Hybrid Kinetic Simulations of Driven Alfvénic Turbulence: spectral anisotropy, perpendicular ion heating and non-thermal features in distribution function

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Hybrid-PIC approach

PEGASUS (Kunz et al. 2014)

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

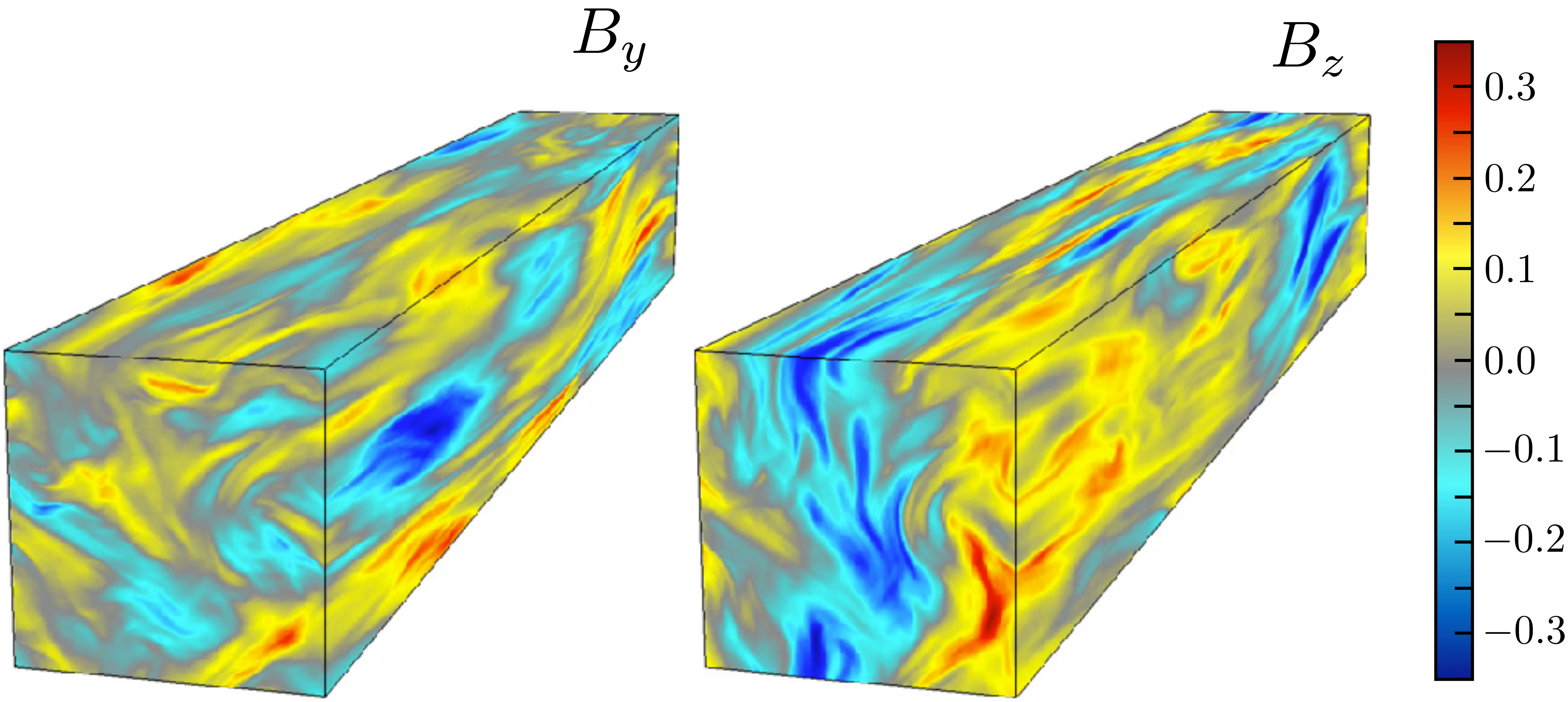
$$\boldsymbol{E} + \frac{\boldsymbol{u}_\mathrm{e}}{c} \times \boldsymbol{B} = -\frac{\nabla p_\mathrm{e}}{e n_\mathrm{e}} = -\frac{T_\mathrm{e} \nabla n_\mathrm{e}}{e n_\mathrm{e}}$$

