LMC1 – Nonequilibrium phase transitions in driven quantum spin systems

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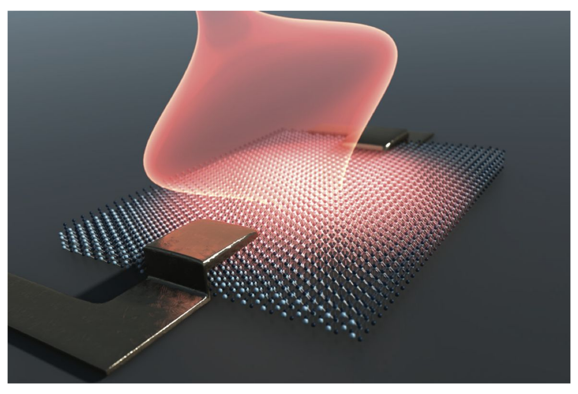
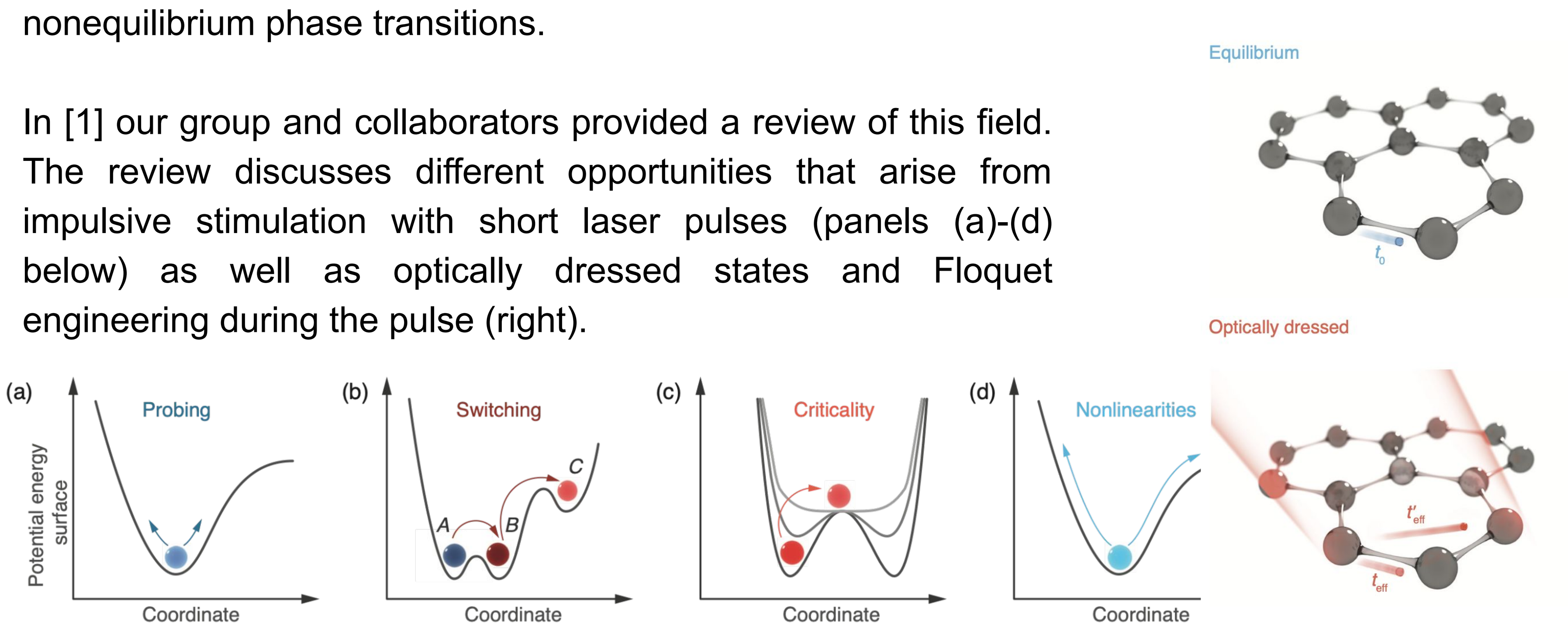
Introduction

