Non-Markovian Quantum Dynamics in the Strong-Coupling Limit of Cavity QED

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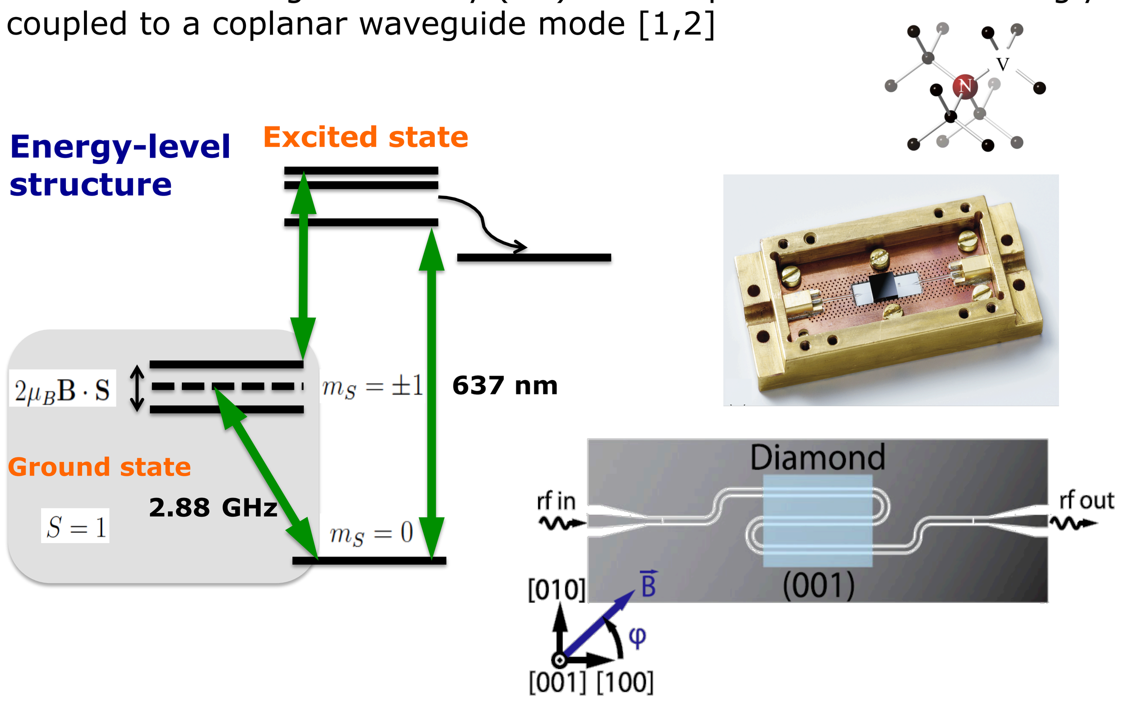
Over the past decade various setups in cavity quantum electrodynamics have been studied in terms of their potential for future technologies involving the storage and processing of quantum information. In this context we theoretically explored the collective dynamics of a large spin ensemble magnetically coupled with a single-mode cavity. Our results showed how the decoherence induced by the inhomogeneous broadening of spins in the ensemble can be suppressed in the strong-coupling regime - a phenomenon known as "cavity protection" [1]. Furthermore, we predicted how to efficiently implement such a protection against decoherence by burning two narrow spectral holes in the spin spectral density at judiciously chosen frequencies [2]. Both of these theoretical findings have meanwhile been confirmed in an experiment based on a superconducting microwave resonator coupled with an ensemble of nitrogen-vacancy centers in diamond [1,3].

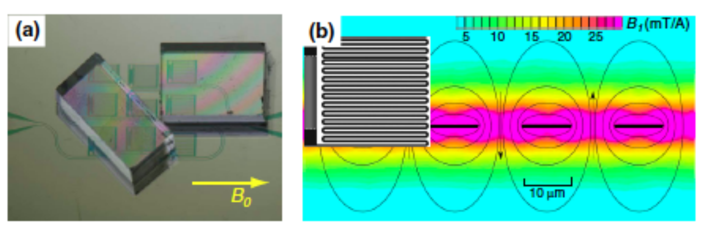
Motivation

Spin ensembles coupled to a single mode cavity (quantum memories)

Ensemble of nitrogen-vacancy (NV) center spins in diamond strongly coupled to a coplanar waveguide mode [1,2]



