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Review of electron-scale current-layer dissipation in kinetic plasma turbulence

Minping Wan

University of Delaware

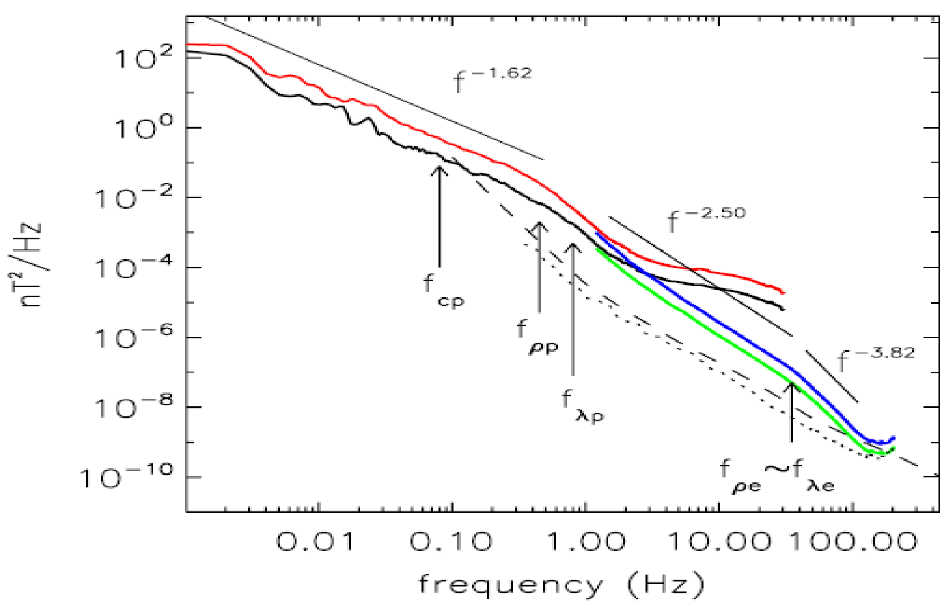
W. H. Matthaeus, P. Wu, M. Shay (*U. Delaware*), H. Karimabadi, V. Roytershteyn (*UCSD & SciberQuest*), W. Daughton (*LANL*), B. Loring (*LBNL*), K. T. Osman, S. Chapman (*U. Warwick*), S. Perri, M. L. Goldstein (*NASA/GSFC*)

Outline

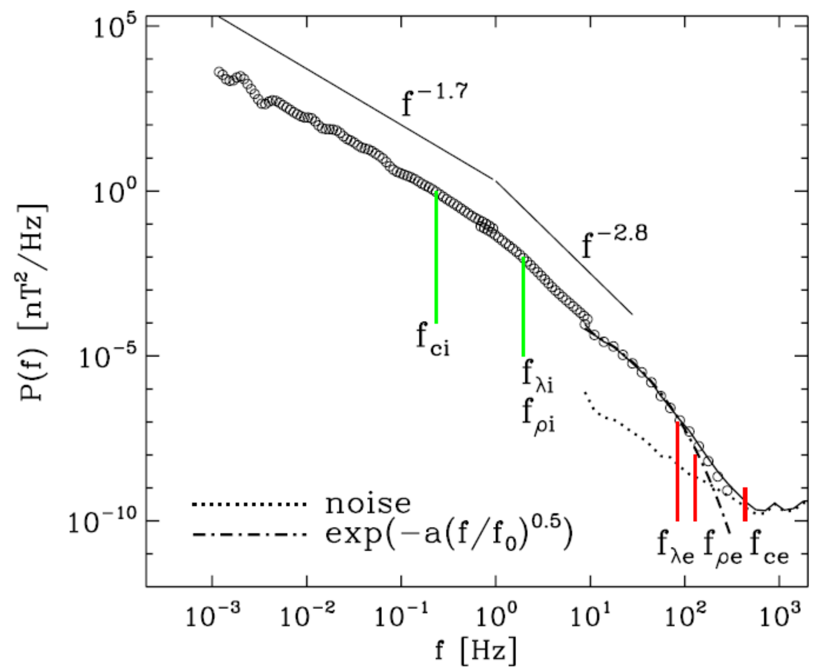
- Introduction: spectrum, observations, etc
- Intermittency and dissipation at electron scales for plasma turbulence
  - Mostly results from PIC simulations
  - Intermittent current structures down to electron scales
  - Heating and dissipation
  - 3D PIC, Gyrokinetic simulations.
  - Karimabadi et al, *PoP*, 2013;
  - Wan et al, *PRL*, 2012;
  - Wu et al, *ApJ*, 2013;
  - Leonardis et al., *PRL*, 2013;
  - Haynes et al., *arXiv*, 2013;
  - TenBarge & Howes, *arXiv*, 2013.
- Conclusions

Introduction

- Recent studies show a second break point of magnetic energy spectrum at electron gyroscale. (Sahraoui et al., 2009; Alexandrova et al., 2009; Karimabadi et al., 2013; Wan et al., 2012; TenBarge & Howes, 2013)
- The slope after the electron break point: power law with slope ~-4? Or exponential?



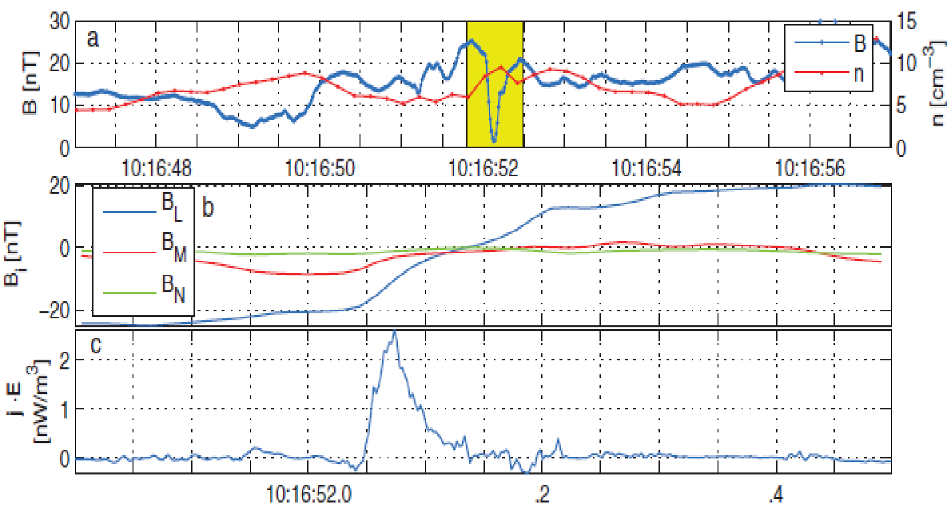
(Sahraoui et al., *PRL*, 2009)

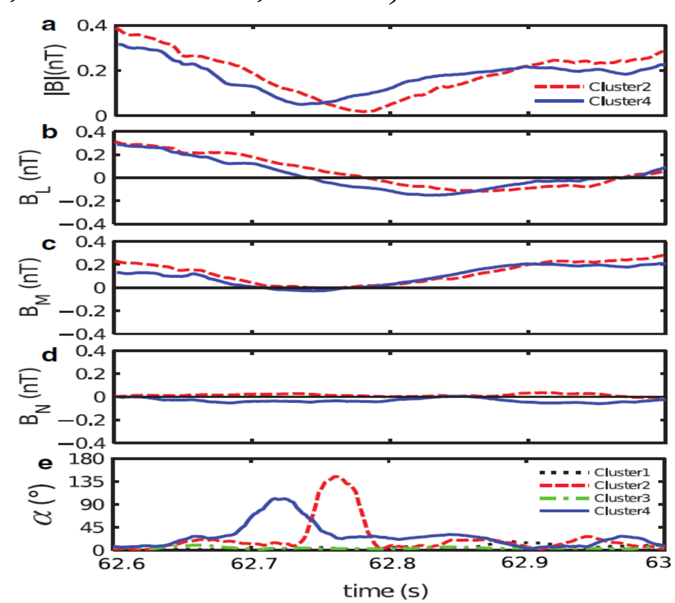


(Alexandrova et al., *PRL*, 2009)

How is energy dissipated at electron scales?

- Wave damping (e.g. whistlers, kinetic Alfven waves, proton and electron Landau damping, etc.)
- Dissipation through kinetic scale current sheets;
- High frequency solar wind observations are found to support current sheet dissipation picture (Sundkvist et al., 2007; Perri et al., 2012)





- Fully kinetic simulations such as PIC simulations are needed;
- PIC simulations have been widely used for the study of dissipation in magnetic reconnection (Shinohara et al, 2001; Shay et al, 2007).

