Bistable turbulence in magnetized plasma with mean flow shear

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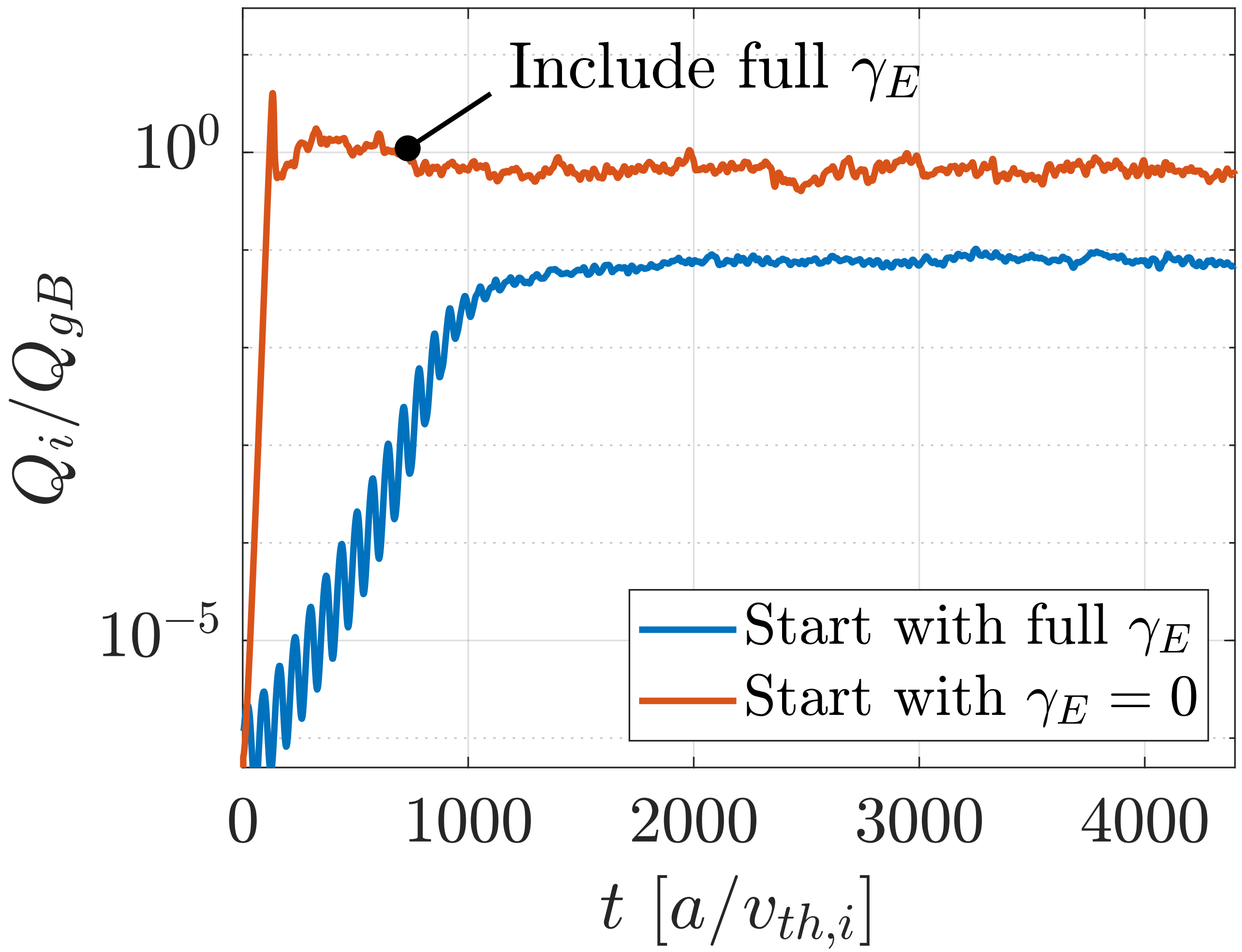
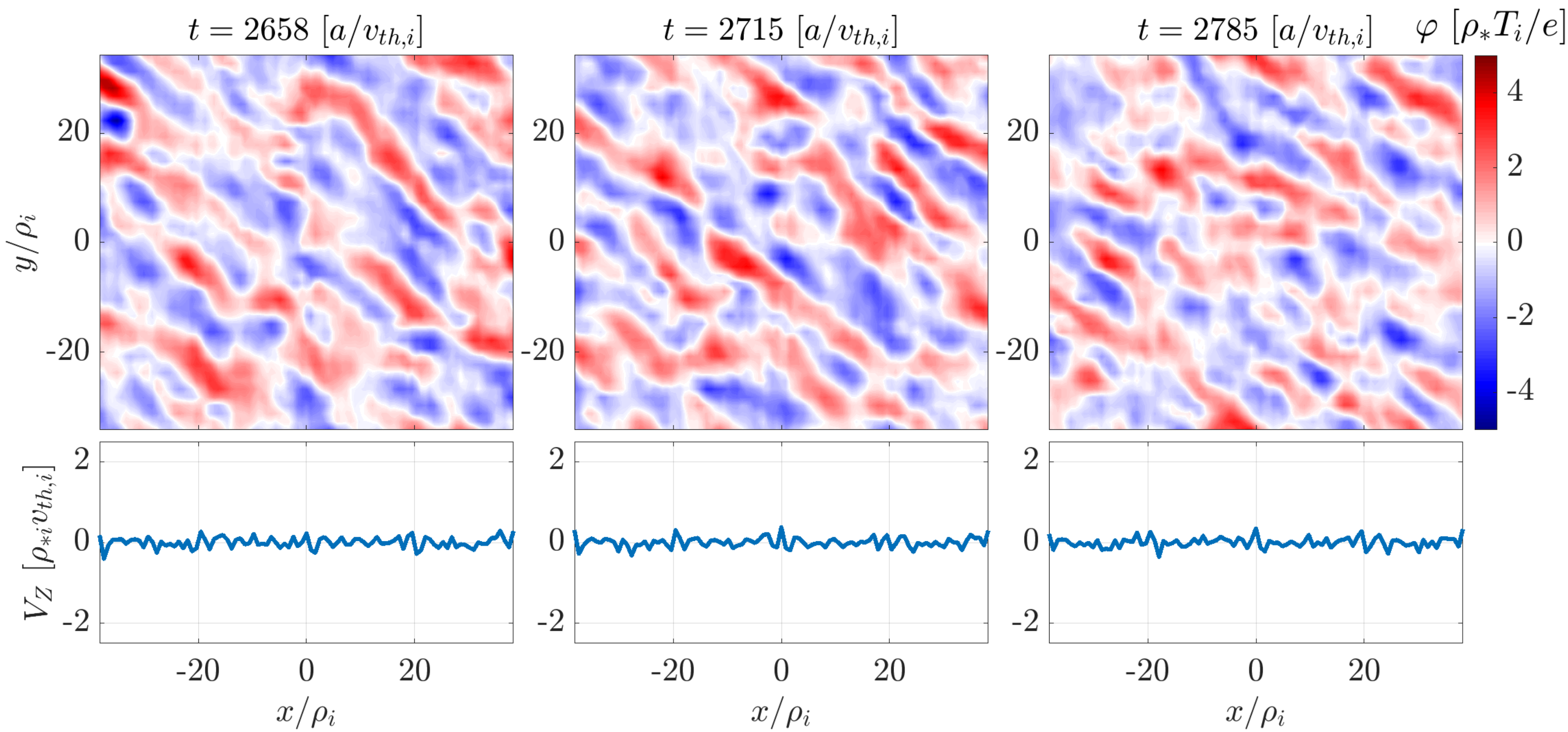
Motivation: numerical observation of bistable turbulence



GS2
Simulation of JET discharge

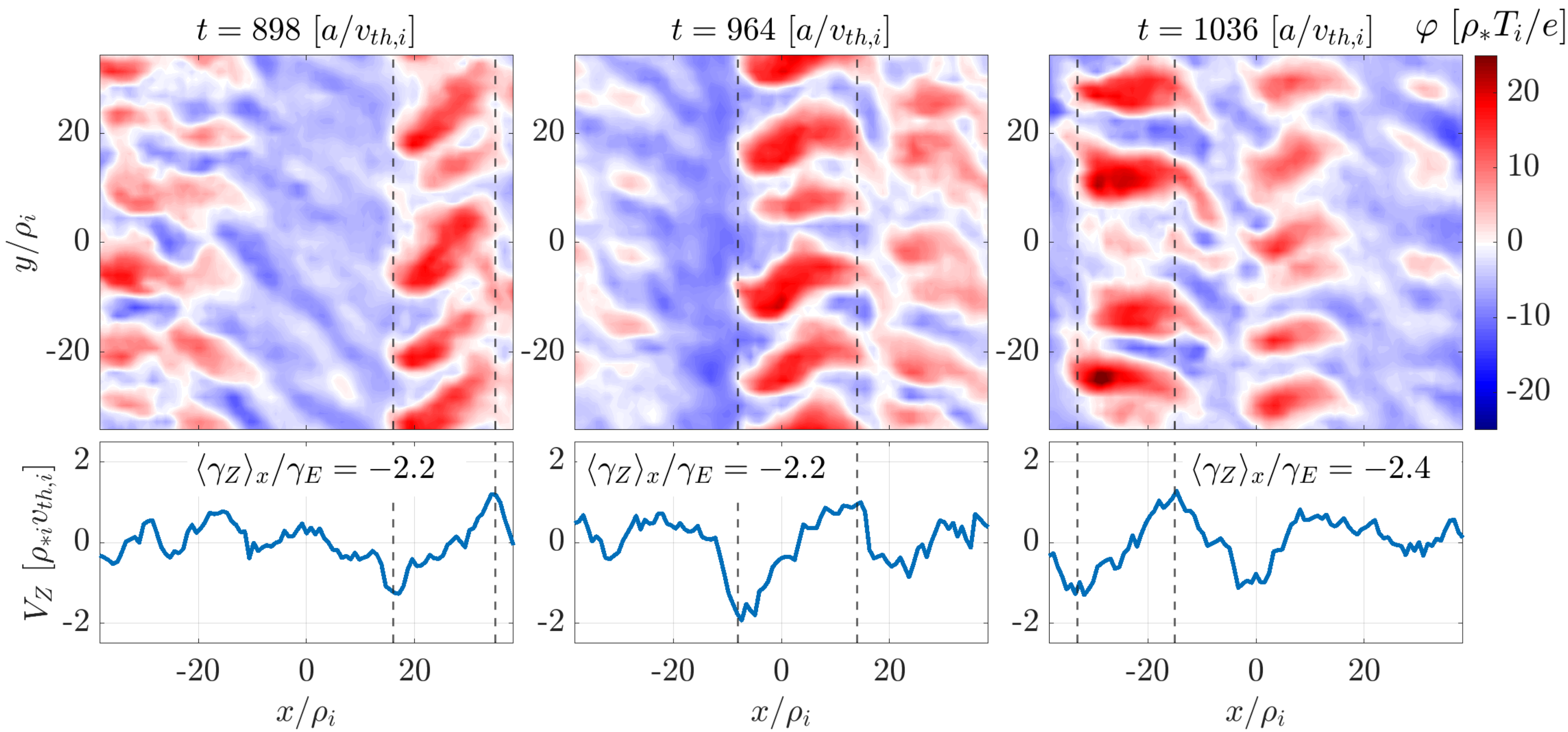
N. Christen, accepted in JPP;
see also recent results in Rath PoP 2022

