

# Kinetic turbulence in high-beta, collisionless plasma

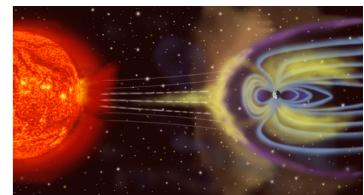
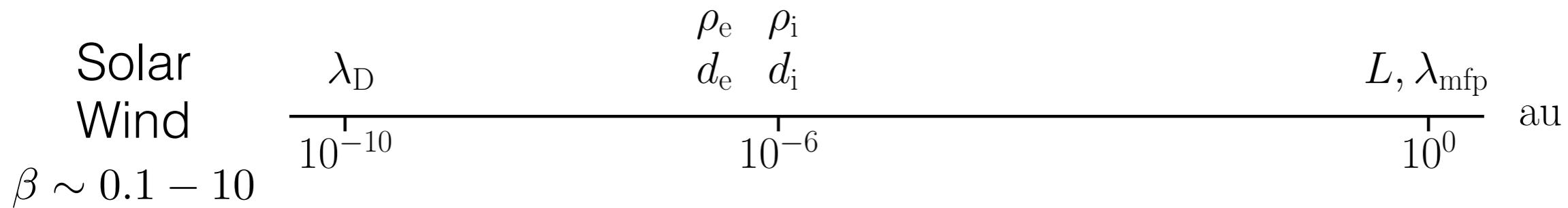
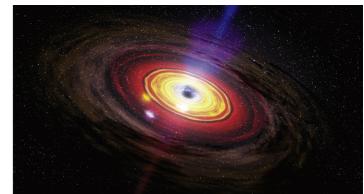
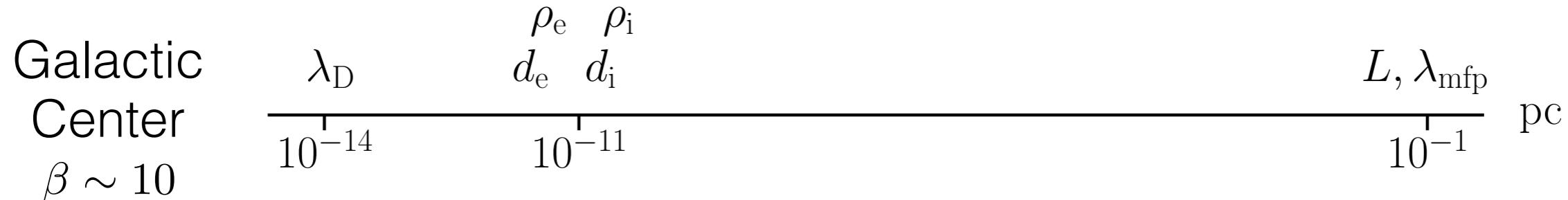
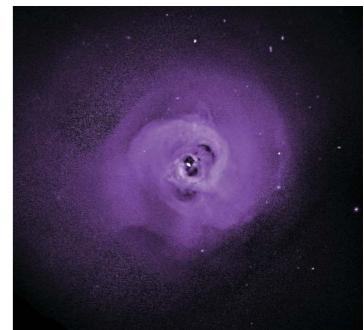
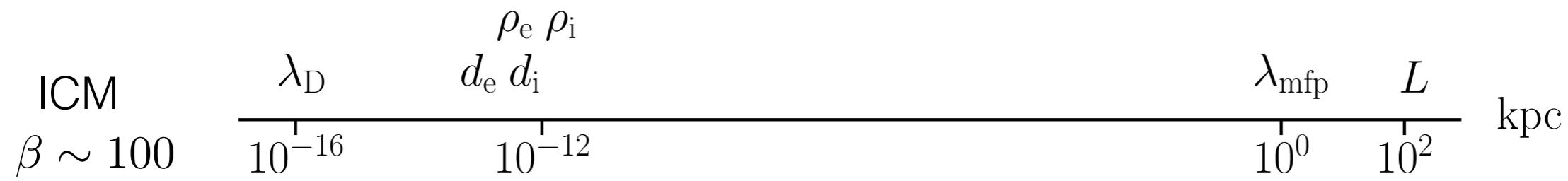
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# Motivation

Astrophysical plasmas are typically weakly collisional or collisionless  
and often have  $\beta \gtrsim 1$



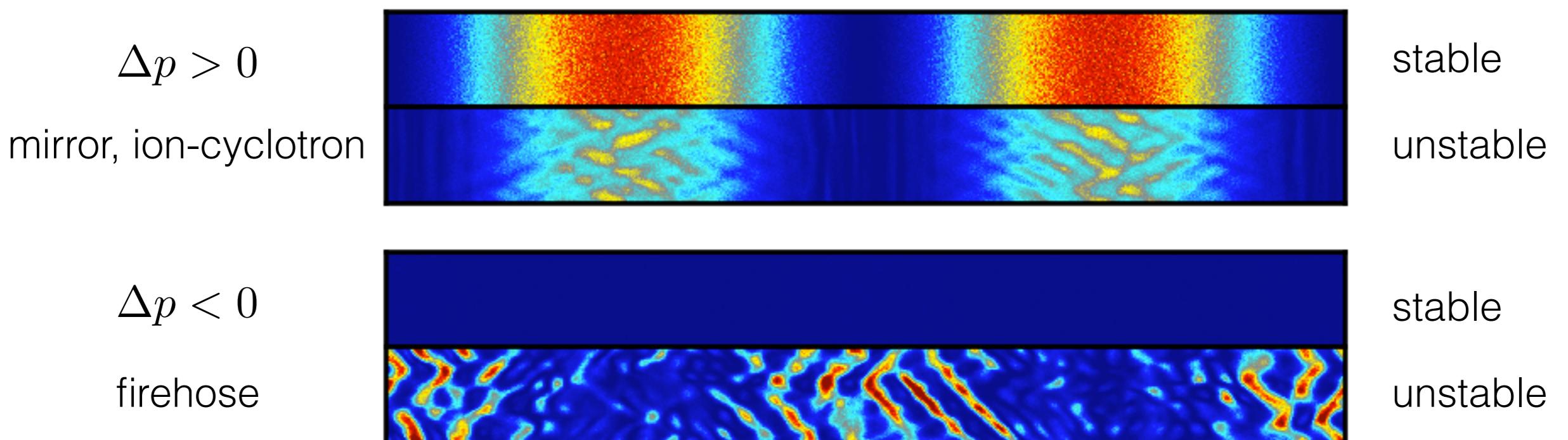
# Kinetic instabilities in high-beta plasmas

Large-scale changes in magnetic field naturally drive pressure anisotropy due to the conservation of magnetic moment  $\mu \propto v_{\perp}^2/B \propto p_{\perp}/B$

$$\begin{aligned}\frac{\partial \rho \mathbf{u}}{\partial t} &= -\nabla \cdot \left[ \rho \mathbf{u} \mathbf{u} + \mathbf{P} + \frac{B^2}{8\pi} \mathbf{I} - \frac{B^2}{4\pi} \hat{\mathbf{b}} \hat{\mathbf{b}} \right] = \\ &= -\nabla \cdot \left[ \rho \mathbf{u} \mathbf{u} + \left( p_{\perp} + \frac{B^2}{8\pi} \right) \mathbf{I} - \left( \frac{B^2}{4\pi} + \Delta p \right) \hat{\mathbf{b}} \hat{\mathbf{b}} \right]\end{aligned}$$

order unity change to magnetic tension for  
 $\frac{\Delta p}{p} \sim \frac{1}{\beta} \lesssim 1$

Magnetic field strength in Alfvén wave



# Some questions

- What is the steady-state value of pressure anisotropy? Is there a dynamical effect of pressure anisotropy on the flow?
- Is the particle heating affected by pressure-anisotropy-driven instabilities? How is the energy partitioned between ions and electrons?
- Is there a cascade in the presence of instabilities? Is there interaction between the cascade and instability-produced fluctuations?