PIC simulation method and set-up

- A large number of simulations with varying parameters were carried out.
  - Kinetic particle-in-cell (PIC) code VPIC is used;
  - Initial set up with uniform density and magnetic field and an imposed velocity shear – Kelvin-Helmholtz instability.
- The results shown here are for the largest two dimensional simulation with
  - m_i/m_e=100,
  - Grid size 8192 x 16384 corresponding to 50 d_i x 100 $d_{i,}$
  - Shear half-thickness of 4di, and shear flow velocity equal to 10 times the Alfven speed based on the small in-plane field,
  - Total of 40 billion particles.

(Karimabadi et al, *Phys. Plasmas*, 2013, Wan et al., *PRL*, 2012)

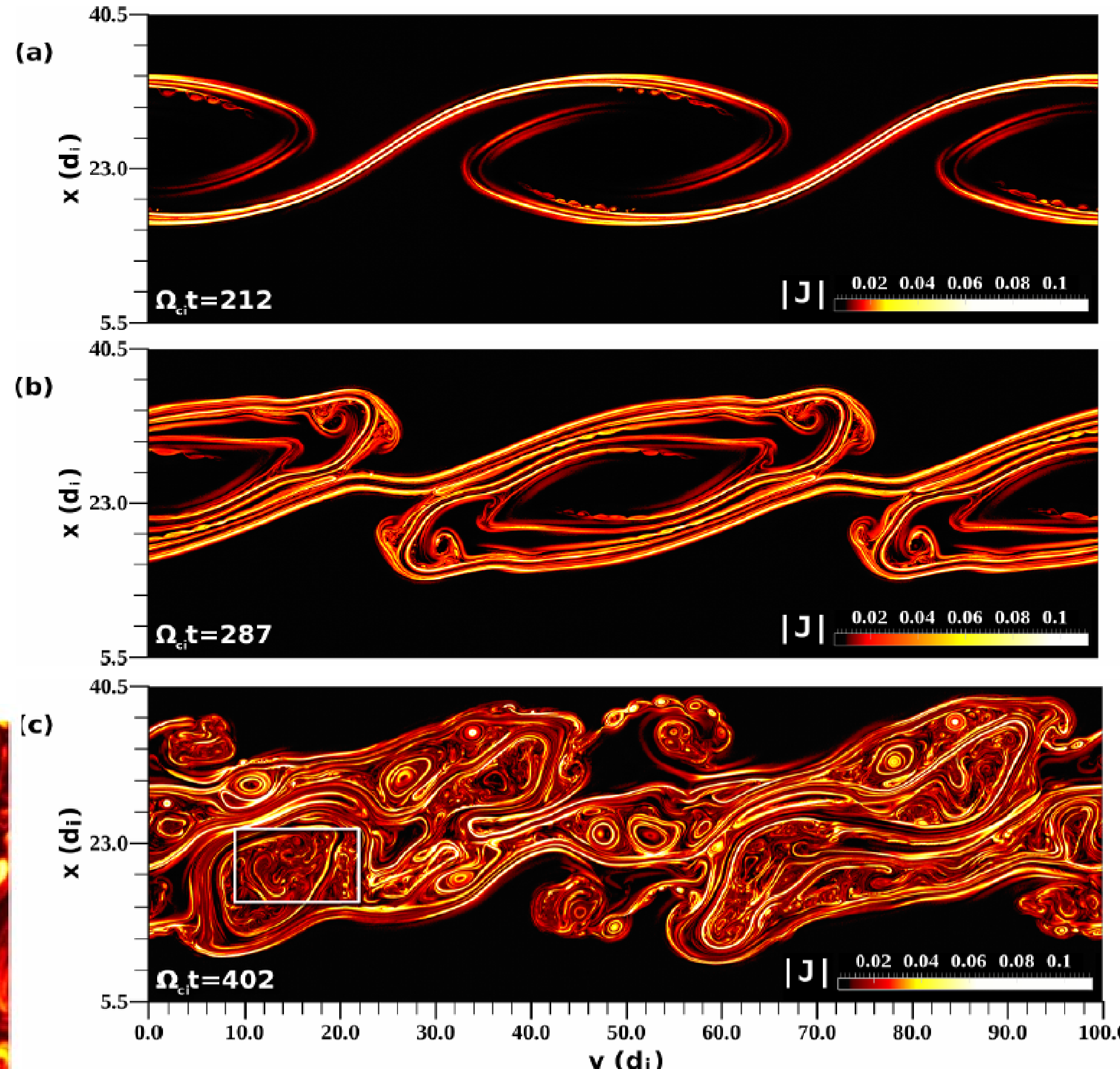
Development of turbulence in physical space

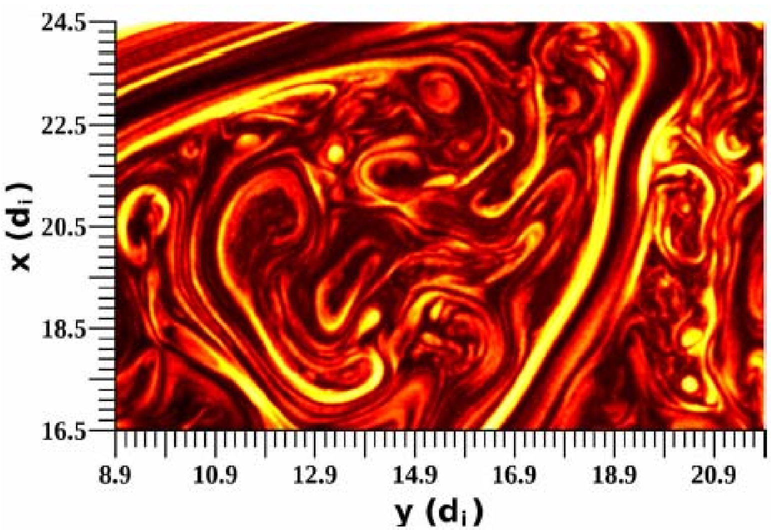
The system evolves in 3 phases:

I. Linear phase at early times;

II. A transitional phase in which strong nonlinear interactions emerge;

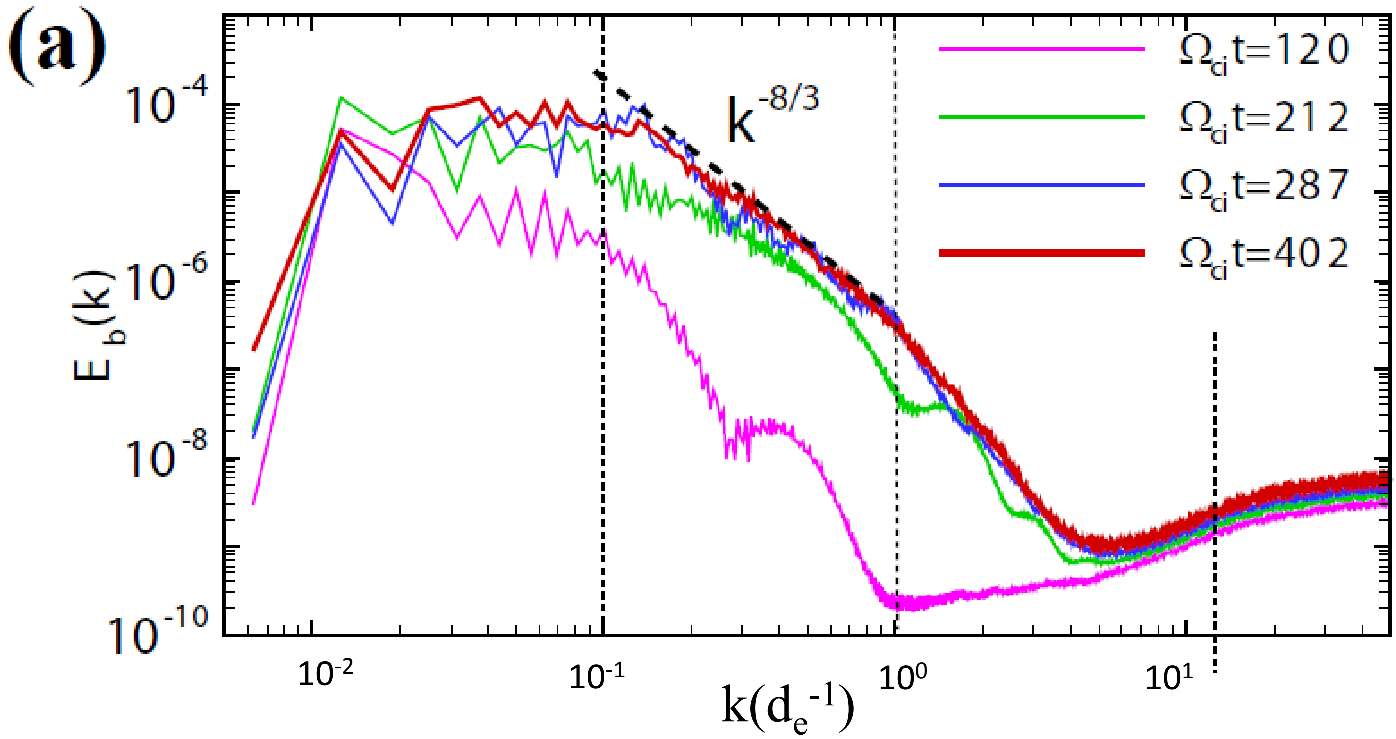
III. By $\Omega_{ci}t$ = 400-500, fully nonlinear phase of kinetic turbulence.