Low-transport state



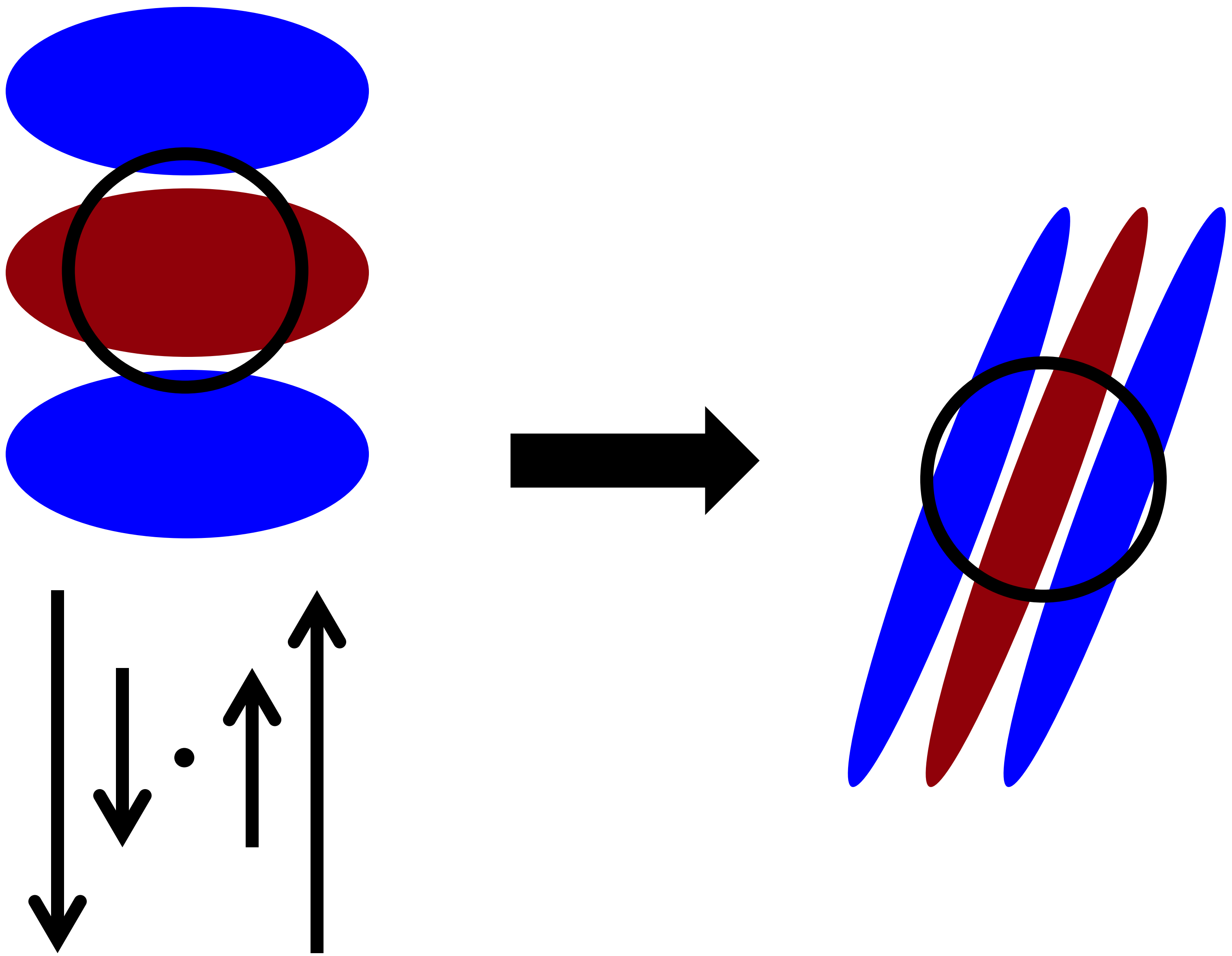
$$V_Z \propto \frac{\partial \varphi_Z}{\partial x} = \text{zonal velocity}$$