Nonthermal pathways for the ultrafast control of quantum materials have been an intense field of research in the past decade [1]. In particular, driven dissipative systems allow for the formation of nonequilibrium steady states (NESS) and the possibility of phase transitions between them. Here we present theoretical results on driven quantum spin systems that help understand different control knobs for driving such nonequilibrium phase transitions.



In [1] our group and collaborators provided a review of this field. The review discusses different opportunities that arise from impulsive stimulation with short laser pulses (panels (a)-(d) below) as well as optically dressed states and Floquet engineering during the pulse (right).

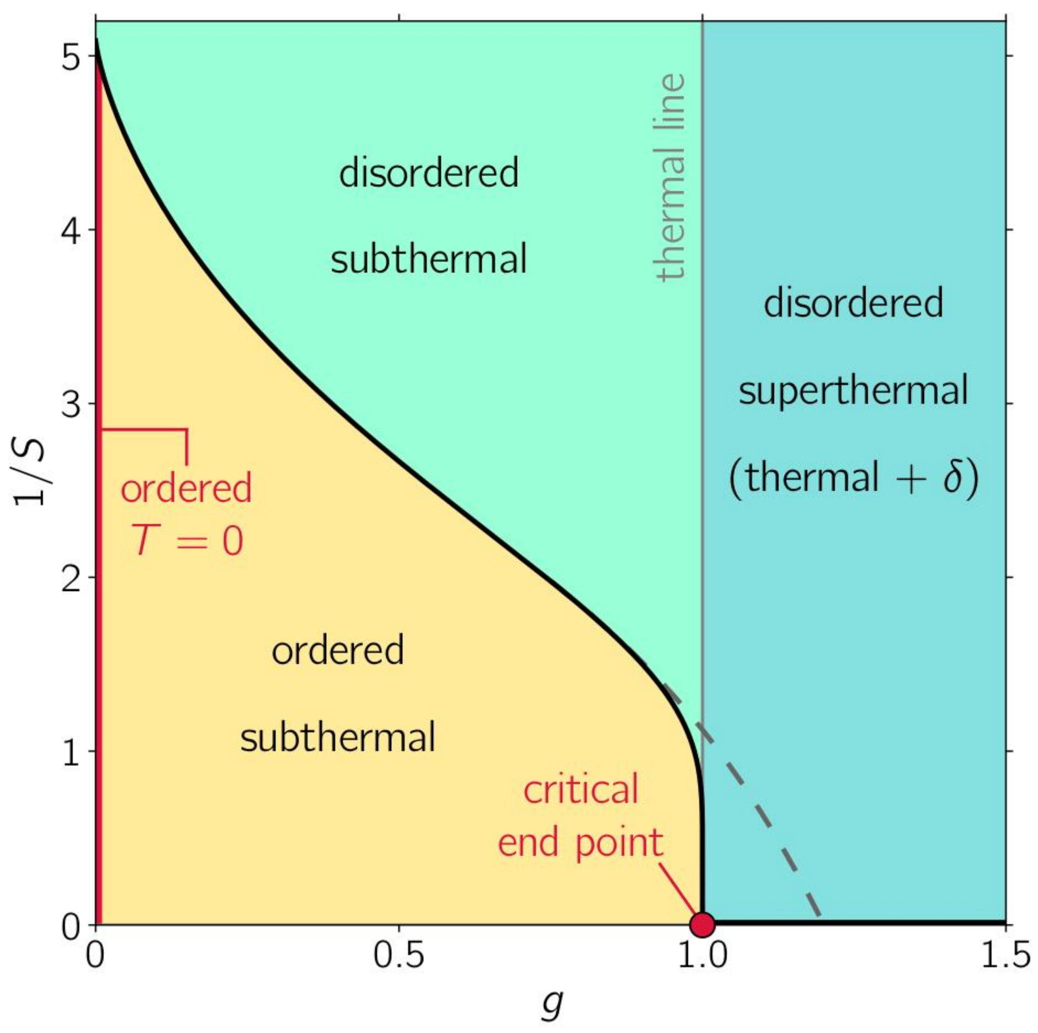


Nonequilibrium phase transition in a driven-dissipative quantum antiferromagnet [2]

