# PhD THESIS DEFENSE: "Quantum many-body approaches to non-conventional topological phases of matter"

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In recent years, the evolution of quantum technologies has resulted in an unprecedented control over individual quantum particles and many-body systems. This remarkable progress has given rise to a new era, marked by the convergence of classical and quantum methodologies to investigate fundamental questions concerning the nature of quantum matter, improving our understanding of the role of entanglement in solid-state systems or the mechanisms behind high-energy physics. From analog quantum simulators to digital quantum computers, these advancements hold potential across diverse domains.

This thesis explores the interplay between classical and quantum methods in understanding topological phases of matter. We concentrate on three distinct directions: non-conventional topological superconductors, interaction-induced topological phases in ultracold atom quantum simulators, and applications of variational quantum algorithms. Each trajectory relies on the combination of different techniques with the aim of understanding and characterizing topological phenomena in different settings.

Exploring non-conventional topological superconductors involves extending the paradigmatic Kitaev chain model by incorporating additional terms in the Hamiltonian such as long-range interactions and quasi-periodic potentials. This investigation is relevant to better understand the impact of real-world conditions on the both the topological and localization properties of systems hosting non-local Majorana modes, which are promising candidates for topological quantum computation.

In the realm of interacting systems, we explore the realization of interaction-induced topological phases in systems of ultracold atoms in optical lattices, both in one and tw dimensions. The remarkable control and versatility of such platforms enable the simulation o both theoretical topological models and strongly correlated physics. Notably, the interpla between interactions and topology can give rise to intriguing phenomena, such a delocalized fractional charges and gapless topological phases, challenging existing intuition We employ advanced numerical methods based on tensor networks to benchmark th experimental proposals that open the door to the realization and detection of nove many-body phases of matter, including topological quantum critical points and higher-order topological Peierls insulator in Bose-Hubbard models with long-rang interactions

Variational quantum algorithms, conversely, have the potential to efficiently tackle a wid range of problems, including ground state search, phase classification or accessin topological invariants. Despite current limitations in trainability and scalability, these hybri classical-quantum algorithms provide practical insights into current quantum hardwar capabilities and can inspire future architectures. We explore the application of variationa quantum algorithms to shed light on topological phenomena, raising questions about thei ability to discern topological phase transitions and compute topological invariants i situations where classical approaches fail

This thesis presents a comprehensive exploration of distinct approaches to topologica quantum matter by leveraging quantum technologies and quantum-inspired classica algorithms. Our results not only advance our understanding of quantum systems but als pave the way for the realization and discovery of novel physics extending to quantu information processing, materials science, and beyond.

**Hosted by:** Prof. Dr. Maciej Lewenstein