Using Field-Particle Correlations to Diagnose Particle Energization in Turbulence, Magnetic Reconnection, & Shocks

Gregory G. Howes
University of Iowa

Connecting Micro and Macro Scales:
Acceleration, Reconnection, and Dissipation in Astrophysical Plasmas
Kavli Institute for Theoretical Physics, UCSB
9-12 Sep 2019

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Collaborators

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Sarah A. Horvath	University of Iowa
Peter Montag	University of Iowa
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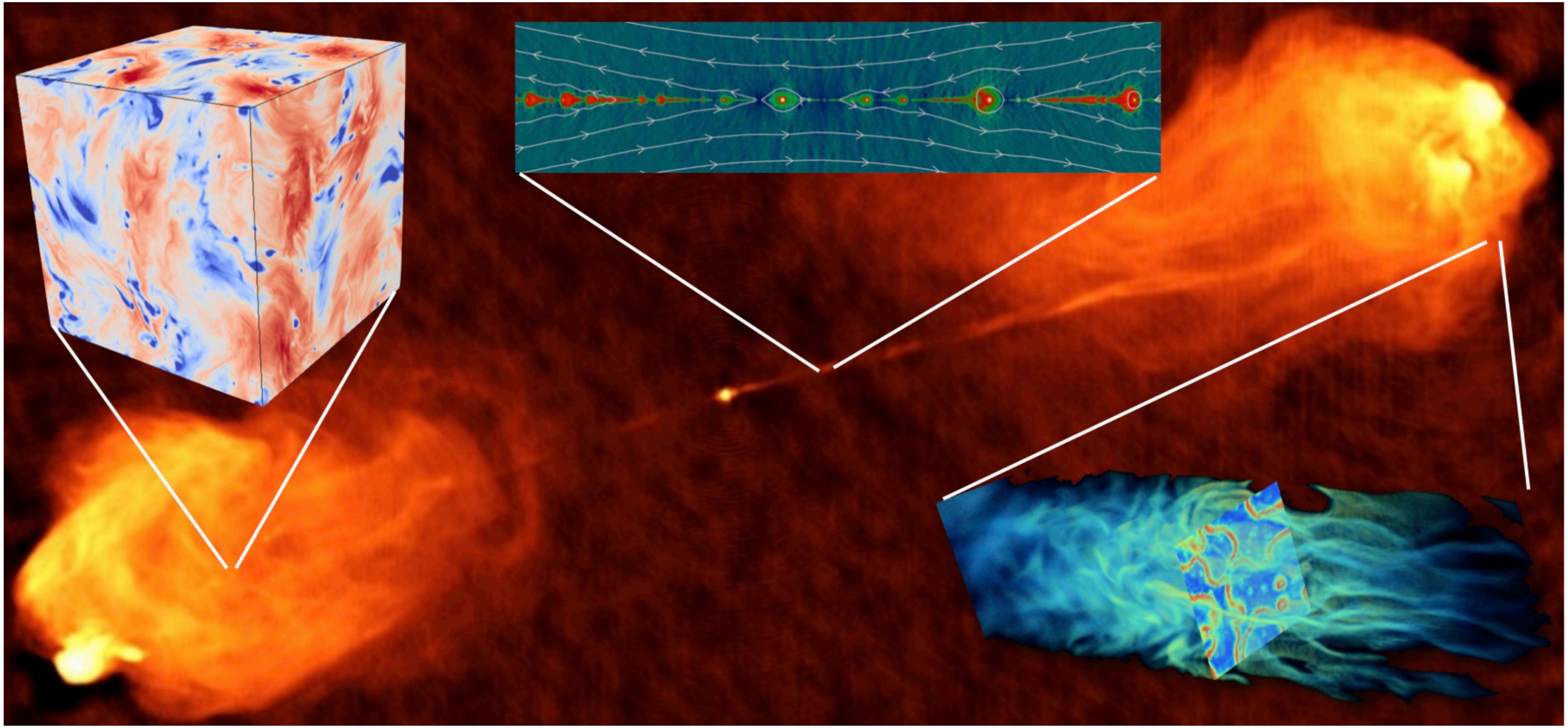
James W. R. Schroeder	Wheaton College
Kristpoher G. Klein	University of Arizona
Jason M. TenBarge	Princeton University
James Juno	University of Maryland
Christopher H. K. Chen	Queen Mary University
Francesco Valentini	University of Calabria

Outline

- The Flow of Energy and Particle Energization in Astrophysical Plasmas
- Kinetic Theory of Particle Energization
  - -Field-Particle Correlation Technique
- Distinguishing Energization Mechanisms
- Application: Experiments of Auroral Electron Acceleration
- Other Applications: Magnetic Reconnection and Collisionless Shocks
- Conclusions

Fundamental Plasma Physics Processes



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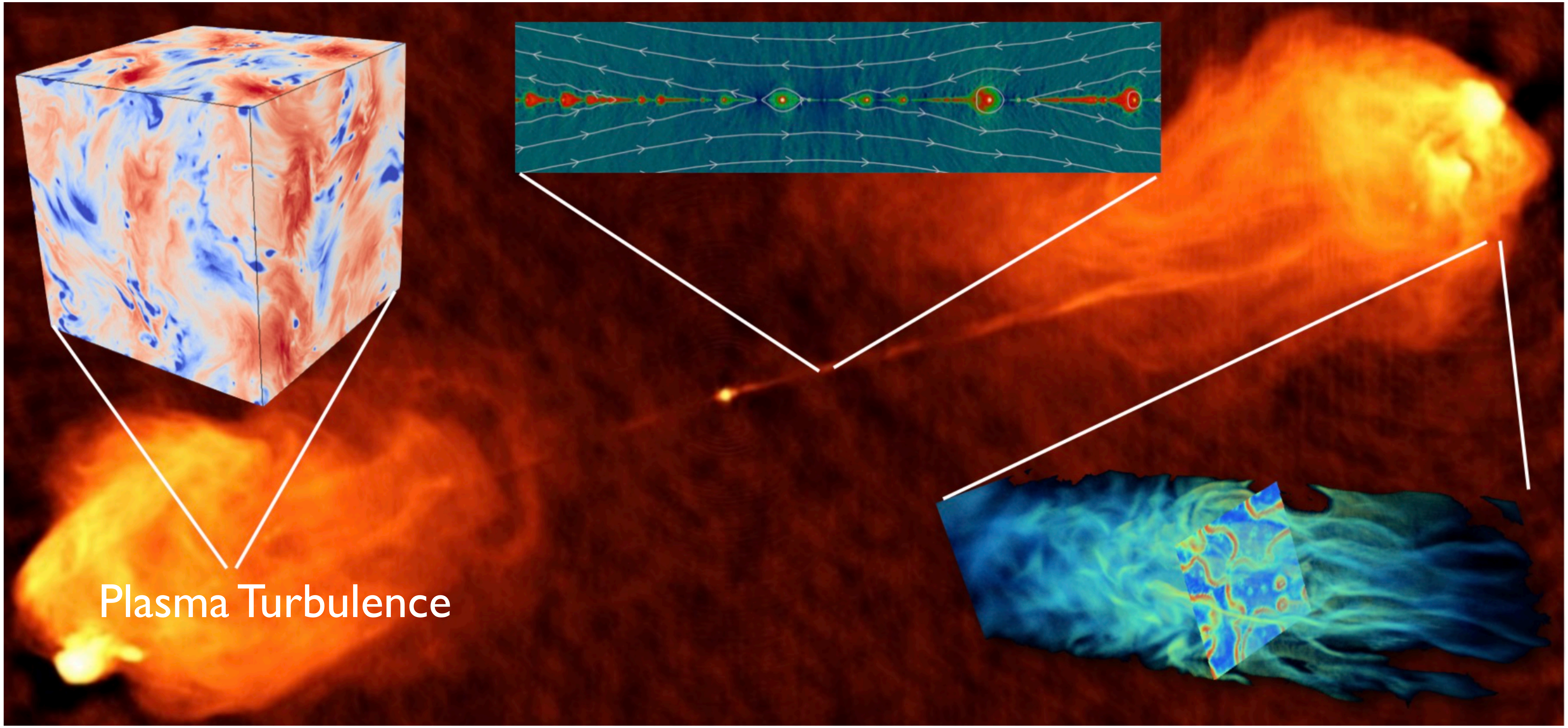

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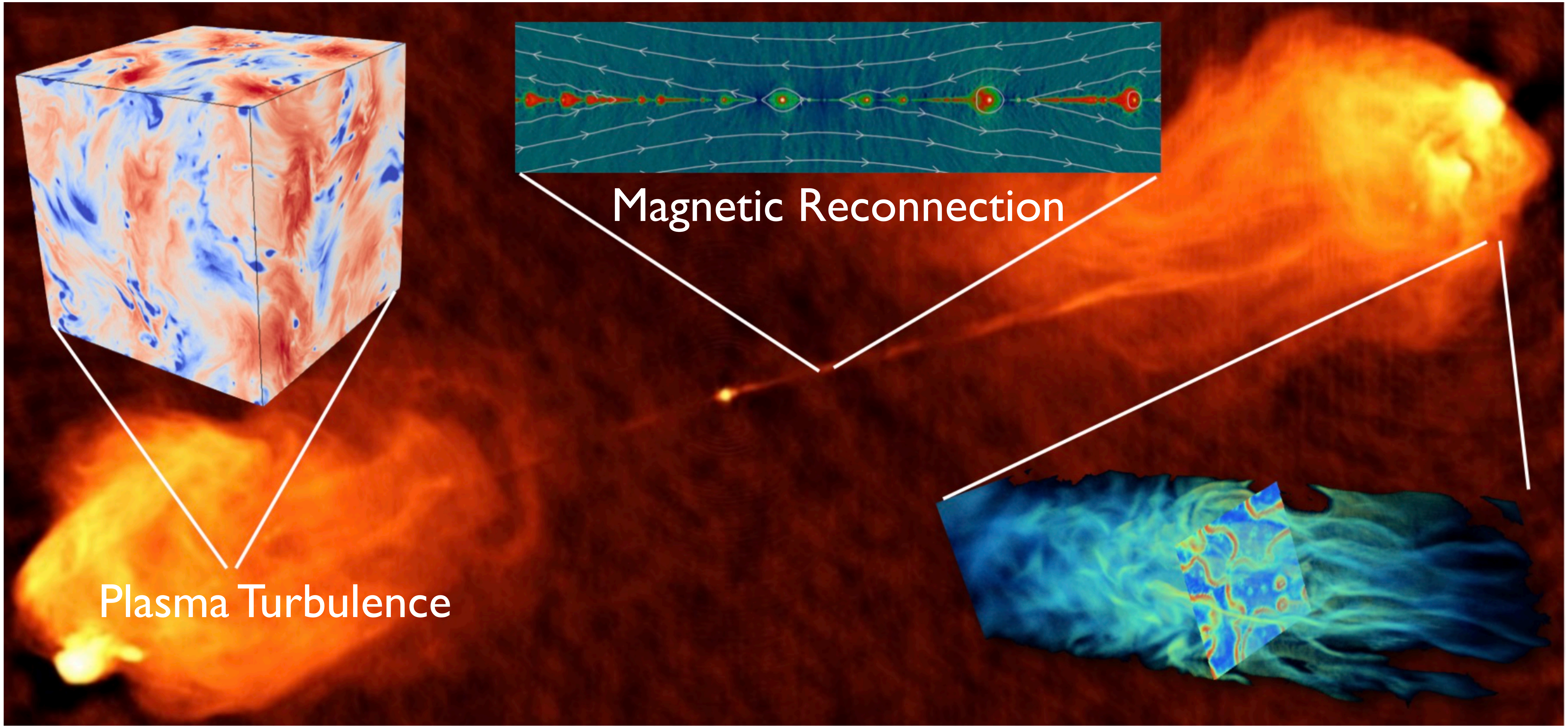

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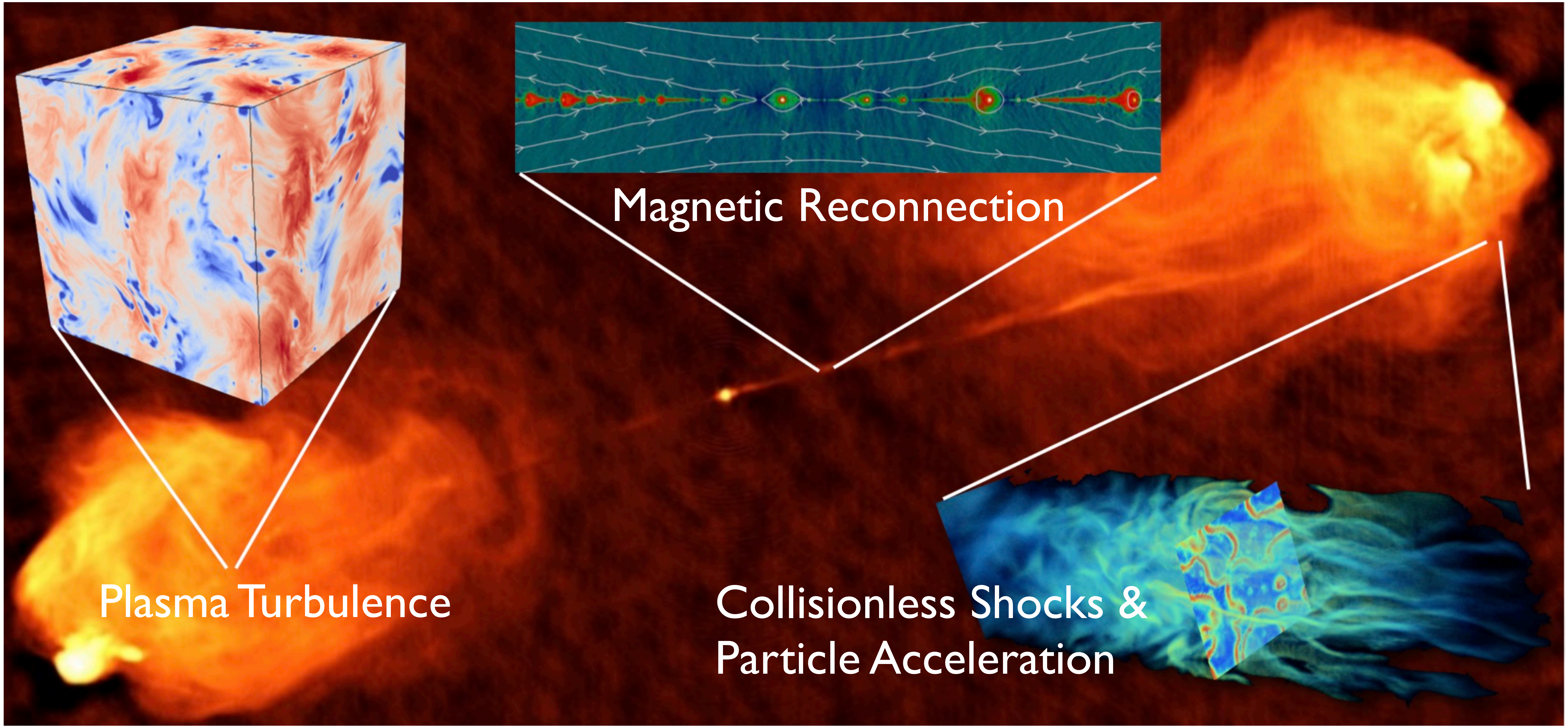
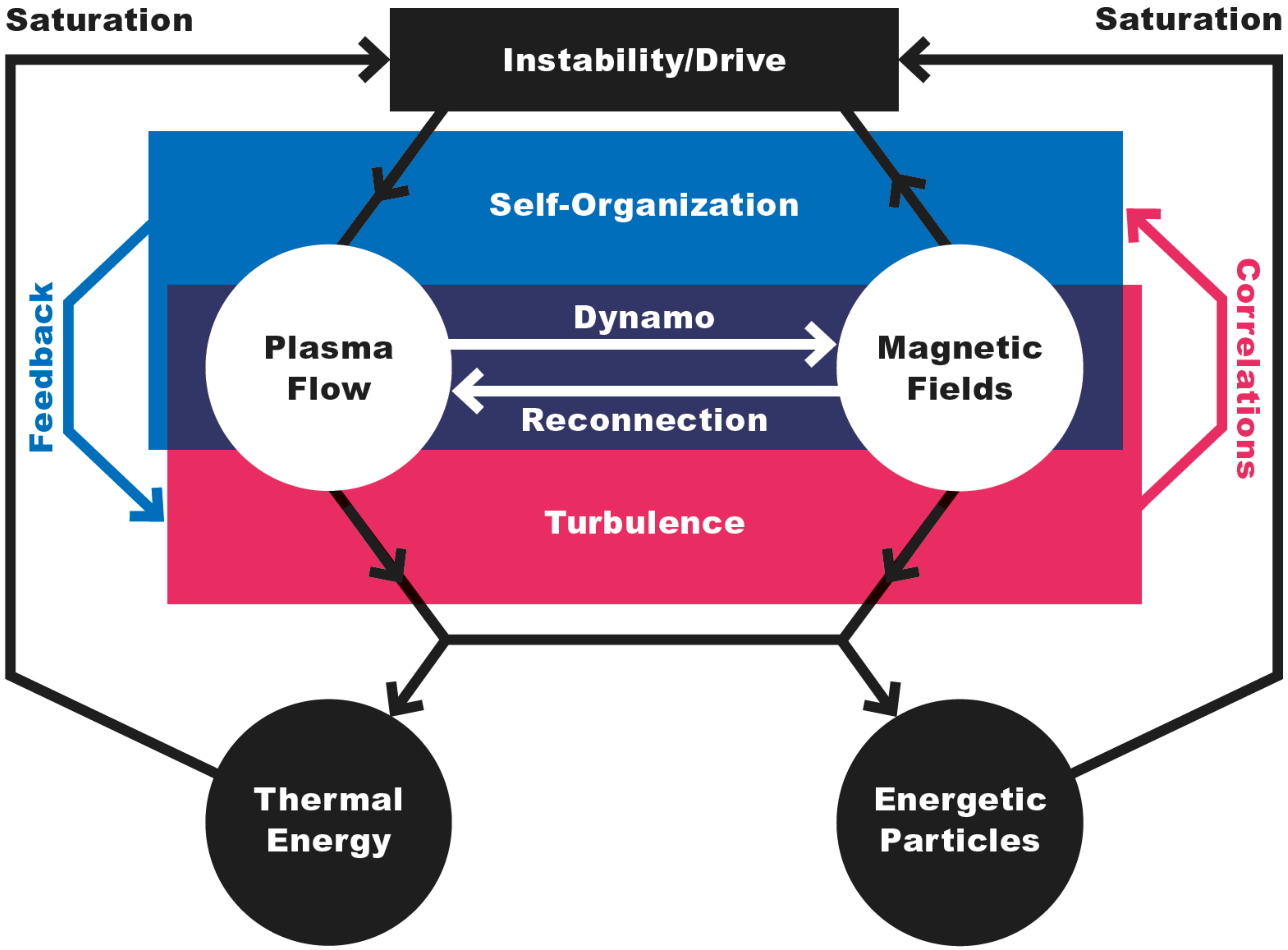


Energetics of the Plasma Universe



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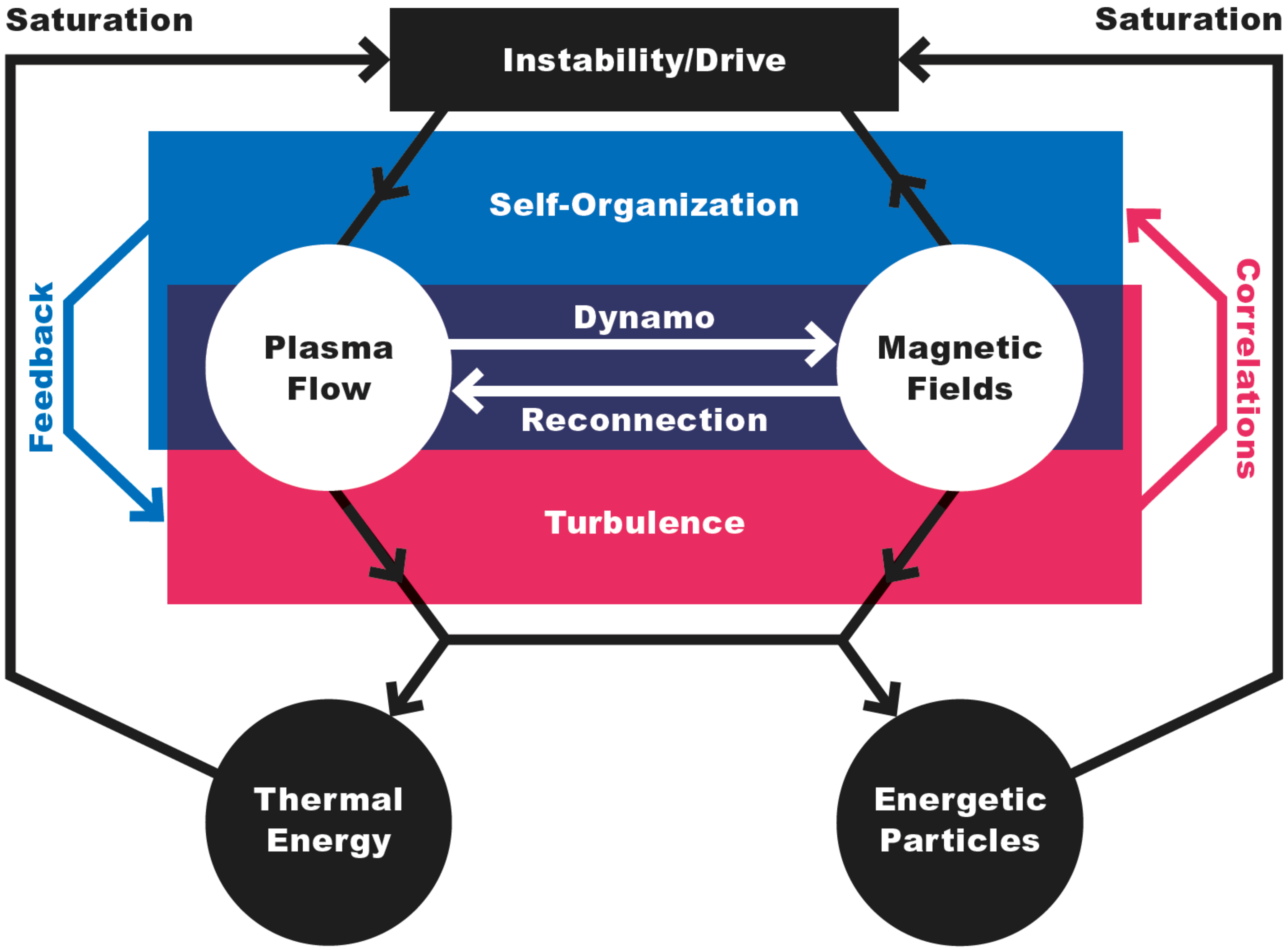

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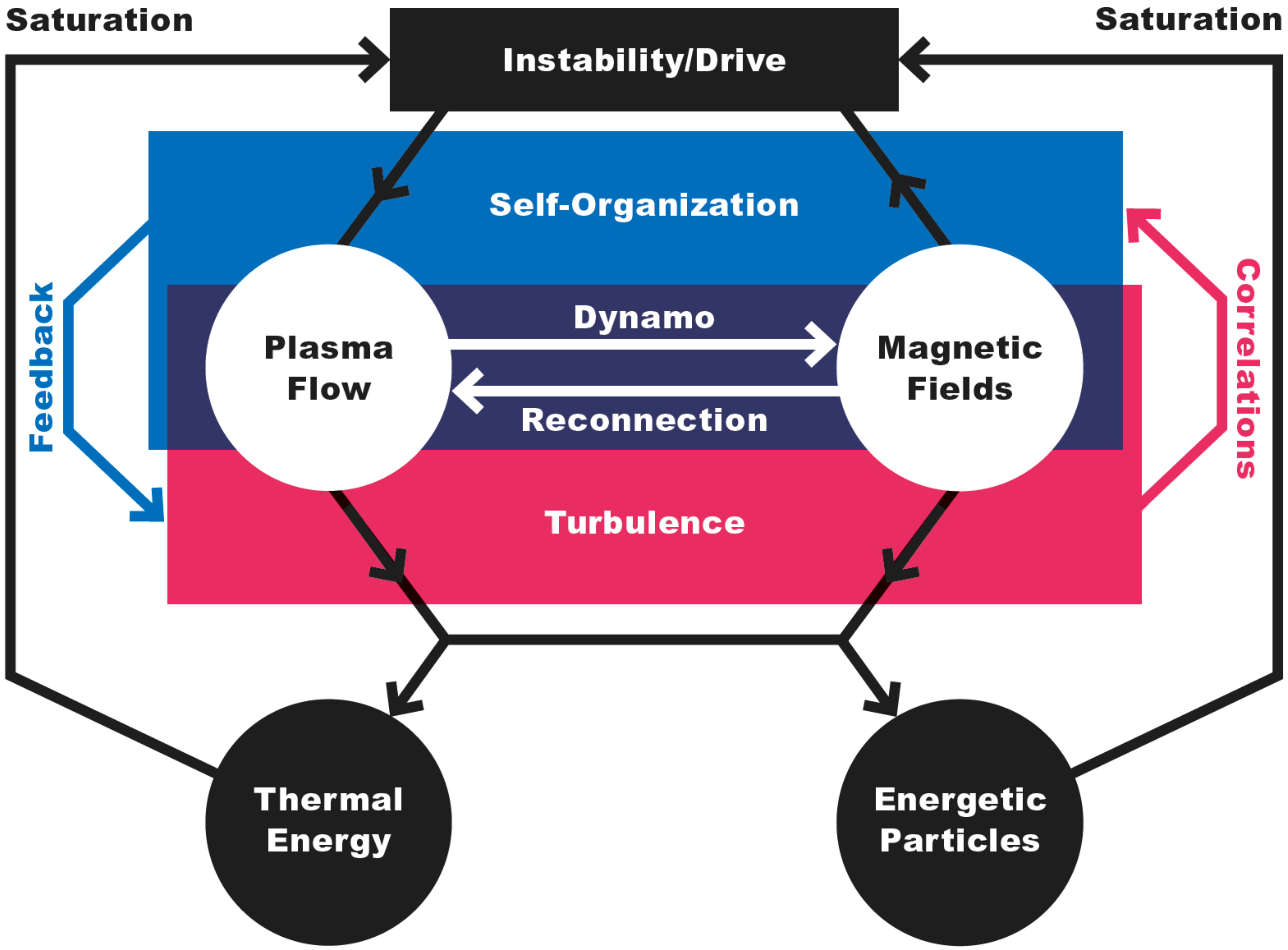

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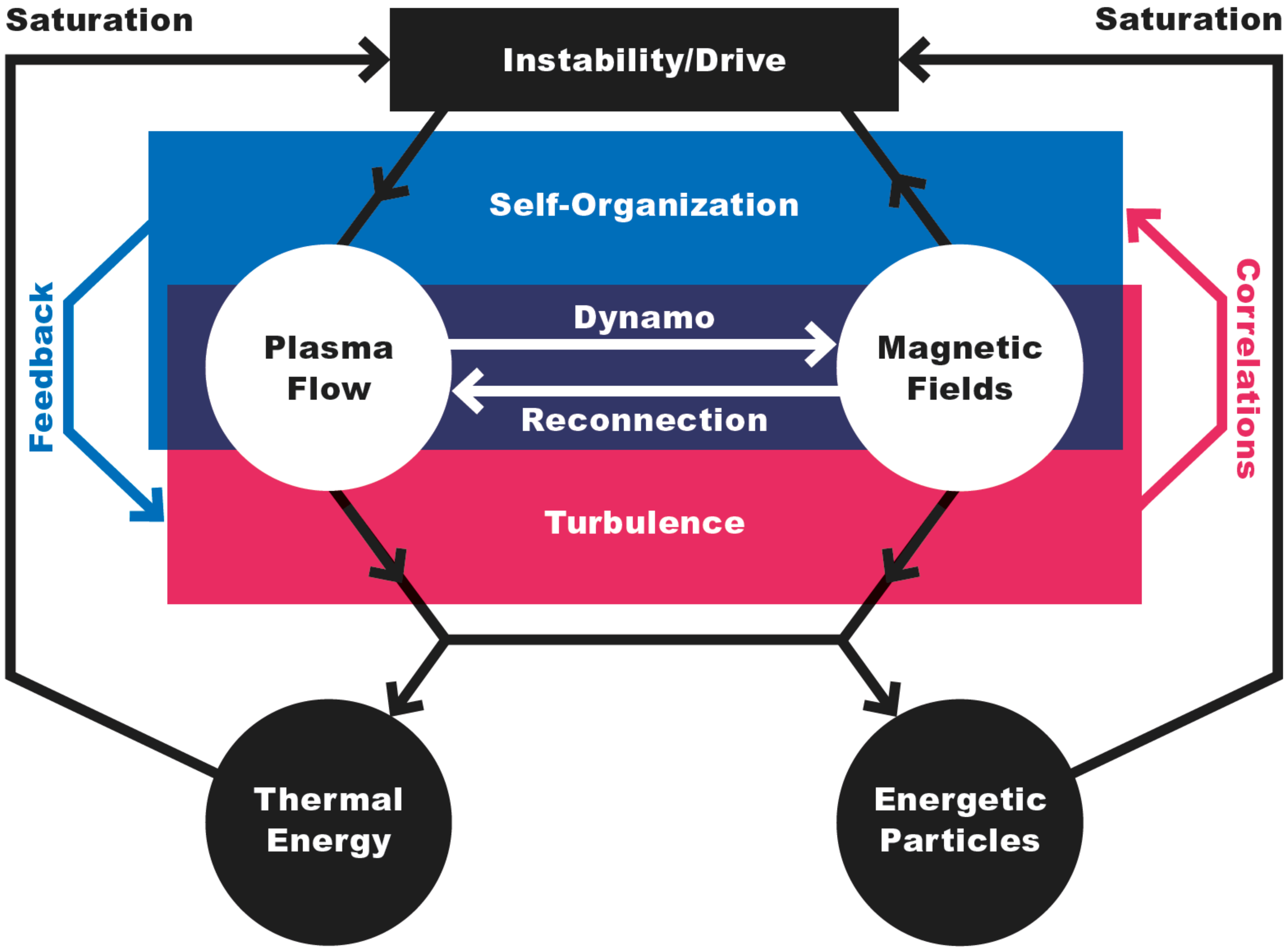

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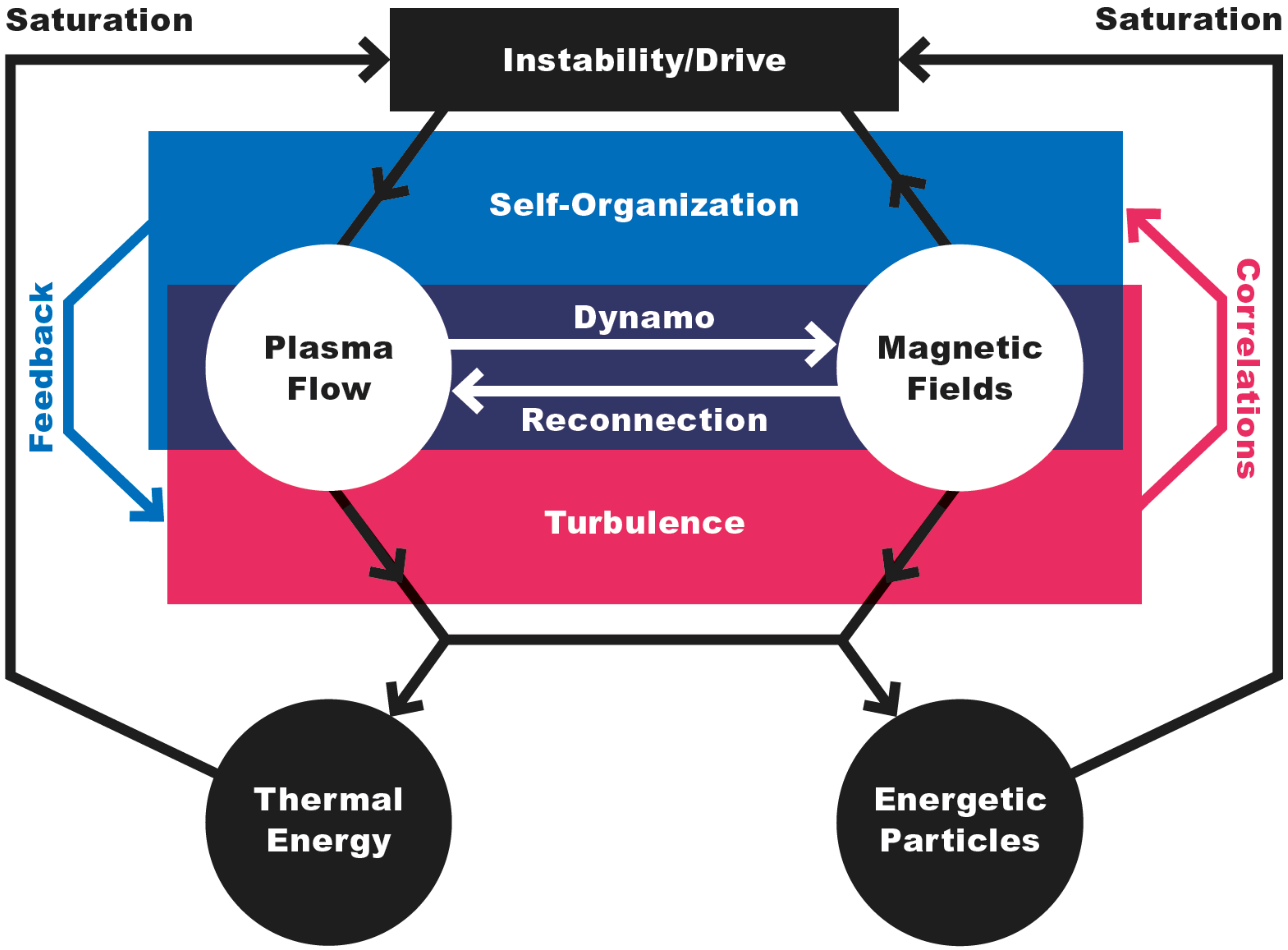

