Addressing non-equilibrium phonon dynamics in semiconductor optomechanics

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Technische Universität Berlin

*Collaborators: Leon Droenner, Nicolas Naumann, Alexander Thoma, Tobias Heindel, Julia Kabuss, Weng W. Chow, Stephan Reitzenstein, and Andreas Knorr

- **Highlights in Semiconductor Quantum Optics**
  - Markovian and non-Markovian features in recent experimental studies
  - Phenomenological model via stochastic forces (photon indistinguishability)
- **Deformation potential (acoustical phonons - LA)**
  - Examples: Line shapes, cavity feeding, and Rabi rotation rephasing
  - Stabilization of the collapse and revival phenomena in cavity-QED
- **Fröhlich potential (optical phonons - LO)**
  - Phonon-induced anticrossing in Mollow-triplet physics
  - Solid-state analogue of optomechanics (lasing and cooling of nanostructures)
- **Acoustic cavities (strong coupling)**
  - Many-emitter phonon lasing (superphonance)
  - Stabilization of coherence properties via phonon quantum feedback

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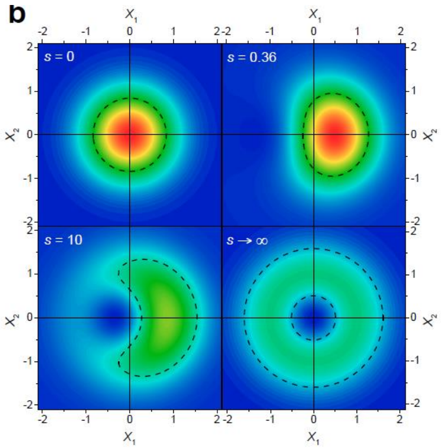
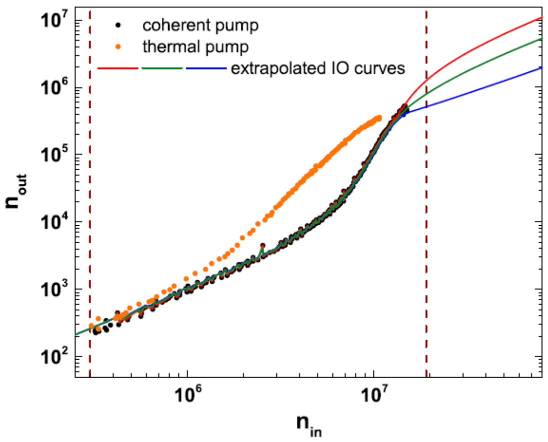
Schulte et al, Nature 525, 222 (2015)



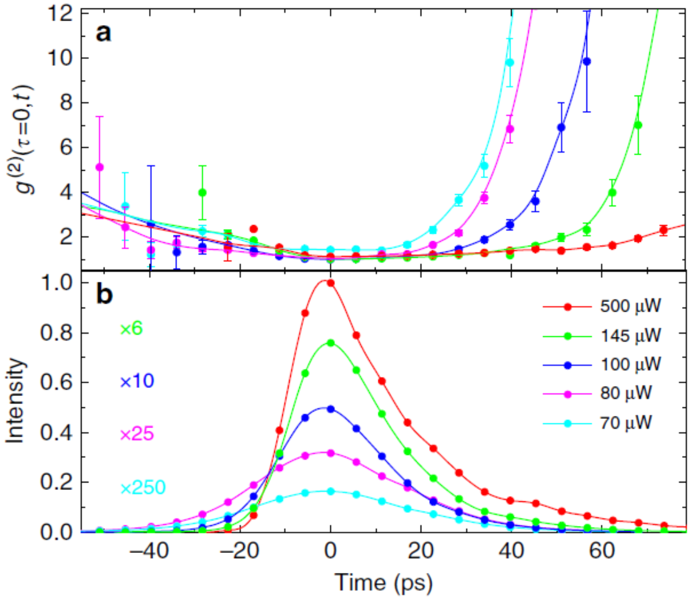
Squeezed Photon Emission from QD



Höfling et al, PRL 115, 027401 (2015)

Strauß et al, PRB 93, 241306 (2016)

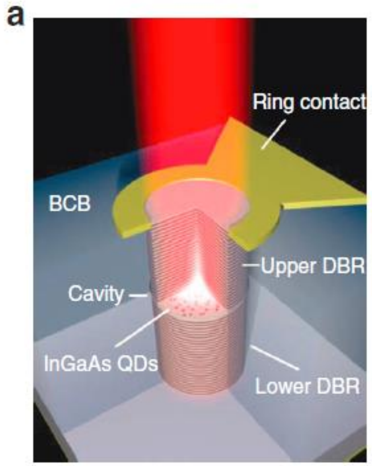
Quantum Light Excitation



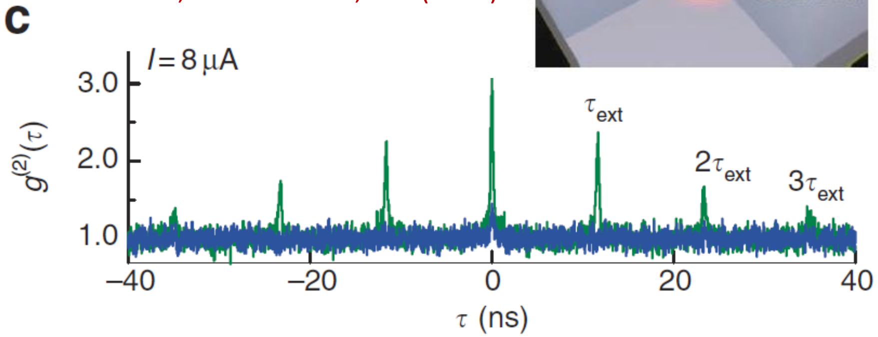
Jahnke et al, Nat. Comm. 7, 11540 (2016)

Giant Photon bunching in QD nanolasers

Quantum Chaos

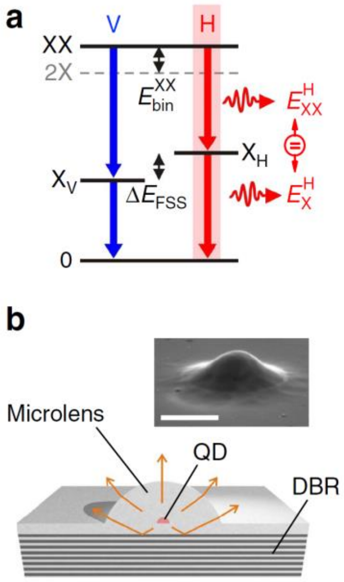


Albert et al, Nat. Comm. 2, 366 (2011)



Semiconductor advantageous due to fixed position / energy level design

→ deterministically fabricated QD microlenses (Reitzenstein)

