Kinetic Turbulence in Astrophysical Plasmas: Waves and/or Structures?

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11th Plasma Kinetics Working Meeting, Vienna, July 23rd, 2018

Acknowledgements

Results were produced in collaboration with:

Alfred Mallet (UNH), Chris Chen (QMUL), Nuno Loureiro (MIT), Ravi Samtaney (KAUST), Kai Schneider (I2M-CNRS), Frank Jenko (IPP)

OSIRIS code [developed and distributed by the OSIRIS Consortium (UCLA & IST, Portugal)]:

- 3D, fully kinetic, fully explicit, & relativistic PIC code
- traditionally used for laser wakefield acceleration studies

$\Rightarrow$ **New application presented here**: massively parallel space/astro plasma turbulence simulations (w/ some code adjustments, e.g., external forcing, extra diagnostics)

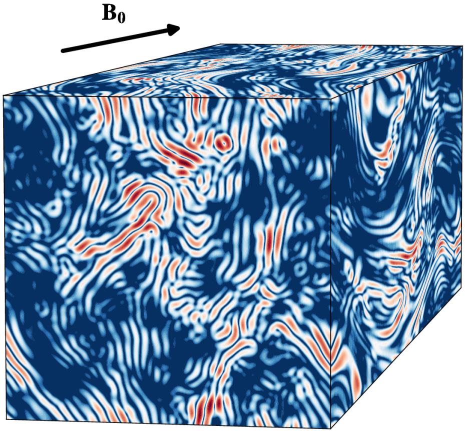
Simulations performed at:

Shaheen II (KAUST Supercomputing Lab) [$\sim$ 50k-core runs], SuperMUC (Leibniz Supercomputing Centre) [$\sim$ 30k-core runs], Hydra (Max Planck Computing and Data Facility) [$\sim$ 4k-core runs]

Nature of kinetic turbulence in space/astro plasmas?

I will address two (open) questions:

1. Most relevant linear modes at sub-ion scales?
   - (a) kinetic Alfvén waves (KAWs)
   - (b) whistler waves (WWs)
   - (c) others (e.g. ion Bernstein modes)
   - (d) combinations of the above
   - (e) none
2. Role of kinetic-scale coherent structures?
   - (a) nonlinear structures dominate and wave physics is not significant
   - (b) structures are there but they are not significant
   - (c) turbulence is a mixture of "coexisting," mutually exclusive, structures and waves



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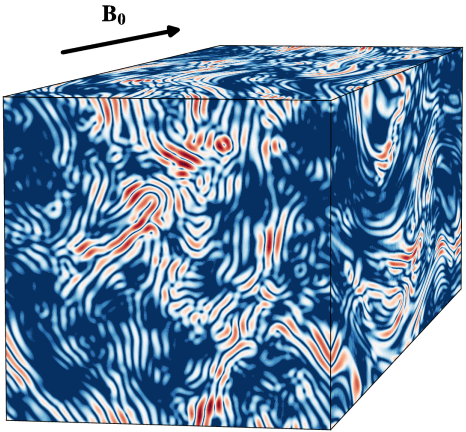

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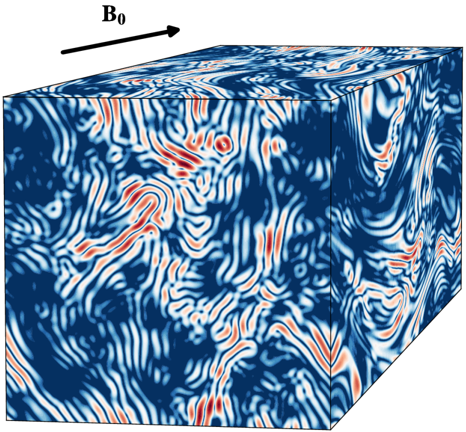

Aspects/regimes covered

Fully kinetic simulation parameters:

- β, $T_i/T_e \sim 1$ (typical solar wind conditions at 1 AU)
- $m_i/m_e = 64,\ 100,\ L_\perp \sim 18 d_i,\ L_z \sim 2.5 \cdot L_\perp$

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Regime of interest:

- weakly collisional (a.k.a. "collisionless")
- strong turbulence ($\chi \approx \tau_l/\tau_{nl} \sim 1$)
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- turbulent spectra and field ratios
- local spectral anisotropy
- spatial intermittency and turbulent structures

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I will *not* cover (but others will):

- turbulent heating and/or velocity-space cascades
- reconnection (in turbulence), particle acceleration, etc.