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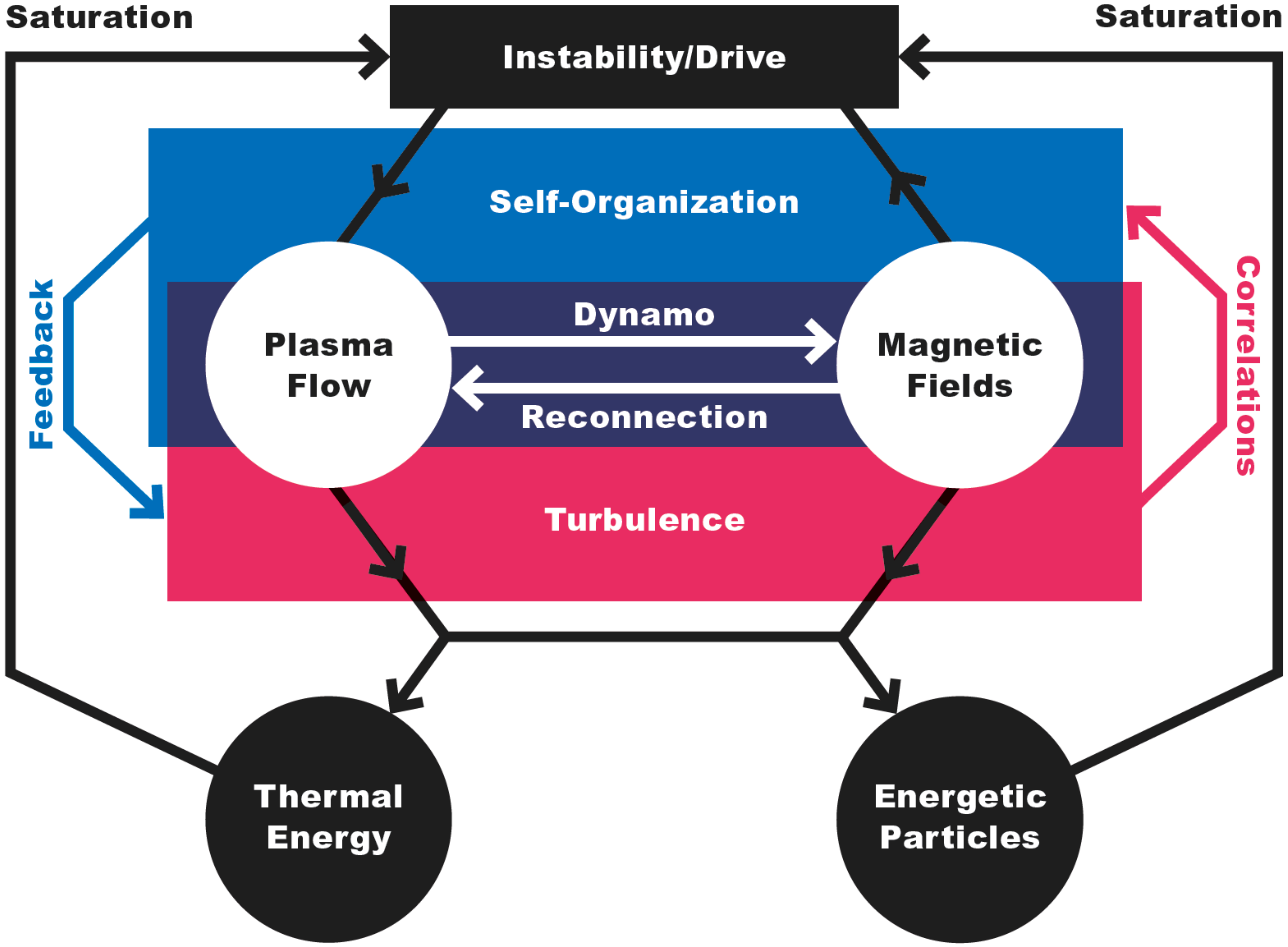

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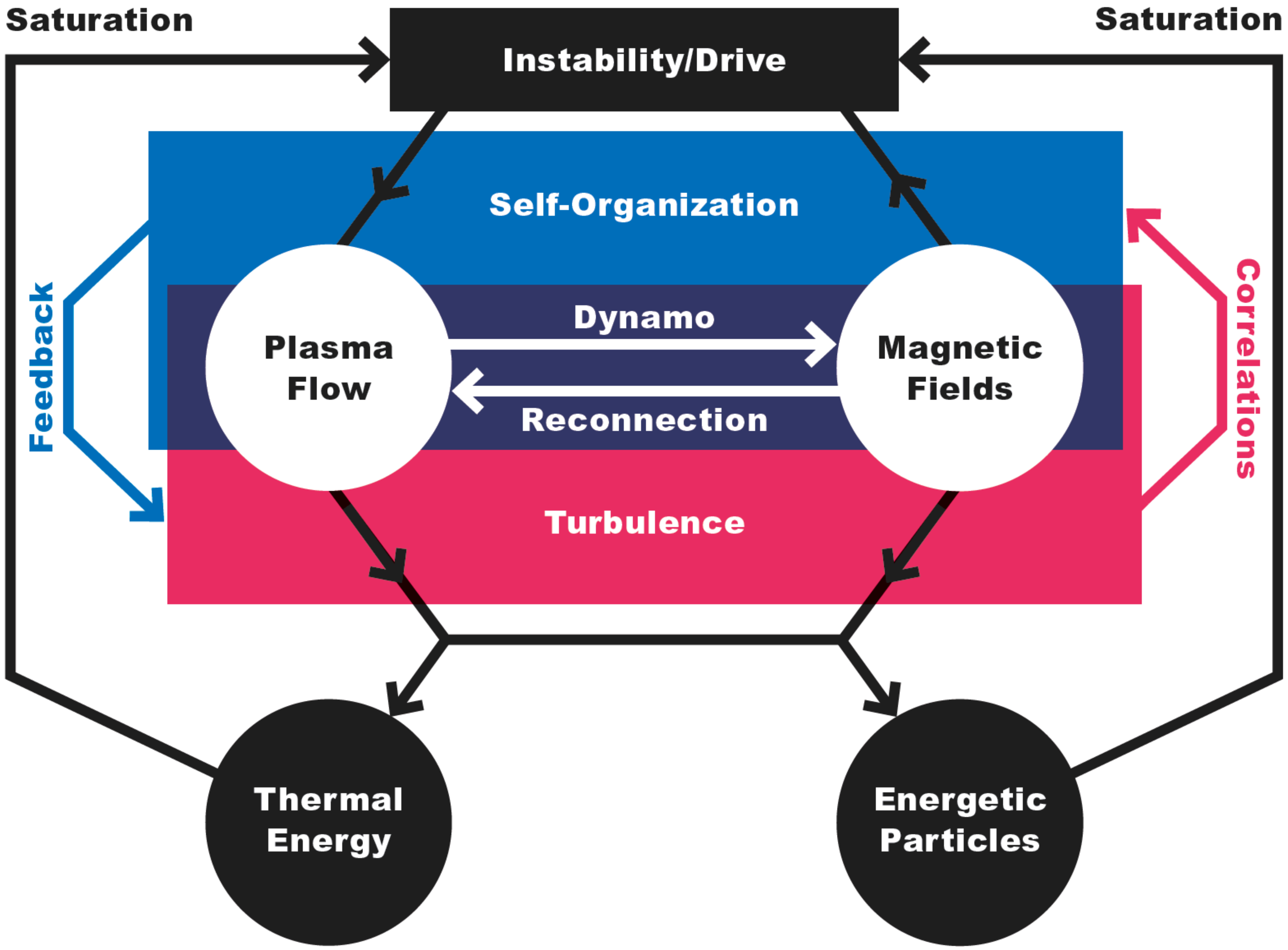

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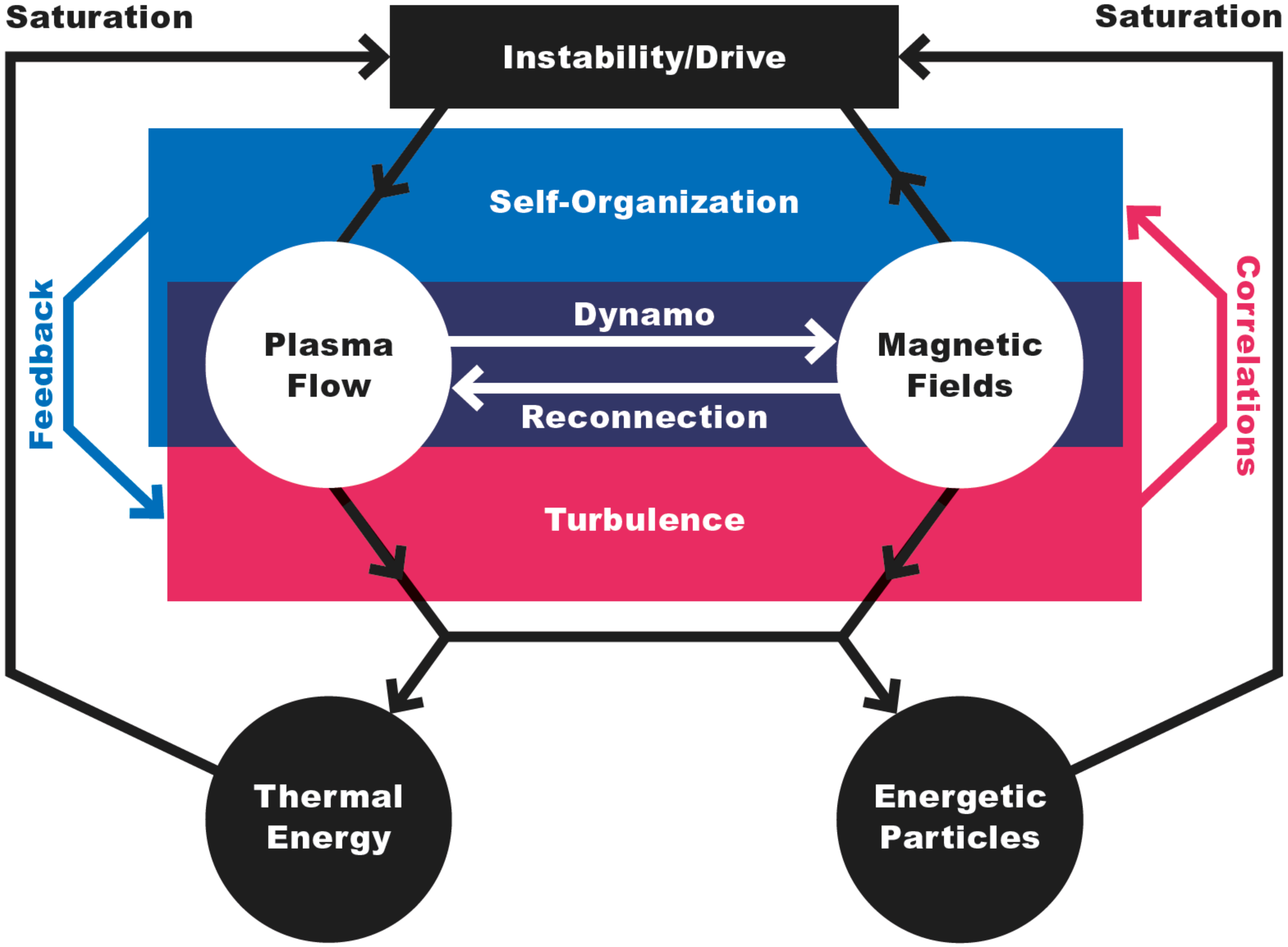

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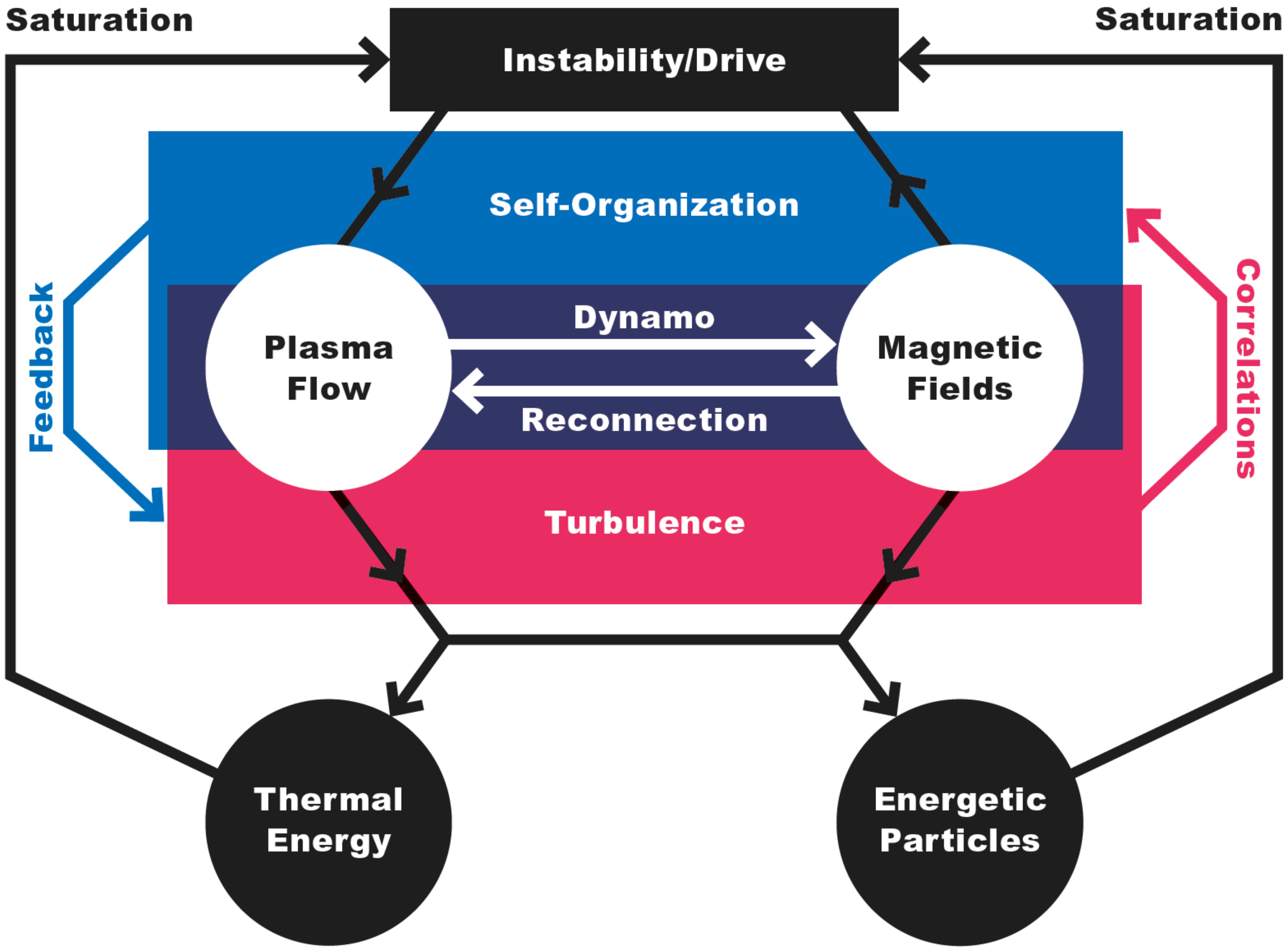

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Under the weakly collisional conditions of most space and astrophysical plasmas, kinetic theory is essential to understand these processes.

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Maxwell-Boltzmann Equations of Kinetic Plasma Theory

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

$$\nabla \times \mathbf{E} = -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t}$$

$$\nabla \cdot \mathbf{E} = 4\pi \rho_q$$

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

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Lorentz Term responsible for interactions between fields and particles

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Particle Energization

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Conserved Vlasov-Maxwell Energy

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

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We want to measure the change in particle energy …

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Particle Energization

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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

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

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Perfect
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Rate of Change of Particle Energy

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Particle Energization

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But this is integrated over velocity and space…

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Not observationally accessible!

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Spacecraft measurements are typically limited to a single-point

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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)

Example of Field-Particle Correlations

Consider Evolution of a single Kinetic Alfven Wave with $k_\perp \rho_i = 1$

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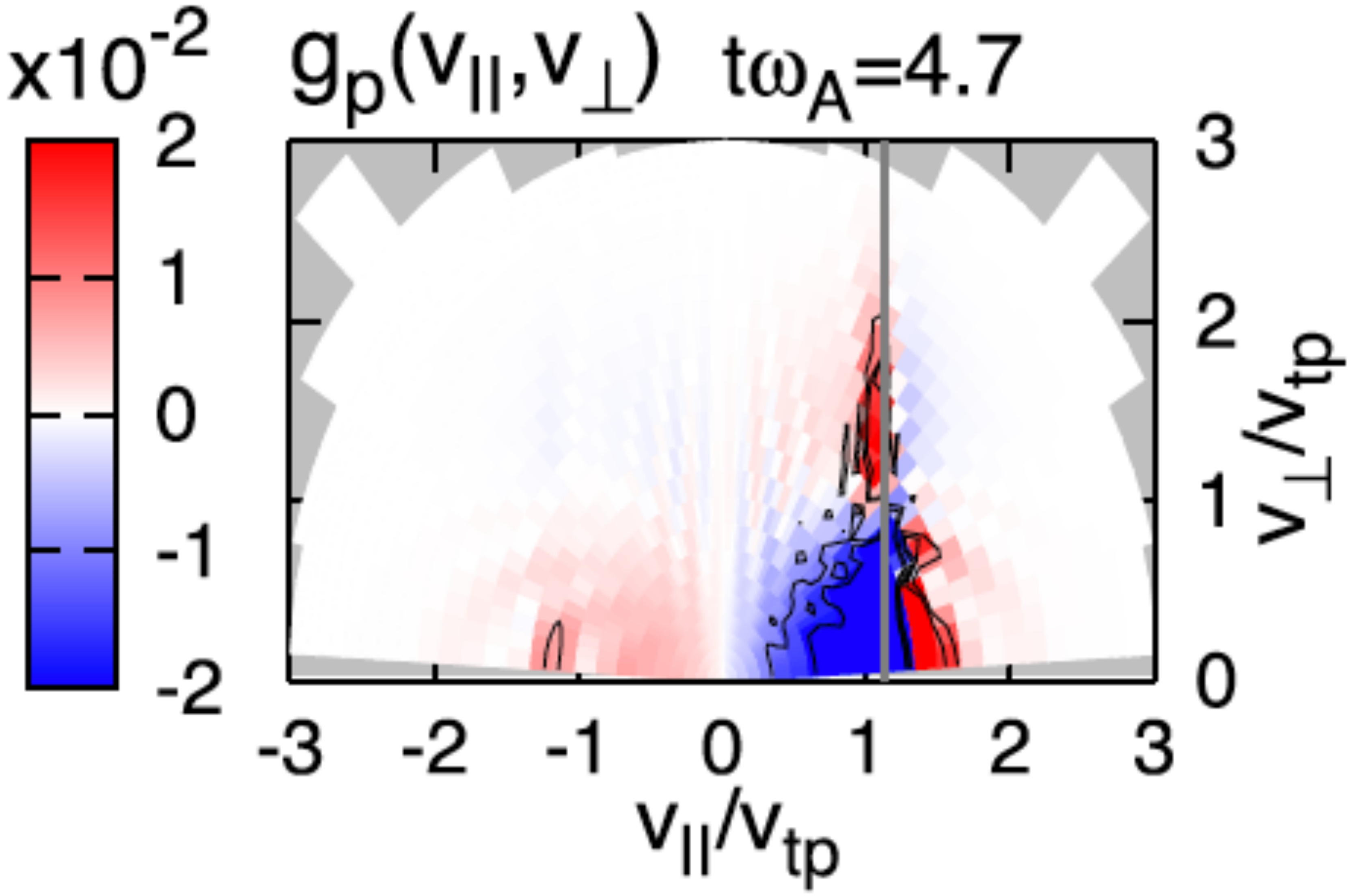

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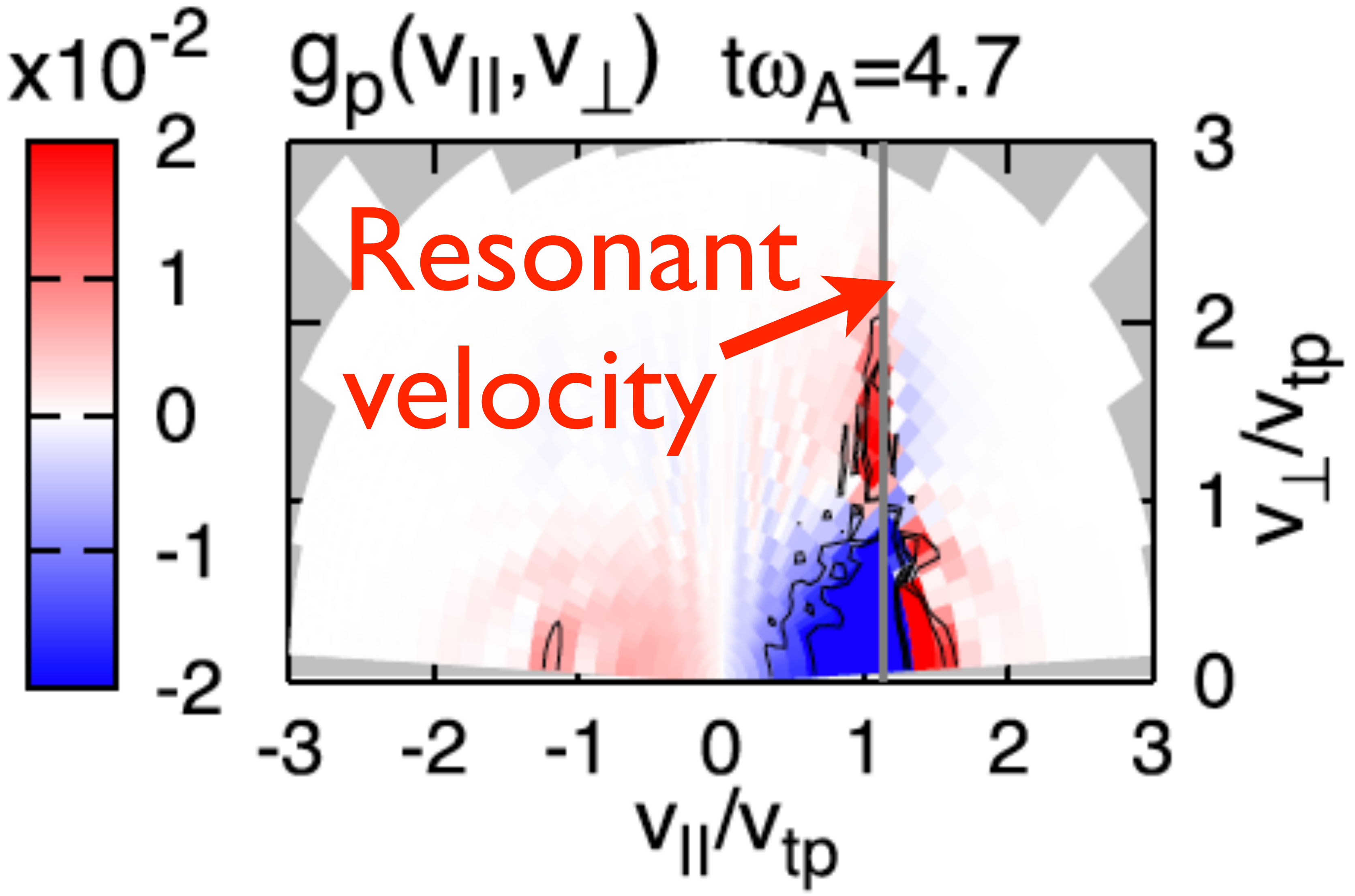

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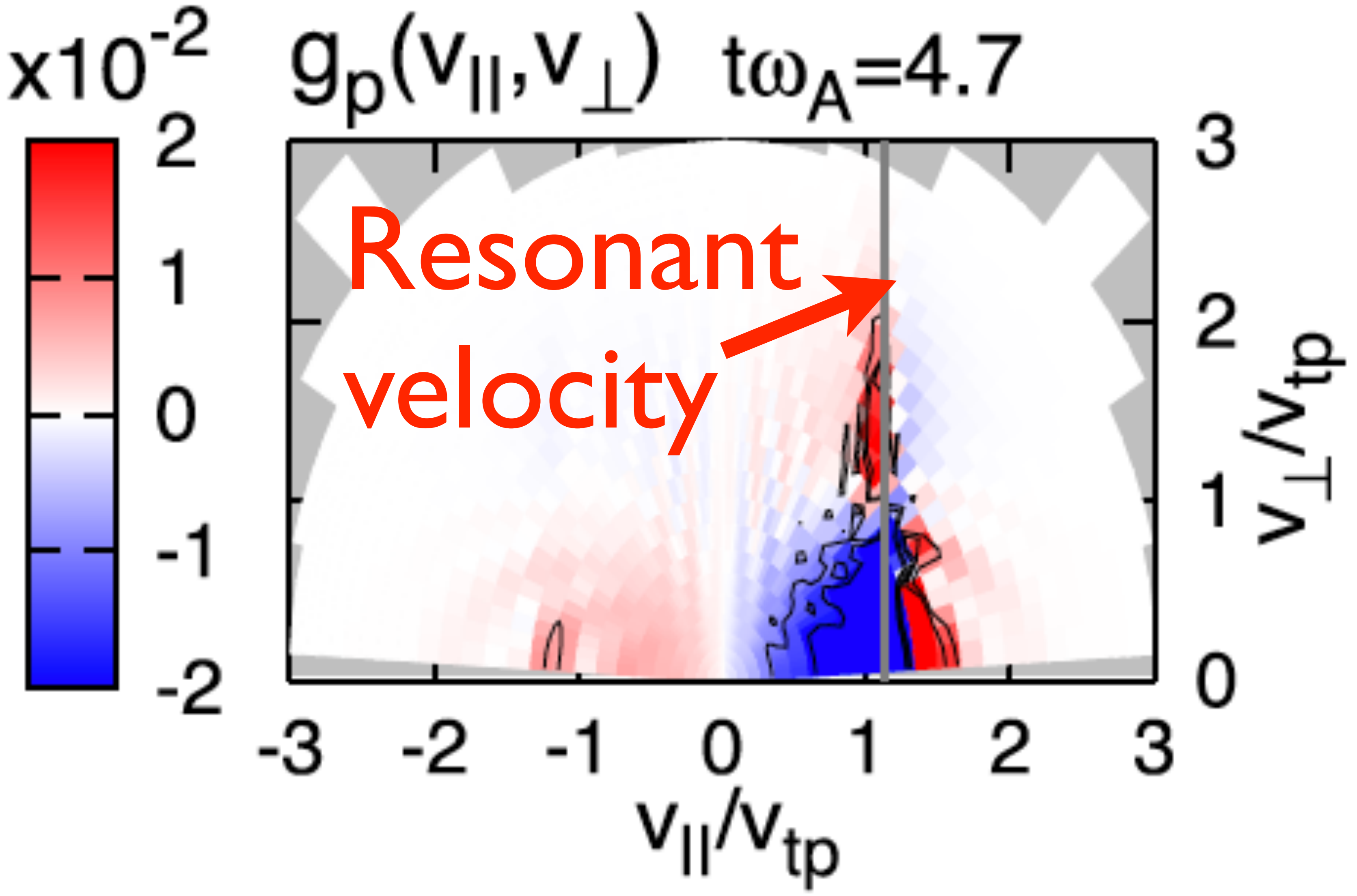

$$C_{E_\parallel} = C\left(-q_s \frac{v_\parallel^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_\parallel}, E_\parallel(\mathbf{r}_0,t)\right)$$

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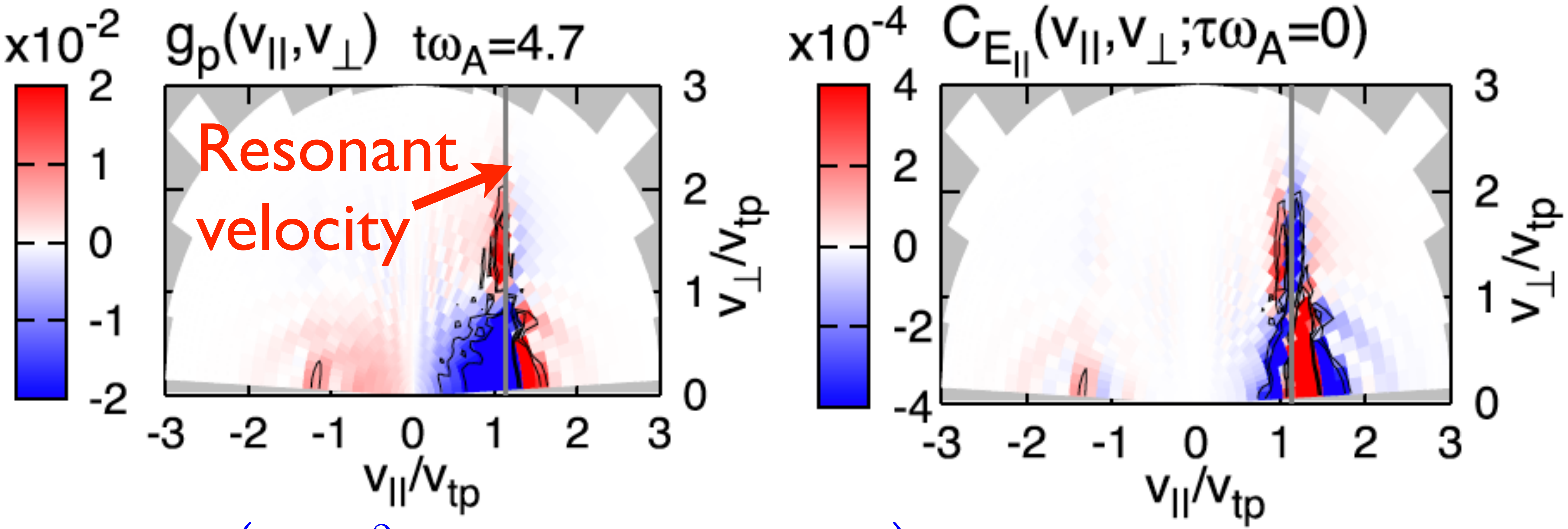

$$C_{E_\parallel} = C\left(-q_s \frac{v_\parallel^2}{2} \frac{\partial f_s(\mathbf{r}_0, \mathbf{v}, t)}{\partial v_\parallel}, E_\parallel(\mathbf{r}_0, t)\right)$$

Example of Field-Particle Correlations

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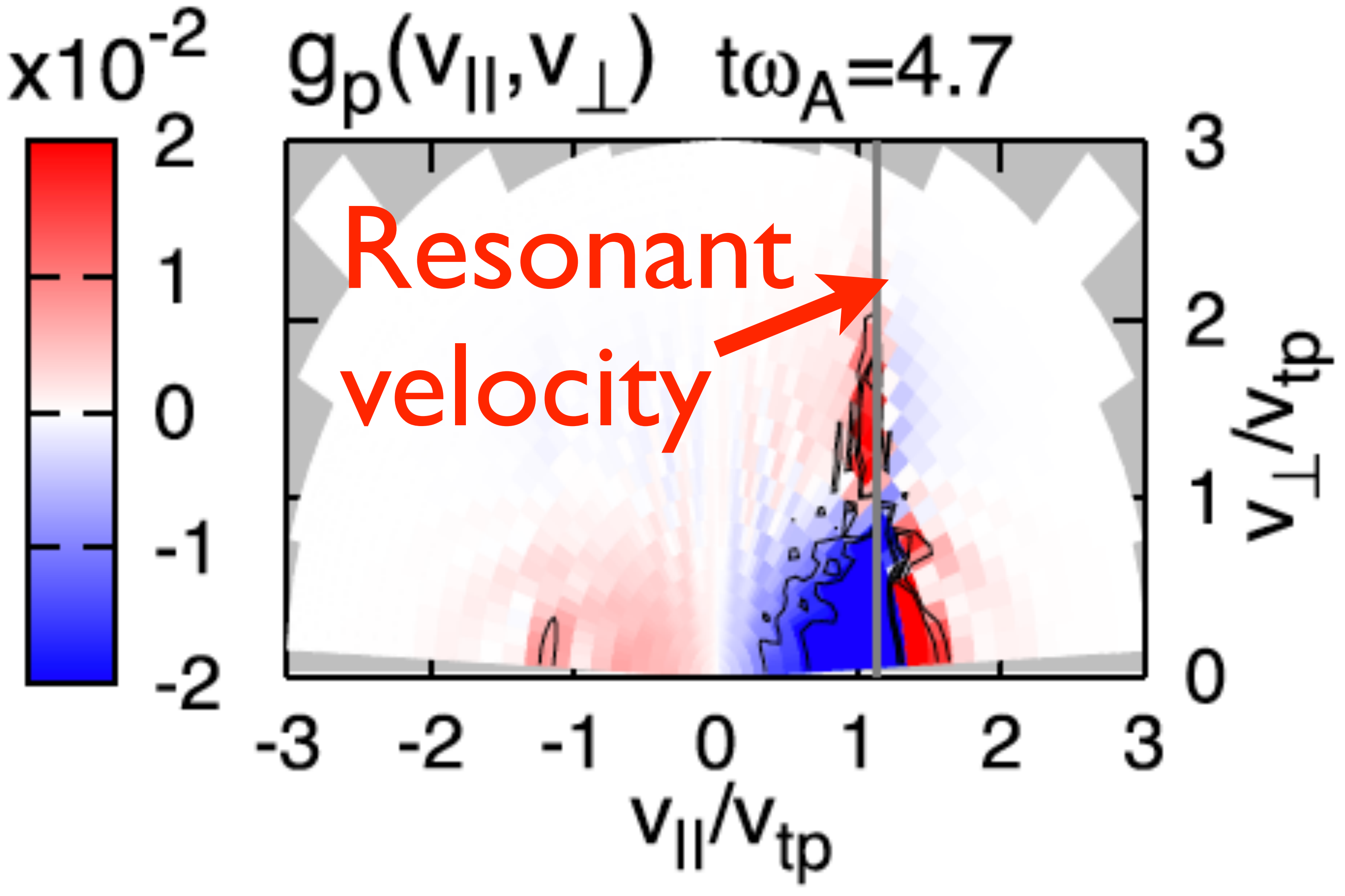