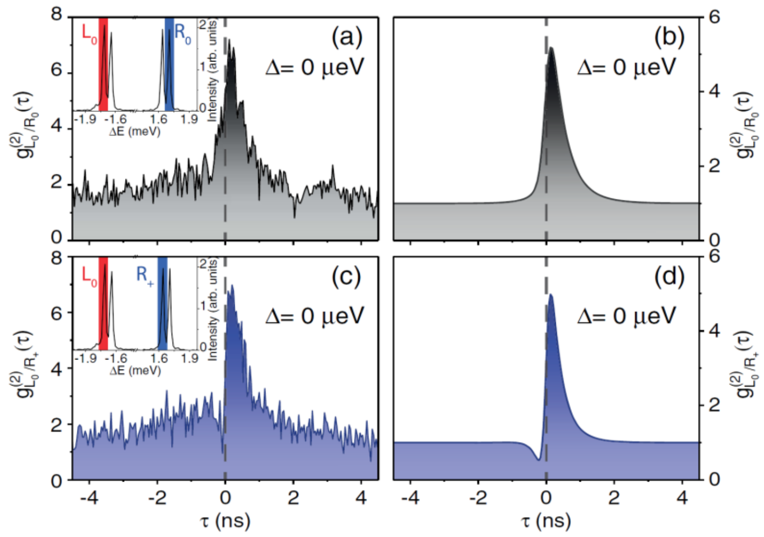


$$\partial_t \, \rho(t) = -\frac{i}{\hbar}\left[H(t),\, \rho(t)\right] + \sum_{\alpha} L[C_\alpha]\rho(t)$$

$$L[C] = C\rho C^\dagger - \frac{1}{2}C^\dagger C\rho + \frac{1}{2}\rho C^\dagger C$$

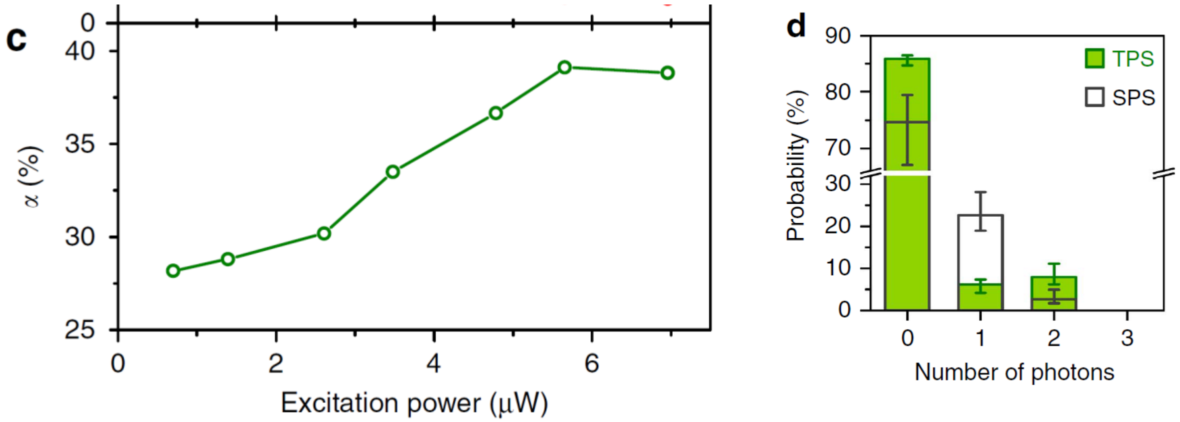
$$C_{|e\rangle\langle e|} = \sqrt{\gamma}\sigma_+\sigma_-$$

Deterministic Twin-Photon Source (incohereht excitation)



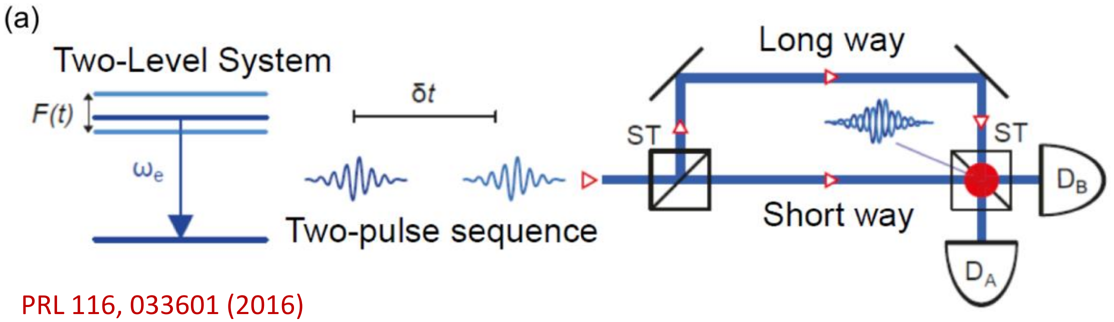
PRL 118, 233601 (2017)

Deterministic photon pair re-ordering in a biexciton cascade (strong driving)



Nat. Comm. 8, 14870 (2017)

Experiments sensible to non-Markovian phonon effects

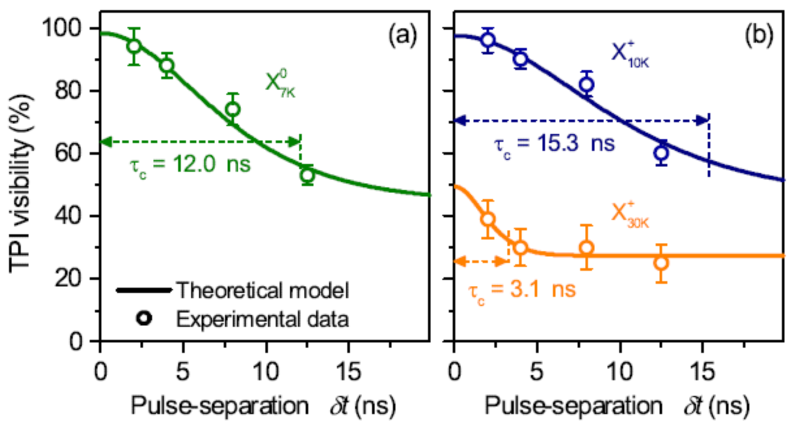


PRL 116, 033601 (2016)

Two-Photon-Inteference with 96% visibility and even higher

Ding et al, PRL 116, 020401 (2016)
Kim et al, Optica 3, 577 (2016)
Wang et al, PRL 116, 213601 (2016)

