Forced hybrid-kinetic turbulence in 2D3V

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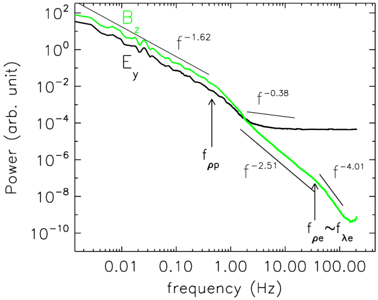
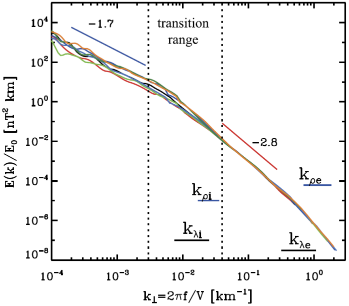
Outline

Solar wind (SW) turbulence below the ion gyroradius

SW in-situ satellite measurements of turbulent energy spectra



[Sahraoui et al., PRL **102** (2009)]

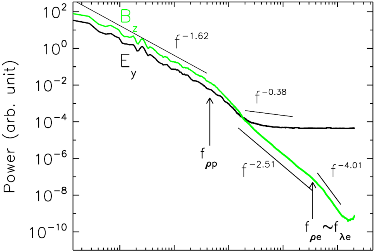


[Alexandrova et al., Space Sci Rev **178** (2013)]

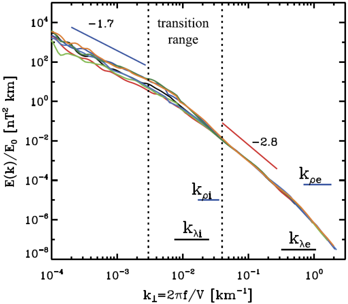
- **large scales**: magnetohydrodynamic (MHD) intertial range → $\sim k_\perp^{-5/3}$ spectrum.
- **first spectral break** at ions' characteristic scales ($k_\perp \rho_i \sim 1$ and/or $k_\perp d_i \sim 1$).
- "dissipation/dispersion" range ($1 \lesssim k_\perp \rho_i \lesssim \rho_i/\rho_e$):
  → **B-field spectrum**: slope in the range $[-2.5, -3]$.
  → **E-field spectrum**: slope in the range $[-0.3, -1.3]$ *(→ noise?)*.
  → energy in the E-field overcomes the magnetic counterpart.

Solar wind (SW) turbulence below the ion gyroradius

SW in-situ satellite measurements of turbulent energy spectra



[Sahraoui et al., PRL **102** (2009)]



[Alexandrova et al., Space Sci Rev **178** (2013)]

A long-lasting debate and open problem in SW turbulence research:

what is the nature of turbulent fluctuations below ion kinetic scales?

Solar wind (SW) turbulence below the ion gyroradius

Theoretical candidates:

kinetic Alfvén waves (KAWs)

[Schekochihin et al., ApJ Supp. Series **182**, 310 (2009)]

$$E_B(k_\perp) \propto k_\perp^{-7/3}$$

$$E_E(k_\perp) \propto k_\perp^{-1/3}$$

whistler waves

[Galtier & Bhattacharjee, PoP **10**, 3065 (2003)]

$$E_B(k_\perp) \propto k_\perp^{-7/3}$$

$$E_E(k_\perp) \propto k_\perp^{-1/3}$$

Same spectra, <u>but</u> different physics
↓
auxiliary methods to distinguish between them

Possible sources of steepening:

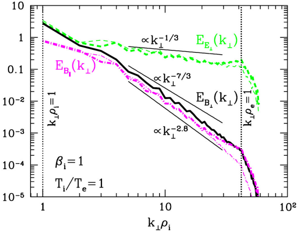
- Landau damping [Howes et al., JGR **113** (2008)]
- Compressiblility effects: $E_B \propto k_\perp^{-7/3-2\xi}$ [Alexandrova et al., ApJ **674** (2008)]
- Intermittency corrections: $E_B \propto k_\perp^{-8/3}$ and $E_E \propto k_\perp^{-2/3}$ [Boldyrev & Perez, ApJL **758** (2012)]