Collaboration with Andrew J. Millis

In order to identify critical behavior in a driven-dissipative spin systems with magnon interactions we study the nonequilibrium steady states of a two-dimensional Heisenberg antiferromagnet with nearest neighbor interactions which is driven by a high frequency laser and coupled to a reservoir.

- We use a standard Holstein-Primakoff method to obtain the spin-wave interactions at leading nontrivial order in 1/|S| (S=spin length). Spin-wave interactions conserve the total energy E and the total number of spin waves N.
- We use a Boltzmann formalism, which treats magnon interactions perturbatively to compute collision integrals **S**
- We take the drive and dissipation from a previous, noninteracting analysis [3] of the driven-dissipative Hubbard model in the limit of a high-frequency drive detuned from charge excitations, and a dissipation arising from particle exchange with a reservoir.
- Combining the noninteracting analysis for drive and dissipation with the interacting Boltzmann theory, we find two distinct phase transitions as a function of the dimensionless tuning parameter g which is the ratio of in- and outscattering. The following phase diagram summarizes our results:



➔ **g<1: subthermal** regime, which for sufficiently large spin length is ordered. The black phase boundary indicates that at large enough spin length, the transition between the ordered and the disordered subthermal regime is the nonequilibrium analogue of a conventional symmetry breaking transition, occurring because the drive creates excitations which push the system away from the ordered state.

➔ **g = 1: thermal behavior,** the NESS is equal to a distribution in thermal equilibrium

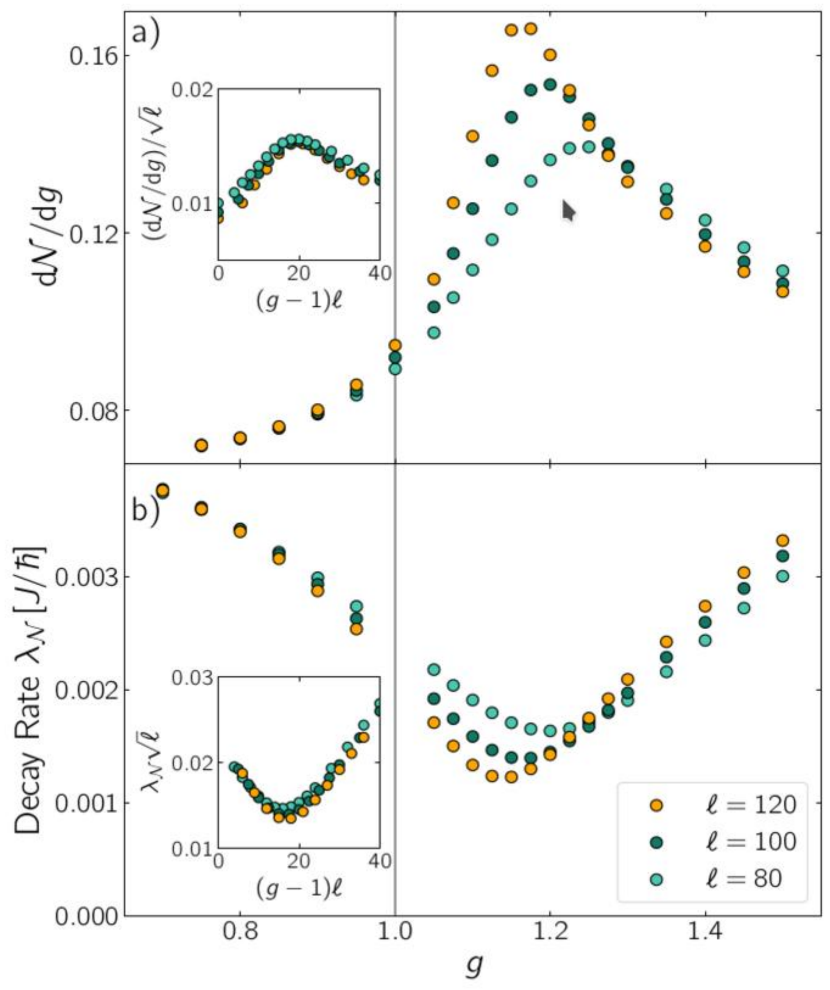
➔ **g>1: superthermal regime:** when the drive exceeds a critical value, some fraction of the drive-induced excitations condense into a zero-momentum ground state. Specifically, we find that the system energy determines the maximal amount of magnons that can be accomodated, and the excess of magnons builds up the condensate fraction. This behavior is reminiscent of previous studies on Bose-Einstein condensation of magnons in ferromagnetic materials, where an evolution into a condensed state of a transiently induced magnon population is analysed.

