Quantum theory of light-matter interaction in dissipative and non-equilibrium environments

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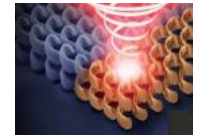
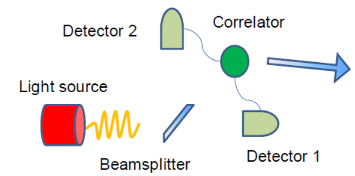
INTERNATIONAL YEAR OF LIGHT 2015

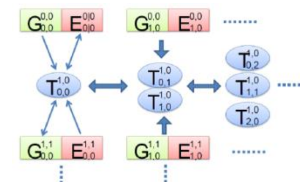
Outline



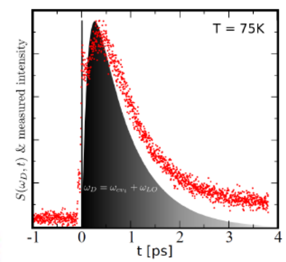
1. Light-matter interaction: Some applications



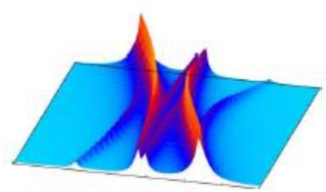
2. Photon-statistics to distinguish light sources
3. Microscopic equation of motion approach



4. Theory and experiment: Unravel underlying physics

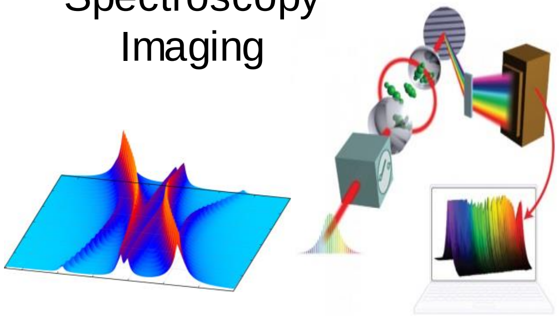


5. Theoretical proposals
6. Outlook

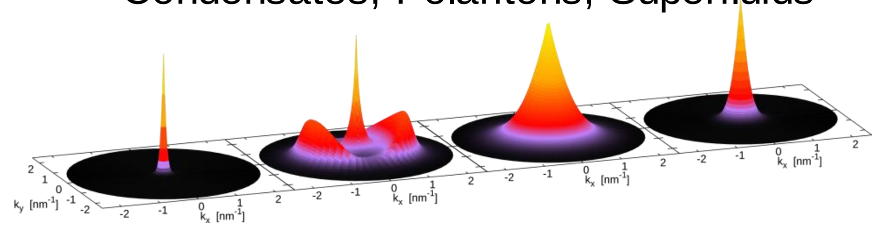


Scientific applications

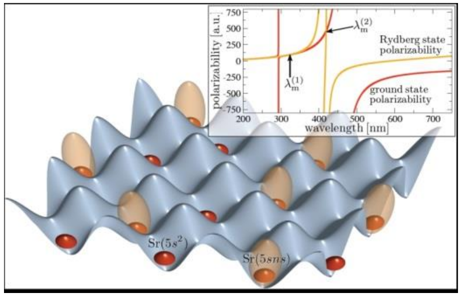
Spectroscopy
Imaging



Generating new states of matter:
Condensates, Polaritons, Superfluids



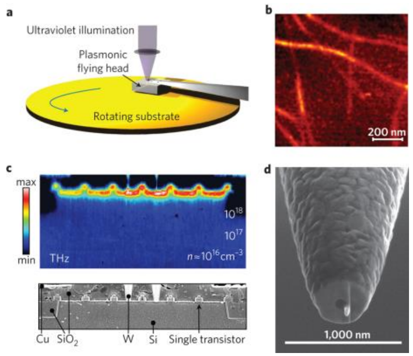
Optical lattices:
Quantum simulators, Quantum algorithms



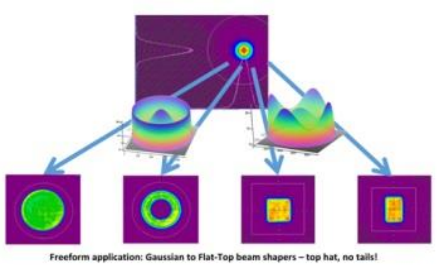
Mukherjee et al, J. Phys. B 44 (2011)

Plasmonics and subwavelength fabrication

Schuller et al, Nat. Materials (2010)

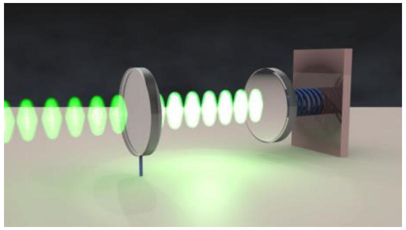


Transform optics, Metamaterials



electrooptics.com/

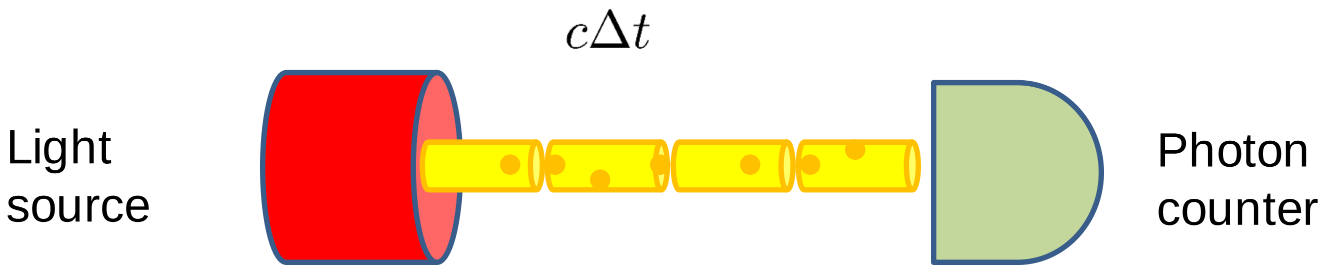
Optomechanics:
Sensing and dissipation studies



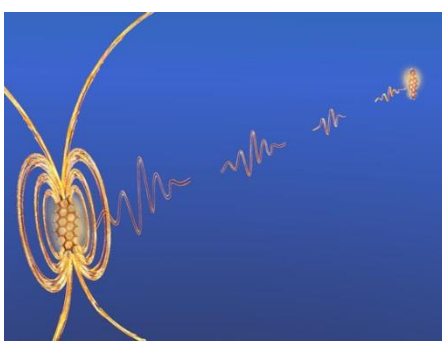
Favero et al, New. J. Phys, 16 (2014)

New types of light

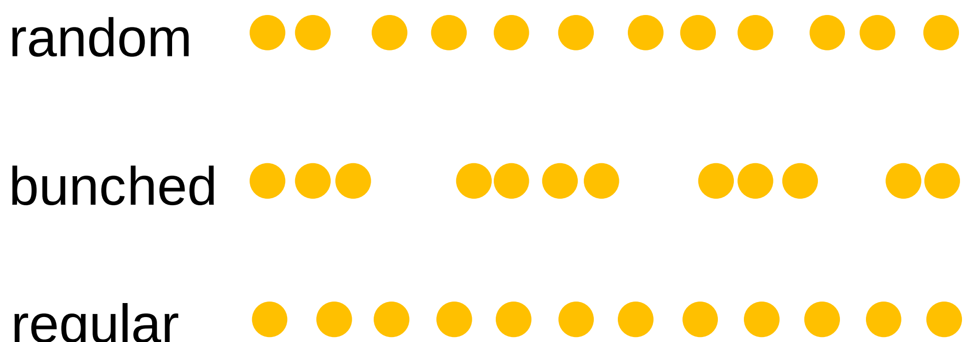
Consider a beam of photons:



Number of photons within the beam segments (regularity within the beam) determines the statistics

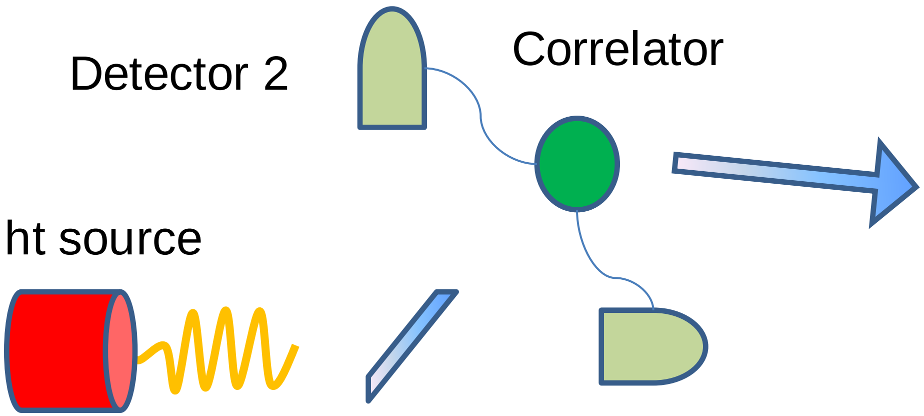


Physics Today (2009)



Measure the photon statistics

Hanbury Brown-Twiss setup



$$g^{(2)} = \frac{\langle E^- E^- E^+ E^+ \rangle}{\langle E^- E^+ \rangle^2}$$

unified description requires a fully quantum optical formulation

$$E(r,t) = \sum_q \left[\epsilon_q^*(r) c_q^\dagger(t) + \epsilon_q(r) c_q(t) \right]$$

$c_q^\dagger$: creation of a photon

c_q : destruction of a photon

$$c^\dagger |n\rangle = \sqrt{n+1}|n\rangle$$

$$c|n\rangle = \sqrt{n}|n-1\rangle$$

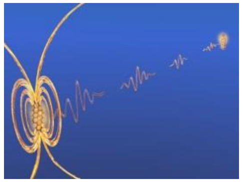
Quantify the light statistics

Intensity-intensity correlation $$g^{(2)}(t,\tau=0)=\frac{\langle c^\dagger c^\dagger c c\rangle}{\langle c^\dagger c\rangle^2}$$

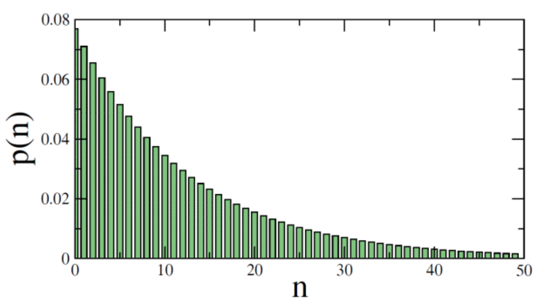
random $g^{(2)}=1$

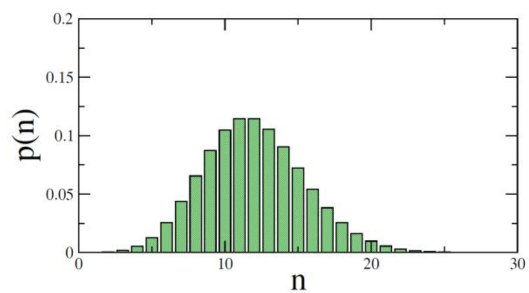
bunched $g^{(2)}>1$

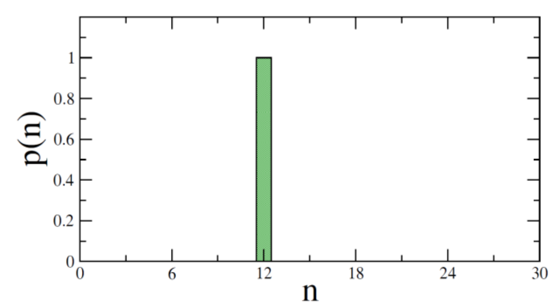
regular $g^{(2)}<1$



$$p_n=\frac{1}{n!}\left(\langle c^{\dagger n}c^n\rangle-\sum_{j=1}^{N}\frac{(n+j)!}{j!}\,p_{n+j}\right)$$



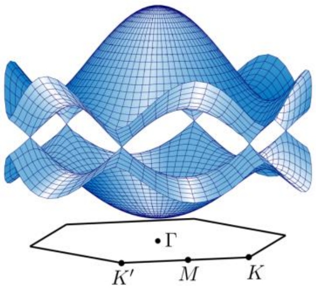


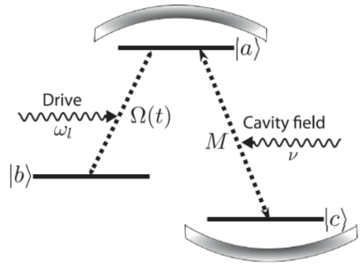


Microscopical equations of motion approach

Microscopic Hamiltonian

$$H = H_{\text{el}} + H_{\text{el-light}} + H_{\text{el-phonon}}$$



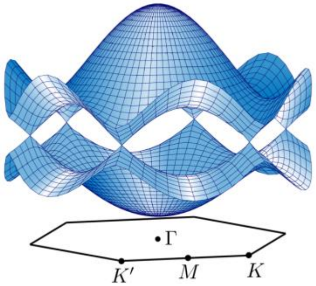


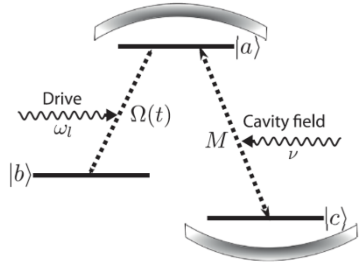
Electronic structure
- continuum
- confined states (few level systems)

$$H_{\text{el}} = \hbar \sum_m \omega_m \; |m\rangle\langle m| + H_{\text{el-el}}$$