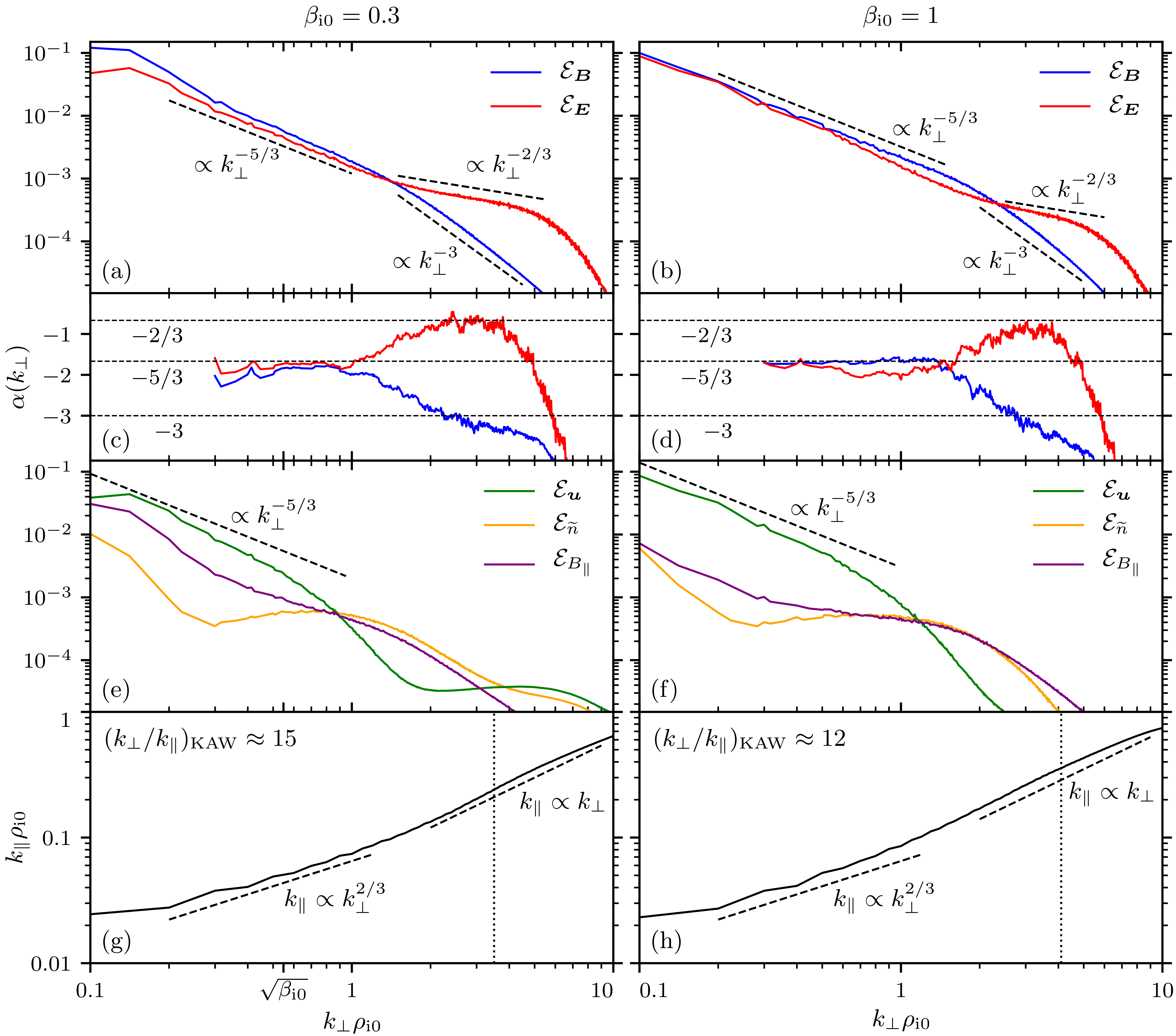
Driving on large scales — Ornstein–Uhlenbeck process

