Constructing a Rosetta Stone for Plasma Heating and Particle Acceleration in Kinetic Plasma Physics

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Princeton Plasma Physics Laboratory Heliophysics Seminar
Virtually anywhere
14 Aug 2020

This work is supported by the NSF CAREER Award AGS-1054061, DOE grant DE-SC0014599, NASA grants 80NSSC18K0643, 80NSSC18K1217, 80NSSC18K1371, & 80NSSC20K1273, and the NSF XSEDE Program.

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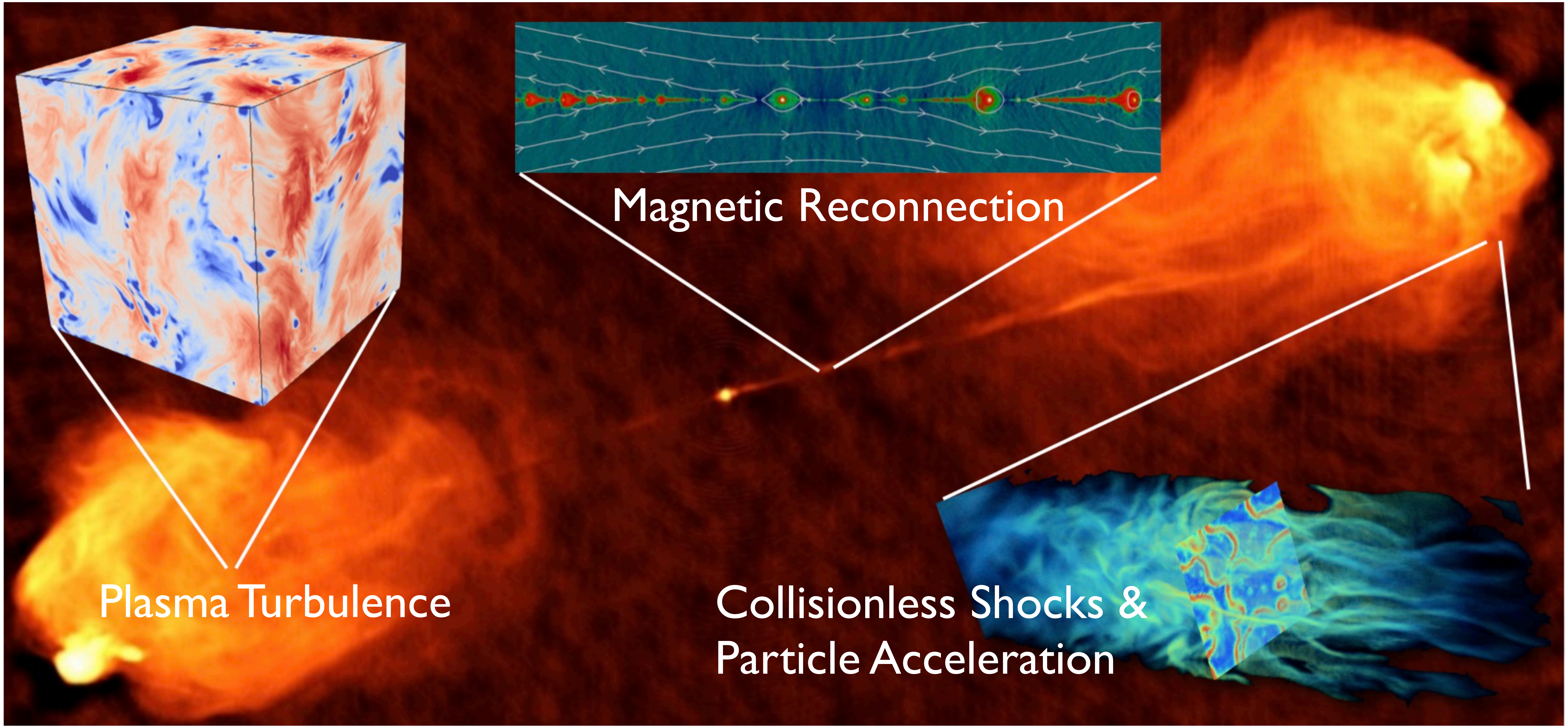
Outline

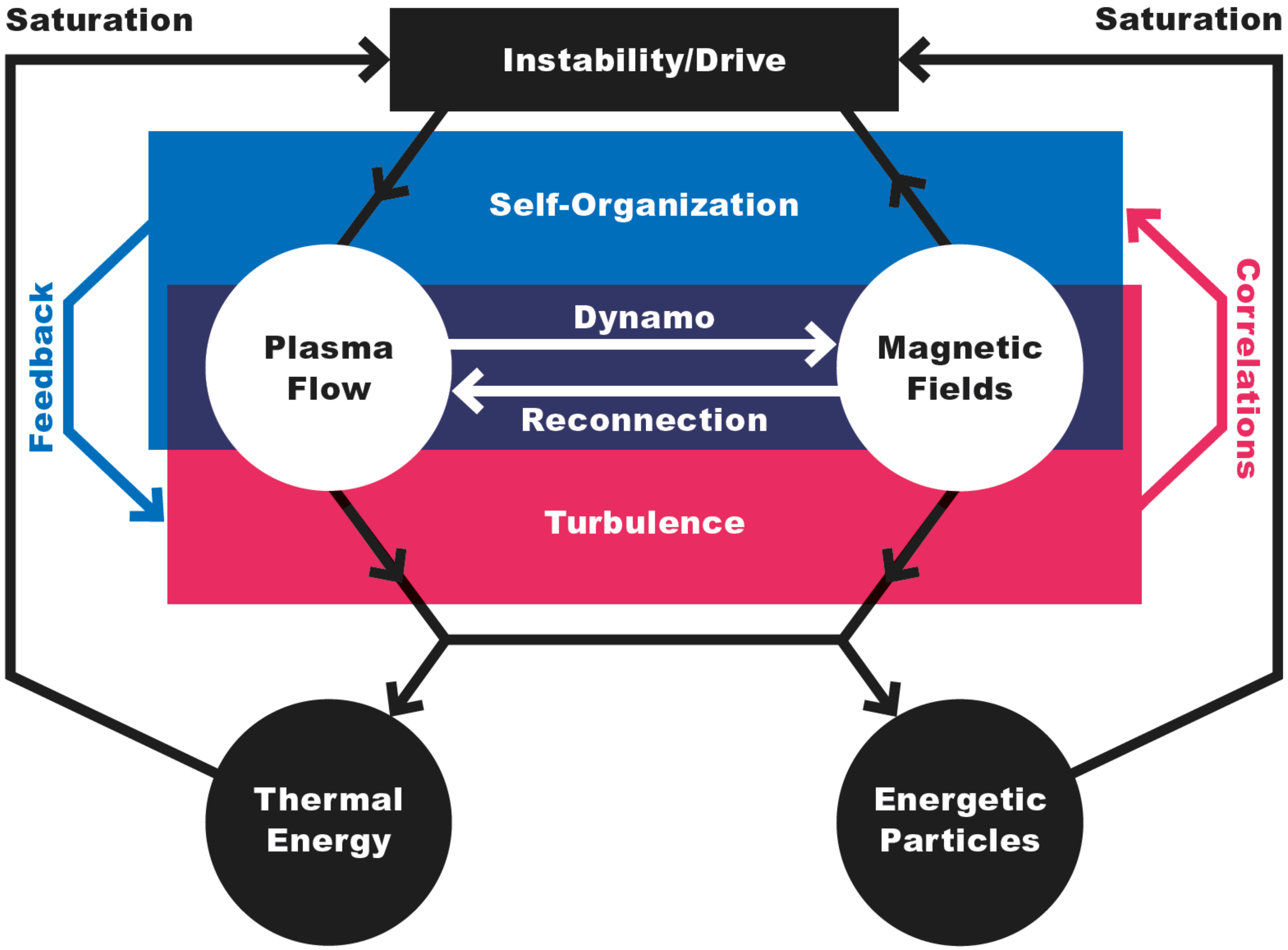
- Plasma Heating and Particle Acceleration in the Heliosphere
- Kinetic Theory of Particle Energization
  -Field-Particle Correlation Technique
- Three Applications of the Field-Particle Correlation Technique
  -Plasma Heating by Dissipation of Plasma Turbulence
  -Ion Energization in Collisionless Shocks
  -Electron Fermi Acceleration in Collisionless Magnetic Reconnection
- Constructing a "Rosetta Stone" for particle energization
- Conclusions

Fundamental Plasma Physics Processes



(Connecting Micro and Macro Scales: Acceleration, Reconnection, and Dissipation in Astrophysical Plasmas, Kavli Institute for Theoretical Physics, UCSB 2019)

Energetics of the Plasma Universe



"Understanding the Energetics of the Plasma Universe",
Plasma: At the Frontier of Scientific Discovery
DOE Report 2015

Understanding the flow of energy in astrophysical plasmas is a key overarching theme:

- Turbulence
- Instabilities
- Magnetic Reconnection
- Collisionless Shocks
- Particle Acceleration
- Magnetic Dynamo

Under the weakly collisional conditions of most space and astrophysical plasmas, kinetic theory is essential to understand these processes.

Developing a Predictive Capability

We need to understand which processes are responsible for particle energization

Example: What heats the Solar Corona to $T > 10^6$ K ?

- Magnetic Reconnection (nanoflares, loop opening, etc.) (Parker, 1991; Fisk et al. 1999)
- Dissipation of Plasma Turbulence (Hollweg, 1986; Cranmer et al. 2003, 2005, 2007)
- Other mechanisms? (velocity filtration, etc.) (Scudder, 1992)

But . . . even if we know the general process, what is the specific mechanism?

Example: Turbulence

- What processes govern the dissipation of turbulence and resulting plasma heating?

Proposed Dissipation Mechanisms in Turbulence

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Weakly Collisional Plasma Turbulence

(1) Resonant 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) Nonresonant Wave-Particle Interactions (stochastic ion heating, magnetic pumping)

(Berger, 1958; 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,Lichko:2017)

(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; Loureiro & Boldyrev, 2017a,b; Boldyrev & Loureiro 2017; Walker, Boldyrev, & Loureiro 2018)

We can use information about the flow of energy in velocity space to distinguish between different mechanisms.

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Maxwell-Boltzmann Equations of Kinetic Plasma Theory

$$\frac{\partial f_s}{\partial t} + \mathbf{v}\cdot\nabla f_s + \frac{q_s}{m_s}\left[\mathbf{E} + \frac{\mathbf{v}\times\mathbf{B}}{c}\right]\cdot\frac{\partial f_s}{\partial \mathbf{v}} = \left(\frac{\partial f_s}{\partial t}\right)_{\text{coll}} \; 0$$

Lorentz Term responsible for interactions between fields and particles

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

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

Distribution Function: 3D-3V phase space $f_s(\mathbf{r},\mathbf{v},t)$

Electromagnetic Fields $\mathbf{E}(\mathbf{r},t), \mathbf{B}(\mathbf{r},t)$

Particle Energization

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Conserved Vlasov-Maxwell Energy

$$W = \int d^3\mathbf{r} \frac{|\mathbf{E}|^2 + |\mathbf{B}|^2}{8\pi} + \sum_s \int d^3\mathbf{r} \int d^3\mathbf{v} \; \frac{1}{2} m_s v^2 f_s$$

EM Field Energy

Particle Energy $W_s = \int d^3\mathbf{r} \int d^3\mathbf{v} \; \frac{1}{2} m_s v^2 f_s$

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

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

$$\frac{\partial W_s}{\partial t} = \int d^3\mathbf{r} \int d^3\mathbf{v} \; \frac{1}{2} m_s v^2 \frac{\partial f_s}{\partial t}$$

Vlasov Equation $$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \nabla f_s + \frac{q_s}{m_s} \left[\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right] \cdot \frac{\partial f_s}{\partial \mathbf{v}} = 0$$

Particle Energization

$$\frac{\partial W_s}{\partial t} = \int d^3\mathbf{r} \int d^3\mathbf{v} \frac{1}{2} m_s v^2 \left[-\mathbf{v} \cdot \nabla f_s - \frac{q_s}{m_s} \mathbf{E} \cdot \frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s}{m_s} \left(\frac{\mathbf{v}}{c} \times \mathbf{B} \right) \cdot \frac{\partial f_s}{\partial \mathbf{v}} \right]$$

0

0

Perfect Differential

Electric field does work on particles

Rate of Change of Particle Energy

$$\frac{\partial W_s}{\partial t} = -\int d^3\mathbf{r} \int d^3\mathbf{v} \left[q_s \frac{v^2}{2} \mathbf{E}(\mathbf{r}, t) \cdot \frac{\partial f_s(\mathbf{r}, \mathbf{v}, t)}{\partial \mathbf{v}} \right]$$

But this is integrated over velocity and space…

Not observationally accessible!

How Does Energy Flow in Phase Space?

Maximize use of 3V phase-space information to characterize energization

Define: Phase-space energy density $w_s(\mathbf{r}, \mathbf{v}, t) = \frac{m_s v^2}{2} f_s(\mathbf{r}, \mathbf{v}, t)$

$$\frac{\partial w_s(\mathbf{r}, \mathbf{v}, t)}{\partial t} = -\mathbf{v} \cdot \nabla w_s - q_s \frac{v^2}{2} \mathbf{E} \cdot \frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s}{c} \frac{v^2}{2} (\mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}}$$

Advection of particle energy

Pressure forces in fluid theory

Work done by electric field

Responsible for net change in particle energy

Work done by magnetic field

Integrates over velocity space to zero

How Does Energy Flow in Phase Space?

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$$\frac{\partial w_s(\mathbf{r},\mathbf{v},t)}{\partial t} = -\mathbf{v}\cdot\nabla w_s - q_s\frac{v^2}{2}\mathbf{E}\cdot\frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s}{c}\frac{v^2}{2}(\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

Note:

1) Advective (pressure) and magnetic terms can convert particle energy

e.g., Bulk flow kinetic energy to thermal kinetic energy

2) Electric field term is the only one that changes the net particle energy

Therefore we focus here on the work on particles done by $\mathbf{E}(\mathbf{r},t)$

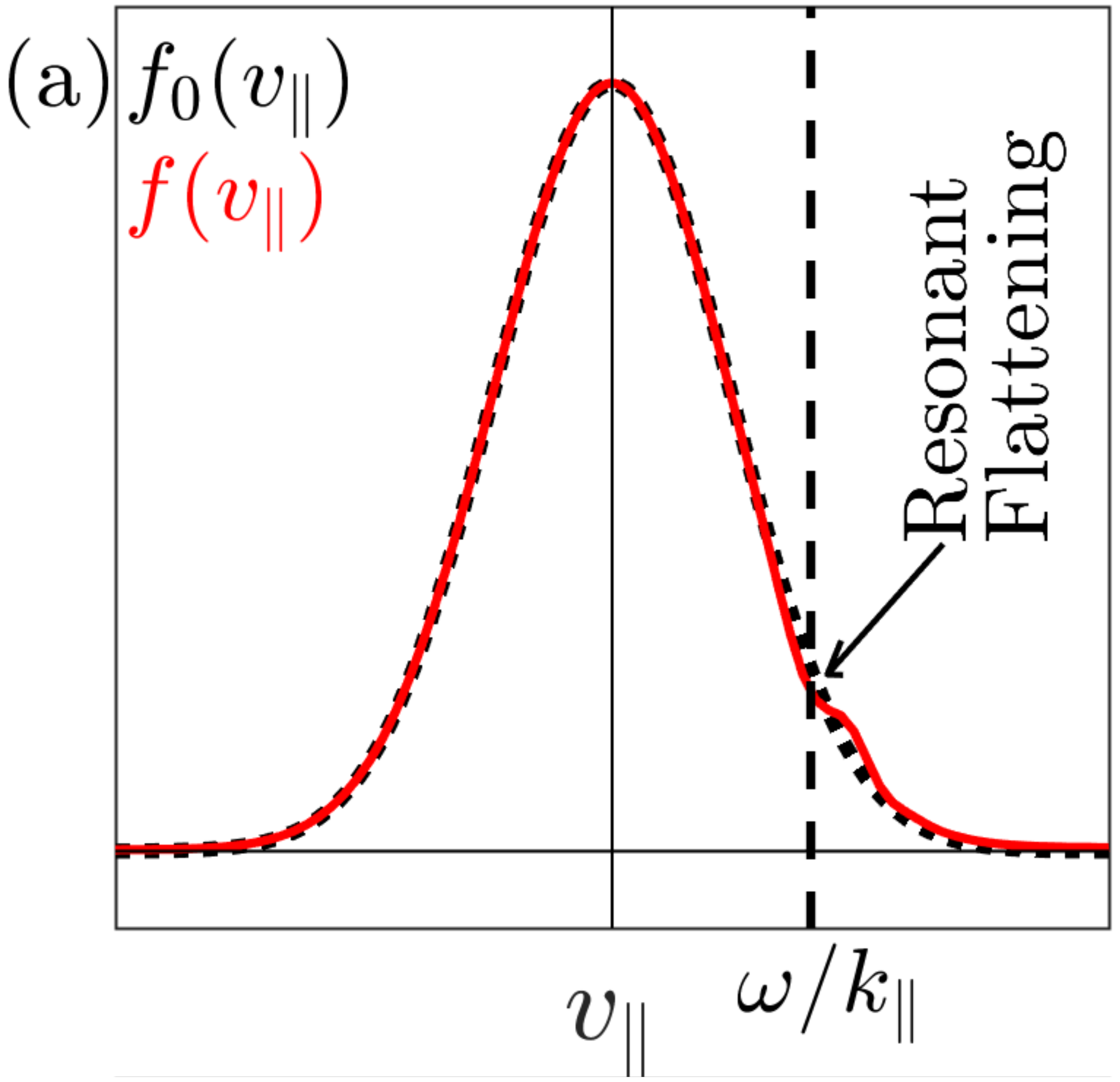
Other applications may require analyzing the other terms!

