



UK Atomic
Energy
Authority

Transition to high-transport states in MTM turbulence

— — Yujia Zhang



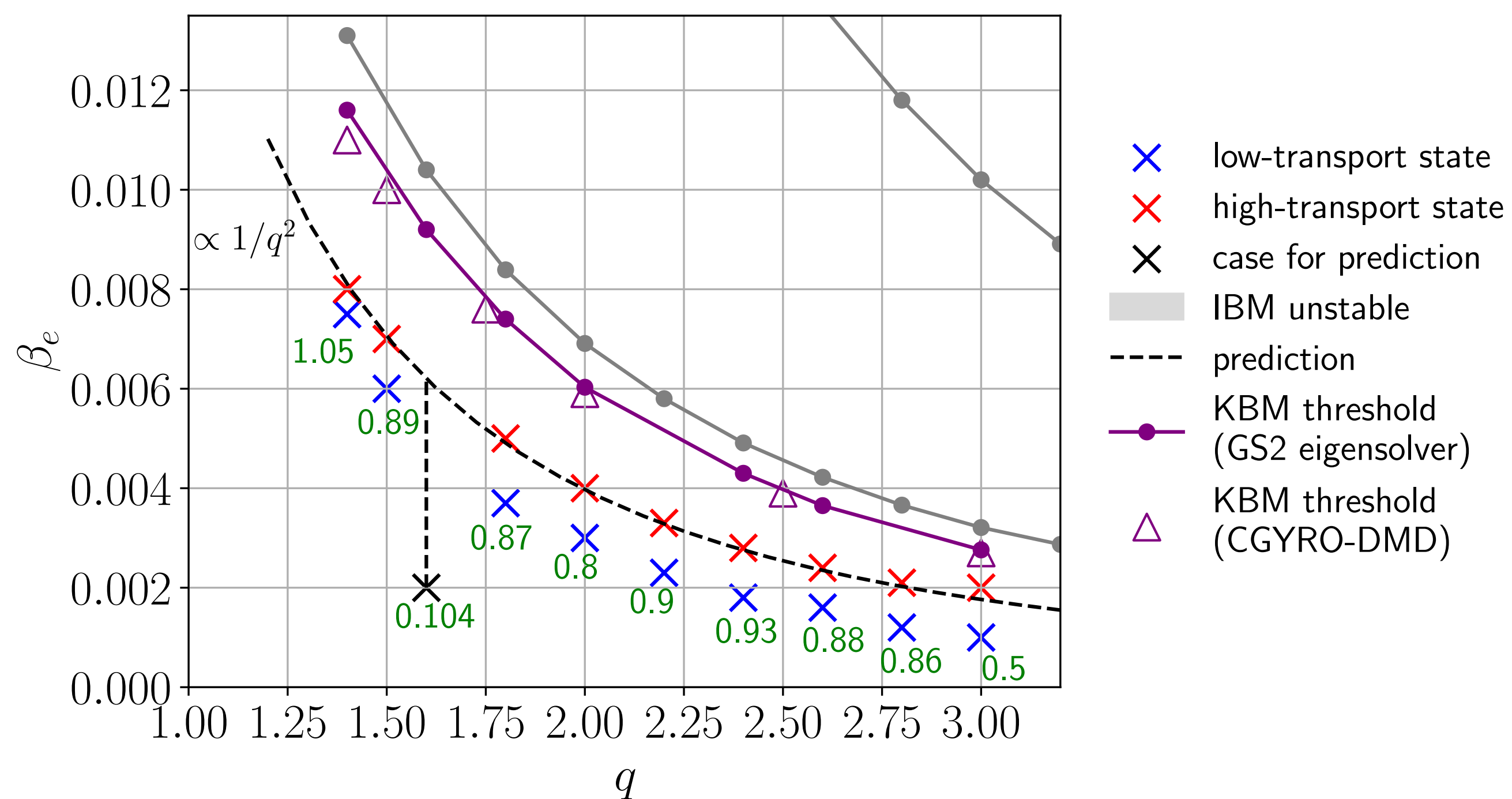
Background: Non-zonal transition

- Non-zonal transitions are known to occur in finite-beta ITG turbulence
- The turbulence transitions from low- to high-transport states once it becomes sufficiently electromagnetic (even in the absence of electromagnetic instabilities).



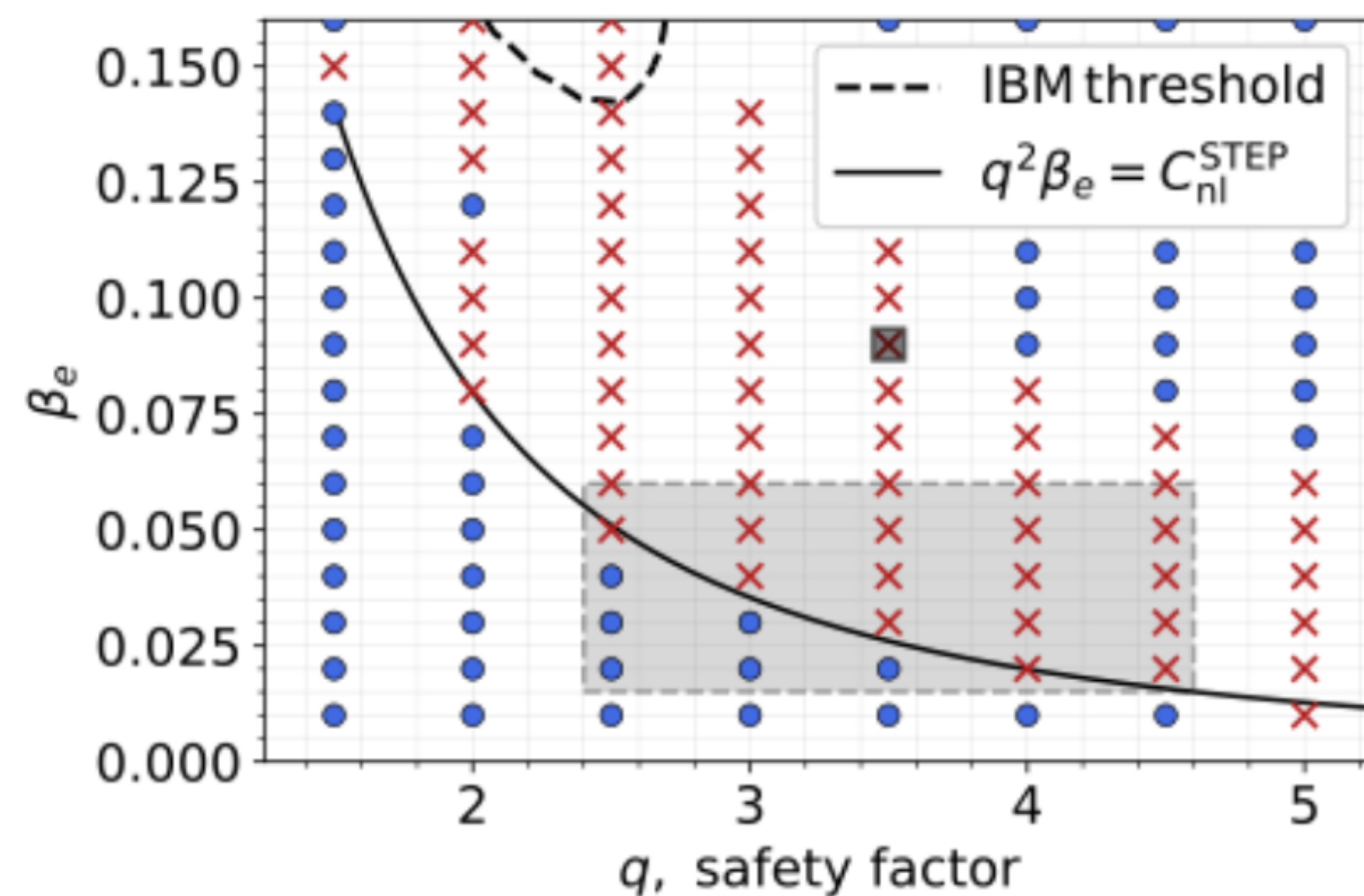
Background: Non-zonal transition

CBC



Y. Zhang et al., 2026

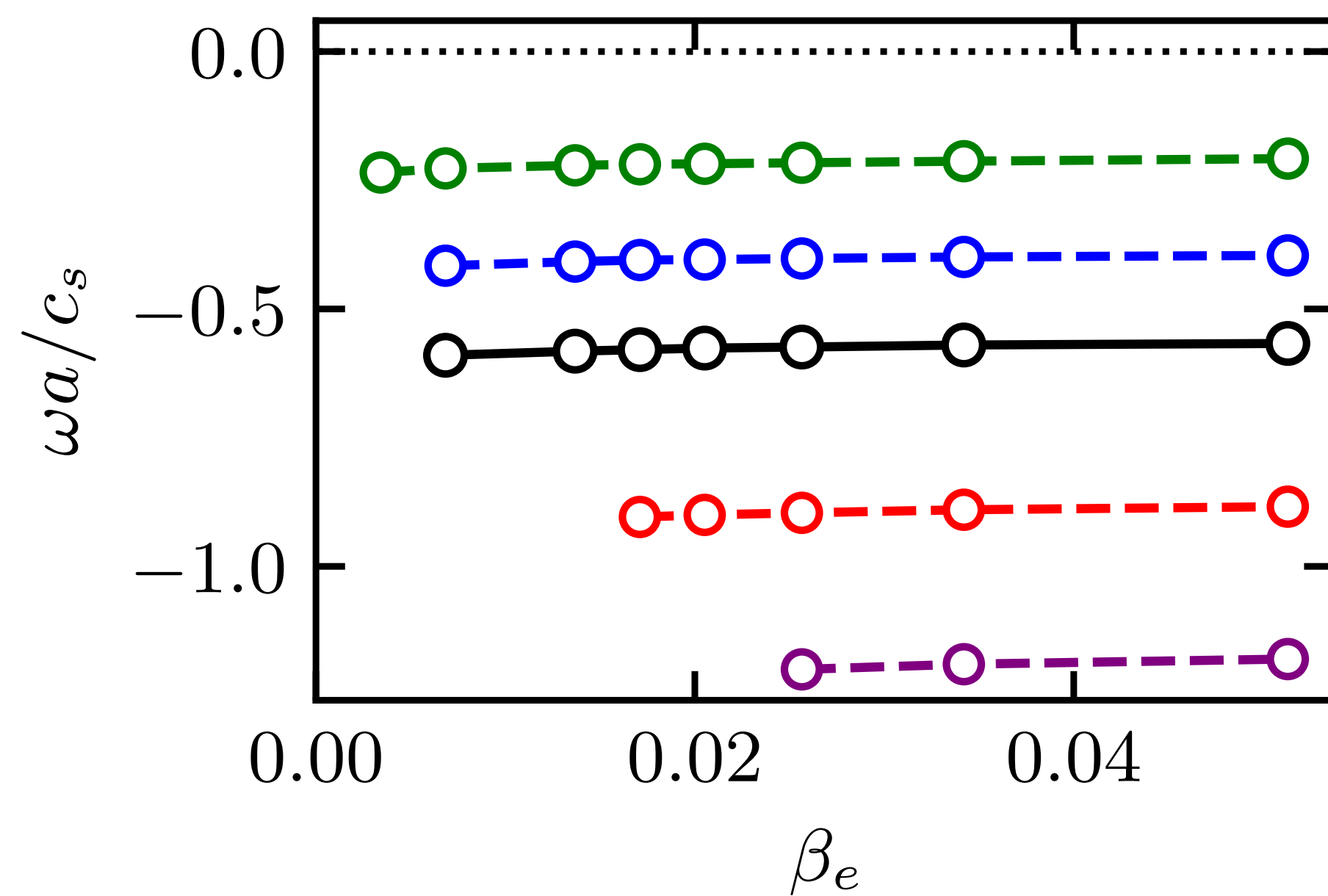
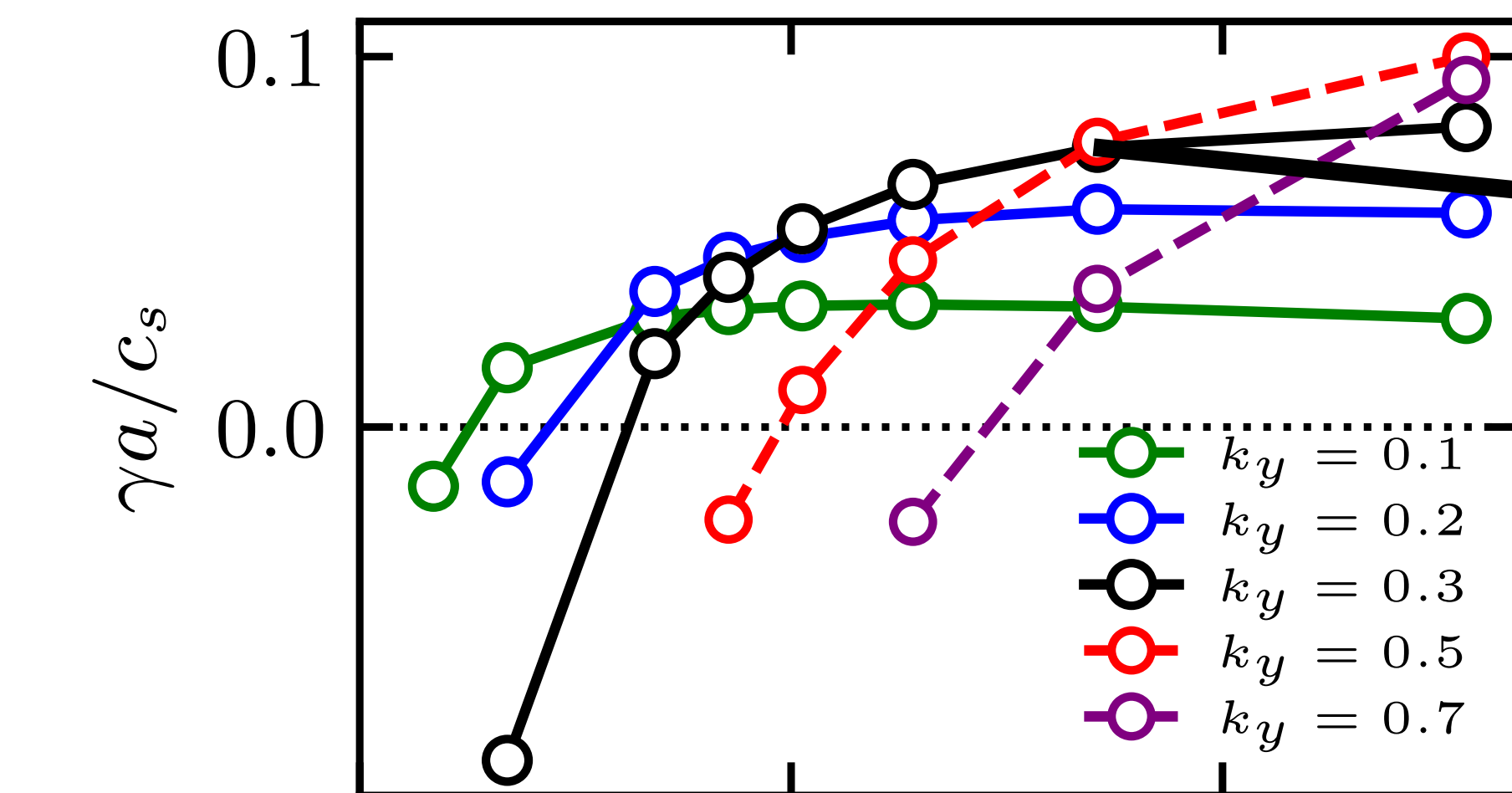
STEP