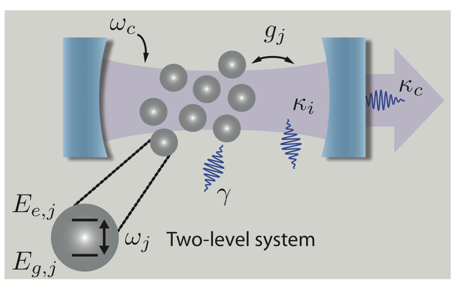
Another realization: rare-earth spin ensemble strongly coupled to a superconducting resonator [3]



Model

Many spins coupled to a single mode cavity

Hamiltonian: $H=\hbar\omega_c a^\dagger a+\frac{\hbar}{2}\sum_j^N\omega_j\sigma_j^z+i\hbar\sum_j^N\left[g_j\sigma_j^- a^\dagger-g_j^*\sigma_j^+ a\right]$



$-i\hbar\left[\eta(t)a^\dagger e^{-i\omega_p t}-\eta(t)^* a e^{i\omega_p t}\right]$

η: amplitude of a microwave signal

g_k: coupling strengths with a cavity

$a^\dagger, a$: cavity mode creation and annihilation operators

$\sigma_k^-,\sigma_k^+,\sigma_k^z$: Pauli operators associated with k-th spin

Problem of decoherence (different local environments → inhomogeneous broadening)

Volterra equation for the cavity amplitude $A(t)=\langle a(t)\rangle$:

$$A(t)=\Omega^2\int_0^t d\tau\mathcal{K}(t-\tau)A(\tau)+\mathcal{F}(t)$$

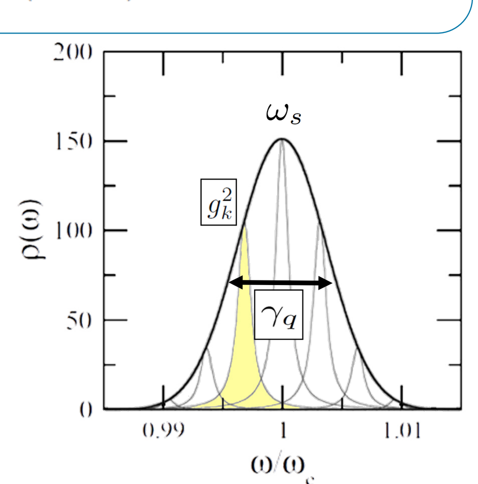
Collective coupling strength: $\Omega=\sqrt{\sum_j^N g_j^2}\sim g\sqrt{N}$

Kernel function: $\mathcal{K}(t-\tau)=\int d\omega\rho(\omega)\mathcal{S}(\omega,t,\tau)$

Modal spectral function $\rho(\omega)$: q-Gaussian [2,4,5]

$$\rho(\omega)=\frac{1}{\Omega^2}\sum_k g_k^2\delta(\omega-\omega_k)$$

$$\int d\omega\rho(\omega)=1$$



Laplace transformation of Volterra equation [5]

Solution: $A(t)=e^{i\omega_c t}\left\{\Omega^2\int_0^\infty d\omega e^{-i\omega t}U(\omega)+\sum_j R_j\right\}$

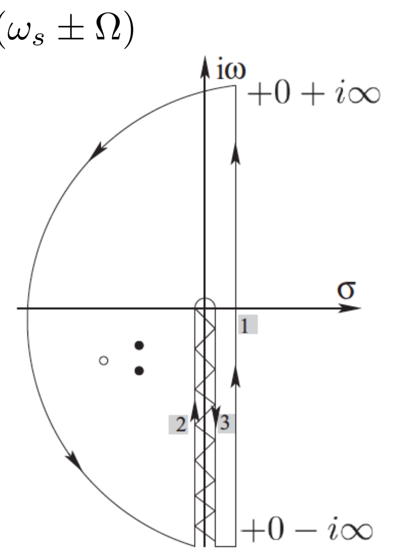
Estimate for the decay rate: $\Gamma=\kappa+\pi\Omega^2\rho(\omega_s\pm\Omega)$

Suppression of decoherence

$\rho(\omega)$ falls fast enough in its tails (cavity protection [4,5])

