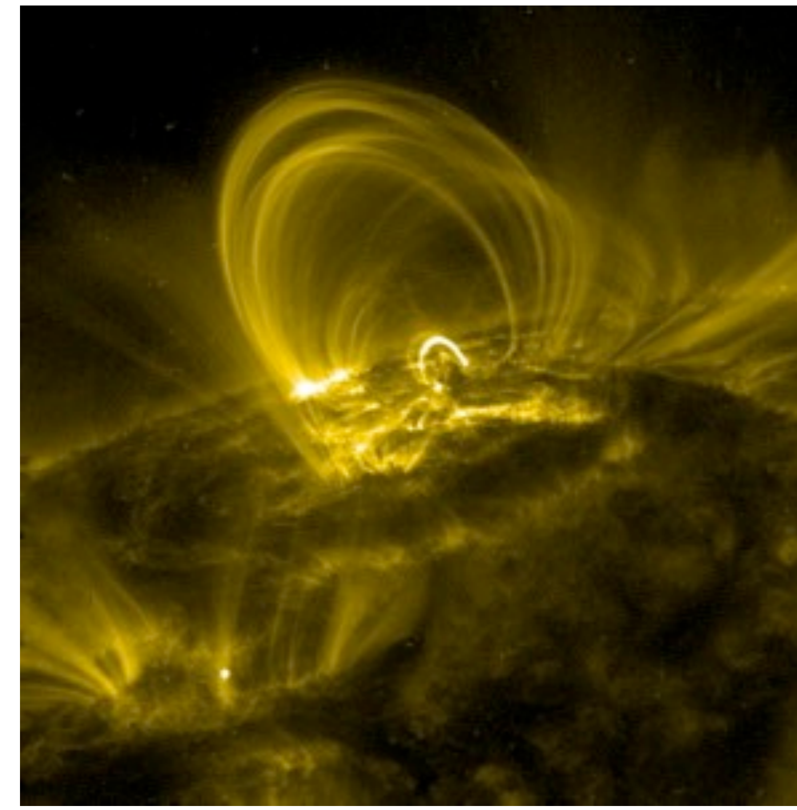
Solar Corona

- Important processes not well understood:
  - Heating of the Solar Corona
  - Acceleration of the Solar Wind



NASA/TRACE Movie

- Turbulence may play a key role in heating the coronal plasma



NASA/ TRACE Image

- Turbulence is driven by
  - Photospheric footpoint motions
  - Magnetic reconnection

Turbulence in Laboratory Plasmas

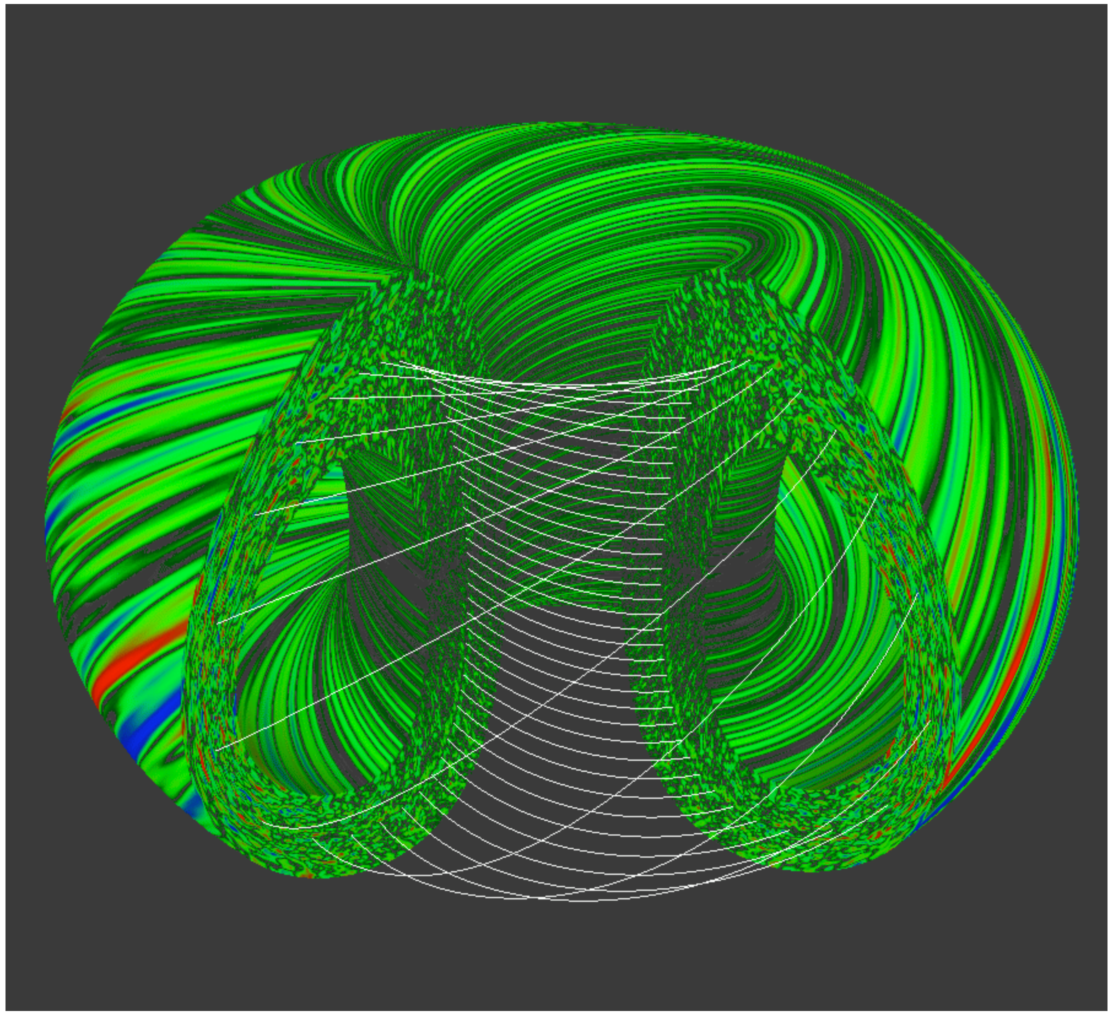
The University of Iowa

Learning about turbulence in space may help us to better control turbulence in the effort to harness fusion energy

Magnetic Confinement Fusion

Plasma from START,
Culham Laboratories, UKAEA

Gyrokinetic Simulation



Gyrokinetic Plasma Simulation
(G D Kerbel)

Outline

- Astrophysical Plasma Heating and Particle Acceleration
- Particle Energization in Weakly Collisional Plasmas
- Particle Energization in Kinetic Plasma Theory
- Numerical Demonstration of Field-Particle Correlation Technique
- Plasma Energization in Electromagnetic Plasma Turbulence
- Conclusions