Microscopic Hamiltonian

$$H = H_{\text{el}} + H_{\text{el-light}} + H_{\text{el-phonon}}$$

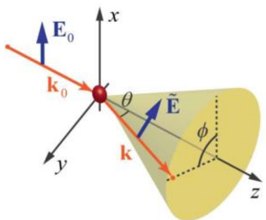


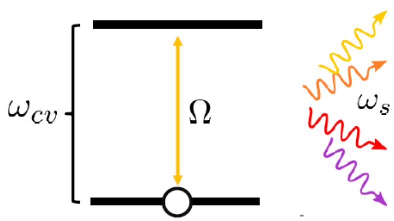


Electronic structure
- continuum
- confined states (few level systems)

$$H_{\text{el}} = \hbar \sum_m \omega_m \; |m\rangle\langle m| + H_{\text{el-el}}$$

$$H_{\text{el-light}} = \hbar \sum_k \omega_k \; c_k^\dagger c_k + \hbar \sum_{m,n} \left(\sum_k M_k^{mn} \; c_k^\dagger + \Omega_n^m(t) \right) |m\rangle\langle n| + \text{H.c.}$$

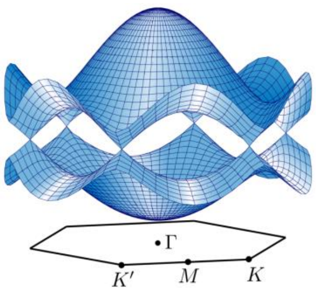


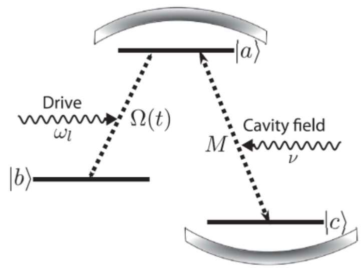


Light-matter interaction
- dipole strength/selection rules
- photon states, polarization, angle

Microscopic Hamiltonian

$$H = H_{\text{el}} + H_{\text{el-light}} + H_{\text{el-phonon}}$$

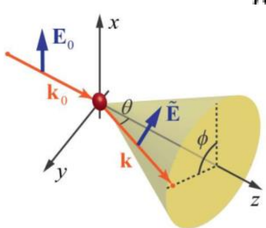


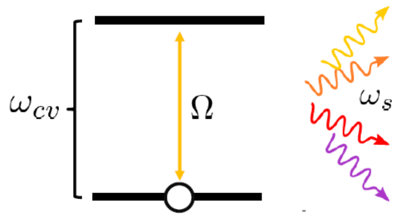


Electronic structure
- continuum
- confined states (few level systems)

$$H_{\text{el}} = \hbar \sum_m \omega_m \; |m\rangle\langle m| + H_{\text{el-el}}$$

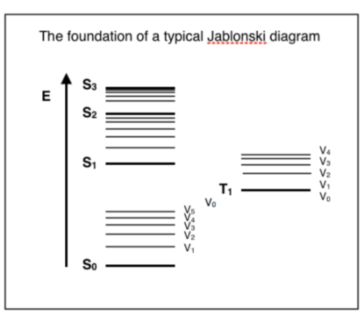
$$H_{\text{el-light}} = \hbar \sum_k \omega_k \; c_k^\dagger c_k + \hbar \sum_{m,n} \left(\sum_k M_k^{mn} \; c_k^\dagger + \Omega_n^m(t) \right) |m\rangle\langle n| + \text{H.c.}$$

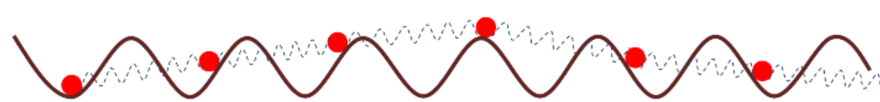




Light-matter interaction
- dipole strength/selection rules
- photon states, polarization, angle

$$H_{\text{el-phonon}} = \hbar \sum_{q,i} \omega_{iq} b_{iq}^\dagger b_{iq} + \sum_{m,q,i} \left(g_m^{q,i} \; b_{q,i}^\dagger + g_m^{q,i*} \; b_{q,i} \right) |m\rangle\langle m|$$





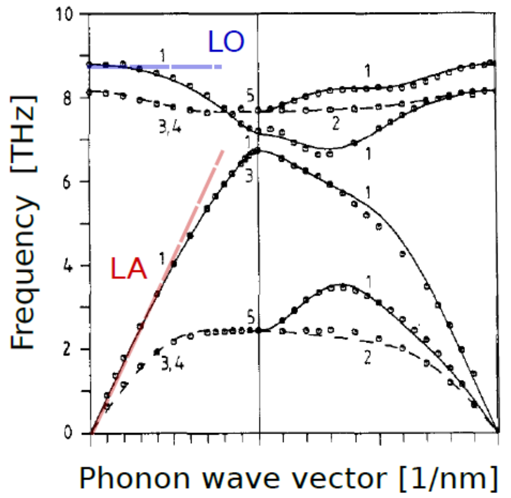
Electron-phonon interaction
- longitudinal optical, acoustical phonon
- diagonal coupling, THz frequencies

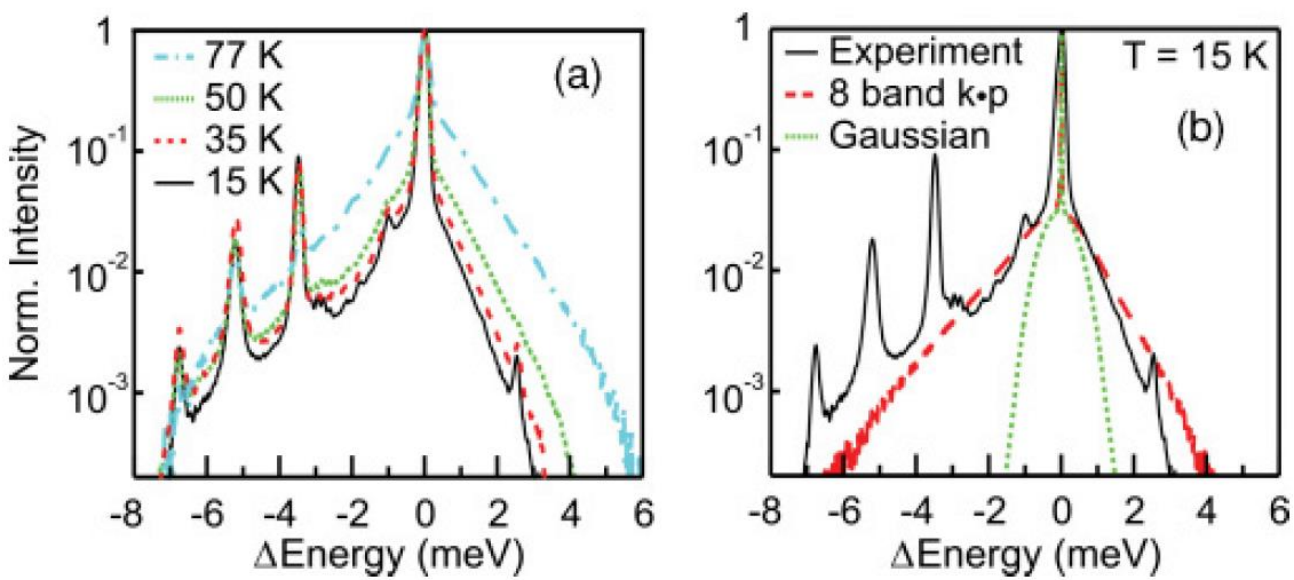
Coupling elements input from material theory

Acoustic deformation potential

$$g_{\mathrm{LA},\mathbf{q}}^{\lambda\mu,\mathrm{3D}} = \delta_{\lambda,\mu}\sqrt{\frac{\hbar q}{2\rho c_s V}}D_\lambda$$

Strong deviations
from Lorentz peaks



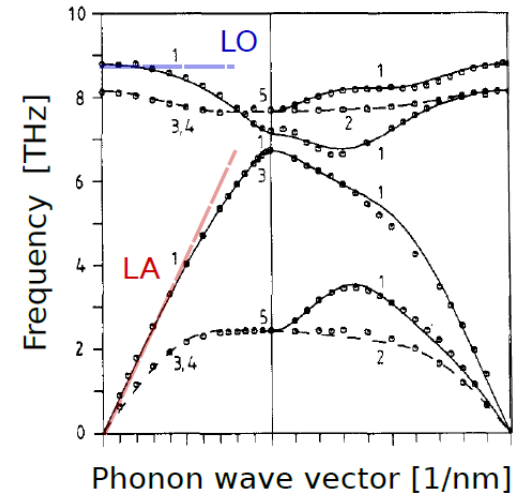


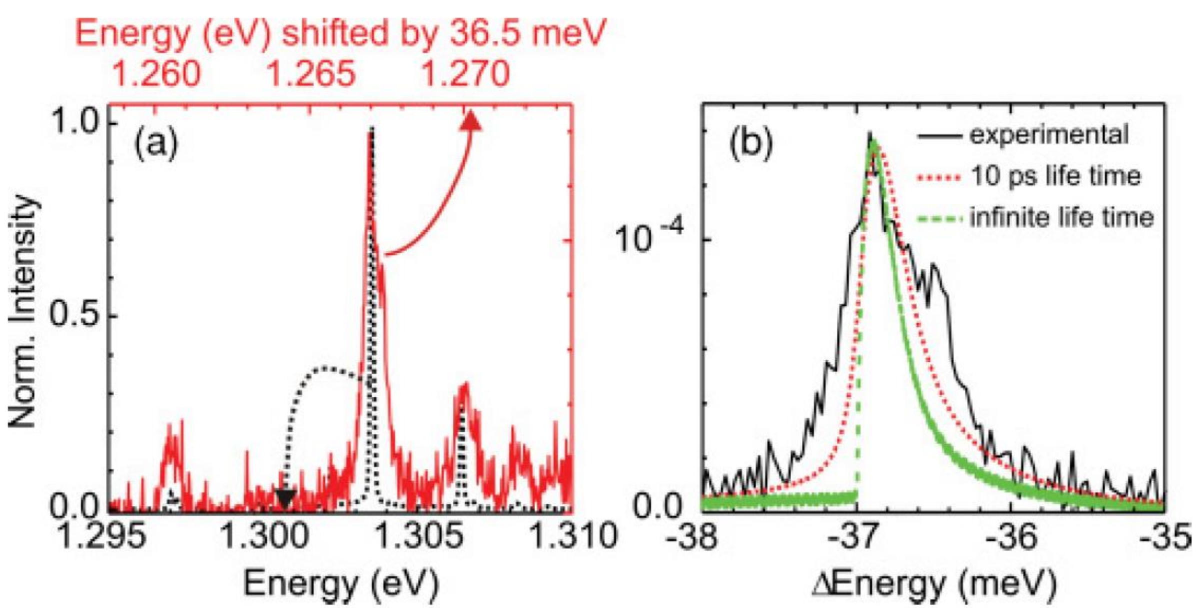
[1]PRB **83**, 041304(R) (2011)

Coupling elements input from material theory

Fröhlich potential[1]

$$g_{\mathrm{LO},q}^{\lambda\mu,\mathrm{3D}} = \frac{1}{q}\sqrt{\frac{e_0^2\hbar\omega_{\mathrm{LO}}}{2\varepsilon_0 V}\left(\frac{1}{\varepsilon_\infty}-\frac{1}{\varepsilon_{\mathrm{st}}}\right)}$$





[1]PRB **83**, 041304(R) (2011)

Observable dynamics

Heisenberg picture:

$$\frac{d}{dt}\hat{O} = \frac{i}{\hbar}\left[H, \hat{O}\right]$$

Input: microscopic Hamiltonian

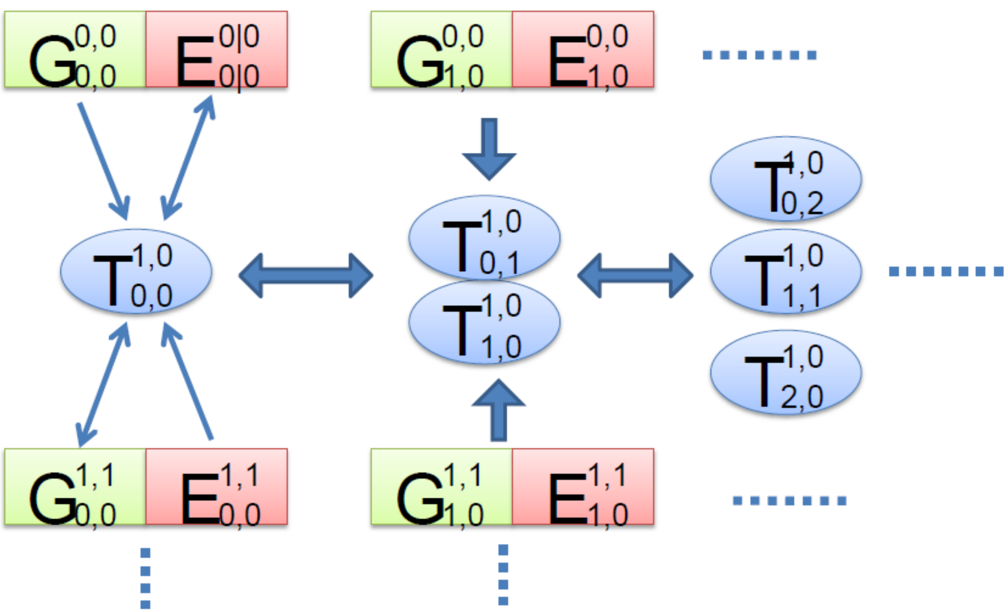
$$H = H_{\text{el}} + H_{\text{el-light}} + H_{\text{el-phonon}}$$

$$G^{p,s}_{n,m} := |g\rangle\langle g|\, c^{\dagger p} c^{s} b^{\dagger m} b^{n}$$

