Nanomechanics Strongly Coupled to a Rydberg Superatom

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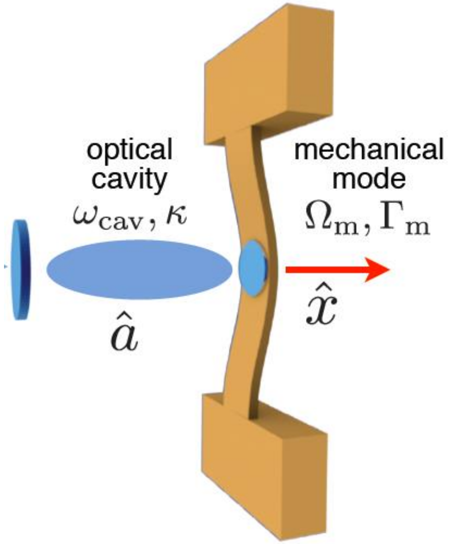
Short explanation: What is cavity optomechanics?

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

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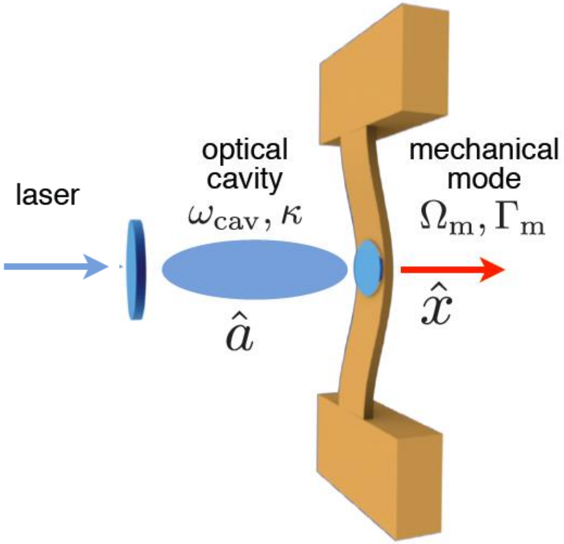


Aspelmeyer et al, arXiv:1303.0733

Cavity optomechanics – laser driven

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

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

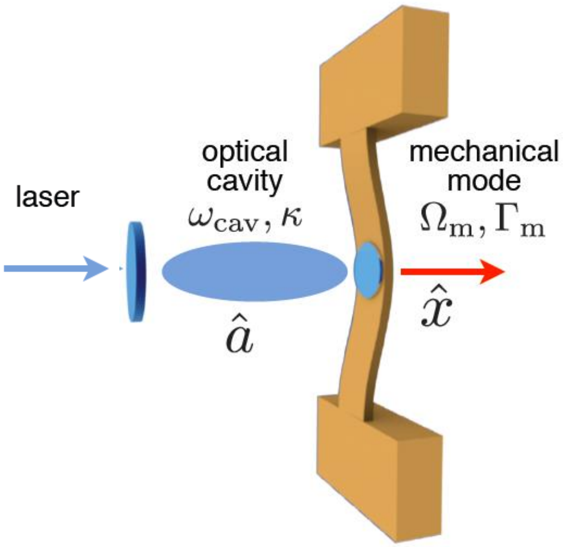
↳

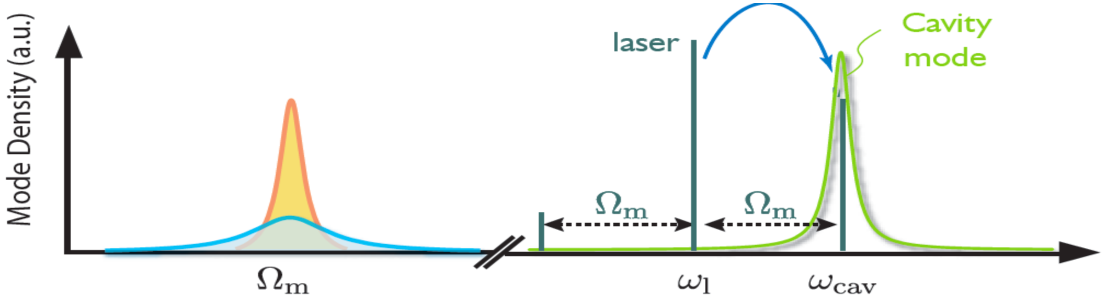
$$\hat{H}_{\mathrm{int}} = -\hbar g_0(\bar{\alpha} + \delta\hat{a})^\dagger(\bar{\alpha} + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

Ground state cooling

Cavity optomechanics

- ground state cooling - down to few phonons
- enables studies of decoherence processes and sensing





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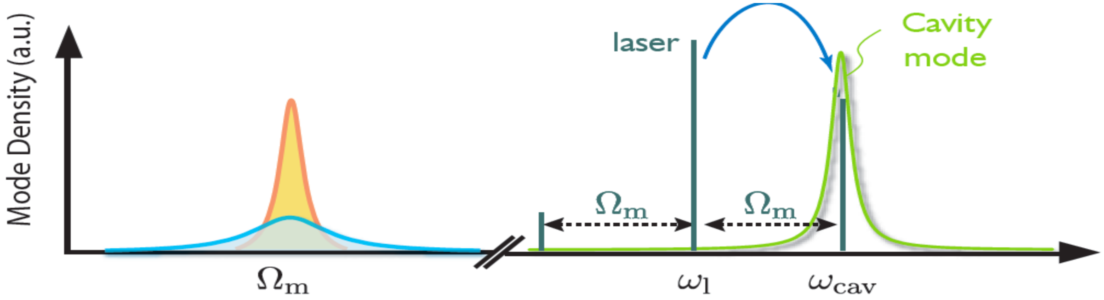
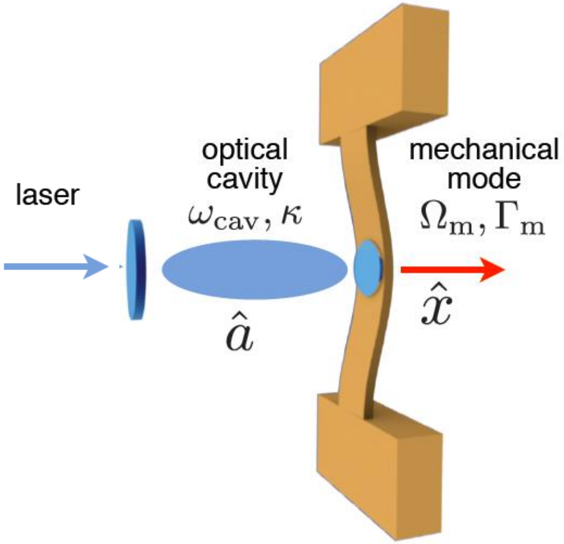
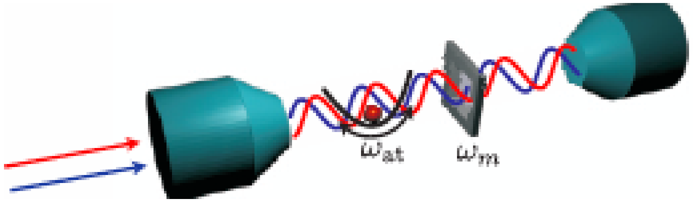


