# Ground state properties of Fermi superfluids in the BEC-BCS crossover

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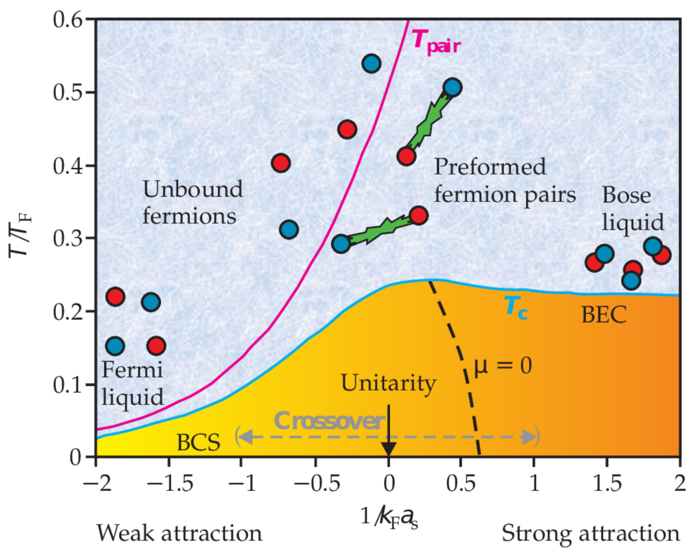
To achieve superfluidity in an ultracold Fermi gas, atoms need to pair up, and a pair condensate has to form. Depending on the interaction strength between the atoms, the pairs can be tightly bound and form a Bose-Einstein condensate (BEC), or weakly bound and form a Bardeen-Cooper-Schrieffer superfluid (BCS). Using Feshbach resonances the interaction strength can be modified, and the entire crossover region between the BEC and BCS regimes can be explored. We start this lecture by reviewing the experimental efforts leading to the creation of a superfluid Fermi gas, and discuss the early observations made regarding its properties. In the experiments, many parameters besides the interaction strength can be tuned, such as dimensionality, temperature, and the population imbalance between the two (hyperfine) spin states that pair up. A theoretical description that is capable of taking into account these adaptable parameters is the path integral or functional integral approach to quantum field theory. This will be the focus of the first lecture. After an explanation of the method in general, it is applied to the ultracold Fermi gases in order to obtain phase diagrams that distinguish the superfluid state from the normal state and reveal the effect of parameters such as the population imbalance (such as the appearance of exotic superfluid phases where pairs condense in a state with non-zero center of mass momentum).




Phase diagram for fermionic superfluids [1].

**References:**

[1] C. A. R. Sá de Melo, Physics Today, Oct., 45 (2008).

# Collective excitations, vortices and solitons in the BEC-BCS crossover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The superfluid properties of ultracold Fermi gases depend on the excitations of the pair condensate. For Bose-Einstein condensates (BECs), the dominant excitations are sound waves - phase excitations of the order parameter, whereas in the Bardeen-Cooper-Schrieffer (BCS) case, Bogoliubov excitations corresponding to broken Cooper pairs determine the low-temperature properties. For Bose-Einstein condensates, vortices can be detected through the dip in the density at the vortex core, whereas in the BCS case the vortex cores fill up with normal state fermions. In this lecture, we explore the excitations and how they transform throughout the BEC-BCS crossover. We investigate how the collective excitations (Anderson-Bogoliubov 'phase' modes and Higgs-like 'amplitude modes) couple, and what their interplay is with the continuum of broken Cooper pairs. As in the previous lecture, we use the functional integral approach, shown to be equivalent to Anderson's RPA approach for the superfluid. To study long-wavelength, low-energy excitations, an effective field theory can be set up, allowing to study excitations such as vortices and solitons. We'll show that these behave quite differently in the BEC and BCS regimes in what regards their dynamics and interactions.

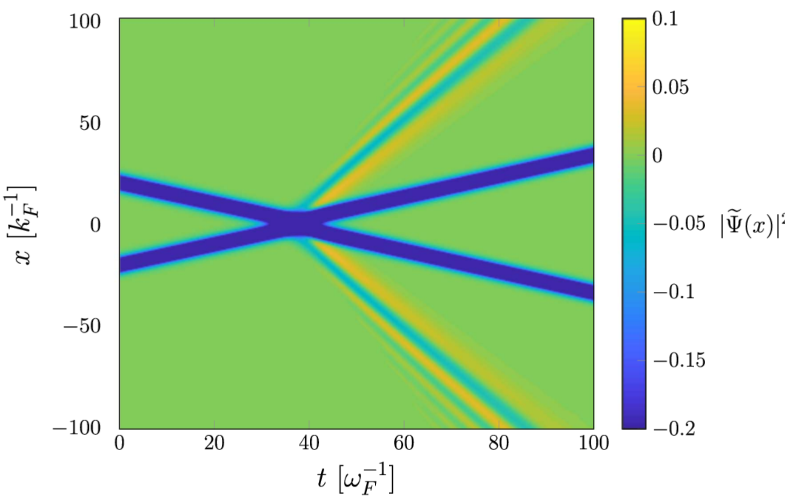


Fig.: The time evolution of the pair density shows two colliding solitons in the BCS regime, generating Anderson-Bogoliubov phonons [1].

## References


[1] W. Van Alphen, G. Lombardi, S.N. Klimin, J. Tempere, New J. Phys. **20**, 053052 (2018).