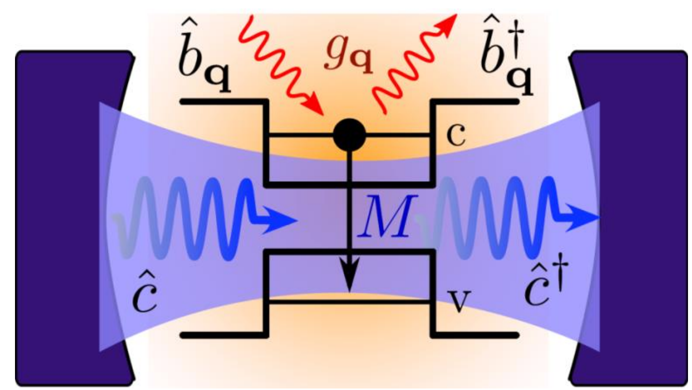
$$T^{p,s}_{n,m} := |g\rangle\langle e|\, c^{\dagger p} c^{s} b^{\dagger m} b^{n}$$

$$E^{p,s}_{n,m} := |e\rangle\langle e|\, c^{\dagger p} c^{s} b^{\dagger m} b^{n}$$

Hierarchy problem occurs



Example: Phonon cQED



Solve with inductive equation of motion approach

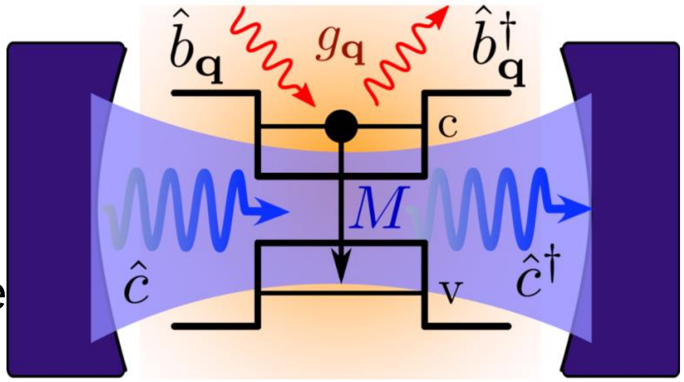
All couplings to higher-order photon-phonon correlations included

$$
\begin{aligned}
\frac{d}{dt}G^{p,s}_{n,m} &= -\left[i(m-n)\omega_{LO} + i(p-s)\omega_k\right] G^{p,s}_{n,m} + iMT^{p+1,s}_{n,m} - iM\left(T^{s+1,p}_{m,n}\right)^* \\
&\quad + isMT^{p,s-1}_{n,m} - ipM^*\left(T^{s,p-1}_{m,n}\right)^* + ing_v G^{p,s}_{n-1,m} - img_v^* G^{p,s}_{n,m}
\end{aligned}
$$

$$
\begin{aligned}
\frac{d}{dt}T^{p,s}_{n,m} &= -i\left[\omega_{eg} - (p-s)\omega_k + (m-n)\omega_{LO}\right] T^{p,s}_{n,m} - iT^{p,s}_{n,m+1} - iT^{p,s}_{n+1,m} \\
&\quad - iM^*(pE^{p-1,s}_{n,m} + E^{p,s+1}_{n,m} - G^{p,s+1}_{n,m}) + ing_v T^{p,s}_{n-1,m} - img_c^* T^{p,s}_{n,m-1}
\end{aligned}
$$

$$
\begin{aligned}
\frac{d}{dt}E^{p,s}_{n,m} &= -\left[i(m-n)\omega_{LO} + i(p-s)\omega_k\right] E^{p,s}_{n,m} - i\ MT^{p+1,s}_{n,m} \\
&\quad + i\ M\left(T^{s+1,p}_{m,n}\right)^* + ing_c E^{p,s}_{n-1,m} - im\ g_c^* E^{p,s}_{n,m-1}
\end{aligned}
$$

- numerically exact, fast and controllable[1]
- fully quantized optical Bloch equations
- non-equilibrium phonon-photon dynamics computable

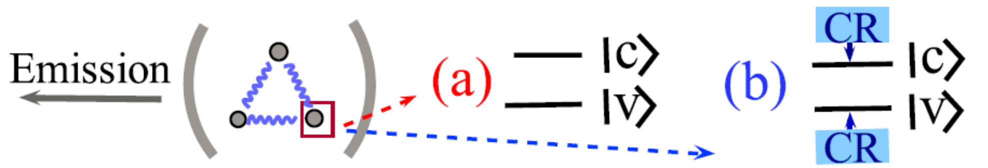


[1]PRL **104**, 156801 (2010)

Solve with inductive equation of motion approach

All couplings to higher-order photon-phonon-electron correlations included

$$\frac{dp_n}{dt} = -2\sqrt{n}N\mathrm{Im}(g\langle|n\rangle\langle n-1|a_{1v}^\dagger a_{1c}\rangle) + 2\sqrt{n+1}N\mathrm{Im}(g\langle|n+1\rangle\langle n|a_{1v}^\dagger a_{1c}\rangle) - 2n\kappa p_n + 2(n+1)\kappa p_{n+1},$$



No particle conservation (electrons, holes)

$$\frac{d}{dt}\langle|n+1\rangle\langle n|a_{1v}^\dagger a_{1c}\rangle = -\gamma\langle|n+1\rangle\langle n|a_{1v}^\dagger a_{1c}\rangle - \kappa(2n+1)\langle|n+1\rangle\langle n|a_{1v}^\dagger a_{1c}\rangle + 2\kappa\sqrt{(n+1)(n+2)}\langle|n+2\rangle\langle n+1|a_{1v}^\dagger a_{1c}\rangle - P\langle|n+1\rangle\langle n|a_{1v}^\dagger a_{1c}\rangle + \mathcal{F}. \quad (2)$$

$$\mathcal{F} = ig^*\sqrt{n+1}(\langle|n+1\rangle\langle n+1|a_{1v}^\dagger a_{1v}\rangle - \langle|n\rangle\langle n|a_{1c}^\dagger a_{1c}\rangle - \langle|n+1\rangle\langle n+1|a_{1v}^\dagger a_{1c}^\dagger a_{1c} a_{1v}\rangle + \langle|n\rangle\langle n|a_{1v}^\dagger a_{1c}^\dagger a_{1c} a_{1v}\rangle) - ig^*\sqrt{n+1}(N-1)\times(\langle|n+1\rangle\langle n+1|a_{1v}^\dagger a_{2c}^\dagger a_{1c} a_{2v}\rangle - \langle|n\rangle\langle n|a_{1v}^\dagger a_{2c}^\dagger a_{1c} a_{2v}\rangle) + ig\sqrt{n+2}(N-1)\langle|n+2\rangle\langle n|a_{1v}^\dagger a_{2v}^\dagger a_{1c} a_{2c}\rangle - ig\sqrt{n}(N-1)\langle|n+1\rangle\langle n-1|a_{1v}^\dagger a_{2v}^\dagger a_{1c} a_{2c}\rangle.$$

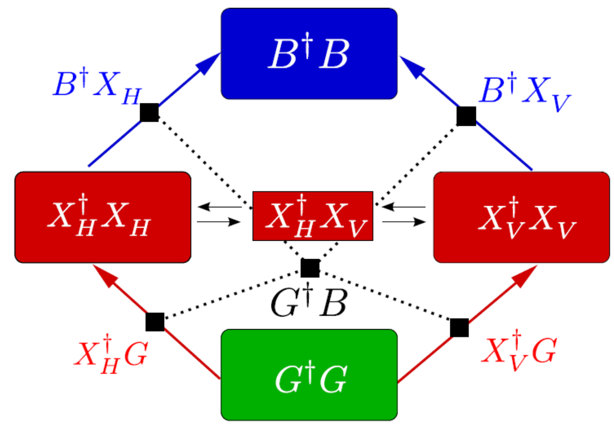
[1]PRL **110**, 113604 (2013)

Solve with inductive equation of motion approach

All couplings to higher-order photon-phonon-electron correlations included

$$\partial_t\langle G^\dagger G H^{m,n} V^{p,q}\rangle \qquad (3.$$
$$= i\left[(m-n)\omega_H^0 + (p-q)\omega_V^0 + i\kappa(m+n+p+q)\right]\langle G^\dagger G H^{m,n} V^{p,q}\rangle$$
$$- iM\ m\langle X_H^\dagger G H^{m-1,n} V^{p,q}\rangle - iM\langle X_H^\dagger G H^{m,n+1} V^{p,q}\rangle - iM\ p\langle X_V^\dagger G H^{m,n} V^{p-1,q}\rangle$$
$$- iM\langle X_V^\dagger G H^{m,n} V^{p,q+1}\rangle + iM\ n\langle G^\dagger X_H H^{m,n-1} V^{p,q}\rangle + iM\langle G^\dagger X_H H^{m+1,n} V^{p,q}\rangle$$
$$+ iM\ q\langle G^\dagger X_V H^{m,n} V^{p,q-1}\rangle + iM\langle G^\dagger X_V H^{m,n} V^{p+1,q}\rangle.$$

$$\partial_t\langle B^\dagger B H^{m,n} V^{p,q}\rangle$$
$$= i\left[(m-n)\omega_H^0 + (p-q)\omega_V^0 + i\kappa(m+n+p+q)\right]\langle B^\dagger B H^{m,n} V^{p,q}\rangle$$
$$- iM\langle X_H^\dagger B H^{m+1,n} V^{p,q}\rangle + iM\langle X_V^\dagger B H^{m,n} V^{p+1,q}\rangle$$
$$+ iM\langle B^\dagger X_H H^{m,n+1} V^{p,q}\rangle - iM\langle B^\dagger X_V H^{m,n} V^{p,q+1}\rangle.$$



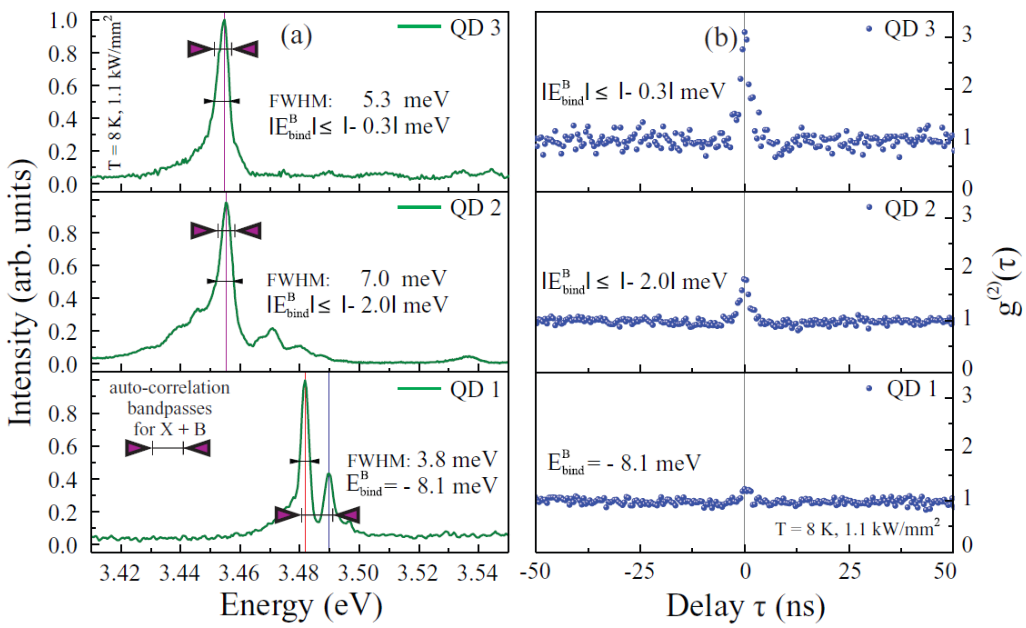
$$\partial_t\langle G^\dagger B H^{m,n} V^{p,q}\rangle$$
$$= i\left[(m-n)\omega_H^0 + (p-q)\omega_V^0 - \omega_B + i\kappa(m+n+p+q)\right]\langle G^\dagger B H^{m,n} V^{p,q}\rangle$$
$$- iM\ m\langle X_H^\dagger B H^{m-1,n} V^{p,q}\rangle - iM\langle X_H^\dagger B H^{m,n+1} V^{p,q}\rangle - iM\langle G^\dagger X_V H^{m,n} V^{p,q+1}\rangle$$
$$- iM\ p\langle X_V^\dagger B H^{m,n} V^{p-1,q}\rangle - iM\langle X_V^\dagger B H^{m,n} V^{p,q+1}\rangle + iM\langle G^\dagger X_H H^{m,n+1} V^{p,q}\rangle$$

