Quantum Simulations and Quantum Devices

N-phonon bundle emission via the anti-Stokes process

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Outline

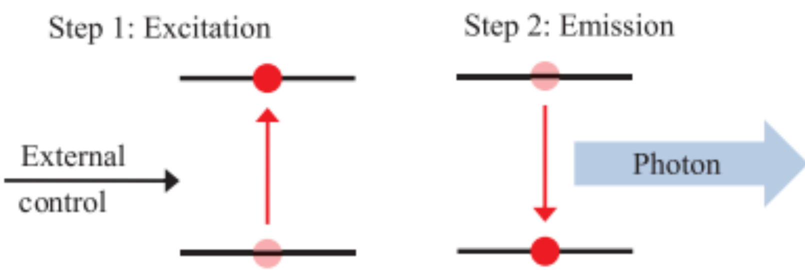
1) Background-bundle emission

2) Anti-Stokes resonance induced Super Rabi oscillation

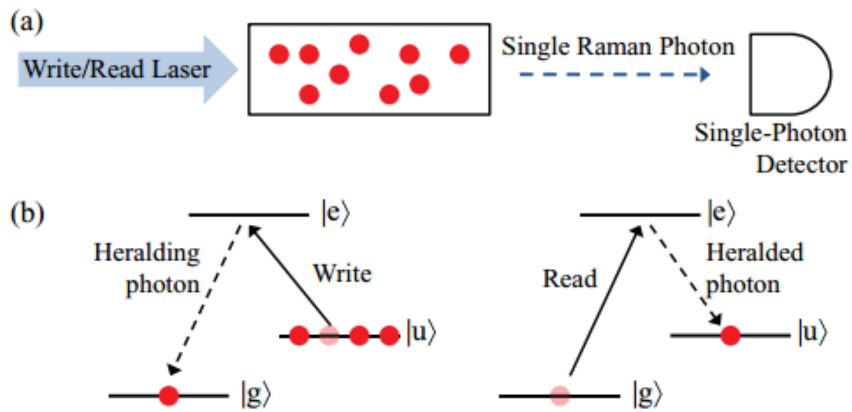
3) N-phonon bundle emission with high purity

4) Conclusions

Single photon emission



Single emitter system

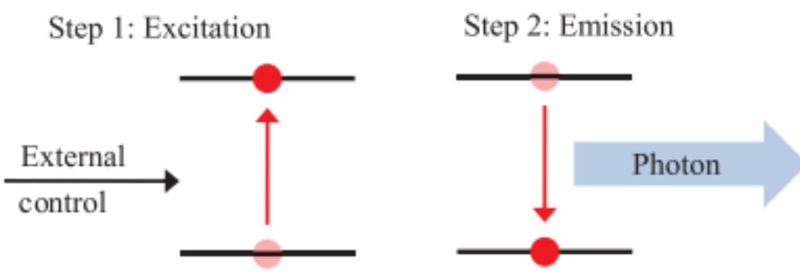


Ensemble-based emitter scheme

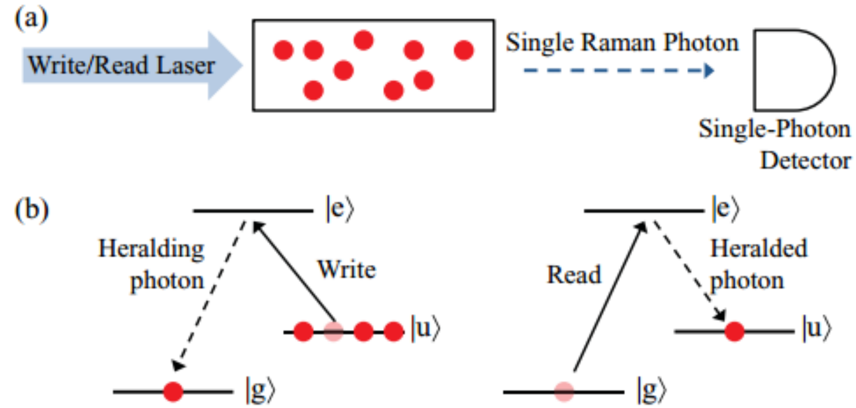
Fock state $|1\rangle$ $\quad$ $\mathrm{Var} = 0$ $\quad$ $g^2(0) = 0$

M. D. Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011)

Single photon emission



Single emitter system



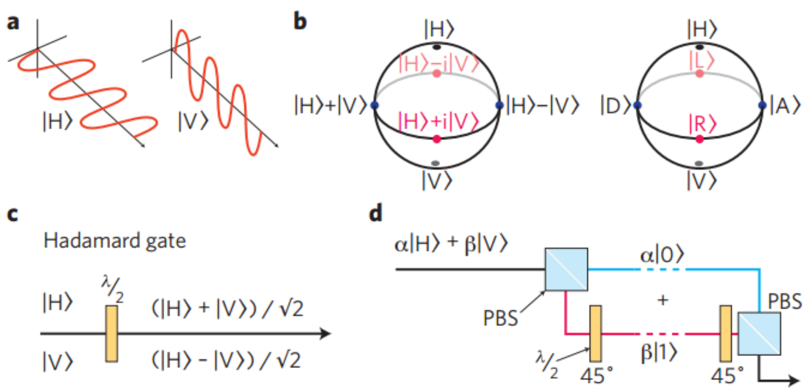
Ensemble-based emitter scheme

Fock state $|1\rangle$ $\mathrm{Var} = 0$ $g^2(0) = 0$

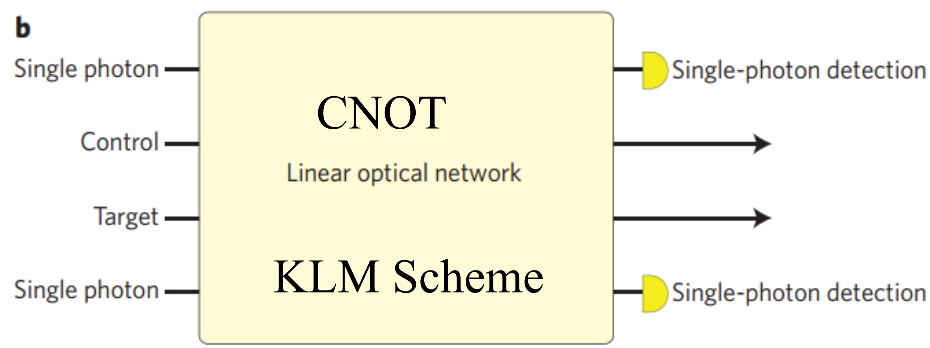
M. D. Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011)

Applications in quantum information science

Quantum Communication



Quantum Computation

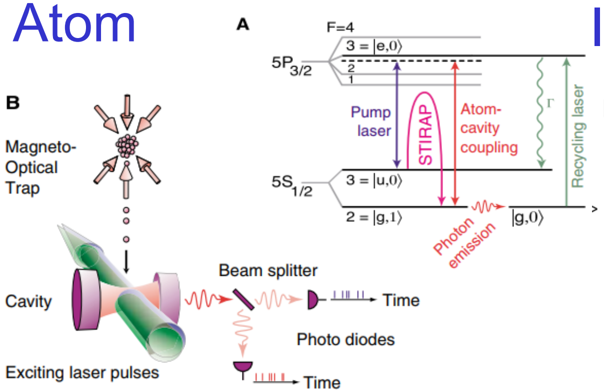


J. L. O'Brien, A. Furusawa and J. Vučković, Nature Photonics 3 , 687–695 (2009)

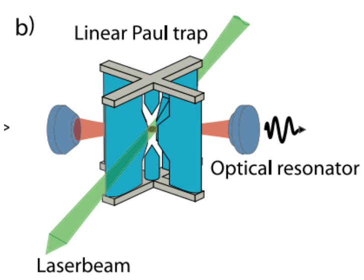
Purcell effect enhancing emission rate

M. D. Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011)

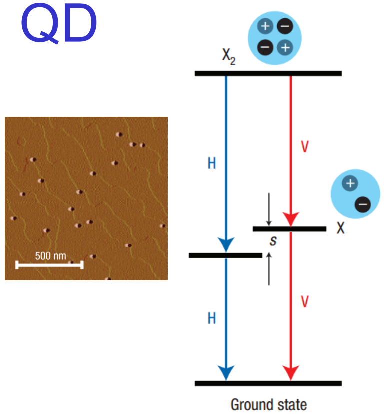
Atom



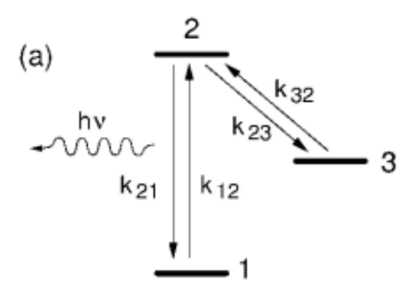
Ions



QD



NV



A. Kuhn et al. PRL 89, 067901 (2002)

C. Maurer et al., NJP 6, 94 (2004).

A. J. Shields, Nature Photon. 1, 215 (2007)

C. Kurtsiefer et al., PRL 85, 290 (2000)

Purcell effect enhancing emission rate

$$F_p = \frac{3}{4\pi^2}\left(\frac{\lambda_{free}}{n}\right)^3\left(\frac{Q}{V}\right)$$

λ_{free} : Wavelength $\quad Q$: Quality factor

n : Refractive index $\quad V$: Mode volume

Density of final states

Cavity: $\rho_c = \dfrac{1}{\Delta\nu V}$

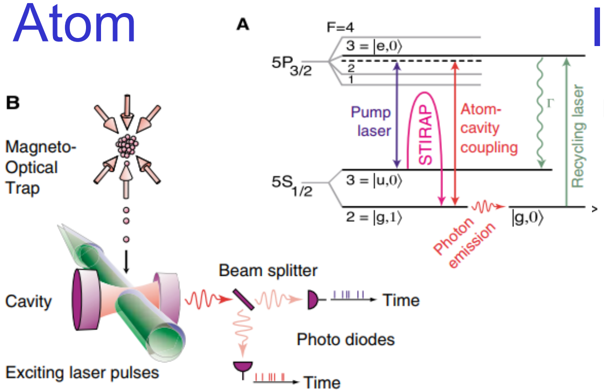
Free space: $\rho_f = \dfrac{8\pi n^3\nu^2}{c^3}$

Fermi's golden rule

$$\rho_c/\rho_f = \frac{c^3}{8\pi n^3\nu^2}\frac{Q}{\nu V} = \frac{1}{8\pi}\left(\frac{\lambda_{free}}{n}\right)^3\left(\frac{Q}{V}\right)$$

M. D. Eisaman et al., Rev. Sci. Instrum. 82, 071101 (2011)

Atom



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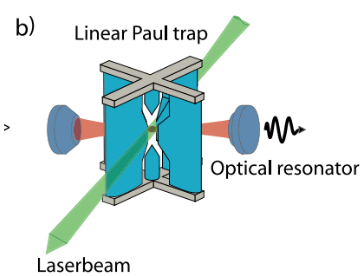
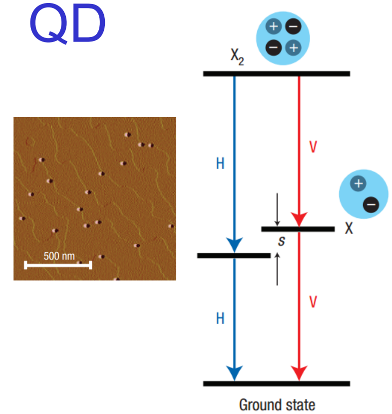
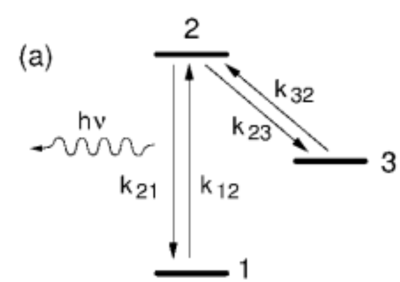


QD



NV



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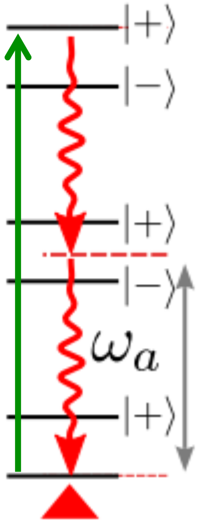
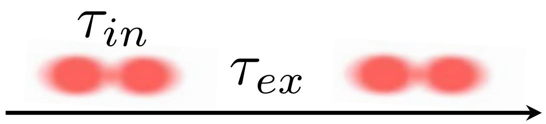
From single-photon emission to *N*-photon bundle emission





