Single-Polariton Optomechanics

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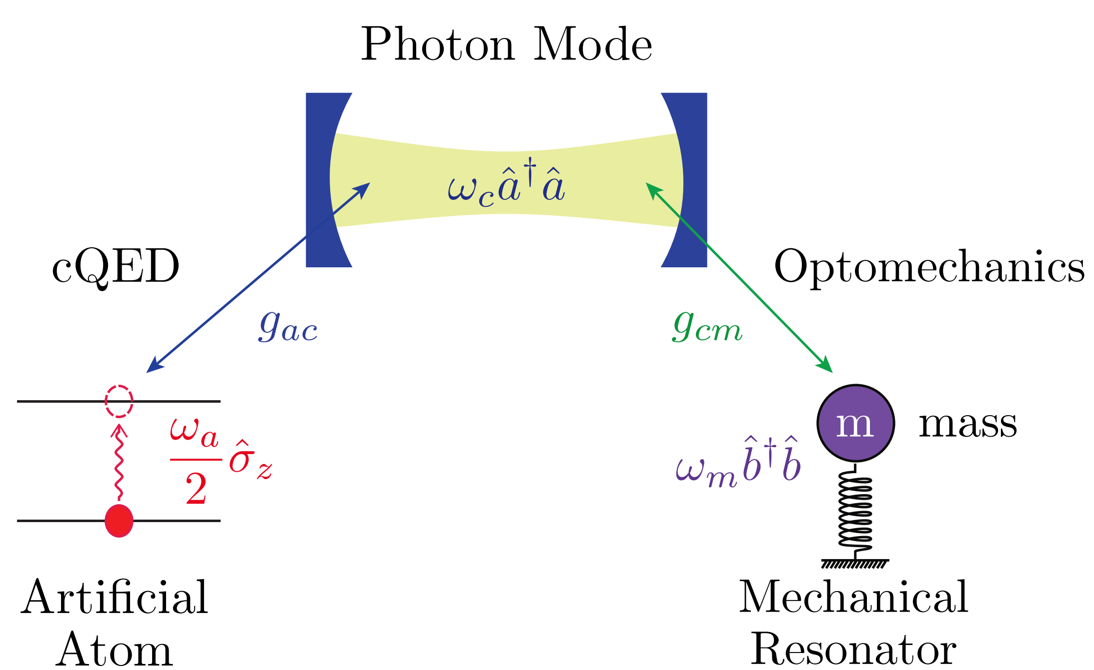
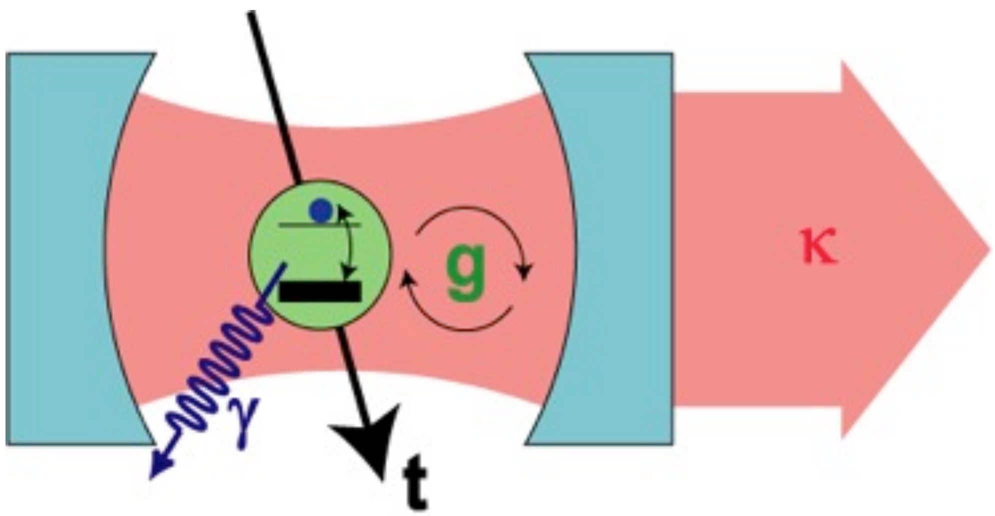
This Letter investigates a hybrid quantum system combining cavity quantum electrodynamics and optomechanics. The Hamiltonian problem of a photon mode coupled to a two-level atom via a Jaynes-Cummings coupling and to a mechanical mode via radiation pressure coupling is solved analytically. The atom-cavity polariton number operator commutes with the total Hamiltonian leading to an exact description in terms of tripartite atom-cavity-mechanics polarons. We demonstrate the possibility to obtain cooling of mechanical motion at the single-polariton level and describe the peculiar quantum statistics of phonons in such an unconventional regime.



