Quantum optics in many-body physics: Quantum feedback, optomechanical quantum nonlinearities, and disorder protected edge states

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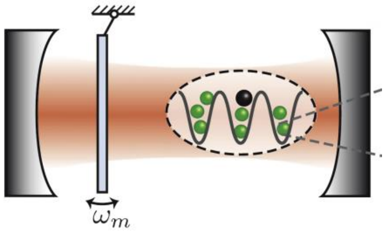
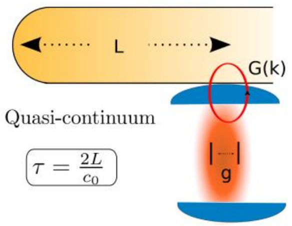
Outline

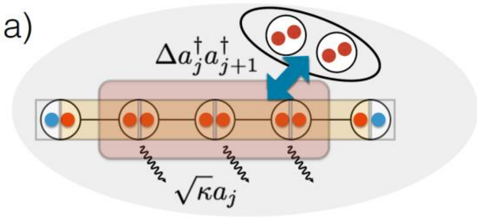
- Motivation: Environment induced enabling features



- Example (i): using *phonons* in non-classical optomechanics via strong coupling to a Rydberg superatom



- Example (ii): using *cavity loss* to stabilize Rabi oscillations via quantum feedback of structured continuum
- Example (iii): using *disorder* (inhomogeneous coupling) to protect Majorana edge modes against decoherence



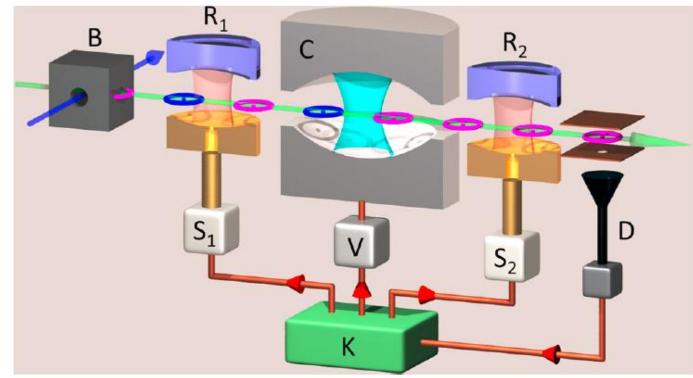
- Conclusion

SPIE. CONNECTING MINDS. ADVANCING LIGHT.

- Protect against dissipation
- or use dissipation

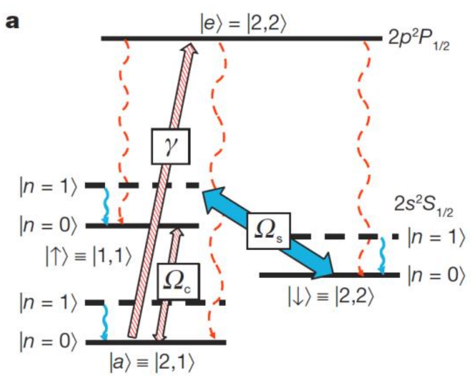
Environment induced enabling features

Feedback stabilized single photon states



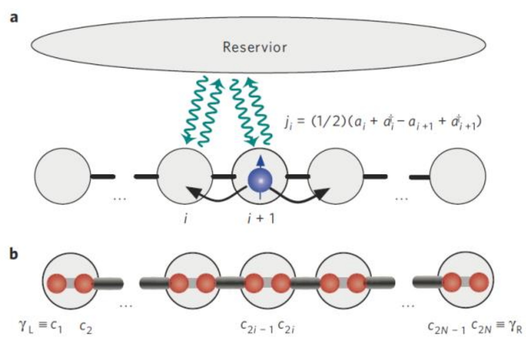
X. Zhou et al, PRL 108, 243602 (2012)

maximally entangled two-qubit state due to radiative dephasing



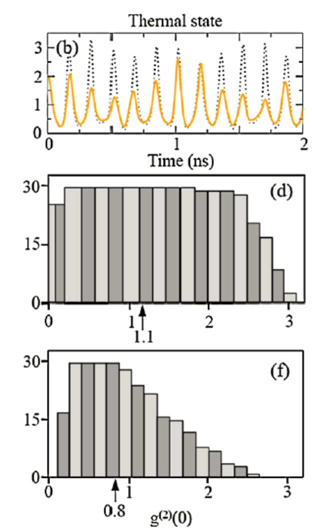
Lin et al, Nature 504, 415 (2013)

Topology by dissipation (particle loss)



S. Diehl et al, Nat.Phys. 7, 971 (2011)

Phonon induced anti-bunching



A. Carmele et al, PRL 104, 156801 (2010)

Nanomechanics Strongly Coupled to a Rydberg Superatom

A. Carmele, B. Vogell, K. Stannigel, and P. Zoller

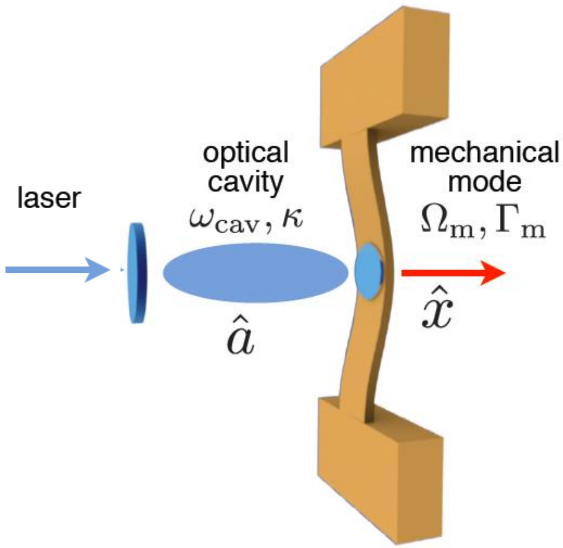
A. Carmele et al, New J. Phys. 16, 63042 (2014)

Cavity optomechanics

- Radiation pressure Hamiltonian
- Small coupling (less than kHz) for membranes

$$\hbar\omega_{\mathrm{cav}}(x)\hat{a}^\dagger\hat{a} \approx \hbar(\omega_{\mathrm{cav}} - G\hat{x})\hat{a}^\dagger\hat{a}$$

$$\hat{H}_{\mathrm{int}} = -\hbar g_0 \hat{a}^\dagger\hat{a}(\hat{b} + \hat{b}^\dagger)$$