(Karimabadi et al, *Phys. Plasmas*, 2013)

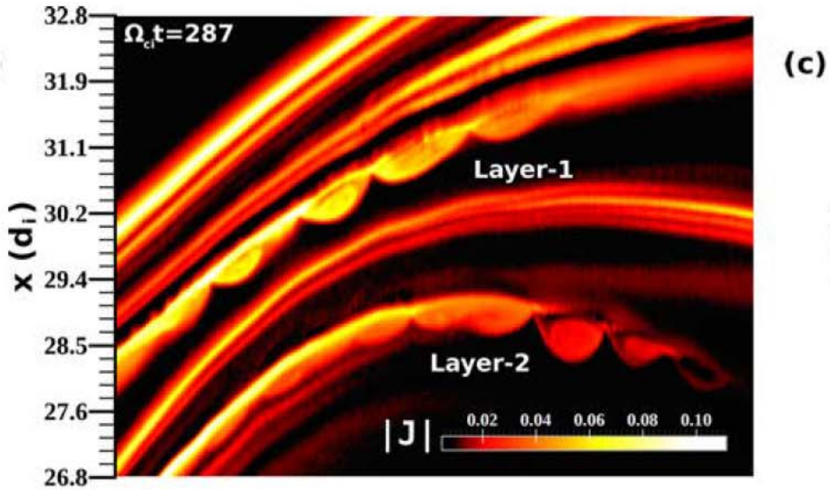
Development of turbulent spectrum

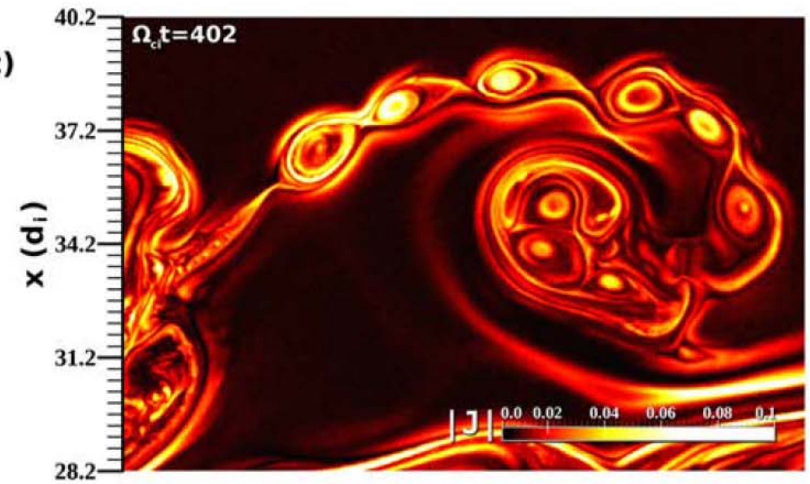


Omnidirectional energy spectra of magnetic field. The magnetic spectra show several point spectral features at early times. The first of these is near the reciprocal proton gyroradius $\rho_i = d_i\sqrt{\beta} \sim d_i/\sqrt{10}$, and the latter features lie between $kd_e = 1$ and $k\rho_e = 1$. These suggest a role of ion gyroresonant and possibly electron gyroresonant effects during the transition to turbulence. These processes may contribute later as well, but these spectral features are completely washed out in the fully turbulent state.

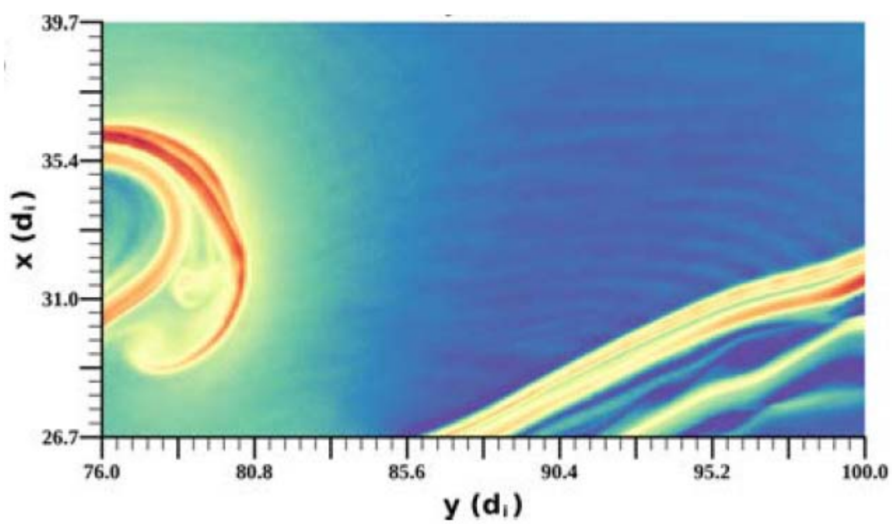
Some features of the flow

- Excitation of secondary instabilities





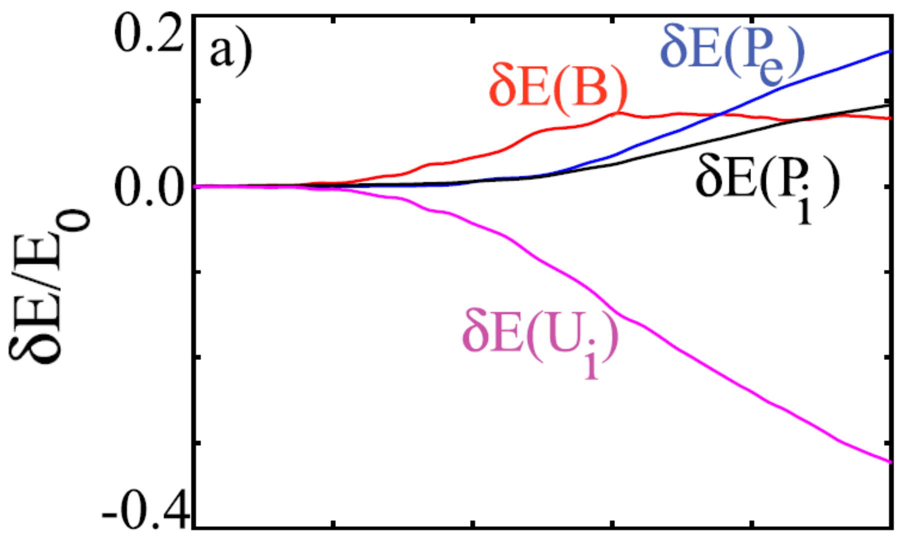
- Wave excitation due to the motion of coherent structures.

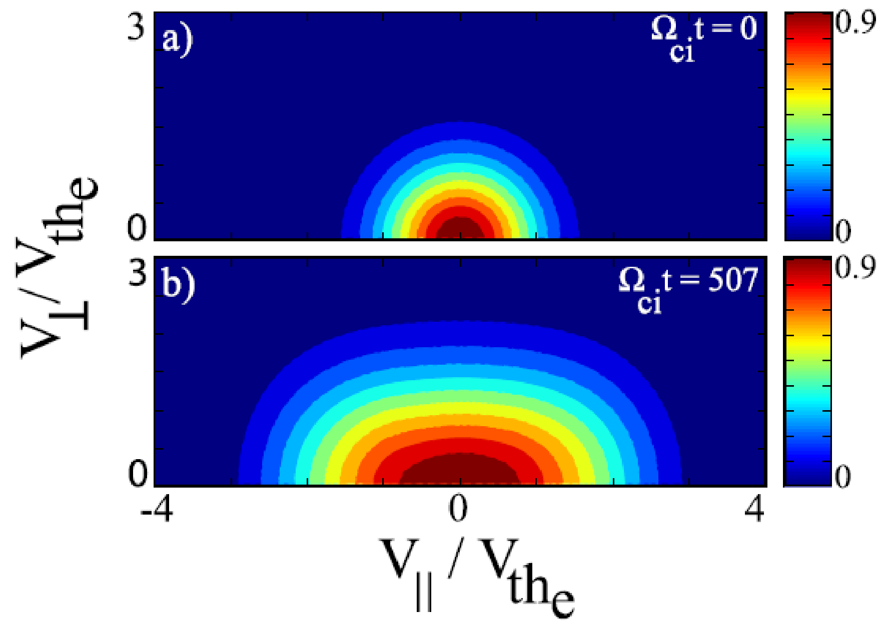


Wave signal is much weaker.