Motivation



cavity quantum electrodynamics

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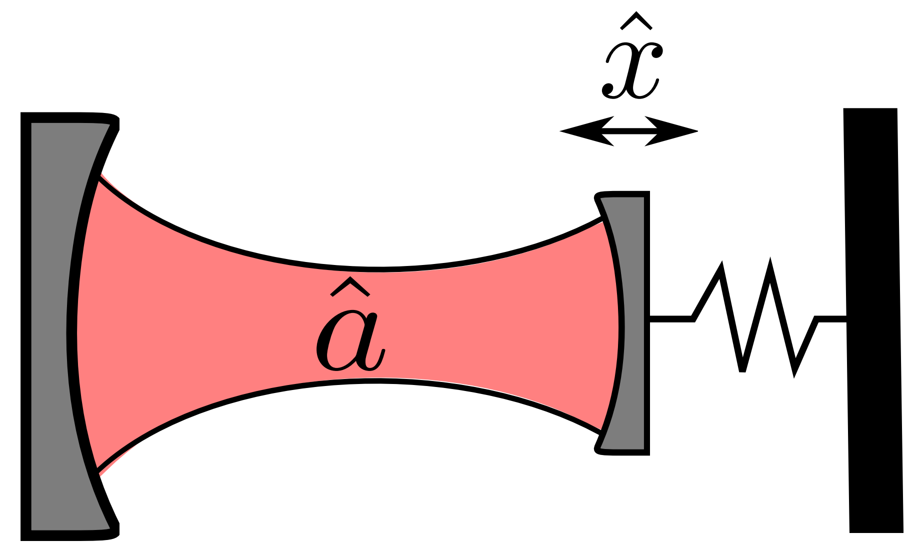
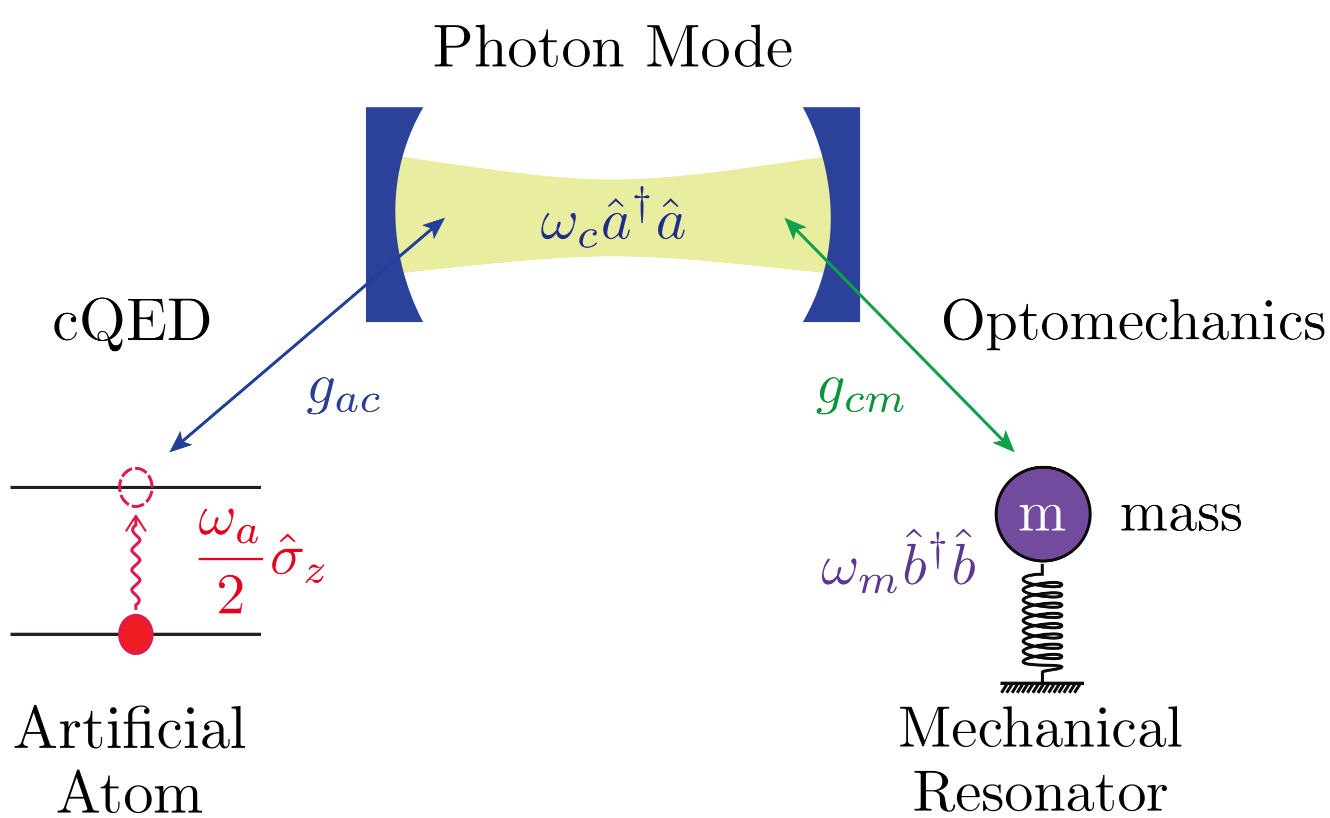