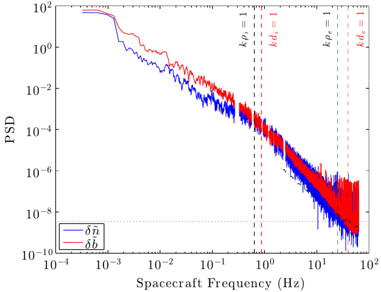
Spectral field ratios

I will rely on spectral field ratios to identify wavelike features:

$$\frac{(|E_\perp|c/v_A)^2}{|B_\perp|^2}, \qquad \frac{(|\delta n_e|/n_0)^2}{(|\delta B|/B_0)^2},$$

$$\frac{(|\delta n_e|/n_0)^2}{(|\delta B_\parallel|/B_0)^2}, \qquad \frac{|\delta B_\parallel|^2}{|\delta B|^2}$$

An example [C. Chen *et al.* (2013)]:



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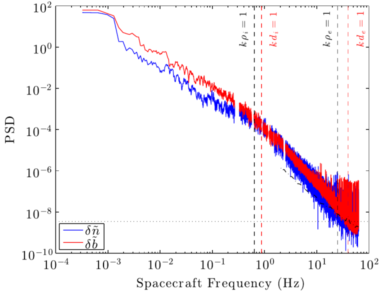

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- easily accessible in simulations and in situ observations
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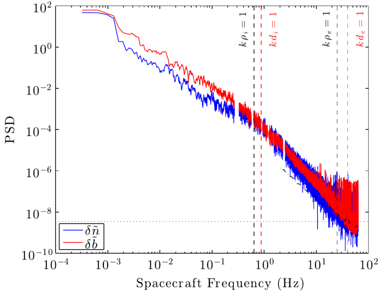

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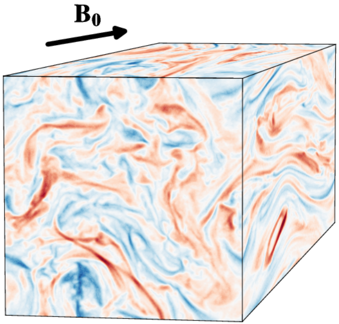
Cons and critics:

- typically only order unity agreement with linear predictions
- additional input is often needed to identify the dominant mode(s)
- being based on Fourier amplitudes, they ignore intermittency

A first-principles test of KAW turbulence phenomenology

3D OSIRIS simulation:

- Decaying turbulence with an initial spectrum of counterpropagating Alfvén waves
- $\beta_i \approx \beta_e \approx 0.5$, $m_i/m_e = 64$
- $L_\perp \approx 17 d_i$ $L_\perp/L_z = \delta B(t{=}0)/B_0 = 0.4$

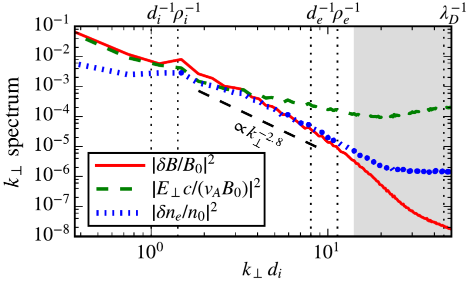


Results are compared against the KAW turbulence predictions:

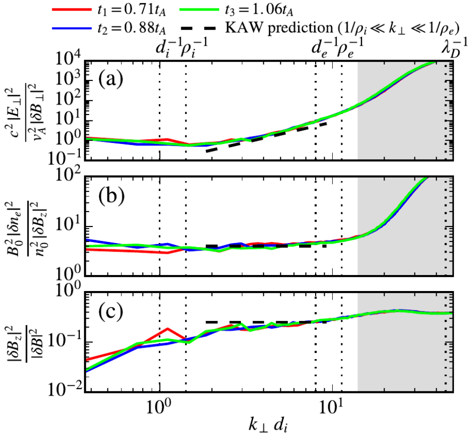
- $\frac{(|\delta n_e|/n_0)^2}{(|\delta B|/B_0)^2} \sim 1/(\beta_i + 2\beta_i^2) \sim 1$, $\frac{(|\delta n_e|/n_0)^2}{(|\delta B_\parallel|/B_0)^2} \sim 1/\beta_i^2$
- $\chi \approx \tau_l/\tau_{nl} \sim 1$ (critical balance) $\Rightarrow k_\parallel < k_\perp$ with $k_\parallel \propto k_\perp^\alpha$ ($\alpha = 1/3$ neglecting dissipative effects and/or intermittency corrections)