[1]PRB **81**, 195319 (2010)

Explain underlying physics in experiments

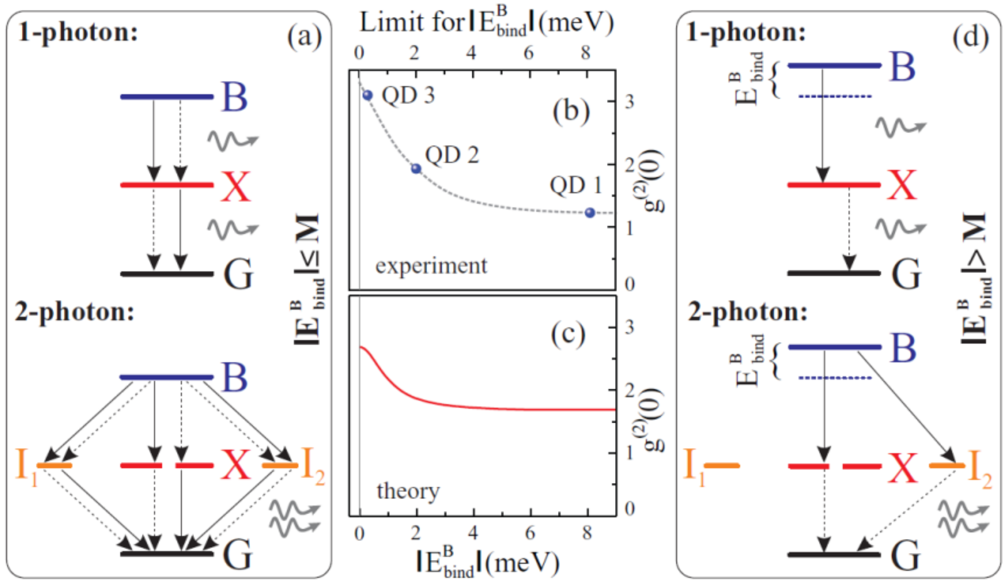
Steering photon-statistics

Experiments with QD of different electronic configuration (biexciton shifts) lead to a different photon statistics



Experimental data not explainable with rate equations, two-photon transition crucial:

$$\langle G^{\dagger} B c^{\dagger} c^{\dagger} \rangle$$



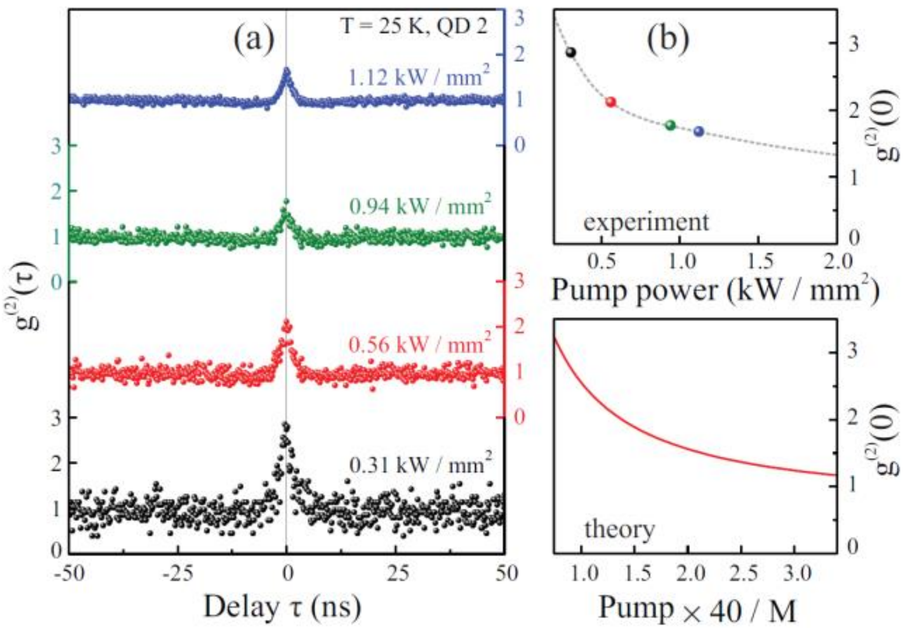
full quantum electron and photon kinetics of four-level system

two-photon transitions is resonant in case of vanishing biexciton shift and two-photon emission is enhanced

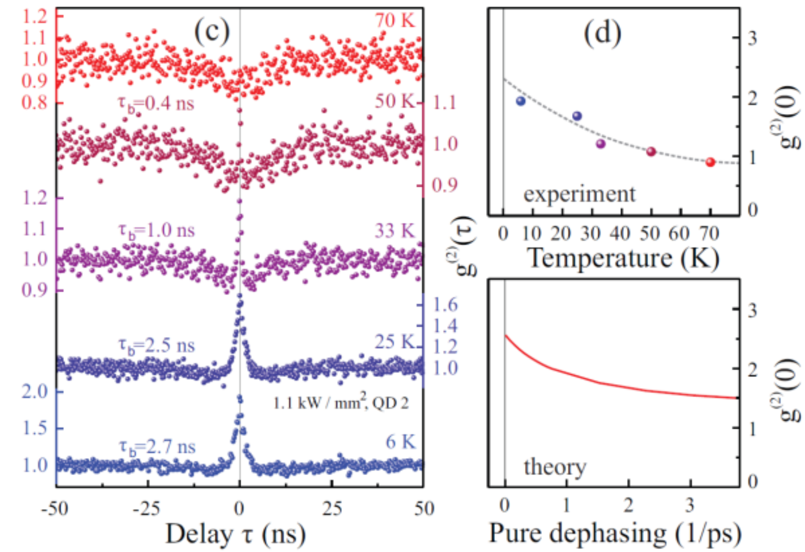
[1]PRB **87**, 245314 (2013)

Steering photon-statistics

Pump strength dependence



Temperature dependence



$$\mathcal{L}\rho := \frac{\kappa}{2}\sum_{i=X,B}\mathcal{L}[c_i]\rho + P\sum_{j=H,V}\mathcal{L}[X_j^\dagger G]\rho + \mathcal{L}[B^\dagger X_j]\rho$$
$$+\Gamma_{\text{rad}}\sum_{j=H,V}\mathcal{L}[G^\dagger X_j]\rho + \mathcal{L}[X_j^\dagger B]\rho$$
$$-\sum_{k=G,X,B}\gamma_k\,(T_k\rho T_k - \rho)\,. \qquad (2)$$

Microscopic model, adaptable to experimental situation

- dissipation included via Lindblad formalism (incoherent)

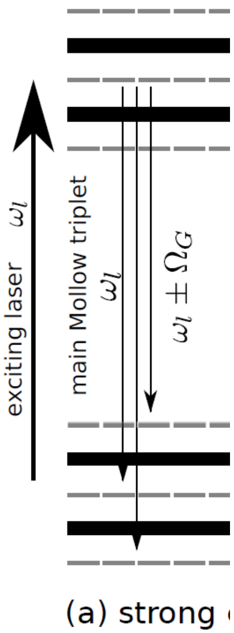
[1]PRB **87**, 245314 (2013)

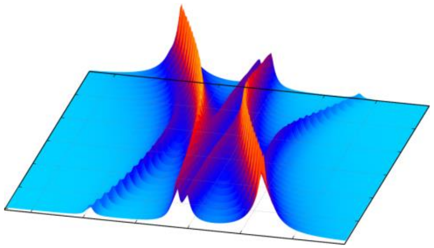
Phonon-assisted Mollow triplets and phonon lasing

Julia Kabuß and Andreas Knorr

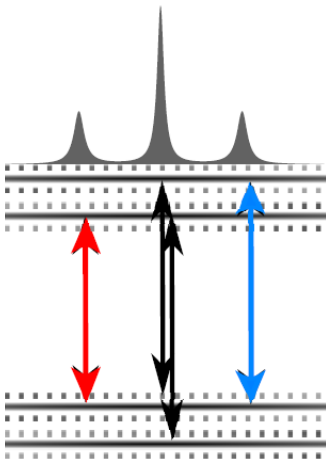
Technische Universität Berlin, Germany

Phonon-assisted Mollow triplet



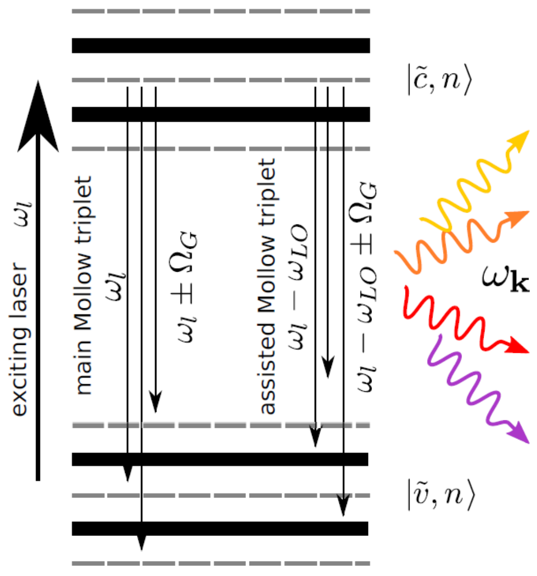


Microscopic derivation of time-resolved
Raman signal strong excitation limit
(non-perturbativ in laser and phonon contributions)

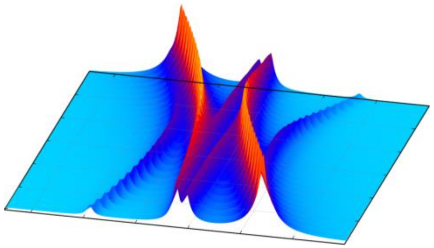


[1]PRB **84**, 125324 (2011)

Phonon-assisted Mollow triplet



(a) strong excitation



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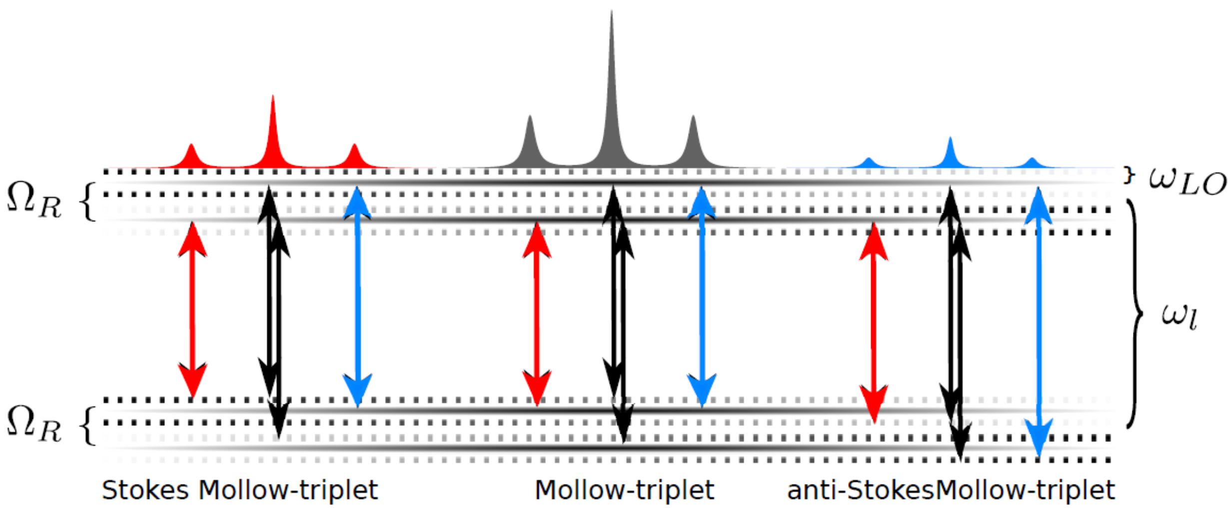
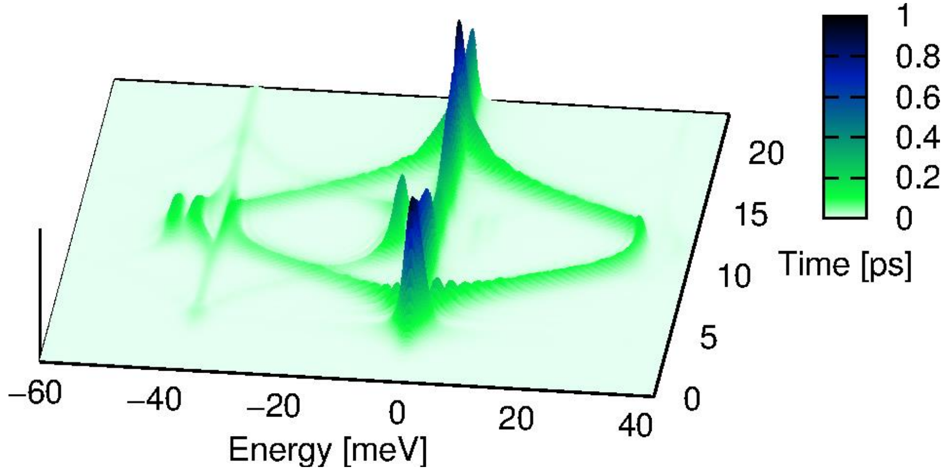