optomechanics

Model



$$\hat{H}_{\text{tot}} = \omega_c \hat{a}^\dagger \hat{a} + \frac{\omega_a}{2}\hat{\sigma}_z + i g_{ac}(\hat{\sigma}_+ \hat{a} - \hat{\sigma}_- \hat{a}^\dagger) + \omega_m \hat{b}^\dagger \hat{b} - g_{cm} \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger), \tag{1}$$

Atom-cavity-mechanics polaritons

$$\hat{H}_{\text{tot}} = \omega_c \hat{a}^\dagger \hat{a} + \frac{\omega_a}{2}\hat{\sigma}_z + i g_{ac}(\hat{\sigma}_+ \hat{a} - \hat{\sigma}_- \hat{a}^\dagger) + \omega_m \hat{b}^\dagger \hat{b} - g_{cm}\hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger), \qquad (1)$$

$\hat{N}_{\text{polariton}} = \hat{a}^\dagger \hat{a} + \hat{\sigma}_+ \hat{\sigma}_-$ is conserved.

$\hat{H}_{\text{JC}} = \omega_c \hat{a}^\dagger \hat{a} + \frac{\omega_a}{2}\hat{\sigma}_z + i g_{ac}(\hat{\sigma}_+ \hat{a} - \hat{\sigma}_- \hat{a}^\dagger)$ for $\omega_a = \omega_c$

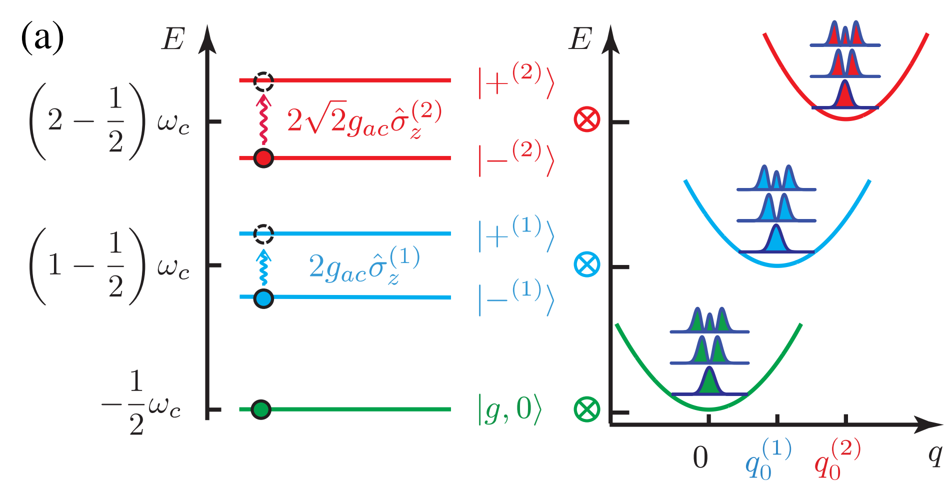
$\hat{H}_{\text{JC}}|\pm^{(n)}\rangle = \omega_\pm^{(n)}|\pm^{(n)}\rangle$ with $\omega_\pm^{(n)} = [(n-1/2)\omega_c \pm \frac{\Omega^{(n)}}{2}]$ and $\Omega^{(n)} = 2\sqrt{n}g_{ac}$

