Compressive wave structures on kinetic scales resulting from a two-dimensional turbulent cascade in the solar wind

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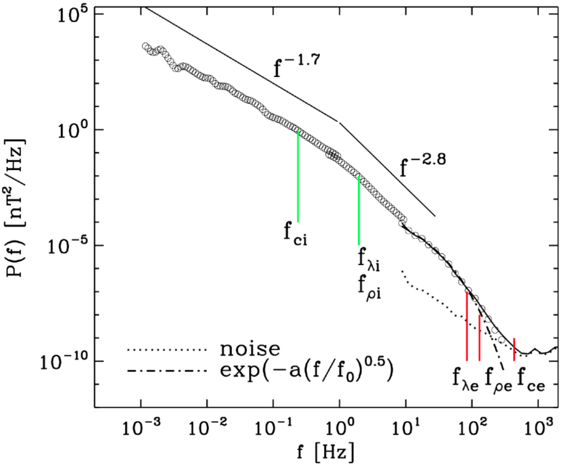
Spectral ranges



(Alexandrova et al., 2009)

A.I.K.E.F. code

Ions are treated as particles following the characteristics of the collisionless Vlasov equation:

$$\frac{\mathrm{d}\boldsymbol{v}_j}{\mathrm{d}t} = \frac{q_j}{m_j}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{v}_j \times \boldsymbol{B}\right),$$

$$\frac{\mathrm{d}\boldsymbol{x}_j}{\mathrm{d}t} = \boldsymbol{v}_j.$$

Electrons are treated as a massless fluid:

$$m_\mathrm{e}\frac{\mathrm{d}(n_\mathrm{e}\boldsymbol{u}_\mathrm{e})}{\mathrm{d}t} = 0 = -en_\mathrm{e}\left(\boldsymbol{E} + \frac{1}{c}\boldsymbol{u}_\mathrm{e} \times \boldsymbol{B}\right) - \operatorname{grad} p_\mathrm{e},$$

leading to a generalized Ohm's law of the form:

$$\boldsymbol{E} = -\frac{1}{c}\boldsymbol{u}_\mathrm{e} \times \boldsymbol{B} - \frac{1}{n_\mathrm{e}e}\operatorname{grad} p_\mathrm{e}.$$

A.I.K.E.F. code

Isothermal equation of state for the electron pressure:

$$p_{\mathrm{e}} = p_{\mathrm{e0}} \left(\frac{n_{\mathrm{e}}}{n_{\mathrm{e0}}} \right)^{\gamma}$$

Magnetic field is described by the induction equation:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \mathrm{curl}\, \left(\boldsymbol{u}_{\mathrm{i}} \times \boldsymbol{B} \right) - \mathrm{curl}\, \left(\frac{c}{4\pi \varrho_{\mathrm{c}}} \mathrm{curl}\, \boldsymbol{B} \times \boldsymbol{B} \right)$$

The code is parallelized. Adaptive mesh refinement is possible.