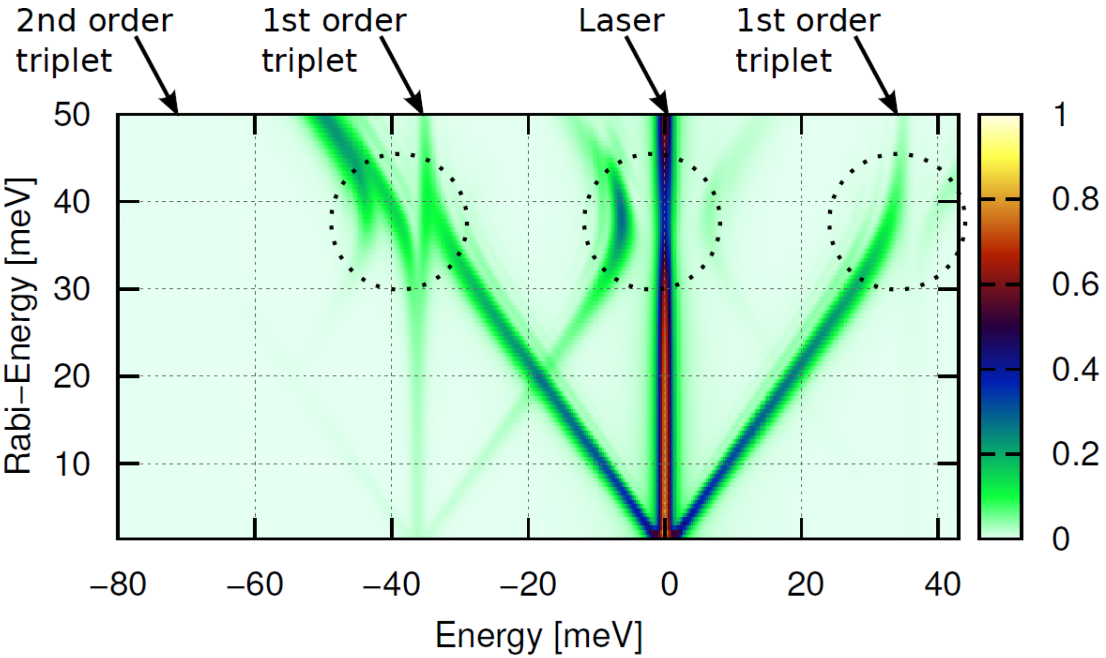
[1]PRB **84**, 125324 (2011)

Phonon-assisted Mollow triplet: Anti-crossings

Time-resolved spectrum of pulsed laser excitation

Laser field amplitude defines hybridisation strength



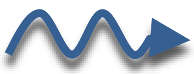


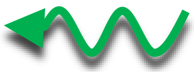
Read out phonon coupling strength by spectral means without relying on intensity measurements

[1]PRB **84**, 125324 (2011)

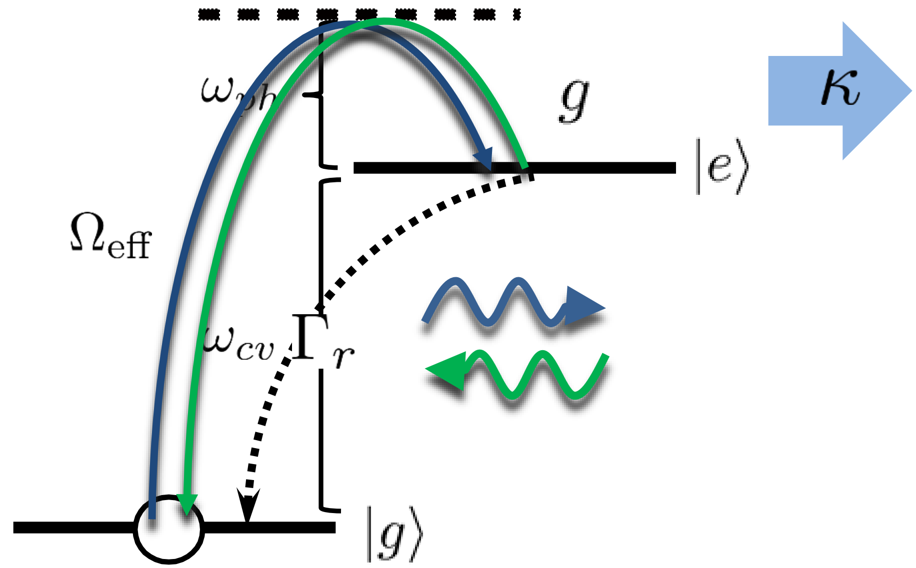
Proposal for phonon laser

Use Stokes process in acoustic cavity


Phonon emission


Phonon absorption

Phonon assisted
Rabi oscillations



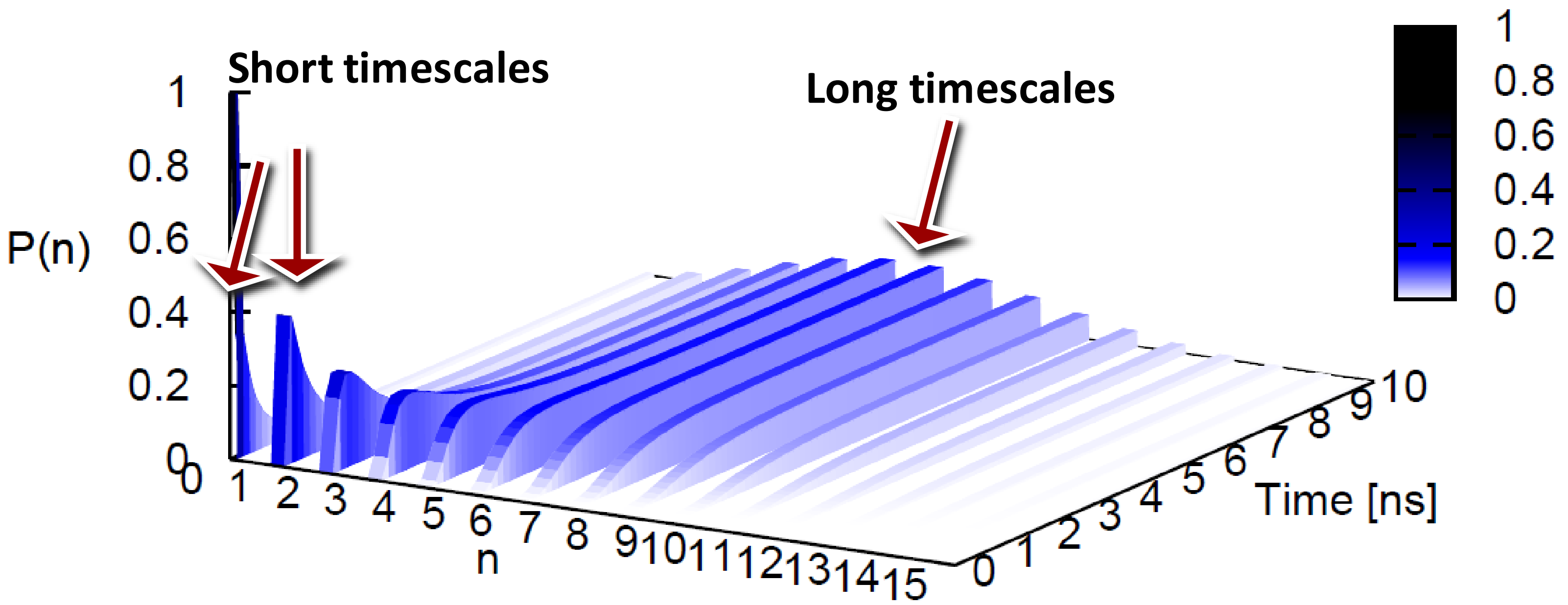
$$\mathcal{H}(t) = \frac{\hbar\omega_{cv}}{2}\sigma_z + \hbar\omega_{ph} b^\dagger b + \Omega(t)\sigma e^{i\omega_L t} + g\sigma^\dagger\sigma b^\dagger + H.c.$$

$$\dot{\rho} = -i[\mathcal{H}(t), \rho] + \mathcal{L}\rho$$

Γ_r closes pump cycle
κ phonon loss
γ_{pd} pure dephasing

[1]PRL **109**, 54301 (2012)

Proposal for phonon laser



Short timescales

- $t < \Omega_{\mathrm{eff}}^{-1}$ — **phonon fluctuations**
- $t \approx \Omega_{\mathrm{eff}}^{-1}$ — **Fock-phonon due to induced Raman process**

Long timescales → $t \approx \Gamma_r^{-1}$ — **Coherent phonons**

[1]PRL **109**, 54301 (2012)

Nanomechanics Strongly Coupled to a Rydberg Superatom

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

Institute of Quantum Optics and Quantum Information, Innsbruck

New J. Phys. **16**, 63042 (2014)

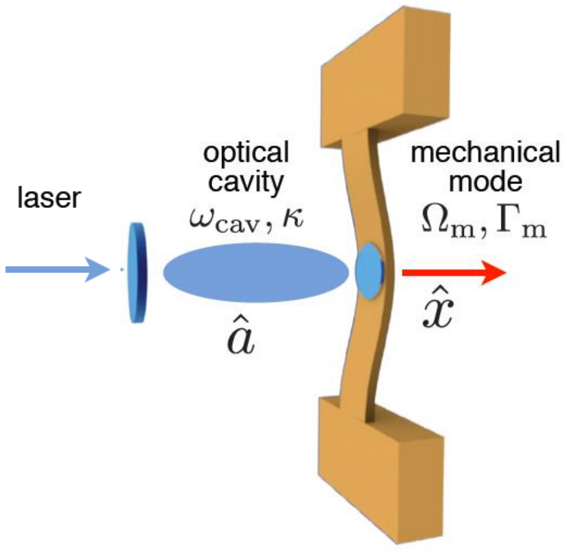
Cavity optomechanics

Cavity optomechanics

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

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

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



Aspelmeyer et al, arXiv:1303.0733

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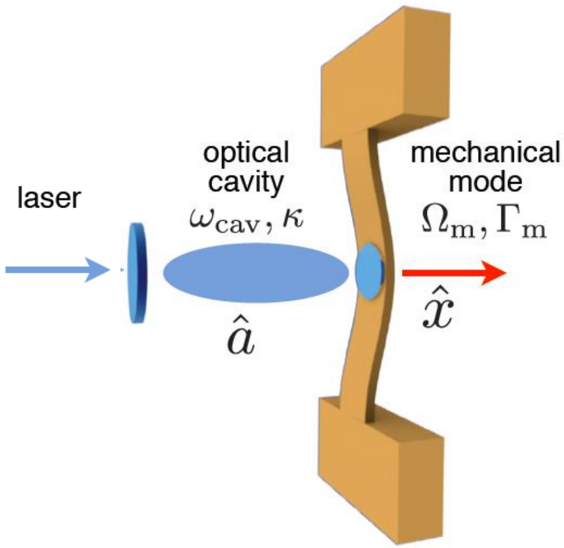

Aspelmeyer et al, arXiv:1303.0733

Cavity optomechanics – laser driven

- ❑ the cavity is driven by a laser → cavity mode is displaced

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

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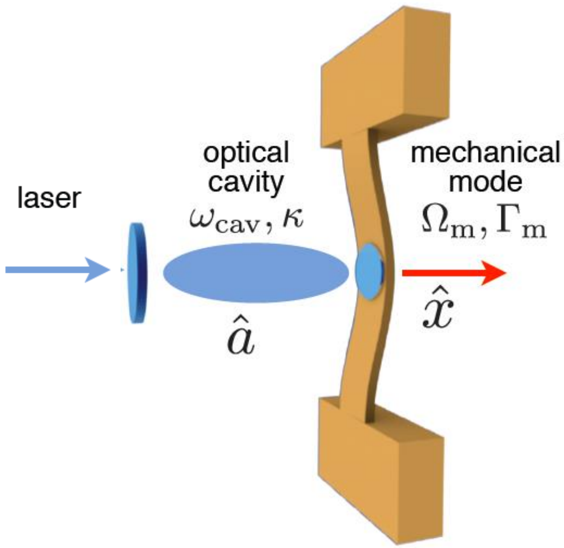