High-transport state

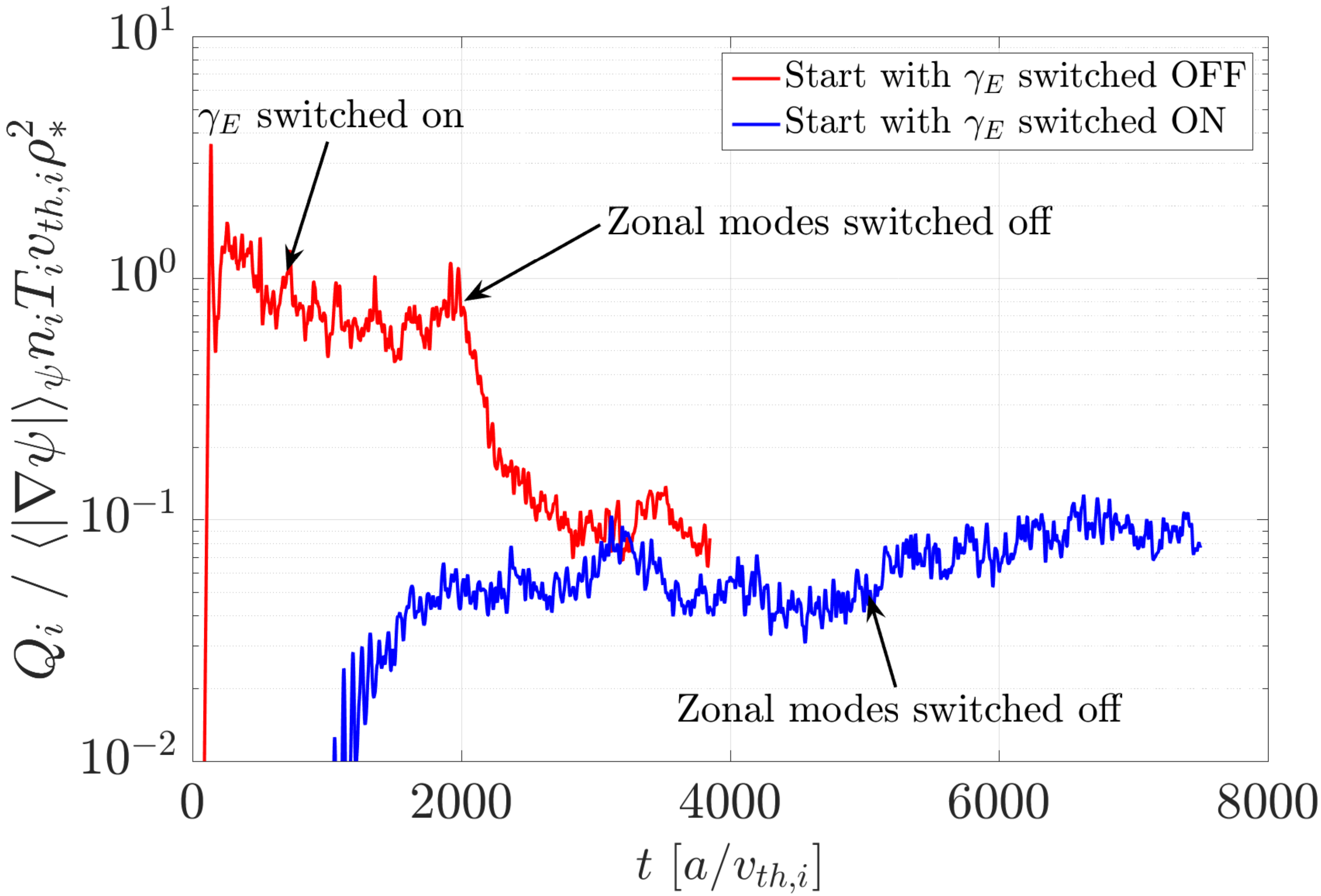


$\gamma_Z \propto \frac{\partial V_Z}{\partial x}$ = zonal flow shear

Turbulence suppression via flow shear

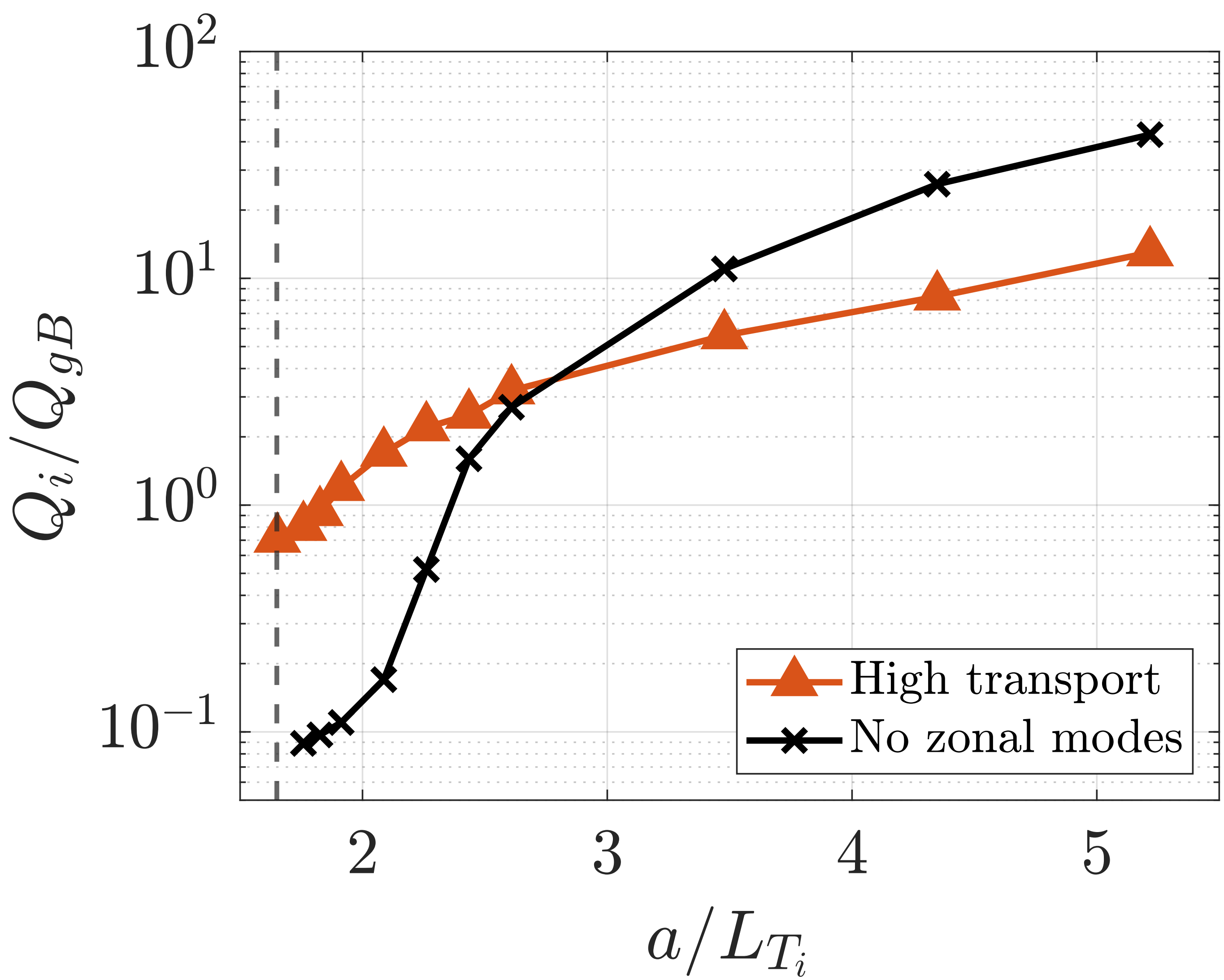


Evidence of competition between mean and zonal flow shear

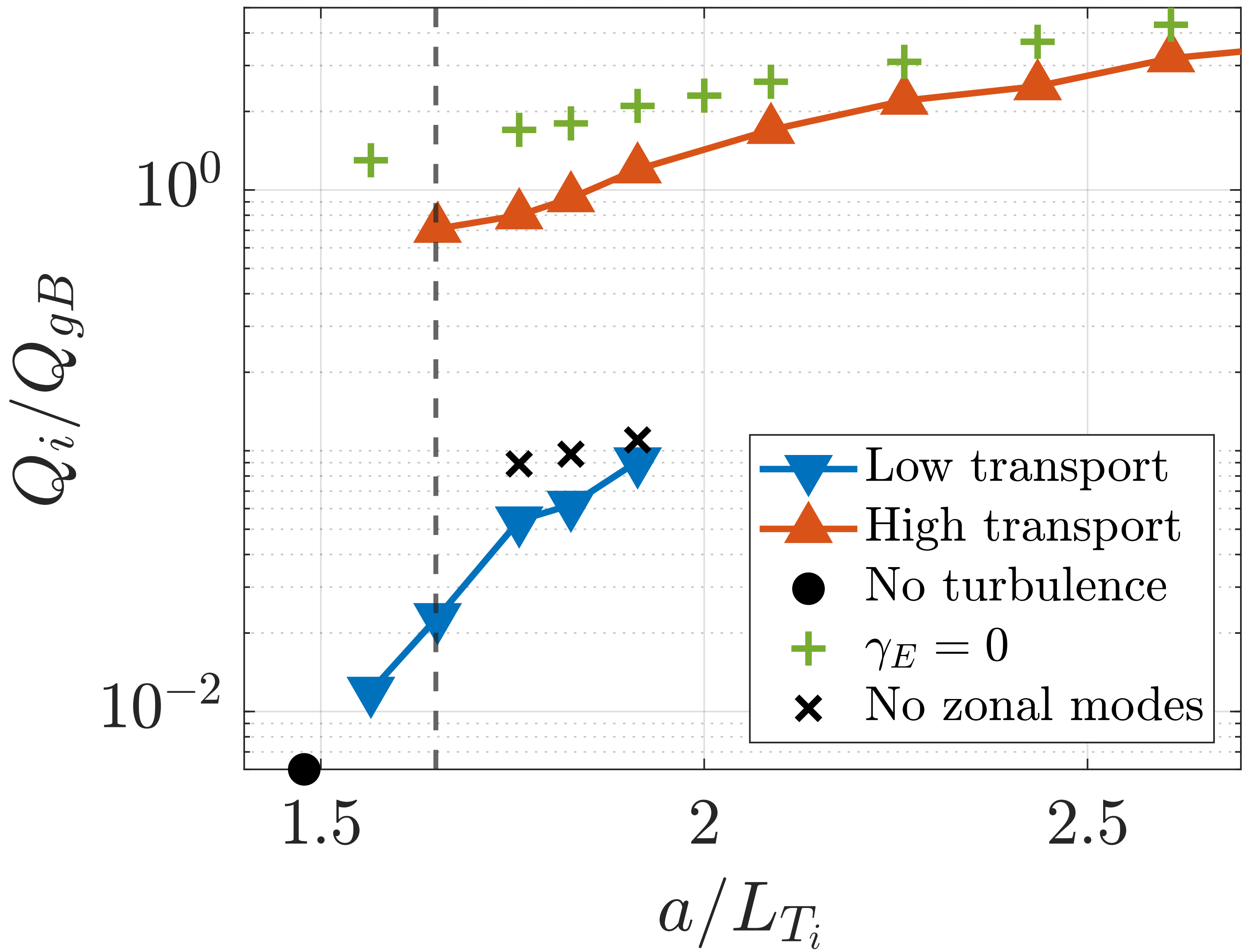


Cf. McMillan JPP 2018, Seiferling PoP 2019

Evidence of competition between mean and zonal flow shear



Region of bistable turbulence

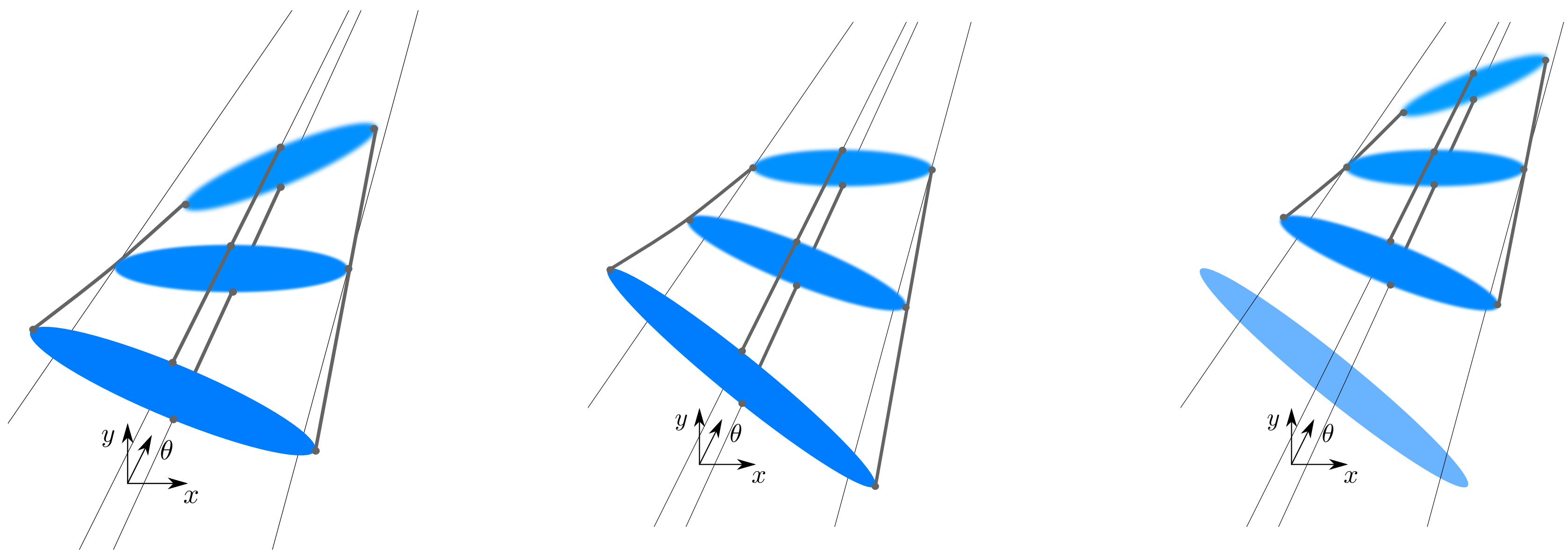


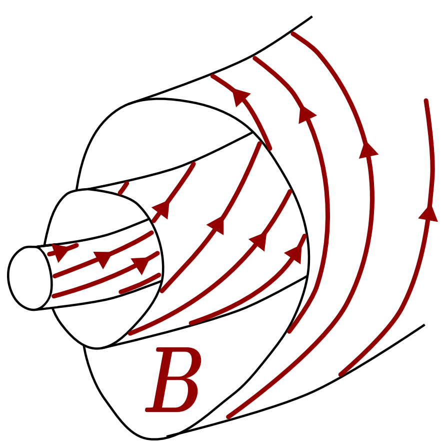
Simple estimate for transition between low- and high-transport states

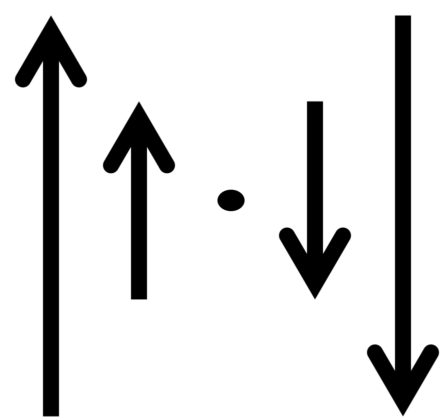
Assumptions:

- Transition occurs when zonal/mean shearing rates comparable: $\gamma_E \sim \gamma_Z \sim \varphi_Z / \ell_{x,Z}^2$
- Turbulence is isotropic: $\ell_{x,Z} \sim \ell_x \sim \ell_y$
- Zonal/non-zonal turbulence amplitudes are comparable: $\varphi_Z \sim \varphi$
- Correlation time in low-transport state is set by Floquet-averaged growth rate: $\tau \sim \langle \gamma \rangle_t^{-1}$

