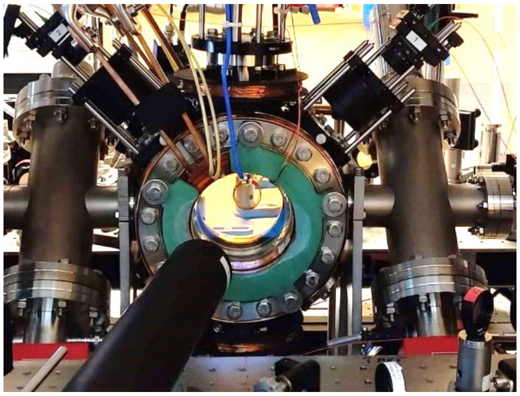
Quantum many-body dynamical localization in a potassium BEC

Potential randomness and interparticle interactions have profound implications for the physical properties of quantum systems. For instance, the presence of disorder can turn a common metal (conductor) into an insulator, while interactions can turn a very poor insulator into a superconductor at fairly high temperatures. Disorder is also relevant for many other physical systems - mesoscopic physics, optics, acoustics, and ultracold atoms. One of the manifestations of randomness in quantum systems is the well-known Anderson localization [1], where wave transport is inhibited by disorder-induced spatial localization of the wavefunction of non-interacting quantum particles. Another kind of localization, similar to the Anderson localization, manifests in periodically-driven (Floquet) systems, and has been coined "Dynamical Localization". Our group in Lille has pioneered experimental observations of dynamical phase transition phenomena, as well as studies of classical-to-quantum transition in such driven ultracold-atom systems [2,3,4].

Inter-particle interactions can alter the localization scenarios in non-trivial manners. In 'regular' disordered systems localization takes place in real (position) space – where usually interactions are short-range (contact interactions). The interplay between disorder and interactions has been a hot topic in the last five years, with the advent of the "Many Body Localization" – which is the reduction or inhibition of transport in a many-body systems – i.e. composed of interacting particles – in the presence of a strong spatial disorder [5,6].



On the other hand, in driven (dynamical) systems localization takes place in reciprocal (momentum) space, where interactions are naturally long-range. For a long time it has been conjectured that, because of this long-range nature of interactions, dynamical localization will be destroyed even at arbitrary small interaction strengths. However, recent theoretical and numerical studies [7,8] pointed out that, when the system is spatially-confined in 1D and the interaction strength is very large (also known as Tonks-Girardeau regime), a new type of many-body localization should emerge: namely that of the system's quasi-particles. These quasi-particles have fermionic-like properties and, depending on the choice of observables measurable through different experimental protocols, the system will exhibit properties coming either from the strongly-interacting bosonic (real) particles or from the fermionic quasi-particle counterparts. This new kind of "Many-Body Dynamical Localization" has not yet been observed experimentally.

The internship/PhD subject proposes to use a Potassium Bose-Einstein condensate experiment to observe and investigate many-body dynamical localization phenomena. The first part of the project will focus on reaching the strongly-correlated 1D regime – namely through the implementation of 2D optical lattices and the use of the Feshbach resonances available for potassium atoms. This will allow to explore the new features of localization in interacting dynamical systems – by applying experimental protocols [9] which will emphasize the particular nature of (quasi-particle) localization in this regime. Ultimately, the project will investigate how the opposing localized limits (non-interacting and strongly-interacting ones) connect, at arbitrary interaction strengths – where neither exact theoretical nor numerical predictions exist – opening new ways towards quantum simulations of many-body physics in disordered quantum systems.

Keywords: Ultracold quantum gas experiments, Quantum disordered systems, Quantum simulations, Many-body dynamical localization, Strongly-correlated quantum systems.

Integration : The thesis will take place in the PhLAM laboratory – University of Lille. The student will be integrated into the "Quantum Systems" team (7 permanent members), and will benefit from their expertise on disordered quantum systems.

Pre-requisites: The candidate should have an advanced level in quantum and statistical physics. Although not compulsory, experimental background and attraction to numerical simulations are welcome.

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[1] Phys. Rev. **109**, 1492 (1958) - *Absence of Diffusion in Certain Random Lattices*
[2] PRL **101**, 25 (2008) - *Experimental observation of the Anderson transition with atomic matter waves*
[3] PRL **121**, 134101 (2018) - E*xperimental observation of time singularity in classical-to-quantum chaos transition*
[4] Nat. Comm. **9**, 1382 (2018) - *Controlling symmetry and localization with an artificial gauge field in a disordered quantum system*
[5] Science **352**, 1547 (2016) - *Exploring the many-body localization transition in two dimensions*
[6] Rev. Mod. Phys. **91**, 021001 (2019) - *Many-body localization, thermalization, and entanglement*
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[9] Science **373**, 1129 (2021) - *Generalized hydrodynamics in strongly interacting 1D Bose gases*