Regimes of steady state turbulence in a quantum fluid

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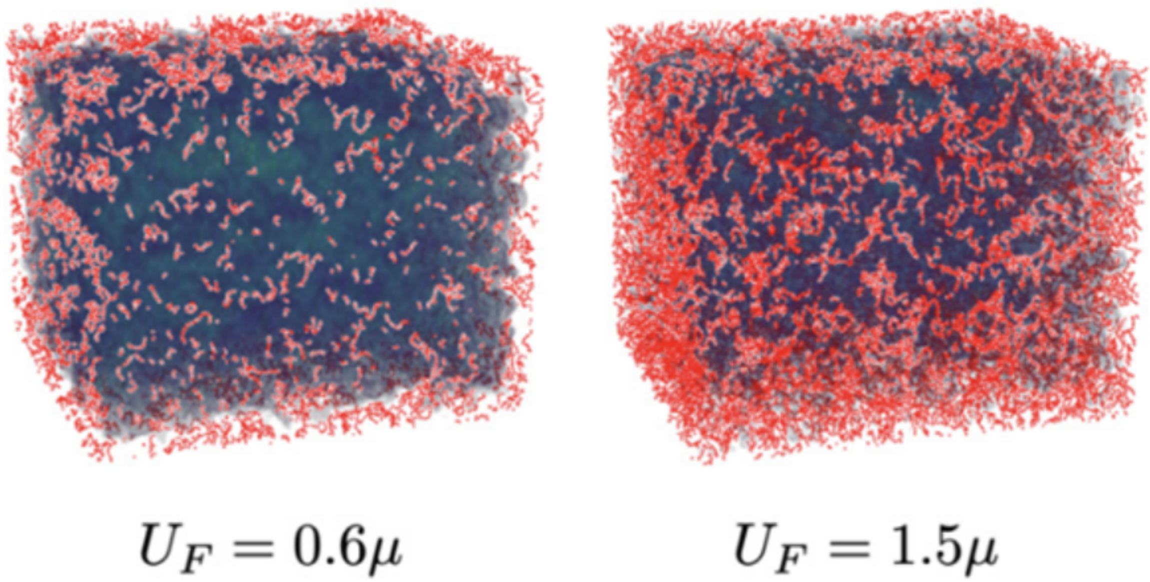
Finite-temperature quantum fluids support coupled wave and vortex excitations, yet the regimes governing steady-state turbulence and their associated scaling laws remain incompletely understood. We investigate turbulence in a driven, dissipative Bose–Einstein condensate using large-scale simulations of the Gross–Pitaevskii equation in a box trap, with energy injected via anisotropic forcing and removed at high momenta.

By varying the forcing strength relative to the chemical potential, we identify three distinct steady-state regimes characterized by their spectral scaling, vortex structure, and coherence properties. For weak forcing, the system remains largely vortex-free and exhibits a robust $k^{-3.5}$ wave-action spectrum over a decade in wavenumber, consistent with a direct cascade of Bogoliubov excitations. In an intermediate regime, bulk vortices proliferate and no clear power-law scaling is observed, marking a transition from wave- to vortex-dominated dynamics. For strong forcing, the condensate develops a dense vortex tangle with coherence reduced to the healing length, and the compressible spectrum approaches a $k^{-7/3}$ scaling consistent with an inverse cascade driven by small-scale vortex annihilation.

A phase-resolved spectral decomposition reveals the distinct roles of compressible excitations, vortices, and quantum pressure across these regimes. These results provide a unified picture of steady quantum turbulence, connecting wave turbulence and vortex turbulence within a single driven-dissipative framework.



References:

T. Fischer and A. S. Bradley, Regimes of steady-state turbulence in a quantum fluid, Physical Review A 111, 023308 (2025)

A. S. Bradley, R. K. Kumar, S. Pal, X. Yu, Spectral analysis for compressible quantum fluids, Physical Review A 106, 043322 (2022)