# Hybrid-PIC

Pegasus++: solve kinetic equation for ions along the characteristics,  
electrons are assumed to be massless

$$\frac{\partial f_i}{\partial t} + \mathbf{v} \cdot \nabla f_i + \frac{Ze}{m_i} \left[ \mathbf{E} + \frac{\mathbf{v}}{c} \times \mathbf{B} \right] \cdot \frac{\partial f_i}{\partial \mathbf{v}} = 0$$

$$\mathbf{E} + \frac{\mathbf{u}_i}{c} \times \mathbf{B} = -\frac{\nabla p_e}{en_e} + \frac{(\nabla \times \mathbf{B}) \times \mathbf{B}}{4\pi Z en_i}$$


must assume something;  
usually isotropic and:  
isothermal or barotropic

Driving of turbulence at large scales — Ornstein-Uhlenbeck process

$$\mathbf{F}(t + \Delta t) = \mathbf{F}(t) \left( 1 - e^{-\Delta t / t_{\text{corr}}} \right) + \tilde{\mathbf{F}} e^{-\Delta t / t_{\text{corr}}}$$

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

# Numerical setup

$\beta_{i0} = 16, 4$

critical balance at large scales

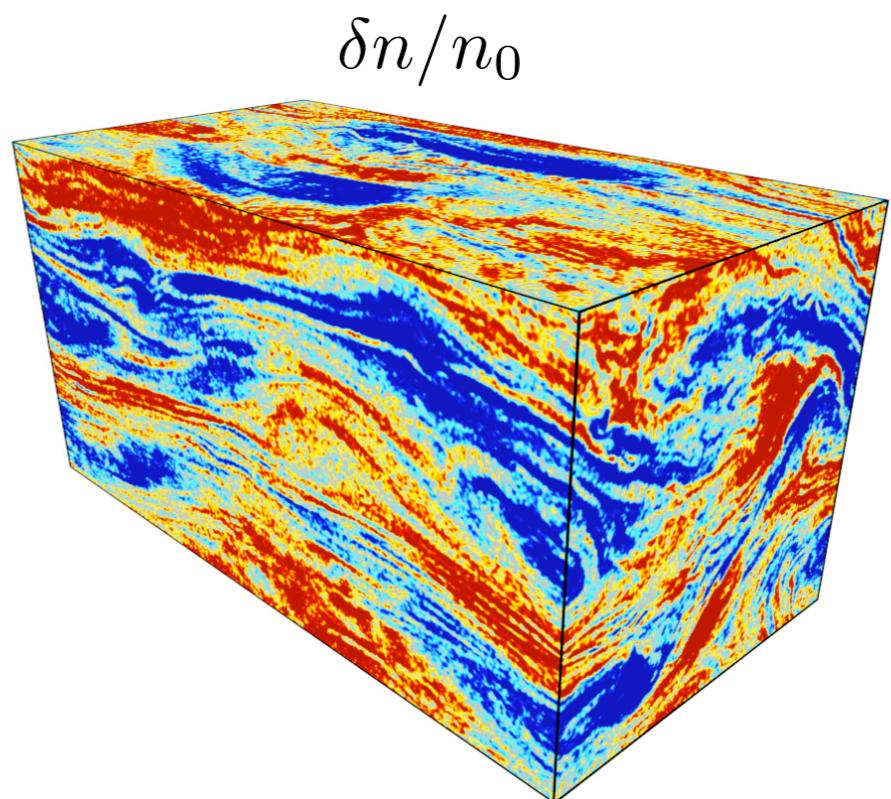
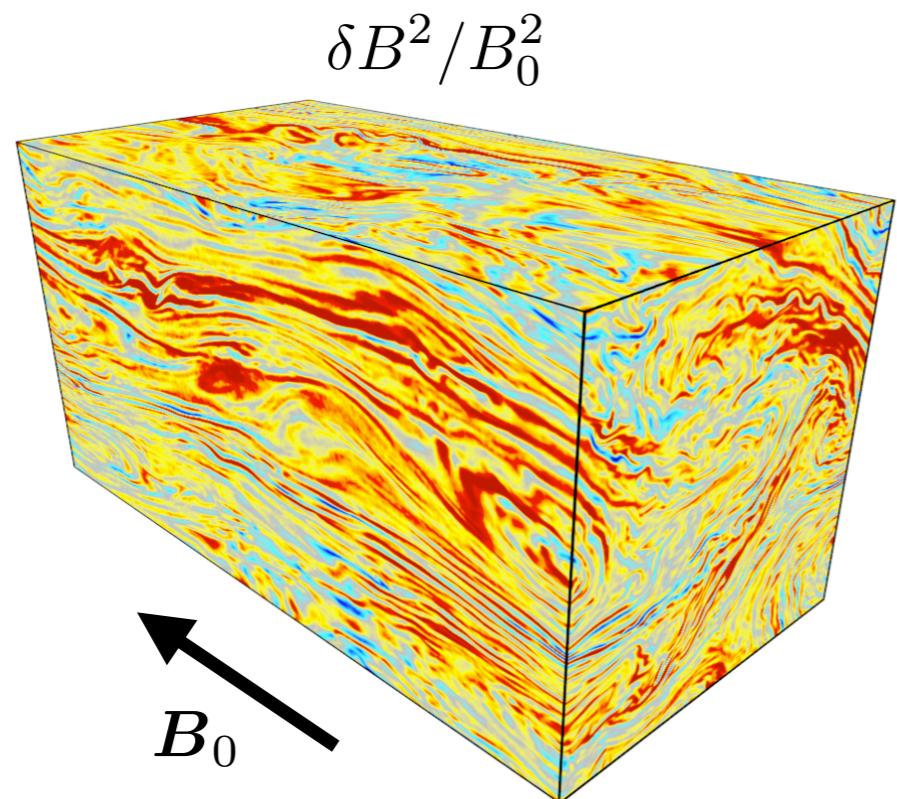
Box shape  $L_{\parallel}/L_{\perp} = 2, 4$

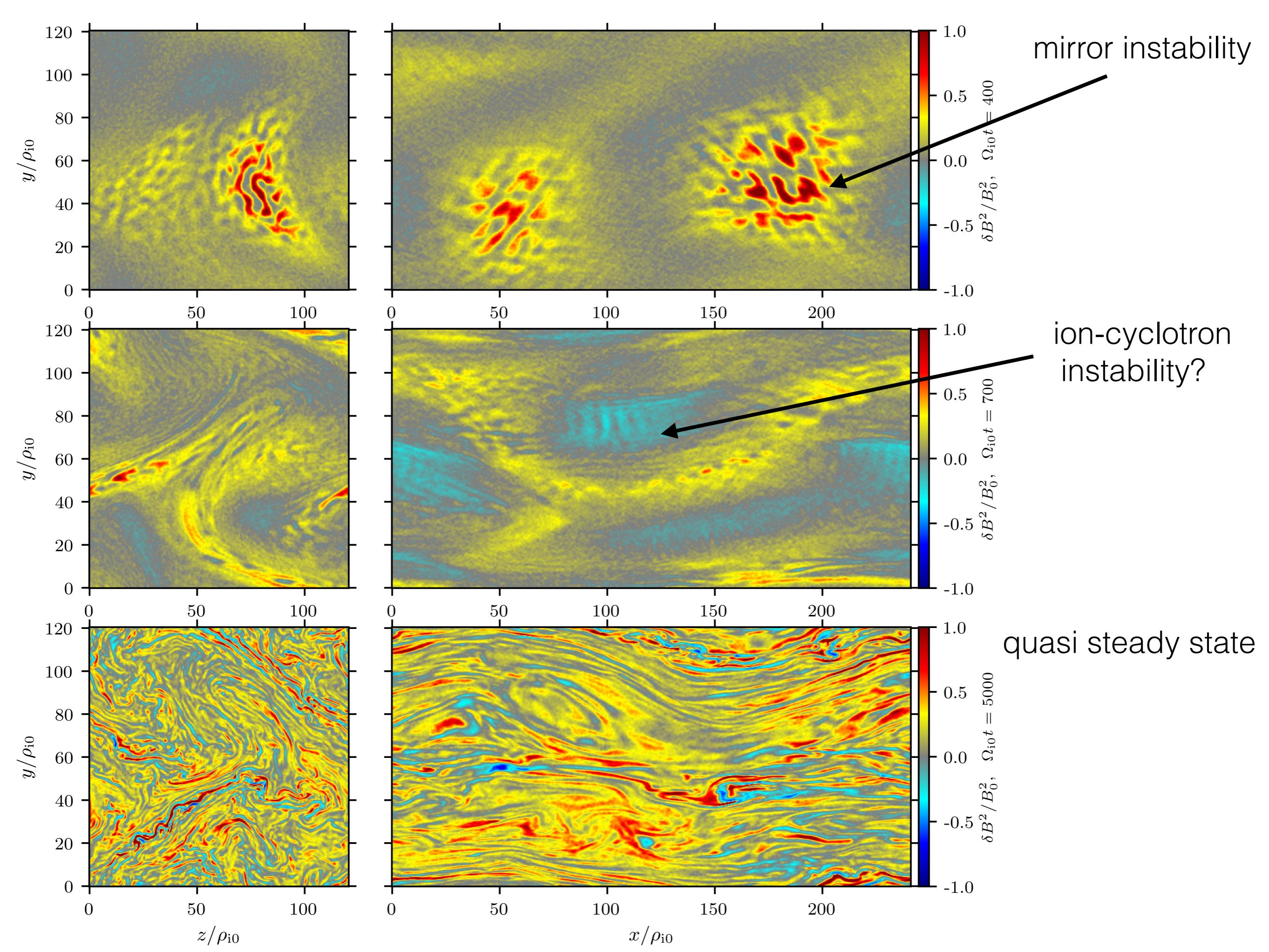
$\tau_{nl} \sim \omega_{lin}^{-1} \Rightarrow u_{rms}/v_{A0} \sim 0.5, 0.25$