Aspelmeyer et al, arXiv:1303.0733

Cavity optomechanics – laser driven

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

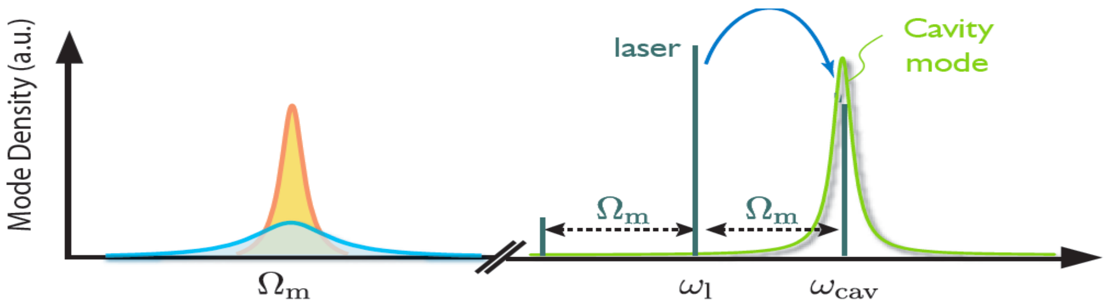
$$\hat{a} = \bar{\alpha} + \delta\hat{a}$$

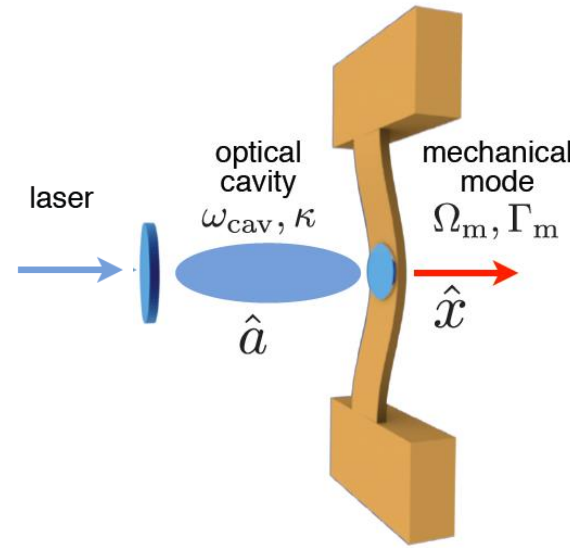
$$\hat{H}_{\mathrm{int}} = -\hbar g_0(\bar{\alpha} + \delta\hat{a})^\dagger(\bar{\alpha} + \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

Ground state cooling

Cavity optomechanics: Accomplishments

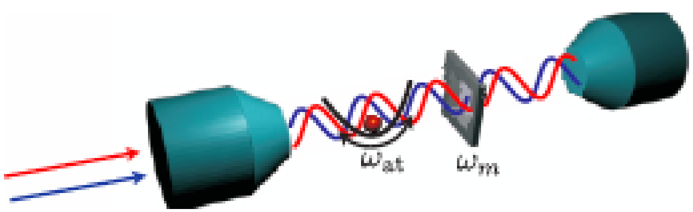
- ❑ successful ground state cooling
- ❑ sensing experiments and studies of dissipation processes



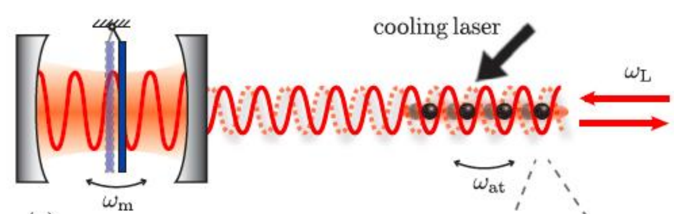


Cooling via hybrid system

- ❑ 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

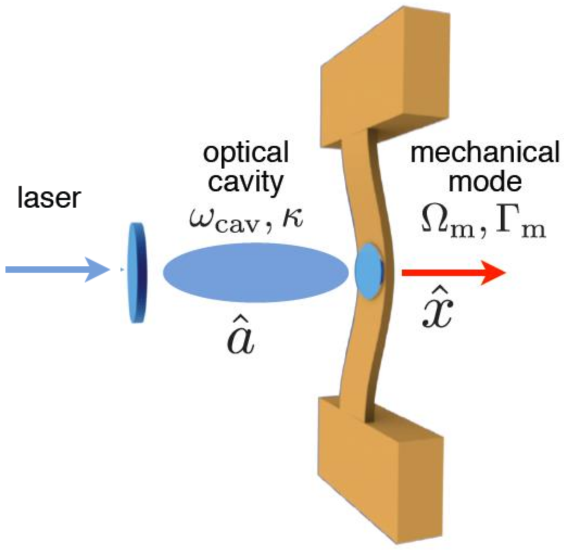
Quantum nonlinearities and cavity optomechanics

Cavity optomechanics: Accomplishments

- ❑ successful ground state cooling
- ❑ sensing experiments and studies of dissipation processes

Cavity optomechanics: New challenges

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



Quantum nonlinearities and cavity optomechanics

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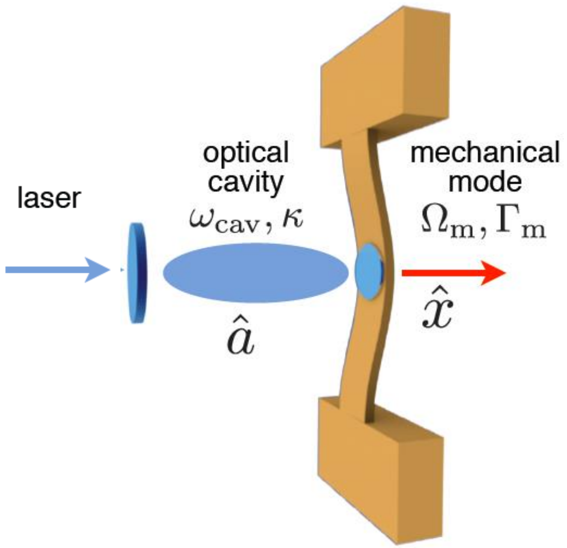


Cavity optomechanics: New challenges

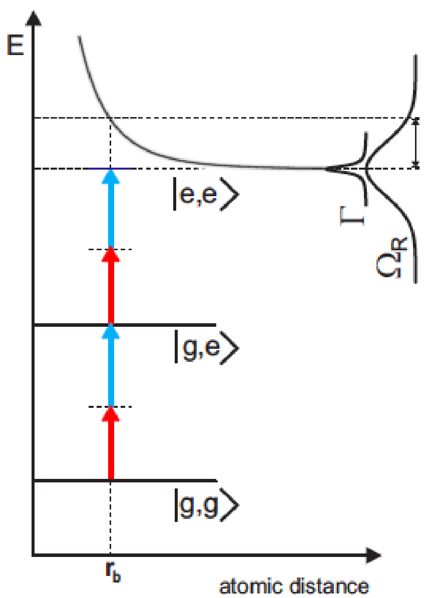
- ❑ experiments so far in the linear regime
- ❑ nonlinearity necessary to create entanglement – to use optomechanics for quantum information processing

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

Rydberg superatom

Rydberg Superatom as an artificial atom

- ❑ An atomic ensemble with a Rydberg state interacts strongly due to the VdW interaction → Rydberg shift

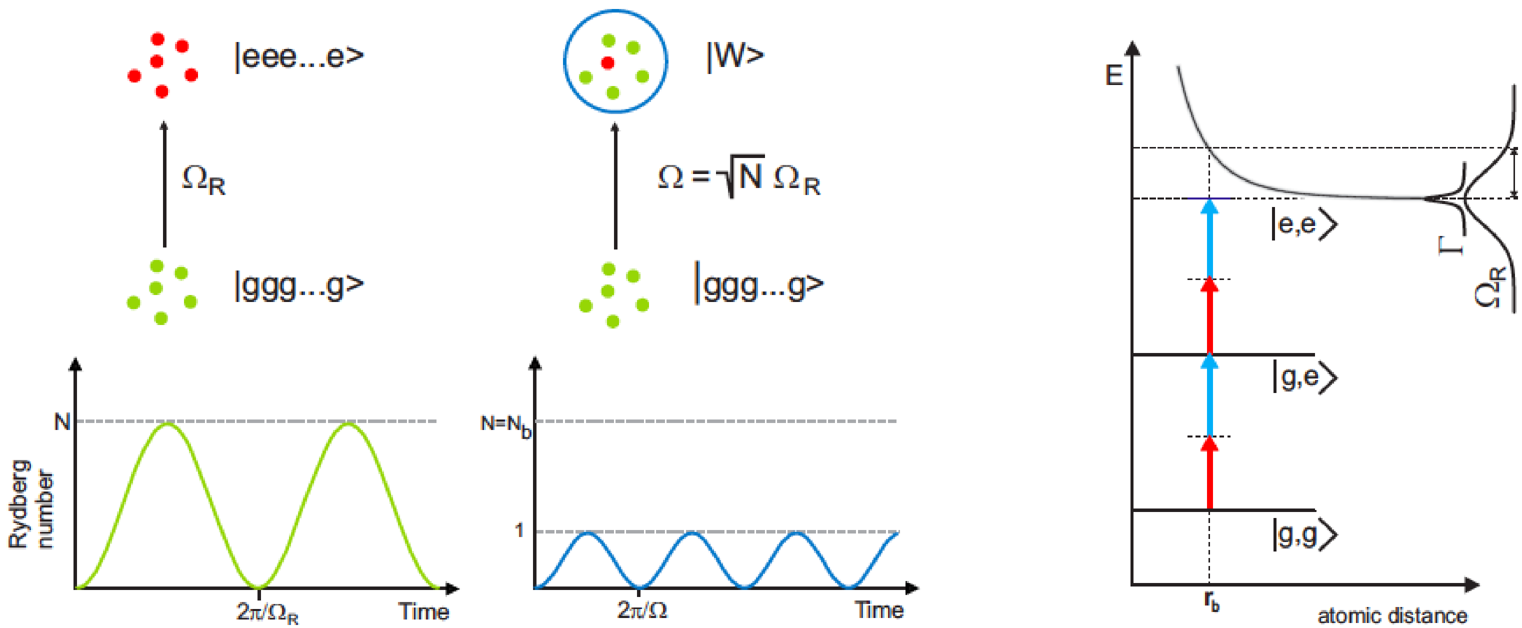


Hoffmann et al, PRL 110, 203601 (2013); Löw et al, J. Phys. B 45, 113001 (2012)

Rydberg 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

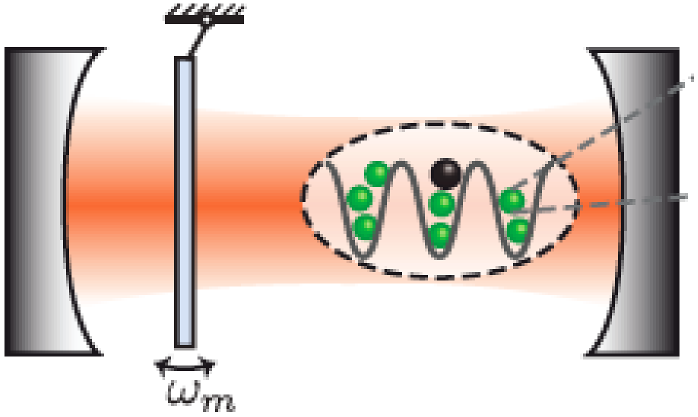


Hoffmann et al, PRL 110, 203601 (2013); Löw et al, J. Phys. B 45, 113001 (2012)