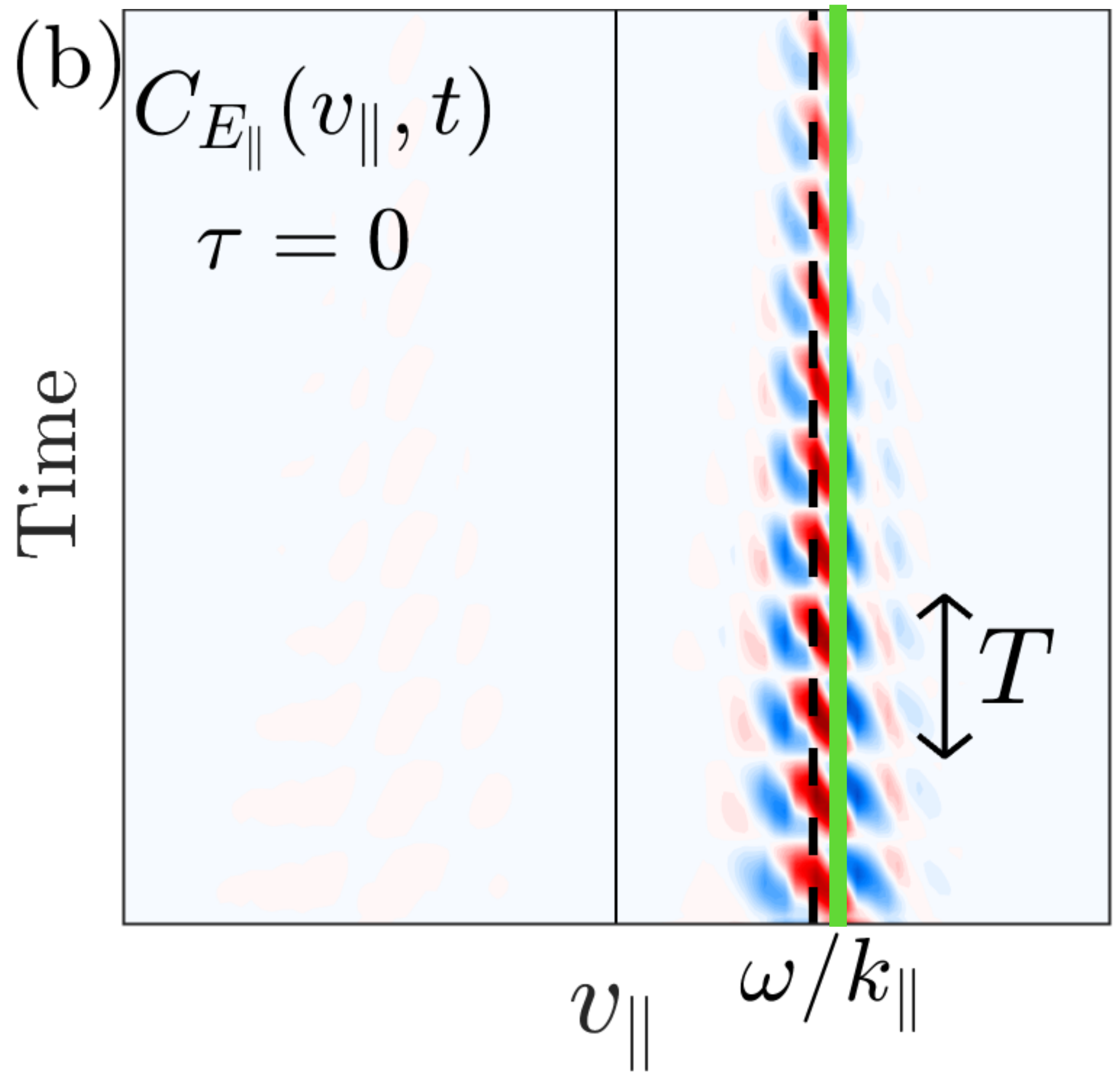
How Do We Exploit Velocity-Space Information?

$$\frac{\partial w_s(\mathbf{r},\mathbf{v},t)}{\partial t} = -\mathbf{v}\cdot\nabla w_s \boxed{- q_s \frac{v^2}{2}\mathbf{E}\cdot\frac{\partial f_s}{\partial \mathbf{v}}} - \frac{q_s}{c}\frac{v^2}{2}(\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

$$C_{E_\parallel}(v_\parallel,t) = -q_i \frac{v^2}{2}\frac{\partial f_i}{\partial v_\parallel}E_\parallel$$

Example:
Ion Landau Damping of a single Kinetic Alfven Wave

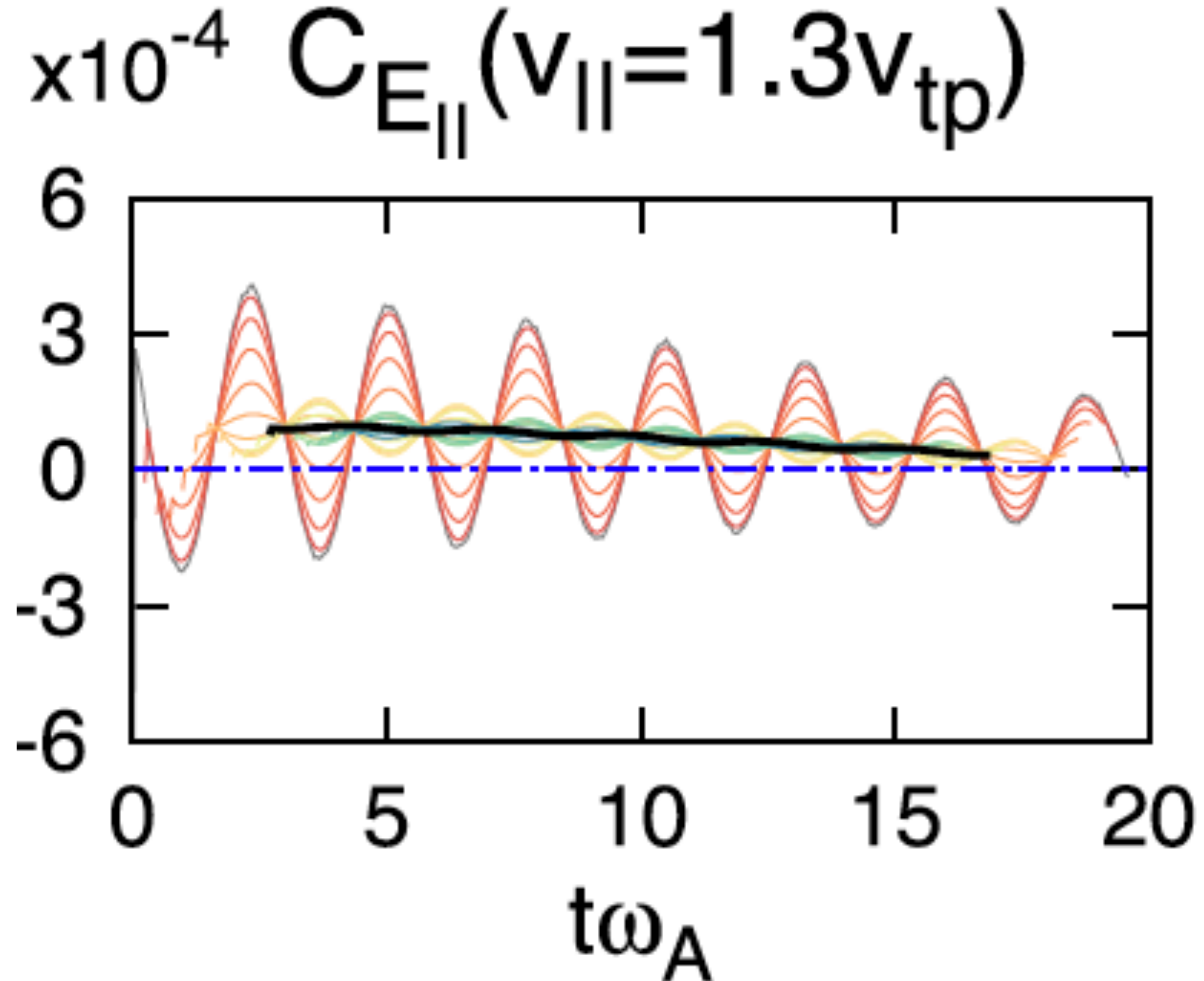




Two parts of signal:

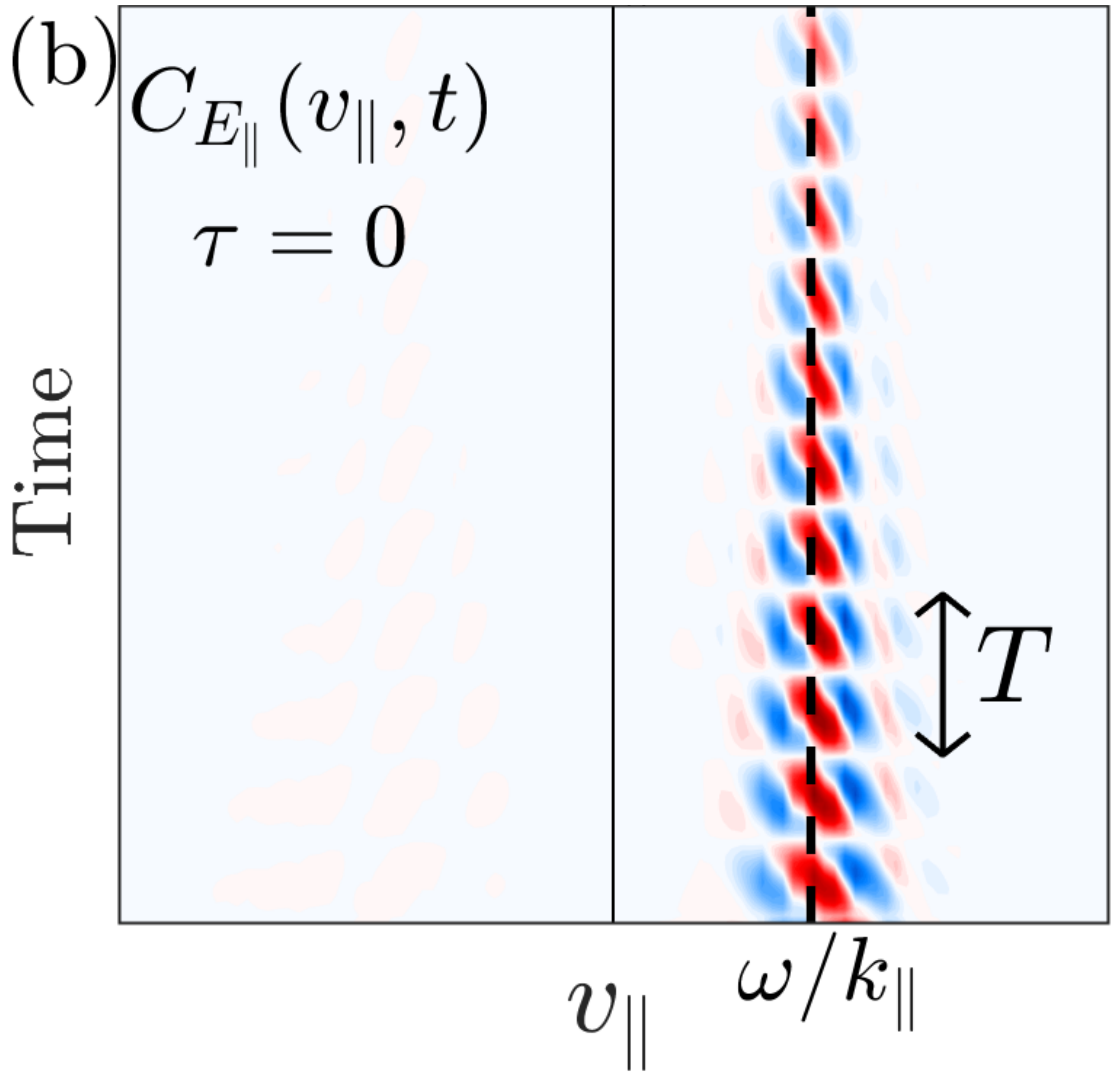
1) Conservative oscillatory energy transfer of undamped wave motion

2) Secular energy transfer of collisionless damping



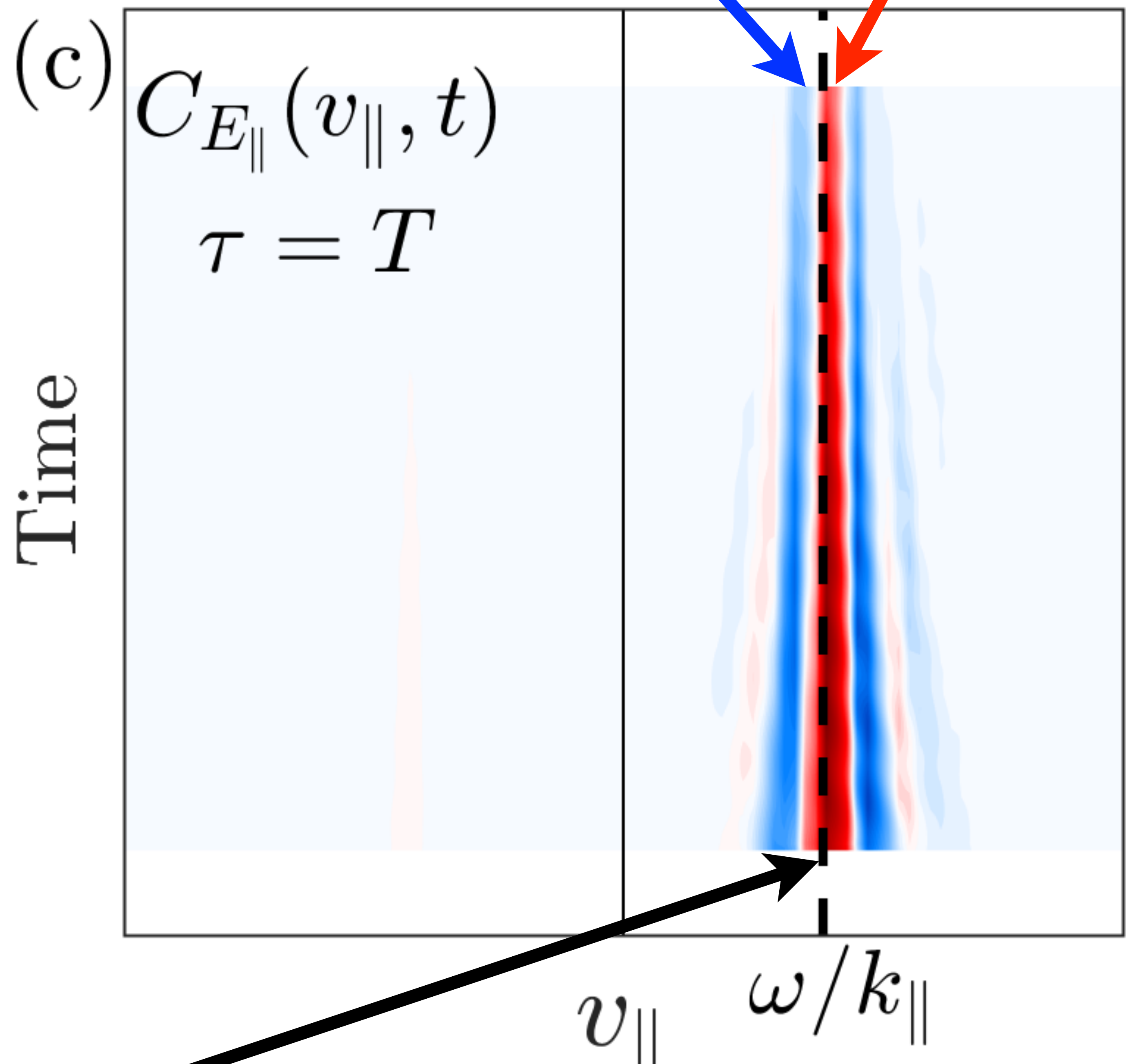
How Do We Exploit Velocity-Space Information?

To eliminate oscillatory energy transfer, take a time average over a correlation interval τ



