Particle heating and instabilities in kinetic turbulence

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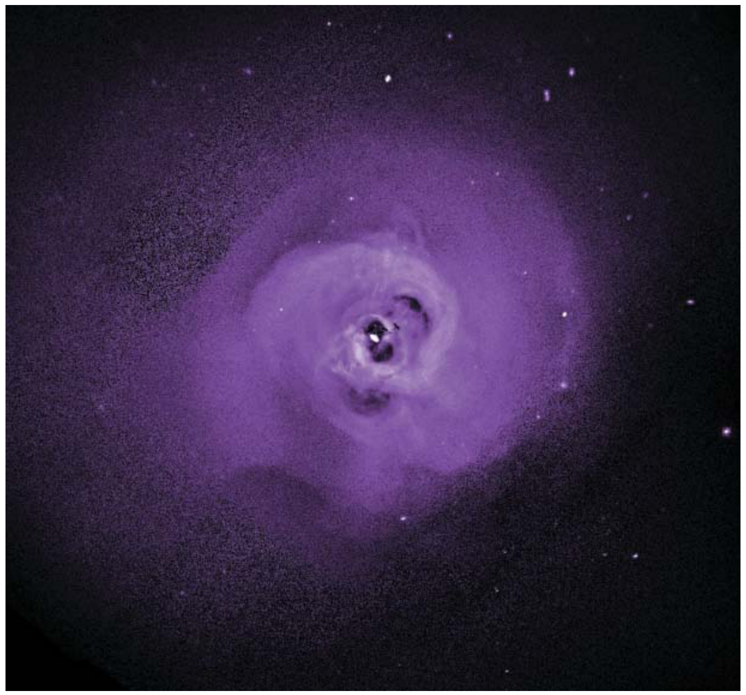
Astrophysical plasmas are typically weakly collisional or collisionless and have $\beta \gtrsim 1$



ICM

$\beta \sim 100$

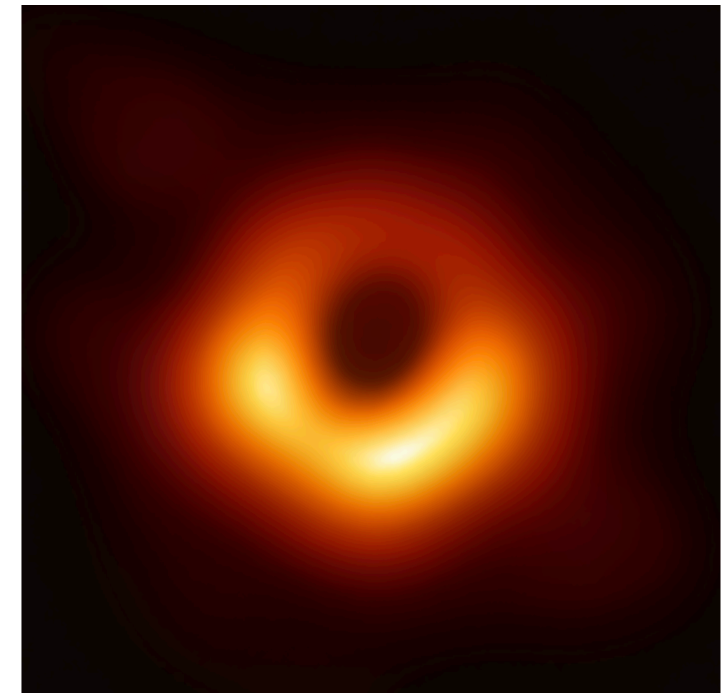
$L \sim 10^2\mathrm{kpc}$

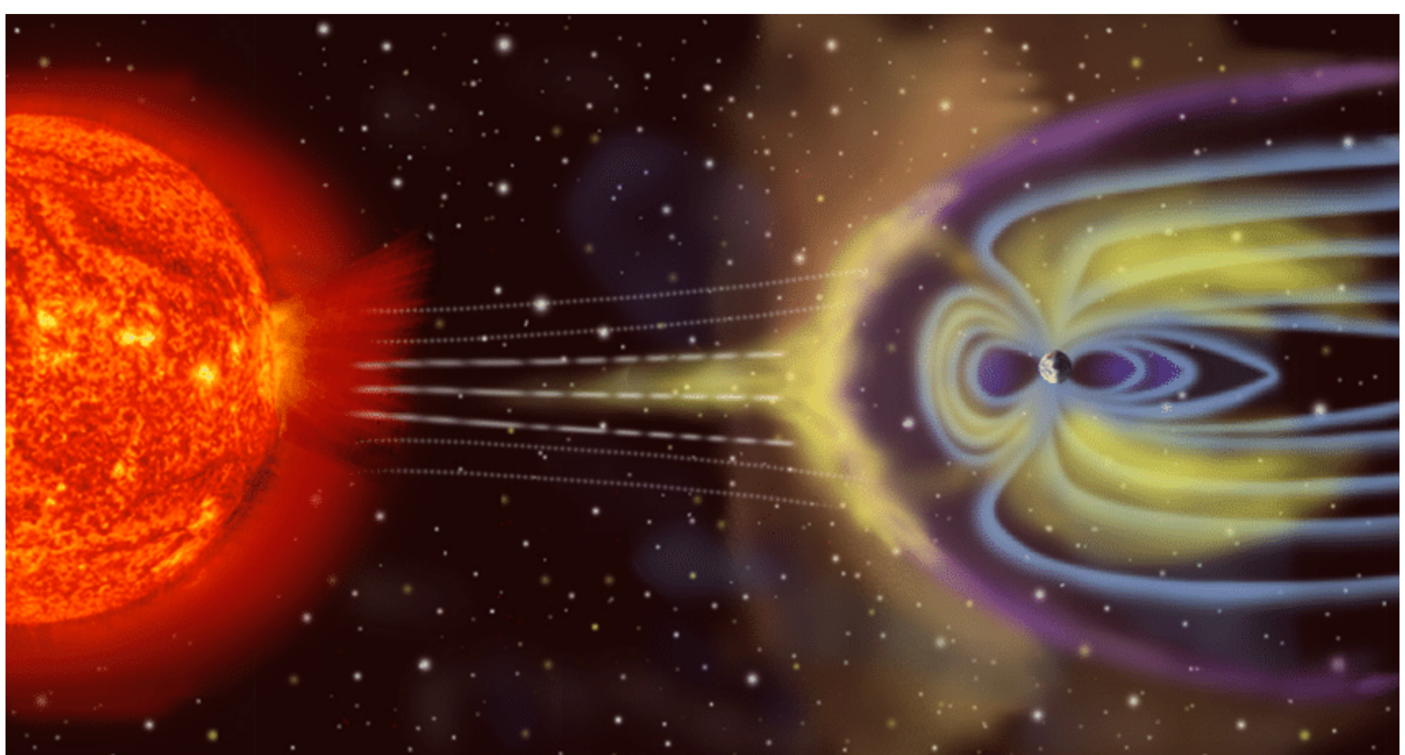
$\lambda_{\mathrm{mfp}} \sim 1\mathrm{kpc}$