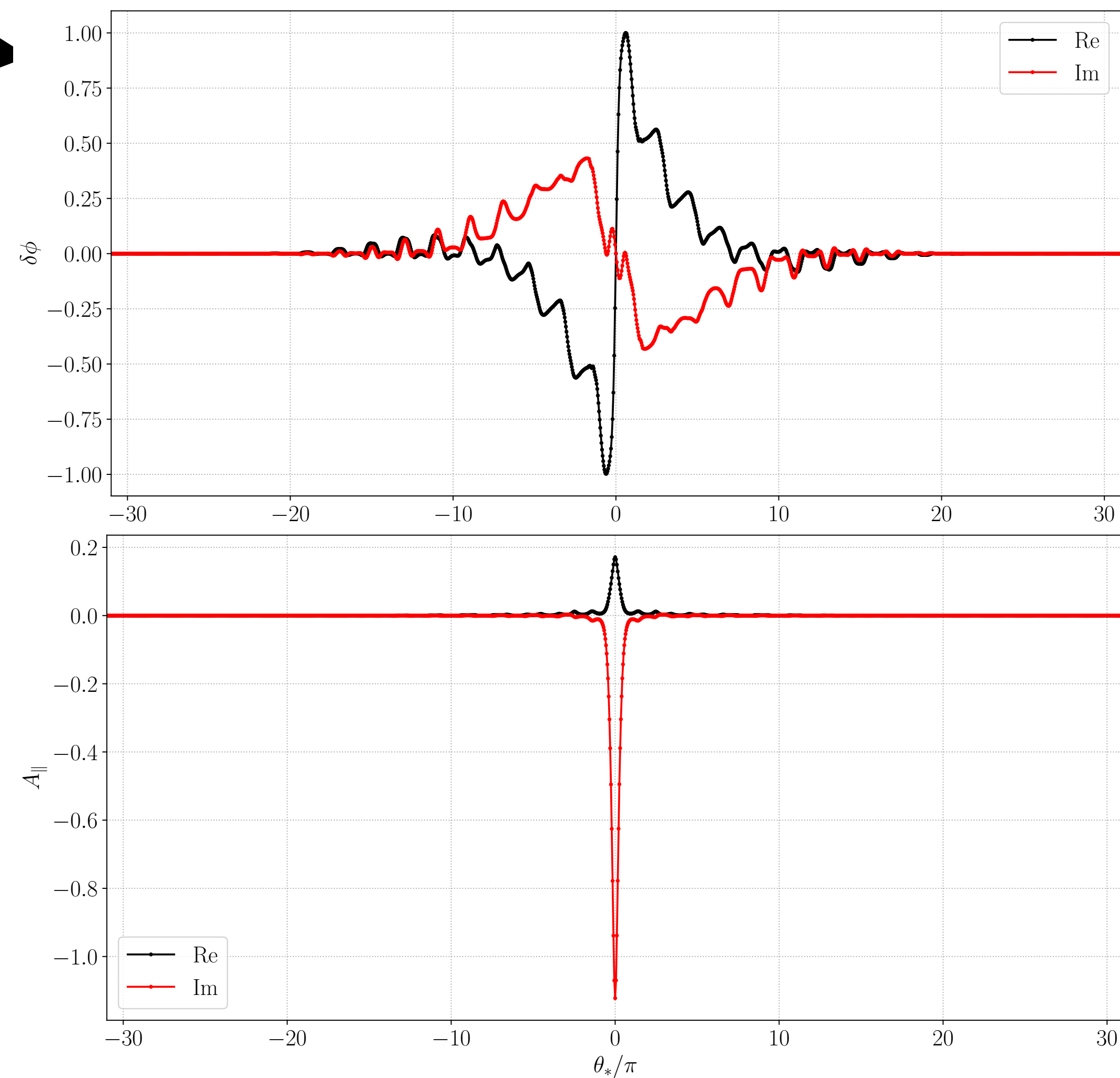
D. Kennedy et al., 2026



Transition in MTM turbulence?



$A_{||}$ retained





Thermal force

A. B. Hassam, 1979

Chapman-Enskog expansion
of the electron FP equation.

$$\frac{\partial n}{\partial t} + \nabla \cdot n \mathbf{u} = 0, \quad (2a)$$

$$\begin{aligned} \alpha'' \left(\frac{\nu_e}{n} \right) \frac{\partial}{\partial t} \left(\frac{n m u_{\parallel}}{(\nu_e/n)} \right) = & -n e E_{\parallel} - \nabla_{\parallel} p_e - \alpha n \nabla_{\parallel} T_e \\ & - (n e)^2 \eta u_{\parallel} + \alpha \alpha' \frac{\nu_e}{n} \frac{\partial}{\partial t} \left(\frac{n}{\nu_e} \frac{n \nabla_{\parallel} T_e}{\nu_e} \right), \end{aligned} \quad (2b)$$

$$\begin{aligned} \frac{3}{2} n \left(\frac{\partial T_e}{\partial t} + \mathbf{u} \cdot \nabla T_e \right) + n T_e \nabla \cdot \mathbf{u} \\ = -\nabla \cdot \mathbf{q}_{\parallel} - \nabla \cdot \mathbf{q}_D + \mathbf{u}_{\parallel} \cdot [\alpha n \nabla_{\parallel} T + (n e)^2 \eta \mathbf{u}_{\parallel}], \end{aligned} \quad (2c)$$

$$\mathbf{q}_{\parallel} \equiv -\kappa_{\parallel} \nabla_{\parallel} T_e + \alpha n T_e \mathbf{u}_{\parallel}, \quad (2d)$$

$$\mathbf{q}_D \equiv - (5/2) (n T_e / e B) \hat{\mathbf{b}} \times \nabla T_e, \quad (2e)$$

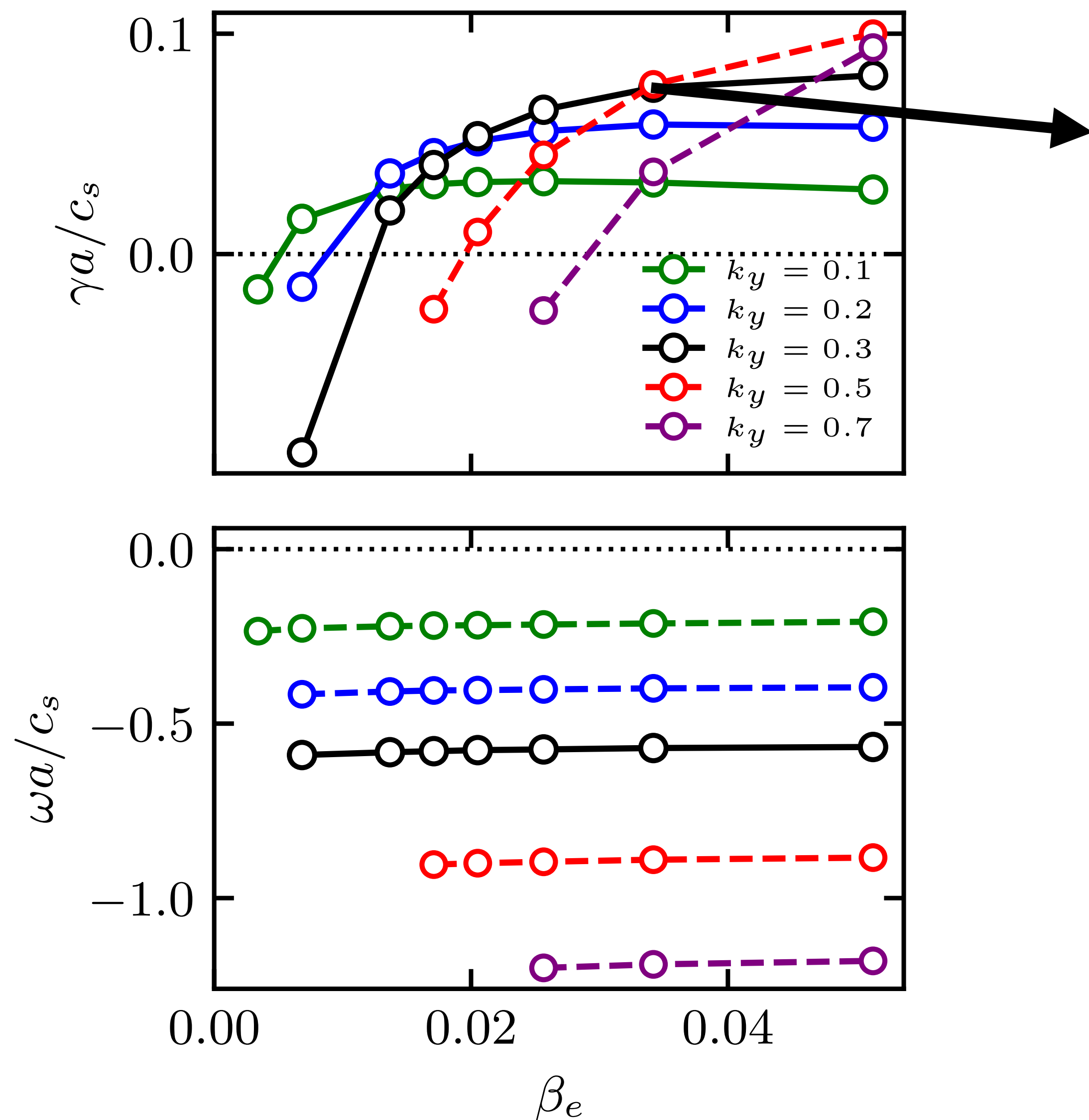
$$\mathbf{u}_{\perp} = \mathbf{E} \times \hat{\mathbf{b}} / B - \hat{\mathbf{b}} \times \nabla p_e / n e B, \quad (2f)$$

$$\alpha'' \frac{\partial}{\partial t} (n m u_{\parallel})$$

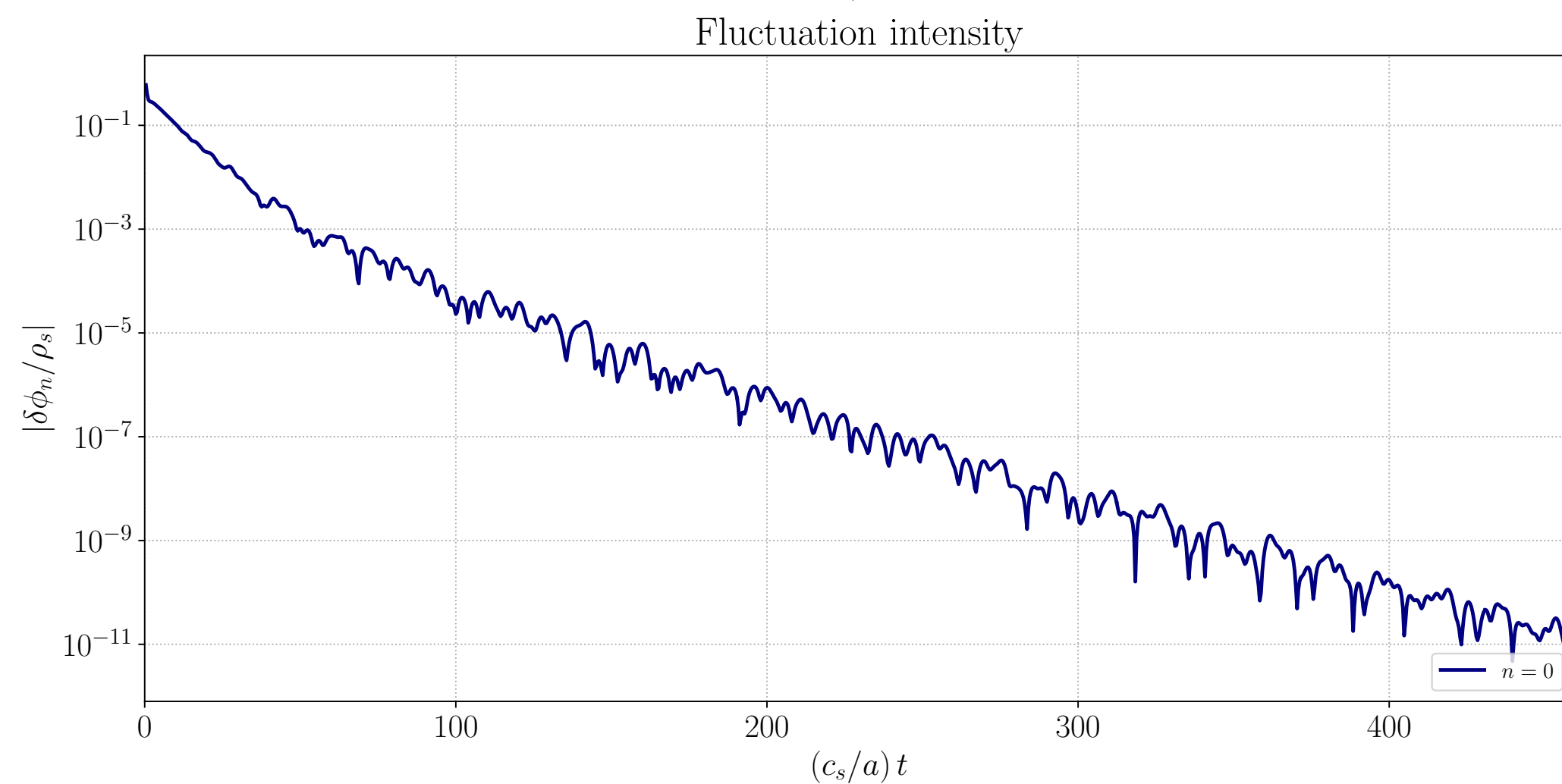
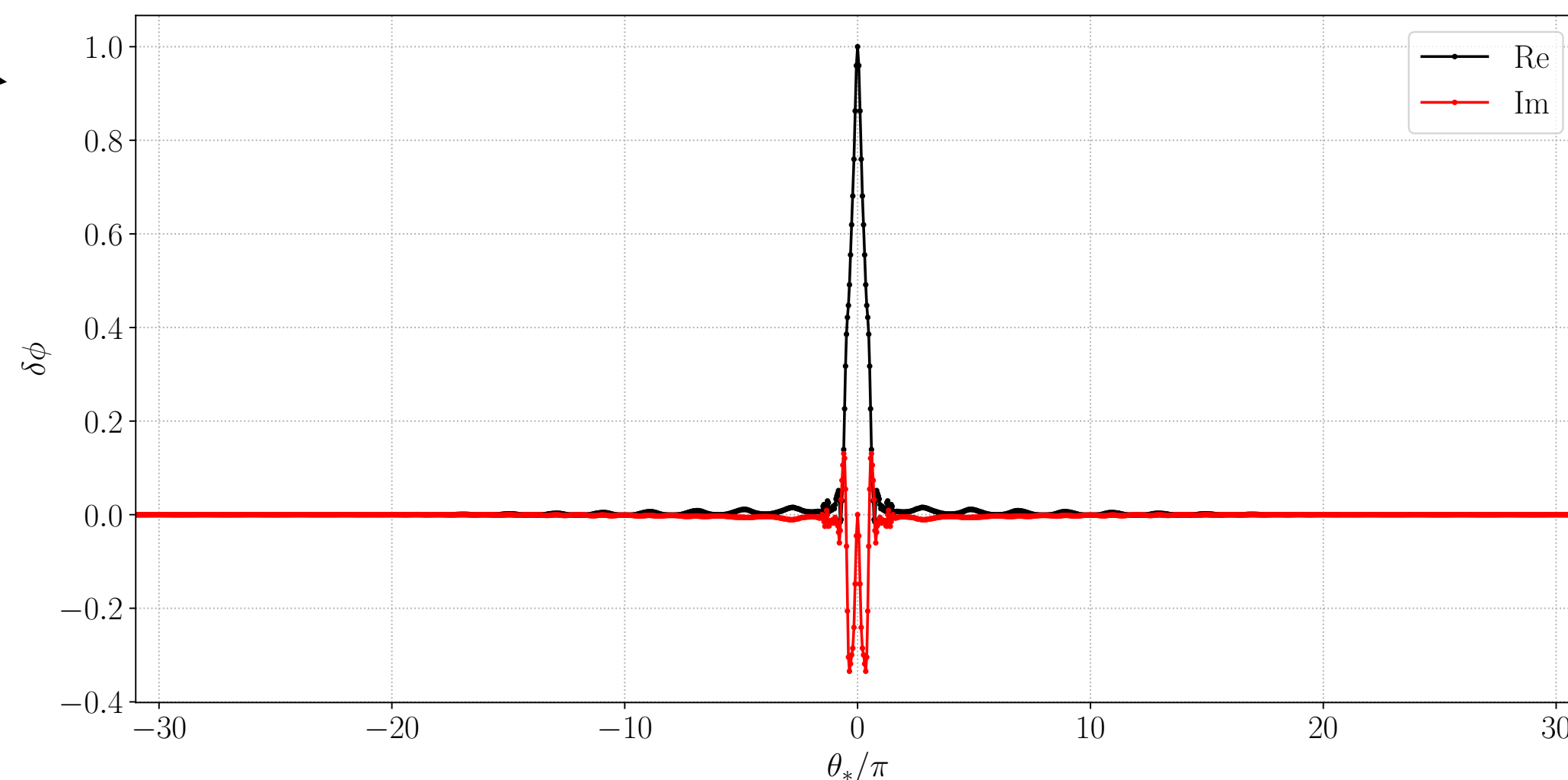
$$\begin{aligned} = & -n e E_{\parallel} - \nabla_{\parallel} p_e - (n e)^2 \eta u_{\parallel} \left[1 + \frac{3}{2} \alpha'' \left(\frac{m}{\eta n e^2} \right) \frac{\partial}{\partial t} \ln T_e \right] \\ & - \alpha n \nabla_{\parallel} T_e \left(1 - \frac{3 \alpha'}{\nu_e} \frac{\partial}{\partial t} \ln T_e - \frac{\alpha'}{\nu_e} \frac{\partial}{\partial t} \ln(\nabla_{\parallel} T_e) \right). \end{aligned}$$



