Kinetic Simulations of MMS Observations

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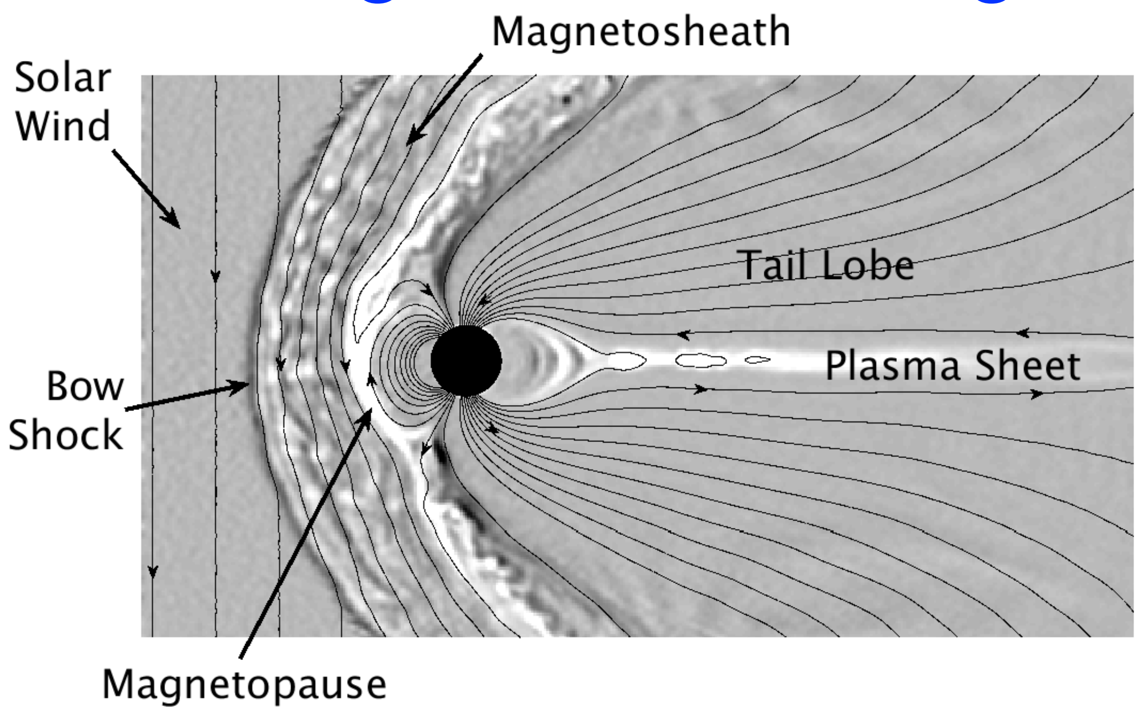
Fully kinetic simulations complement our team's global modeling efforts



- We study electron and ion physics of reconnection with local fully kinetic simulations, mainly with explicit code VPIC
- Useful for code comparison/verification of hybrid and fluid reduced models (e.g., Ng et al. PoP 2015, Stanier et al. PRL 2015)
- Detailed validation now possible with MMS measurements (so far, primarily of magnetopause reconnection) that resolve electron kinetic scales

Recent Large 3D Kinetic PIC Calculation

- MMS observations of magnetopause reconnection confirm many features consistent with 2D kinetic simulations - *Burch et al, 2016*

- However, we know that 2D simulations suppress a range of interesting 3D physics: flux ropes, field line chaos, kinetic instabilities

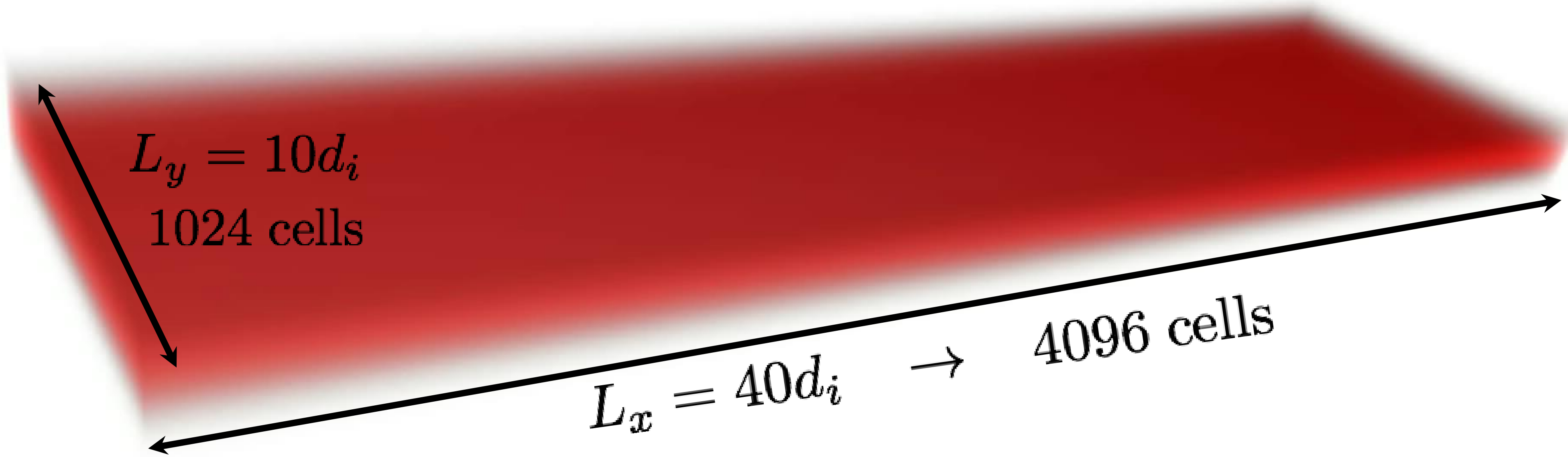
- Lower-hybrid drift instability (LHDI) has long been considered as one possible source of anomalous dissipation:
  - Theory, simulation, spacecraft observations + lab expt suggest LHDI is too weak to generate anomalous dissipation at X-line, but can generate dissipation along separatrices (*Roytershteyn et al,* 2012, 2013)
  - Recent 3D kinetic simulations suggest significant anomalous dissipation within electron dissipation region - *Price et al, 2016*

- We re-consider this MMS event using the VPIC code, running on Trinity ... newest supercomputer at Los Alamos

- Conclusions: 1. Anomalous resistivity is weak / viscosity significant
  2. Electron mixing and parallel heating are strongly modified
  3. Electron crescent distributions survive

Fully kinetic simulation matching parameters of MMS diffusion region encounter - Oct 16, 2015

$m_i/m_e = 100$

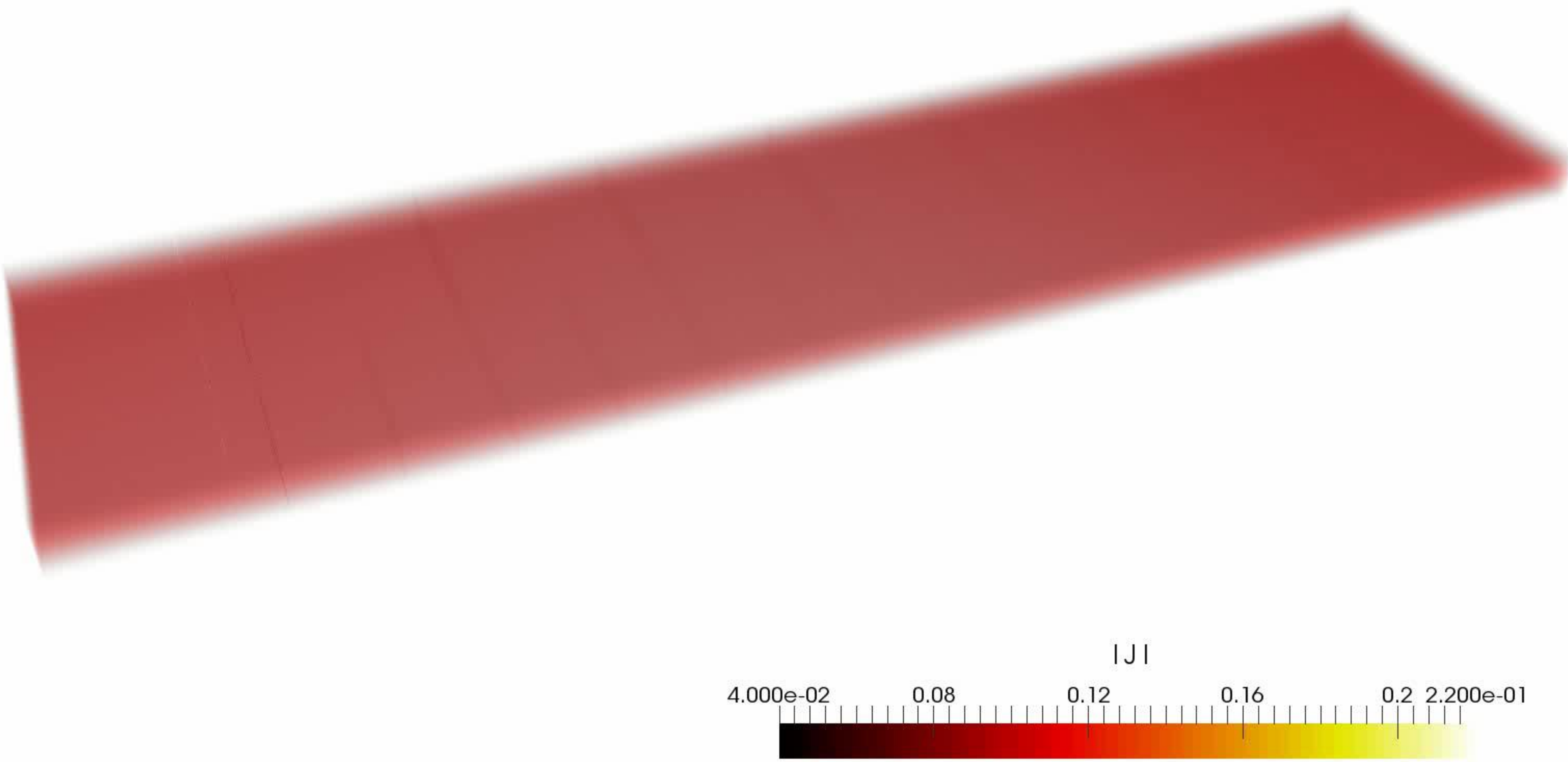


$L_z = 20d_i \rightarrow$ 2048 cells

$B_g \sim 0.1\ B_{sheath}$
$n_{sh}/n_{sph} \sim 16$
$T_{ish}/T_{isph} \sim 6$

- Sphere & sheath particles tracked separately
- Different macroparticle weights
- 150/part cell - 2.6 trillion particles total
- Good statistics on BOTH sides of layer
- 2x spatial resolution ... run 2x longer

Fully kinetic simulation matching parameters of MMS



$n_{sh}/n_{sph} \sim 16$

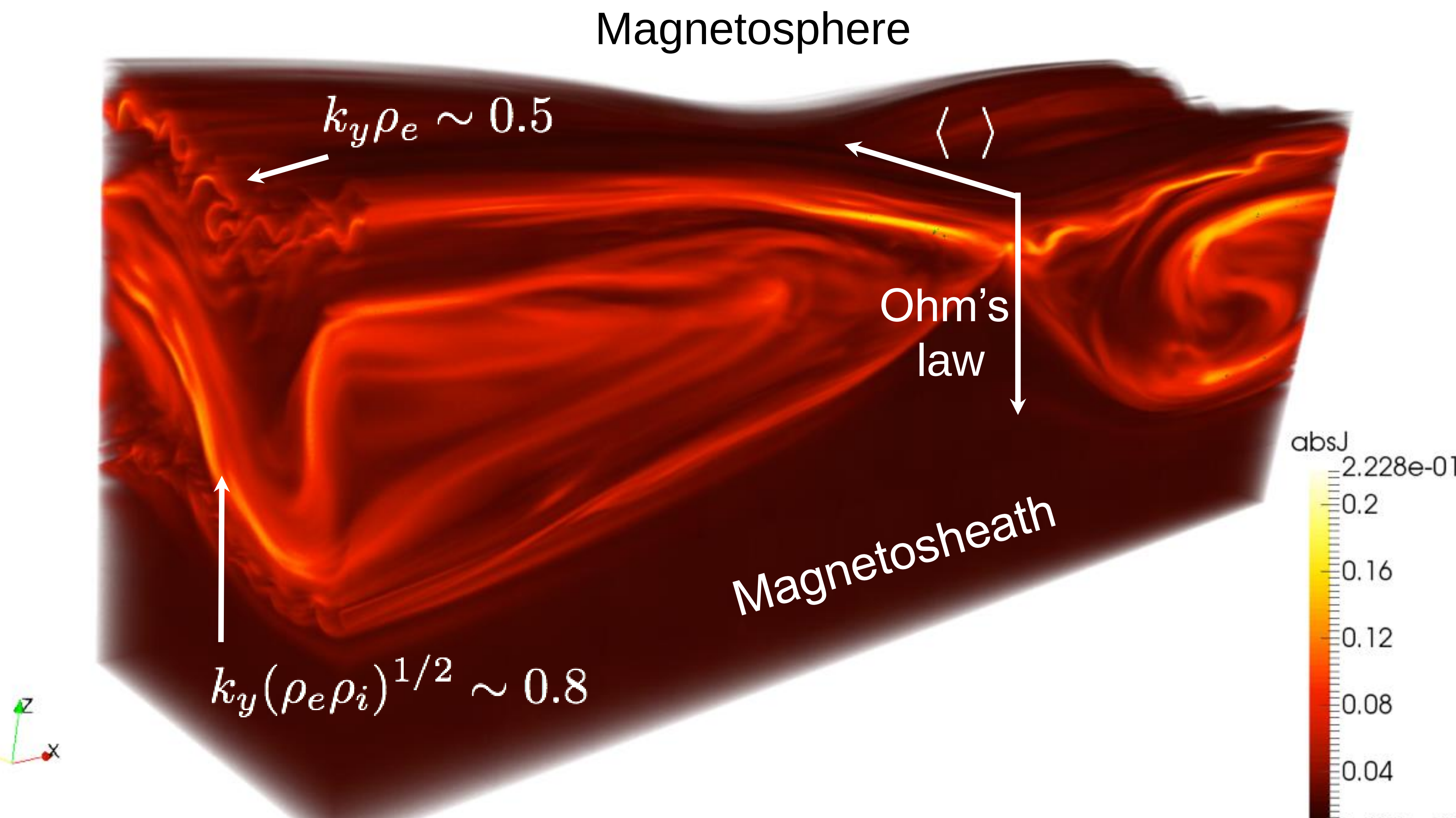
$T_{ish}/T_{isph} \sim 6$

- Good statistics on BOTH sides of layer
- 2x spatial resolution ... run 2x longer

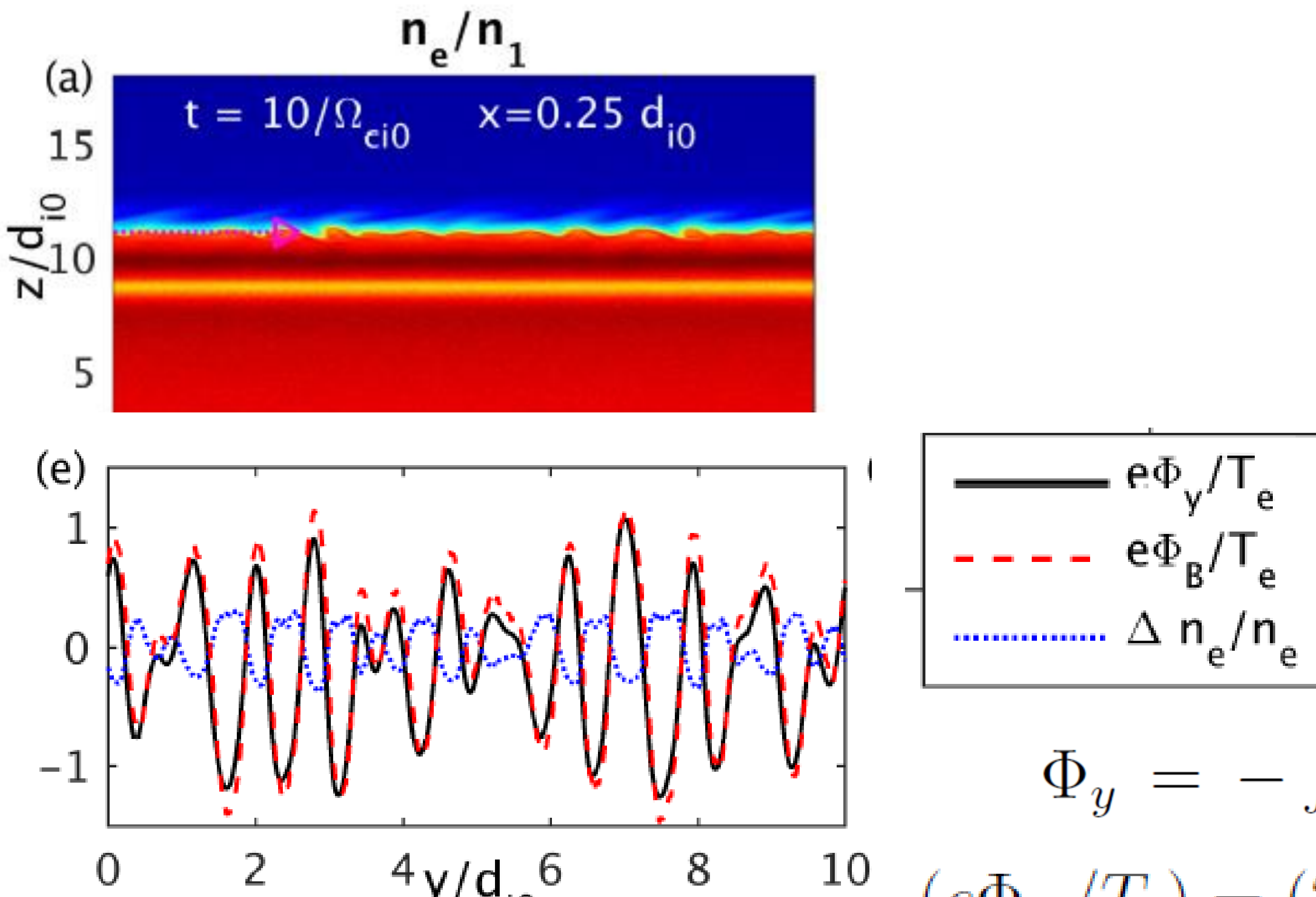
Spectrum of LHDI modes observed, consistent with Vlasov theory & previous kinetic simulations