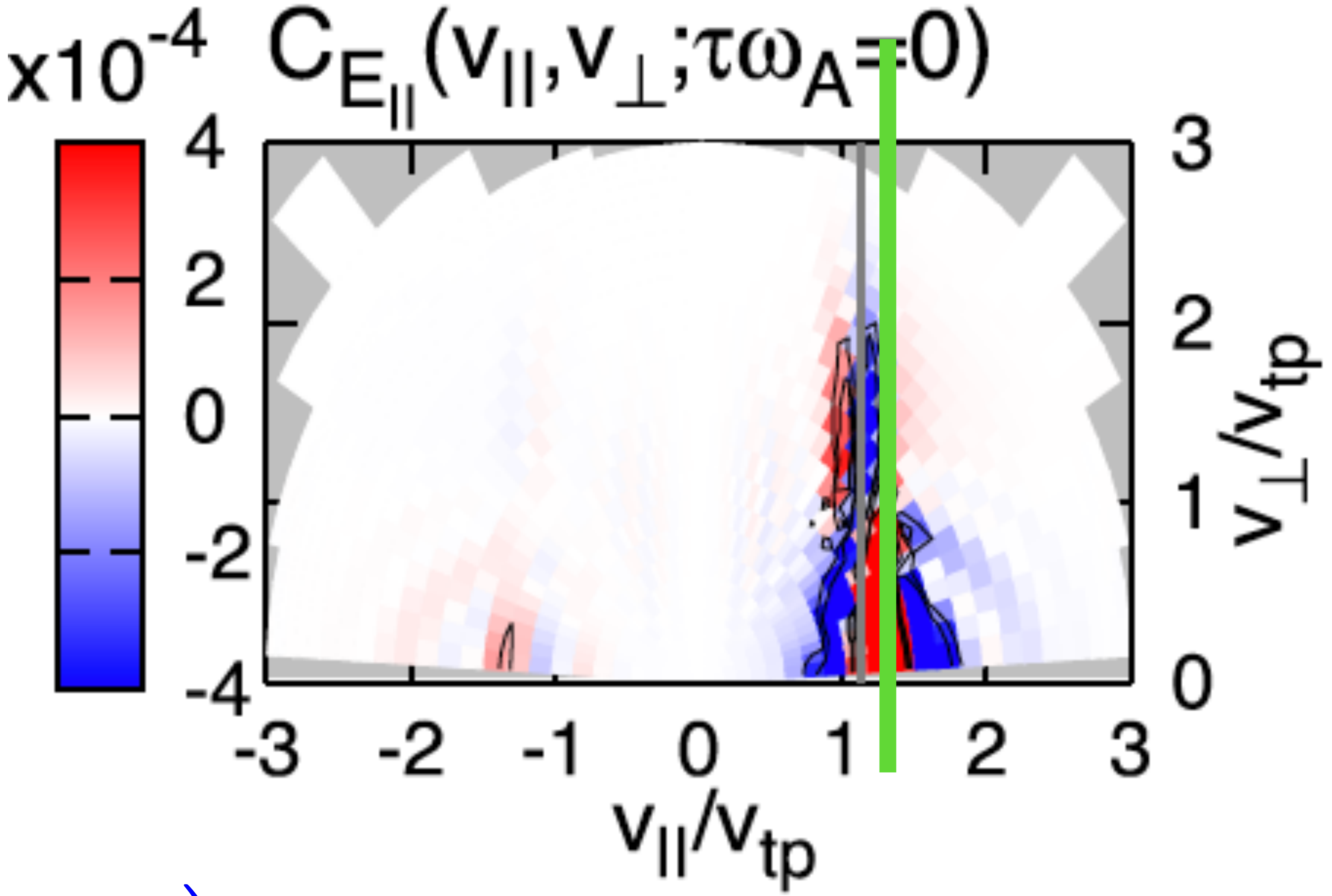

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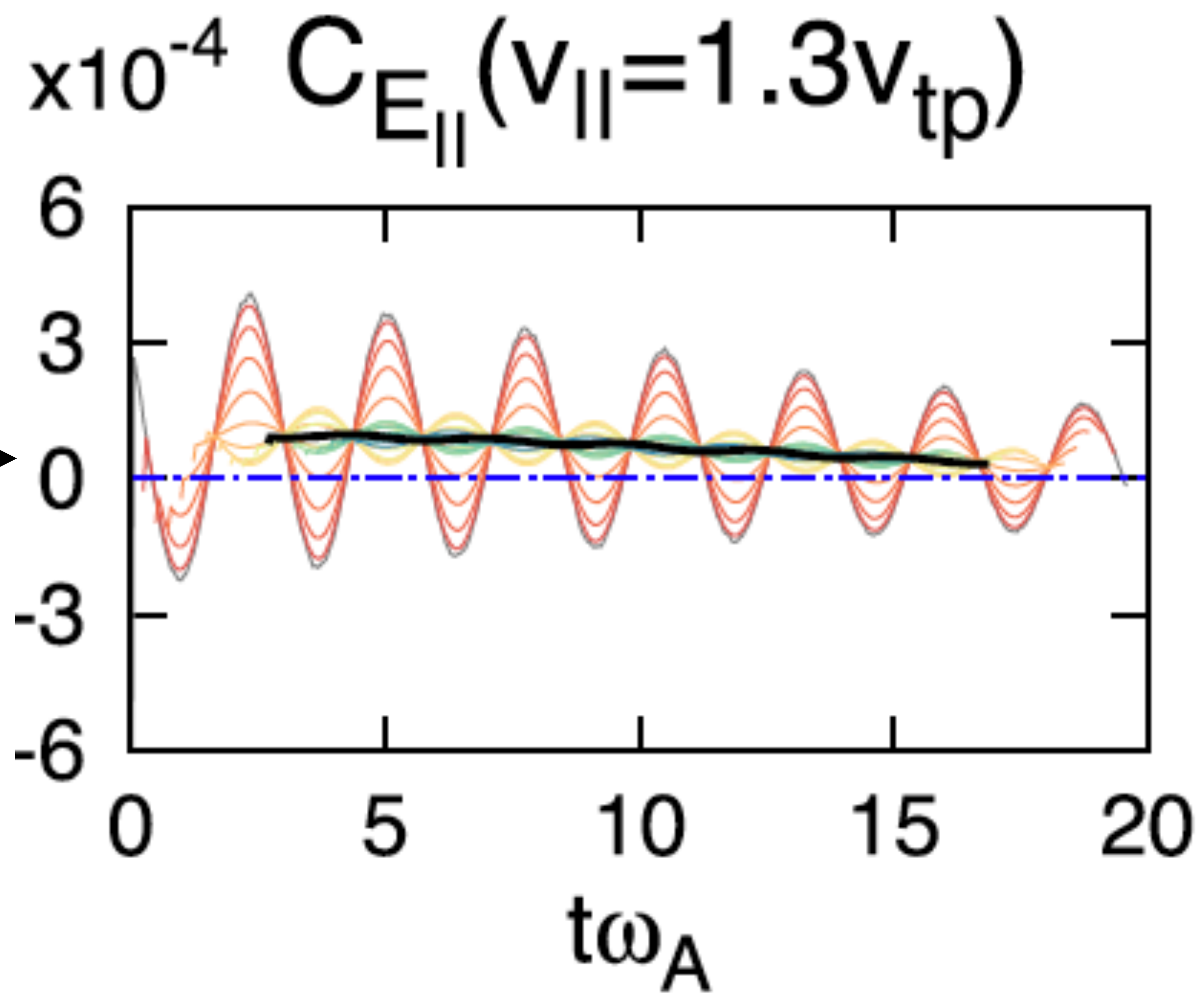
But much of the energy transfer is oscillatory



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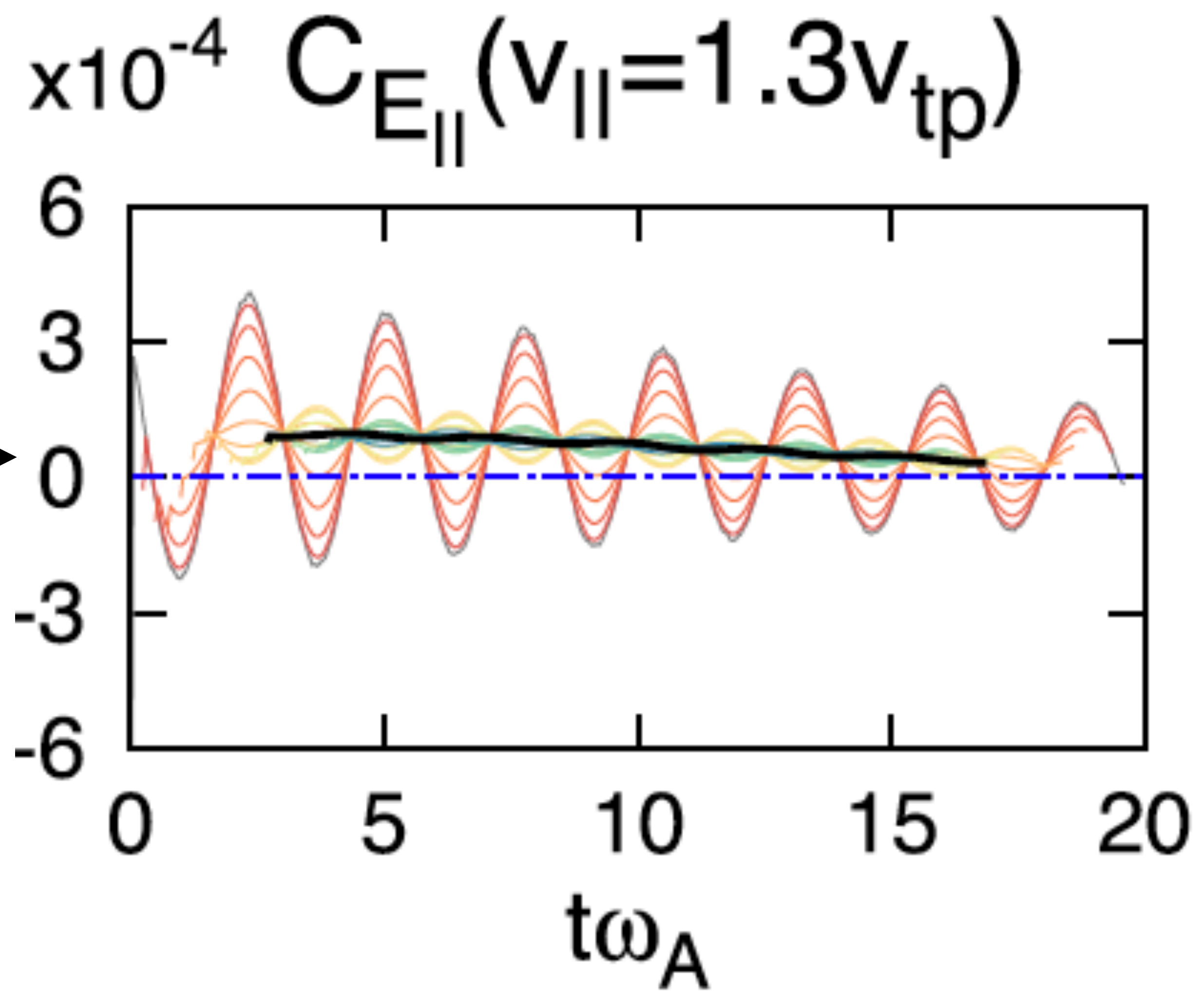

Example of Field-Particle Correlations

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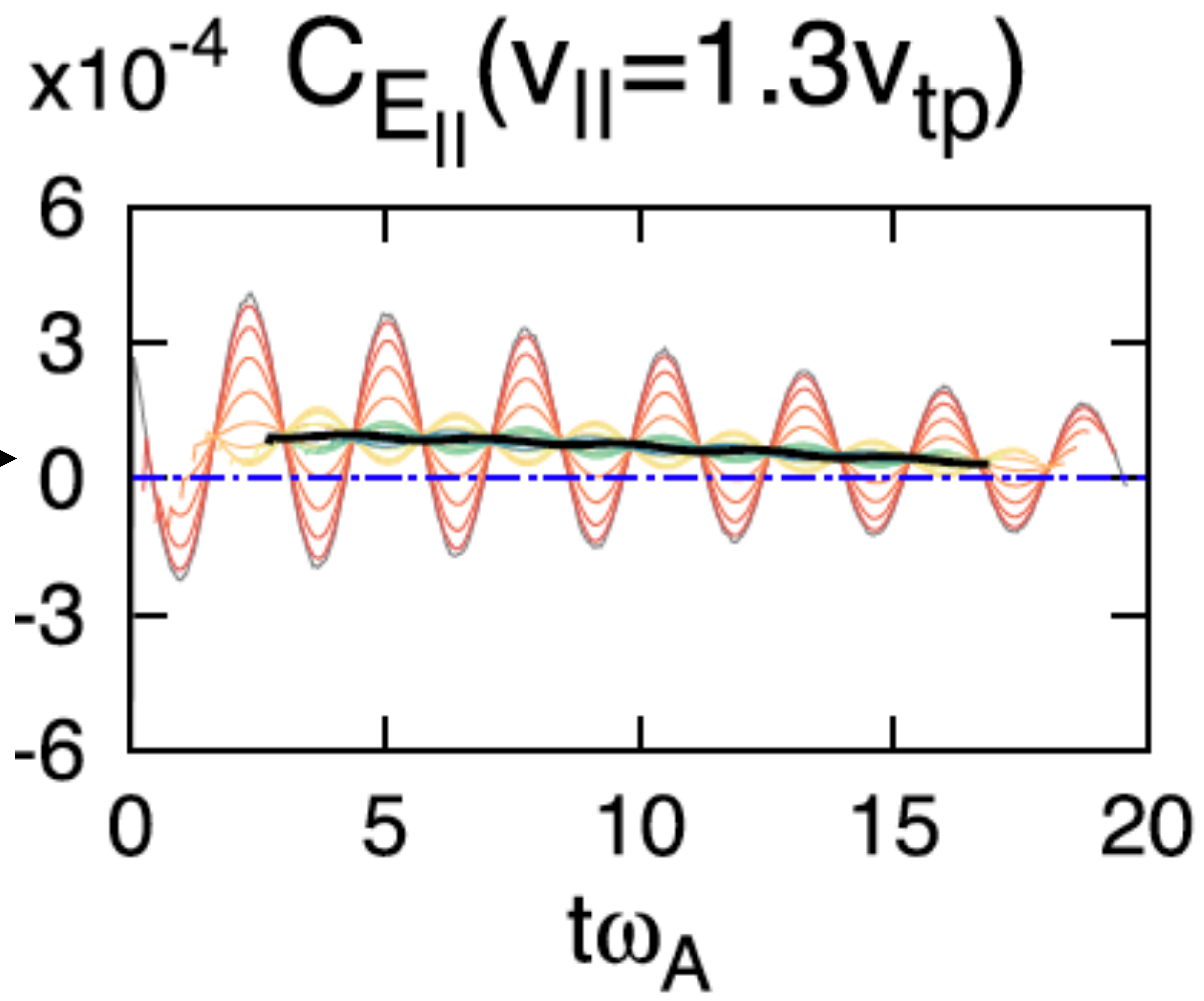

With a sufficiently long correlation interval, net effect yields the velocity-space signature of Landau damping

Velocity-Space Signature

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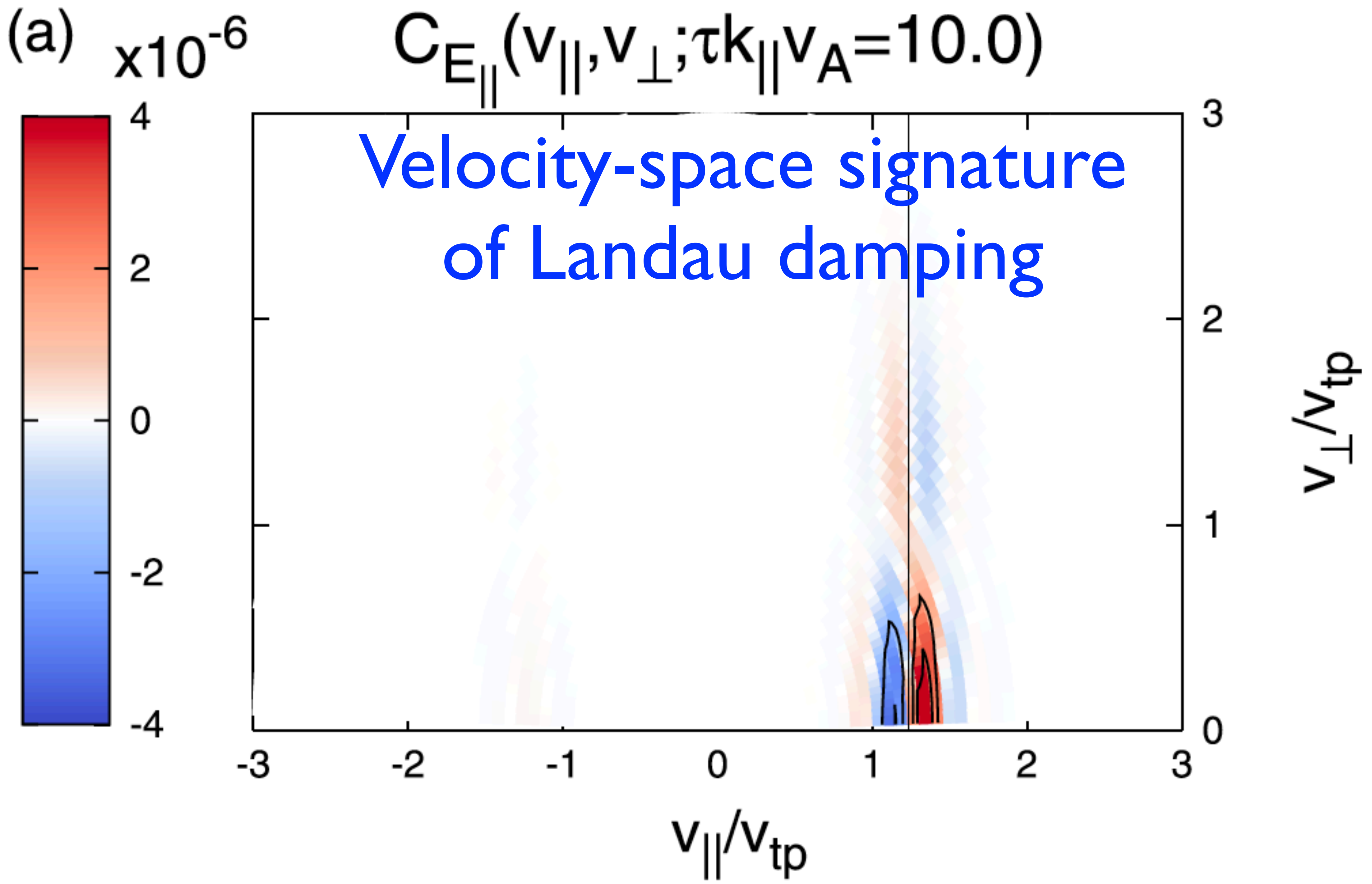

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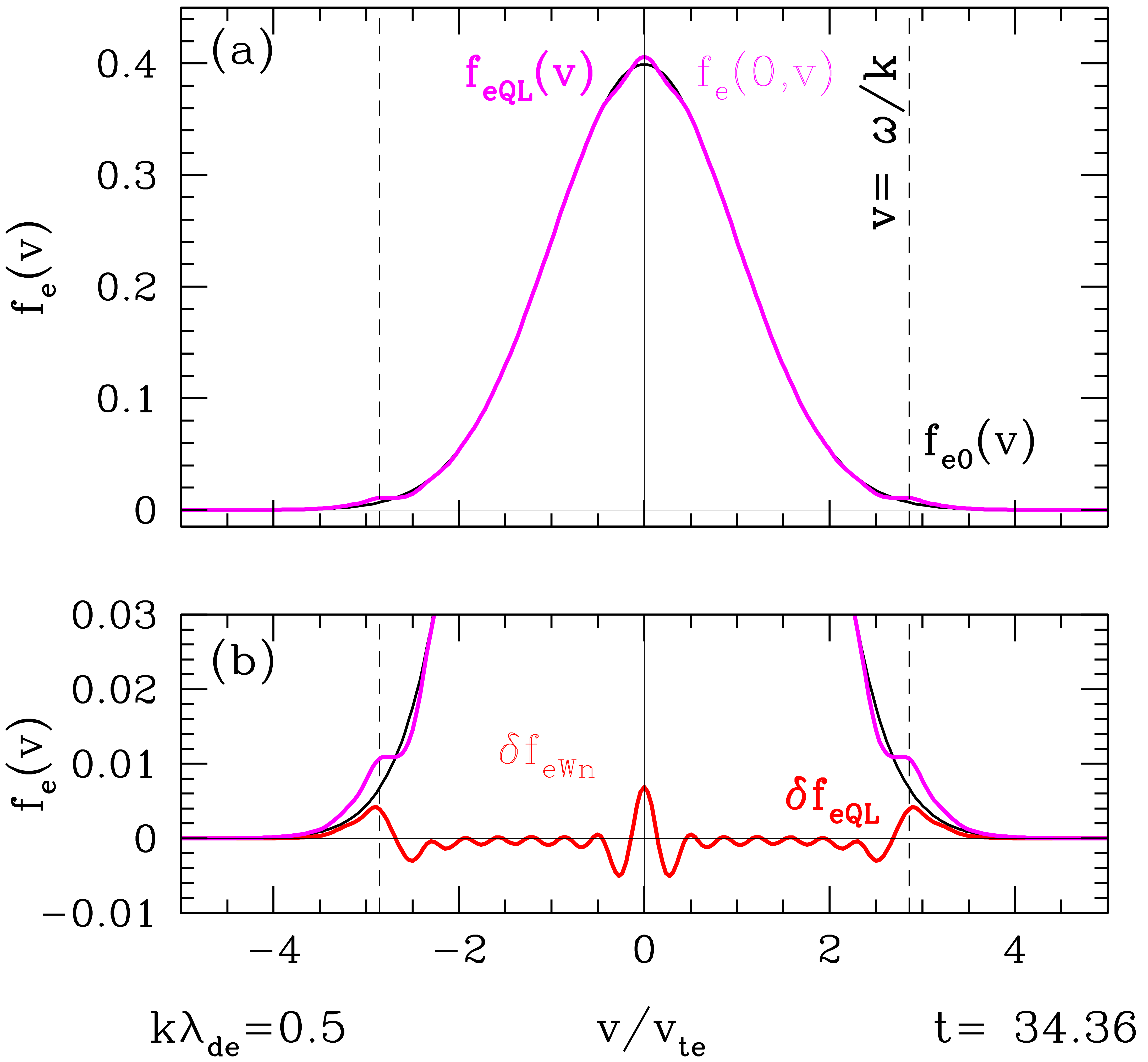

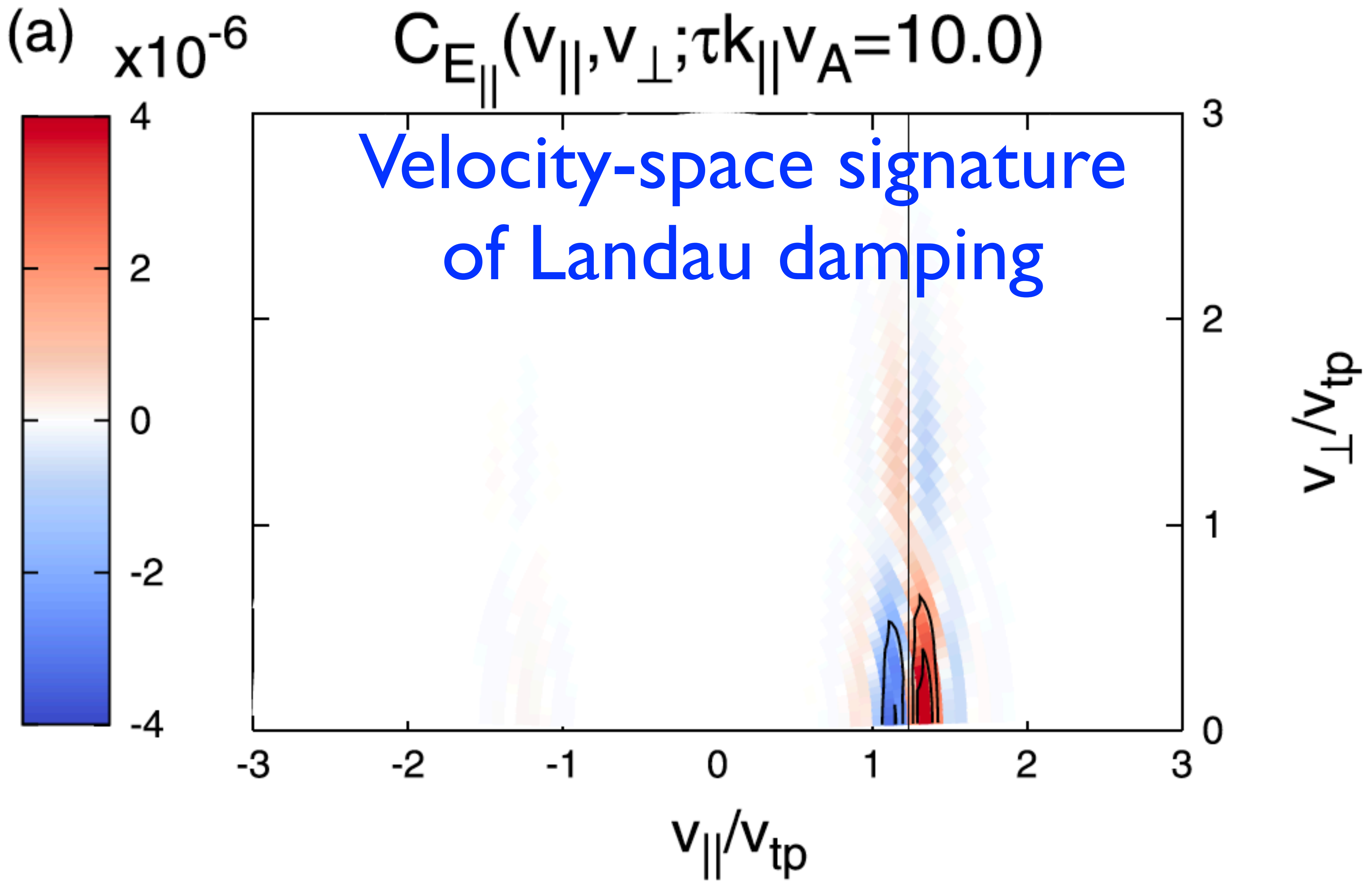

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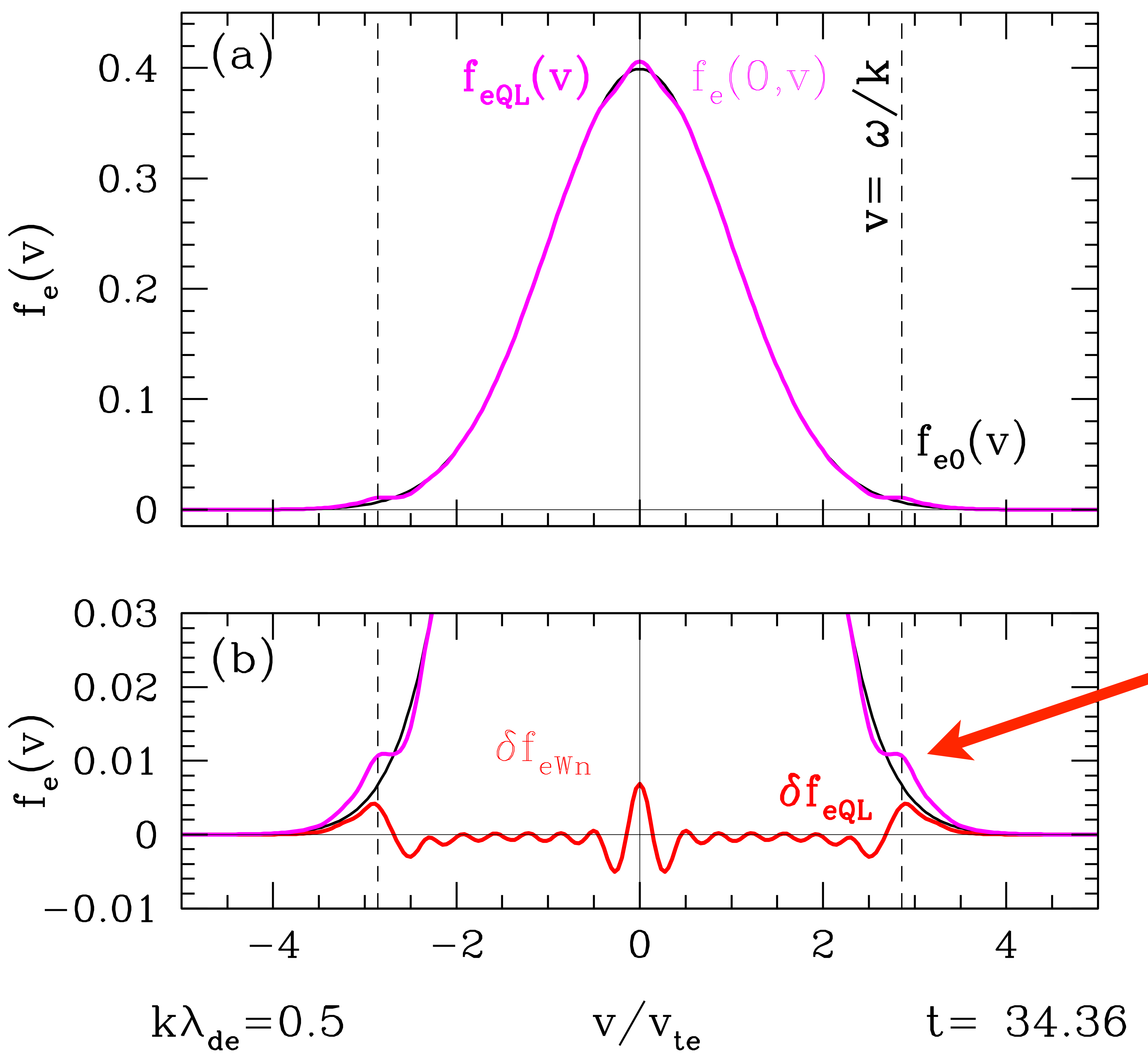

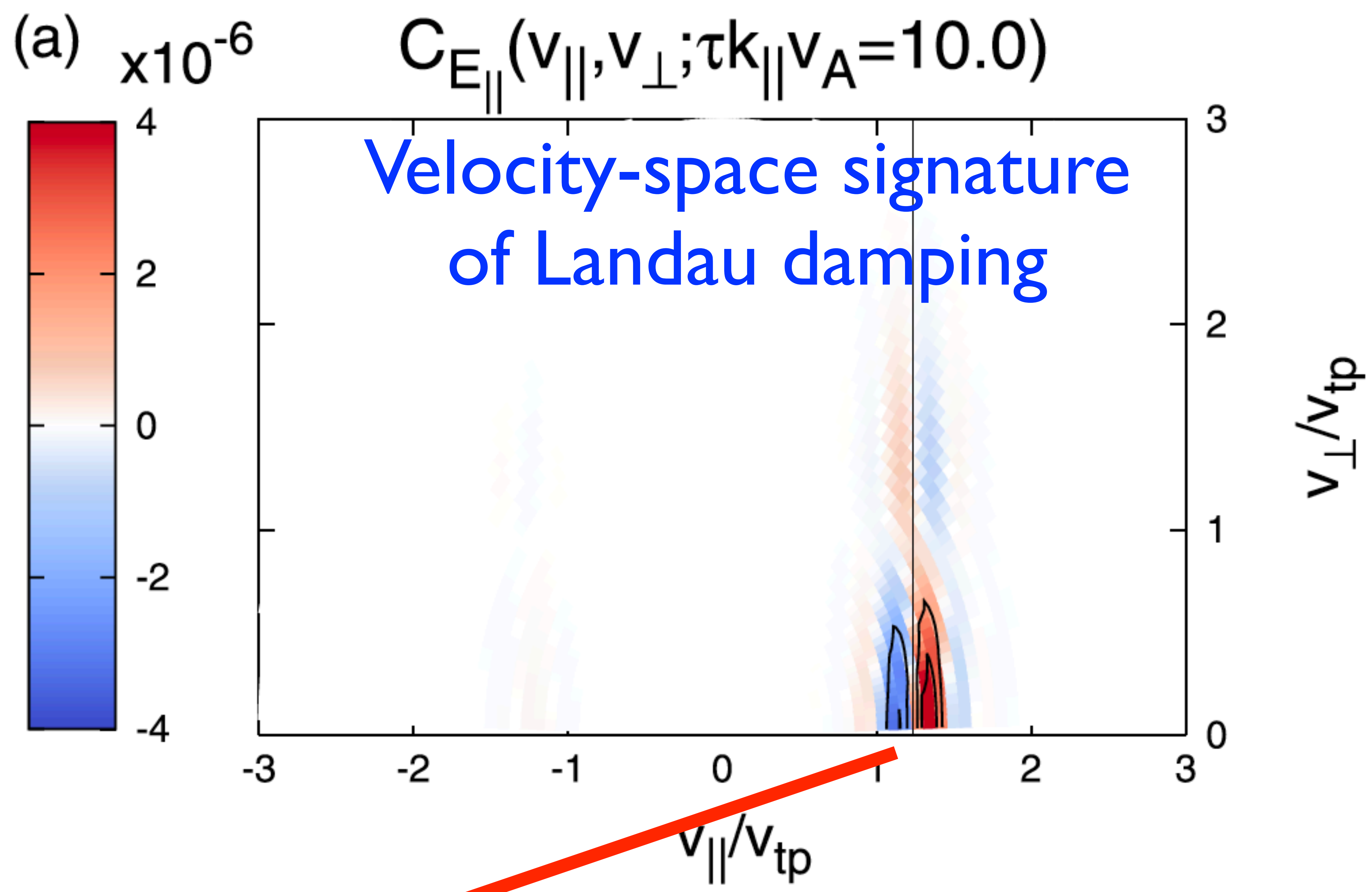

Bipolar signature corresponds to quasilinear flattening . . .