(Karimabadi et al, *Phys. Plasmas*, 2013)

Electron Heating



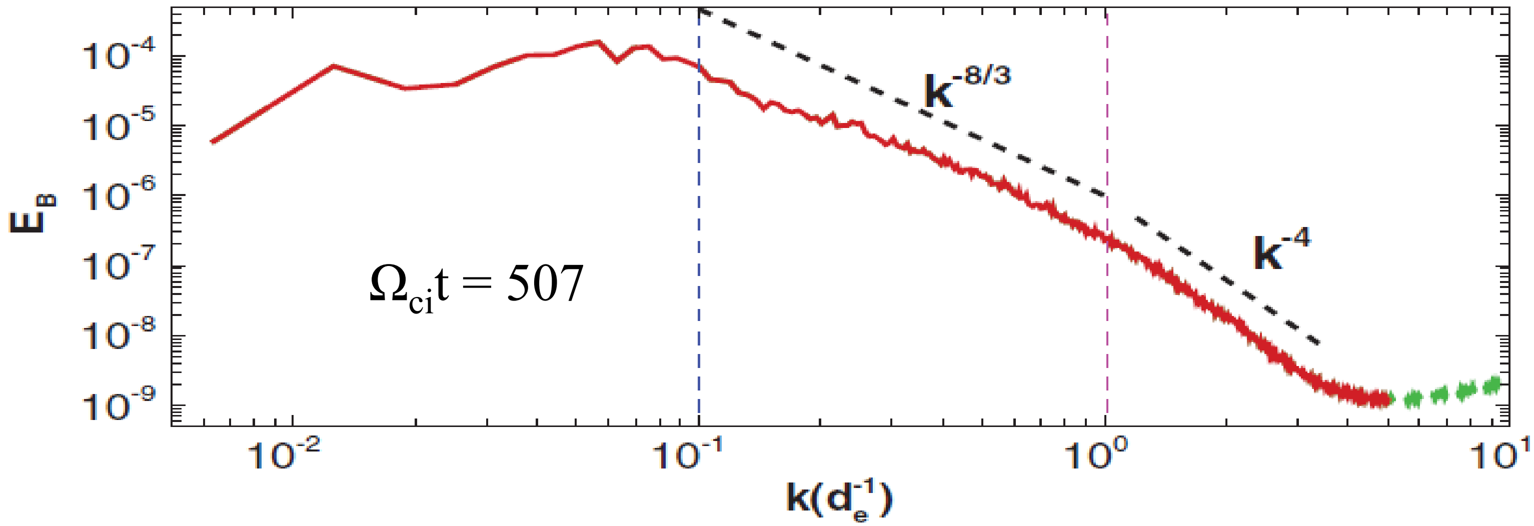


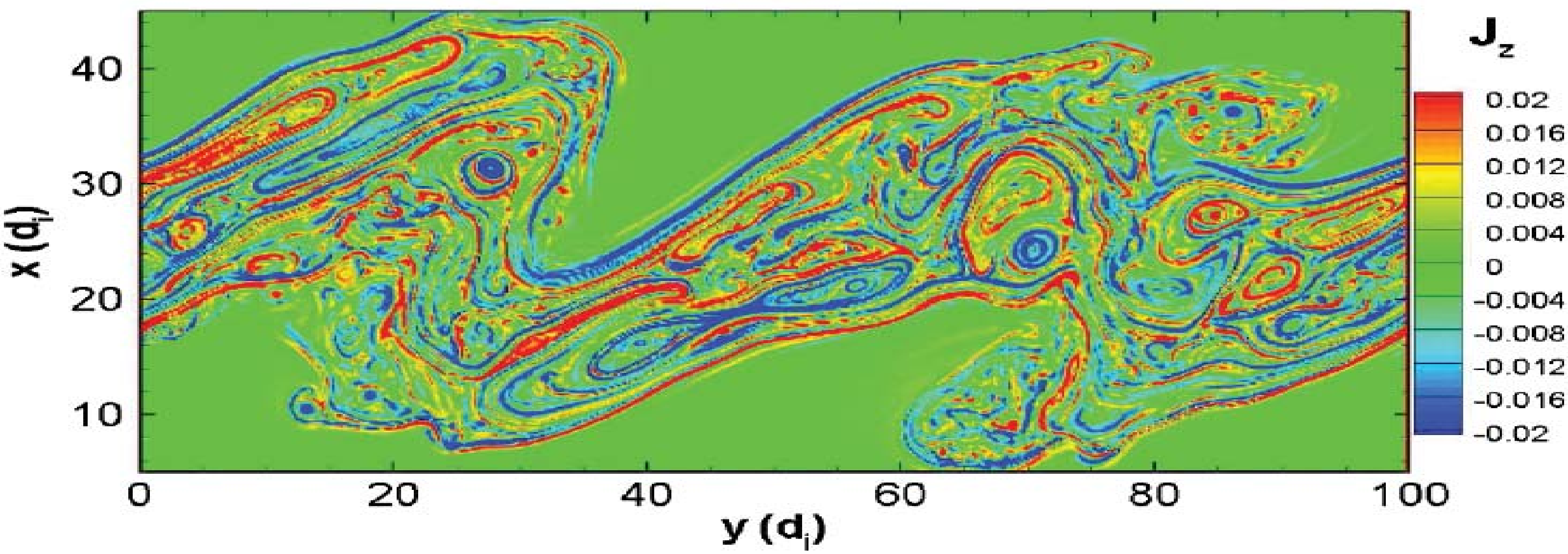
50% is for electron heating

Electrons are preferentially heated in the direction parallel to the magnetic field.

(Karimabadi et al, *Phys. Plasmas*, 2013)

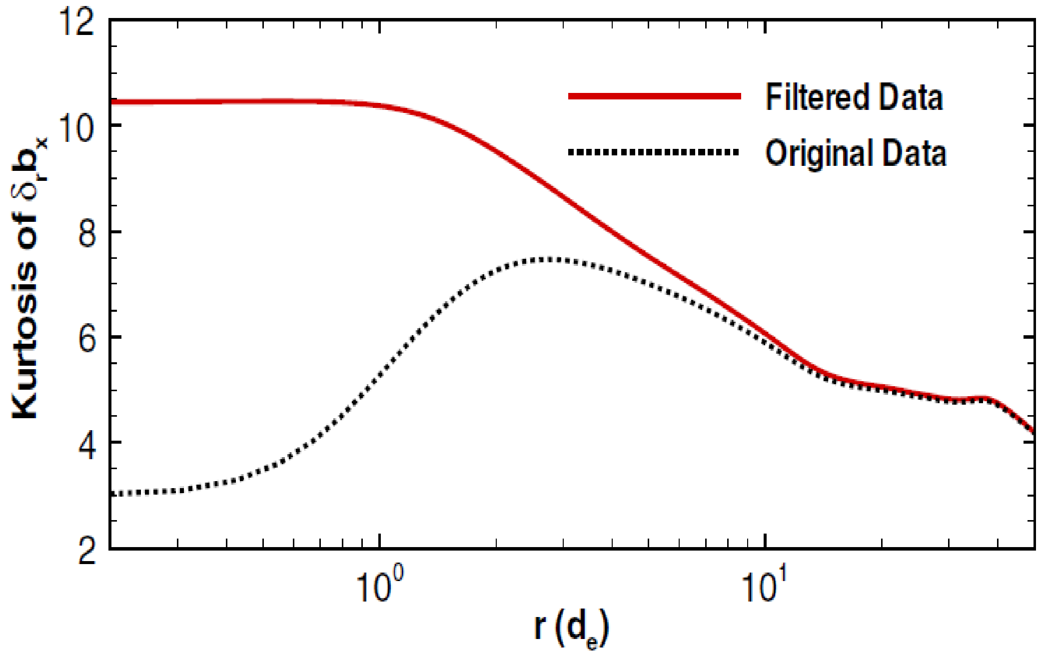
Energy spectra at turbulent state



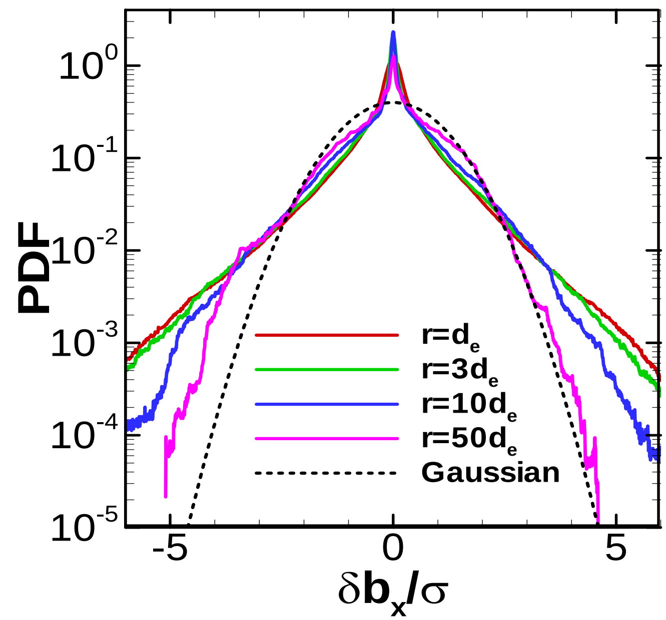


Wan et al., *PRL*, 2012

Intermittent features and non-Gaussian statistics



Kurtosis of $\delta b_x = b_x(y + r) - b_x(y)$ as a function of spatial lag r.