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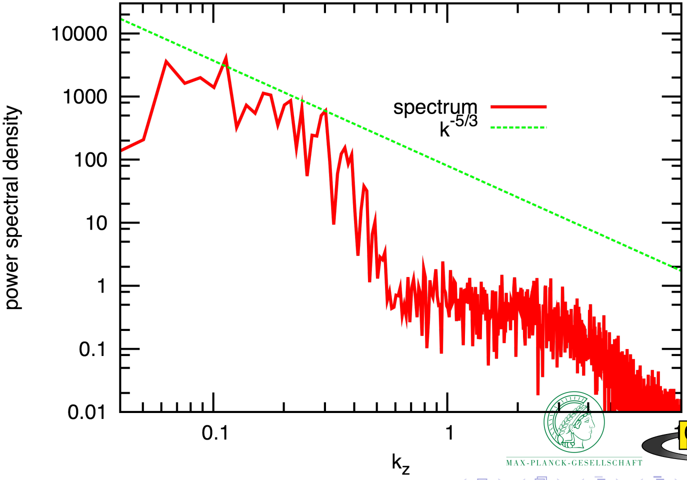
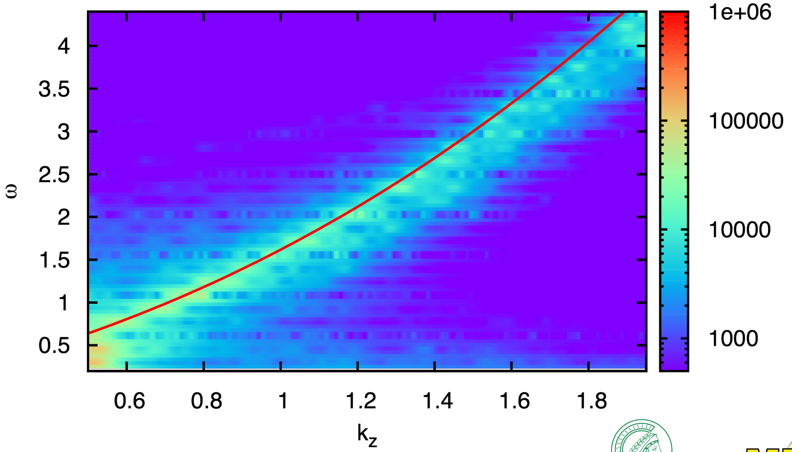
One-dimensional simulation
Initialization

- $\beta_{\mathrm{p}} = 0.08$, $\beta_{\mathrm{e}} = 0.5$
- Box size: 2048 grid points over a spatial size of $500\ell_{\mathrm{p}}$
- 400 (pseudo-)particles per cell
- superposition of 60 Alfvén/ion-cyclotron waves following a Kolmogorov spectrum ($k^{-5/3}$) in interval $k = 0.06 \ldots 0.2$
- amplitudes correspond to a wave with amplitude $\delta B / B_0 = 0.1$
- $\mathrm{d}t = 0.01$

One-dimensional simulation
PSD B-field



One-dimensional simulation
Dispersion, PSD B-field



- $\beta_{\mathrm{p}} = 0.05$, $\beta_{\mathrm{e}} = 0.5$
- Box size: 1024×1024 over a spatial size of $250\ell_{\mathrm{p}} \times 250\ell_{\mathrm{p}}$
- 1000 (pseudo-)particles per cell
- superposition of 20 incompressible MHD Alfvén waves following a Kolmogorov spectrum ($k^{-5/3}$) in interval $k = 0.05 \ldots 0.2$ for each direction
- 360° covered by 60 steps
- amplitudes correspond to a wave with amplitude $\delta B / B_0 = 0.01$
- $\mathrm{d}t = 0.01$