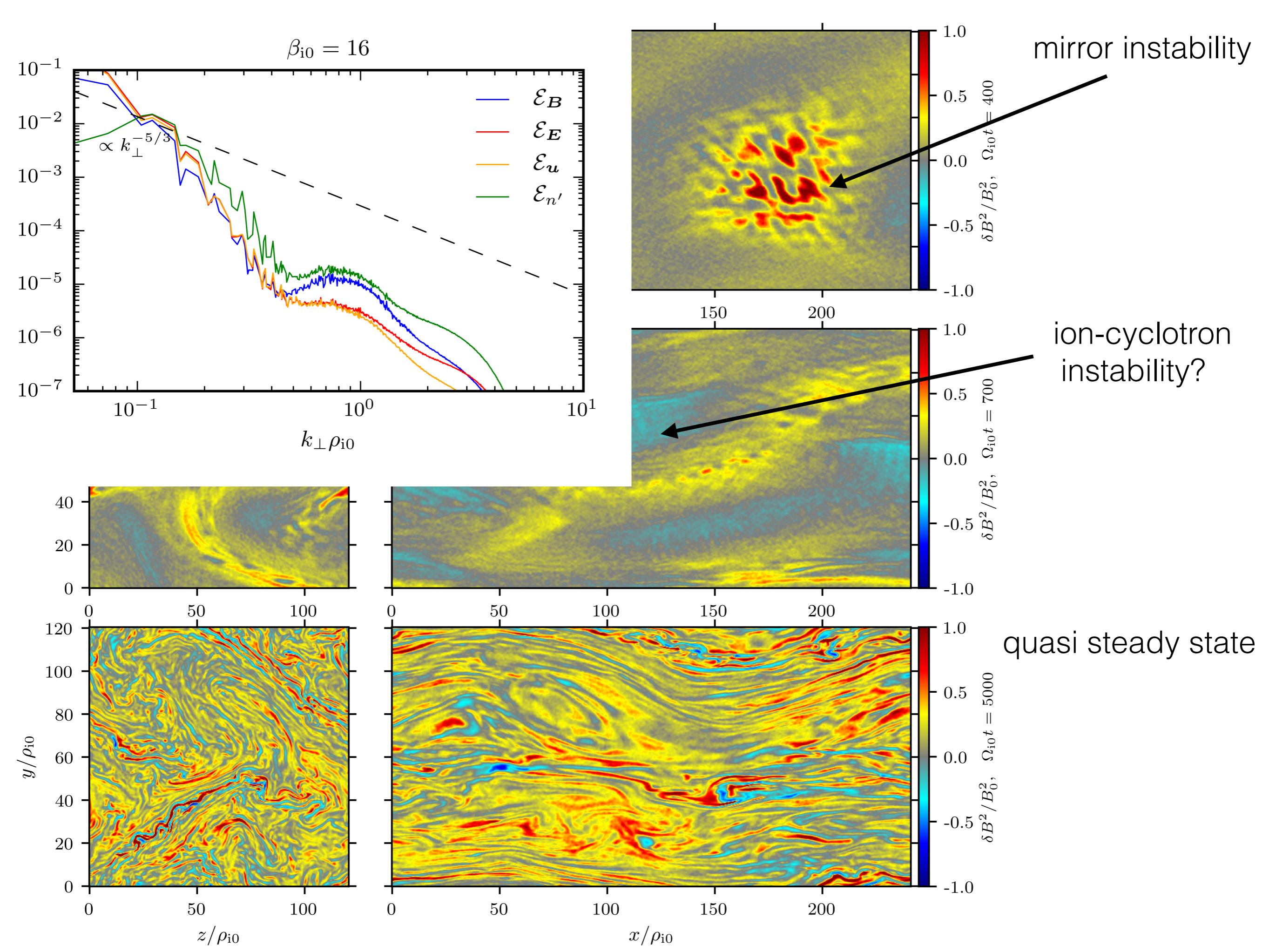
Box size  $768 \times 384 \times 384$

$k_{\perp}\rho_{i0} \in [0.05, 10]$

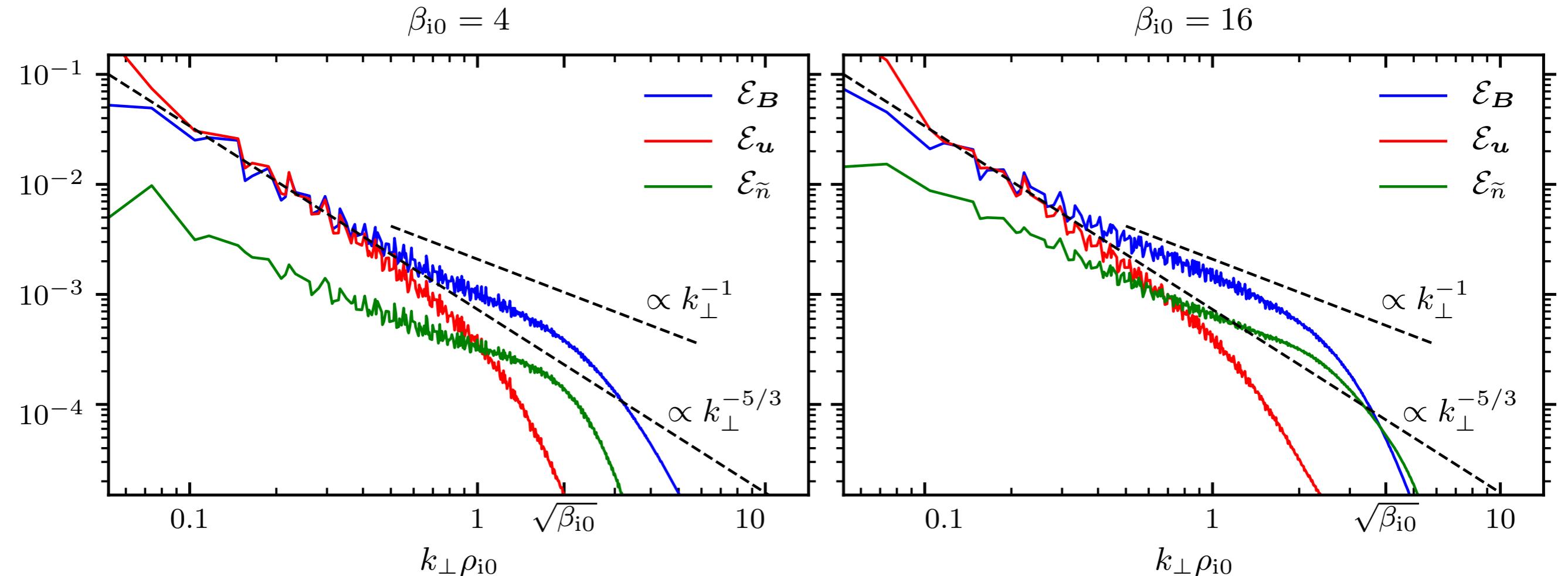
$ppc_0 = 1000$  ( $\sim 10^{11}$  total particles)