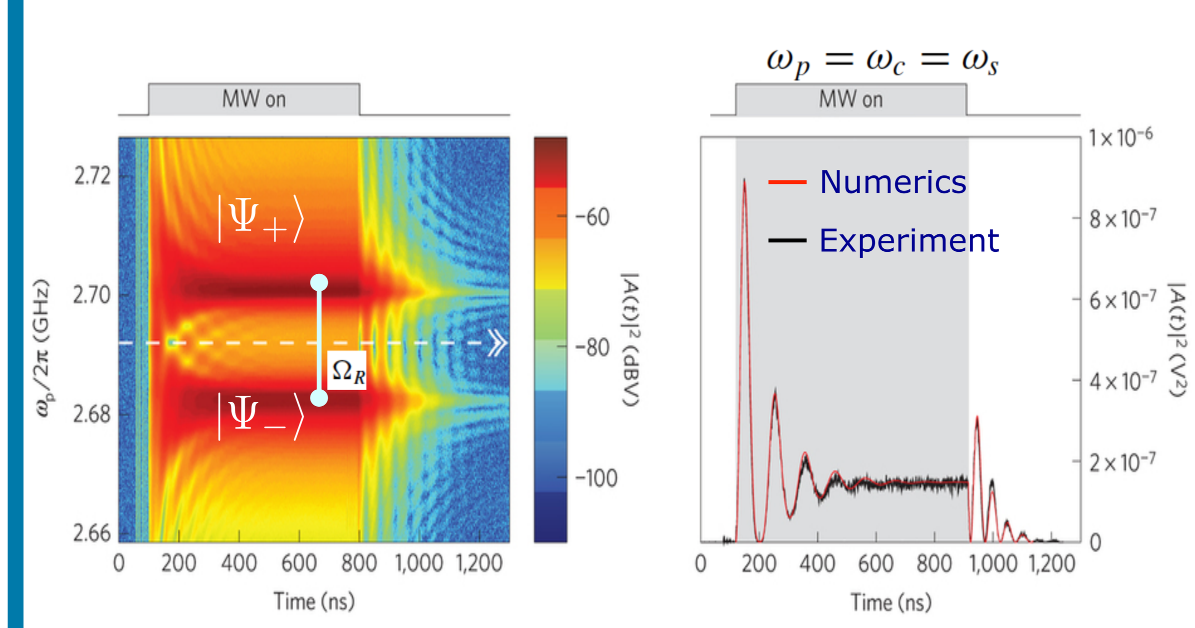
or

$\rho(\omega_s\pm\Omega)=0$ (hole burning [6])



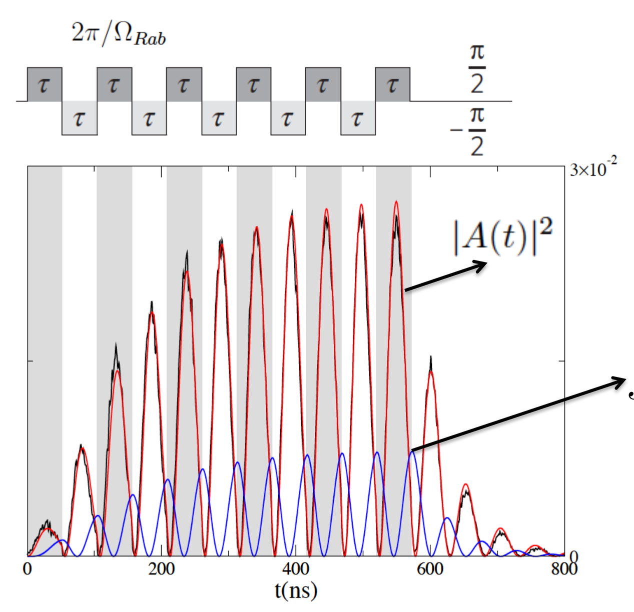
Dynamics

Dynamics under the action of long rectangular pulse [4,5]



Efficient energy feeding into strongly-coupled cavity-spin system [4,5]

Sequence of rectangular pulses with a carrier frequency $\omega_p=\omega_c=\omega_s$



