# Nonequilibrium phase transition in an optically driven 2D Heisenberg antiferromagnet

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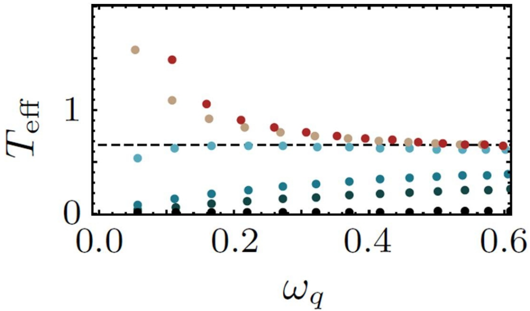
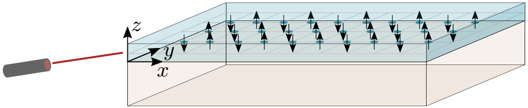
## Phase transitions occurring in a non-equilibrium steady state




Nonequilibrium phase transition in the antiferromagnetic phase of the driven Hubbard model
[N. Walldorf *et al* Phys. Rev. B **100**, 121110(R) (2019)]

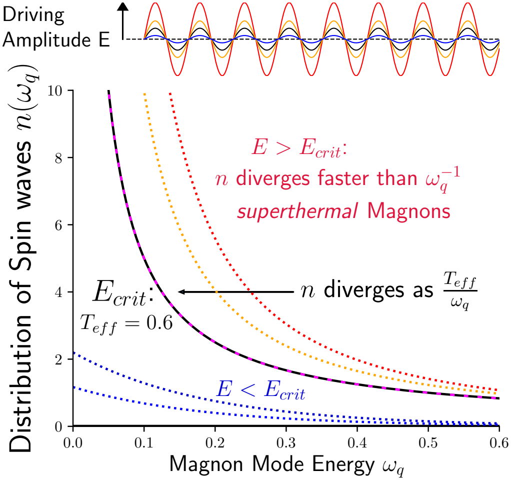
# Floquet-driven Antiferromagnet




[N. Walldorf *et al* Phys. Rev. B **100**, 121110(R) (2019)]

→ Superthermal magnons at large driving amplitudes

→ **Nonequilibrium Phase Transition**



# Floquet-driven Antiferromagnet

[N. Walldorf *et al* Phys. Rev. B **100**, 121110(R) (2019)]

→ Superthermal magnons at large driving amplitudes

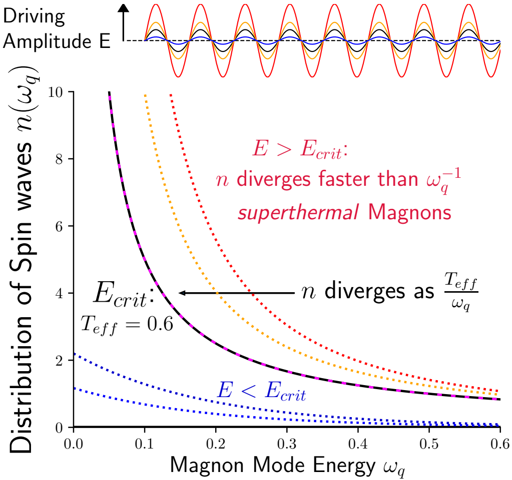
→ Nonequilibrium Phase Transition

## Limitations of the calculation

- Mean Field + one loop calculation (**non-interacting** magnon approximation)
- The transition is driven by the **external drive** and the magnon-relaxation into the **bath**, magnon-magnon scattering is not included.

**Question**

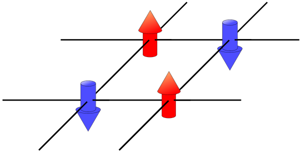
Does this Nonequilibrium phase transition persist in an interacting theory?



