Summary

Thermodynamics is one of the founding scientific pillars that has helped us better understand heat engines, biology, ecosystems, and even black holes. While it fundamentally describes large systems by examining the bulk behavior of their constituents, it is anchored in the statistical equivalence of equilibrium configurations of a formally infinite number of microscopic constituents. A question of its validity arises when one scales down to small quantum systems. Here, we have derived dynamic non-equilibrium relations that surprisingly resemble the classical thermodynamics laws, with a mix of quantum features that encode the dynamics of quantum information. Understanding the relation between post-quench dynamics of finite-size quantum systems and their initial thermodynamic state might have been a purely academic exercise fifteen years ago. But now, thanks to ultra-cold atomic quantum simulators and progress in quantum computers, the thermodynamics of finite-size quantum systems has practical implications too. The findings of this thesis contribute to understanding quantum many-body systems, particularly in the context of entanglement, non-equilibrium dynamics, thermalization, and charge transport.

Chapter 2 focuses on the out-of-equilibrium dynamics of two initially thermal and independent reservoirs of Fermi gas that are quench-coupled and, after a short time, decoupled again. Those quenches lead to an energy gain in both systems, regardless of the initial temperature imbalance, and the quenches' work is proportional to the mutual correlations of the systems, expressed through their von Neumann entropies. Based on this finding, in a follow-up paper, we showed that on the timescale of the Fermi time, the von Neumann entropies grow faster than the thermal transport between the systems. In the same work, we proved that the time-frame and temperature regime of this phenomenon are experimentally accessible in ultracold atoms, providing a platform for the measurement of quantum correlations.

Then, in Chapter 3, we studied the post-quench dynamics of two other classes of systems. Firstly, we analyzed the Sachdev-Ye-Kitaev (SYK) model, a toy system for strong quantum correlations, and proved that the same early-time energy increase appears for any temperature and system size, however, there is no thermal flux from the colder to the hotter system. Through the relative entropy, we were able to show that the initial thermal state is not immediately destroyed, which

refuted a previous claim that such a quench can heat a system with a colder bath. Then we studied a quench between two Mixed Field Isings (MFI) and demonstrated that the initial energy increase appears for all temperatures only when the systems are tuned to the quantum critical point, otherwise, we discovered a transition temperature above which the energy of the hotter system decreases right after the quench, re-establishing our classical intuition. Additionally, we have shown that in the thermodynamic limit, the energy increase persists only for highly entangled systems, like the SYK or MFI at the critical point, but is absent for generic quantum systems. This proves that the early-time quantum behavior does not contradict the late-time classical evaporation.

In Chapter 4, we analyzed the time evolution of the energies and how it relates to the before-quench state of the systems. By expanding the density matrix in a time series, we showed that when systems start from a thermal state, the early time evolution of the SYK is purely determined by the thermodynamics state. The situation is more complicated when the systems under consideration are Mixed Field Isings, whose energy evolution additionally depends on particular correlations within the individual systems. This provided an analytical explanation of the results presented in Chapter 3 and a better understanding of the appearance of a system-dependent transition temperature, above which the energy of the hotter MFI does not have a post-quench increase.

Chapter 5 turns the attention to charged SYK systems and explores the applicability of the same quench protocol in the experimental detection of a laboratory realization of an SYK. We found that the dynamics of the discharging process of the SYK quantum dot reveal a distinctive characteristic of the SYK non-Fermi liquid state. For example, when analyzing the quench-induced tunneling current between a charged SYK and a neutral reservoir, there is a temperature-dependent contribution to the current's half-life, which, at low temperatures, scales as T for the SYK and as T^2 for Fermi liquids. This provides an experimental feature for differentiating an SYK state from a conventional charged system. Additionally, we link this feature of the SYK current to the prominent observation of a linear in T resistivity of strange metals, which aligns with other reported results on conductivity in SYK chains.