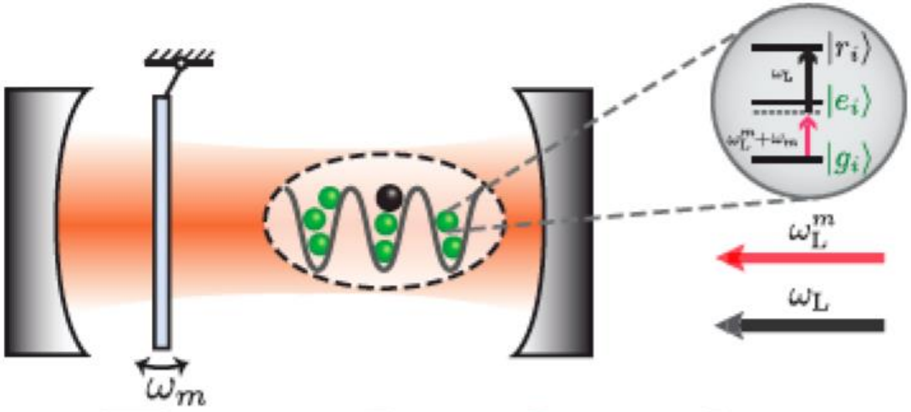
Nanomechanics coupled to a superatom

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



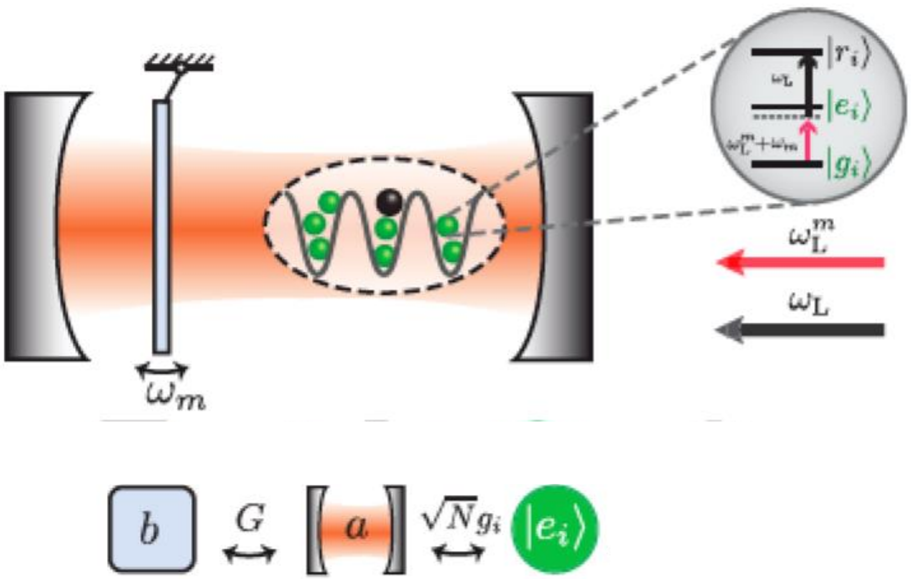
Nanomechanics coupled to a superatom



Principle setup without dissipation processes

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

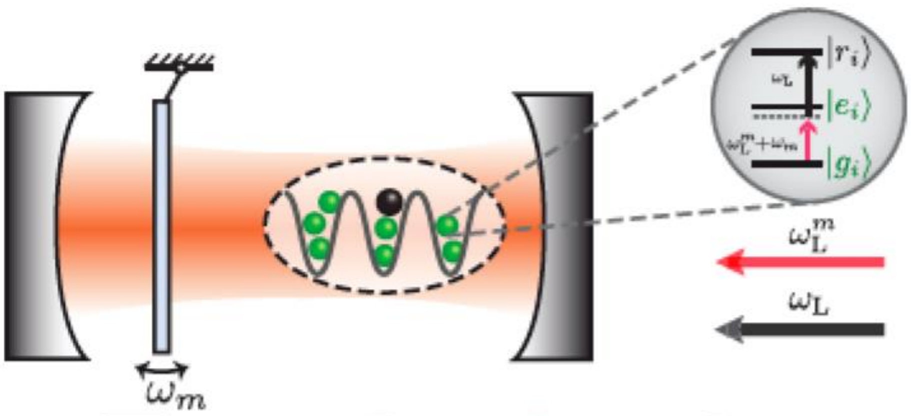
Nanomechanics coupled to a superatom



Principle setup without dissipation processes

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

Nanomechanics coupled to a superatom



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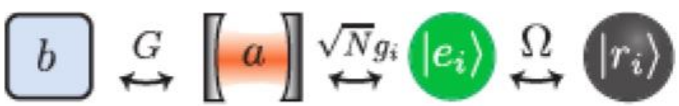
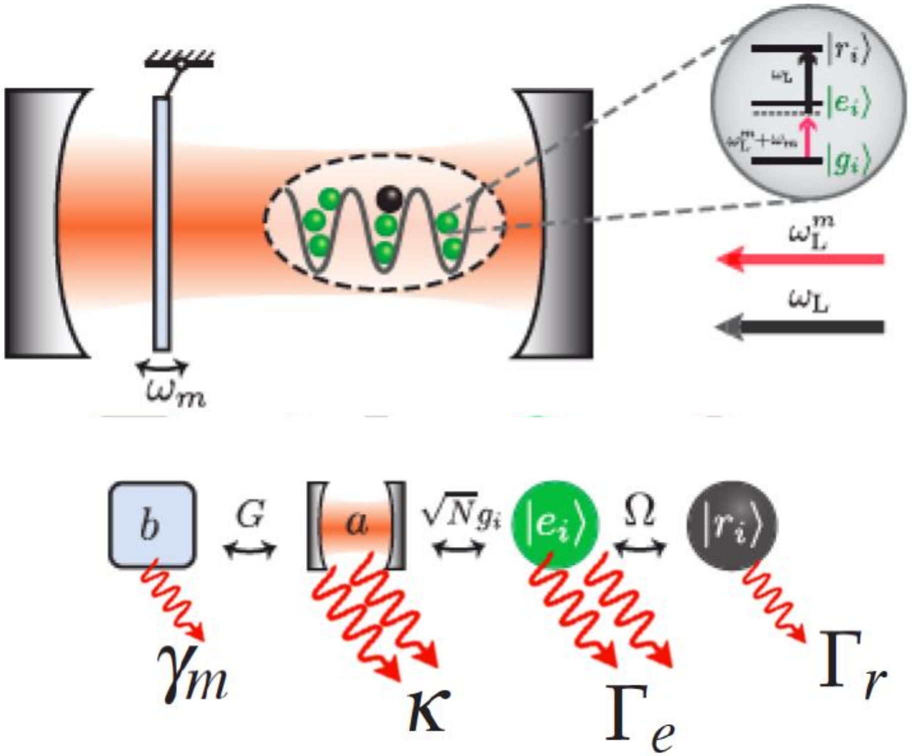


$$H_{\text{int}} = G\left(a^\dagger b + b^\dagger a\right) + \sum_{i=1}^{N}\left(g_i\, a\, |e_i\rangle\langle g_i| + \Omega e^{-i\omega_L t}\, |r_i\rangle\langle e_i|\right) + \text{h.c.}$$

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

Nanomechanics coupled to a superatom: dissipation

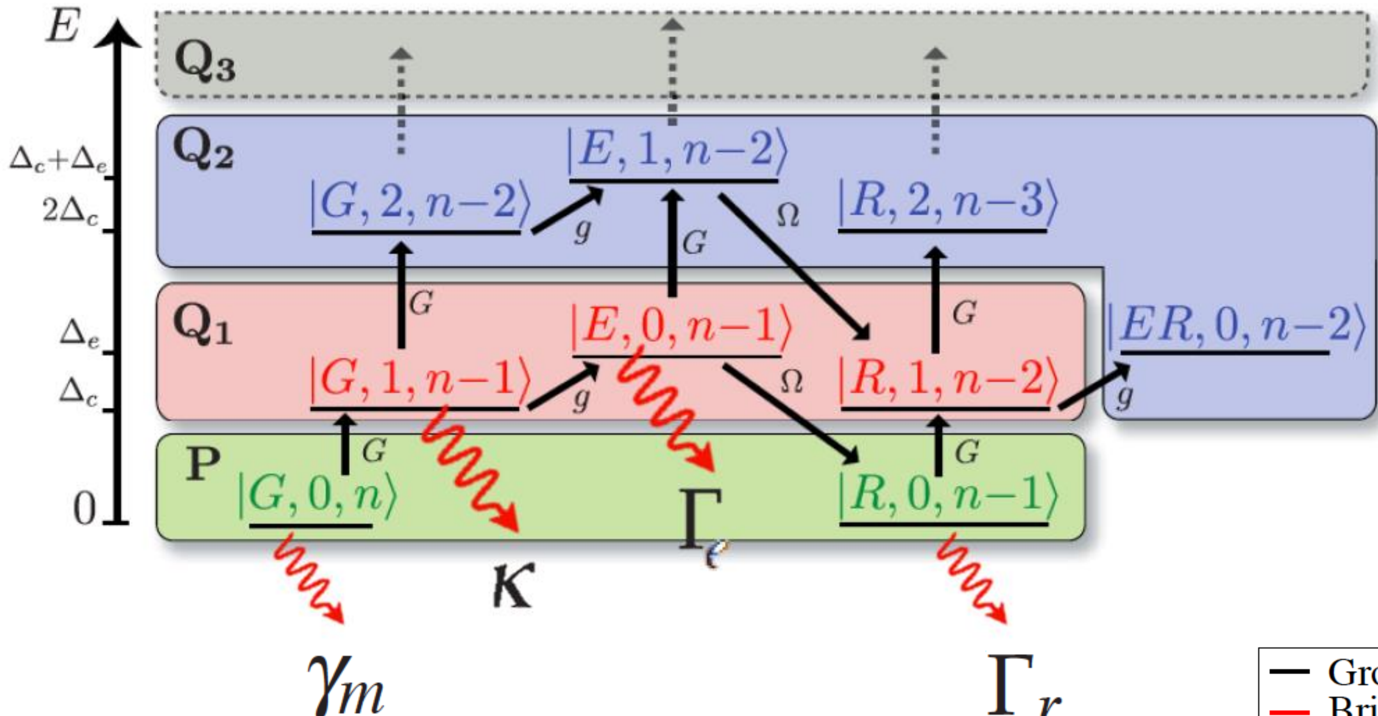


Principle setup with dissipation processes

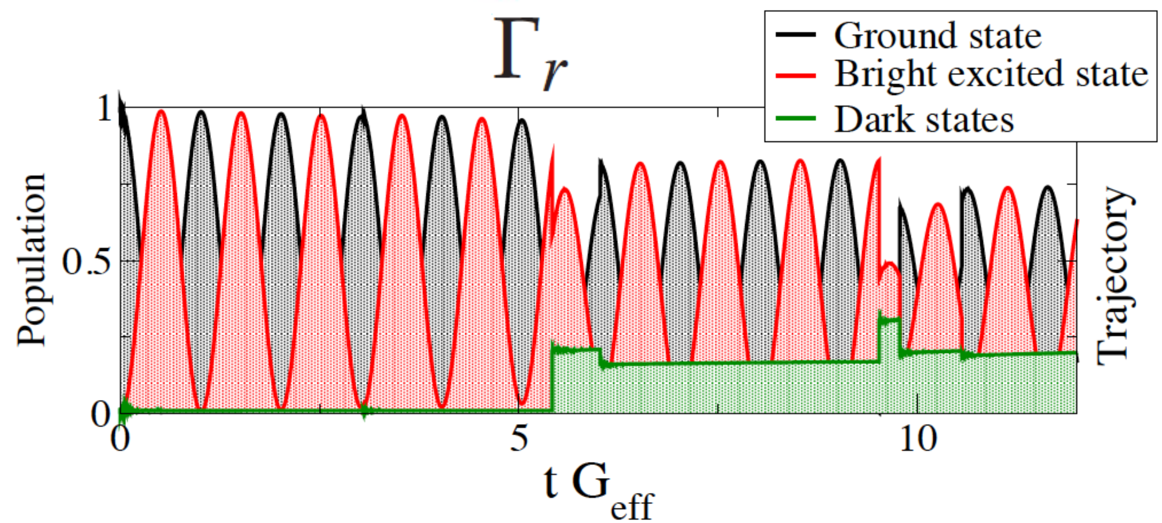
Cavity – mediated membrane – Rydberg superatom coupling

- ❑ 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

Nanomechanics coupled to a superatom: dissipation



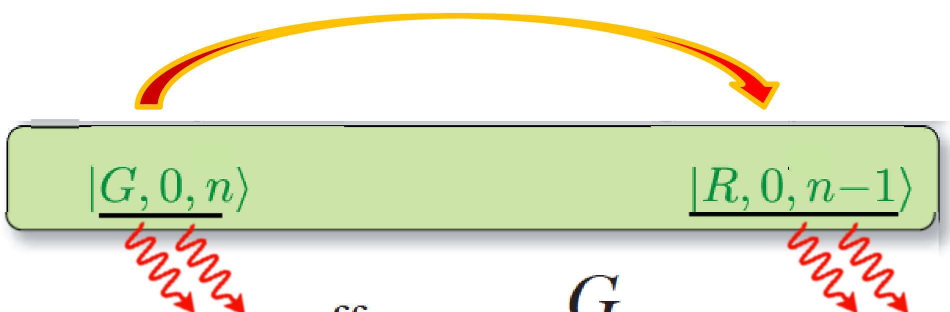
Quantum Monte Carlo Simulation for an ensemble of N=10 three-level atoms



Nanomechanics strongly coupled to superatom

Strong coupling limit is accessible:

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



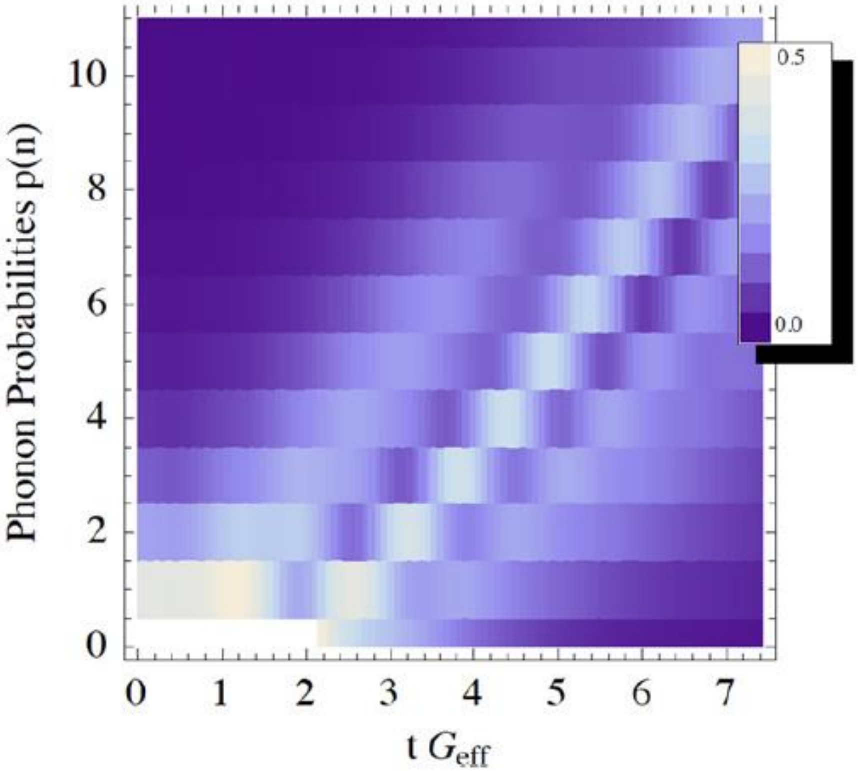
γ_m $\quad \Gamma_m^{\text{eff}} \approx n\kappa\frac{G}{\Delta_c^2}$ $\quad \Gamma_r$ $\quad \Gamma_r^{\text{eff}} \approx \Gamma_e\frac{\Omega}{\Delta_e^2}$

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

New J. Phys. **16**, 63042 (2014)

Nanomechanics driven to non-classical state

preparation of non-classical states even at finite temperatures.