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

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

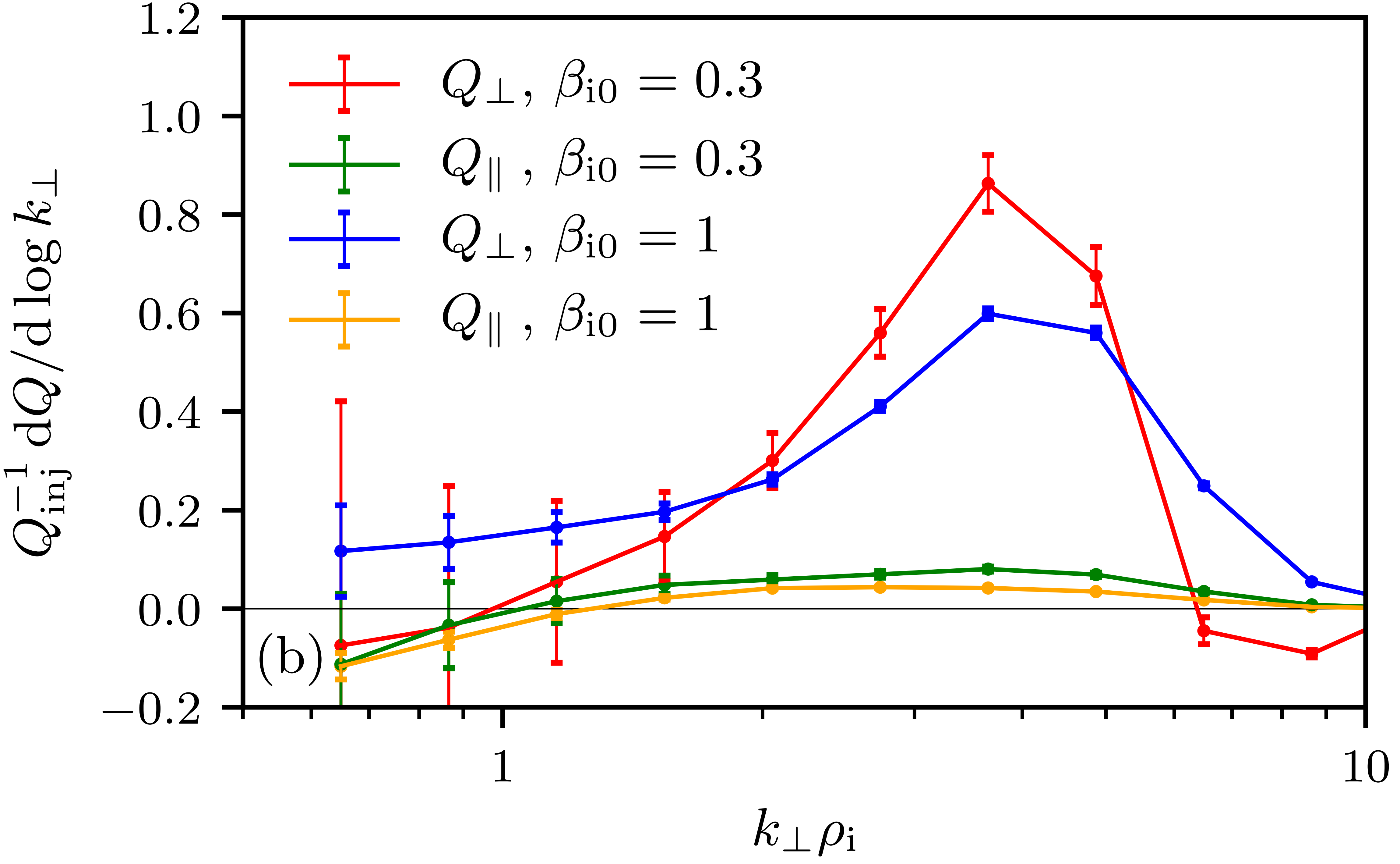
Quasi-Steady State



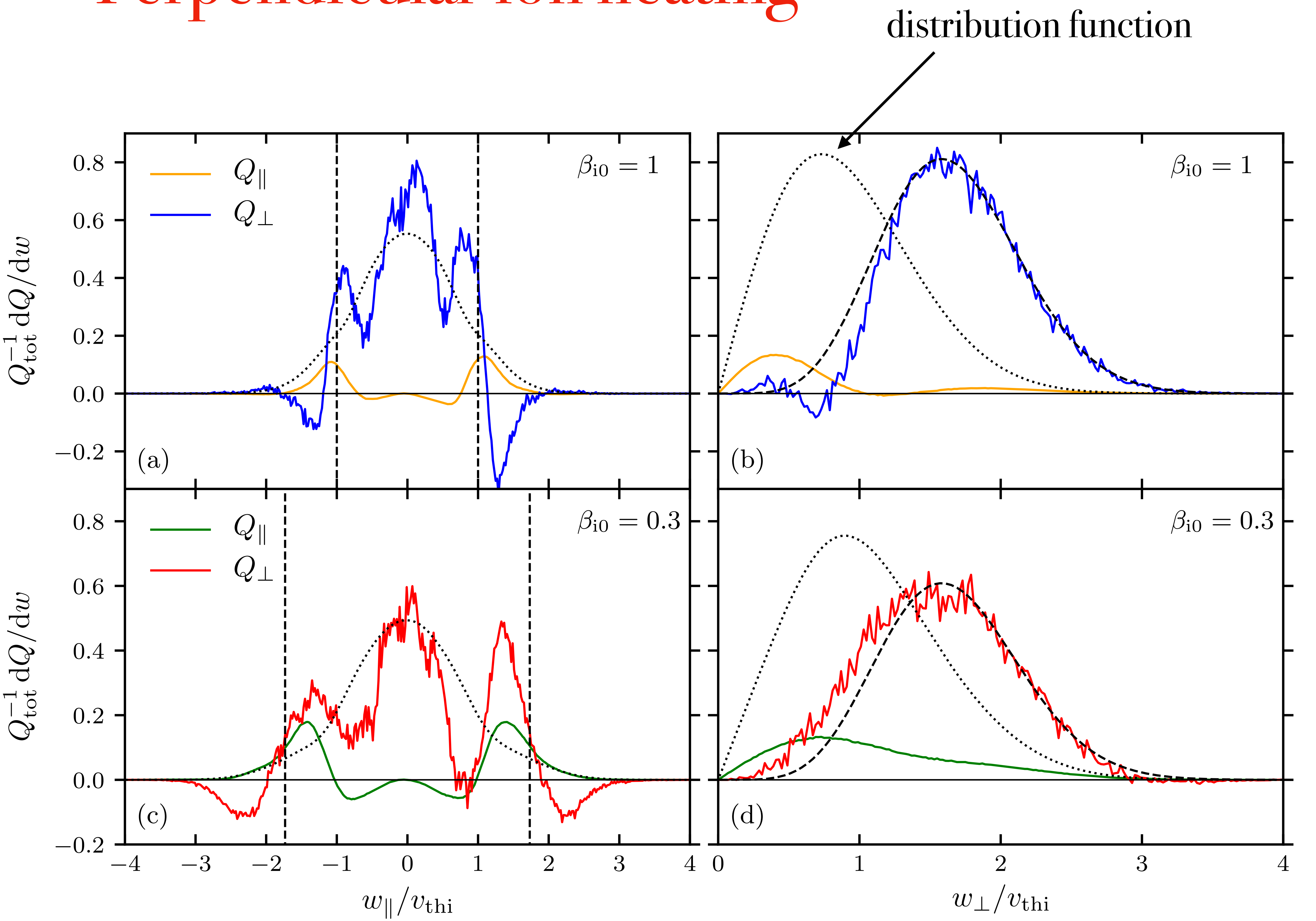


$\beta_{i0} = 0.3$
$\beta_{i0} = 1$
$\mathcal{E}_{\boldsymbol{B}}$
$\mathcal{E}_{\boldsymbol{E}}$
$\propto k_\perp^{-5/3}$
$\propto k_\perp^{-2/3}$
$\propto k_\perp^{-3}$
(a)
(b)
$\alpha(k_\perp)$
$-2/3$
$-5/3$
-3
(c)
(d)
$\mathcal{E}_{\boldsymbol{u}}$
$\mathcal{E}_{\tilde{n}}$
$\mathcal{E}_{B_\parallel}$
(e)
(f)
$(k_\perp/k_\parallel)_{\rm KAW} \approx 15$
$(k_\perp/k_\parallel)_{\rm KAW} \approx 12$
$k_\parallel \propto k_\perp$
$k_\parallel \propto k_\perp^{2/3}$
$k_\parallel \rho_{i0}$
(g)
(h)
$\sqrt{\beta_{i0}}$
$k_\perp \rho_{i0}$