Spectra from the 3D simulation

- Qualitative agreement with spacecraft measurements, showing spectral slopes around ~ -2.8 at sub-ion scales
- The spectral ratios from the 3D fully kinetic simulation agree well with linear KAW predictions



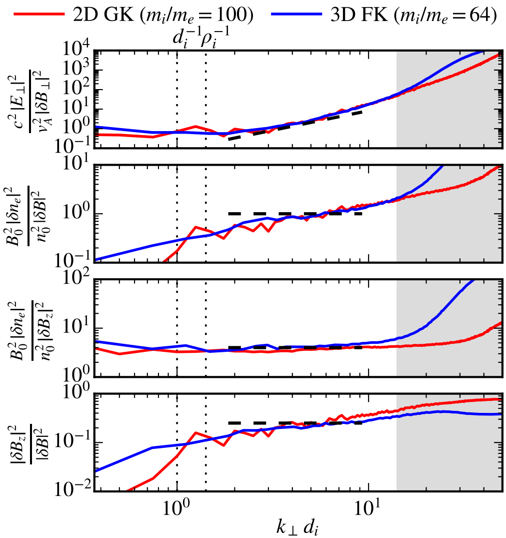
[PRL **120**, 105101 (2018)]



[+ good agreement with a 2D GK sim. (next slide)]

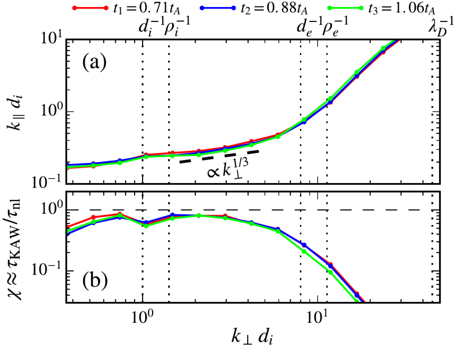
Good agreement with a 2D GK simulation

- both simulations have $\beta_i \approx \beta_e \approx 0.5$
- GK: 2D decaying turbulence simulation with $m_i/m_e = 100$ [Grošelj *et al.*, ApJ **847**, 28 (2017)]
- FK: 3D decaying turbulence with $m_i/m_e = 64$



Local anisotropy and critical balance

- The anisotropy is scale dependent with $k_\| < k_\perp$ & $k_\| d_i < 1$ (for $k_\perp \lesssim 1/d_e$)
- Broad agreement with critical balance ($\chi \sim 1$) at sub-ion scales



$$k_\| \approx \left(\frac{\left\langle \left| \mathbf{B}_{0,k_\perp} \cdot \nabla \delta \mathbf{B}_{k_\perp} \right|^2 \right\rangle}{\langle B_{0,k_\perp}^2 \rangle \langle \delta B_{k_\perp}^2 \rangle} \right)^{1/2}$$

[Cho & Lazarian (2009)]

$$\chi \approx \tau_l/\tau_{nl} \approx k_\perp \delta B_{\perp,k_\perp}/(k_\| B_0)$$

KAWs seem to play a role, but what about coherent structures?

Question: Would it be possible to calculate a "coherent structure field ratio"? Perhaps yes!

Use complex-valued Morlet wavelets to obtain for some field "f":

- a scale-dependent fluctuation: $\delta f(k_\perp, \mathbf{r}) \propto \Re\{\widetilde{f}(k_\perp, \mathbf{r})\}$
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We construct 2 sets of generalized field ratios:

$$\left(\frac{\langle|\delta n_e|^m\rangle}{\langle|\delta b_\perp|^m\rangle}\right)^{2/m}, \qquad \left(\frac{\langle|\delta n_e|^m\rangle}{\langle|\delta b_\parallel|^m\rangle}\right)^{2/m}, \qquad \left(\frac{\langle|\delta b_\parallel|^m\rangle}{\langle|\delta b_\perp|^m\rangle}\right)^{2/m}, \qquad m = 1, 2, 3, 4, 5, 6$$

$$\frac{\langle|\widetilde{n}_e|^2\,|\mathrm{LIM} > \xi\rangle}{\langle|\widetilde{b}_\perp|^2\,|\mathrm{LIM} > \xi\rangle}, \qquad \frac{\langle|\widetilde{n}_e|^2\,|\mathrm{LIM} > \xi\rangle}{\langle|\widetilde{b}_\parallel|^2\,|\mathrm{LIM} > \xi\rangle}, \qquad \frac{\langle|\widetilde{b}_\parallel|^2\,|\mathrm{LIM} > \xi\rangle}{\langle|\widetilde{b}_\perp|^2\,|\mathrm{LIM} > \xi\rangle}, \qquad \mathrm{LIM} = \frac{\mathcal{E}_{KAW}(k_\perp, \mathbf{r})}{\left\langle \mathcal{E}_{KAW}(k_\perp, \mathbf{r})\right\rangle_{\mathbf{r}}},$$

where $\mathcal{E}_{KAW} = |\widetilde{b}_\perp|^2 + |\widetilde{n}_e|^2$ is the (normalized) KAW energy density.