## Magnon Interactions in a 2d Heisenberg antiferromagnet

$$\mathcal{H}_{XXZ} = J \sum_{\langle ij \rangle} \left\{ \frac{1}{2} \left( S_i^+ S_j^- + S_i^- S_j^+ \right) + \Delta S_i^z S_j^z \right\} \rightarrow \underbrace{\mathcal{H} = E_0 + H_0 + V}$$

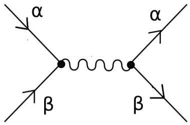
Magnon expansion around ordered ground state



$E_0 =$ Ground State Energy

$H_0 = \hbar \sum_{\boldsymbol{k}} \omega_{\boldsymbol{k}} \left( \alpha_{\boldsymbol{k}}^\dagger \alpha_{\boldsymbol{k}} + \beta_{\boldsymbol{k}}^\dagger \beta_{\boldsymbol{k}} \right) =$ Bilinear Hamiltonian

$V =$ Magnon Interactions




$\rightarrow$ Use Boltzmann Formalism to include magnon interactions (perturbative, leading order $\frac{1}{S}$)

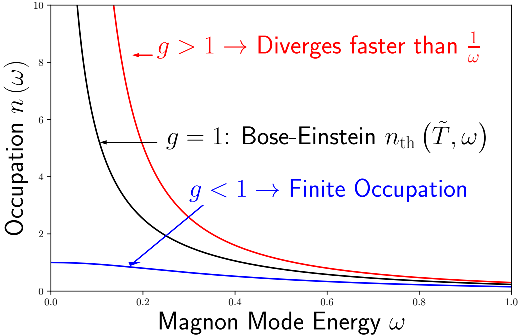
# The Driven-Dissipative System without interactions

[N. Walldorf *et al* Phys. Rev. B **100**, 121110(R) (2019)]

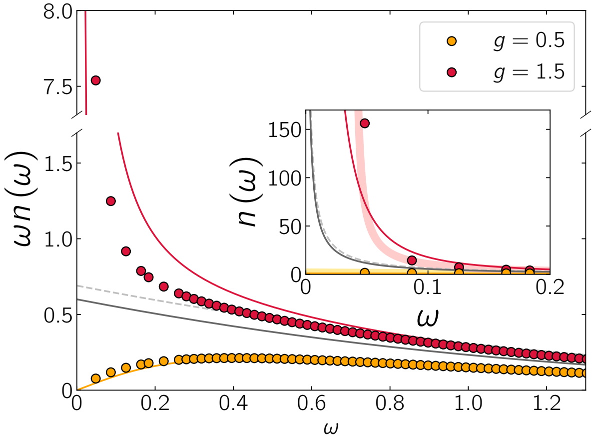
$$\partial_t n = g_{\text{in}}(1+n) - \gamma_{\text{out}}\left(n + \left(\frac{n}{n_{\tilde{T}}(\omega)}\right)^2\right) \quad \text{with} \quad g = \frac{g_{\text{in}}}{\gamma_{\text{out}}}$$

## Dynamical Critical Point $g = 1$

- $g > 1 \rightarrow n(\omega)$ diverges faster than $1/\omega$
- $g < 1 \rightarrow n(\omega)$ is finite for all $\omega$
- $g = 1$ Thermal Distribution at temperature $\tilde{T}$