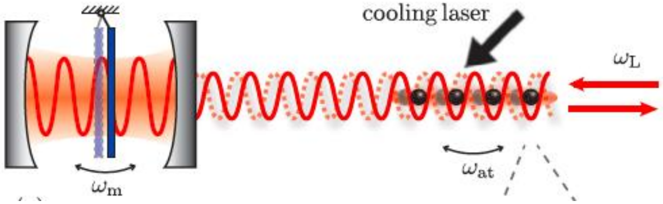


Cooling via hybrid system

- utilizing the toolbox of AMO physics to cool down atomic ensemble
- sympathetic cooling by coupling the center of mass motions to the membrane



Hammerer et al, PRL 103, 063005 (2009)



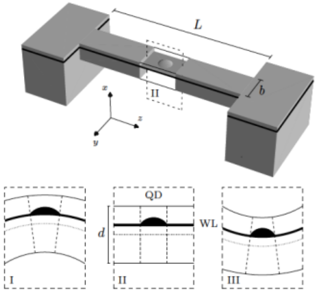
Camerer et al, PRL 107, 223001

Goal: Generation of non-classlcal mechanical states

Cavity optomechanics: New challenges

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

Goal: Generation of non-classlcal mechanical states



PRL 92, 75507 (2004)

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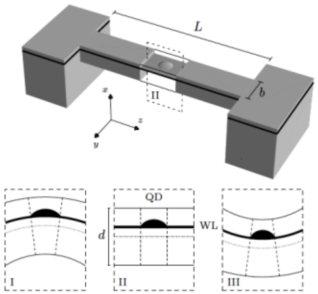
Nanomechanics Coupled to a Nonlinearity: Solid-state realization

- Semiconductor beam (GaAs) with a quantum dot

Goal: Generation of non-classlcal mechanical states



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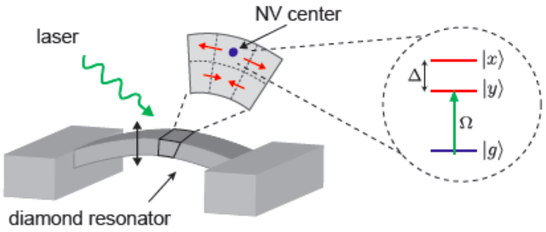
- NV– defect center in all-diamond doubly clamped beam



PRB 88, 64105 (2013)

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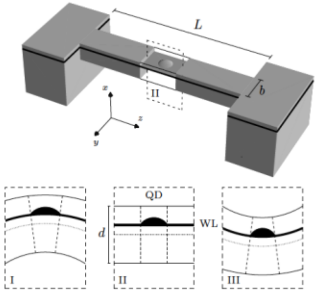

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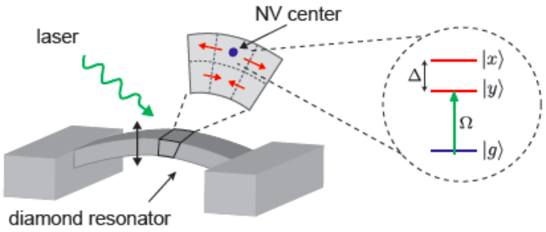
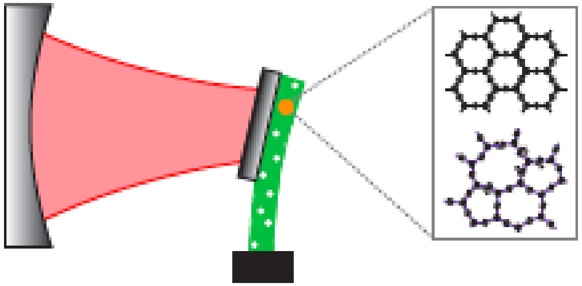
Nanomechanics Coupled to a Nonlinearity: Solid-state realization

- ❑ 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)



PRL 110, 193602 (2013)

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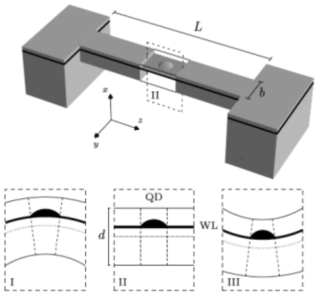

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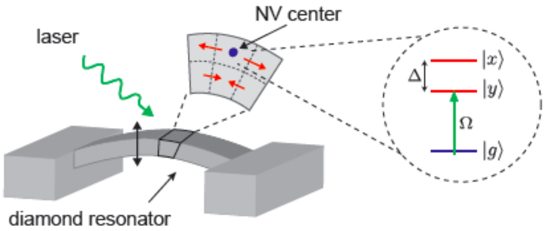
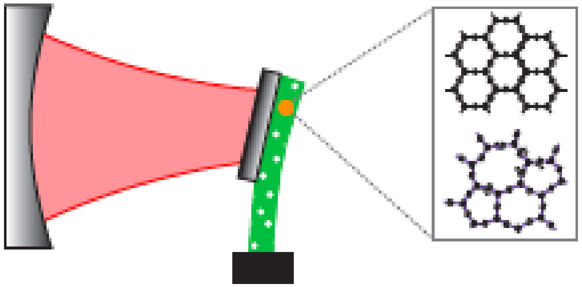


PRB 88, 64105 (2013)

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

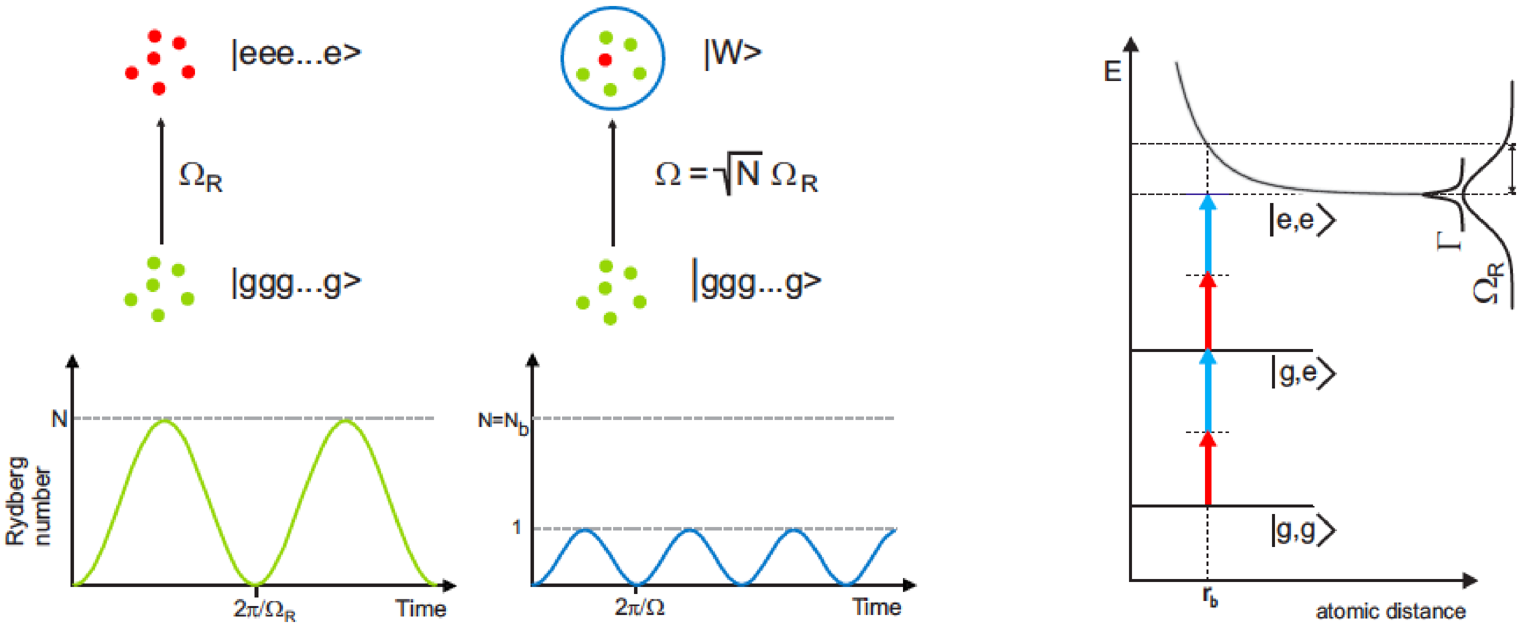


PRL 110, 193602 (2013)

What is a superatom?