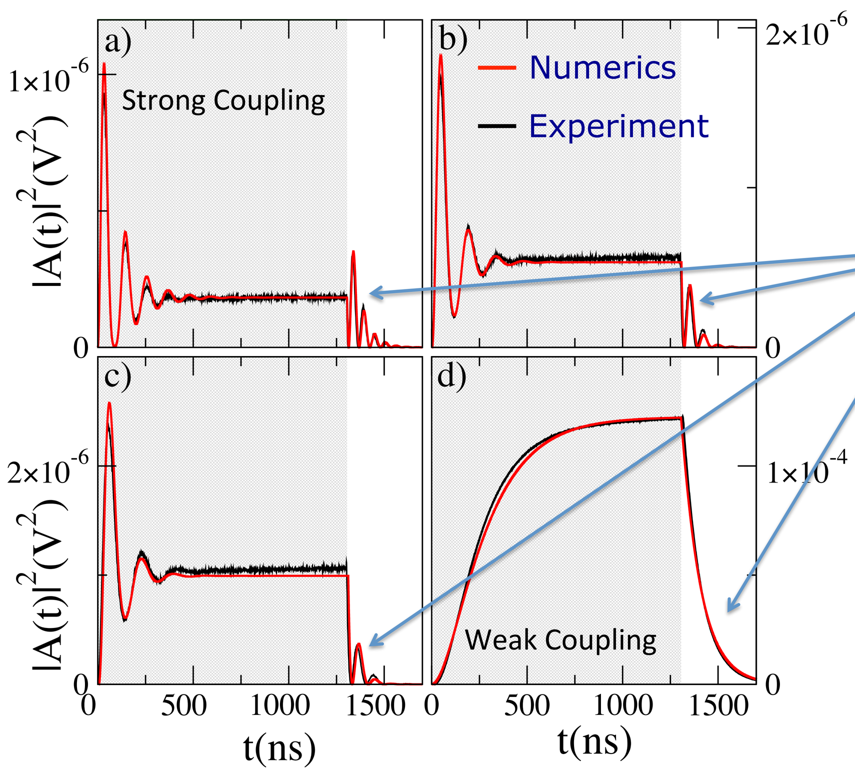
Coherent energy exchange between spin ensemble and the cavity

$J_x(t)^2$ collective spin component

Numerics

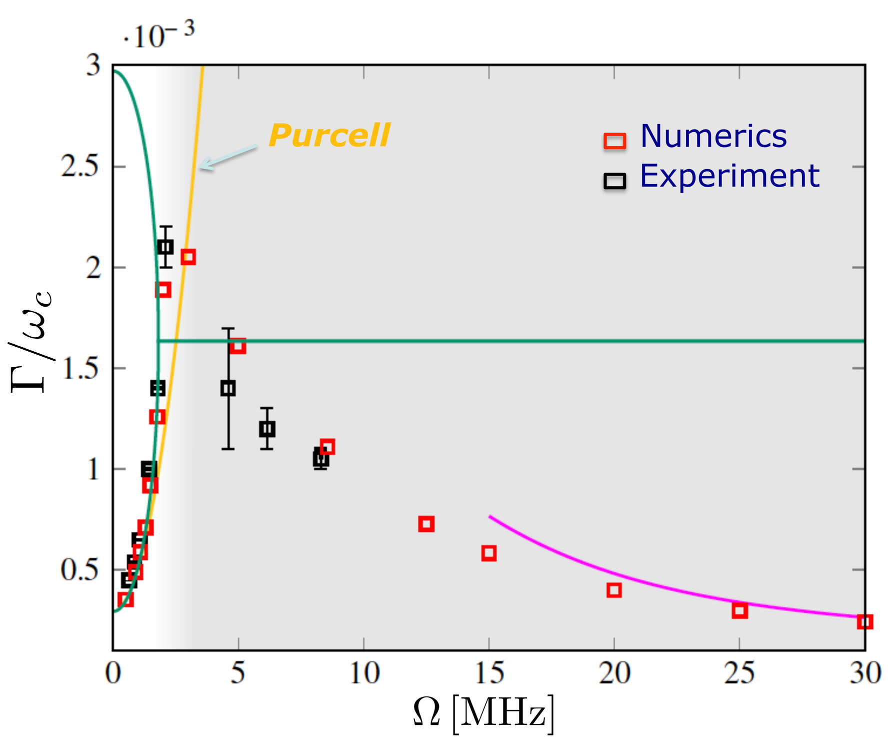
Experiment

Varying coupling strength [5]



Total decay rate $\Gamma(\Omega_R)$ extracted from here

Cavity protection effect [4]