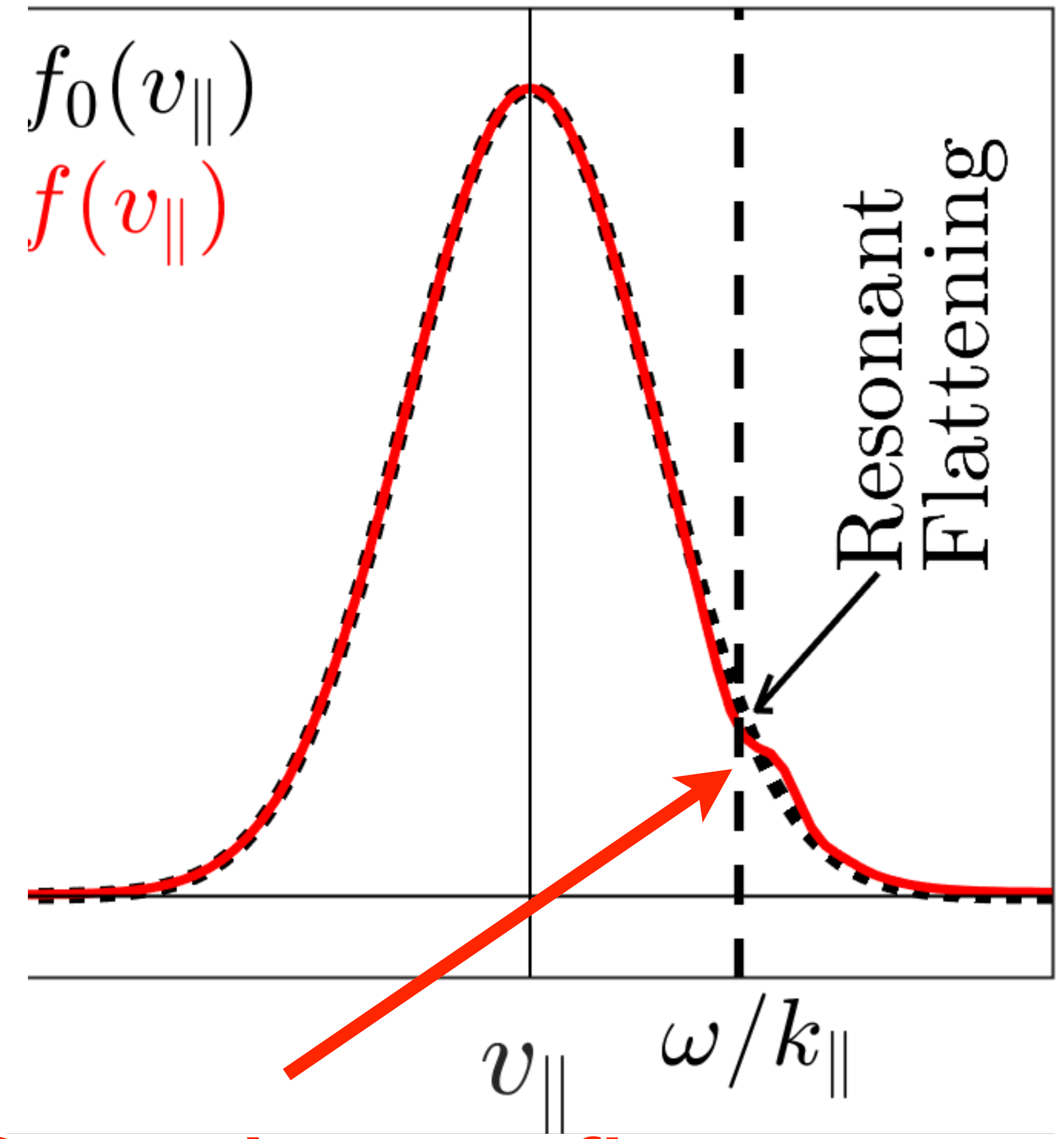
Loss of energy below

Gain of energy above → Bipolar signature



Timestack Plot

Resonant phase velocity



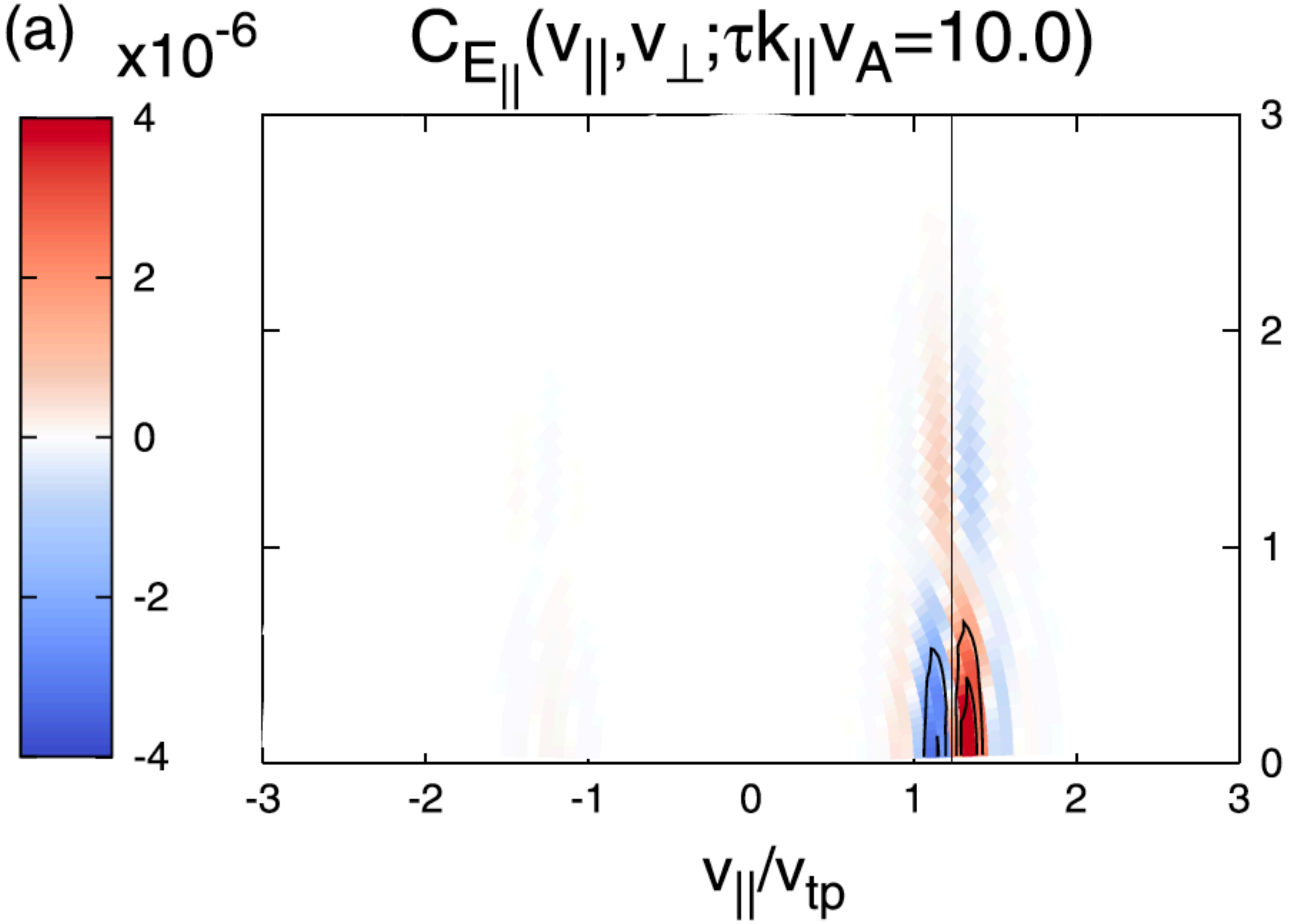
Quasilinear flattening

$$w_i = \frac{1}{2} m v^2 f_i(v_\parallel, t)$$

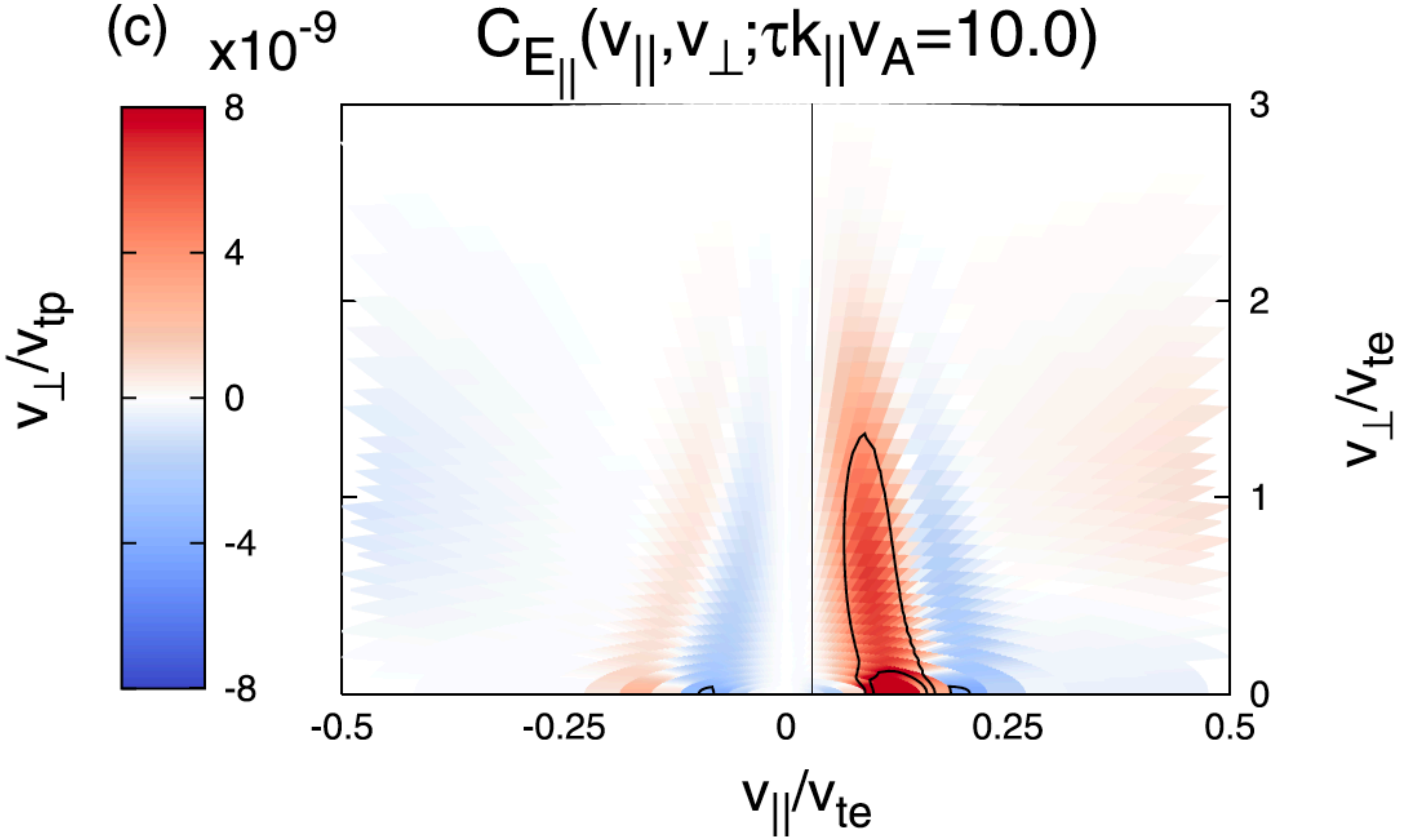
Gyrotropic Velocity-Space Signatures

Velocity-space signatures in gyrotropic velocity space $(v_\parallel, v_\perp)$ (Howes, PoP, 2017)

Single KAW with: $\beta_i = 1$ $T_i/T_e = 1$ $k_\perp \rho_i = 1.3$



Velocity-space signature of ion Landau damping



Velocity-space signature of electron Landau damping

Field-Particle Correlation Technique

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

$$\frac{\partial w_s(\mathbf{r},\mathbf{v},t)}{\partial t} = -\mathbf{v}\cdot\nabla w_s \boxed{- q_s \frac{v^2}{2}\mathbf{E}\cdot\frac{\partial f_s}{\partial \mathbf{v}}} - \frac{q_s}{c}\frac{v^2}{2}(\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

At a single-point $\mathbf{r}_0$, compute correlation of field $\mathbf{E}$ and particle $f_s(\mathbf{v})$ measurements over correlation interval τ

Field-particle correlation

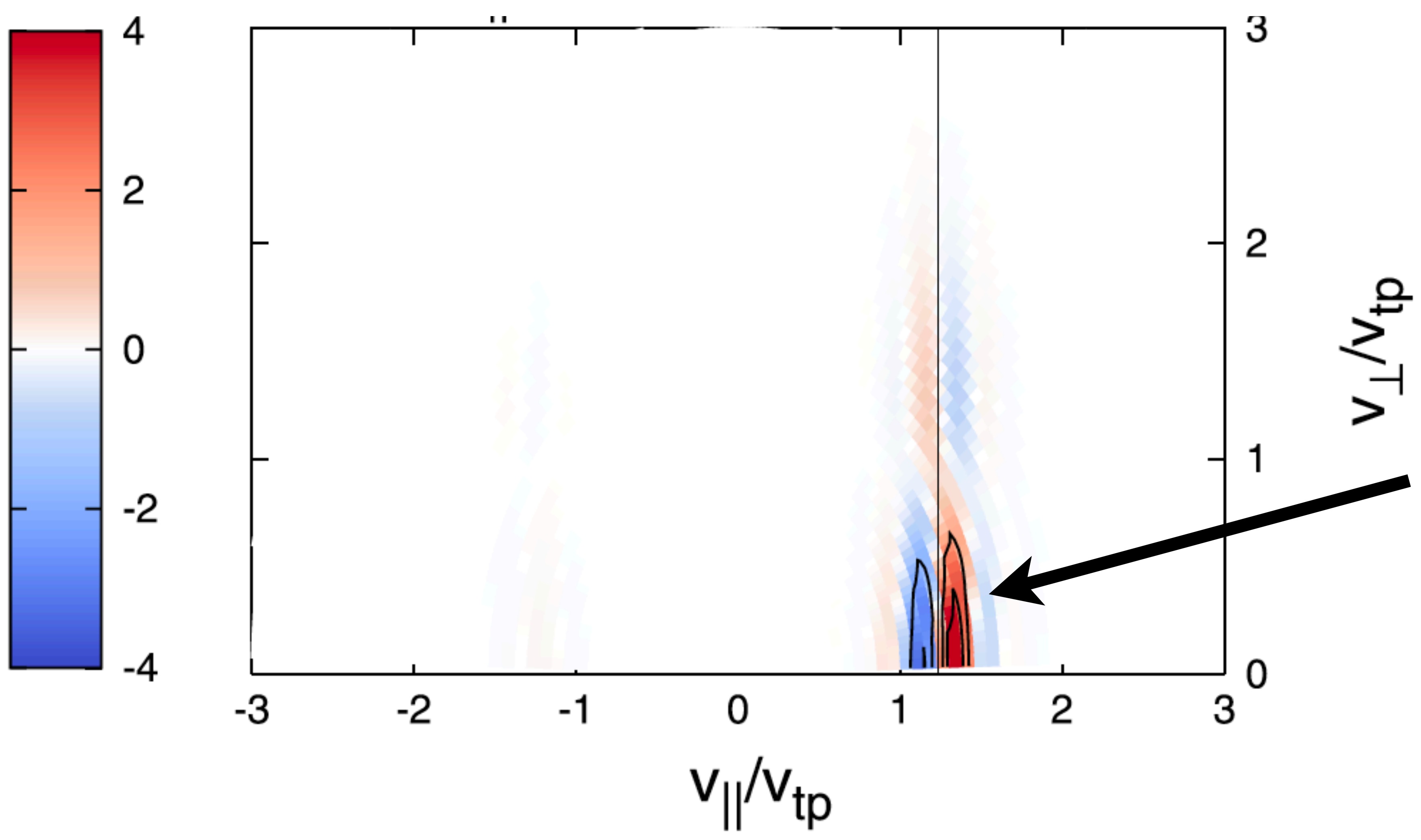
$$C_{E_\parallel}(\mathbf{v},t,\tau) = C\left(-q_s\frac{v_\parallel^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_\parallel}, E_\parallel(\mathbf{r}_0,t)\right)$$

(Klein & Howes, 2016; Howes, Klein, & Li, 2017; Klein, Howes, & TenBarge, 2017)

Depending on the problem, one can alternatively, can compute correlations with $E_\perp$ or with (E_x, E_y, E_z)

Scientific Insight from Field-Particle Correlations

1) Distinguish and identify kinetic energization mechanisms through unique velocity-space signature



Bipolar signature of Landau damping

2) Determine rate of change of spatial energy density $W_s(\mathbf{r},t) \equiv \int d^3\mathbf{v} \frac{1}{2} m_s v^2 f_s(\mathbf{r},\mathbf{v},t)$

$$\frac{\partial W_s}{\partial t} = \int d^3\mathbf{v}\ C_{E_\parallel}(\mathbf{v},t) = -\int d^3\mathbf{v}\ q_s \frac{v_\parallel^2}{2}\frac{\partial f_s}{\partial v_\parallel} E_\parallel = \int d^3\mathbf{v}\ q_s v_\parallel E_\parallel f_s = j_{\parallel,s} E_\parallel$$

Integrate correlation over velocity space

Rate of work done on species s by $E_\parallel$

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Strong Plasma Turbulence

Driven nonlinear gyrokinetic simulation of solar wind turbulence

(Klein, Howes, & Tenbarge, 2017)

Plasma parameters: $\beta_i = 1$, $T_i/T_e = 1$

Turbulence parameters: $k_\perp \gg k_\parallel$ (Anisotropic), $\chi \sim 1$ (Critical balance)

Evidence of Landau Damping in strong plasma turbulence

Proposed Dissipation Mechanisms in Turbulence

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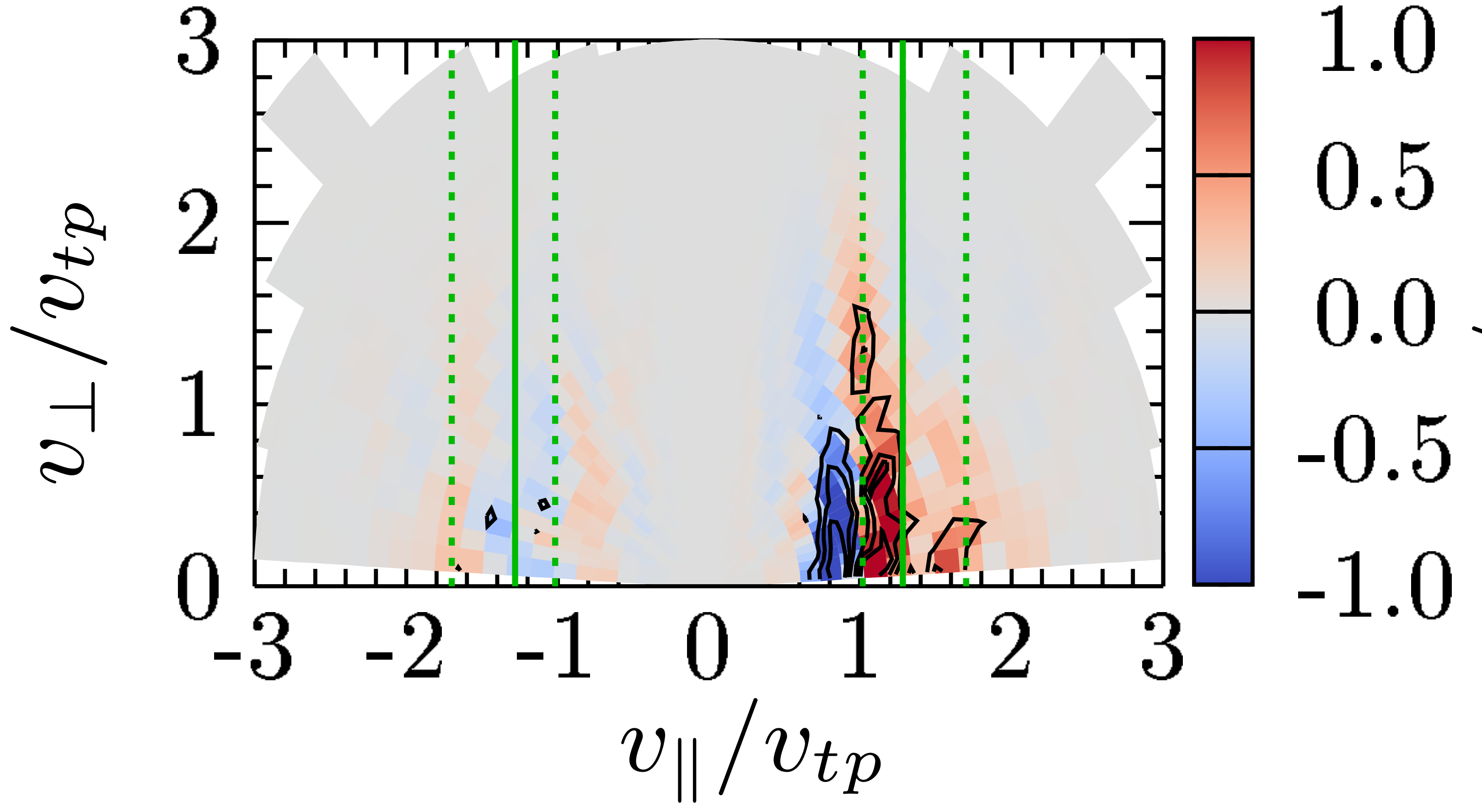
The velocity-space signature obtained from field-particle correlations has the potential to distinguish between different mechanisms.