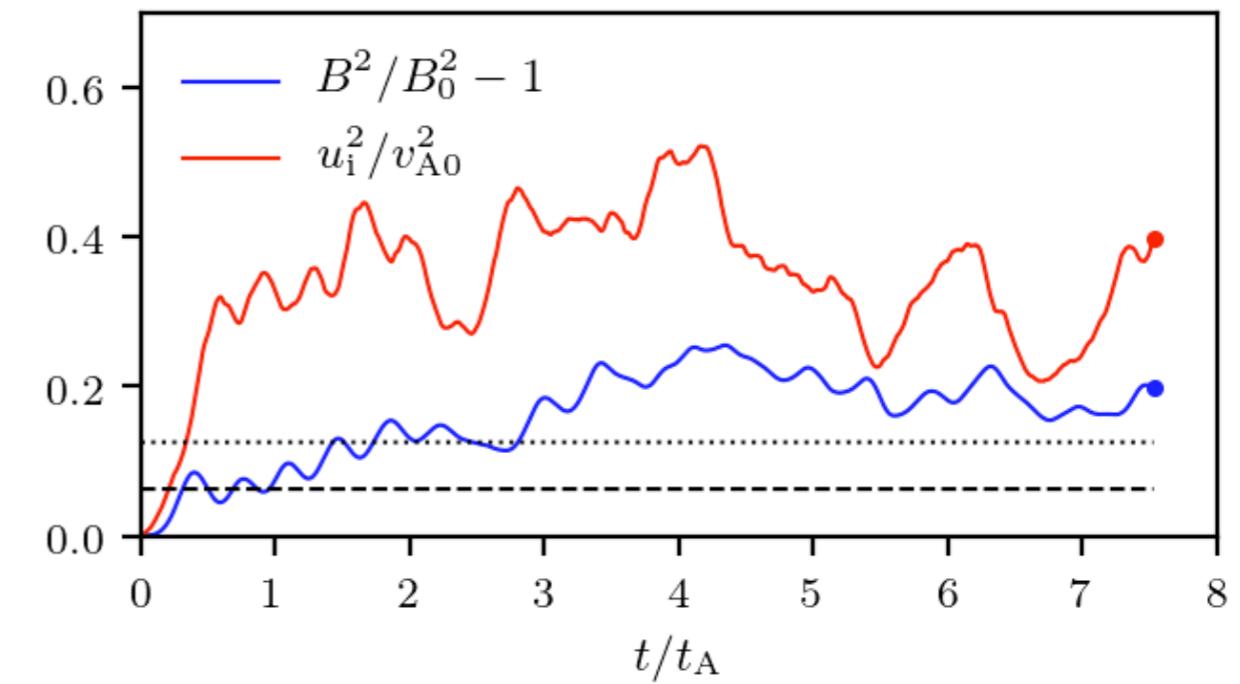
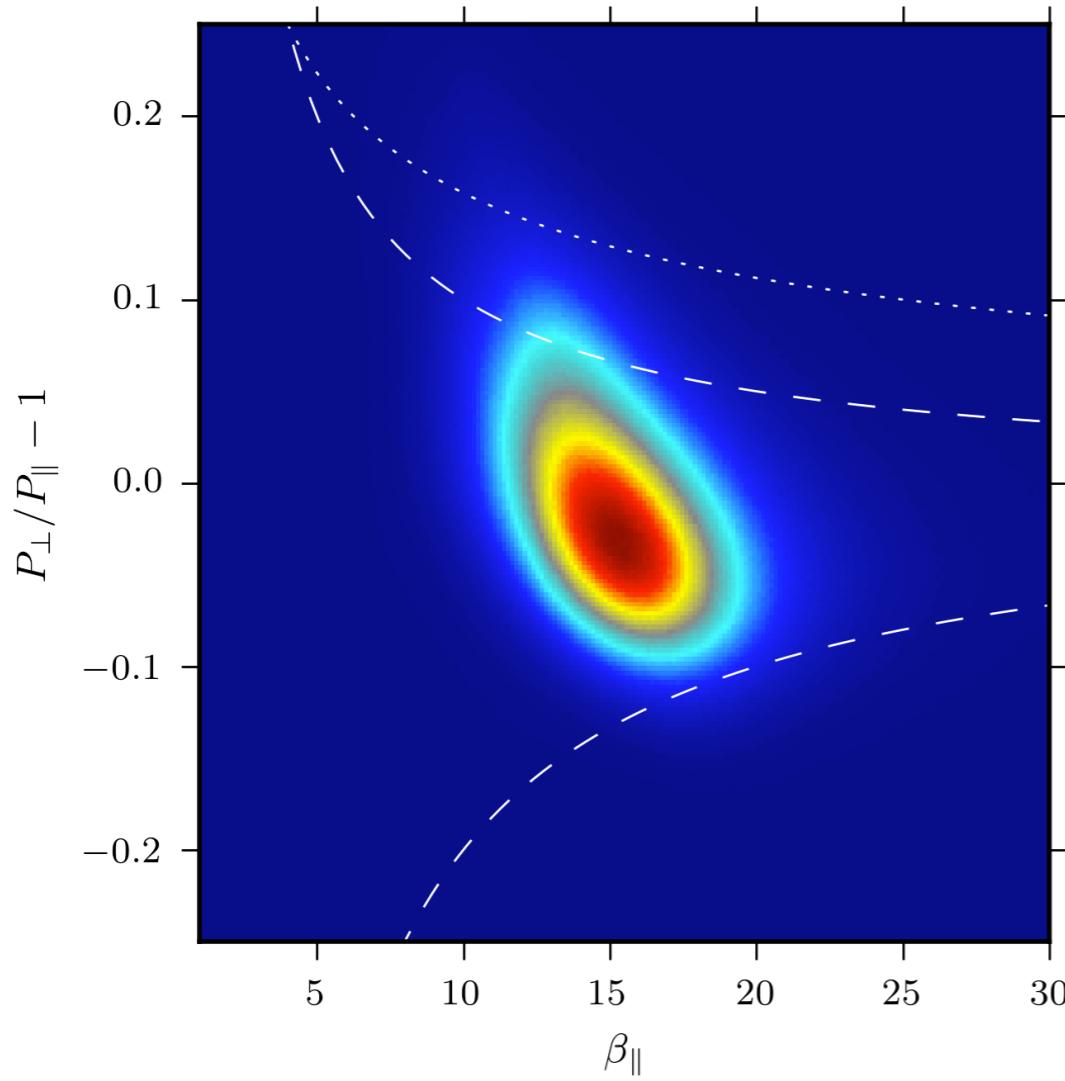




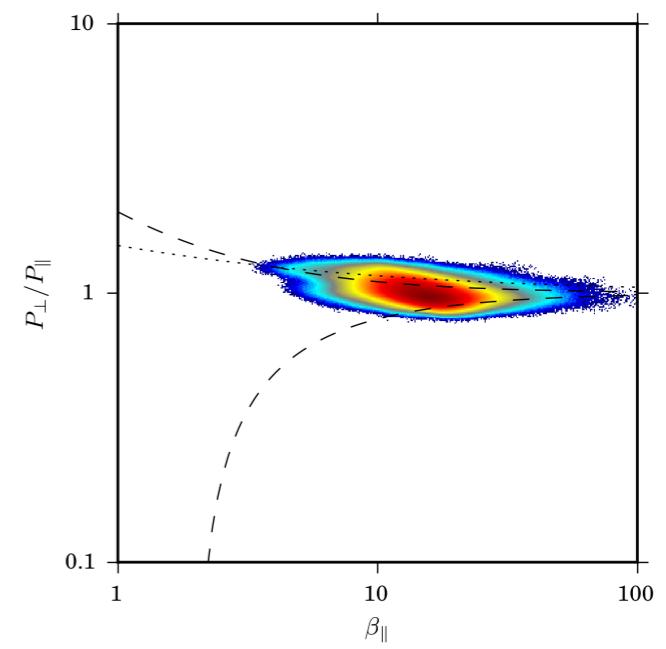
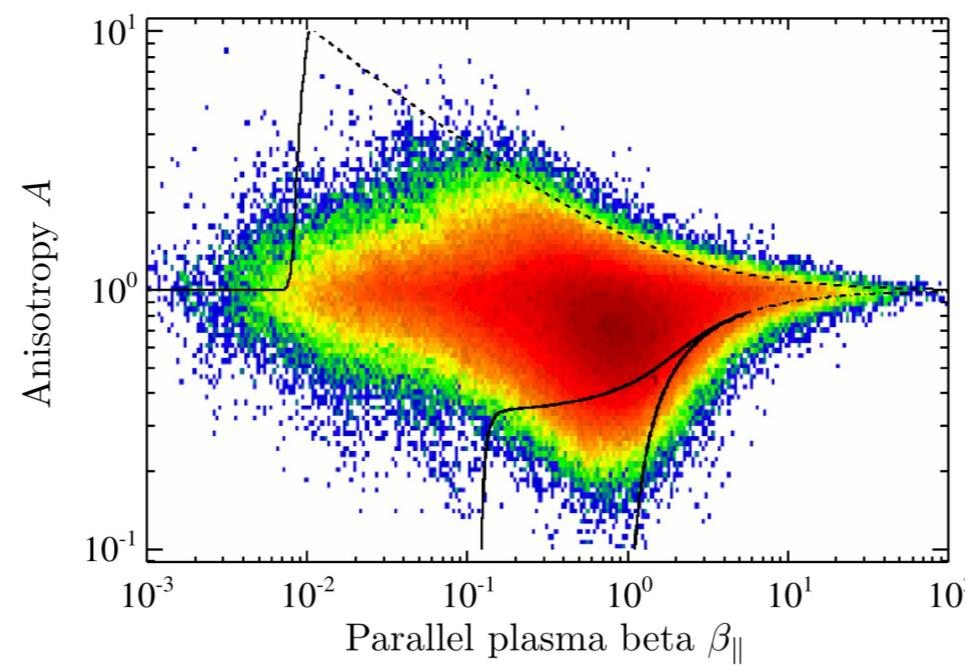
# Quasi-steady-state spectra