Green: decay rates for Lorentzian

Orange: Markovian process $\Gamma=\kappa+\pi\Omega^2\rho(\omega_c\pm\Omega)$

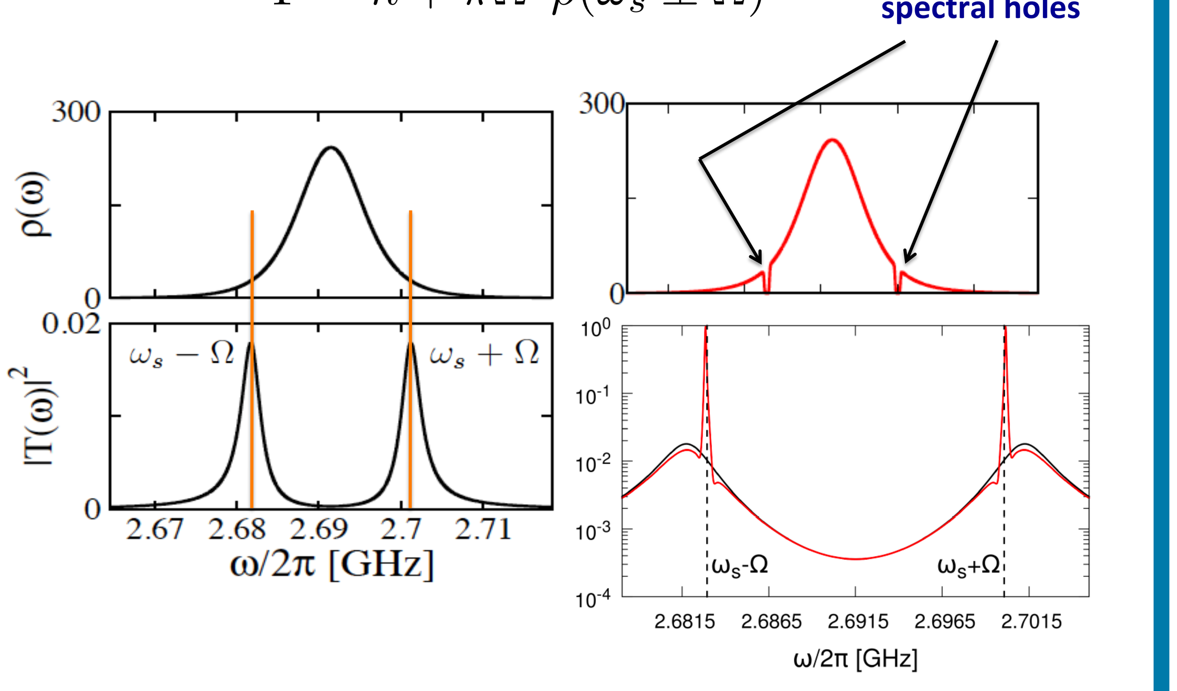
Magenta: $\Gamma=2[\kappa+\pi\Omega^2\rho(\omega_s)]$

The minimally reachable value of the decay rate achieved due to the cavity protection effect $\Gamma=\kappa$

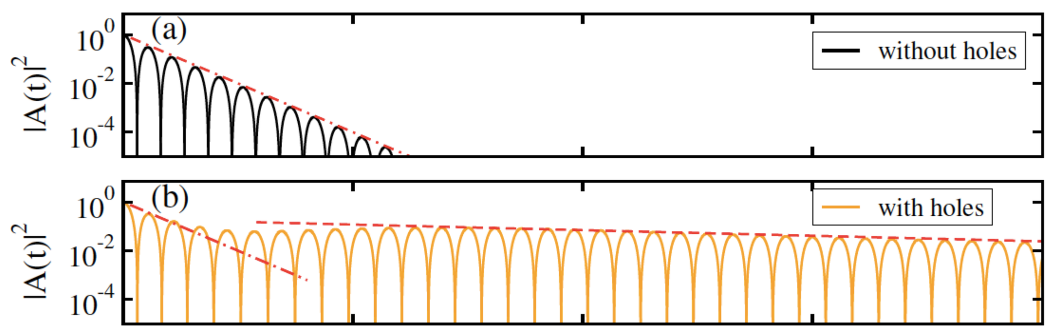
Spectral hole burning [6,7]

Transmission with and without holes [6]