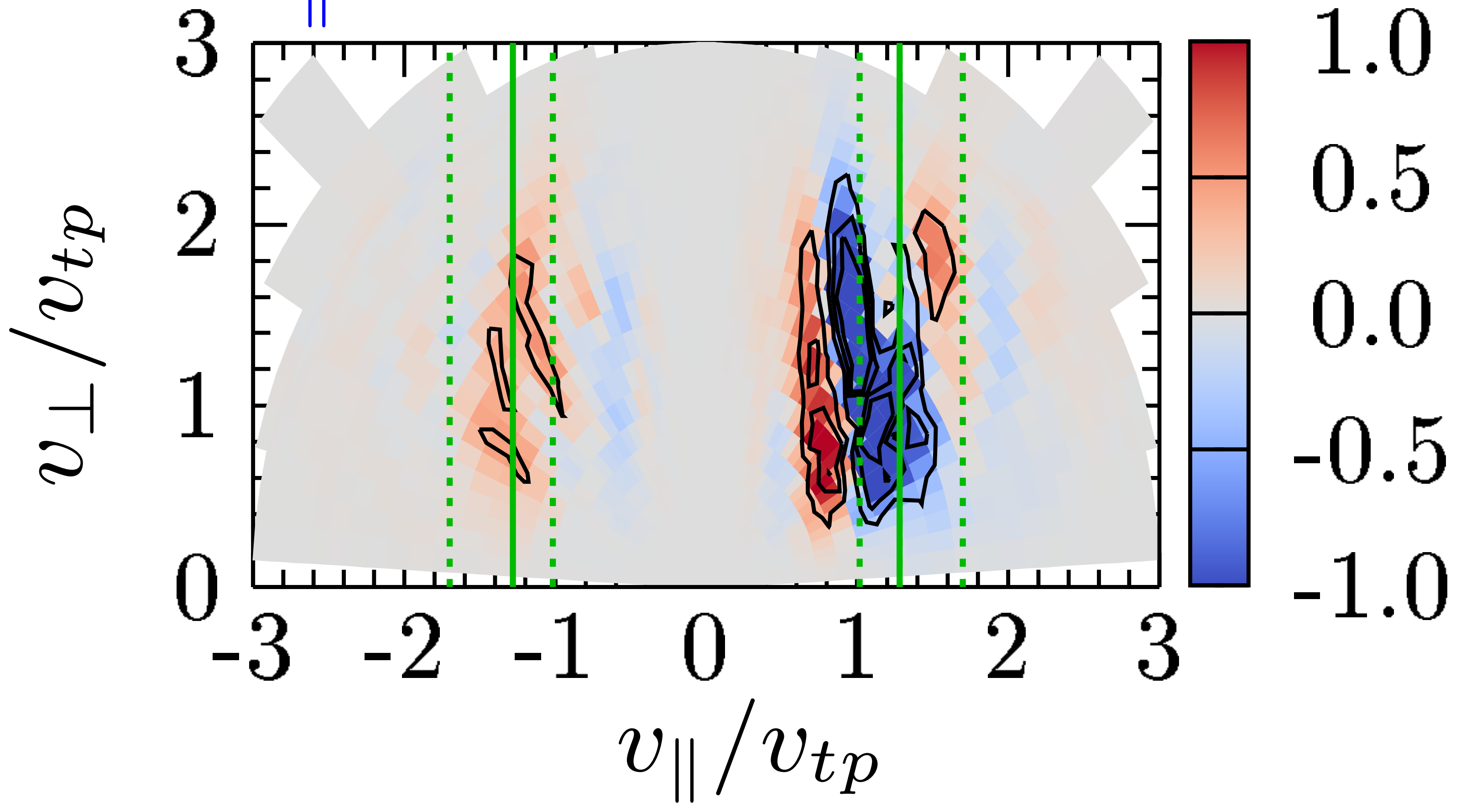
Distinguishing Energization Mechanisms

AstroGK Simulation

$C_{E_\parallel}$ Landau

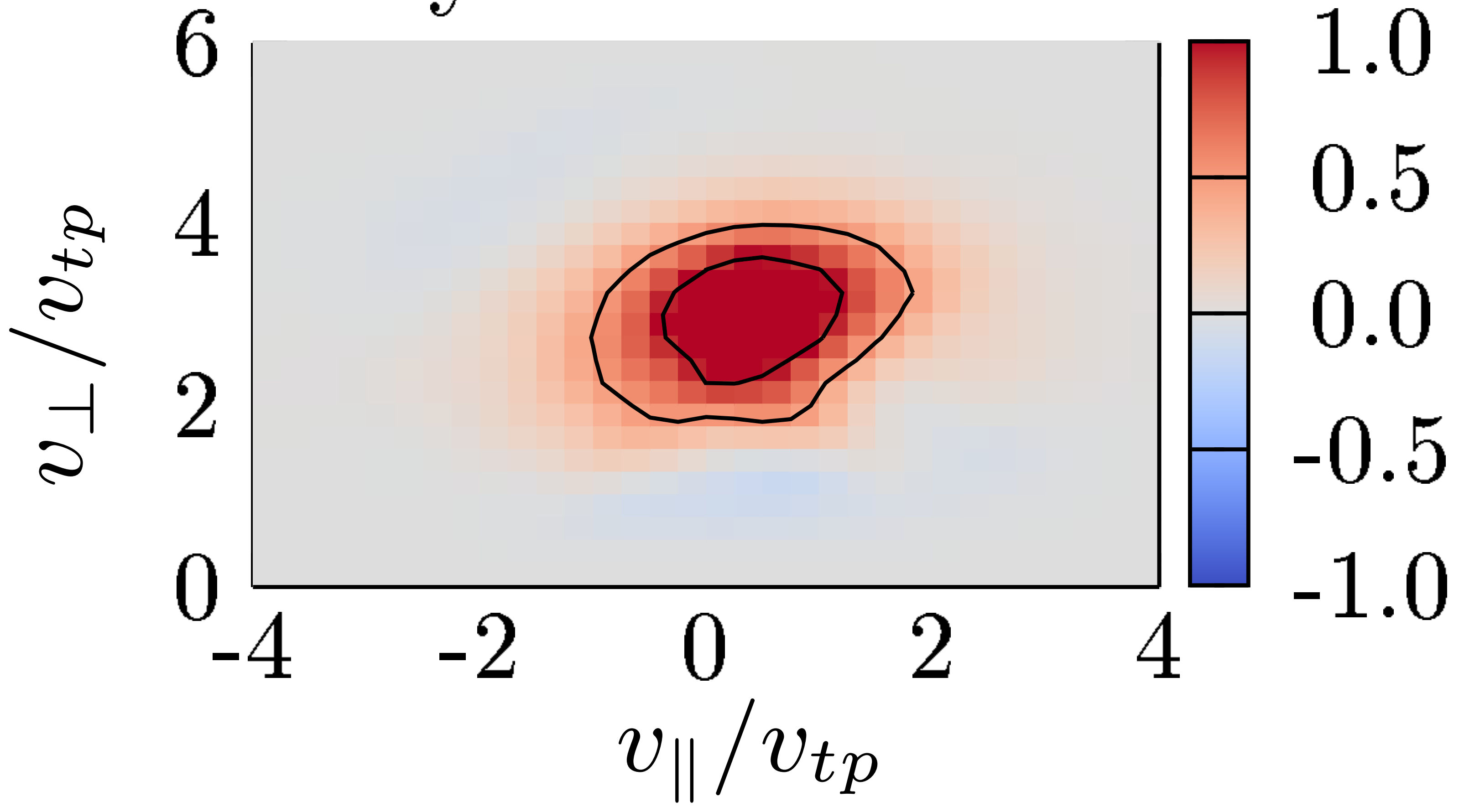


$C_{\delta B_\parallel}$ Transit-Time



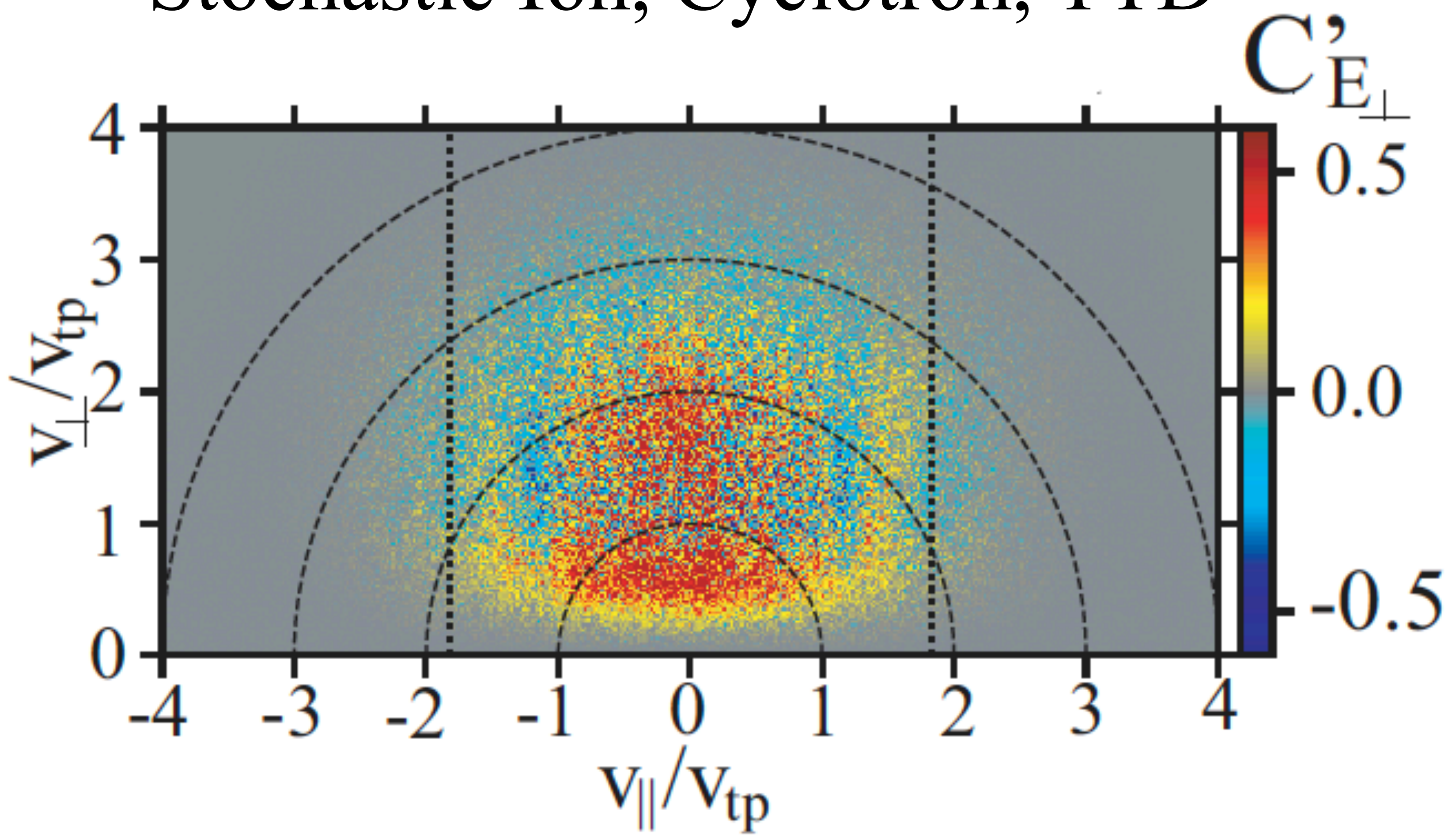
HVM Simulation

$C_{E_\perp}$ Cyclotron



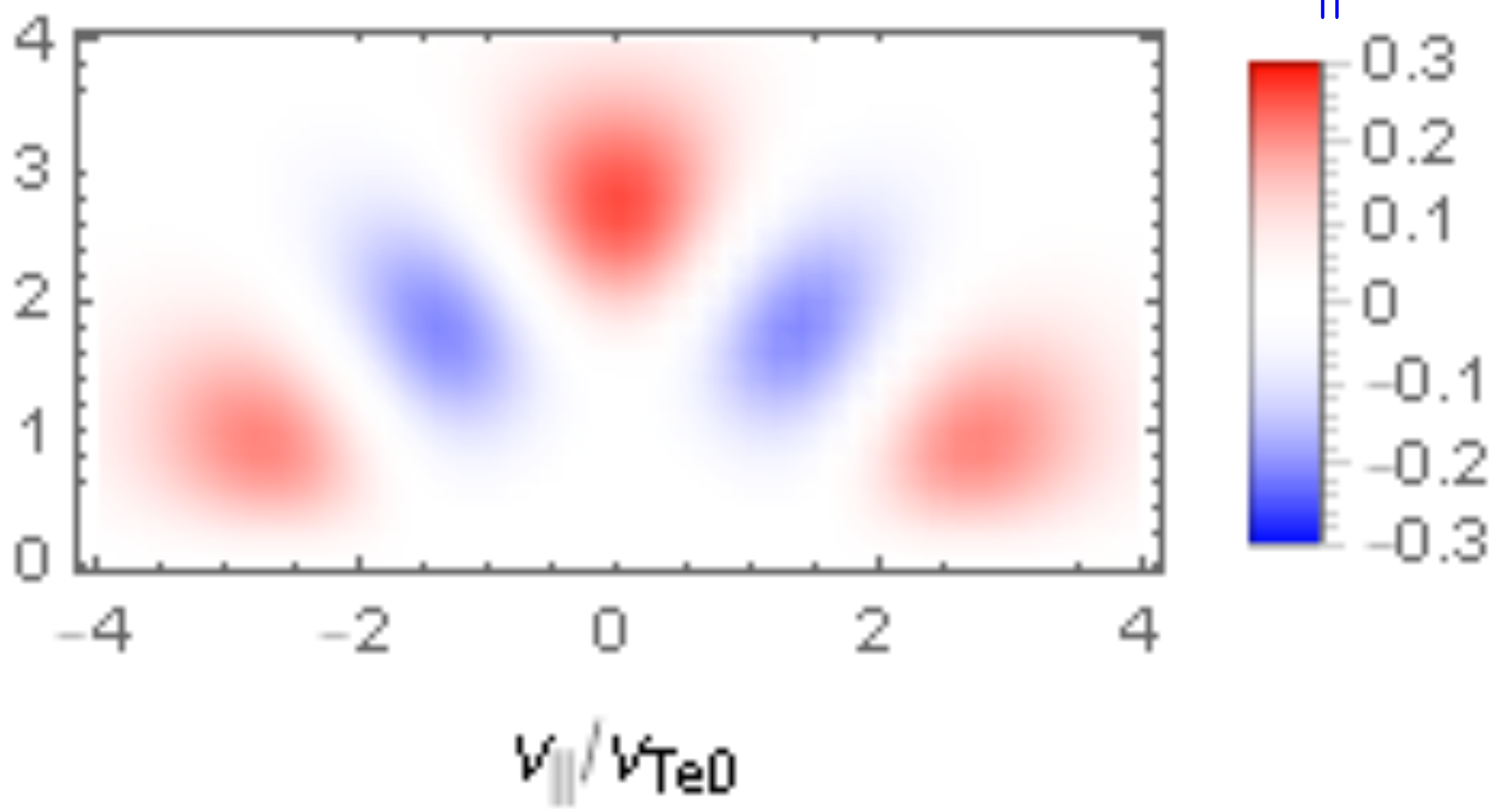
Pegasus Simulation

Stochastic Ion, Cyclotron, TTD



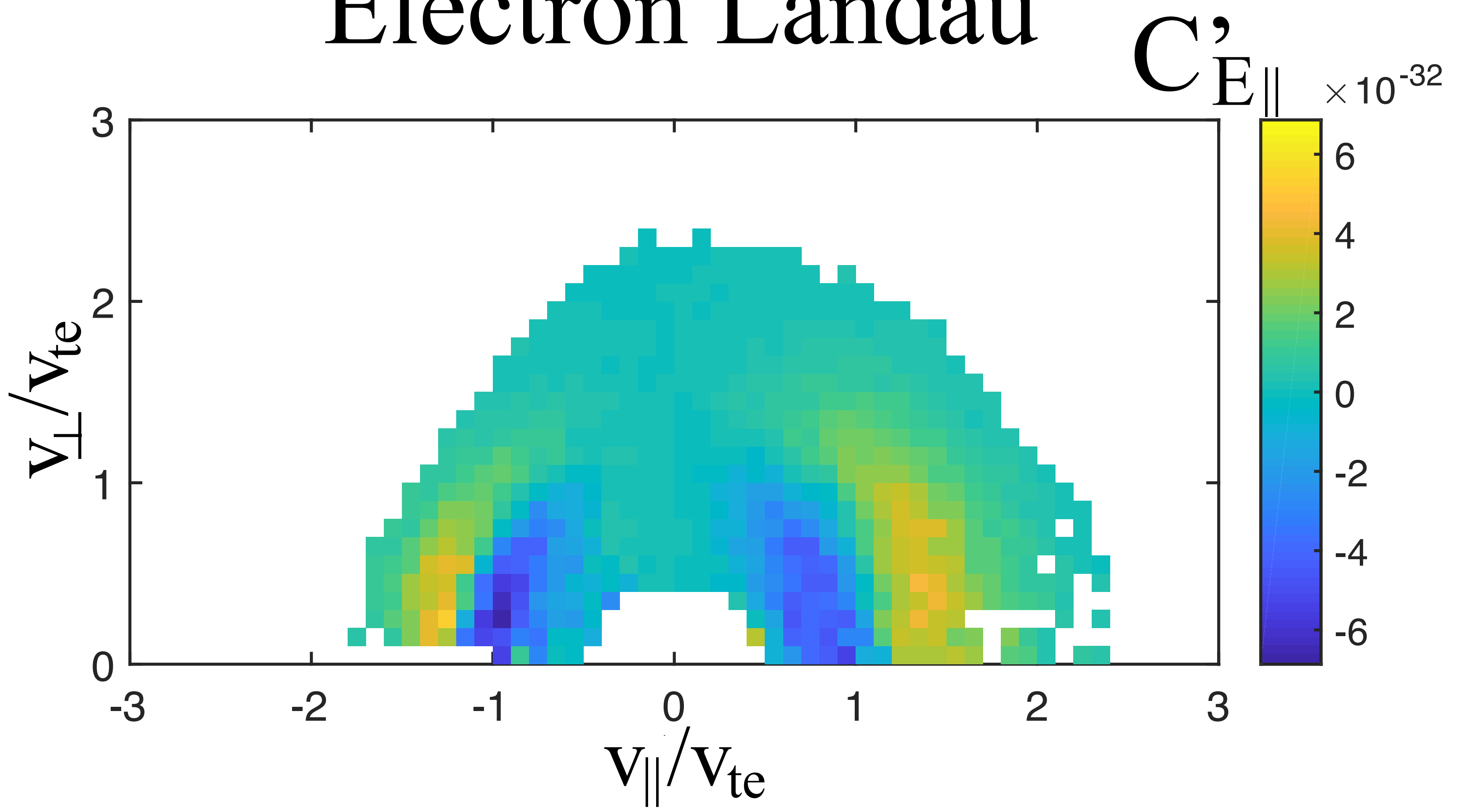
Analytical Model

Magnetic Pumping $C_{E_\parallel}$



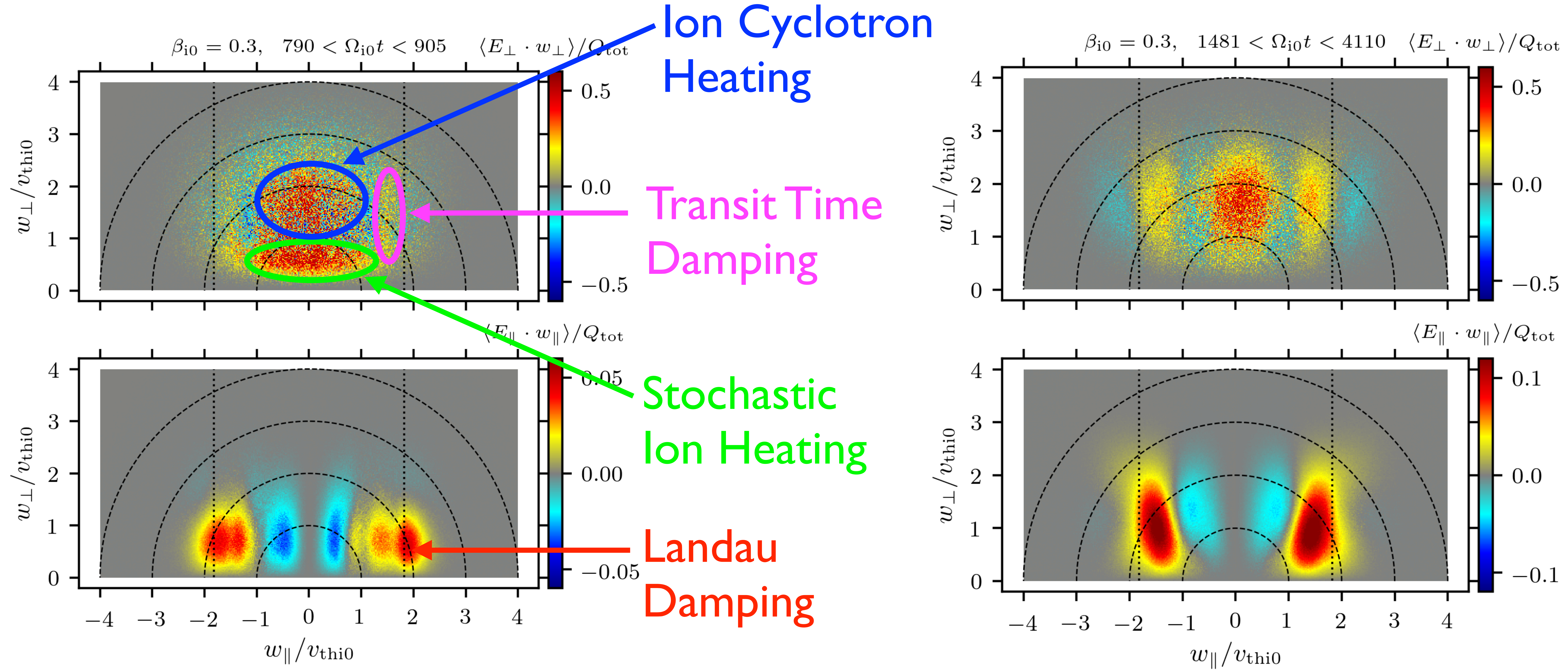
MMS Observation

Electron Landau



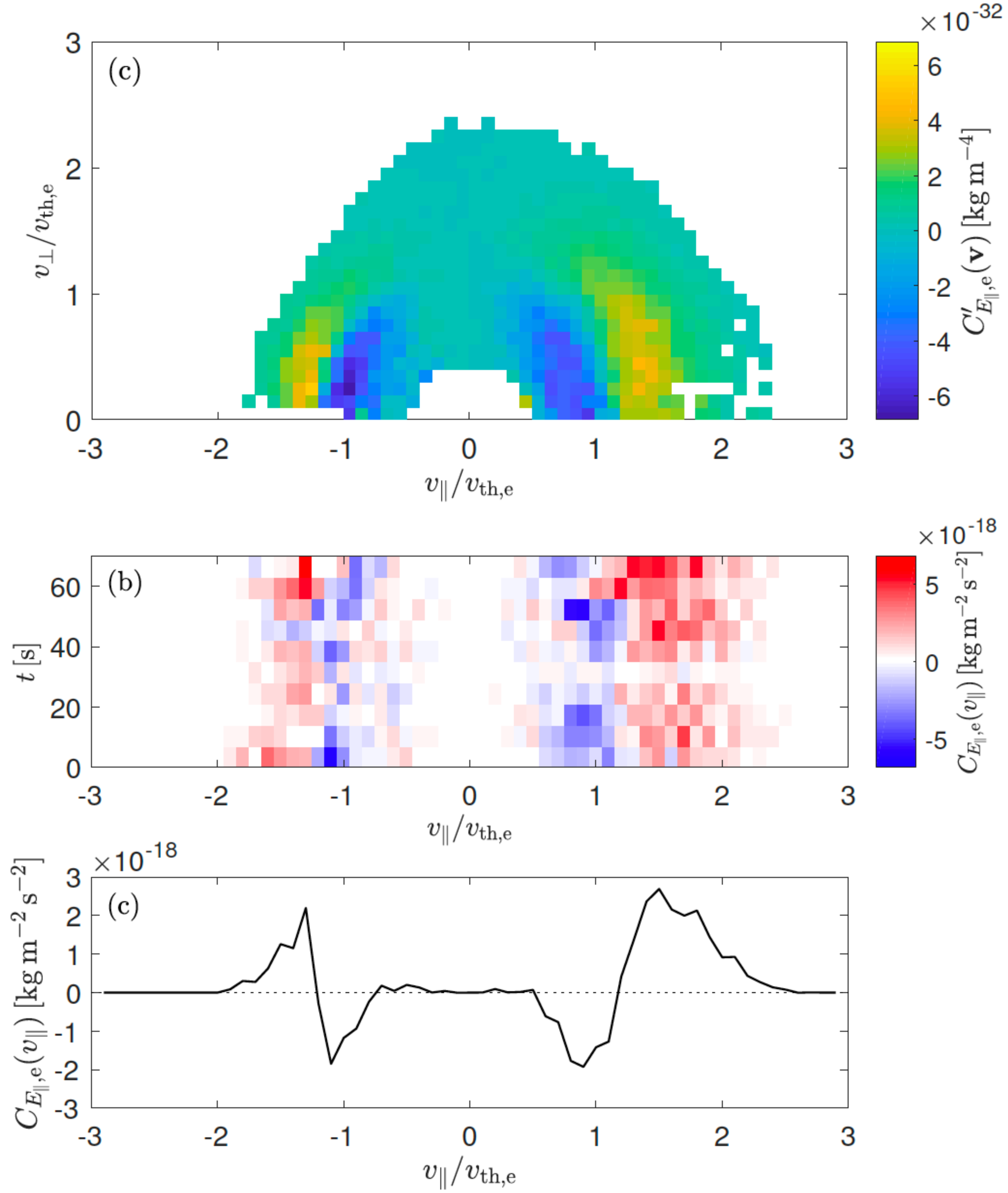
Identifying Mechanisms by Velocity-Space Signatures

Pegasus hybrid simulations of anisotropic turbulence



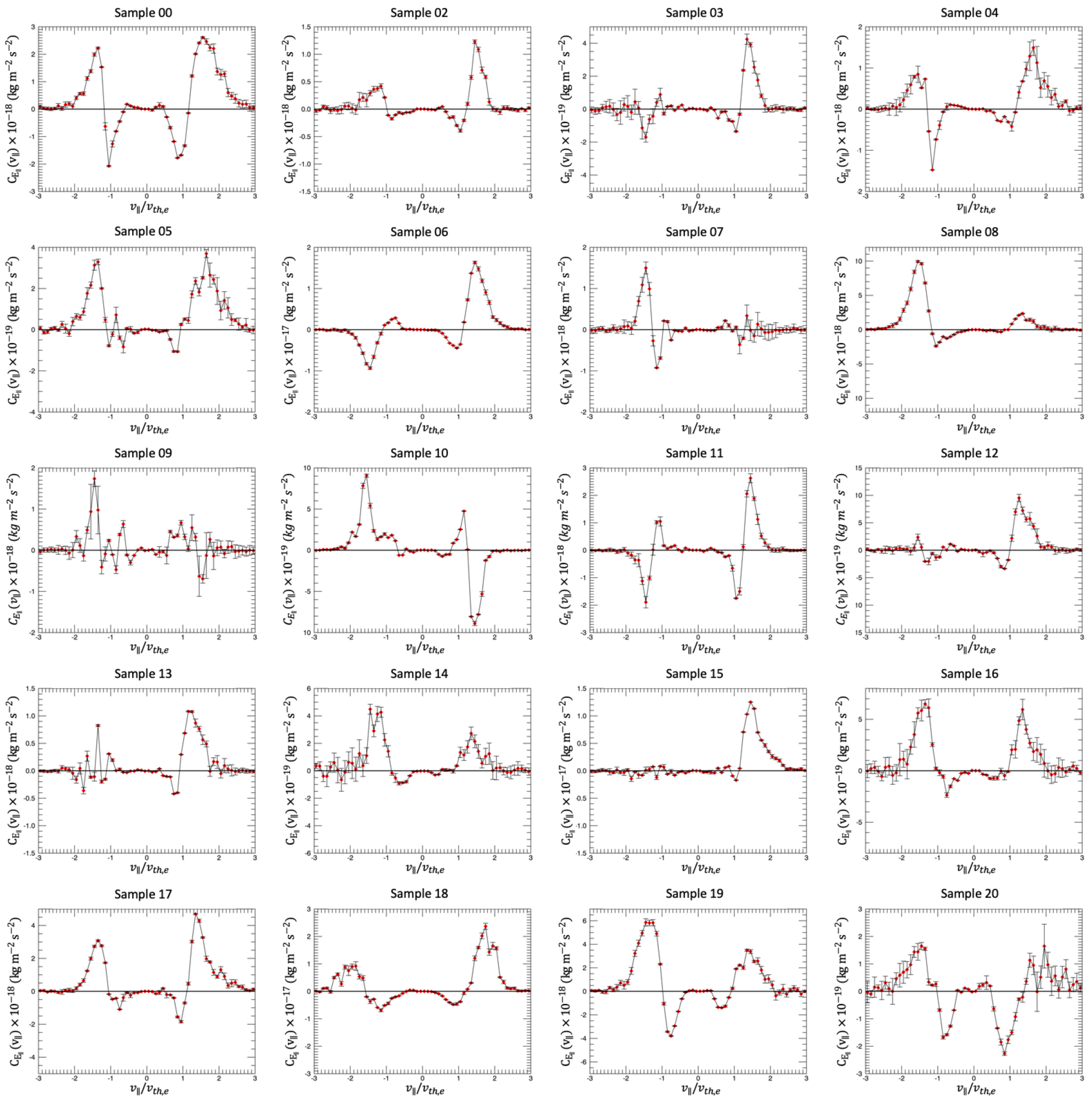
Determining Rate of Particle Energization

Observations of electron energization in Earth's magnetosheath using *MMS*