Particle Energization in the Solar Wind

THE UNIVERSITY OF IOWA

- 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

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

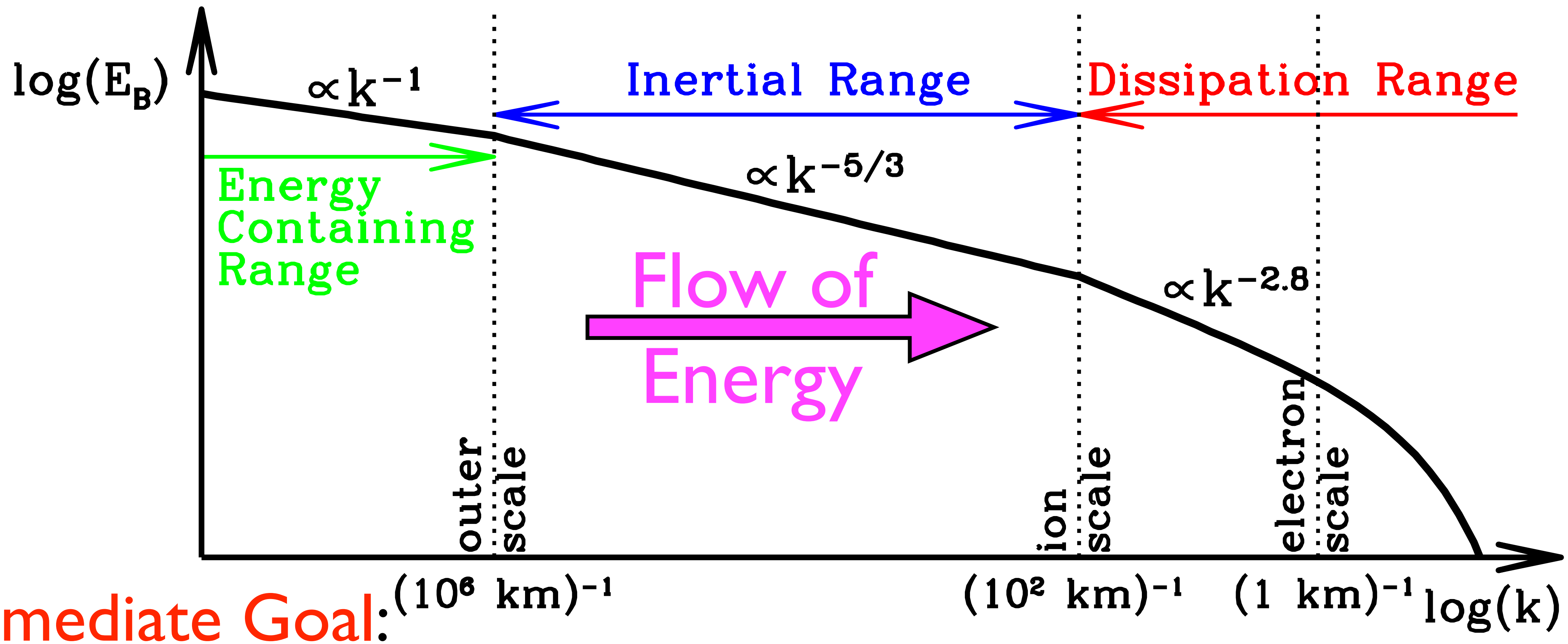
- Damping of turbulent fluctuations, and the resulting energization of the particles, requires collisonless interactions between the electromagnetic fields and the plasma particles

FIELD-PARTICLE CORRELATIONS

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

Turbulence in the Near-Earth Solar Wind

THE UNIVERSITY OF IOWA



Immediate Goal:

To understand the dynamics and energetics of the entire cascade

Flow of energy from large scale turbulent motions to plasma heat

FIELD-PARTICLE CORRELATIONS

(Klein & Howes, ApJL, **826**:L30 2016)

1) Compute the rate of energy transfer from fields to particles
2) Determine the velocity-space signature of energy transfer

Can be used to distinguish kinetic dissipation mechanism!

Particle Acceleration

The University of Iowa

- Kinetic plasma theory provides a robust framework to investigate the acceleration of particles to high energy

- Fundamentally, field-particle correlations can also highlight the energization occuring in particle acceleration, but . . .
  - fast particle velocities effectively mean the mechanism is nonlocal
  - particle measurements at high energy are limited to very low count rates

- Future work will investigate how field-particle correlations can be used to explore particle acceleration
  - At the very least, the technique can be used to determine how to energize the suprathermal seed population needed for subsequent Fermi acceleration

NASA IMAP mission (Interstellar Mapping and Acceleration Probe)

Outline

The University of Iowa

- Astrophysical Plasma Heating and Particle Acceleration
- Particle Energization in Weakly Collisional Plasmas
- Particle Energization in Kinetic Plasma Theory
- Numerical Demonstration of Field-Particle Correlation Technique
- Plasma Energization in Electromagnetic Plasma Turbulence
- Conclusions

Maxwell-Boltzmann Equations of Kinetic Plasma Theory

THE UNIVERSITY OF IOWA

Boltzmann Equation

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

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

1D-1V Vlasov-Poisson Equations

The University of Iowa

Vlasov-Possion Equations

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

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

Distribution Function

$$f_s(x,v,t)$$

Electrostatic Potential

$$\phi(x,t)$$

$$E = -\frac{\partial \phi}{\partial x}$$

Electrostatic Limit of Poynting's Theorem

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

Conserved Vlasov-Poisson Energy

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

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.

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

Change of Total Particle Energy

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

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

0 0

Perfect Differential Perfect Differential

Rate of Change of Particle Energy

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

But this is integrated over velocity and space.

Not observationally accessible!

Change of Particle Energy in Phase Space

The University of Iowa

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*

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

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

The University of Iowa

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

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

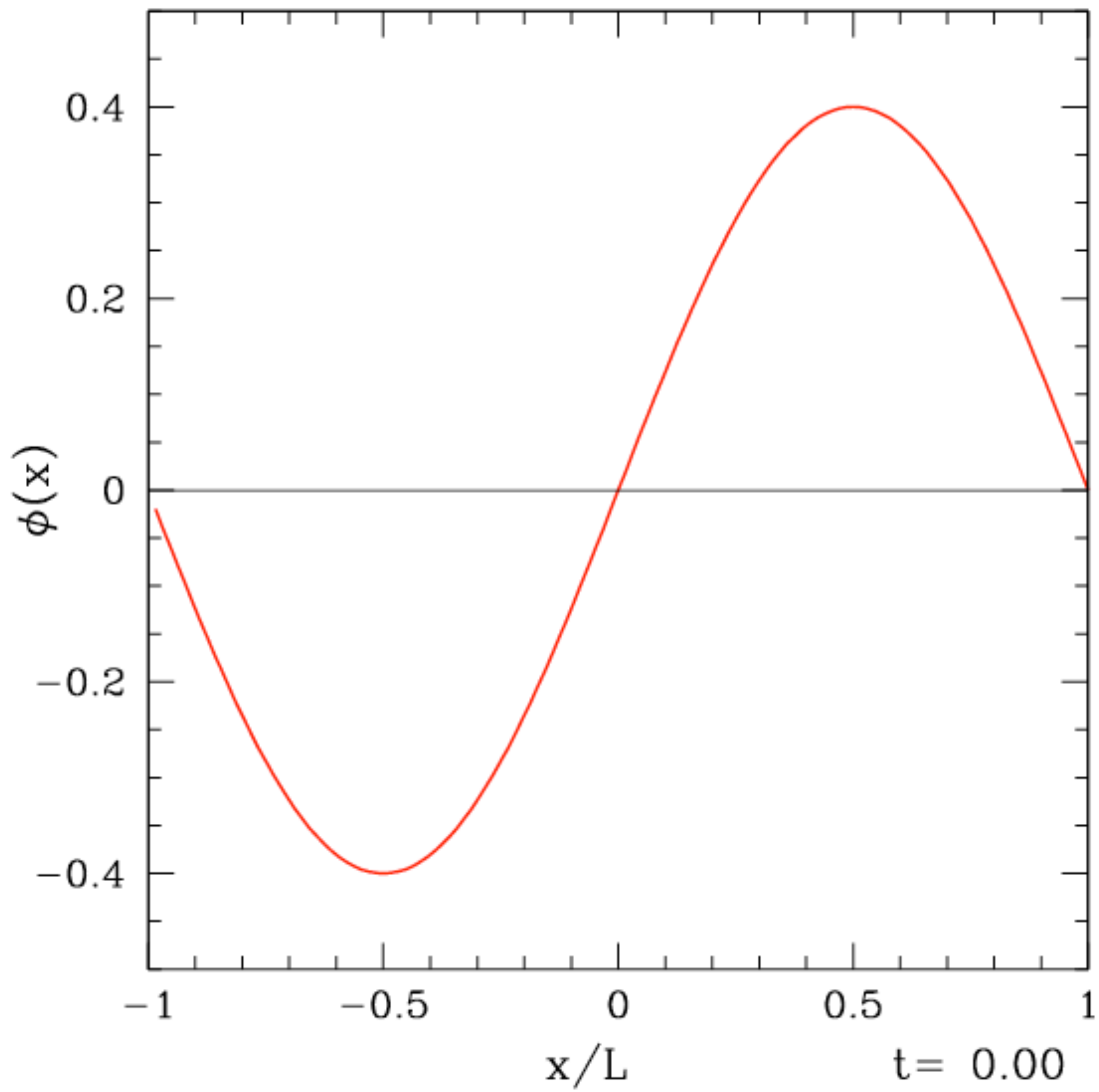
Outline

- Astrophysical Plasma Heating and Particle Acceleration
- Particle Energization in Weakly Collisional Plasmas
- Particle Energization in Kinetic Plasma Theory
- Numerical Demonstration of Field-Particle Correlation Technique
- Plasma Energization in Electromagnetic Plasma Turbulence
- Conclusions