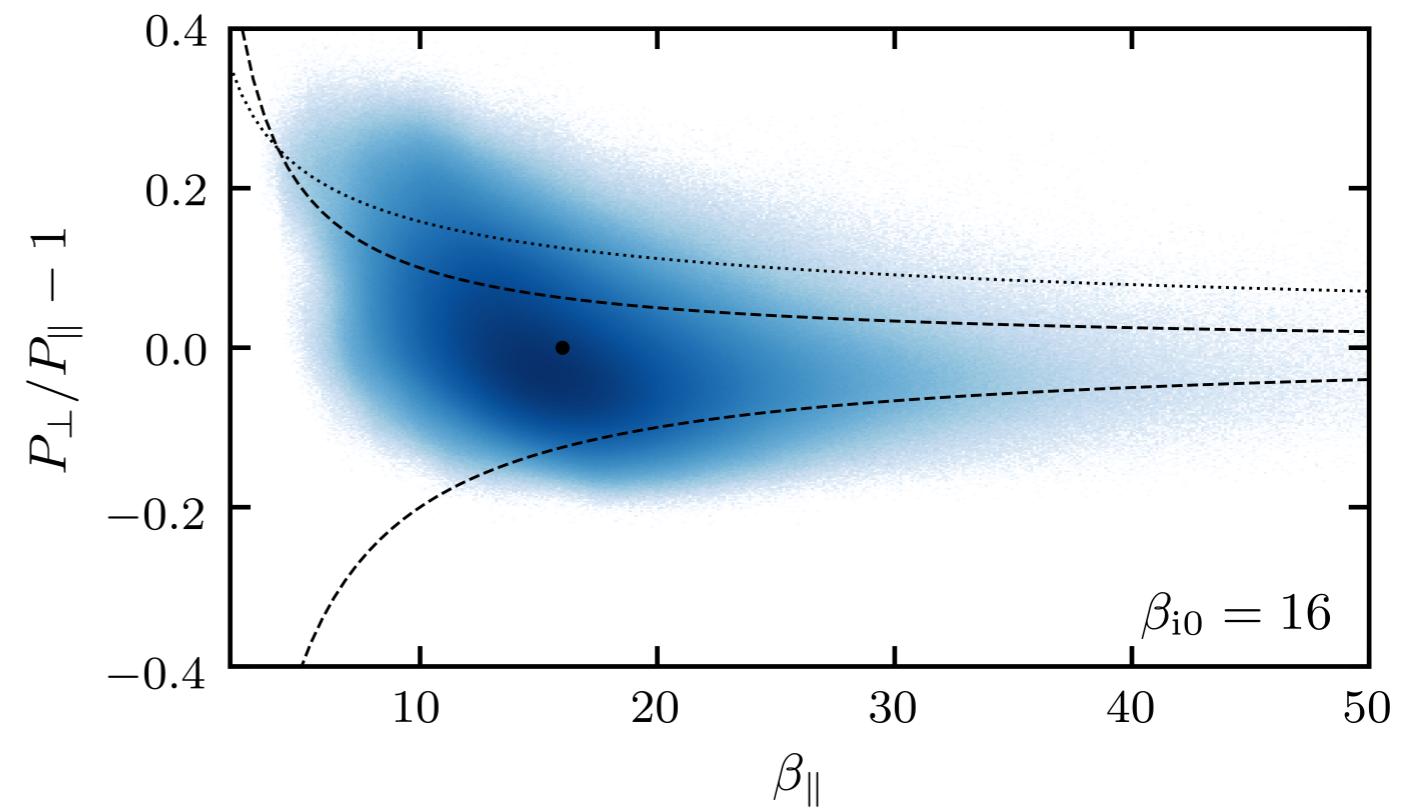
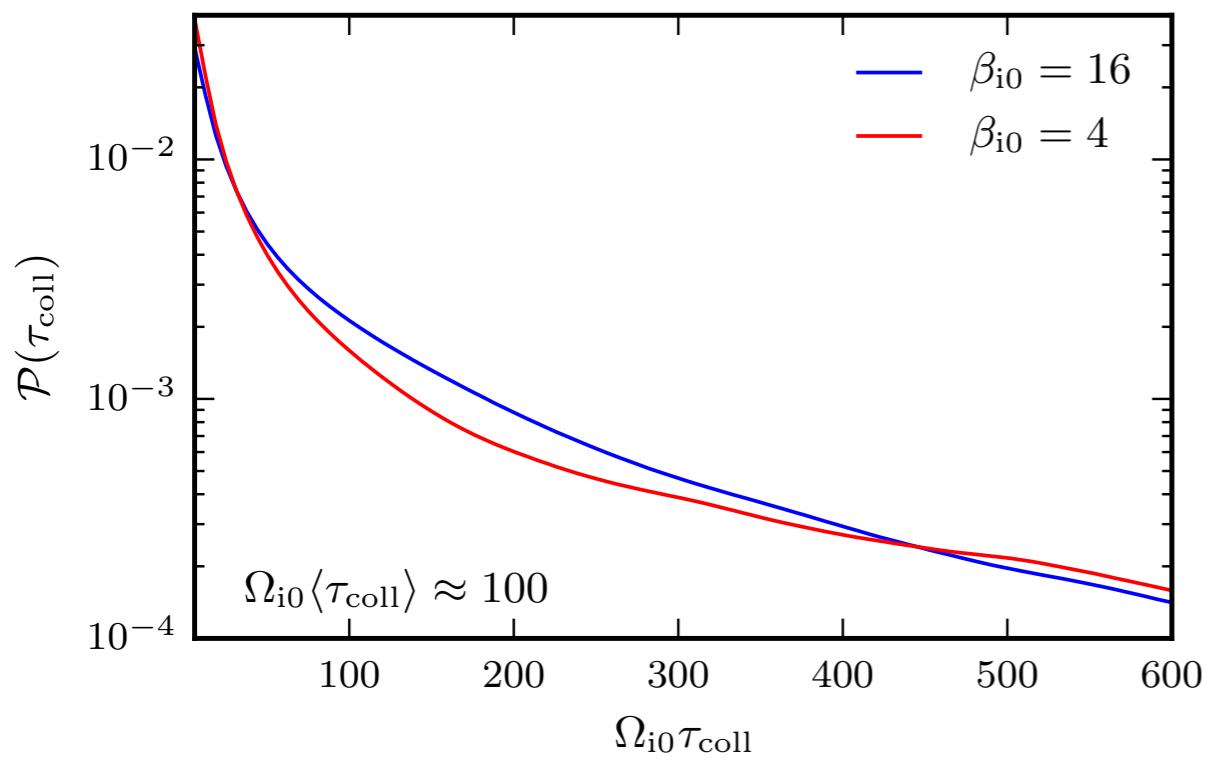
# Pressure anisotropy



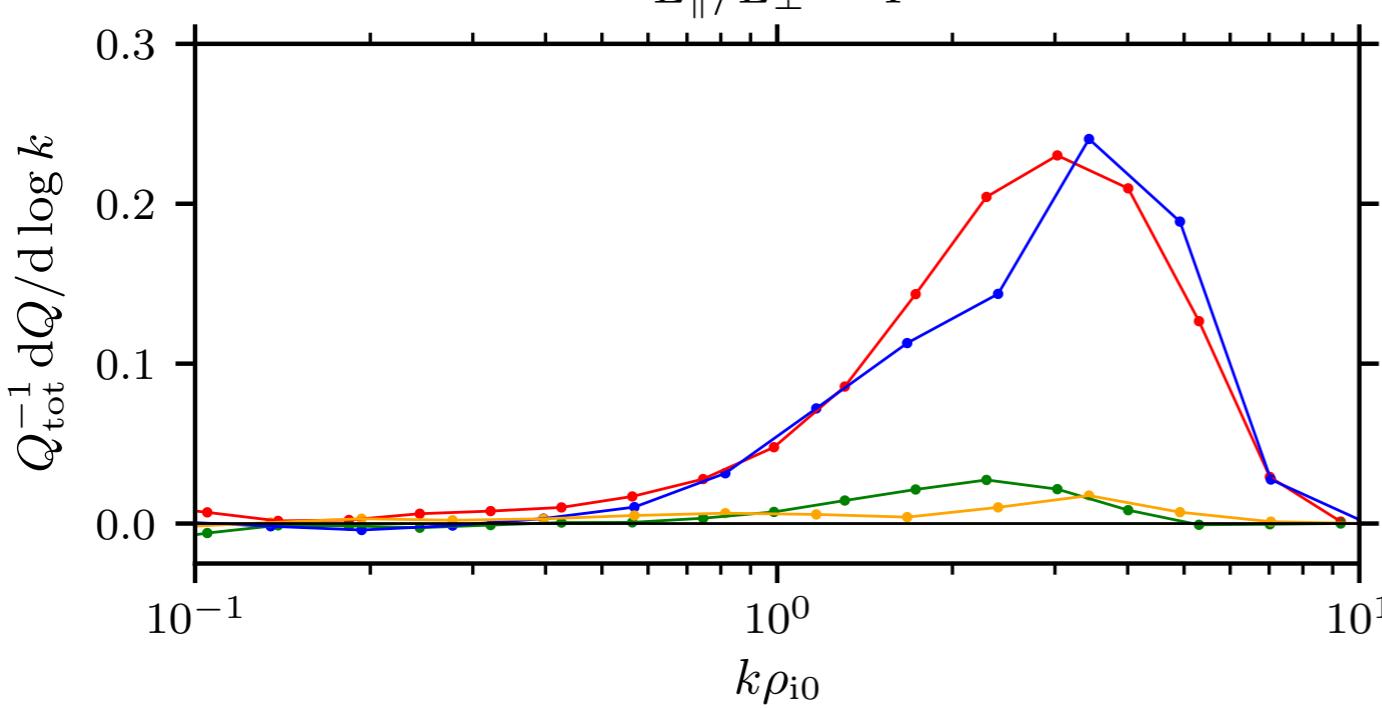
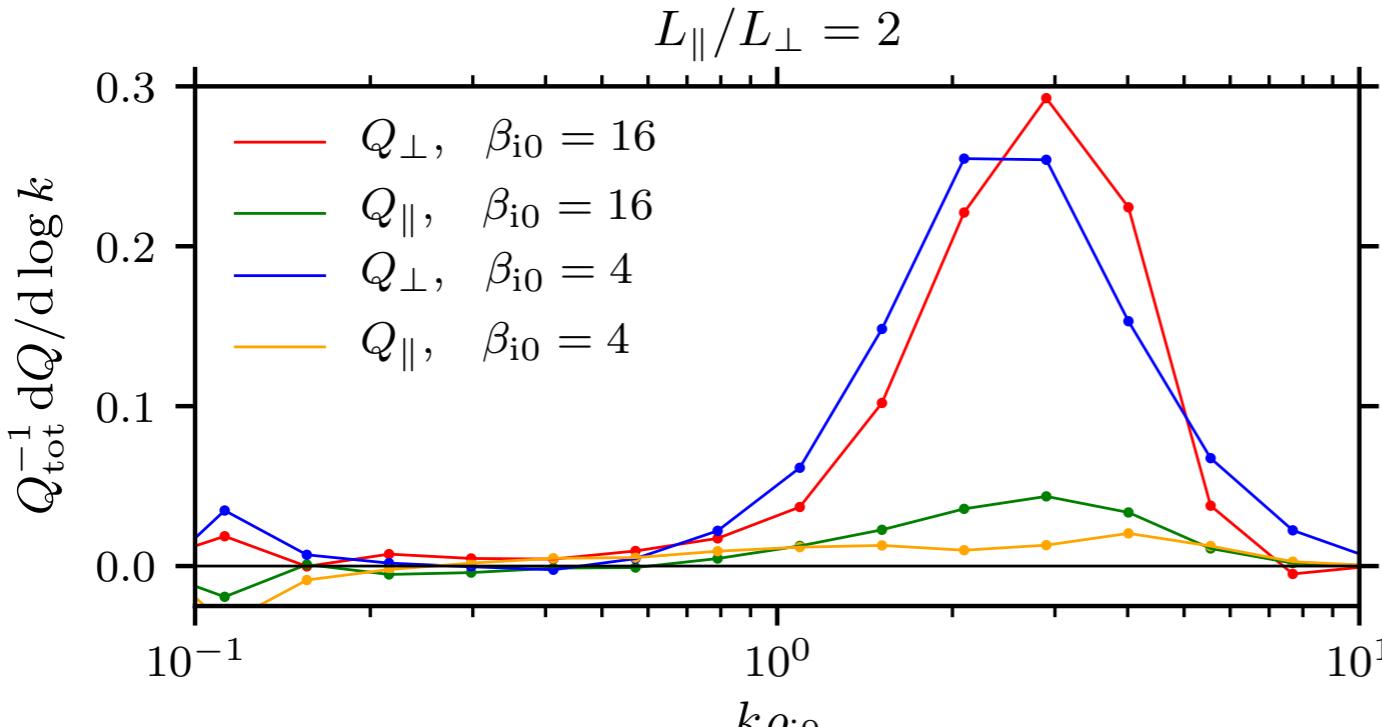
Solar wind observation  
for comparison



