Three-Dimensional Hybrid Kinetic Simulations of Driven Alfvénic Turbulence in the Solar Wind

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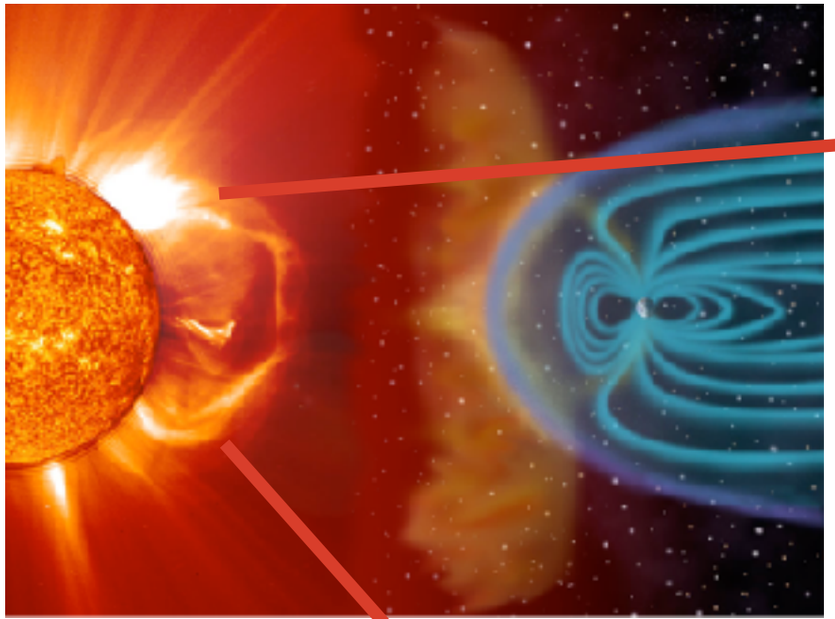
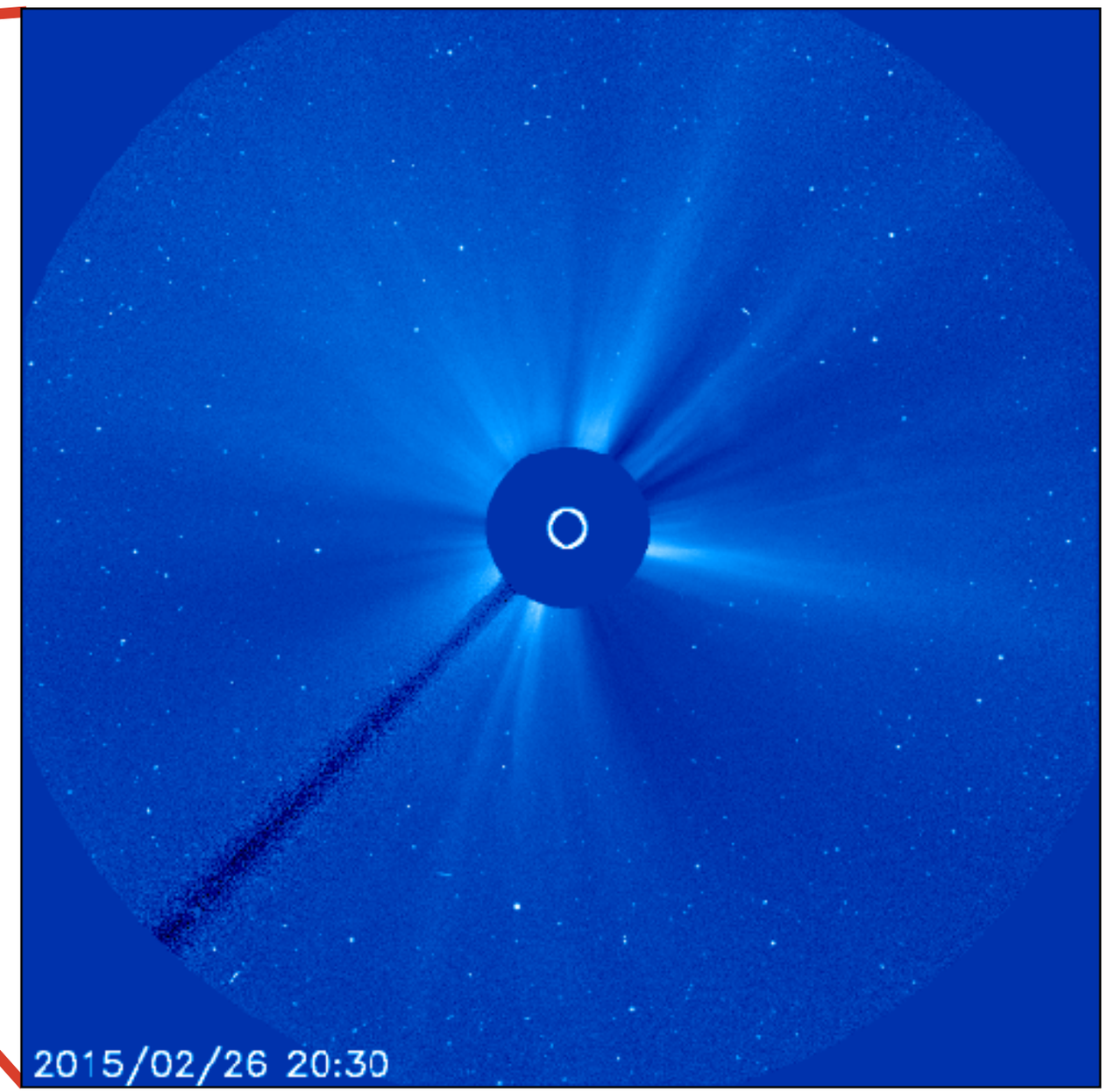
Solar Wind Observations