PRL 116, 033601 (2016)



$$\mathcal{H}/\hbar = (\mathcal{H}_0 + \mathcal{H}_\mathrm{W} + \mathcal{H}_\mathrm{A})/\hbar = (\omega_\mathrm{e} + F(t))\,\sigma_\mathrm{ee} + \Omega(t)\left(e^{-i\omega_\mathrm{pt}}\sigma_\mathrm{eg} + e^{+i\omega_\mathrm{pt}}\sigma_\mathrm{ge}\right) + \int_0^\infty d\omega\left(\omega\; c_\omega^\dagger c_\omega + g_\omega\; c_\omega^\dagger\sigma_\mathrm{ge} + g_\omega^*\sigma_\mathrm{eg}c_\omega\right).$$

$$\mathcal{H}_\mathrm{I} = \Omega(t)(\sigma_\mathrm{eg} + \sigma_\mathrm{ge}) + g\int d\omega\; e^{i(\omega-\omega_\mathrm{e})t - i\phi_0(t)}c_\omega\sigma_\mathrm{ge} + e^{-i(\omega-\omega_\mathrm{e})t + i\phi_0(t)}\sigma_\mathrm{eg}c_\omega$$

$$\phi_{t_1} = \int_{t_1}^{t} dt' F(t')$$

$$\langle\phi_{t_1}(t_2)\phi_{t_3}(t_4)\rangle = \int_{t_1}^{t_2} dt \int_{t_3}^{t_4} dt'\,\langle F(t)F(t')\rangle = e^{-\frac{(t_1-t_3)^2}{\tau_c^2}}\,(\mathrm{min}[t_2,t_4] - \mathrm{max}[t_1,t_3])$$

Classical noise modelling via imposed memory kernels

Microscopic theory to reveal advantageous properties

→ Microscopic phonon modelling in semiconductor QDs

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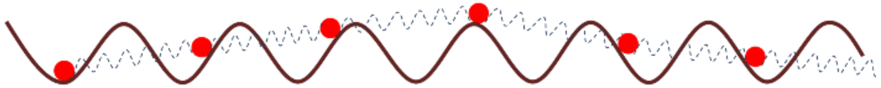
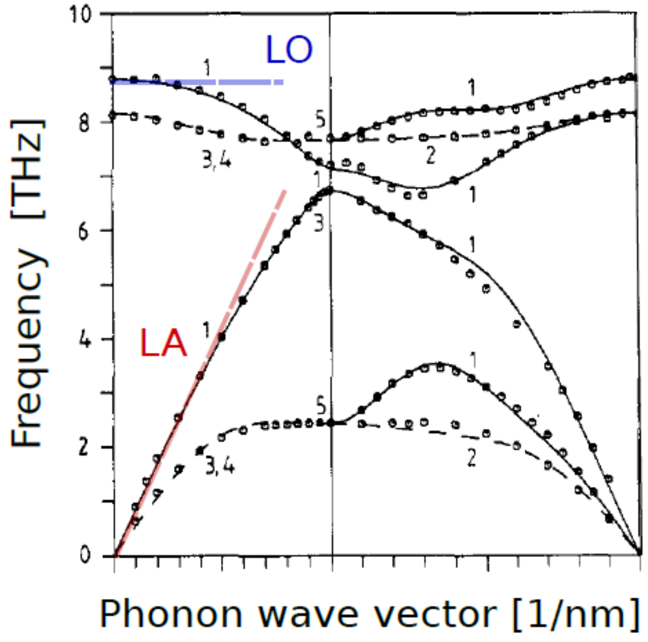
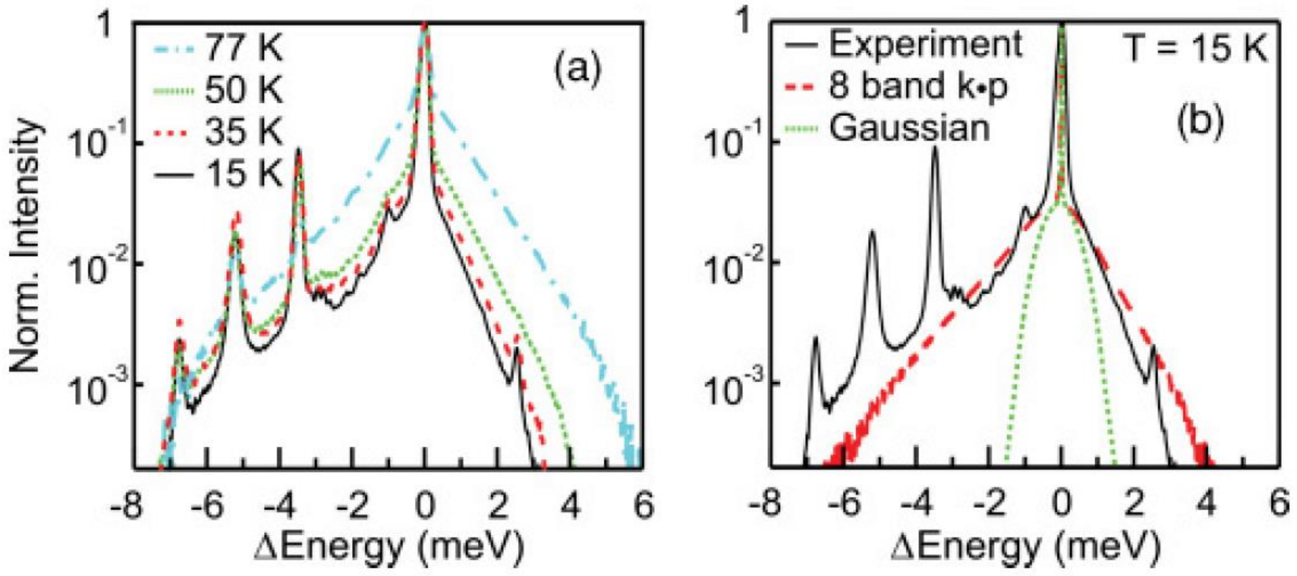


$$H_{\text{el-phonon}} = \hbar \sum_{q,i} \omega_{iq} b^\dagger_{iq} b_{iq} + \sum_{m,q,i} \left(g^{q,i}_m \, b^\dagger_{q,i} + g^{q,i*}_m \, b_{q,i} \right) |m\rangle\langle m|$$