(Chen, Klein, & Howes, *Nature Comm.*, **10**:740, 2019)

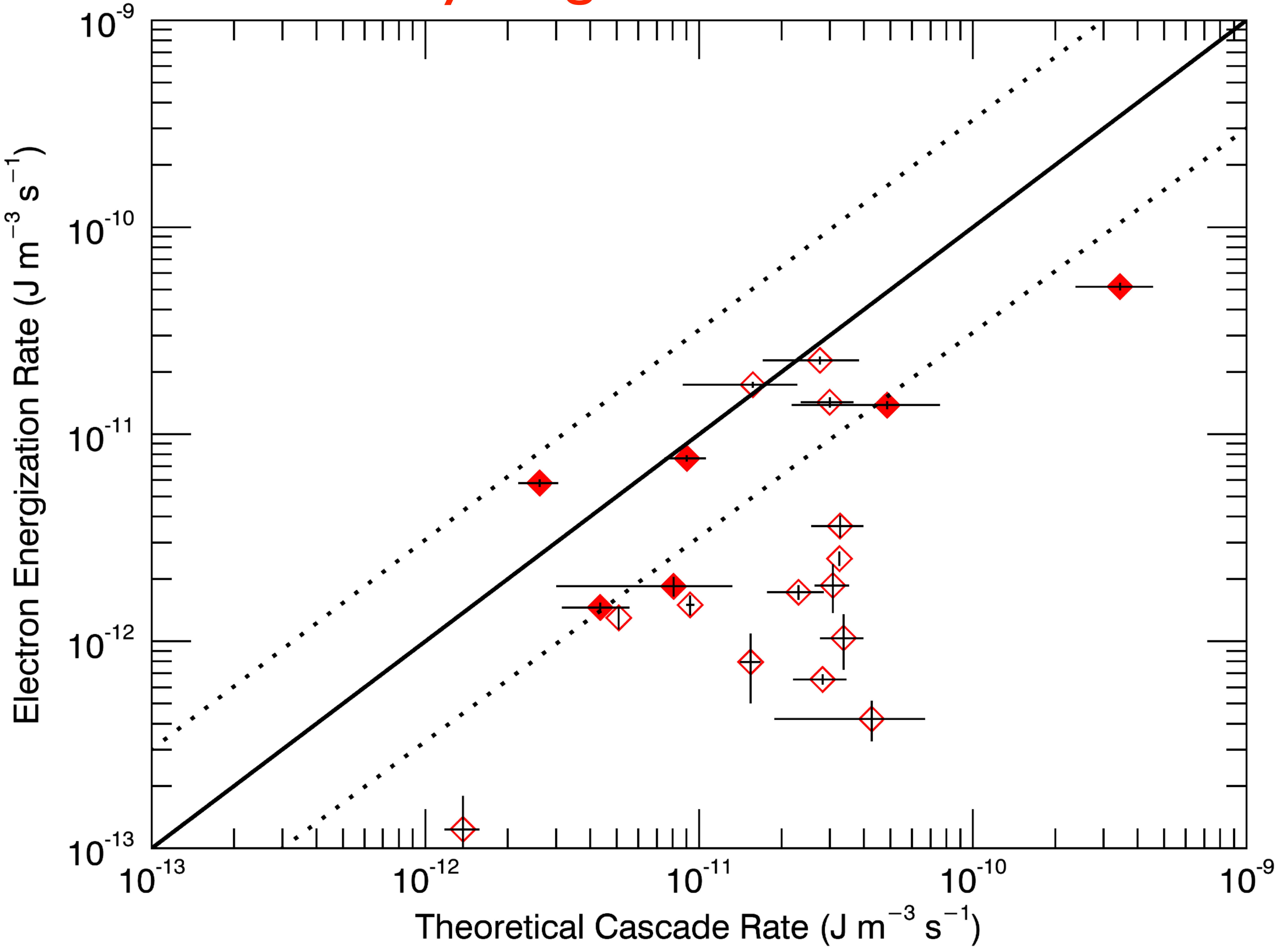
Twenty magnetosheath intervals



(Afshari *et al*., *GRL*, submitted 2020)

Determining Rate of Particle Energization

Twenty magnetosheath intervals



(Afshari *et al*., *GRL*, submitted 2020)

Two Major Findings:

- 19 of 20 intervals show velocity-space signatures of electron Landau damping
- Nearly half of intervals have electron Landau damping rates comparable to the estimated turbulent cascade rate

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Simulation of Perpendicular Collisionless Shock

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Gkeyll Simulation

- Exactly Perpendicular
  $\theta_{nB} = 90^\circ$
- $1\text{D-}2\text{V}$ simulation
- Supercritical
  $M_f \simeq 3$
  $M_A \simeq 5$
- $\beta_i = 1.3$
- $\beta_e = 0.7$
- $m_i/m_e = 100$