Daughton, 2003

Roytershteyn et al, 12, 13



LHDI Mode Structure Near Edge of Simulation Domain



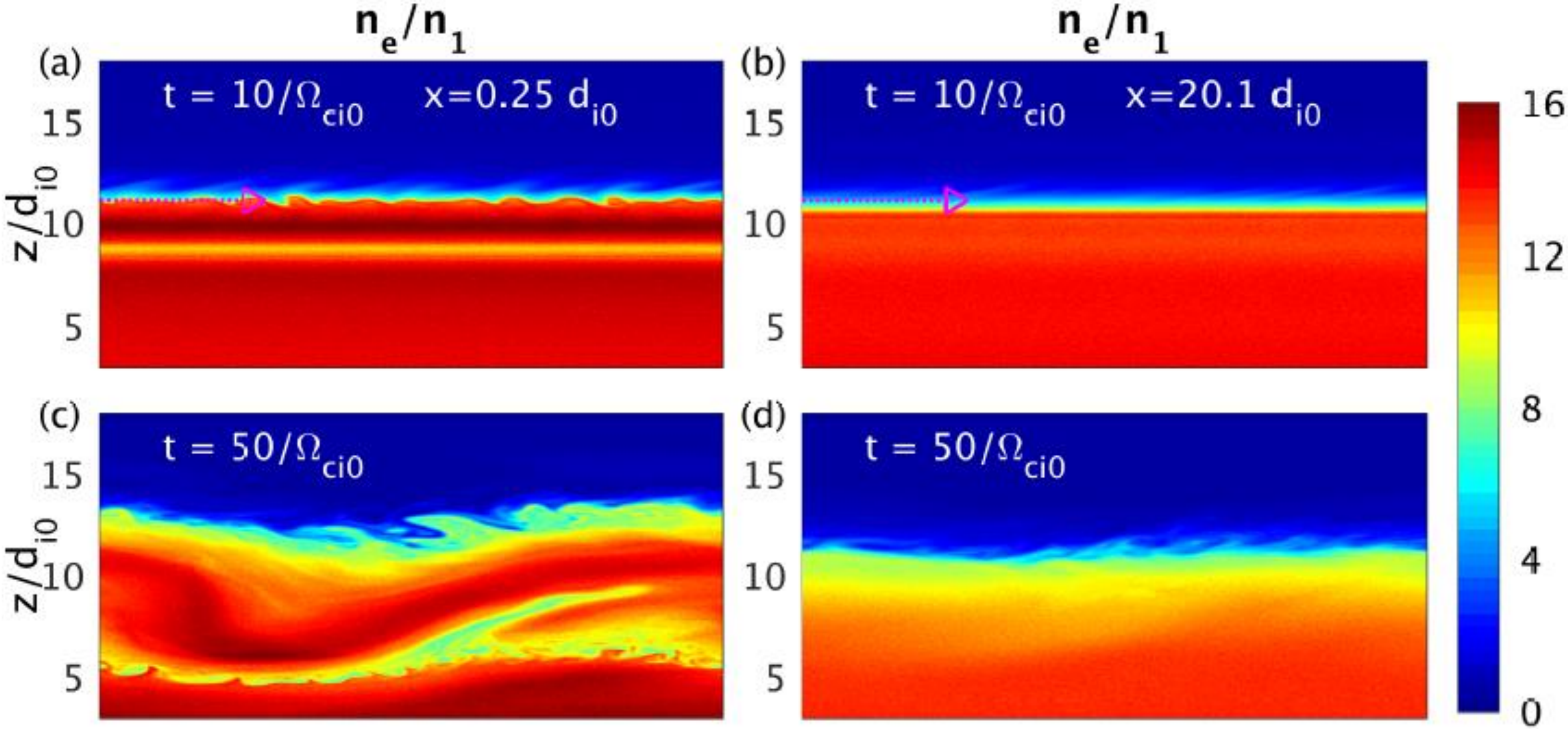
$$\Phi_y = -\int E_y dy$$

$$(e\Phi_B/T_e) = (2/\beta_e)(\Delta B_x/B_x)$$

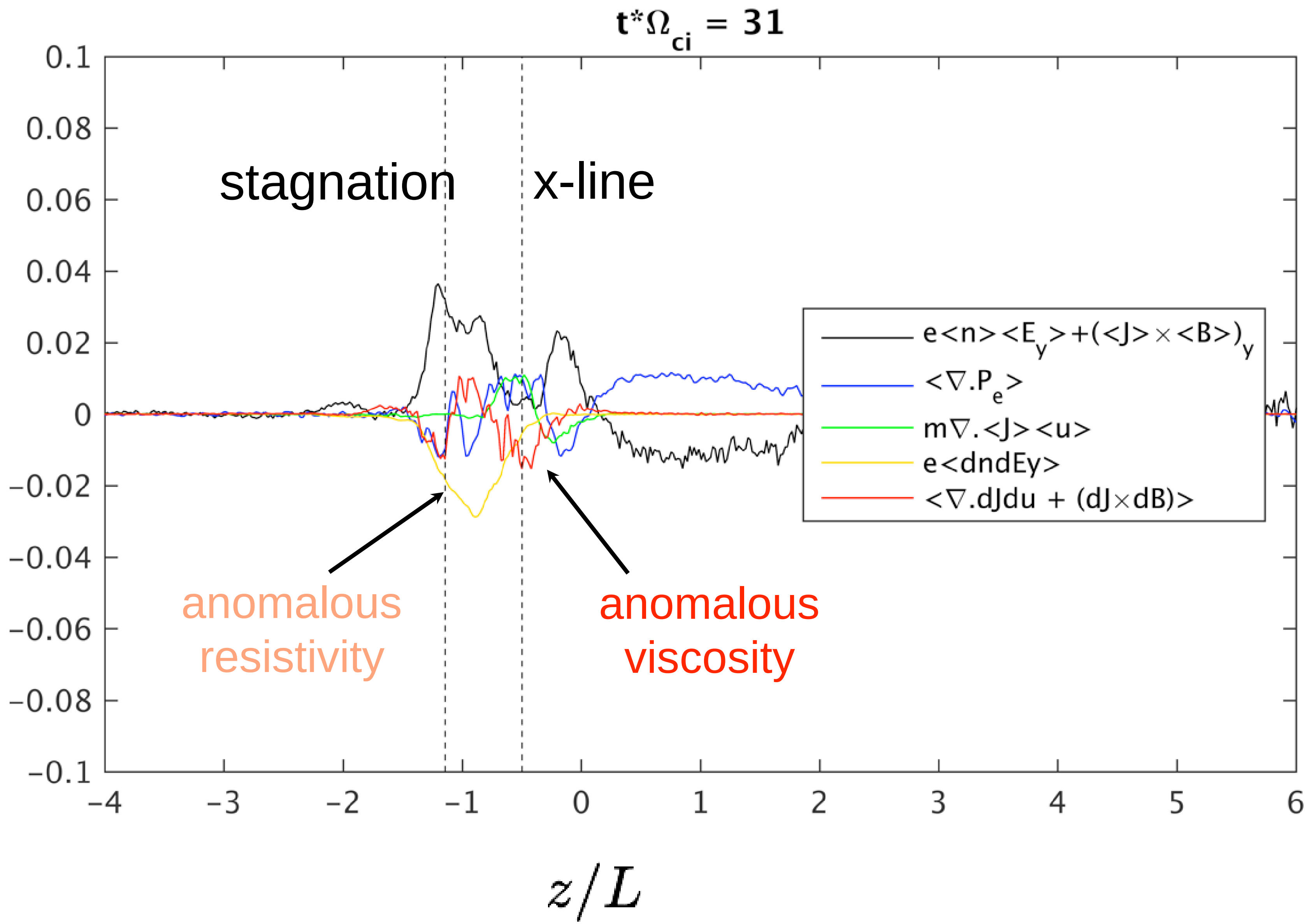
Current flow (y, out of plane) direction

Norgren et al. PRL (2012)

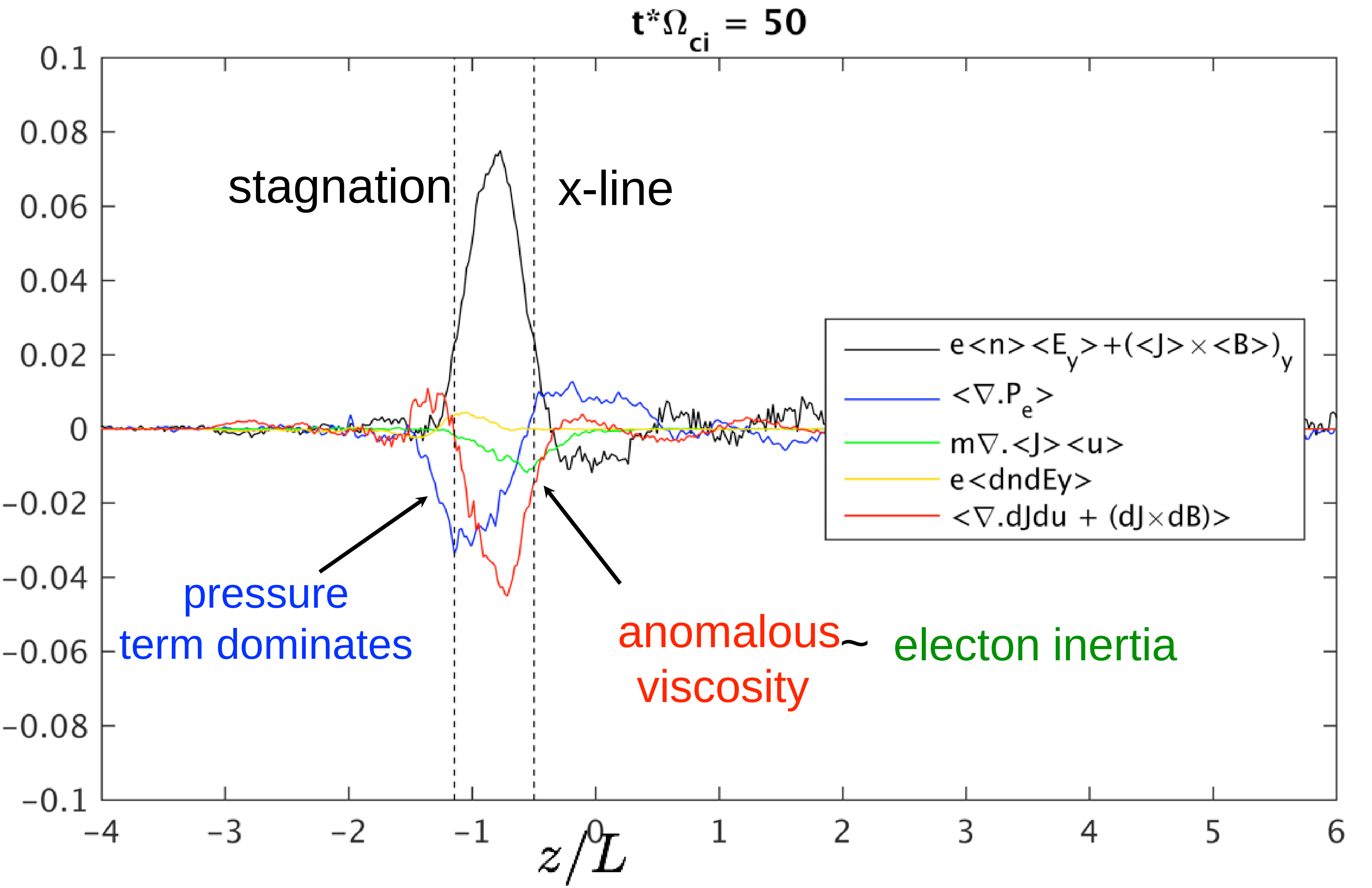
Fluctuations Become Turbulent at Later Time



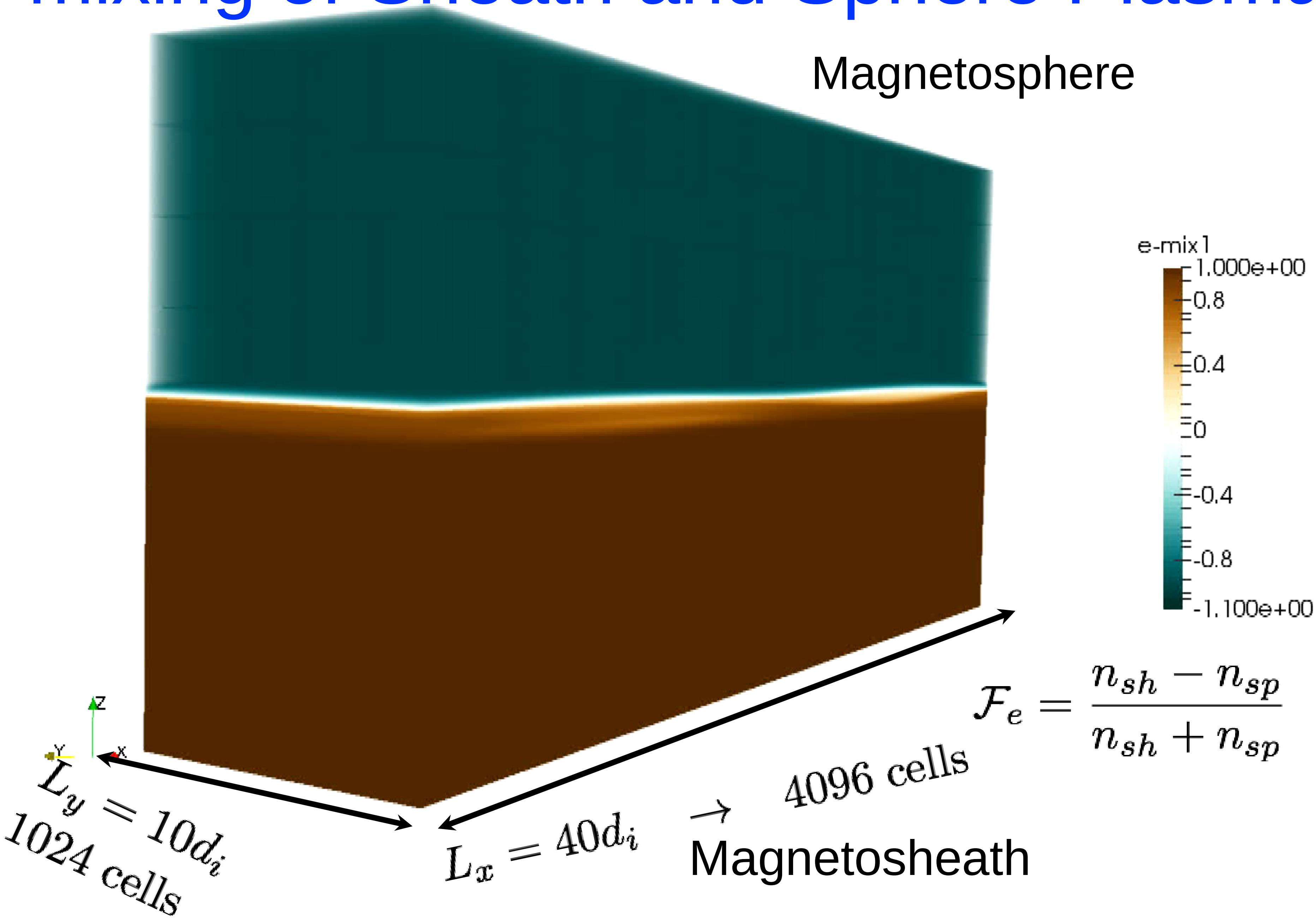
Early time evolution shows evidence of anomalous resistivity and viscosity



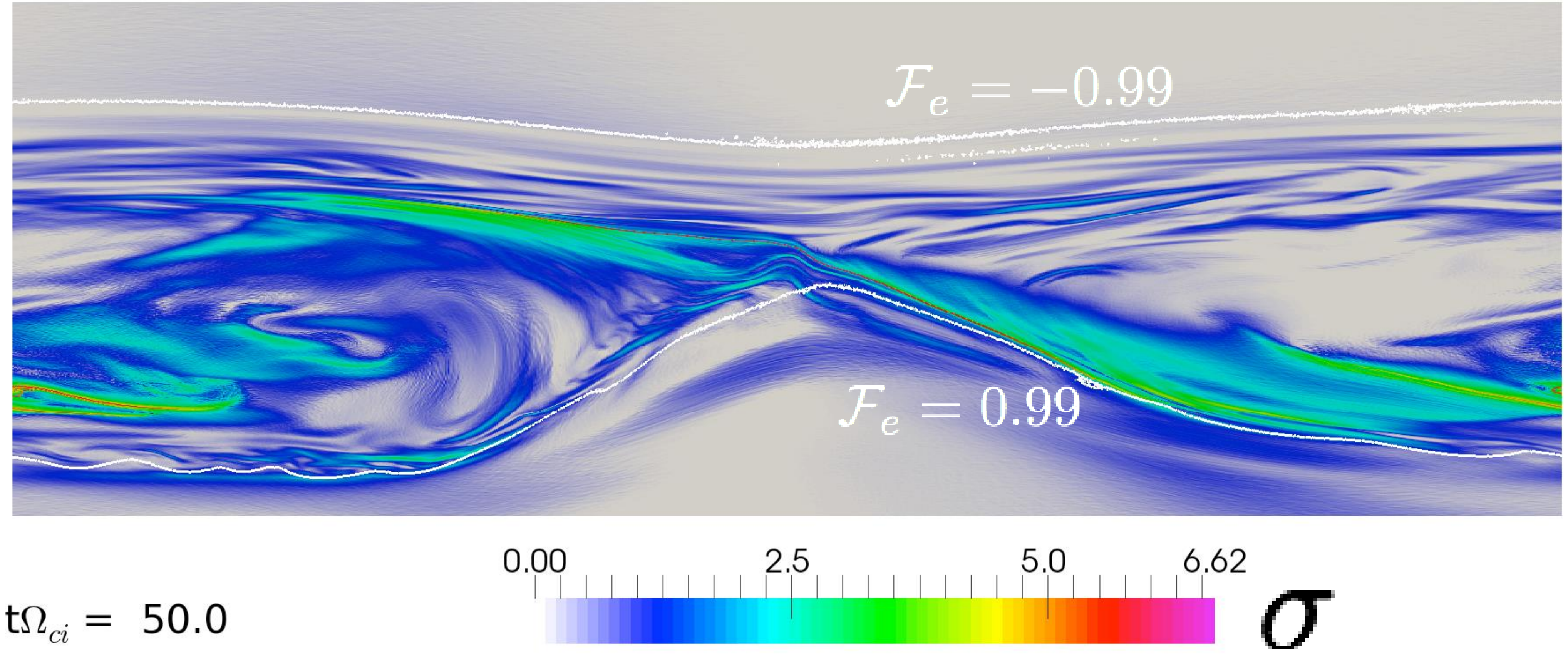
At later times, anomalous resistivity is small but anomalous viscosity is significant