Galactic center

$\beta \sim 10$

$L \sim \lambda_{\mathrm{mfp}} \sim 0.1\mathrm{pc}$





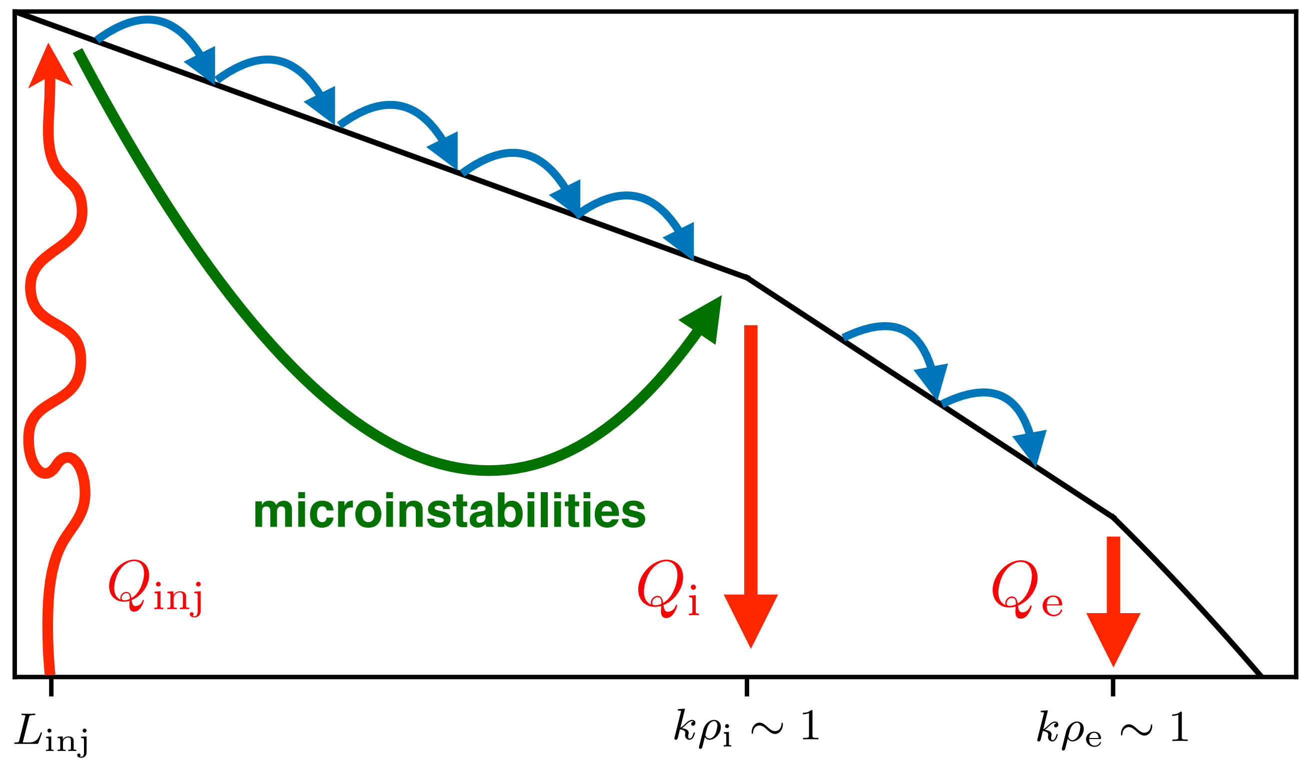
Solar wind

$\beta \sim 1$

$L \sim \lambda_{\mathrm{mfp}} \sim 1\mathrm{au}$

$$\beta \equiv 8\pi nT/B^2$$

high$-\beta$

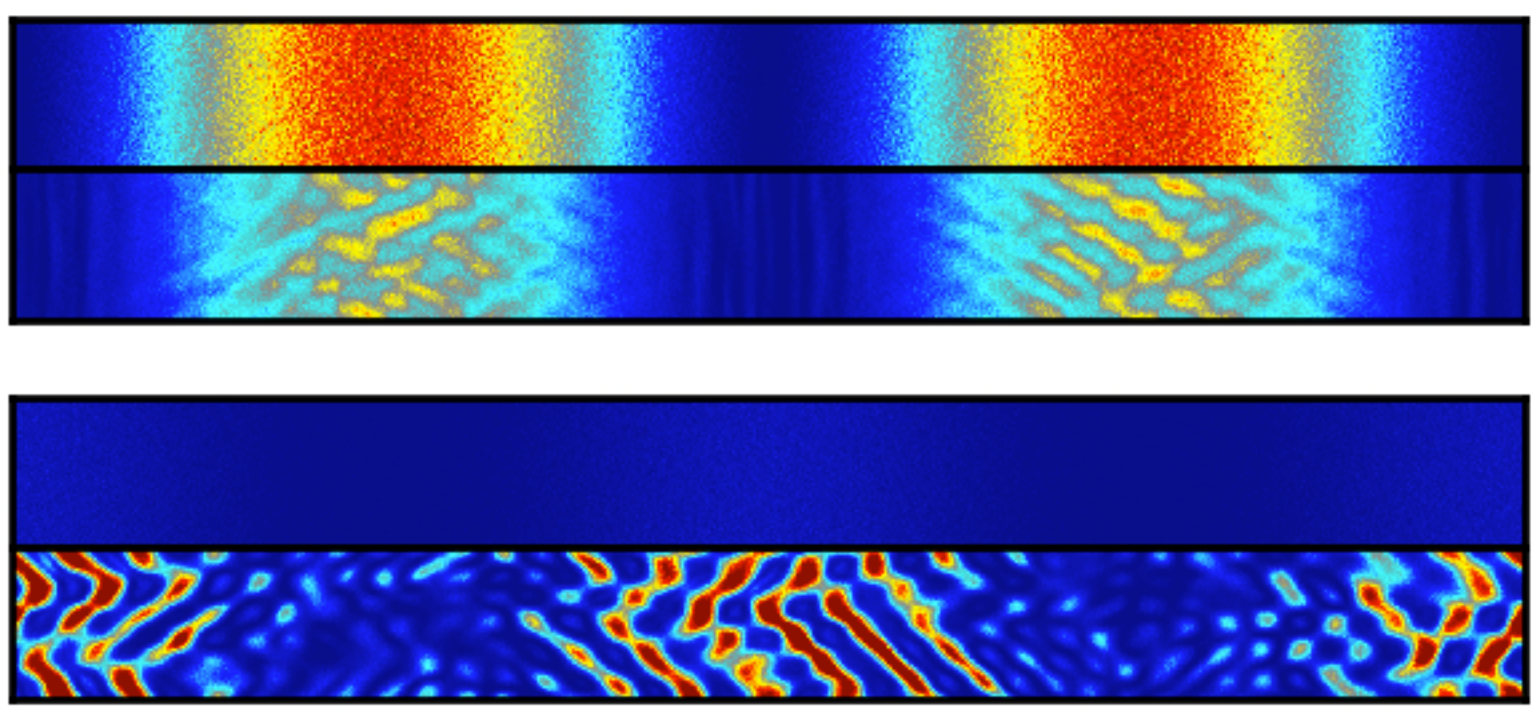


Large-scale changes in magnetic field naturally drive pressure anisotropy due to the conservation of magnetic moment $\boldsymbol{\mu} \propto v_\perp^2/B \propto p_\perp/B$

Magnetic field strength in Alfvén wave

$\Delta p > 0$

mirror, ion-cyclotron



stable

unstable

$\Delta p < 0$

firehose

stable

unstable

Squire et al. 2017

Hybrid-PIC

Pegasus++: new hybrid-PIC code based on the algorithm of Pegasus (Kunz et al. 2014) and infrastructure of Athena++ (Stone et al. 2019); highly-optimized (runs more than an order of magnitude faster on modern architectures than Pegasus)

Solves kinetic equation for ions along the characteristics (particle-in-cell), electrons are assumed to be massless

$$\frac{\partial f_{\rm i}}{\partial t} + \boldsymbol{v}\boldsymbol{\cdot}\boldsymbol{\nabla} f_{\rm i} + \frac{Ze}{m_{\rm i}}\left[\boldsymbol{E} + \frac{\boldsymbol{v}}{c}\times\boldsymbol{B}\right]\boldsymbol{\cdot}\frac{\partial f_{\rm i}}{\partial \boldsymbol{v}} = 0$$

$$\boldsymbol{E} + \frac{\boldsymbol{u}_{\rm i}}{c}\times\boldsymbol{B} = -\frac{\boldsymbol{\nabla} p_{\rm e}}{e n_{\rm e}} + \frac{(\boldsymbol{\nabla}\times\boldsymbol{B})\times\boldsymbol{B}}{4\pi Z e n_{\rm i}}$$

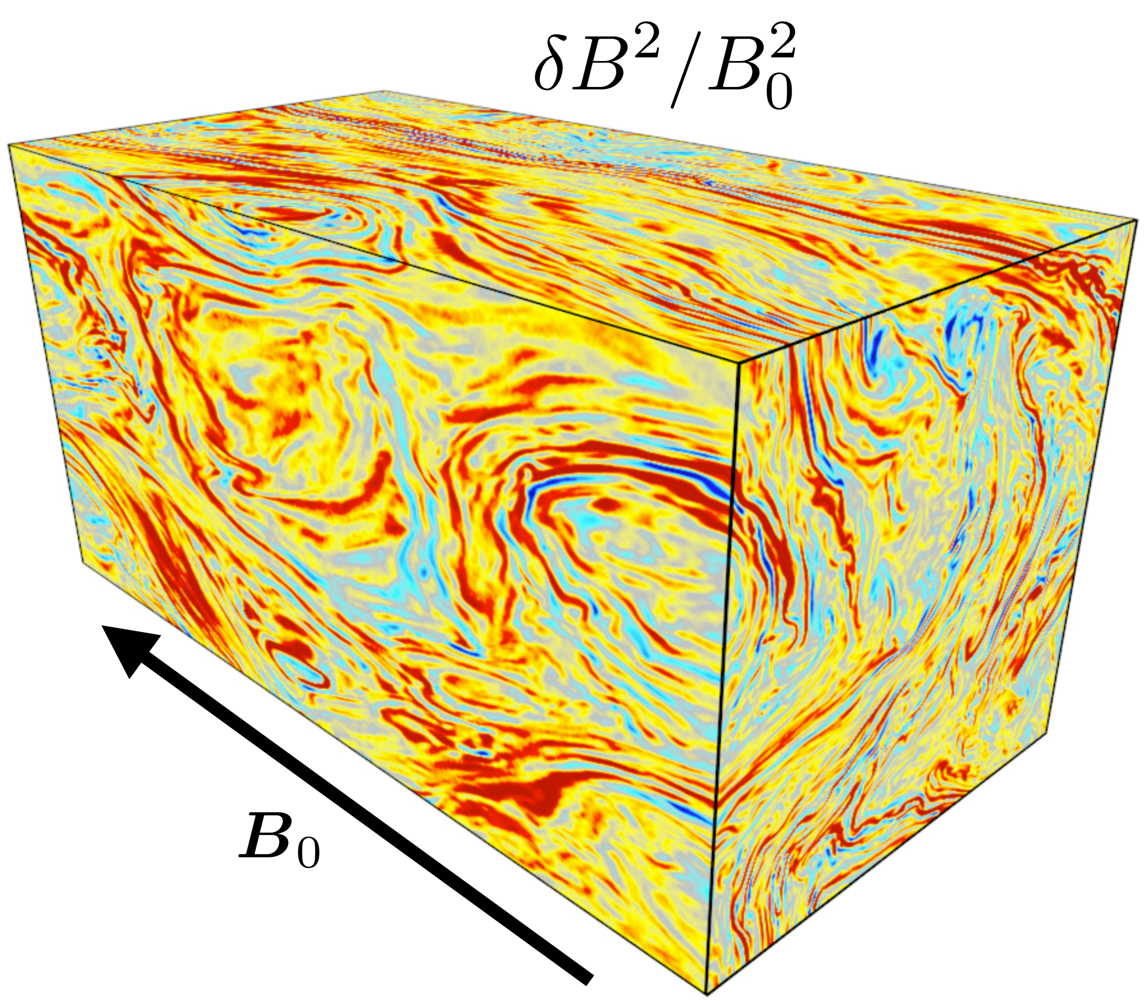
must assume something;
usually isotropic and:
isothermal or barotropic

Simulation setup

Driving of turbulence at large scales — Ornstein-Uhlenbeck process

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

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

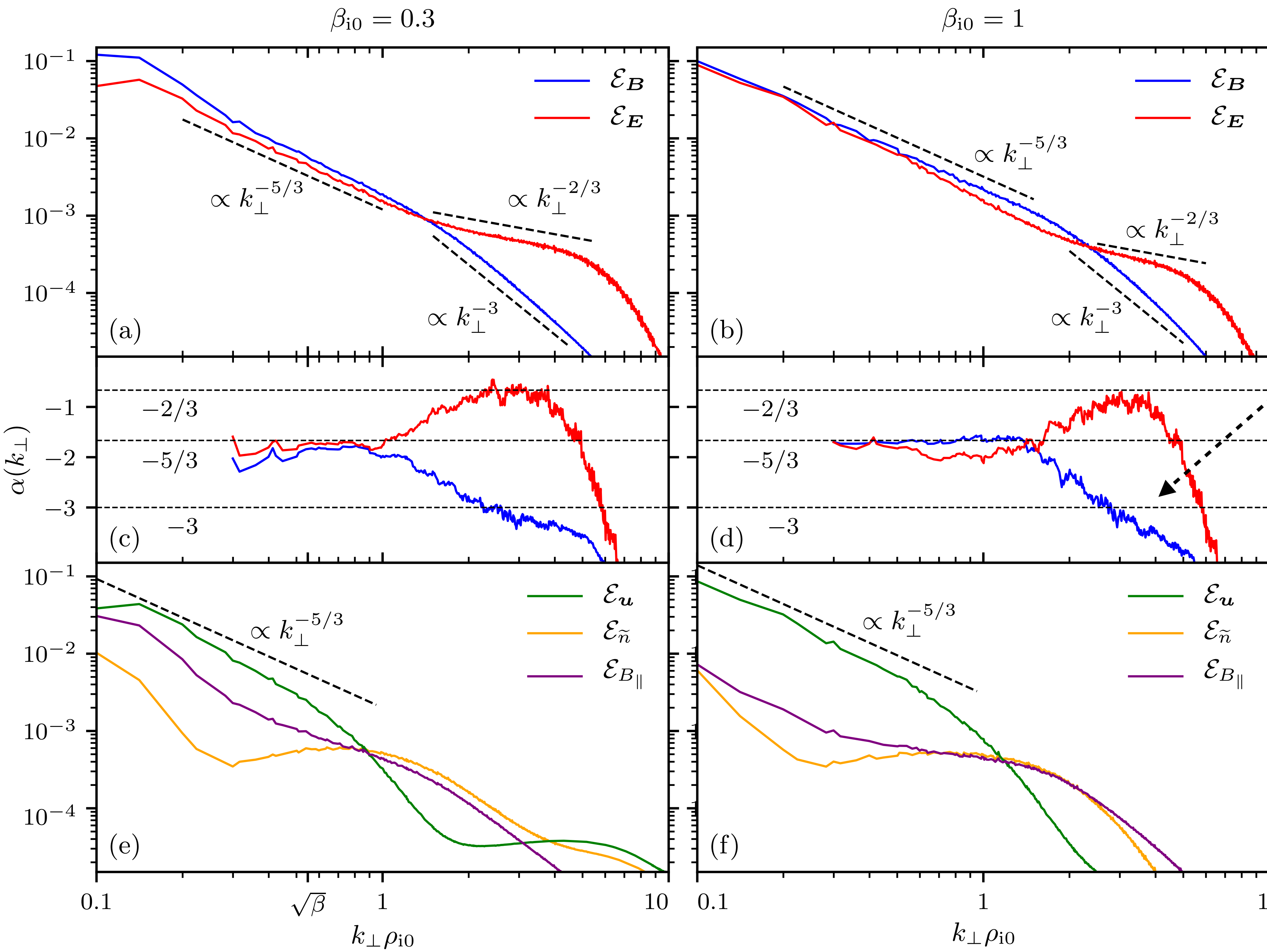


Box-scale fluctuations are in critical balance, so the aspect ratio of the box controls the strength of fluctuations

