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Theoretical study of quantum gas experiments in an Earth-orbiting research laboratory

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Ultra-cold atomic ensembles are a prime choice for sources in quantum sensing experiments. In the case of atom interferometry, long interrogation times are highly desirable to obtain high precision results. This requires a great control of the input states in term of size and position
dynamics, as well as an efficient description of the dynamics along the different steps of the evolution time.

Space provides an environment where atom clouds can float for extended times of several seconds, as well as miscibility conditions not possible on ground. However, simulating such dynamics of single species Bose-Einstein Condensates (BEC) or interacting dual species BEC mixtures presents computational challenges due to the long expansion times and centre of mass motion induced by a displacement of the atom clouds. I will present a novel theoretical framework elaborated in [A. Pichery et al., AVS Quantum Sci. 5, 044401 (2023)], which is based on re-scaled computation grids that allowed to follow the extended free dynamics of quantum mixtures in space

The theoretical concepts presented are illustrated by experiments performed in the NASA Cold Atom Laboratory (CAL) aboard the International Space Station as part of the Consortium for Ultracold Atoms in Space (CUAS). This multi-user BEC machine allows the manipulation of single species BEC at its installation as well as dual-species mixtures of K and Rb after upgrades. Following this chronology, I will present techniques used to study the dynamics of single species BEC and then extend the work to the manipulation of an interacting mixture of two BECs. This includes the design of fast and robust transport protocols to move the atoms away from the atom chip with Shortcut-To-Adiabaticity protocols, and the implementation of atomic lenses using the Delta-Kick Collimation techniques to control the expansion of the atomic clouds, as illustrated in [N. Gaaloul et al., Nat. Commun. 13, 7889 (2022)]. In addition, there will be a report about the first quantum mixture experiments in space [E. Elliott et al., Nature 623, 502 (2023)], which is a first step to the preparation of dual-species atom interferometry and future tests of the Universality of Free Fall.

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