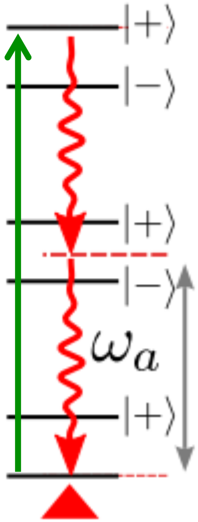
Fundamental unit of excitation

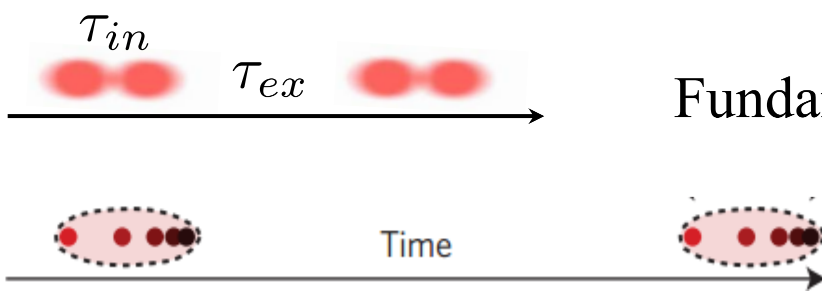
$$E = N\hbar\omega$$

Release the energy exclusively in **groups of *N* photons**

C. S. Munoz et al., Nat. Photonics 8, 550 (2014); Y. Chang et al., Phys. Rev. Lett. 117, 203602 (2016)

From single-photon emission to N-photon bundle emission





Fundamental unit of excitation

$$E = N\hbar\omega$$

Release the energy exclusively in **groups of N photons**

Expanding Glauber's theory by replacing the **photon** with **bundle** of N photons

$$g_N^{(n)}(t_1, \dots, t_n) = \frac{\langle \mathcal{T}_-\{\Pi_{i=1}^n a^{\dagger N}(t_i)\}\mathcal{T}_+\{\Pi_{i=1}^n a^N(t_i)\}\rangle}{\Pi_{i=1}^n \langle a^{\dagger N} a^N\rangle(t_i)} \qquad \tau_{ex} \gg \tau_{in}$$

$$g_N^{(2)}(\tau) = \frac{\langle a^{\dagger N}(0) a^{\dagger N}(\tau) a^N(\tau) a^N(0)\rangle}{\langle (a^{\dagger N} a^N)(0)\rangle \langle (a^{\dagger N} a^N)(\tau)\rangle}$$

C. S. Munoz et al., Nat. Photonics 8, 550 (2014); Y. Chang et al., Phys. Rev. Lett. 117, 203602 (2016)

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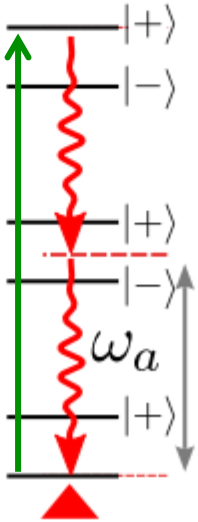

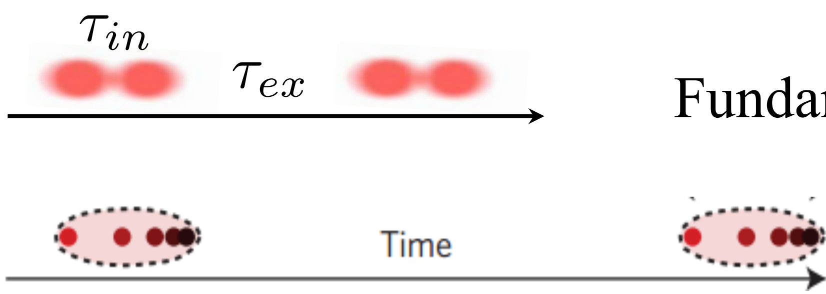

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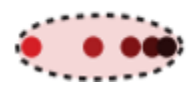
$$\tau_{ex} \gg \tau_{in}$$



Bunching

$$g_N^{(2)}(\tau) = \frac{\langle a^{\dagger N}(0)a^{\dagger N}(\tau)a^N(\tau)a^N(0)\rangle}{\langle (a^{\dagger N}a^N)(0)\rangle\langle (a^{\dagger N}a^N)(\tau)\rangle} \xrightarrow{N=1} g^{(2)}(\tau) = \frac{\langle a^\dagger(0)a^\dagger(\tau)a(\tau)a(0)\rangle}{\langle (a^\dagger a)(0)\rangle\langle (a^\dagger a)(\tau)\rangle}$$

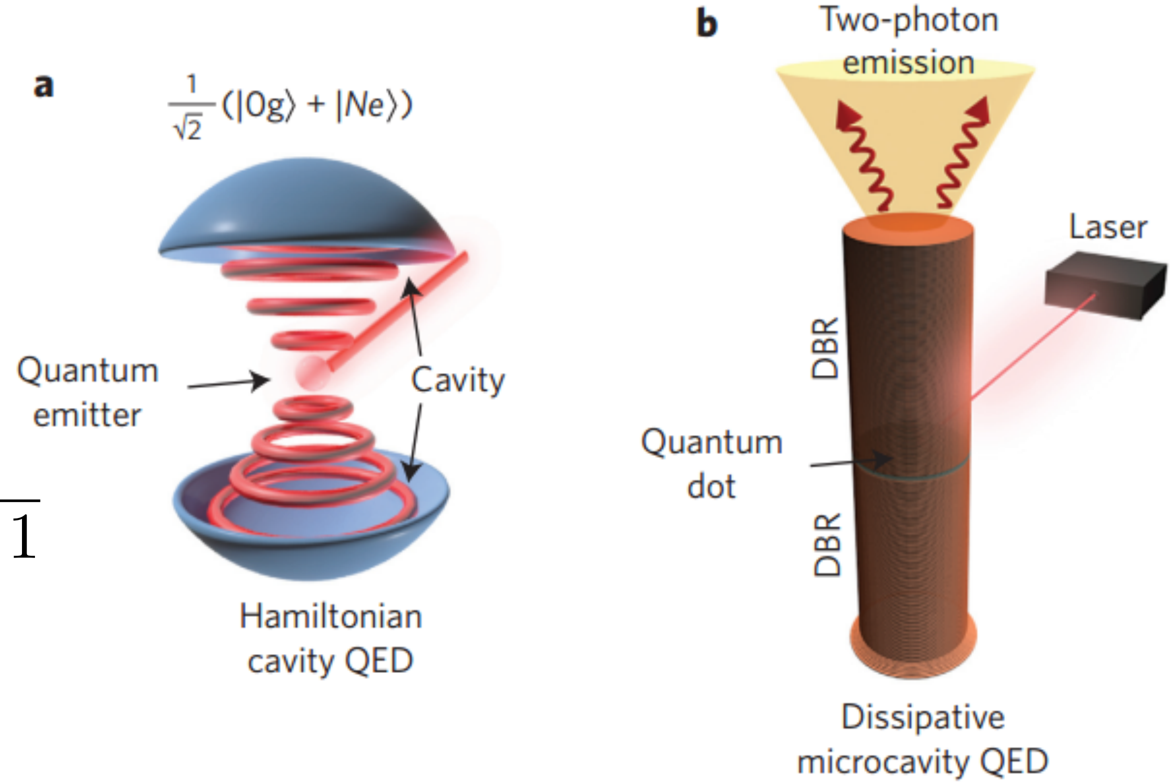
C. S. Munoz et al., Nat. Photonics 8, 550 (2014); Y. Chang et al., Phys. Rev. Lett. 117, 203602 (2016)

N-photon bundle emission-coherent

Cavity QED system

Dispersive regime

$$|\omega_a - \omega_\sigma| \gg g\sqrt{N+1}$$



Hamiltonian

$$H = \omega_a a^\dagger a + \omega_\sigma \sigma^\dagger \sigma + g(a^\dagger \sigma + \sigma^\dagger a) + \Omega(\sigma^\dagger e^{-i\omega_L} + \sigma e^{i\omega_L})$$

C. S. Munoz et al., Nat. Photonics 8, 550 (2014) D. V. Strekalov, Nat. Photonics 8, 500 (2014)

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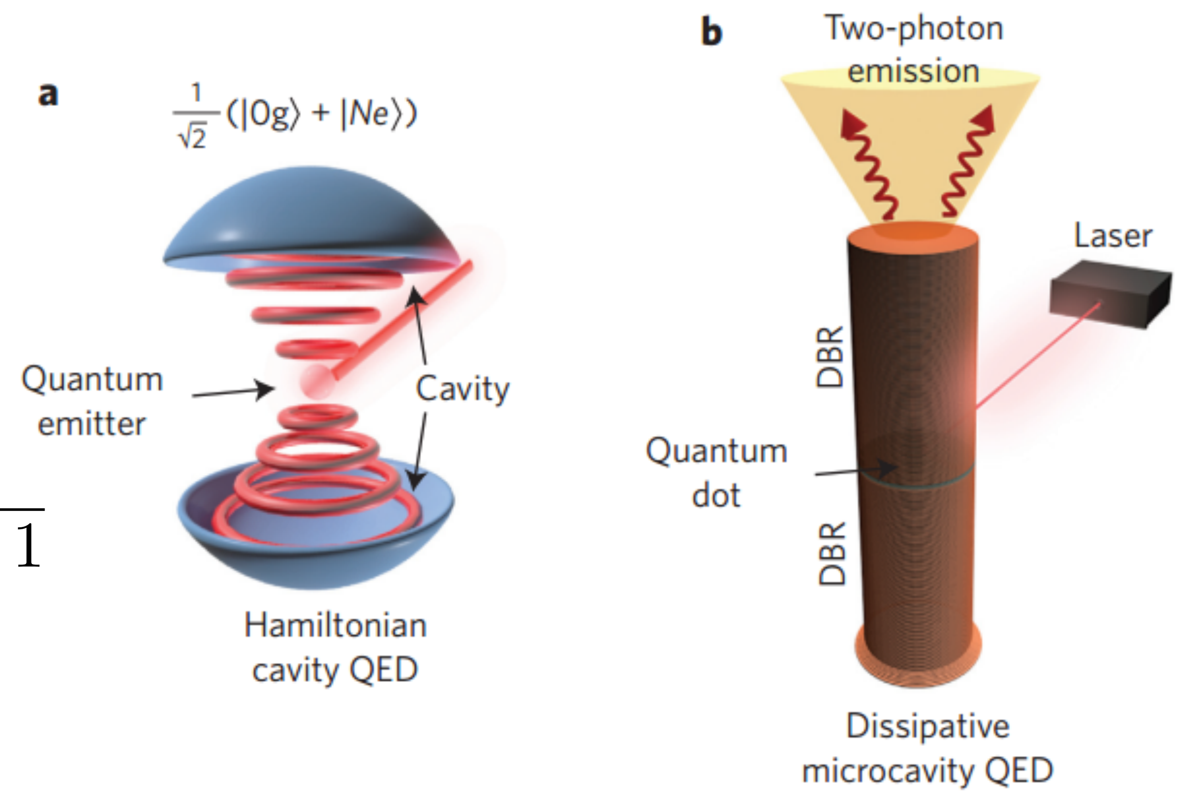


Hamiltonian

$$H = \omega_a a^\dagger a + \omega_\sigma \sigma^\dagger \sigma + g(a^\dagger \sigma + \sigma^\dagger a) + \Omega(\sigma^\dagger e^{-i\omega_L} + \sigma e^{i\omega_L})$$