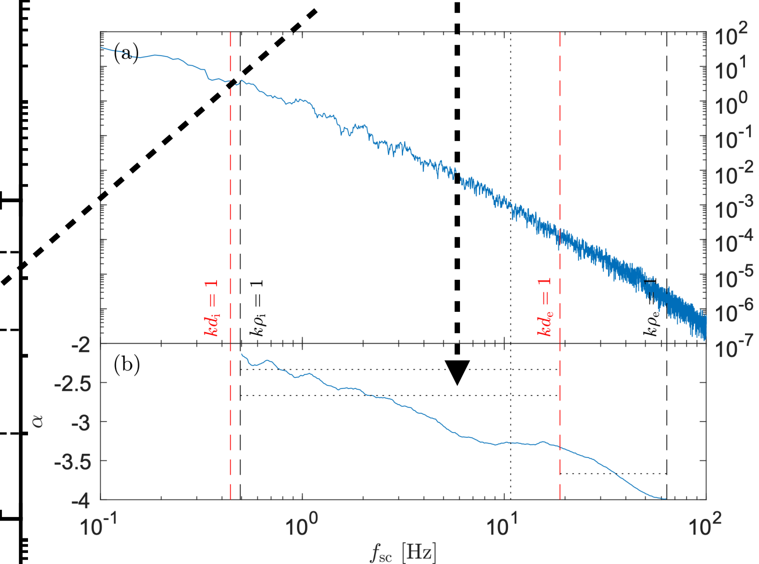
$$k_{\|} v_{\rm A} \sim k_{\perp} u_{\rm rms}$$

low beta: use aspect ratios of 6-8 to mimic realistic values of ion-Larmor-scale anisotropy (motivated by solar-wind observations)
high beta: use aspect ratios of 2-4 to look at the disruption of strong fluctuations

Turbulence in beta~1 plasmas

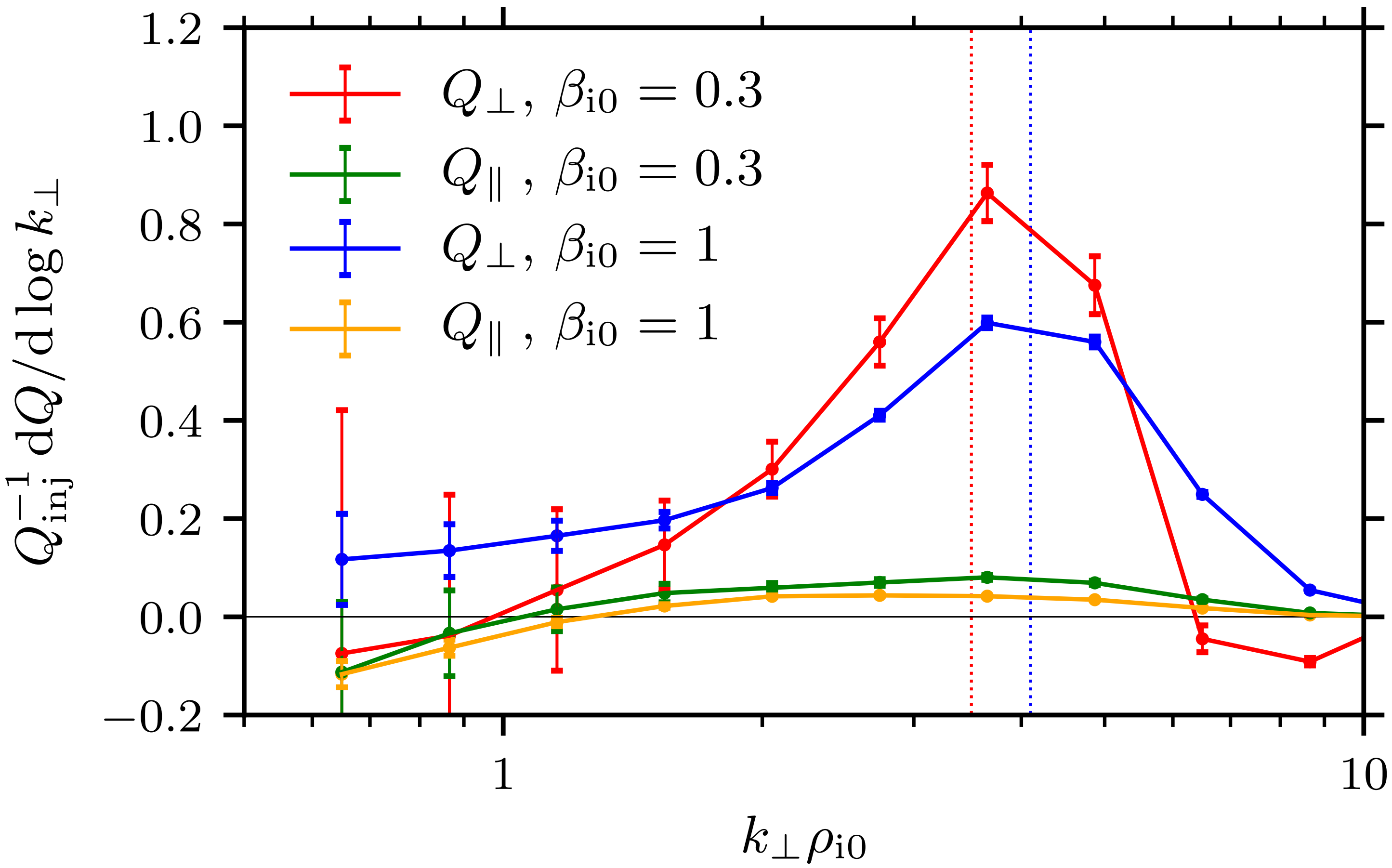


similar steepening is observed in the solar wind (Chen et al. 2019)