Simulation Setup

Sinusoidal Electron Density Perturbation

Generates a standing Langmuir wave pattern that damps in time



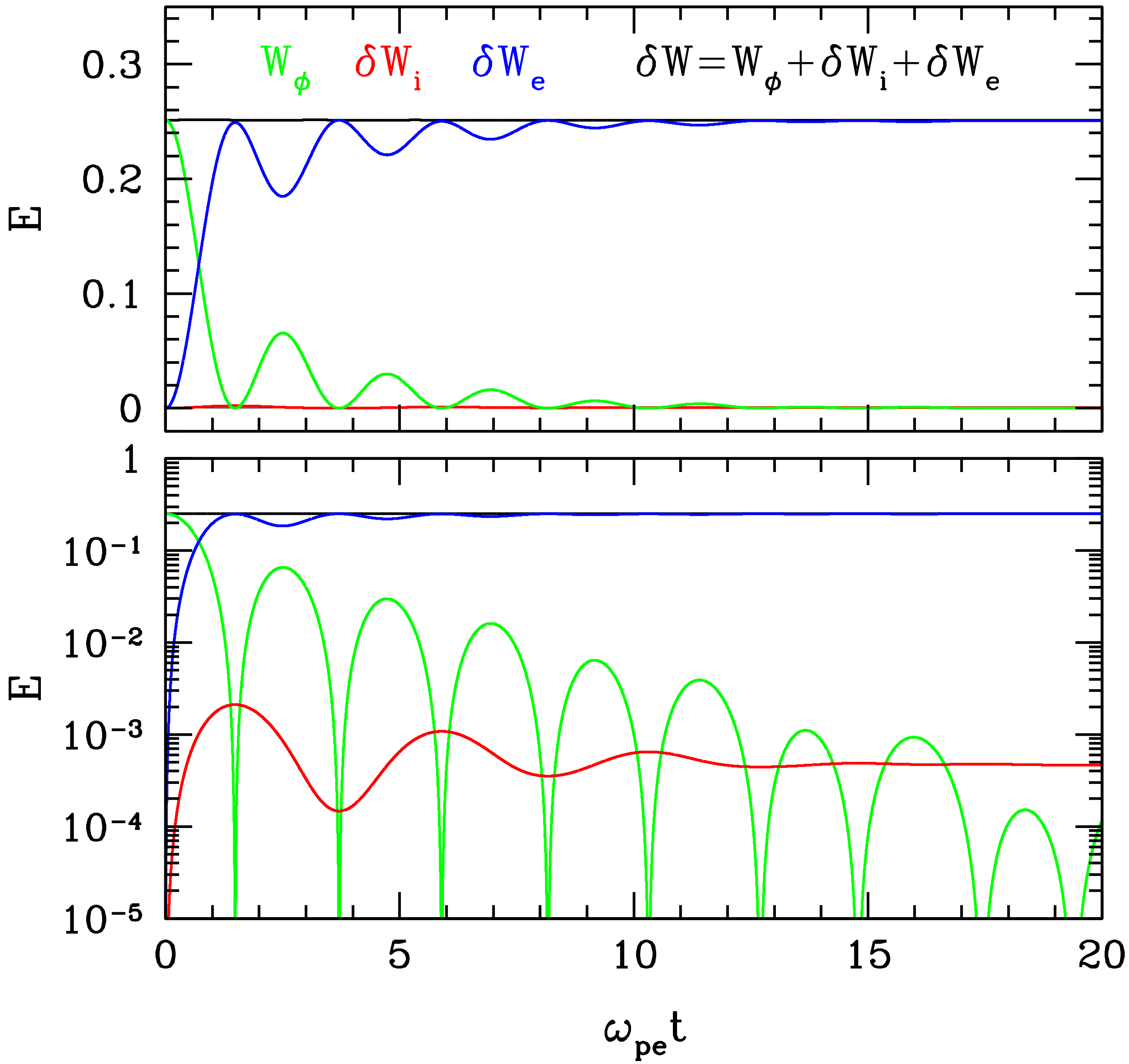
$$k\lambda_{de} = 0.5$$

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

Numerical Simulation of Landau Damping

The University of Iowa

Nonlinear Vlasov-Poisson simulation of the Landau damping of a Standing Langmuir Wave pattern