LH Turbulence gives rise to strong mixing of Sheath and Sphere Plasmas

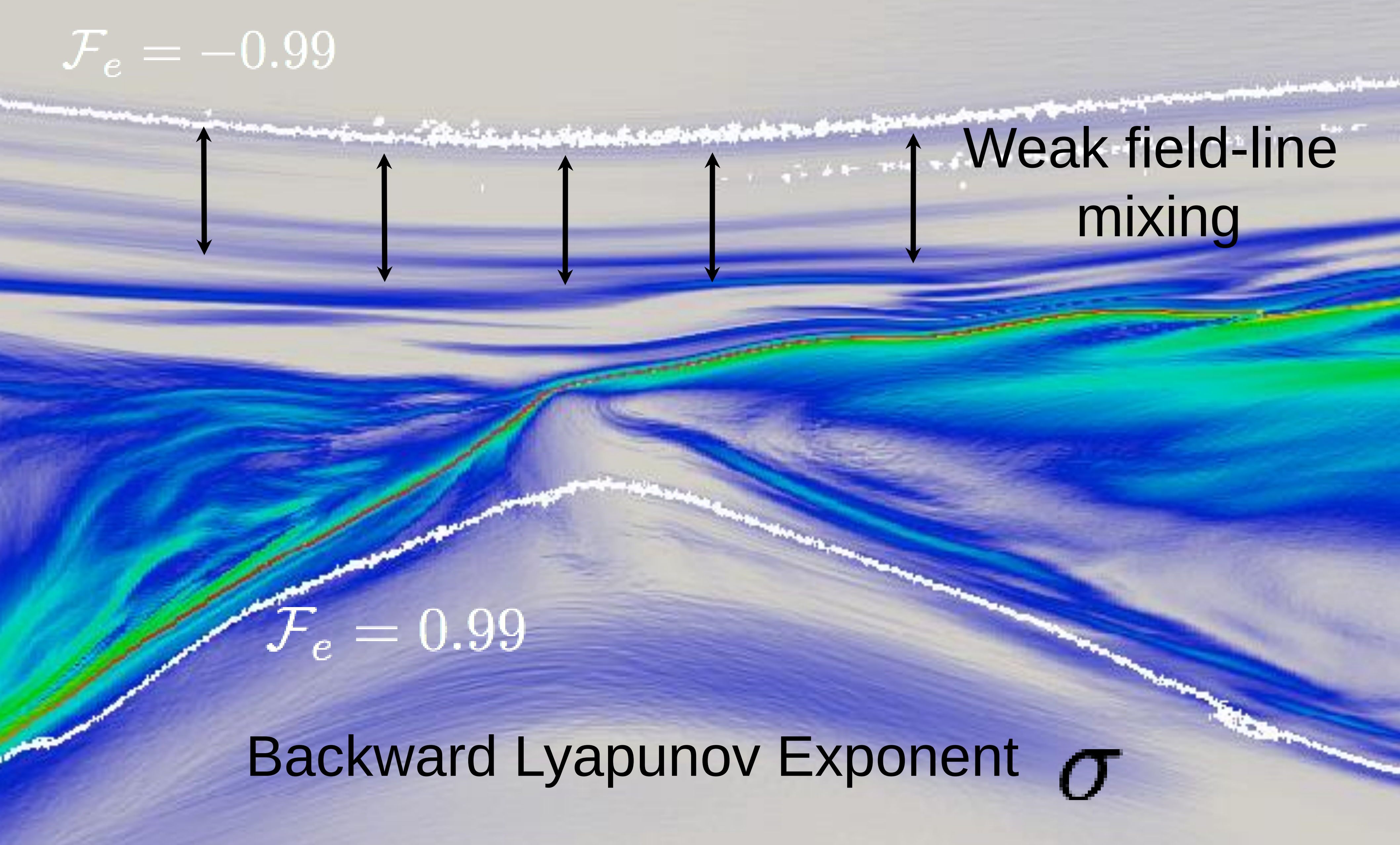


Turbulence leads to strong particle mixing but NOT strong field line mixing

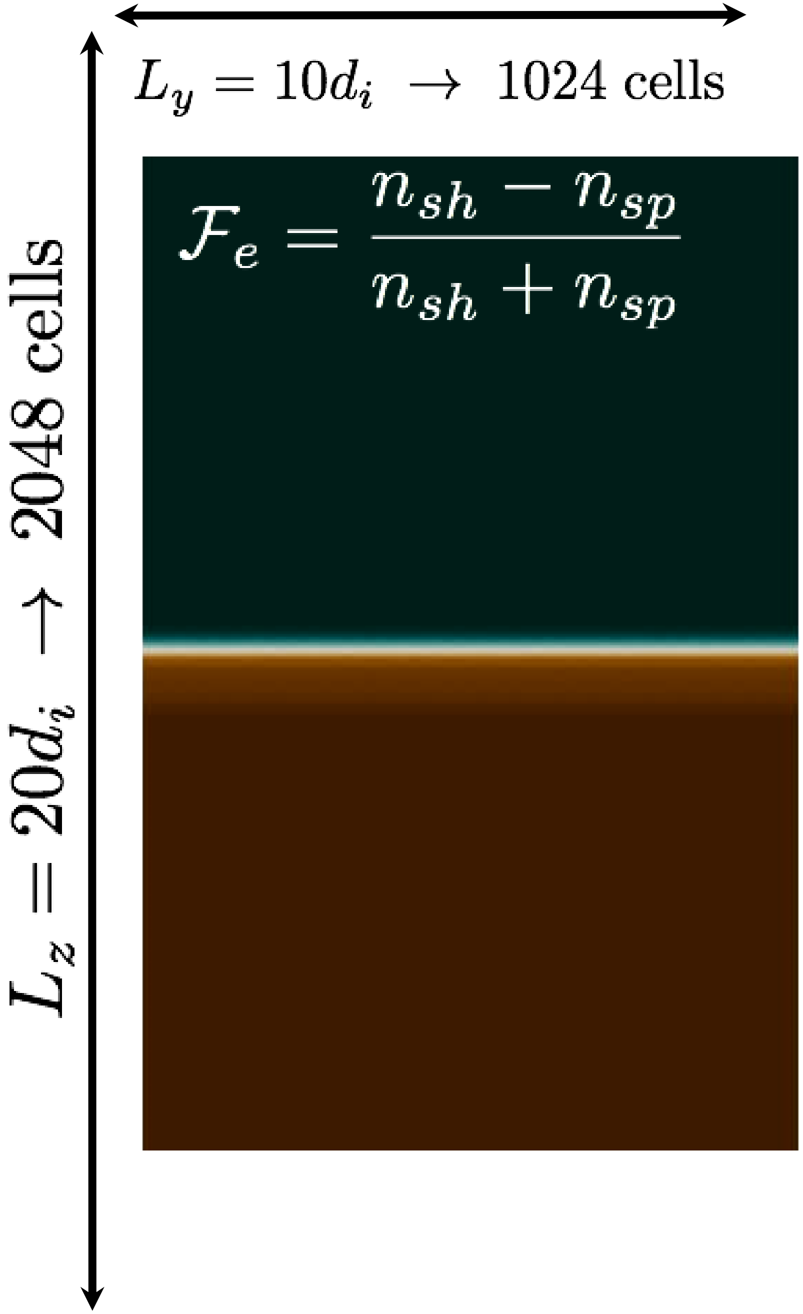


Forward Lyapunov Exponent

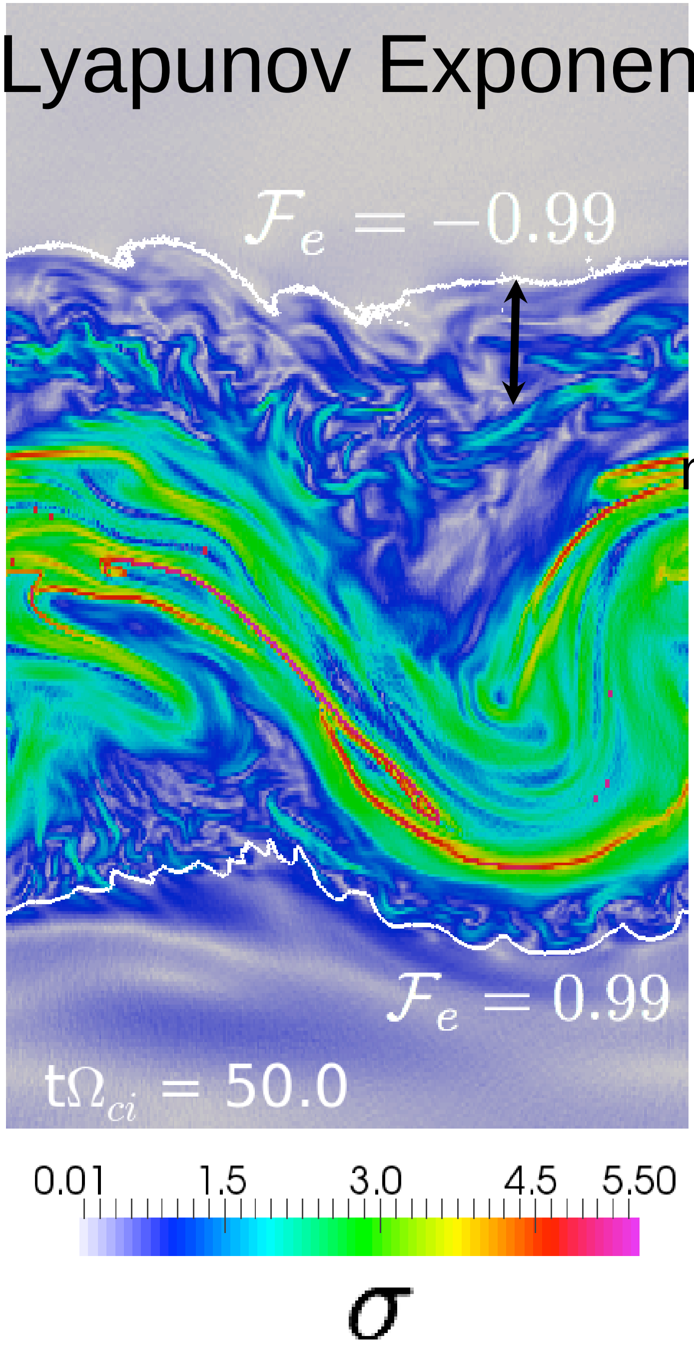
Turbulence leads to strong particle mixing but NOT strong field line mixing



Side View of Mixing Dynamics

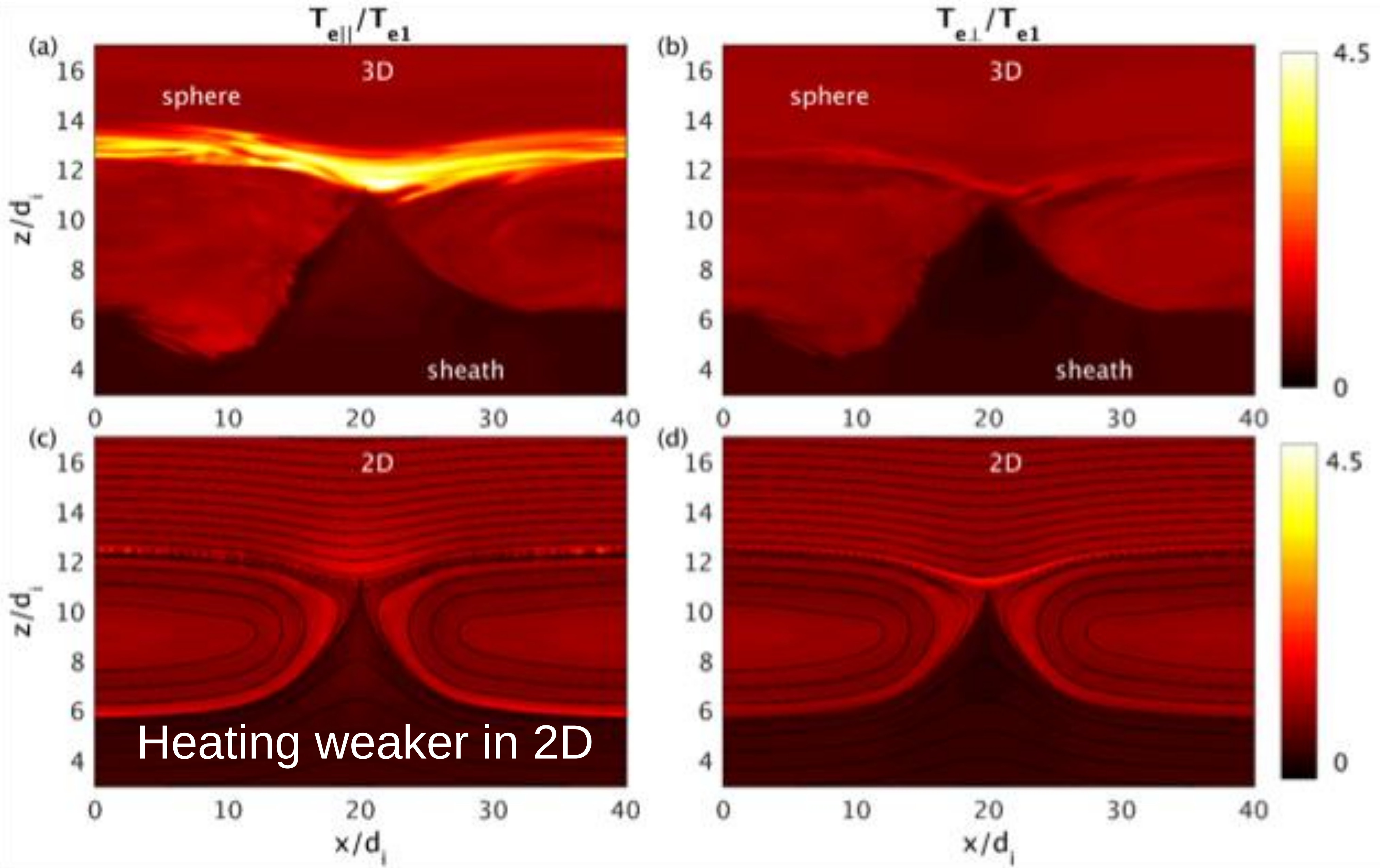


Lyapunov Exponent

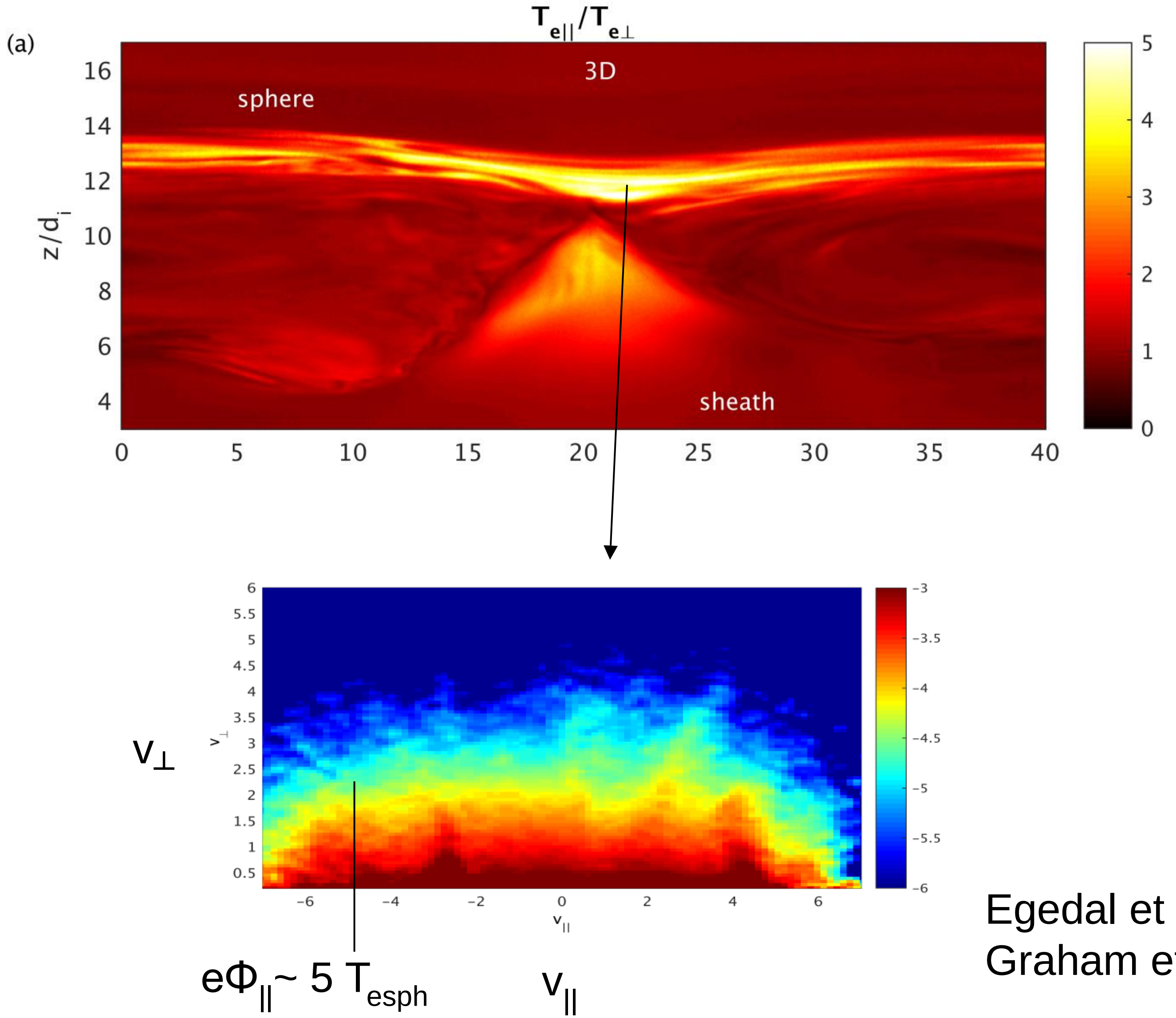


Mixing of particles but NOT magnetic field lines

Electron parallel heating is observed within mixing layer along the sphere separatrix in 3D