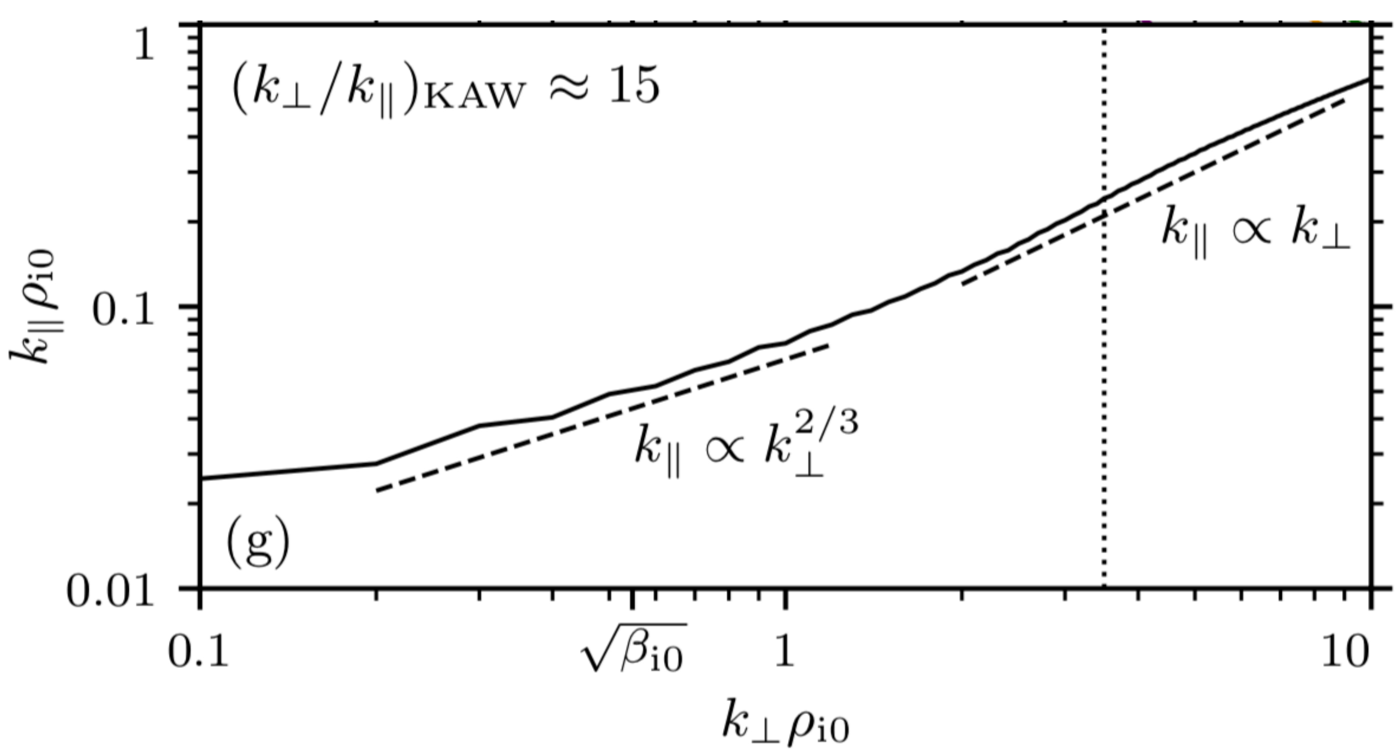


Arzamasskiy, Kunz, Chandran, Quataert 2019

Ion heating in beta~1 turbulence



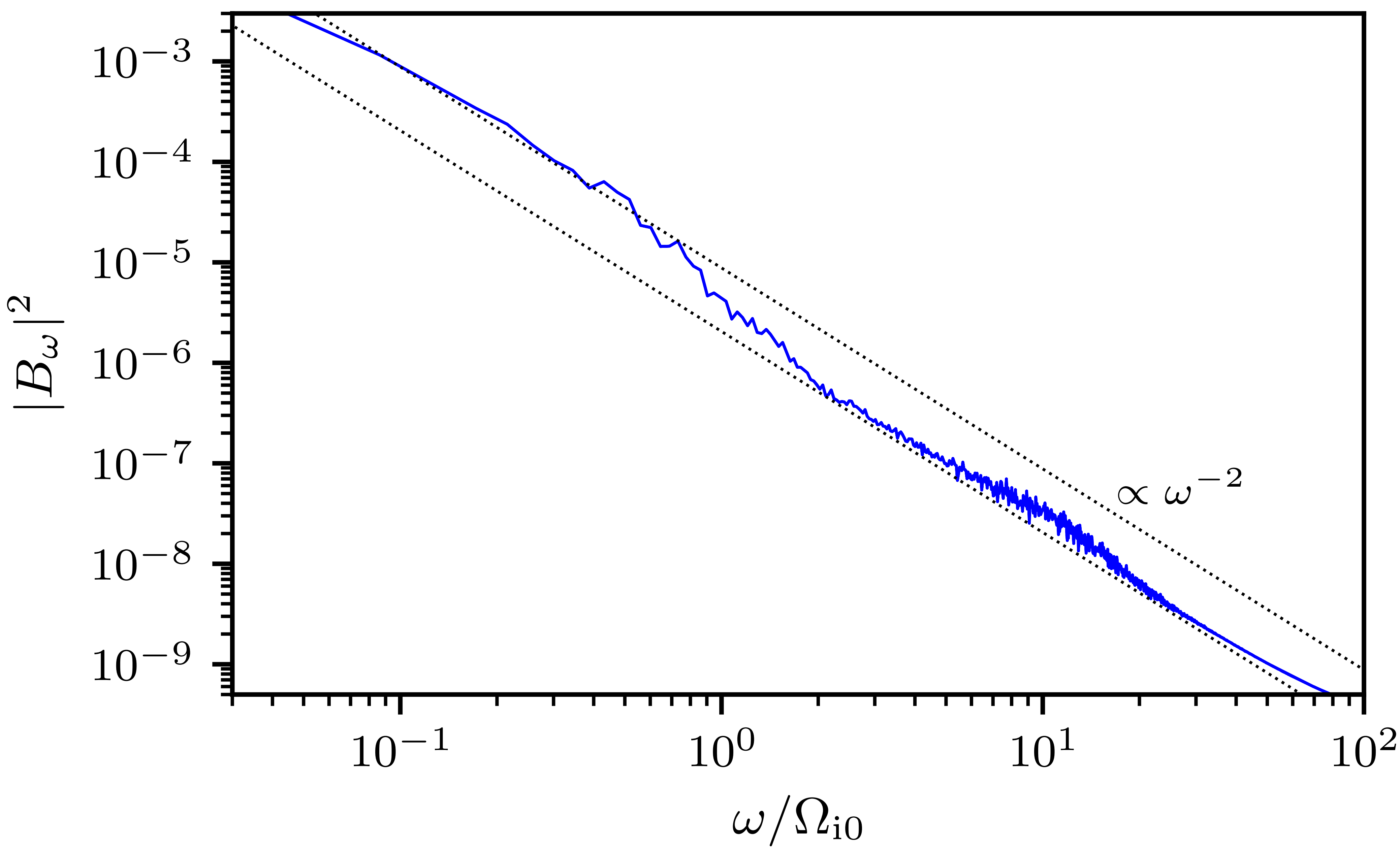
time-averaged work done by k-filtered electric field $\langle \boldsymbol{E}_k \cdot \boldsymbol{v} \rangle$



ion heating

- is mostly perpendicular
- happens at sub-ion-Larmor scales
- is mediated by waves oscillating at high frequencies $\omega \sim \Omega_i$

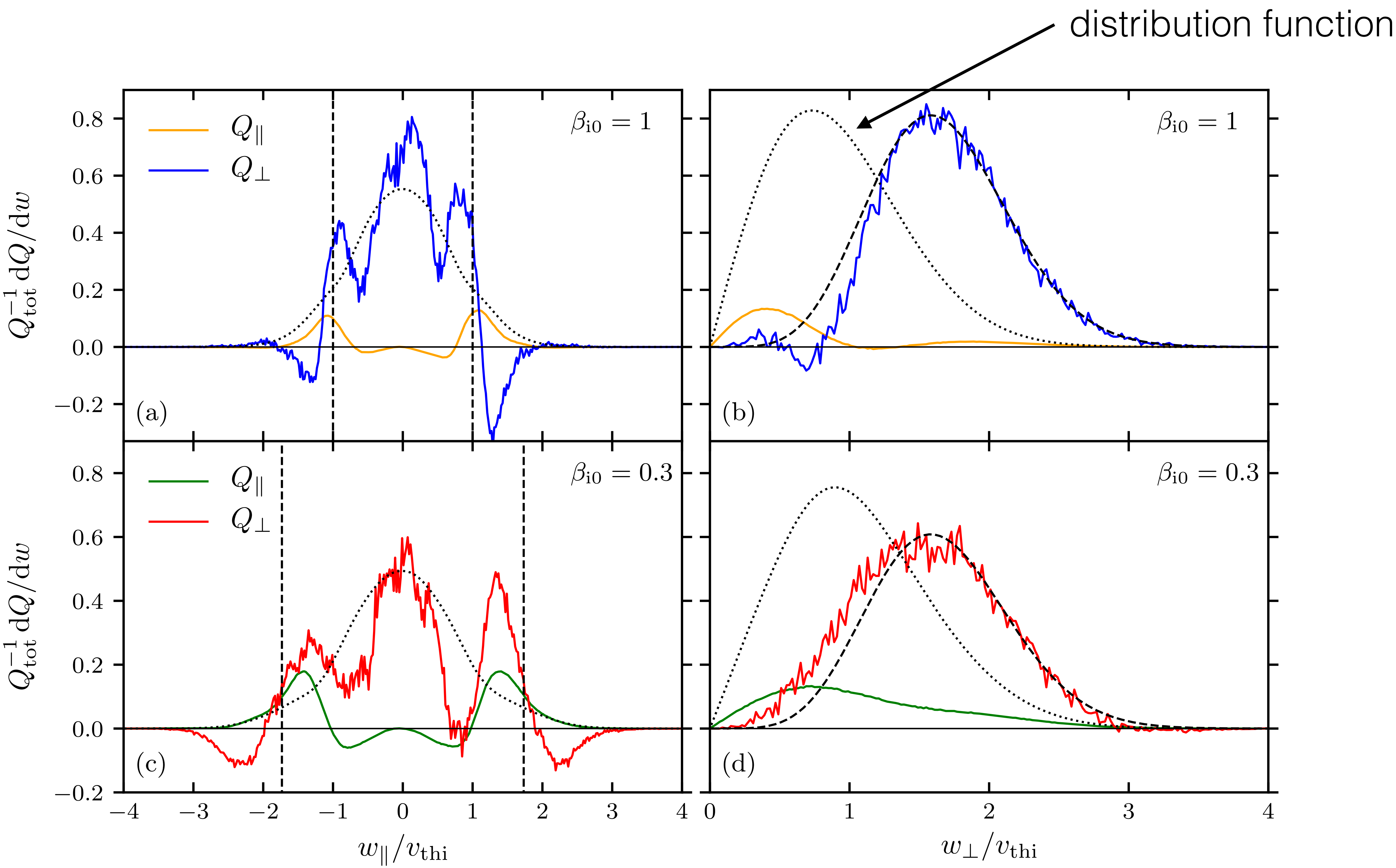
frequency spectrum of the waves in the box



in critically-balanced turbulence, the energy flux is constant if

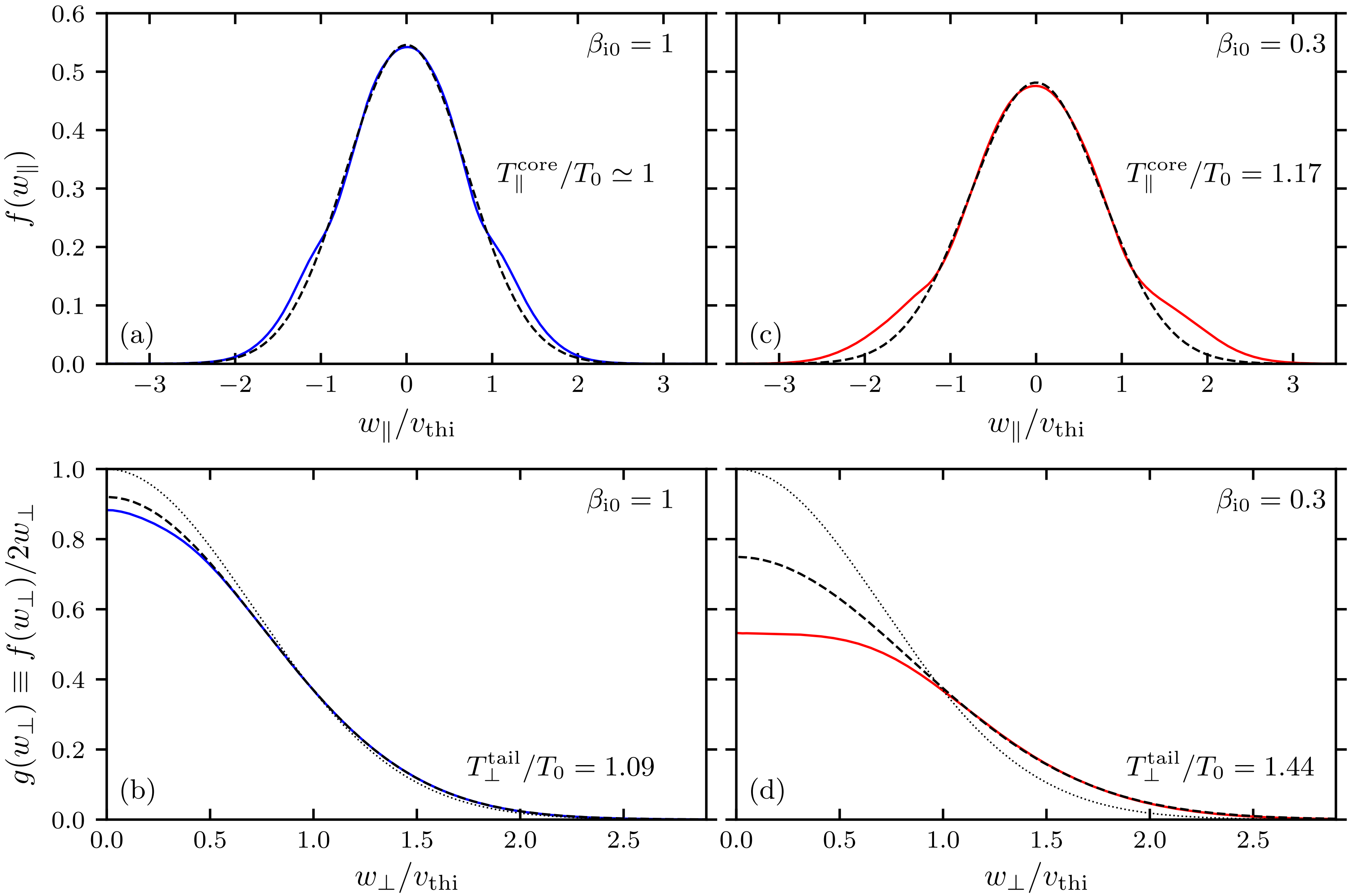
$$\varepsilon \sim \delta B^2/\tau_{\mathrm{nl}} \sim \omega \delta B^2 \Rightarrow |B_\omega|^2 \propto \mathrm{d}\delta B^2/\mathrm{d}\omega \propto \omega^{-2}$$

