Simulating non-equilibrium quantum matter in the highly entangled regime

Implementing reliable quantum computers is one of the most challenging goals of modern scientific research. A key step towards their realization requires the ability to generate and control entanglement in quantum many-body systems. Understanding how entanglement is created and how it grows in diverse quantum systems is then of the uttermost relevance for the further development of the field. While ergodic quantum matter is known to quickly reach thermal equilibrium, and consequently scramble local information through a fast entanglement growth, its non-ergodic counterpart presents a rather different behavior. In the paradigmatic example of many-body localization (MBL), due to the presence of disorder local information is maintained for extremely long times and entanglement grows slowly. Thanks to the logarithmic slow growth of entanglement, MBL systems can be efficiently simulated using classical algorithms, such as tensor network techniques, allowing the study of their dynamics in large systems and on long timescales.

In our work we investigate the outcome of the interaction of these two paradigmatic scenarios for quantum many-body systems: ergodicity, leading to thermal equilibrium, and many-body localization. In particular, we aim at understanding the stability of MBL in presence of weak coupling to an external environment, a relevant issue in view of ongoing experiments. The presence of small ergodic regions leads to high entanglement within the system. Due to the high entanglement, the simulation of the dynamics becomes extremely demanding, and to obtain reliable results the use of parallel-implemented algorithms is crucial.

Thanks to the resources of the PRACE HPC, we managed to capture the effect of small thermal baths on many-body localized systems in a variety of regimes and in unprecedentedly large systems. In particular, we show that when the coupling is strong, the bath is localized by the back-action of the MBL system, a phenomenon known as many-body localization proximity effect. Furthermore our results provide evidence for the stability of localization in the case of a bath composed by a single disorder-free particle, additionally showing the relaxation of the bath's localization as the strength of the interaction with the MBL system is decreased. Reducing the coupling strength, we also observe a qualitatively different entanglement formation throughout the system. At strong coupling entanglement grows only in the neighboring regions of the bath, however, as the interaction is weakened the system starts generating entanglement more homogeneously. We further investigate the effect of increasing the number of degrees of freedom forming the ergodic region. As expected, a large number of thermal particles yields signatures of delocalization, characterized by a fast growth of entanglement and a partial loss of the initial information. Reducing the density of the disorder-free particles, however, results in a more stable localization, reproducing features akin to the ones observed in the single-particle bath case.

Thanks to the development of HPC techniques for the description of strongly entangled quantum matter, our research provides valuable insights into the high entanglement regime of non-ergodic quantum systems induced by the interaction with small thermal baths. The deeper understanding of the mechanism behind the MBL proximity effect can lead to a better control of current experiments, consequently improving the investigation of exotic phases of matter.