Static and dynamic criticality

In the proximity of the phase transition from the subthermal to the superthermal regime, we observe static and dynamic criticality

- The derivative of the number of magnons N as a function of g develops a **singularity** which approaches the critical value in the thermodynamic limit
- There is a universal decay rate in all observables when evolving from the noninteracting towards the interacting NESS, and this decay rate as a function of g also shows singular behavior and in fact a **critical slowing down** in the thermodynamic limit.

Linearizing the collision integral **S** around a thermal distribution yields a non-symmetric matrix, which has real, non-negative eigenvalues.



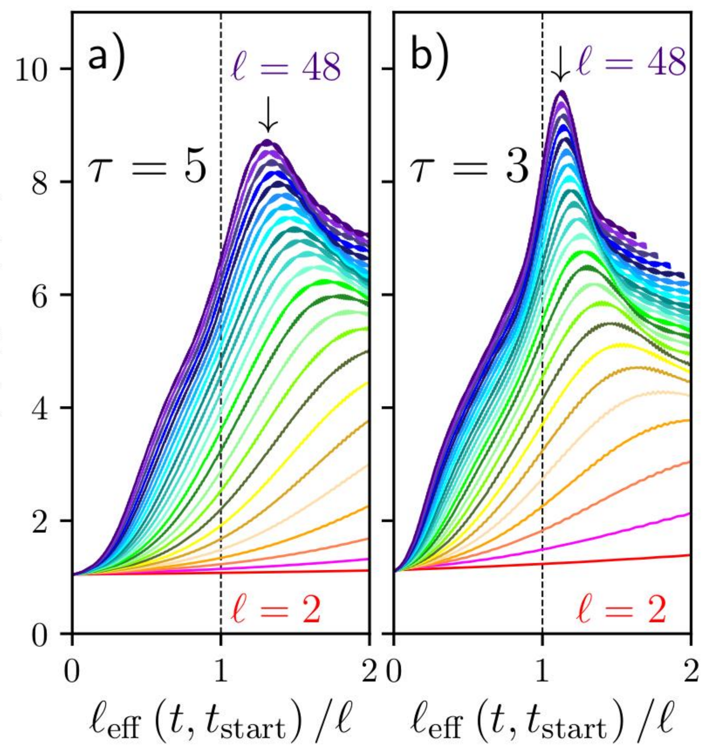
The numerically extracted scattering matrices for different system sizes all show two zero modes (E and N are conserved). All other modes have eigenvalues and therefore relaxation rates that remain nonzero in the infinite system size limit.