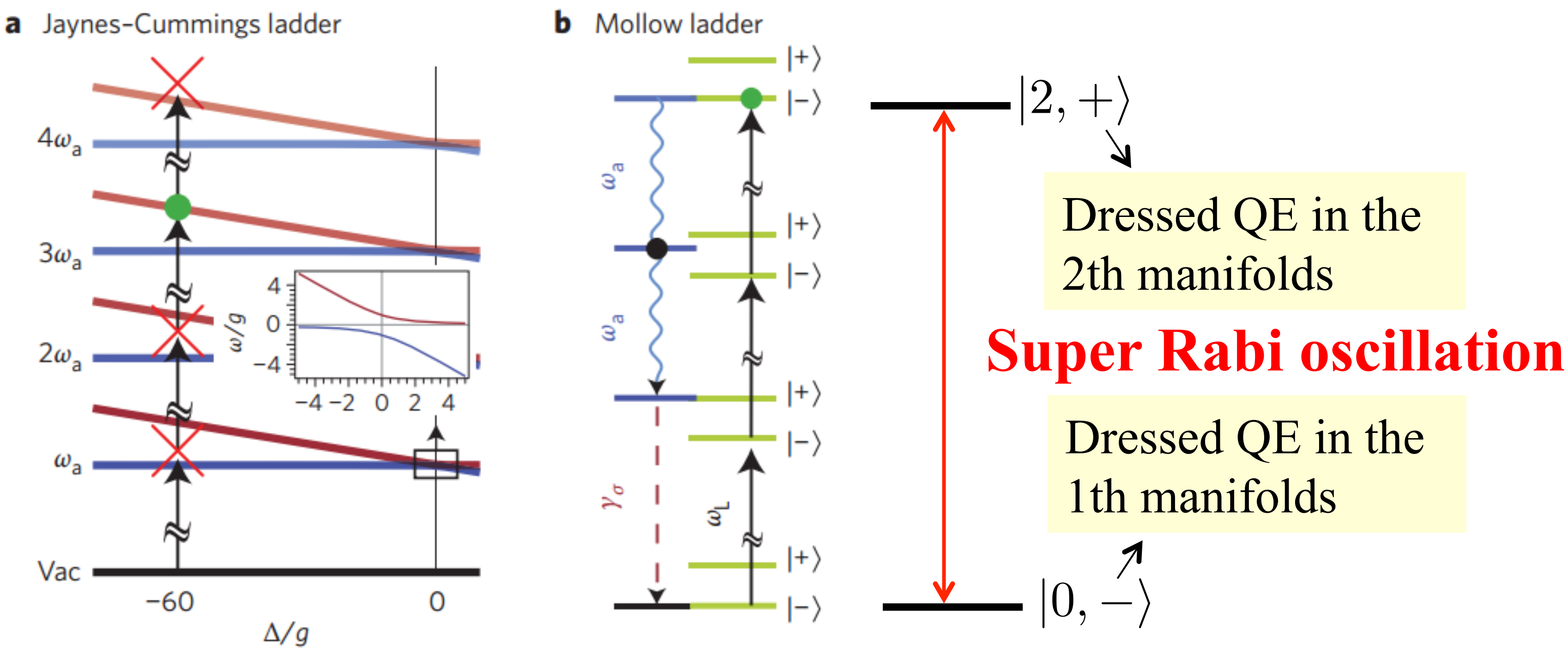
Super Rabi oscillation + **Dissipation Window**

$|0, g\rangle \leftrightarrow |N, e\rangle$ or $|0, -\rangle \leftrightarrow |N, +\rangle$

$\mathcal{L}[a] + \mathcal{L}[\sigma]$

C. S. Munoz et al., Nat. Photonics 8, 550 (2014) D. V. Strekalov, Nat. Photonics 8, 500 (2014)

N-photon bundle emission-coherent



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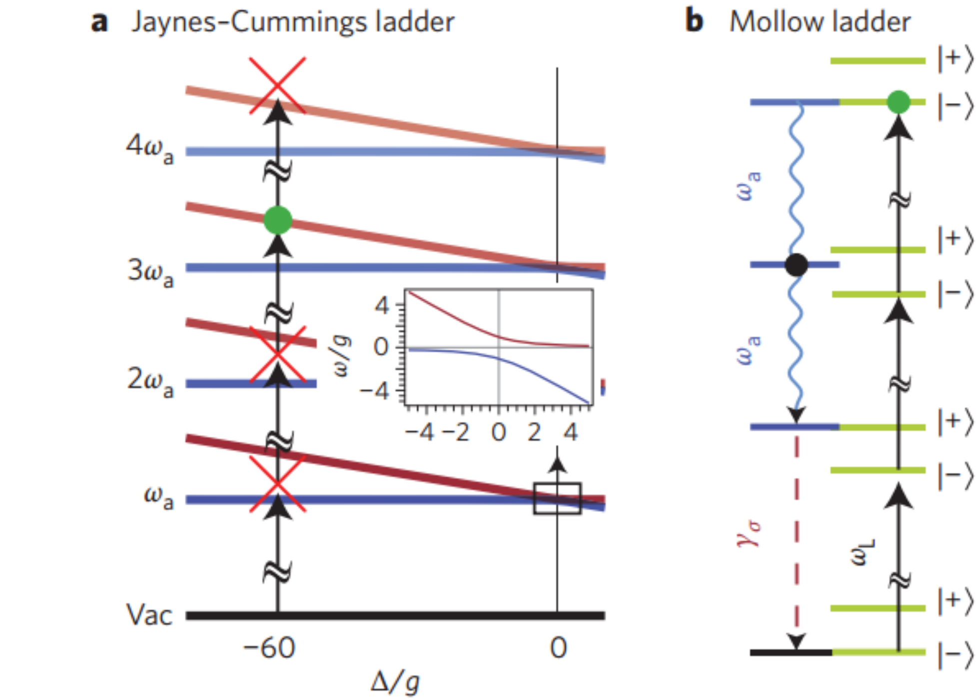
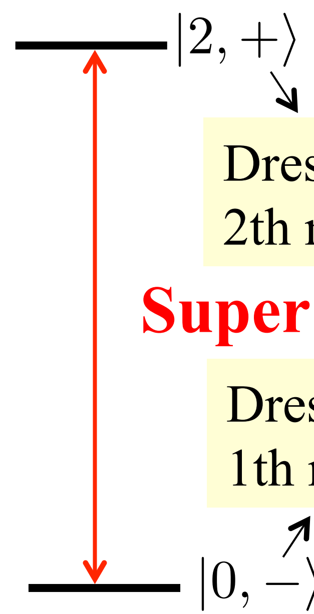
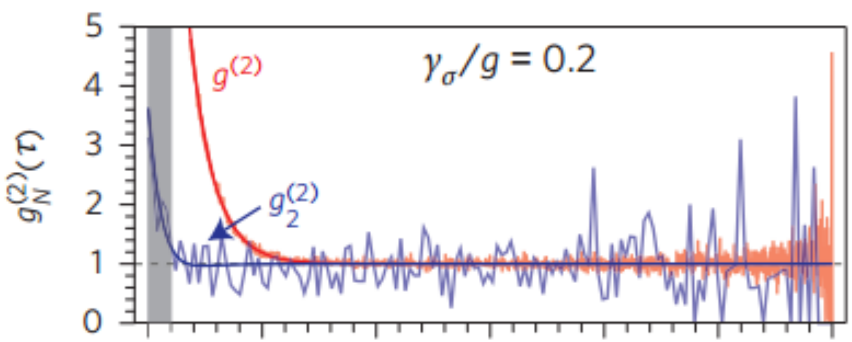




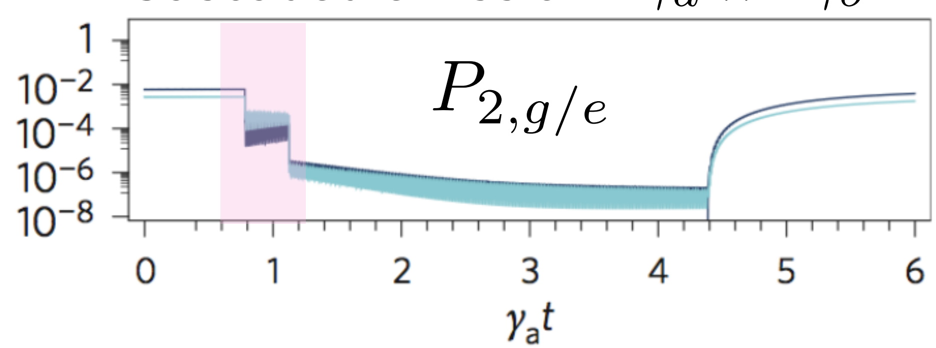
Dressed QE in the 2th manifolds

Super Rabi oscillation

Dressed QE in the 1th manifolds

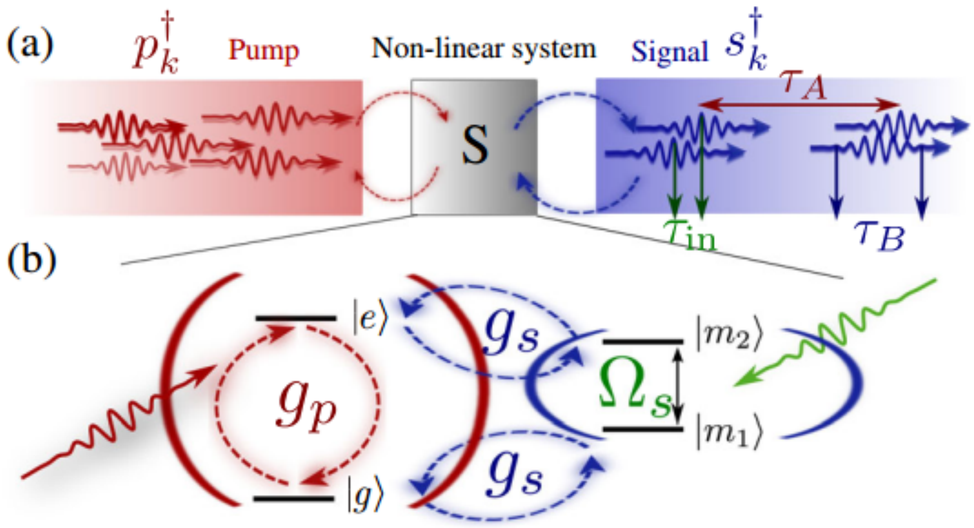


Cascaded emission $\gamma_a \gg \gamma_\sigma$



C. S. Munoz et al., Nat. Photonics 8, 550 (2014) D. V. Strekalov, Nat. Photonics 8, 500 (2014)

N-photon bundle emission-antibunching in bad-cavity limit



N-photon source

$$g^{(2)}(0) \gg 1$$

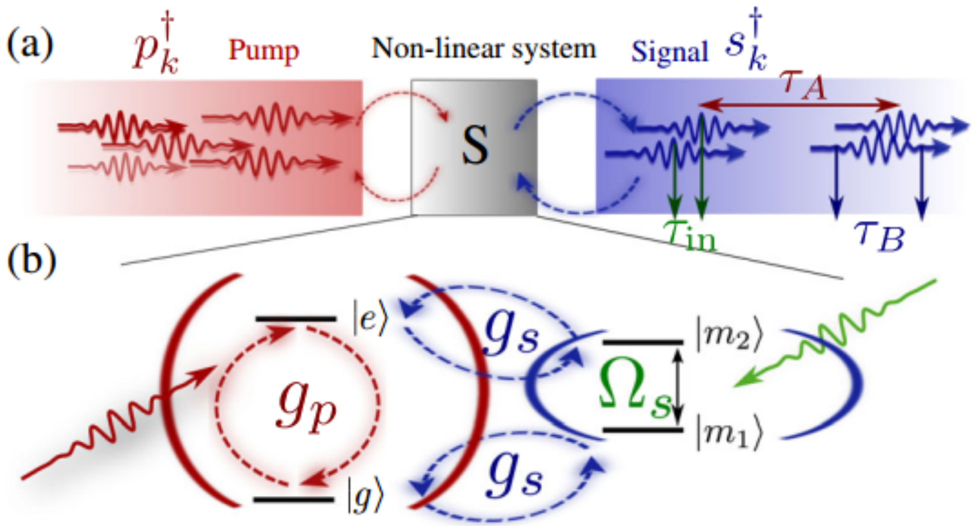
$$g_N^{(2)}(0) < g_N^{(2)}(\tau)$$

$$g_N^{(2)}(0) \to 0$$

$$H = g_p a_p^\dagger |g\rangle\langle e| + \Omega_s |m_2\rangle\langle m_1| + g_s a_s^\dagger (|m_2\rangle\langle e| + |g\rangle\langle m_1|) + H.c.$$

