Centre for Quantum Science & Technology Theory - 2025 Honours Projects

1. Theory of One-Dimensional Fermi/Bose Polarons

Supervisors: A/Prof Hui Hu, Prof Xia-Ji Liu, and Dr. Jia Wang (hhu@swin.edu.au)

Project description: The theory of strongly interacting fermions/bosons is of great interest. Interacting fermions/bosons are involved in some of the most important unanswered questions in condensed matter physics, nuclear physics, astrophysics, and cosmology. Though weakly interacting fermions/bosons are well understood, new approaches are required to treat strong interactions. In these cases, one encounters a "strongly correlated" picture which occurs in many fundamental systems ranging from strongly interacting electrons to quarks.

This project will consider a simplified case of "polarons", which involves one impurity immersed in a background of N fermions or bosons. In this N+1 problem, the strongly interaction between impurity and background atoms might be handled. To further simplify the problem, we will focus on the one-dimensional situation by using the Bethe Ansatz technique. The results of this project can be tested in future cold atom experiments.

[1] Hui Hu, Peter Drummond, and Xia-Ji Liu, ***Nature Physics*** 3, 469 (2007).

2. Few-body physics and virial expansions

Supervisors: Prof Xia-Ji Liu, A/Prof Hui Hu, and Dr. Jia Wang (xiajiliu@swin.edu.au)

Project description: Few-body systems have become increasingly crucial to the physics of strongly correlated ultracold atomic gases. Because of large interaction parameters, conventional perturbation theory approaches such as mean-field theory, simply break down. A small ensemble of a few fermions and/or bosons, which is either exactly solvable or numerically tractable, is more amenable to non-perturbative quantal calculations. The few-body solutions can be efficiently used for investigating high temperature properties of strongly correlated quantum gases, through the well documented virial expansion method. This Honours project will investigate few-body exact solutions and high-temperature properties of ultracold atomic gases with s-wave and p-wave interactions. In particular, the project will focus on the few-body solutions of a one-dimensional Bose/Fermi gas and obtain several low-order virial expansion coefficients.

[1] Xia-Ji Liu, ***Physics Reports***, Vol 524, Issue 2, Pages 37-83 (2013).

3. Ultradilute quantum droplets

Supervisors: A/Prof Hui Hu, Prof Xia-Ji Liu, and Dr. Jia Wang (hhu@swin.edu.au)

Project description: Over the past few years, a newly discovered phase of ultracold, dilute quantum droplets has attracted increasingly attention in different fields of physics. In sharp contrast to other gas-like phases in containers, quantum droplets are self-bound, liquid-like clusters of ten to hundred thousands of atoms in free space, formed by the delicate balance between the attractive mean-field force and repulsive force from quantum fluctuations. The purpose of this project is to develop better microscopic theories of quantum droplets and to solve some challenging theoretical difficulties in this field. This Honours project will focus on the theory of quantum droplets in low-dimensional and mass-imbalanced binary Bose mixtures. Furthermore, the project will explore collective excitations of an ultradilute quantum droplet.

[1] Hui Hu and Xia-Ji Liu, **Physical Review Letters**, 125 (19) 195302 (2020).

4. Ultracold Atoms with Synthetic Spin-Orbit Coupling

Supervisors: Prof Xia-Ji Liu, A/Prof Hui Hu, and Dr. Jia Wang (xiajiliu@swin.edu.au)

Project description: Recent realization of synthetic gauge fields in ultracold atoms, i.e., the creation of a spin- orbit coupling between the spin and the orbital degrees of freedom, has led to a new frontier that is endowed with a strong interdisciplinary character and a close connection to other research fields, including condensed matter physics, quantum computation and astrophysics. This Honours project will investigate the characterization of novel topological fermionic superfluids and possible exotic Bose-Einstein condensates (BECs) with non-trivial spin- textures.

[1] Hui Hu, B. Ramachandhran, Han Pu, and Xia-Ji Liu, **Physical Review Letters** 108, 010402 (2012).

5. Quantum Fluids of Light

Supervisors: Prof. Xia-Ji Liu, A/Prof. Hui Hu and Dr. Jia Wang (xiajiliu@swin.edu.au)

Project description: Polaritons - often referred to as quantum fluids of light – are half-light, half-matter “particles” that keep most characteristics of the underlying photons but also possess intrinsic nonlinearities for easy manipulation. Polariton – based novel photonic technologies such as energy - efficient polariton laser and practical optical transistor will someday radically improve our everyday life, similar to the monumental development of electronic transistor in the last century. In this project we will review recent development in this field and learn basic theoretical method to investigate quantum fluids of light.