Aspelmeyer et al, arXiv:1303.0733

Cavity optomechanics – laser driven

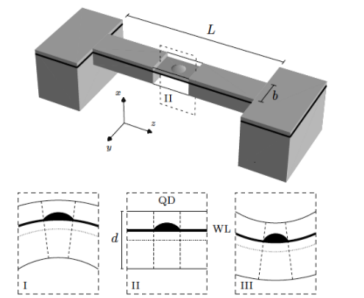
- the cavity is driven by a laser → cavity mode is deplaced
- Radiation pressure Hamiltonian can be linearized → enhanced coupling

$$\hat{a} = \bar{\alpha} + \delta\hat{a}$$

$$\hat{H}_{\mathrm{int}} = -\hbar g_0(\bar{\alpha} + \delta\hat{a})^\dagger(\bar{\alpha} + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

Cavity optomechanics: New challenges

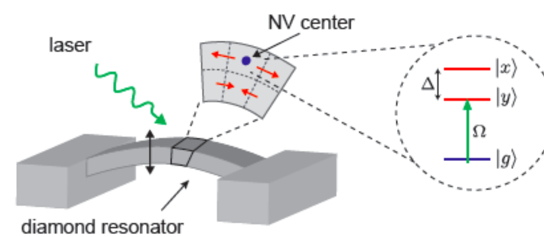
- ❑ experiments so far in the linear regime
- ❑ nonlinearity necessary to create entanglement – to use optomechanics for quantum information processing



PRL 92, 75507 (2004)

Nanomechanics Coupled to a Nonlinearity: Solid-state realization

- ❑ Semiconductor beam (GaAs) with a quantum dot
- ❑ NV– defect center in all-diamond doubly clamped beam
- ❑ Intrinsic two-level defects in the mechanical oscillator

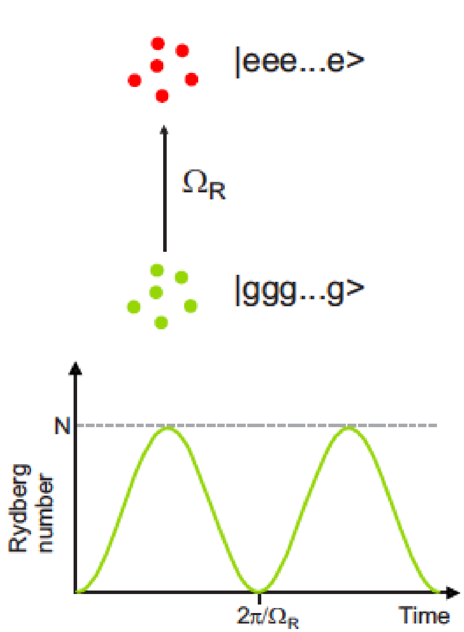


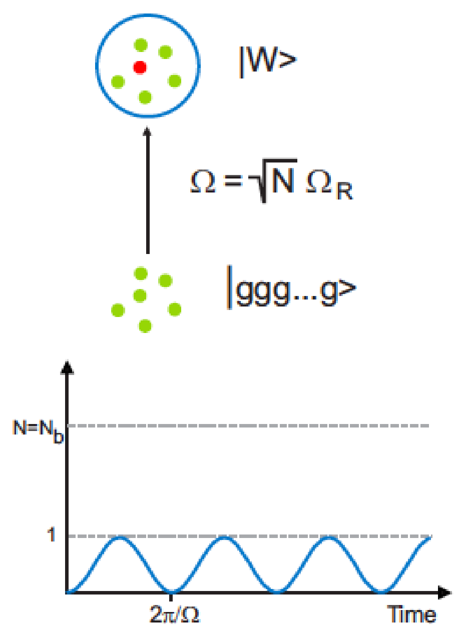
PRB 88, 64105 (2013)

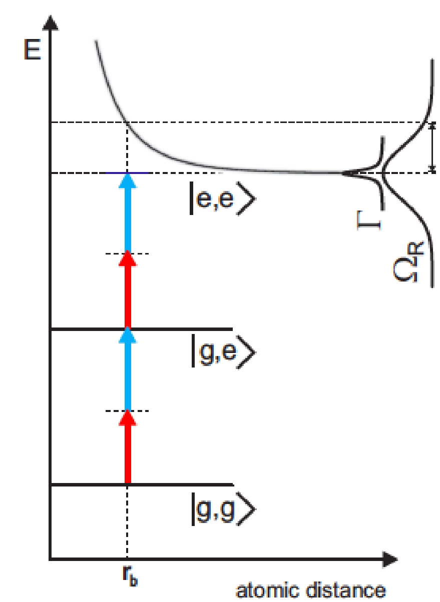
Our proposal:
use a Rydberg superatom as the nonlinearity in a hybrid system

Rydberg Superatom as an artificial atom

- ❑ An atomic ensemble with a Rydberg state interacts strongly due to the VdW interaction → Rydberg shift
- ❑ Rydberg shift leads to the Rydberg blockade mechanism
- ❑ Coupling to the light field is increased by the collective enhancement factor



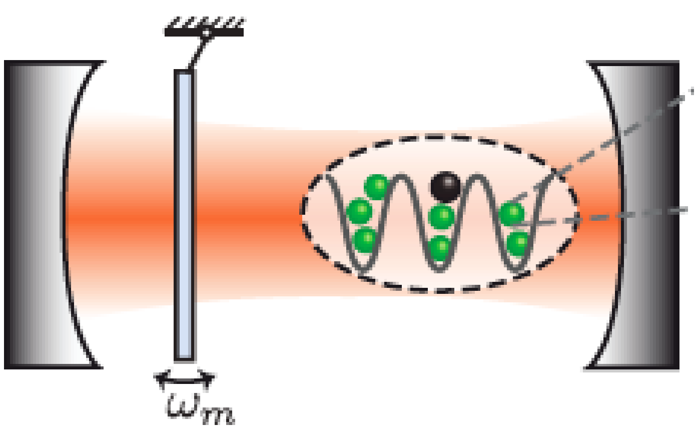




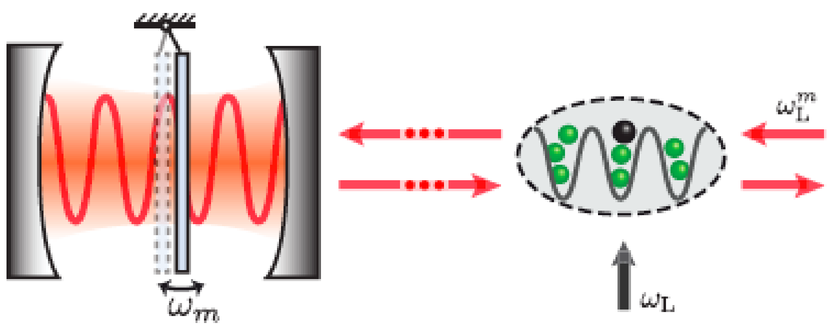
Hoffmann et al, PRL 110, 203601 (2013); Löw et al, J. Phys. B 45, 113001 (2012)