Transition in MTM turbulence?

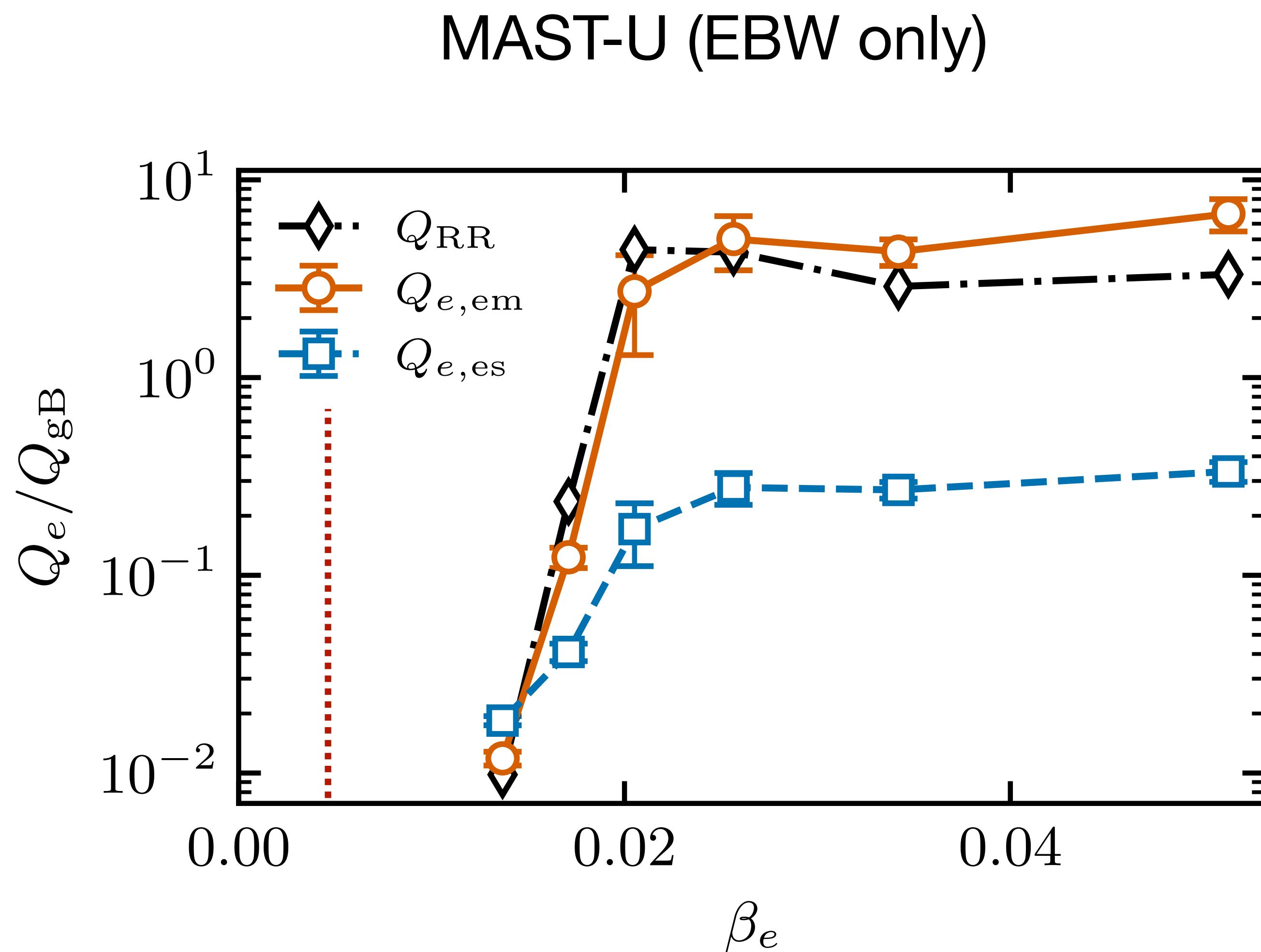
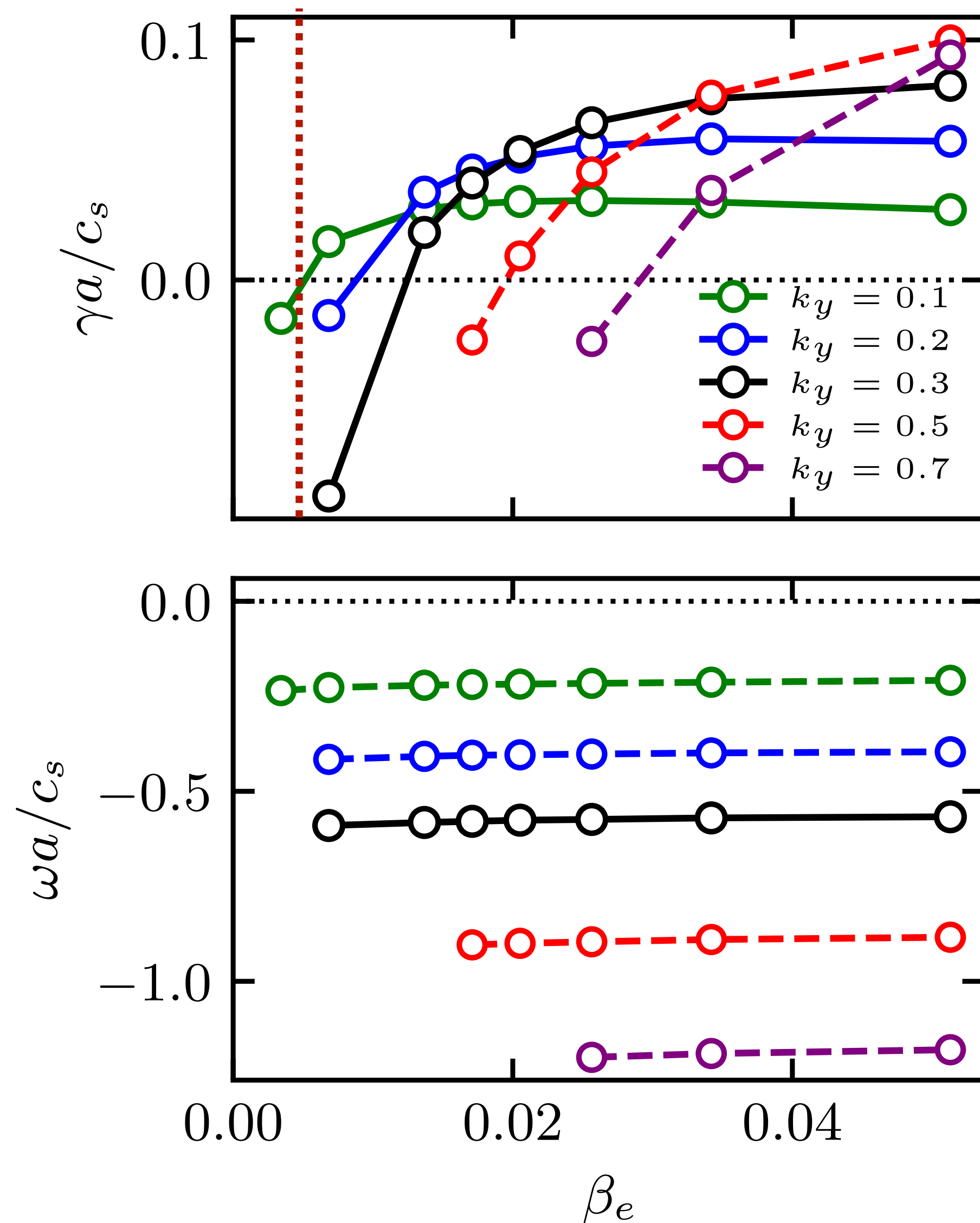


$A_{||}$ turned off



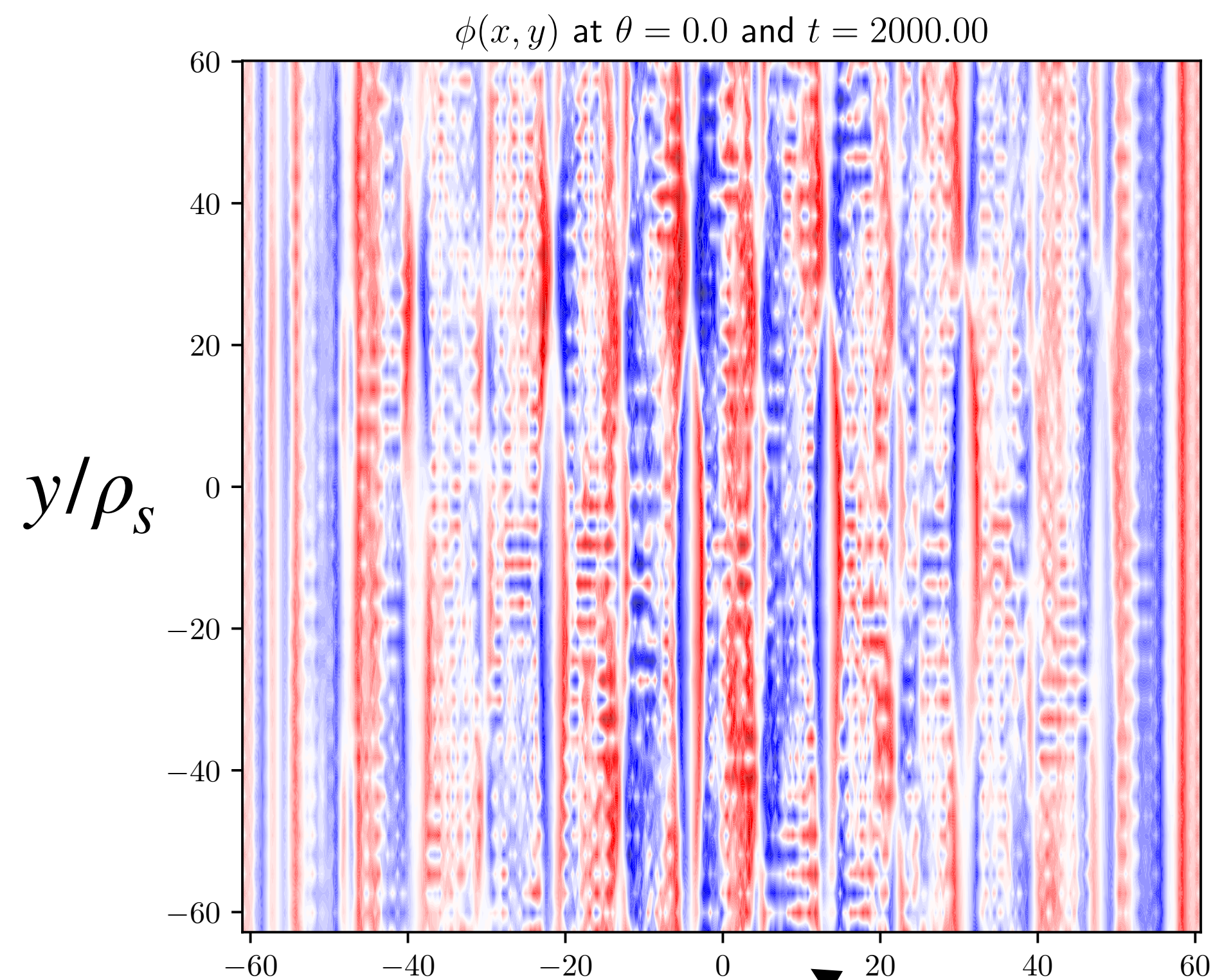


Transition in MTM turbulence?

