Quantum Spin Liquids and other nontrivial low-dimensional spin structures

In the last decades, condensed matter physicists have discovered an unknown land of surprising states of matter. States, which are very different from traditional solids, liquids, and gases. All matter is made up of building blocks, elemental, such as electrons, and complex, such as atoms. When many of them come together in a material, they start to interact. And these interactions along with their inherent quantum nature, lead to these unexpected states.

As the temperature changes, the state of matter starts to change. When it is sufficiently low, thermal effects fade away, and the manifestation of the quantum-mechanical nature of the matter constituents becomes apparent. This is the *terra incognita*, which we only recently began exploring. It exhibits new kinds of emergent order and exotic properties related to topology and symmetry, entanglement and frustration, fractionalization and deconfinement, etc. This exotic behavior is particularly pronounced in two-dimensional systems, which are predicted to host exotic quasiparticles obeying *anyonic* statistics, different from the well-known fermionic and bosonic. Low-dimensionality also enhances quantum fluctuations, which may prevent formation of a long-range order down to zero temperature. As a result, a very interesting state, called *quantum spin liquid* (QSL), can be formed.

QSLs are an intriguing and highly attractive phase of matter because of several unique and compelling properties that make them significant for both theoretical research and potential practical applications. They represent a state of matter where spins remain in a fluid-like disordered state even at absolute zero temperature. The strong quantum entanglement present in QSLs offers a natural playground for studying the principles of quantum information theory. Understanding how entanglement works in these systems can provide insights into quantum error correction, entanglement entropy, and other foundational aspects of quantum mechanics. The non-Abelian anyons that can emerge in certain QSLs are promising candidates for topological quantum computing. Their non-local encoding of information makes them inherently resistant to local sources of decoherence, a major challenge in building practical quantum computers.

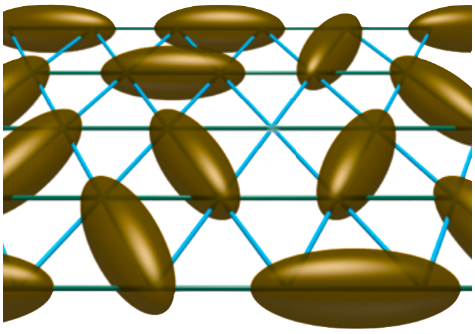

FIG. 1: Artistic illustration of fluctuating bonds in a QSL.

QSL is only one example from the entire zoo of exotic phases that are observed or theoretically predicted in two-dimensional quantum systems. There are many more, but all they are formed due to strong interactions between electrons. Unfortunately, despite the attractiveness of these phases, the strong interactions render their theoretical study very difficult. Although models which we use to describe these systems are quite simple to write down, they prove very complicated to solve. Apart from a few special cases, they cannot be solved analytically. Numerical calculations are also extremely difficult: The exponentially large size of the Hilbert space prevents an exact diagonalization and the fermion sign problem makes Quantum Monte Carlo methods inefficient. However, the rapid increase of modern computing power and the development of computational algorithms open new possibilities. In this project, we will exploit these possibilities by developing and applying new computational methods to study the exotic quantum phases of two-dimensional systems. One of the novel techniques that we will use is Machine Learning, a part of artificial intelligence. We plan to use this family of approaches in two ways: one is to develop new methods for studying correlated quantum systems, and the other is to improve the efficiency of more “traditional” methods, such as quantum Monte Carlo. We expect that these new and improved methods will allow us to study systems that until now were beyond the reach of the currently available methods. In particular, we will try to answer a few important questions about the nature of spin states in strongly interacting two-dimensional quantum systems. Our research will focus, among others, on topological matter and quantum critical spin liquids. These emergent states feature long-range quantum entanglement that can be potentially exploited to realize robust quantum computation.

With close contact with experimental results, we hope to make significant progress in understanding the mechanisms responsible for the unconventional behavior in these novel and technologically important materials.