Heating in velocity space

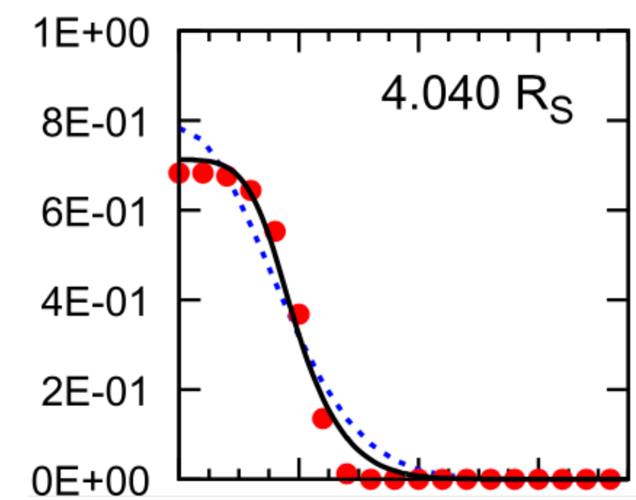


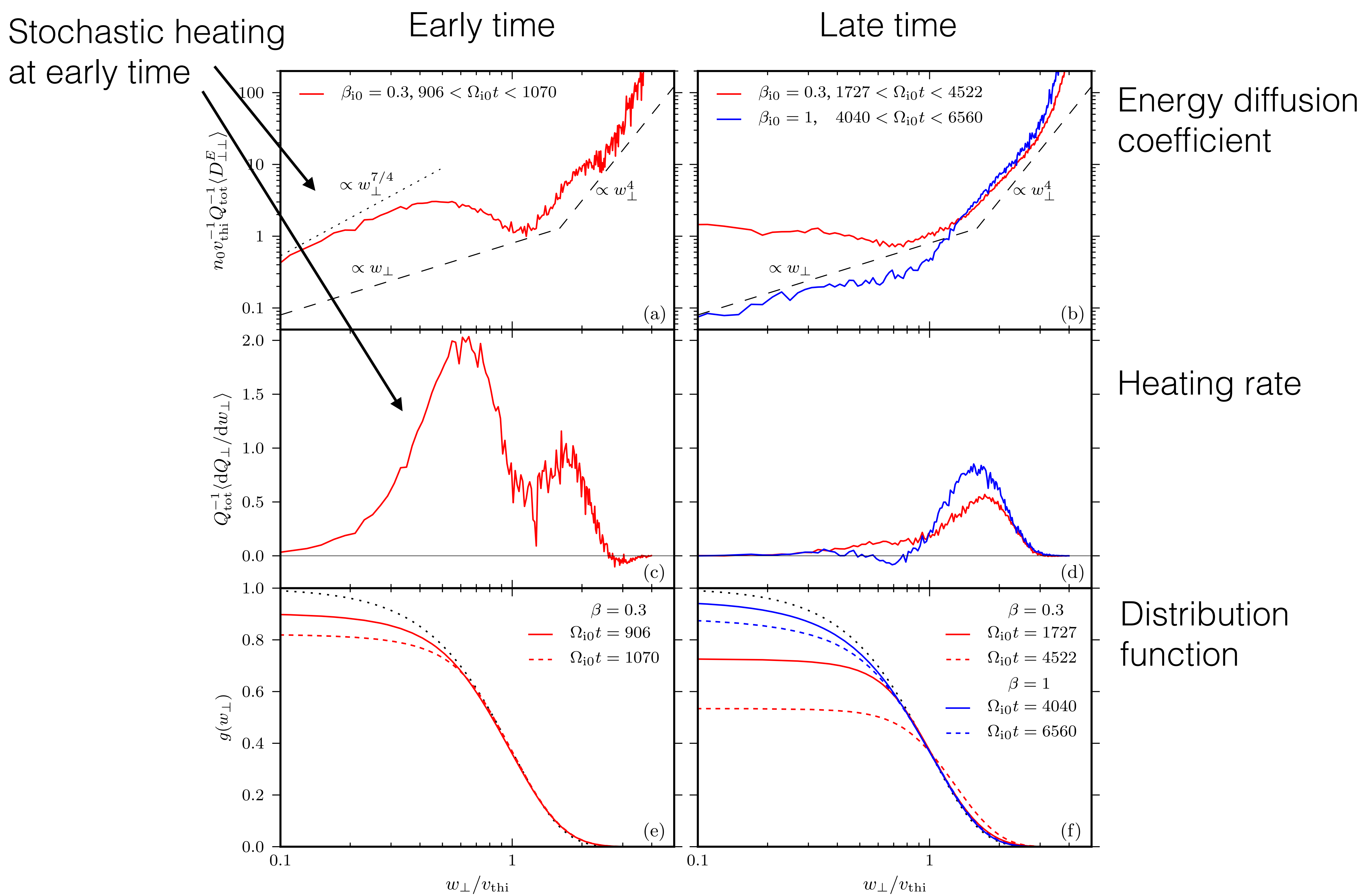
following field-particle correlation technique (Howes et al. 2017)

Distribution function



- Non-thermal tails in parallel distribution produced by pitch-angle scattering of perpendicular tails
- Flattened core in perpendicular distribution, consistent with stochastic heating (Chandran et al. 2010, Klein & Chandran 2016)

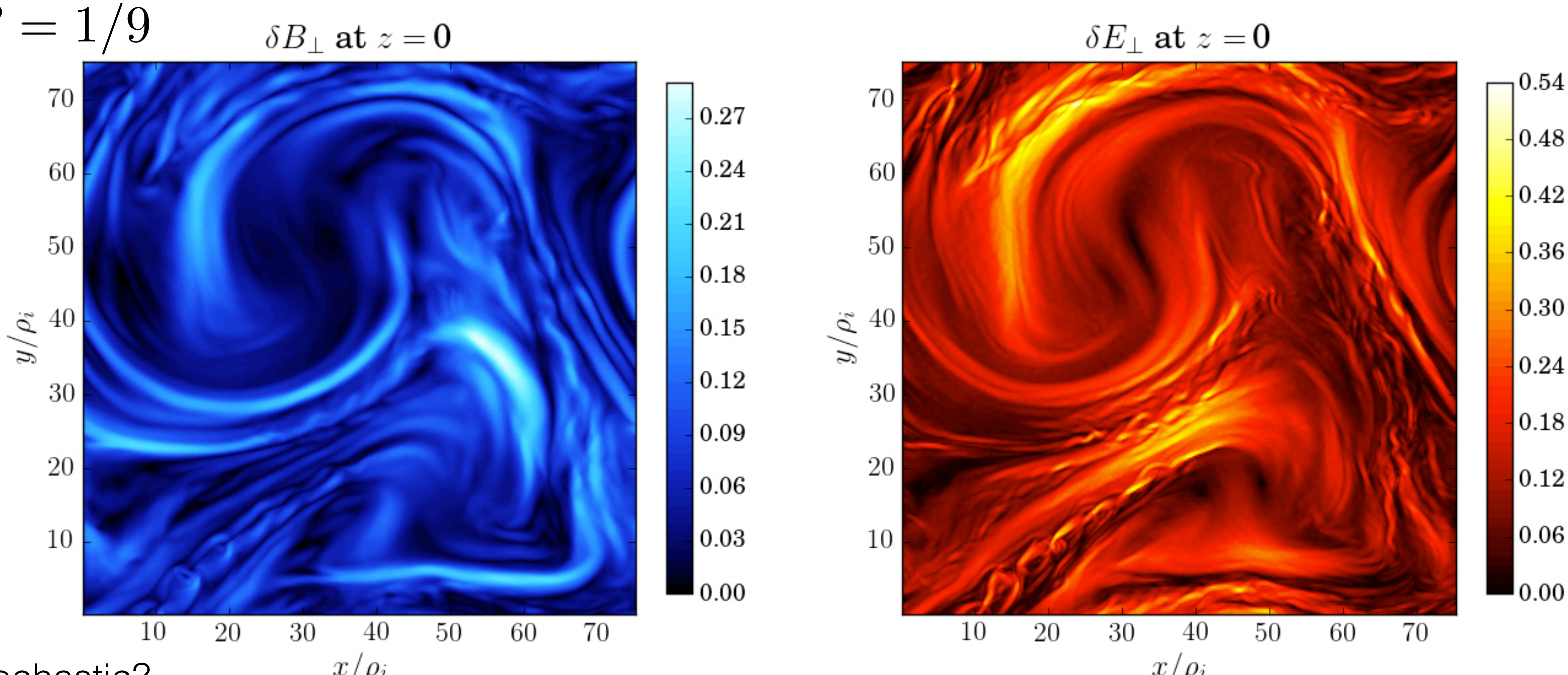




Stochastic heating
at early time
Early time
Late time
Energy diffusion
coefficient
Heating rate
Distribution
function
$\beta_{i0} = 0.3, 906 < \Omega_{i0}t < 1070$
$\beta_{i0} = 0.3, 1727 < \Omega_{i0}t < 4522$
$\beta_{i0} = 1, \quad 4040 < \Omega_{i0}t < 6560$
$\propto w_\perp^{7/4}$
$\propto w_\perp^4$
$\propto w_\perp$
$n_0 v_{\rm thi}^{-1} Q_{\rm tot}^{-1} \langle D_{\perp\perp}^E \rangle$
$Q_{\rm tot}^{-1} \langle {\rm d}Q_\perp / {\rm d}w_\perp \rangle$
$g(w_\perp)$
$w_\perp / v_{\rm thi}$
(a)
(b)
(c)
(d)
(e)
(f)
$\beta = 0.3$
$\Omega_{i0}t = 906$
$\Omega_{i0}t = 1070$
$\Omega_{i0}t = 1727$
$\Omega_{i0}t = 4522$
$\beta = 1$
$\Omega_{i0}t = 4040$
$\Omega_{i0}t = 6560$

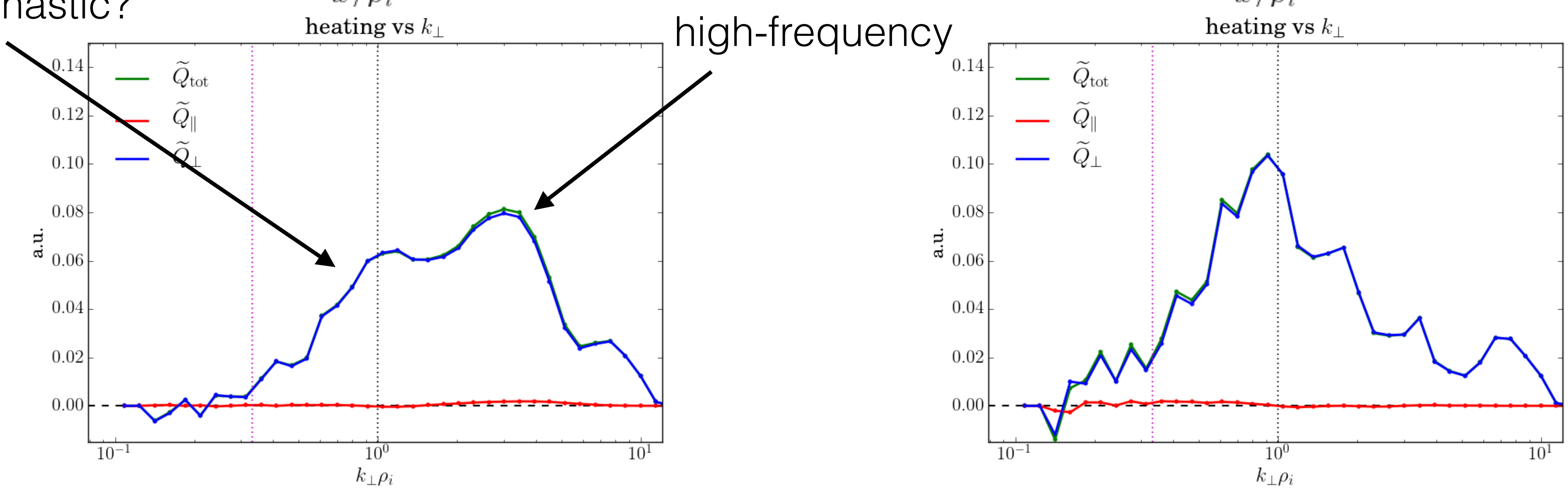
Check out Silvio Cerri's poster!

