Understanding the Kinetic Physics of Particle Energization at Collisionless Shocks Using the Field-Particle Correlation Technique

Gregory G. Howes, University of Iowa
Collin R. Brown (University of Iowa)
James Juno (Princeton Plasma Physics Lab)
Colby C. Haggerty, Sage Constantinou (University of Hawaii)
Damiano Caprioli (University of Chicago)
Jason M. TenBarge, Anatoly Spitkovsky (Princeton University)
Lynn B. Wilson III (Goddard Space Flight Center)

Solar Heliospheric and INterplanetary Environment (SHINE) Workshop 2022
Honolulu, HI
19 – 26 Jun 2022

THE UNIVERSITY OF IOWA

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

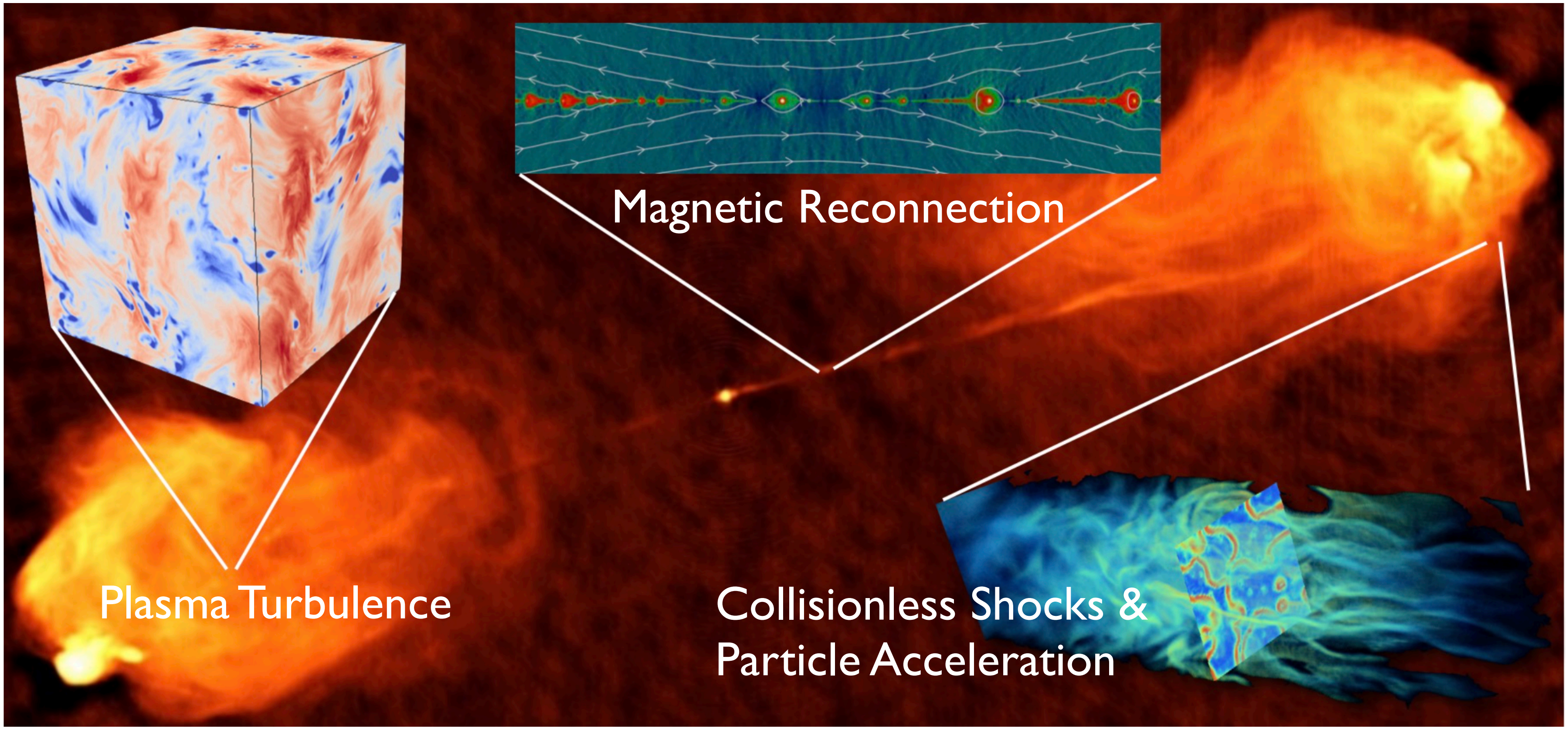
Abstract

THE UNIVERSITY OF IOWA

Collisionless shocks play an important role in the conversion of supersonic flow energy to thermal energy at important boundaries in the heliosphere, such as at planetary bow shocks, the termination shock in the outer heliosphere, and interplanetary shocks propagating through the solar wind. In addition, collisionless shocks can lead to the acceleration of a small fraction of particles to high energy. Many of these energization mechanisms remain poorly understood, but kinetic simulations and spacecraft observations present valuable opportunities to improve our understanding of the fundamental kinetic physics. The recently developed field-particle correlation technique was devised to identify and characterize the mechanisms that energize particles in the six-dimensional (3D-3V) phase space of kinetic plasmas---such mechanisms underlie the fundamental plasma processes of kinetic turbulence, collisionless magnetic reconnection, collisionless shocks, and kinetic instabilities. Here we present an overview of how the field-particle correlation method can be applied to gain deeper insight into the kinetic plasma processes that govern how particles are energized at collisionless shocks. Requiring only single-point measurements in space, the technique can be used to identify well-known acceleration mechanisms, such as shock drift acceleration and shock surfing acceleration. In addition, it shows promise to be able to separate the energization mediated by micro-instabilities arising in the shock transition from that due to the macroscopic shock fields.