Eigenstates are polaritons: $|\pm^{(n)}\rangle = (1/\sqrt{2})\,(|g, k=n\rangle \pm i|e, k=n-1\rangle)$

pho-bit

qu-ton

$$\hat{H}_{\text{tot}} = \sum_{n\in\mathbb{N}} \Big\{ (n-1/2)\omega_c \mathbb{1}^{(n)} + \frac{\Omega^{(n)}}{2}\hat{\sigma}_z^{(n)} - g_{cm}\Big(\underbrace{\frac{1}{2}\hat{\sigma}_x^{(n)}}_{\text{coupling}} + \underbrace{\Big(n-\frac{1}{2}\Big)\mathbb{1}^{(n)}}_{\text{displacement}}\Big)(\hat{b}+\hat{b}^\dagger)\Big\} + \omega_m \hat{b}^\dagger \hat{b}, \qquad (2)$$



$$q_0^{(n)} = \sqrt{2}g_{cm}(n-1/2)/\omega_m$$

displaced position

Atom-cavity-mechanics polaritons

$$\hat{H}_{\text{tot}} = \sum_{n\in\mathbb{N}}\left\{(n-1/2)\omega_c \mathbb{1}^{(n)} + \frac{\Omega^{(n)}}{2}\hat{\sigma}_z^{(n)} - g_{cm}\left(\frac{1}{2}\hat{\sigma}_x^{(n)} + \left(n-\frac{1}{2}\right)\mathbb{1}^{(n)}\right)(\hat{b}+\hat{b}^\dagger)\right\} + \omega_m \hat{b}^\dagger \hat{b}, \tag{2}$$

$$\hat{H}^{(n)} = \frac{\Omega^{(n)}}{2}\hat{\sigma}_z^{(n)} + \omega_m \hat{b}_n^\dagger \hat{b}_n - \frac{g_{cm}}{2}(\hat{\sigma}_-^{(n)}\hat{b}_n^\dagger + \hat{\sigma}_+^{(n)}\hat{b}_n) \quad \text{RWA}$$

$$\cancel{- g_{cm}\frac{\sqrt{2}}{2}q_0^{(n)}\hat{\sigma}_x^{(n)}} + \left(\omega_0^{(n)} - \frac{\omega_m}{2}q_0^{(n)^2}\right)\mathbb{1}^{(n)}, \tag{3}$$