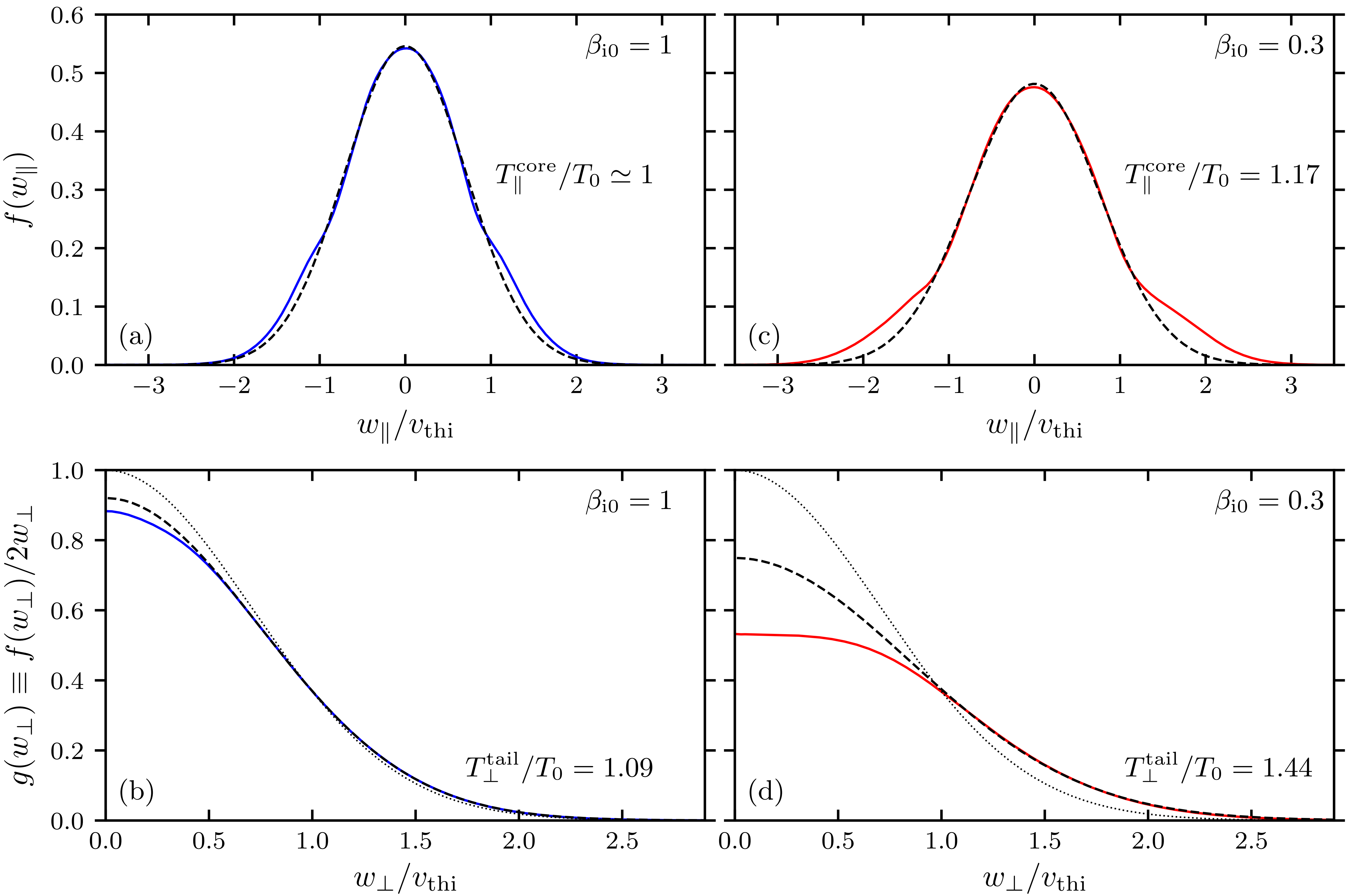
Perpendicular ion heating



Perpendicular ion heating

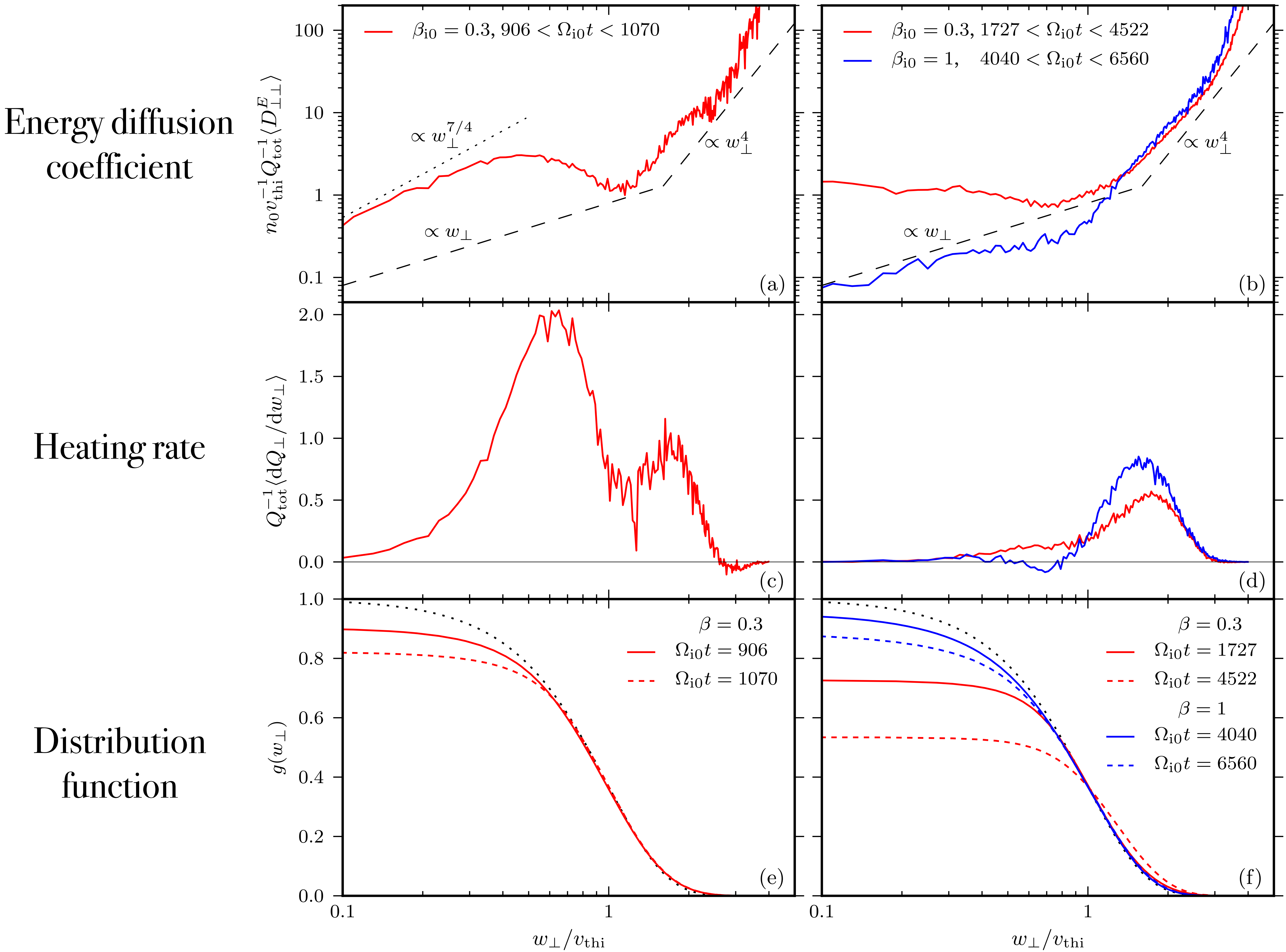


Distribution function



Potential heating mechanisms

- Landau damping
- Ion-cyclotron resonance
- Transit-time damping
- Low-frequency stochastic heating

