Chaos and Ergotropy: Dichotomy Across the Integrability-to-Chaos Transition

J. Bharathi Kannan, P.G Sreeram and M. S. Santhanam

Department of Physics, IISER, Pune

How does chaos influence ergotropy—the maximum work that can be extracted from a quantum system through unitary evolution? This question is fundamental to quantum statistical physics. It also has practical relevance for quantum batteries, where charging and discharging involve energy storage and controlled work extraction. Understanding this interplay is crucial for optimizing energy extraction in chaotic quantum systems. We have demonstrated a dichotomy in the effects of chaos on ergotropy [1]. Since chaos generally enhances entanglement, one might naturally expect it to increase ergotropy as well. However, our findings reveal a more nuanced picture—chaos can either assist or inhibit ergotropy, depending on the observer's knowledge of the system. When the observer has full knowledge of the state, and an ancilla-assisted setup is used, chaos enhances ergotropy by leveraging entanglement growth.

However, when the state is partially unknown, two competing effects emerge—while chaos enhances ergotropy, it simultaneously obstructs state characterization through coarse-grained measurements. This interplay gives rise to an optimal balance, resulting in a sweet spot in the chaos parameter where maximal work extraction occurs. We demonstrate this phenomenon using standard quantum chaos models, the kicked top and kicked Ising chain. Additionally, we extend this idea to more general random matrix ensembles that exhibit a transition from integrability to chaos [2]. Our findings suggest that quantum chaos-assisted batteries could enhance energy extraction. While the chaotic regime is often viewed as detrimental to quantum computing, our results highlight its potential for next-generation energy storage devices, emphasizing the need for further exploration of chaos-assisted battery designs.

References

[1] Sreeram PG, J Bharathi Kannan, S Harshini Tekur, and MS Santhanam. Dichotomy in the effect of chaos on ergotropy. *Physical Review B*, 111(5):054314, 2025.

[2] J Bharathi Kannan, Sreeram PG, and MS Santhanam. Ergotropy across the integrability-chaos transition in random matrix ensembles. *Manuscript under prep.*