$$g_{cm} \ll \omega_m$$

$$q_0^{(n)} = \sqrt{2}g_{cm}(n-1/2)/\omega_m$$

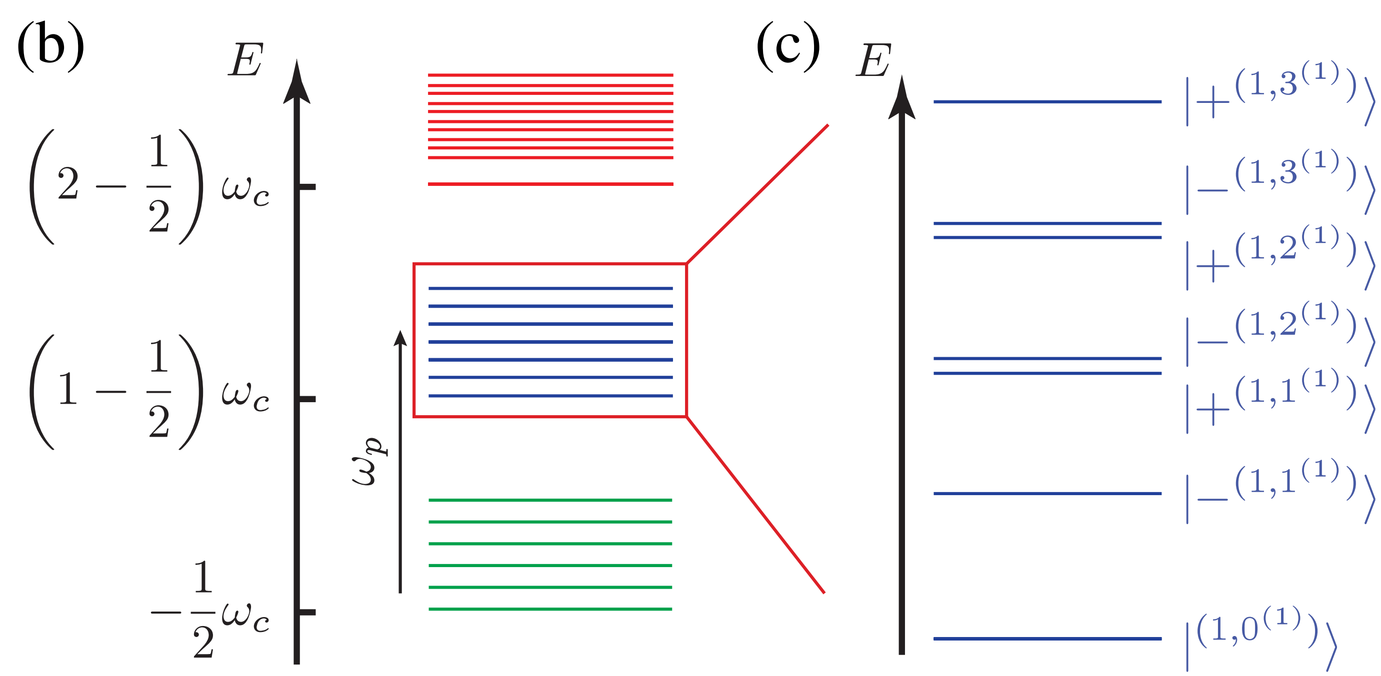
displaced position

effective Jaynes-Cummings model

$m^{(n)}$ new effective polaron number

n previous polariton number

Atom-cavity-mechanics polaritons



$$\hat{H}^{(n)}|\pm^{(n,m^{(n)})}\rangle = \omega_0^{(n)} - \frac{\omega_m}{2} q_0^{(n)^2} + \left(m - \frac{1}{2}\right)\omega_m \pm \nu^{(n,m)}, \quad (4)$$

where

$$\nu^{(n,m)} = \sqrt{\left(\frac{\Omega^{(n)} - \omega_m}{2}\right)^2 + \frac{m^{(n)}}{4} g_{cm}^2}. \quad (5)$$

effective Jaynes-Cummings model

$m^{(n)}$ new effective polaron number

n previous polariton number

Master equation

$$\frac{d\hat{\rho}(t)}{dt} = -i[\hat{H}_{\mathrm{tot}} + \hat{V}_p(t), \hat{\rho}] + \gamma_{ac} L[\hat{a}]\hat{\rho} + \gamma_{ac} L[\hat{\sigma}_-]\hat{\rho}$$
$$+ n_{\mathrm{th}}\gamma_m L[\hat{b}^\dagger]\hat{\rho} + (n_{\mathrm{th}} + 1)\gamma_m L[\hat{b}]\hat{\rho}, \qquad (6)$$

$$\hat{V}_p(t) = iF_p(\hat{a}^\dagger e^{i\omega_p t} - \hat{a} e^{-i\omega_p t})$$

coherent drive

$$L[\hat{o}]\hat{\rho} = \hat{o}\,\hat{\rho}\,\hat{o}^\dagger - \tfrac{1}{2}(\hat{o}^\dagger \hat{o}\,\hat{\rho} + \hat{\rho}\hat{o}^\dagger \hat{o})$$