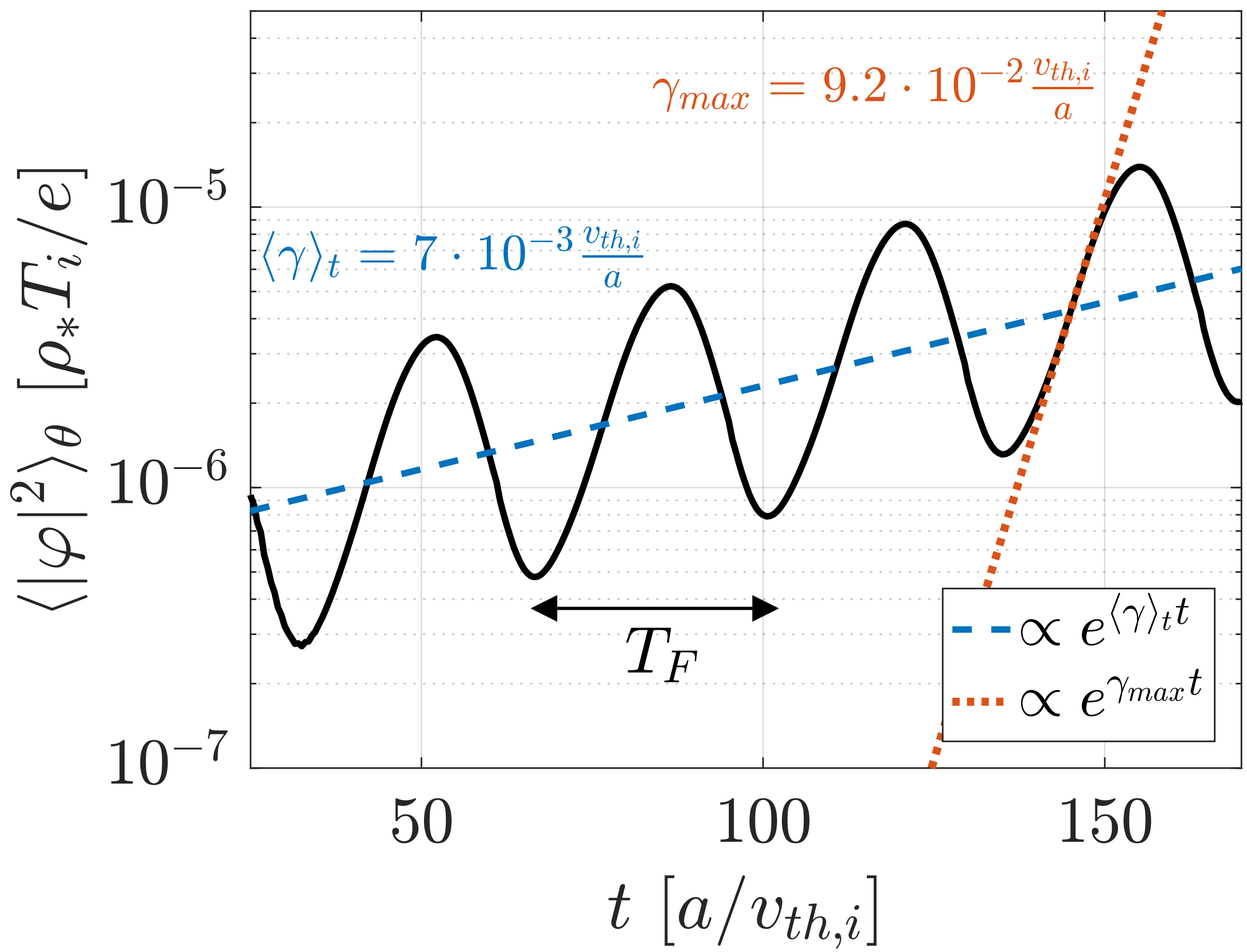
Flow shear and Floquet oscillations in tokamaks







Flow shear and Floquet oscillations in tokamaks



For $\langle\gamma\rangle_t$ to be relevant nonlinearly, need $\tau \gtrsim T_F$

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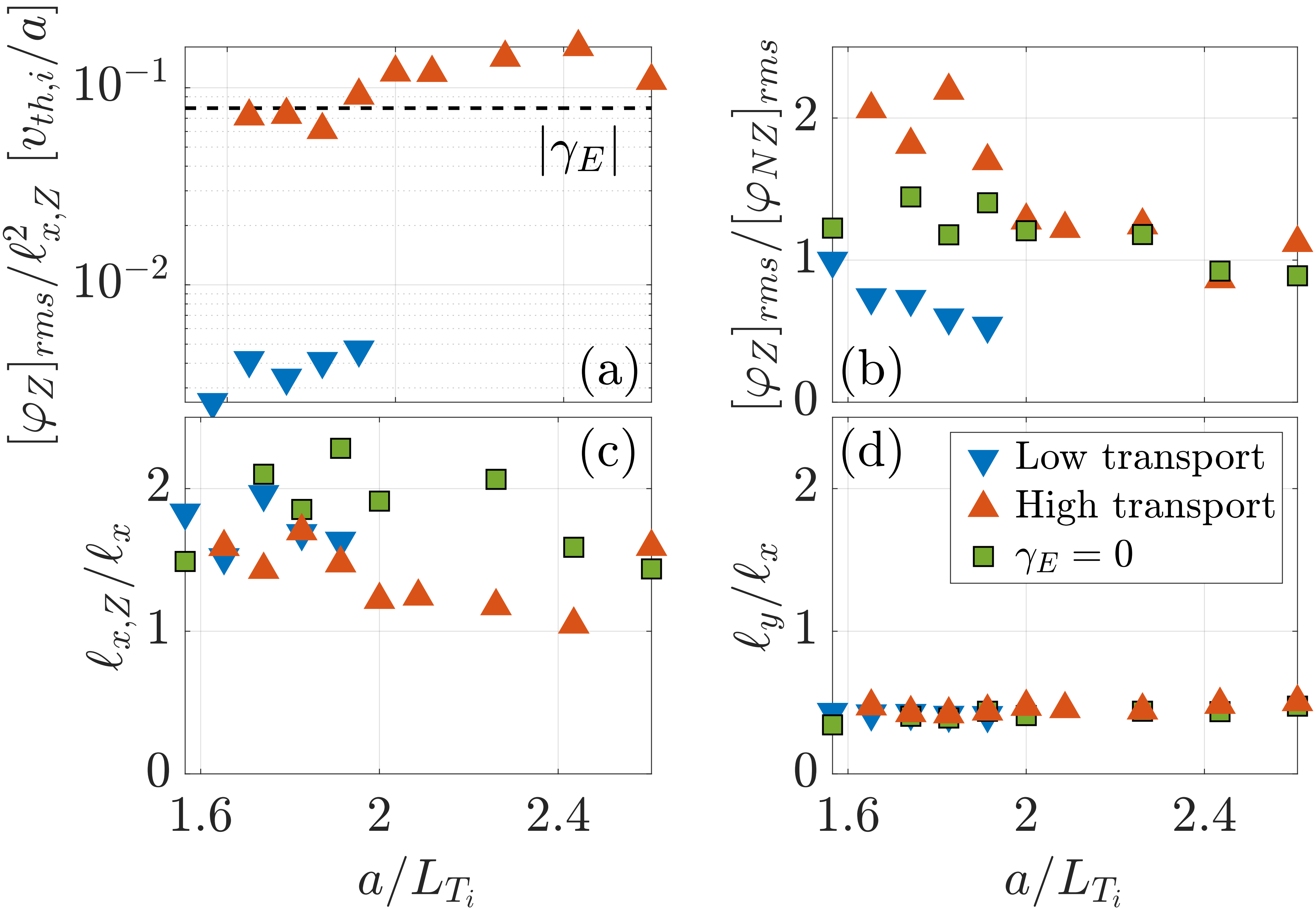
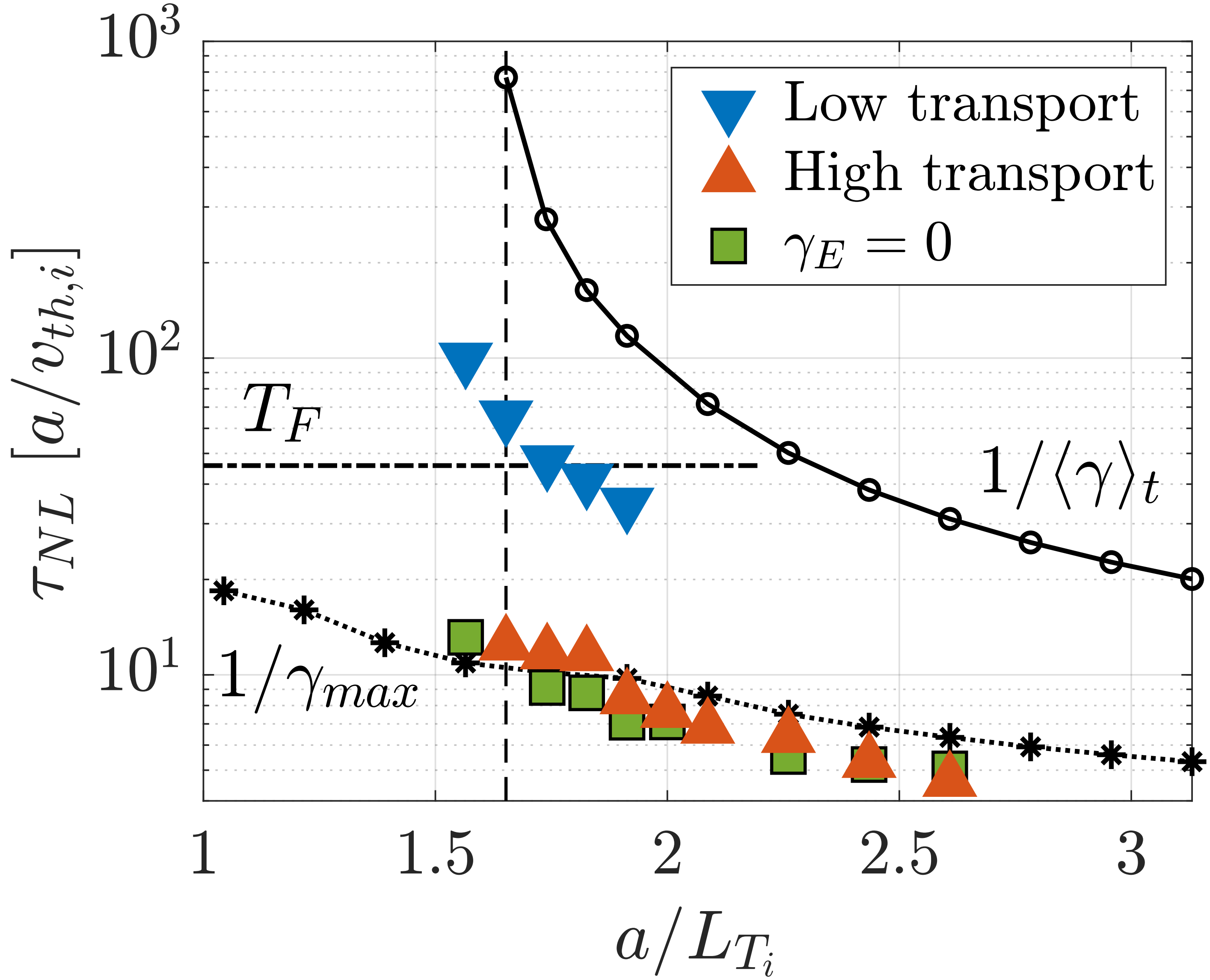
- Correlation time in low-transport state is set by Floquet-averaged growth rate: $\tau \sim \langle\gamma\rangle_t^{-1}$