Pure dephasing due to acoustical phonons (LA) – deformation potential

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



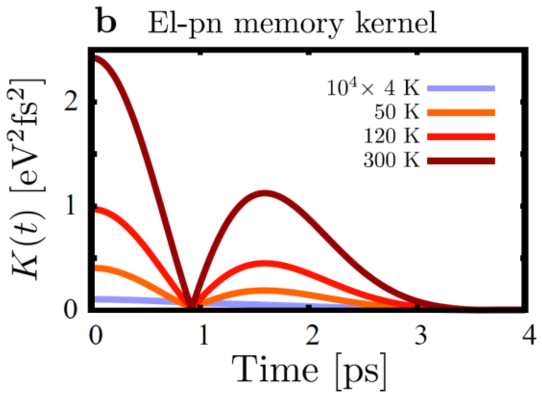


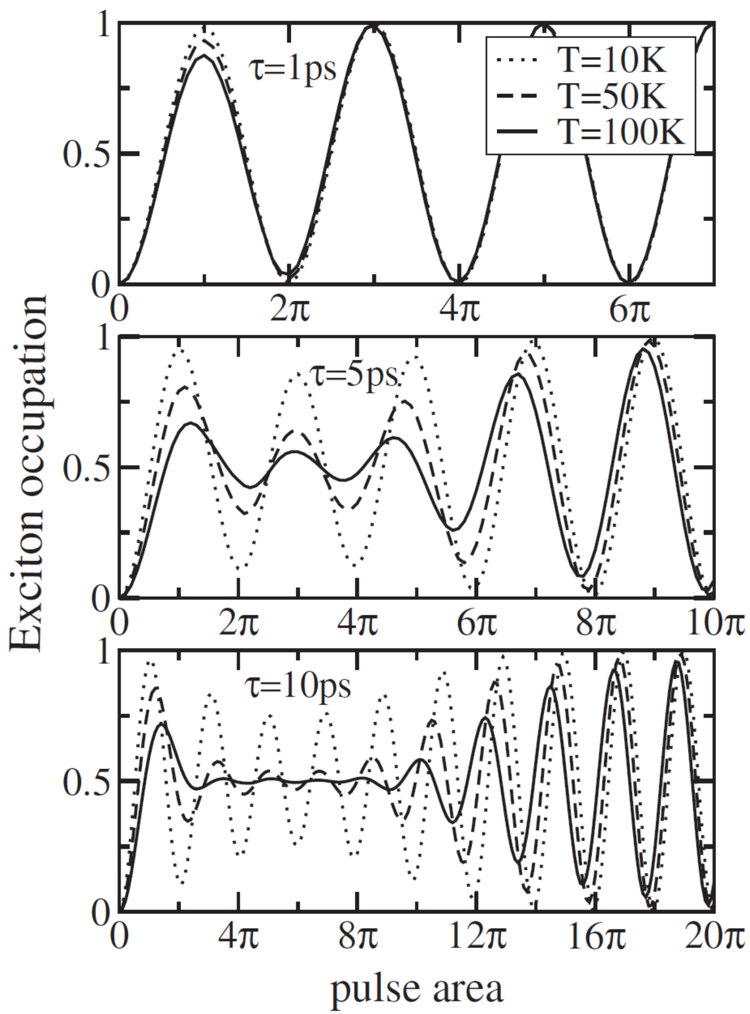
Carmele et al, in: Jahnke (Ed.) "Quantum optics with Semiconductor Nanostructures" (2012)

Microscopic phonon modelling in semiconductor QDs

Phonon spectral density
(spherical QD)

$$J(\omega) = \frac{\omega^3}{4\pi^2\rho\hbar v_c^5}\left[D_e e^{(-\omega^2 a_e^2/4v_c^2)} - D_h e^{(-\omega^2 a_h^2/4v_c^2)}\right]^2$$

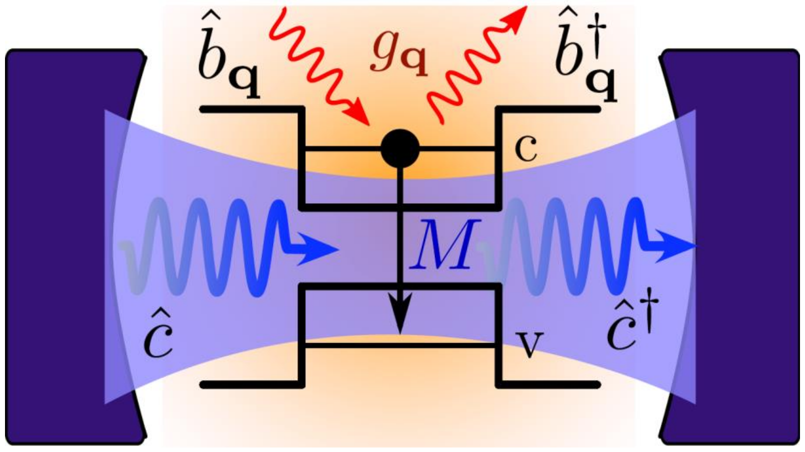




Rephasing of excitonic Rabi oscillations due to limited memory depth (Rabi frequency exceeds the width of phonon background spectrum)

Vagov et al, PRL 98, 227403 (2007)
Forstner et al, PRL 91, 127491 (2003)

→ Rephasing in cQED control of Collapse and revival feature



New J. Phys. 15, 105024 (2013)

Collapse and revival phenomenon is enhanced due to LA phonon dephasing – the intermixing of different Rabi frequencies suppressed and thereby stabilized

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

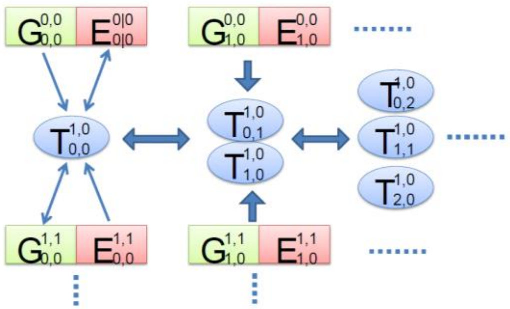
$$\partial_t G^p = iM\left[T^{p+1} - \left(T^{p+1}\right)^* + pT^{p-1} - p\left(T^{p-1}\right)^*\right]$$

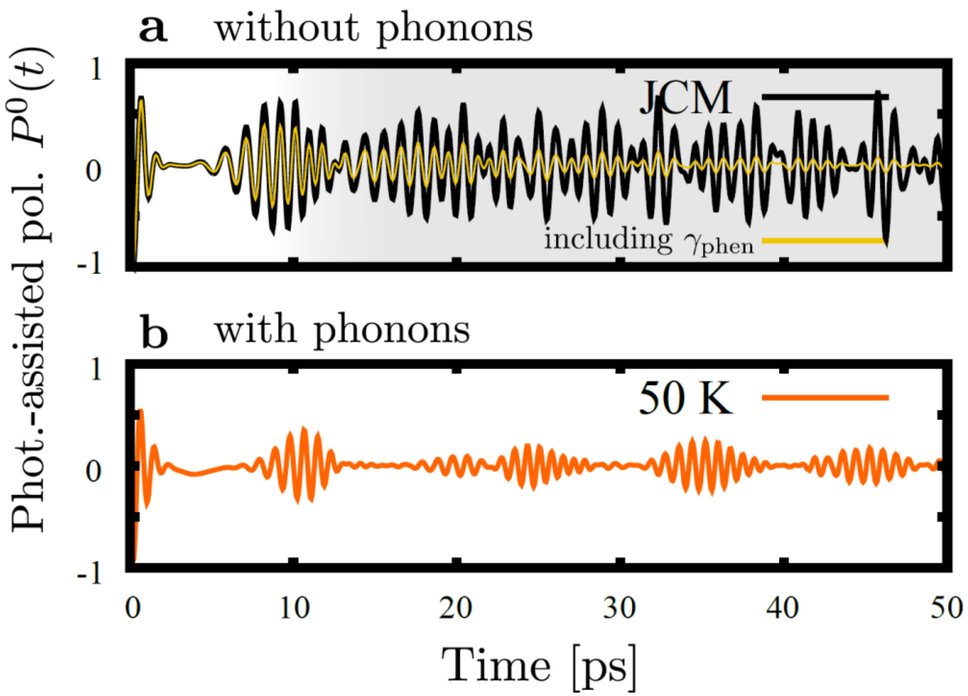
$$\partial_t E^p = -i\, MT^{p+1} + i\, M\left(T^{p+1}\right)^*$$