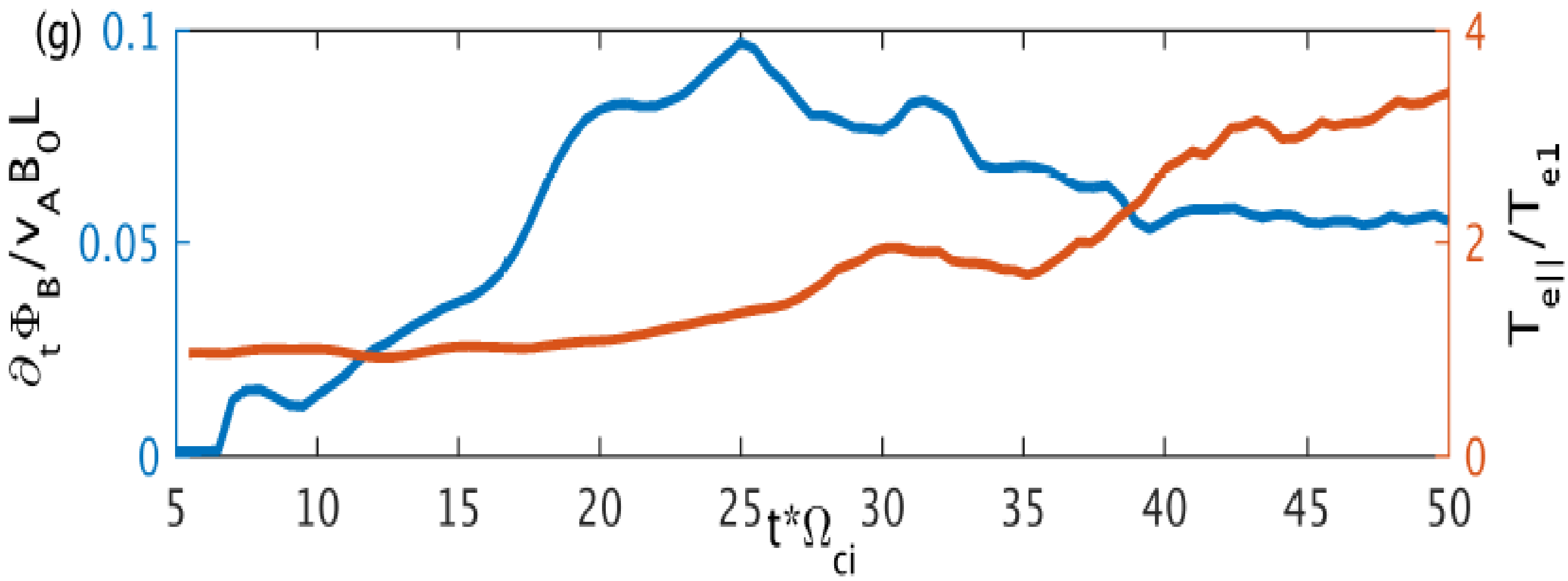


Characteristic Electron Distribution in Magnetosphere Inflow



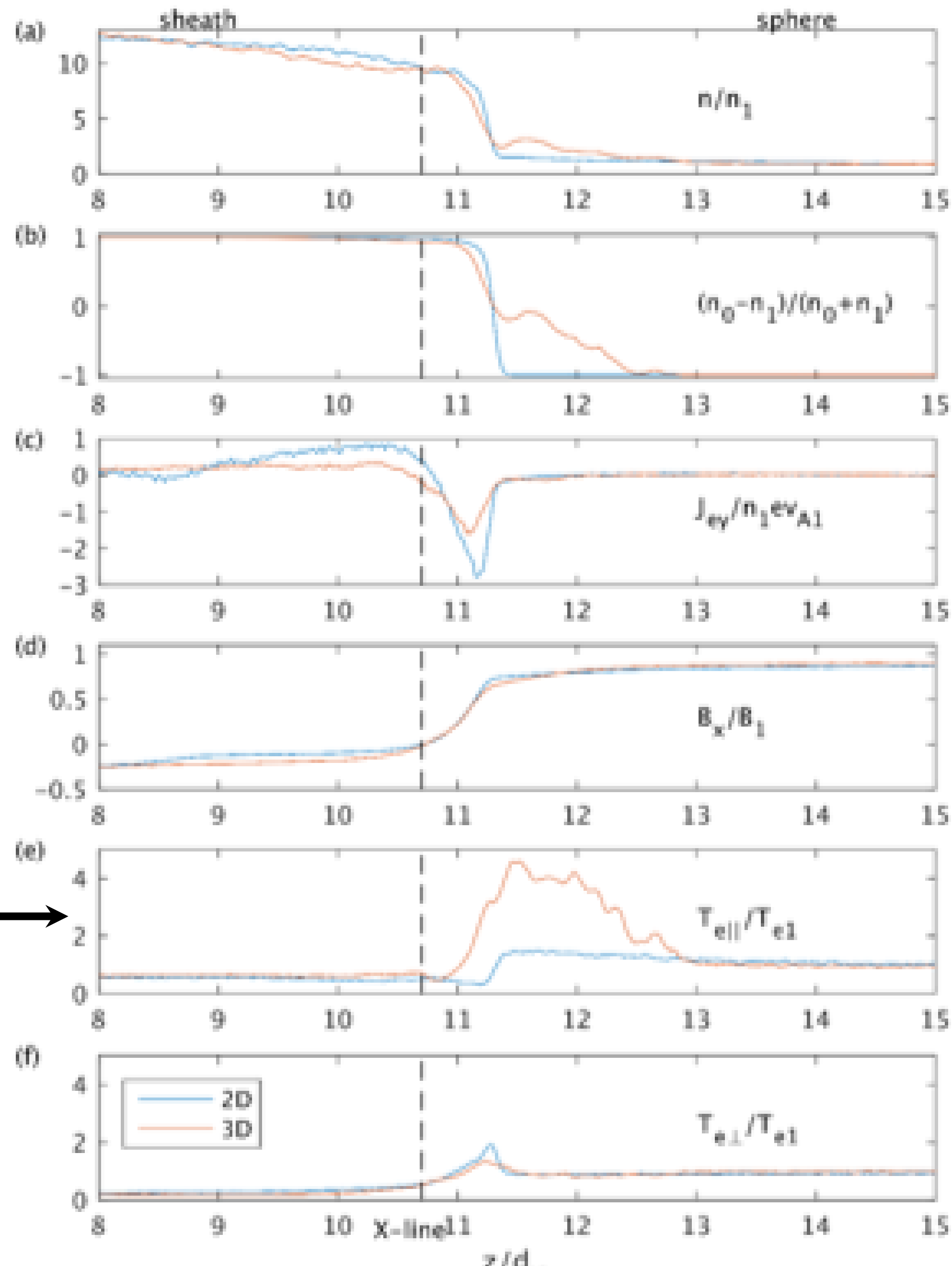
Egedal et al., JGR (2008)
Graham et al., GRL (2016)

Parallel electron temperature rises after transient peak in reconnection rate



Cut through x-line show enhanced mixing and electron heating in 3D

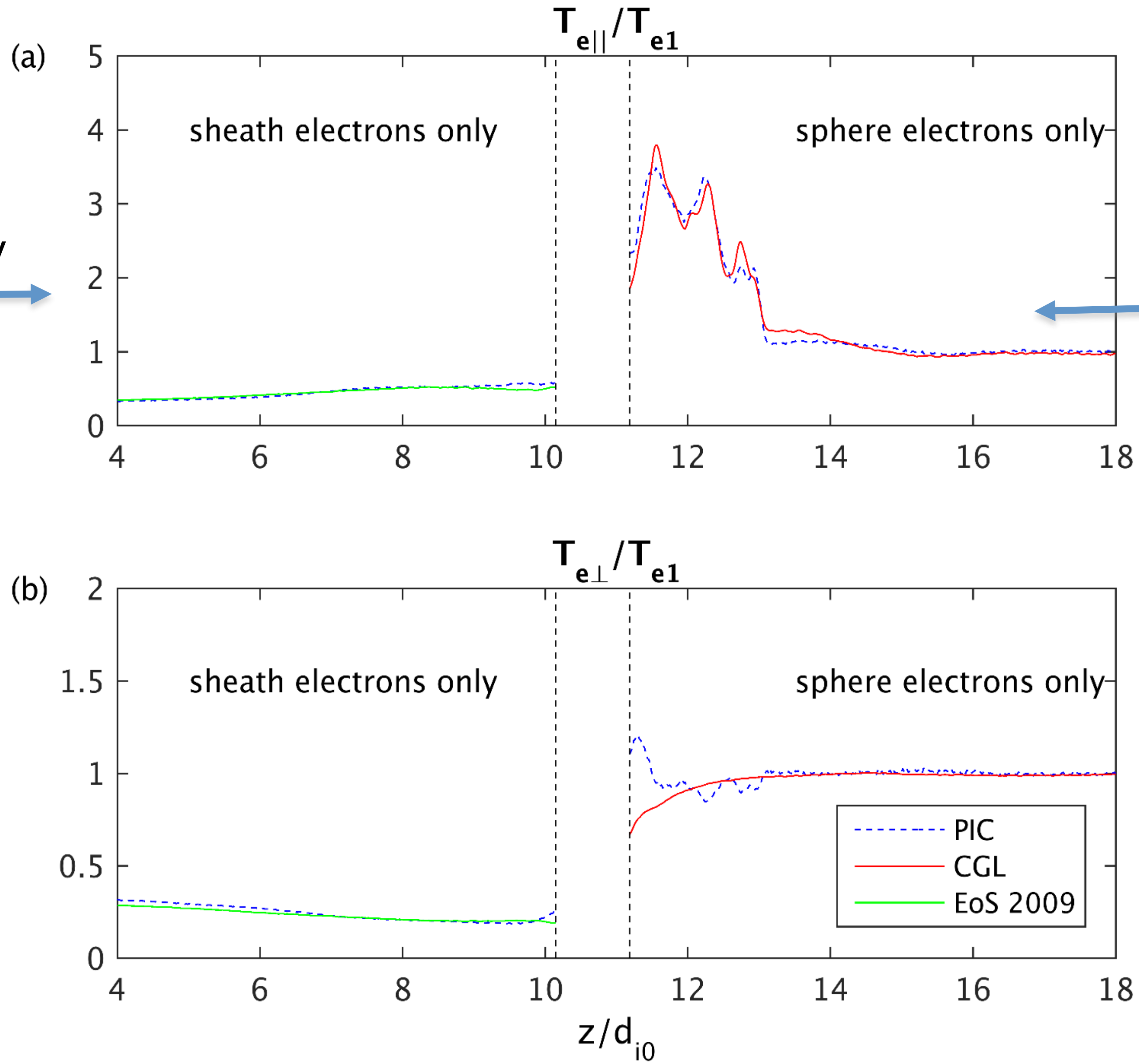
Electron mixing



Strong parallel electron heating Also observed by MMS (Burch et al., Science, 2016)

Parallel heating of magnetosphere electrons is consistent with CGL scaling

Sheath inflow electrons obey EoS of Le et al. PRL (2009)



Sphere electrons follow CGL EoS

$$T_{e||} \propto n^2/B^2$$

$$T_{e\perp} \propto B$$

Electron parallel heating observed in 3D simulations is consistent with MMS observations

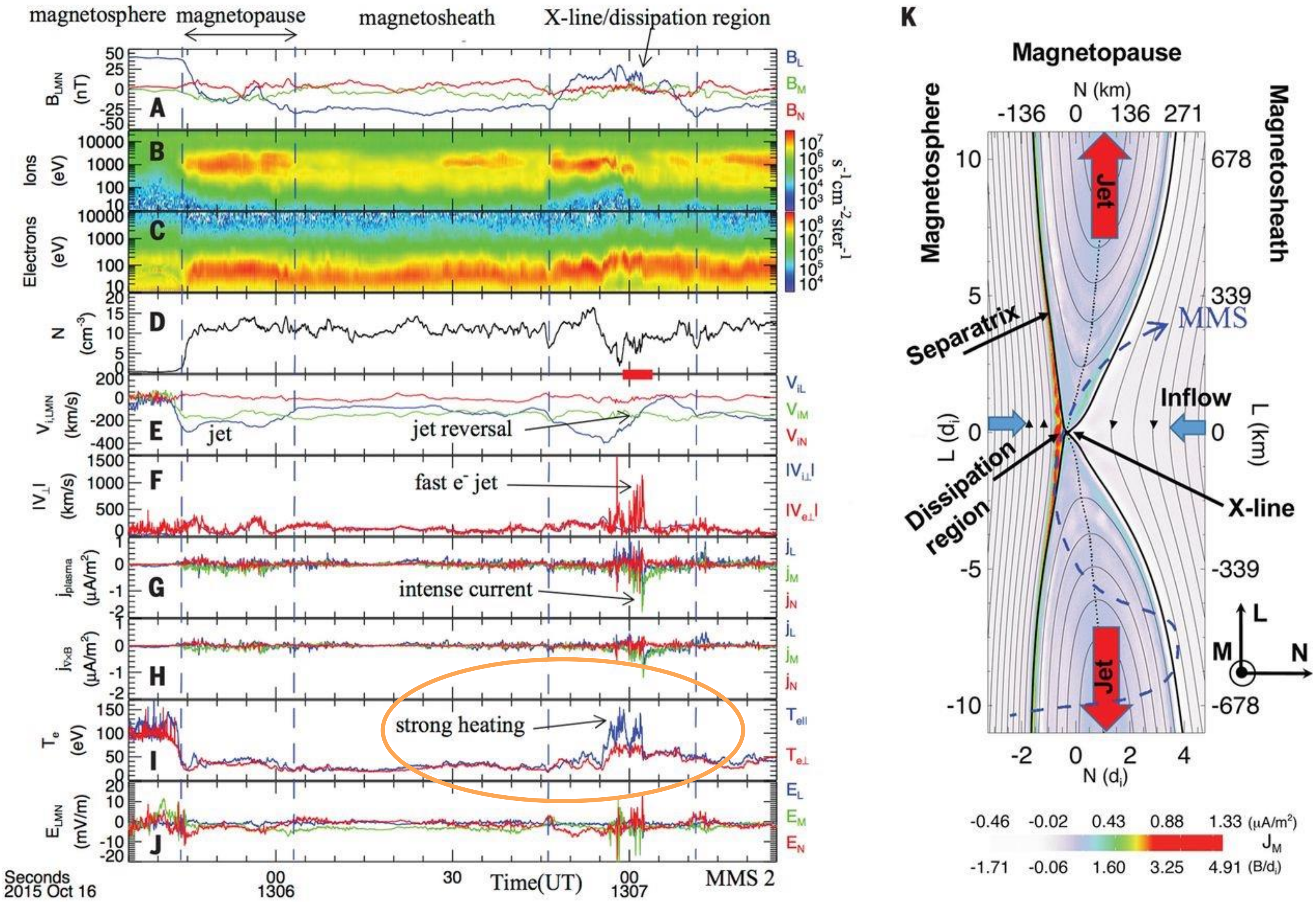
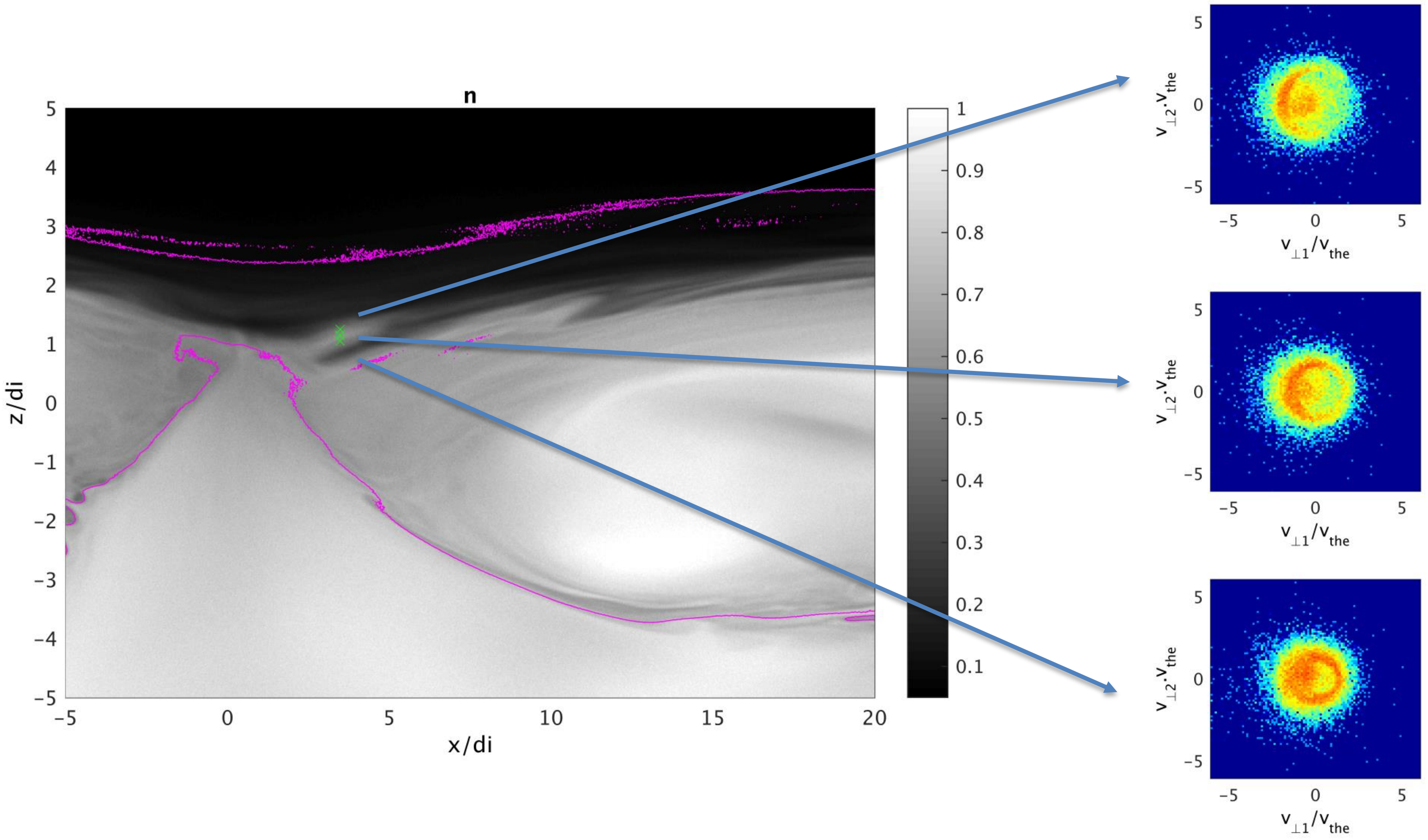


