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Solvable Random Unitary Dynamics in a Disordered Tomonaga-Luttinger Liquid

Tiangang Zhou and Thierry Giamarchi

University of Geneva

Disordered one-dimensional interacting systems have long been characterized through conventional correlation-function observables. A complementary perspective from quantum information theory uses the frame potential to quantify the randomness of the unitary ensemble generated by a quantum system, yet no analytical treatment has so far been achieved for interacting one-dimensional systems. In this Letter, we derive a closed-form, nonperturbative expression for the frame potential of a Tomonaga-Luttinger liquid with quenched Gaussian forward-scattering disorder. Exploiting the exactly quadratic structure of the disorder-averaged Keldysh action, we show that the frame potential ratio decays as a power law at early times and saturates to a late-time plateau controlled by a single coupling parameter. Strongest randomness is achieved near the Heisenberg ferromagnetic point and can be exponentially enhanced through a multiple-quench protocol. We validate our results against the microscopic random field XXZ spin chain across the entire gapless phase, with direct implications for algorithm design in analog quantum simulation platforms.