$$\partial_t T^p = -i\Delta T^p - iM(pE^{p-1} + E^{p+1} - G^{p+1}) - i\sum_q g_q^*\, T_+^p(q) + g_q\, T_-^p(q)$$

$$\partial_t T_+^p(q) = i\left[\Delta + c_{LA}\, q\right] T_+^p(q) - i\, n_{LA}(q)\, g_q^*\, T^p$$

$$\partial_t T_-^p(q) = i\left[\Delta - c_{LA}\, q\right] T_-^p(q) - i\, (n_{LA}(q) + 1)\, g_q\, T^p$$





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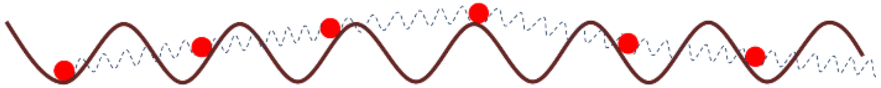

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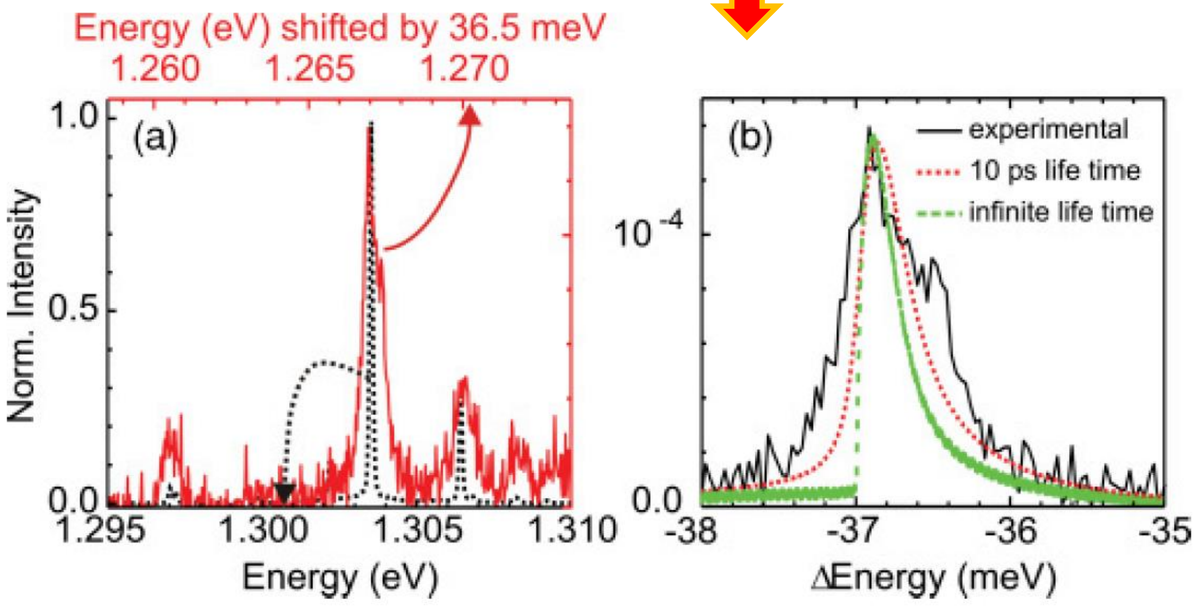
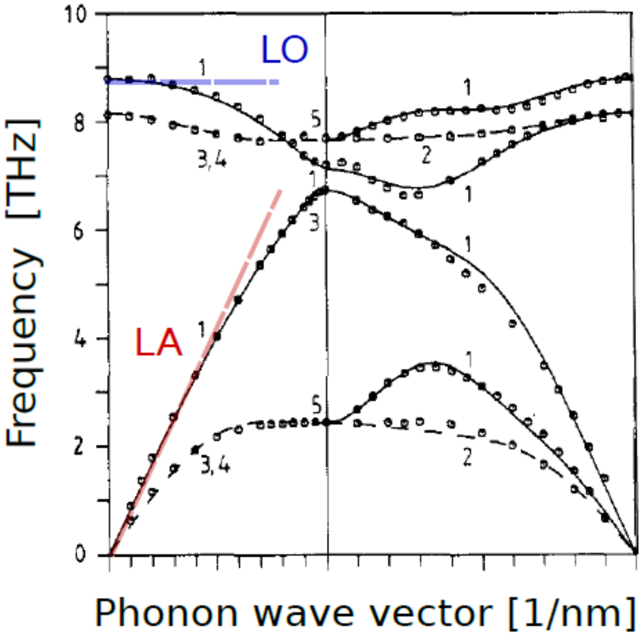
Dephasing due to optical phonons (LO) – Fröhlich potential

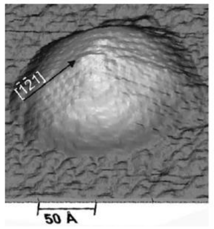
$$g_{\text{LO},q}^{\lambda\mu,\text{3D}} = \frac{1}{q}\sqrt{\frac{e_0^2 \hbar \omega_{\text{LO}}}{2\varepsilon_0 V}\left(\frac{1}{\varepsilon_\infty} - \frac{1}{\varepsilon_{\text{st}}}\right)}$$