Nanomechanics Coupled to a Nonlinearity: Hybrid system realization

- ❑ use a Rydberg superatom as two-level system
- ❑ collective enhancement allows for strong coupling
- ❑ Superatom can be pumped, quenched, and can easily be read out

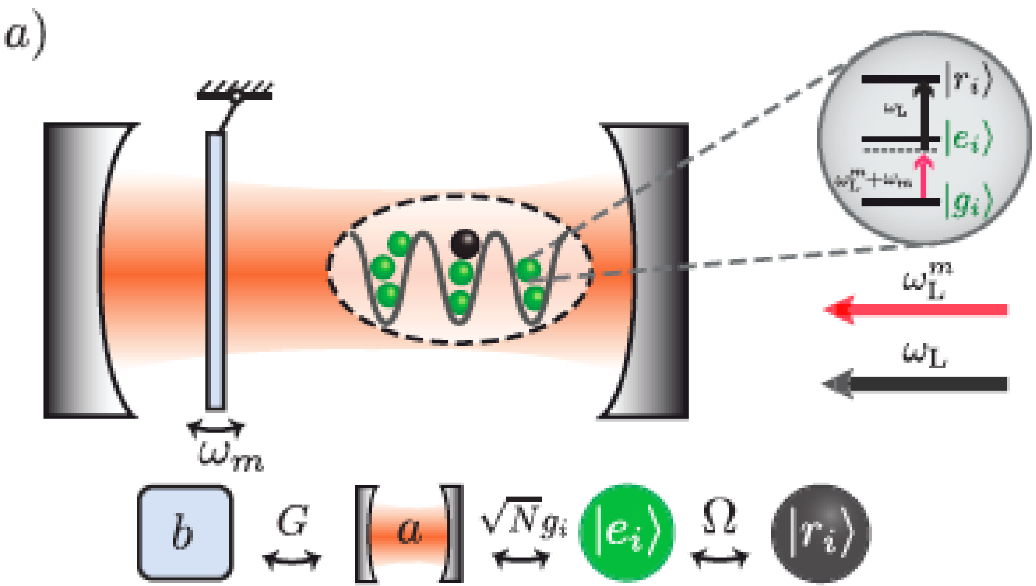


And a modular setup is possible



Cyrogenic environment

UHV

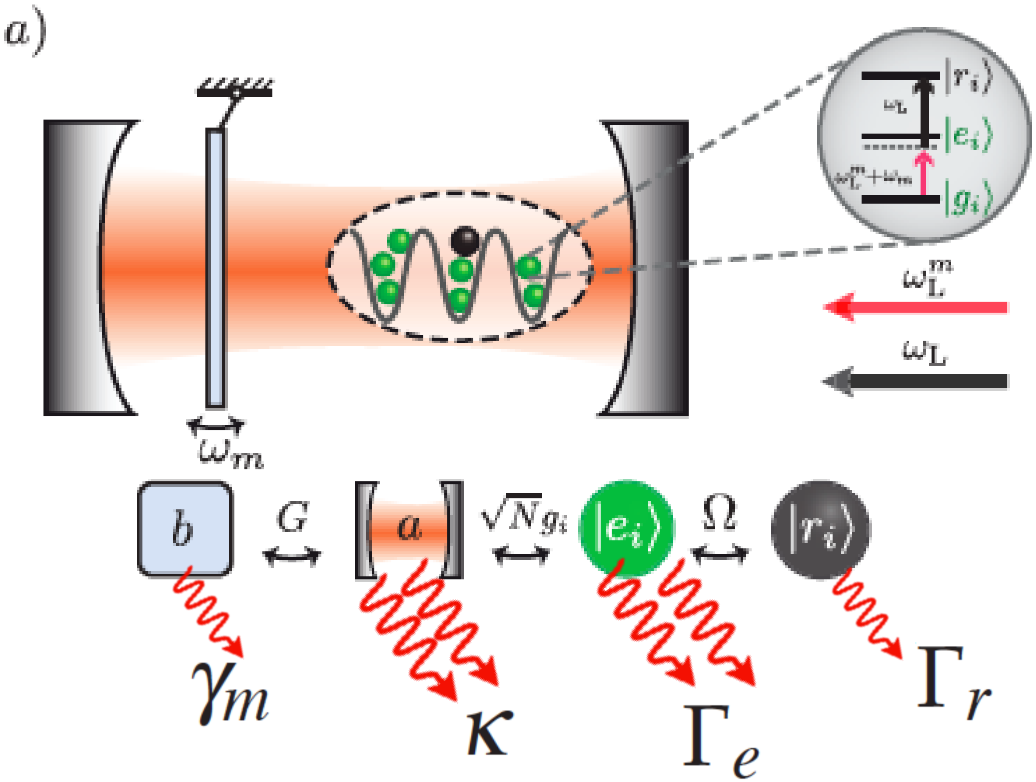


Principle setup without dissipation processes

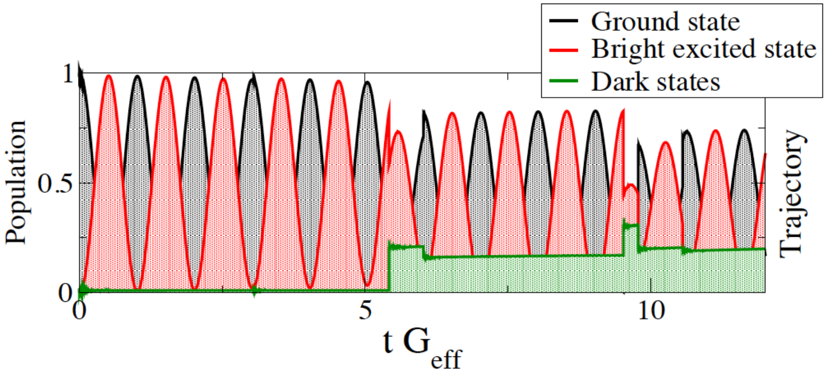
$$H_{\text{int}} = G\left(a^\dagger b + b^\dagger a\right) + \sum_{i=1}^{N} \left(g_i\, a\,|e_i\rangle\langle g_i| + \Omega e^{-i\omega_L t}\,|r_i\rangle\langle e_i|\right) + \text{h.c.}$$

$$+ \sum_{\substack{i,j=1\\ j>i}}^{N} \Delta_R^{ij}\,|r_i r_j\rangle\langle r_i r_j| + \text{h.c.}$$