Y. Chang, A. G.-Tudela, C. S. Muñoz, C. N.-Benlloch, and T. Shi, Phys. Rev. Lett. 117, 203602 (2016)

N-photon bundle emission-antibunching in bad-cavity limit



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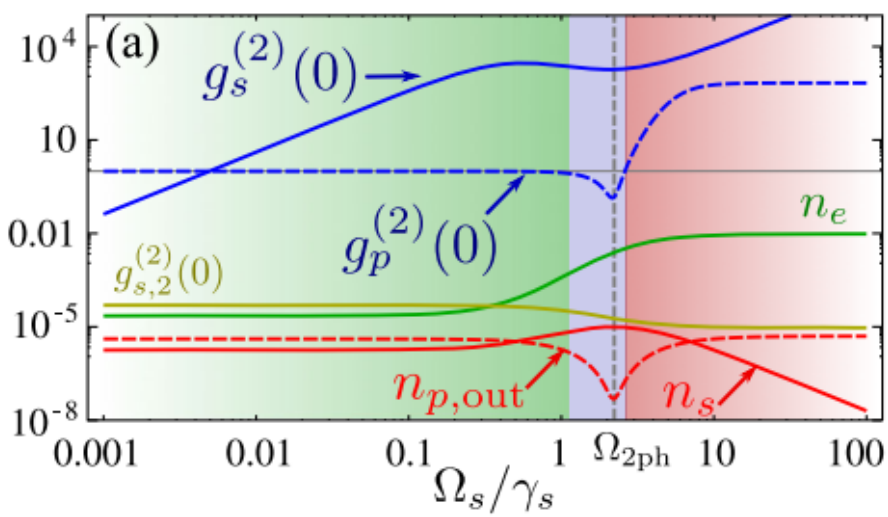
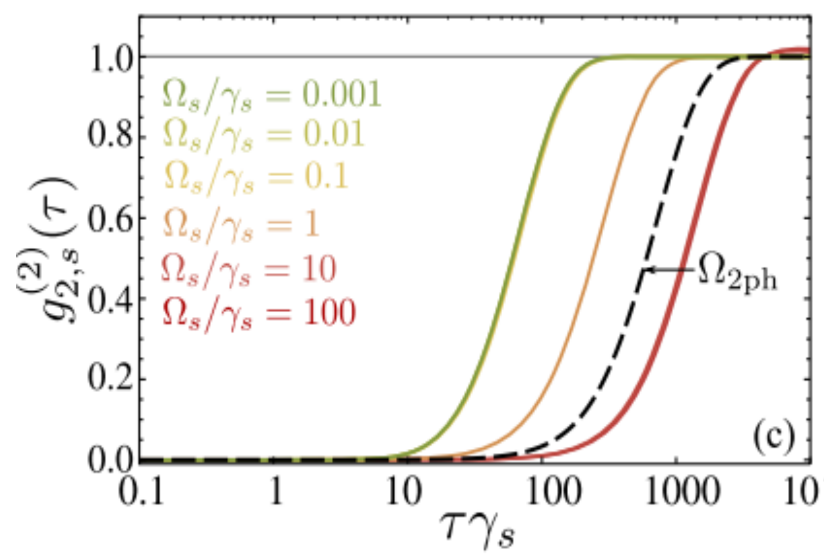
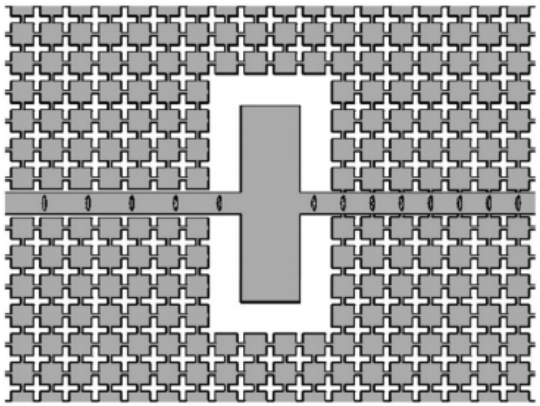




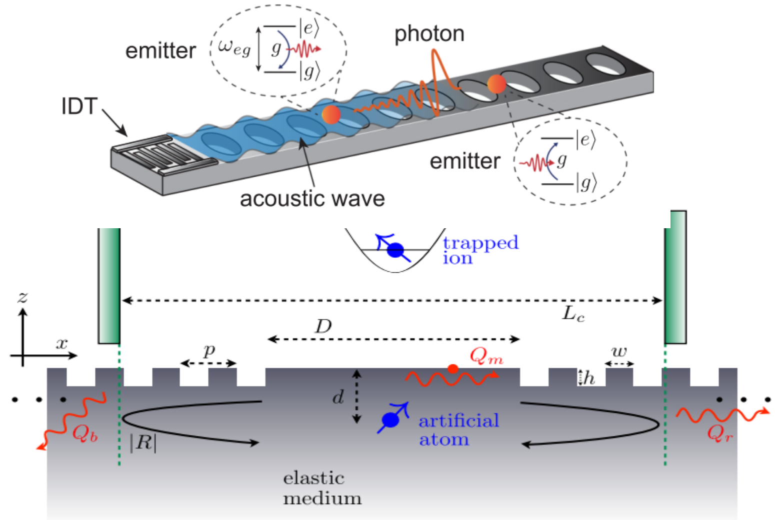
Y. Chang, A. G.-Tudela, C. S. Muñoz, C. N.-Benlloch, and T. Shi, Phys. Rev. Lett. 117, 203602 (2016)

From photon to phonon



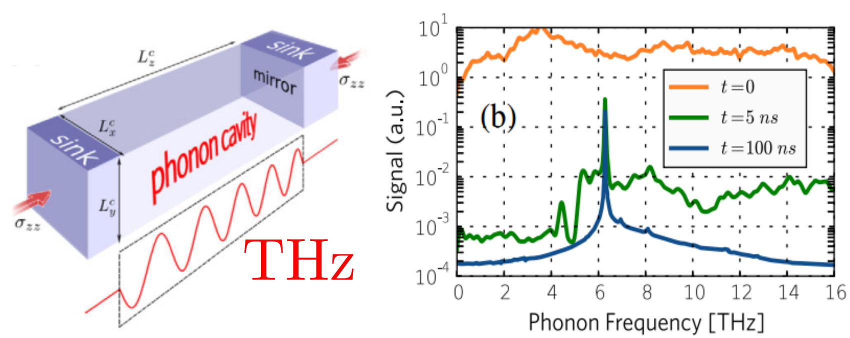
On-Chip Communication

C. Kuzyk and H. L. Wang, Phys. Rev. X 8, 041027 (2018)

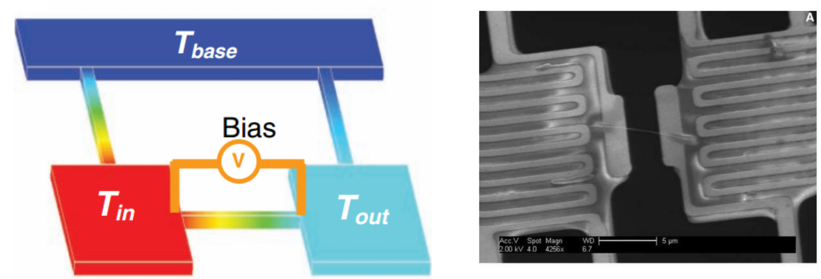


Phonon-photon Hybrid networks

M. J. A. Schuetz et al., Phys. Rev. X 5, 031031 (2015); G. Calajó et al., Phys. Rev. A 99, 053852 (2019)



Sensing and imaging



Nanophononic devices

H. Han et al., Phys. Rev. Lett. 114, 145501 (2015); A. J. Kent et al., Phys. Rev. Lett. 96, 215504 (2006); R. Xie et al., Adv. Funct. Mater. 21, 1602 (2011); C. W. Chang et al., Science 314, 1121 (2006)

Outline

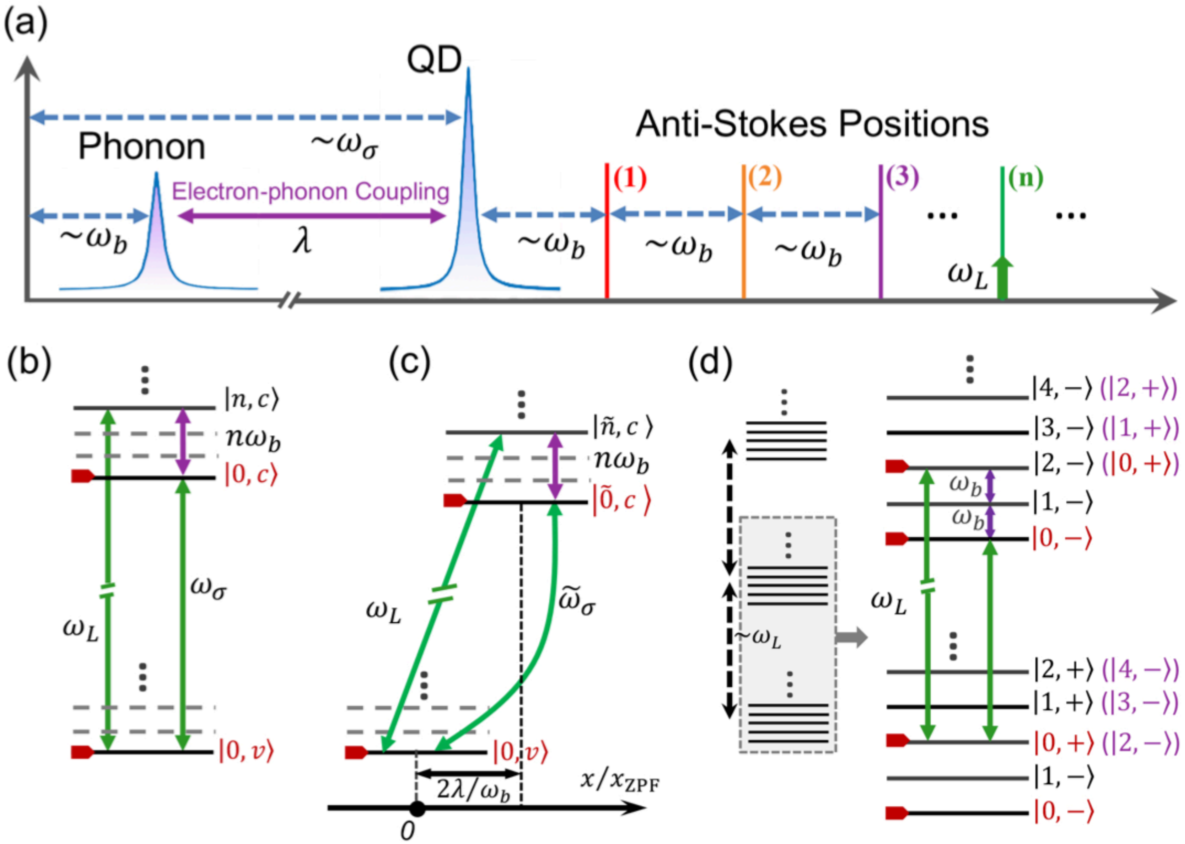
1) Background-bundle emission

2) Anti-Stokes resonance induced Super Rabi oscillation

3) N-phonon bundle emission with high purity

4) Conclusions

N-phonon Bundle Emission via the Anti-Stokes Process



$$H = \omega_b b^\dagger b + \omega_\sigma \sigma^+\sigma + \lambda\sigma^+\sigma(b^\dagger + b) + \Omega(e^{i\omega_L t}\sigma + h.c.)$$

Q. Bin, Xin-You Lü*, F. P. Laussy, F. Nori, and Y. Wu*, arXiv:1907.12714

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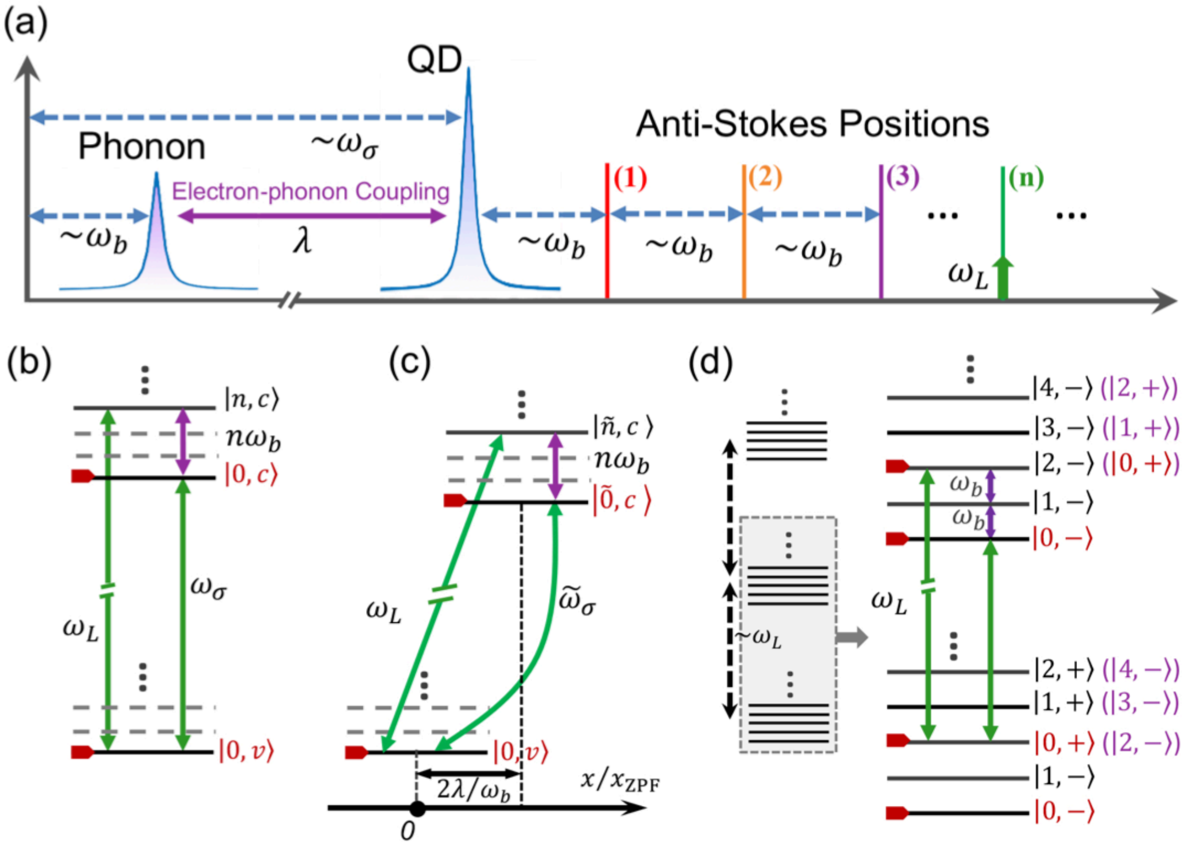