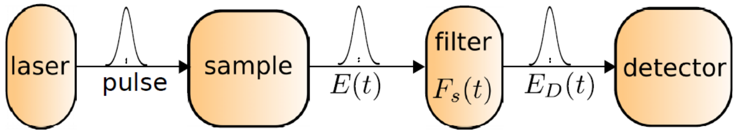


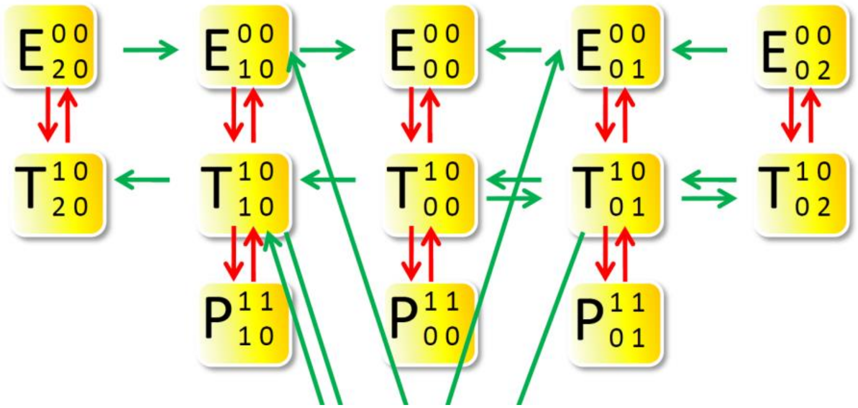


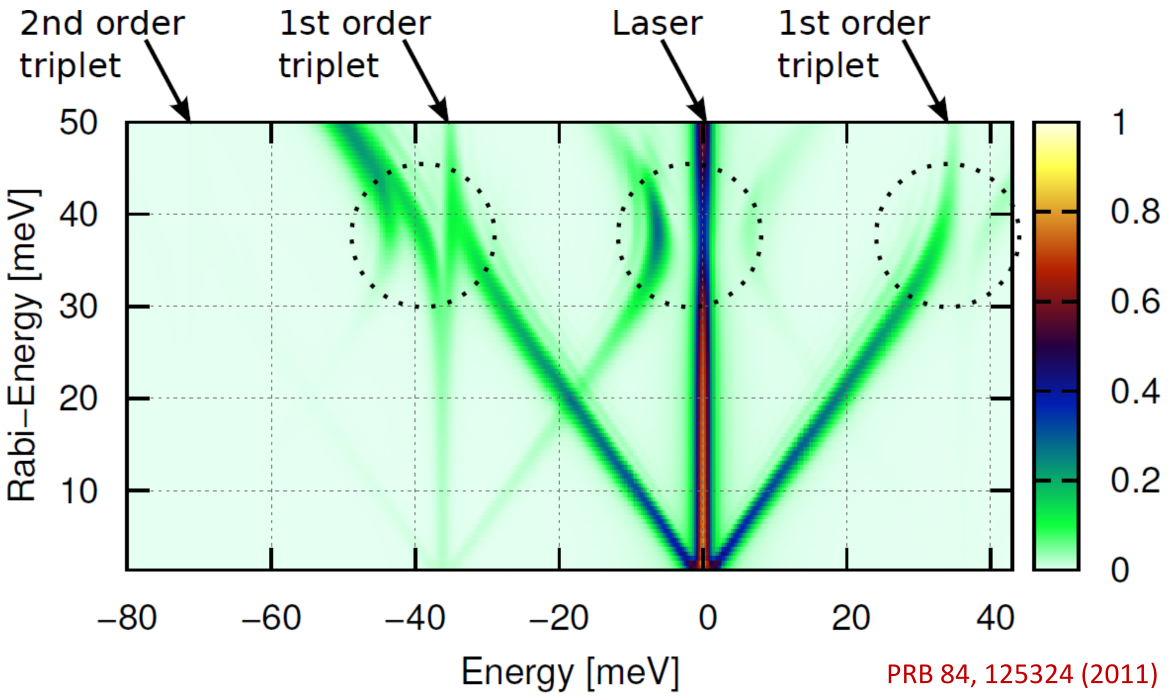
Carmele et al, in: Jahnke (Ed.) "Quantum optics with Semiconductor Nanostructures" (2012)

Quasi-particle formation as estimate for coupling strength







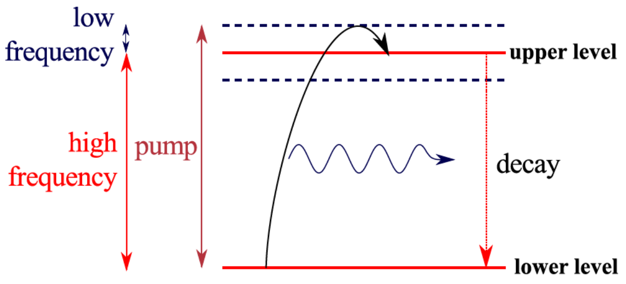


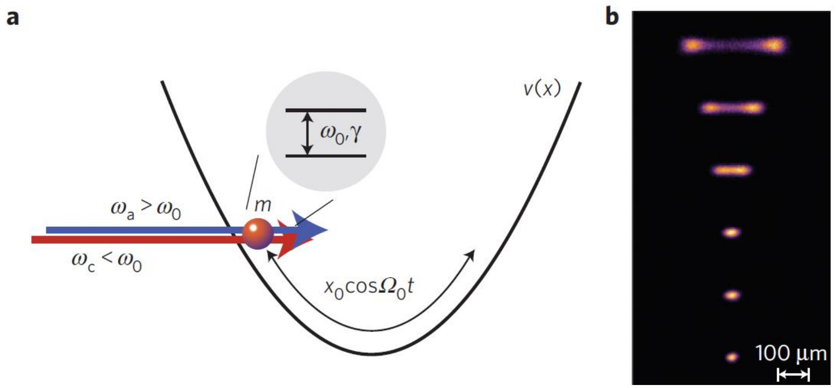
PRB 84, 125324 (2011)

- Spectrum shows usual Mollow triplet but also phonon-assisted Mollow triplet features
- Additional anticrossings, when Rabi energy matches the phonon energy
- The emerging anticrossings allow to read-out the electron-phonon coupling strength