Solar wind (SW) turbulence below the ion gyroradius

Numerical simulations: reproducing energy spectra

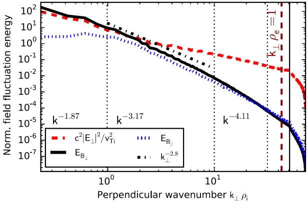
3D GK driven KAWs

[Howes et al., PRL **107** (2011)]



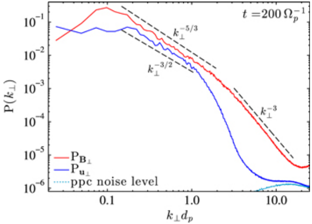
3D GK driven KAWs

[Told et al., PRL **115** (2015)]



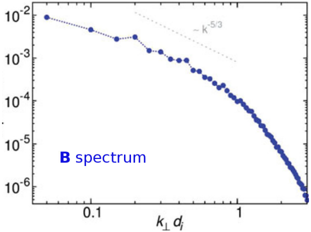
2D hybrid-PIC freely-decaying

[Franci et al., ApJ **812** (2015)]



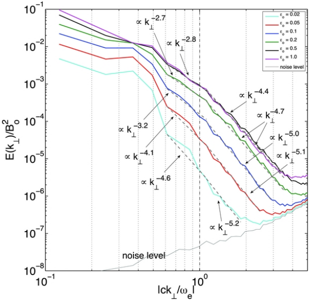
3D HVM freely-decaying

[Servidio et al., JPP **81** (2015)]



3D PIC freely-dec. whistlers

[Gary et al., ApJ **755** (2012)]



So far, freely-decaying simulations and/or focus on one scenario at a time

Hybrid Vlasov-Maxwell (HVM) model

Fully kinetic ions & massless electron fluid:

[Valentini et al., JCP **225**, 753 (2007)]

$$\frac{\partial f_{\rm i}}{\partial t} + \mathbf{v}\cdot\frac{\partial f_{\rm i}}{\partial \mathbf{x}} + (\mathbf{E} + \mathbf{v}\times\mathbf{B} + \mathbf{F})\cdot\frac{\partial f_{\rm i}}{\partial \mathbf{v}} = 0 \quad \text{(Vlasov equation)}$$

$$\mathbf{E} = -\mathbf{u}_{\rm i}\times\mathbf{B} + \frac{1}{n}(\mathbf{J}\times\mathbf{B}) - \frac{1}{n}\nabla P_{\rm e} + \eta\mathbf{J} \cancel{+\mathcal{O}\left(\frac{m_e}{m_i}\right)} \quad \text{(gener. Ohm's law)}$$

$$\frac{\partial \mathbf{B}}{\partial t} = -\nabla\times\mathbf{E}\,, \qquad \nabla\times\mathbf{B} = \mathbf{J} \cancel{+\frac{\partial \mathbf{E}}{\partial t}} \quad \text{(Maxwell's equations)}$$

$\mathbf{F} = \mathbf{F}(\mathbf{x}, t)$: random forcing, δ-correlated in time.

$$m_{\rm e} = 0\,, \quad n_{\rm i} = n_{\rm e} = n\,, \quad \omega/k \ll c\,, \quad P_{\rm e} = nT_{\rm e0}$$

Simulations setup

- **2D-3V phase space**:

$$1024^2 \times 51^3 \text{ grid points } (\mathbf{k_\perp d_i} \in [\mathbf{0.1}, \mathbf{51.2}])$$

- **initial condition**:

$$f_{\rm i}(\mathbf{x}, \mathbf{v}, t=0) = \text{isotropic Maxwellian}$$

$$\mathbf{B}(\mathbf{x}; t=0) = B_0 \mathbf{e}_z + \delta\mathbf{B}(\mathbf{x}) \quad (\,|\delta\mathbf{B}| \ll B_0 \text{ and } 0.1 \leq (k_\perp d_{\rm i})_{\delta B} \leq 0.3\,)$$