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

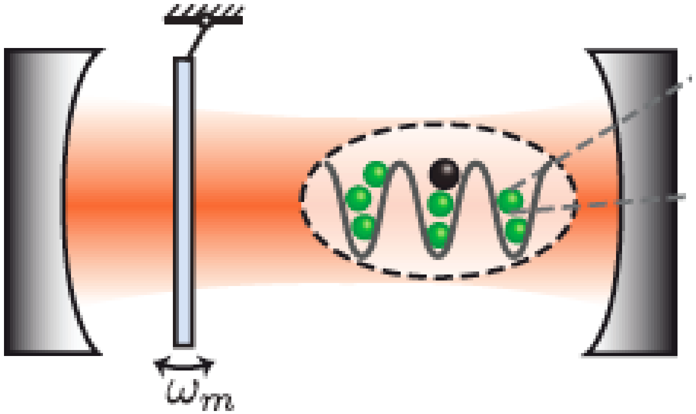


Hoffmann et al, PRL 110, 203601 (2013); Löw et al, J. Phys. B 45, 113001 (2012)

Hybrid system with a superatom as toolbox

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



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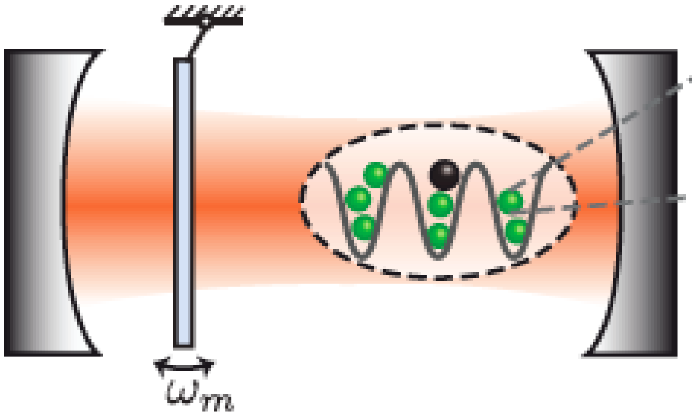
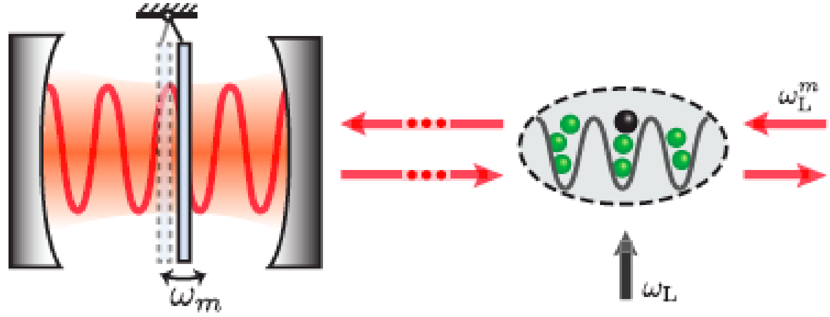