A. Carmele et al, New J. Phys. 16, 63042 (2014)

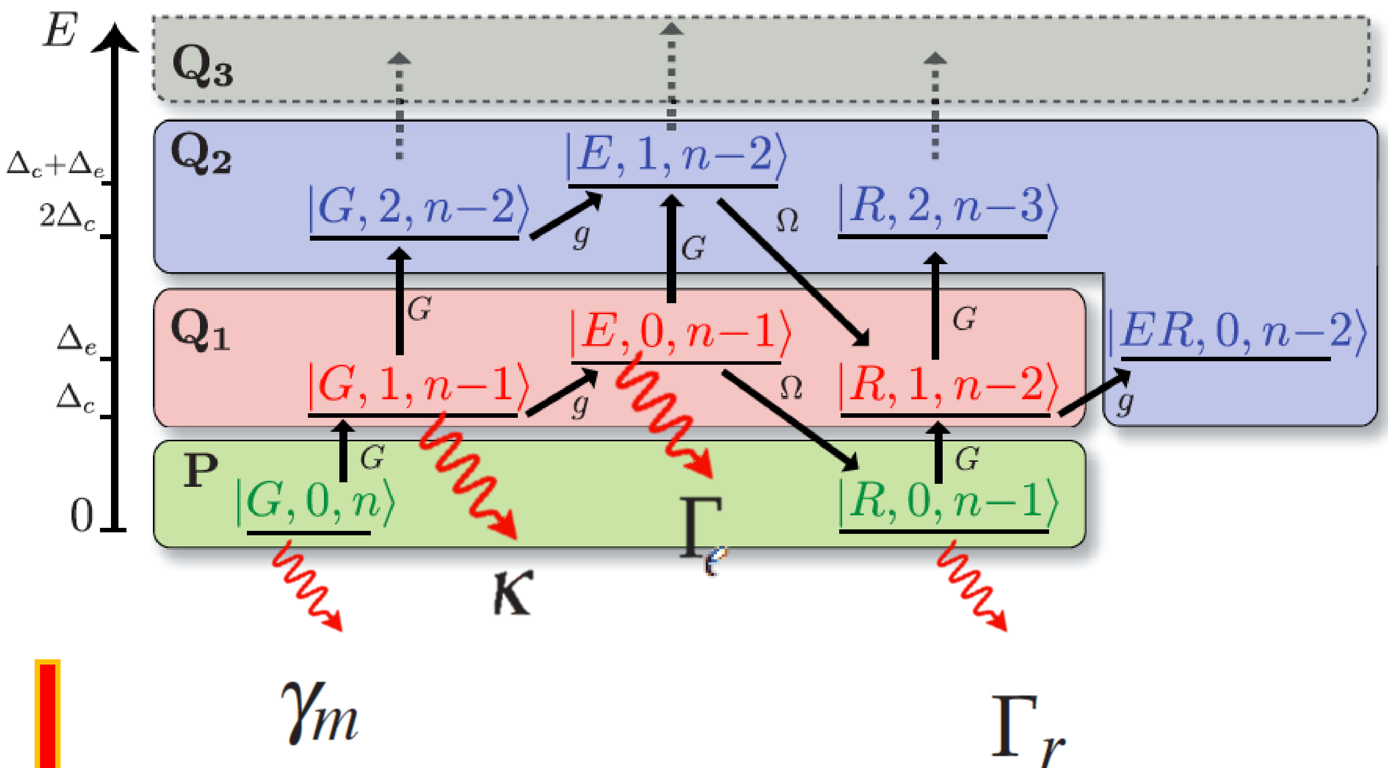


Principle setup with dissipation processes



Cavity – mediated membrane – Rydberg superatom coupling

- Major obstacles: Dissipation during the excitation transfer
- Phonon decoherence and radiative decay from Rydberg state few kHz
- But: photon leakage and radiative decay from intermediate state MHz

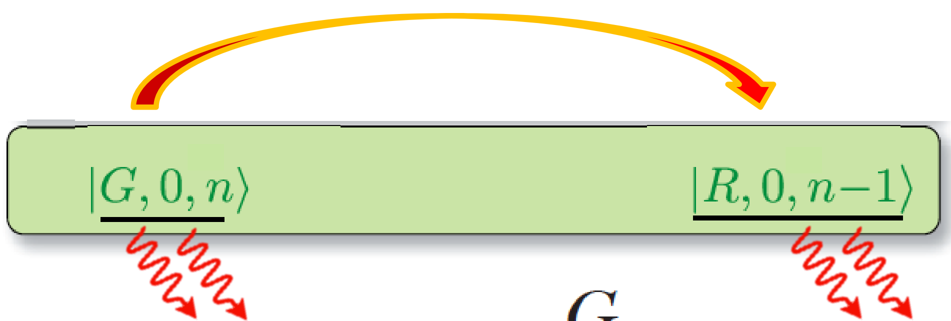


Cavity photons and intermediate excited states are detuned from the coherent interaction

A. Carmele et al, New J. Phys. 16, 63042 (2014)

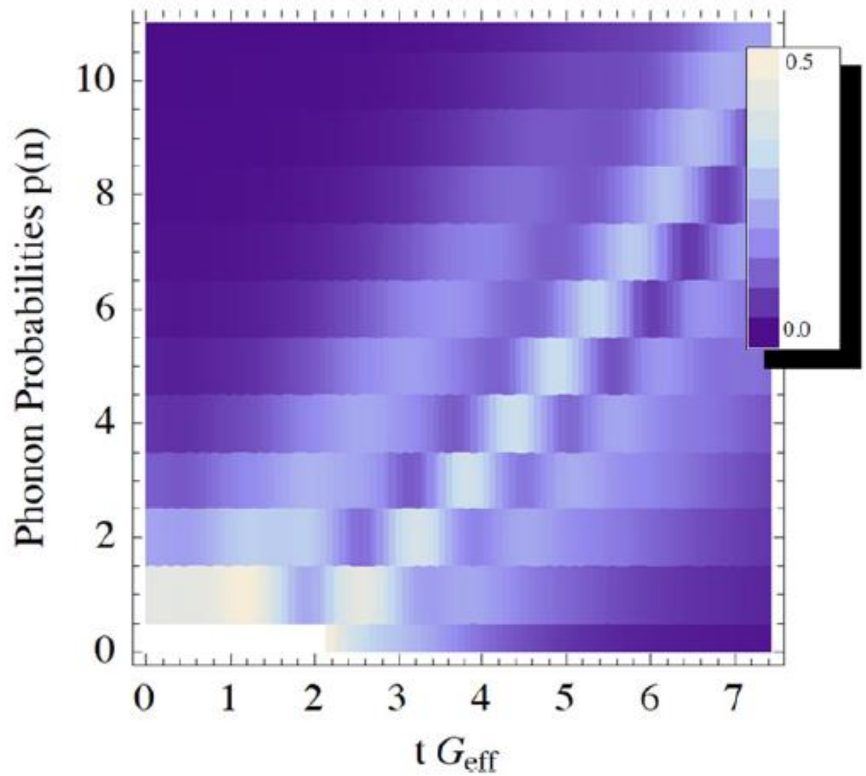
Strong coupling limit is accessible:

$$G_{\text{eff}} \approx \sqrt{N}\frac{gG\Omega}{\Delta_e\Delta_c} \gg \Gamma_m^{\text{eff}}, \Gamma_r^{\text{eff}}, \Gamma_r, \gamma_m(N_m+1)$$