- **F injection scale**:

$$0.1 \leq (k_\perp d_{\rm i})_{\rm F} \leq 0.2 \text{ (continuously forced)}$$

→ forcing contributions: $\sim$ 50% compressible, $\sim$ 50% incompressible

- **beta regimes investigated**:

$$\beta = 0.2,\ 1 \text{ and } 5$$

The quest for a compromise: model & setup

Major "weak" points

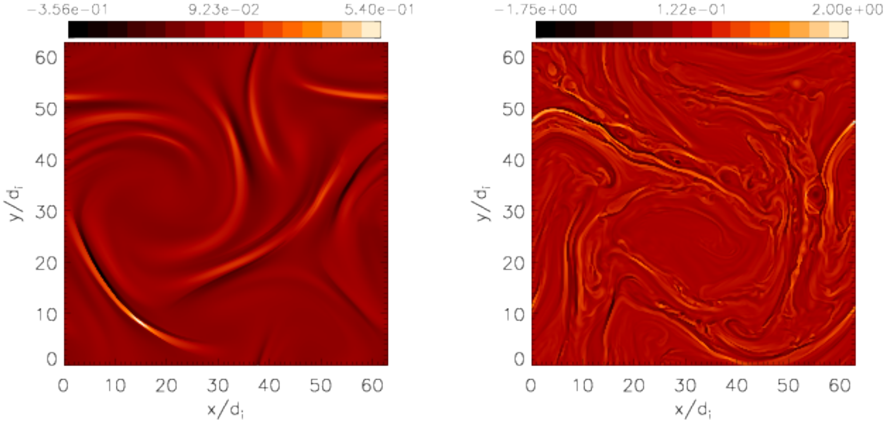
- reduced dimensionality (2D) of the simulations
- electron Landau damping (LD) is missing on all modes

Major "strong" points

- in 2D we can include three decades in the spectra
- fully kinetic ions (e.g., ion cyclotron resonances are included)
- we do not focus on a particular mode (both KAWs and whistler are allowed)
- **F** allows to reach a quasi-steady turbulent state
- the growth of in-plane magnetic fluctuations allows for $k_{\parallel} \neq 0$

we expect these "2.5D" simulations to retain some important dynamical features of the fully 3D case

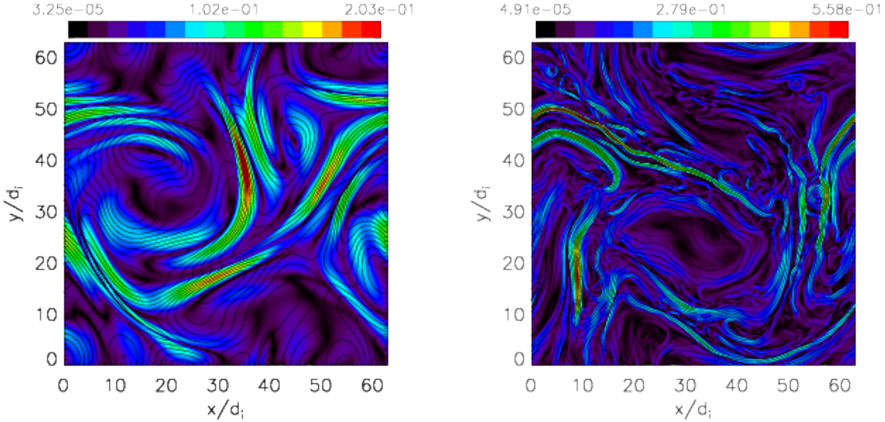
Developing plasma turbulence (J_z)



Example of J_z contours for $\beta_{\mathrm{i}} = 1$, at $\Omega_{\mathrm{ci}} t = 120$ (left) and $\Omega_{\mathrm{ci}} t = 225$ (right).

- formation of small-scale structures → kinetic regime
- current sheets → magnetic reconnection → fully developed turbulence

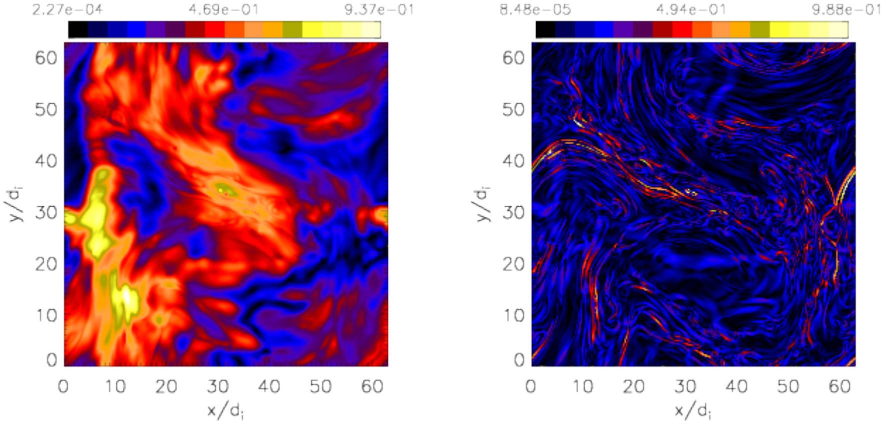
Developing plasma turbulence ($B_\perp$)



Example of $B_\perp$ contours and A_z lines for $\beta_\mathrm{i} = 1$, at $\Omega_\mathrm{ci} t = 120$ (left) and $\Omega_\mathrm{ci} t = 225$ (right).