SOHO



at 1 au

$\lambda_{\rm mfp} \sim 1$ au

$\rho_{\rm i} \sim 10^{-6}$ au

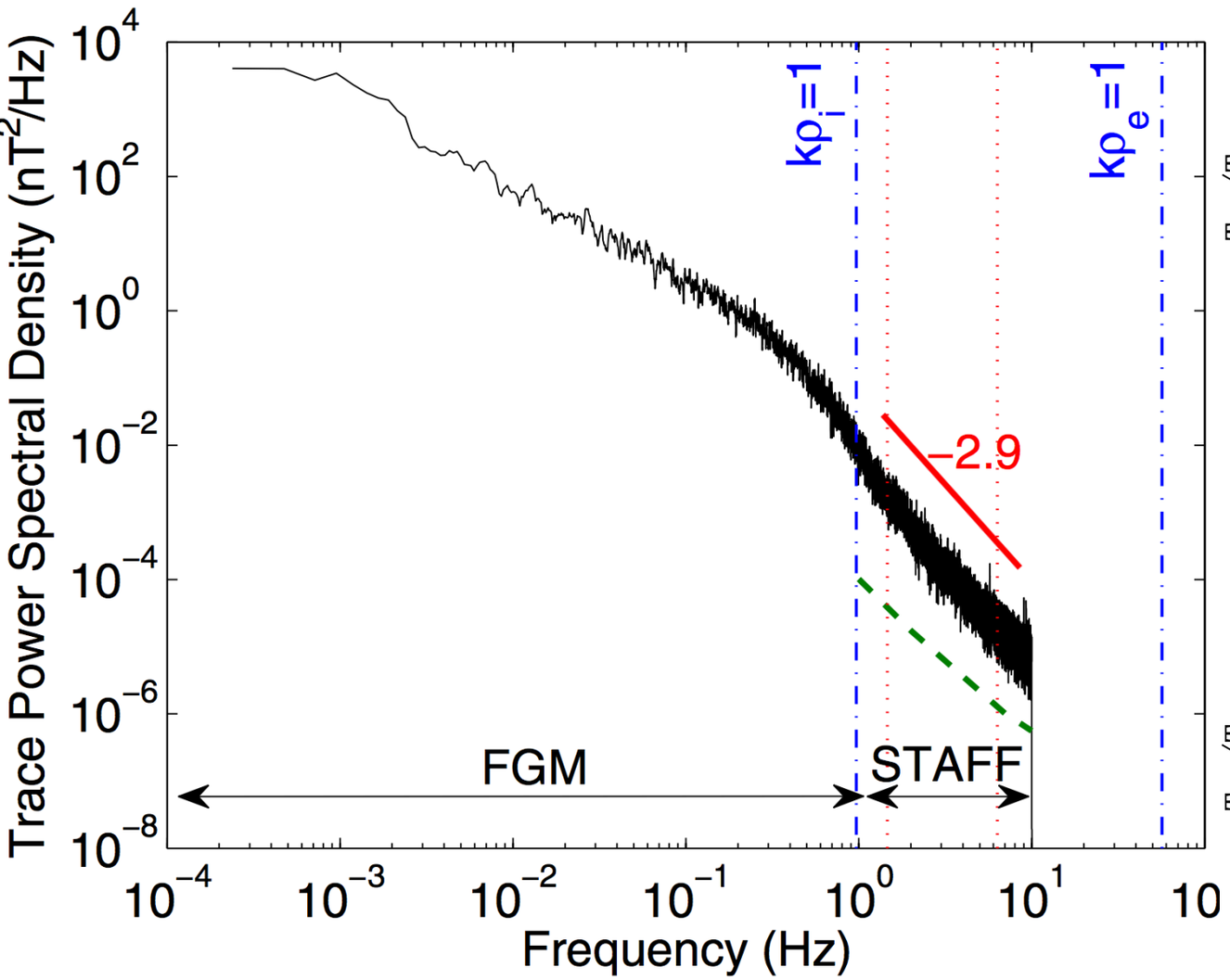
$\Omega_{\rm i} \sim 1$ Hz $\quad B \sim 10^{-4}$ Gs