And a modular setup is possible

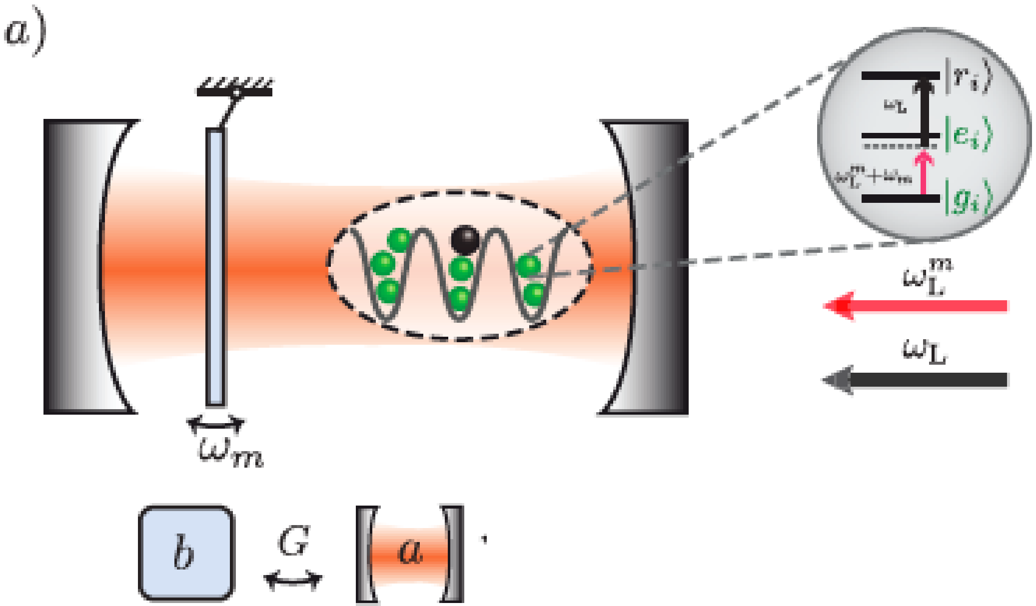


Cyrogenic environment

UHV

cavity-mediated membrane – Rydberg superatom coupling

Goal: Generation of non-classlcal mechanical states



Principle setup without dissipation processes

$$H_{\text{int}} = G\left(a^\dagger b + b^\dagger a\right)$$

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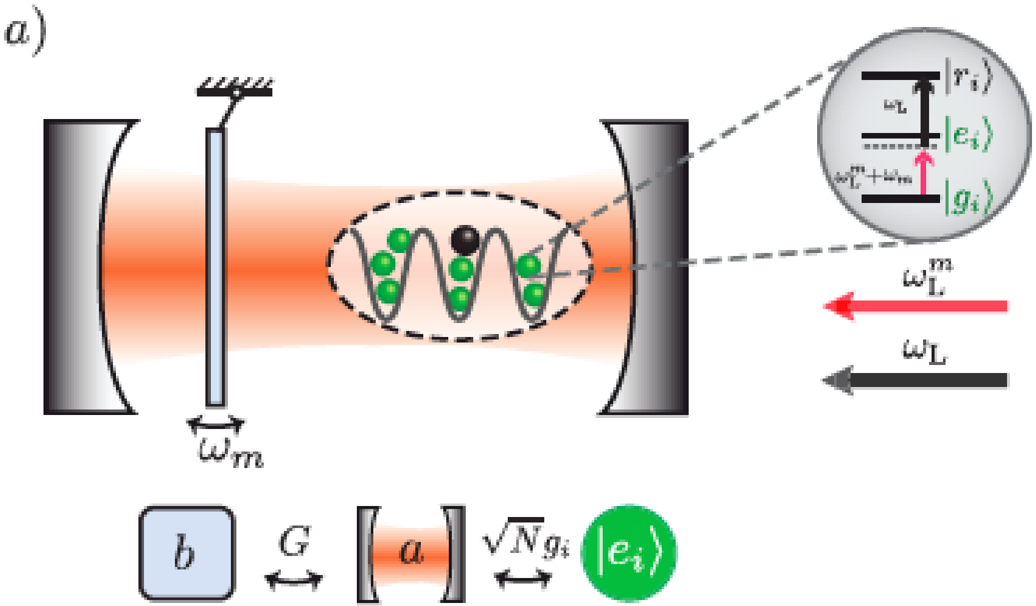
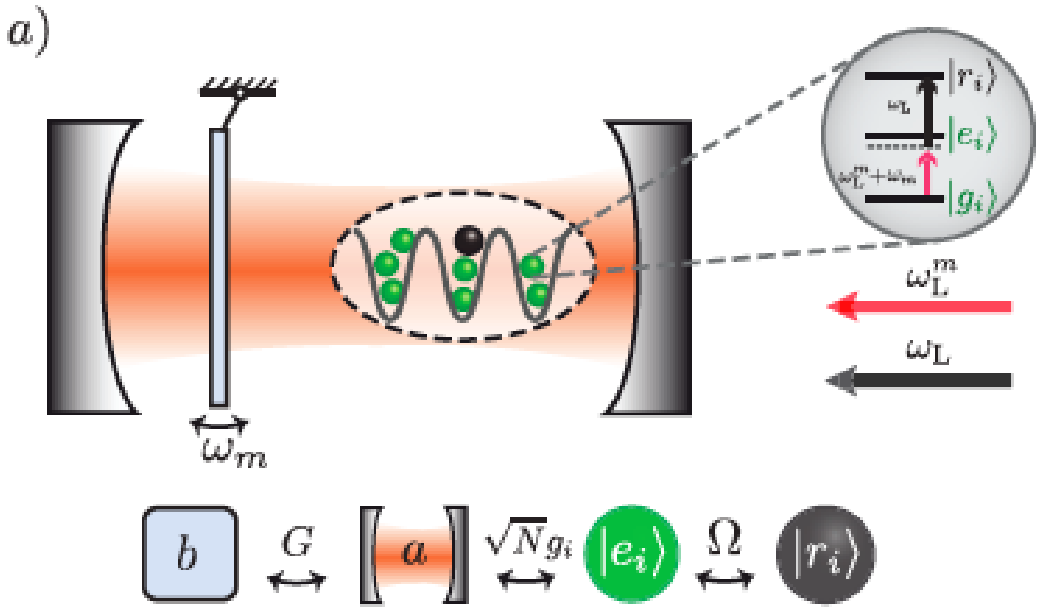


Principle setup without dissipation processes

$$H_{\mathrm{int}} = G\left(a^\dagger b + b^\dagger a\right) + \sum_{i=1}^{N} (g_i\, a\,|e_i\rangle\langle g_i|$$

Goal: Generation of non-classlcal mechanical states



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

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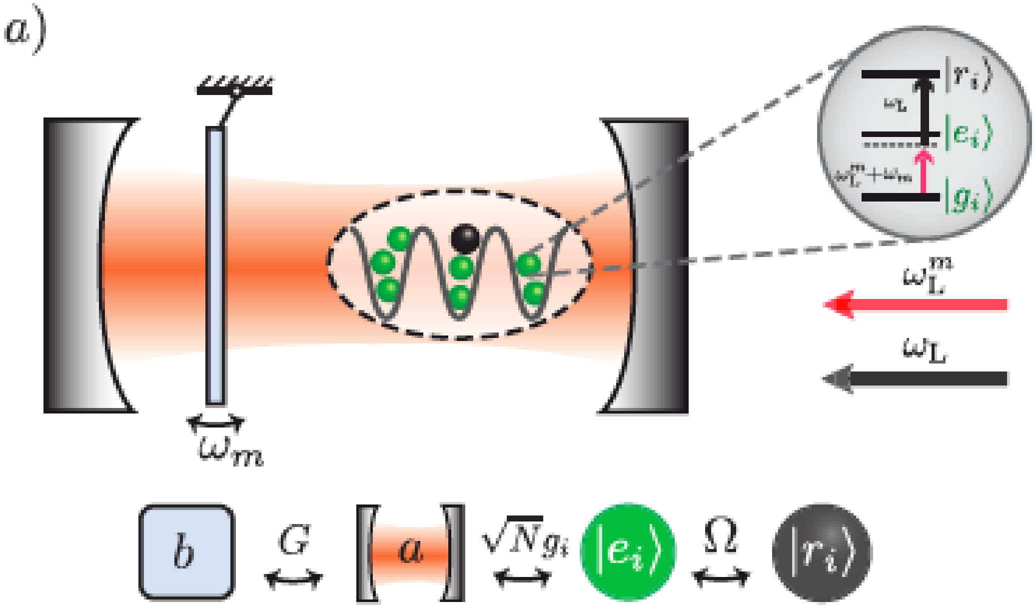

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$$+ \sum_{\substack{i,j=1\\ j>i}}^{N} \Delta_R^{ij}\, |r_i r_j\rangle\langle r_i r_j| + \text{h.c.}$$