(b) Weak-driving and coupling

$$\Omega, \lambda \ll \omega_b, \omega_\sigma$$

(c) Strong coupling

$$\lambda \sim \omega_b$$

(d) Strong-driving (Mollow)

$$\Omega \sim \omega_b$$

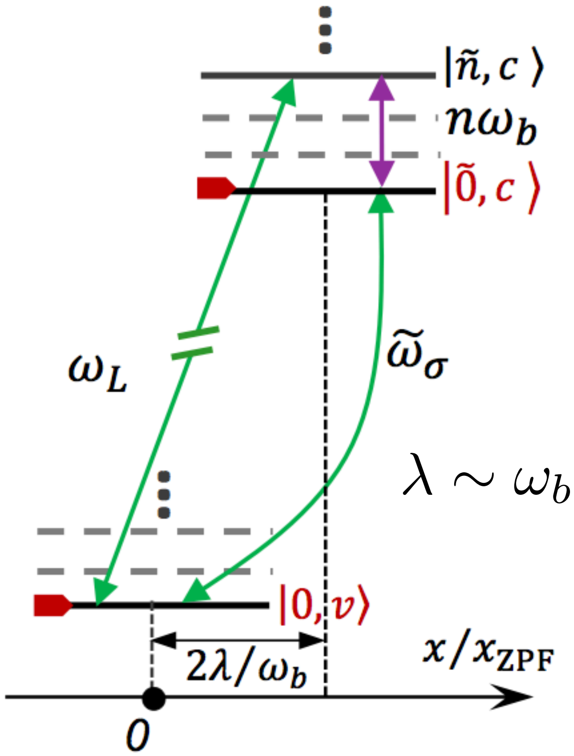
$$H = \omega_b b^\dagger b + \omega_\sigma \sigma^+ \sigma + \lambda \sigma^+ \sigma (b^\dagger + b) + \Omega(e^{i\omega_L t}\sigma + h.c.)$$

Anti-Stokes resonance ➡ Super Rabi oscillation $|0,\downarrow\rangle \leftrightarrow |n,\uparrow\rangle$

Q. Bin, Xin-You Lü*, F. P. Laussy, F. Nori, and Y. Wu*, arXiv:1907.12714

N-phonon associated Anti-Stokes resonances

(c) $\omega_L = \omega_\sigma - \lambda^2/\omega_b + n\omega_b$



$$|n,\nu\rangle, |\tilde{n}, c\rangle = D^\dagger |n, c\rangle$$

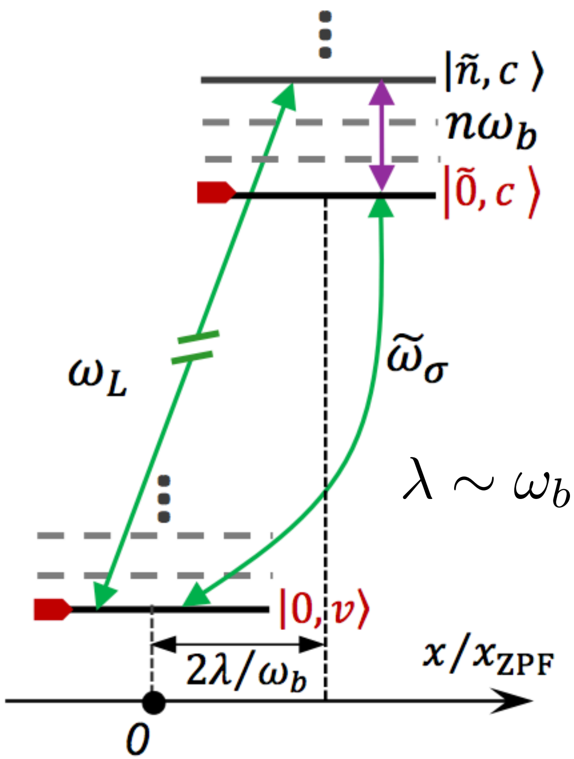
$$D = \exp[(\lambda/\omega_b)\sigma^\dagger\sigma(b^\dagger - b)]$$

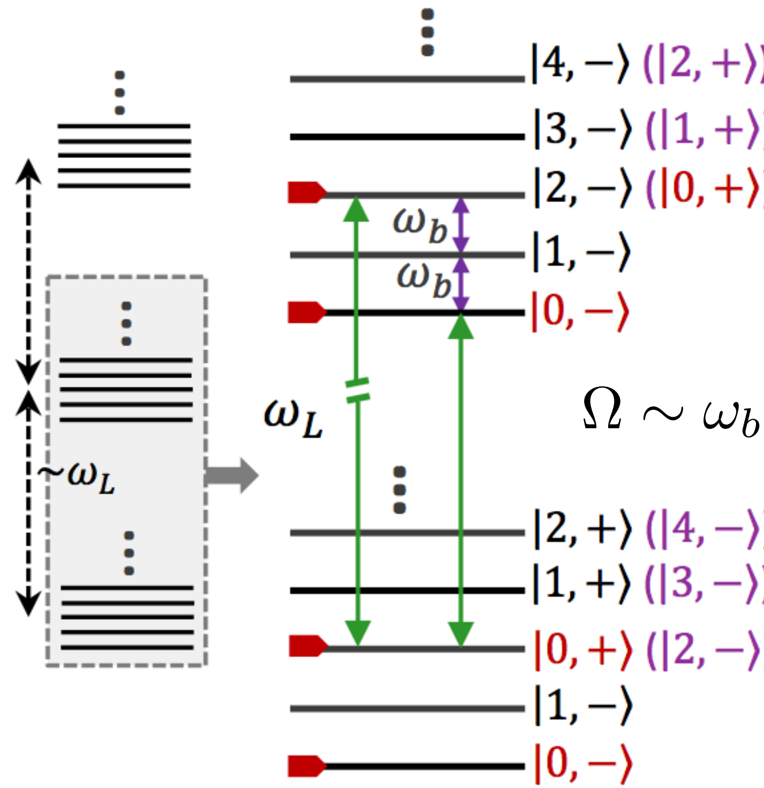
$$\tilde{\omega}_\sigma = \omega_\sigma - \lambda^2/\omega_b$$

N-phonon associated Anti-Stokes resonances

(c) $\omega_L = \omega_\sigma - \lambda^2/\omega_b + n\omega_b$

(d) $\omega_L = \omega_\sigma + \sqrt{(n\omega_b)^2 - 4\Omega^2}$





$$|n, \nu\rangle, |\tilde{n}, c\rangle = D^\dagger |n, c\rangle$$

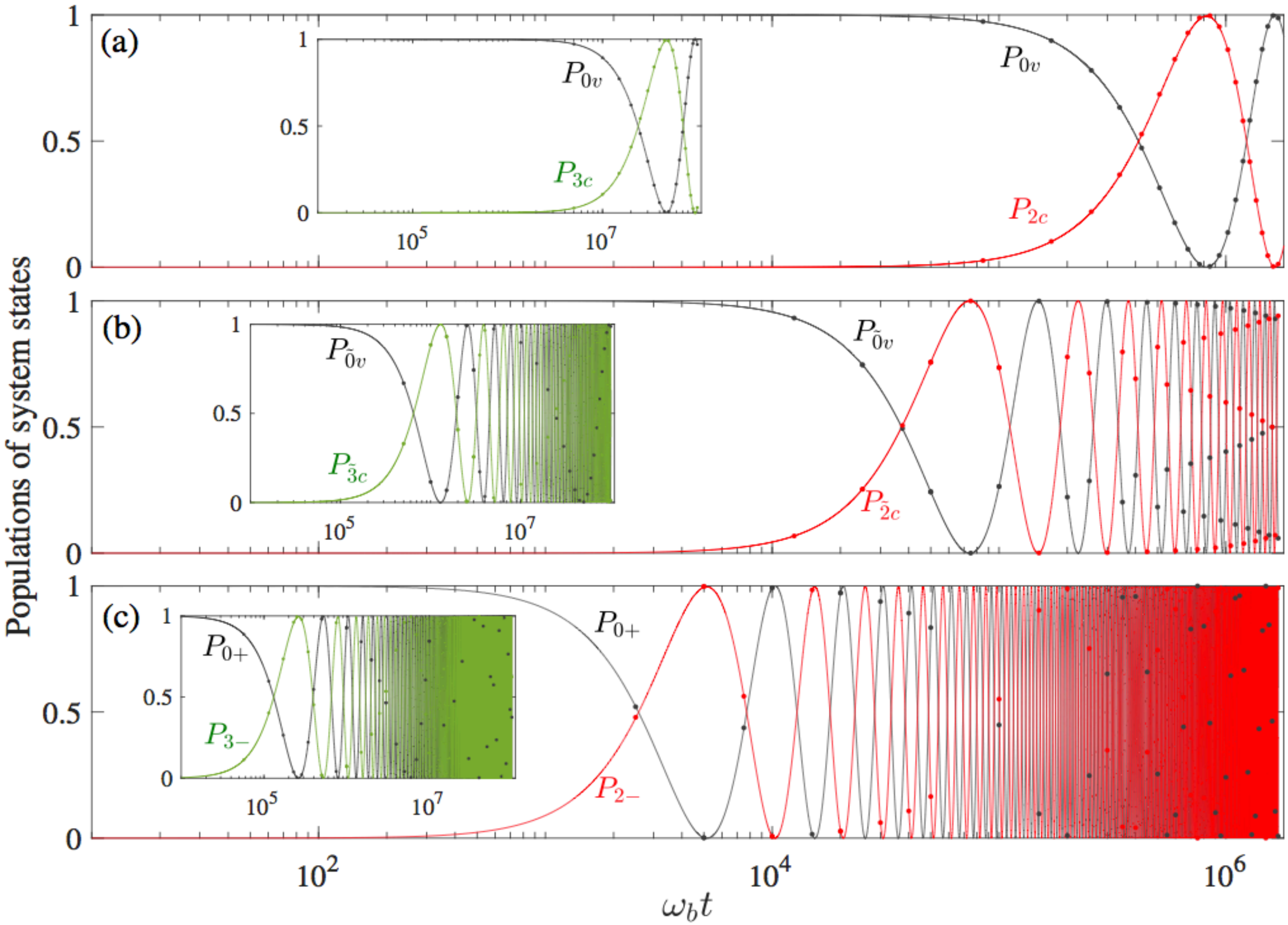
$$D = \exp[(\lambda/\omega_b)\sigma^\dagger\sigma(b^\dagger - b)]$$