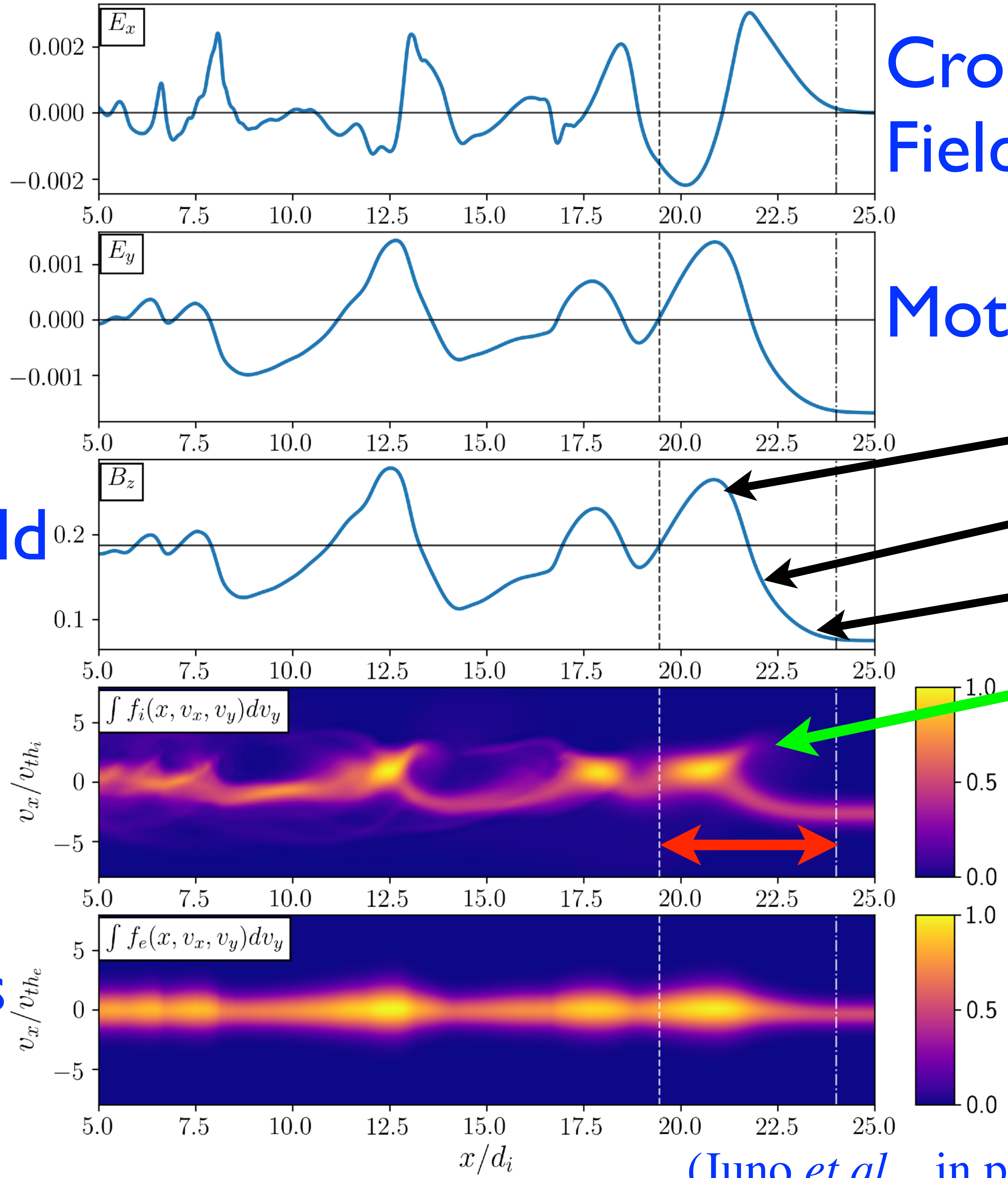
Cross-Shock Electric Field

Motional Electric Field

Magnetic Field

Ions

Electrons



Overshoot

Ramp

Foot

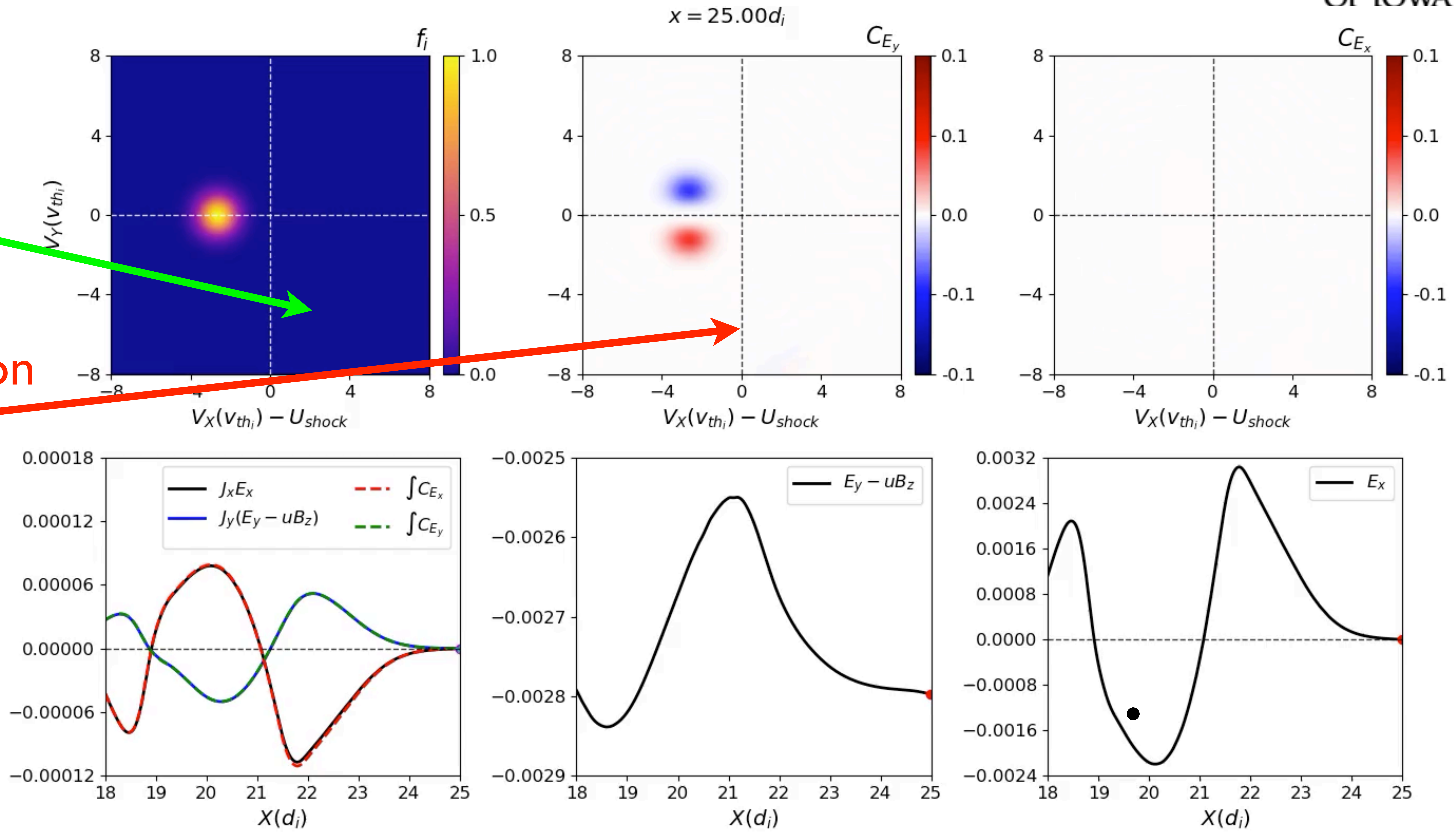
Reflected Ions

(Juno *et al.*, in prep, 2020)

Distribution Function and Velocity-Space Signatures

Reflected Ions

Ion Energization by motional electric field E_y



Model of Perpendicular Collisionless Shock

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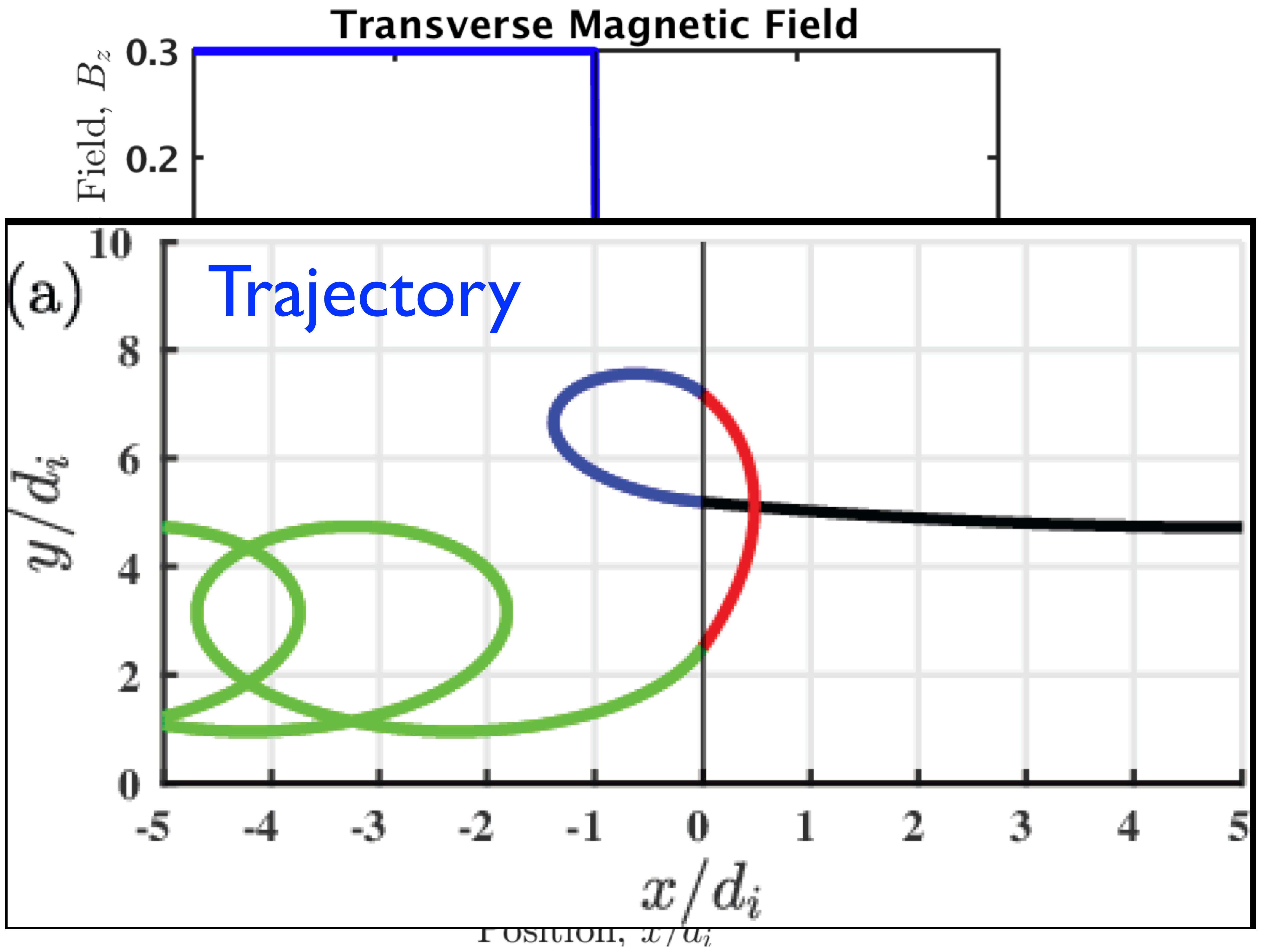
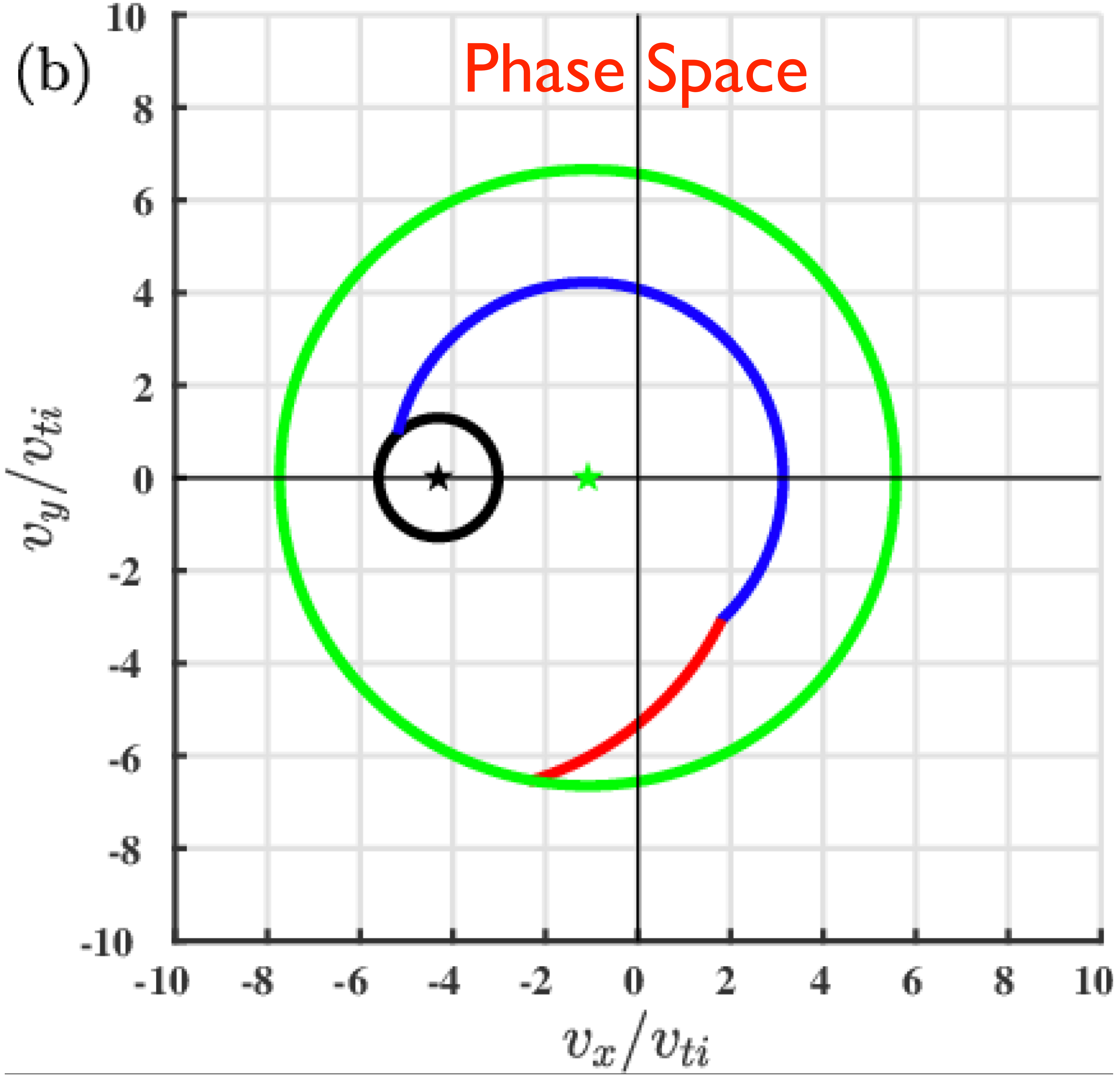
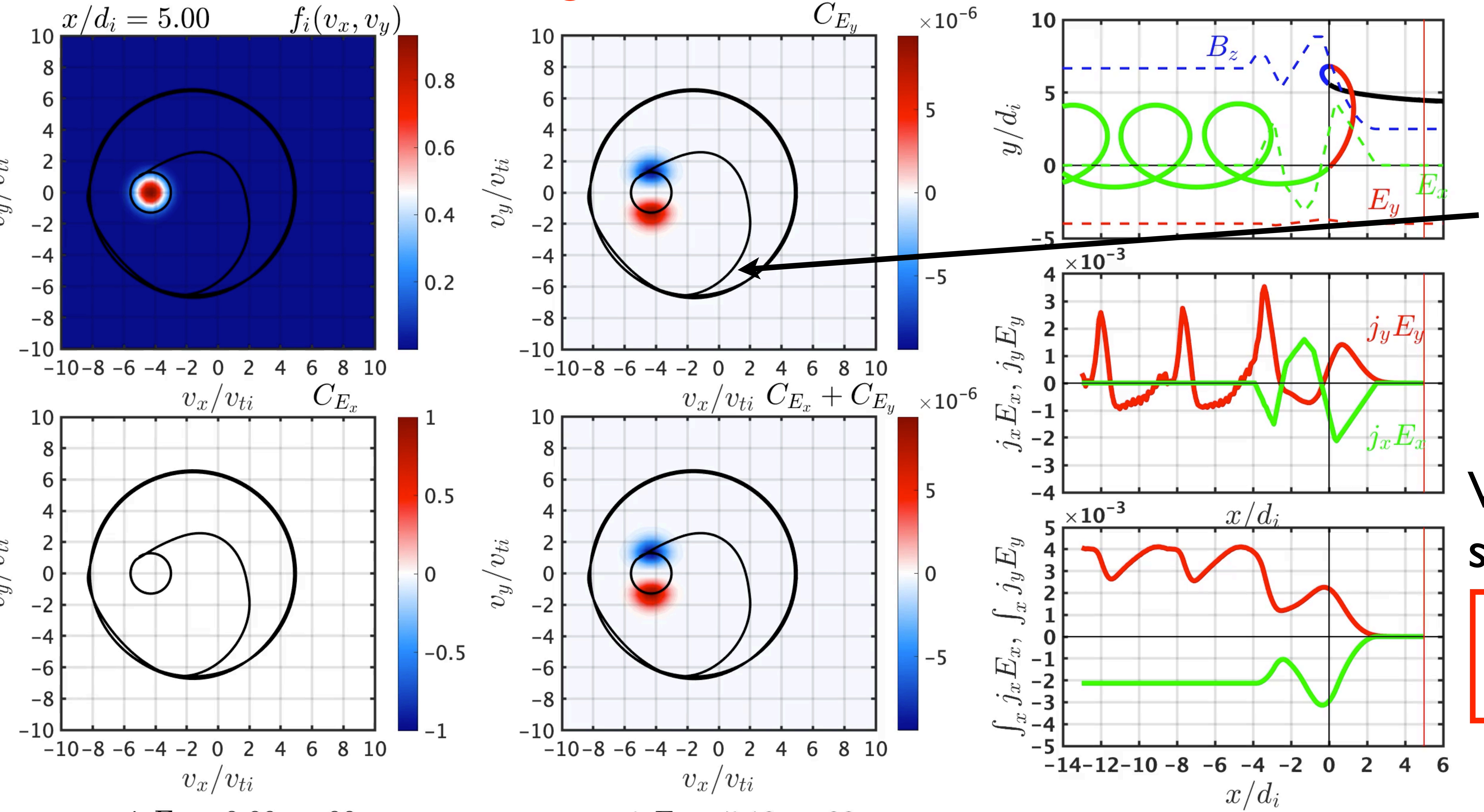
Idealized Perpendicular Shock Model





