

Semiclassical picture of the Heisenberg spin glass in two dimensions: from weak localization to hydrodynamics

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We study the two-dimensional frustrated quantum Heisenberg model with bond disorder, focusing on the emergence and nature of spin-glass order in the quantum regime. Combining large-scale quantum simulations with a semiclassical expansion around classical states, we identify an extended region of the zero temperature quantum phase diagram where conventional long-range magnetic order disappears in the thermodynamic limit, while the overlap order parameter remains finite, signaling a stable quantum spin-glass phase. The semiclassical analysis provides a microscopic characterization of this regime: at leading order, the effective quadratic spin-wave Hamiltonian reveals that the character of low-energy excitations is controlled by the correlations inherited from the underlying classical order. Around magnetically ordered states, spin-wave modes remain delocalized and hydrodynamic despite disorder, even in two dimensions; around spin-glass states, by contrast, excitations become weakly localized. This sharp distinction links spontaneous spin-rotation-symmetry breaking in the original Heisenberg model to the symmetry class and transport properties of the corresponding spin-wave problem.