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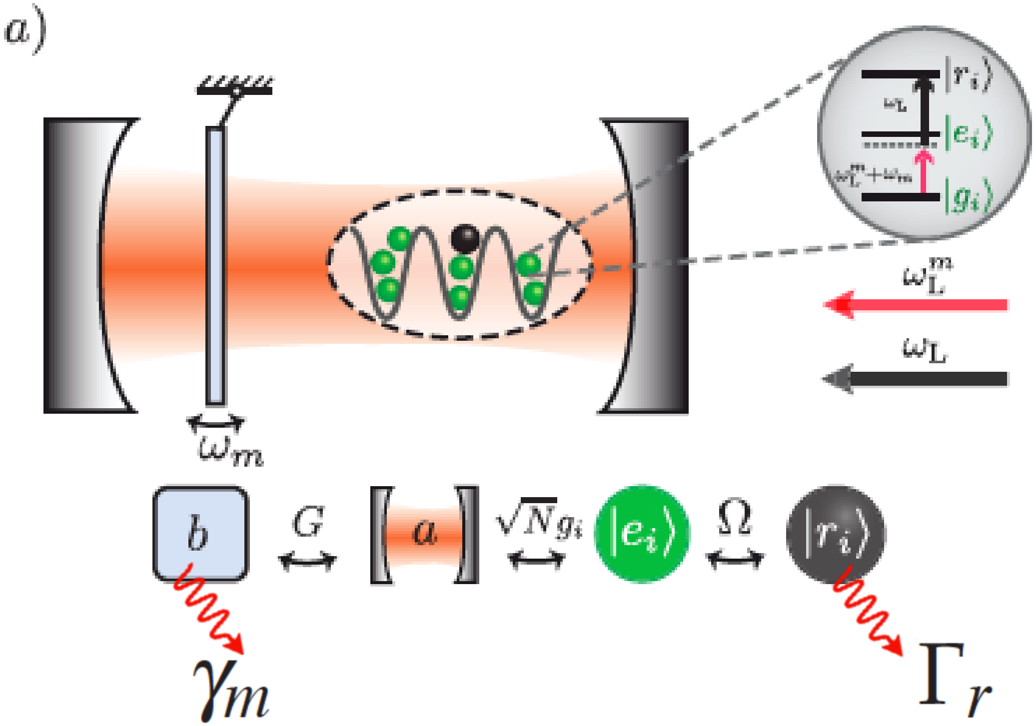
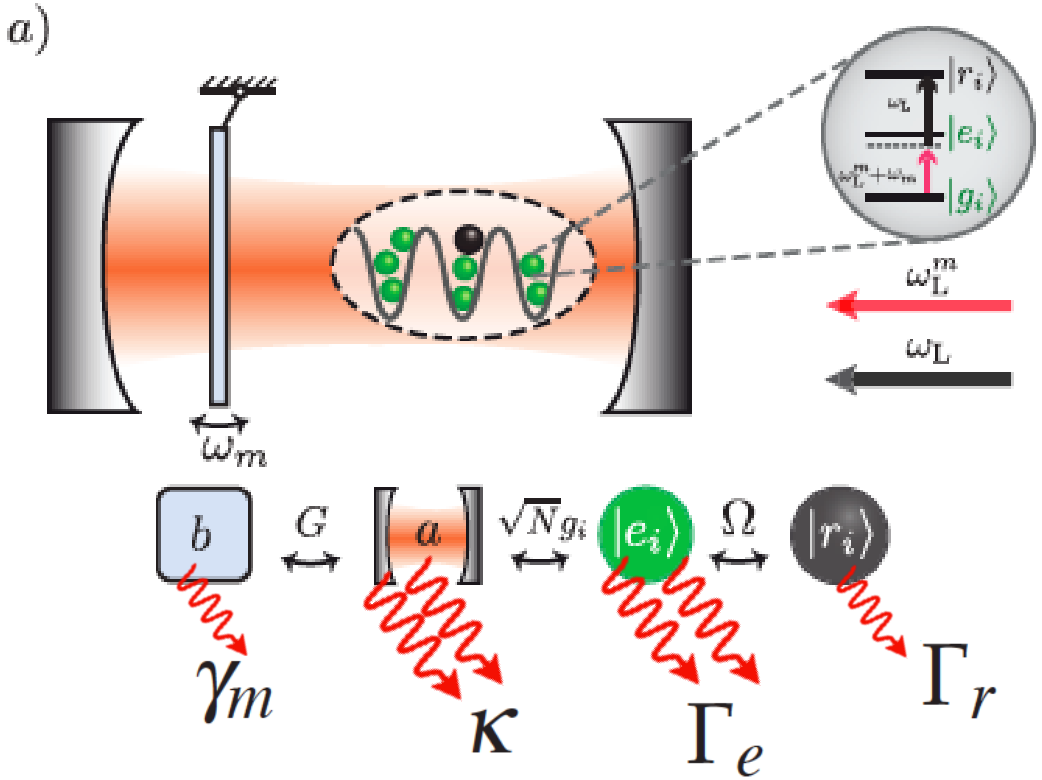


Principle setup with dissipation processes

Cavity – mediated membrane – Rydberg superatom coupling

❑ Major obstacles: Dissipation during the excitation transfer
❑ Phonon decoherence and radiative decay from Rydberg state few kHz

Goal: Generation of non-classlcal mechanical states

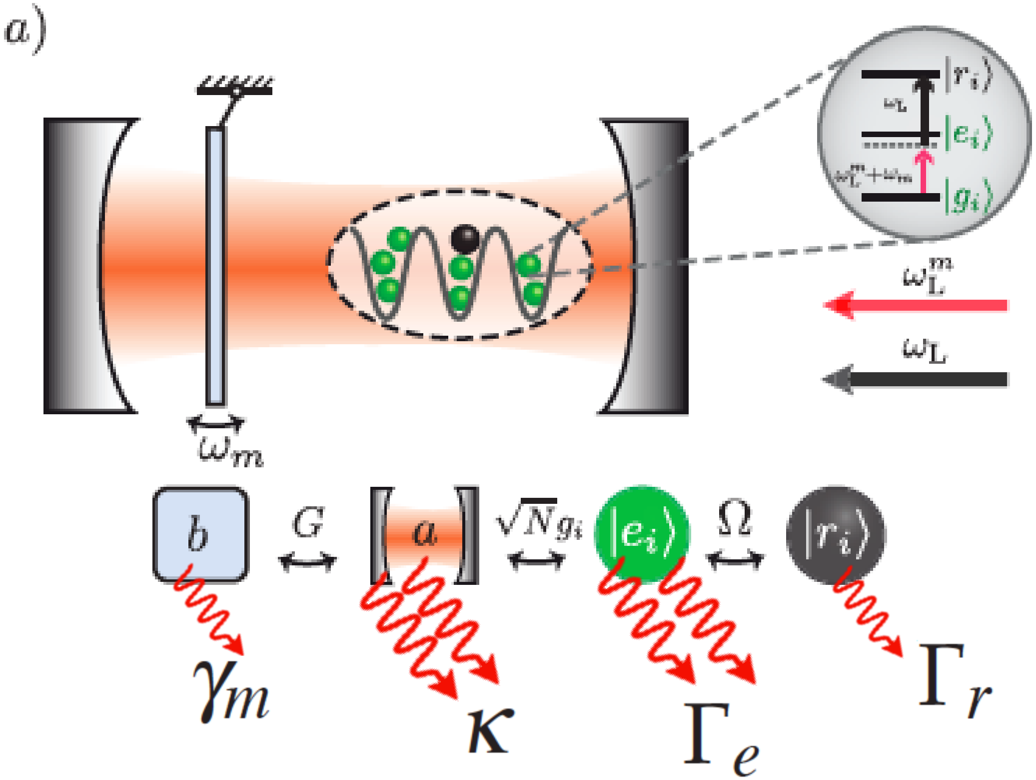


Principle setup with dissipation processes

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

Goal: Generation of non-classlcal mechanical states



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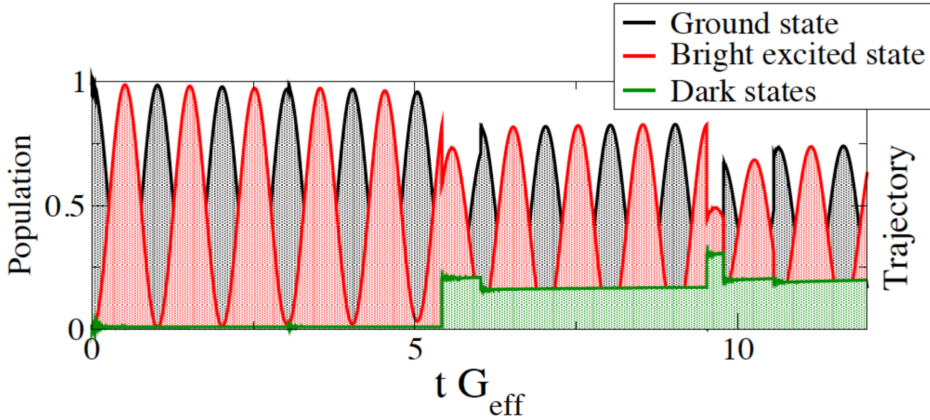