$\beta = 1/9$



stochastic?

high-frequency

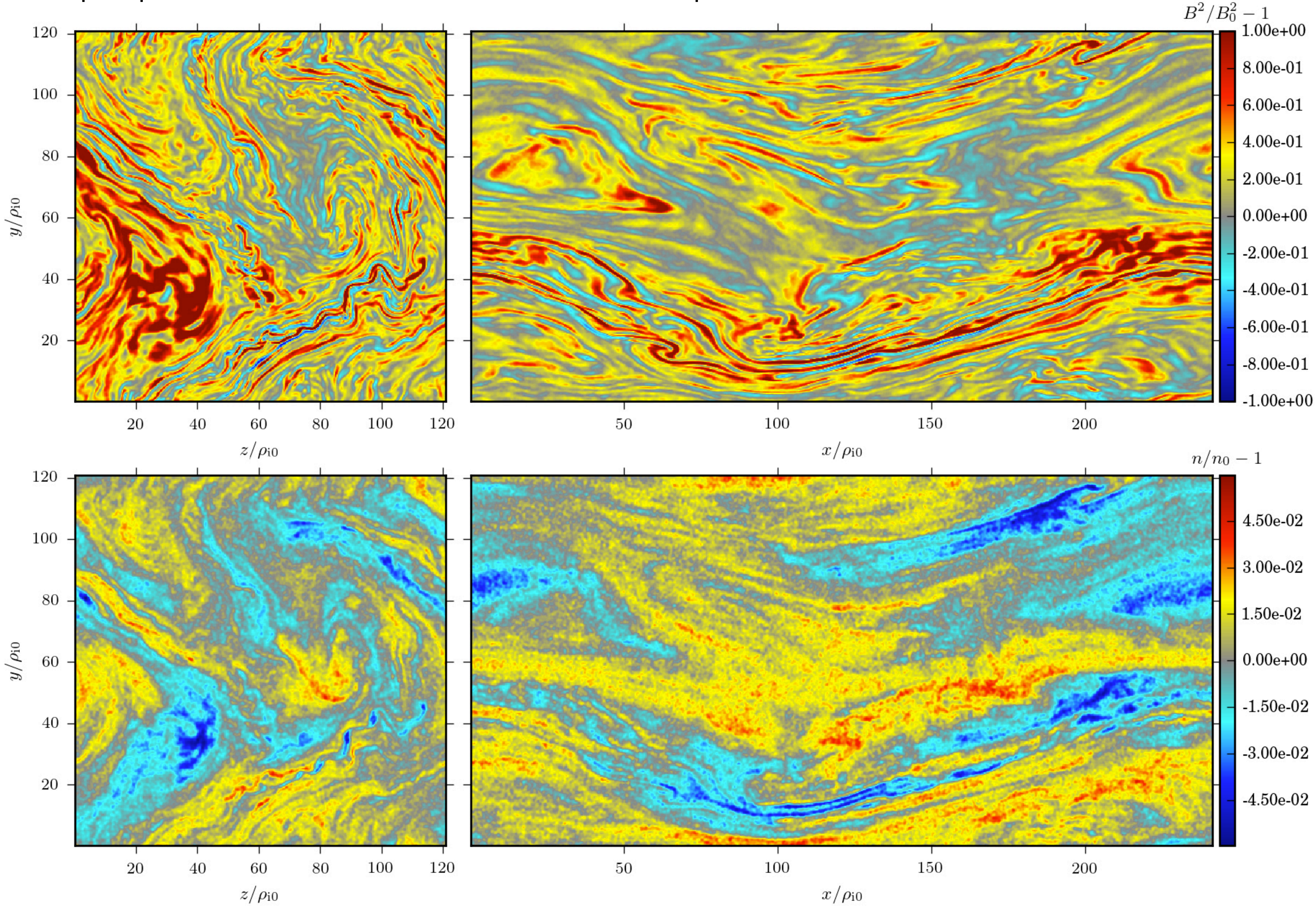


Cerri, Arzamasskiy, Kunz, in preparation

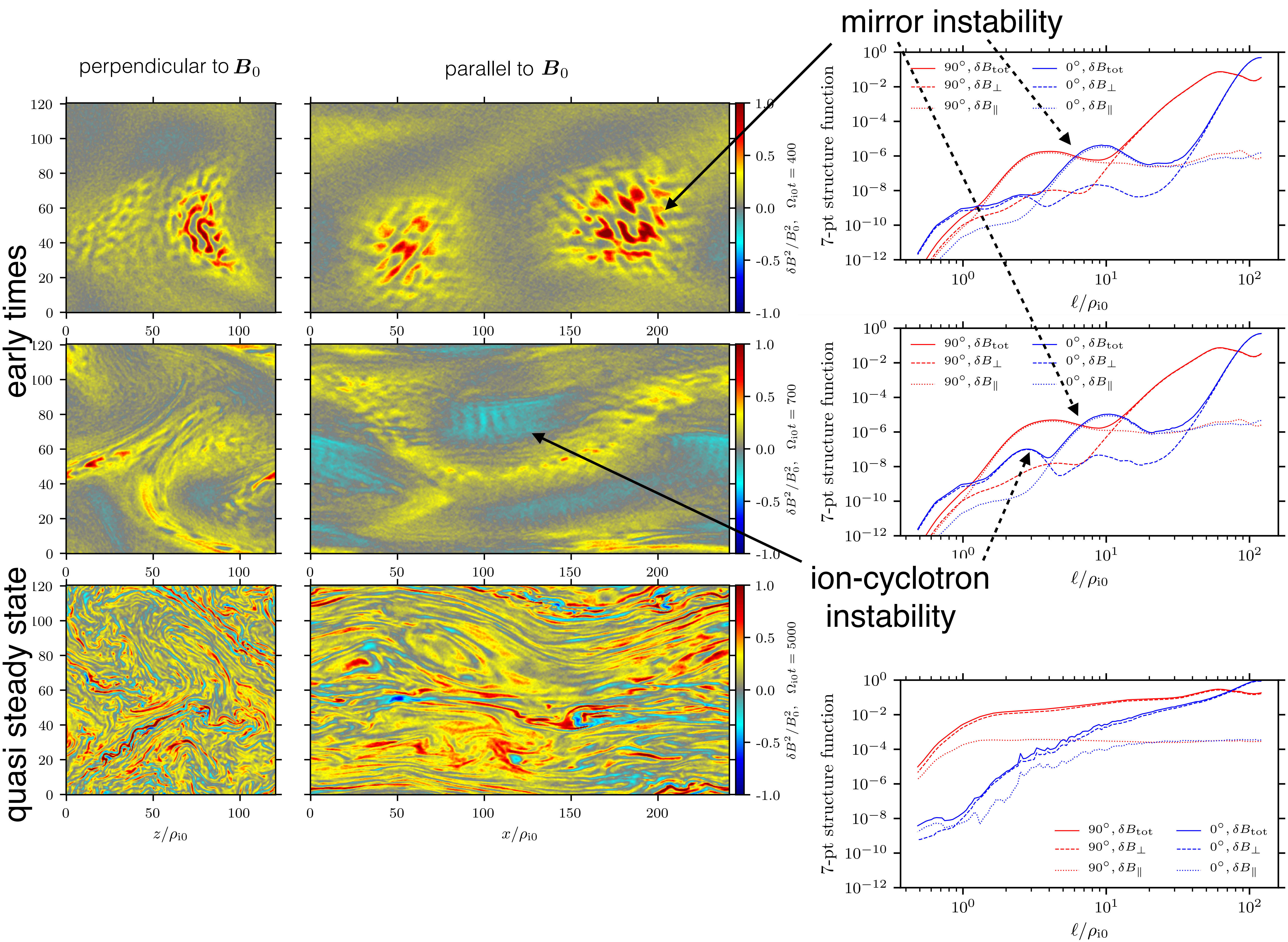
Moving to high beta

$\beta = 16$

perpendicular to $\boldsymbol{B}_0$ parallel to $\boldsymbol{B}_0$

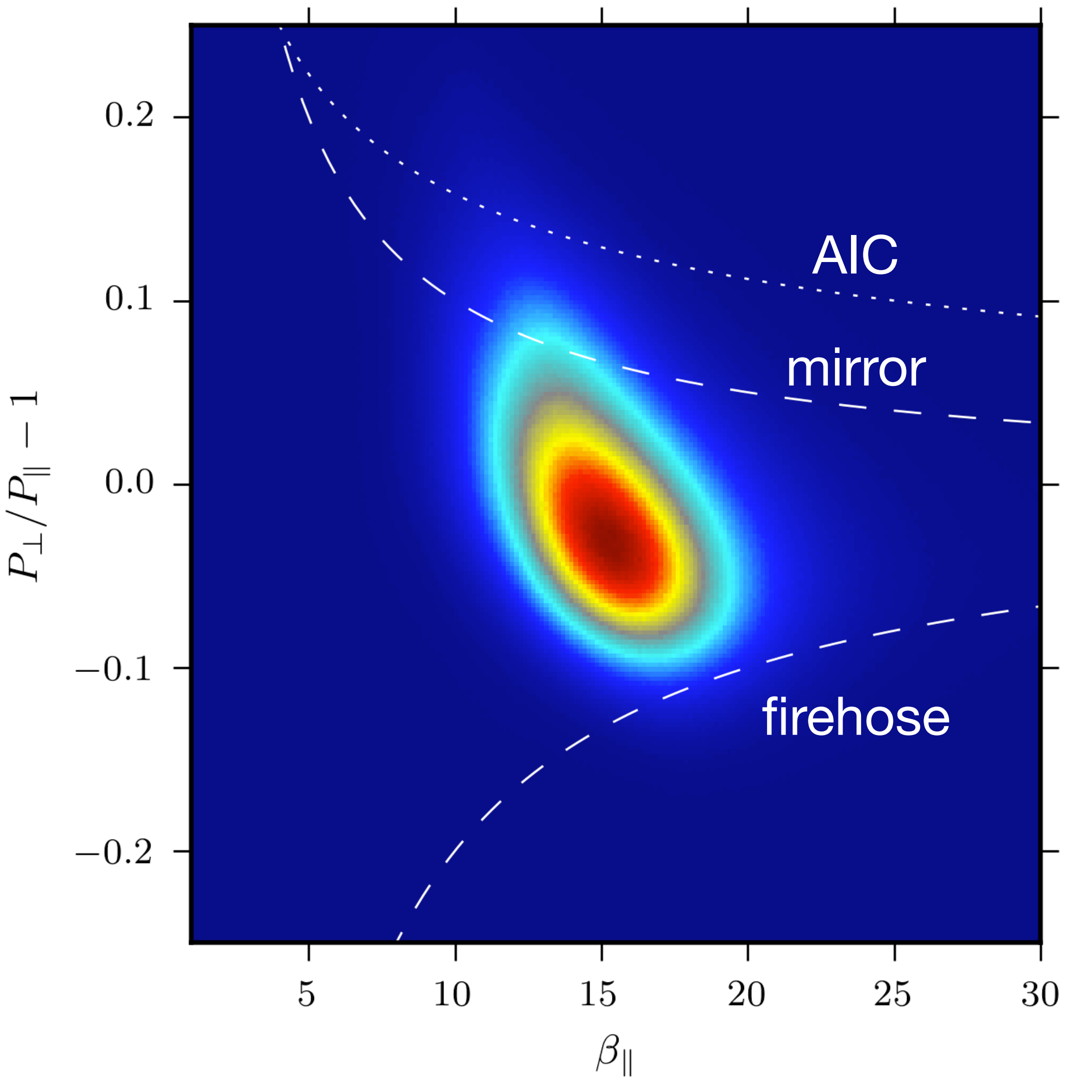


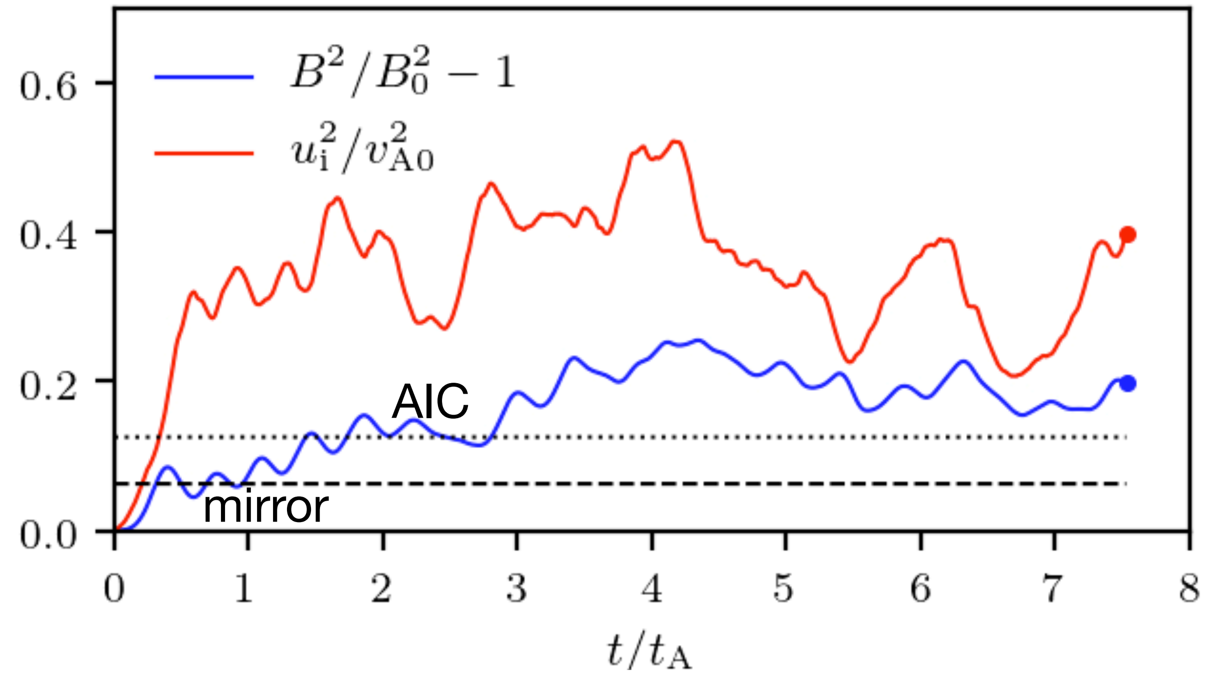
Arzamasskiy, Kunz, Squire, Quataert, Schekochihin, in preparation

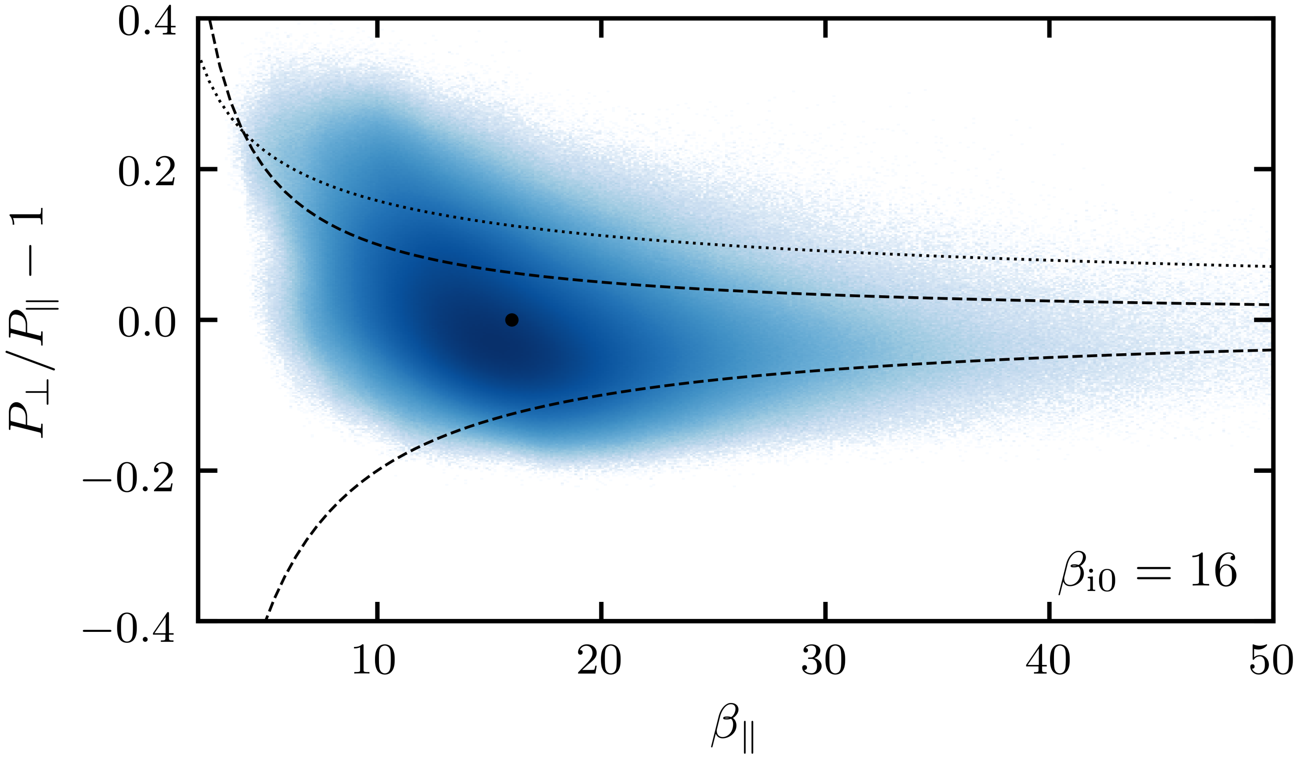


mirror instability
perpendicular to $\boldsymbol{B}_0$
parallel to $\boldsymbol{B}_0$
early times
quasi steady state
ion-cyclotron instability
$\delta B^2/B_0^2, \ \Omega_{\rm i0}t = 400$
$\delta B^2/B_0^2, \ \Omega_{\rm i0}t = 700$
$\delta B^2/B_0^2, \ \Omega_{\rm i0}t = 5000$
$z/\rho_{\rm i0}$
$x/\rho_{\rm i0}$
7-pt structure function
$\ell/\rho_{\rm i0}$
$90^\circ, \delta B_{\rm tot}$
$90^\circ, \delta B_\perp$
$90^\circ, \delta B_\parallel$
$0^\circ, \delta B_{\rm tot}$
$0^\circ, \delta B_\perp$
$0^\circ, \delta B_\parallel$