[1] Hui Hu, Hui Deng, and Xia-Ji Liu, ***Physical Review A*** 106 (6), 063303 (2022)

6. Excitations of Quantum Droplets at dimension crossover

Supervisors: Dr. Jia Wang, A/Prof Hui Hu, and Prof Xia-Ji Liu (jiawang@swin.edu.au)

Project description: Quantum droplets, stabilized by quantum fluctuations, represent a fascinating quantum phenomenon—autonomous, self-bound systems that achieve equilibrium under zero pressure in free space. These droplets have been experimentally observed in two-component Bose-Einstein condensates (BECs) with inter-species interactions, as well as in dipolar BECs. Within these systems, the droplets exhibit collective excitations, which are categorized as bulk or surface modes, depending on the droplet’s finite size. A particularly intriguing aspect of small quantum droplets is the existence of an excitation-forbidden regime, where no bound collective excitations exist below the particle-emission threshold. The nature of these excitations plays a crucial role in determining the self-evaporation dynamics of the quantum droplet. In this project, we will conduct a systematic investigation of the collective excitations of quantum droplets as they transition from three-dimensional free space to lower-dimensional confinements, such as quasi-two-dimensional and quasi-one-dimensional geometries. By examining how these excitations evolve under varying degrees of spatial confinement, we aim to uncover deeper insights into the stability and dynamical behavior of quantum droplets. These findings may have significant implications for understanding exotic phases of matter in low-dimensional quantum systems.

7. Investigating the Scaling Law of Entanglement Entropy in Low-dimensional Systems

Supervisors: Dr Jia Wang, A/Prof Hui Hu, and Prof Xia-Ji Liu (jiawang@swin.edu.au)

Project description: Quantum entanglement, the non-classical correlation between separate systems, is a fundamental resource in quantum computation and information. Recently, it has also been recognized as a crucial element in understanding quantum phase transitions in many-body systems. The entanglement entropy of a free scalar bosonic field adheres to the well-known area law, initially explored in the context of black-hole physics. In contrast, Fermi liquids exhibit a subtle violation of the area law, featuring a multiplicative logarithmic correction. In this study, we aim to develop an exact method for calculating quantum entanglement in fermionic systems and apply it to investigate the scaling law in systems with effective fractional dimensions, such as quasi-crystals. Additionally, we plan to explore quantum entanglement in bilayer systems with twisted angles, with particular focus on the regime near the so-called "magic angle”, where the system's properties undergo dramatic changes.

8. Multidimensional Spectroscopy of Heavy Polarons in Quantum Hall Liquid

Supervisors: Dr Jia Wang, A/Prof Hui Hu, and Prof Xia-Ji Liu (jiawang@swin.edu.au)

Project description: When an impurity is immersed in a quantum medium, its behavior can be profoundly altered, leading to the formation of a quasiparticle known as a polaron. The properties of a polaron are fundamentally determined by the dispersion of excitations in the quantum medium. In the context of a quantum Hall liquid composed of non-interacting fermions, the system exhibits a macroscopic degeneracy in its single-particle spectrum. We have discovered that introducing immobile impurities into this system allows for exact solutions to the many-body polaron states and polaron-polaron interactions. However, to experimentally observe these polaron-polaron interactions, it is essential to identify their spectroscopic signatures. In this project, we aim to calculate these signatures in a multidimensional spectroscopy, a technique that measures the correlations between absorption and emission photons coupled to the system.

9. Coherent Ising Machine with quantum feedback and many-body interactions

Supervisors: Dr. Manushan Thenabadu, Dr. Jia Wang, Prof Magaret Reid, and Prof Peter Drummond (mthenabadu@swin.edu.au , jiawang@swin.edu.au)

Project description: Many computationally challenging (NP-complete or NP-hard) problems, such as the maximum cut problem (MAX-CUT) in a graph, protein folding, and the traveling salesman problem, can be mapped onto the Ising model with pairwise spin-spin interactions. The Coherent Ising Machine (CIM) is an effective optical computational device for solving these problems by finding the ground state of the corresponding Ising model. However, some NP-hard problems stem from the presence of many-body interactions in spin systems. For instance, the Boolean satisfiability (k-SAT) problem becomes NP-hard when $k \geq 3$, where k represents the order of interactions or constraints. In this project, we aim to investigate CIMs incorporating many-body interactions via a measurement-feedback scheme. We will implement and compare two techniques: the positive-P phase-space representation and the Monte Carlo Wavefunction method, to explore the effectiveness of these approaches in solving complex many-body interaction problems.

