Quantum gas cavity QED – Fundamentals

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As matter influences the propagation of light waves, light can be used to manipulate matter wave dynamics. In typical experiments as optical traps or cavity QED one of the two effects dominates. However, confining cold atoms in a high finesse optical resonator creates a novel situation, where particles and photons are dynamically coupled by momentum and energy exchange on equal footing. The particles act as a dynamic refractive index for the light waves, which can form structured optical potentials guiding the particles motion, see Fig. 1.

The zero temperature limit of an atomic BEC in an optical lattice trapped in a high Q cavity represents a genuine quantum model system for quantum optics with quantum gases. Due to the dynamical entanglement of atomic motion and light in a weakly coupled system, a measurement of the scattered light detects atomic quantum statistics properties and projects the many-body atomic state to corresponding eigenstates. Similarly measurements on the atoms exhibit nonclassical properties of the light.

For larger interaction strength the light induced long-range coupling of the particles can induce regular crystallization of the particles bound by light and the appearance of new exotic quantum phases with short- and long-range order as found in a supersolid. Recently the analogous appearance of density wave order was also seen in an interacting quasi degenerate Fermi gas.

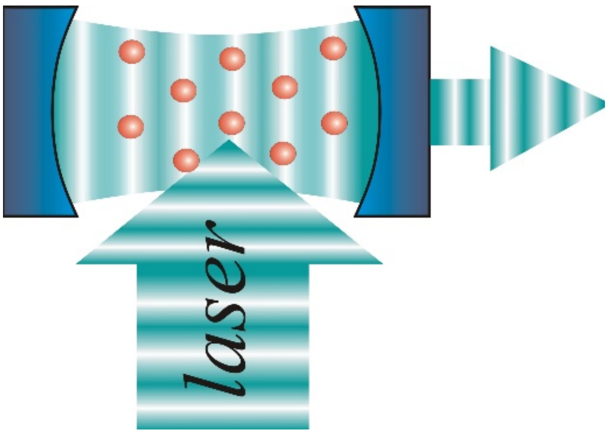

Fig. 1: Generic experimental set up for quantum gas cavity QED.

References:

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[2] F. Mivehvar, F. Piazza, T. Donner, and H. Ritsch, Adv. Phys. **70**, 1 (2021)

Quantum gas cavity QED – Applications

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We study emerging ordered quantum phases of ultracold quantum gases in multimode optical cavities to synthesize dynamic gauge fields, spin-orbit coupling, or long-range spin interactions. Quantum particles coupled to field modes of optical resonators hybridize with cavity photons, which collectively couple spin and motional dynamics. By help of multiple polarization modes one is able to engineer spin-dependent dynamic optical potentials as well as tailored long-range density and spin-spin interactions towards a versatile analogue quantum simulator. The emerging spin- and density-ordered complex quantum phases can often be characterized in situ via properties of the cavity output spectra. For larger interaction strength the light-induced long-range coupling of the particles can induce regular crystallization of the particles bound by light and the appearance of new exotic quantum phases with short- und long-range order as found in a supersolid or in quasicrystals. Applications range from improved quantum sensing to quantum optimization.

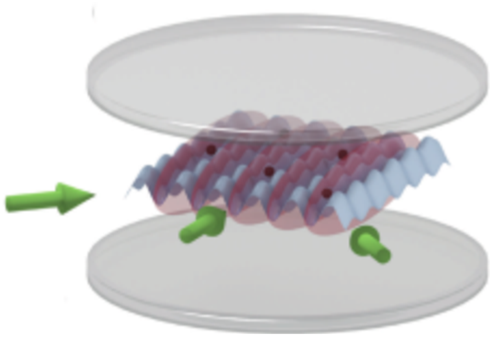

Fig.: Cavity QED with lattice quantum gases.

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[1] F. Mivehvar, F. Piazza, T. Donner, and H. Ritsch, Adv. Phys. **70**, 1 (2021)