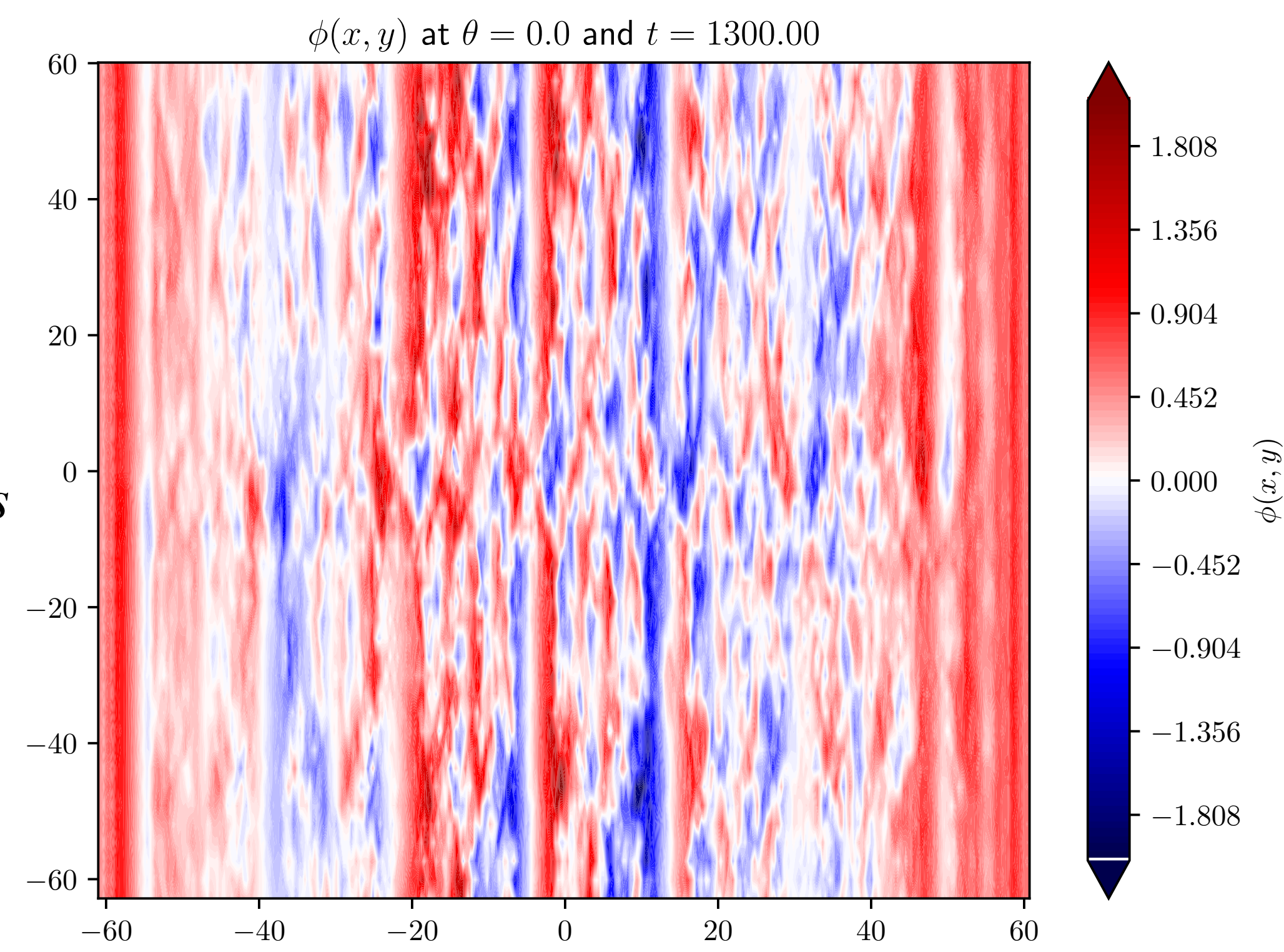




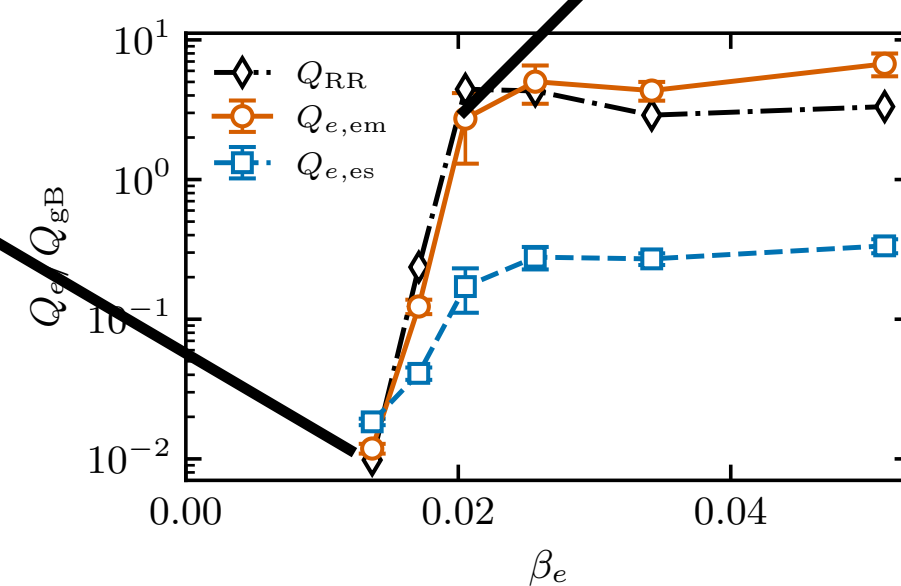
Snapshots of ϕ (out-board mid-plane)



$\beta_e = 0.014$

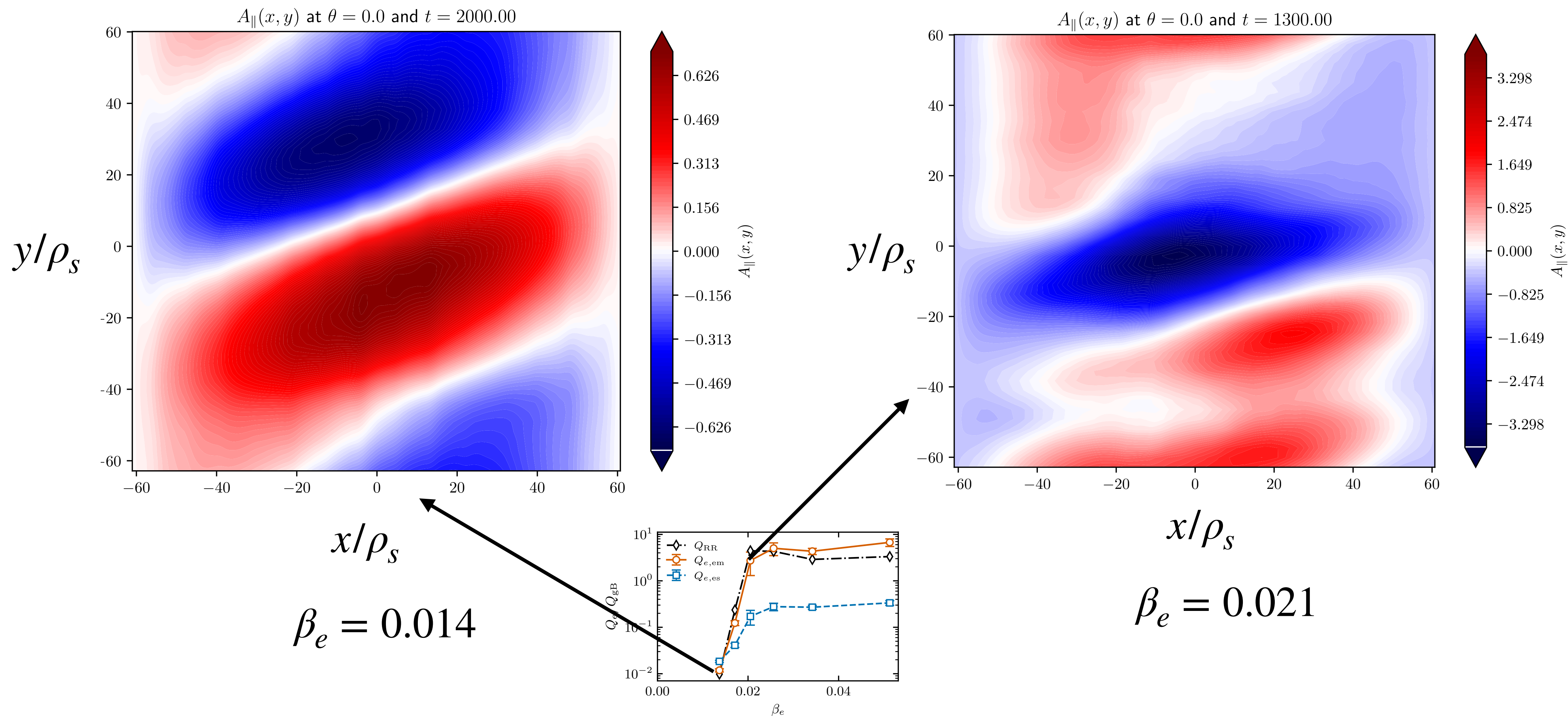


$\beta_e = 0.021$





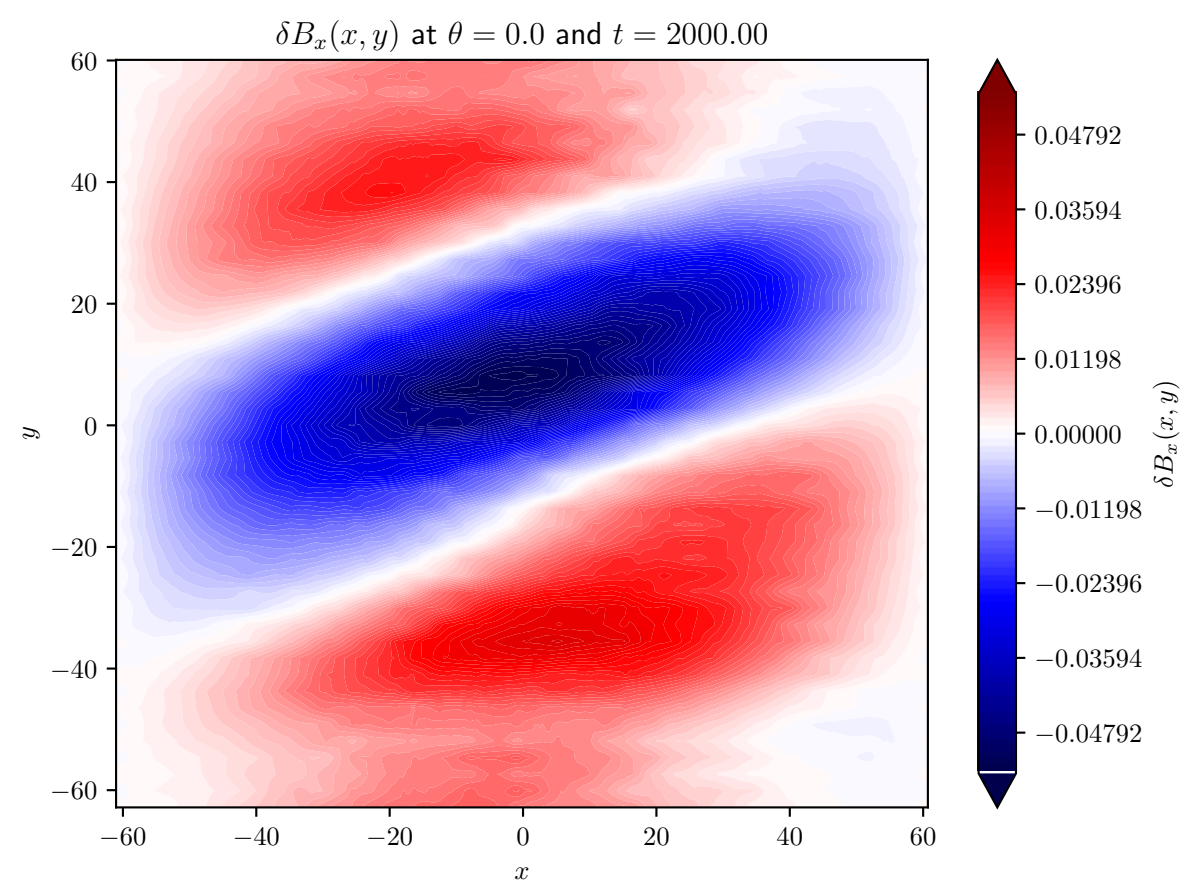
Snapshots of $A_{\parallel}$ (out-board mid-plane)



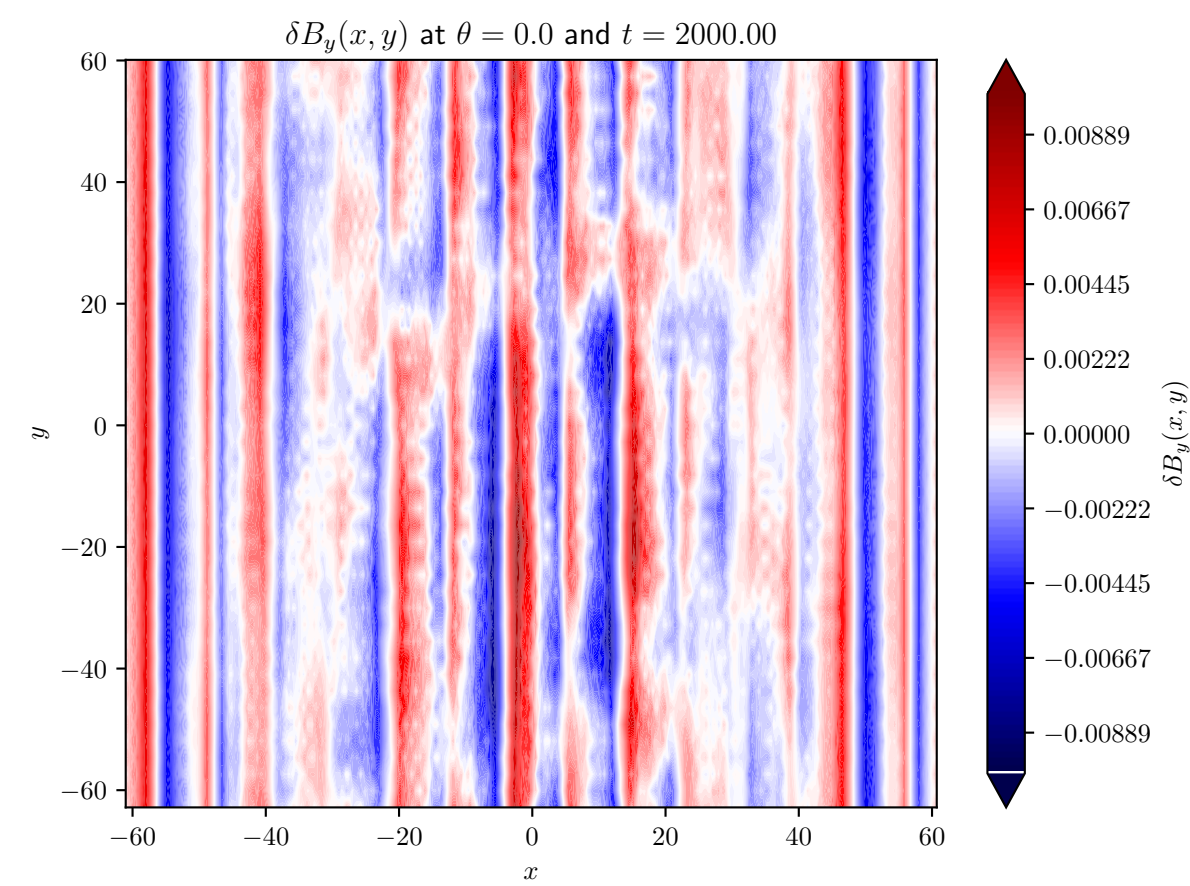


Snapshots of $\delta\mathbf{B}$ (out-board mid-plane)