Normalized PDF δb_x from the filtered data

The effects of counting statistics at very high k influence kurtosis at much larger scales. Results are improved by using the filtered data.

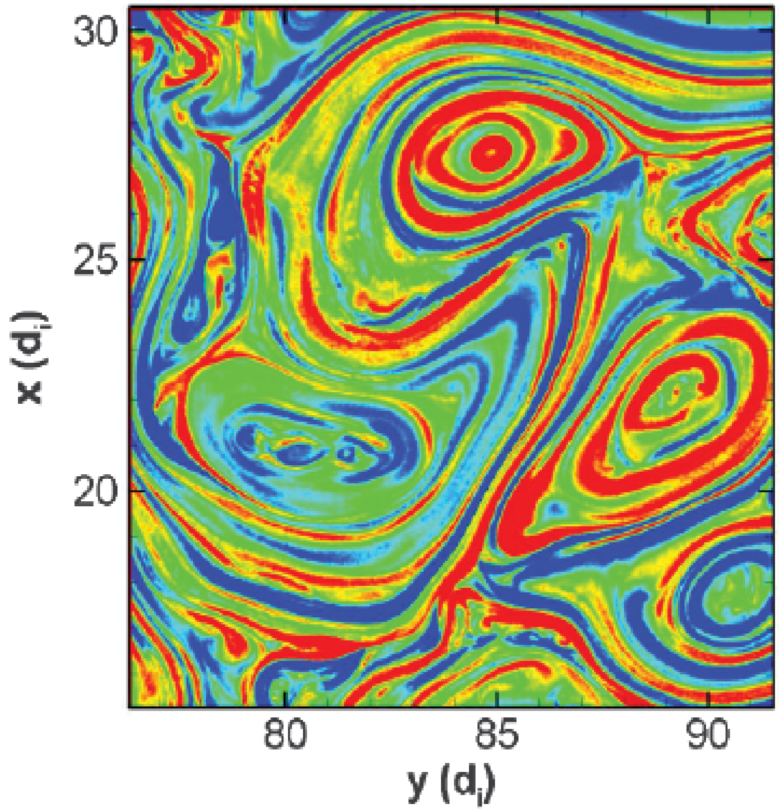
(Wan et al, *PRL*, 2012)

Dissipation at kinetic scales: proxies

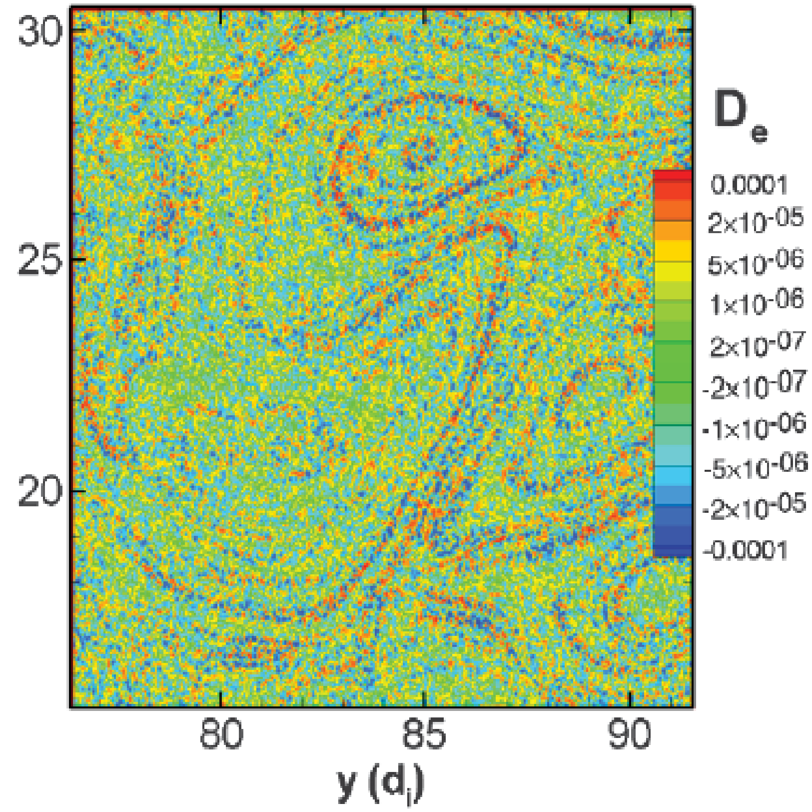
To identify regions that contain elevated dissipation, we studied $D = \mathrm{J} \cdot E$ in several frames of reference, as well as the work on electrons $\mathrm{J}_e \cdot E$.

- $D = \mathrm{J} \cdot E$, the work done by electromagnetic fields on the particles in the laboratory frame.
- $D_e = \mathrm{J} \cdot (E + \mathrm{v}_e \times B) - \rho_c(\mathrm{v}_e \cdot E)$, which is evaluated in the local electron frame. (Zenitani et al., *PRL*, 2011)
- $D_\parallel = \mathrm{J}_\parallel \cdot E_\parallel = (\mathrm{J} \cdot B)(E \cdot B)/|B|^2$, the "parallel dissipation".
- $\mathrm{J}_e \cdot E$, the contribution of electron current.

Dissipation at kinetic scales: a physical picture



J_z in a close-up region showing hierarchy of coherent structures;

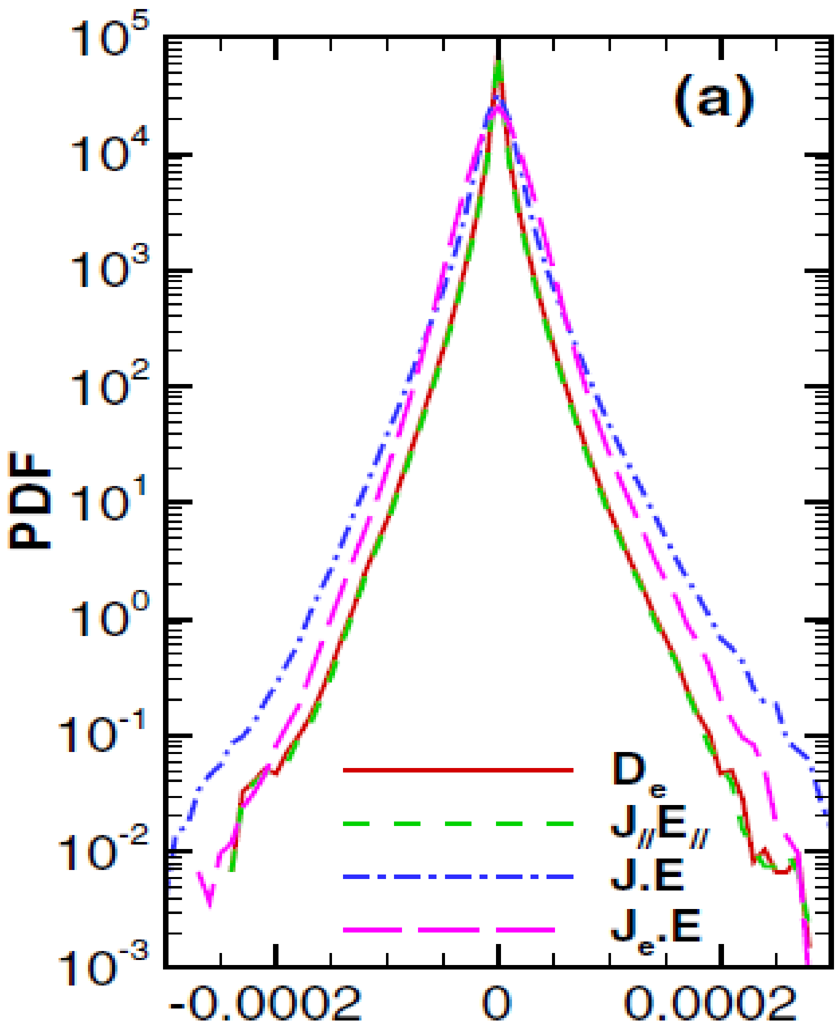


Contour of electron-frame dissipation D_e.

D_e spatially resemble the electric current structures providing qualitative evidence of inhomogeneous dissipation.

(Wan et al., *PRL*, 2012.)