Fig. 3 Summary data for two magnetopause crossings of MMS2 on 16 October 2015.
Reproduced from J. L. Burch et al. Science 2016;352:aaf2939

Science AAAS

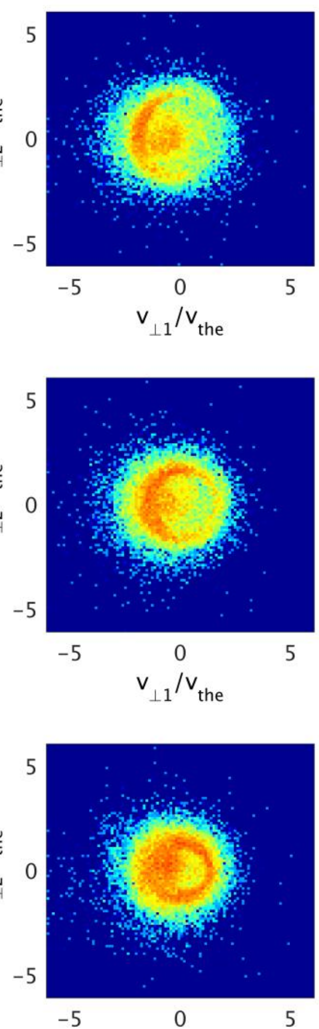
Crescent Electron Distributions Persist in 3D



Price et al., GRL (2016)

Result from ~Gyrotropic Guiding-Center Distributions + Strong Pressure Gradient

Egedal et al., (PRL 2016)



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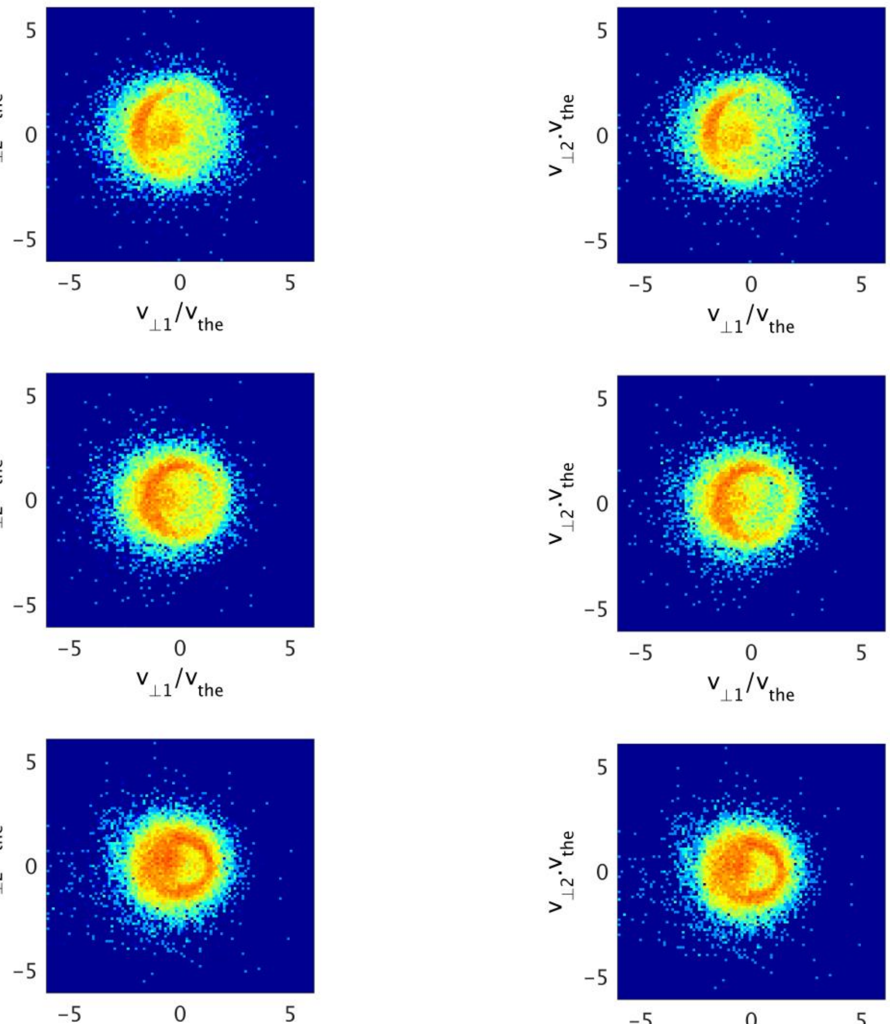
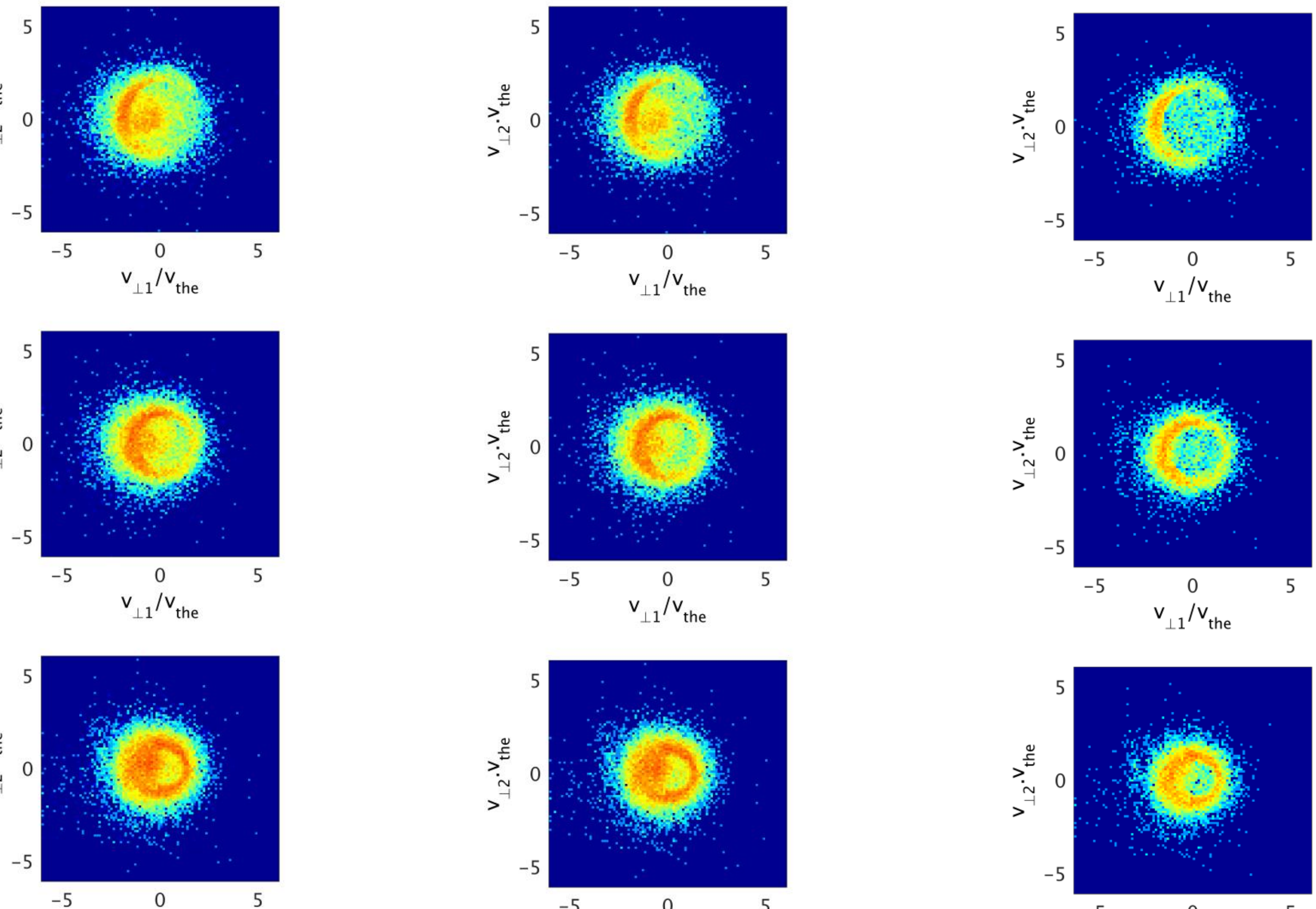
Egedal et al., (PRL 2016)



Look only at electrons originating in sheath

Result from ~Gyrotropic Guiding-Center Distributions + Strong Pressure Gradient

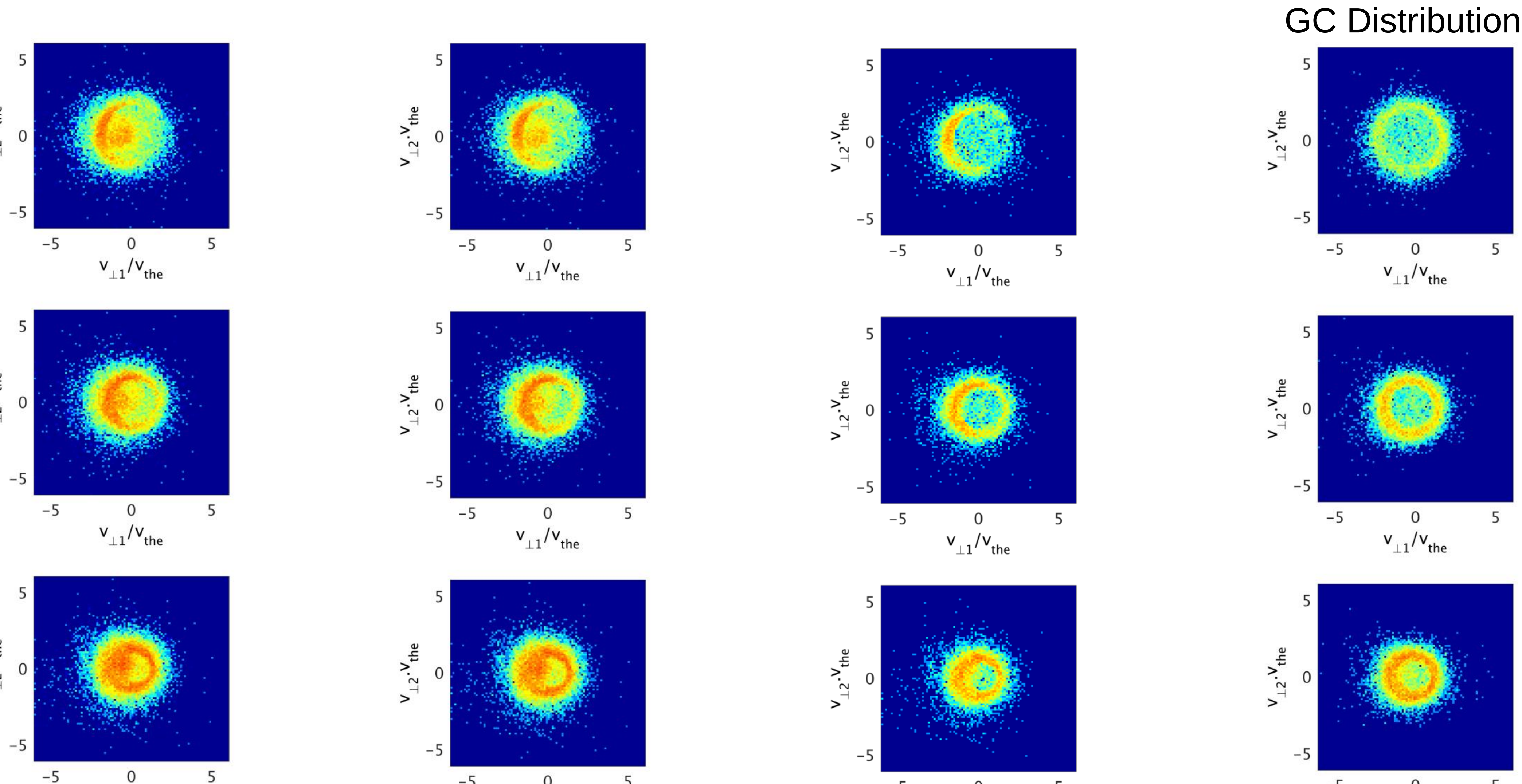
Egedal et al., (PRL 2016)



Remove
recirculating
(v|| < 0) electrons

Result from ~Gyrotropic Guiding-Center Distributions + Strong Pressure Gradient

Egedal et al., (PRL 2016)

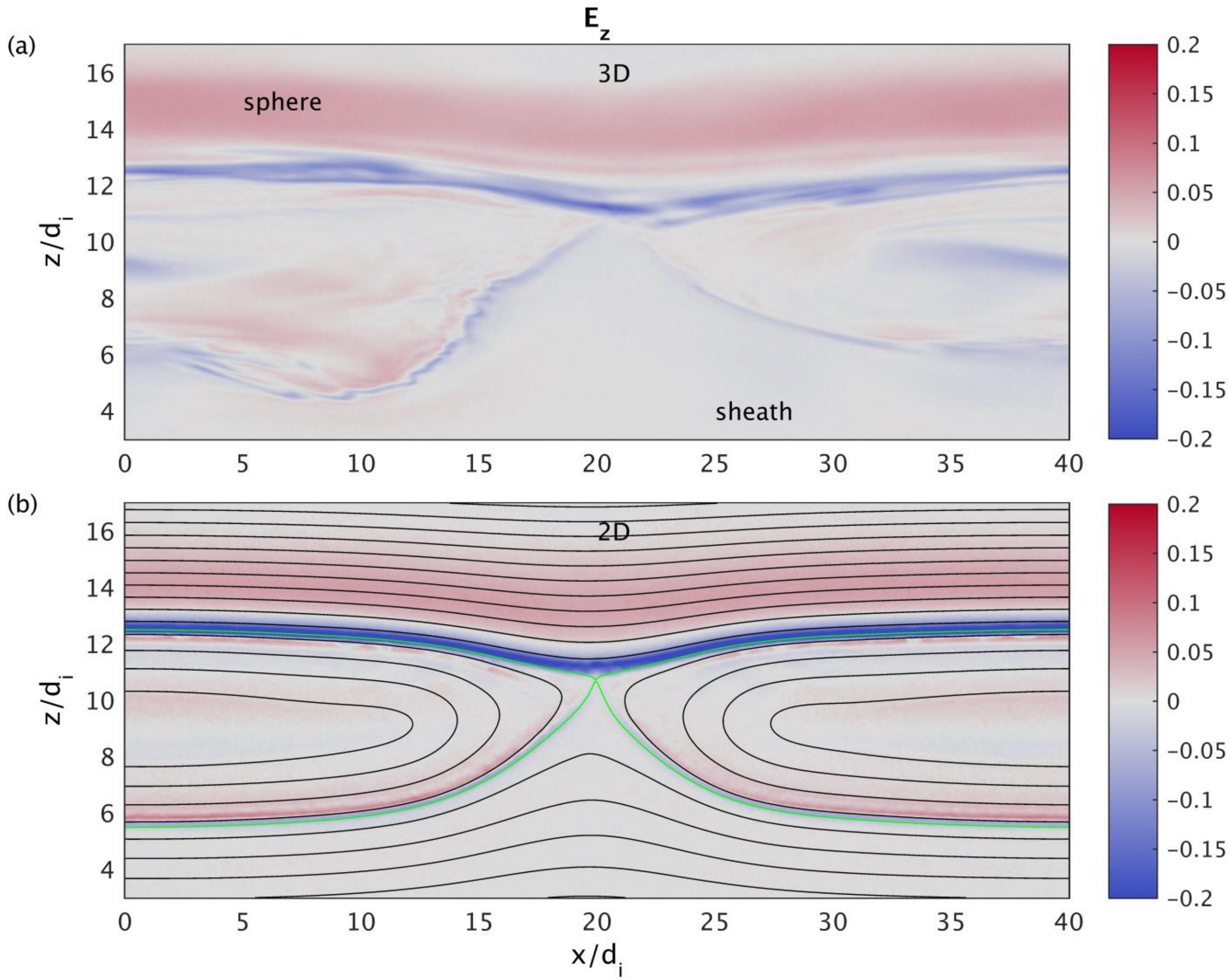


Summary

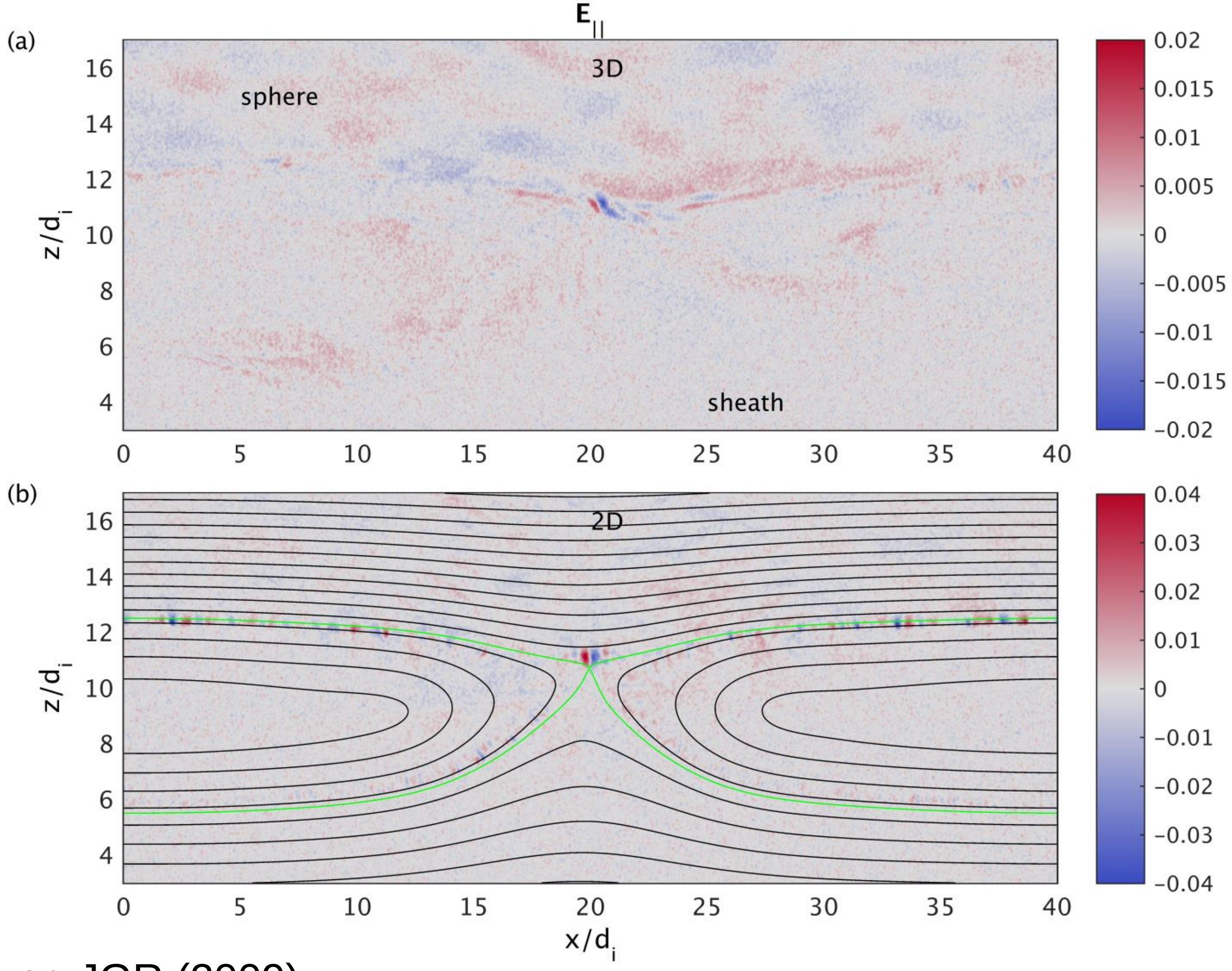
- Three-dimensional fully kinetic simulation was performed for reconnection event from MMS - Oct. 16, 2015
- Careful attention given to grid resolution, particle statistics, and the decay of initial transients
- Anomalous resistivity is small, anomalous viscosity is significant between x-line & stagnation
- Biggest 3D effect: turbulence leads to enhanced mixing, and enhanced parallel electron heating within mixing layer
- Certain drift instabilities can be captured by multi-fluid models & initial 3D Gkyell calculations reproduce many features of PIC
- Nice crescent distributions survive turbulence
- Features consistent with MMS data