Model of Perpendicular Collisionless Shock

Single-Particle-Motion Model



Ion Energization by E_y

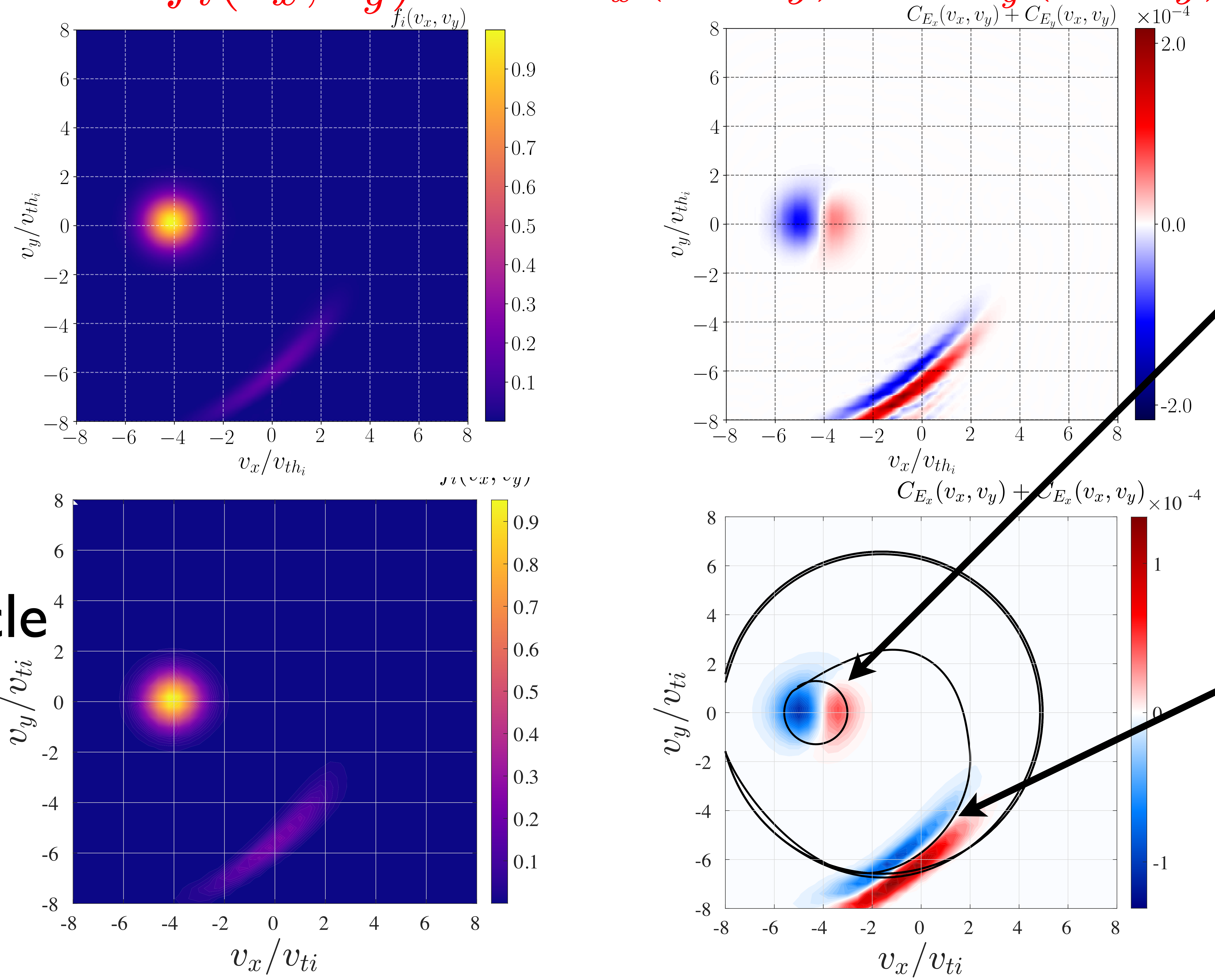
Velocity-space signature of **Shock Drift Acceleration**

Comparison of Simulation and Model

$f_i(v_x, v_y)$ $C_{E_x}(v_x, v_y) + C_{E_y}(v_x, v_y)$

Gkeyll Simulation

Single-Particle Motion Model



Deceleration of Incoming beam by E_x

Shock Drift Acceleration by E_y

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    - -Field-Particle Correlation Technique
- Three Applications of the Field-Particle Correlation Technique
    - -Plasma Heating by Dissipation of Plasma Turbulence
    - -Ion Energization in Collisionless Shocks
    - -Electron Fermi Acceleration in Collisionless Magnetic Reconnection
- Constructing a "Rosetta Stone" for particle energization
- Conclusions

Collisionless Magnetic Reconnection

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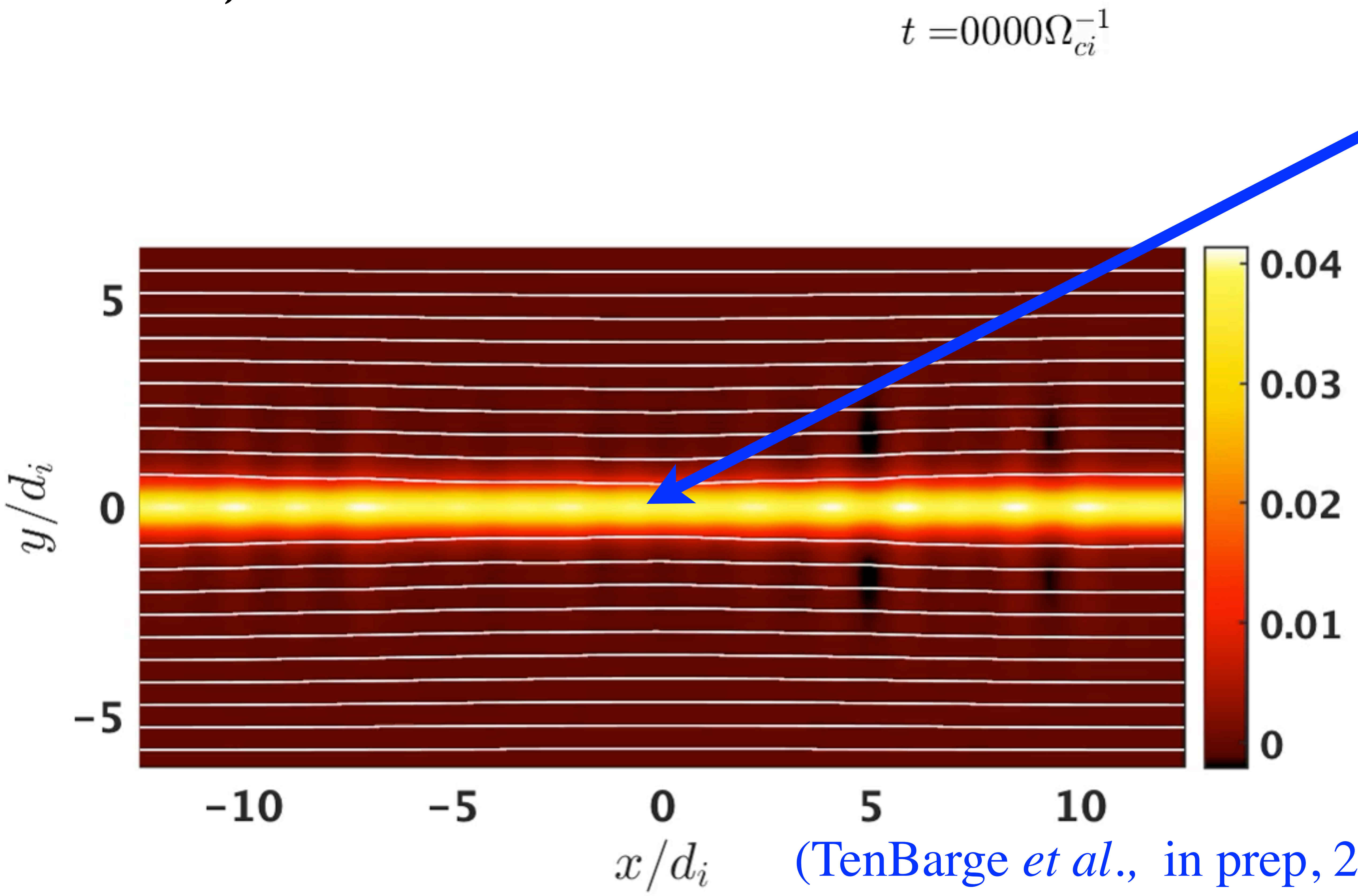
Gkeyll Simulation

- Zero Guide-Field Magnetic Reconnection
- 2D, GEM initial conditions

- $\beta_i = 5/6$
- $T_i/T_e = 5$
- $m_i/m_e = 25$

How are electrons energized in the exhaust?



(TenBarge *et al.*, in prep, 2020)

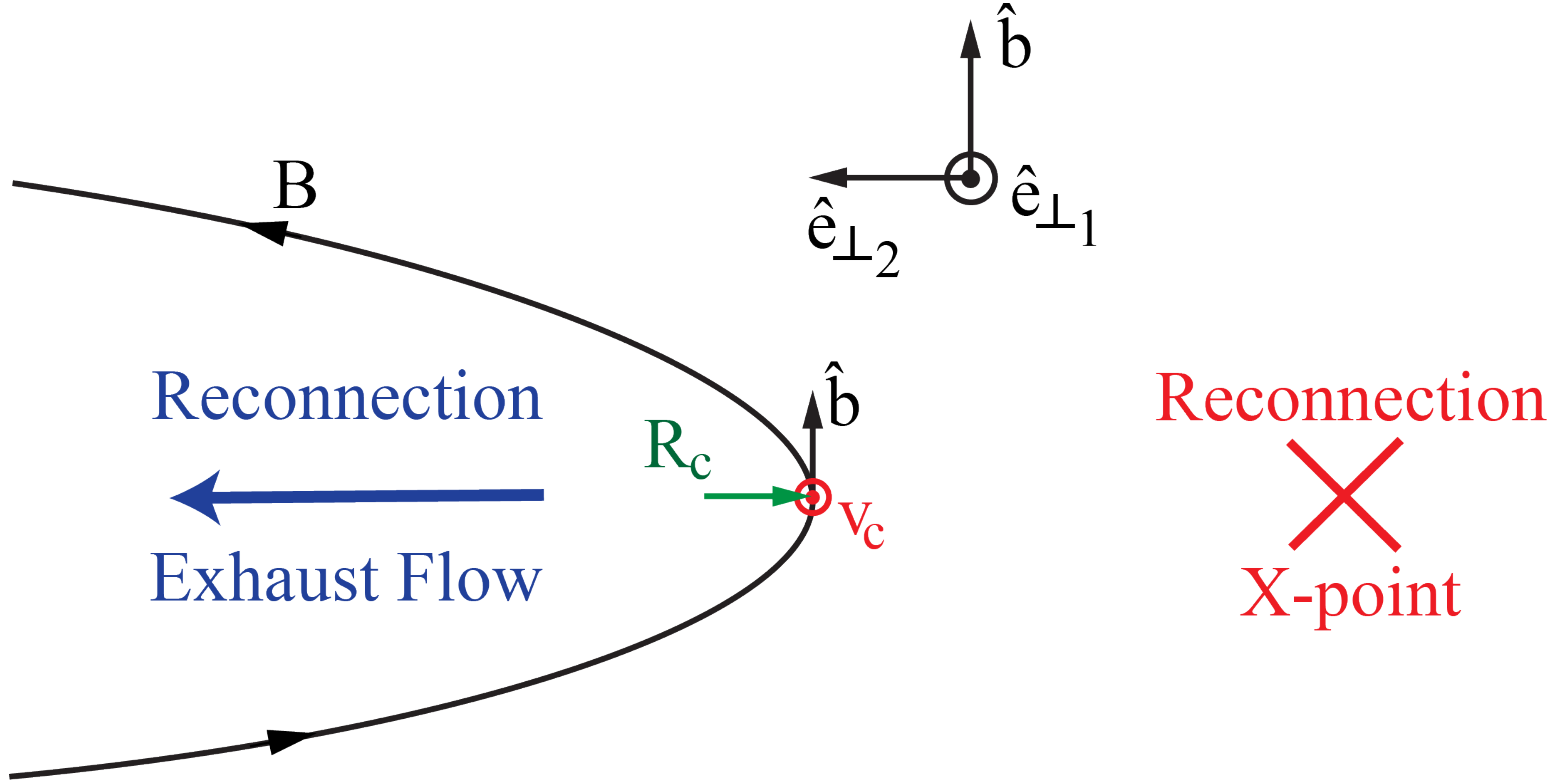
Dahlin, Drake, & Swisdak have demonstrated Fermi acceleration of electrons by the curvature drift (Dahlin, Drake, & Swisdak, 2014, 2015, 2016, 2017)

What is the velocity-space signature of this curvature drift acceleration?

Collisionless Magnetic Reconnection

The University of Iowa

Field-Aligned Coordinate System



$$\mathbf{v}_c = \frac{m v_\parallel^2}{q B^2} \frac{\mathbf{R}_c \times \mathbf{B}}{R_c^2}$$

- Curvature drift is in the $\hat{e}_{\perp 1}$ direction
- Compute Correlations

$$C_{E_{\perp 1}}(v_{\perp 1}, v_\parallel)$$
$$C_{E_{\perp 1}}(v_{\perp 2}, v_\parallel)$$
$$C_{E_{\perp 1}}(v_{\perp 1}, v_{\perp 2})$$

Velocity-Space Signature of Curvature Drift Acceleration

Non-zero $v_\parallel$ needed for significant curvature drift

Accelerated electrons have $2 \lesssim v_{\perp 1}/v_{te} \lesssim 4$

→ Tail of the distribution

→ Electron acceleration!

Velocity-space signature of Fermi Acceleration by the Curvature Drift

Outline

The University of Iowa

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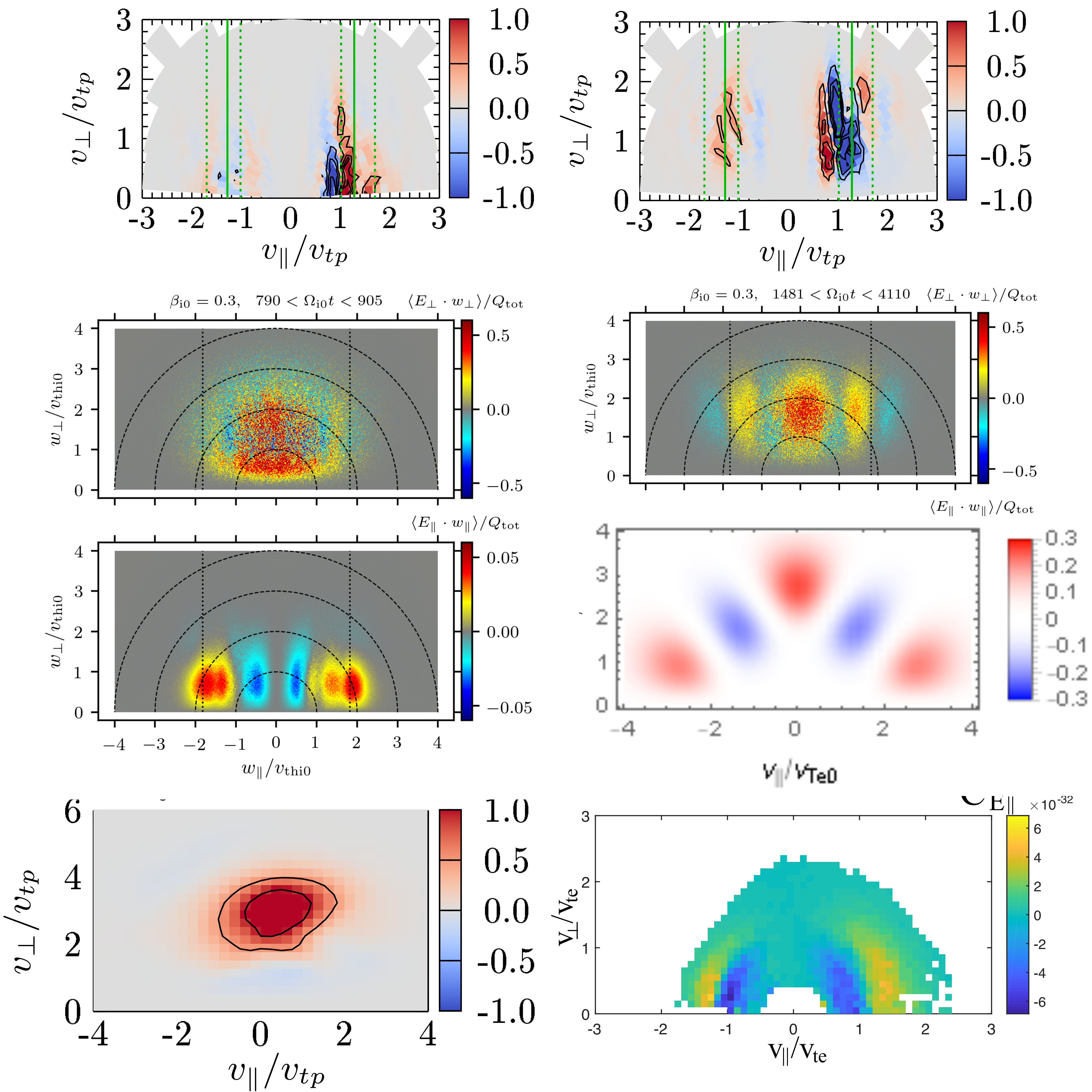
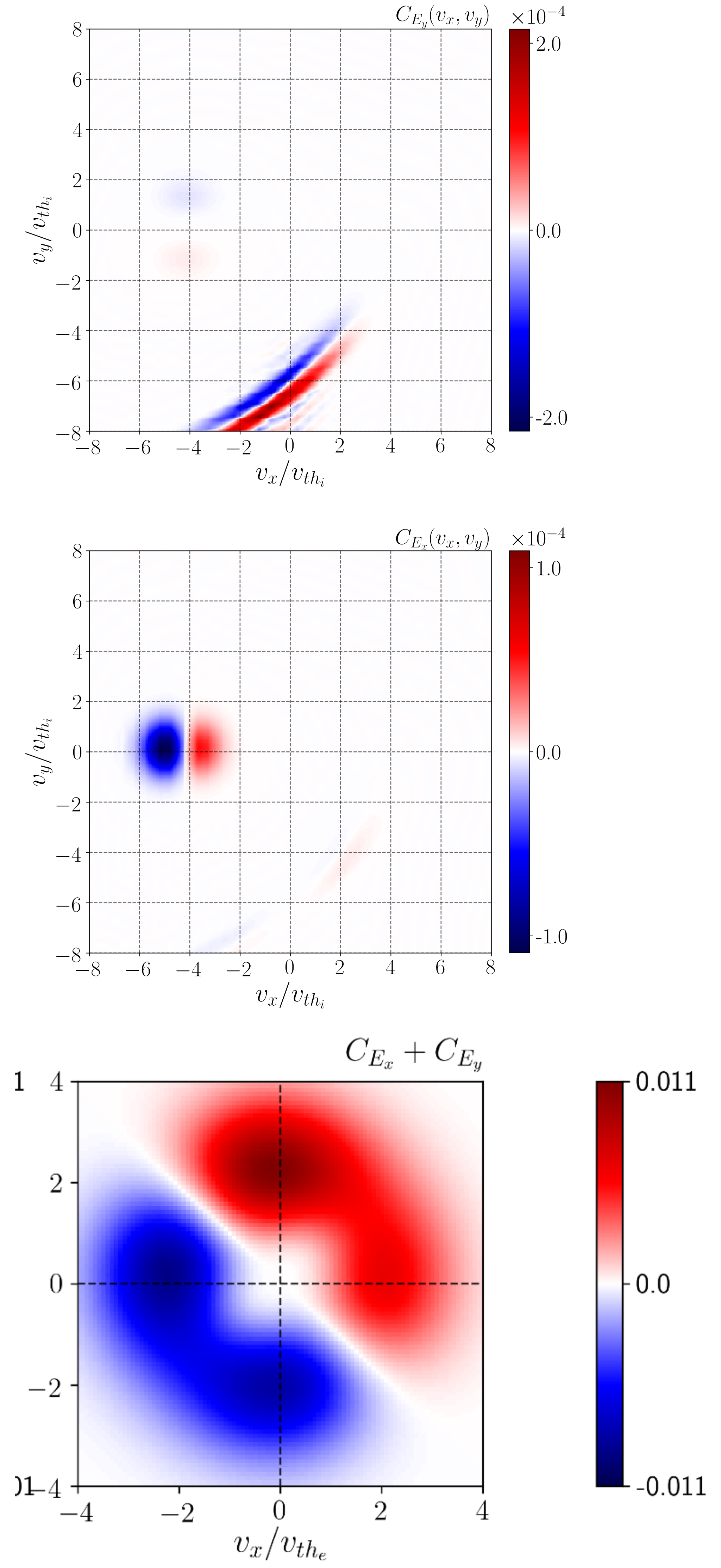
A Rosetta Stone for Particle Energization