Fundamental Plasma Physics Processes

THE UNIVERSITY OF IOWA



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

Maxwell-Boltzmann Equations of Kinetic Plasma Theory

THE UNIVERSITY OF IOWA

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

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

The University of Iowa

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

Field-Particle Correlation Technique

THE UNIVERSITY OF IOWA

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

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

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)

Field-Particle Correlations for Shocks

Separate energization by different components of the electric field

$$C_{E_x}(\mathbf{r}_0,\mathbf{v},t) = -q_s \frac{v_x^2}{2} \frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_x} E_x(\mathbf{r}_0,t)$$

$$C_{E_y}(\mathbf{r}_0,\mathbf{v},t) = -q_s \frac{v_y^2}{2} \frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_y} E_y(\mathbf{r}_0,t)$$

$$C_{E_z}(\mathbf{r}_0,\mathbf{v},t) = -q_s \frac{v_z^2}{2} \frac{\partial f_s(\mathbf{r}_0,\mathbf{v},t)}{\partial v_z} E_z(\mathbf{r}_0,t)$$

For turbulent particle energization, time average over a correlation interval

For shock energization, just compute this value instantaneously

- If instabilities play a role, then a short time average may be necessary

Simulation of Perpendicular Collisionless Shock

THE UNIVERSITY OF IOWA

Gkeyll Simulation

- Exactly Perpendicular

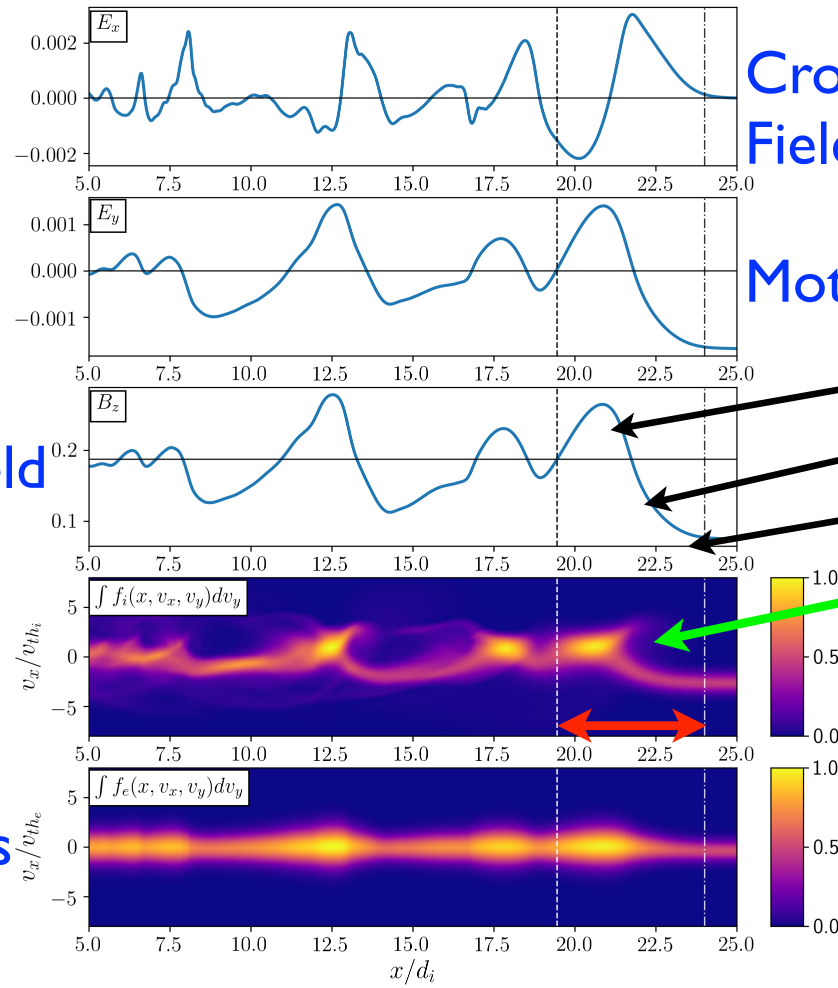
  $\theta_{Bn} = 90^\circ$

- 1D-2V 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

Overshoot

Ramp

Foot

Reflected Ions

Ions

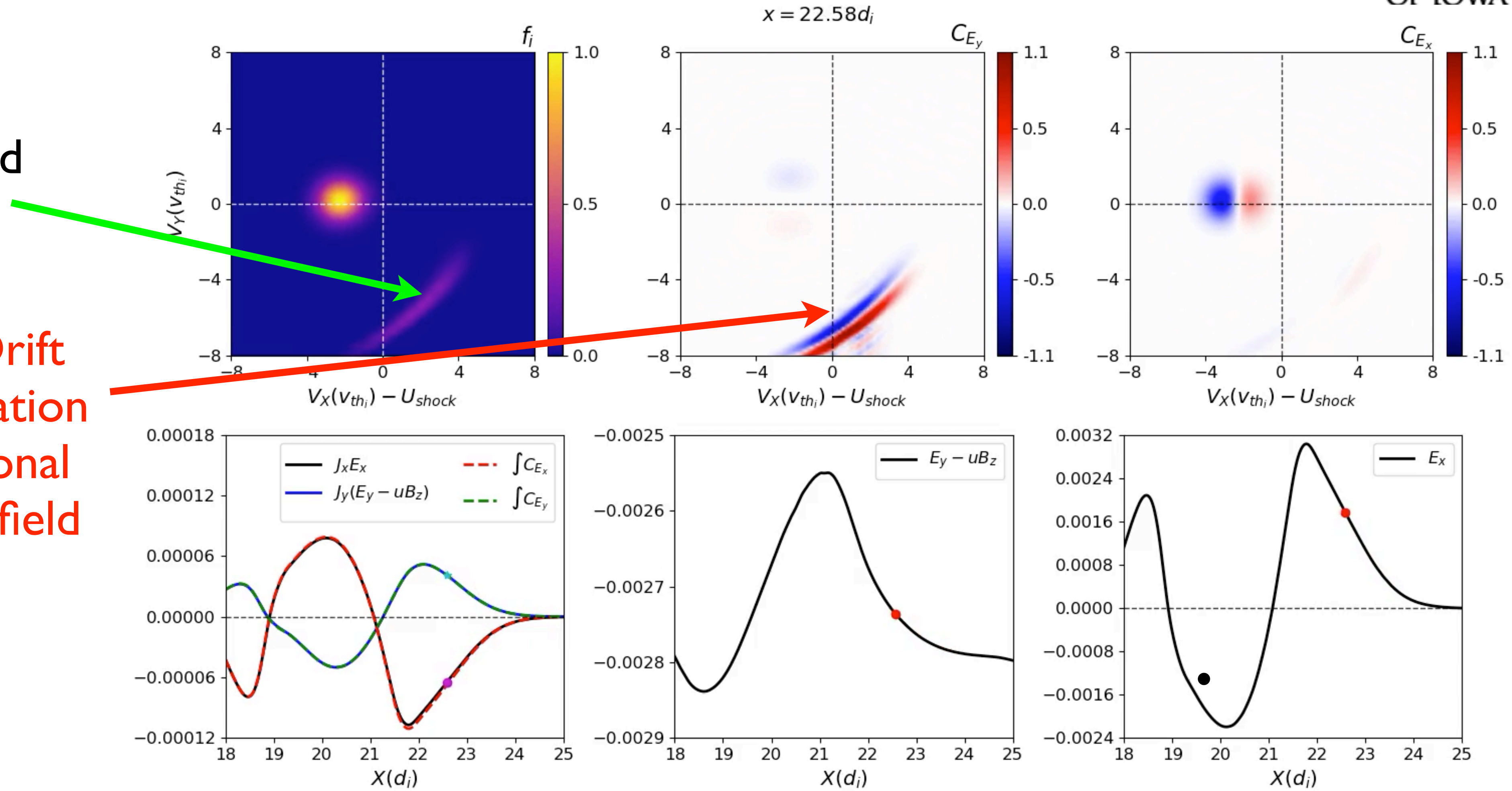
Electrons

(Juno *et al.*, *J. Plasma Phys.*, **87**:905870316, 2021)