Low/high transition is along curve of constant $\langle\gamma\rangle_t/\gamma_E$

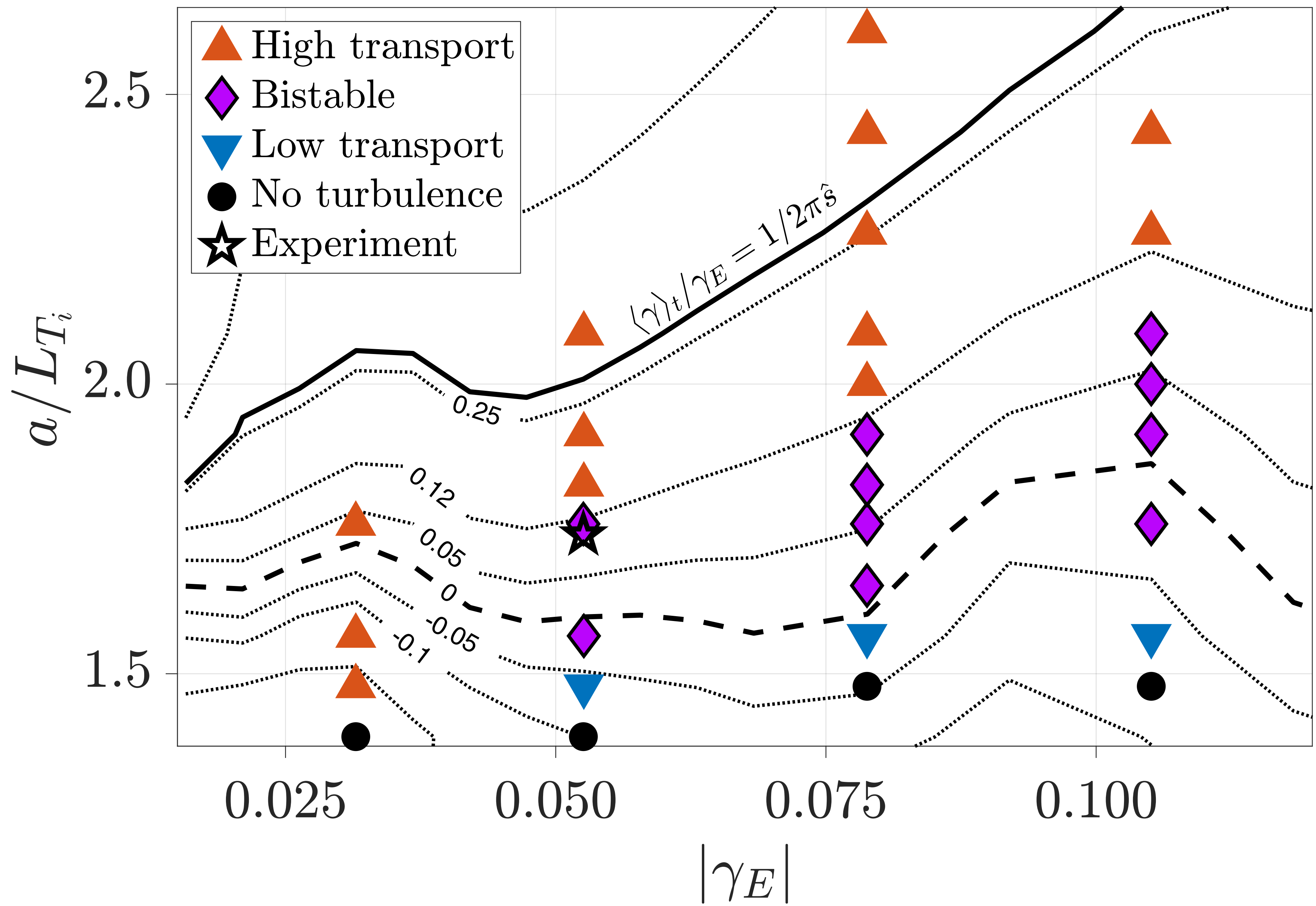
Checking assumptions (I)



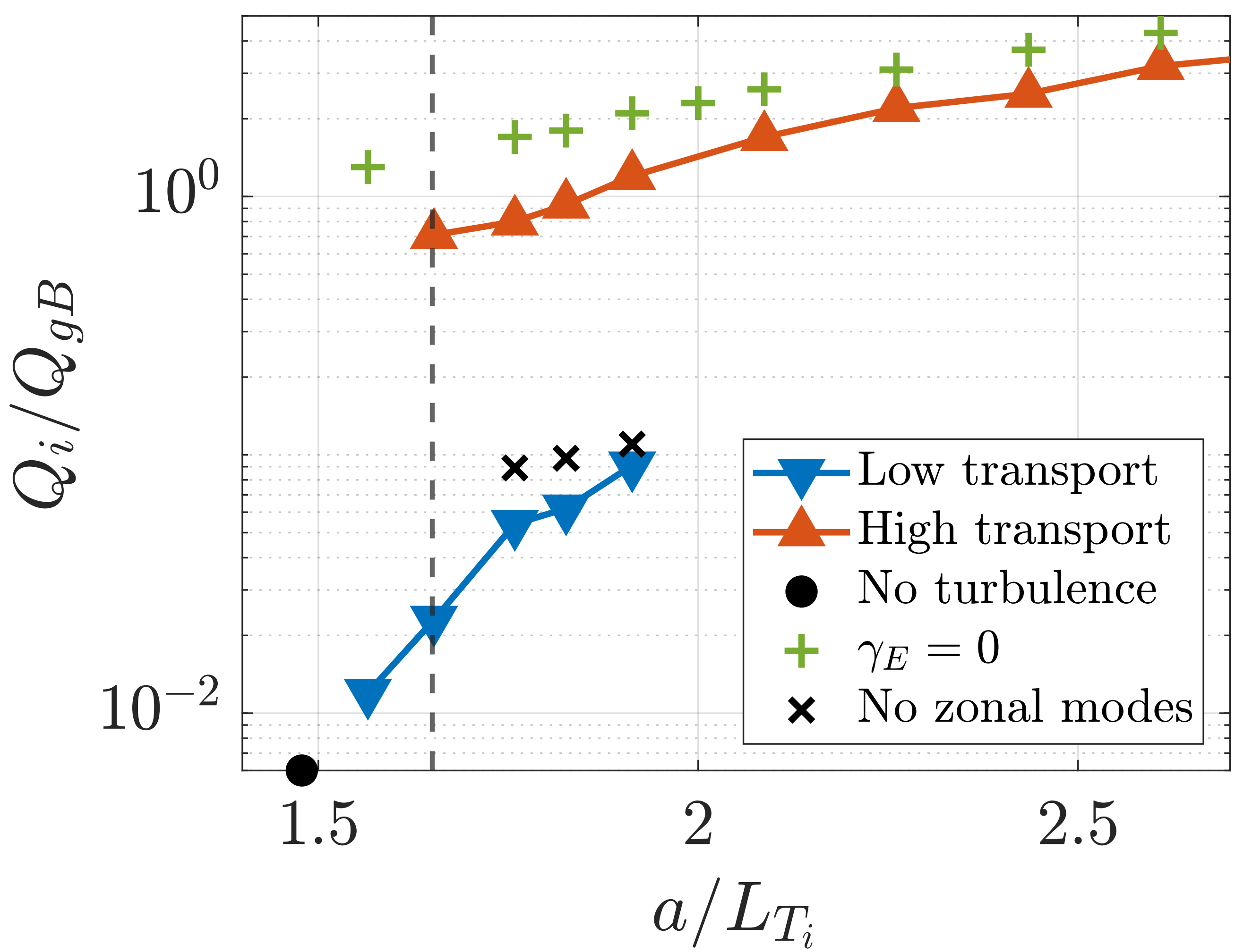
Checking assumptions (II)