Electrostatic Field Energy

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

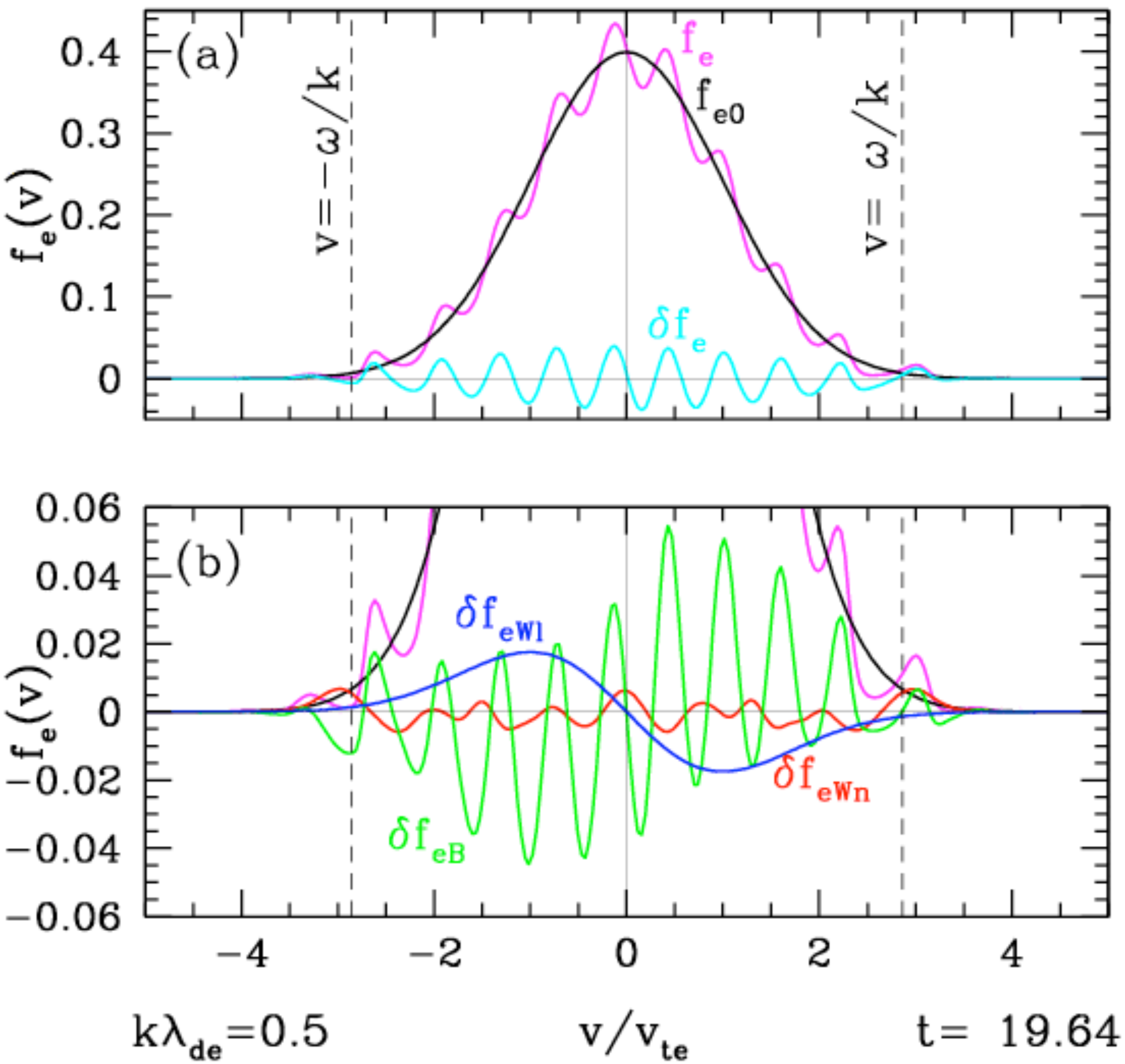
is converted to

Microscopic electron kinetic energy

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

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

Fluctuations of Distribution Function in time



Total $f_e(x_0, v, t)$

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

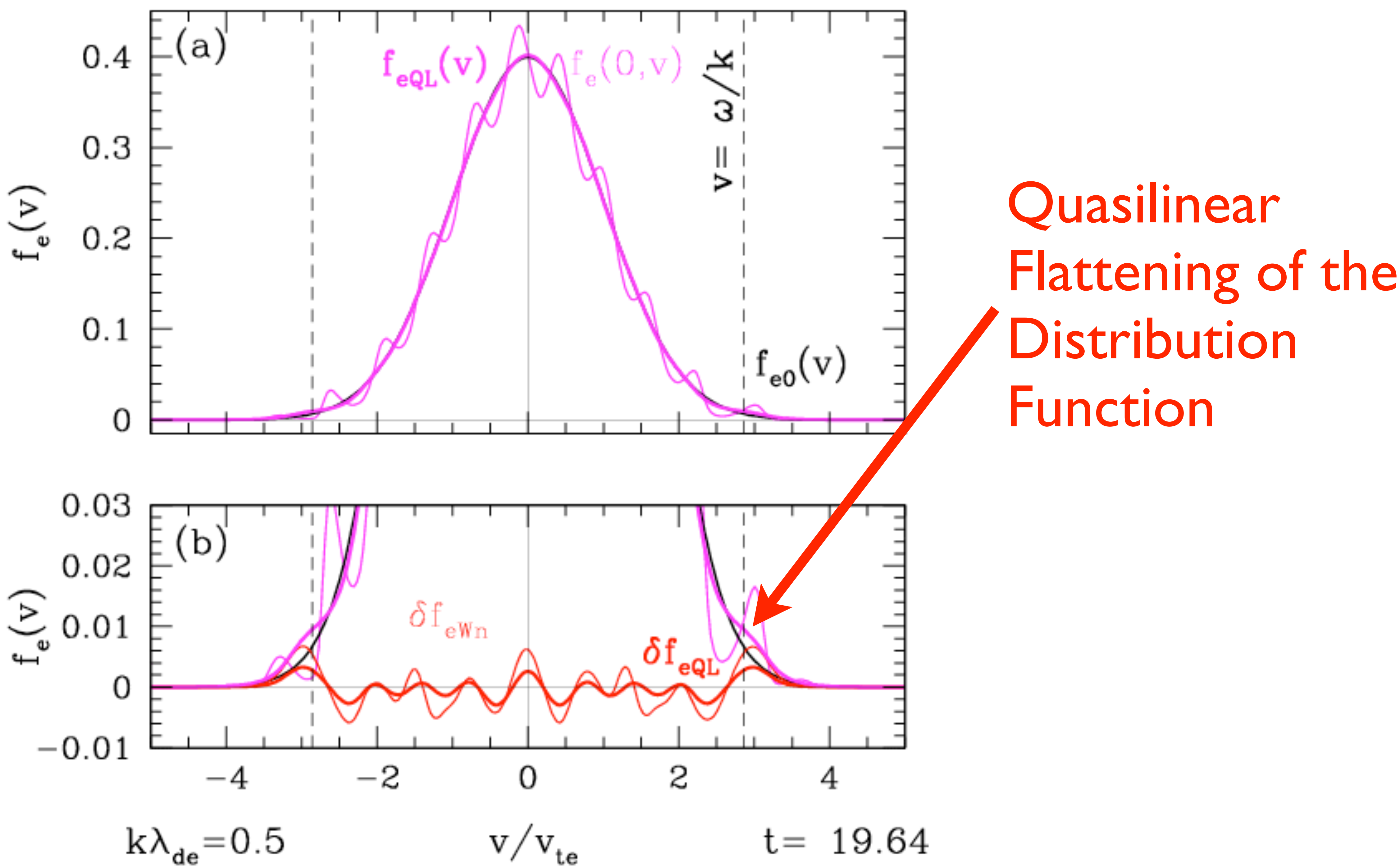
Ballistic Term $\delta f_{eB}(x_0, v, t)$

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

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

Quasilinear Evolution

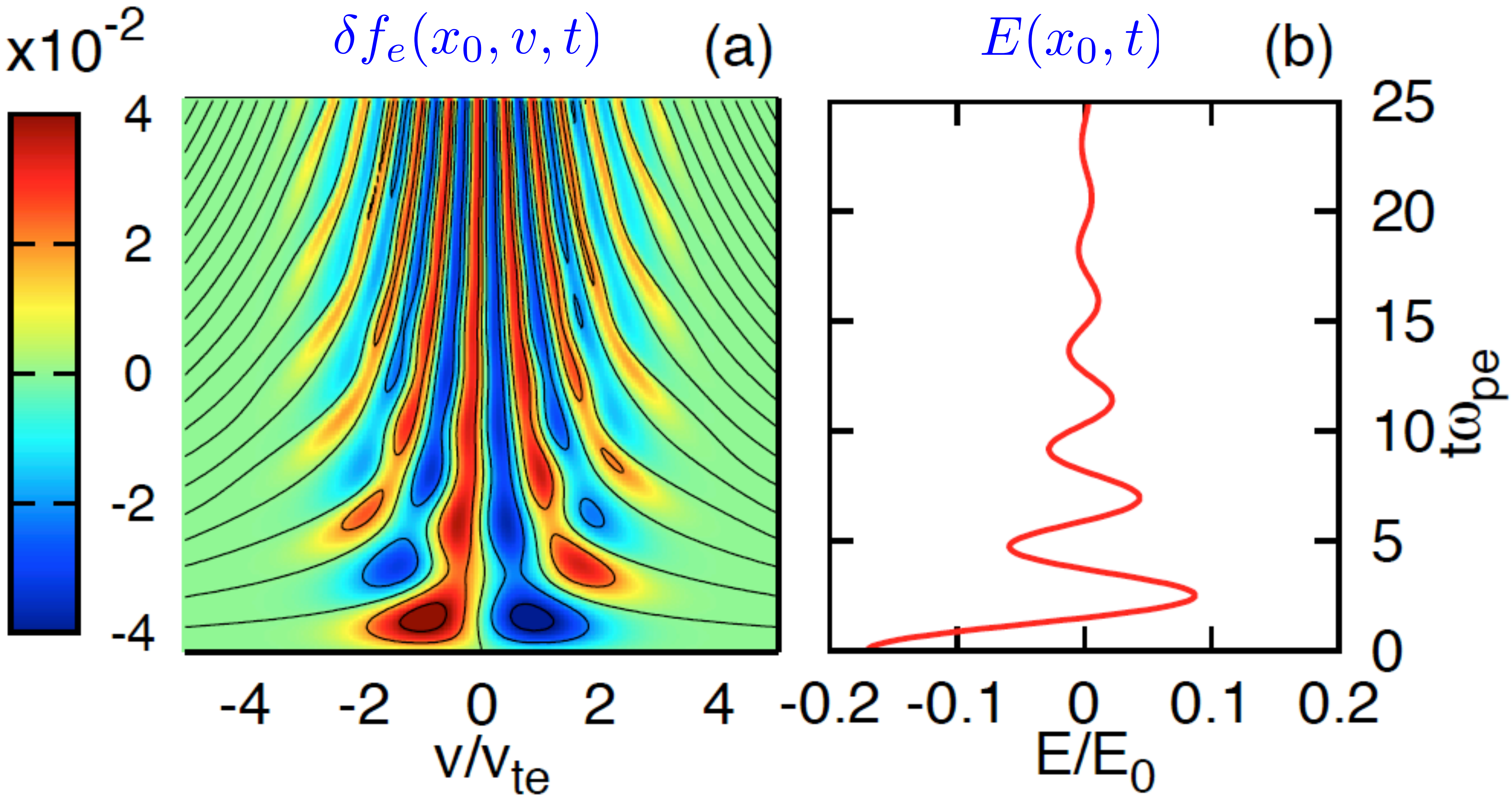
Integrating $\int dx$ yields quasilinear evolution of $f_{eQL}(v,t)$