Distribution Function and Velocity-Space Signatures

Reflected Ions

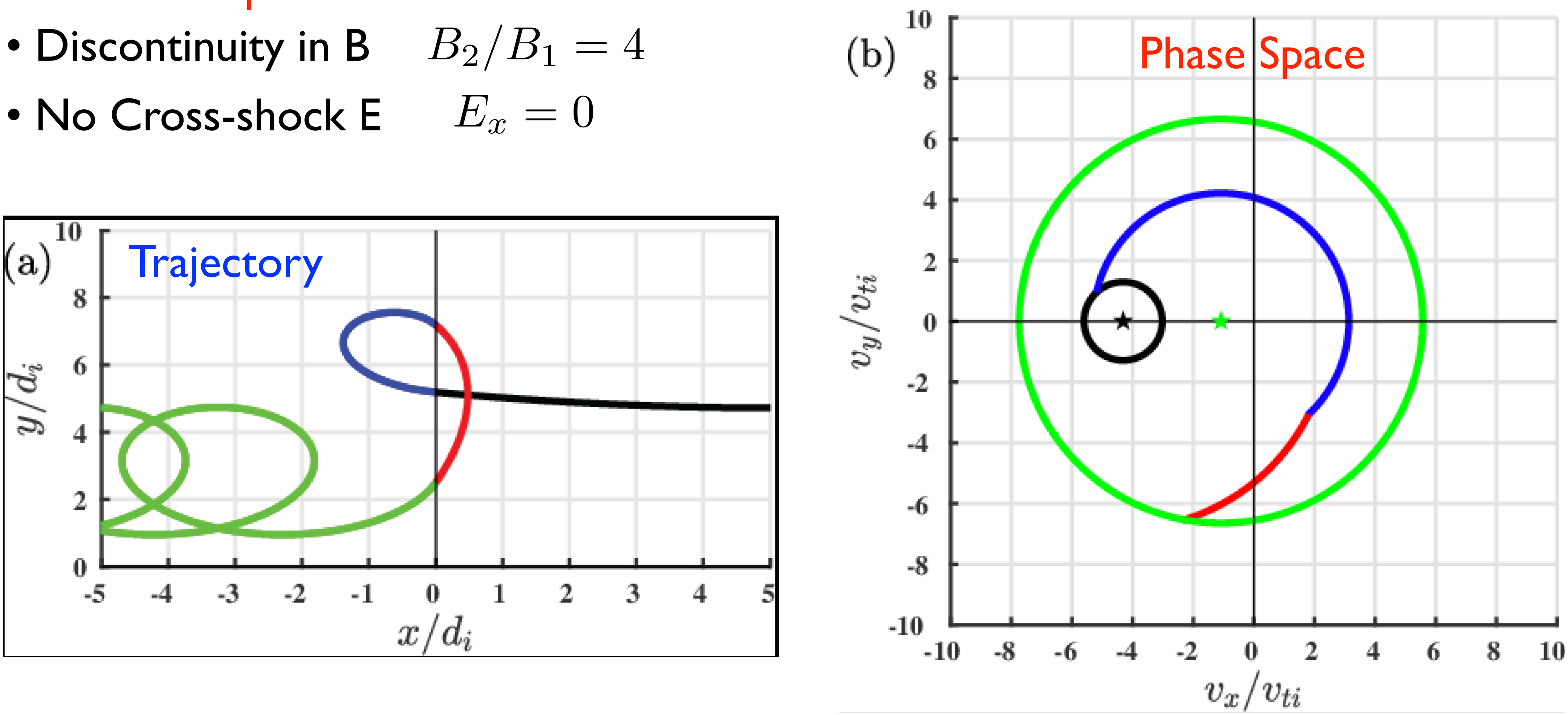
Shock Drift Acceleration by motional electric field E_y