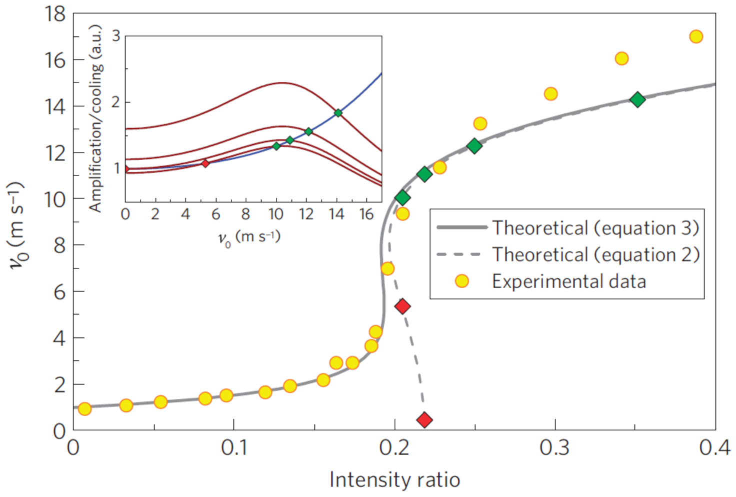
Solid-state based optomechanics

Ion trap phonon lasing with input/output curve

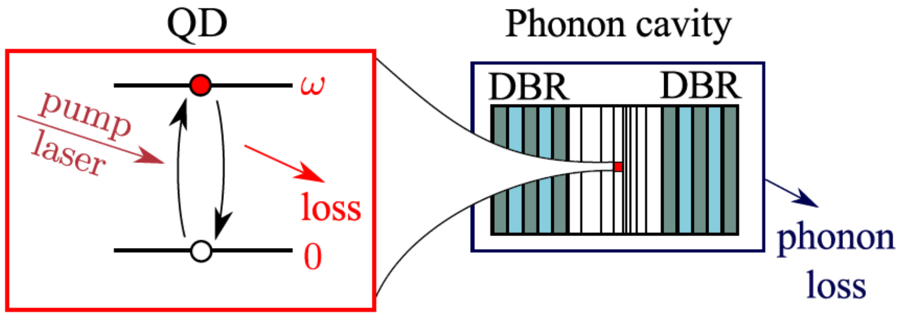


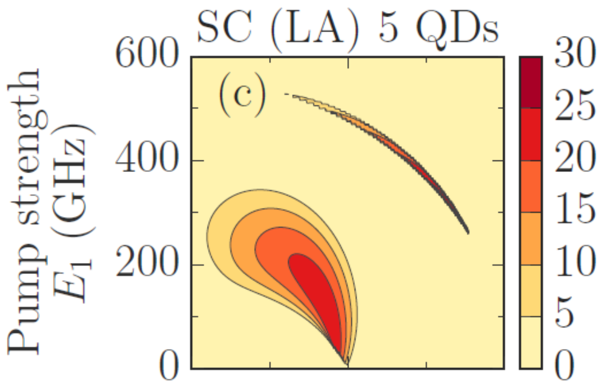


Vahala, Nat. Phys. 5, 682 (2009)



Semiconductor analogue of optomechanics





JOSA B 33, 1492 (2016)

$$H = \hbar\Omega\hat{b}^\dagger\hat{b} + \hbar\omega\hat{\mathbf{p}}^\dagger\hat{\mathbf{p}} + \hbar g\hat{\mathbf{p}}^\dagger\hat{\mathbf{p}}\left(\hat{b} + \hat{b}^\dagger\right)$$
$$+ i\hbar\mathbf{E}\left(\hat{\mathbf{p}}^\dagger e^{-i\omega_{\mathrm{L}}t} - \hat{\mathbf{p}}e^{i\omega_{\mathrm{L}}t}\right)$$

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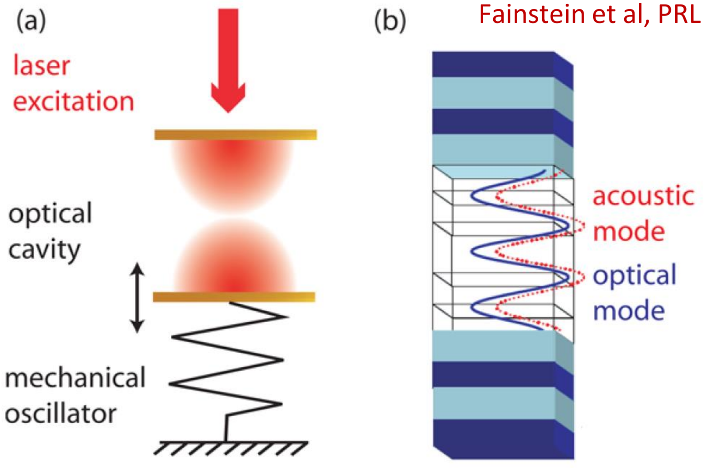
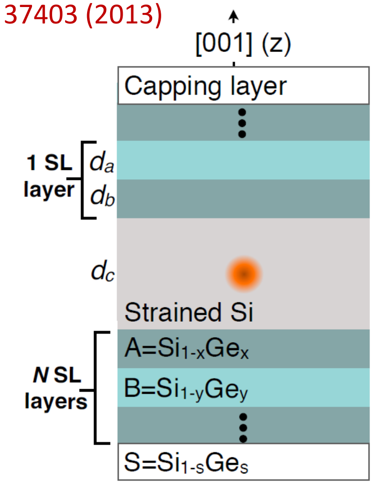
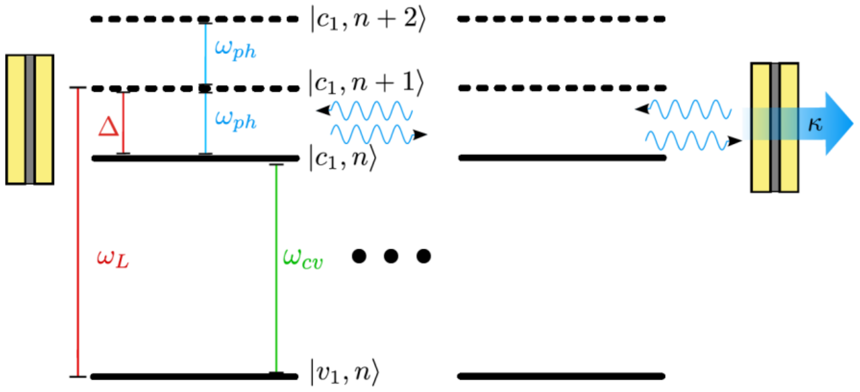
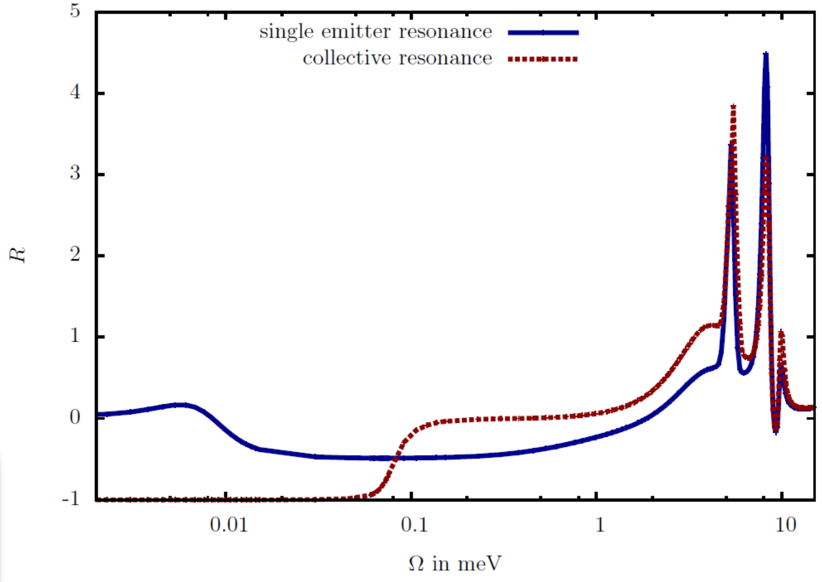
Confine acoustical modes in superlattice structures – high quality factors possible



Fainstein et al, PRL 110, 37403 (2013)







PRA 96, 43805 (2017)