$T_{\rm i} \sim 10$ eV

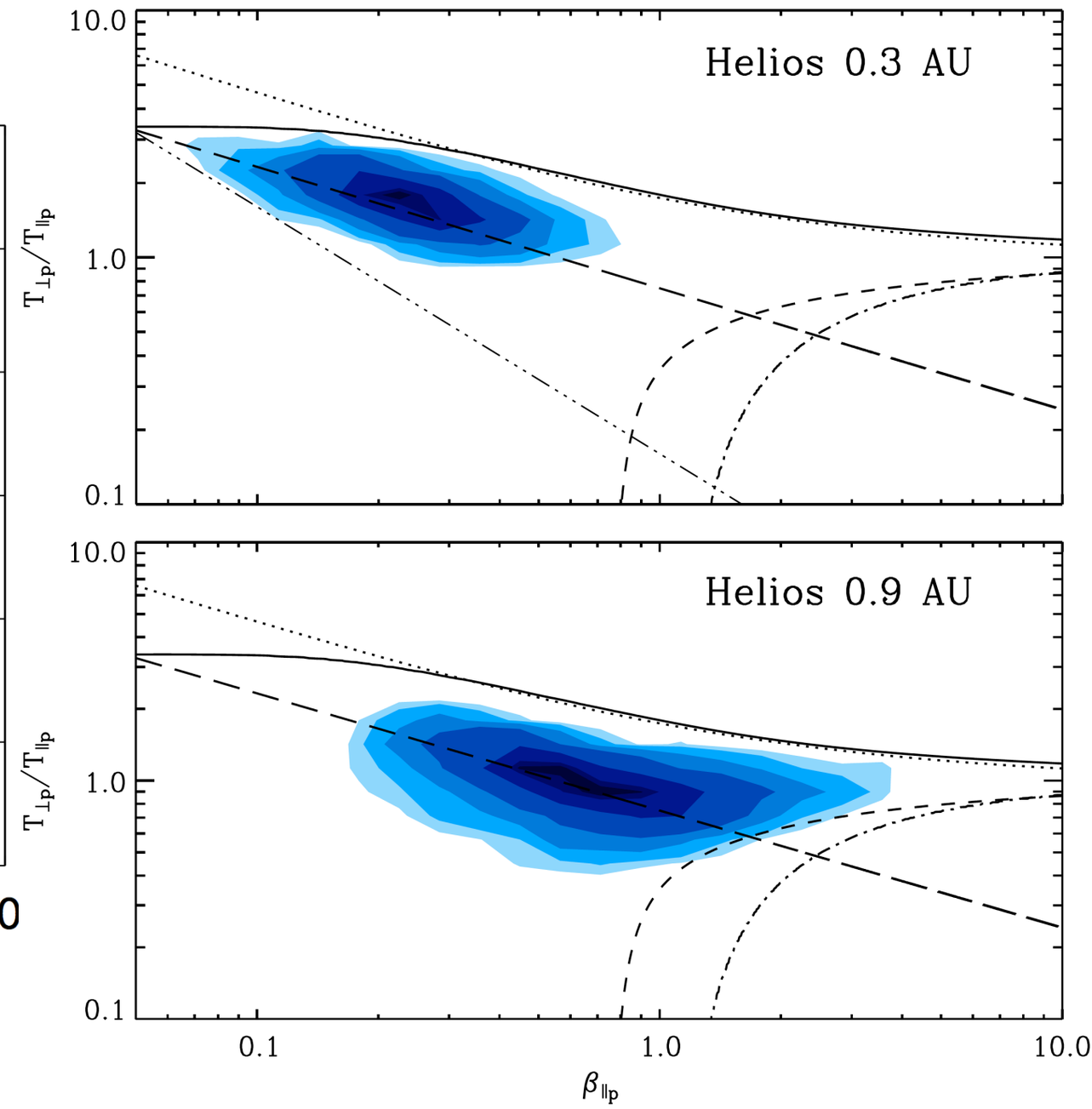
$v_{\rm sw} \sim 250 - 800$ km s^{-1}

$(v_{\rm th} \sim 40$ km s$^{-1})$

Solar Wind Observations

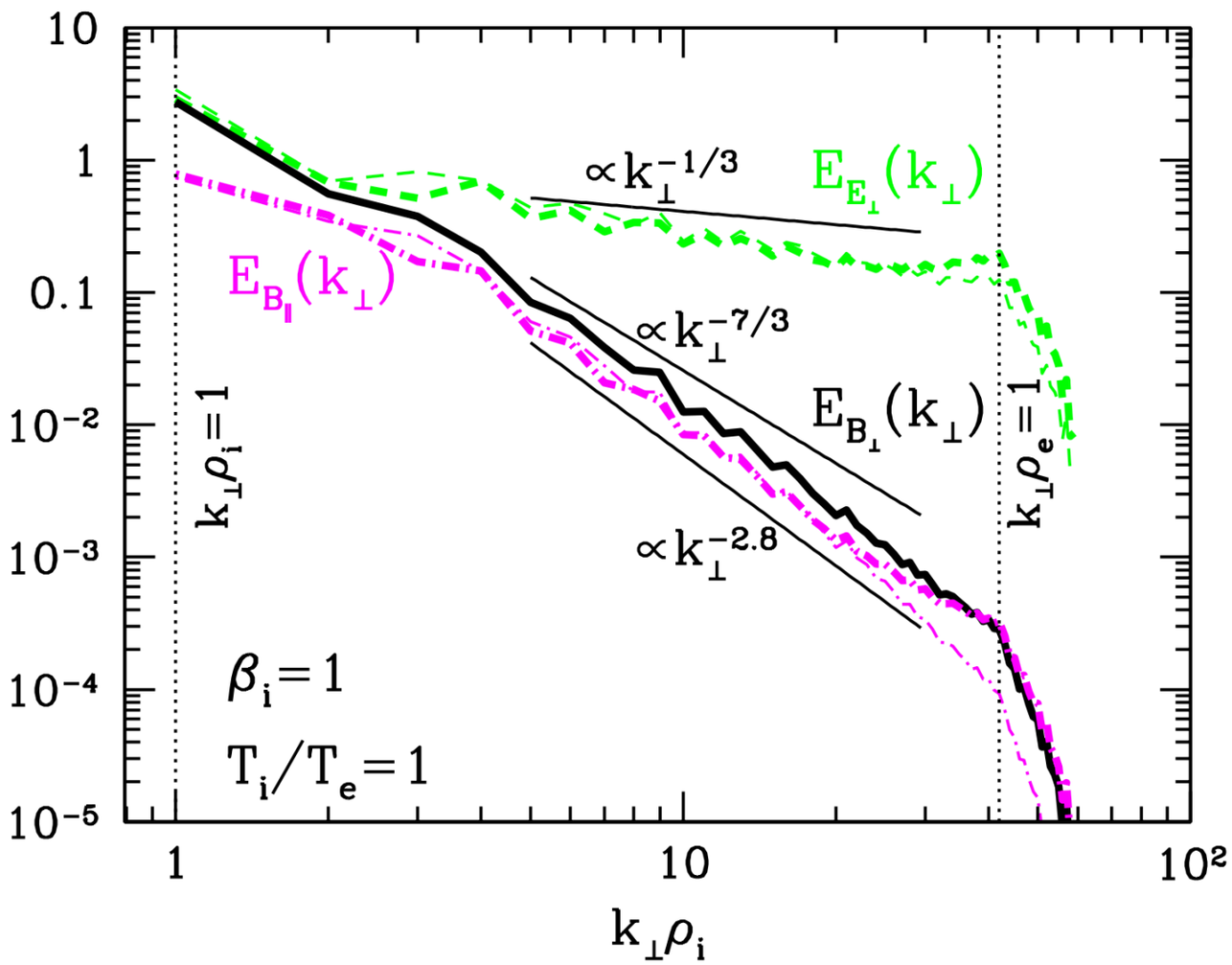


Chen et al. 2010



Matteini et al. 2007

Gyrokinetic Simulations



Howes et al. 2011, see also Told et al. 2015

- Gyrokinetics can reproduce observed spectrum slopes of the turbulence
- Gyrokinetics prevents the study of perpendicular heating
- More general approach is needed to explain both spectra and heating