Model of Perpendicular Collisionless Shock

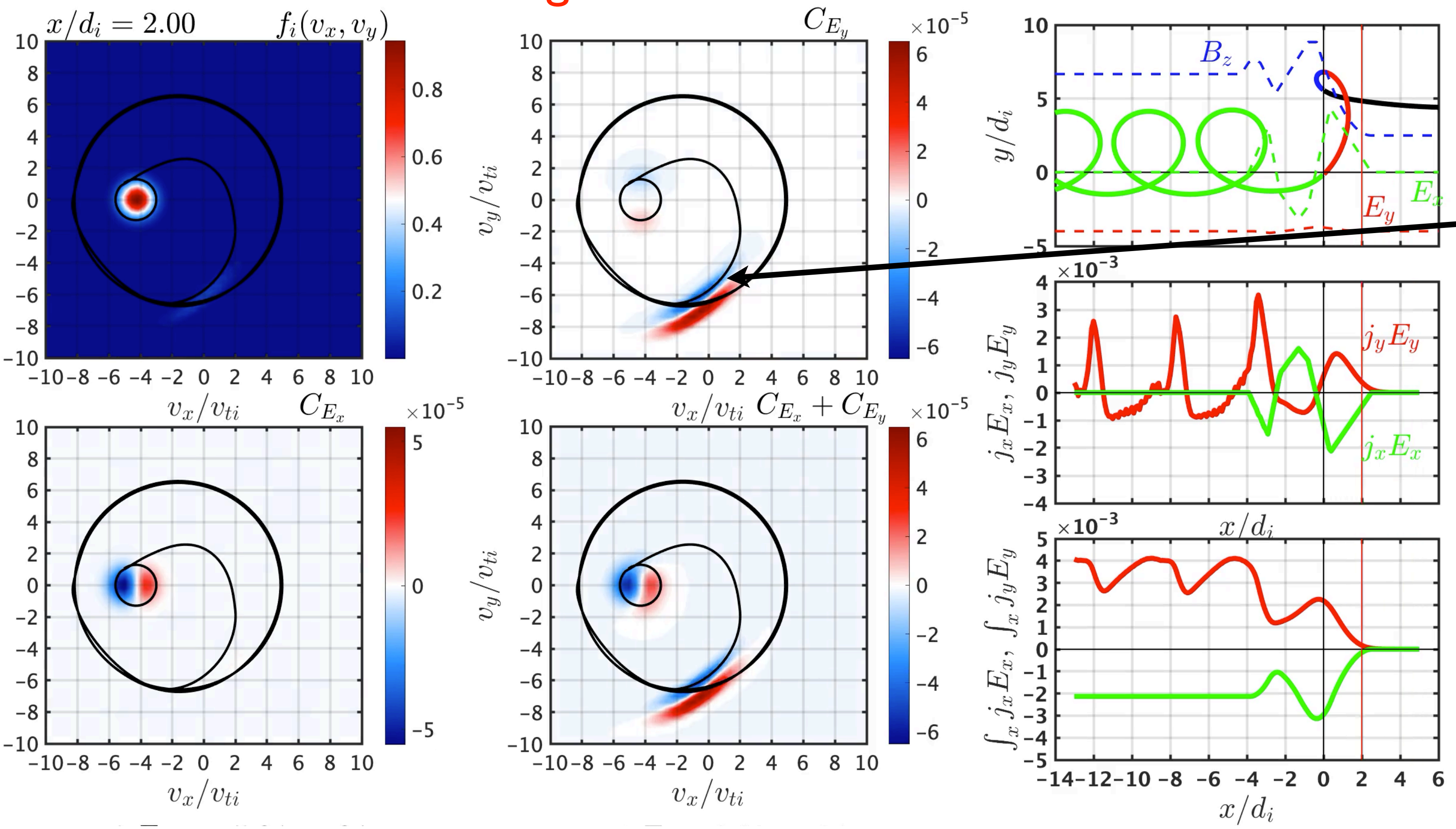
Idealized Perpendicular Shock Model

- Discontinuity in B $B_2/B_1 = 4$
- No Cross-shock E $E_x = 0$



Model of Perpendicular Collisionless Shock

Single-Particle-Motion Model



Ion Energization by E_y

Velocity-space signature of

Shock Drift Acceleration

Quasiperpendicular Shock $\theta_{Bn} = 45^\circ$

THE UNIVERSITY OF IOWA

Gkeyll Simulation