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

Observable Quantities

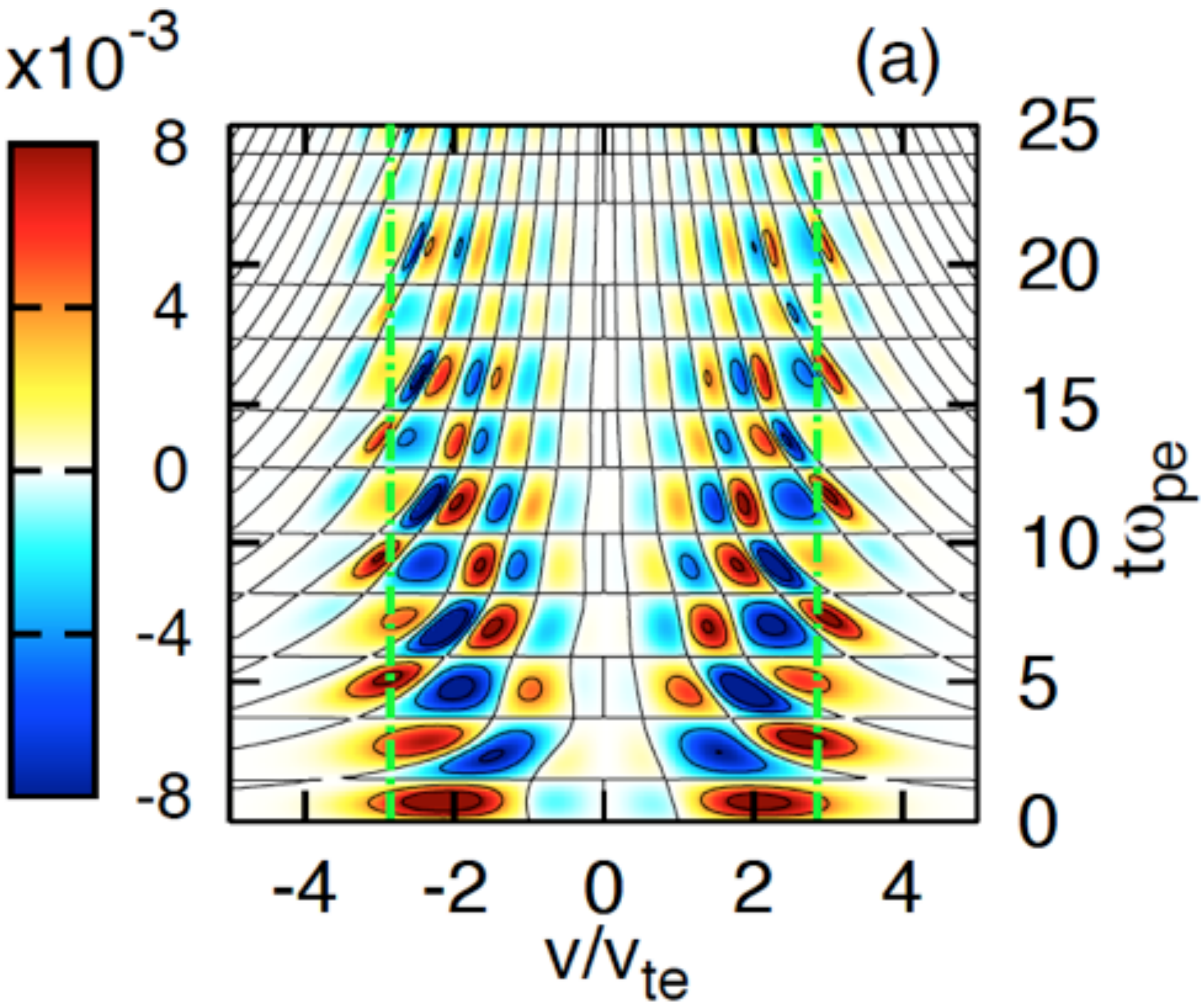
Single-point measurements of $\delta f_e(x_0, v, t)$ and $E(x_0, t)$