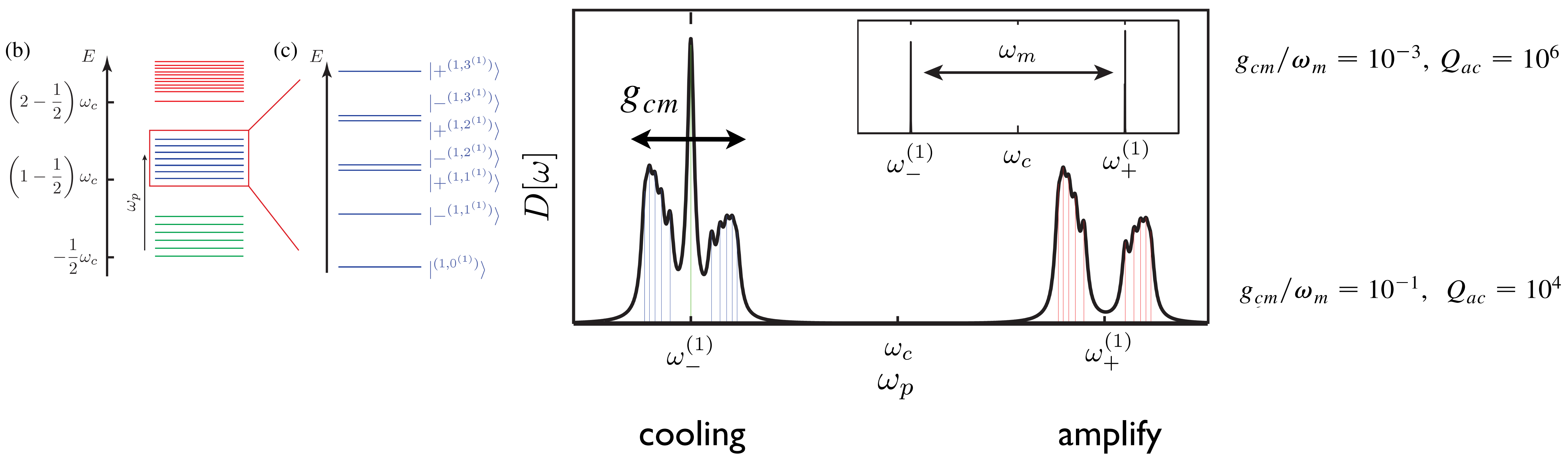
Simulation parameters (photon blockade regime):
$\omega_c/\omega_m = 10^2$, $\omega_a = \omega_c$, $g_{ac}/\omega_m = 1/2$, $g_{cm}/\omega_m = 10^{-1}$, $Q_m = \omega_m/\gamma_m = 10^4$, $Q_{ac} = \omega_{a,c}/\gamma_{ac} = 10^4$, $F_p/\gamma_{ac} = 1$, and $n_{\mathrm{th}} = 3.45$.