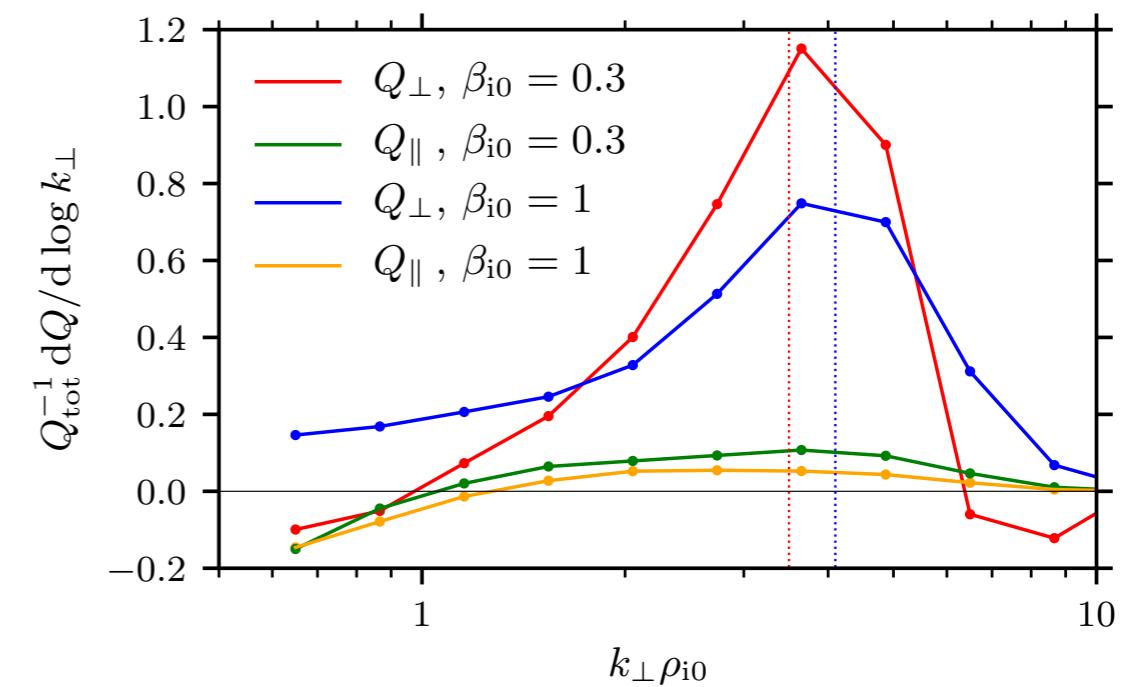
# Effective collisionality



# Ion heating



beta = 1 and 0.3 results from  
Arzamasskiy et al. 2019 for  
comparison

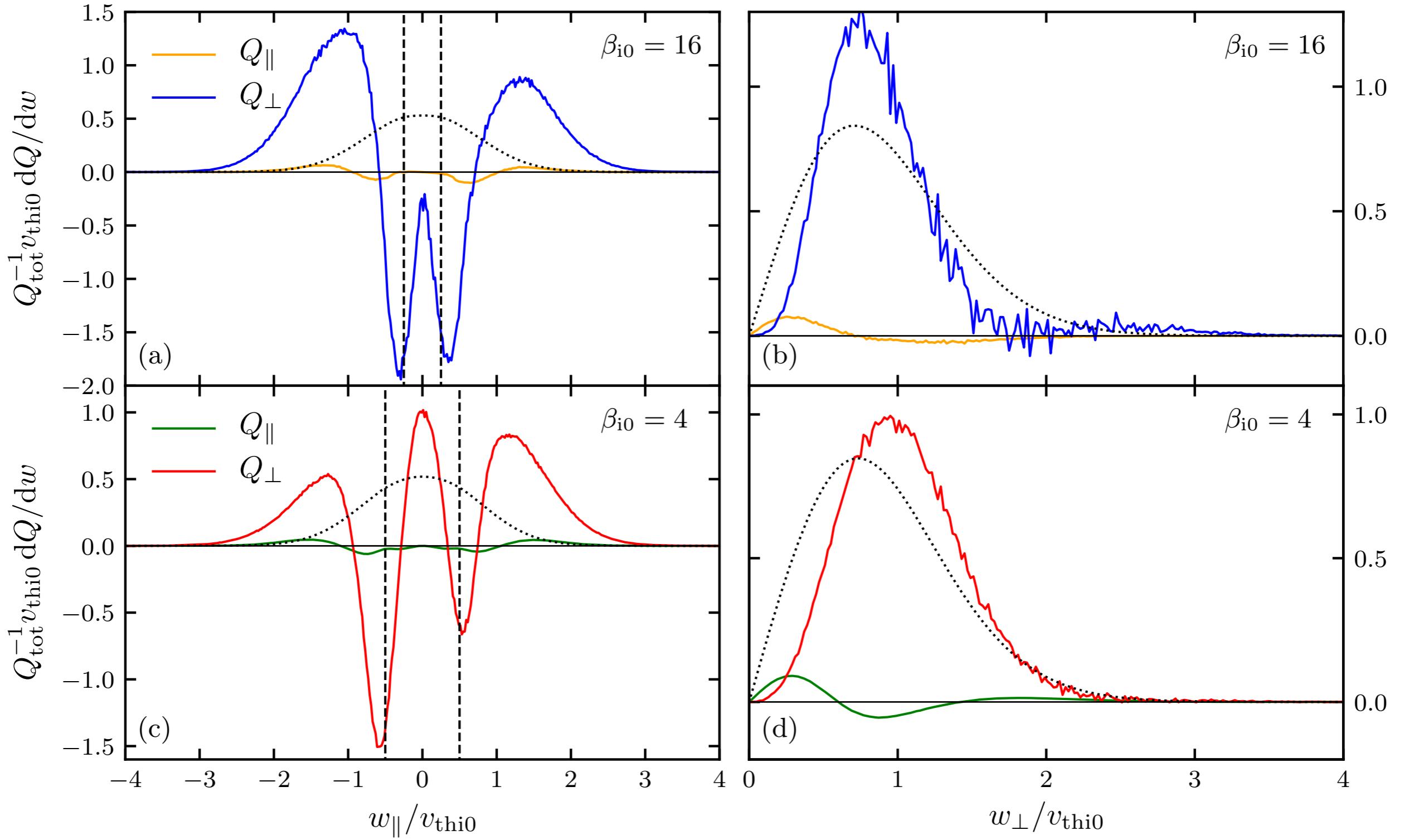


$$\frac{Q_i}{Q_{\text{inj}}} \sim 0.75$$

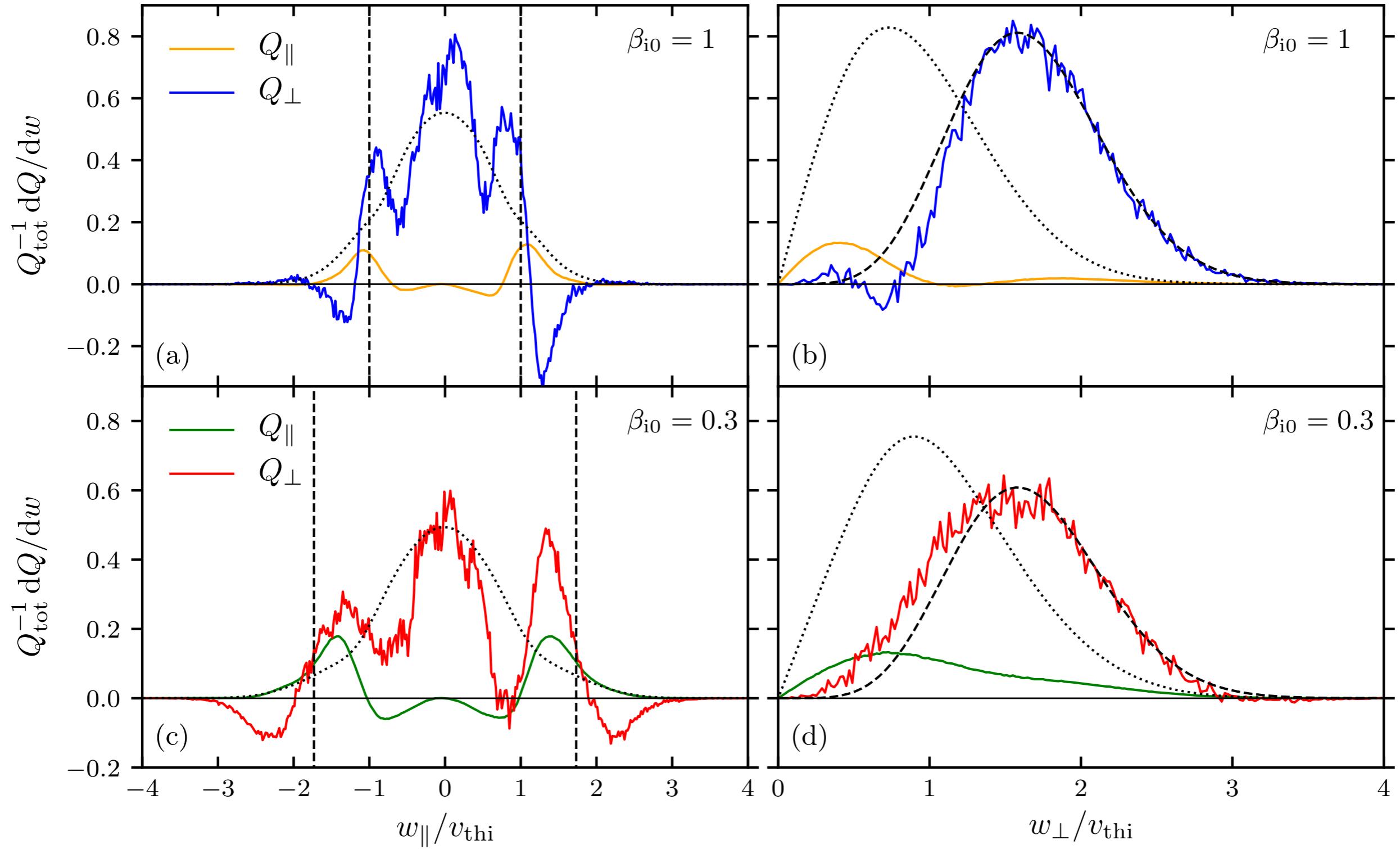
$$\frac{\langle \mathbf{E}_{\perp} \cdot \mathbf{v}_{\perp} \rangle}{\langle \mathbf{E}_{\parallel} \cdot \mathbf{v}_{\parallel} \rangle} \sim 9$$