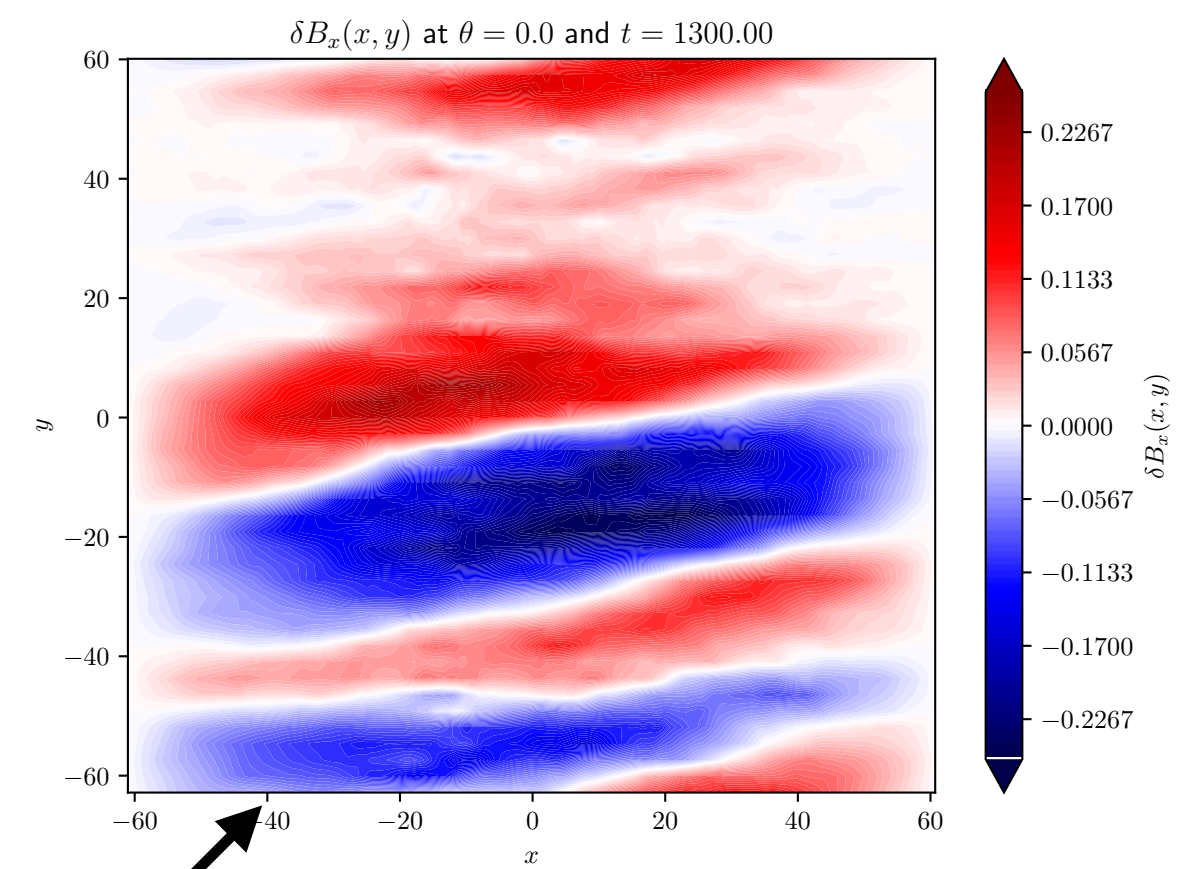
δB_x



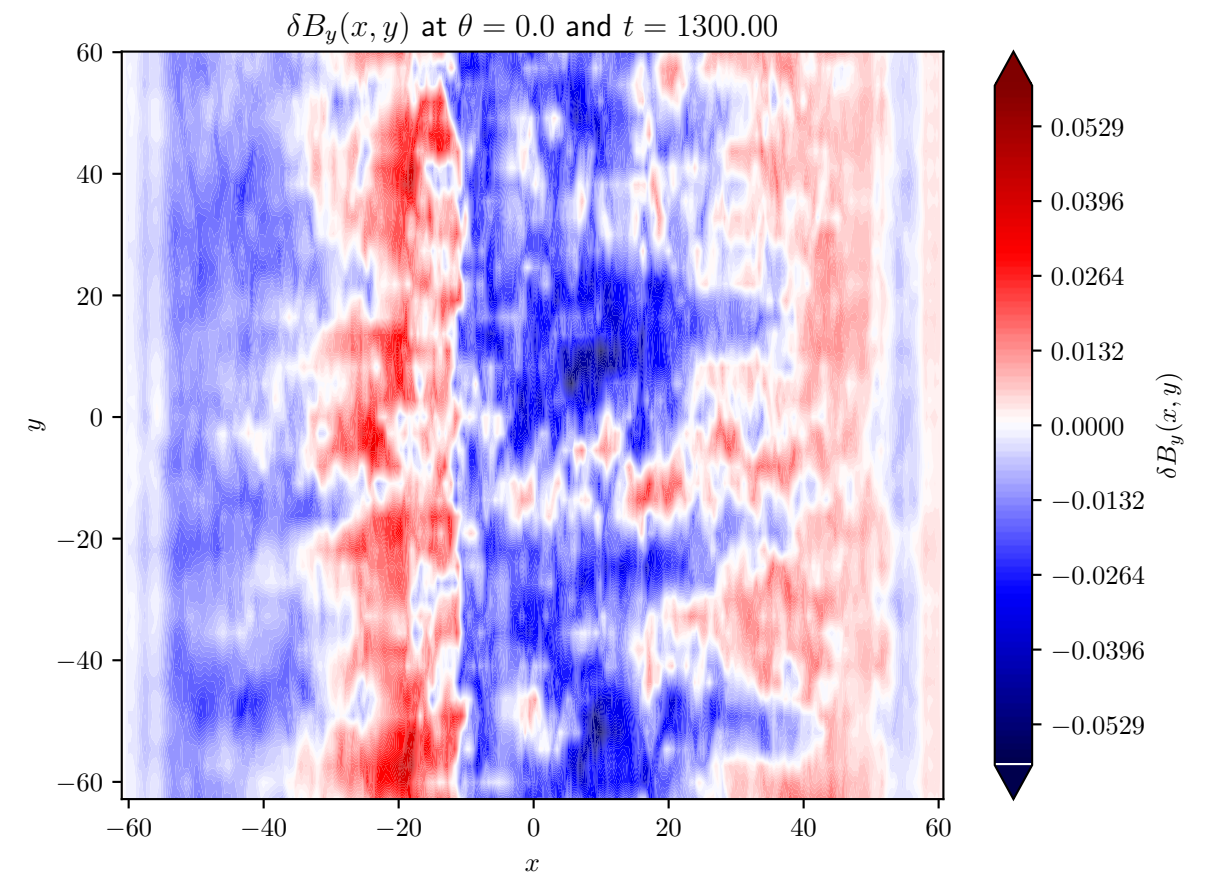
δB_y



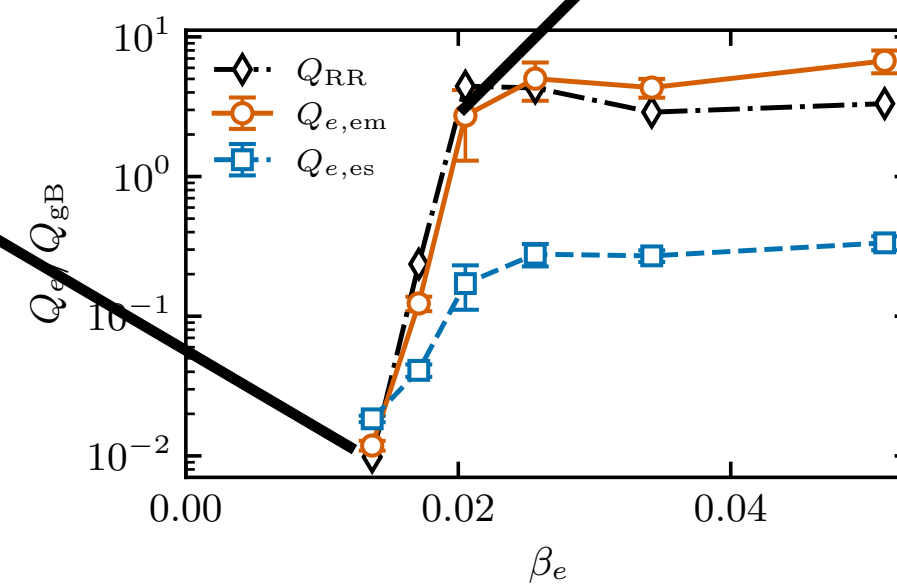
δB_x



δB_y



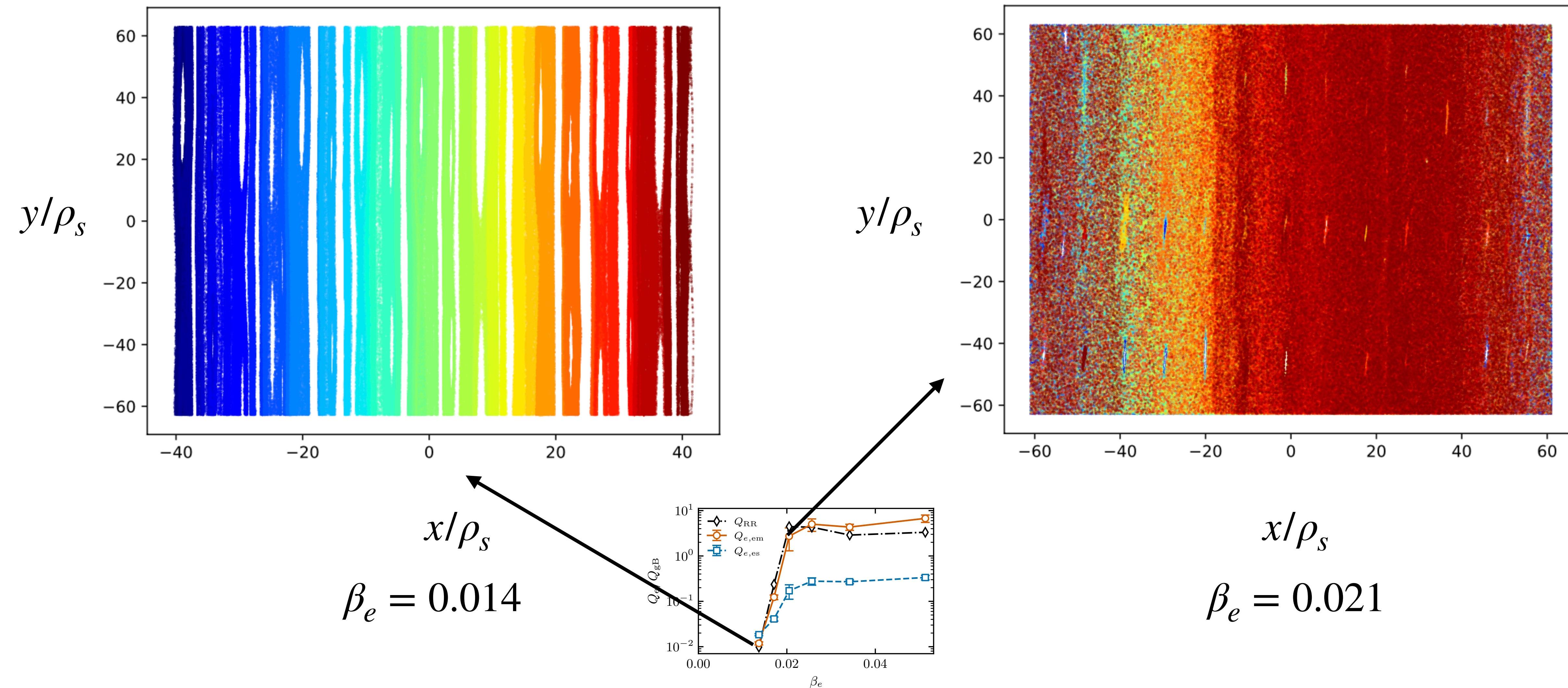
$\beta_e = 0.014$



$\beta_e = 0.021$

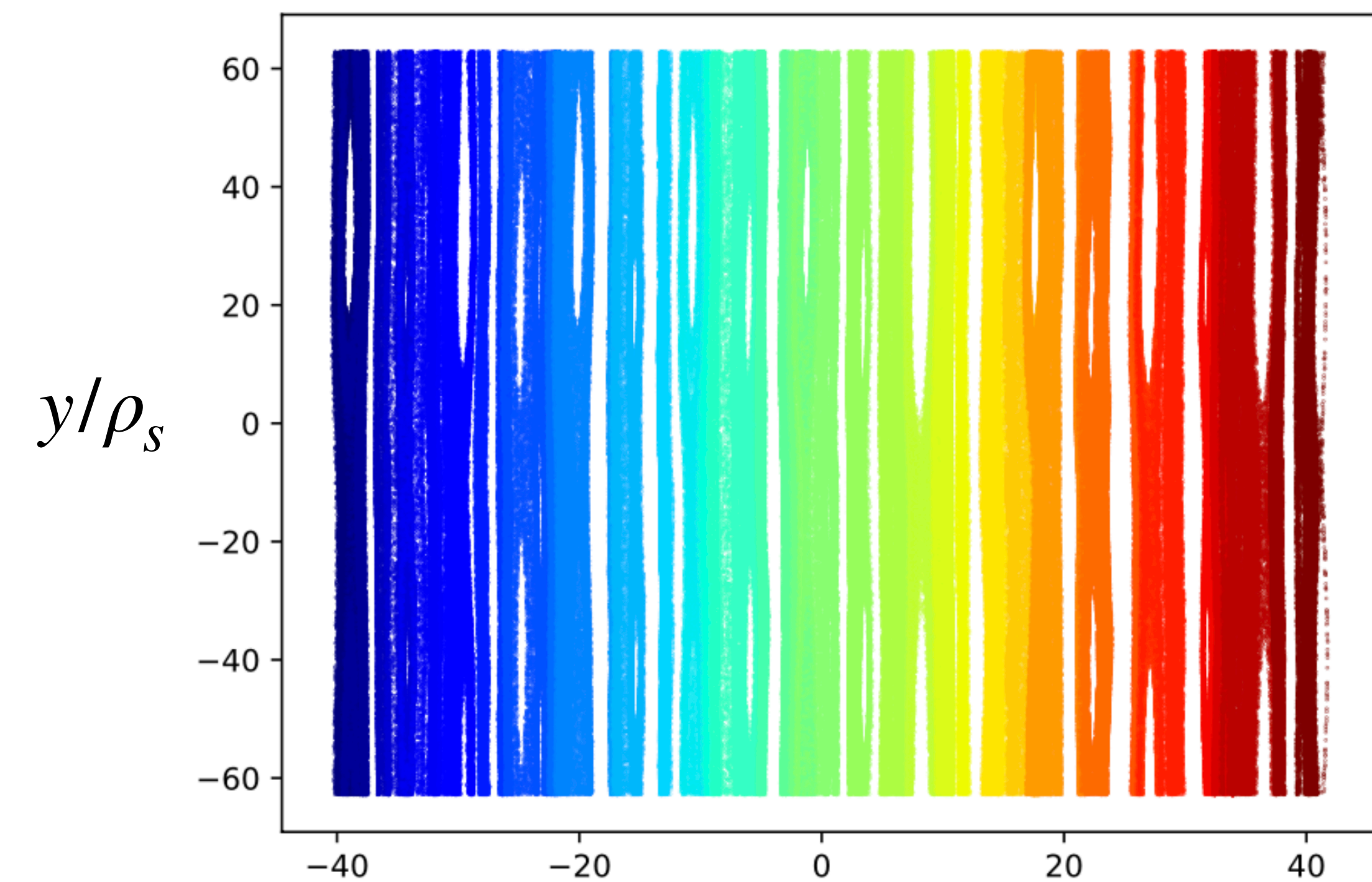


Poincaré plots





Magnetic island overlap