Hybrid-PIC approach

PEGASUS (Kunz et al. 2014)

$$\frac{\partial f_\mathrm{i}}{\partial t} + \boldsymbol{v} \cdot \nabla f_\mathrm{i} + \left[\frac{Z_\mathrm{i} e}{m_\mathrm{i}} \left(\boldsymbol{E} + \frac{\boldsymbol{v}}{c} \times \boldsymbol{B} \right) + \frac{\boldsymbol{F}}{m_\mathrm{i}} \right] \cdot \frac{\partial f_\mathrm{i}}{\partial \boldsymbol{v}} = 0$$

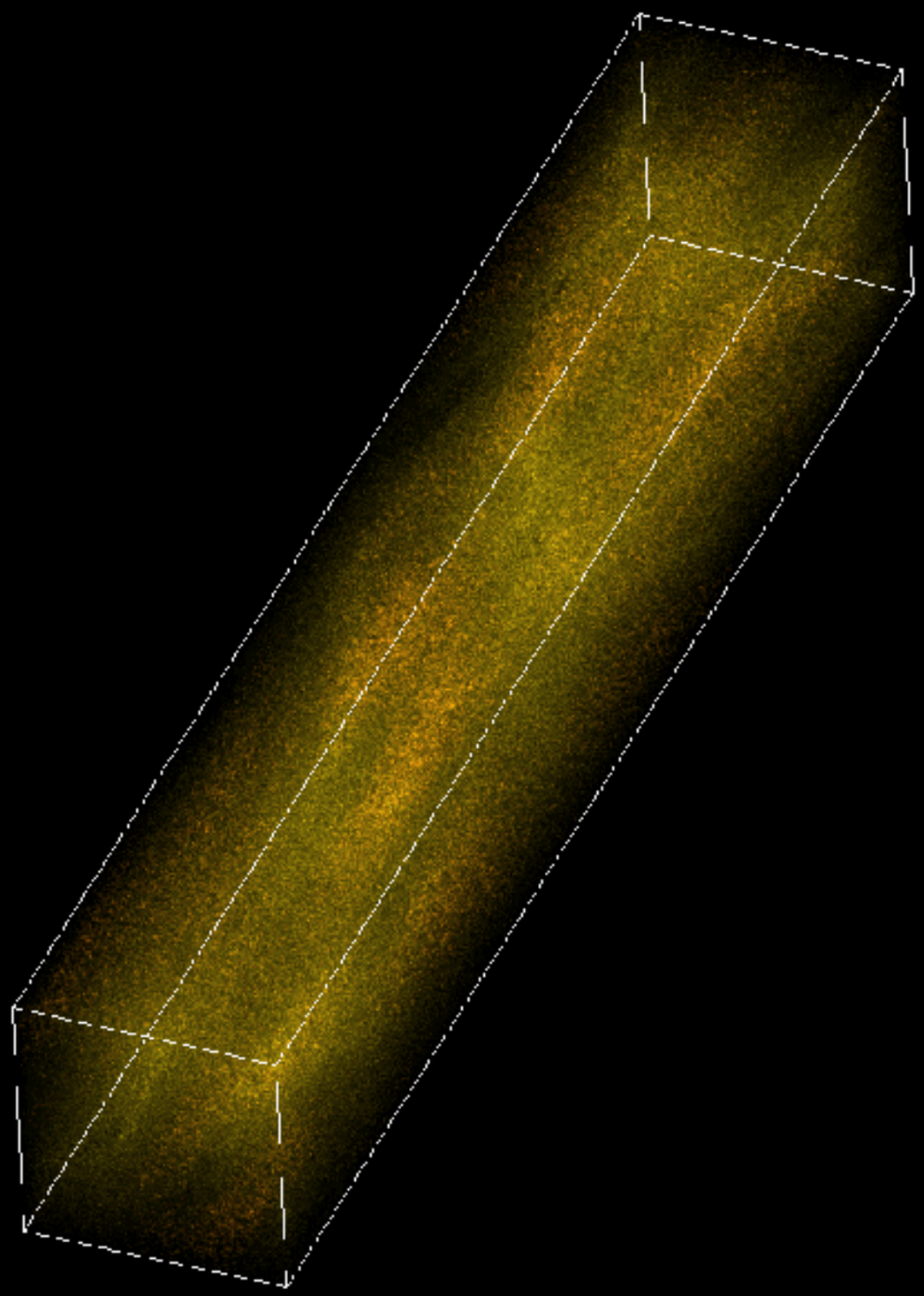
+ fluid equations for electrons

Driving on large scales — Ornstein–Uhlenbeck process

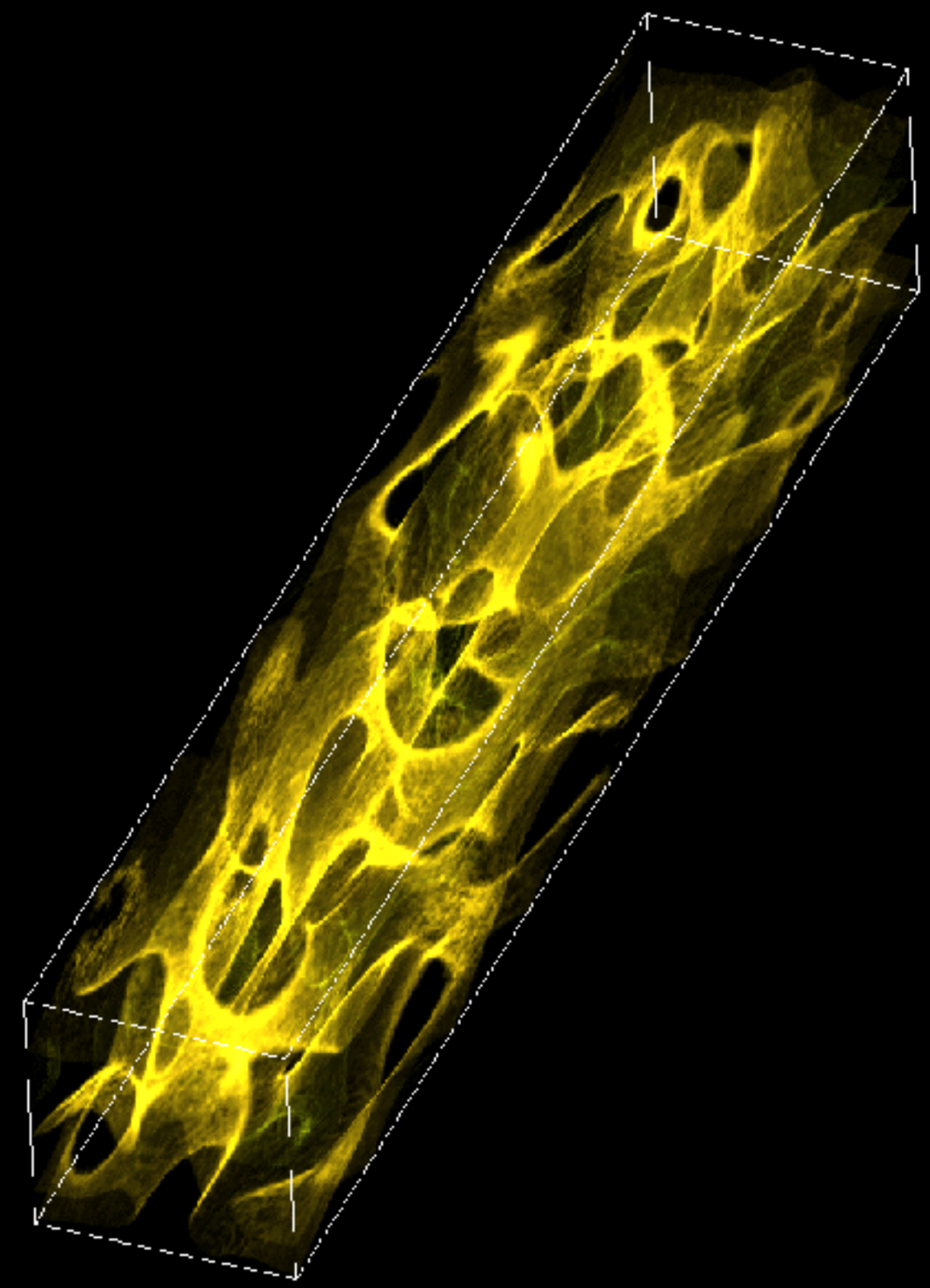
$$\boldsymbol{F}(t + \Delta t) = \boldsymbol{F}(t)(1 - e^{-\Delta t / t_\mathrm{corr}}) + \tilde{\boldsymbol{F}}(t) e^{-\Delta t / t_\mathrm{corr}}$$