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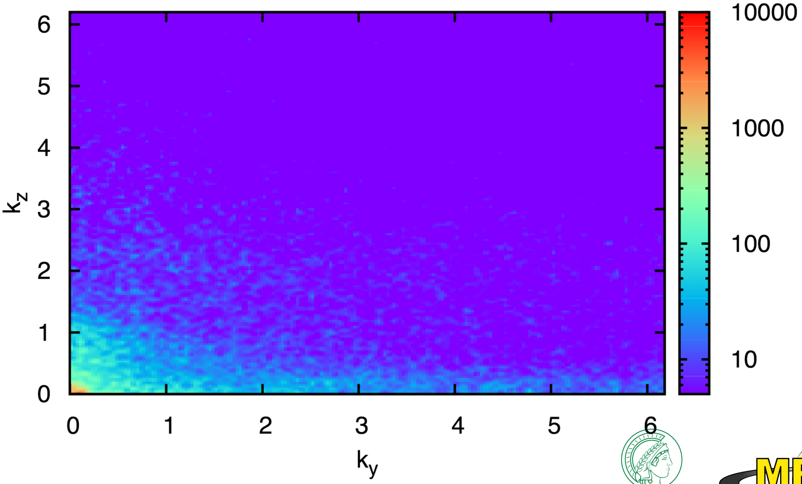
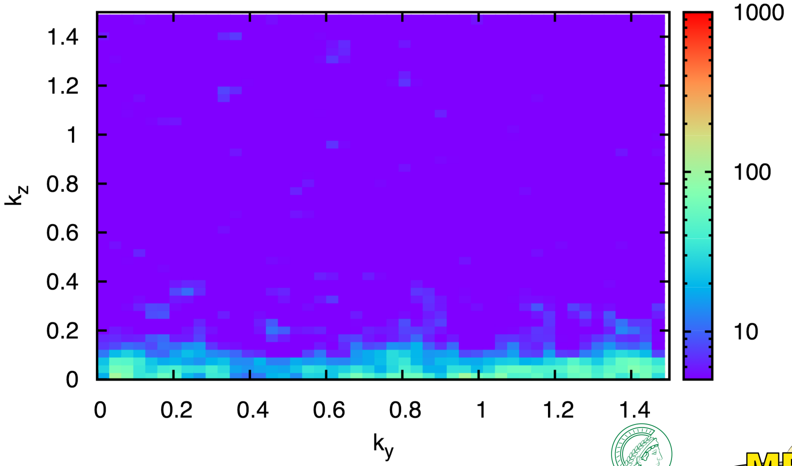
Two-dimensional simulation