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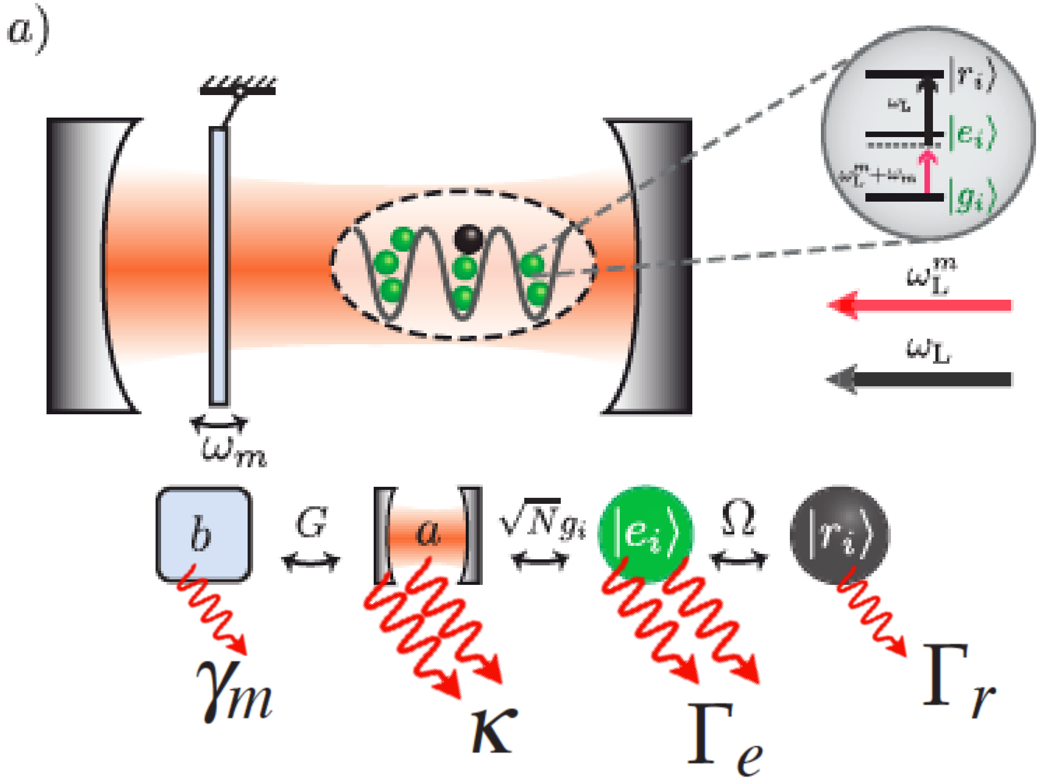
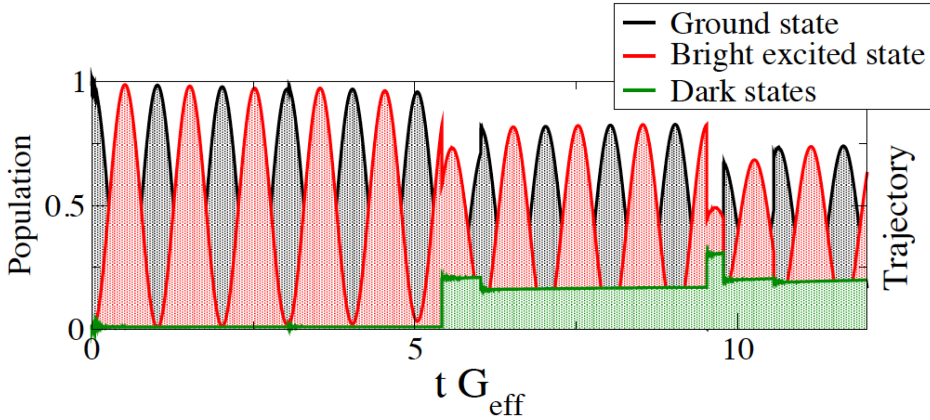
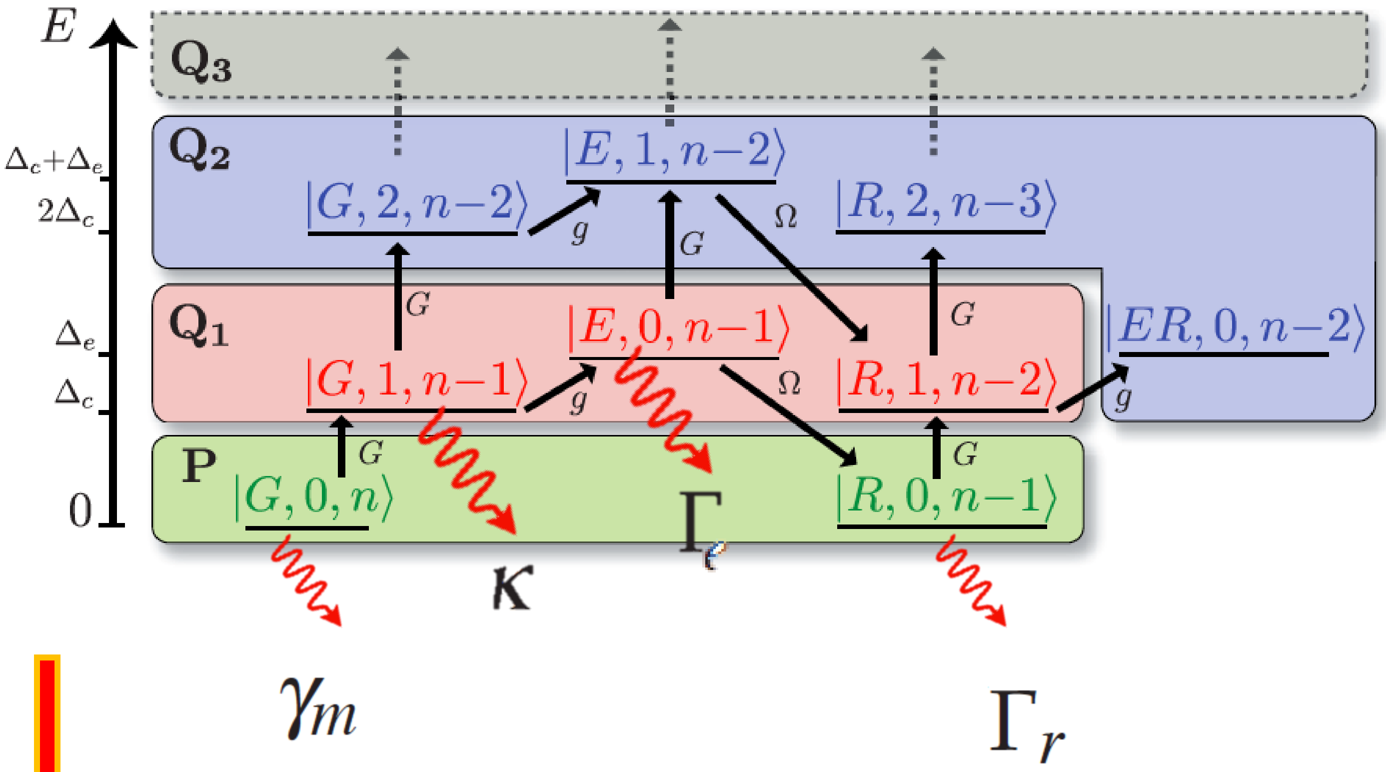


