Quantum correlations: or how to turn a quantum simulator into a quantum sensor

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In quantum systems correlations can take forms which are impossible in classical mechanics. The most famous, yet elusive form of quantum correlation is represented by entanglement, a property well defined and investigated for pure states, and envisioned as a resource for nearly all technological tasks harnessing quantum many-body physics. In the real life of mixed states, on the other hand, incoherent fluctuations appear in the game, making the distinction of quantum vs. classical correlations less sharp. Being able to discern the ?quantumness" of correlations in mixed states, and to identify many-body regimes in which correlations have a pronounced quantum character, represents a formidable question of both fundamental as well as technological nature.

We have recently introduced a statistical-physics definition of quantum correlations which reveals the existence of a fundamental emerging length (the quantum coherence length) beyond which correlations are purely of incoherent (classical) origin. This definition lends itself very naturally to large-scale numerical calculations in quantum many-body systems, as well as to experiments with quantum simulators - either via thermodynamic or spectroscopic measurements. Once quantified, quantum correlations unveil the metrological interest of quantum many-body states, as they represent the fundamental ingredient which allows interferometric protocols to beat the shot-noise limit. We apply our statistical physics analysis of quantum correlations to quantum phase transitions in models of atomic physics quantum simulators – quantum Ising transition in spin models for trapped ions, Rydberg atoms or ultracold binary mixtures. Our analysis reveals the impressive metrological potential of adiabatically prepared equilibrium states close to the quantum phase transition, owing to the quantum-critical enhancement of quantum correlations.