$$\tilde{\omega}_\sigma = \omega_\sigma - \lambda^2/\omega_b$$

$$|n, \pm\rangle, |\pm\rangle = c_\pm |\nu\rangle \pm c_\mp |c\rangle$$

$$E_{|n,\pm\rangle} = n\omega_b + \Delta/2 \pm \sqrt{\Delta^2 + 4\Omega^2}/2$$

Super-Rabi Oscillations

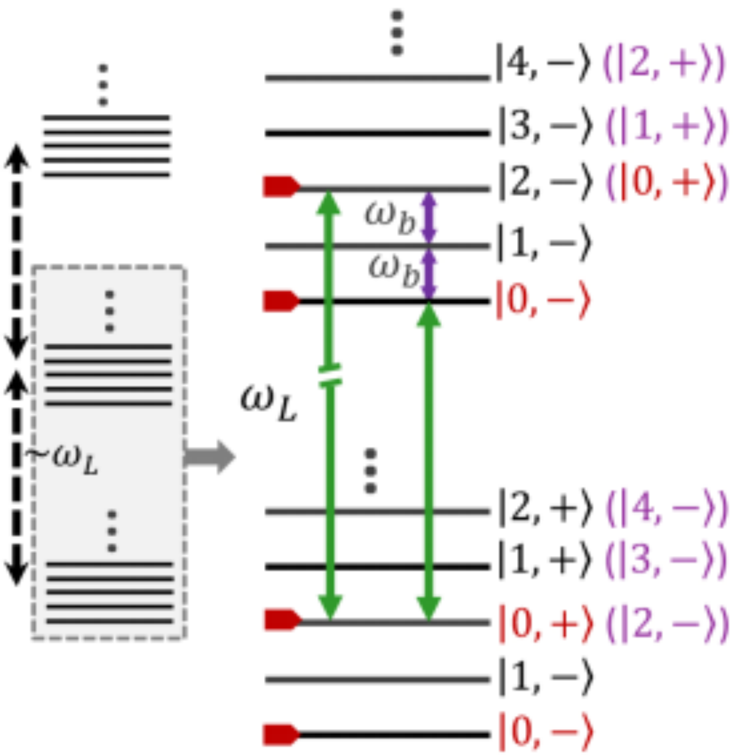


$$\Omega_{\text{eff}}^{(2)} = \frac{\sqrt{2}\Omega\lambda^2}{(2\Omega^2 - \lambda^2 + 2\omega_b^2)}$$

$$\Omega_{\text{eff}}^{(2)} = \frac{\Omega\lambda^2}{\sqrt{2}\omega_b^2} e^{-\lambda/2\omega_b}$$

$$\Omega_{\text{eff}}^{(2)} = -\sqrt{2}c_+c_-\lambda^2 \ldots$$

Different from the JC regime



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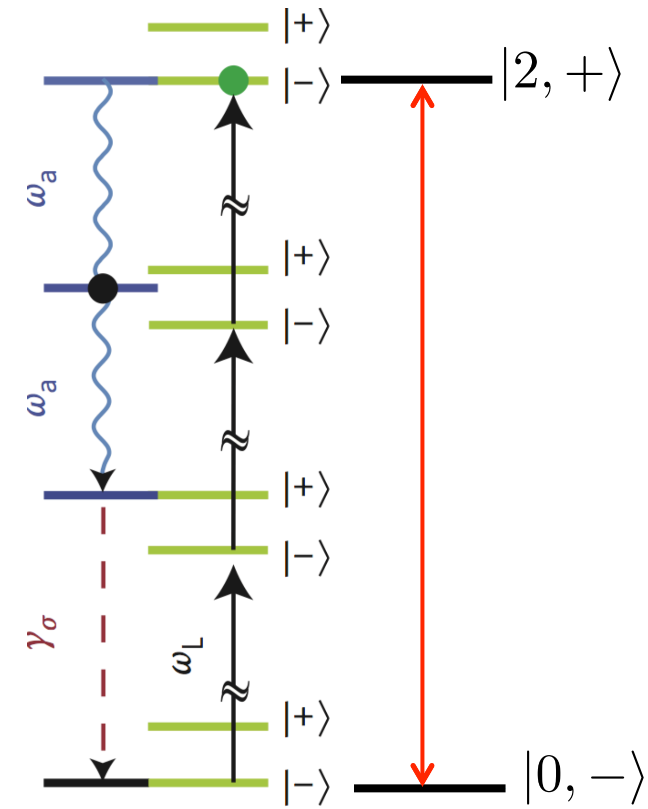

$$H = \omega_b b^\dagger b + \omega_\sigma \sigma^+ \sigma + \lambda \sigma^+ \sigma (b^\dagger + b) + \Omega(e^{i\omega_L t}\sigma + h.c.)$$

$$H = \omega_b b^\dagger b + \omega_\sigma \sigma^+ \sigma + g(b^\dagger \sigma + b\sigma^+) + \Omega(e^{i\omega_L t}\sigma + h.c.)$$

Super Rabi Oscillation

+

Proper Dissipation Channel

↓

N-phonon bundle emission

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3) N-phonon bundle emission with high purity

4) Conclusions

Dissipation dynamics with master equation

$$\frac{d\rho}{dt} = -i[H, \rho] + \kappa\mathcal{L}[b] + \gamma\mathcal{L}[\sigma]$$

Cavity decay rate: κ

$$\mathcal{L}[O] = (2O\rho O^\dagger - \rho O^\dagger O - O^\dagger O\rho)/2$$

QD decay rate: γ

$\tau_{in} \sim 1/\kappa$ $\tau_{ex} \sim 1/\gamma$ $\kappa \gg \gamma$

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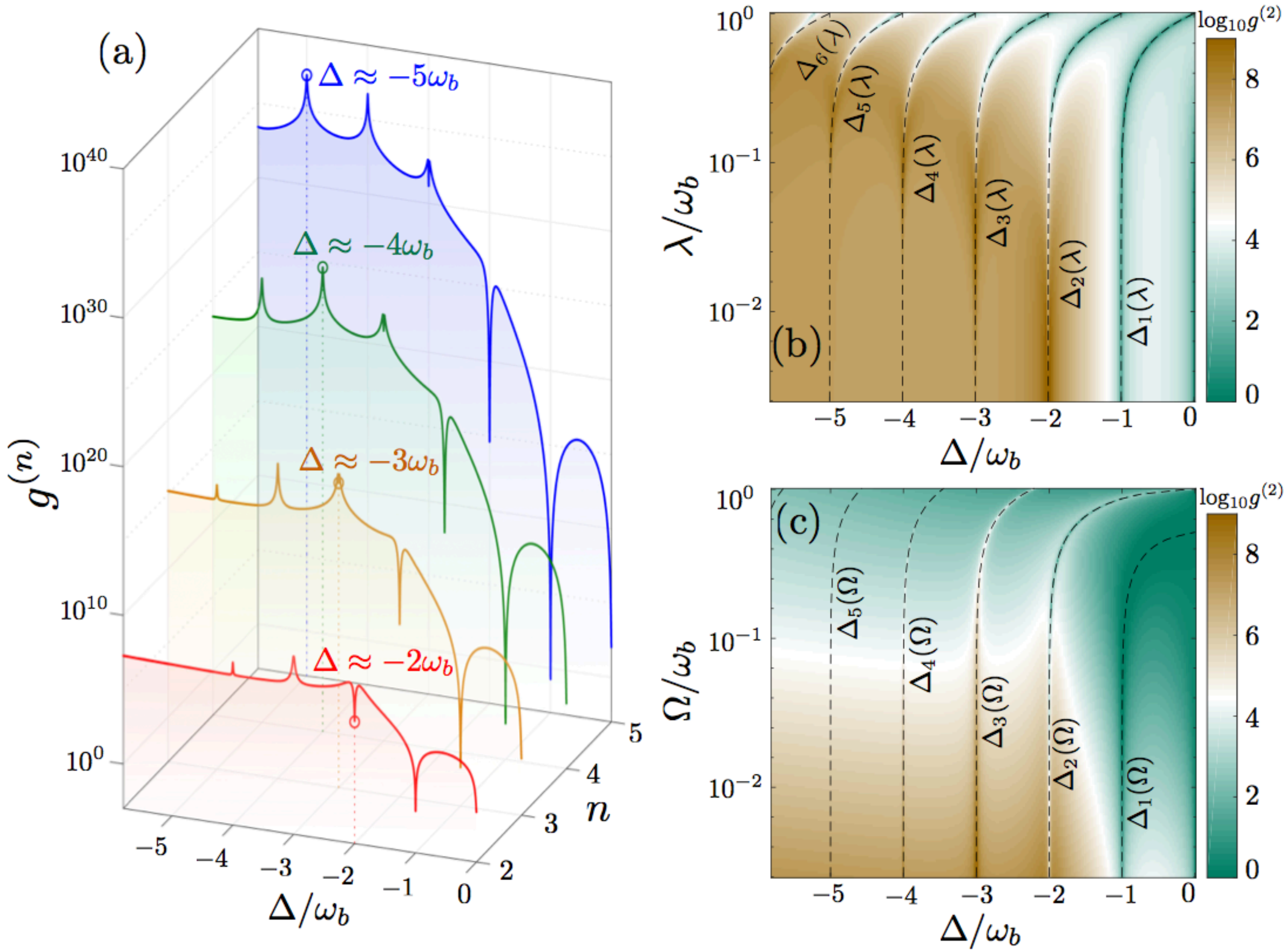
Phonons correlation functions

$$g^{(n)} = \frac{\langle b^{\dagger n} b^n\rangle}{\langle b^\dagger b\rangle^n}$$

Bundle correlation functions

$$g_N^{(n)}(t_1,\ldots,t_n) = \frac{\langle \mathcal{T}_-\{\Pi_{i=1}^n b^{\dagger N}(t_i)\}\mathcal{T}_+\{\Pi_{i=1}^n b^N(t_i)\}\rangle}{\Pi_{i=1}^n \langle b^{\dagger N} b^N\rangle(t_i)}$$

Bundles of strongly correlated phonons

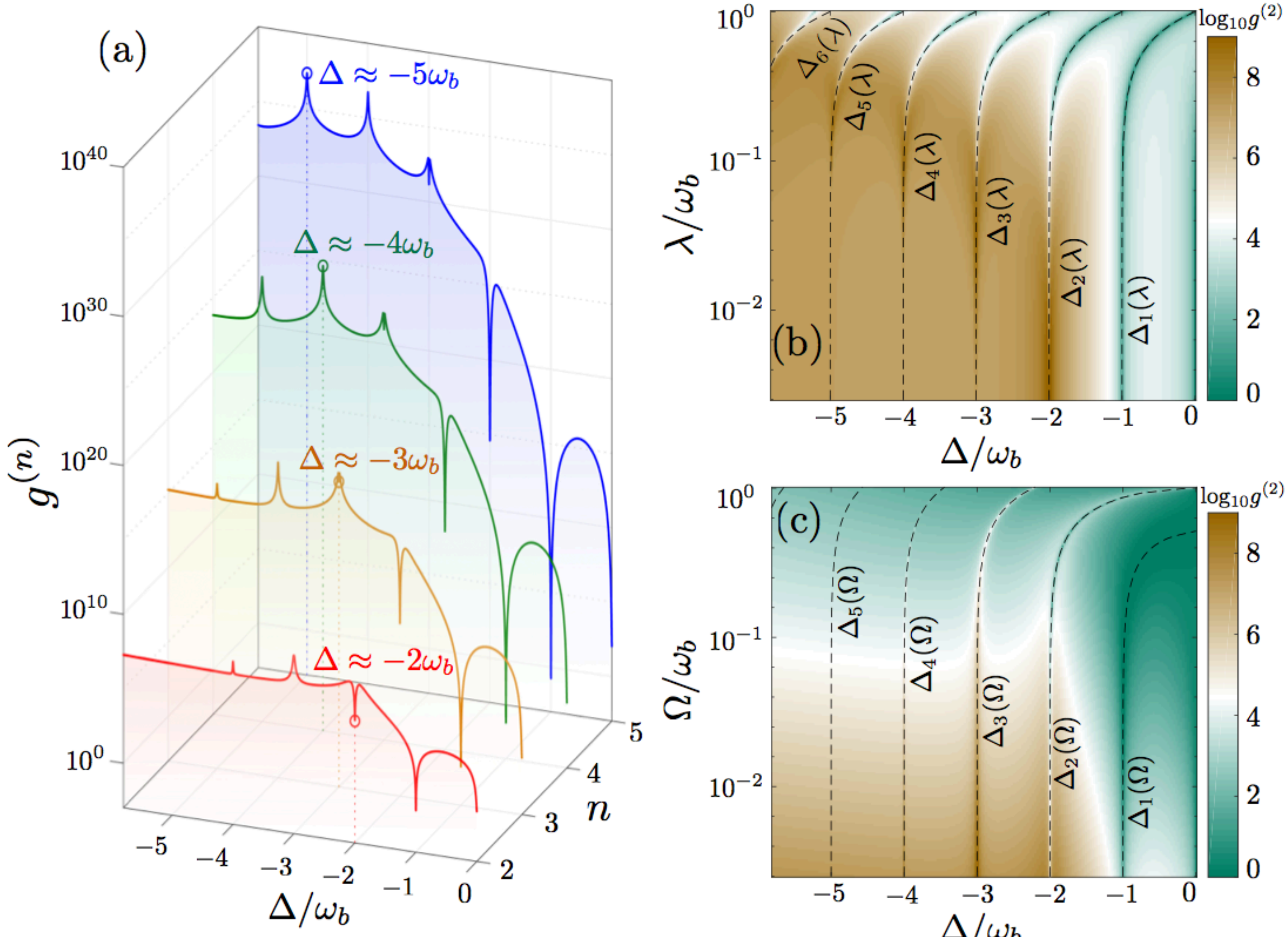


$$g^{(n)} = \frac{\langle b^{\dagger n} b^n \rangle}{\langle b^\dagger b \rangle^n}$$