Floquet-engineered light-cone spreading of correlations

By simulating the dynamics of a quantum chain with Luttinger liquid and charge-density wave phases under both continuous and pulsed laser driving with **t-DMRG** calculations, we show that the drive causes a **light-cone spreading of density-density correlations** with a Floquet-engineered propagation velocity through the system [4].

- At large time scales, the employed continuous, off-resonant, large frequency driving protocol leads to the formation of a Floquet steady state with negligible heating.
- The formation of a discontinuity in form of a kink at the edge of the light cone is observed. This kink shows similarities with the discontinuity that has been observed in quenched systems, which indicates that dynamical quantum criticality can be achieved in Floquet-driven systems.

These results directly connect to the field of time-resolved spectroscopy, aiming at measuring correlations in low-dimensional materials.



Quantum Fisher information as entanglement witness

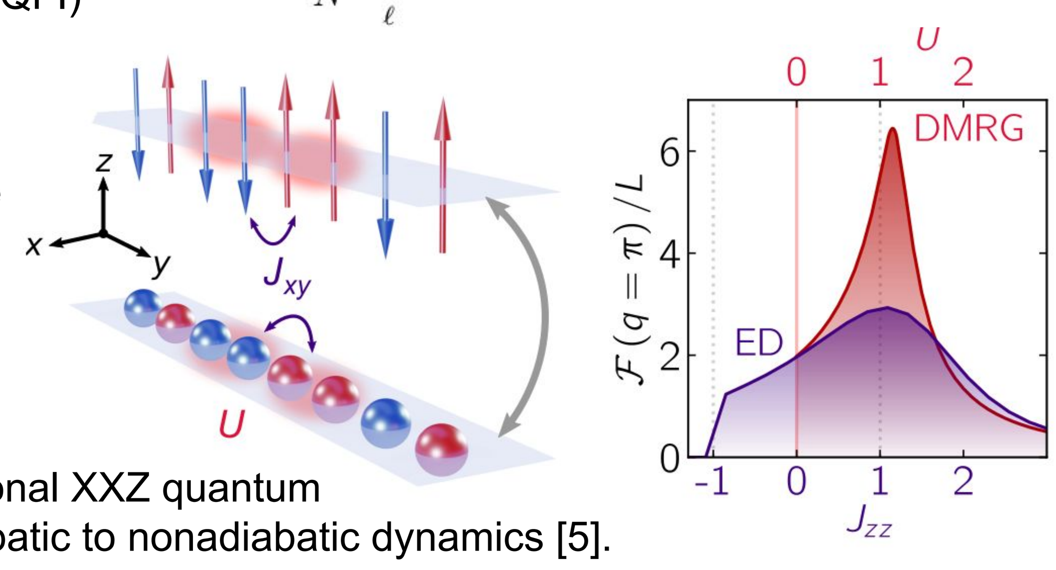
In collaboration with Denitsa R. Baykusheva, Matteo Mitrano (Havard), Martin Claassen (University of Pennsylvania).

- Scattering experiments measure frequency-dependent susceptibilities, whose sum rules are related to the **Quantum Fisher Information** (QFI) which is given by the Fourier transform of the fluctuations evaluated at q=π.

$$\mathcal{F}(q,t) = \frac{2L}{N}\sum_{\ell} e^{iq\ell}\left\{\langle S_0^z(t)\, S_\ell^z(t)\rangle - \langle S_0^z(t)\rangle\langle S_\ell^z(t)\rangle\right\}$$

- QFI can be used to discriminate criticality at non-zero temperatures from thermal phase transitions and acts as an **entanglement witness.**

We investigate the QFI in an interaction-quenched one dimensional XXZ quantum chain, transitioning from from adiabatic to nonadiabatic dynamics [5].



References

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[3] Walldorf et al., Phys. Rev. B 100, 121110 (2019).
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[5] D. Baykusheva, MHK, DH, M. Claassen, DMK, MAS, M. Mitrano (in preparation).

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