Pressure anisotropy

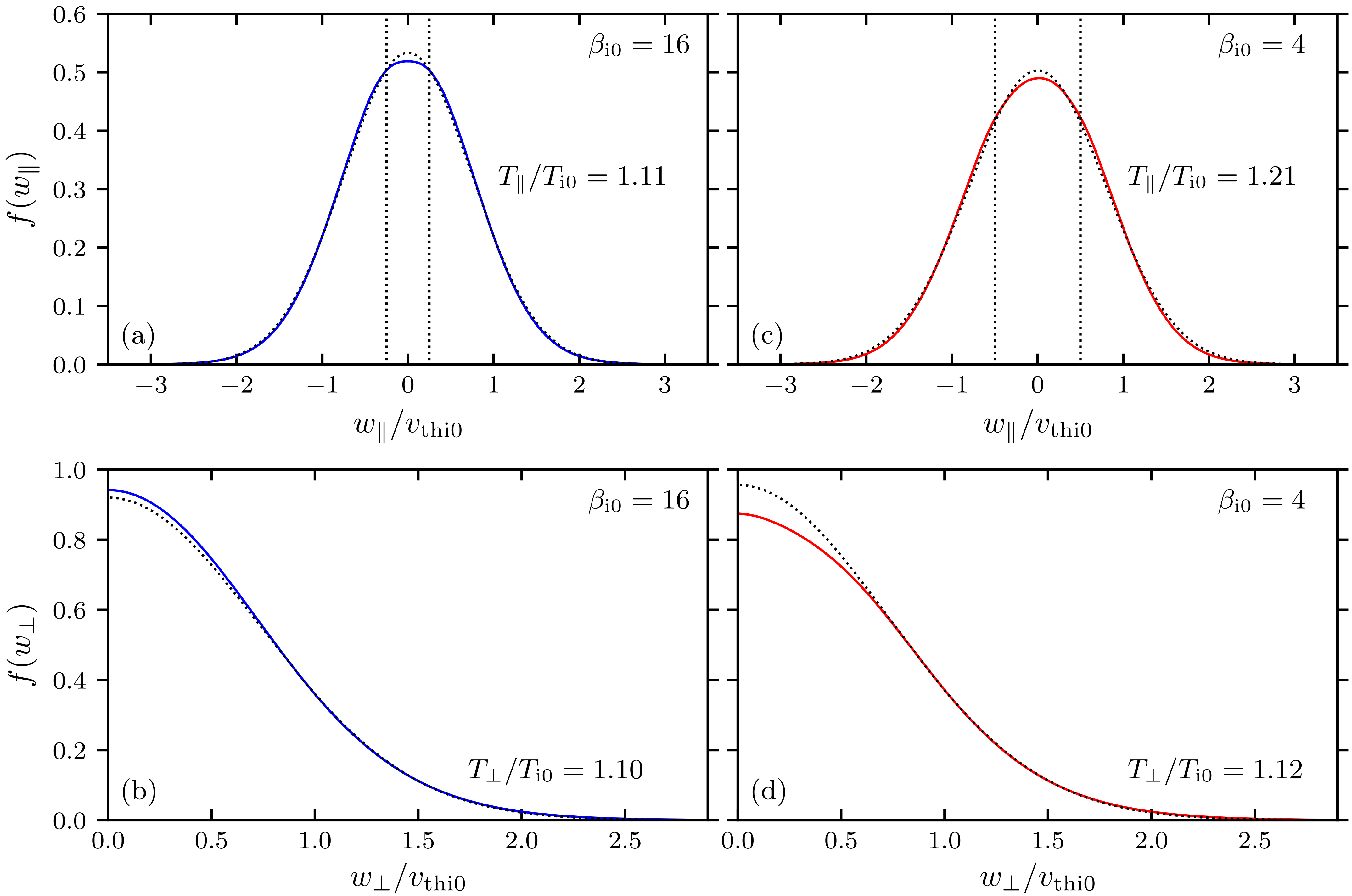






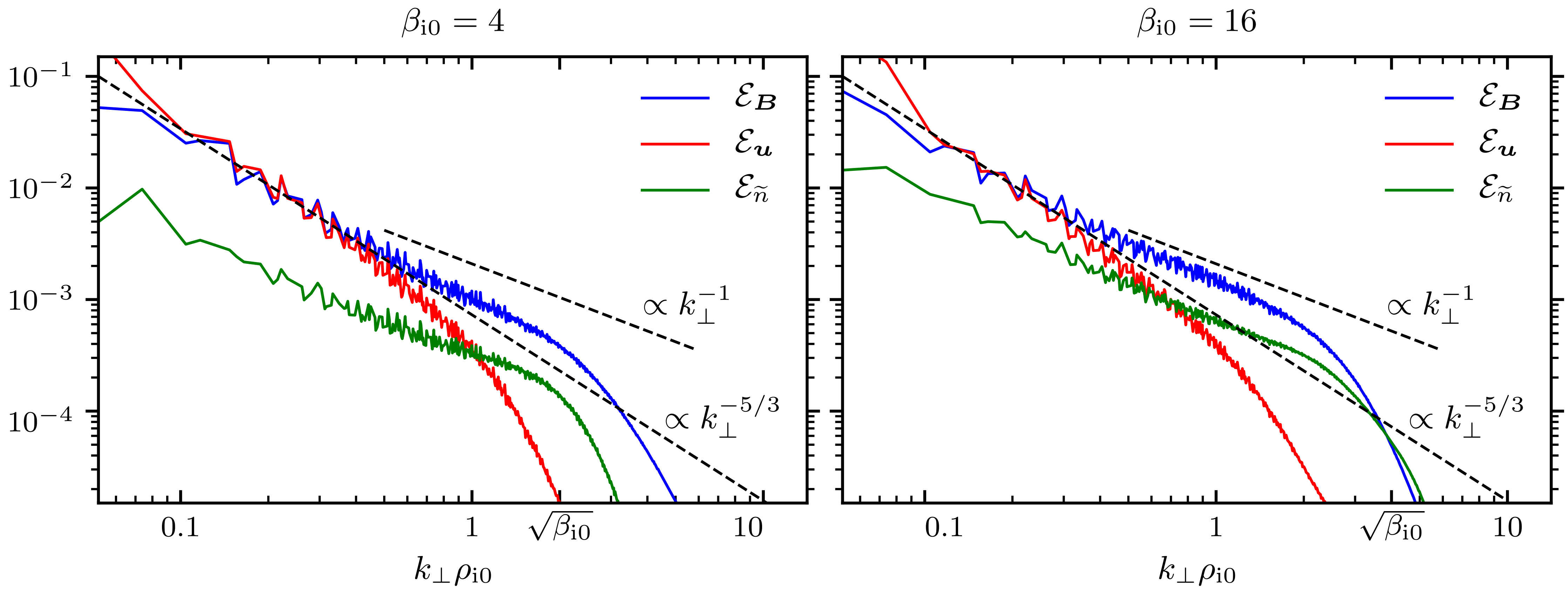
- Steady-state pressure anisotropy is bound between the instability thresholds
- Average pressure anisotropy is small, so effective viscosity is suppressed

Distribution function



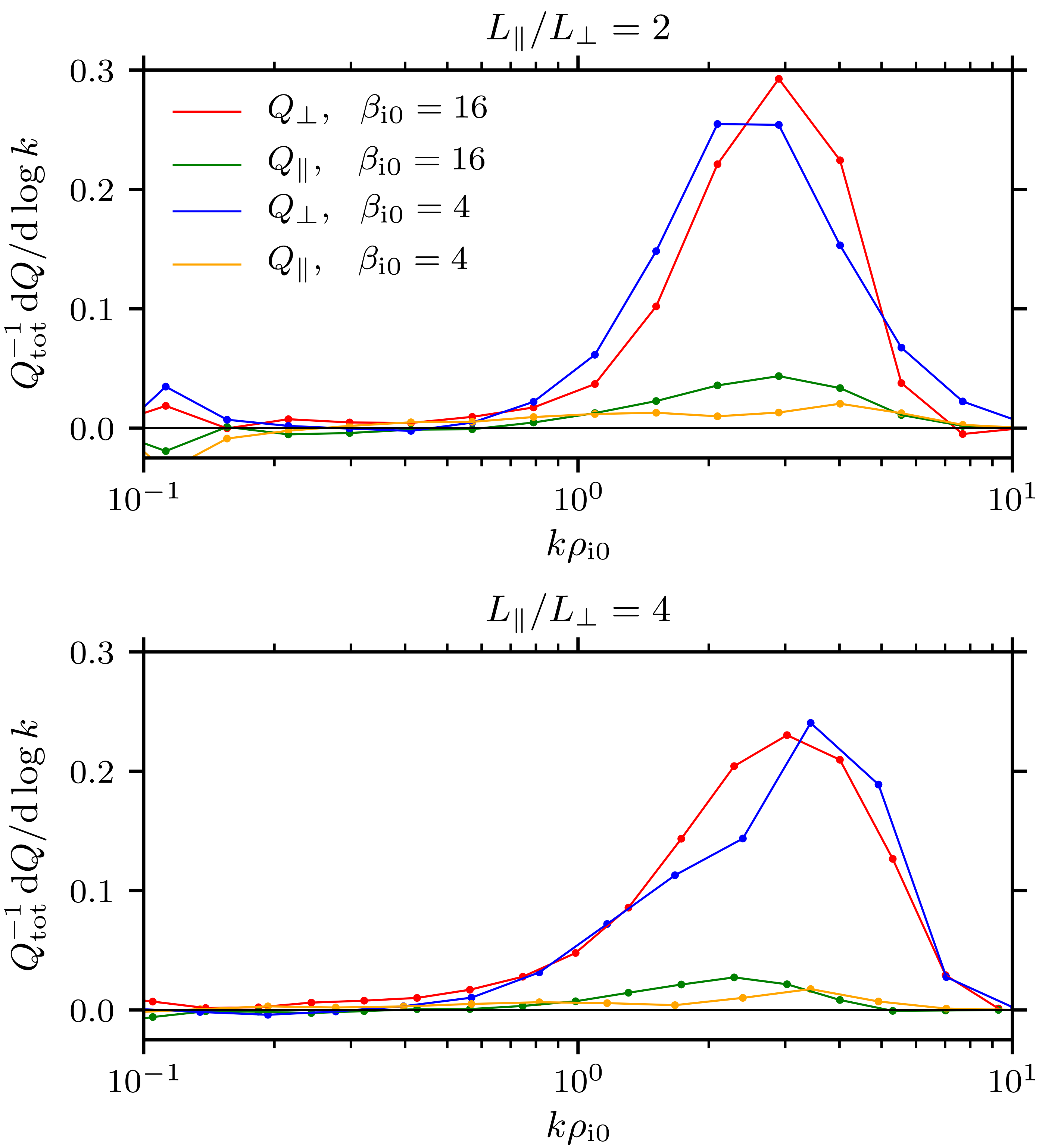
- final perpendicular and parallel temperatures are almost equal
- slightly flattened core in parallel distribution

Quasi-steady-state spectra

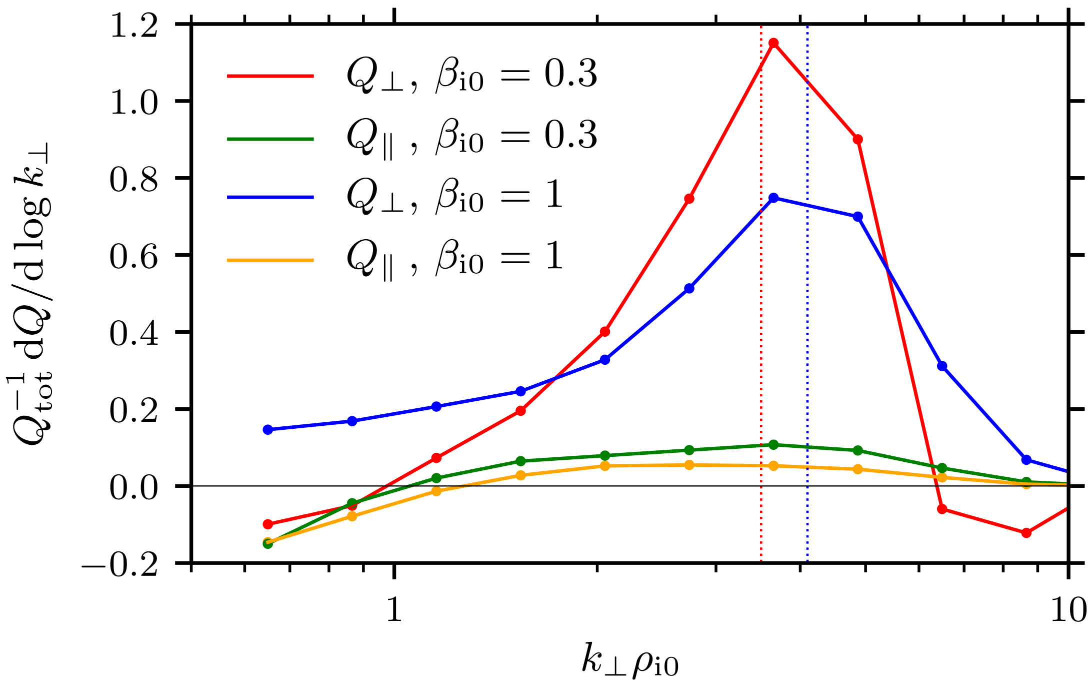


- beta-dependent break in inertial range, after which the kinetic spectrum steepens, magnetic spectrum becomes shallow
- scales below the break are affected by the viscous stress and it causes kinetic spectrum to steepen
- magnetic spectrum has a slope of -1 similar to sub-viscous MHD cascade (Cho, Vishniac & Lazarian 2002)

Ion heating



beta = 1 and 0.3 results for comparison



$$\frac{Q_{\rm i}}{Q_{\rm inj}} \sim 0.75 \qquad \frac{\langle \boldsymbol{E}_\perp \cdot \boldsymbol{v}_\perp \rangle}{\langle \boldsymbol{E}_\parallel \cdot \boldsymbol{v}_\parallel \rangle} \sim 9$$

Almost independent of beta in this range

Conclusions

- Ion heating in turbulence is caused primarily by field-particle interactions with high-frequency sub-ion-Larmor-scale fluctuations
- Ion energization is mostly perpendicular
- At low beta, distribution function develops flattened core via stochastic heating and non-thermal parallel tails via pitch-angle scattering from heated perpendicular distribution
- About 80% of the cascade energy is dissipated on ions
- At high beta, inertial-range Alfvén waves become unstable to kinetic microinstabilities
- Fluctuations produced by instabilities introduce an effective collisionality
- Pressure anisotropy is bound between instability thresholds with average value close to zero, so viscous stress is suppressed at large scales
- Below the break, magnetic spectrum has a shallow slope, close to -1, caused by the advection of instability-produced fluctuations by viscous-scale velocity (potentially observable in solar wind)
- Ion energization at high-beta is similar to low-beta, but is redistributed between parallel and perpendicular directions more effectively