- in-plane magnetic fluctuations: randomly oriented, $\langle B_\perp \rangle < 0.1$
- local high-$B_\perp$ spots: current sheets, coherent structures

Developed plasma turbulence ($E_\perp$)

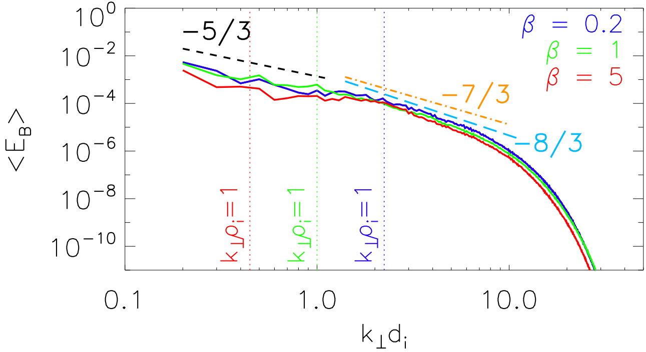


Contours of $E_{\rm MHD}$ (left) and of $E_{\rm Hall}$ (right) for $\beta_{\rm i} = 1$ at $\Omega_{\rm ci}t = 225$.

- $\mathbf{E}_{\rm MHD} = \mathbf{u}_{\rm i} \times \mathbf{B}$ dominates at large-scales (left)
- $\mathbf{E}_{\rm Hall} = (\mathbf{J} \times \mathbf{B})/n$ dominates at small-scales, inside current sheets (right)

Magnetic energy spectrum

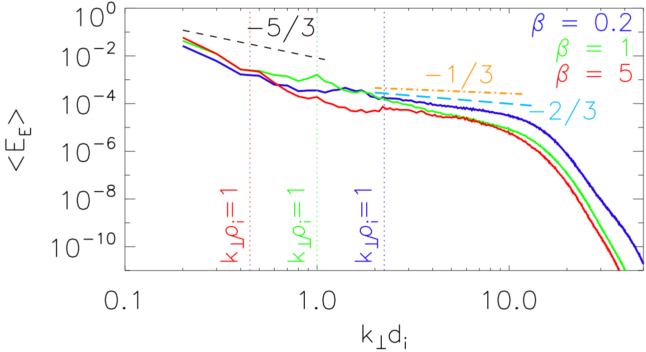
Cerri et al., ApJL **822**, L12 (2016)



- $k_\perp d_\mathrm{i} < 1$: Kolmogorov-type $k_\perp^{-5/3}$ spectrum
- spectral break at $1 \lesssim k_\perp d_\mathrm{i} \lesssim 2$
- $k_\perp d_\mathrm{i} > 1$: consistent with $k_\perp^{-8/3}$ at $\beta = 0.2, 1$ ($k_\perp^{-3}$ at $\beta_\mathrm{i} = 5$)

Electric energy spectrum

Cerri et al., ApJL **822**, L12 (2016)



- electric energy overcomes magnetic counterpart at $k_\perp d_\mathrm{i} \sim 2$
- spectral slopes generally steeper than theory predictions (observed in other simulations and some SW measurements → feedbacks?)

KAWs or whistlers? (Auxiliary method I)

Cerri et al., ApJL **822**, L12 (2016)

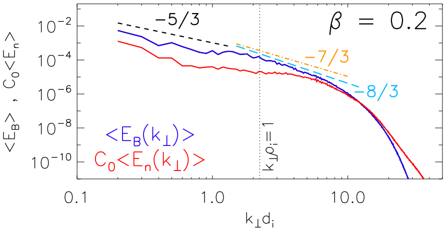
Auxiliary method I:

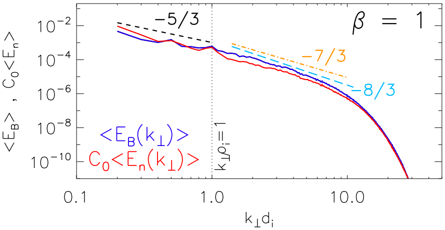
[Chen et al., PRL **110**, 225002 (2013)]

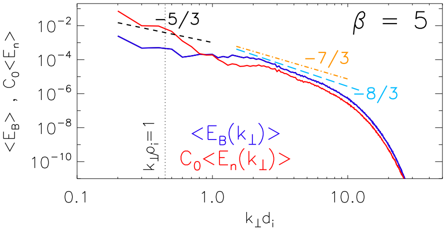
comparing the level of E_B and $C_0 E_n$

(with $C_0 = [\beta_\mathrm{i}(1+\tau)/2][1+\beta_\mathrm{i}(1+\tau)/2]$)

- **KAWs** → $C_0 E_n \simeq E_B$.
- **whistlers** → $C_0 E_n \ll E_B$.







KAWs or whistlers? (Auxiliary method II)

Cerri et al., ApJL **822**, L12 (2016)

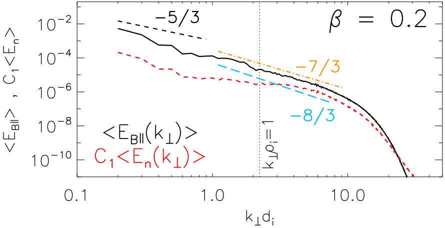
Auxiliary method II:

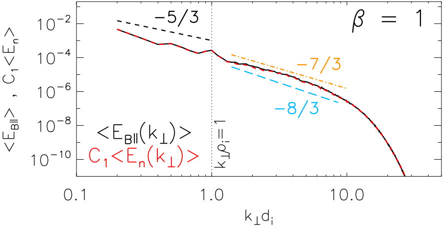
[Boldyrev et al., ApJ **777**, 41 (2013)]

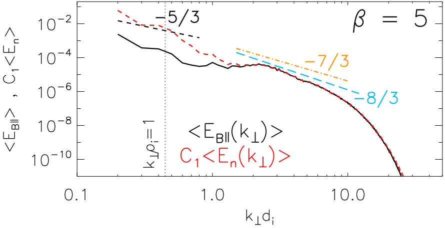
KAWs fluctuations would obey the following relation:

$$C_1 E_n \;=\; E_{B\|}$$

(with $C_1 = [\beta_{\rm i}(1+\tau)/2]^2$)

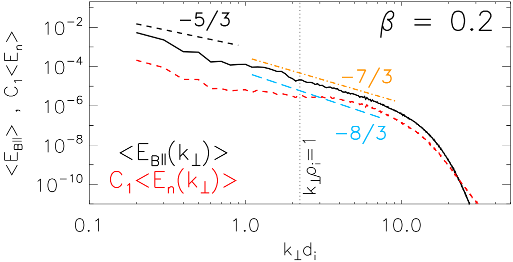






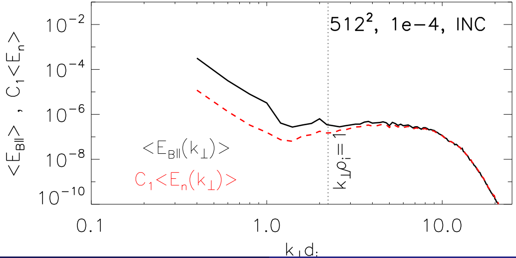
Partially compressible vs incompressible injection ($\beta = 0.2$)

Partially compressible forcing ($\nabla \cdot \mathbf{F} \neq 0$):



→ well separated even at $k_\perp \rho_\mathrm{i} > 1$

Purely incompressible forcing ($\nabla \cdot \mathbf{F} = 0$):



→ transition to KAWs at $k_\perp \rho_\mathrm{i} \sim 1$

Conclusions

- general agreement of spectral properties of the turbulence (e.g., power laws and spectral breaks) with observations/theory.
- in this setup turbulence mainly involves **whistler fluctuations at low β**, and **KAWs at somewhat higher β**.
- KAW ↔ whistler turbulence transition: possible correlation with resonant/non-resonant damping of the modes.
  (not straightforward: linear damping and/vs non-linear effects)
- **compressibility level** of injected fluctuations matters → non-universality and possible implications on time and space variability of SW.

→ **call for further investigations on these topics...**

Thanks for your attention!