Dissipation at kinetic scales: PDFs and mean values



(Wan et al, *PRL*, 2012)

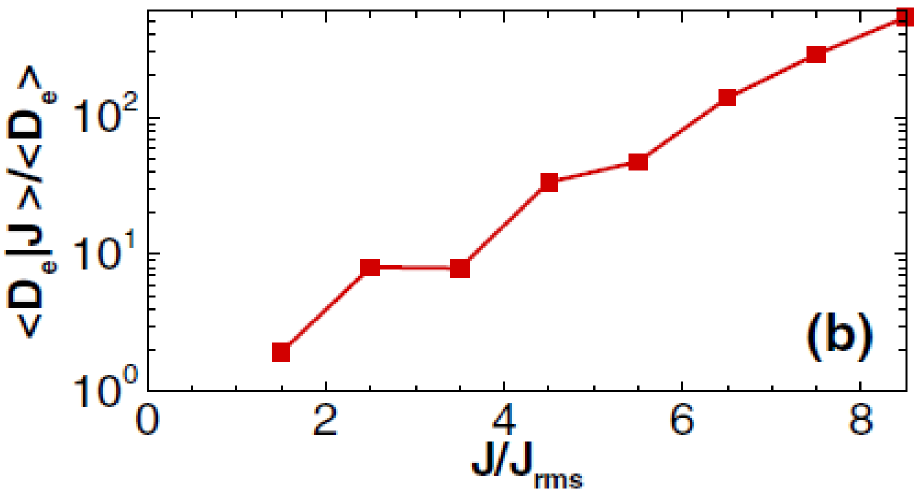
PDFs of four dissipation proxies: D_e, D, $D_{//}$, and $J_e \cdot E$.

$D = J \cdot E$ has the broadest distribution, as it includes fluid scale stresses that exchange magnetic and flow energies.

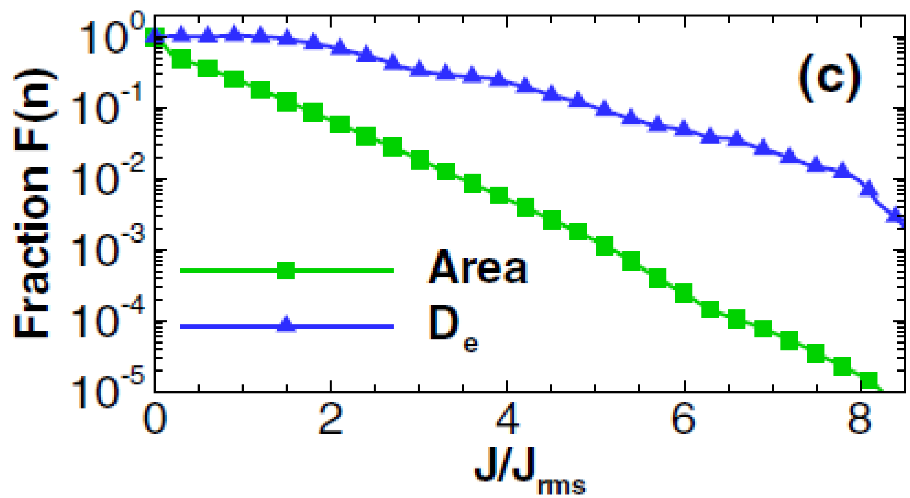
Mean values: $<D_e>=5.78 \times 10^{-8}\, c^3/d_e$, $<D_{//}>=5.81 \times 10^{-8}\, c^3/d_e$;

Good agreement of global average values suggesting that these are reasonable (but imperfect) estimates of net dissipation of fluid scale energy into plasma internal energy.

Intermittent dissipation at kinetic scales



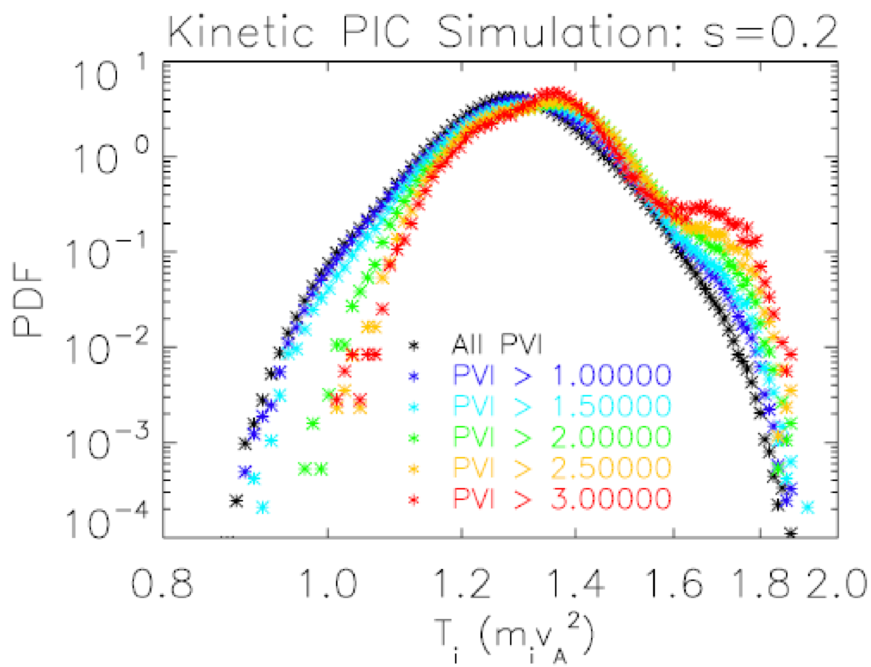
(b) Conditional average of dissipation D_e calculated conditioning on the value of current density.



(c) Fraction of area where the normalized current density J/J_{rms} is larger than some value n,. Also shown is the fraction of dissipation contributed to the total dissipation from those corresponding areas.

Regions of stronger electric current density occupy smaller areas, but make disproportionate contributions to total dissipation measure.

Heating is associated with intermittent coherent structures

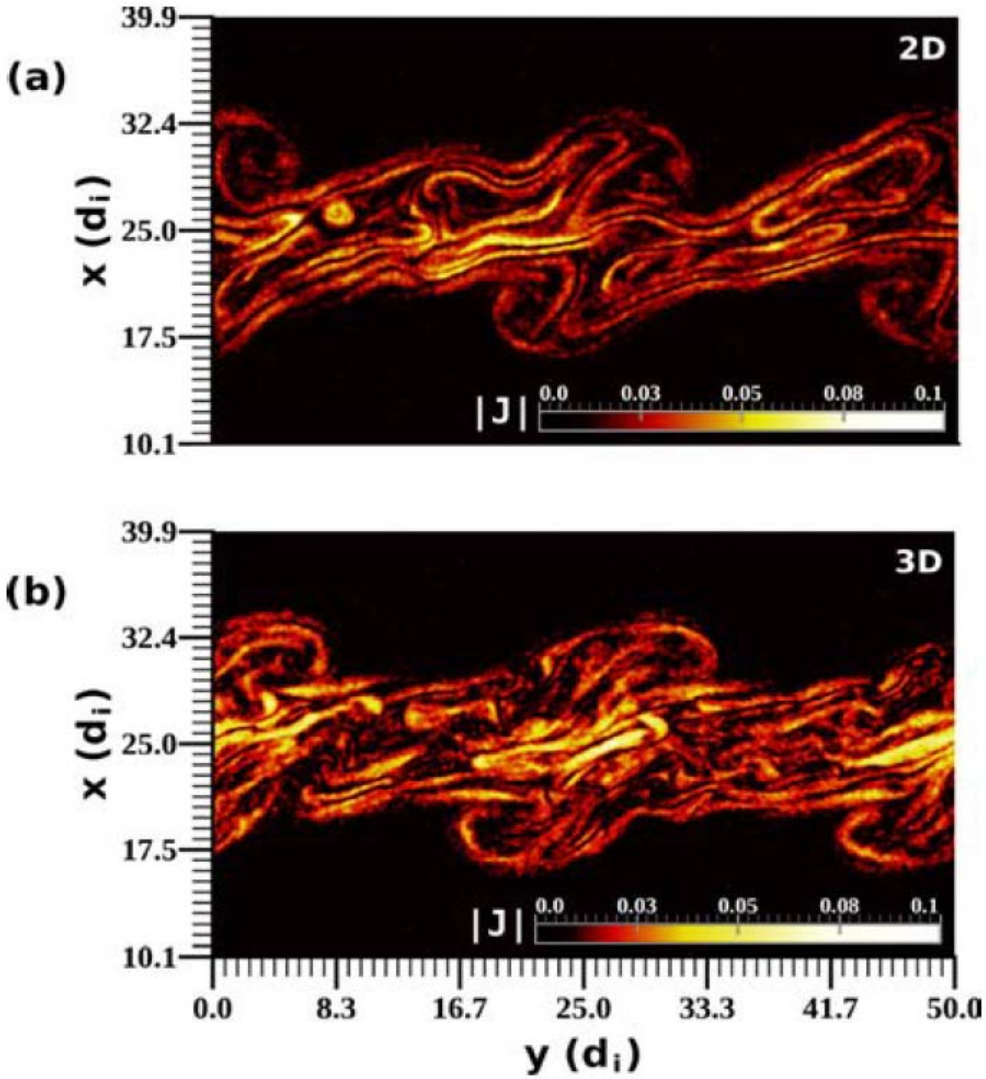


From PIC simulations (P3D, isotropic and homogeneous initial field), distribution of proton temperature conditioned on PVI threshold for increasing PVI thresholds.

