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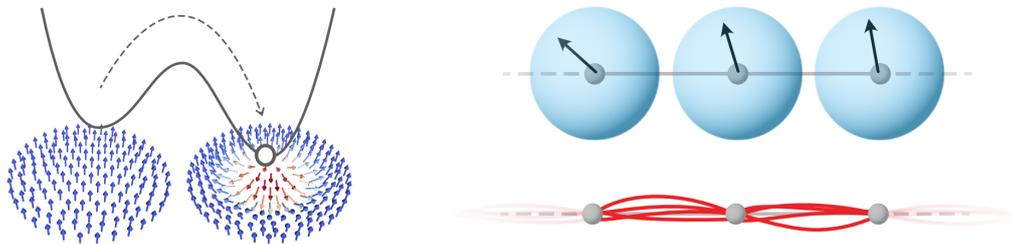MC 351 & online (URL in E-Mail)

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Nonlinear spin dynamics under thermal and quantum fluctuations

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Although magnetism is fundamentally quantum mechanical, classical nonlinear models such as micromagnetism and atomistic spin dynamics have proven remarkably successful in describing a wide range of static and dynamic phenomena — including topological solitons and spin textures, parametric resonance, ultrafast switching, auto-oscillations, and even chaos. In quantum mechanics, the nonlinearity of magnetism originates from the angular-momentum algebra of spin operators and manifests in classical theories through spin vectors of fixed length. This geometric constraint gives rise to the rich nonlinear behavior of magnetic systems. It also plays a key role in the existence of topologically nontrivial spin textures, such as skyrmions, which can appear in chiral magnets and whose emergent dynamics are captured by collective-variable theories, such as the Thiele model. However, the aforementioned theories begin to fail when fluctuations, both thermal and quantum, become strong.

Here, we present two complementary theoretical frameworks that address this breakdown from different directions. First, strong laser excitation of chiral magnets can induce significant thermal fluctuations, thereby driving the ultrafast nucleation of skyrmions. Because the Thiele model cannot capture these nonlinear dynamics, numerical simulations using Langevin atomistic spin models are required. To describe them at the emergent soliton level, we propose an effective theory in which the skyrmion number is treated as a stochastic variable evolving through thermally activated nucleation and annihilation events [1]. Secondly, on even shorter spatiotemporal scales, quantum fluctuations become increasingly essential and undermine the very notion of classical spin vectors [2]. While numerical quantum many-body techniques can capture specific nonlinear spin dynamics, they are computationally demanding and often obscure the connection between nonlinear dynamics and its geometric origin in angular-momentum algebra. To bridge this gap, we introduce a semiclassical spin-correlation theory that evolves spin correlations on lattice bonds rather than on individual spins, thereby incorporating nonlinear dynamics beyond classical models while retaining the su(2) geometry — and thus the intrinsic nonlinearity — of the spins. These two approaches provide stepping stones toward understanding nonlinear spin dynamics in regimes of strong thermal or quantum fluctuations.

R. Liefferink *et al.*, arXiv:2504.11013 (2025)

F. Formisano *et al.*, APL Mater. 12, 011105 (2024)