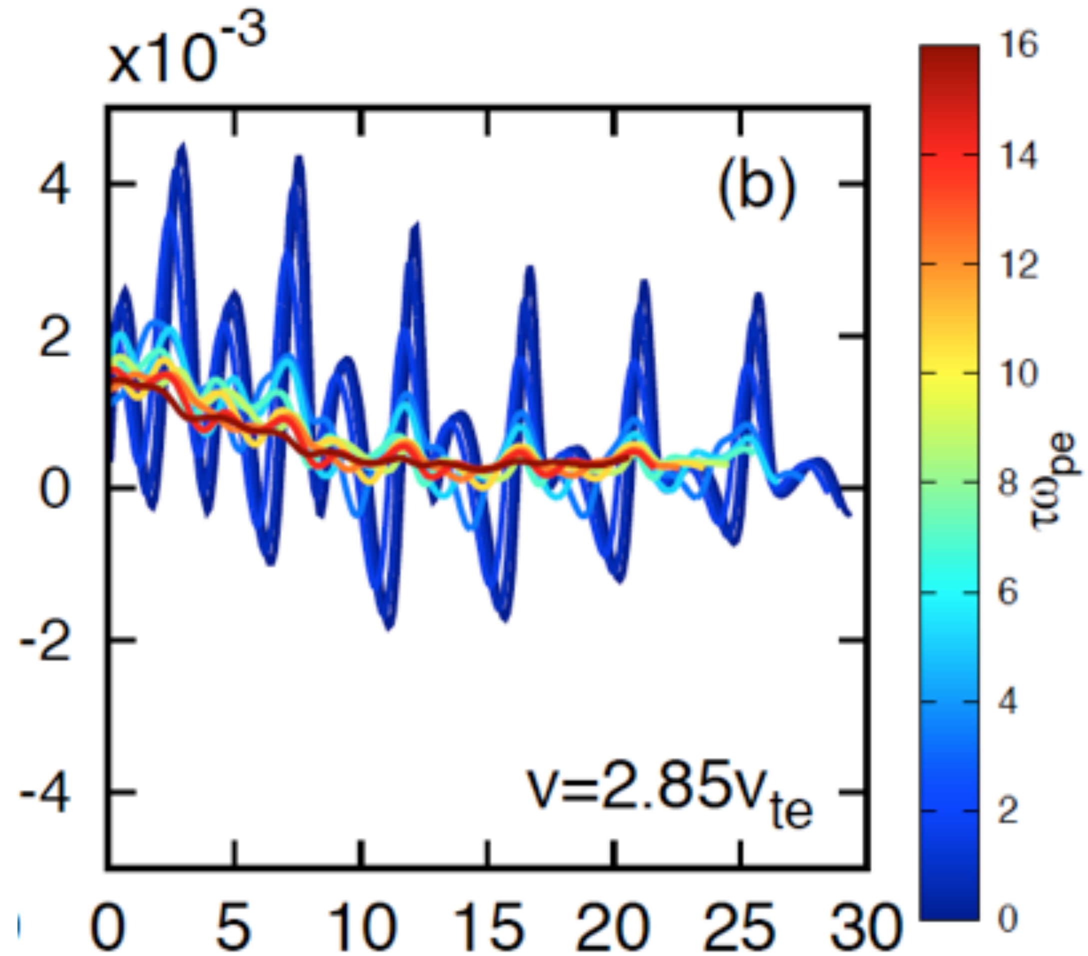


Correlation Eliminates Oscillation

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

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





Wave Period

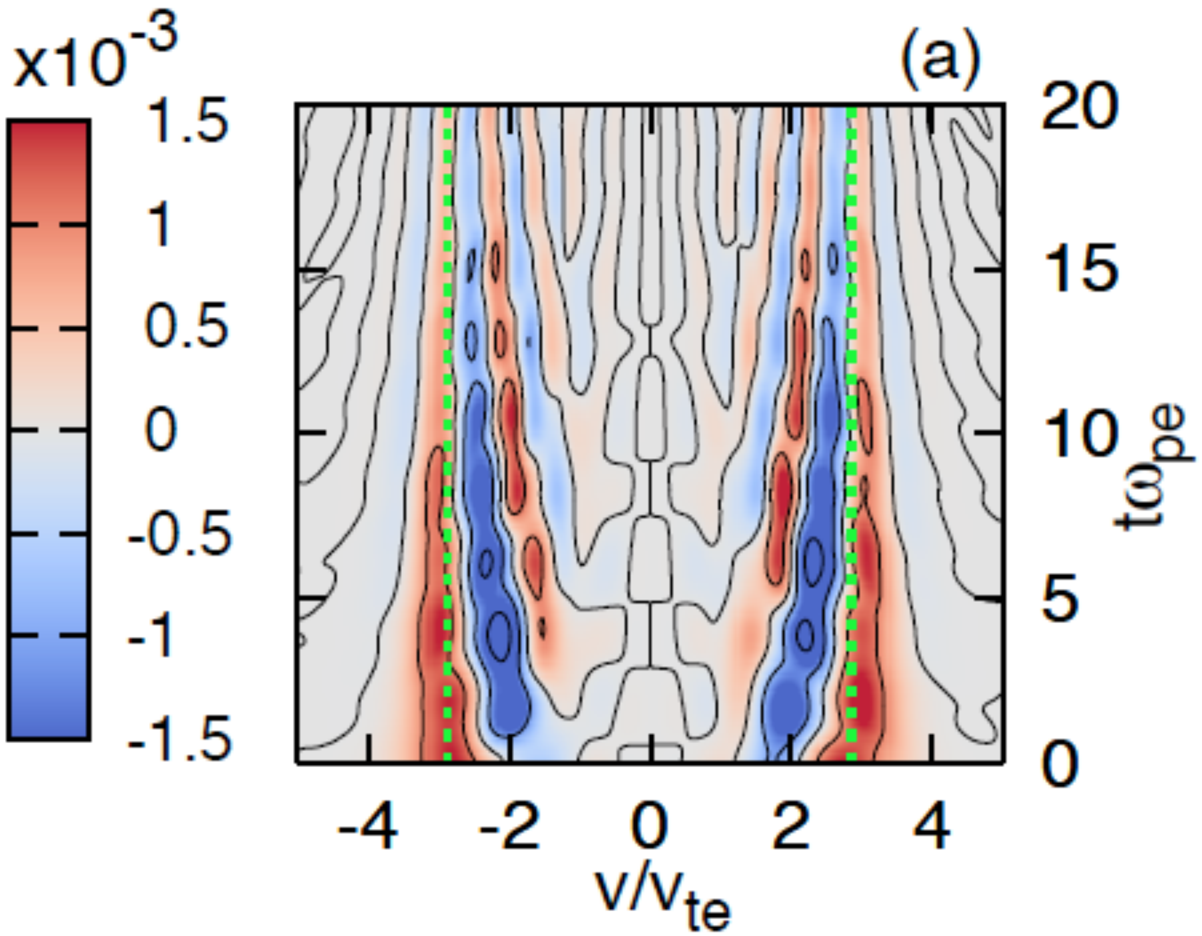
$$T\omega_{pe} = 4.39$$

Increasing correlation time τ helps to eliminate oscillation

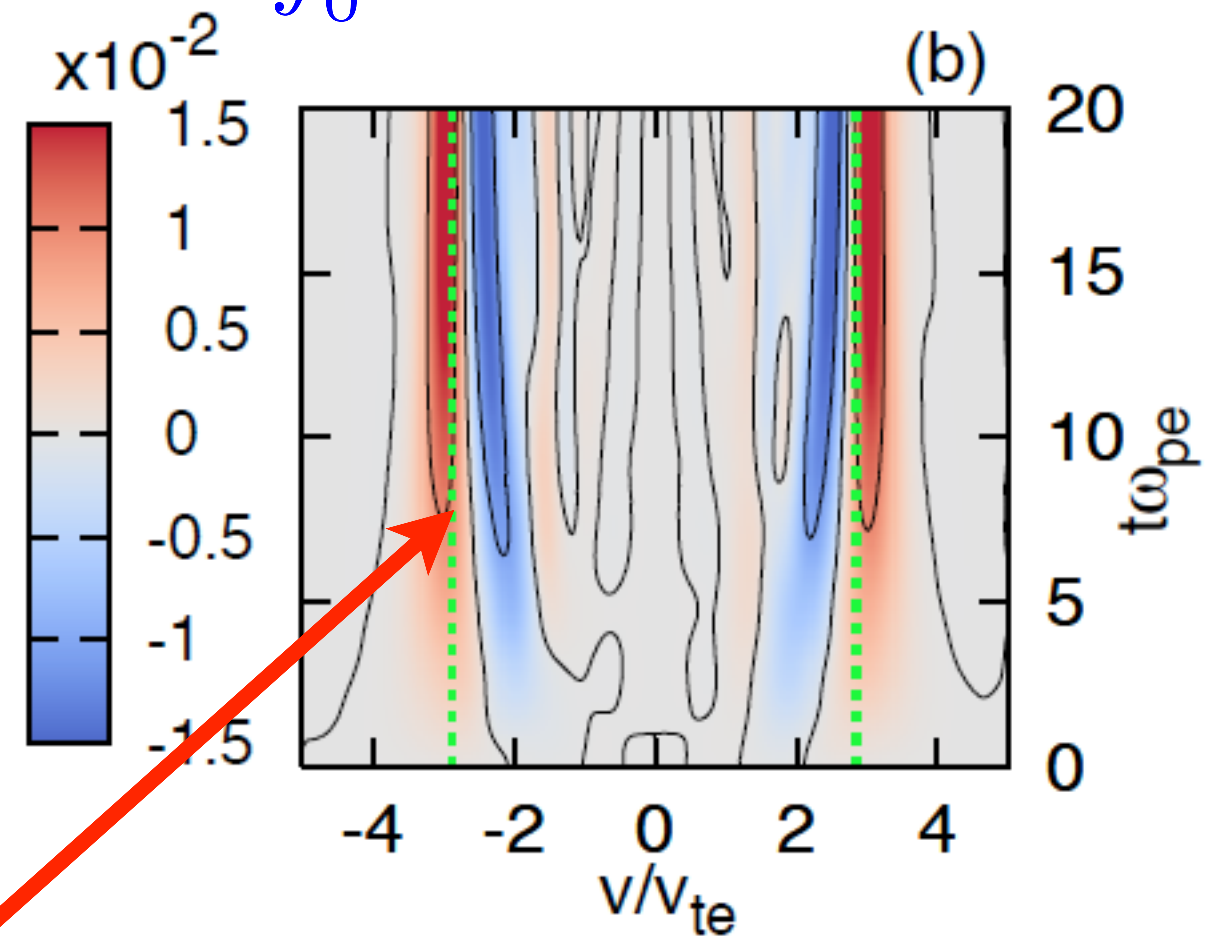
Field-Particle Correlation Results

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!