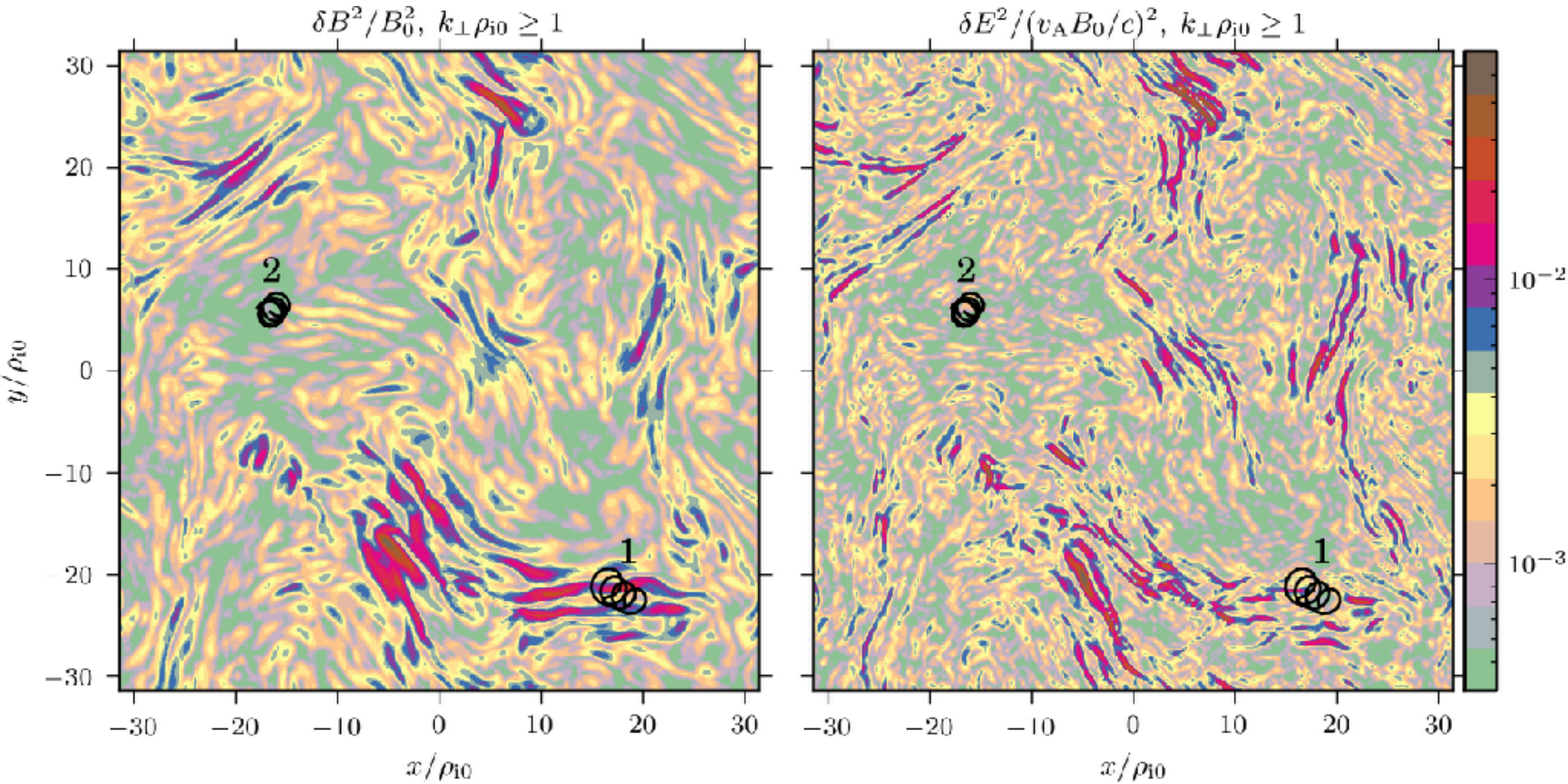


Energy diffusion coefficient
Heating rate
Distribution function
$n_0 v_{\rm thi}^{-1} Q_{\rm tot}^{-1} \langle D_{\perp\perp}^E \rangle$
$\beta_{\rm i0} = 0.3$, $906 < \Omega_{\rm i0} t < 1070$
$\propto w_\perp^{7/4}$
$\propto w_\perp$
$\propto w_\perp^4$
(a)
$\beta_{\rm i0} = 0.3$, $1727 < \Omega_{\rm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