γ_m $\quad \Gamma_m^{\text{eff}} \approx n\kappa\frac{G}{\Delta_c^2}$ $\quad \Gamma_r$ $\quad \Gamma_r^{\text{eff}} \approx \Gamma_e\frac{\Omega}{\Delta_e^2}$

The cavity loss and radiative decay of the intermediate state are suppressed and an effective two-level dynamics take place preparation of non-classical states even at finite temperatures.



Fidelity for the individual state transfer:

$$\mathscr{F} \approx 1 - \frac{\pi}{2G_{\mathrm{eff}}}\left(4N_m\gamma_m + \gamma_m + \Gamma_r^{\mathrm{eff}} + \Gamma_r\right)$$

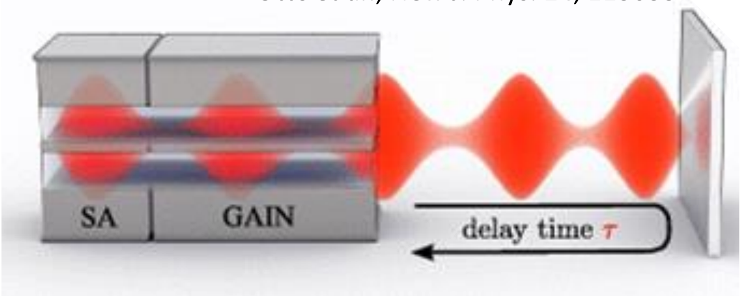
A. Carmele et al, New J. Phys. 16, 63042 (2014)

Pseudo photon path representation of quantum feedback

J. Kabuss, K. Stannigel, D. Krimer, S. Rotter, A. Knorr, and A. Carmele

J. Kabuss et al, in preparation (2015)

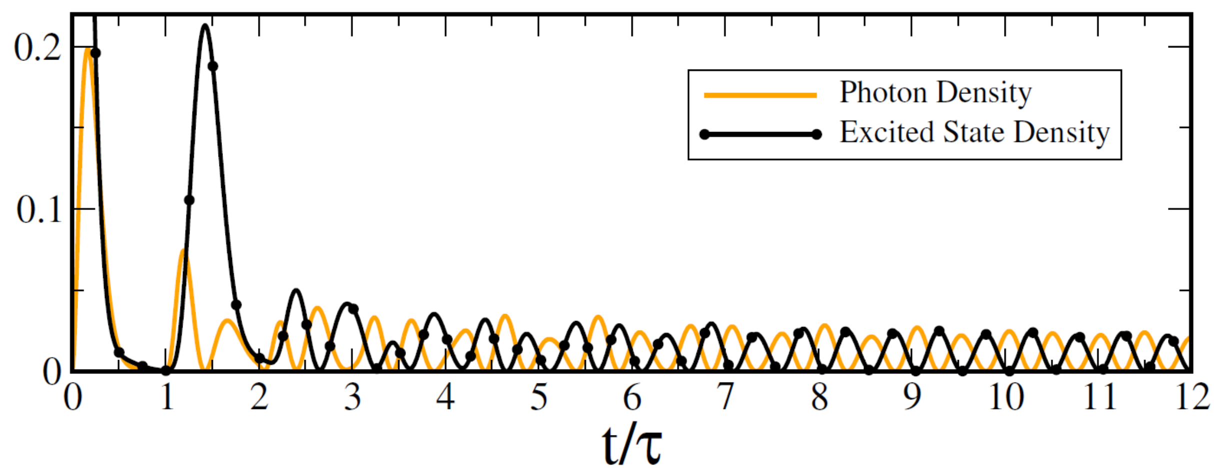
Otto *et al.*, New J. Phys. **14**, 113033



Non-invasive Feedback
used in semiclassical limit (Lang-Kobayashi)

Control of quantum state by shaping the environment

Here, Rabi oscillations are recovered in the weak coupling limit

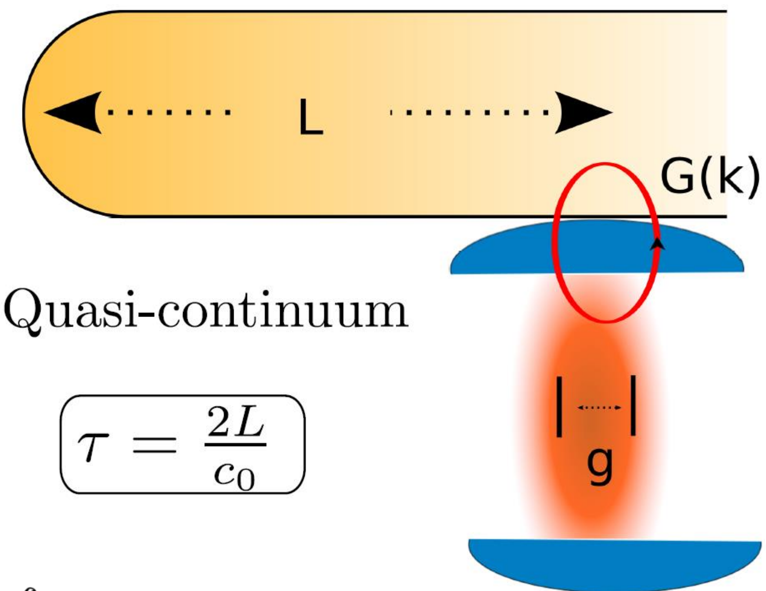


Carmele et al, PRL 110, 013601 (2013)