$$\nabla \cdot \boldsymbol{F} = 0$$

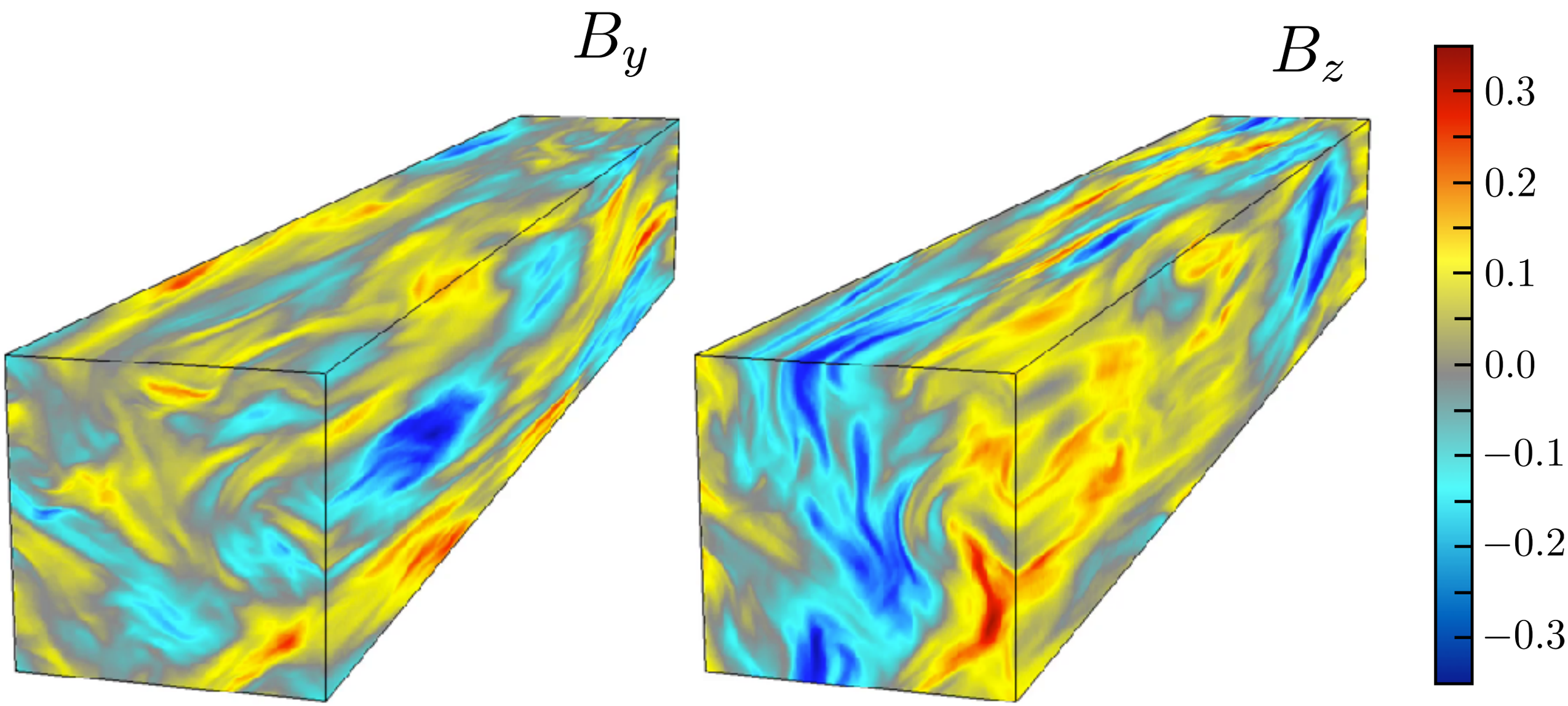
Density



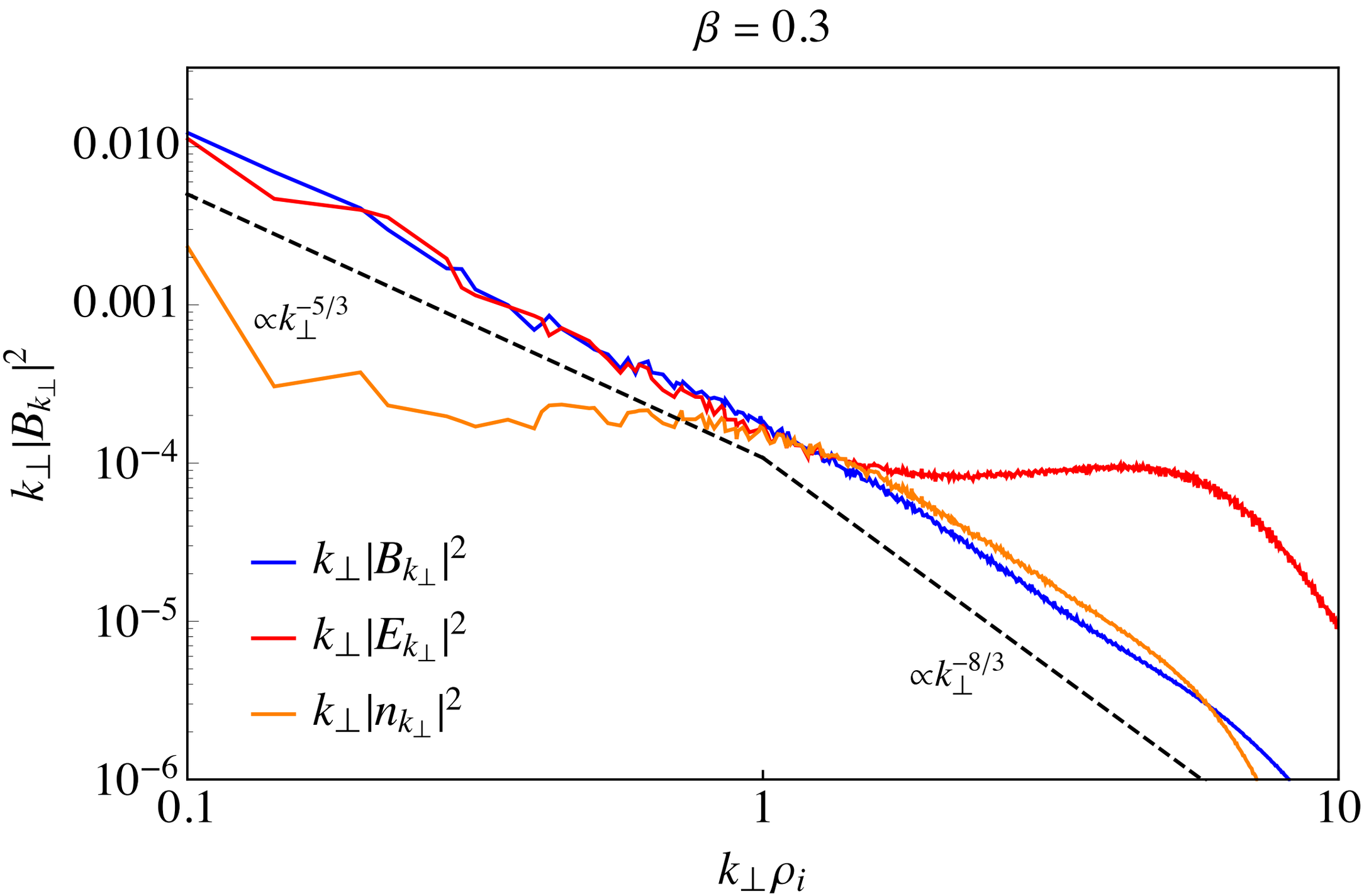
Magnetic Field



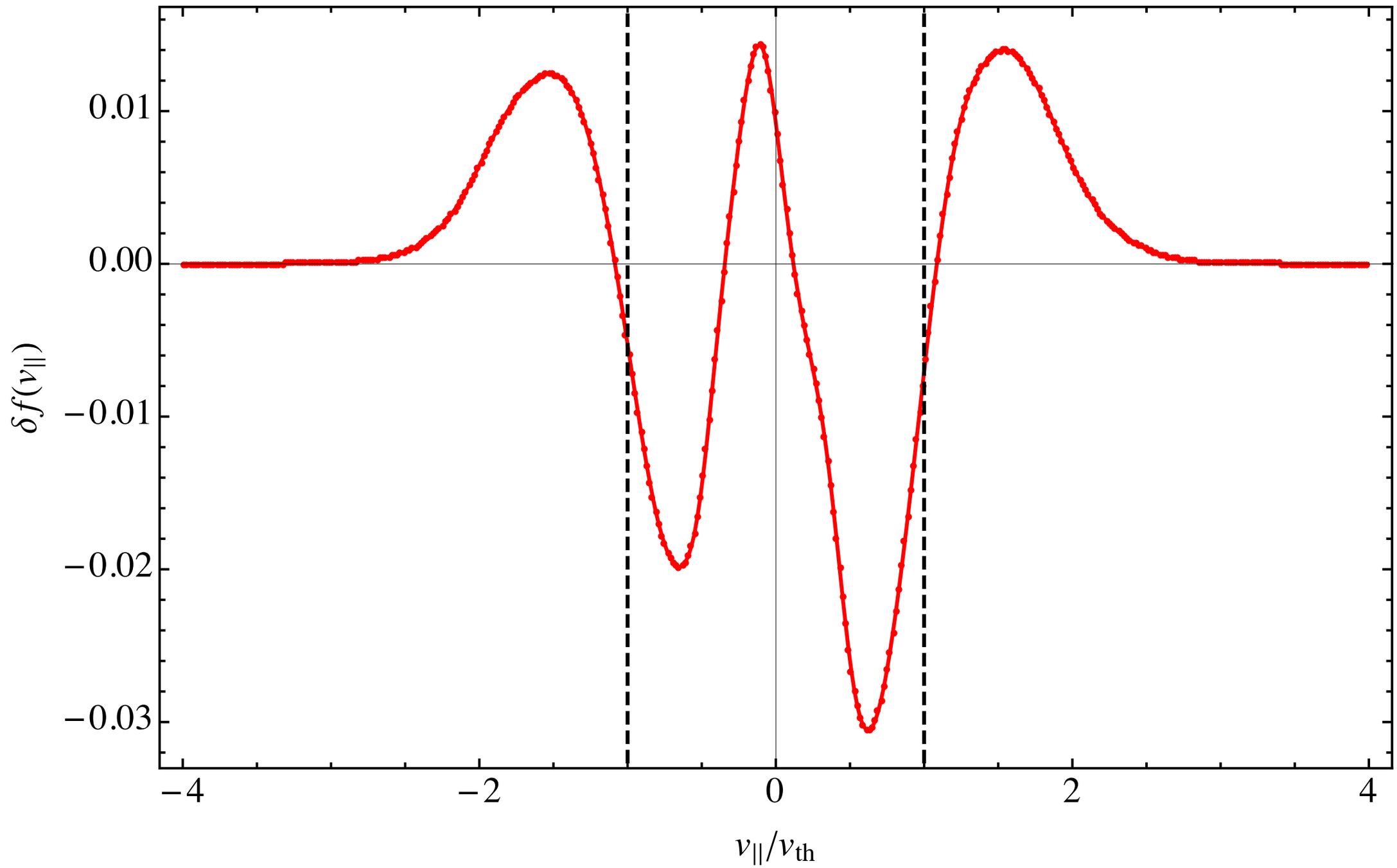