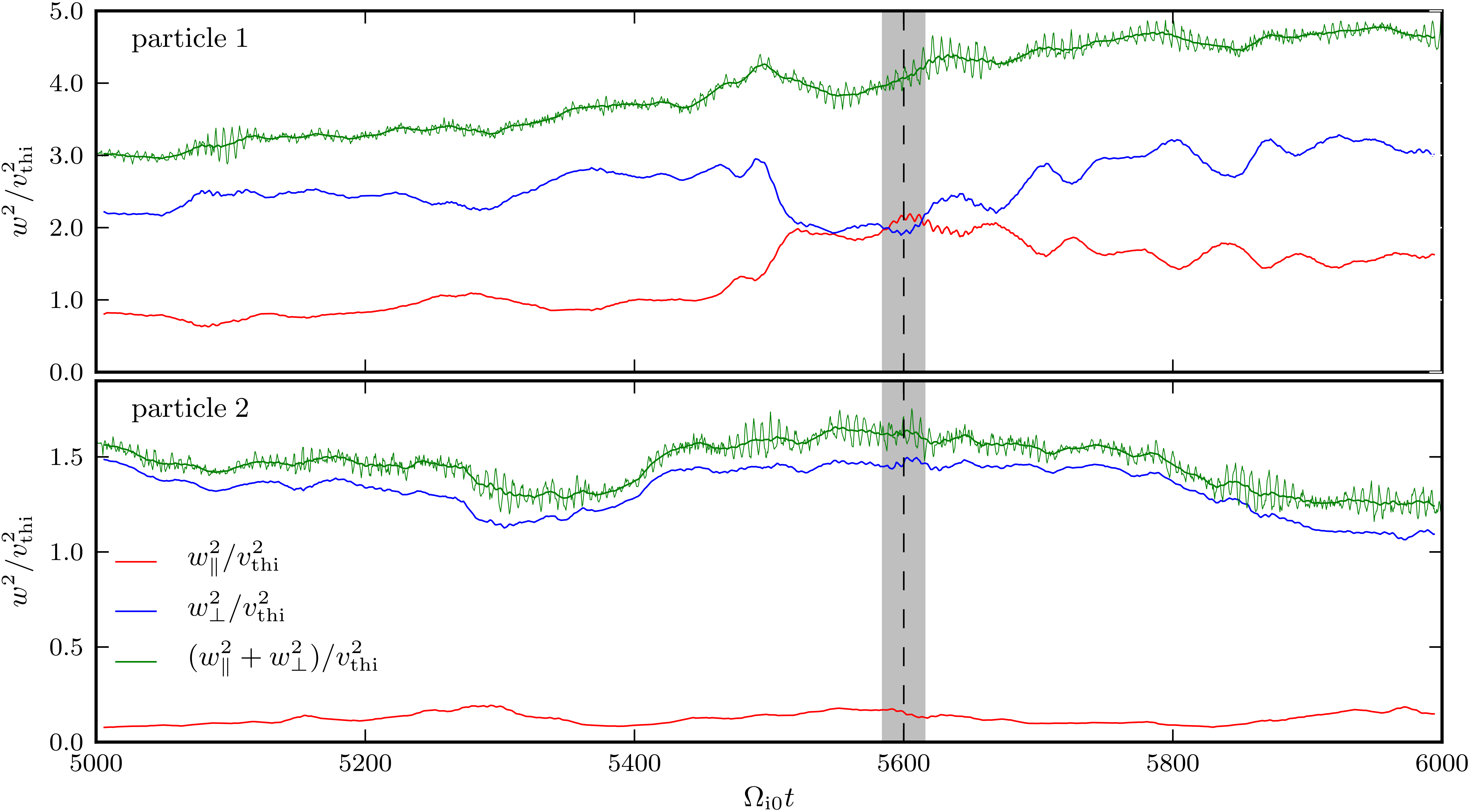
Particle orbits

small-scale B

small-scale E

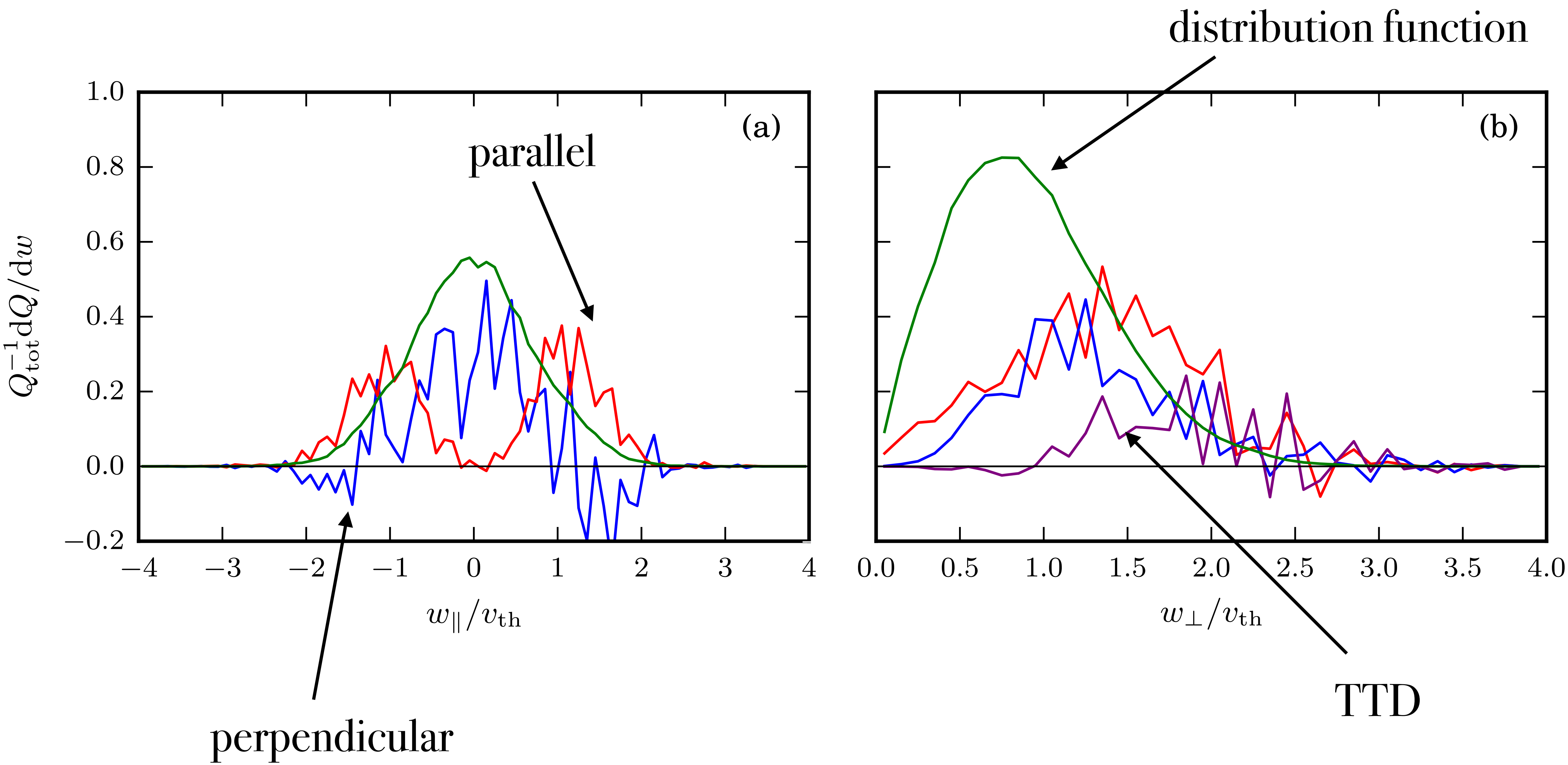


Particle orbits



Transit-time damping

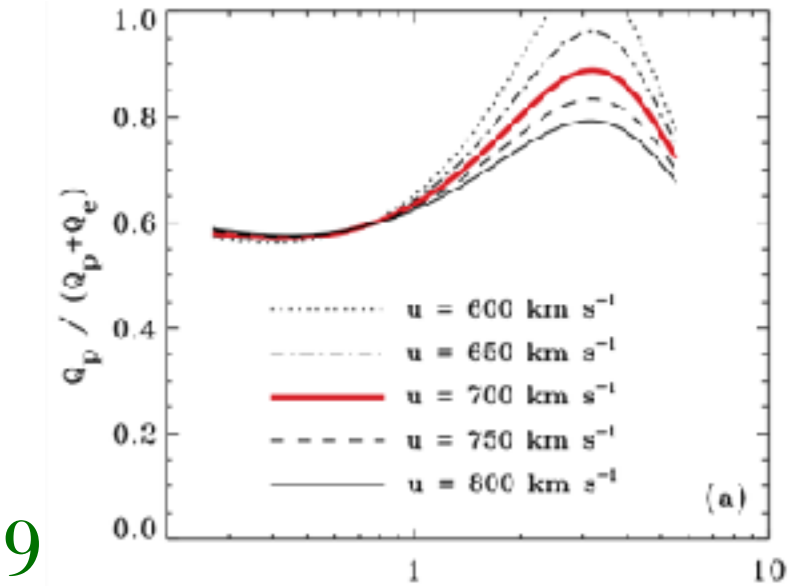
Energization of the small subset of particles



Potential heating mechanisms

- Landau damping – present, but not very strong
- Ion-cyclotron resonance – does not have the right scaling with particle velocity
- Transit-time damping – present, subdominant
- Low-frequency stochastic heating – important during early stages of the simulation
- Stochastic energization by high-frequency intermittent fluctuations (KAWs?)