Principle setup with dissipation processes

Use a detuned excitation setup to suppress dissipation

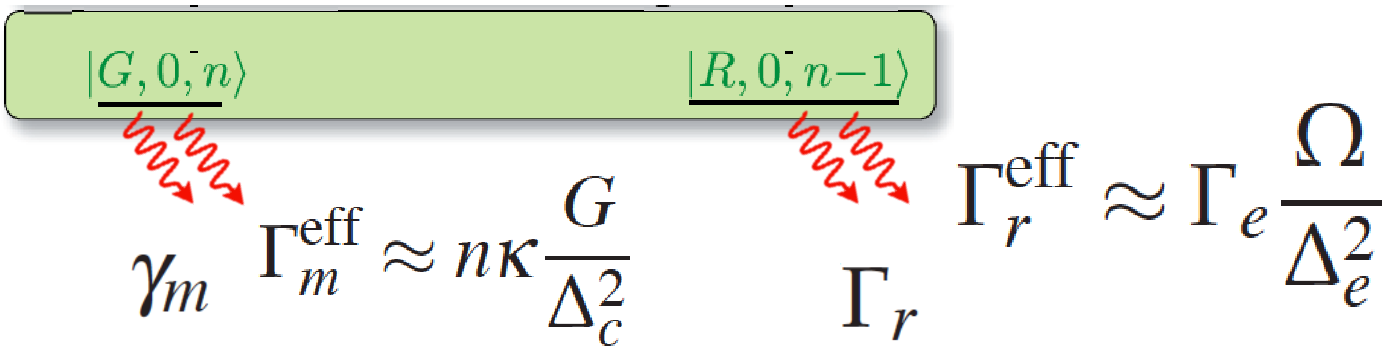


Detuned excitation leads to suppressed dissipation



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

Effective two-level system dynamics in the strong coupling limit

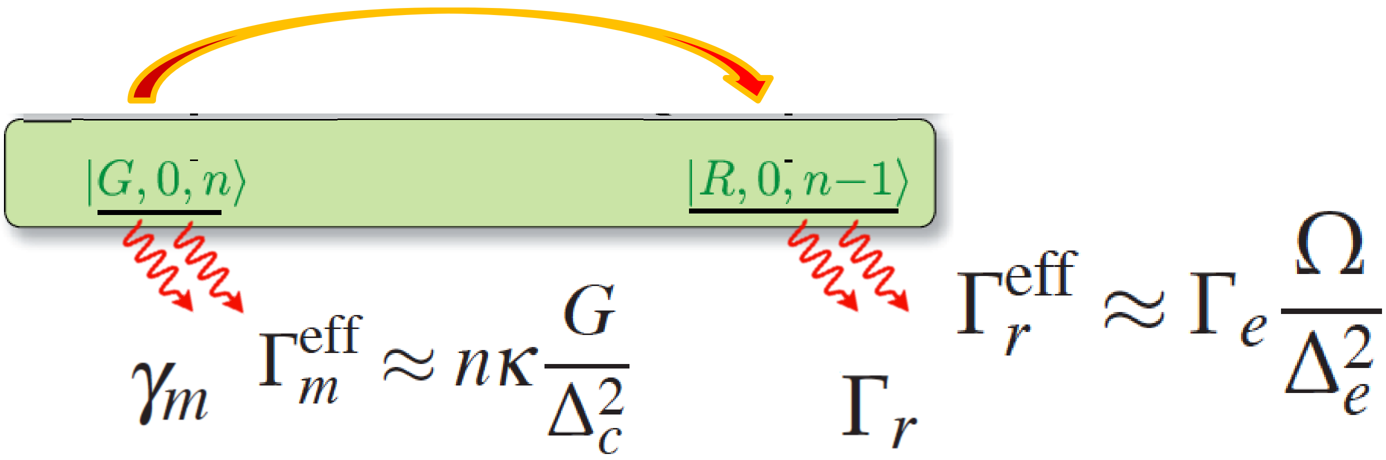


The cavity loss and radiative decay of the intermediate state are suppressed and an effective two-level dynamics take place

Effective two-level system dynamics in the strong coupling limit

Strong coupling limit is accessible:

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



$$|G,0,n\rangle \qquad |R,0,n-1\rangle$$

$$\gamma_m \qquad \Gamma_m^{\text{eff}} \approx n\kappa\frac{G}{\Delta_c^2}$$

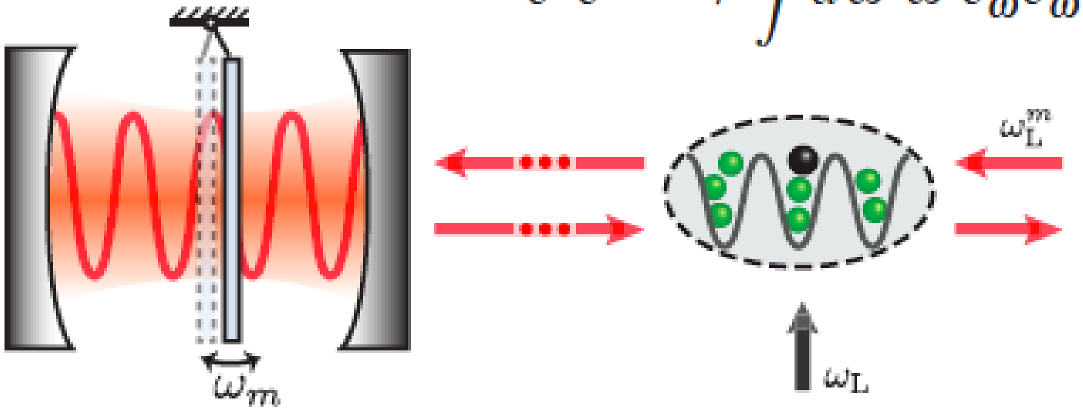
$$\Gamma_r \qquad \Gamma_r^{\text{eff}} \approx \Gamma_e\frac{\Omega}{\Delta_e^2}$$

The cavity loss and radiative decay of the intermediate state are suppressed and an effective two-level dynamics take place

membrane – Rydberg superatom coupling in free space

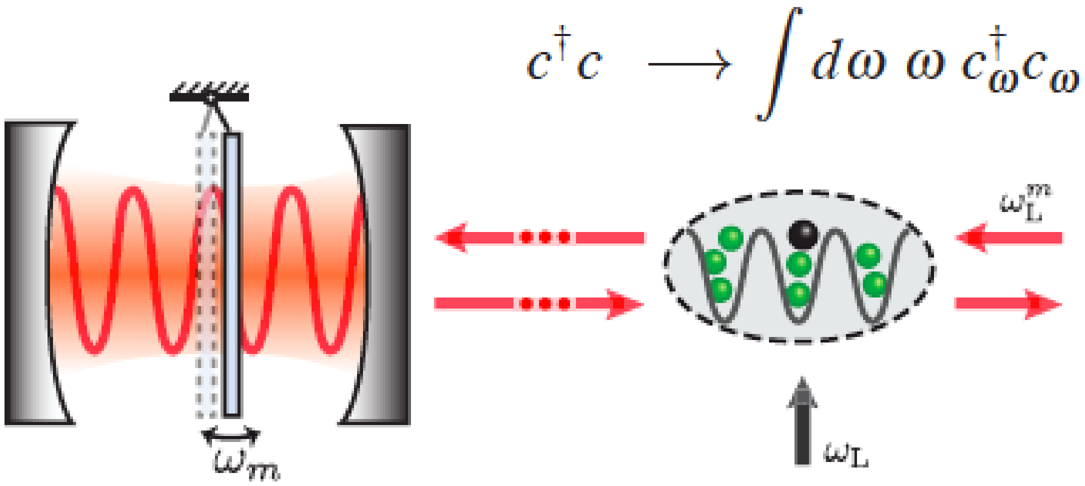
Free space coupling via an optical photon bus

$$c^\dagger c \longrightarrow \int d\omega\, \omega\, c^\dagger_\omega c_\omega$$



A membrane-superatom coupling can also be realized in a modular setup.
A laser field mediates the excitation transfer.

