# Driven-dissipative dynamics with trapped ions and qubit-arrays

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Laser cooling of atoms and ions has revolutionized the study of quantum physics. Ions can be cooled by light down to a thousandth degree above absolute zero. Despite this reality, existing theories are mostly limited to the final stage of cooling where the time-dependent drive and anharmonicity of the potential of real ion traps can be neglected. We have developped a semiclassical framework based on using action-angle phase-space coordinates, that advances the understanding of ion dynamics far from thermal equilibrium. It captures the driven stochastic motion by using a Fokker-Planck equation for the probability distribution, adiabatically averaged over the angles in phase-space, with drift and diffusion expressed in terms of the action. Important open questions, like the optimal trapping potential and the most advantageous settings of the cooling laser, can now be quantitatively answered for realistically modeled traps and an arbitrary large-amplitude motion [1]. Extending this theory [2], we have predicted that due to the time-dependent trap drive, an ion subject to laser damping can nonetheless be captured in large-amplitude, nonequilibrium stationary states [3].

At the same time, trapped-ion experiments are well suited for experiments of nonequilibrium many-body dynamics. An extensive toolbox has been developed for coherent manipulation of electronic states forming, e.g., a two-level system in each ion, that is equivalent to a spin-1/2. Within one- and two-dimensional crystals of trapped ions, a coupling between the spins can be induced using light. When driven away from equilibrium and at the presence of dissipative processes, interacting spins form a fundamental model of nonequilibrium dynamics, which describes also solid-state systems such as superconducting circuits coupled to an array of light cavities [4]. The possibility of studying emergent collective quantum phenomena in those systems raises a number of theoretical questions. Among those we focus on three main questions; (i) What phases can be stabilized with nontrivial quantum correlations. (ii) What is the role of the correlations, and (iii) how does it depend on the dimension, the interaction range, and other system parameters?

We have studied [5] a model characterized by a frequency splitting $\Delta$ between the ground and excited state of the two-level systems, with XY interaction between nearest-neighbour spins of strength $J$, coherently driven at a Rabi frequency $\Omega$, with damping at a fixed rate $\Gamma$ introduced by a Lindblad superoperator. We identify regions where the system state is well described by its mean-field (MF) limit, while beyond these regions correlations build up in the lattice and must be included in the dynamics. In particular, the correlated regimes include parameters for which the MF manifests two coexisting stable steady states and the MF phase shows hysteresis. We are studying the role of quantum fluctuations by using two approaches: by solving approximate MF-dynamics coupled to a leading order expansion of the quantum correlations, and by using advanced numerical approaches based on Matrix Product Operators (MPO). The results of these two approaches are compared in Fig. 1 with the mean-field. We find that in regions of meanfield bistability and at nearby parameters, the system develops large correlations over a large spatial scale, accompanied by an increase in the time-scale of relaxation. These correlations are responsible for stabilizing the system state between its two MF-limit states. We are continuing to explore the nature of the resulting phases with large correlations and their dependence on the system parameters and dimension.

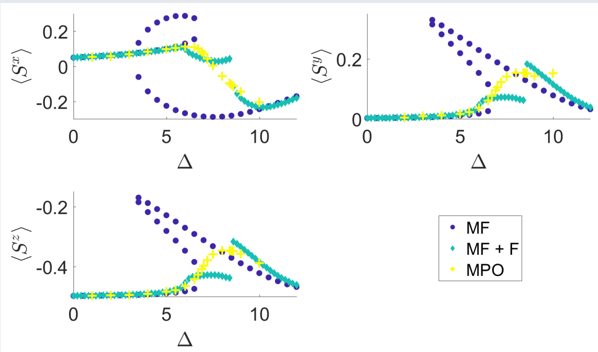


*Figure 1:* Mean values of the spin projection along the three directions, as a function of the spin up and down splitting $\Delta$, at fixed values of the other paramaters, $\Gamma = 1$, $\Omega = 0.5$, $J = 5$, on a one-dimensional lattice. The mean-field (MF) limit manifests bistability, seen as a region of parameters with three co-existing solutions, two of which are stable. When quantum fluctuations are included at leading order (MF+F), the bistability is replaced by a jump, while an essentially exact treatment using Matrix Product Operators (MPO) shows that the jump is smoothened. This behavior results from long-range spin-spin correlations forming in this region of parameters, as a separate analysis indicates.

[1] A. Maitra, D Leibfried, D. Ullmo, and H. Landa, *Far-from-equilibrium noise heating and laser cooling dynamics in radio-frequency Paul traps*, arXiv:1808.07816.
[2] H. Landa, *Tuning nonthermal to thermal distributions in time-dependent Paul traps*, arXiv:1809.10519.
[3] A. Maitra, D. Leibfried, D. Ullmo, and H. Landa, *Can a periodically driven particle resist laser cooling and noise?*, arXiv:1810.01856.
[4] See the ongoing work at the LPS/N2S, in the group of J. Gabelli and J. Estève.
[5] H. Landa, M. Schiró, and G. Misguich, *in preparation*.

**Résultats obtenus dans le cadre du projet DriDisMBS financés par le LabEx PALM et portés par G. Misguich.**