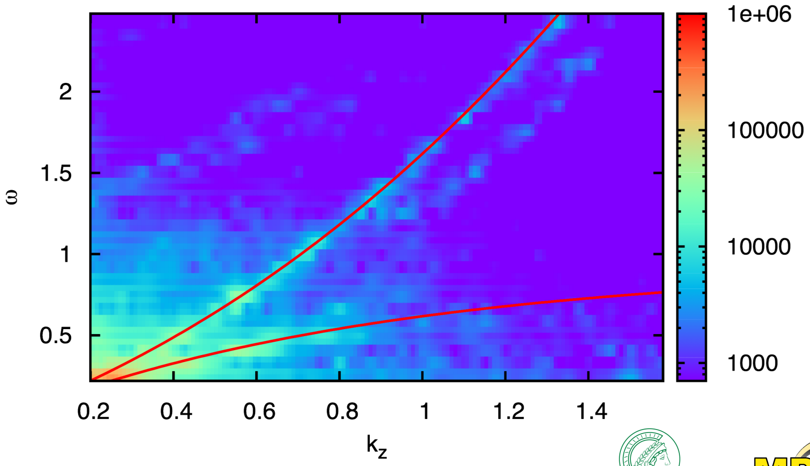
PSD B-field



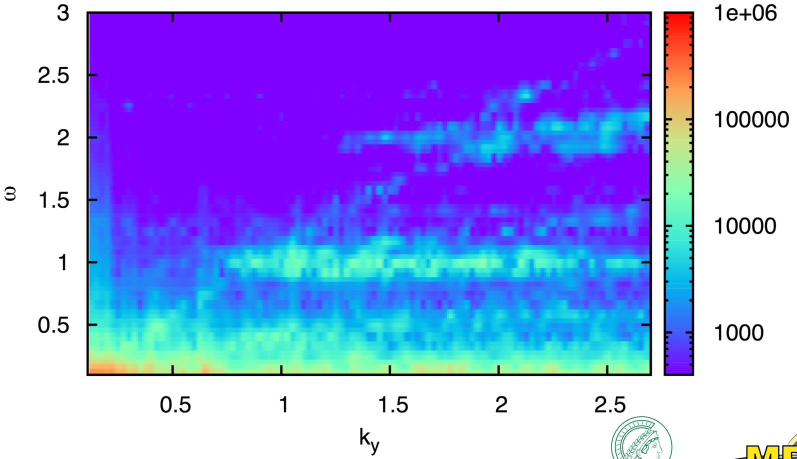
Two-dimensional simulation
PSD density



Two-dimensional simulation
Dispersion, PSD B-field parallel



Two-dimensional simulation
Dispersion, PSD B-field perpendicular



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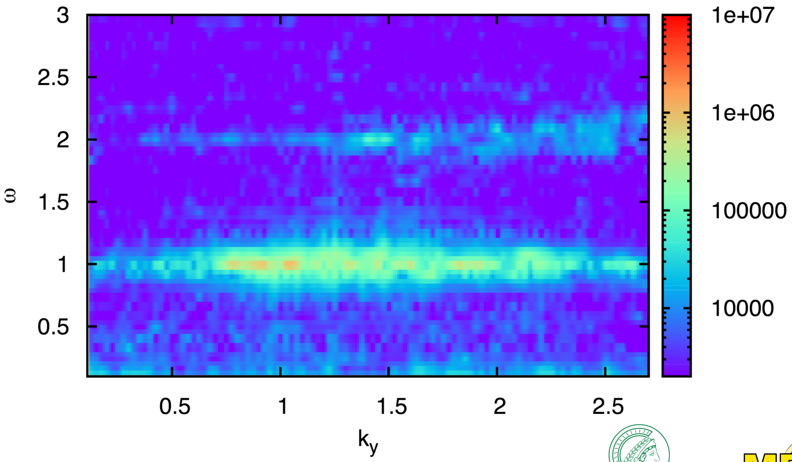
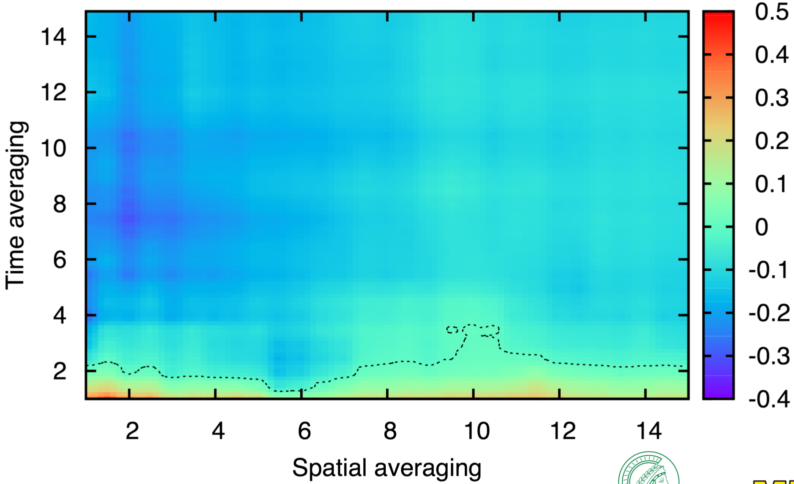
Two-dimensional simulation

Dispersion, PSD density perpendicular



Two-dimensional simulation
Correlation: Pressure-balanced structures?



$$C = \frac{\langle \delta\varrho \, \delta|\boldsymbol{B}|^2\rangle}{\sqrt{\langle(\delta\varrho)^2\rangle\langle(\delta|\boldsymbol{B}|^2)^2\rangle}}.$$

But it is not universal!

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Conclusions

- Wave–wave interactions excite linear normal modes at higher wavenumbers.
- Parallel: L-mode until cyclotron resonance, R-mode continues.
- Density fluctuations are essentially perpendicular.
- Ion-Bernstein waves and pressure-balanced structures (PBSs) might explain the perpendicular fluctuations.
- The spectral break occurs rather at the inertial length scale than at the gyroradius.

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Literature

O. Alexandrova, J. Saur, C. Lacombe, A. Mangeney, J. Mitchell, S. J. Schwartz, and P. Robert. Universality of Solar-Wind Turbulent Spectrum from MHD to Electron Scales. *Phys. Rev. Lett.*, 103(16):165003, October 2009. doi: 10.1103/PhysRevLett.103.165003.

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