# The driven-dissipative system with magnon-interactions

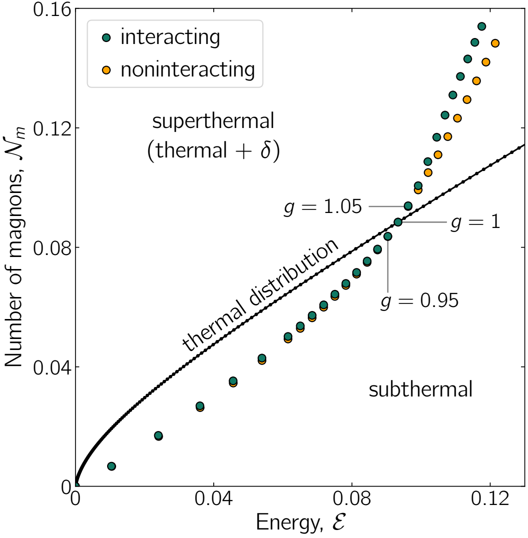


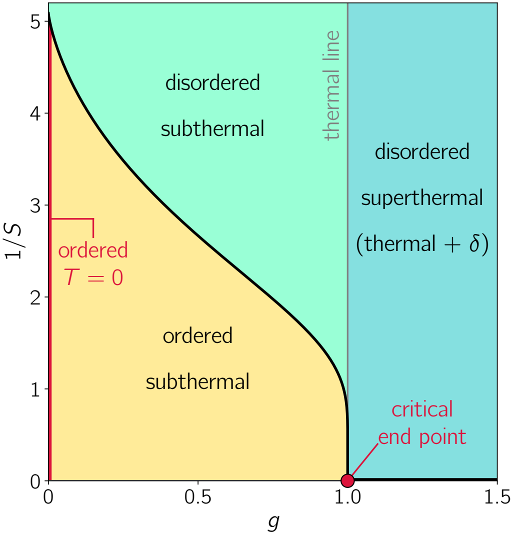

**The transition survives the inclusion of interactions**

$g < 1$: Magnons get shifted to lower frequencies, but there is no fundamental change in behavior.

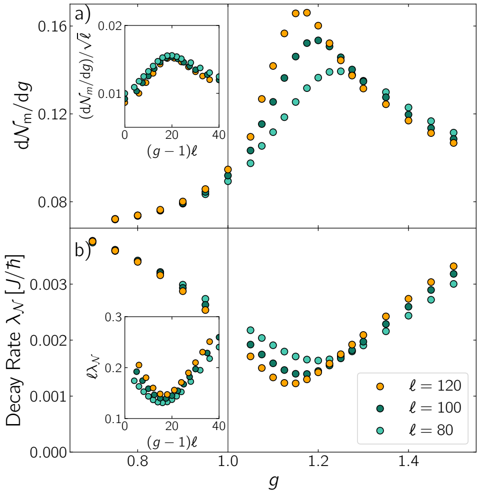
$g > 1$: Interactions drive system towards a thermal distribution plus a $\delta$-Function at $\omega = 0$

Nonequilibrium Phase transition: From subthermal to superthermal



# Static and dynamic criticality




- $\mathrm{d}\mathcal{N}_\mathrm{m}/\mathrm{d}g$ develops singularity that moves closer to $g = 1$ as $\ell \to \infty$
- Decay Rate goes to zero as $\ell \to \infty$

  $\downarrow$

  Time scale diverges as $\ell \to \infty$
- Characteristic scaling behavior

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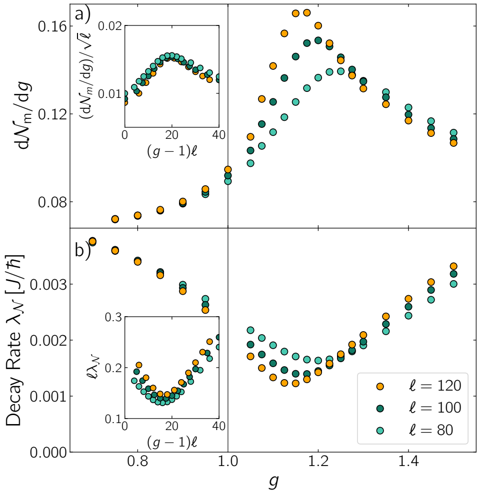


- $d\mathcal{N}_m/dg$ develops singularity that moves closer to $g = 1$ as $\ell \to \infty$
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  $\downarrow$

  Time scale diverges as $\ell \to \infty$
- Characteristic scaling behavior

**Summary**

Does the nonequilibrium phase transition persist in an interacting theory?

**Yes:** Superthermal magnons $\to$ thermal distribution $+$ $\delta$-function