10. Quantum enhanced gradient sensing in optomechanics

Supervisors: Peter Drummond and Margaret Reid

Project Description: The topic is to investigate gradient sensing in opto-mechanics. These are cryogenic nano-cantilever systems that can couple to an optical cavity. They are driven externally, and damped internally. They can experience a non-equilibrium steady-state when input and output powers are equal. With recent technology improvements, such devices can be fabricated in a variety of configurations and topologies. The project will investigate different possible topologies, including rectangular arrays. The devices themselves can either be coupled to each other, or uncoupled. The objective of the topic is to investigate the potential applications of such novel arrays of interacting quantum systems. There is an analogy with quantum optics, in that a single opto-mechanical cantilever has the properties of an atom or molecule, but with much greater mass. As a terrestrial sensor, the cantilever design is the most practical, and an investigation will be carried out on the combination of Gaussian boson sampling techniques involving Fourier transforms to obtain quantum enhanced sensing of gravitational field gradients. Current experiments on optomechanical systems are operated at Oxford University (UK) and Caltech (USA, as well as at UQ, with proposed experiments at Sydney U. The use of optomechanical arrays is a new feature, with a fabrication facility at Caltech for silicon arrays. The largest gaussian boson sampling experiments are at USTC (China), Xanadu Corp/NIST (Canada/US), at Imperial College (UK) and Paderborn U in Germany. These are currently used for quantum computing. This project will investigate adapting QC to gravitational sensing.

11. AI code translation: Matlab to Julia

Supervisors: Peter Drummond and Run Yan The

Project Description: The topic is to investigate the use of artificial intelligence LLM to carry out a code translation project from Matlab to Julia. The target code is the xSPDE toolbox, which treats stochastic partial and ordinary differential equations. This is currently written in Matlab. The existing code computes averages, including time-step and/or sampling error estimation, with applications in biology, chemistry, engineering, medicine, physics and quantum technologies, as well as providing higher order convergence, Fourier spectra and probability densities. The advantage of Julia, a new language developed at MIT, is that it is faster and is a free open source project, as opposed to the licensed model of Matlab. While the two languages are similar, there are sufficient differences so that much of the code has to be rewritten. Recoding by hand is possible, but it is labor intensive, and can give errors. The project will investigate the use of artificial intelligence large language models to generate efficient Julia code. As xSPDE is modular, the project will only treat part of the entire package. The project will use as a reference, two earlier partial translations of xSPDE, and the goal is to obtain equal features and speed to earlier Julia codes. Provided testing benchmarks are achieved, a full translation may be feasible, leading to a complete Julia version. xSPDE is currently hosted on Github, and is used in the CQSTT theory group. Extending this to Julia could make it faster and much more widely available. The new version will then have its own Github open source project, provided that the pilot translation is successful.

12. Equation of state for hard cube and hard sphere models

Supervisor: Dr Nathan Clisby nclisby@swin.edu.au

Project description: The hard sphere model is the simplest non-trivial model in classical statistical mechanics: it is also called the billiard ball model of a gas, and involves spheres bouncing off each other elastically but otherwise not interacting. Fascinatingly, this model undergoes a freezing transition if you compress it, going from a gas to a crystalline state. A related model which is less physical but easier to work with is the hard parallel cube model, which involves cubes bouncing off each other instead. In this project you will be calculating virial coefficients for the hard cube and hard sphere models. For hard cubes, the calculations involve some fun combinatorics, and there is an opportunity to make significant progress on the state of the art. For hard spheres, the necessary calculations involve integrals over arrangements of spheres, and the goal is to calculate some quantities exactly for the first time. In each case there is a combination of mathematical and physical insight required, together with some computer programming or use of Mathematica, and your calculations will allow for deeper insight into the physics of these important systems.

13. Studies of self-avoiding walks

Supervisor: Dr Nathan Clisby nclisby@swin.edu.au

Project description: Self-avoiding walks are walks on a grid that never re-visit a previously visited site, and are the most fundamental model of polymer systems. Through the magic of universality we can discover exact information about real-world polymer systems by studying this highly idealised model! For example, we can study the typical size of a polymer with N atoms in the chain, which theoretical arguments demonstrate grows as N^ν, where ν is the so-called Flory exponent. Real-world light scattering experiments with polymers in solution have determined that ν = 0.59(1), while fast Monte Carlo computer simulations of self-avoiding walks using the pivot algorithm have determined that ν = 0.5875970(4) - a dramatically more accurate result. In this project you will perform Monte Carlo computer simulations of self-avoiding walks to explore interesting phenomena, including the effect of confinement on polymer behaviour. You will need to be willing to understand C code, run simulations, and analyse data, and if you are so inclined you will have the opportunity to develop and implement your own algorithms.