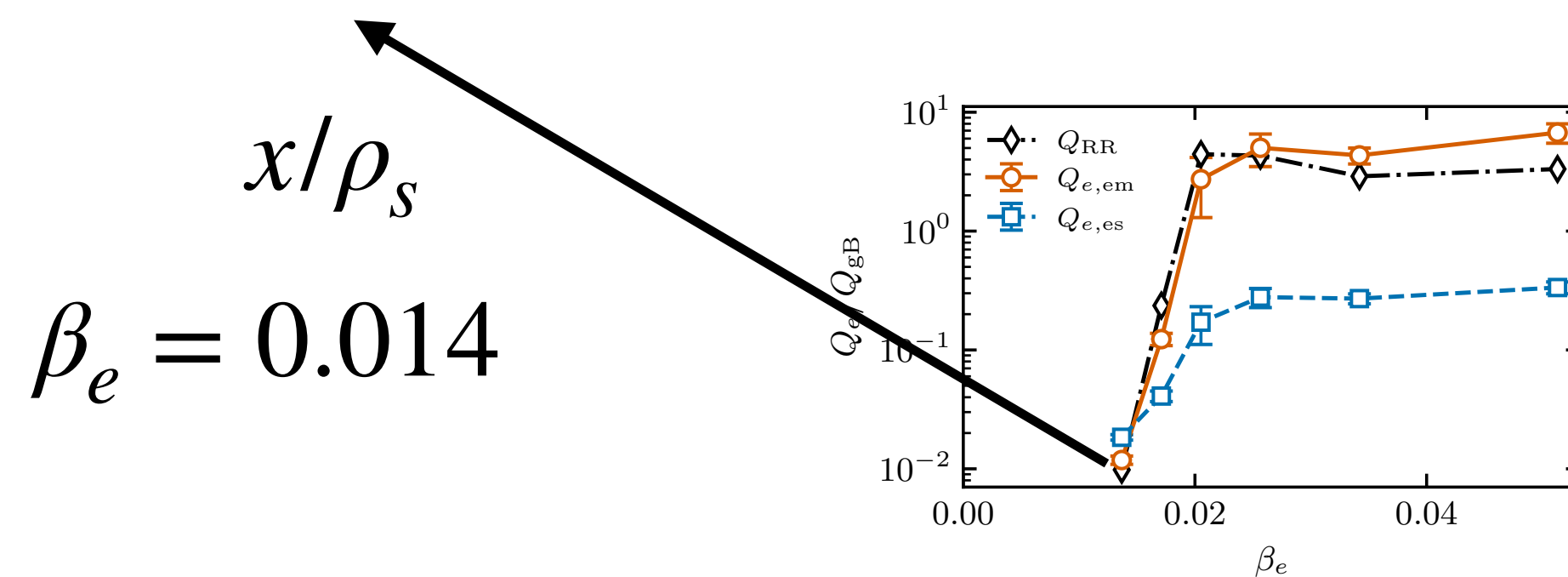


island width:

$$w = 4 \sqrt{\frac{\delta B}{B_0} \frac{qR}{k_y \hat{s}}}$$

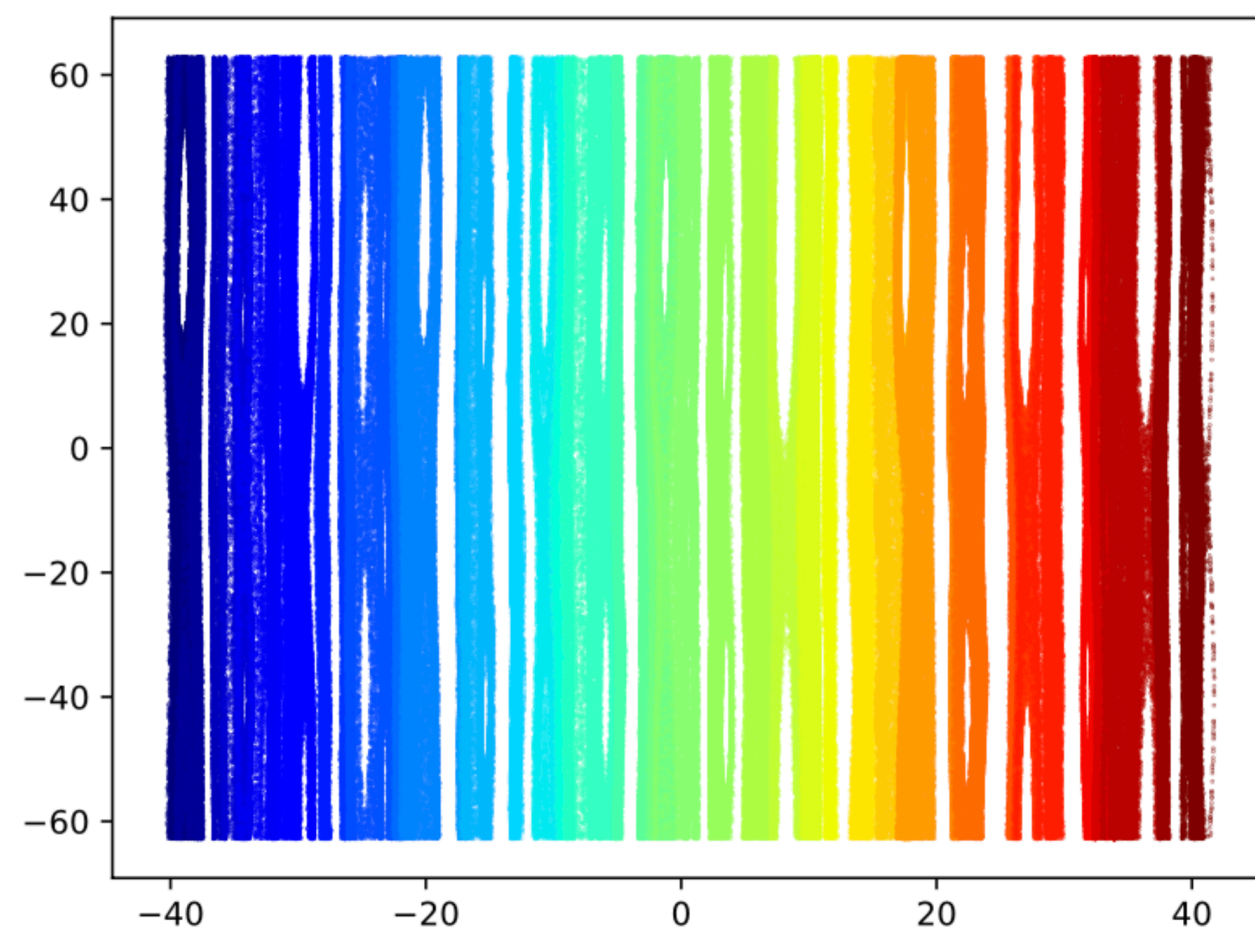
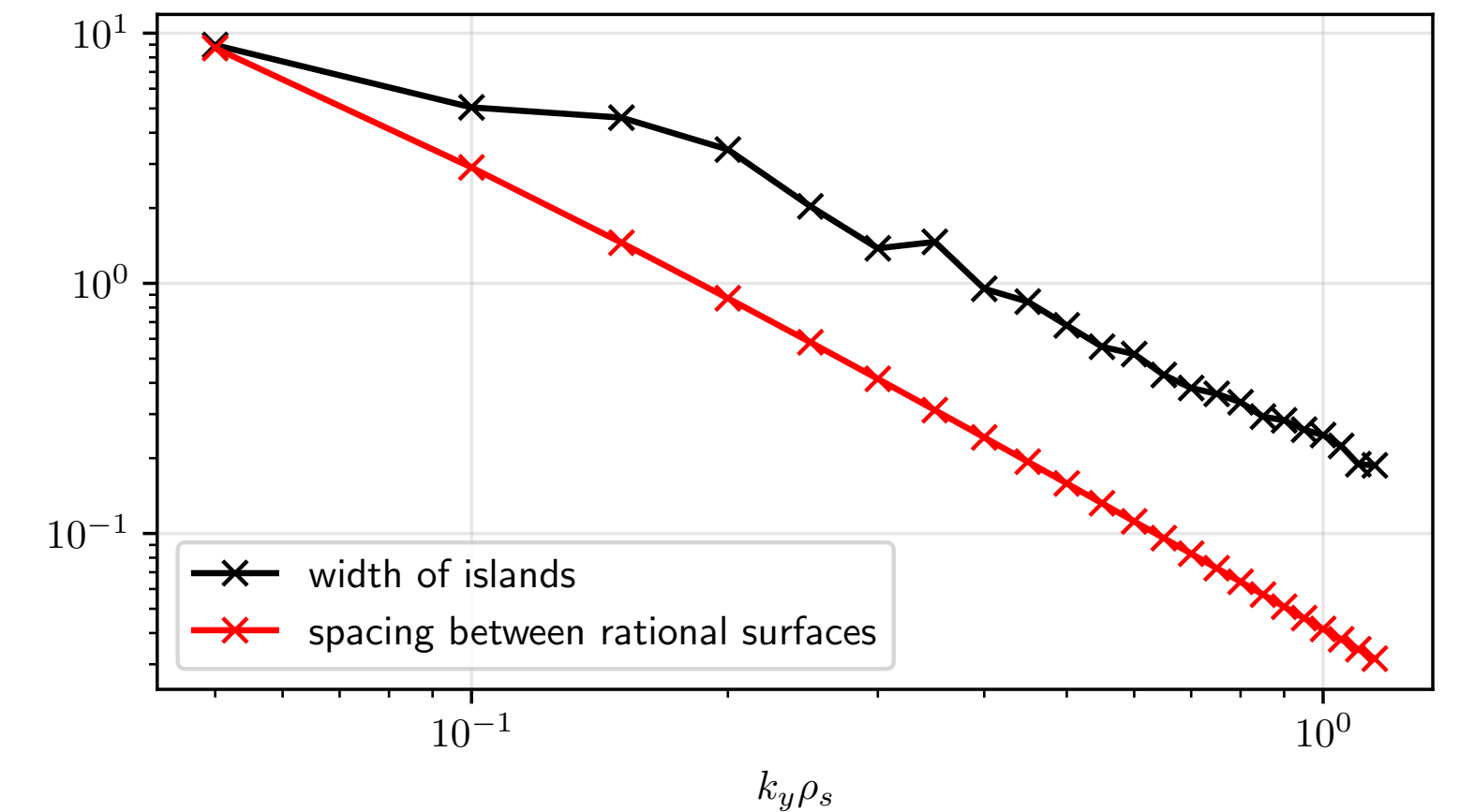
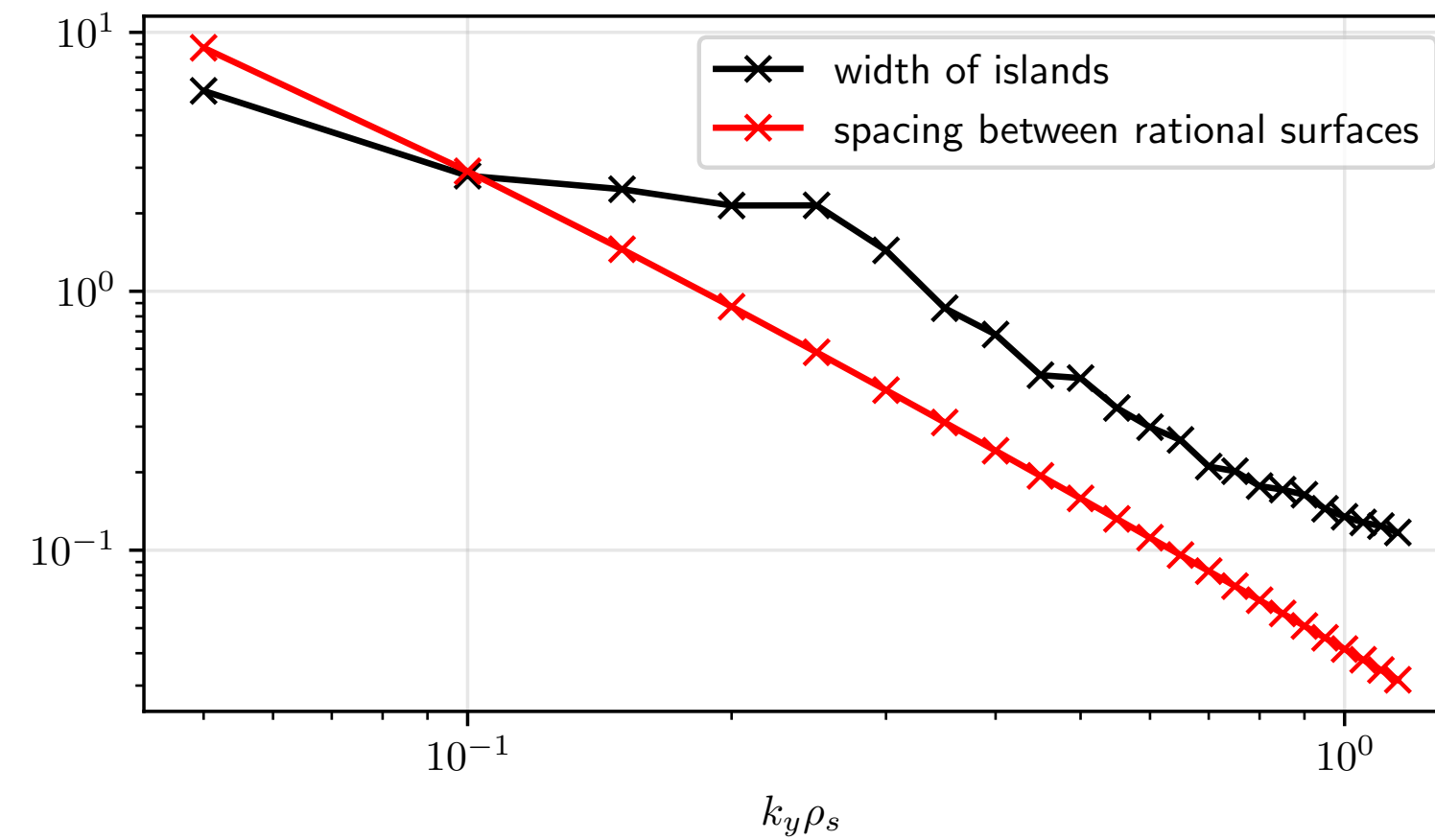
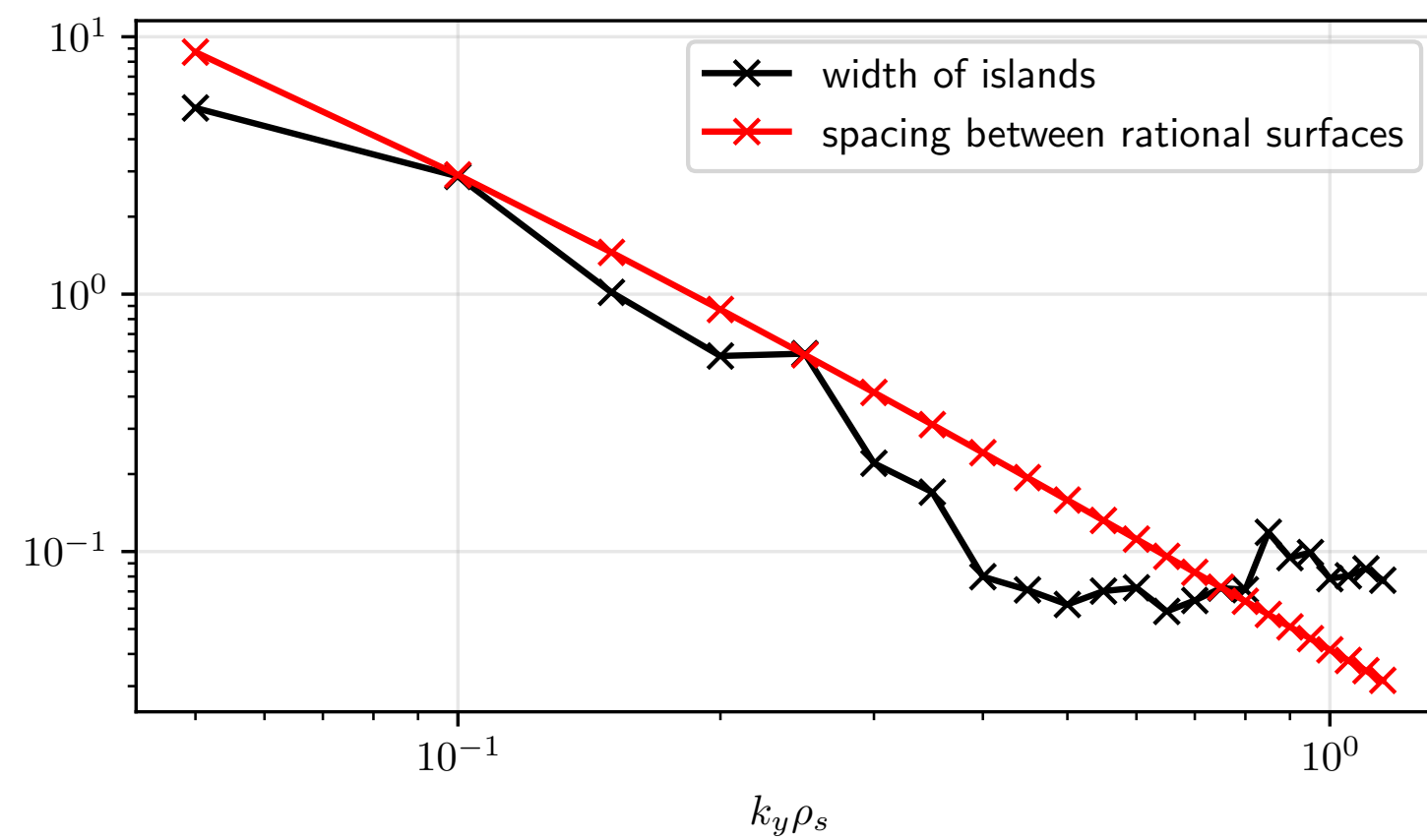
spacing between islands:

$$\Delta r_{\text{rat}} = \frac{1}{\hat{s} k_y (k_y / k_{y,\text{min}} + 1)}$$

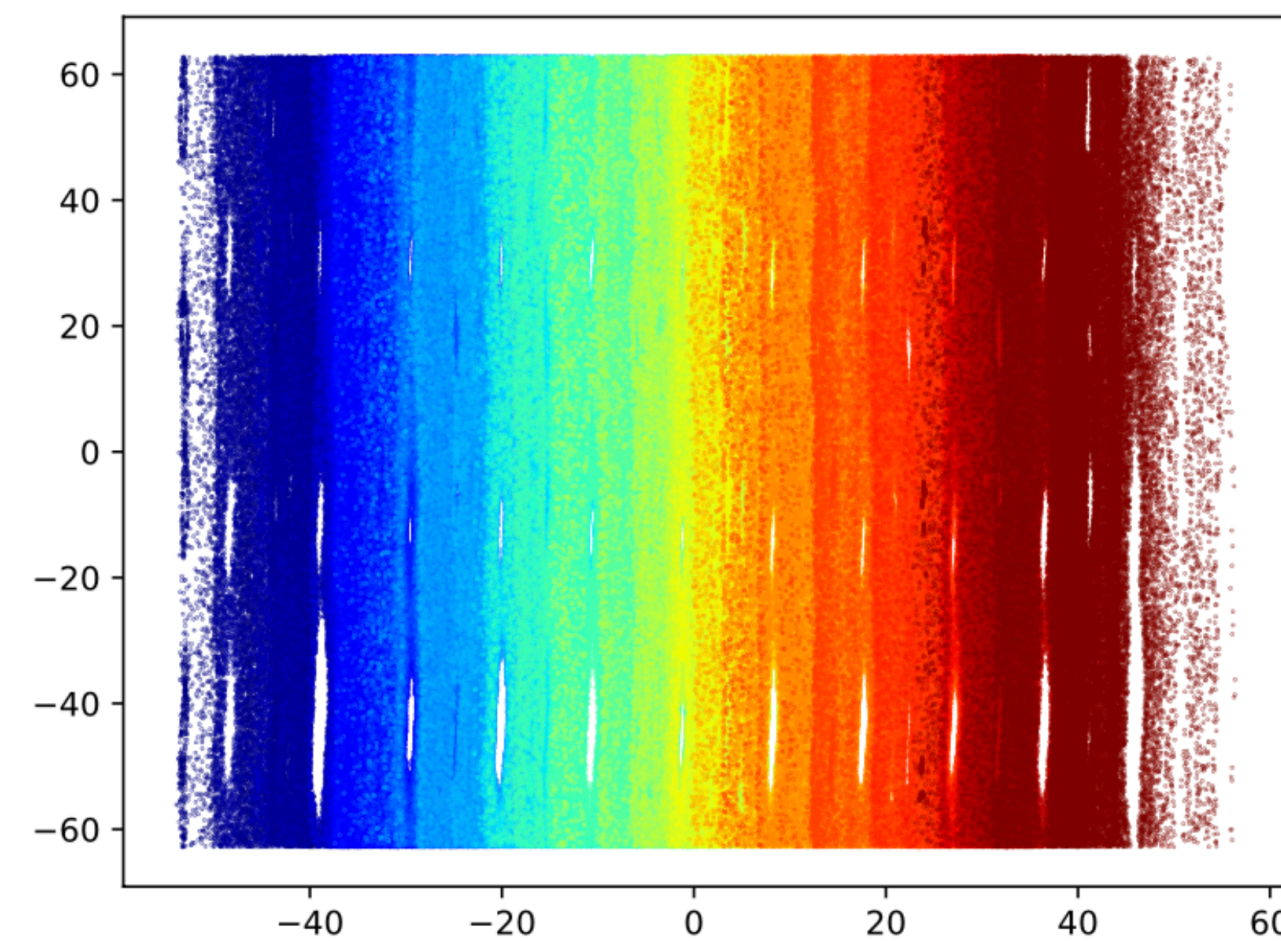




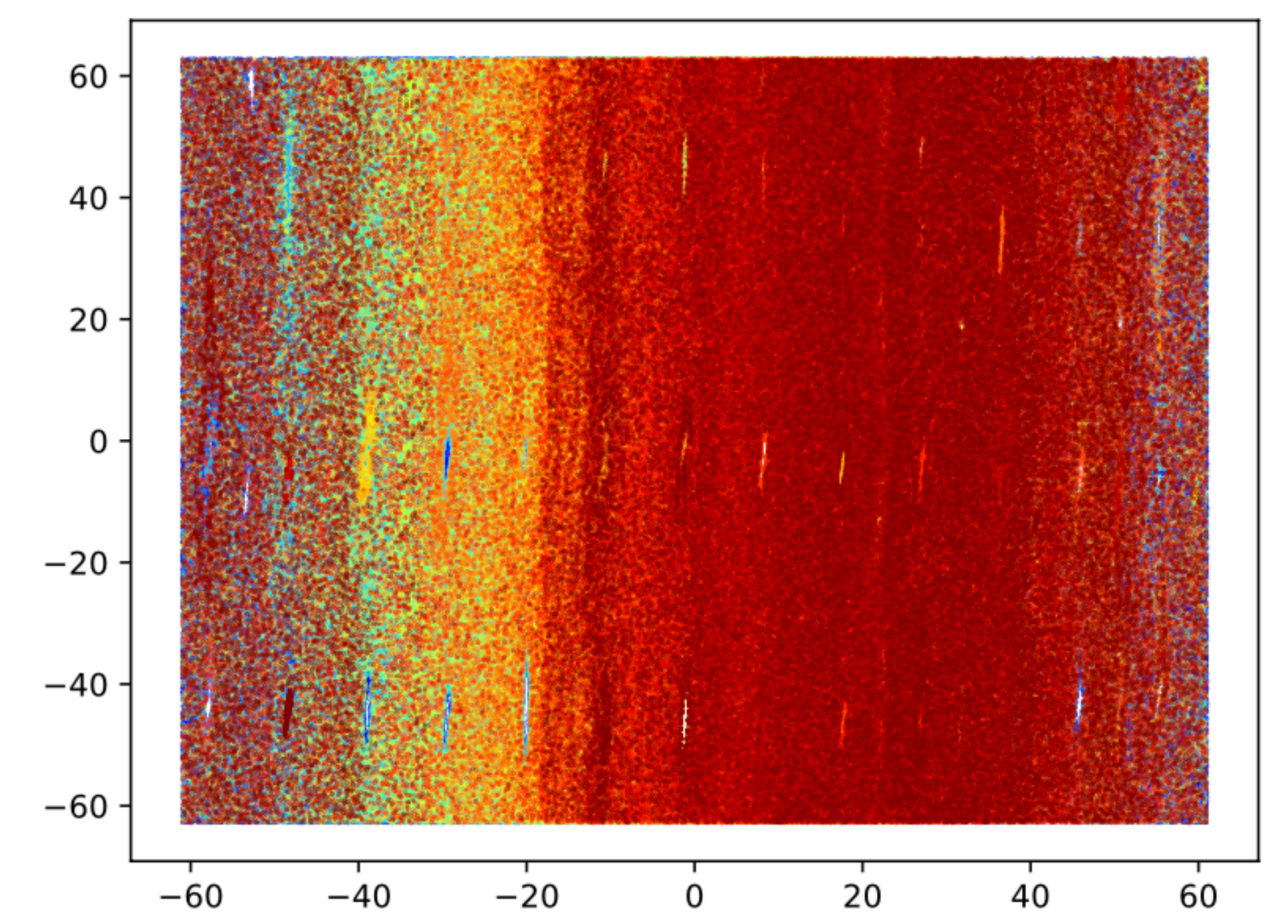
Magnetic island overlap



$$\beta_e = 0.014$$



$$\beta_e = 0.017$$



$$\beta_e = 0.021$$



Conclusion

- MTM turbulence exhibits a transition from low- to high-transport states as β_e is increased, accompanied by an abrupt increase in electromagnetic heat flux.
- The onset of the high-transport state is consistent with the overlap of MTM magnetic islands, suggesting magnetic stochasticity as the physical mechanism underlying the transport transition.