Strong bunching at *n*-phonon associated anti-Stokes resonances

(a) $\Delta = -n\omega_b$ (b) $\Delta = \Delta_n(\lambda)$ (c) $\Delta = \Delta_n(\Omega)$

Bundles of strongly correlated phonons



$$g^{(n)} = \frac{\langle b^{\dagger n} b^n \rangle}{\langle b^\dagger b \rangle^n}$$

is robust to varying system parameters

Strong bunching at *n*-phonon associated anti-Stokes resonances

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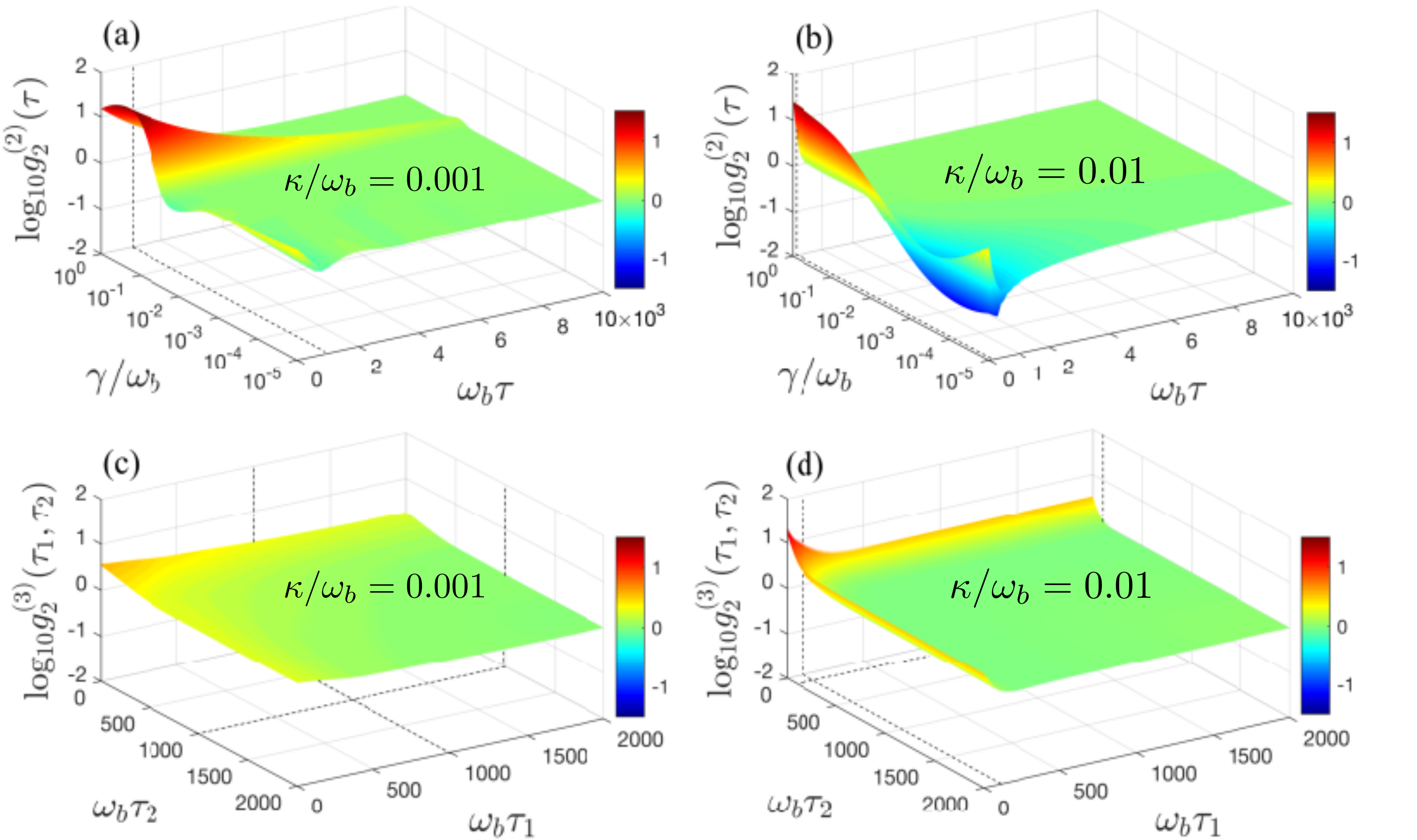
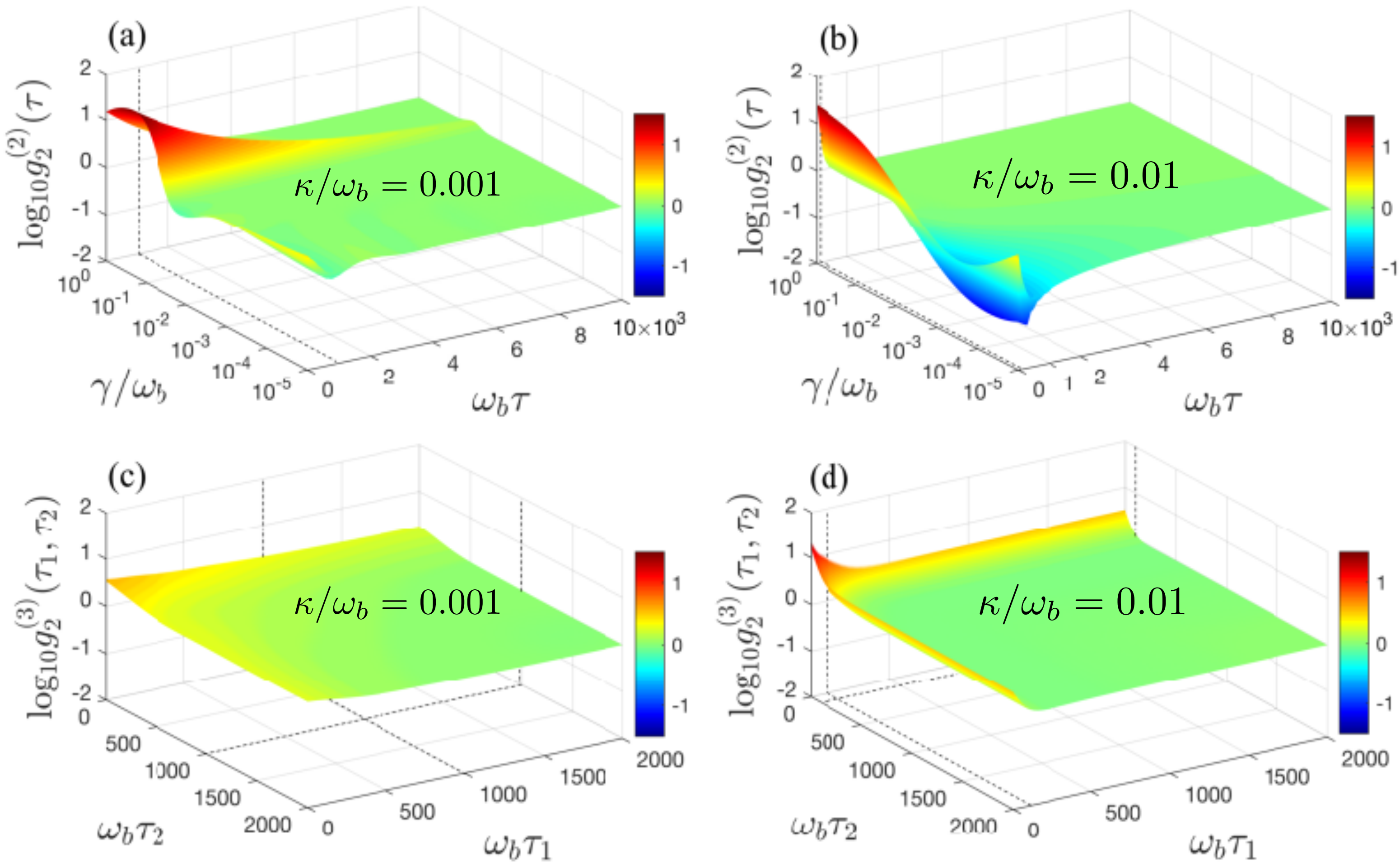
Statistic characteristics of emitted *n*-phonon bundles



Valid regime: $\tau > 1/\kappa$

Statistic characteristics of emitted *n*-phonon bundles



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Bunching $\xrightarrow{\gamma}$ Uncorrelated $\xrightarrow{\gamma}$ Antibunching