$\Rightarrow$ The above are compared against linear KAW predictions

Joint analysis of simulation and SW data [arXiv:1806.05741]

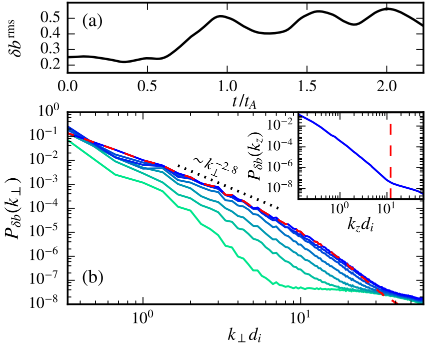
Externally driven 3D fully kinetic simulation:

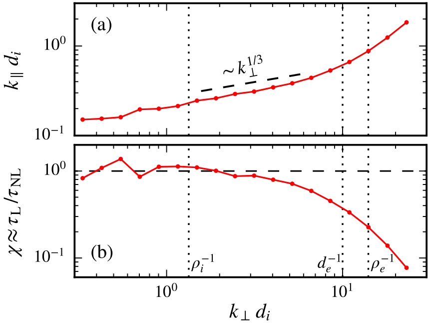
- Langevin antenna [TenBarge *et al.* (2014)]
- $\beta_i \approx \beta_e \approx 0.5$, $m_i/m_e = 100$, $L_\perp \approx 19 d_i$
  $L_\perp / L_z \approx 0.4$
- spatial resolution $928^2 \times 1920$, about 0.5 trillion particles in total

SW data selection:

- 7 h interval from Cluster ($\mathbf{B}$ data) [Chen *et al.* (2015)] ($\beta_i \approx 0.3$, $\beta_e \approx 0.6$)
- 159 s interval from MMS ($\mathbf{B}$ & n_e data) [Gershman *et al.* (2018)] ($\beta_i \approx 0.3$, $\beta_e \approx 0.03$)

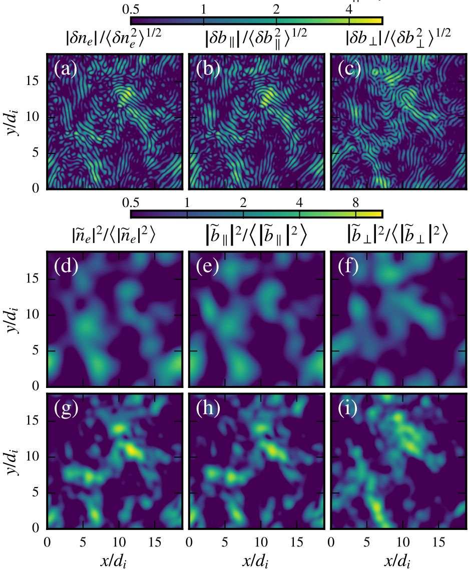
[MMS interval too short for a reliable stat. analysis (results included for reference; more suitable *simultaneous* $\mathbf{B}$ and n_e traces presently not available)]

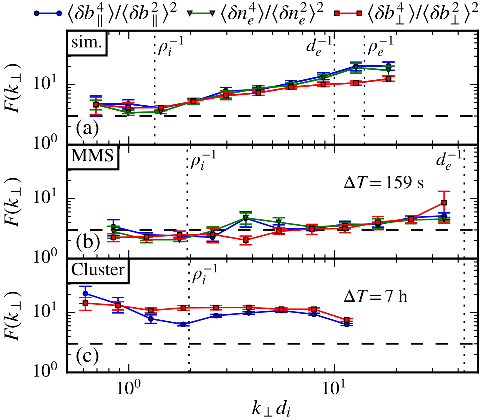




Spatial structure of fluctuations and intermittency

- the spectra are spatially non-uniform and the fluctuations display non-Gaussian statistics
- a mixture of sheetlike and filamentary structures is seen
- δn_e profiles match those of $\delta b_\parallel$ ($\Rightarrow \perp$ pressure balance; additional info on backup slide)