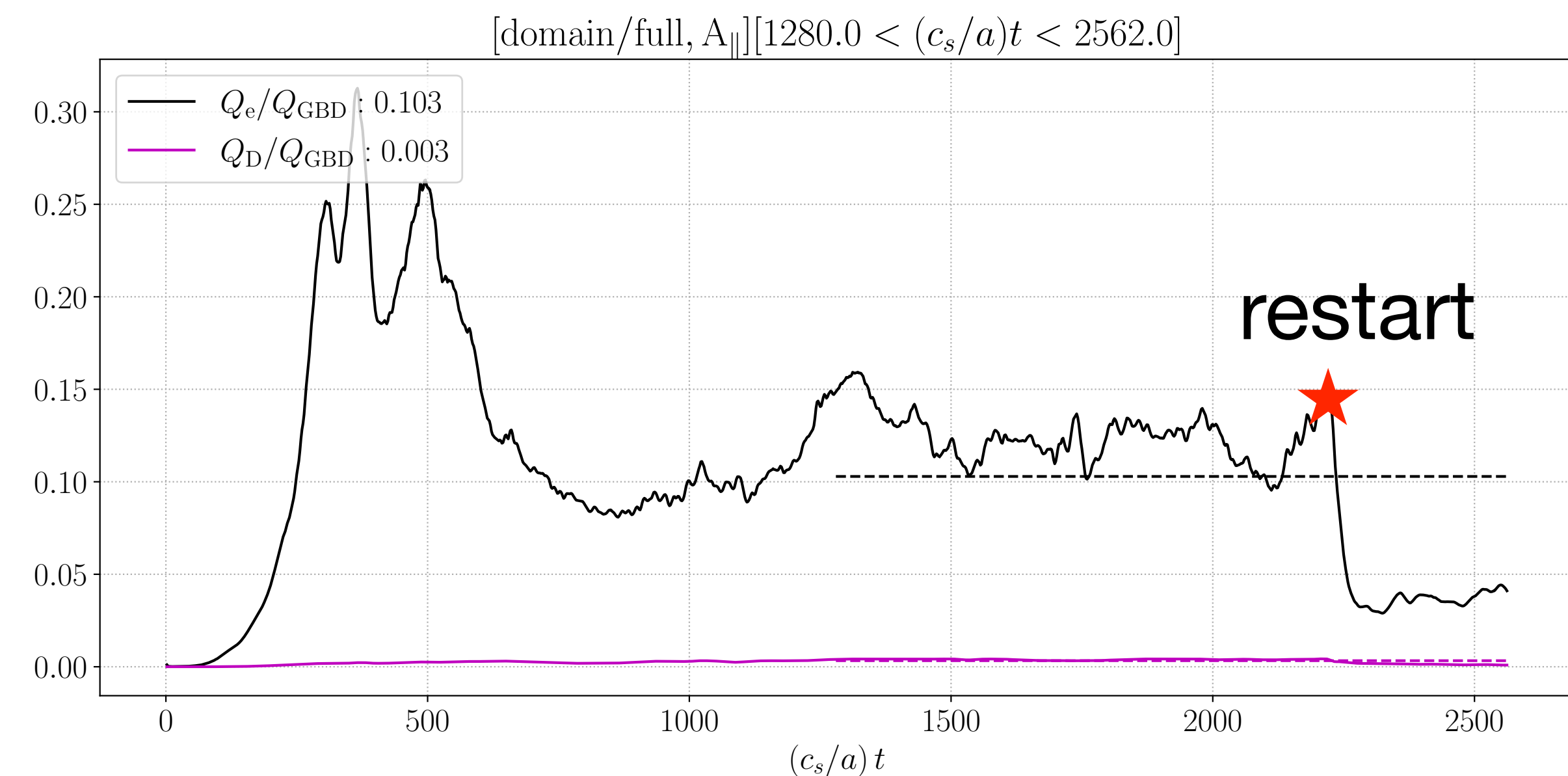


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Back up slides

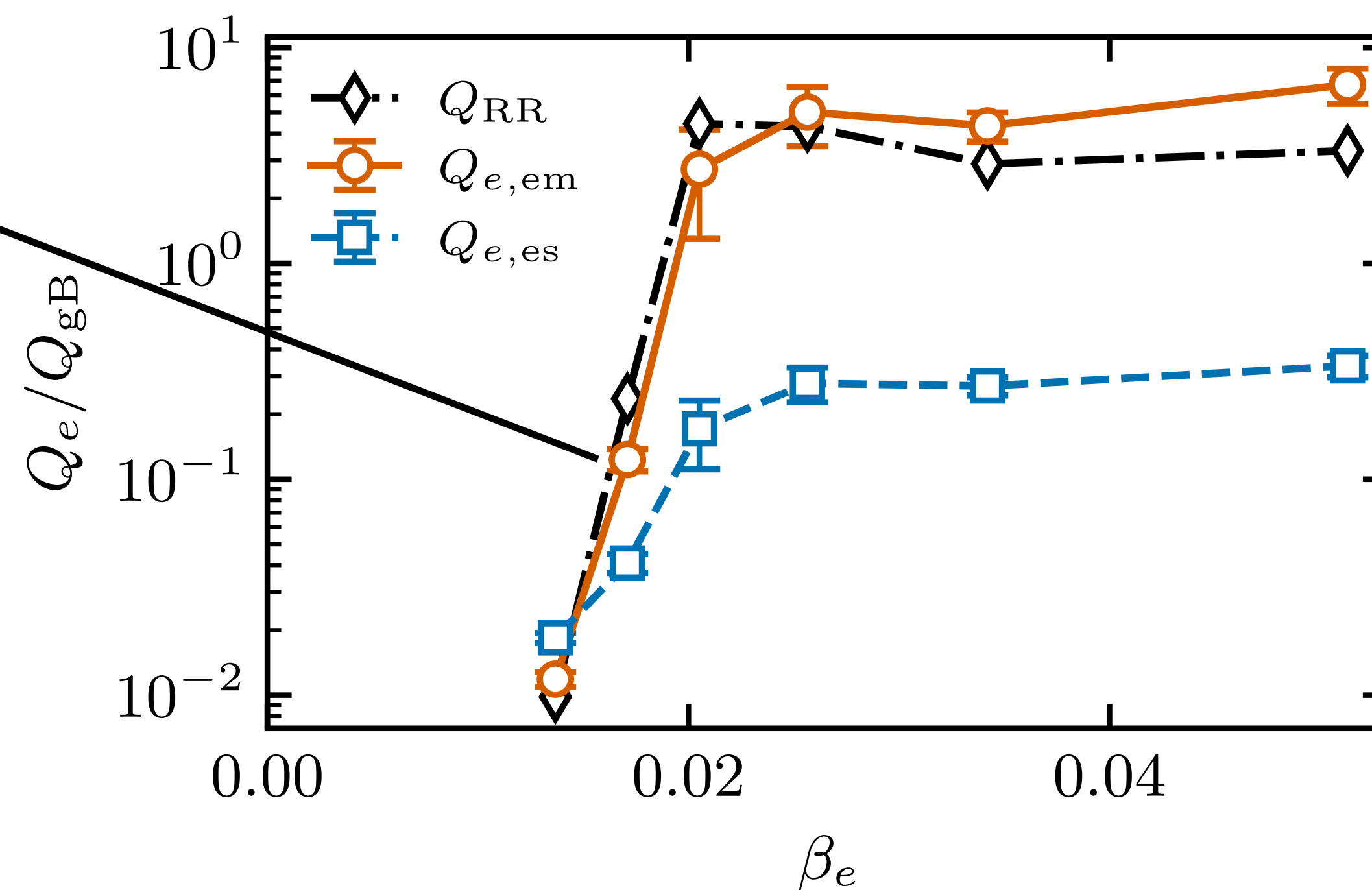


Zonal flow NOT crucial for the low-flux states



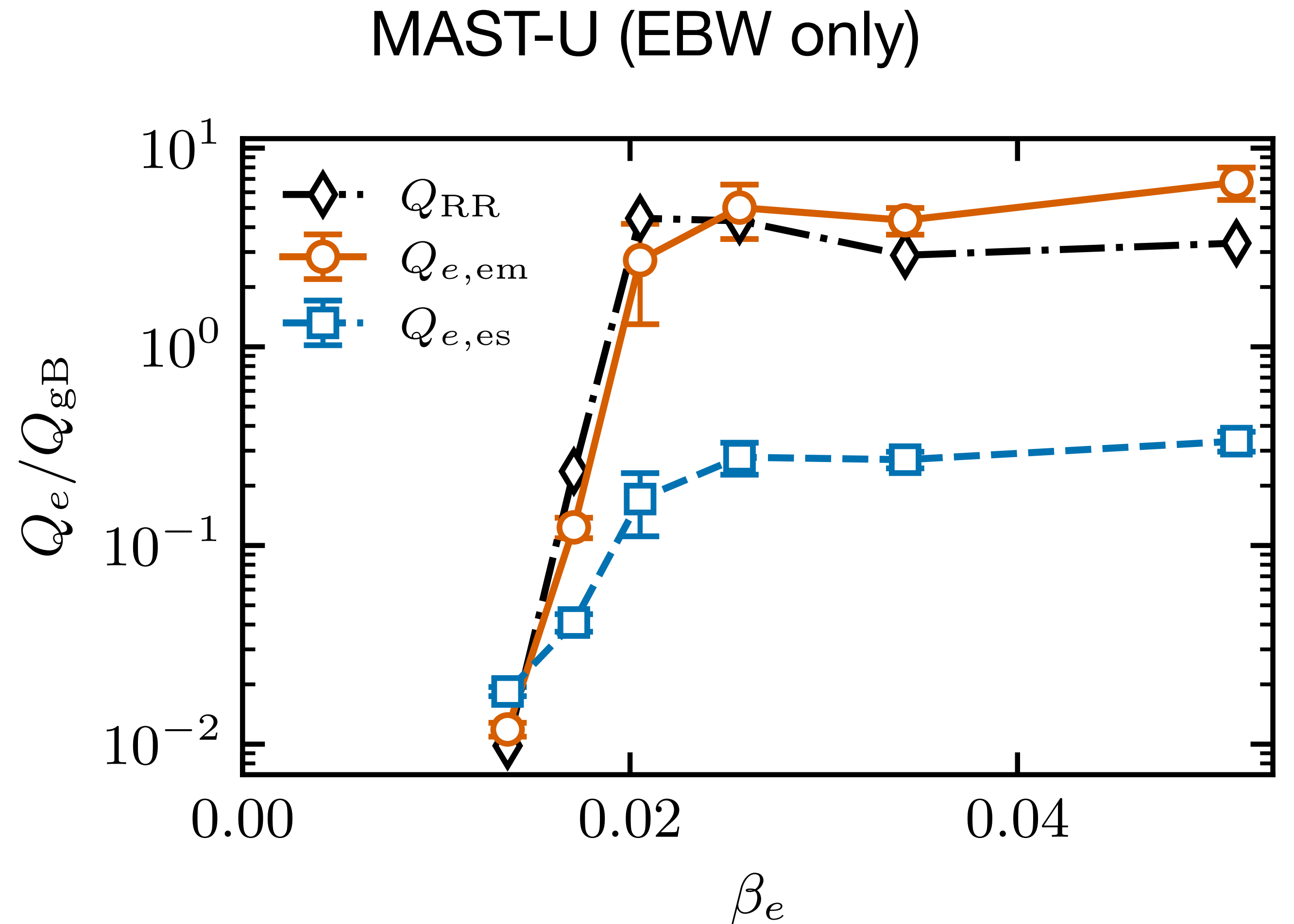
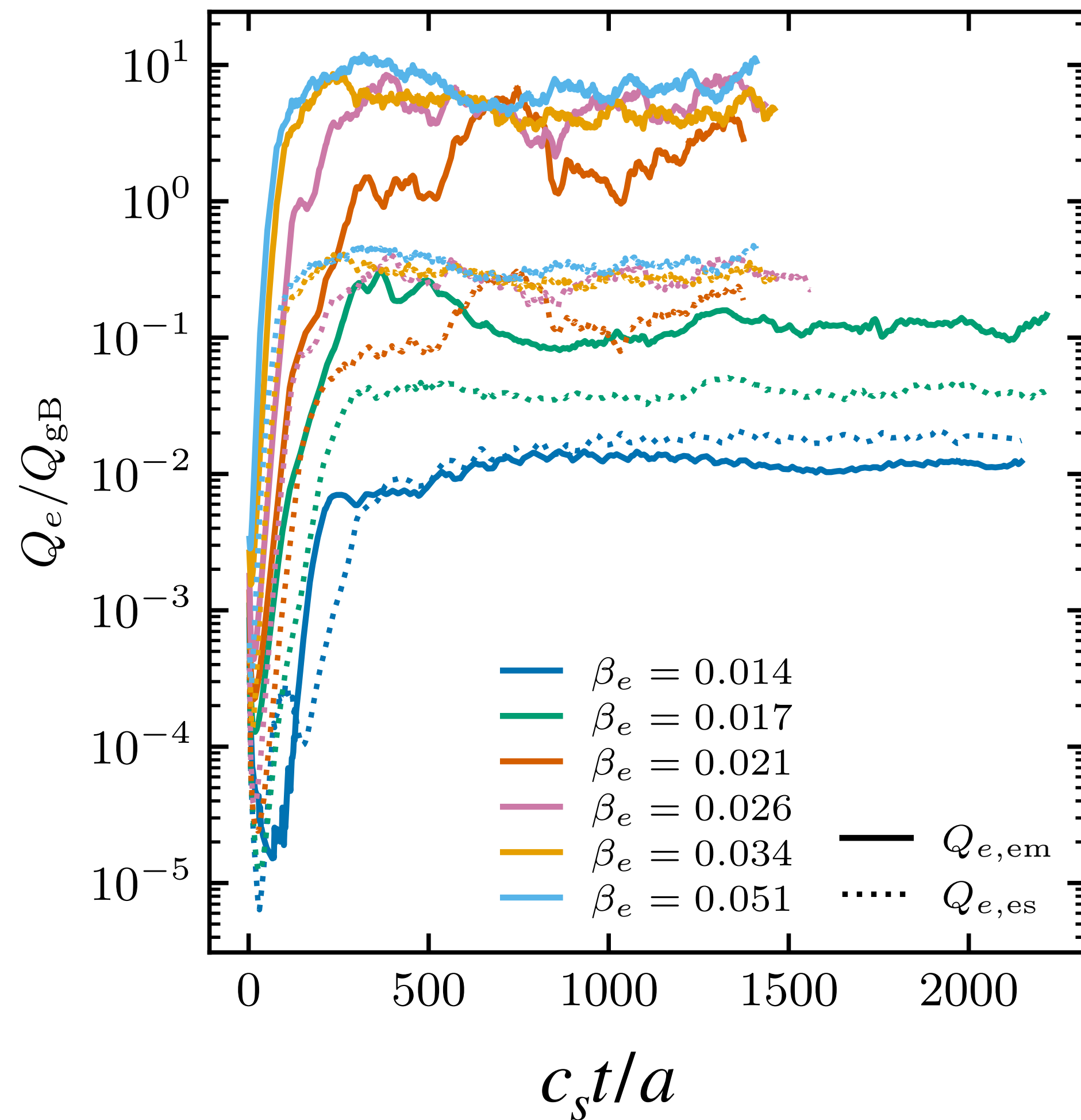
restart: zonal phi is turned off
in the nonlinearity.

MAST-U (EBW only)





Transition in MTM turbulence?





Rational surface spacing

$$q = \frac{m}{n}, \quad \Delta q = \frac{m + \Delta m}{n + \Delta n} - \frac{m}{n}$$

$$\longrightarrow \Delta q = \frac{n\Delta m - m\Delta n}{n(n + \Delta n)}$$

In a flux tube: $n = jn_0$

$$\Delta q = \frac{j\Delta m - m}{n_0 j(j+1)} \geq \frac{1}{n_0 j(j+1)} = \frac{n_0}{n(n+n_0)}$$
$$\Delta r_{\text{rat}} = \Delta q / q' = \frac{n_0}{n(n+n_0)q'}$$



Rechester-Rosenbluth model

$$D_m = \frac{1}{N} \sum_{i=1}^N \lim_{\ell \rightarrow \infty} \frac{[r_i(\ell) - r_i(0)]^2}{2\ell}$$

W. Guttenfelder et al., 2011

$$Q_{RR} = n_e T_e \left(2\sqrt{2}\pi f_p D_m v_{te} \right) \frac{1}{L_{T_e}}$$

$$\frac{Q_{RR}}{Q_{GB}} \simeq 761.5 f_p \left(\frac{D_m}{\rho_{\text{ref}}} \right) \left(\frac{a}{L_{T_e}} \right) \frac{1}{\rho_*}$$