Exchange of cavity- with waveguide photons

$$\begin{aligned} H/\hbar &= -M\left(\sigma^- a^\dagger + \sigma^+ a\right) \\ &\quad - \int \mathrm{d}k\; G(k,t)\; a^\dagger d_k + G^*(k,t)\; d_k^\dagger a, \end{aligned}$$

$$G(k) = G\sin(kL)$$



$$\tau = \frac{2L}{c_0}$$

Single photon limit:
(emitter prepared initially in excited state)

$$|\Psi\rangle = c_e\,|e,0,\{0\}\rangle + c_g\,|g,1,\{0\}\rangle + \int \mathrm{d}k\; c_{g,k}\,|g,0,\{k\}\rangle$$

Solution via Laplace-transformation:

$$\begin{aligned} s\ c_e(s) &= 1 + i\ M\ c_g(s) \\ s\ c_g(s) &= i\ M\ c_e(s) - \kappa\ c_g(s) + \kappa\ c_g(s)\ e^{-(s-i\omega_0)\tau} \end{aligned}$$

Dynamics with and without feedback

$t \leq \tau:$

$$c_g(t) = i\ \frac{\sin\left[\sqrt{1-(\kappa/2M)^2}\ Mt\right]}{\sqrt{1-(\kappa/2M)^2}}\ e^{-\kappa/2\ t}$$

altered Rabi-frequency

$t \geq \tau:$

$$c_g(t) = \frac{i}{2}\sum_{n=0}^{\infty} n!2^{n+1} e^{-\kappa/2(t-n\tau)+i\omega_0 n\tau}\Theta(t-n\tau) \times \sum_{k=0}^{n} \frac{(-1)^k}{k!(n-k)!}\frac{[\kappa/2(t-n\tau)]^{n+1+k}}{(n+1+k)!}$$

System of equations in the Laplace domain:

$$\int d\omega \, \frac{G^2(\omega)}{s - i\omega}$$

$$\begin{pmatrix} c_e(0) \\ c_g(0) \end{pmatrix} = s\,[1 - \mathbb{L}] \begin{pmatrix} c_e(s) \\ c_g(s) \end{pmatrix} \qquad \mathbb{L} = \begin{pmatrix} 0 & i\,\frac{M}{s} \\ i\,\frac{M}{s} & -\frac{\kappa}{s}\,(e^{-\tau s} - 1) \end{pmatrix}$$

von Neumann series reveals scattering matrix:

$$\begin{aligned} \begin{pmatrix} c_e(s) \\ c_g(s) \end{pmatrix} &= \frac{1}{s} \sum_{n=0}^{\infty} \mathbb{L}^n \begin{pmatrix} c_e(0) \\ c_g(0) \end{pmatrix} \\ &= \sum_{n=0}^{\infty} \left[\frac{(iM)^n}{s^{n+1}} \begin{pmatrix} 0 & 1 \\ 1 & \frac{\kappa}{iM}(e^{-\tau s} - 1) \end{pmatrix}^n \right] \begin{pmatrix} c_e(0) \\ c_g(0) \end{pmatrix} \end{aligned}$$

Single events per time step: emission/absorption of photons

Alber *et al.*, Phys. Rev. A 88, 023825

$$c_g(0) = 0$$

$$c_e(0) = 1$$

$$\underbrace{}_{}\begin{pmatrix} c_e(s) \\ c_g(s) \end{pmatrix} = \overbrace{\boxed{\frac{1}{s}\begin{pmatrix} 1 \\ 0 \end{pmatrix}}}^{n=0} + \overbrace{\boxed{\frac{1}{s^2}\begin{pmatrix} 0 \\ iM \end{pmatrix}}}^{n=1} + \overbrace{\boxed{\frac{1}{s^3}\begin{pmatrix} (-iM)^2 \\ -iM\kappa(e^{-s\tau}-1) \end{pmatrix}}}^{n=2} + \overbrace{\boxed{\frac{1}{s^4}\begin{pmatrix} (-iM)^2\kappa(e^{-s\tau}-1) \\ (-iM)^2 - iM\kappa^2(e^{-s\tau}-1)^2 \end{pmatrix}}}^{n=3} + \dots$$