Results in A. Le et al, GRL, 2017

Normal Electric Field

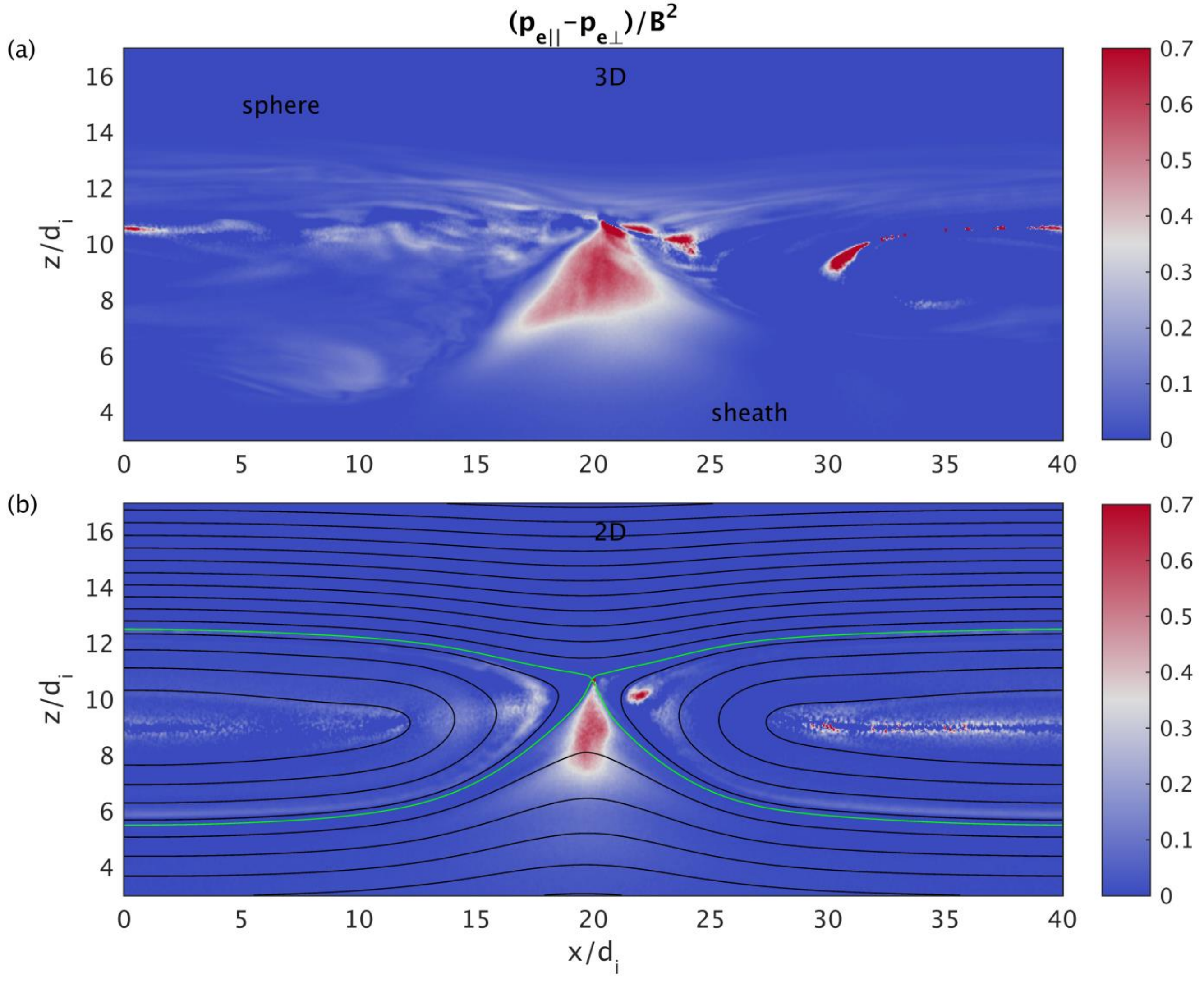


Strong Bipolar $E_{||}$ Between X-Line and Stagnation Point

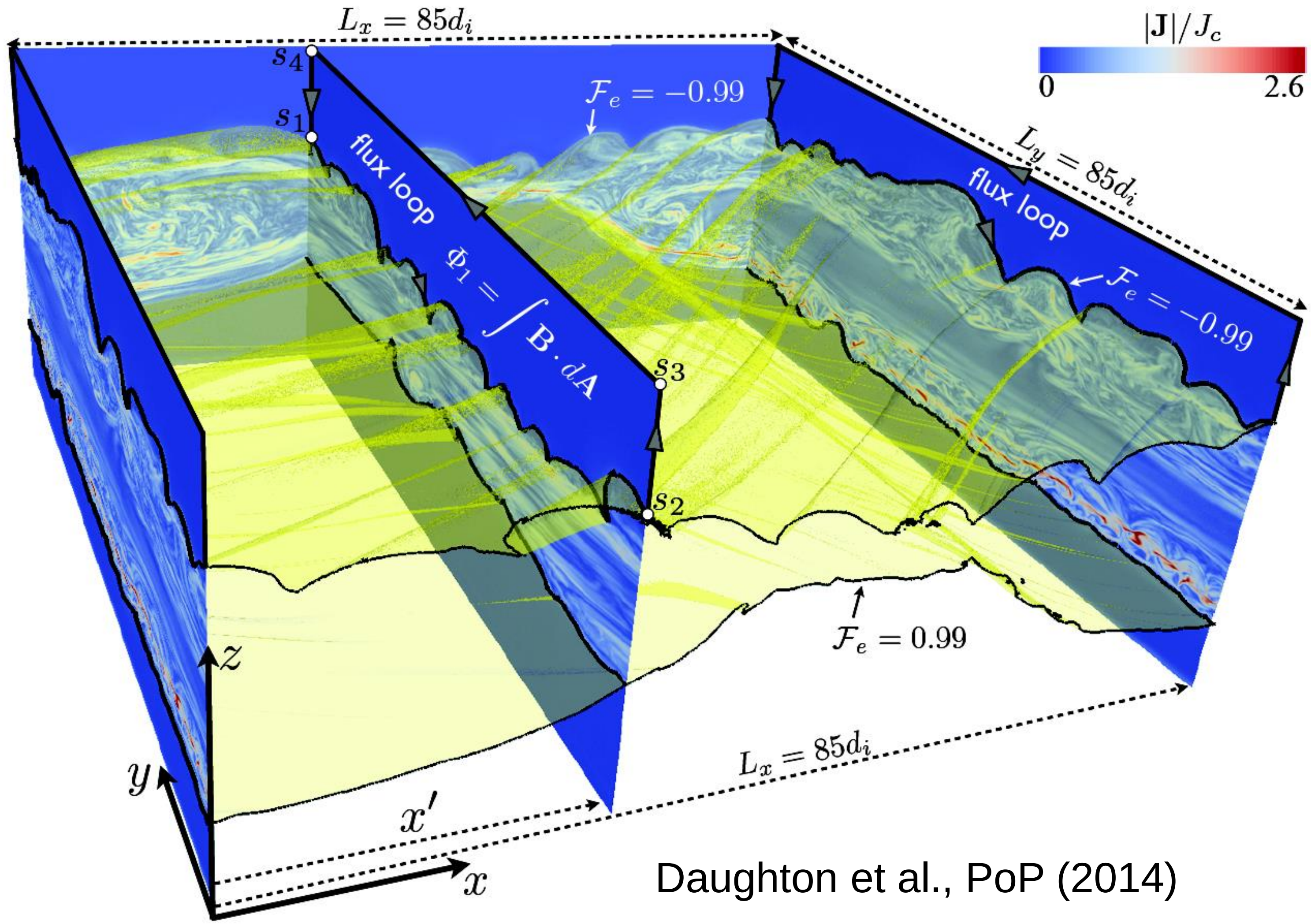


Pritchett and Mozer, JGR (2009)

Electron Firehose Condition—Closer to Threshold on Sheath Side

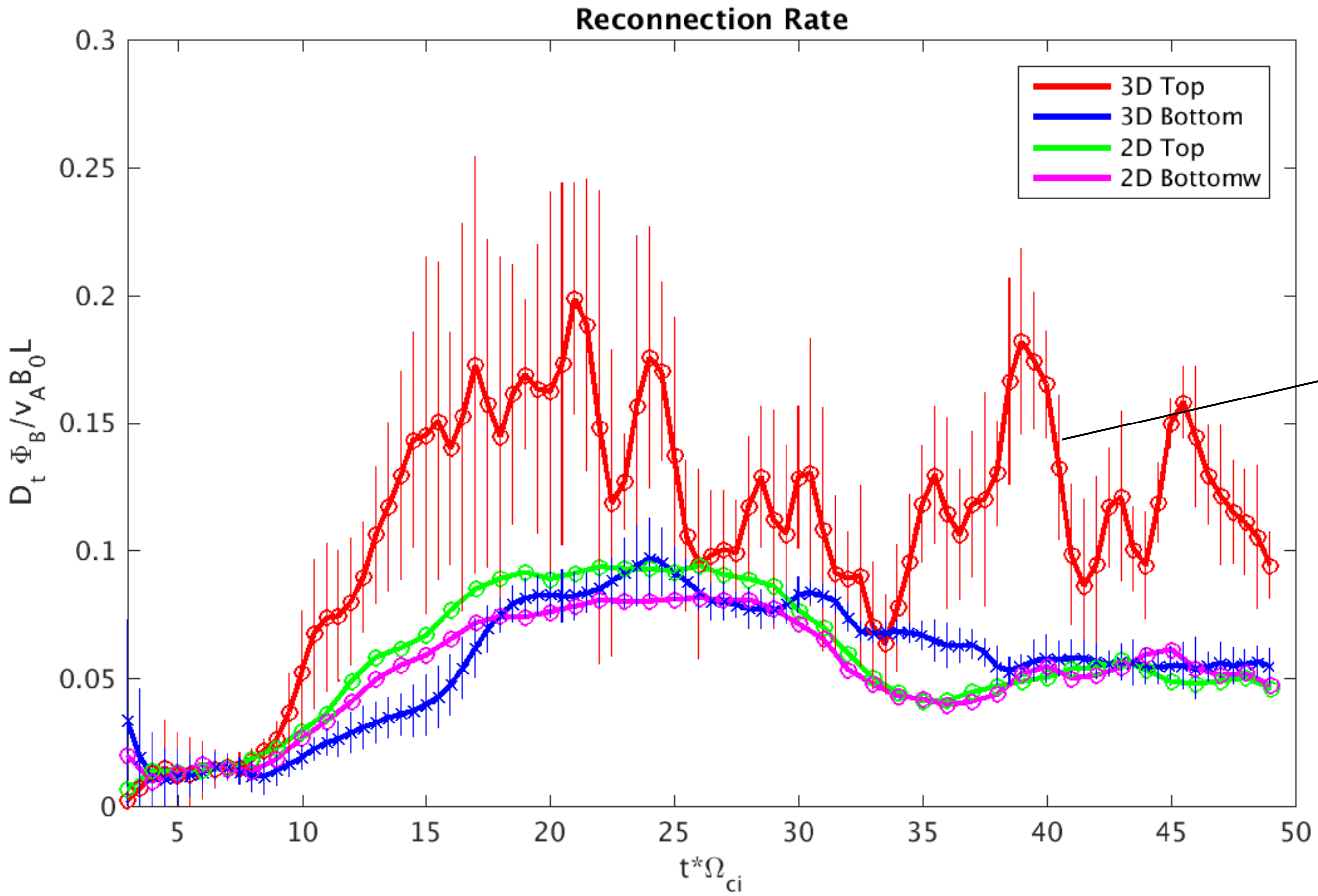


Estimating Reconnection Rate From Electron Mixing



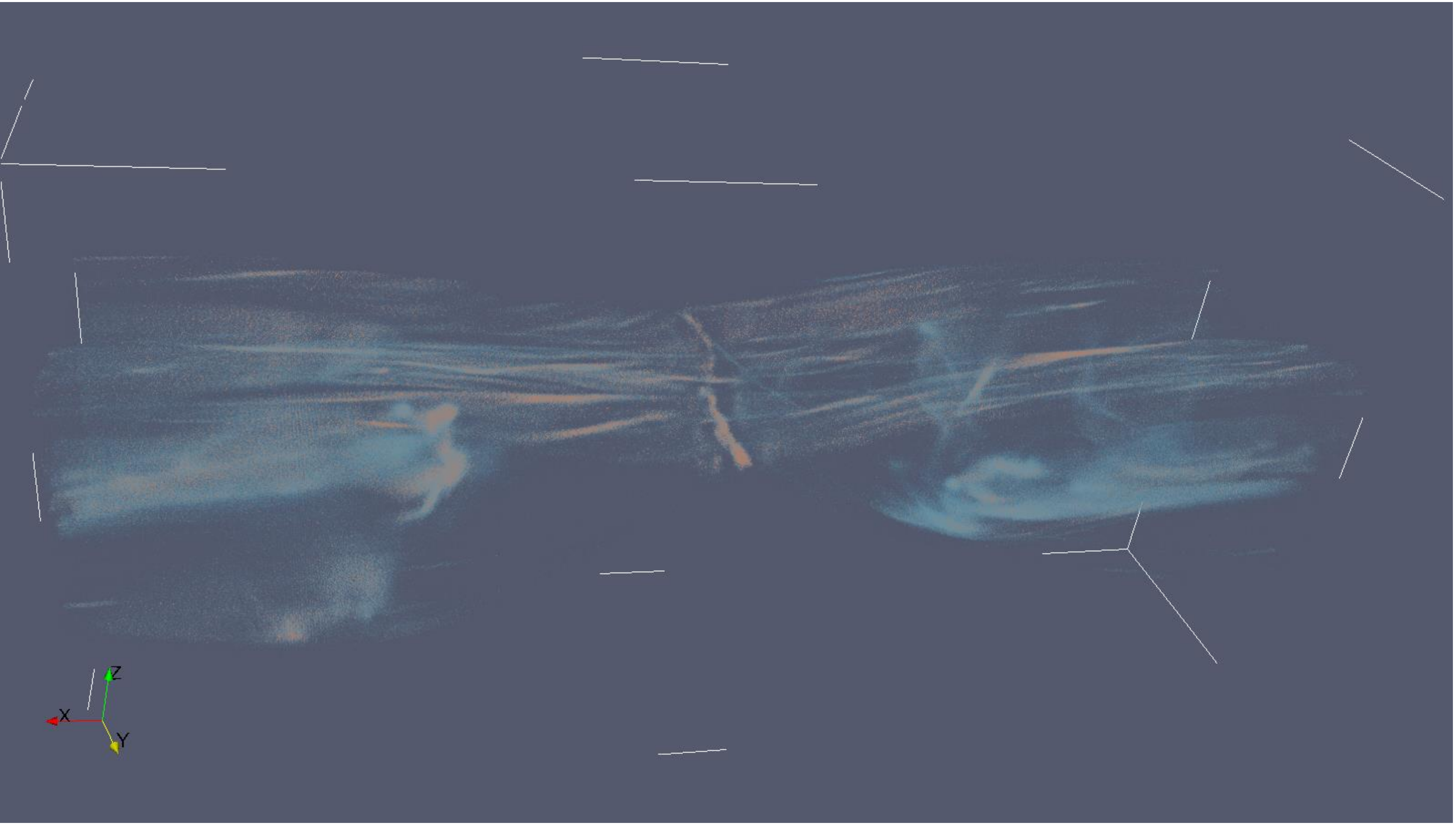
Daughton et al., PoP (2014)