Region of bistability

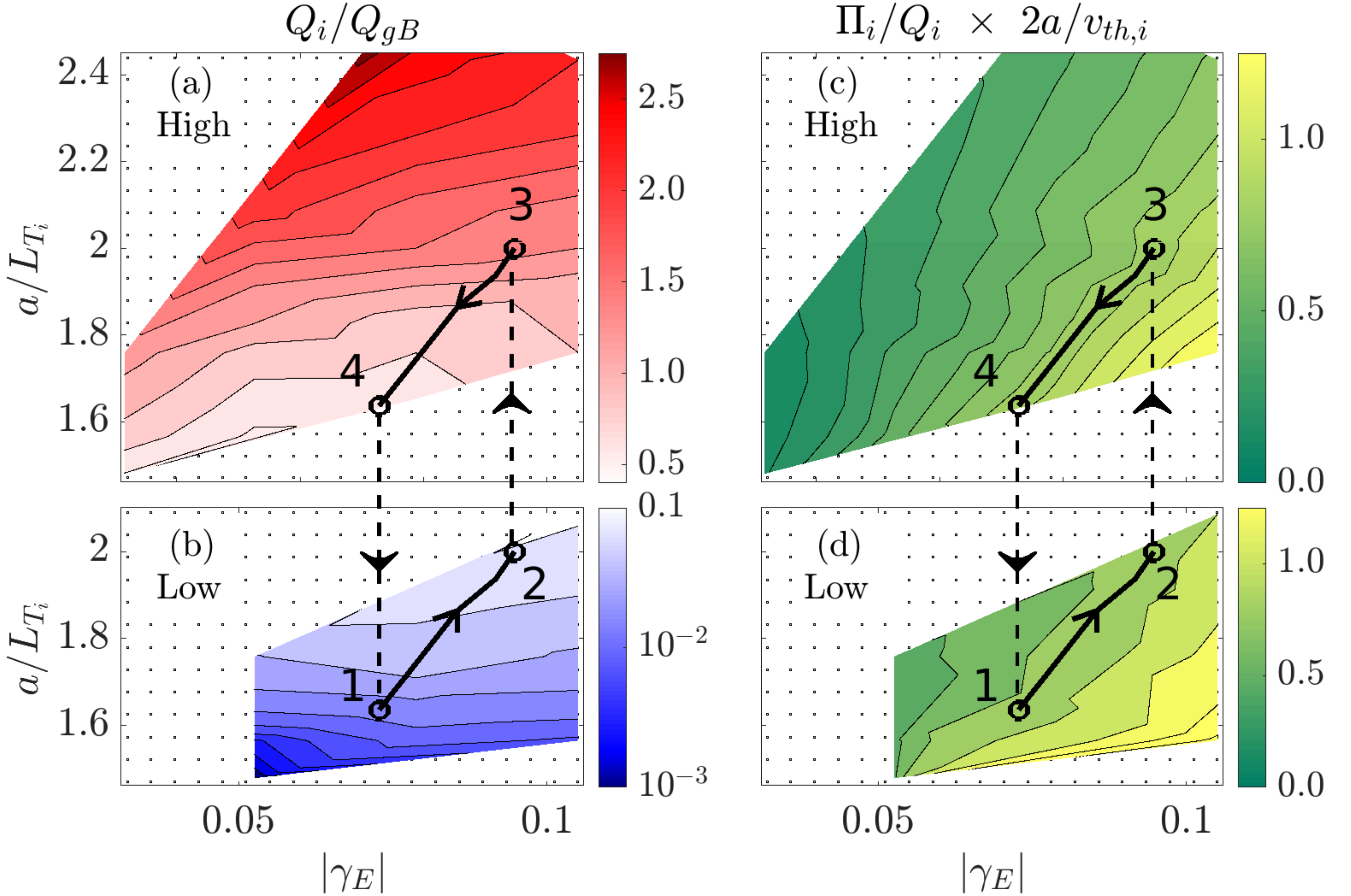


Consequences: forbidden region in local simulations

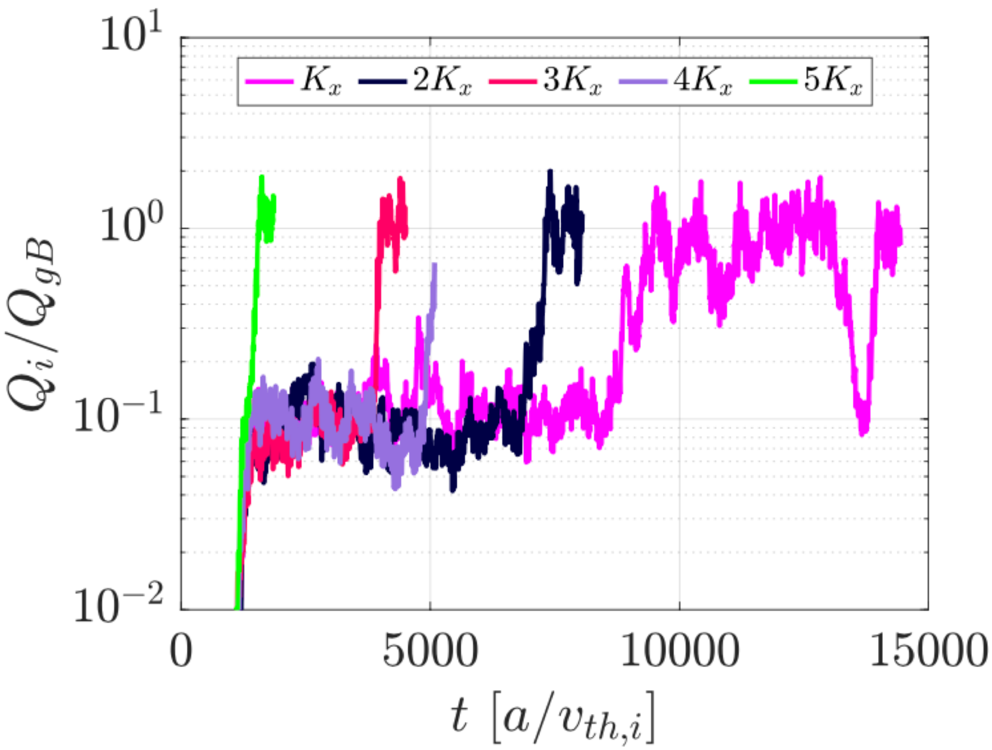


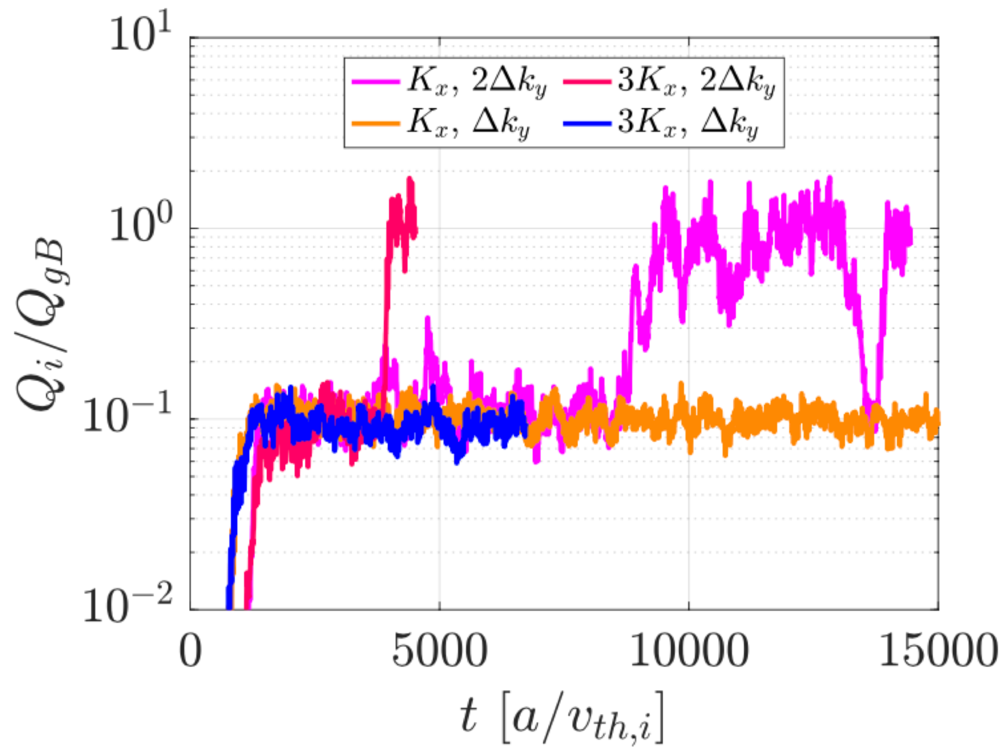
See also Weikl PoP 2017 for forbidden region near Dimits threshold

Consequences: relaxation cycles?