Outline

- Astrophysical Plasma Heating and Particle Acceleration
- Particle Energization in Weakly Collisional Plasmas
- Particle Energization in Kinetic Plasma Theory
- Numerical Demonstration of Field-Particle Correlation Technique
- Plasma Energization in Electromagnetic Plasma Turbulence
- Conclusions

Physical Dissipation Mechanisms for Kinetic Turbulence

The University of Iowa

In the weakly collisional solar wind,

Three mechanisms have been proposed:

(1) Coherent Wave-Particle Interactions

(Landau damping, transit-time 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)

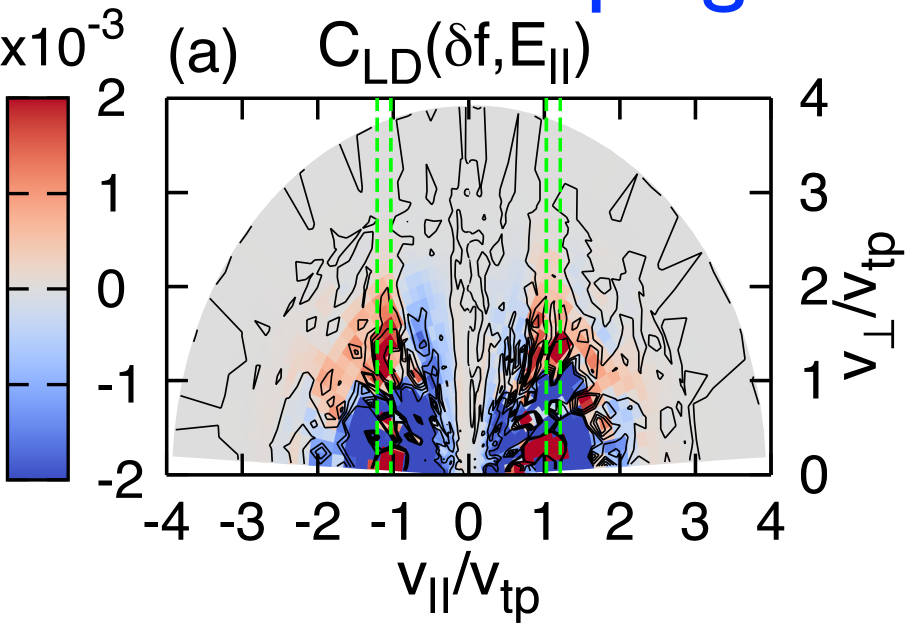
(Dmitruk *et al*. 2004; Markovskii & Vasquez 2011; Matthaeus & Velli 2011; Osman *et al*. 2011; Servidio 2011; Osman *et al*. 2012a,b; Wan *et al*. 2012; Karimabadi *et al*.2013; Zhdankin *et al*. 2013; Osman *et al*. 2014a,b; Zhdankin *et al*. 2015a,b;)

Form of correlation for each mechanism differs ($E_\parallel$, $\delta B_\parallel$, $E_\perp$)

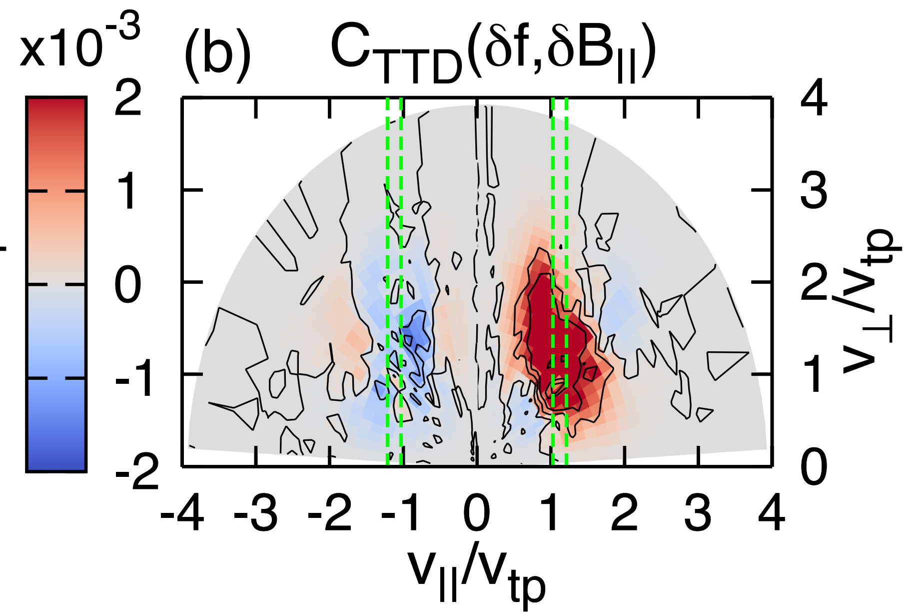
Applicability to Strongly Turbulent Systems