Transport of Electrons Increases Inferred Reconnection Rate



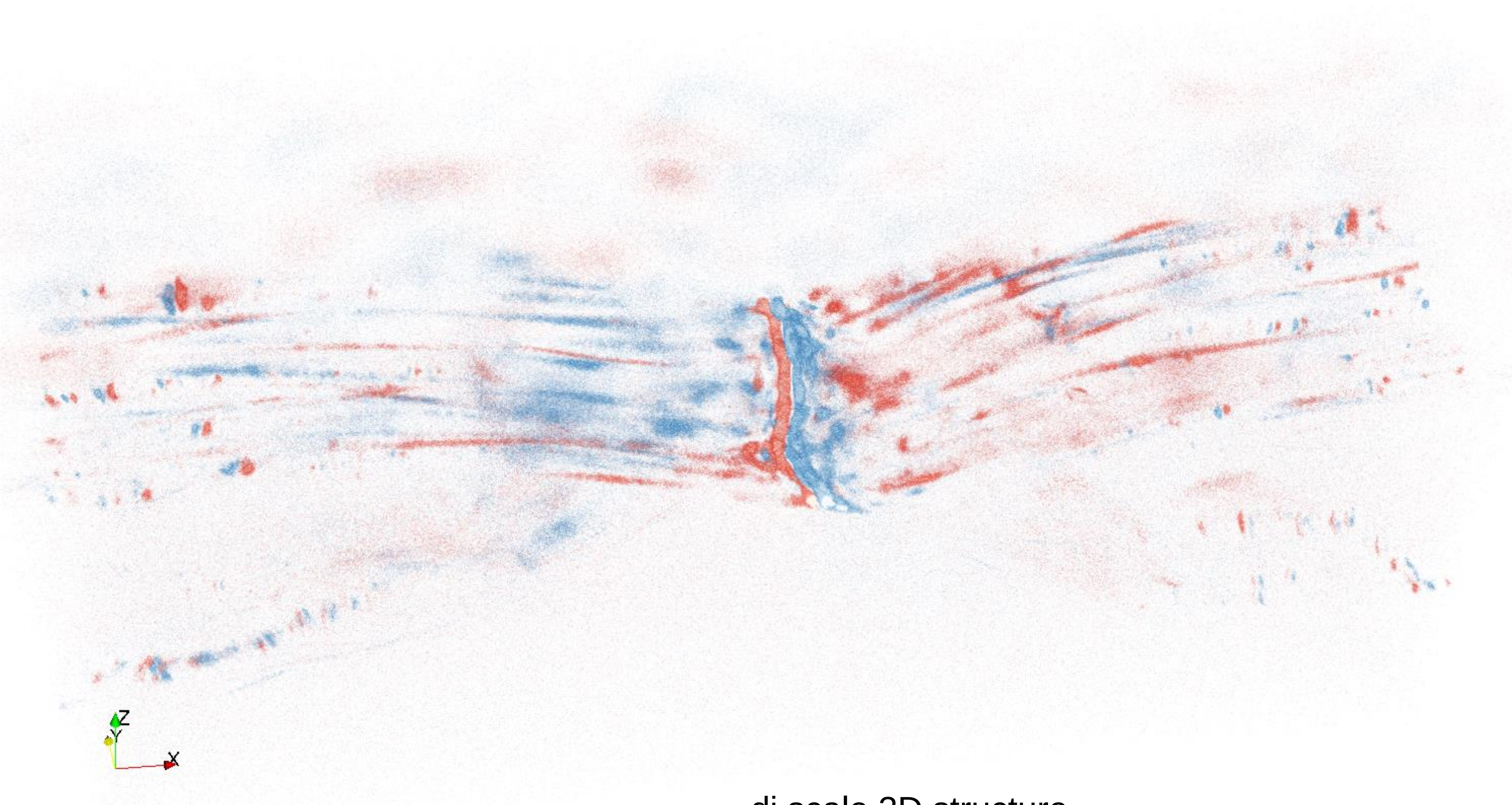
Rate enhanced by electron mixing on sphere side

Twisted Flux Ropes on Sphere Side



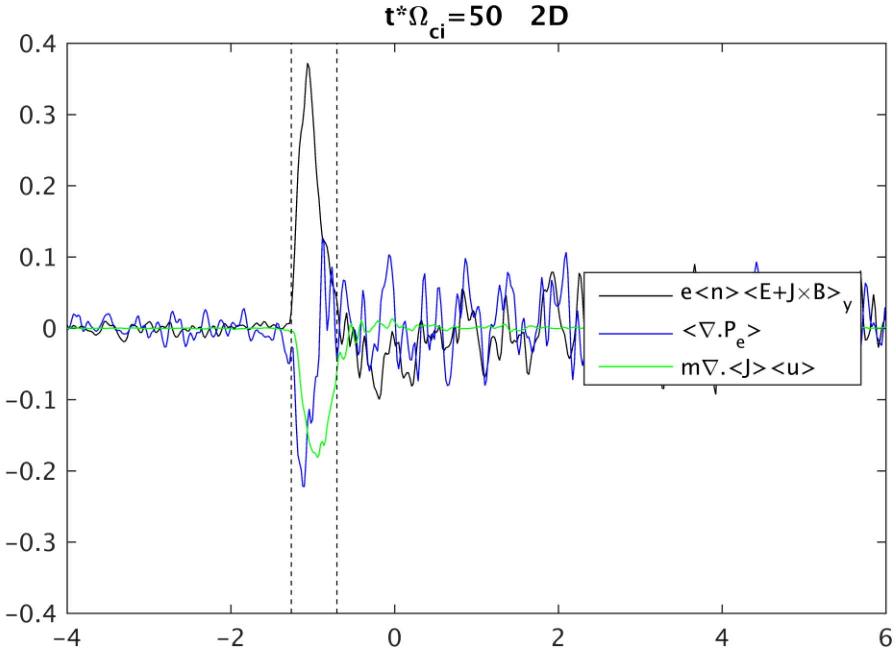
Ergun et al. PRL (2016)

$E_{||}$ in 3D Run



di scale 3D structure
Chen et al. GRL (2016)

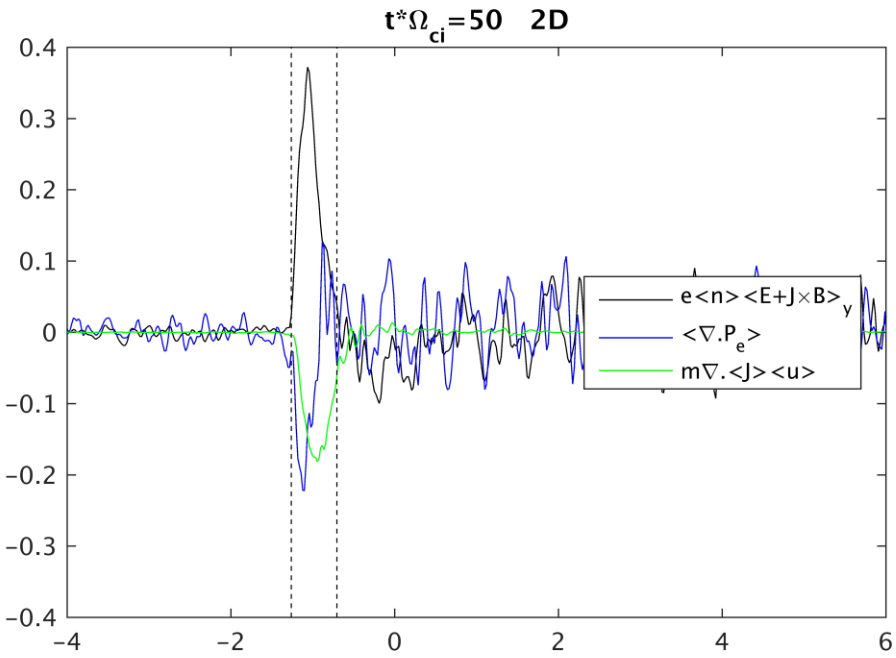
Ohm's Law 2D

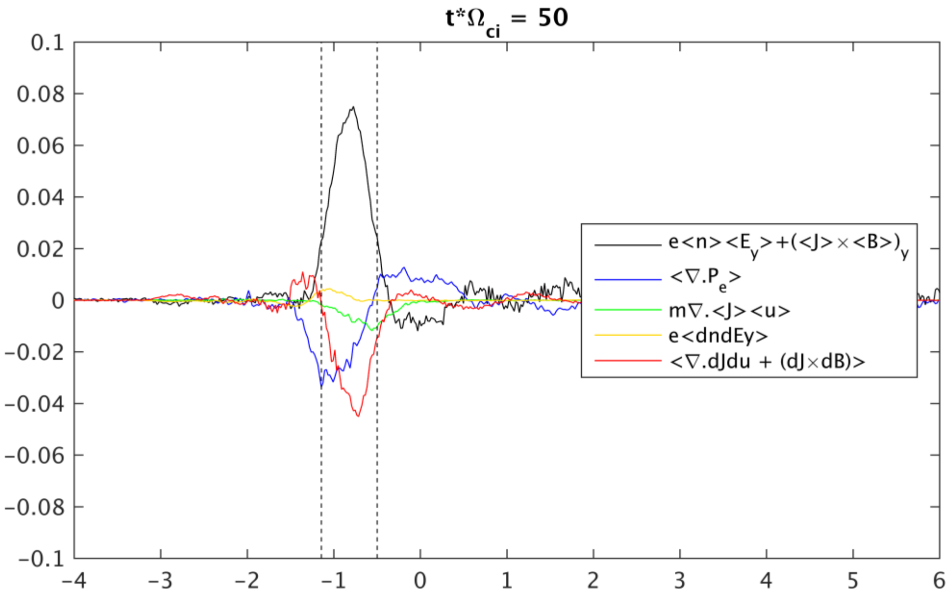


Inertia balances E at X-line

Divergence of Pe large
near stagnation point

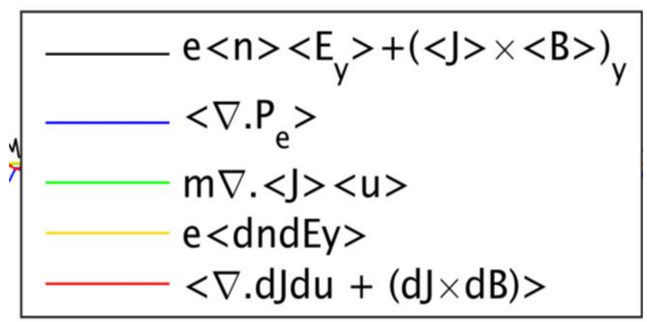
Ohm's Law 2D vs 3D





For 3D: Split into out-of-plane average and fluctuation

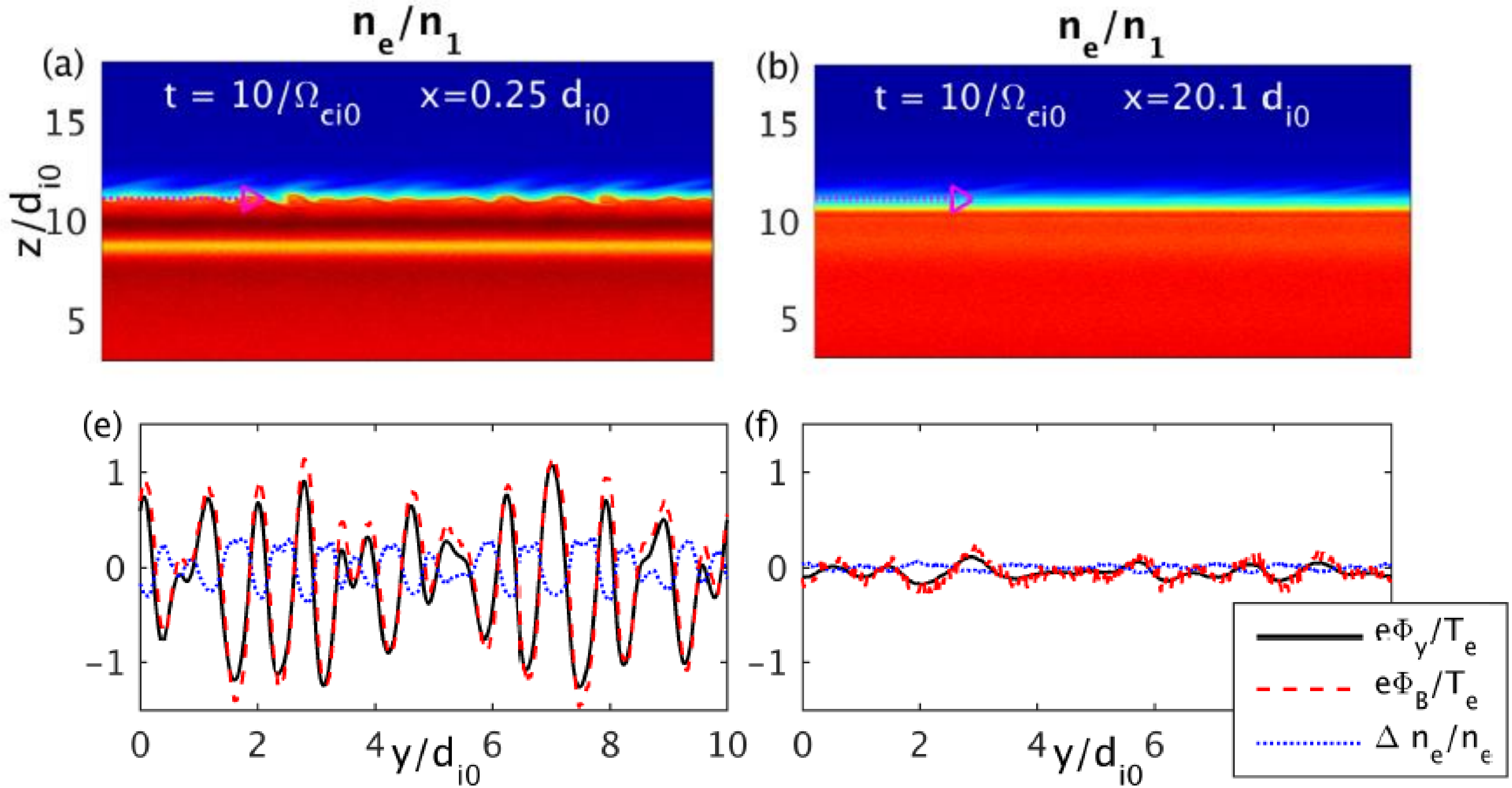
Q = <Q> + dQ



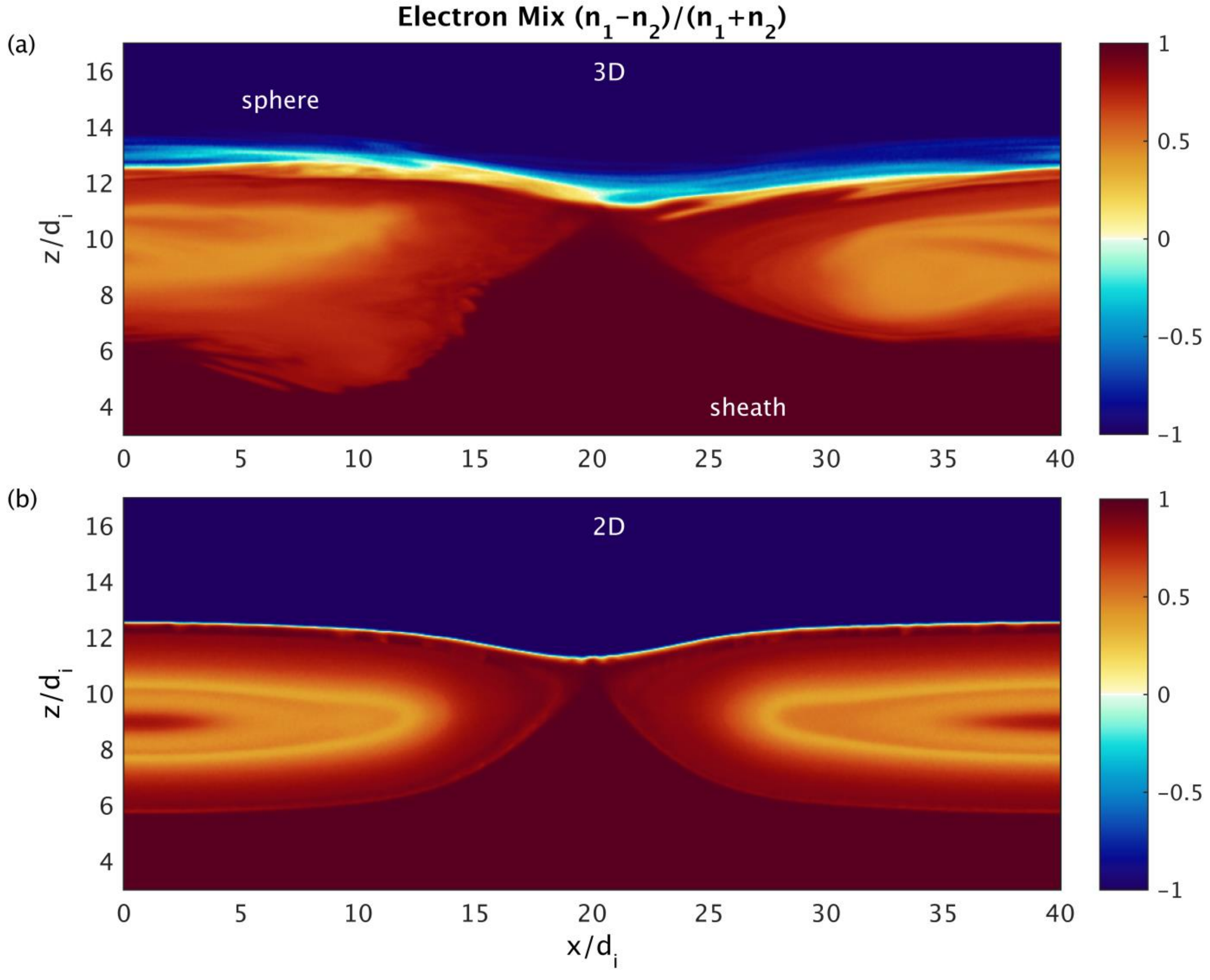
Price et al., GRL (2016)