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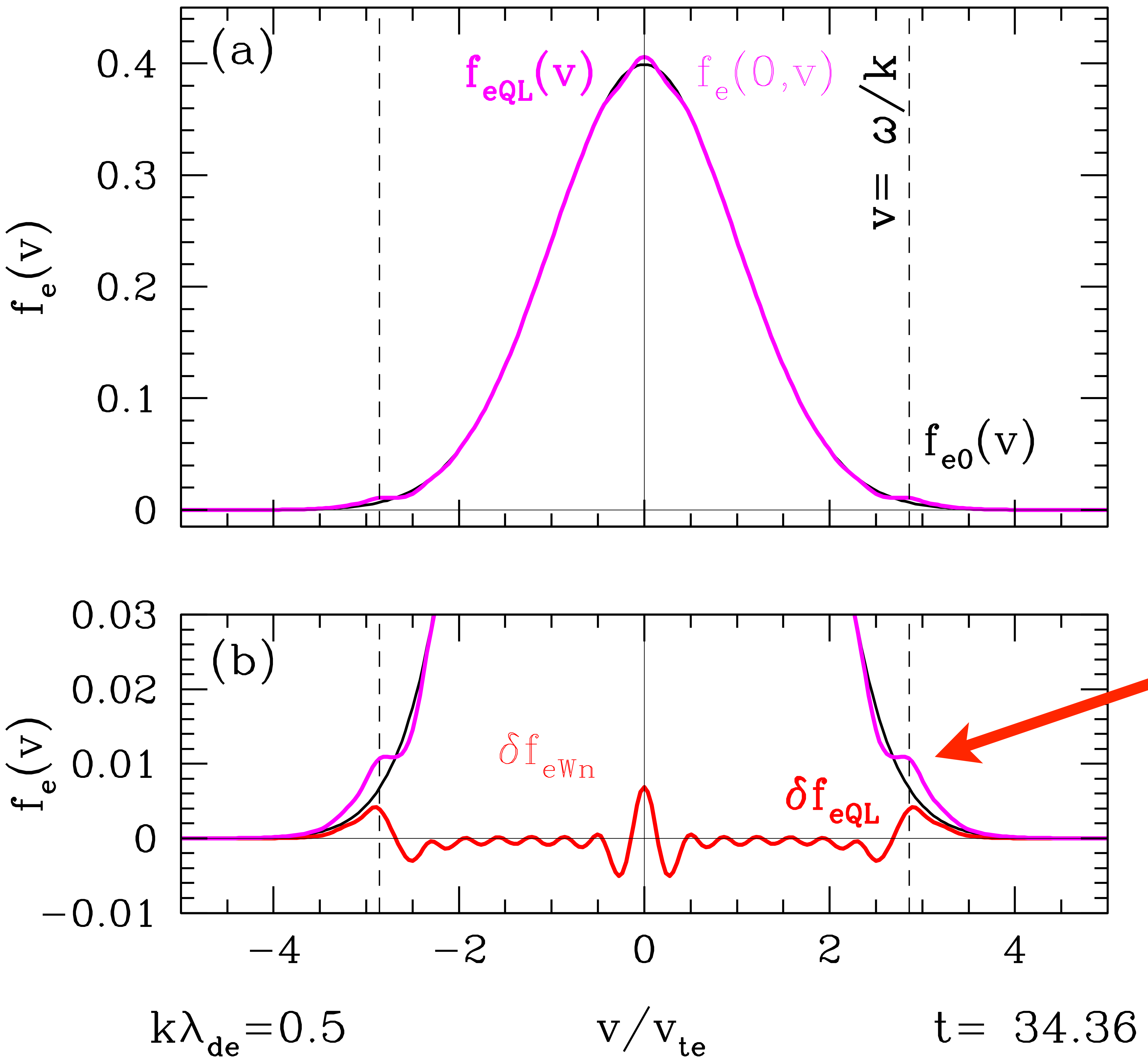

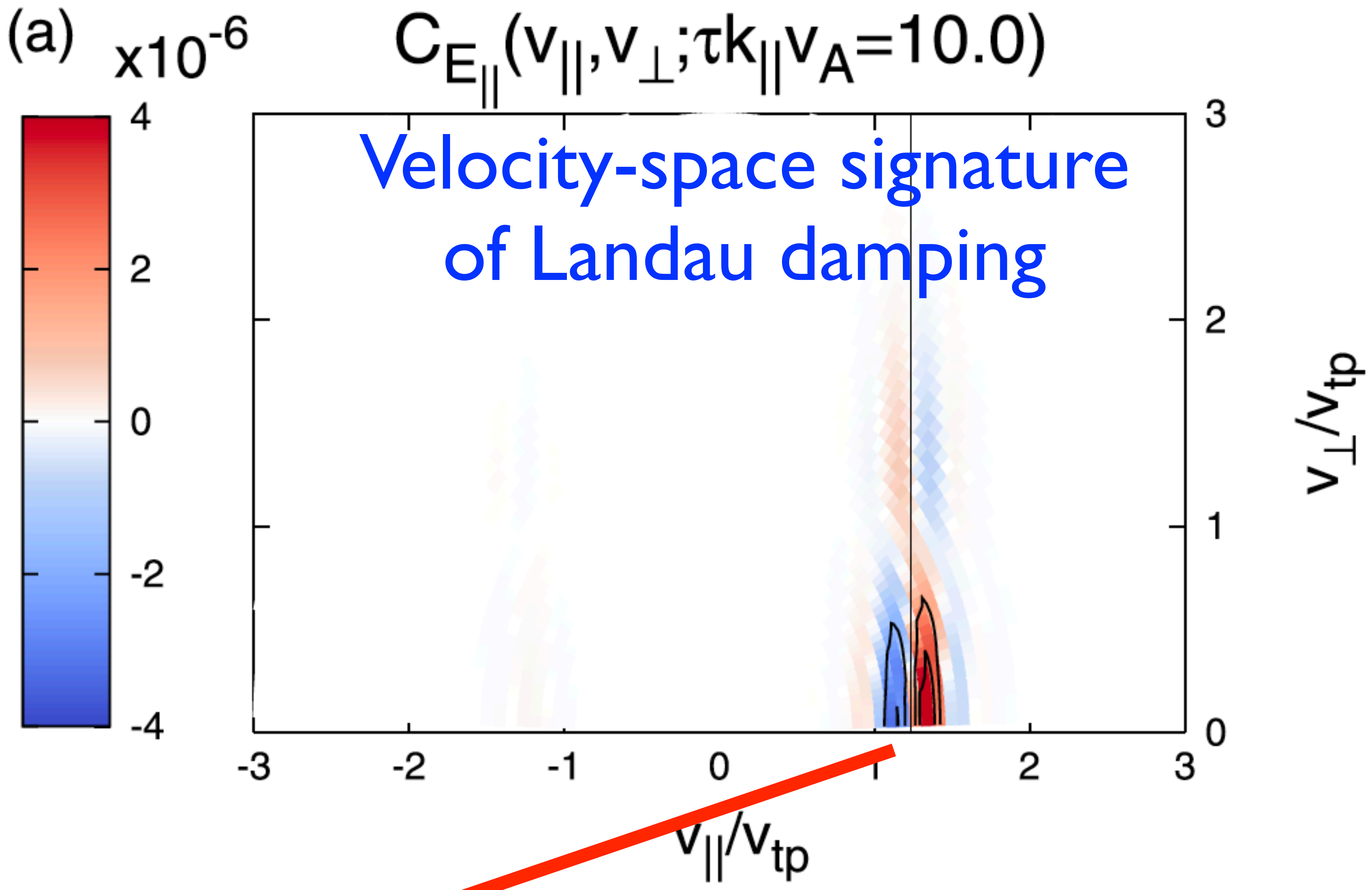

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. . . but from single-point measurements!

Strong Plasma Turbulence

Driven nonlinear gyrokinetic simulation of solar wind turbulence

(Klein, Howes, & Tenbarge, 2017)

Plasma parameters: $\beta_i = 1$

$T_i/T_e = 1$

Strong Plasma Turbulence

The University of Iowa

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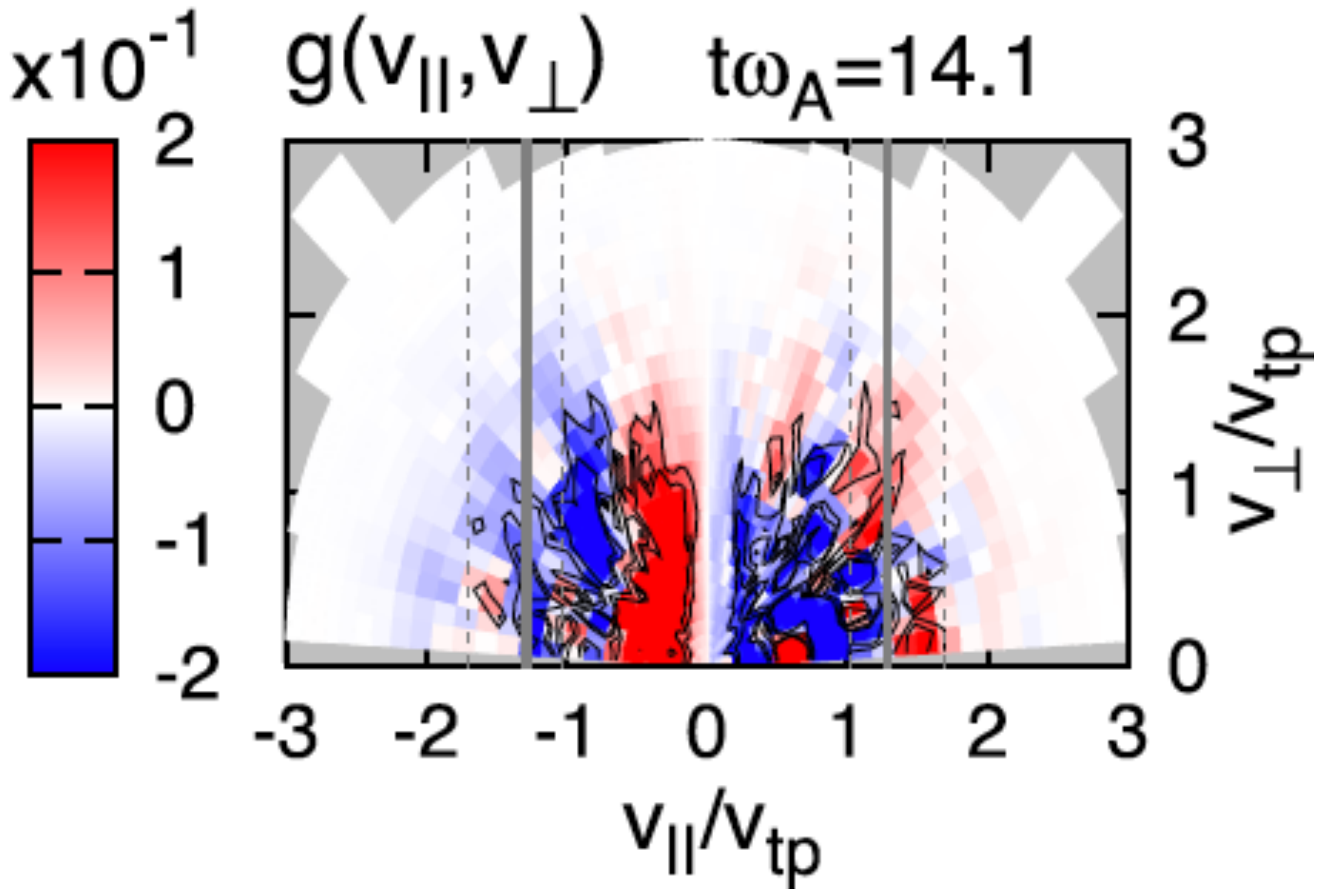

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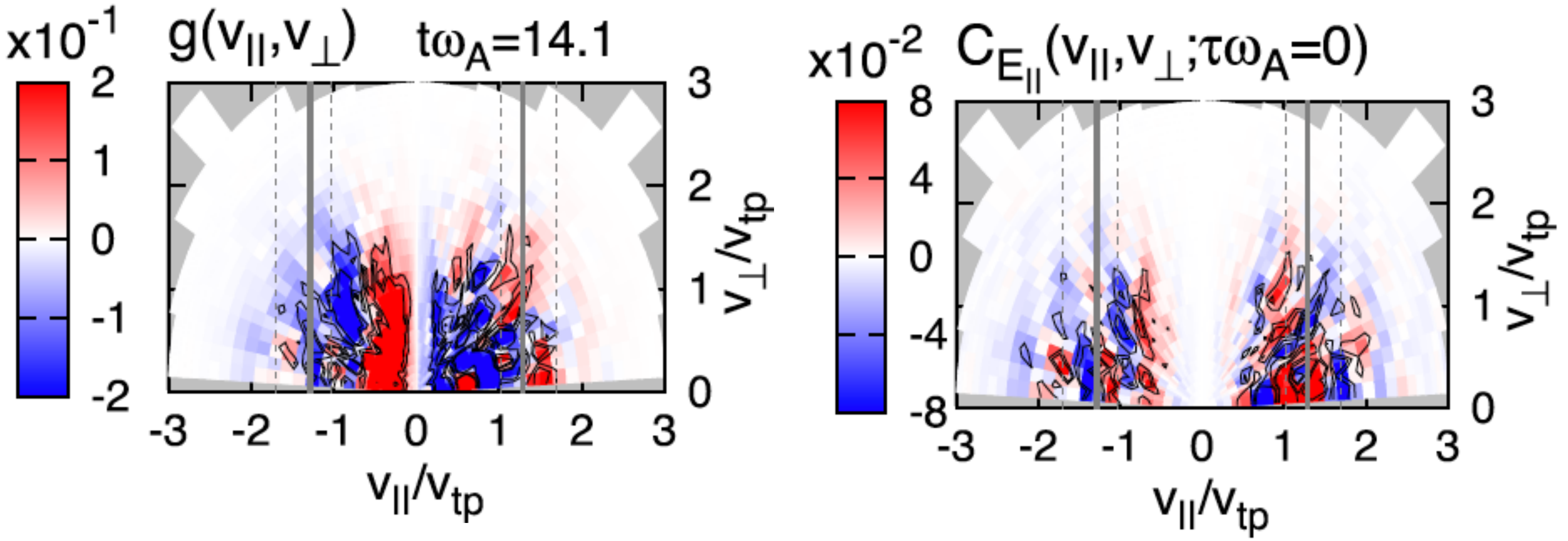

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Evidence of Landau Damping in strong plasma turbulence

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Proposed Dissipation Mechanisms in Turbulence

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Weakly Collisional Kinetic Turbulence

Proposed Dissipation Mechanisms in Turbulence

The University of Iowa

Weakly Collisional Kinetic 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

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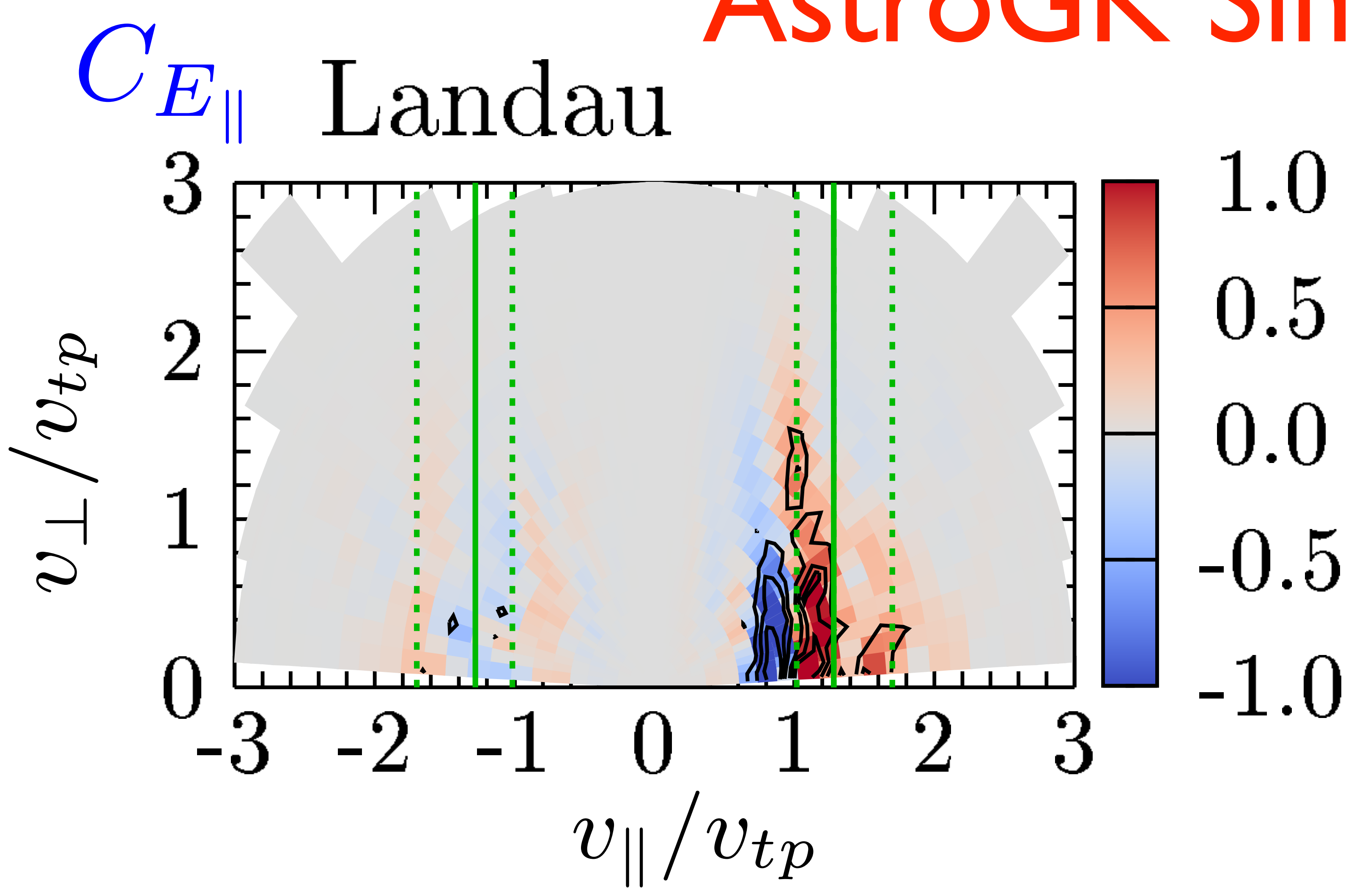

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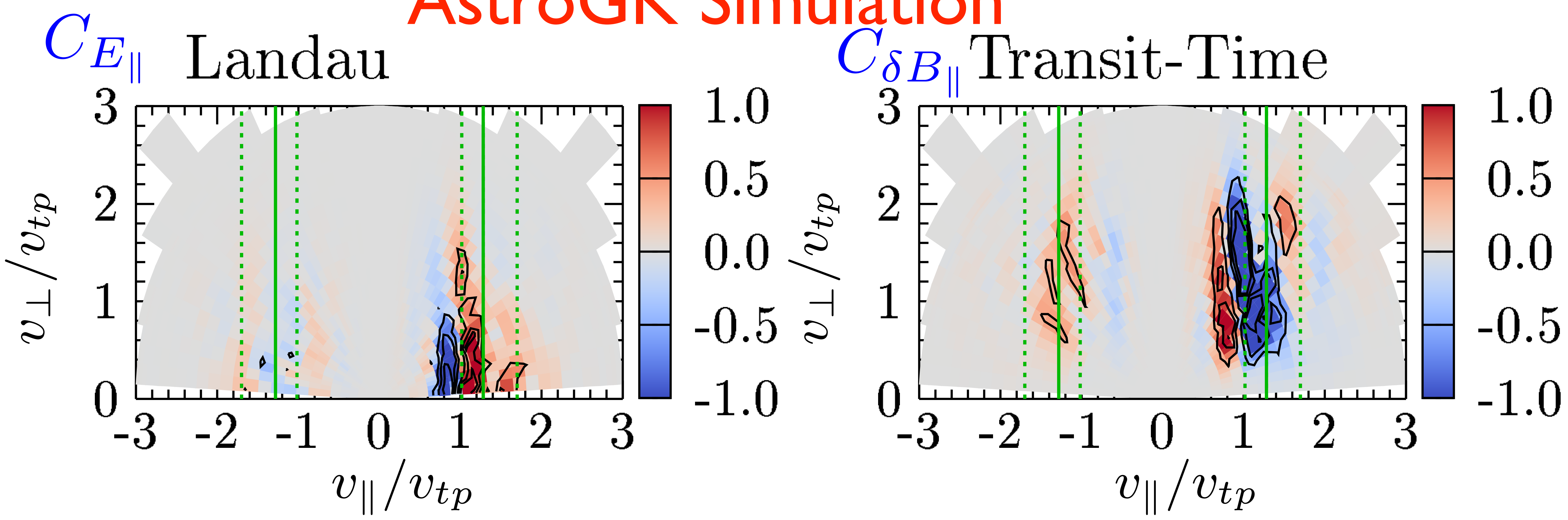

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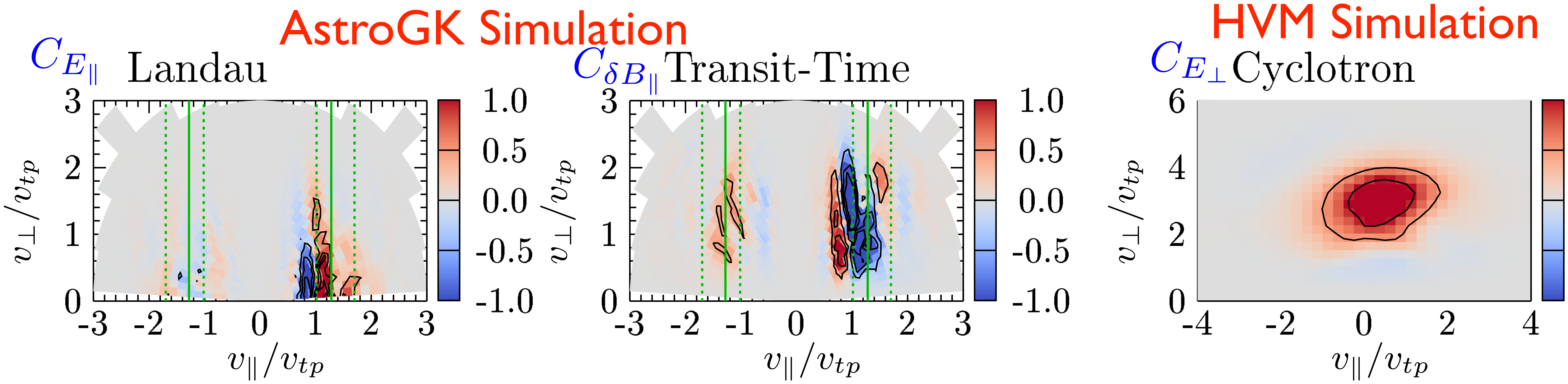

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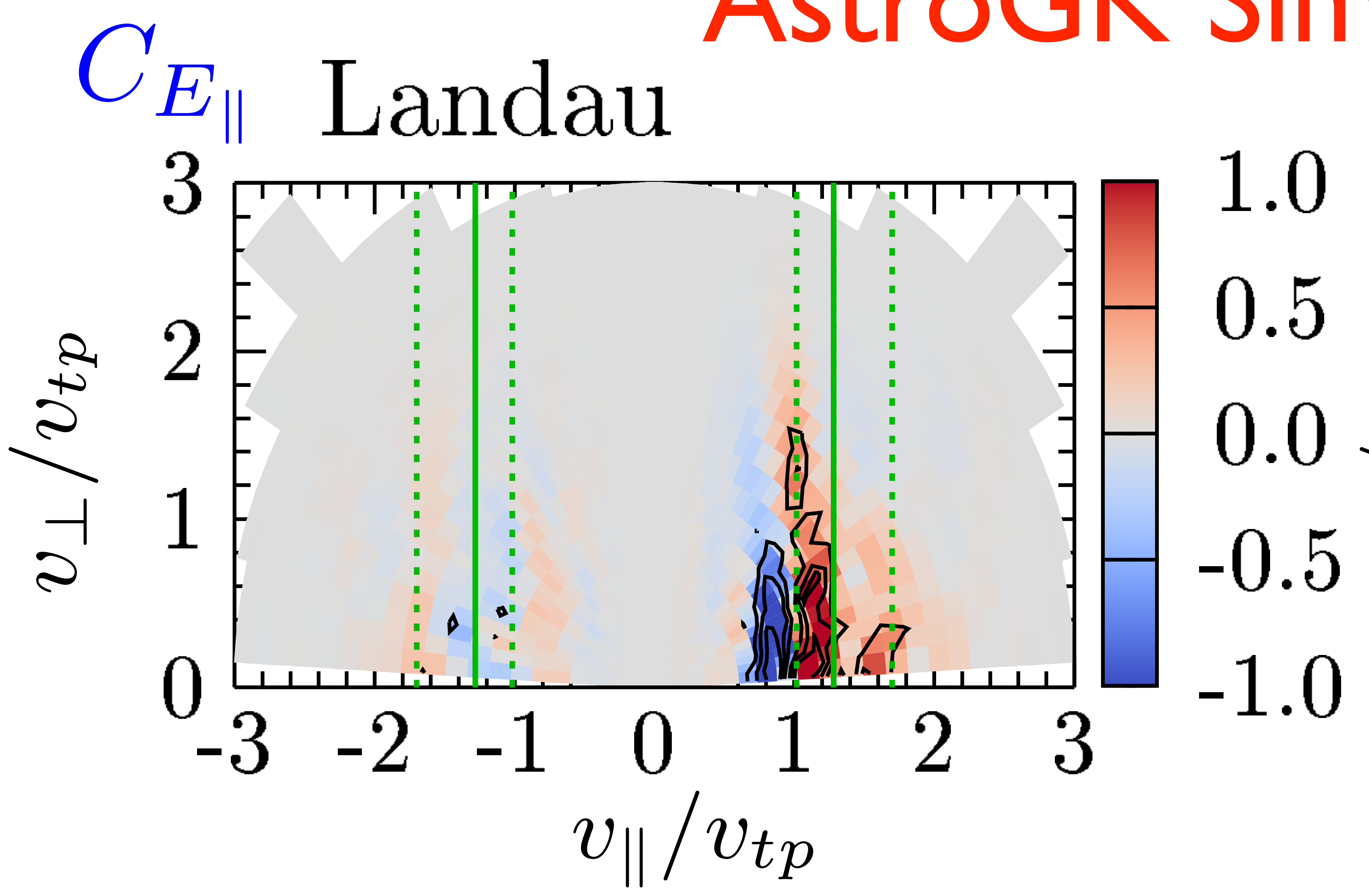
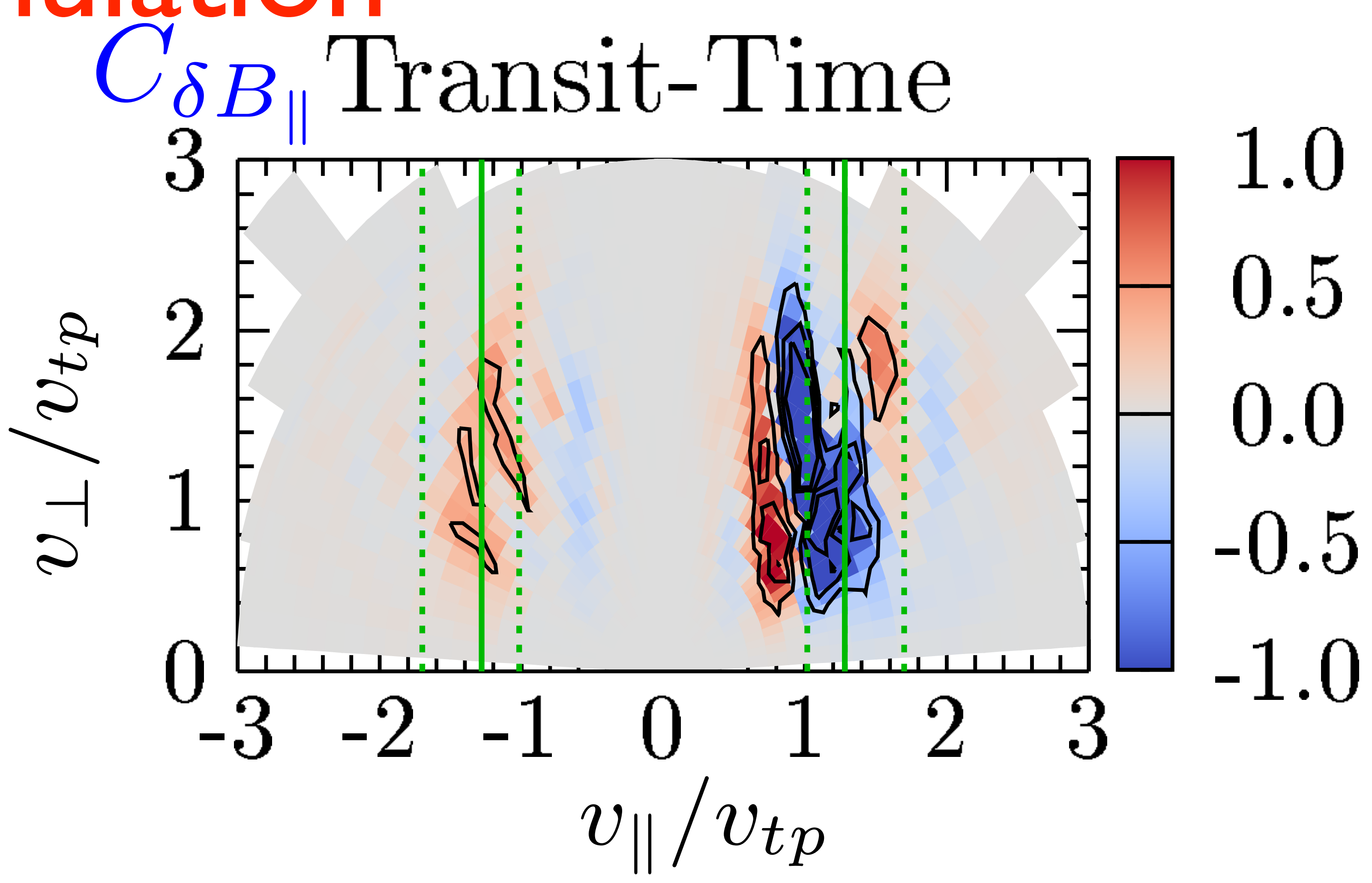
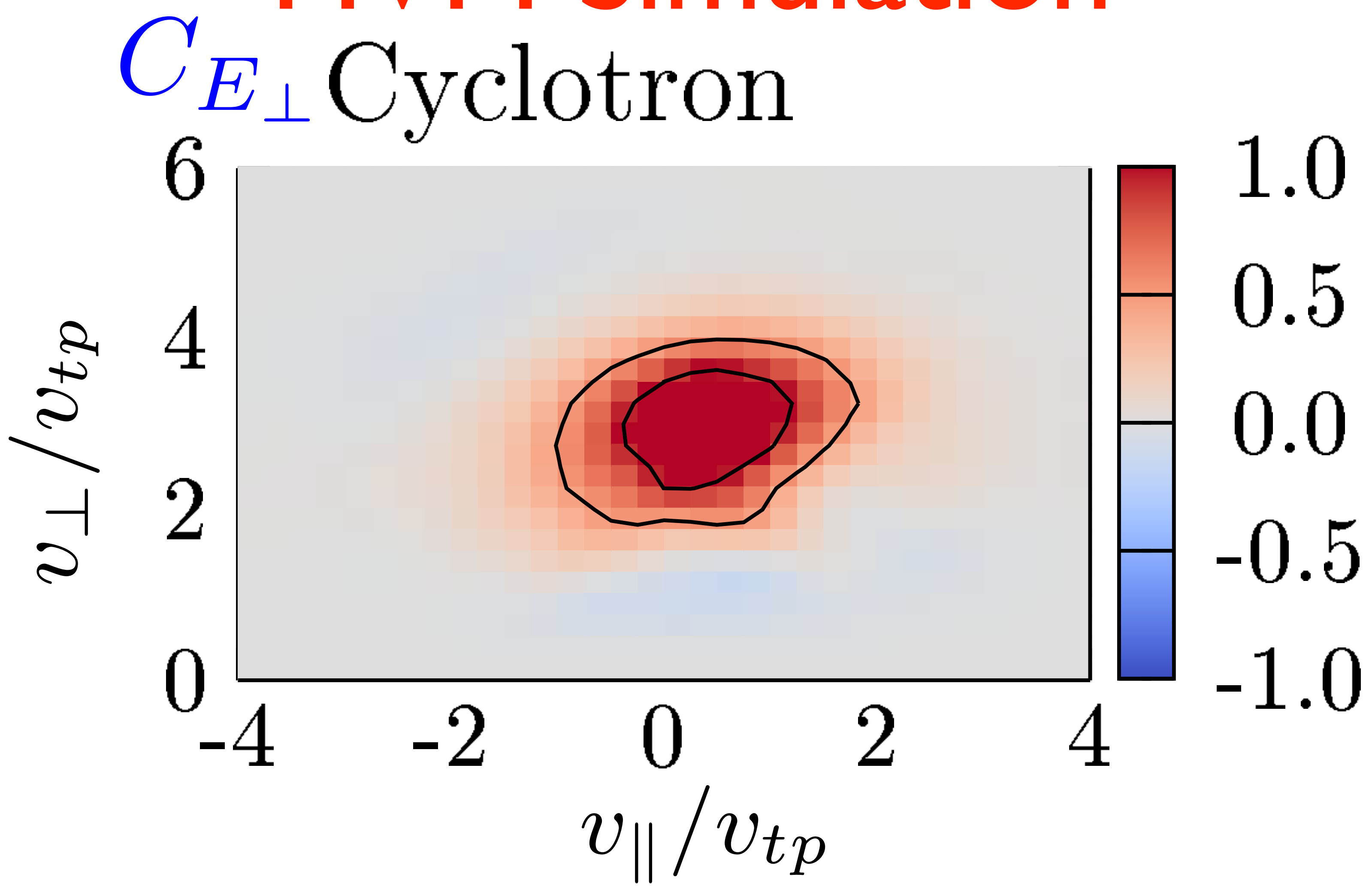