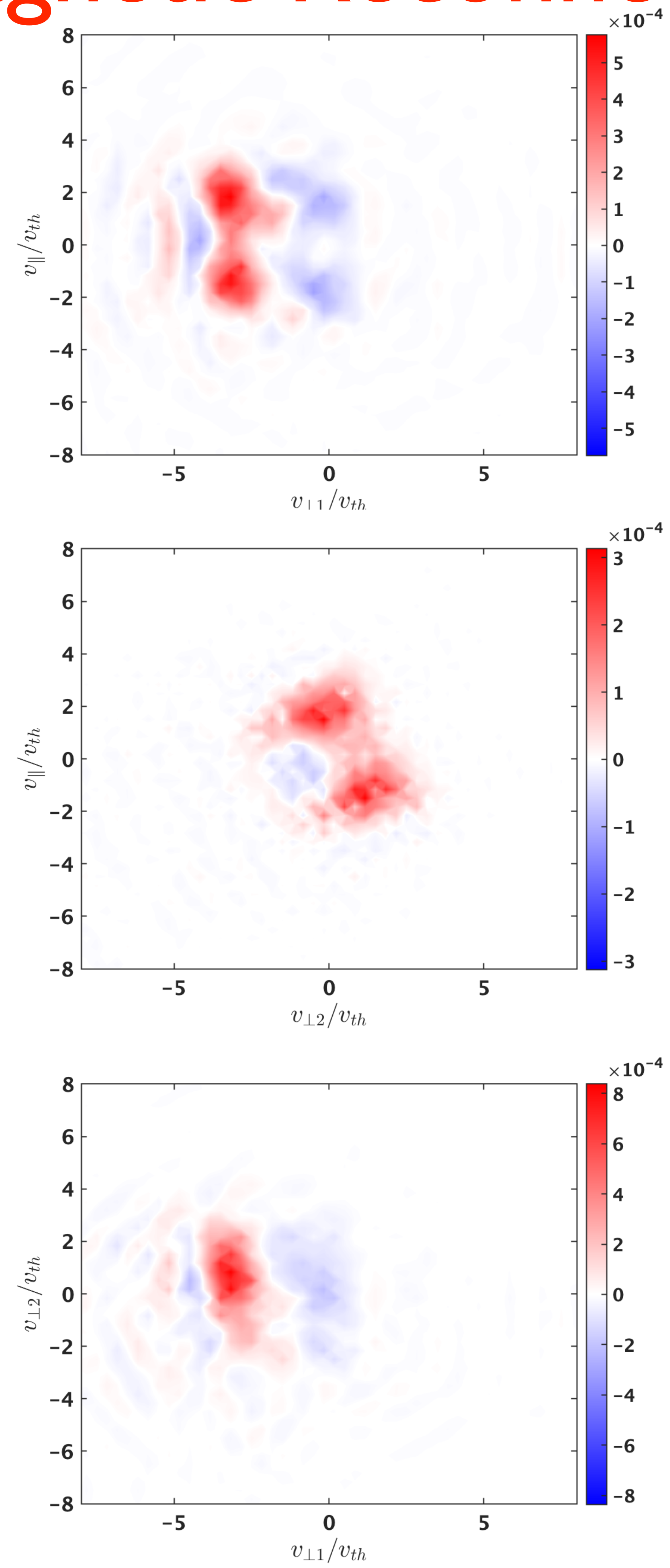
Kinetic Turbulence



Collisionless Shocks



Magnetic Reconnection



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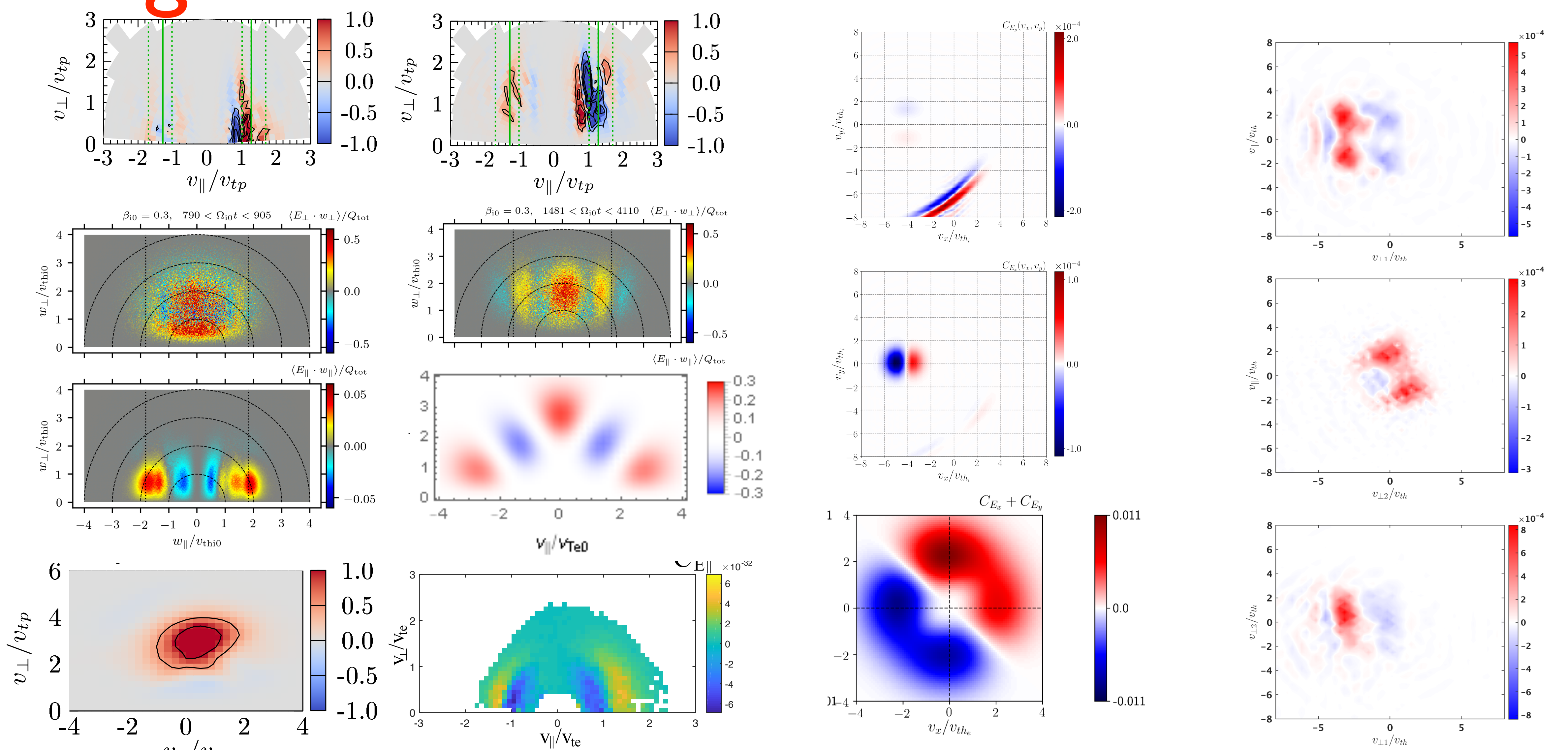
Conclusions

- Turbulence, reconnection, and shocks govern energy flow in the heliosphere
  - Understanding the mechanisms of particle energization in these processes is essential to develop a predictive understanding of the heliospheric evolution
- Full velocity-space information of 3D-3V phase space is often under-utilized
- The field-particle correlation method fully exploits velocity-space (single-point)
  - Velocity-space signature can be used to identify mechanisms of energization
  - Quantify the rate of particle energization

A Rosetta Stone for Particle Energization in Heliospheric Plasmas



The End

Alternative Lagrangian Formulation

$$\frac{dw_s(\mathbf{r},\mathbf{v},t)}{dt} = \frac{\partial w_s}{\partial t} + \mathbf{v}\cdot\nabla w_s + q_s\left(\mathbf{E} + \frac{1}{c}\mathbf{v}\times\mathbf{B}\right)\cdot\frac{\partial w_s}{\partial \mathbf{v}} = q_s\mathbf{v}\cdot\mathbf{E}f_s$$

Along particle trajectory in phase space . . .

rate of change of phase-space energy density $w_s(\mathbf{r},\mathbf{v},t)$ is force times velocity

$$\frac{dW}{dt} = \mathbf{F}\cdot\mathbf{v} = (q\mathbf{E})\cdot\mathbf{v}$$

Compare to Eulerian Form

$$\frac{\partial w_s(\mathbf{r},\mathbf{v},t)}{\partial t} = -\mathbf{v}\cdot\nabla w_s - q_s\frac{v^2}{2}\mathbf{E}\cdot\frac{\partial f_s}{\partial \mathbf{v}} - \frac{q_s}{c}\frac{v^2}{2}(\mathbf{v}\times\mathbf{B})\cdot\frac{\partial f_s}{\partial \mathbf{v}}$$

Analysis of Magnetosheath Turbulence with MMS

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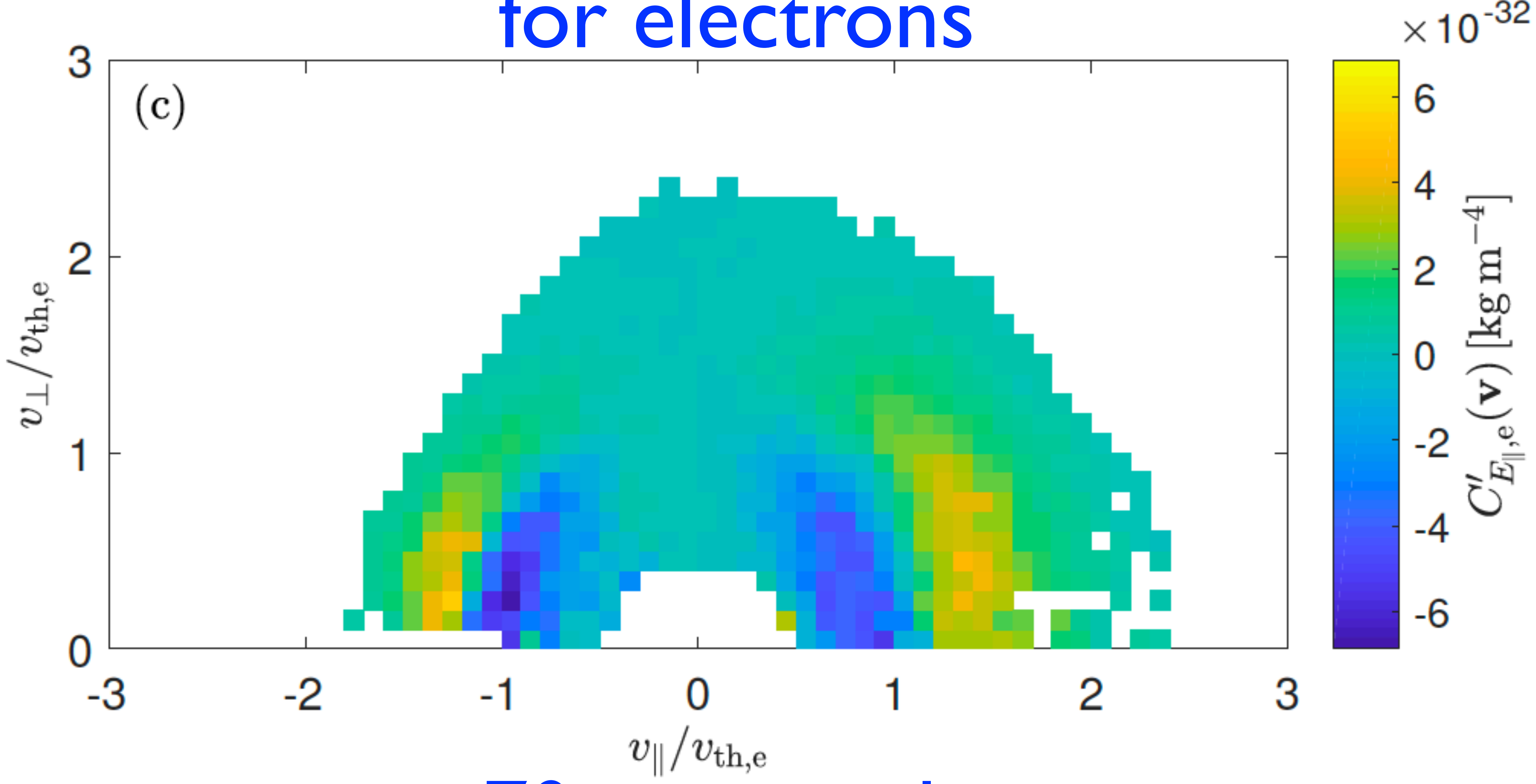
MMS Observations of Magnetosheath Turbulence

(Chen, Klein, & Howes, *Nature Comm.*, **10**:740, 2019)

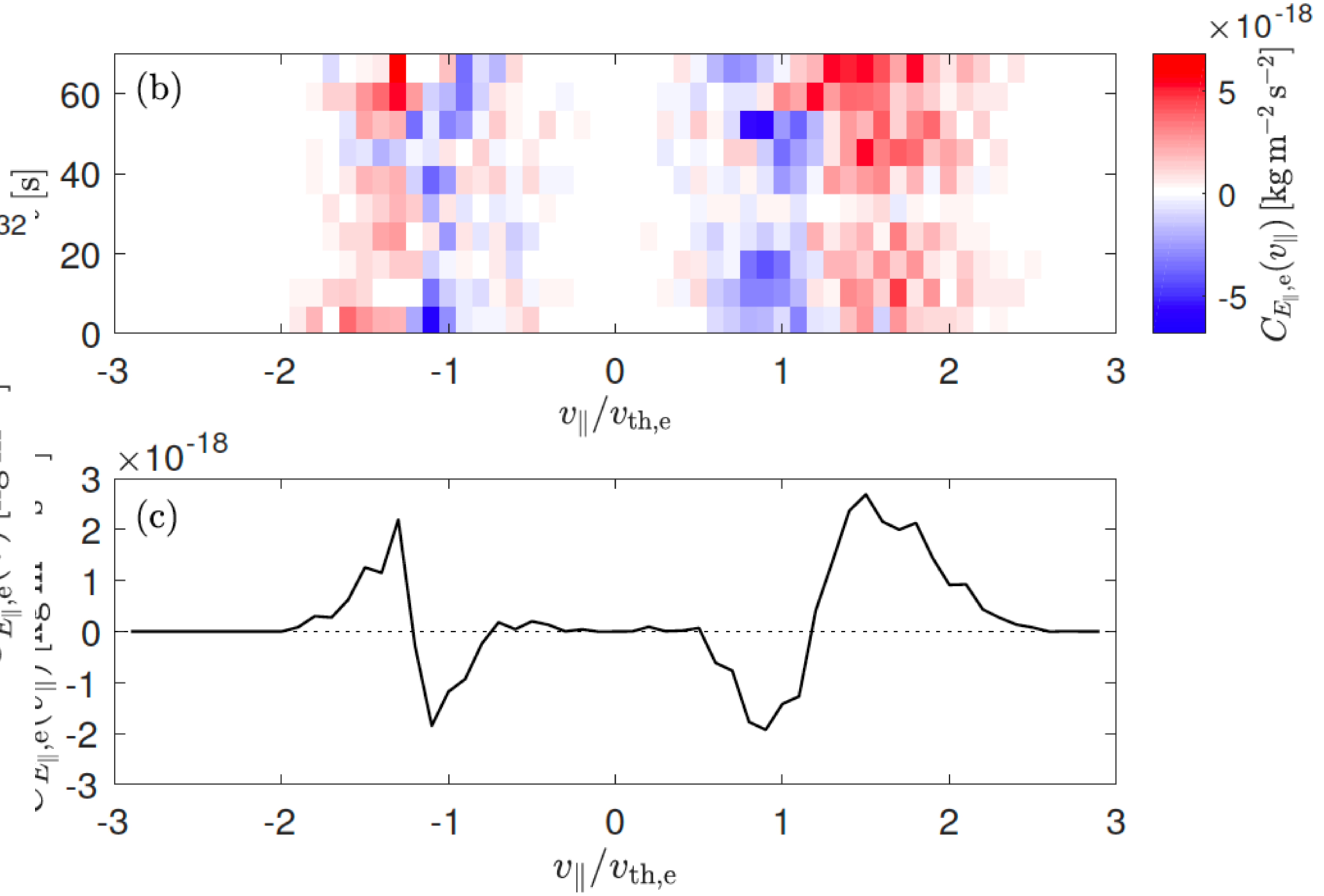
Plasma parameters: $\beta_i = 0.80$

$T_i/T_e = 10$

Field-particle correlation for electrons



70 s interval



First definitive evidence of electron Landau damping in space!