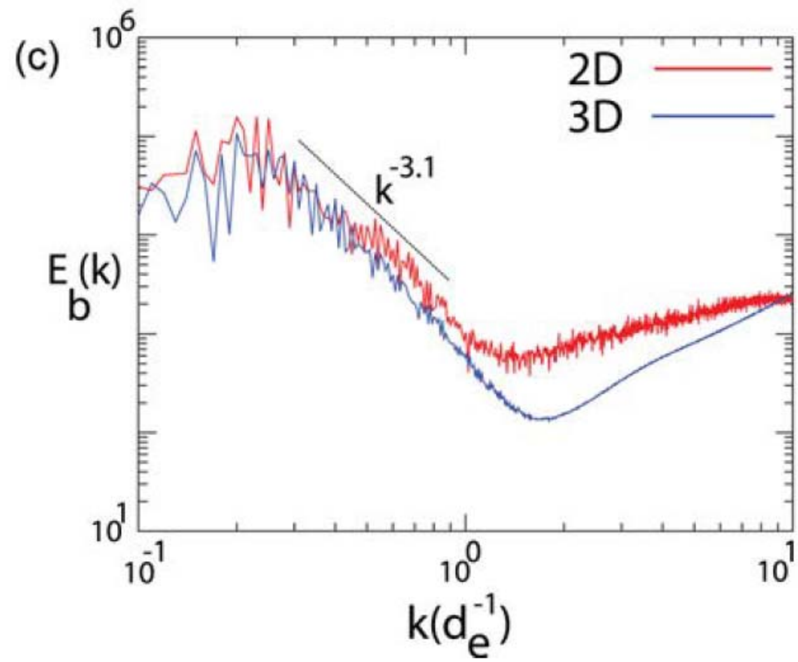
$$PVI = \frac{|\Delta \mathbf{b}(s, \Delta s)|}{\sqrt{\langle |\Delta \boldsymbol{b}(s, \Delta s)|^2 \rangle}}$$

(Wu et al., *ApJ*, 2013)

3D PIC simulations

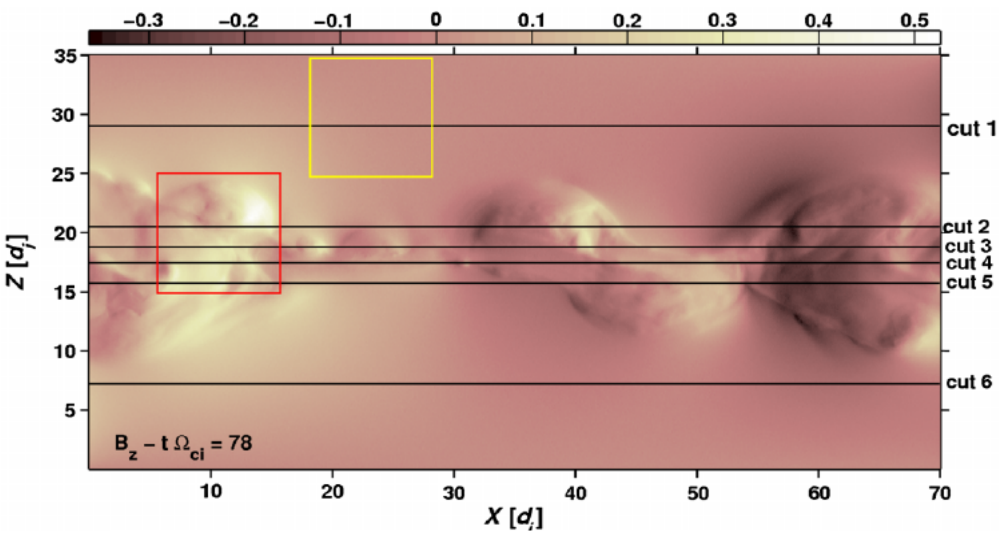


- The essence of shear driven turbulence remains similar in 2D and 3D; the spectrum of the magnetic energy are not drastically different.

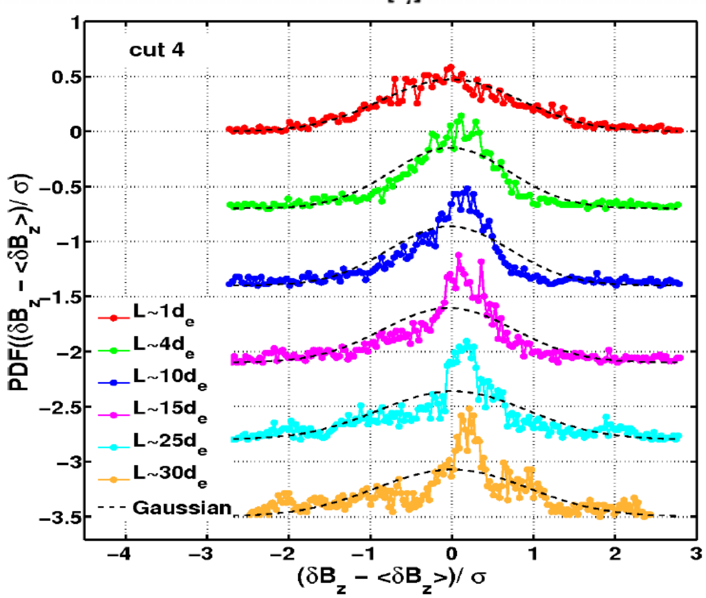


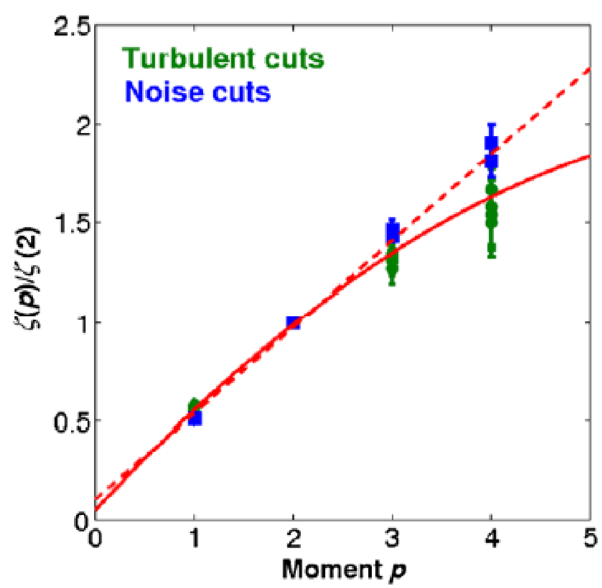
(Karimabadi et al, *Phys. Plasmas*, 2013)

Intermittency in 3D PIC simulations



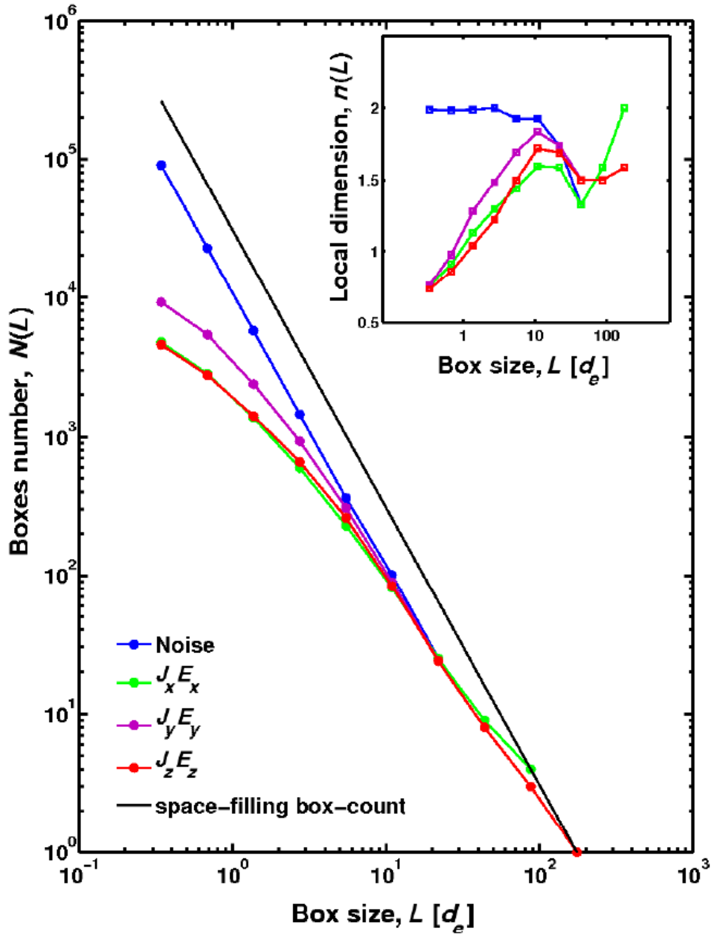
Leonardis et al., 2013 found the magnetic field fluctuations generated by reconnection exhibit turbulent features: non-Gaussian distributions, Extended Self-Similarity in their scaling and multi-fractal.