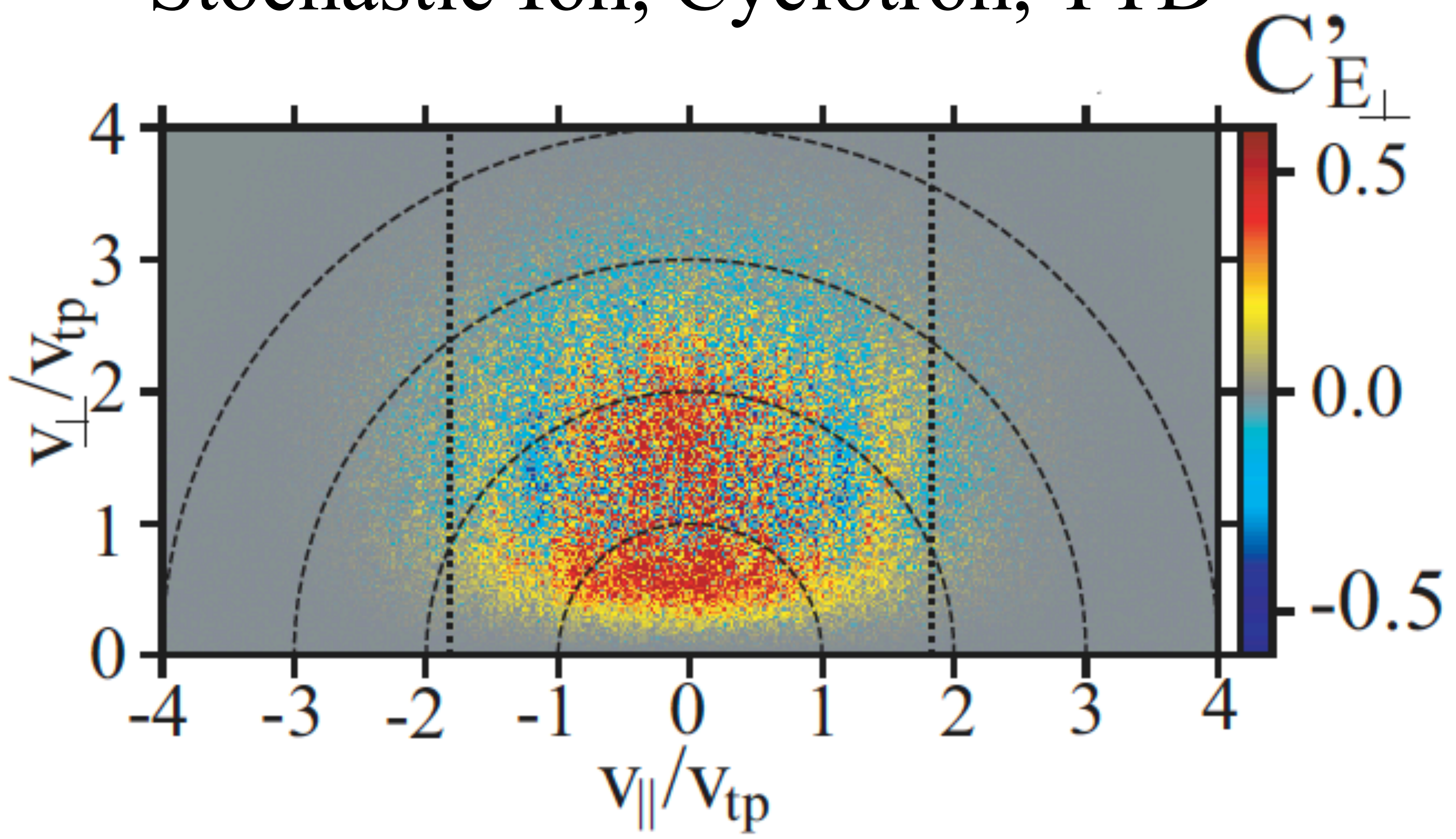


HVM Simulation



Pegasus Simulation

Stochastic Ion, Cyclotron, TTD



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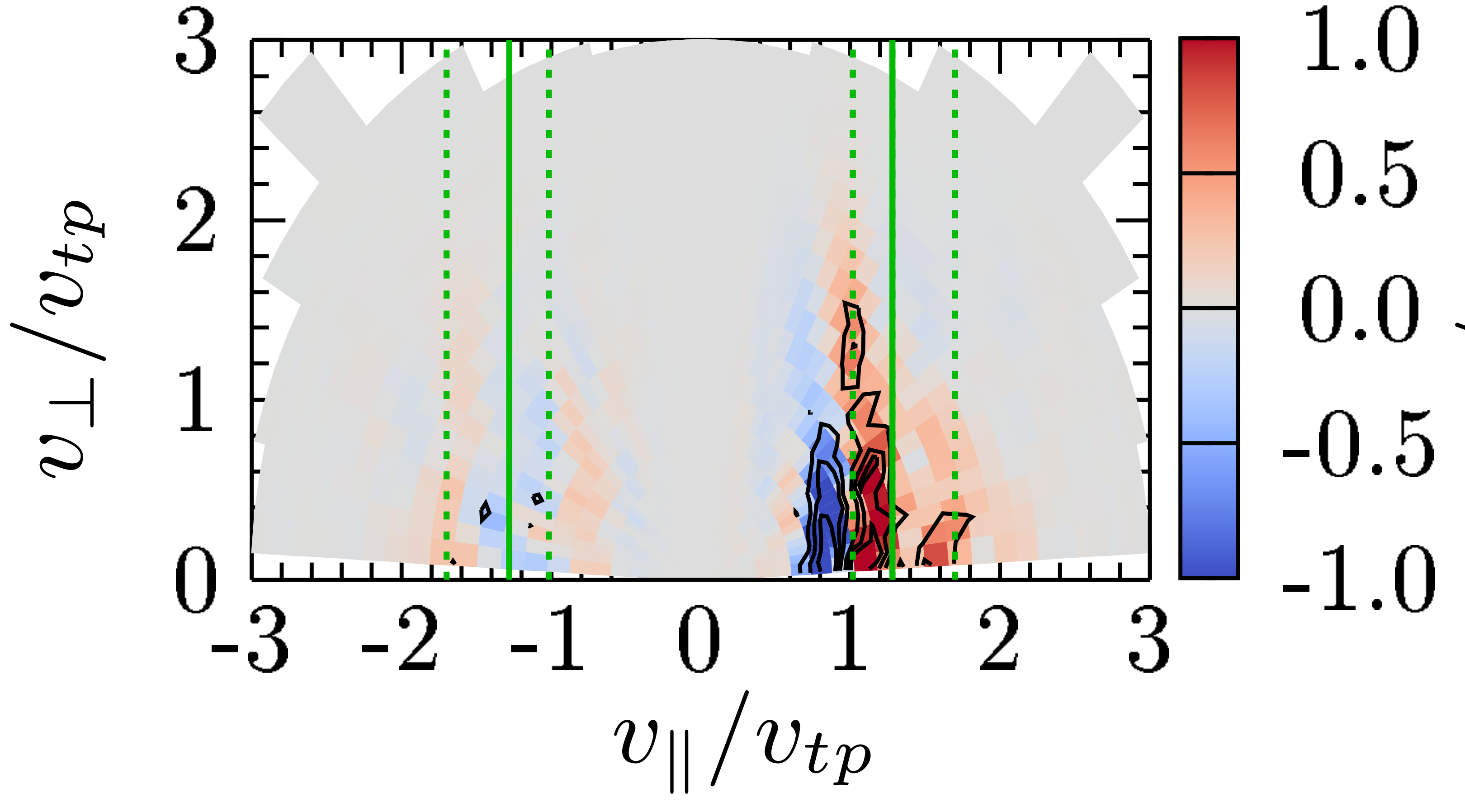
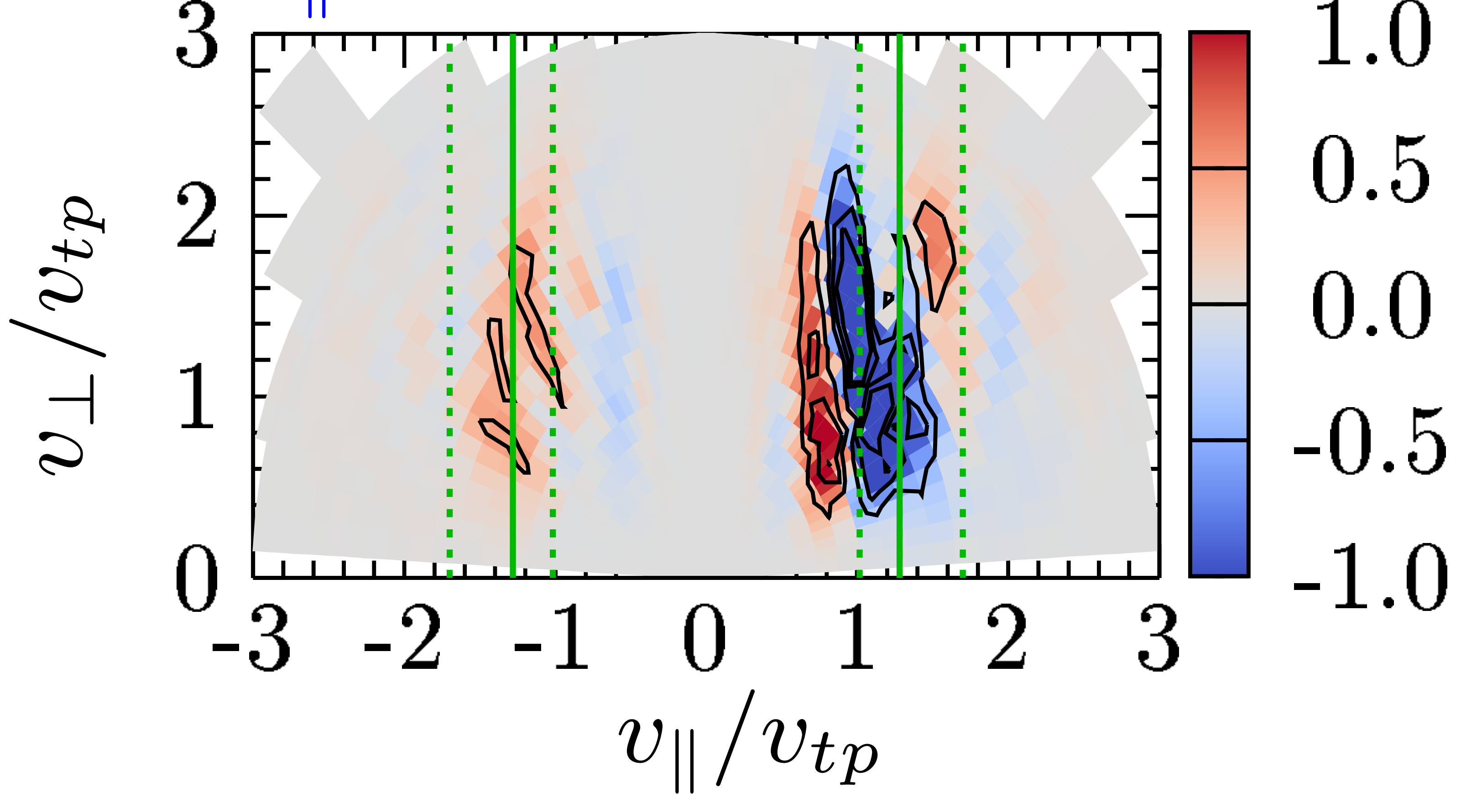
$C_{E_\parallel}$ Landau

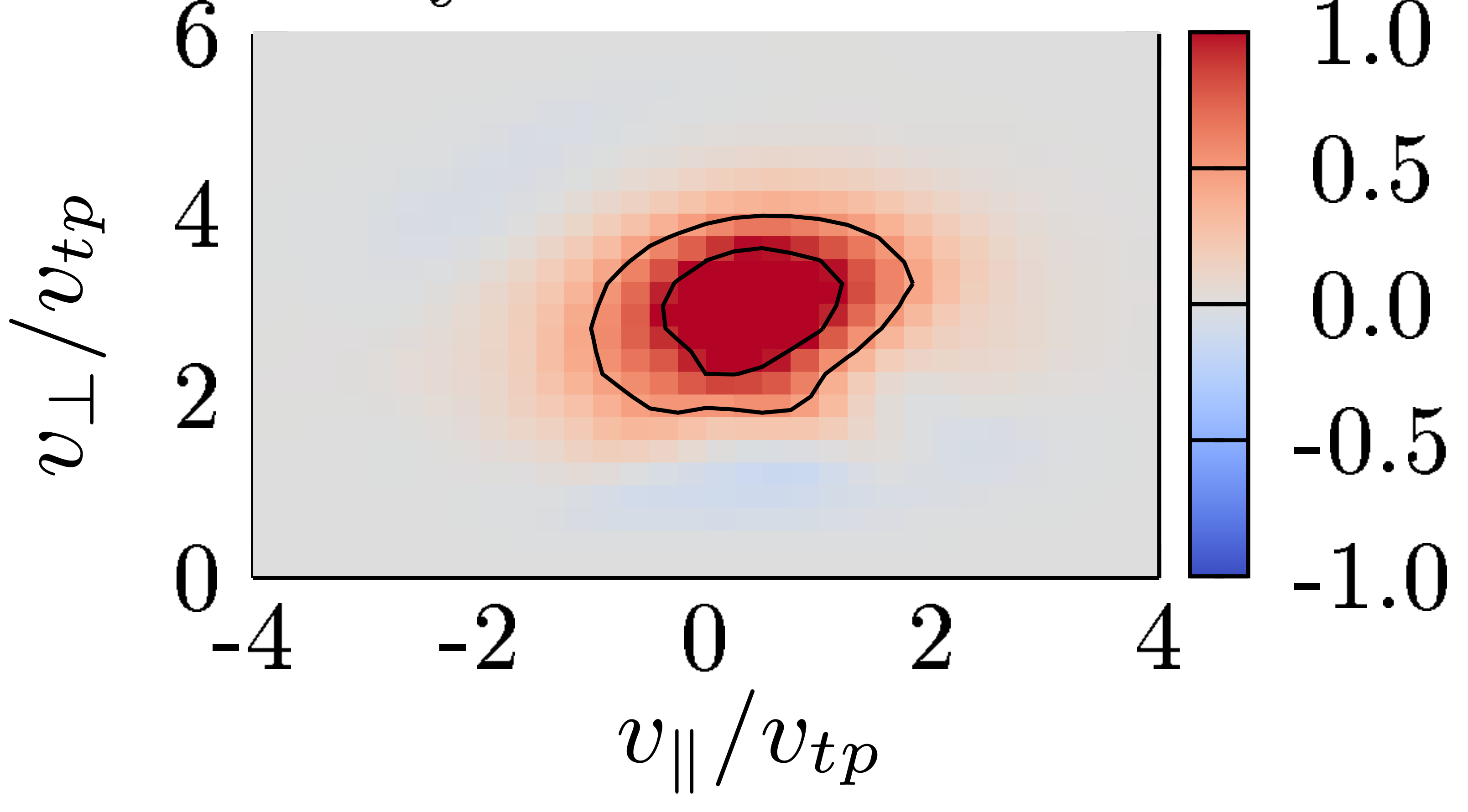


$C_{\delta B_\parallel}$ Transit-Time



HVM Simulation

$C_{E_\perp}$ Cyclotron



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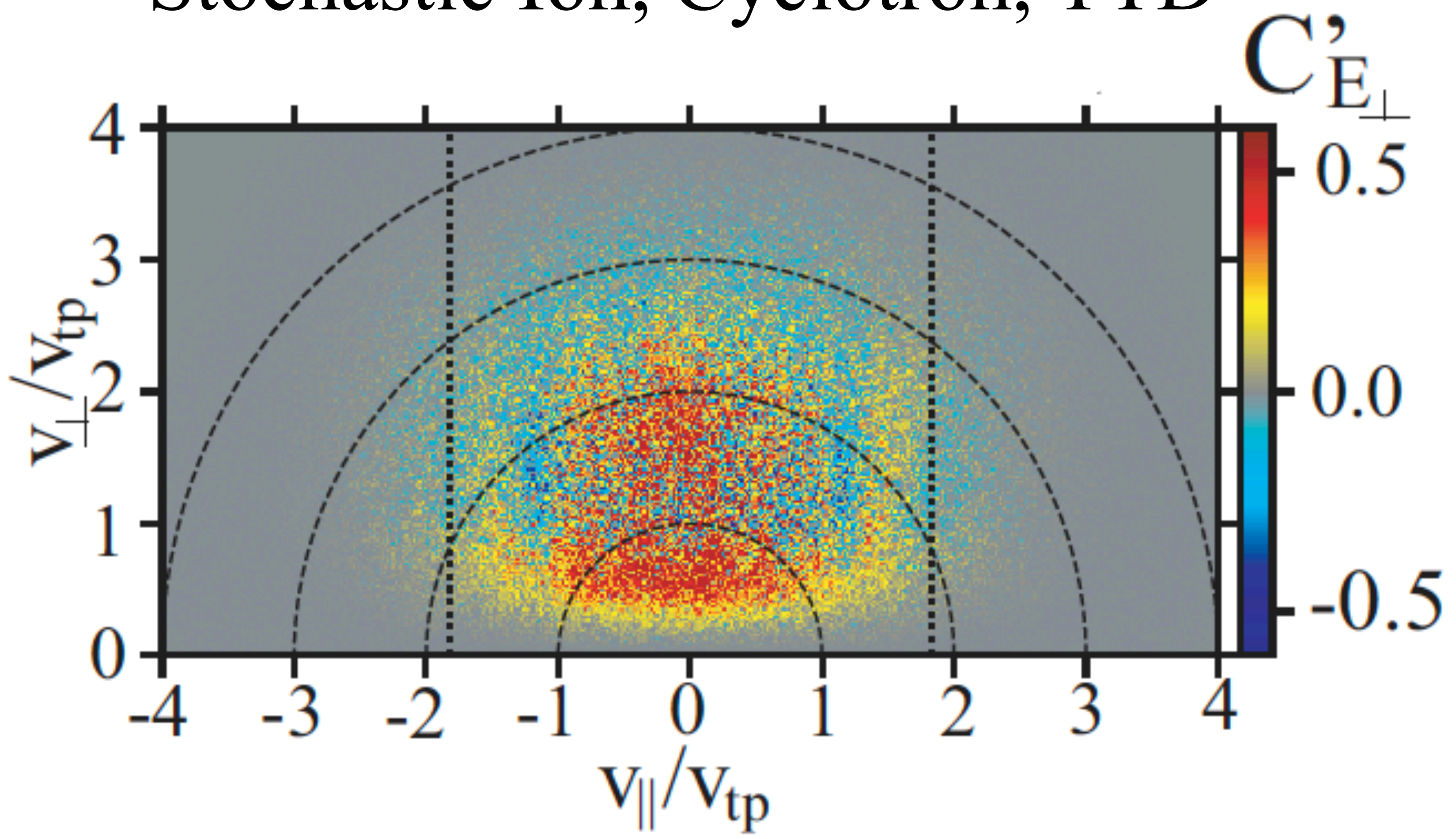
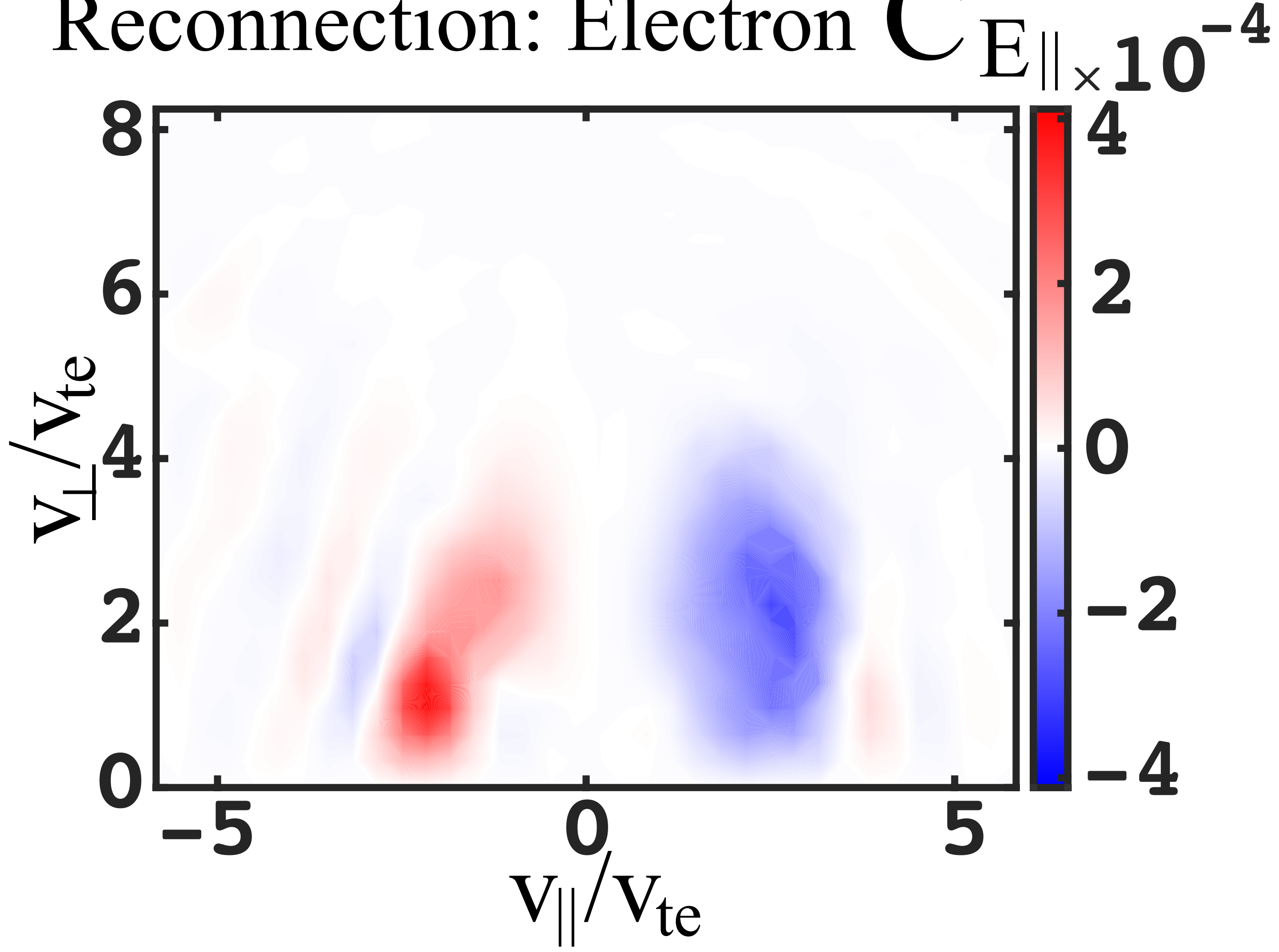


Gkeyll Simulation

Reconnection: Electron $C_{E_\parallel}$



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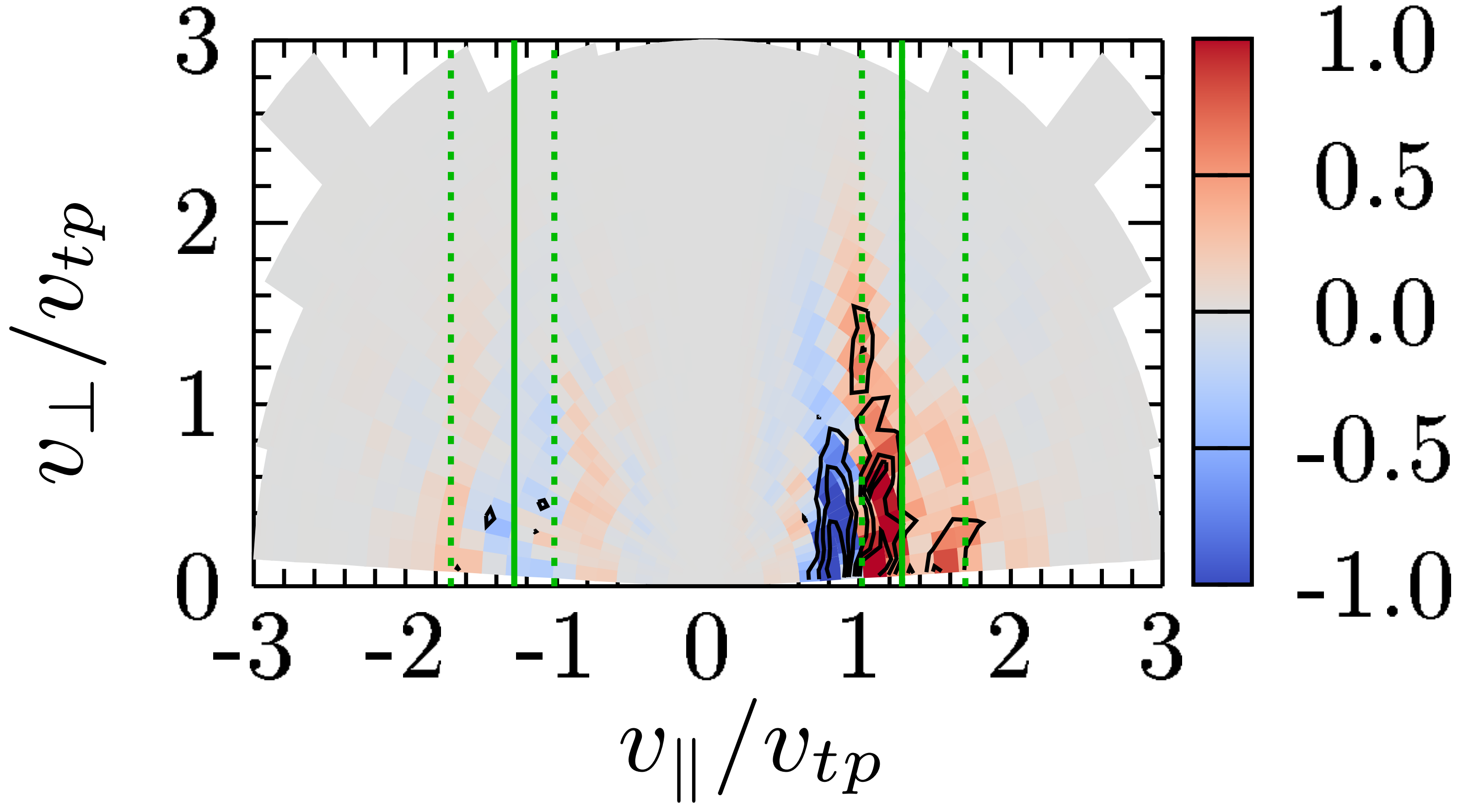

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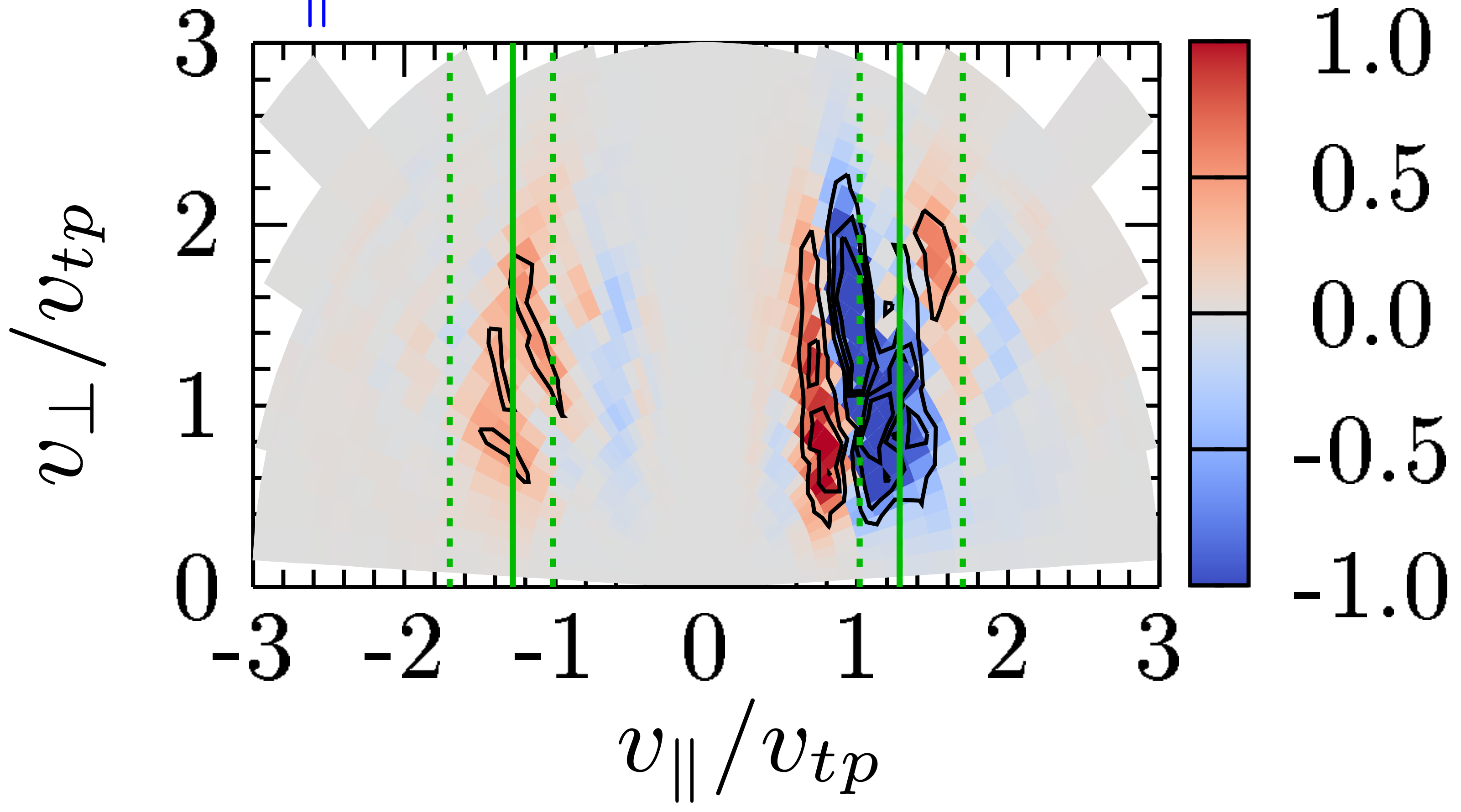

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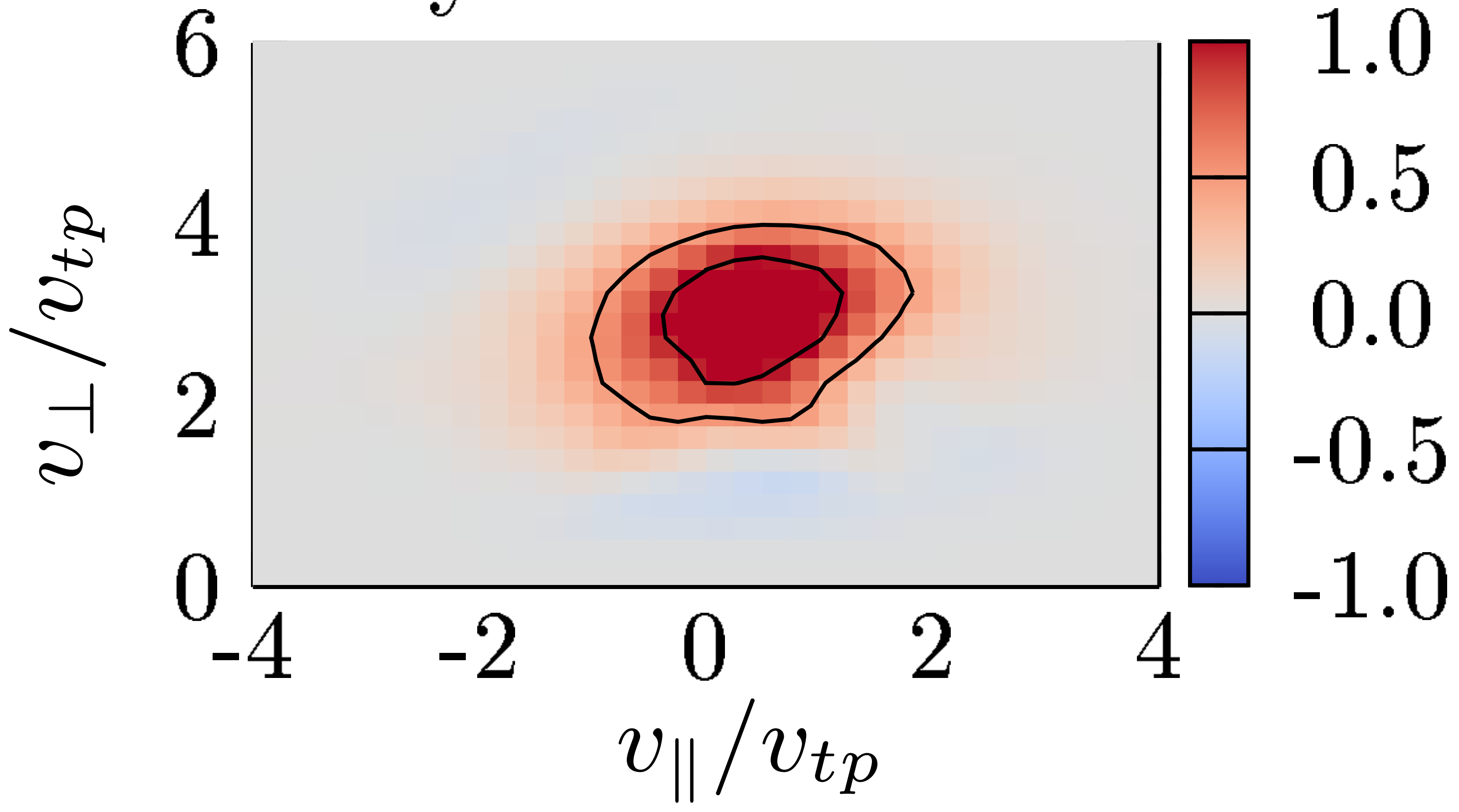

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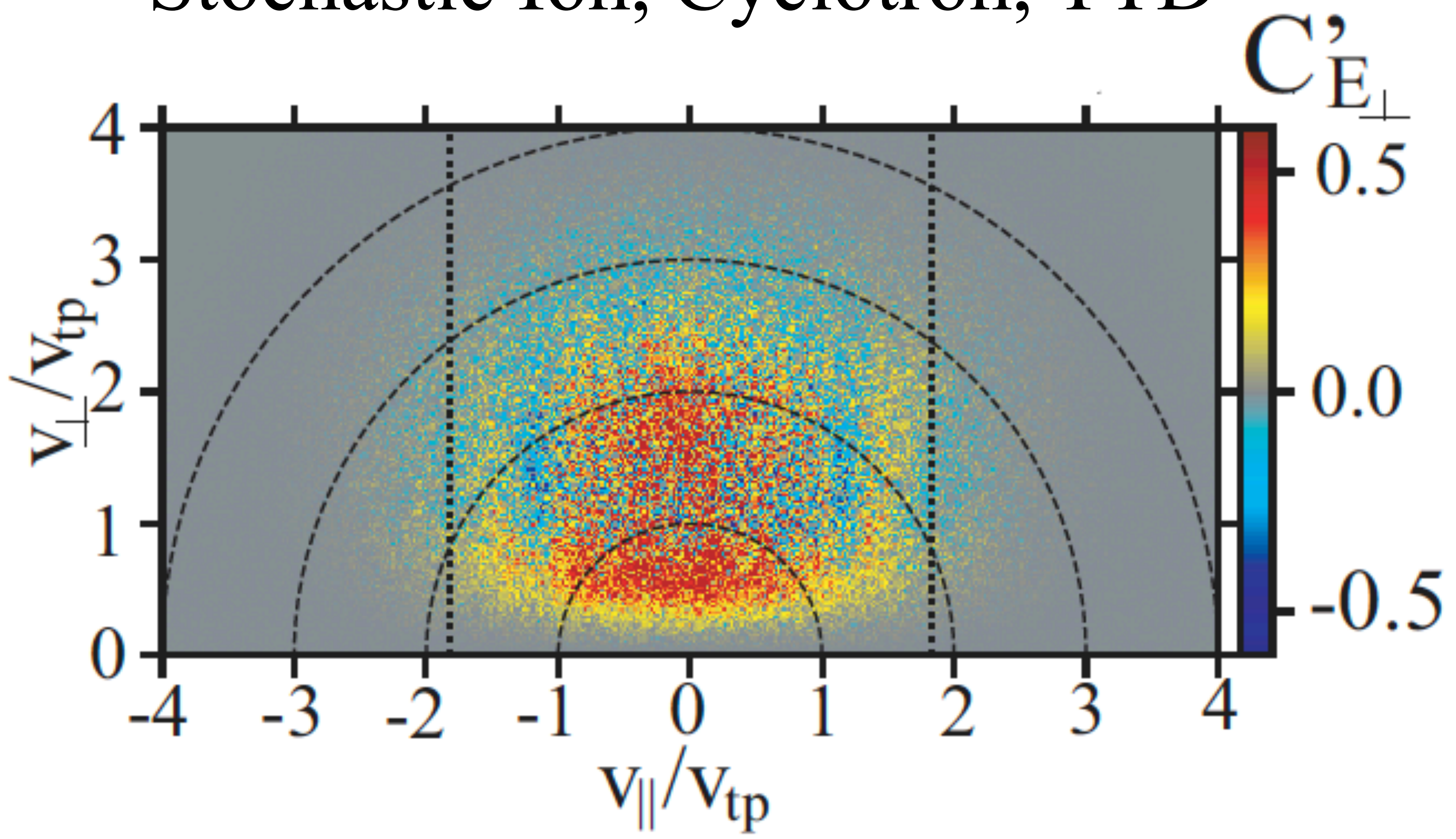