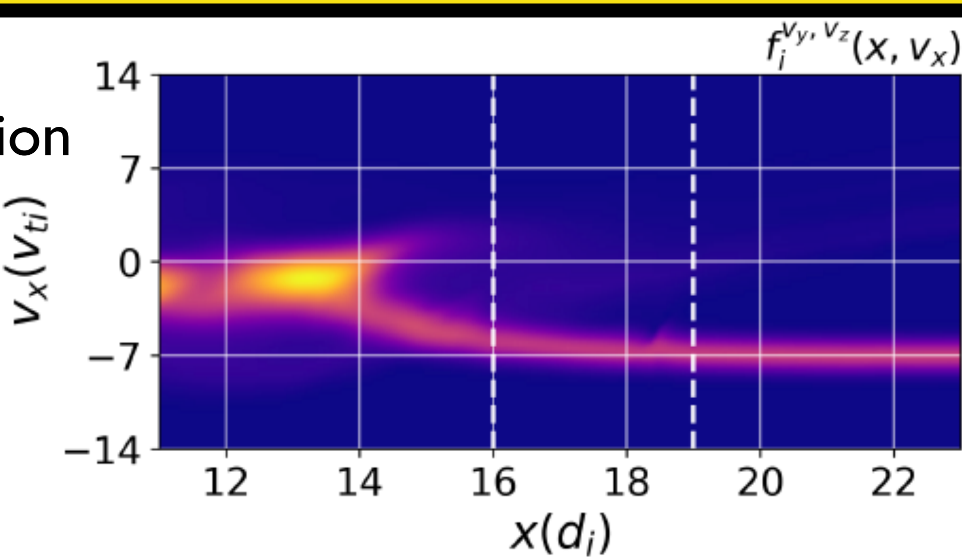
- 1D-3V simulation
- Supercritical

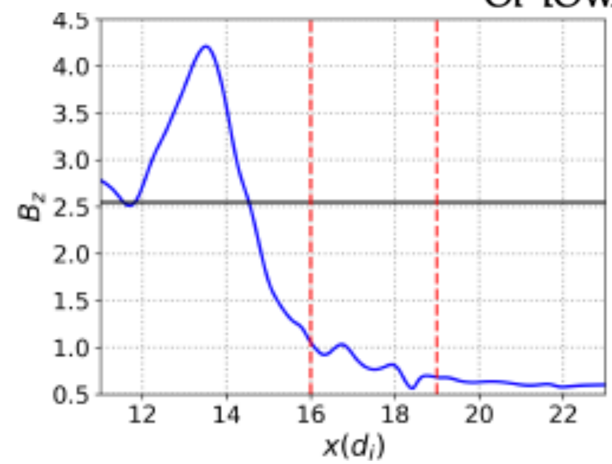
$M_A \simeq 8.3$

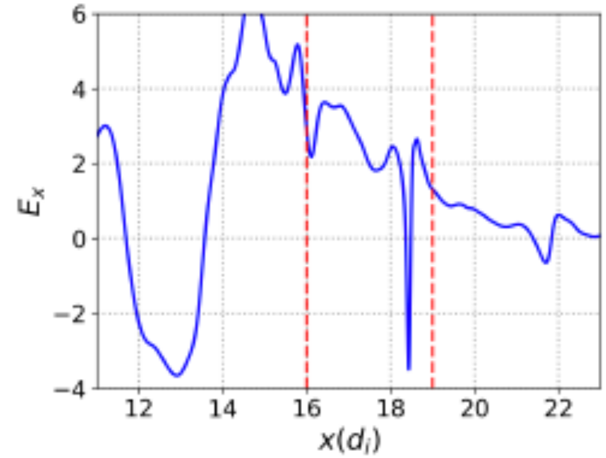
$\theta_{Bn} = 45^\circ$

$\beta_i = 1.3$

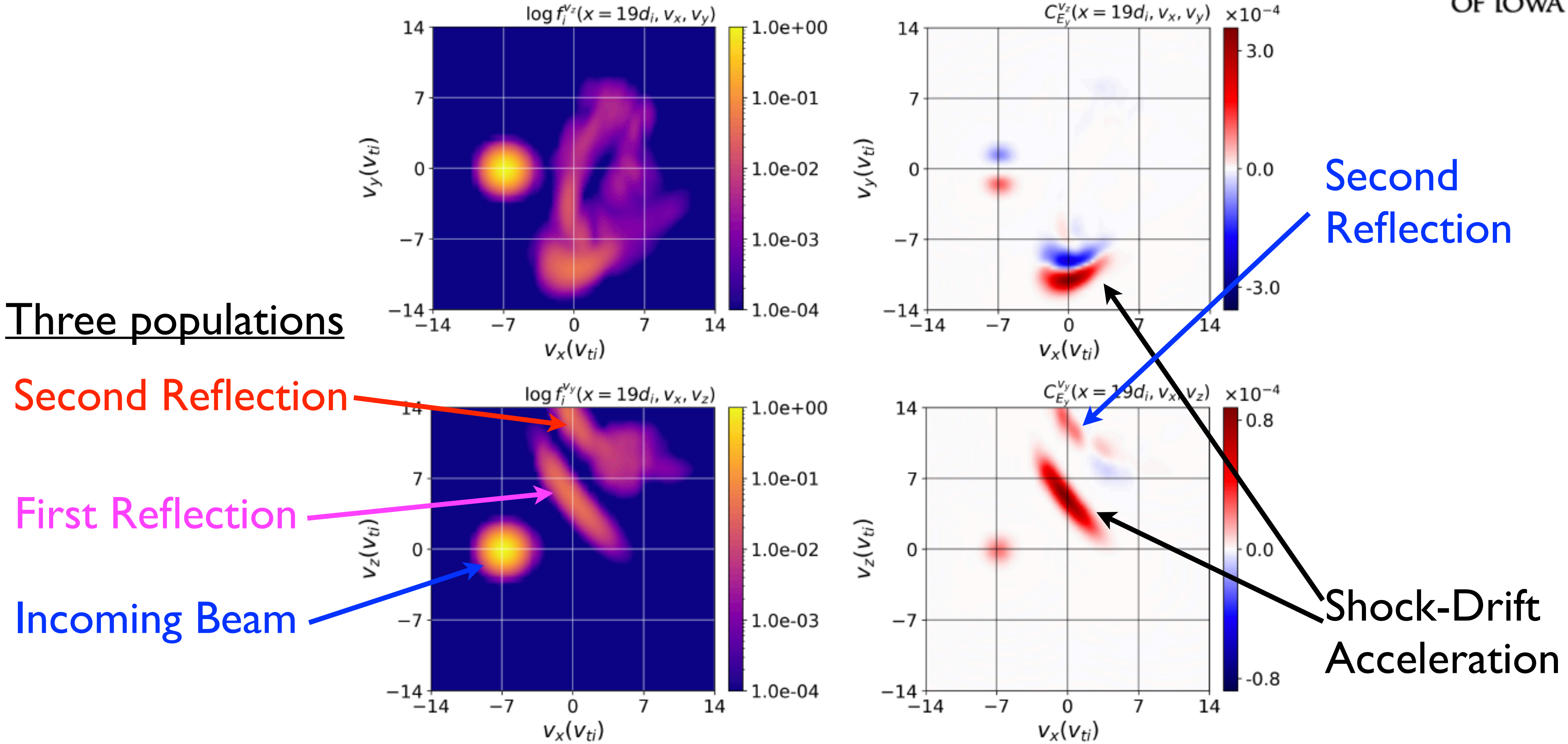
$\beta_e = 0.7$







Multiple Reflections $\theta_{Bn} = 45^\circ$

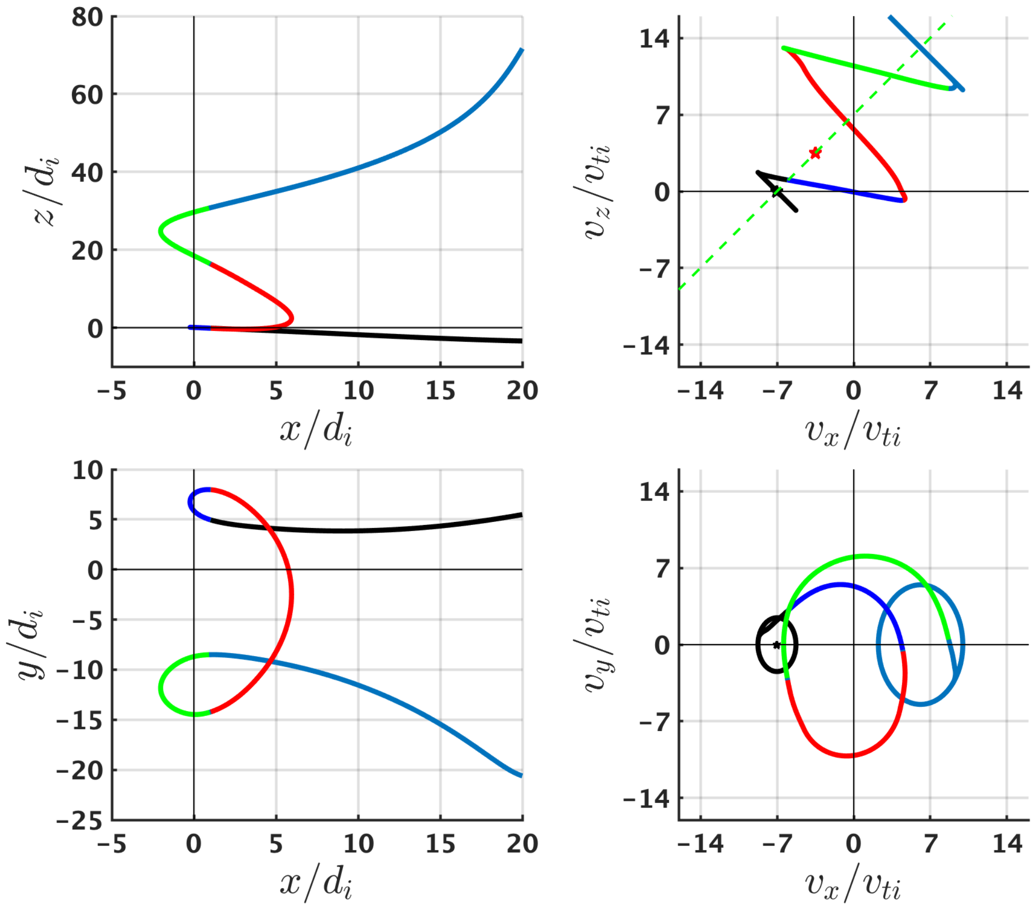


Multiple Reflections $\theta_{Bn} = 45^\circ$

The University of Iowa