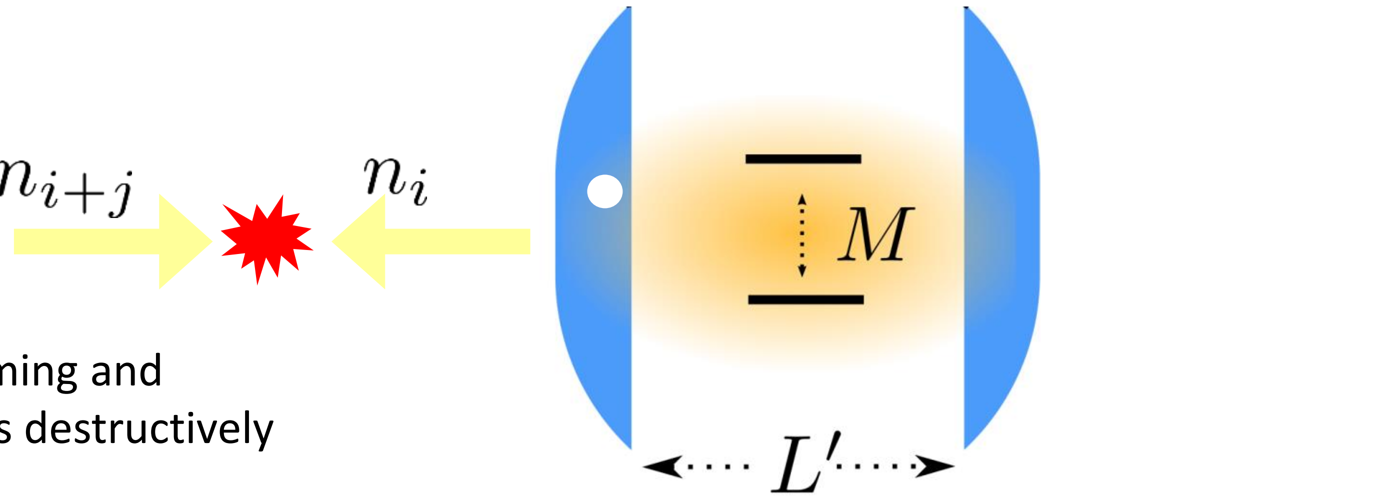
electron in excited state

swap of excitation

reabsorption t>roundtrip

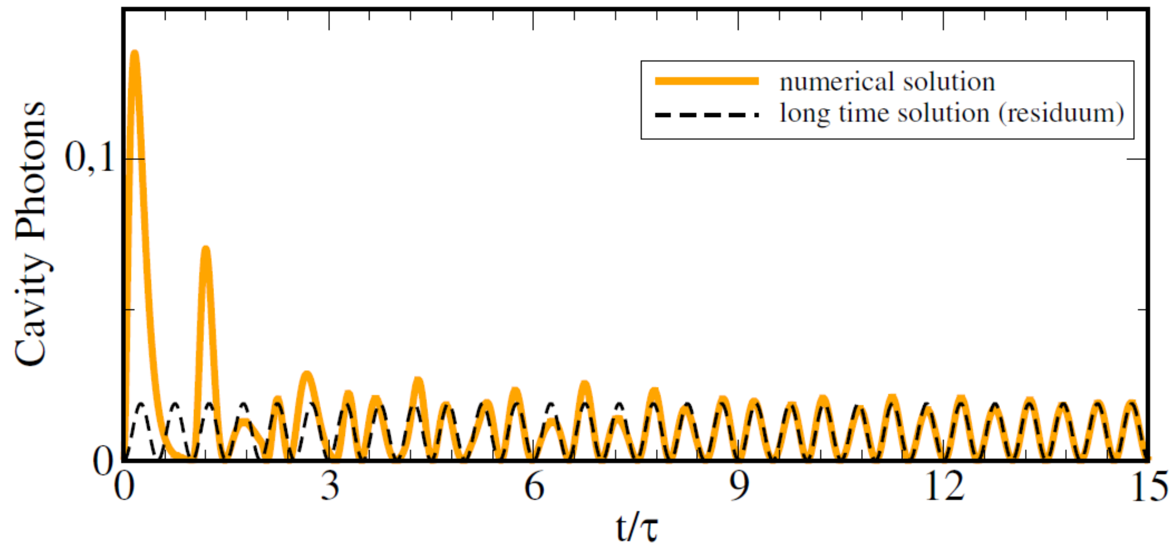
spontaneous emission

interference with previous paths



Choose delay that incoming and outgoing wave packages destructively interfere

Stabilized Rabi oscillations after a couple roundtrips – destructive interference complete



Calculate the long time limit without transient effects:

$$c_g^{(i)}(t) = \frac{1}{2\pi i}\oint \mathrm{d}s\ c_g(s)\ e^{st} = \sum_{\text{Poles}} \mathrm{Res}\left[c_g(s)e^{st}\right]$$

$$c_g^{(i)}(t) = \frac{i\sin[Mt]}{1+\kappa n\pi/M}$$

clean coupling element

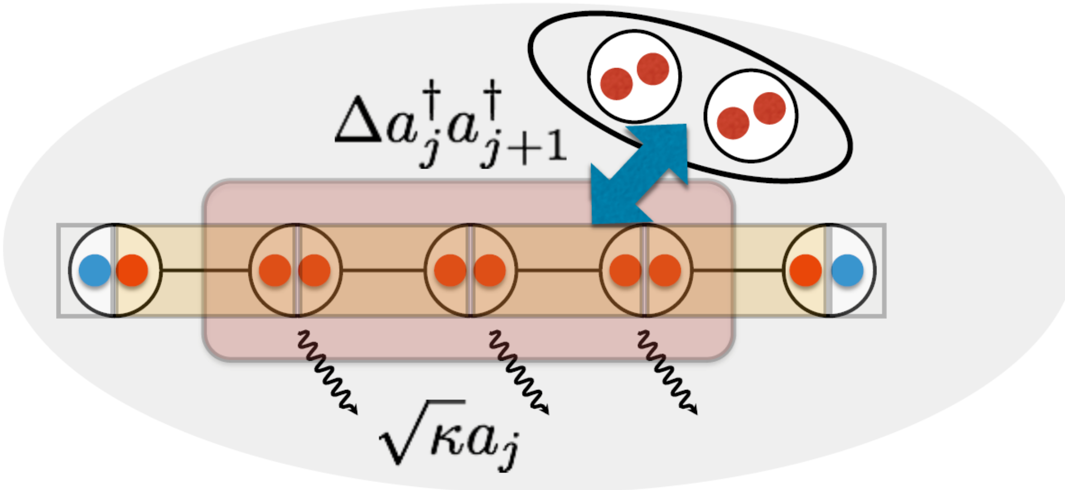
$$c_g^{(i)}(t) = \frac{i\sin[Mt]}{1+\kappa(2n+1)\pi/2M}$$

Stabilizing Majorana edge modes against symmetry-breaking losses via disorder

A. Carmele, C. Kraus, M. Dalmonte, M. Heyl, and P. Zoller

A. Carmele et al, in preparation (2015)

Goal: store and protect quantum states
in Majorana edge states
even in the presence of
symmetry breaking losses



Ideal case:

$$H_{\mathrm{K}} = -\sum_{l=1}^{N-1} \left[\left(J_l \; c_l^\dagger c_{l+1} - \Delta_l \; c_l c_{l+1} \right) + \mathrm{h.c.} \right] + \mu \sum_{l=1}^{N} c_l^\dagger c_l$$

Symmetry breaking
next-neighbor interaction

$$H = H_{\mathrm{K}} + V, \quad V = U \sum_{l=1}^{N-1} \left[n_l - \frac{1}{2} \right] \left[n_{l+1} - \frac{1}{2} \right]$$

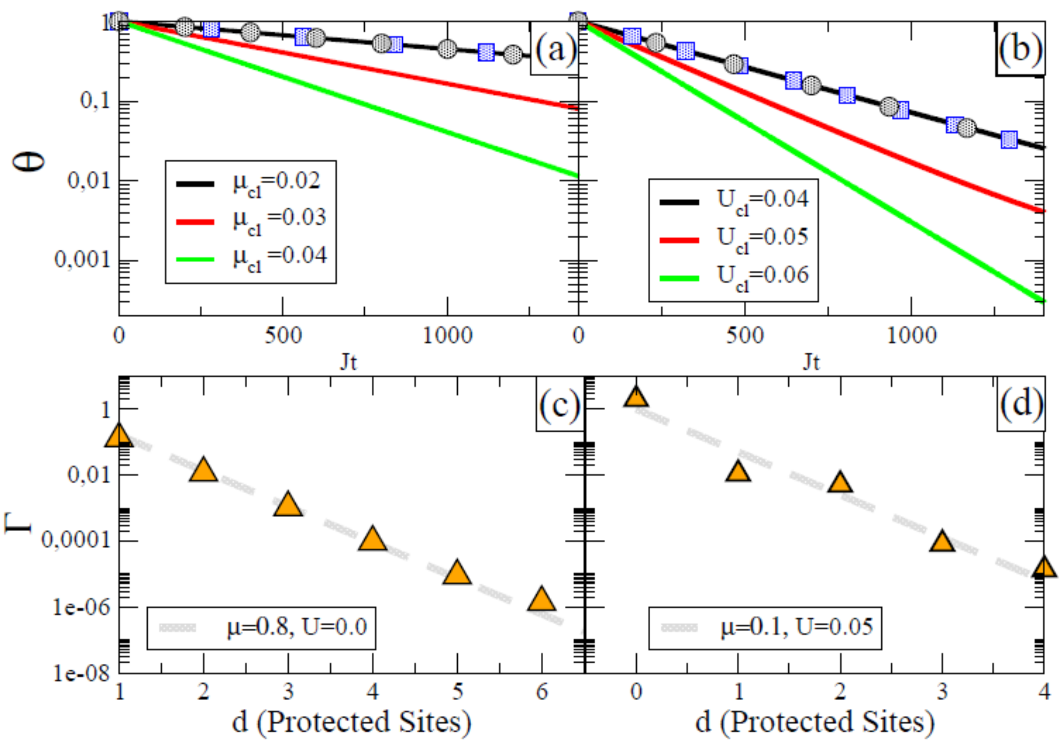
Particle loss:

$$\partial_t \rho = -\frac{i}{\hbar} [H, \rho] + \sum_{l=1}^{N} \kappa_l \; \left[c_l \rho c_l^\dagger - \frac{1}{2} \left\{ c_l^\dagger c_l, \rho \right\} \right]$$

Figure of merit: Survival time of the edge-edge correlation

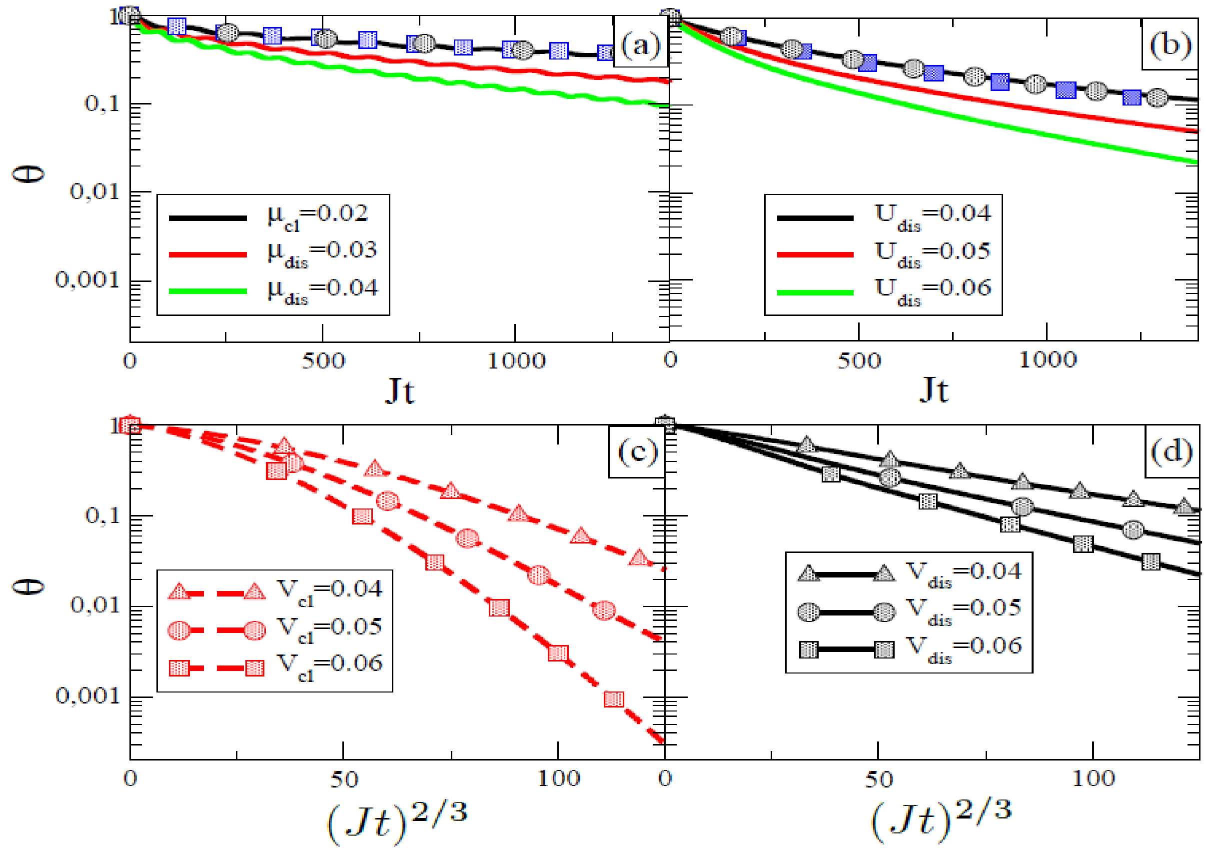
$$\theta = \langle \psi_0 | \Theta | \psi_0 \rangle = 1, \quad \Theta = i \left(c_1 + c_1^\dagger \right) \left(c_N - c_N^\dagger \right)$$

Edge-edge correlation equals 1 in an initally half-filled chain



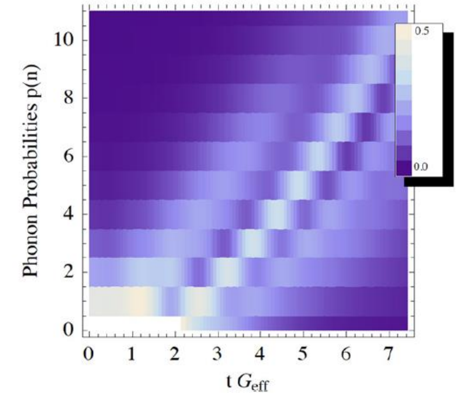
Number of protected sites protects the edge-edge correlation – protection time scales exponentially with number of protected sites

Switching on disorder in the tunneling coupling leads to strongly changed decay dynamics – stretched exponential



Disorder protects edge states from symmetry breaking interaction and particle loss by “increasing” the path length to a dissipating site

Conclusion



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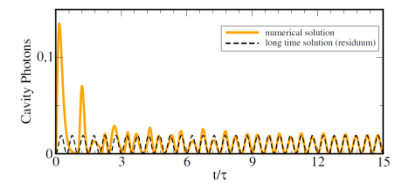

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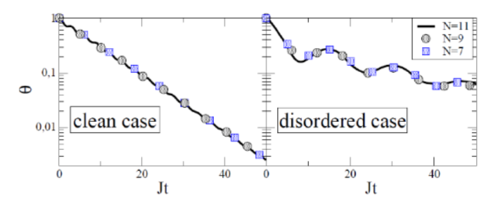

Thank you!!