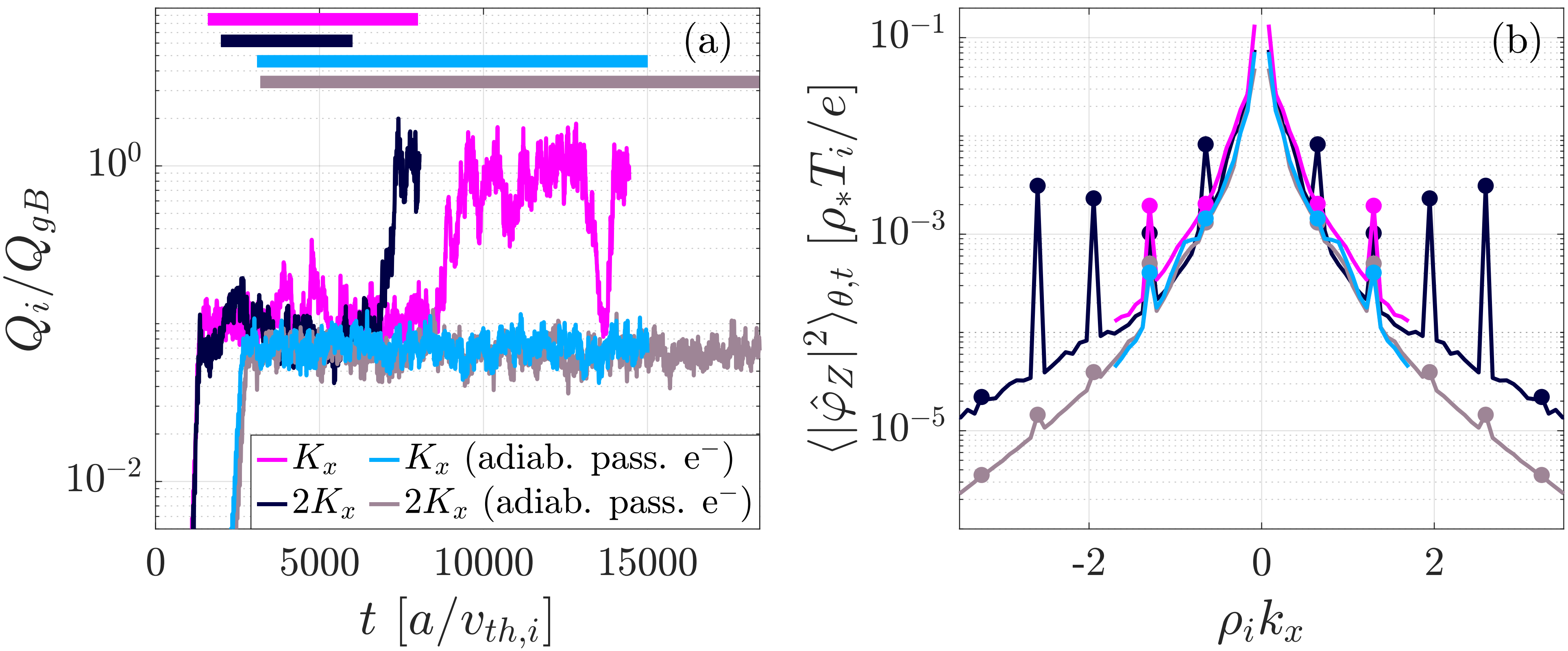


Fragility of bistable states near boundary

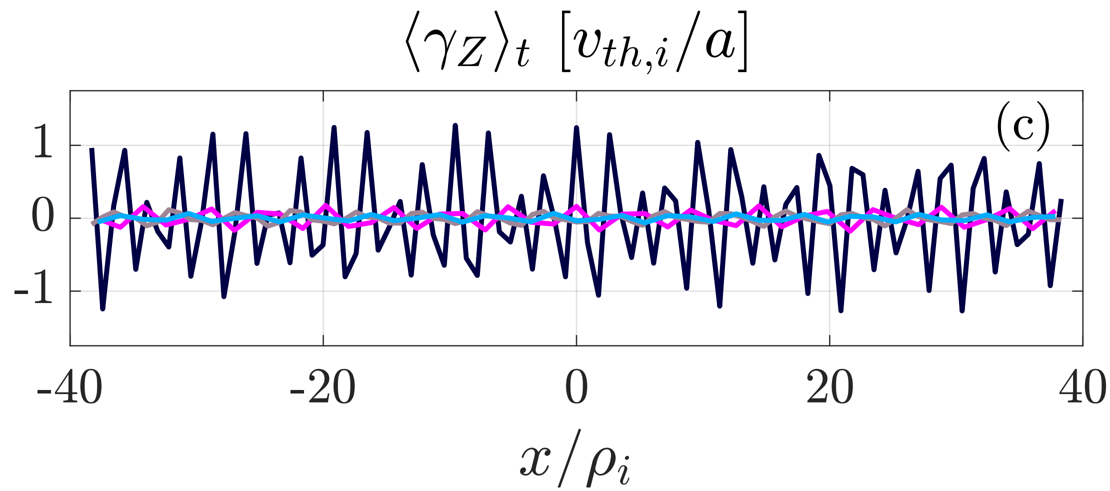




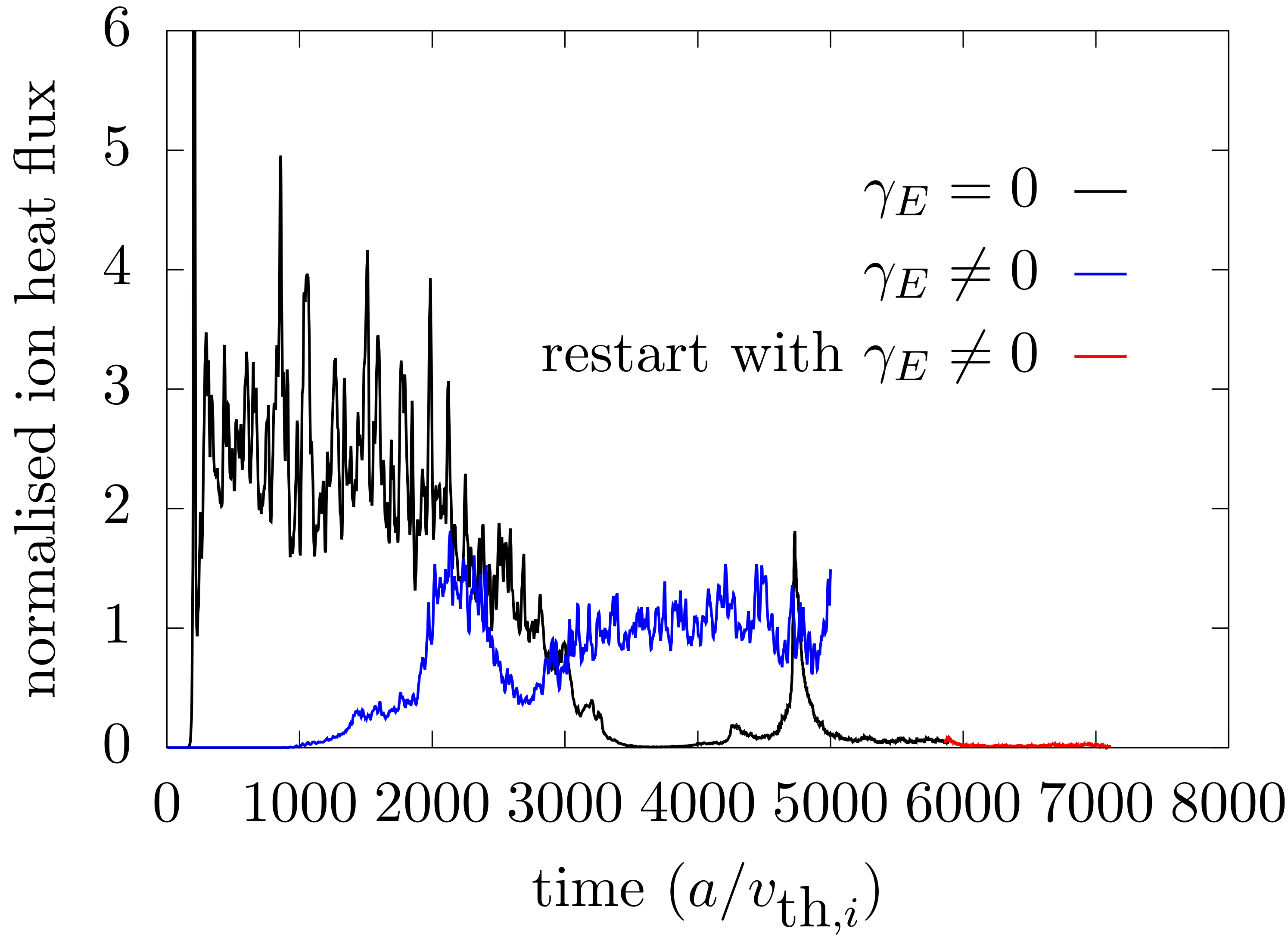
Impact of mode rational surfaces



Cf. Candy PoP 2005,
Dominski PoP 2015,
Weikl PoP 2018,
Ajay C. J. JPP 2020,
Ball JPP 2020

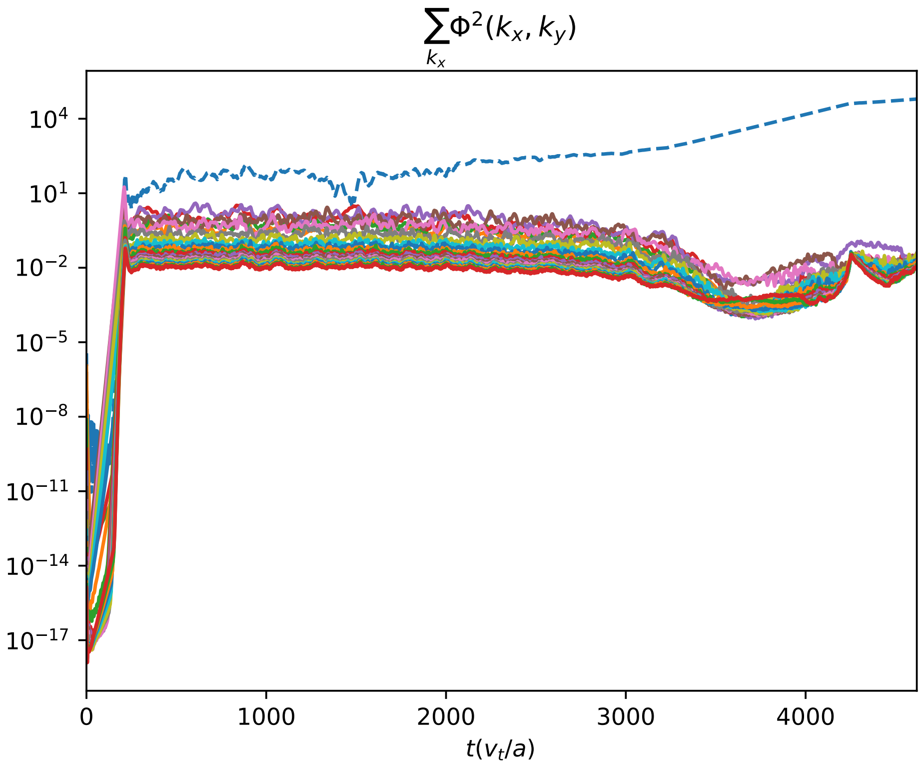


And now for something completely different…

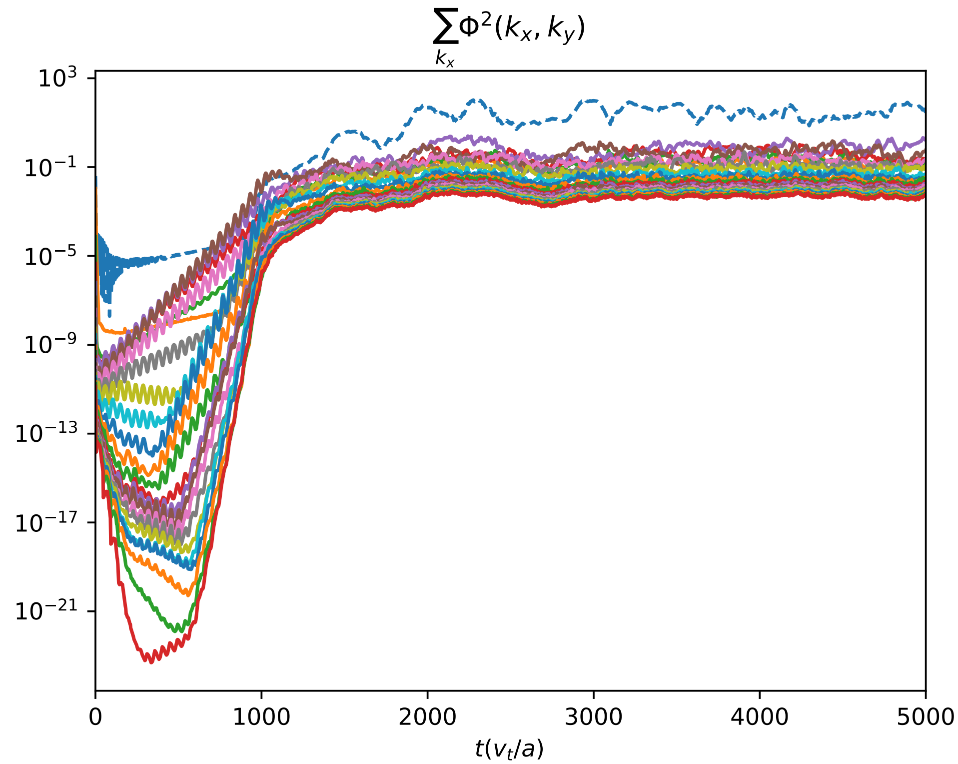


Same simulation parameters, but deforming flux surface to have concentric circles