Almost independent of beta in this range

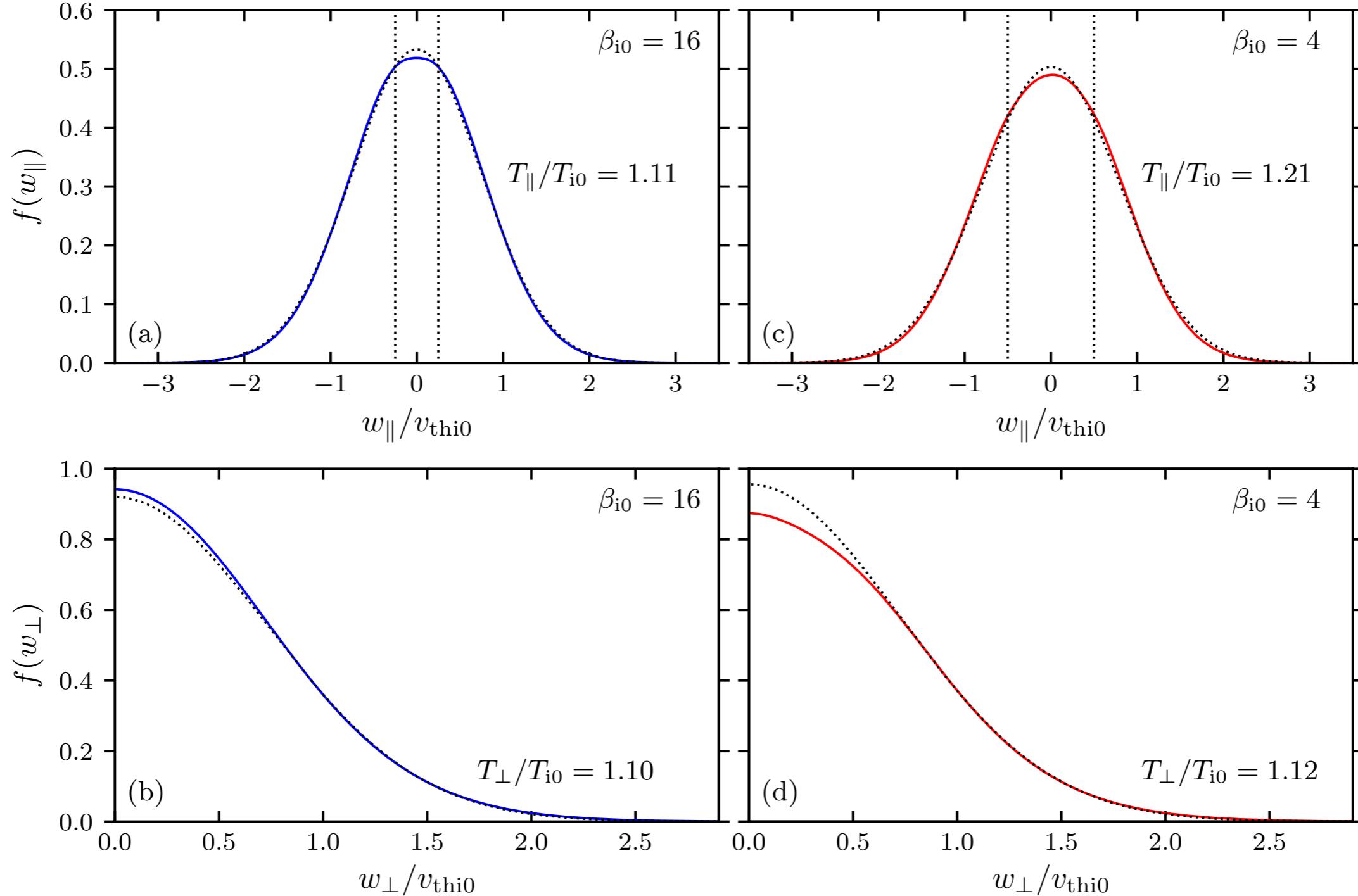
# Ion heating in velocity space



# Ion heating in velocity space

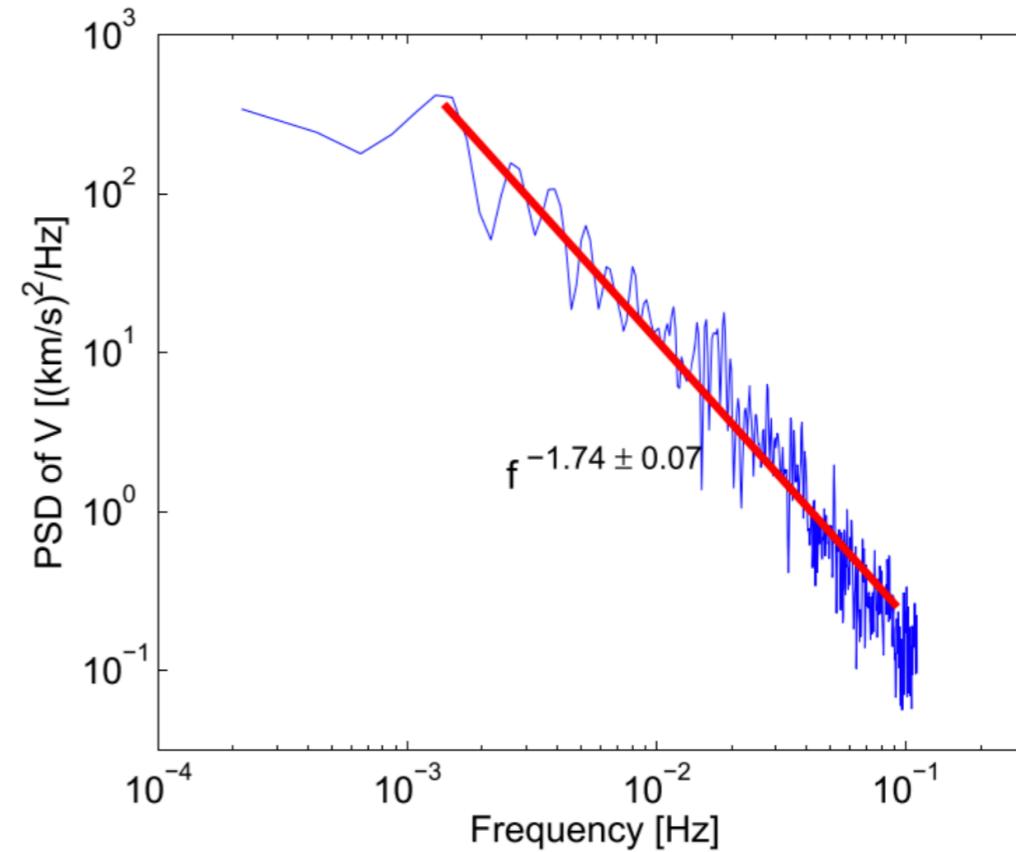
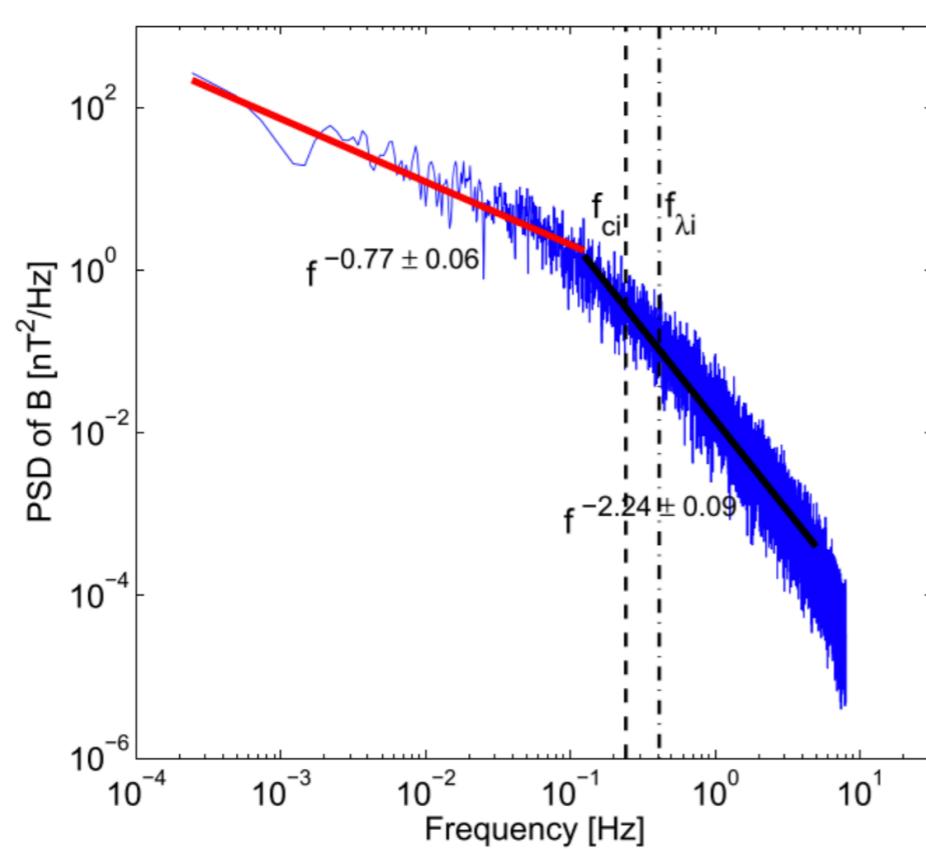


# Distribution function

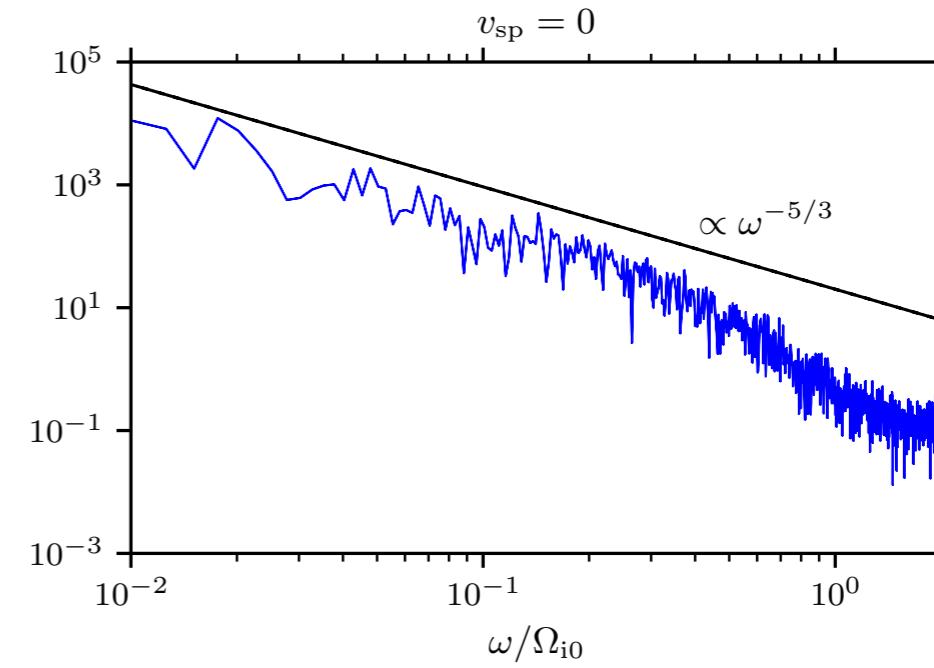
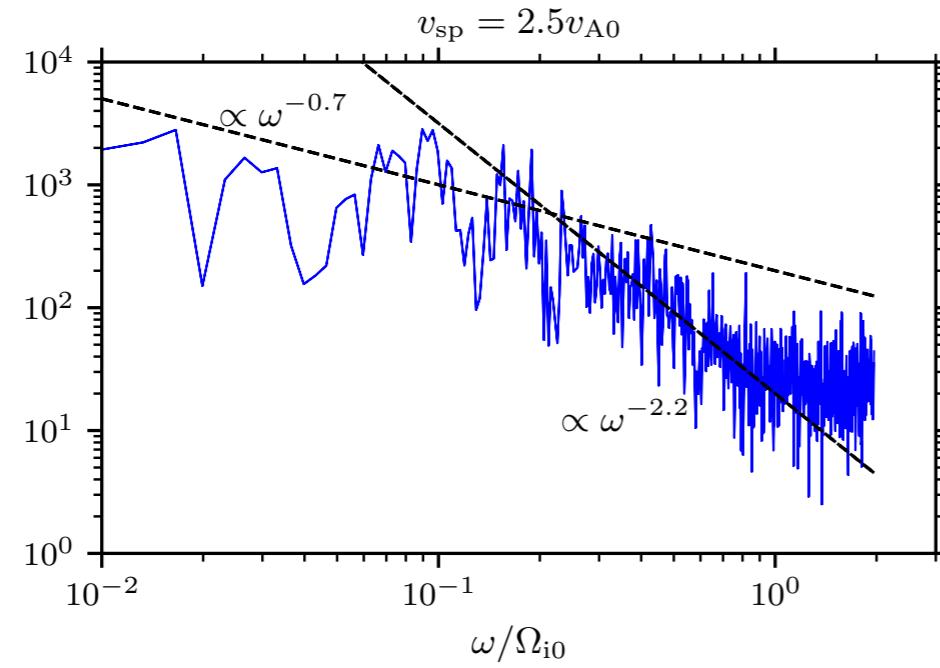


- final perpendicular and parallel temperatures are almost equal
- slightly flattened core in parallel distribution

# Observations: magnetosheath



Hadid et al. 2015, Huang et al. 2017



# Summary

- Large-scale turbulent fluctuations are unstable to kinetic micro-instabilities
- Instability-produced fluctuations introduce effective collisionality in collisionless high-beta plasma ( $\lambda_{\text{mfp}} \sim 100\rho_{i0}$ )
- Magnetic field spectrum has a shallow slope (with index close to -1) near ion-Larmor-radius scale (testable prediction in SW)
- Turbulence preferentially heats the ions (70-80% of the cascade rate) at sub-Larmor scales
- Steady-state ion distribution function is close to Maxwellian, with flattened core in parallel distribution