AstroGK Simulations

Landau Damping

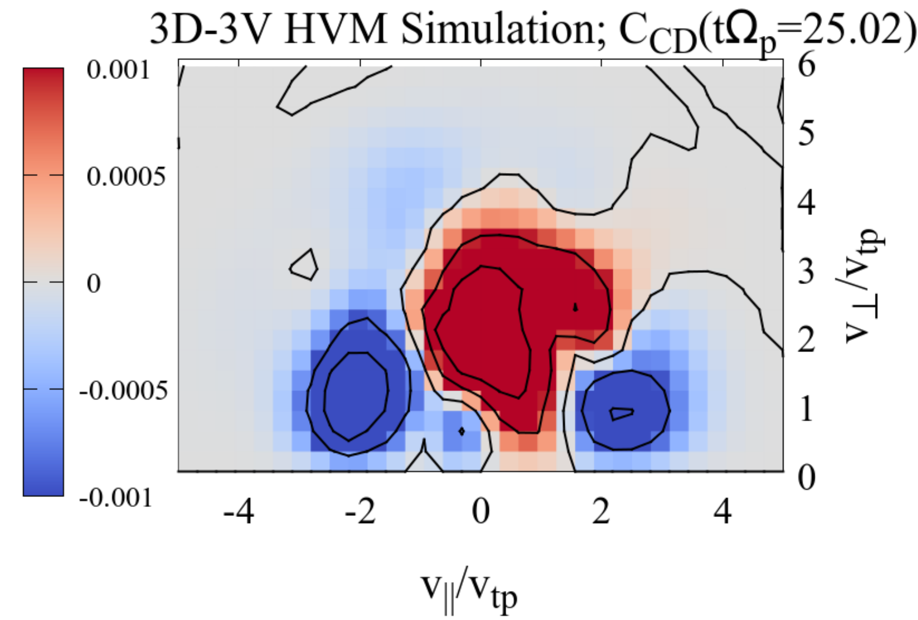


Transit Time Damping



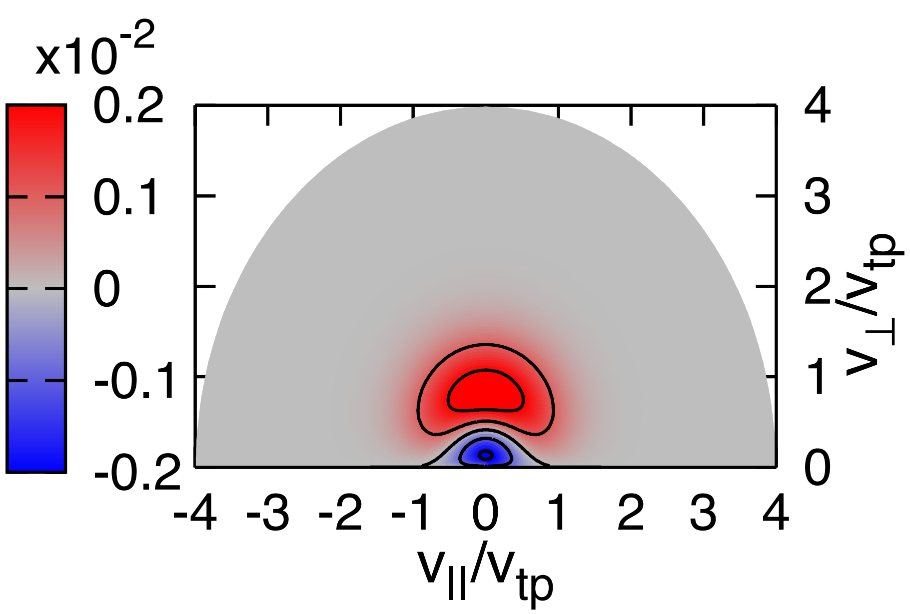
HVM Simulation

Cyclotron Damping



Theoretical Prediction

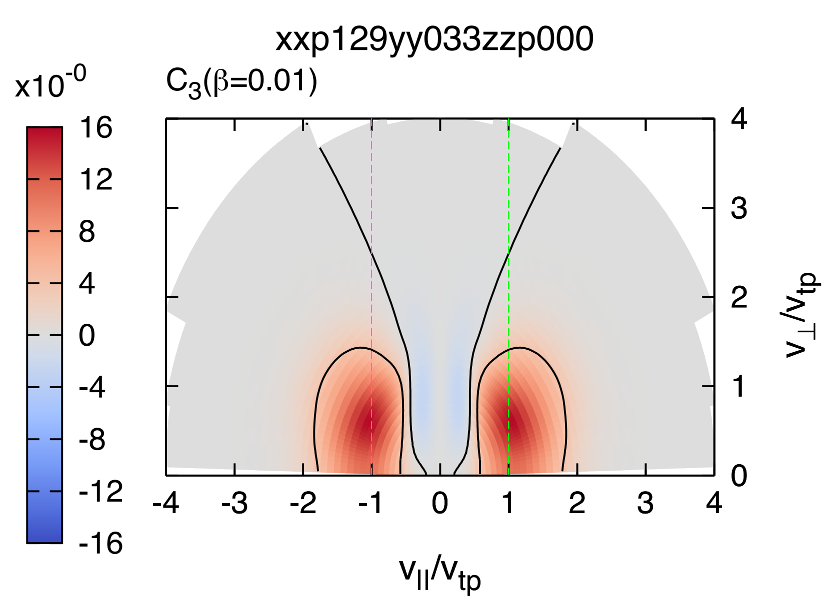
Stochastic Ion Heating



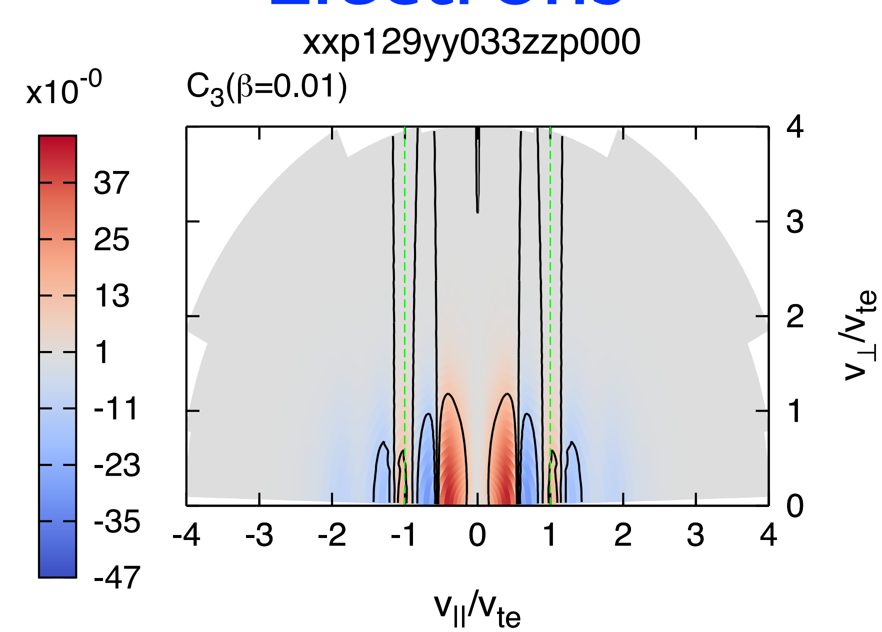
AstroGK Simulation

Magnetic Reconnection

Ions

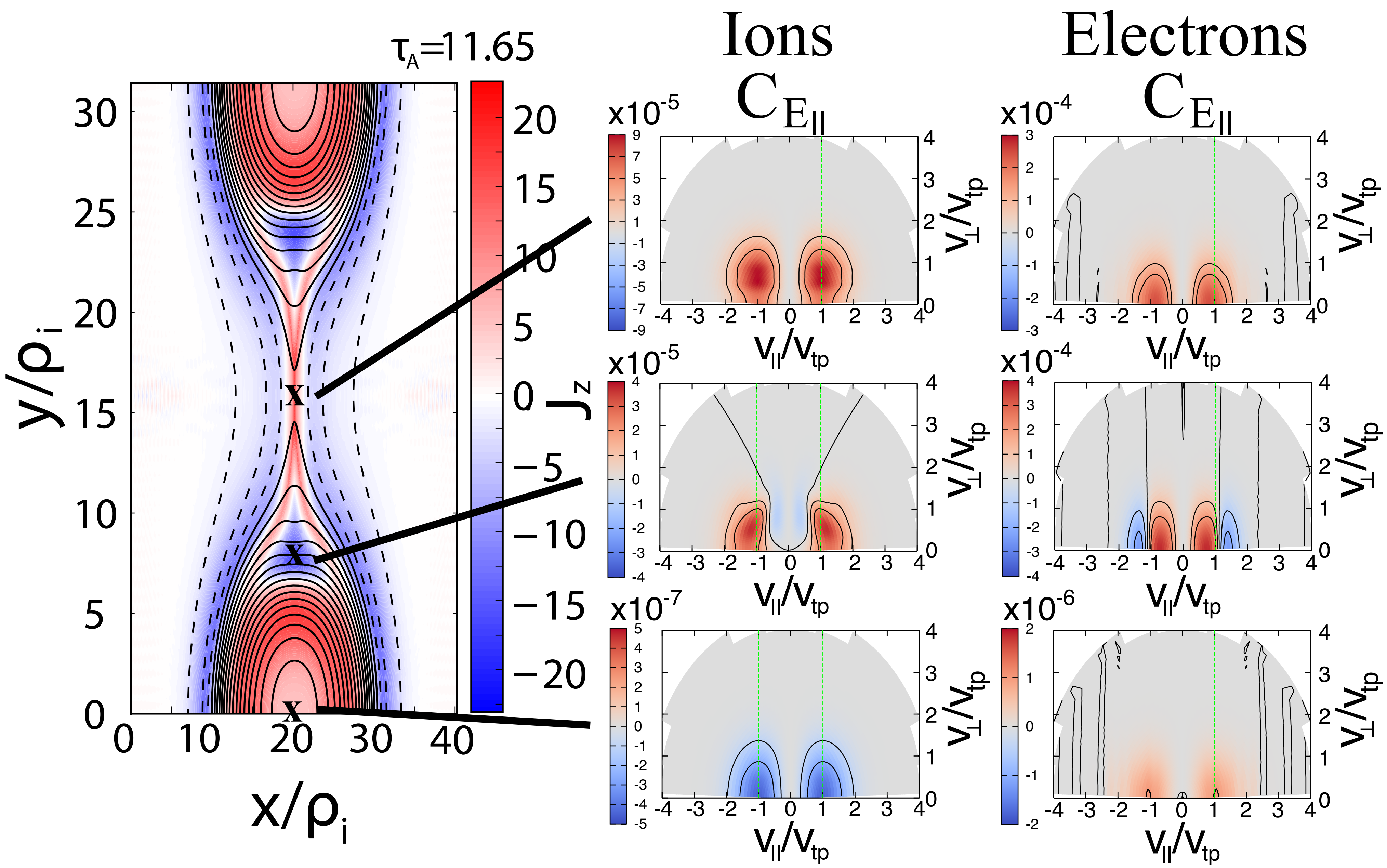


Electrons



Magnetic Reconnection

Particle energization varies by spatial position within the reconnection geometry



Conclusions

THE UNIVERSITY OF IOWA

- Challenge: Measure energy transfer and damping of turbulence in weakly collisional plasmas
  - Must isolate small secular transfer from large oscillating transfer
- 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
- Nonlinear kinetic turbulence simulations show that different mechanisms indeed have different velocity-space signatures
- Future: Extend technique to explore particle acceleration

FIELD-PARTICLE CORRELATIONS
Powerful new technique to study
any particle energization process in astrophysical plasmas

THE UNIVERSITY OF IOWA

END