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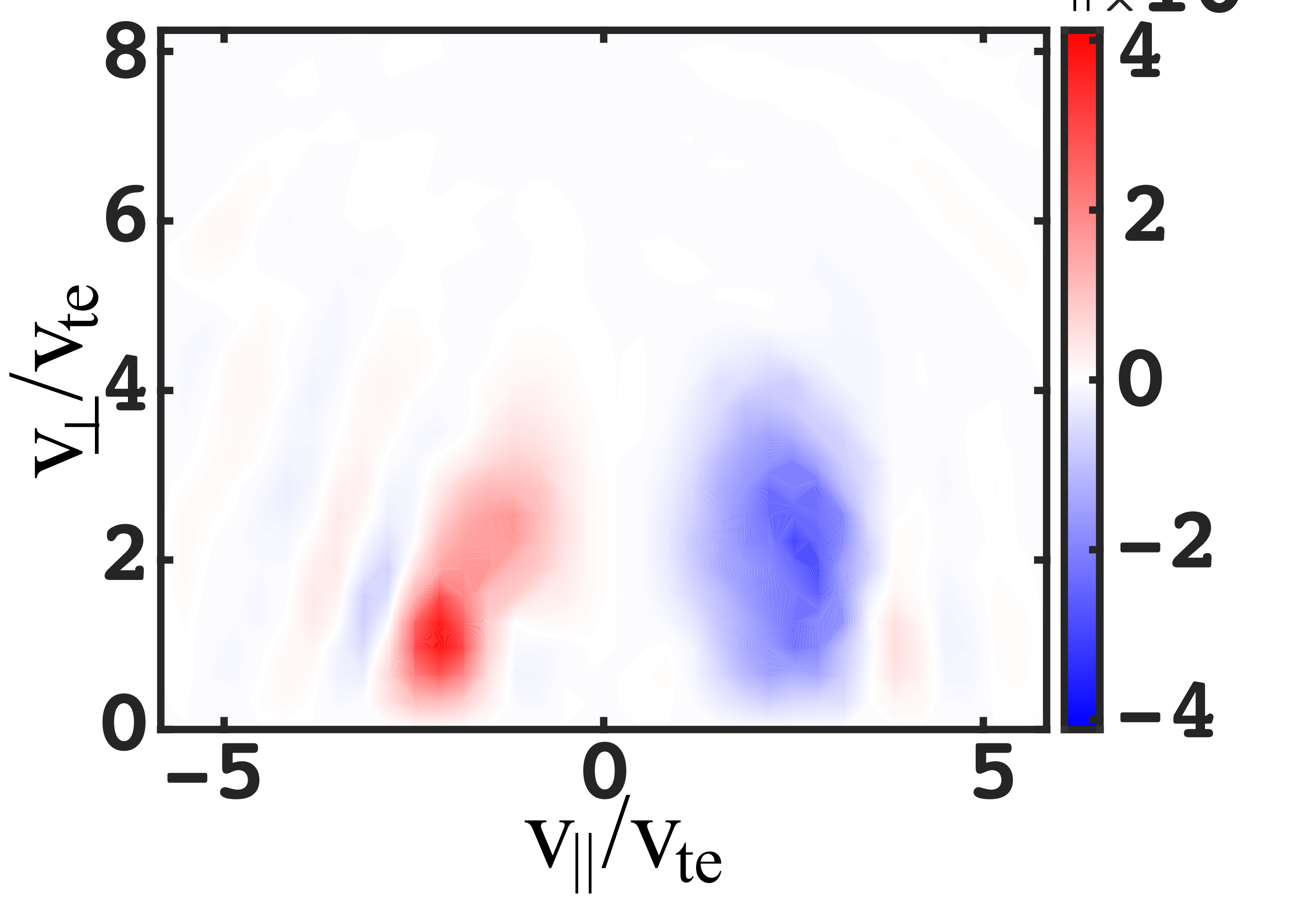
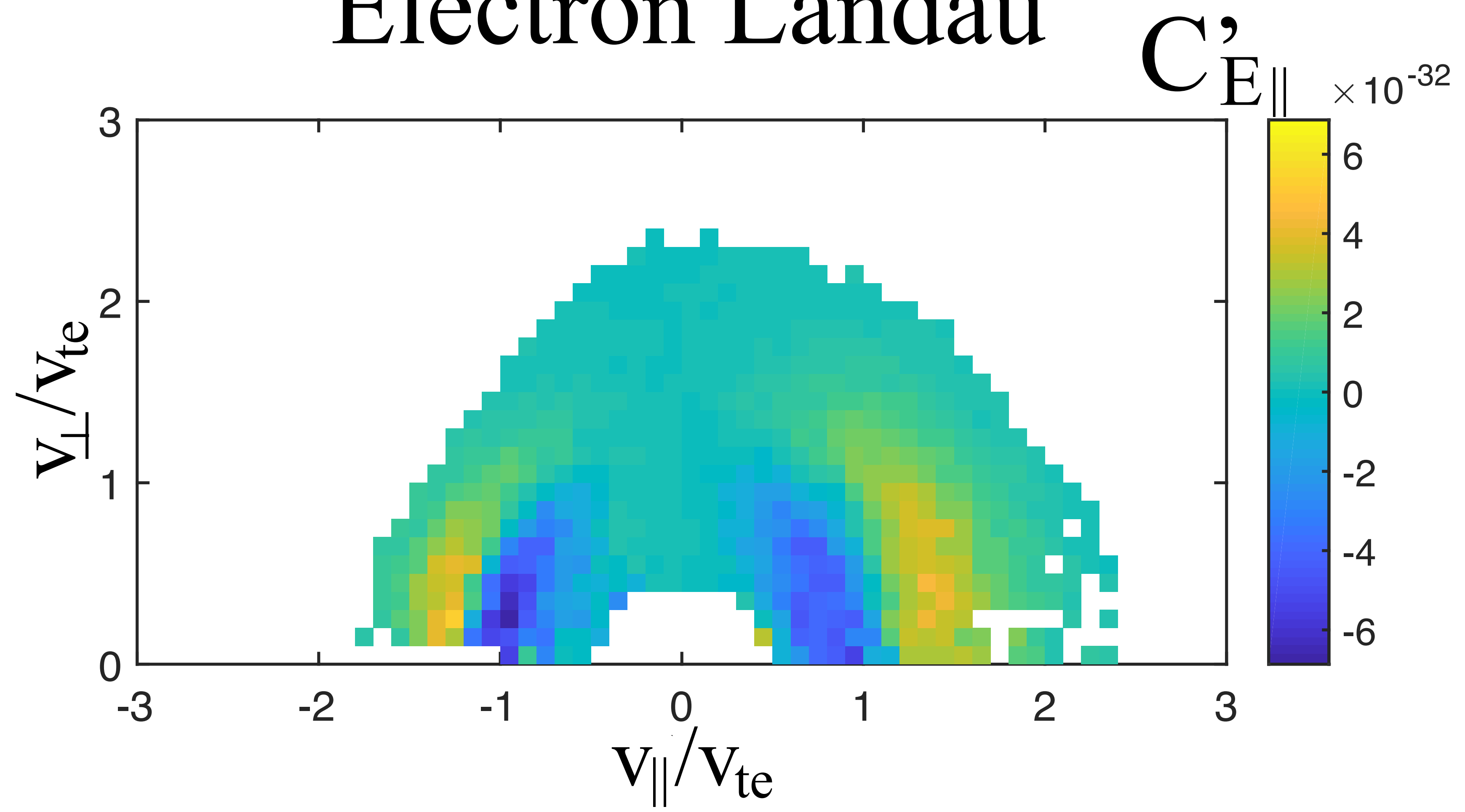


MMS Observation

Electron Landau



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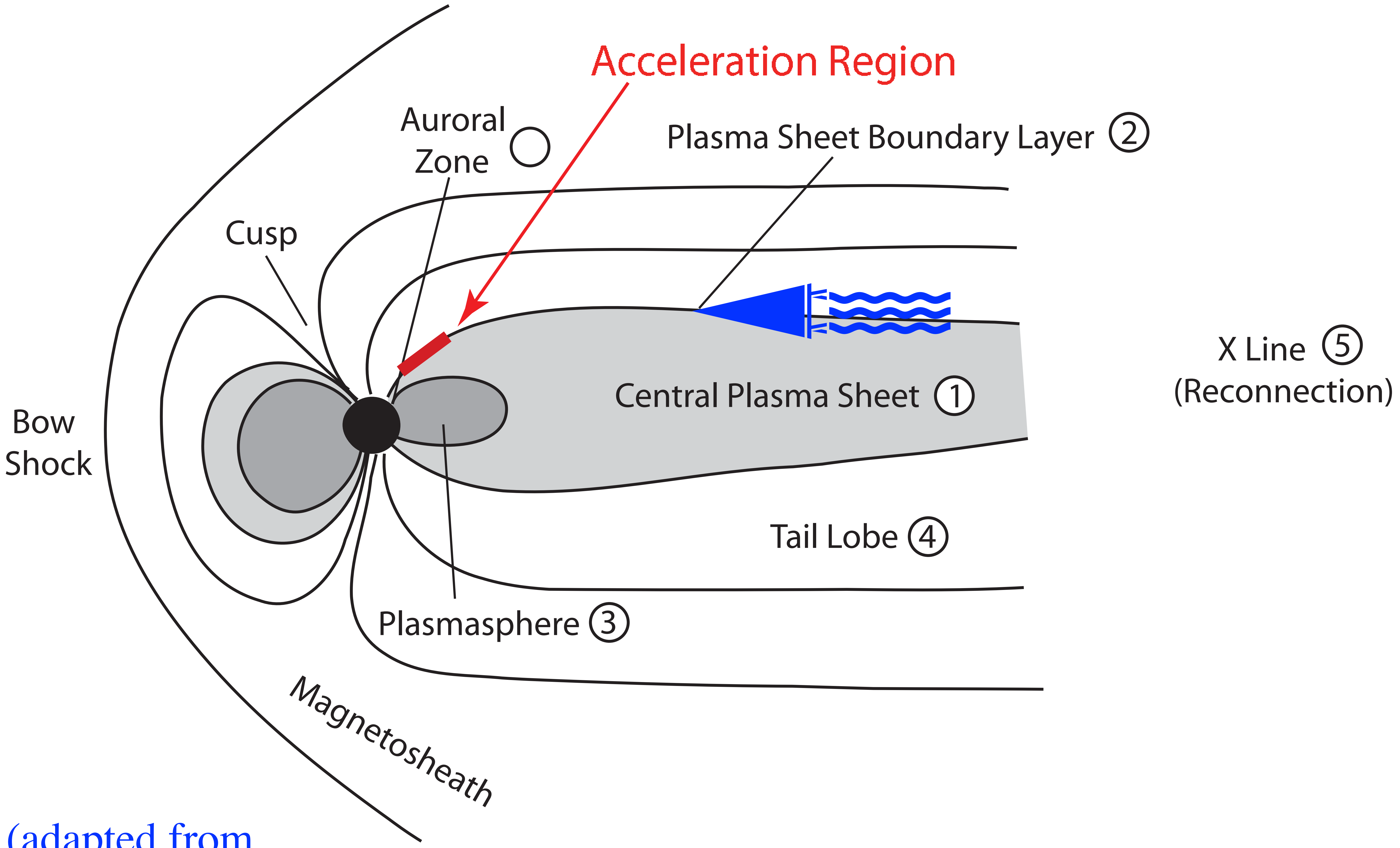

(adapted from
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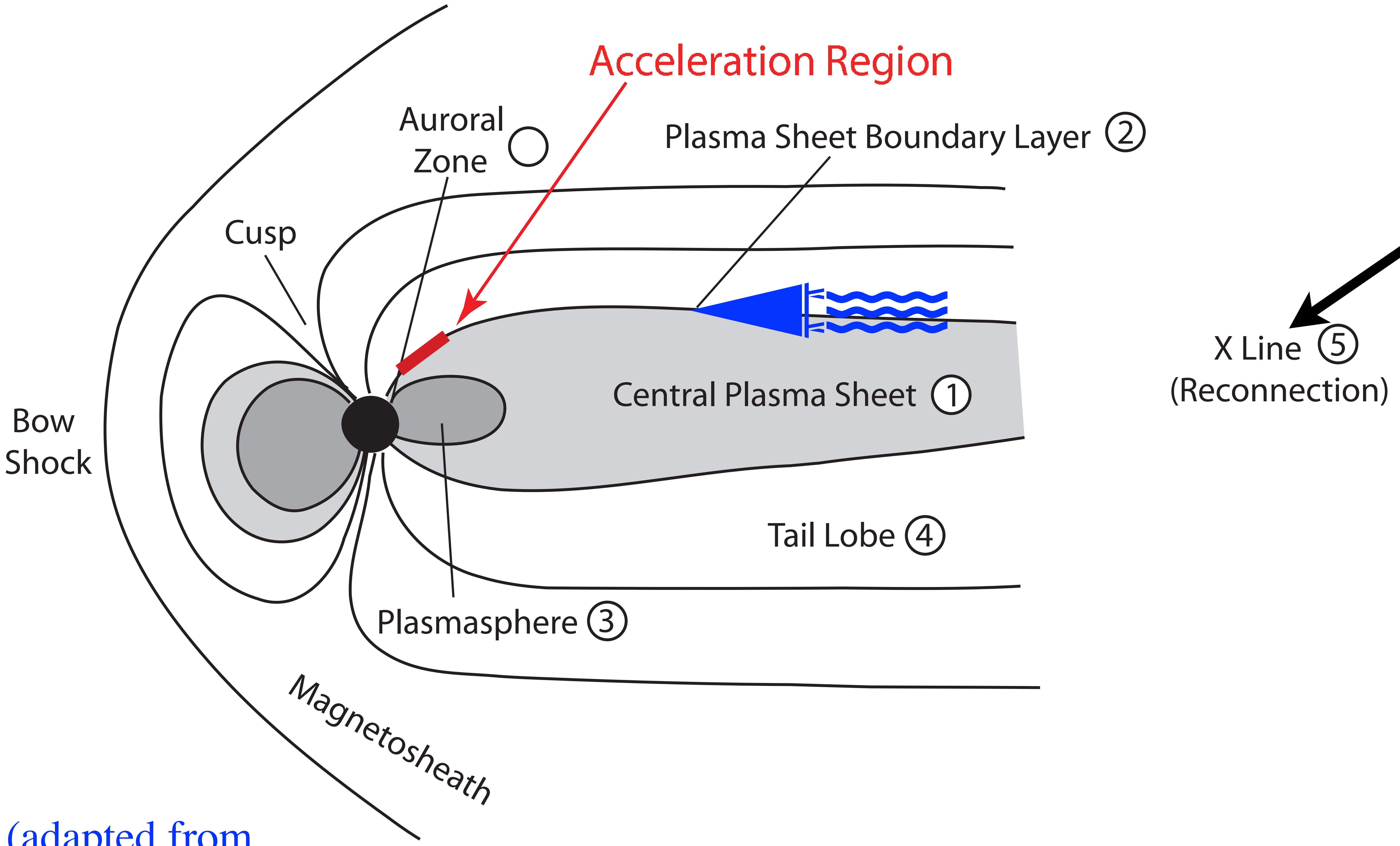

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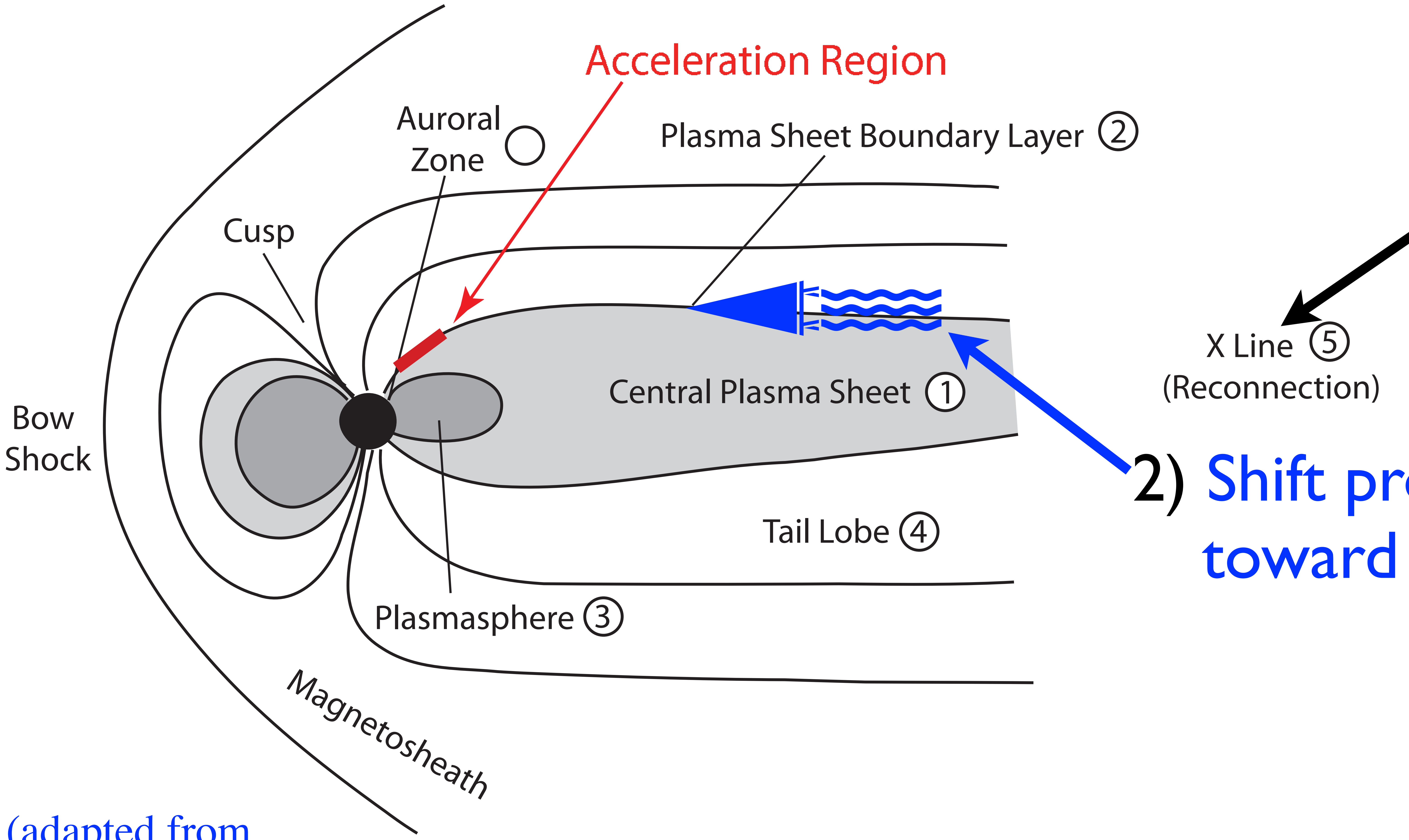

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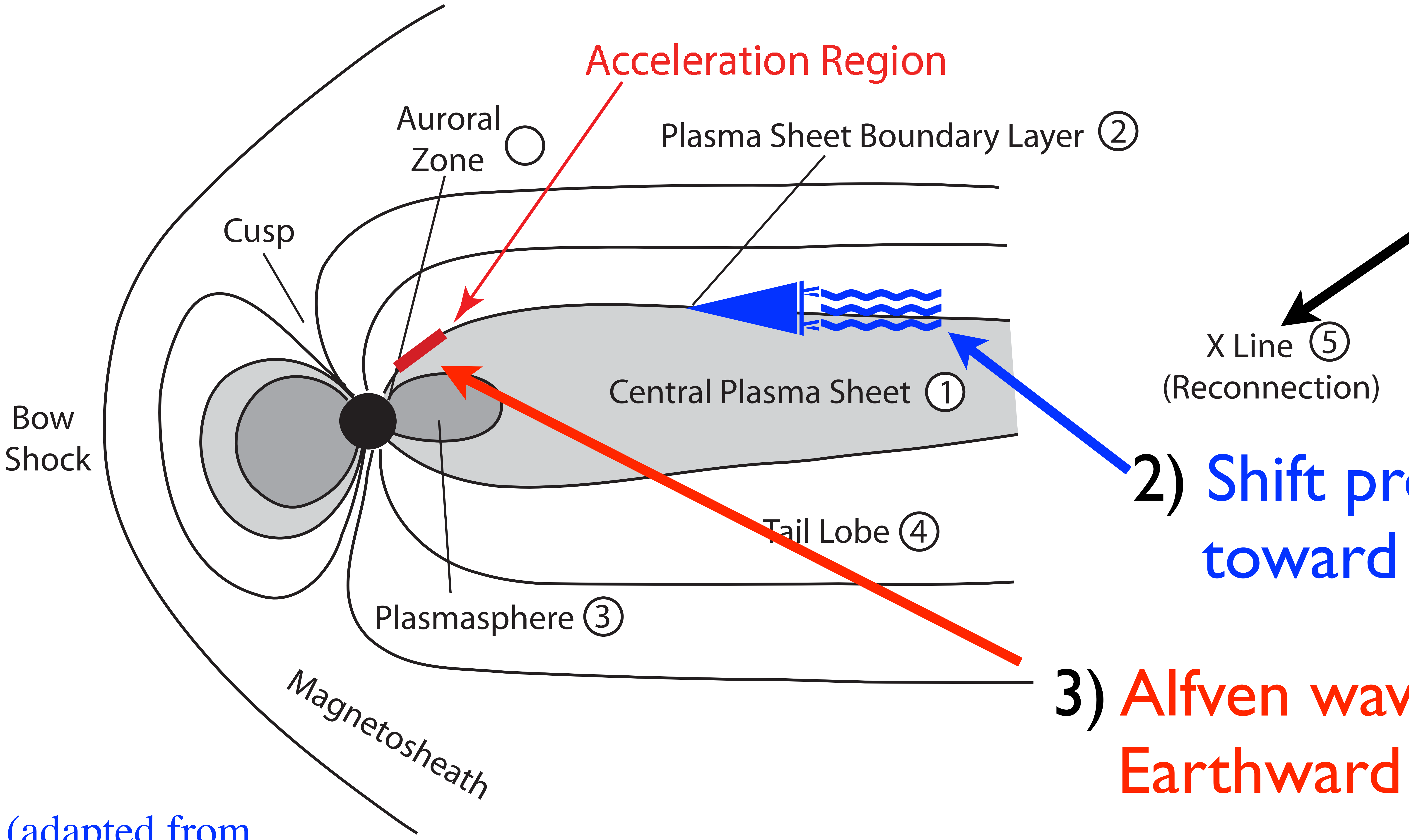
The University of Iowa



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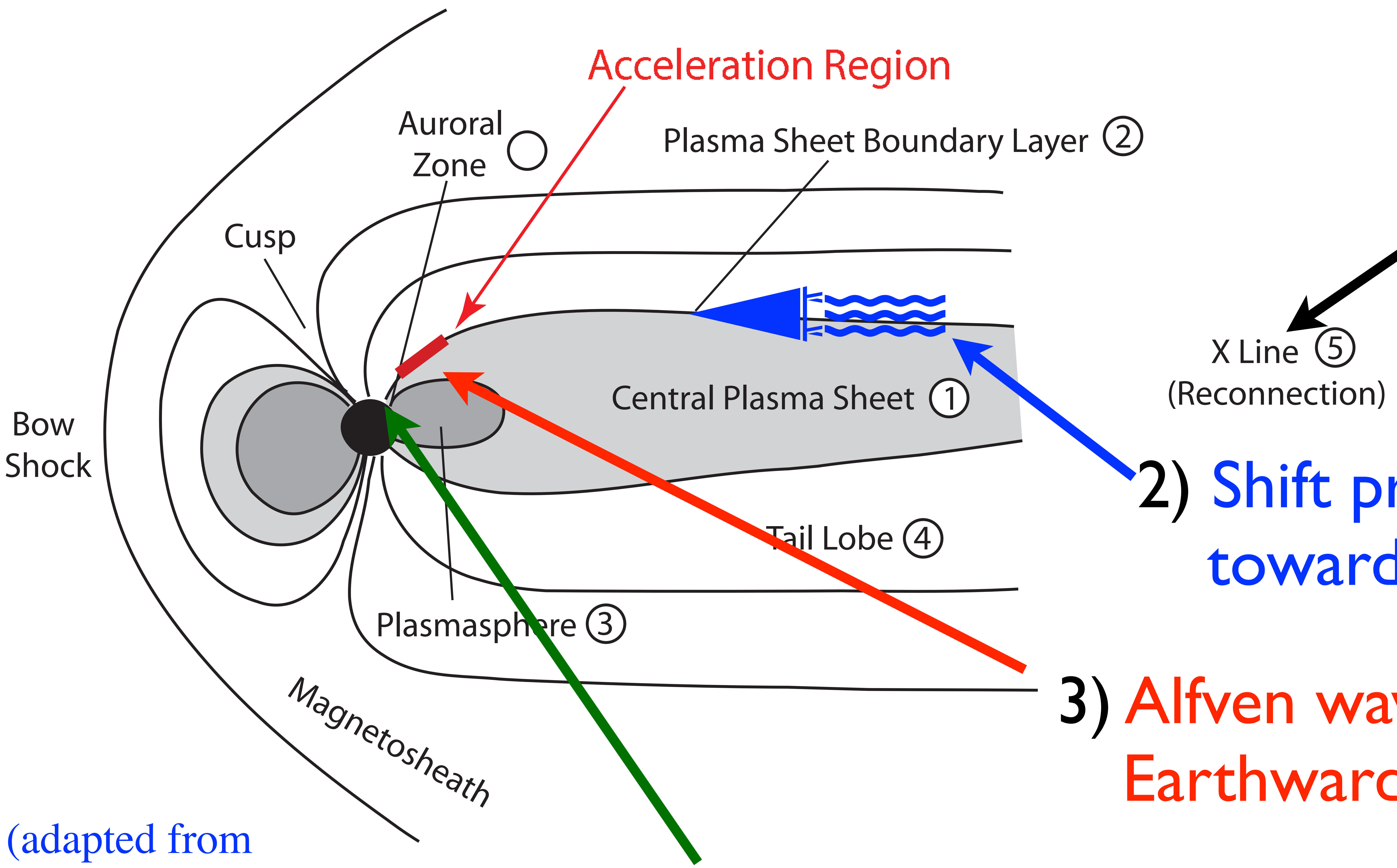

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4) Accelerated electrons precipitate onto ionosphere, exciting atoms that cause the auroral glow

LAPD Experiments of Auroral Electron Acceleration

THE UNIVERSITY

LAPD Experiments of Auroral Electron Acceleration

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Inertial Alfven waves accelerate electrons in tail of distribution

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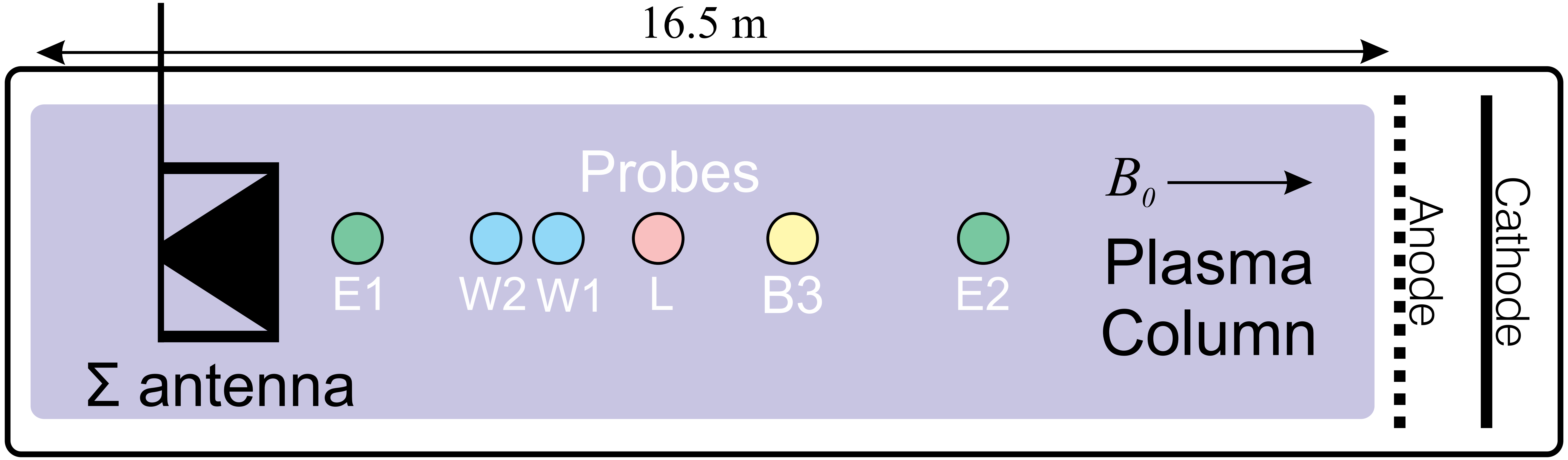

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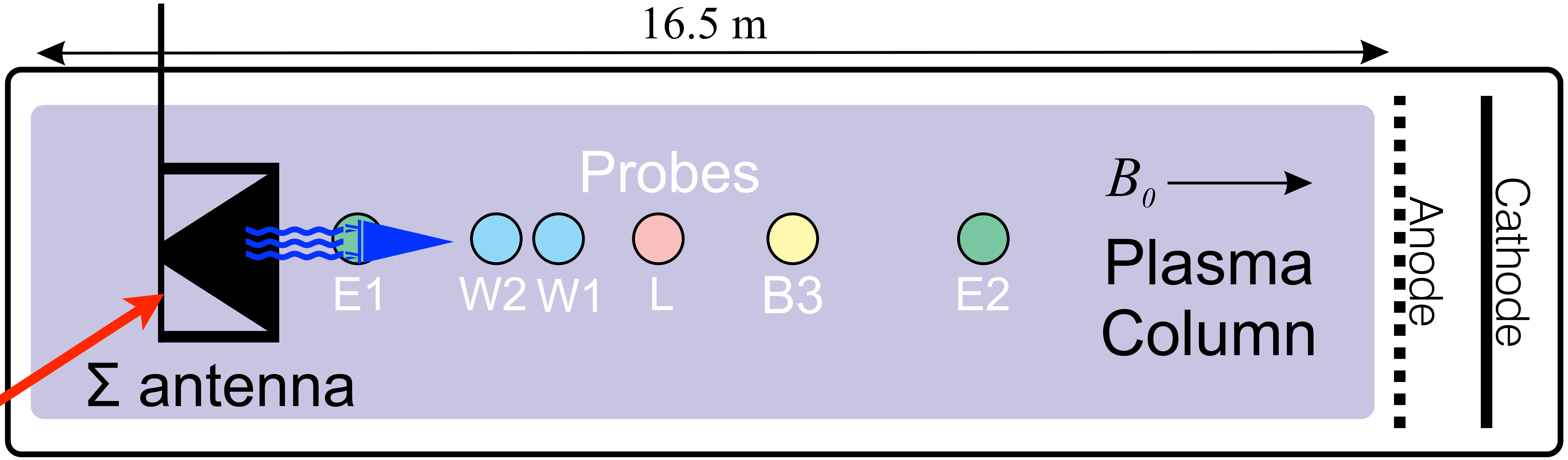

- $v_A = 3.4 \times 10^8$ cm/s
- $\beta = 3.4 \times 10^{-5} < m_e/m_i$
- $v_{te}/v_A = 0.18$

Inertial Alfven waves accelerate electrons in tail of distribution

Antenna

LAPD Experiments of Auroral Electron Acceleration

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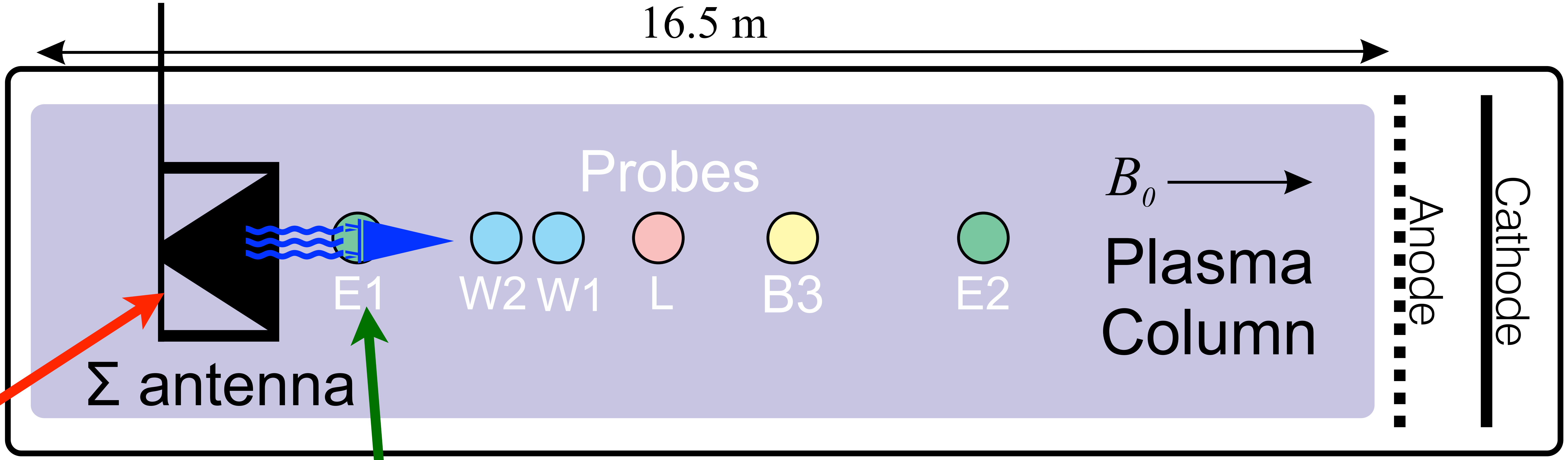