Leonardis et al., *PRL*, 2013

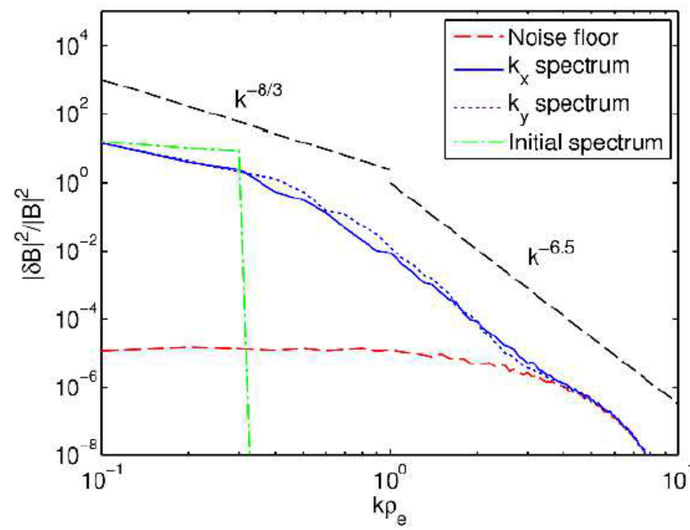
Leonardis et al., 2013 also found that the field J · E is multi-fractal, so that magnetic energy is converted to plasma kinetic energy in a manner that is spatially intermittent.

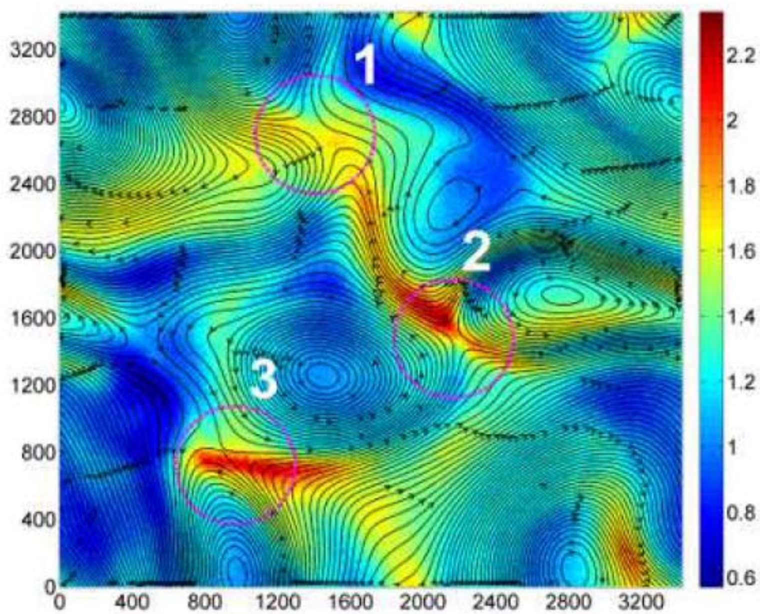


Box-counting method. The number of boxes, N(L), versus the box size L within a reconnection dominated turbulent region and a noise region for each component of J·E.

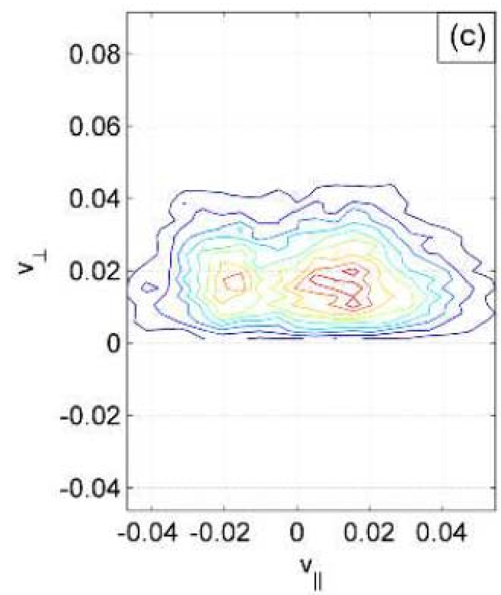
PIC simulation of turbulent reconnection

- Power spectrum with approximately power law down to electron scales ;
- Electron scale reconnection sites are generally associated with strong parallel electron temperature anisotropy.





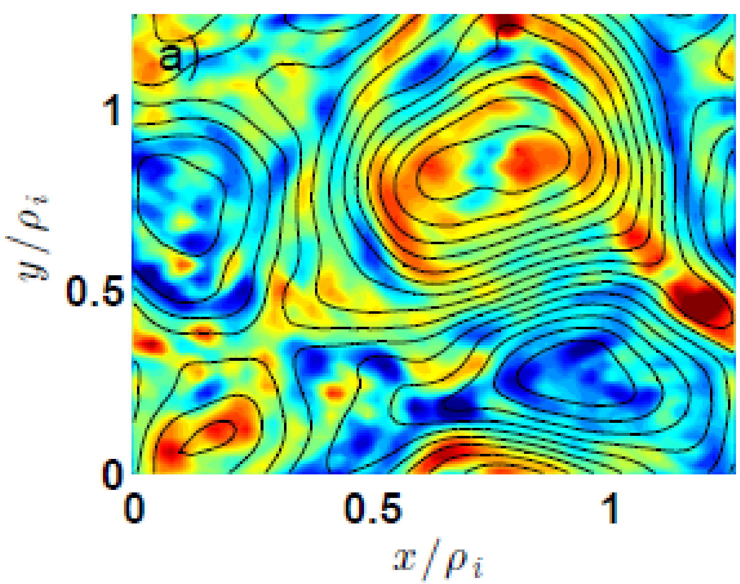
$T_{e//}/T_{e\perp}$

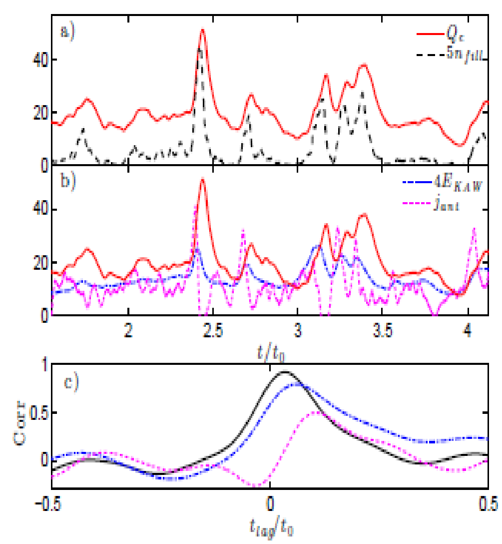


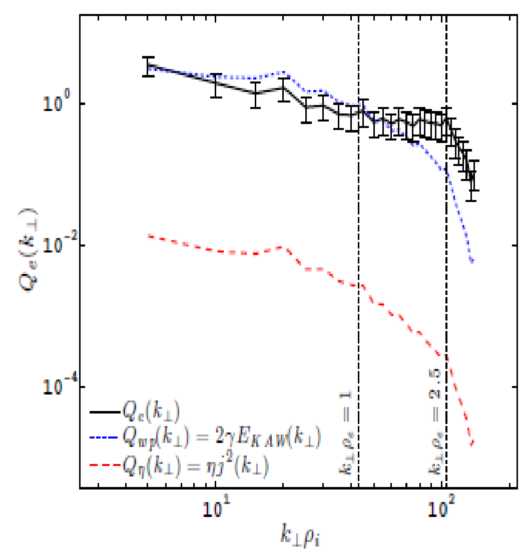
Haynes et al., *arXiv*, 2013

Current sheets in Gyrokinetics simulations

- TenBarge & Howes, studied the formation and dissipation of current sheets at electron scales in a wave-driven Gyrokinetics simulations.
- The electron heating rate is well correlated with the volume filling fraction of current sheets.
- Current sheets are found not significantly dissipated via *Ohmic dissipation*. Rather, collisionless damping via the Landau resonance with the electrons is sufficient to account for the measured heating.







TenBarge & Howes, arXiv, 2013

Conclusions

- PIC simulations of strong plasma turbulence are characterized by generation of highly structured current sheets extending through scales from several d_i to d_e. Consequently intermittent features are found down to electron scales.
- Computation of the work done by the electromagnetic field on the particles shows that dissipation occurs non-uniformly, and is strongly associated with current sheets. Proton temperature distributions suggest heating associated with coherent structures. These results reinforce the association of intermittent turbulence, coherent structures, and kinetic plasma dissipation.
- More needs to be done to understand the dissipation at kinetic current sheets.
- Solar wind? Waves?