Quasi-Steady State



Spectrum of the Turbulence

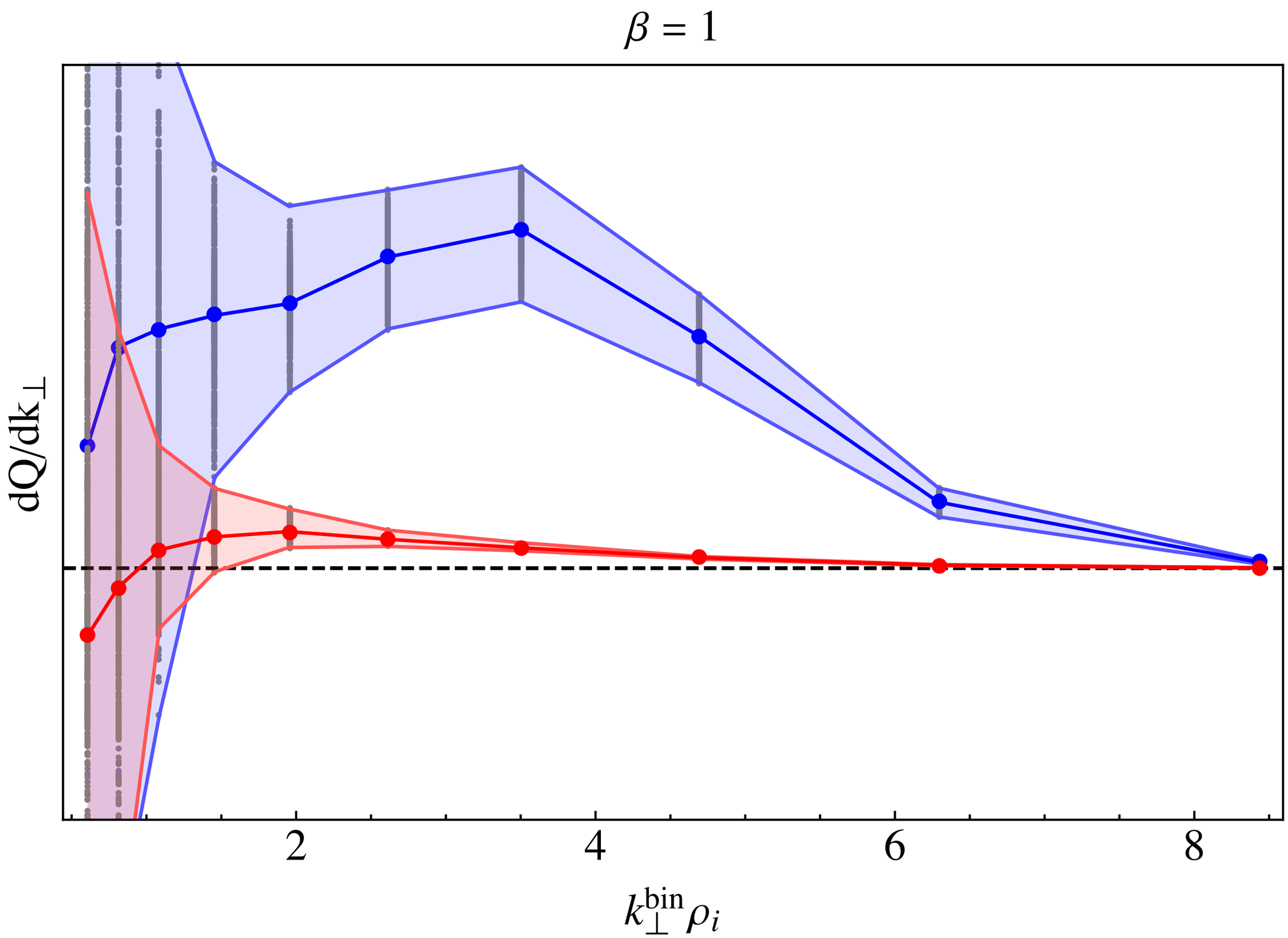


Evidence for Landau Damping

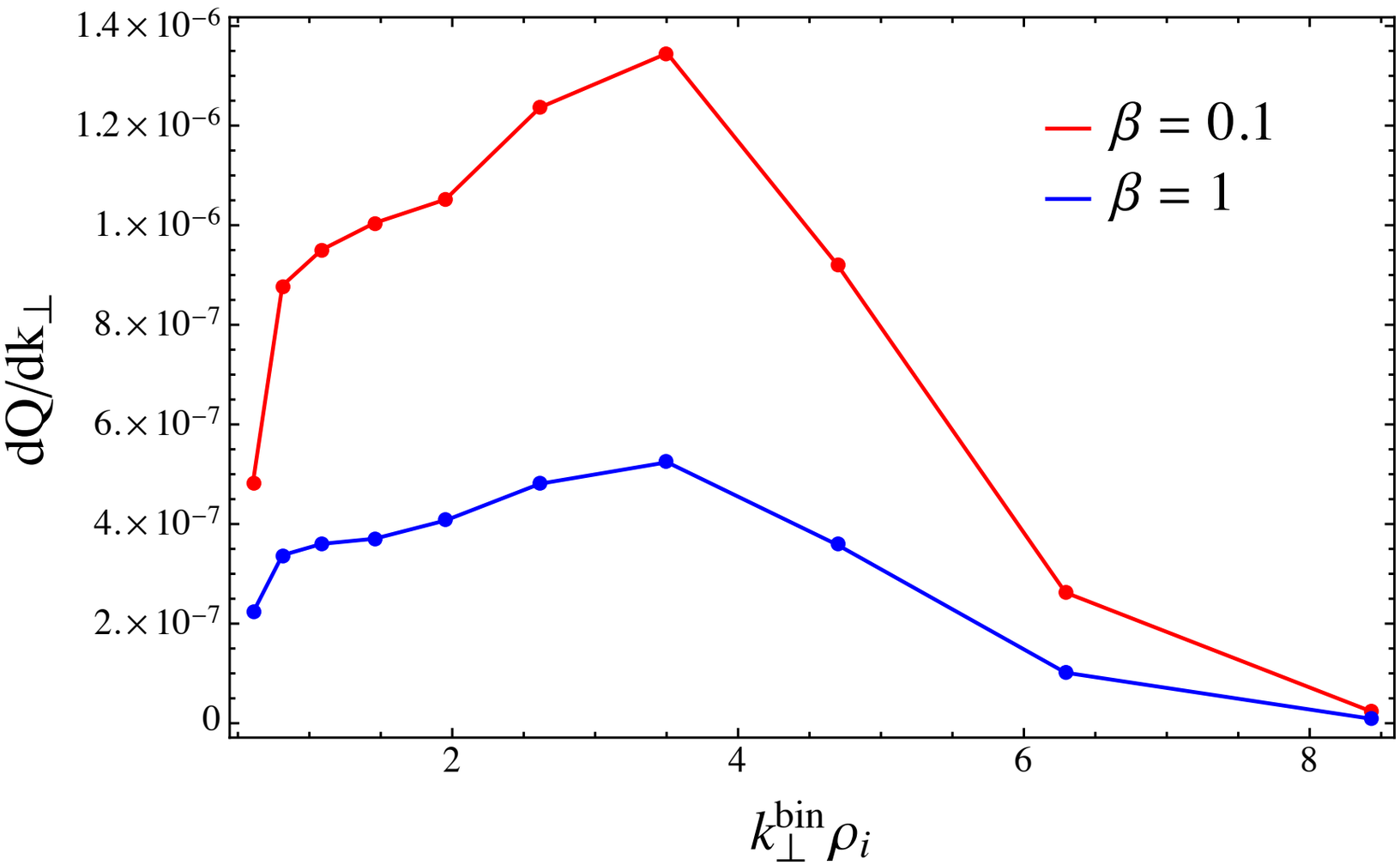