No long-time zonal flow growth in system with mean flow shear

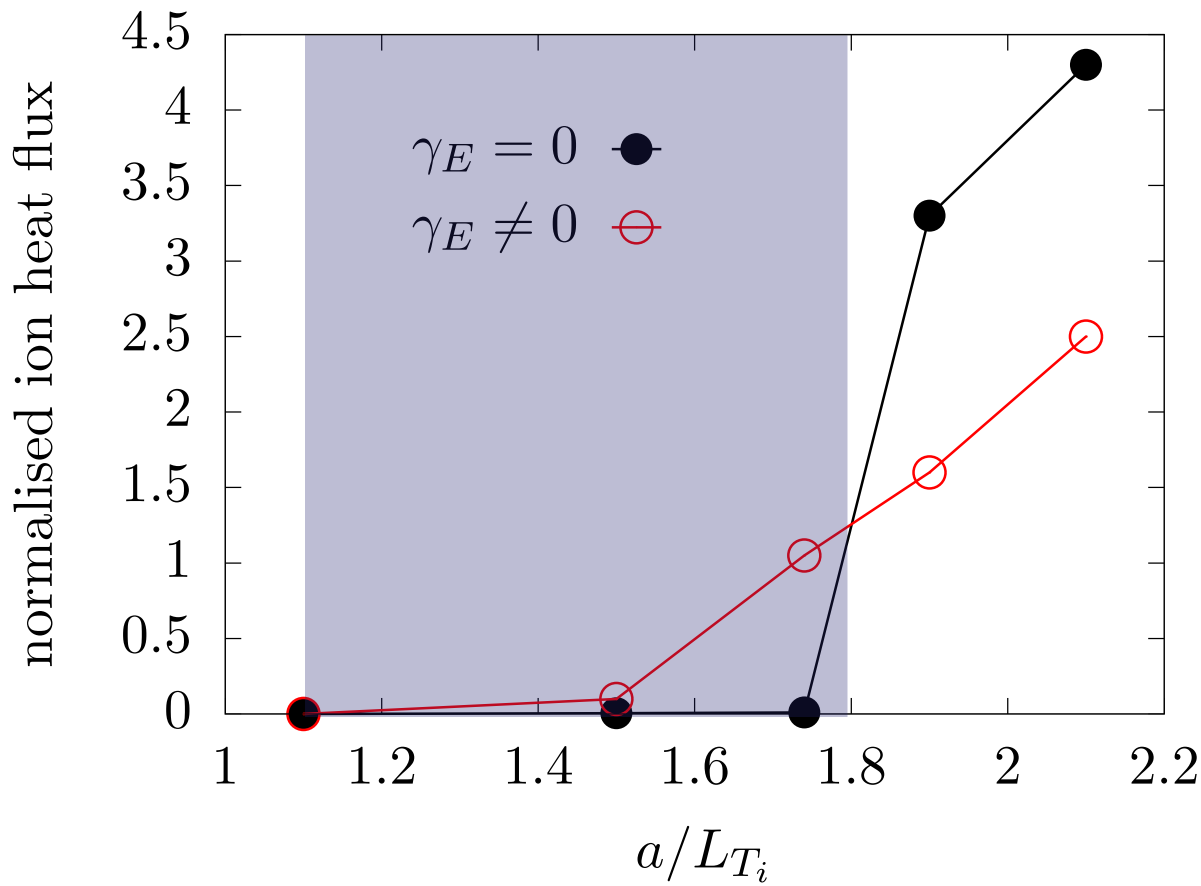


Without mean flow



With mean flow

Consequences for Dimits shift and beyond

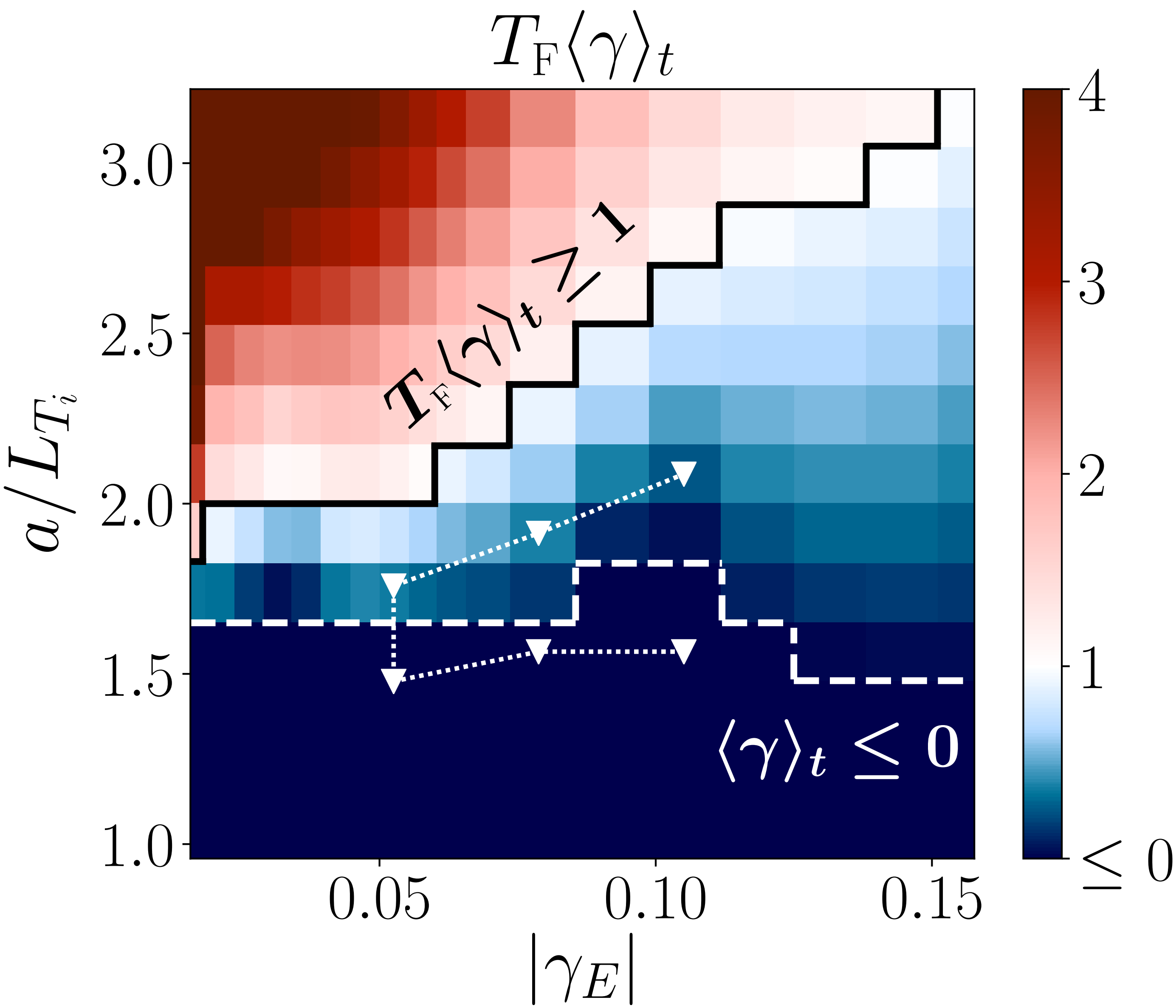


Inclusion of γ_E at outset eliminates discontinuous jump in fluxes reported in Weikl PoP 2017

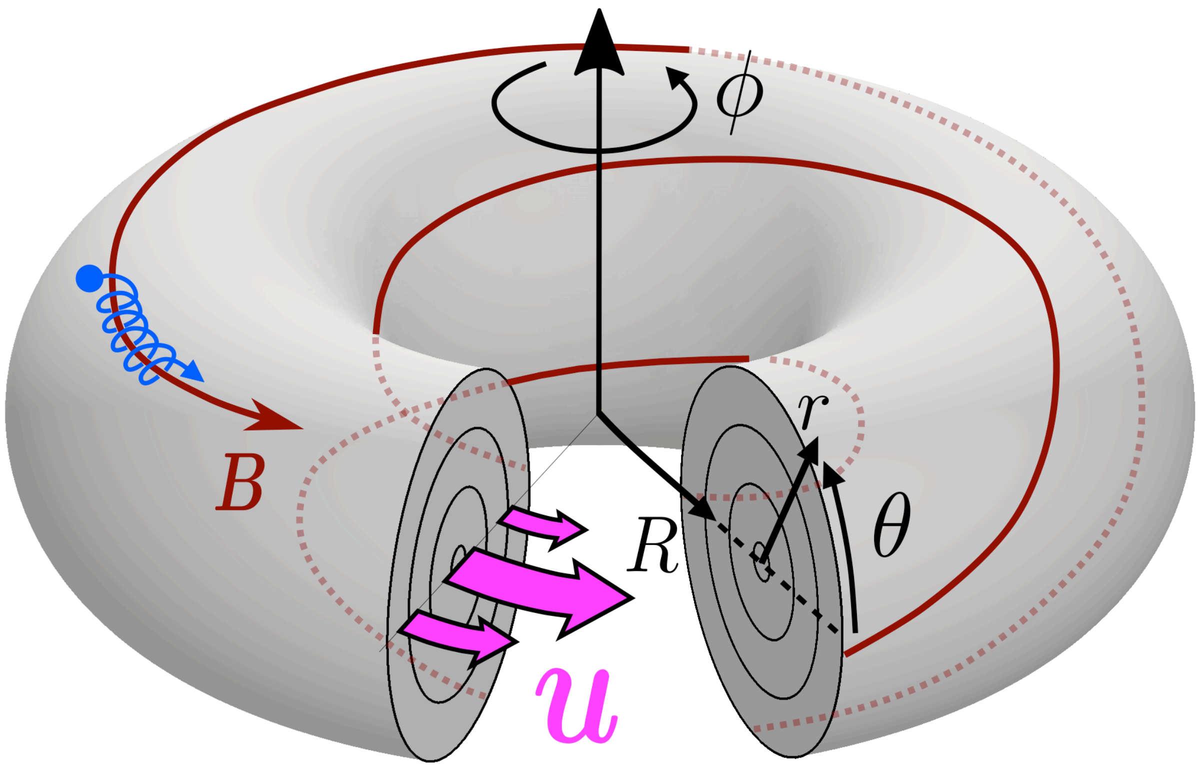
Summary and open questions

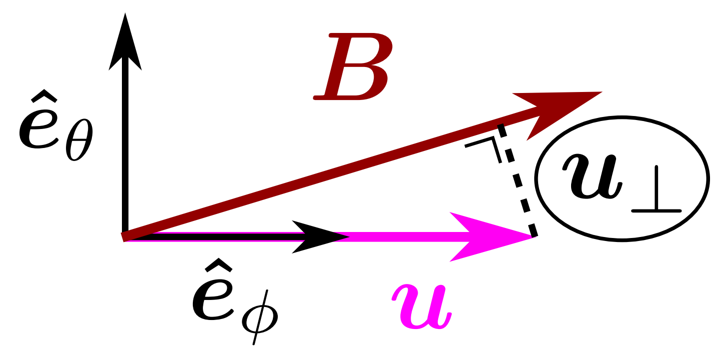
- Multiple turbulent steady-states can be obtained for the same plasma parameters in the presence of mean flow shear
- Competition between mean and zonal flow shear key for states we have observed
- What determines the appearance of bistable turbulence?
- Are there experimental signatures that can distinguish between bistable states?
- Do we really care about bistable turbulence? Ubiquity? Fragility? Usefulness (or inconvenience) experimentally or numerically?

Checking assumptions (II)



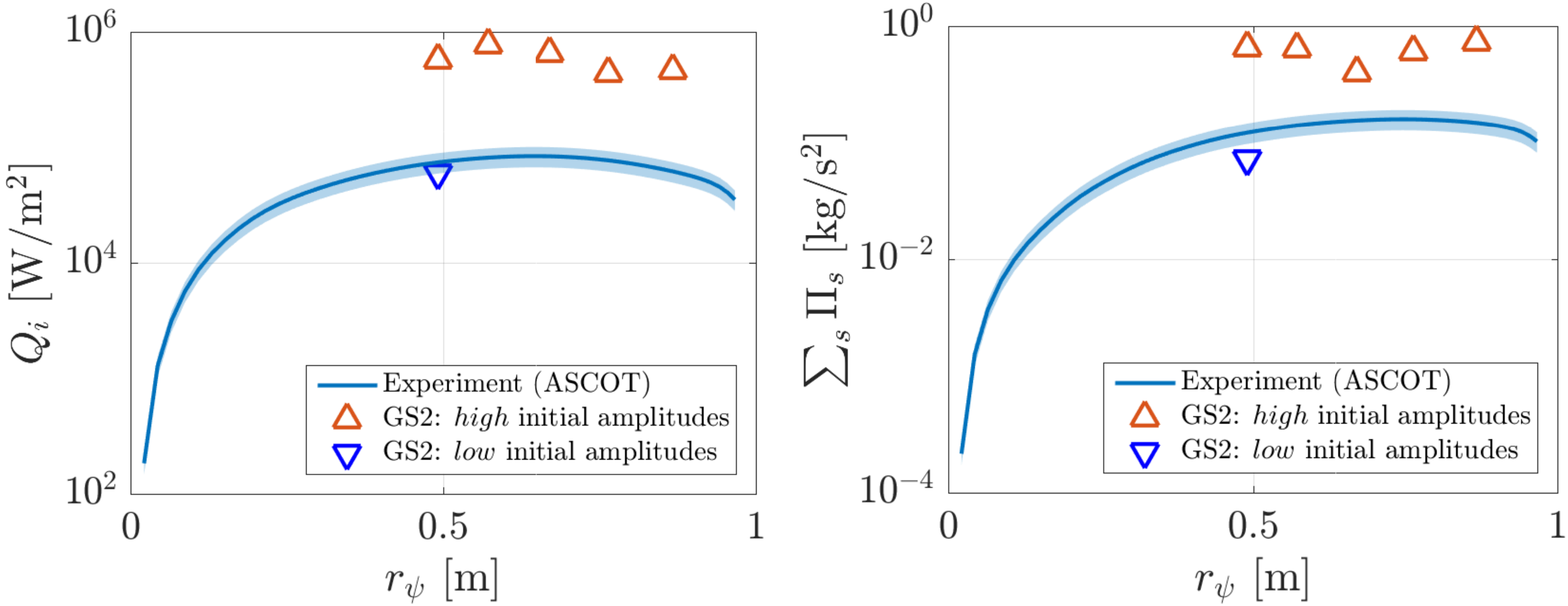
Two types of flow shear: **mean** and zonal





- Plasma free to rotate about symmetry axis: sheared toroidal rotation of flux surfaces (γ_E)
- Evolves on equilibrium space-time scales

Motivation: numerical observation of bistable turbulence and comparison with experiment



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