$$|g, k = 0\rangle\langle g, k = 0| \otimes \hat{\rho}_m$$

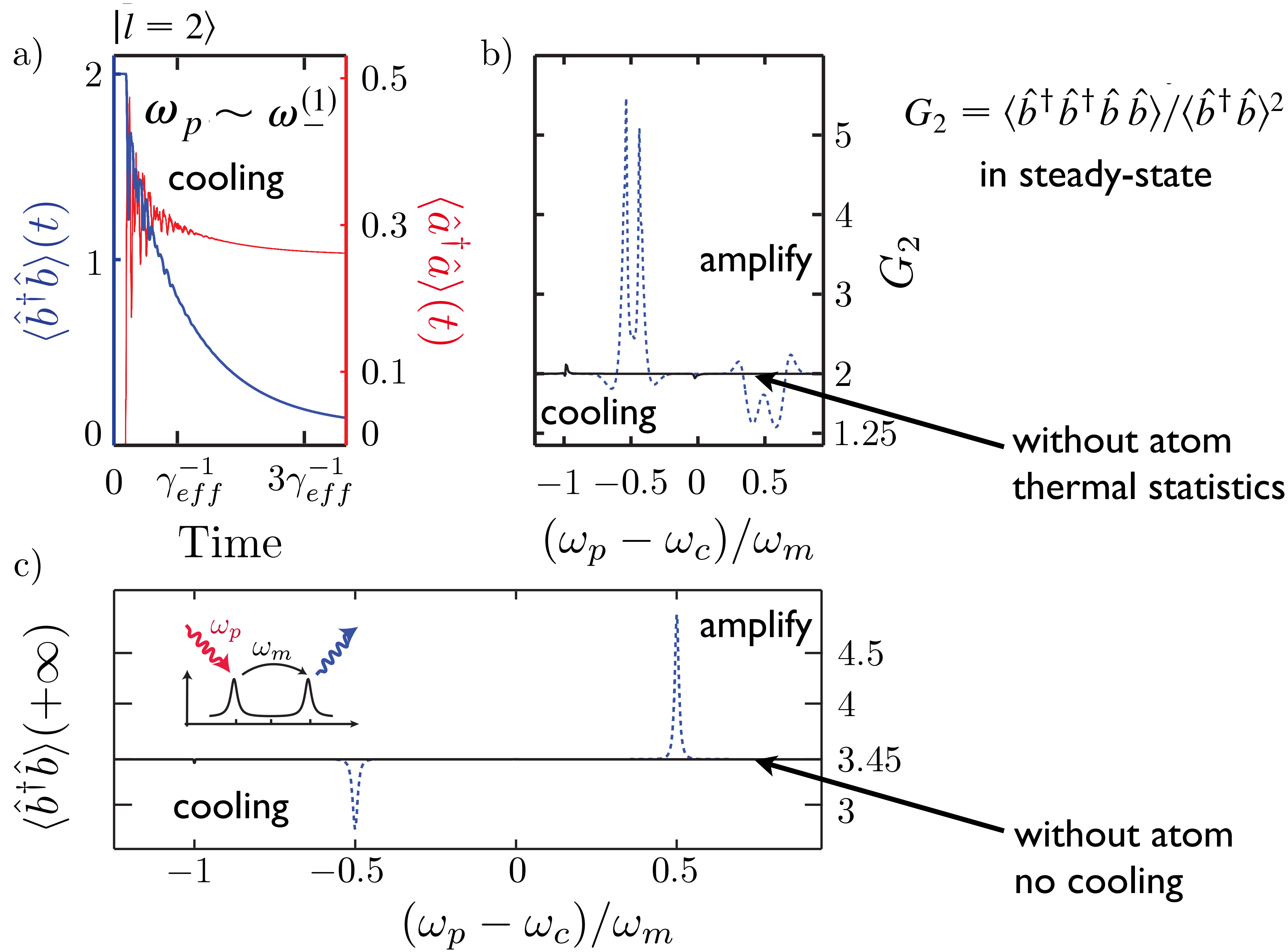
initial state

Density of states

$$D[\omega] = \sum_{\substack{s',s=\pm \\ m',m\in\mathbb{N}}} |\langle s'^{(1,m')}|\hat{V}_p|s^{(0,m)}\rangle|^2 \delta(\omega - (\omega_{s'^{(1,m')}} - \omega_{s^{(0,m)}})). \tag{7}$$