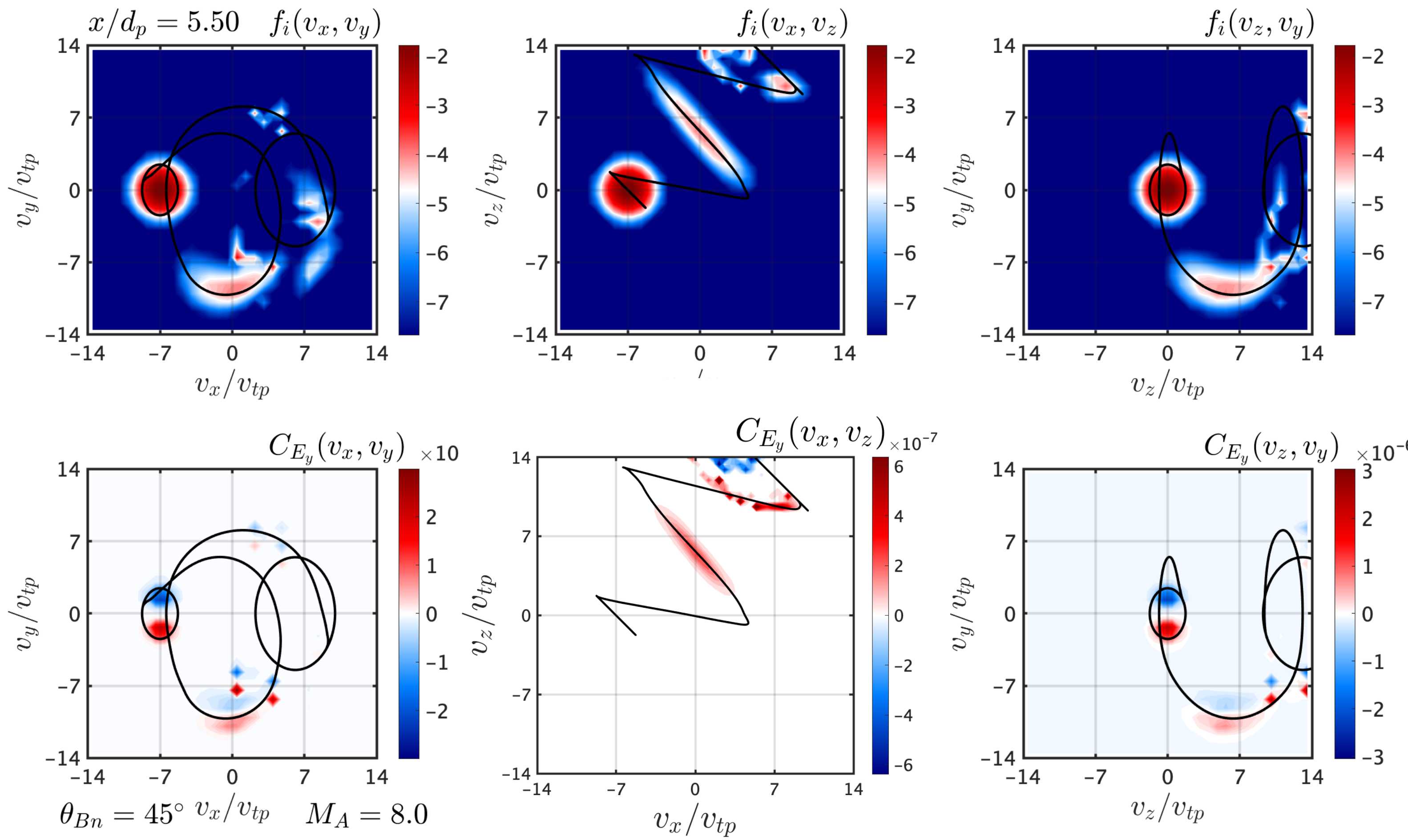
Spatial Trajectory

Velocity Trajectory



Multiple Reflections $\theta_{Bn} = 45^\circ$

Single Particle Motion Model



3D Simulation: Quasiperpendicular Shocks

THE UNIVERSITY OF IOWA

dHybridR Simulation

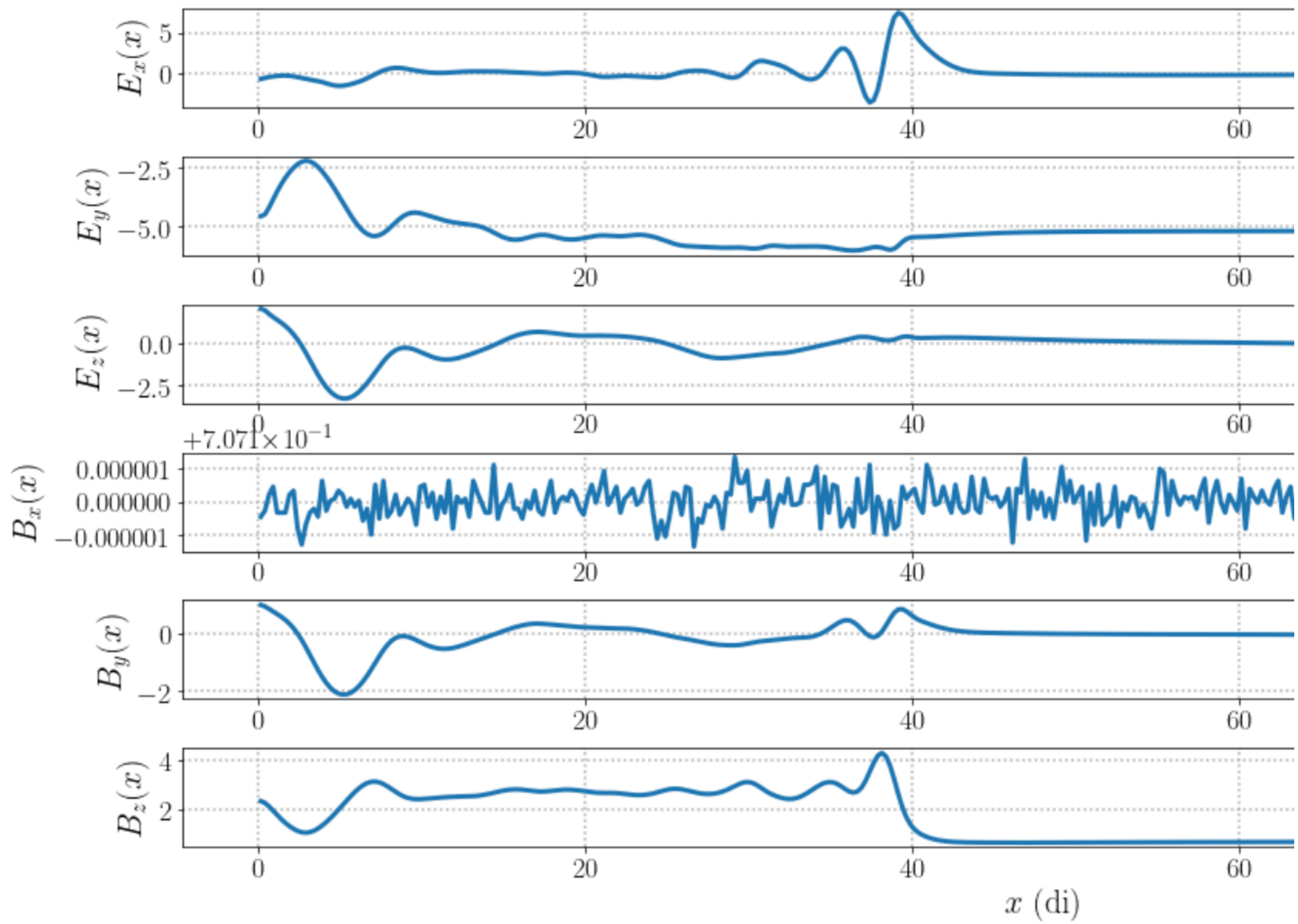
- 3D-3V simulation
- Supercritical

$$M_A \simeq 8.5$$

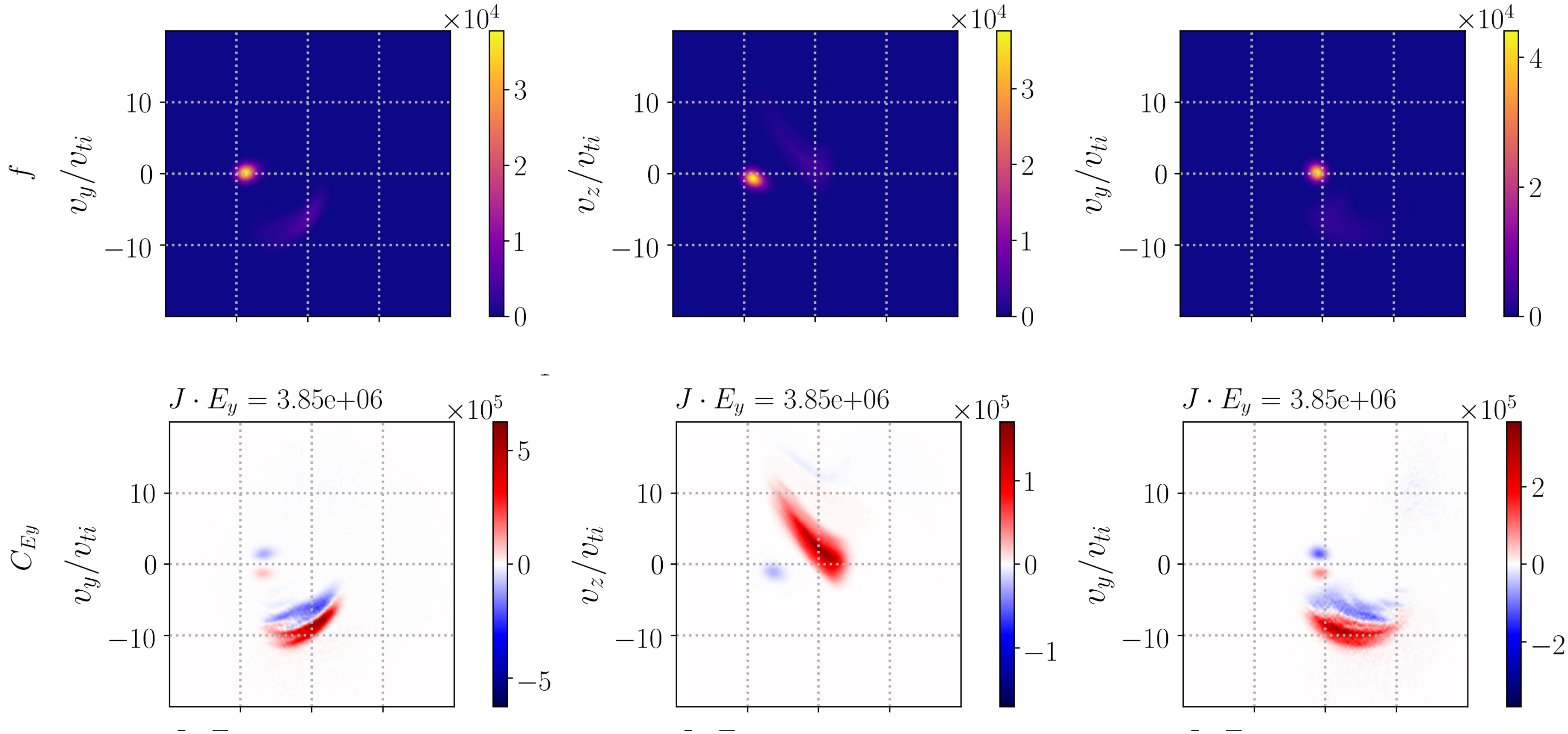
$$\theta_{Bn} = 45°$$

$$\beta_i = 1$$

$$\beta_e = 1$$