Free space coupling via an optical photon bus



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Derivation of a master equation via
the quantum stochastic Schrödinger equation

PRA 82, 021803(R) (2010)

$$\frac{d}{dt}|\Psi\rangle = -i\,H(t,t^-,t^+)|\Psi\rangle$$

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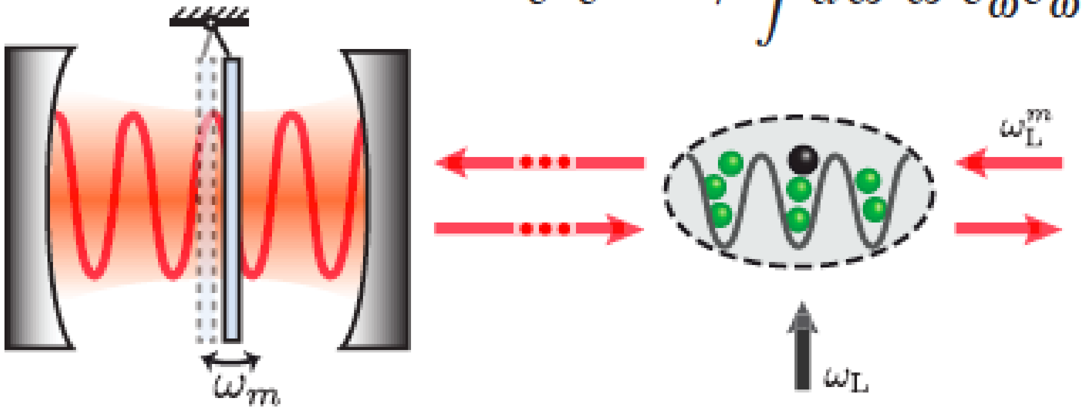

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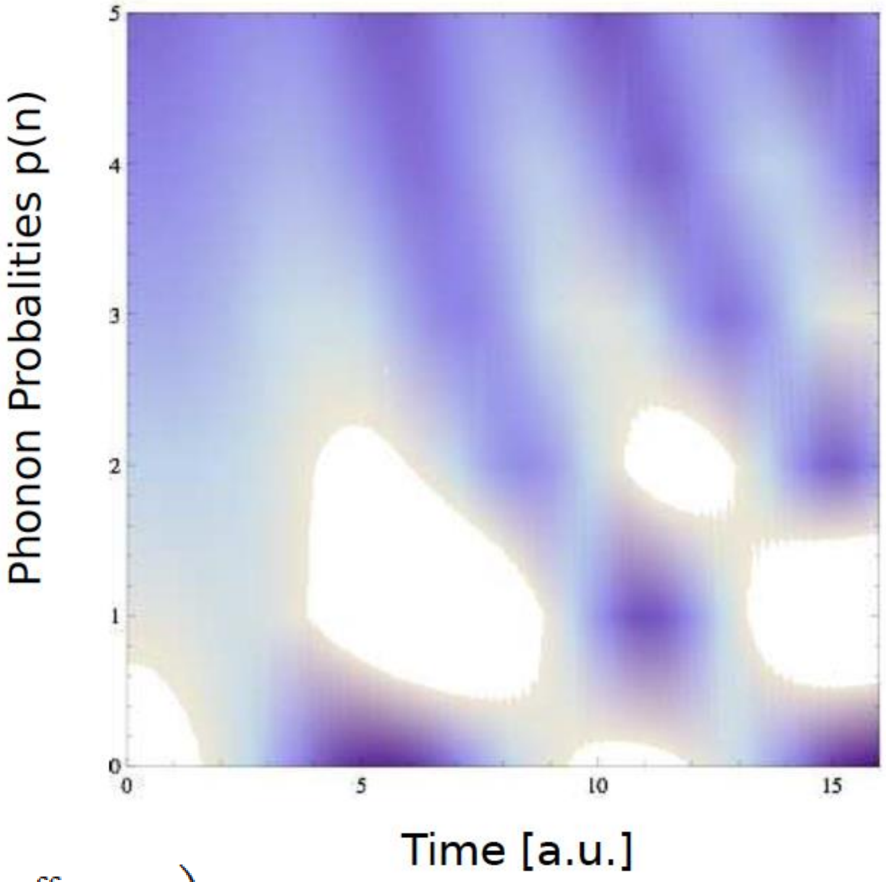
$$\frac{d}{dt}|\Psi\rangle = -i\,H(t,t^{-},t^{+})|\Psi\rangle$$

$$\dot{\rho} = -iG_{\text{eff}}\left[b^{\dagger}\sigma_{GR} + \sigma_{RG}b, \rho\right] + \frac{G^2}{2}\mathscr{D}[b]\rho + \frac{\gamma_m}{2}(N_m+1)\mathscr{D}[b]\rho + \frac{\gamma_m}{2}N_m\mathscr{D}\left[b^{\dagger}\right]\rho + \frac{\gamma_r}{2}\mathscr{D}[\sigma_{GR}]\rho$$

Goal: Preparation of non-classical states even for a membrane not in the ground state

preparation of non-classical states even at finite temperatures.

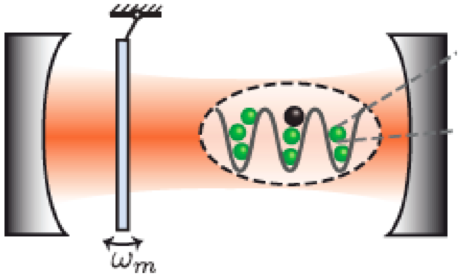


Fidelity for the individual state transfer:

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

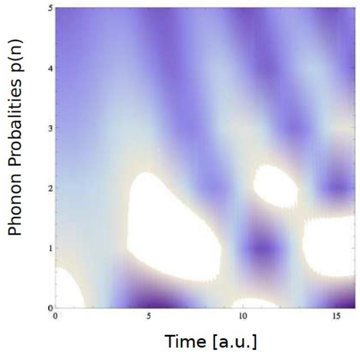
conclusion

Conclusion



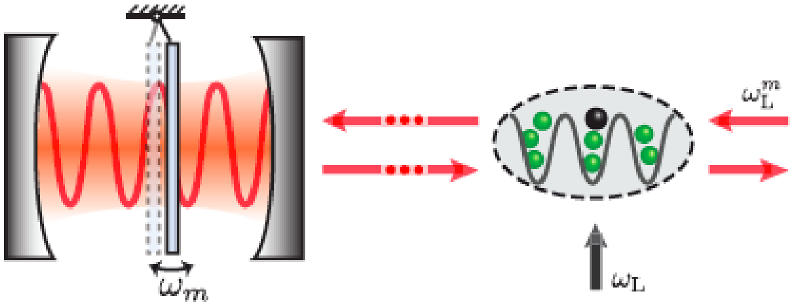
Nanomechanics with a Rydberg Superatom

- Benefiting from the collective enhancement factor, a Rydberg superatom can be strongly coupled to a nanomechanical oscillator



- Ground state cooling, state transfers with high fidelities are possible as well as generation of non-classical states even at finite temperatures

- The membrane-superatom experiment can be realized in a modular setup, in which the cryogenic environment (for the membrane) can be spatially separated from the UHV (for the atoms)



Thank you for your attention !!