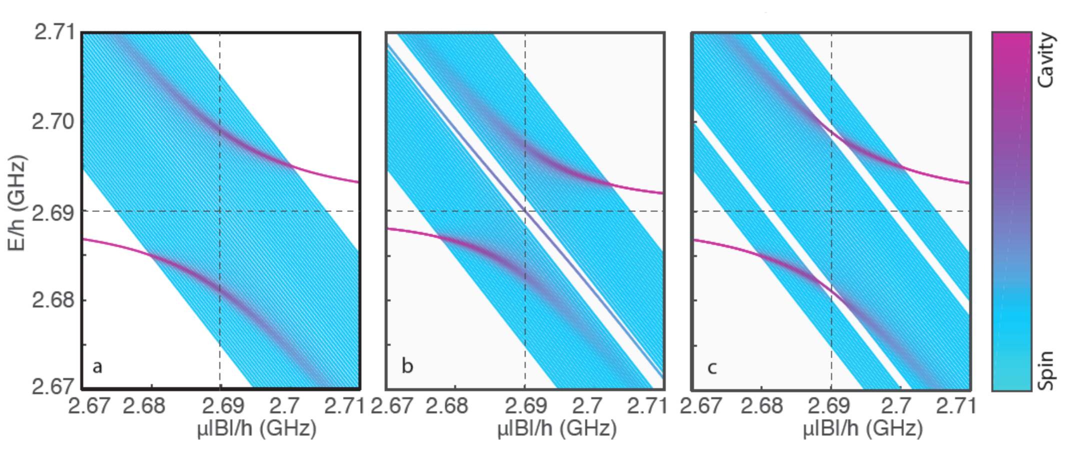
$$\Gamma=\kappa+\pi\Omega^2\rho(\omega_s\pm\Omega)$$



Dynamics with and without holes [6]



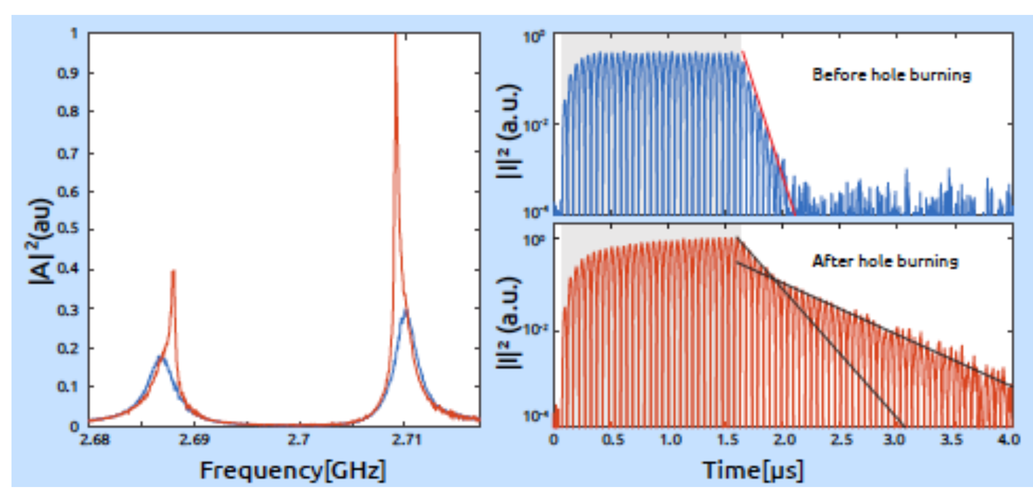
Eigenenergy spectrum



Eigenenergy spectrum: (a) no holes; (b) central hole at $\omega=\omega_s$; (c) two holes at polaritonic peaks $\omega=\omega_s\pm\Omega$

Hole burning technique: coupling to the collective dark state

Experimental realization



Transmission and the dynamics under the action of sinusoidally modulated signal pulse with frequency $\Omega_R/2$ and $\omega_p=\omega_c=\omega_s$

For the case with hole burning our prediction [6] to go substantially beyond the limit $\Gamma=\kappa$ was successfully realized [7]

References

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[2] K. Sandner et al, PRA 85, 053806 (2012)
[3] S. Probst et al, PRL 110, 157001 (2013)
[4] S. Putz, D.O. Krimer, R. Amsüss, A. Valookaran, T. Nöbauer, J. Schmiedmayer, S. Rotter, and J. Majer Nature Physics 10, 720 (2014)
[5] D.O. Krimer, S. Putz, J. Majer, and S. Rotter, PRA 90, 043852 (2014)
[6] D.O. Krimer, B. Hartl, and S. Rotter, PRL 115, 033601 (2015)
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