Fluctuations are Weaker Very Near X-line

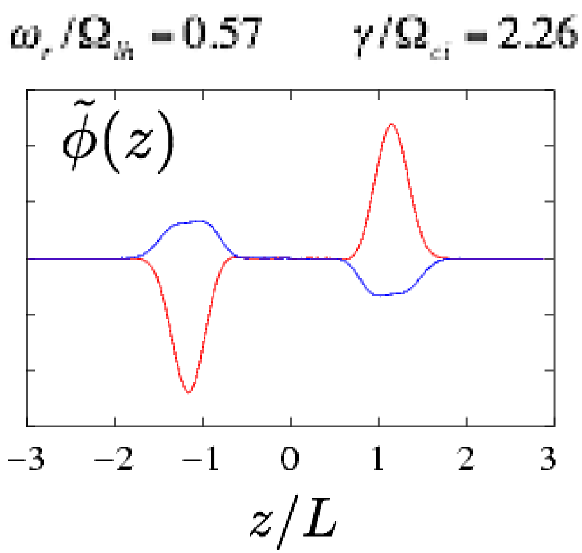
Edge of Domain | At x-line



Electron Mixing Diagnostic: Enhanced Particle Transport on Sphere Side in 3D

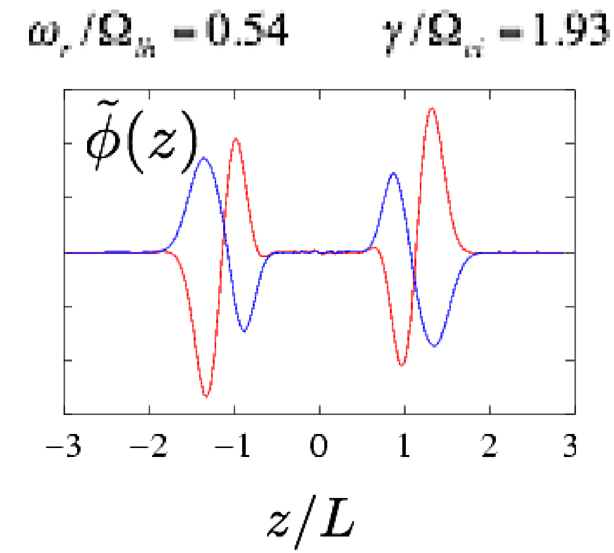


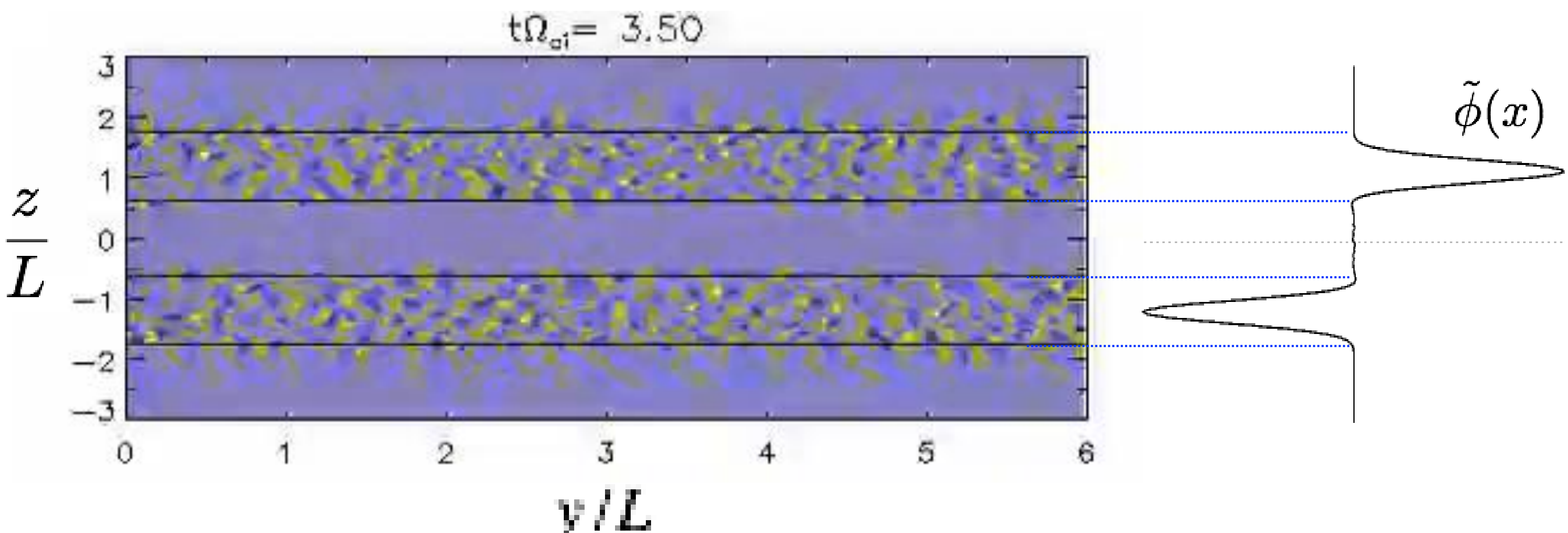
Fastest growing LHDI is nearly electrostatic & localized in low-β edge regions - see Daughton et, 2003



Two fastest Growing modes

$k_y \rho_e = 0.75$

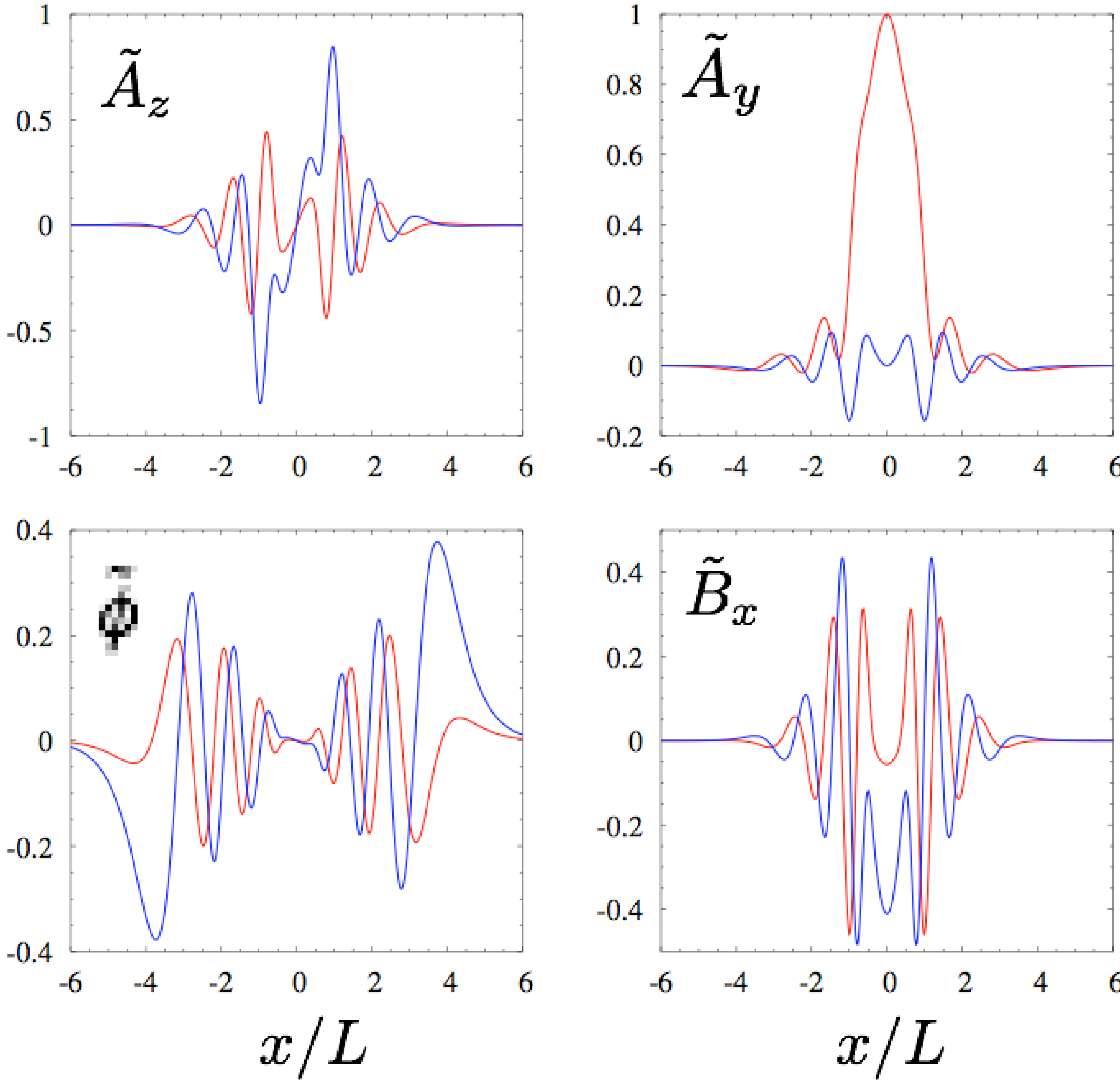




Fluctuations are confined to the edge of the sheet

Lower wavelength LHDI is global & electromagnetic

$$k_y L = 2 \quad \Rightarrow \quad k_y \sqrt{\rho_i \rho_e} = 0.84$$



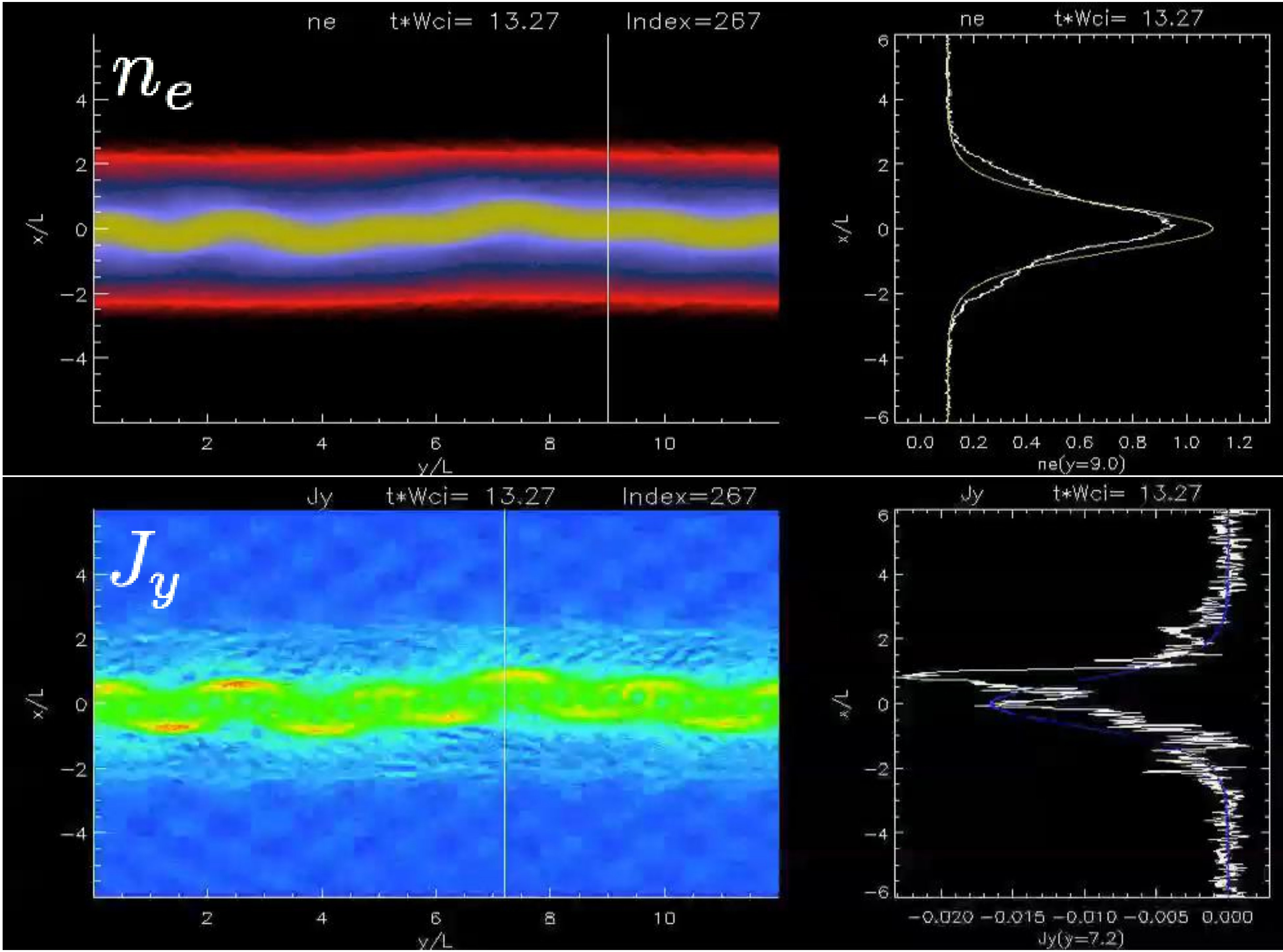
Eigenfunction

$$\hat{\mathbf{A}} = \tilde{\mathbf{A}}(z) \exp\left[-i\omega t + ik_x + ik_y y\right]$$

$$\hat{\phi} = \tilde{\phi}(z) \exp\left[-i\omega t + ik_x + ik_y y\right]$$

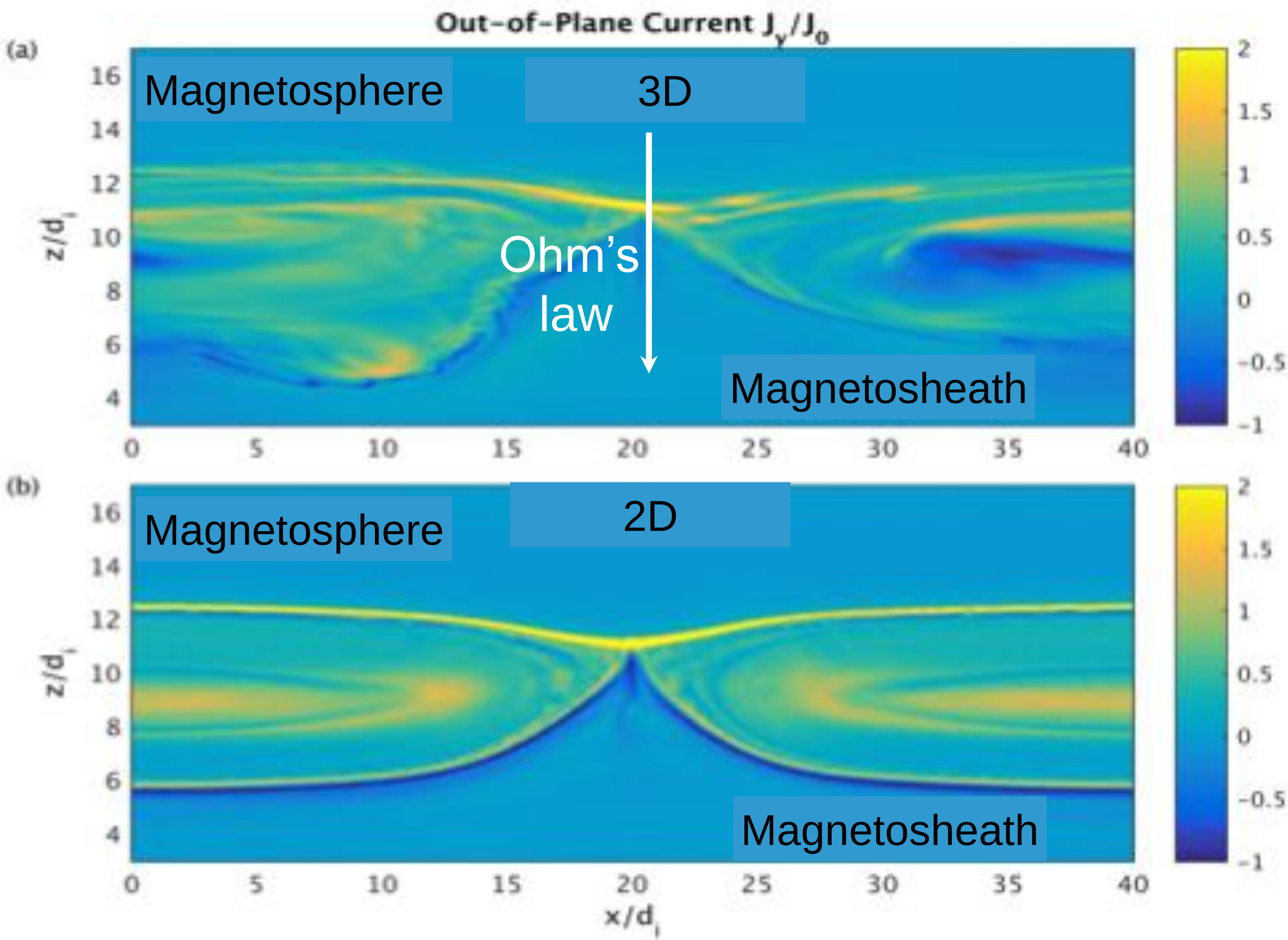
Eigenvalue

$$\frac{\omega_r}{\Omega_{ci}} = 6.2 \qquad \frac{\gamma}{\Omega_{ci}} = 0.84$$



ne t*Wci= 13.27 Index=267
n_e
x/L
y/L
ne t*Wci= 13.27
ne(y=9.0)
Jy t*Wci= 13.27 Index=267
J_y
Jy t*Wci= 13.27
Jy(y=7.2)

Comparison of 3D vs 2D slices illustrate some turbulent broadening of separatrices



Local Electrostatic LHDI Dispersion Relation

Local dispersion relation (electrostatic low-beta, fluid ion response):

$$(\omega - k_y v_E)\left[\frac{\omega^2}{\omega_{pi}^2}\left(1 + \frac{4\pi n m c^2}{B^2}\right) - 1\right] = -\frac{k_y v_\Delta}{k^2 \lambda_D^2}\frac{\omega^2}{\omega_{pi}^2}$$

Couples drift wave and lower hybrid oscillation:

$$\omega = k_y v_E$$

$$\omega^2 = \omega_{pi}^2\left(1 + \frac{4\pi n m c^2}{B^2}\right)^{-1} \approx \omega_{pi}^2, \quad B^2 \gg 4\pi n m c^2$$

$$\approx \omega_{HB}^2, \quad B^2 \ll 4\pi n m c^2$$

Driven by density, |B| gradients:

$$v_\Delta = -\frac{T_e}{m\omega_{ce}}\left[\frac{1}{n_e}\frac{dn_e}{dx} - \frac{1}{B}\frac{dB}{dx} - \frac{k^2 a_e^2}{2}\frac{1}{T_e}\frac{dT_{\perp e}}{d_x}\right]$$

Flute-like mode with k rhoe< ~1, w~w$_{LH}$

Krall and Liewer, Phys. Rev. A (1971)

Some Pitfalls of 3D Simulations

1. Grid resolution - influence anomalous dissipation?
2. Big density jump + particle statistics
3. Spatial vs temporal averaging
4. Influence of mass ratio - m_i/m_e=100
5. Transients vs steady/state ?