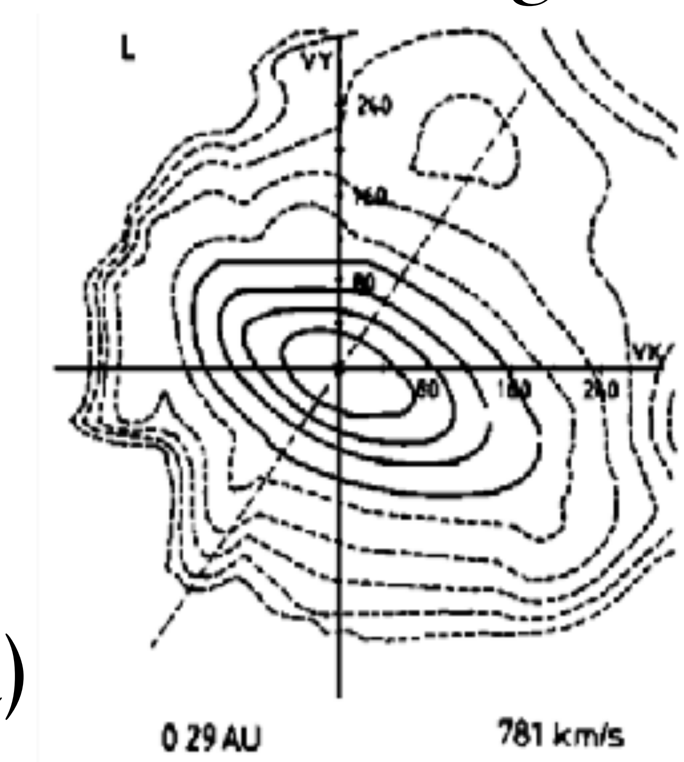
Summary



- For both values of beta most of the cascade energy (around 75-80%) goes into ions (observed value is 60-80%)

Cranmer et al. 2009

- Ion heating is mostly perpendicular (consistent with observations)
- Perpendicular distribution function develops a flattened core, consistent with predictions from low-frequency stochastic heating (Klein & Chandran 2016)
- Parallel distribution function has non-thermal tails because of pitch-angle scattering
- Heating peaks at sub-ion-Larmor scales and increases with particle velocity (no good theory yet)



Marsch et al. 1992