Modelling multi-scale interaction in sheared turbulence: transport barriers, self-organisation, and intermittency

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A need for statistical theory of plasma turbulence has significantly grown over the past decade with accumulating evidence from simulation and experiments showing highly intermittent and bursty turbulent transport. Probability distribution functions (PDFs) inferred from these experiments are strongly non-Gaussian, especially in the tails caused by rare events of large amplitude. For instance, exponential scalings appear to be a robust feature of the tails of heat, particle and momentum fluxes in a variety of tokamaks. These observations thus suggest that Gaussian statistics and average transport coefficients based on a mean field theory badly fail in capturing essential transport processes of intermittency, demanding a proper nonlinear theory for events of large amplitude. Given the potentially disastrous impact of these events on confinement, a predictive theory of the PDF tails thus cannot be overemphasized.

While these structures mediate significant transport, they can also play a complementary role of inhibiting transport. The improvement of plasma confinement by shear (mean and zonal) flows and the formation of transport barriers are important examples to be noted. Given the importance of structures in intermittency and transport, the PDF of the formation of structure itself is a quantity of ultimate interest. For instance, an interesting issue is the prediction of the PDF of shear flows to understand L-H transition.

Here, we present a non-perturbative statistical theory of intermittency and self-organization in multi-scale turbulence. First, we present an analytical statistical theory of intermittency in plasma turbulence based on short-lived coherent structures and predict intermittent exponential PDFs of fluxes. Second, we predict the PDF of self-organised shear flows. Specifically, the PDFs of the local shear are calculated numerically and analytically non-perturbatively in reduced 1D and 0D models where the PDFs are shown to highly intermittent and to converge to a bimodal distribution in case of finite correlated forcing. This bimodal PDF are shown to result from a self-organizing shear flow with linear profile. We confirm these results by nonlinear simulation of 2D hydrodynamic turbulence where similar bimodal PDFs are found. Furthermore, we demonstrate that shear flows self-organise into a quasi-equilibrium state as its growth of shear is balanced by shear relaxation. Our theory can provide a powerful mechanism for ubiquitous exponential scalings of the PDFs, often observed in various tokamaks. Implications of the results, in particular, on structure formation are discussed.