Fidelity for the individual state transfer:

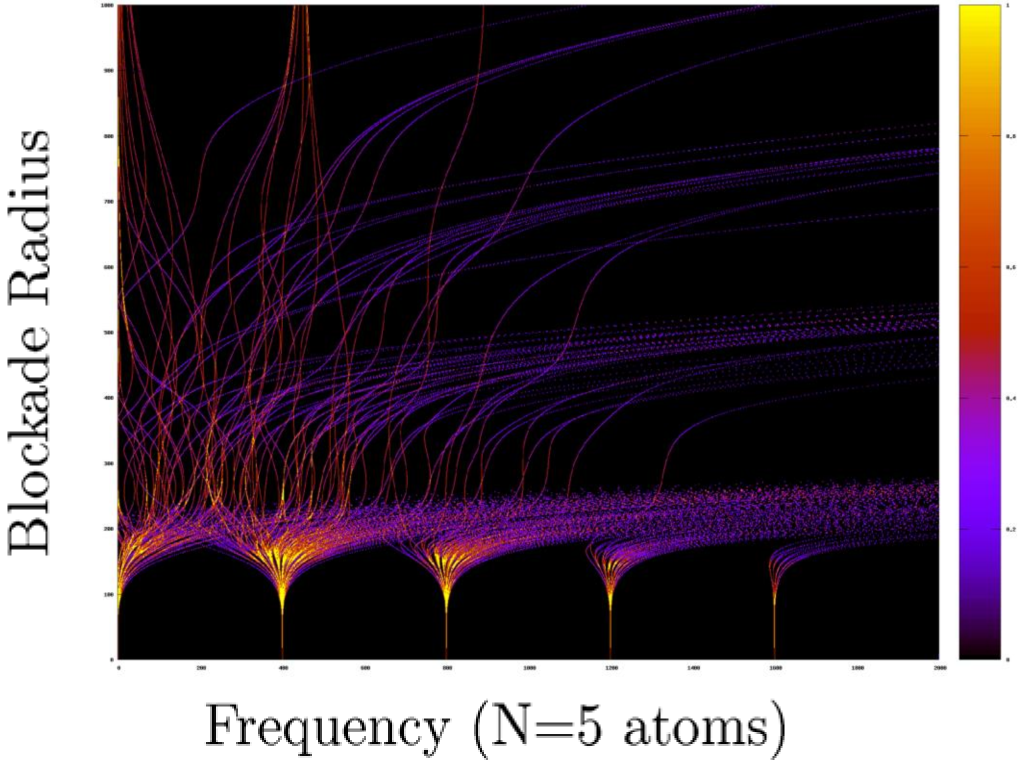
$$\mathscr{F} \approx 1 - \frac{\pi}{2G_{\text{eff}}}\left(4N_m\gamma_m + \gamma_m + \Gamma_r^{\text{eff}} + \Gamma_r\right)$$

New J. Phys. **16**, 63042 (2014)

What's next

Outlook

- Rydberg physics: transitions from quantum mechanical to classical regimes - quantum path resonances



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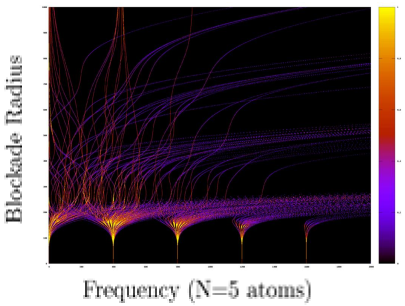
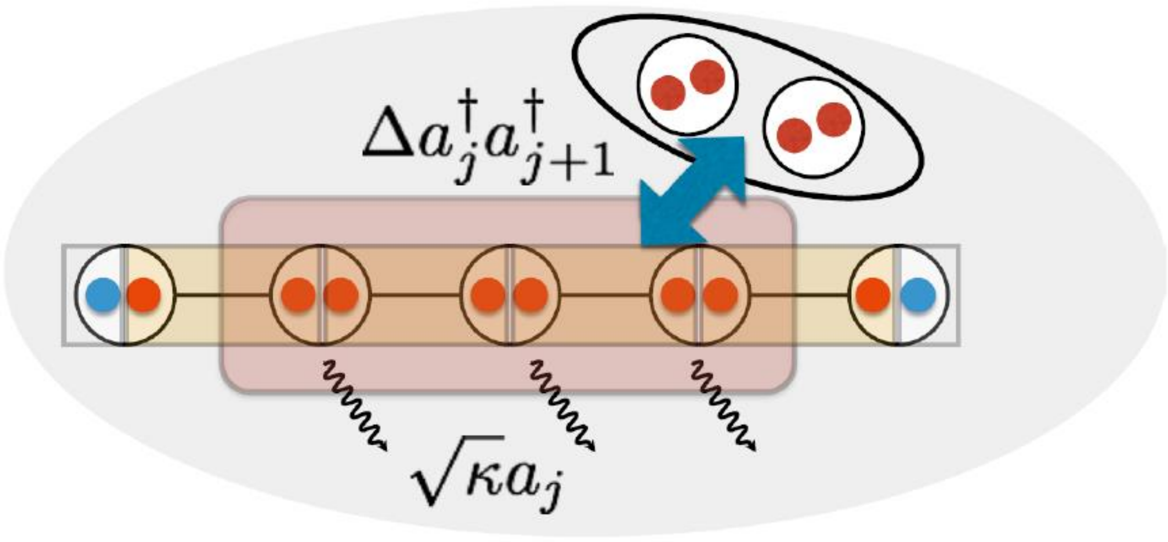


- Condensed matter physics: disorder in spin chains and disorder induced phase transitions into many-body localization



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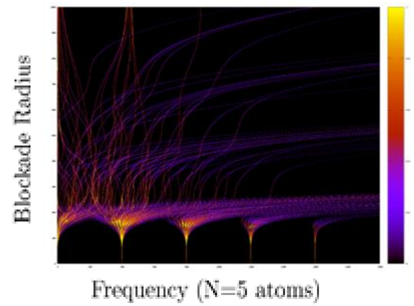

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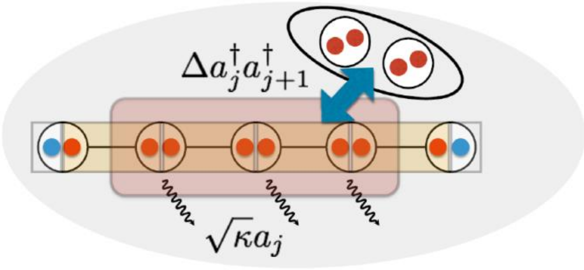
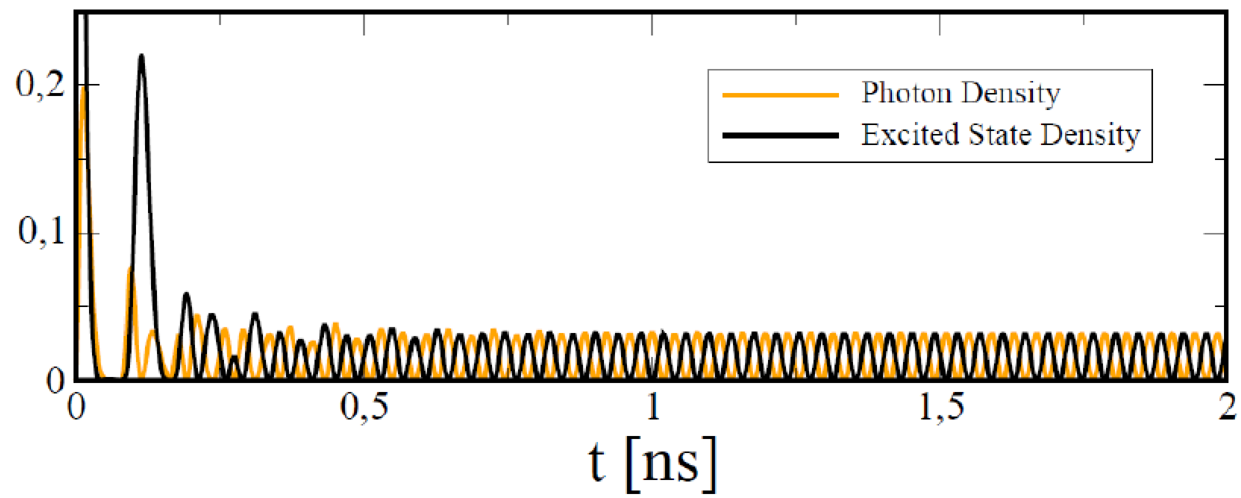


- investigate non-invasive quantum control schemes based on structured continua and develop unified operator technique for quantum feedback



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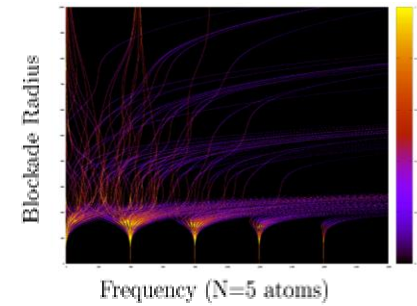

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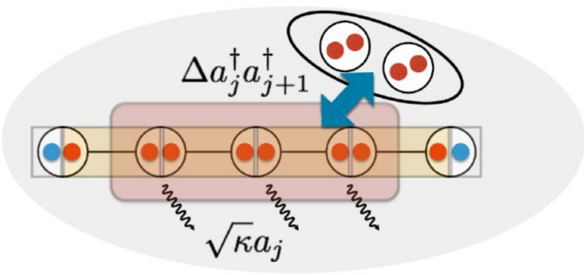

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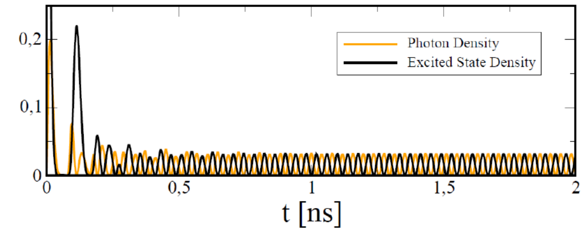

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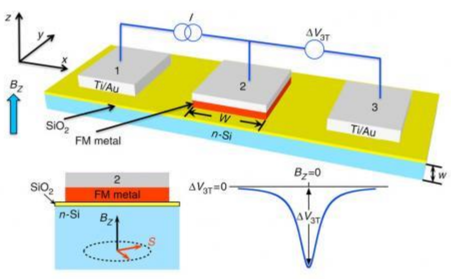
- study impact of coherent phonon waves on electronic transport properties (current), cooling, and heating of solids



Outlook

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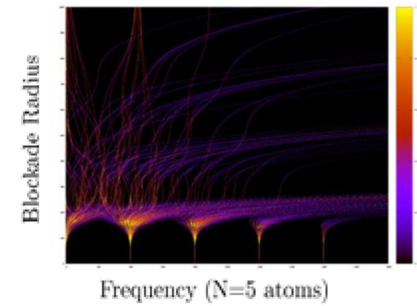

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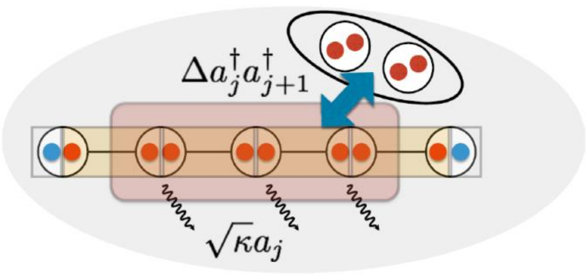

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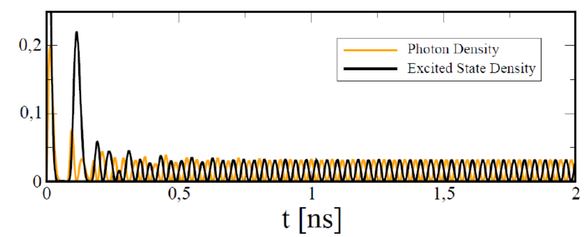
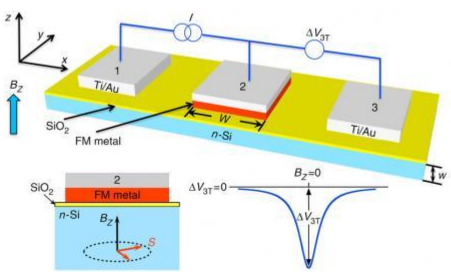


- study impact of coherent phonon waves on electronic transport properties (current), cooling, and heating of solids



Thanks for the attention!