Atom-assisted cooling



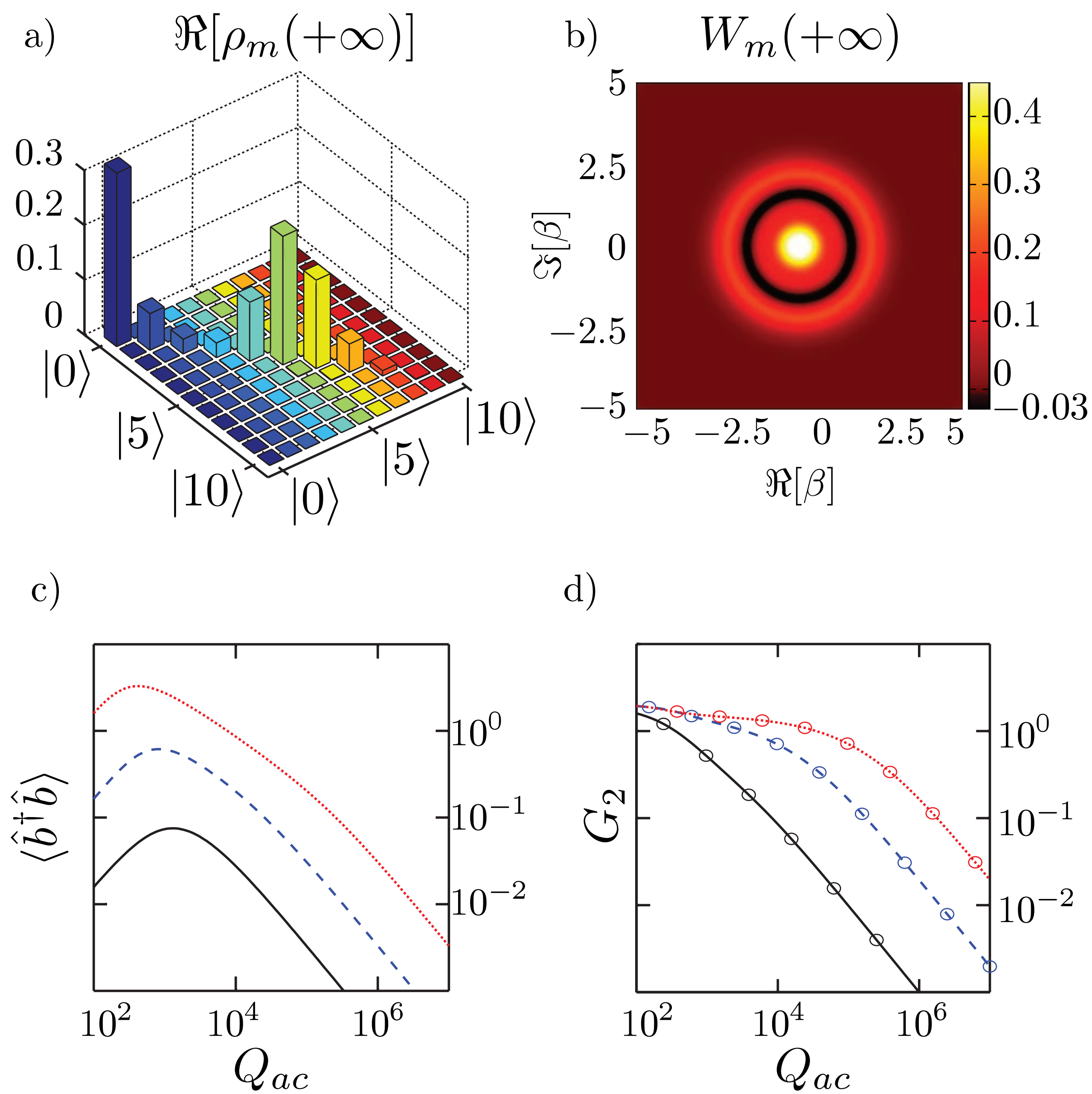
Mechanical steady-state

$\omega_p \sim \omega_+^{(1)}$

amplify

coherent pump

non-classical mechanical steady-states



$$Q_m = 10^1,\ 10^2,\ \text{and}\ 10^3$$

$\omega_p \sim \omega_+^{(1)}$

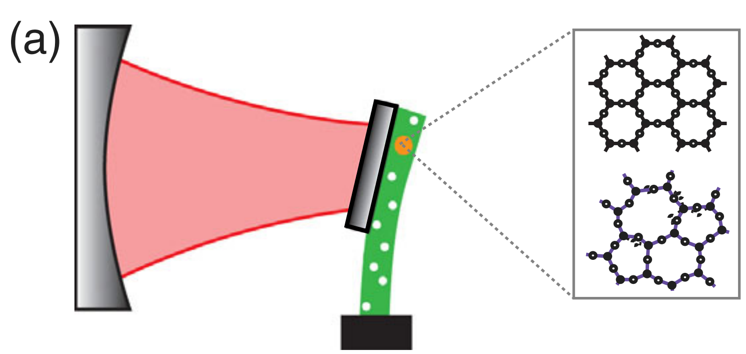
amplify

incoherent pump

excitation of polarons and emission of phonons with sub-Poissonian statistics

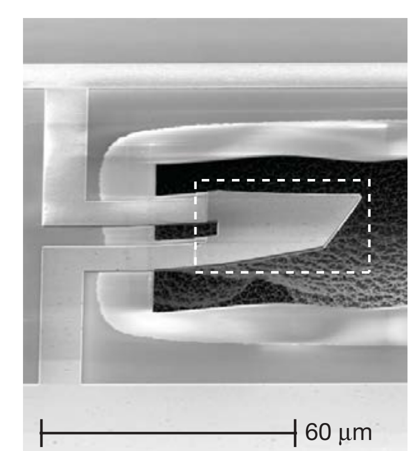
Conclusions

- atom-cavity-mechanics polaron eigenstates
- atom enhances single-phonon cooling
- atom leads to strong bunching of phonons
- atom yields non-classical mechanical states
- atom leads to single-phonon emission



defects in silica toroids

GaAs resonators



microwave resonators