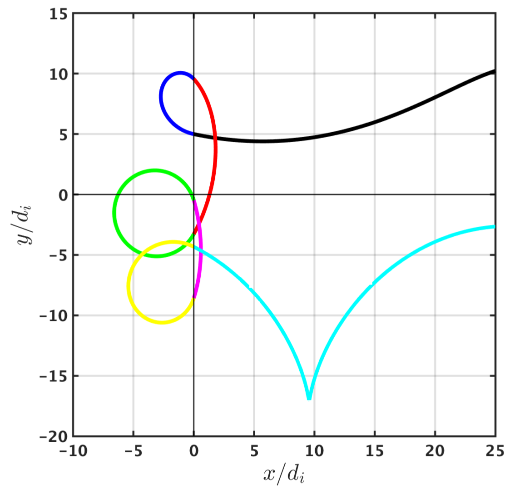


Quasiperpendicular Shocks: Multiple Reflections

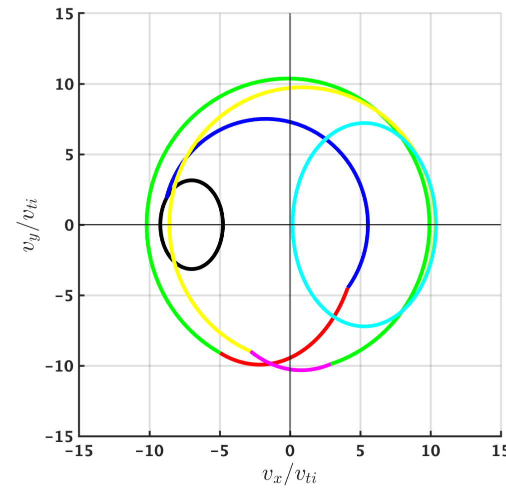


Quasiperpendicular Shocks: Multiple Reflections

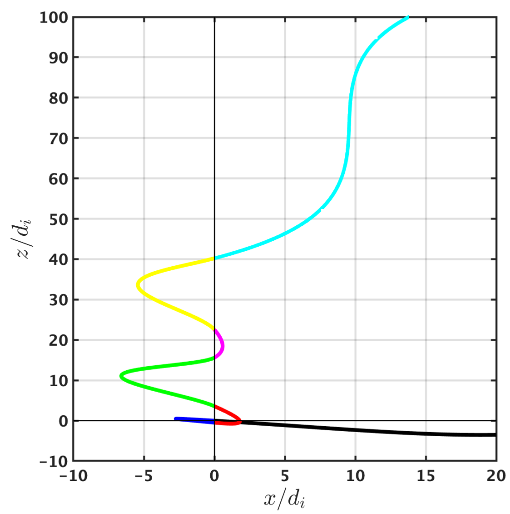
(x, y)



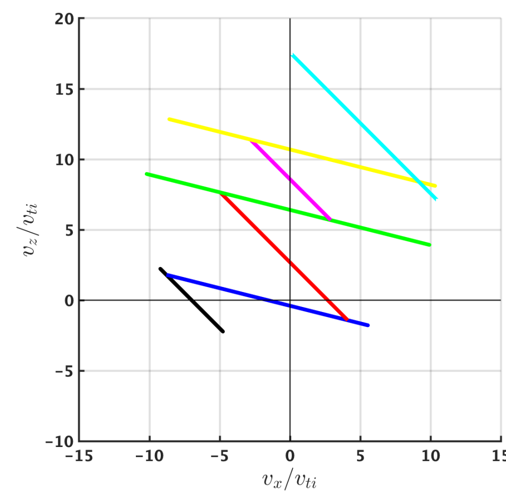
(v_x, v_y)



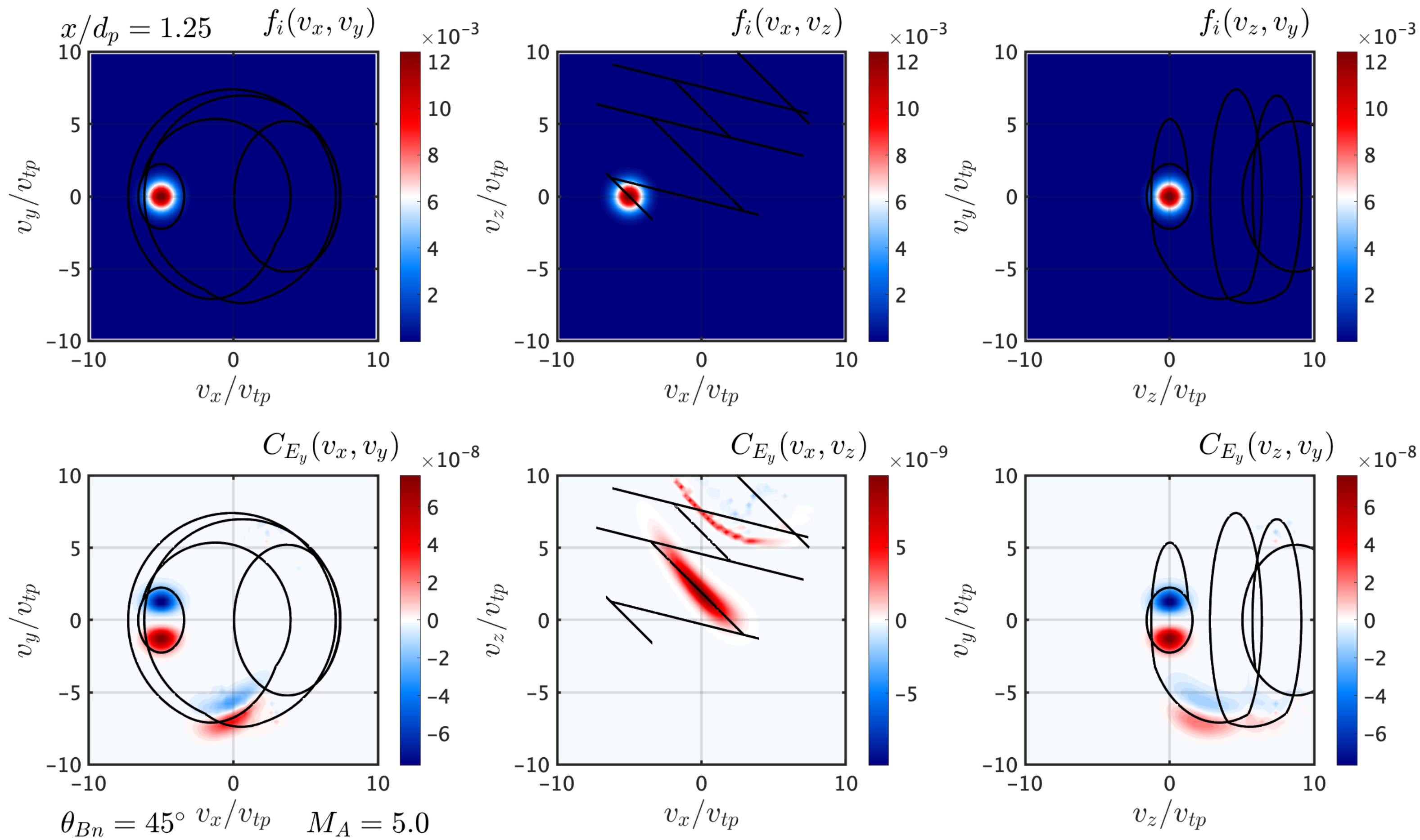
(x, z)



(v_x, v_z)



Quasiperpendicular Shocks: Multiple Reflections



Conclusions

- The Field-Particle Correlation Technique is an approach to quantify the energization of particles and identify the physical mechanism responsible

- Application to a Perpendicular Shock shows the energization by shock drift acceleration
- Application to a Quasiperpendicular Shock can separate energization of populations that experience different numbers of reflections

- Additional application (see Collin Brown's poster) to Energization by Instabilities may identify the instabilities at play