Quantum yield factor

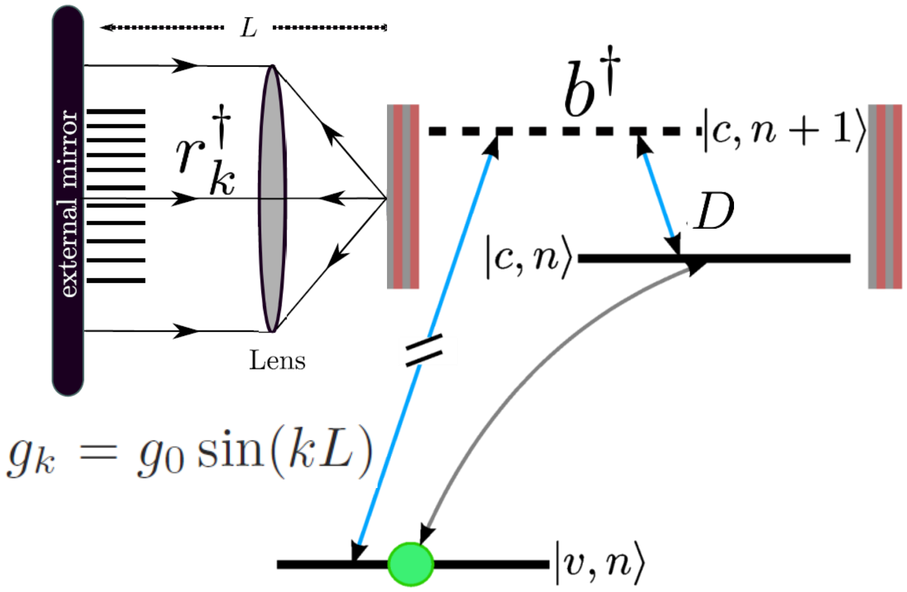
$$R = \frac{\langle b^\dagger b \rangle_2 - 2\langle b^\dagger b \rangle_1}{2\langle b^\dagger b \rangle_1}$$

More emitters to render phonon laser more efficiently (superphonance)

Stabilization of coherence via quantum feedback

Physics and Simulation of Optoelectronic Devices XXVI: 29th Jan – 1st Feb

"Addressing non-equilibrium phonon dynamics in semiconductor optomechanics (Alexander Carmele)

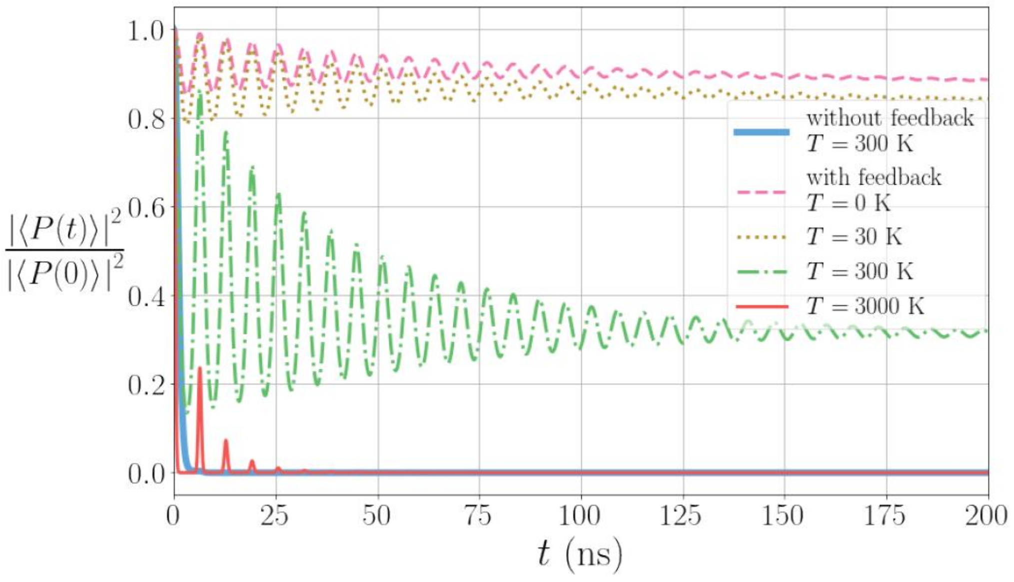


$$H = H_S + H_E \qquad H_S = \hbar\left[\omega_e + D(b^\dagger + b)\right] P^\dagger P$$

$$H_E = \hbar\omega_0 b^\dagger b + \int dk\ \omega_k\ r_k^\dagger r_k + \int dk\ g_k \left(r_k^\dagger b + b^\dagger r_k\right)$$

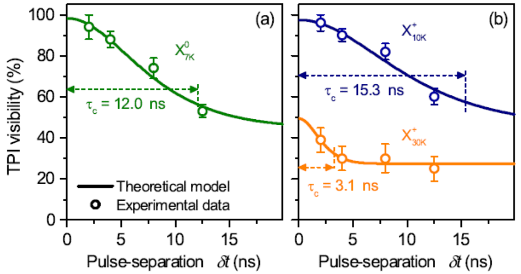
Environment controlled phonon cavity dynamics

Quantum feedback allows to cancel out phonon-induced dephasing by destructive quantum interferences

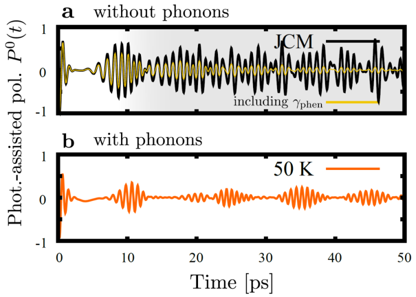


In preparation (2018)

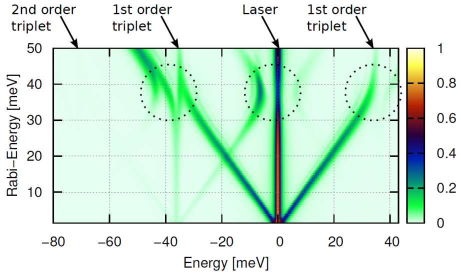
Addressing non-equilibrium phonon dynamics in semiconductor optomechanics



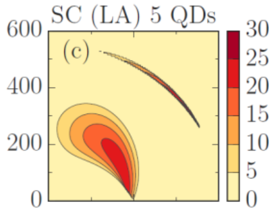
Read-out memory depth
PRL 116, 033601 (2016)



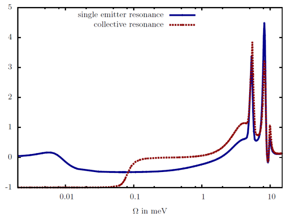
Stabiliized Collapse and revival
New J. Phys. 15, 105024 (2013)



Phonon-induced Anticrossings
PRB 84, 125324 (2011)



Solid-state optomechanics
JOSA B 33, 1492 (2016)



Superphonance
PRA 96, 43805 (2017)

Thank you for your attention!

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