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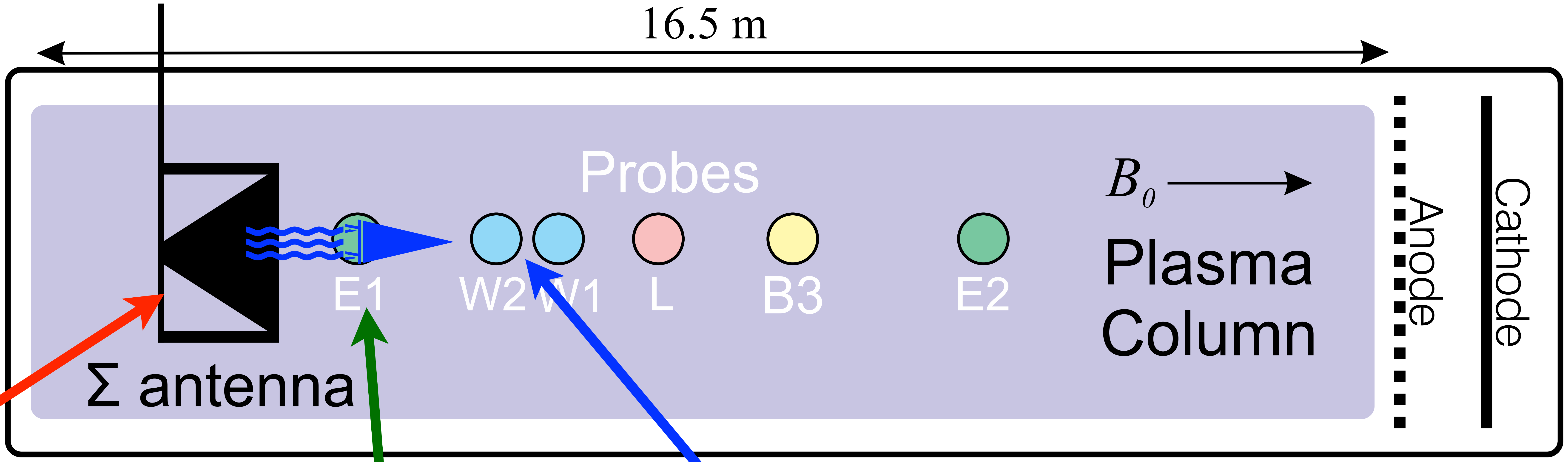

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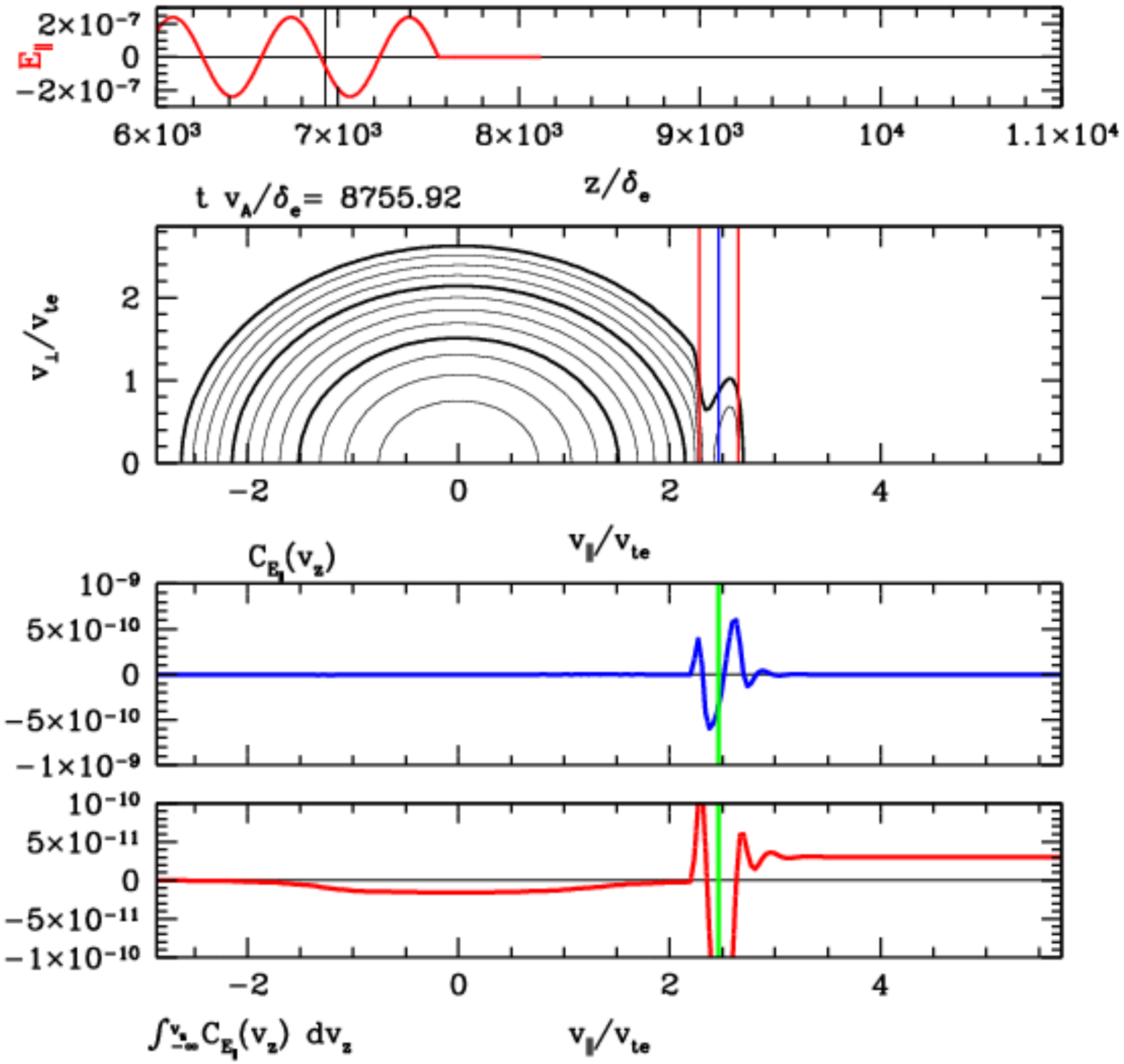
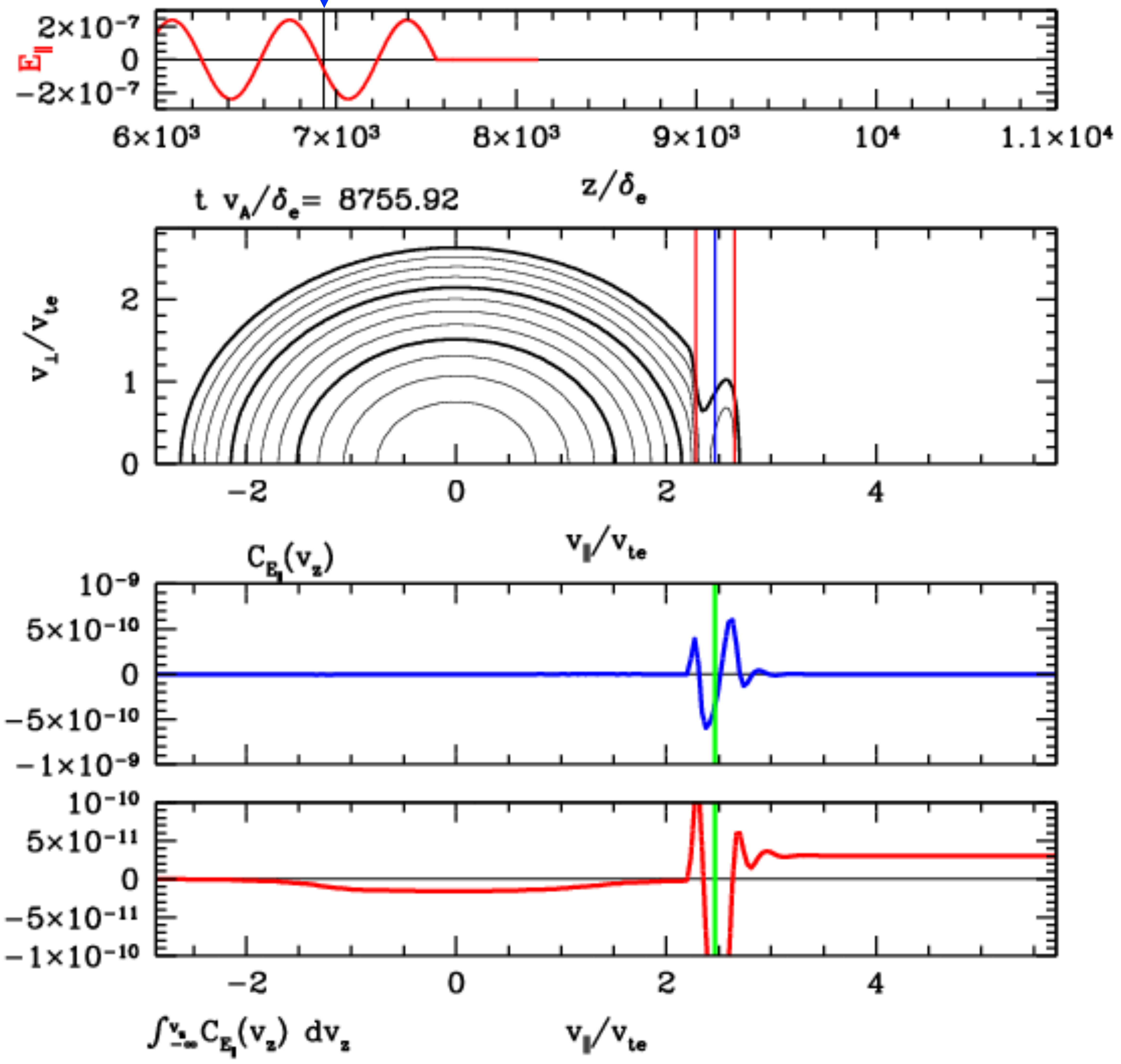
Whistler wave diagnostic $f_e(v_\parallel)$

Modeling Effect on Electron Distribution



Modeling Effect on Electron Distribution

Point of Observation



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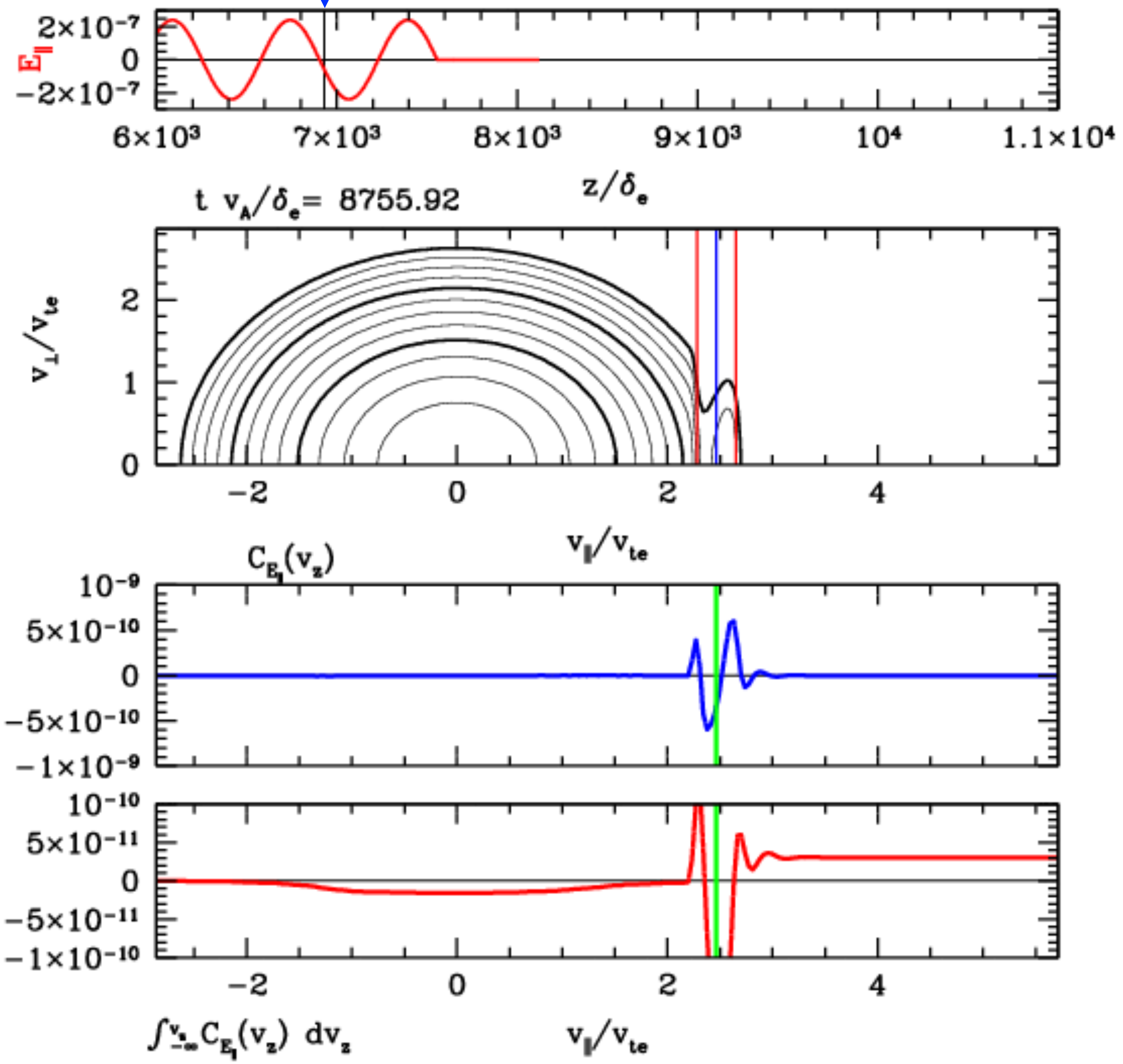

Parallel Electric Field of Alfven Wave

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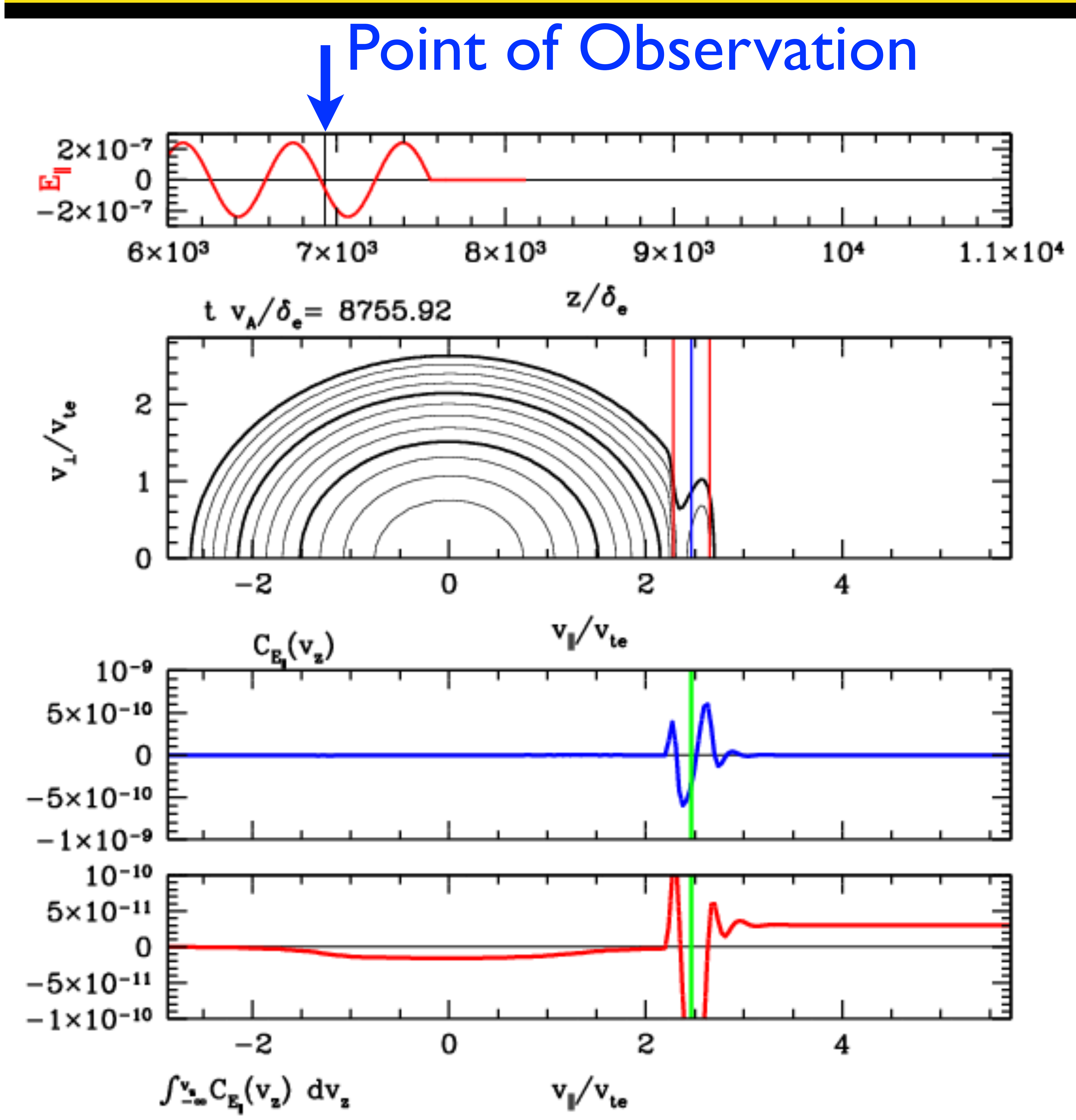
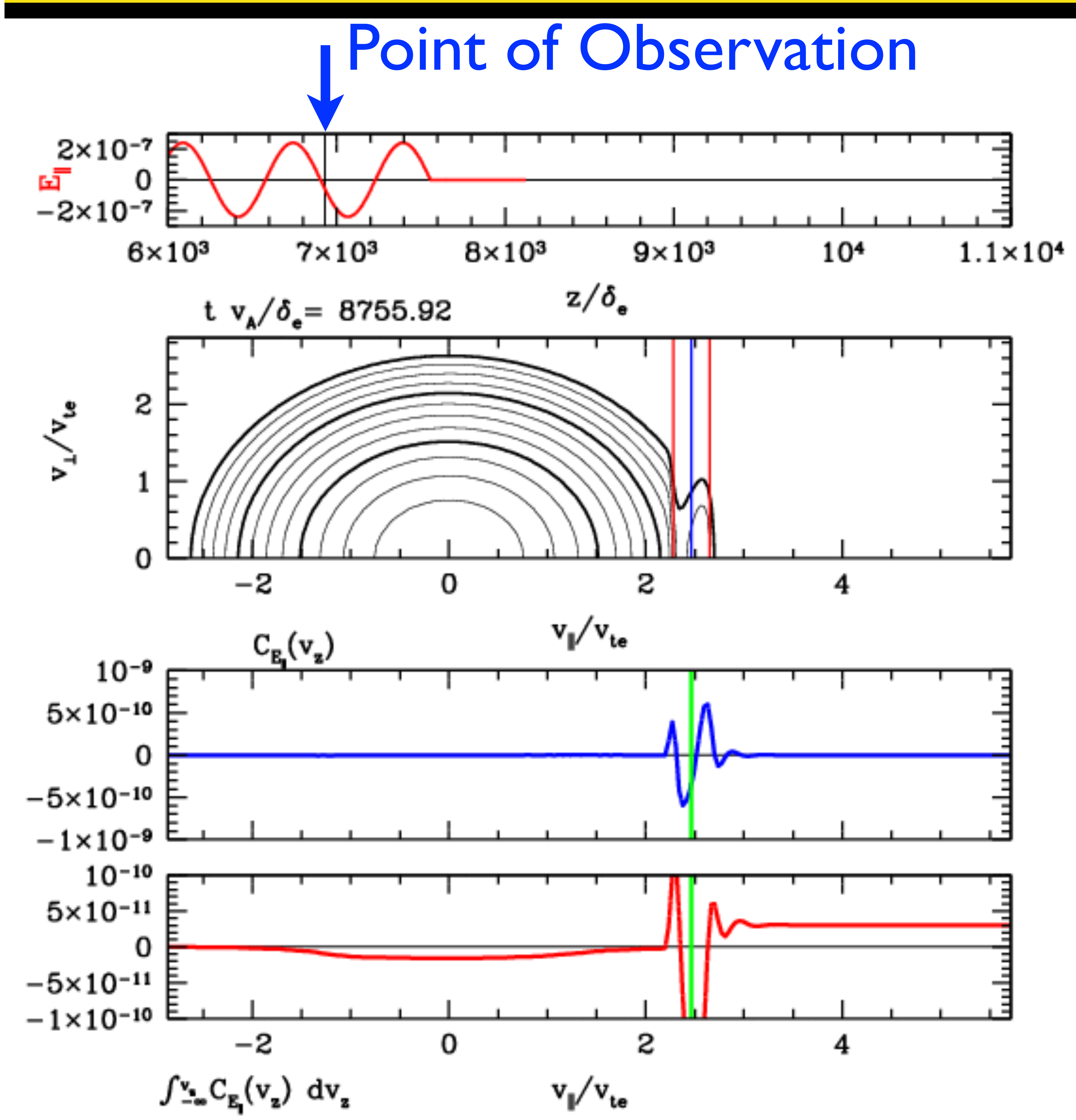


Parallel Electric Field of Alfven Wave

Gyrotropic Electron Distribution Function

Modeling Effect on Electron Distribution



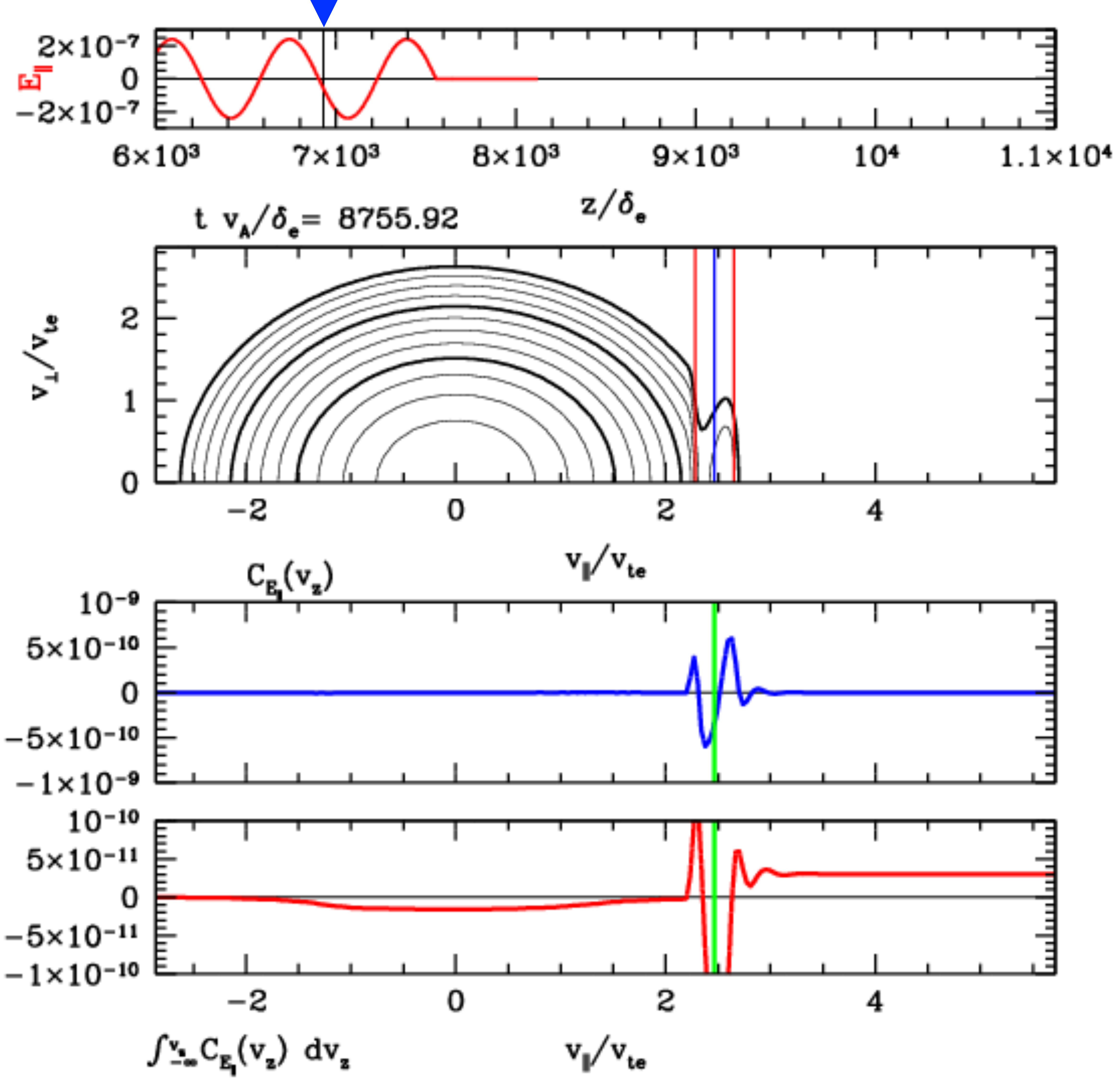
Parallel Electric Field of Alfven Wave

Gyrotropic Electron Distribution Function

Parallel Field-Particle Correlation $C_{E_\parallel}$

Modeling Effect on Electron Distribution

Point of Observation



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Modeling Effect on Electron Distribution

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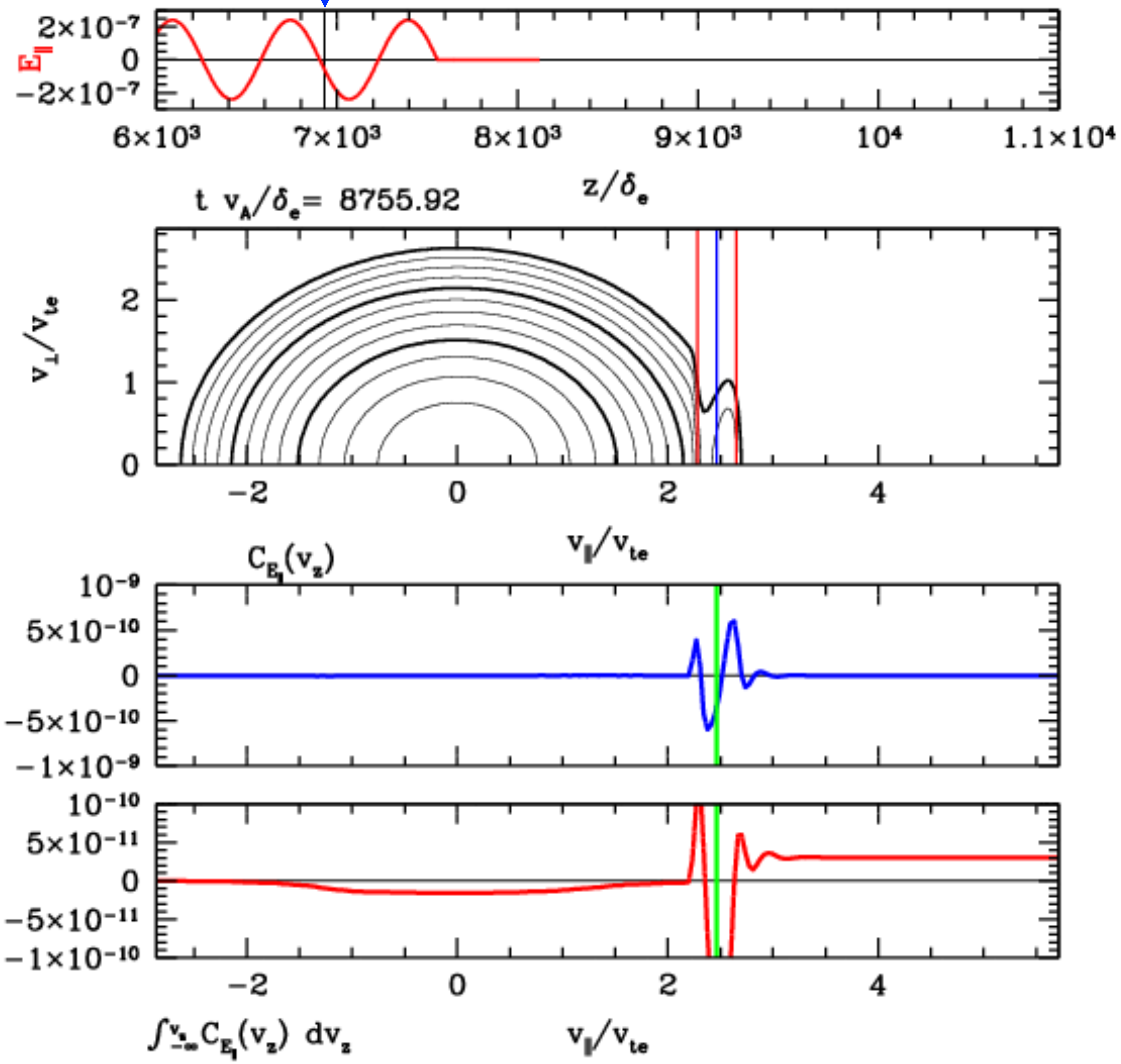

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Net Rate of Electron Energization

Modeling Effect on Electron Distribution

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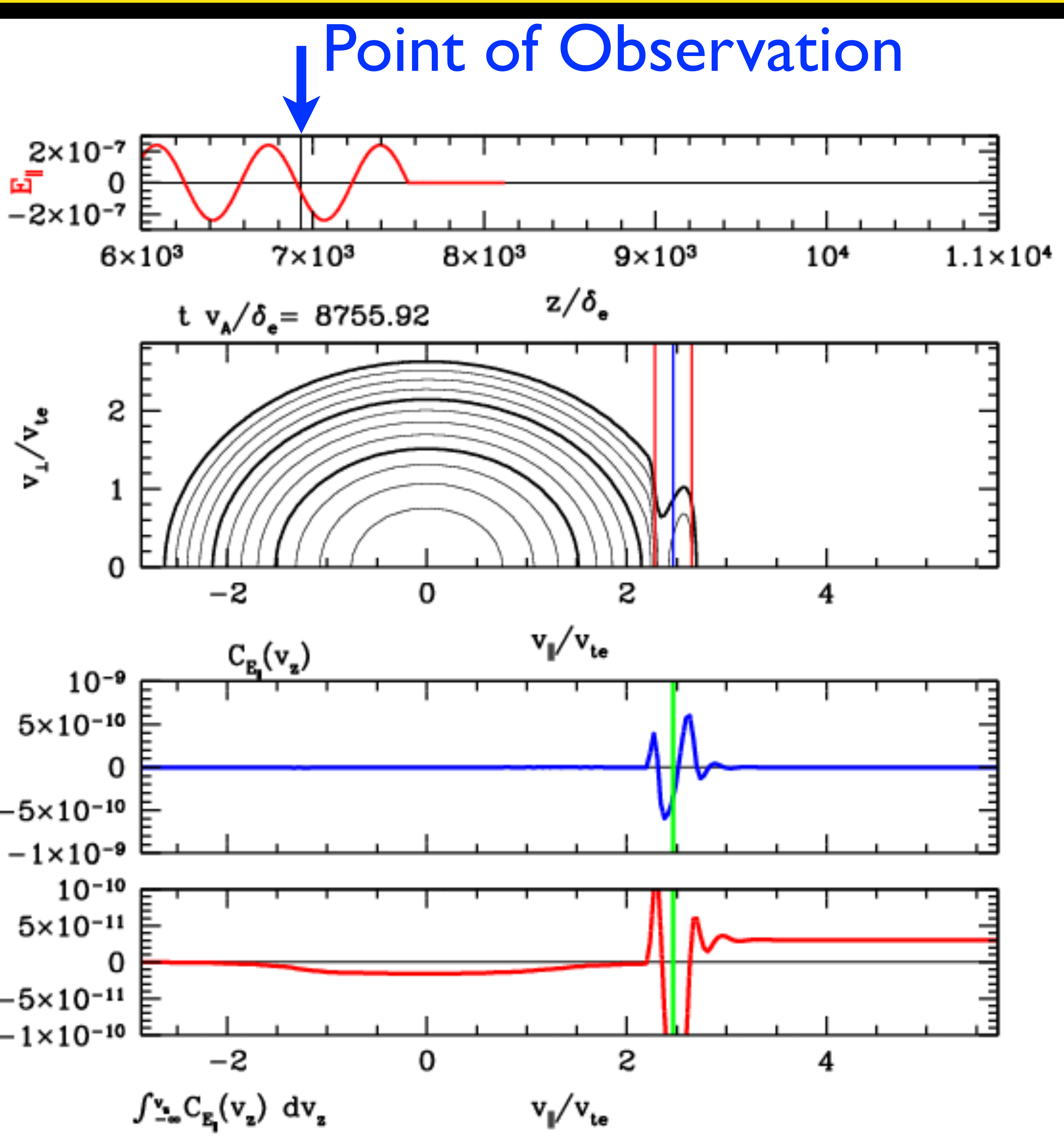

