Non-equilibrium phenomena in unconventional Fermi superfluids

Superfluidity describes a state where a fluid flows without any resistance, defying our everyday experiences with liquids and gases. This remarkable phenomenon was first discovered by Kapitsa (1938) in liquid helium-4, which remains a liquid even at temperatures near absolute zero. Since then, superfluidity has fascinated physicists, not only for its fundamental implications but also for its potential applications in quantum technologies, such as ultra-sensitive gyroscopes and superconducting circuits. However, some of the most intriguing superfluid phenomena occur in the extreme environments of the universe, including the interiors of neutron stars and pulsars, where dense quantum fluids are expected to play a crucial role in their dynamics.

One of the defining features of superfluidity is the formation of quantized vortices, which are tiny whirlpools that behave unlike anything in classical fluids. These vortices are not just theoretical curiosities—they are responsible for how superfluids respond to rotation and how they transfer momentum. In neutron stars, vortex dynamics play a crucial role in the sudden changes in their rotation rate, known as pulsar glitches. But even in the controlled environment of laboratory experiments, understanding how vortices move and dissipate energy remains a major open question in modern physics.

This research focuses on vortex dynamics and dissipation in unconventional superfluid systems, particularly in ultracold quantum gases, where superfluidity can be precisely controlled and studied. In these gases, we can simulate extreme quantum conditions that may be impossible to reproduce elsewhere. One especially interesting scenario arises in spin-imbalanced superfluids, where an unequal number of quantum particles modify the usual superfluid state, potentially leading to new types of transport and dissipation effects. Another interesting case is multi-component superfluidity, where different types of particles can form new pairing mechanisms and give rise to exotic quantum phases.

A central question in this study is whether a controversial force, known as the Iordanskii force, plays a role in superfluid vortex dissipation. This force, if confirmed, could provide new insights into how quantum vortices interact with their environment and how energy is lost in strongly interacting quantum fluids. Beyond fundamental interest, understanding these processes could have implications for both quantum technologies and astrophysical systems, helping us refine models of neutron stars, pulsars, and other extreme quantum environments.

To tackle these questions, this project will develop advanced computational simulations using high-performance computing. By leveraging density functional theory approaches, we can model vortex dynamics with unprecedented accuracy and compare the results to cutting-edge experiments at the European Laboratory for Non-Linear Spectroscopy (LENS). This collaboration between theory and experiment aims to push the boundaries of our understanding of quantum superfluidity, bridging the gap between laboratory research and some of the most extreme and mysterious objects in the universe.