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Quantum phases from competing short- and long-range interactions in an optical lattice

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The theoretical and experimental characterization of complex systems and their phase transitions is, often times, exceedingly challenging. Simulation experiments with ultra-cold atoms can help in this regard by allowing for almost perfect control over the system's characteristics. We experimentally realize a bosonic lattice model and observe the rich phase diagram resulting from the competition between the different terms in the Hamiltonian: kinetic energy, on-site interactions, and infinite ranged interactions. Our system is based on an atomic quantum gas trapped in an optical lattice inside a high finesse optical cavity. The strength of the short-ranged on-site interactions is controlled by means of the optical lattice depth. The infinite-ranged interaction potential is mediated by scattering of a transverse pump laser beam into a vacuum mode of the cavity and is independently controlled by the detuning of the pump to cavity resonance. We observe the phase diagram of the system, composed of a superfluid, a super-solid, a Mott insulator and a charge density wave insulator. The phase transition between the two insulating phases is impeded by the presence of metastable states separated by energetic barriers. By monitoring the system across the insulator to insulator boundary, we observe a hysteresis loop and the emergence of two distinct time scales in the dynamics of the corresponding order parameter. We interpret our findings in the context of a mean-field model featuring metastable many-body states.