Development of fine-scale structure in distribution function

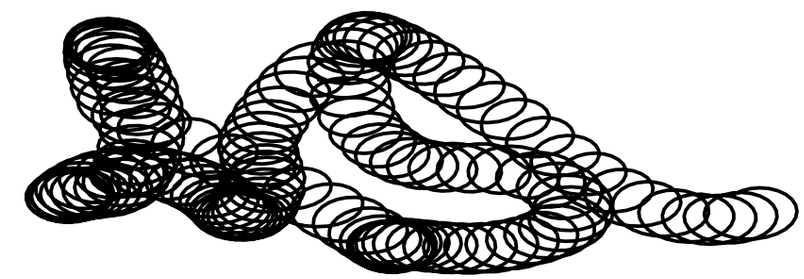
Evidence for perpendicular ion heating



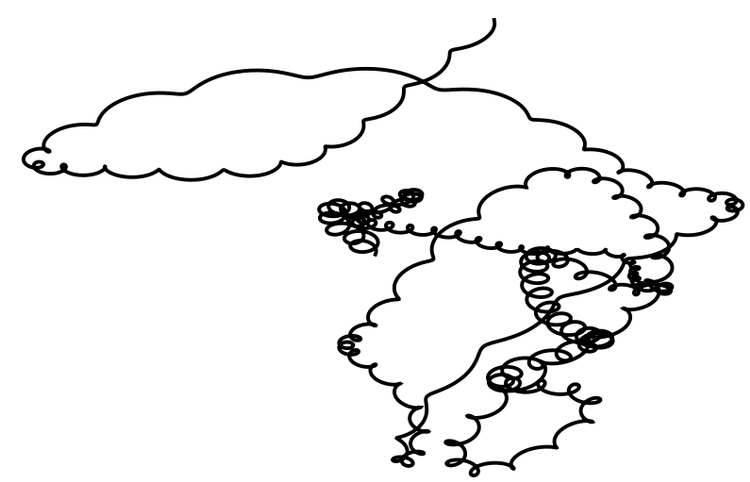
Evidence for perpendicular ion heating



regular orbits



stochastic orbits



stochastic heating (Chandran et al. 2010)? cyclotron resonance?

Evidence for perpendicular ion heating

Klein and Chandran 2016