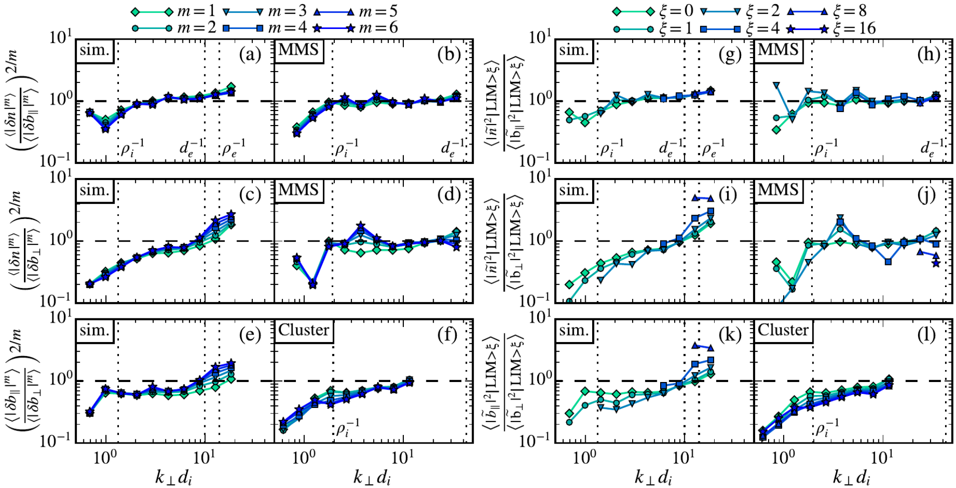




$\Rightarrow$ $\delta b_\parallel$, δn_e, and $\delta b_\perp$ have similar flatness in range $1/\rho_i \lesssim k_\perp \lesssim 1/d_e$

Large-amplitude, turbulent structures preserve KAW signatures

- reasonable agreement between generalized ratios and KAW predictions ($\delta b_\perp$, $\delta b_\parallel$, δn_e each separately display signatures of non-Gaussian statistics!)
- good agreement between the simulation and SW data
- linear predictions are generally accurate only to order unity ($\Rightarrow$ nonlinear effects)



Summary

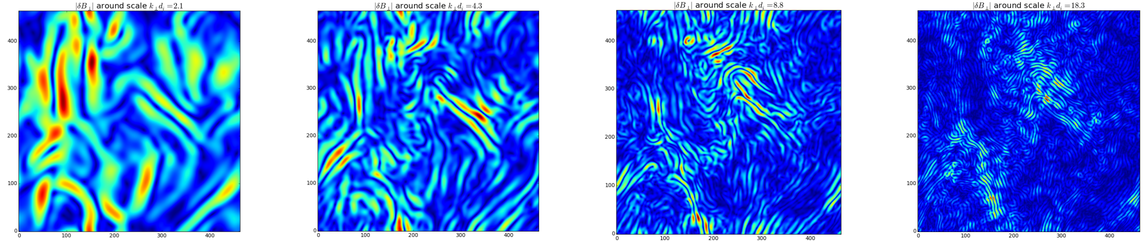
- For $\beta_e \sim \beta_i \sim 1$ (solar wind at 1 AU), the sub-ion-scale fluctuations seem to be predominantly of kinetic Alfvén type
- The anisotropy of the kinetic turbulence is scale-dependent and in broad agreement with critical balance
- Large-amplitude turbulent structures tend to preserve linear wavelike signatures

  $\Rightarrow$ structures could be perhaps viewed as the (critically balanced) "eddies" of KAW turbulence (similar to MHD range turbulence [e.g., Boldyrev (2006), Howes (2016), Mallet & Schekochihin (2017)])

  $\Rightarrow$ there is no sudden breakdown of linear predictions within the structures, only gradual deviation due to nonlinear effects

Some remarks

- The $k_{||}$ vs. $k_{\perp}$ scaling *might* be non-intermittent or very weakly intermittent (backup slide), similar to MHD [e.g., Mallet et al. (2016)]
- Kinetic range turbulence *might* also be locally 3D anisotropic ($\Rightarrow$ interesting for reconnection):



- One often finds $|\delta b_{||}|^2 \sim |\delta n_e|^2 \lesssim |\delta b_\perp|^2$ [e.g., Boldyrev & Perez (2012), Chen et al. (2013), this work] $\Rightarrow$ Analogy with residual energy in MHD turbulence?
- Can we ignore structures since they preserve KAW-like features? No!
  $\Rightarrow$ intermittent structures may significantly affect different heating mechanisms [Mallet et al., preprint soon], but their KAW properties could be exploited in theoretical predictions