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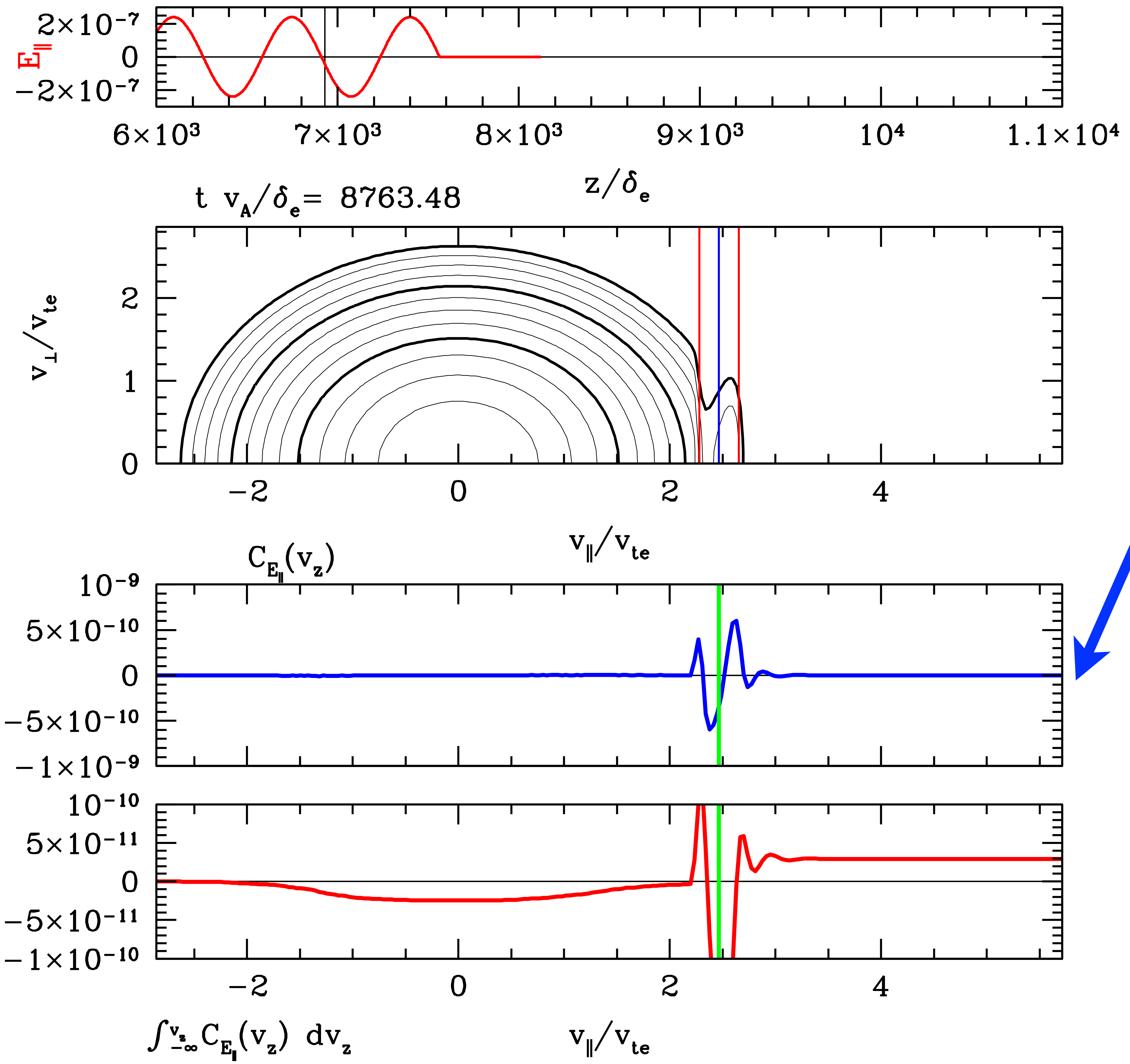

Field-Particle Correlation $C_{E_\parallel}$

Velocity-space signature shows zero crossing at resonant velocity

Outline

- The Flow of Energy and Particle Energization in Astrophysical Plasmas
- Kinetic Theory of Particle Energization
  - -Field-Particle Correlation Technique
- Distinguishing Energization Mechanisms
- Application: Experiments of Auroral Electron Acceleration
- Other Applications: Magnetic Reconnection and Collisionless Shocks
- Conclusions

Collisionless Magnetic Reconnection

Force-free current sheet reconnection simulation (strong guide-field limit)

(McCubbin *et al*., in prep)

Collisionless Magnetic Reconnection

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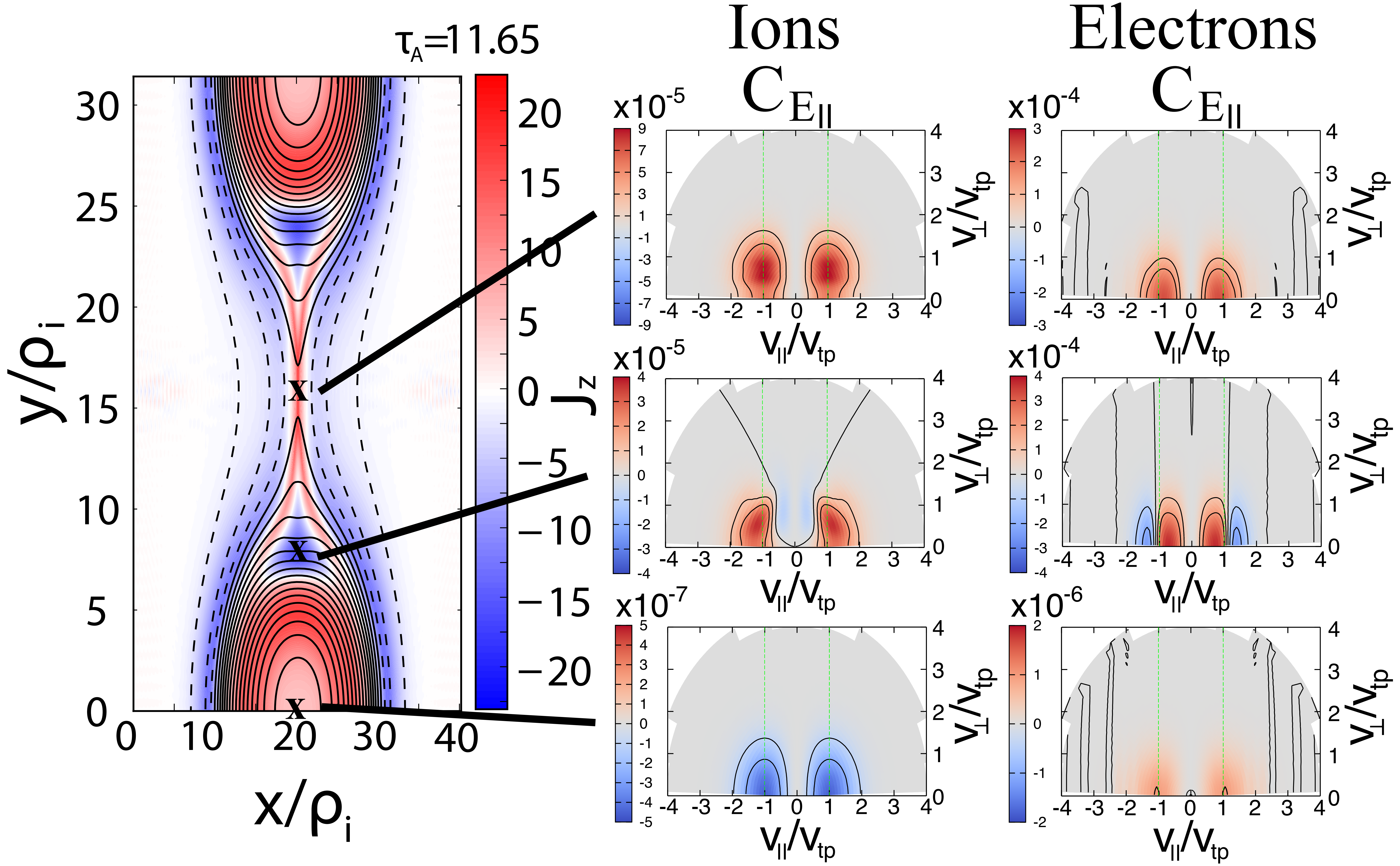

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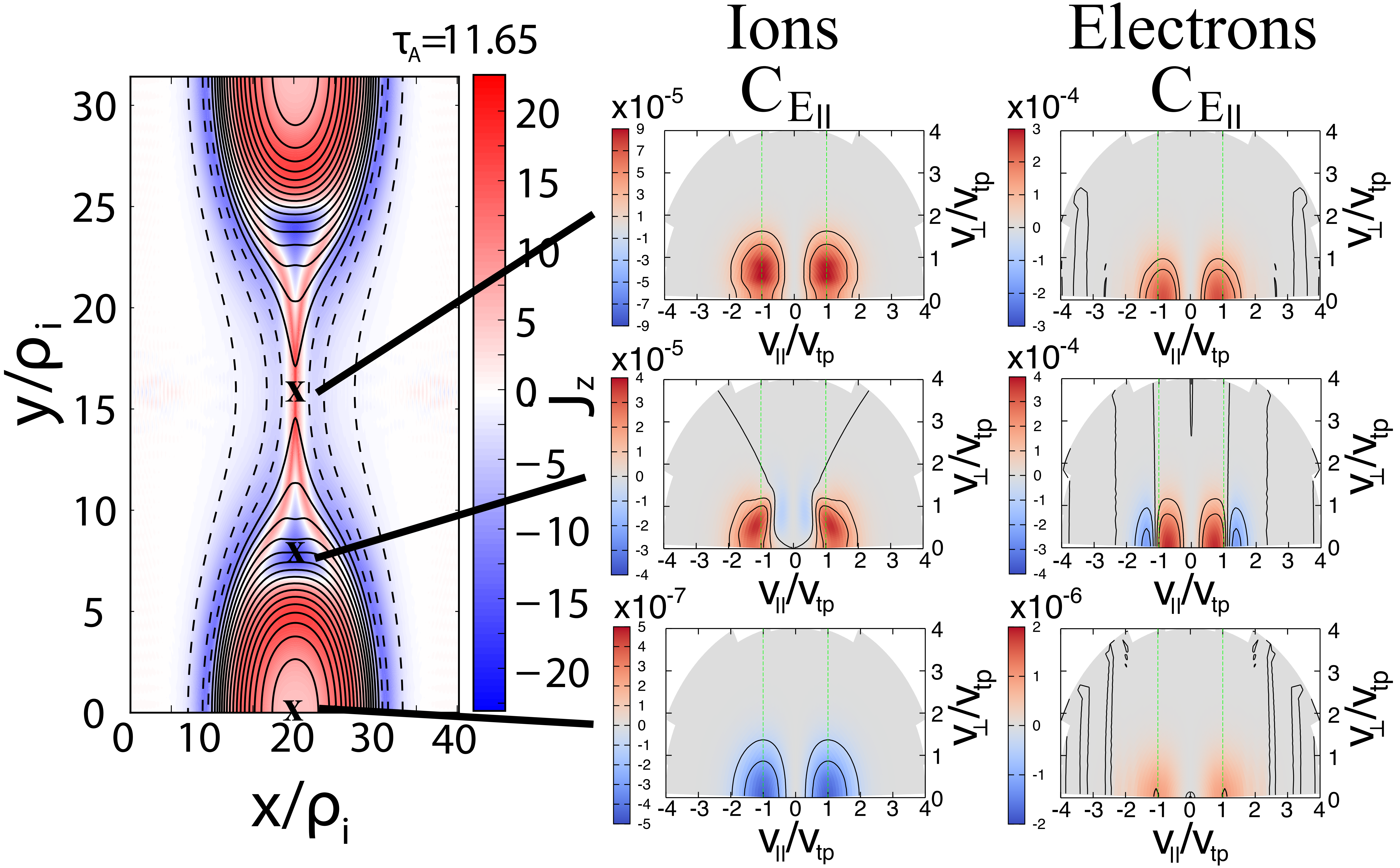
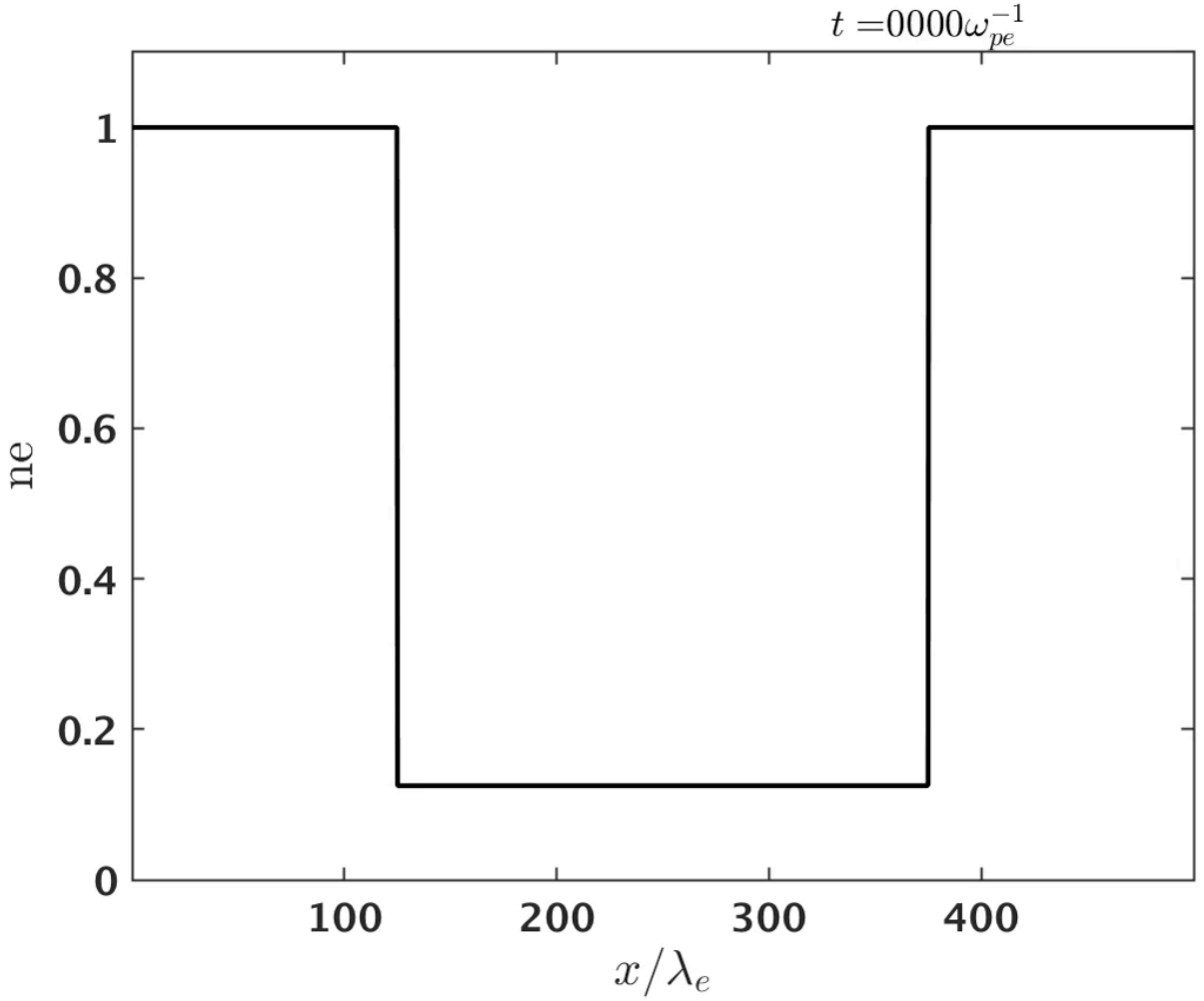


Velocity-space signature of particle energization depends on position within reconnection geometry

Collisionless Shocks

Vlasov (Gkeyll) simulation of collisionless electrostatic Sod shock problem

(Tenbarge, Juno, & Howes, in prep)



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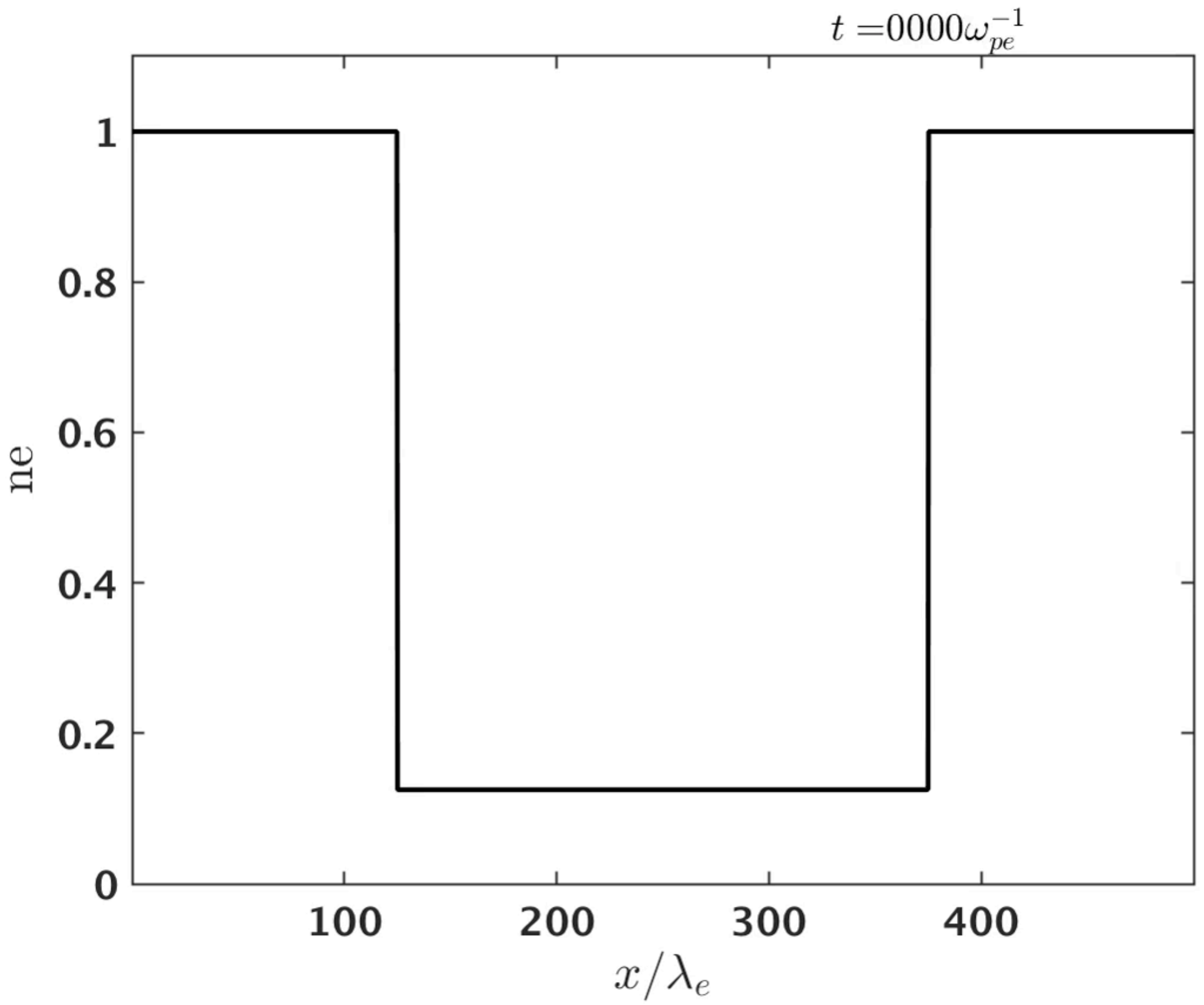

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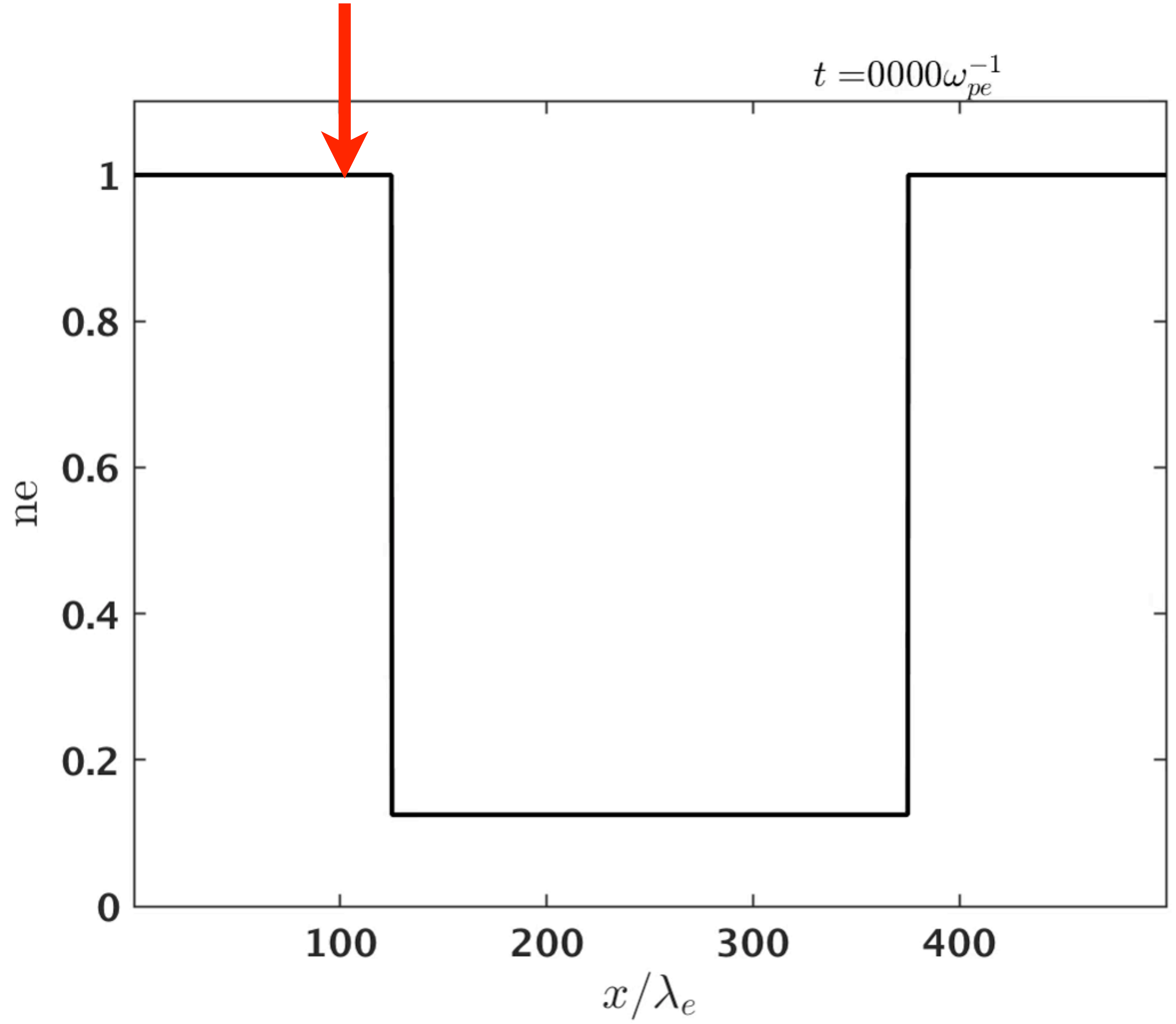
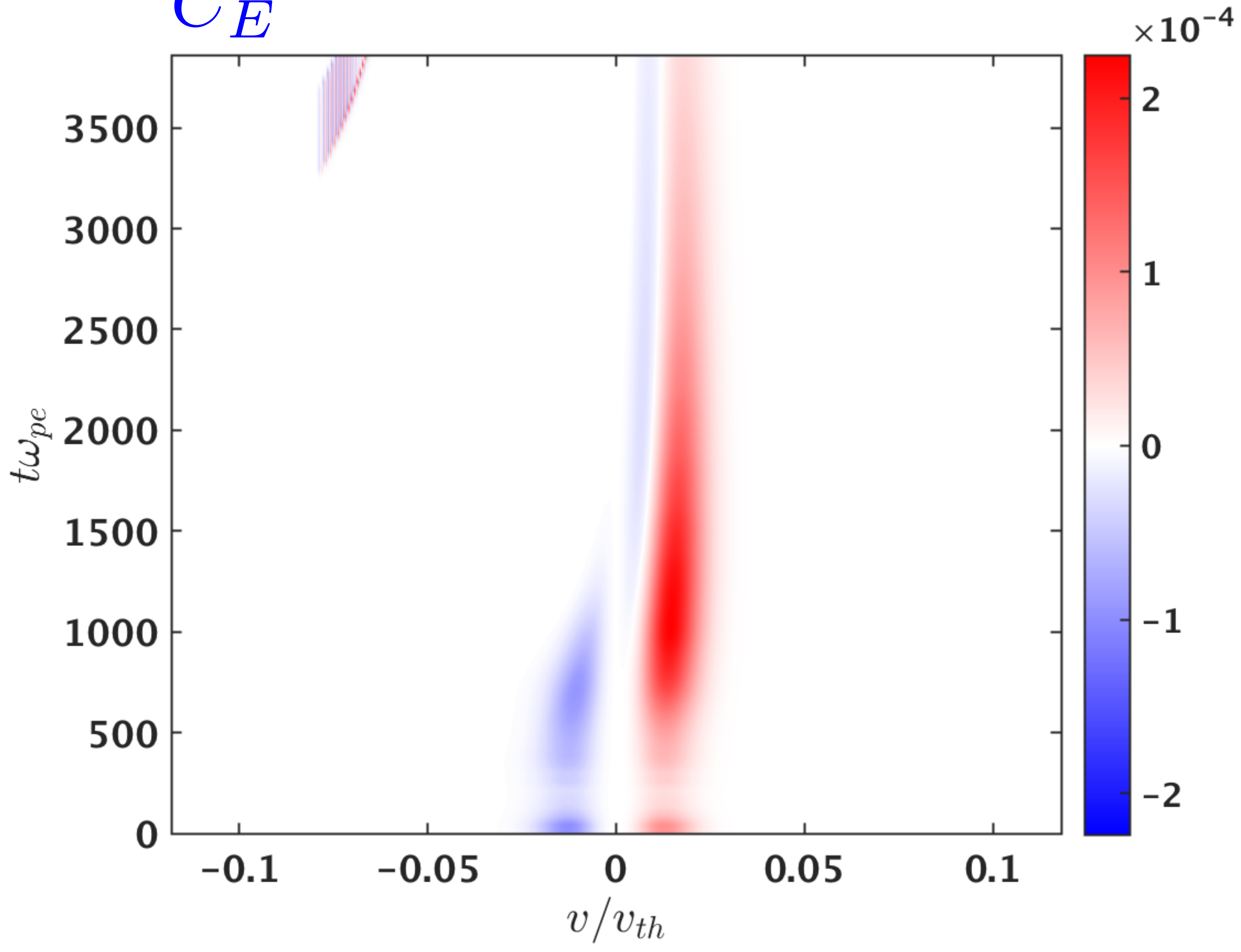
Explore ion energization here



C_E



Collisionless Shocks

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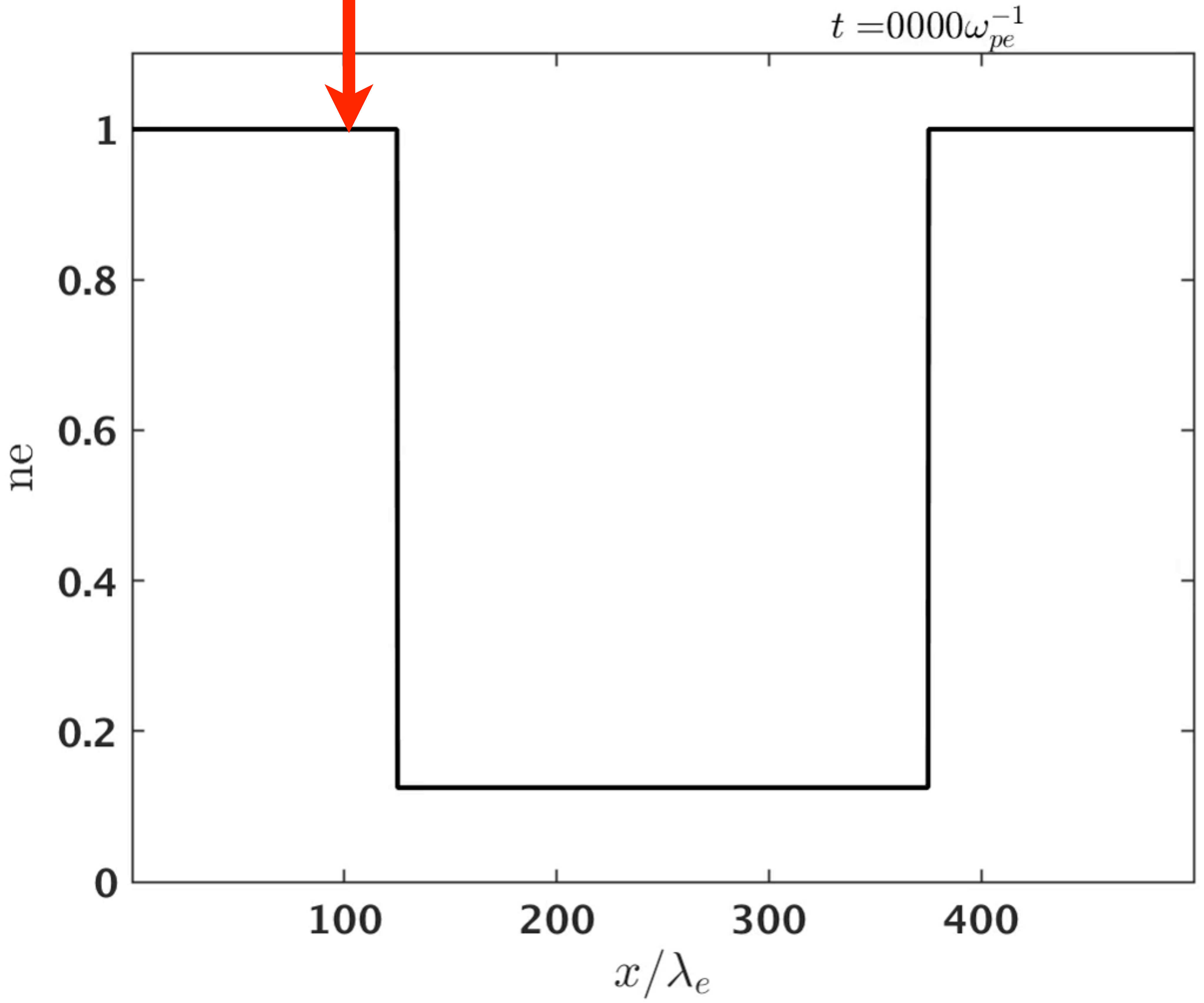

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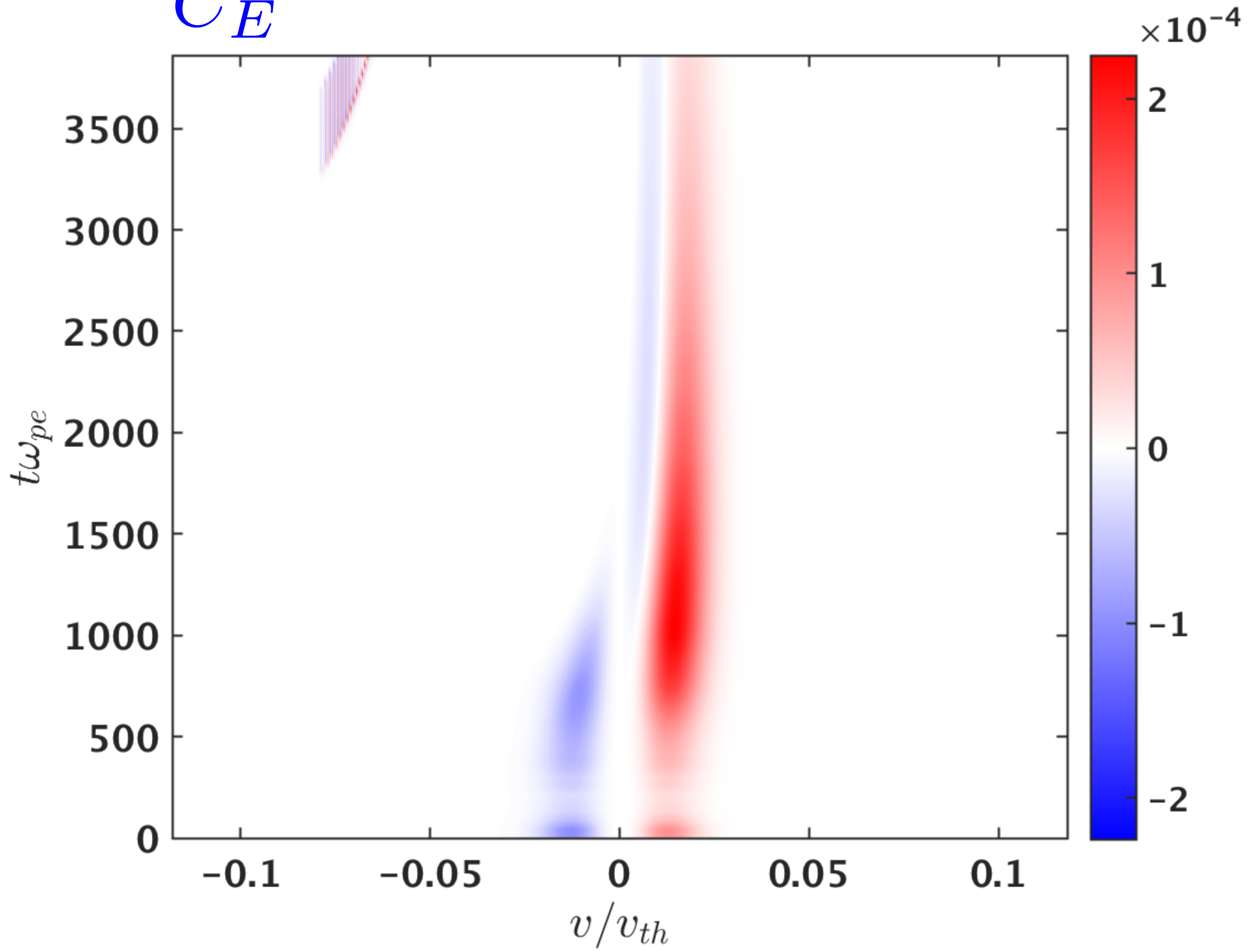

Velocity-space signature of direct ion acceleration

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The Field-Particle Correlation Technique has the potential to identify and characterize the flow of energy to particles in space and astrophysical plasmas

The End

Field-Particle Correlations

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Kinetic equation governing change of phase-space energy density

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

Parallel Electric Field Correlation

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

Perpendicular Electric Field Correlation

$$C_{E_\perp}(\mathbf{v},t,\tau) = C\left(-q_s\frac{v_x^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_x}, E_x(\mathbf{r}_0,t)\right) + C\left(-q_s\frac{v_y^2}{2}\frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_y}, E_y(\mathbf{r}_0,t)\right)$$

Alternative Field-Particle Correlations

Integrate by parts to obtain an alternative form with same total energization

$$\frac{\partial W_s}{\partial t} = -\int d^3\mathbf{r} \int d^3\mathbf{v}\ q_s \frac{v^2}{2} \frac{\partial f_s}{\partial \mathbf{v}} \cdot \mathbf{E} = \int d^3\mathbf{r} \int d^3\mathbf{v}\ q_s \mathbf{v} \cdot \mathbf{E} f_s = \int d^3\mathbf{r}\ \mathbf{j}_s \cdot \mathbf{E}$$

Alternative Parallel Electric Field Correlation

$$C'_{E_\parallel}(\mathbf{v}, t, \tau) = C\left(q_s v_\parallel f_s(\mathbf{r}_0, \mathbf{v}, t), E_\parallel(\mathbf{r}_0, t)\right)$$

Alternative Perpendicular Electric Field Correlation

$$C'_{E_\perp}(\mathbf{v}, t, \tau) = C\left(q_s v_x f_s(\mathbf{r}_0, \mathbf{v}, t), E_x(\mathbf{r}_0, t)\right) + C\left(q_s v_y f_s(\mathbf{r}_0, \mathbf{v}, t), E_y(\mathbf{r}_0, t)\right)$$