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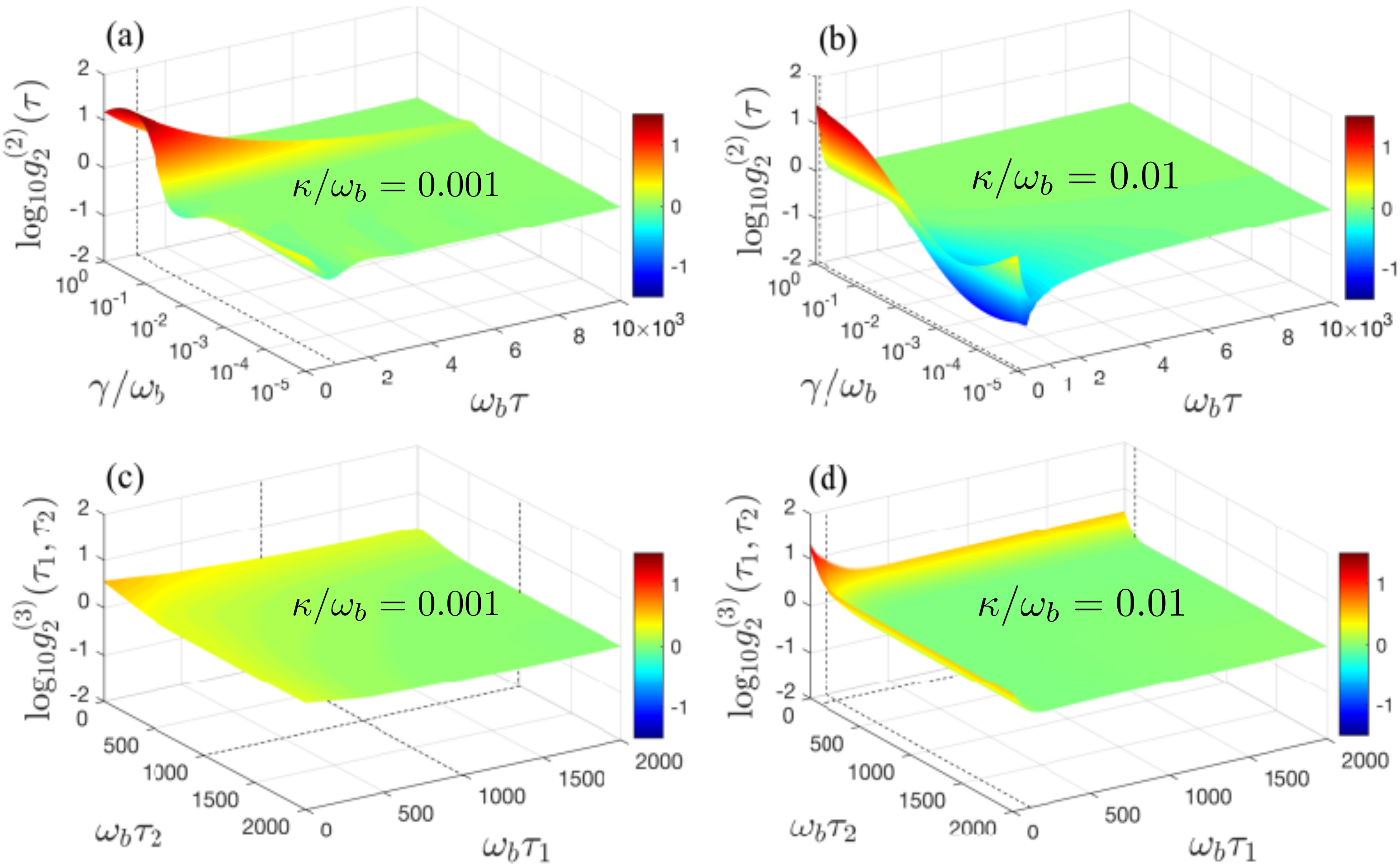
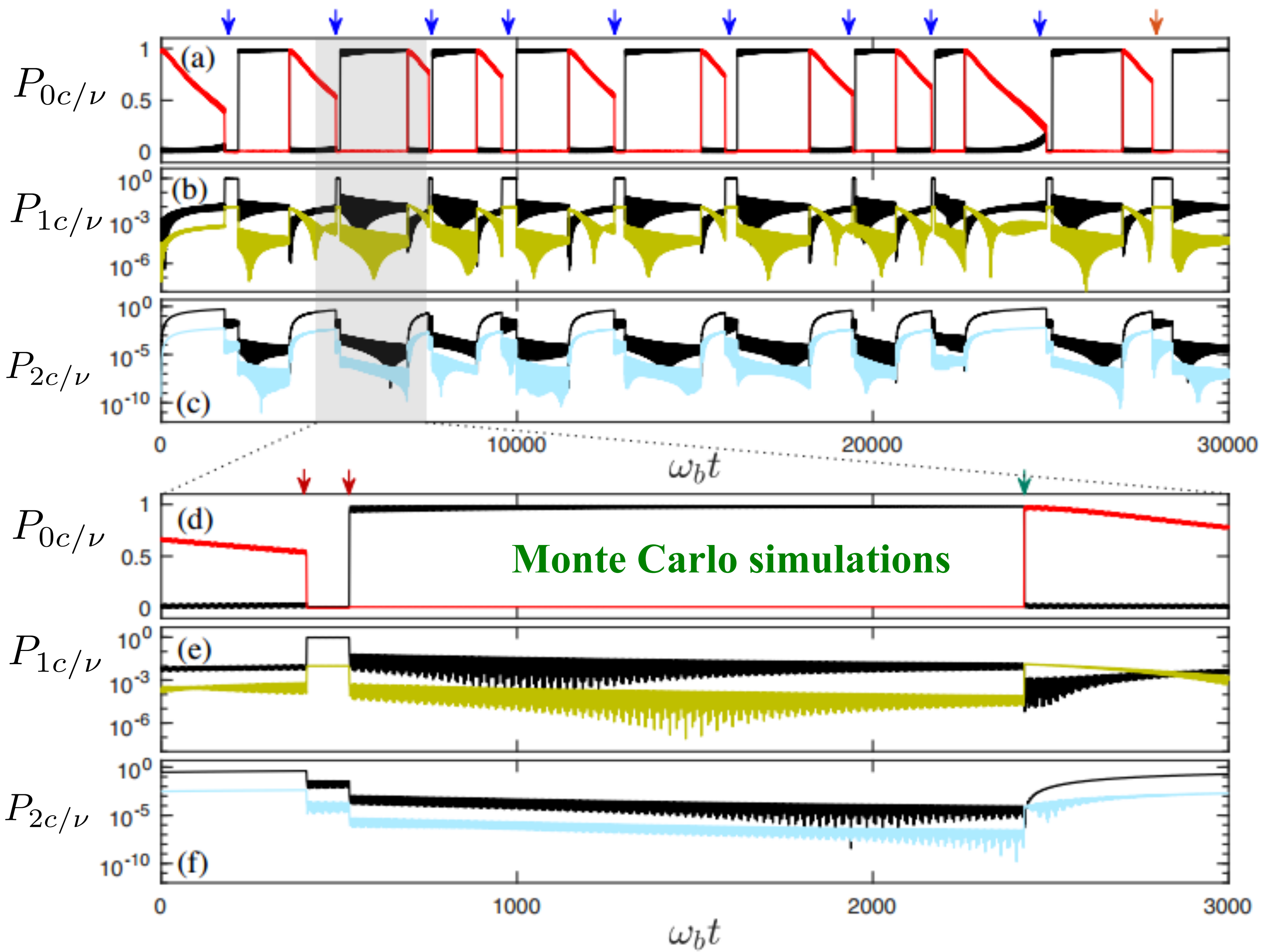


Valid regime: $\tau > 1/\kappa$

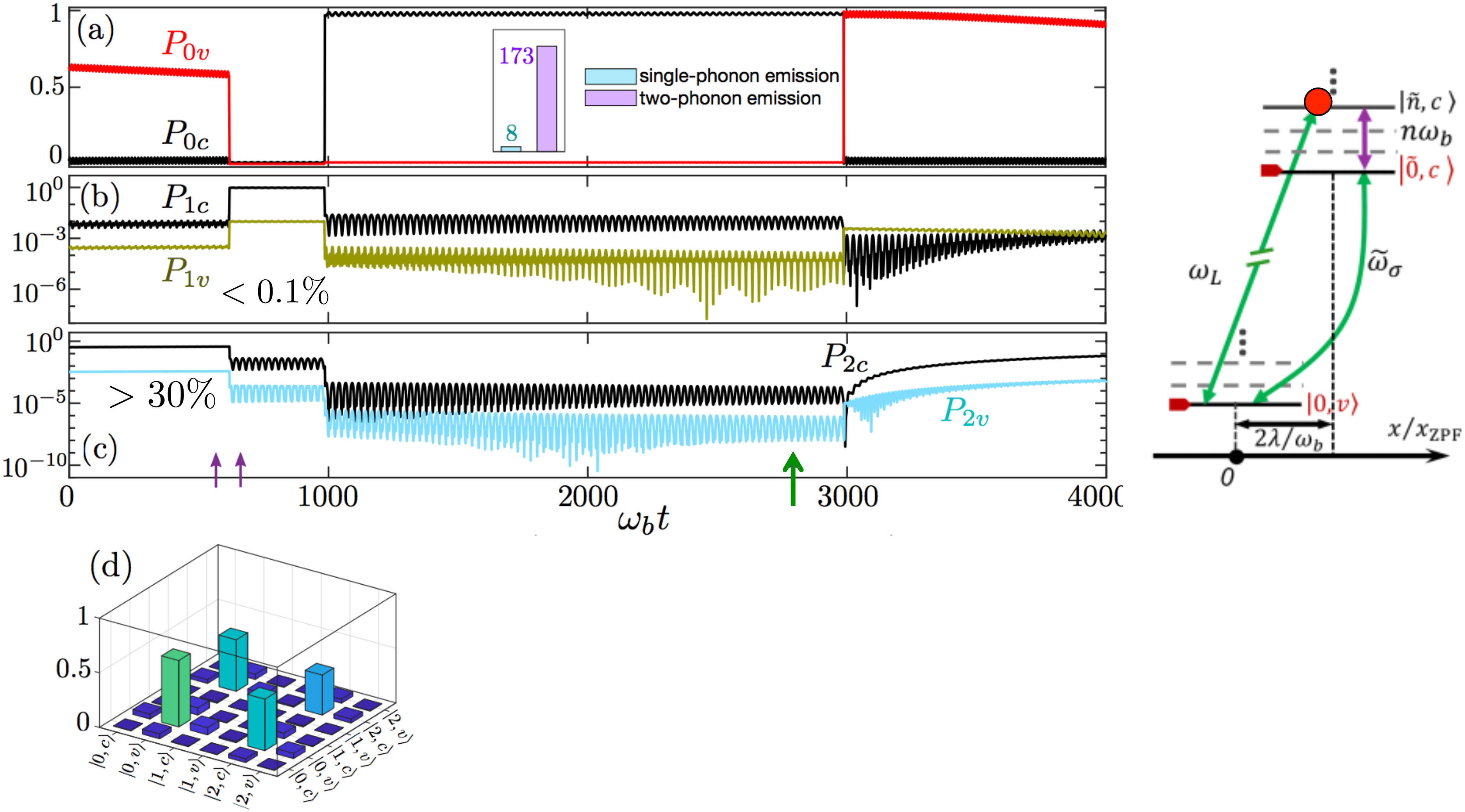
Two-phonon laser

Bunching $\xrightarrow{\gamma}$ Uncorrelated $\xrightarrow{\gamma}$ Antibunching $g^{(2)}(\tau) \approx 1, g^{(3)}(\tau_1, \tau_2) \approx 1$

N-phonon bundle emission- dynamics trajectories

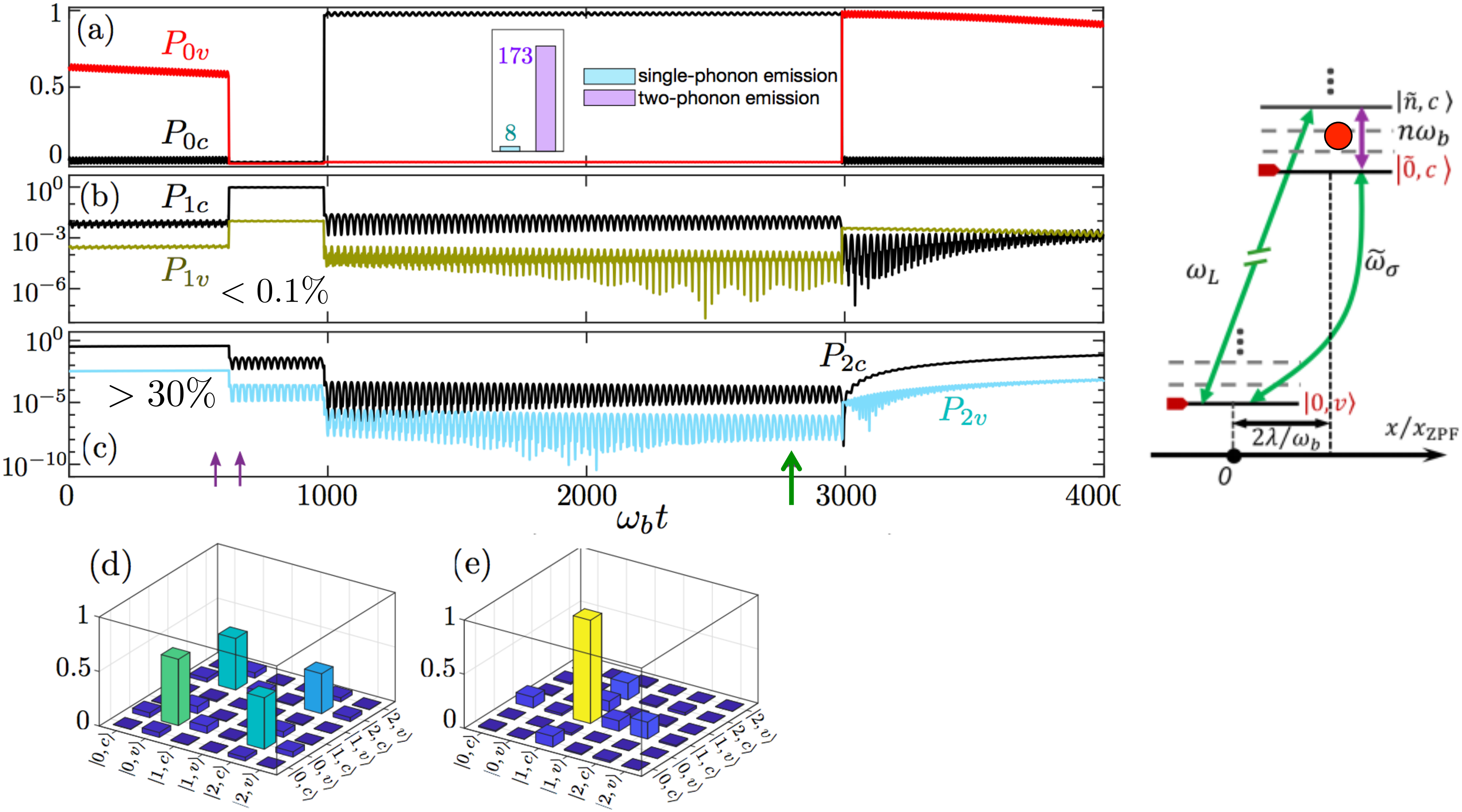


Cascade emission of Fock states in a short time window



$$c_1|0,\nu\rangle + c_2|n,c\rangle$$

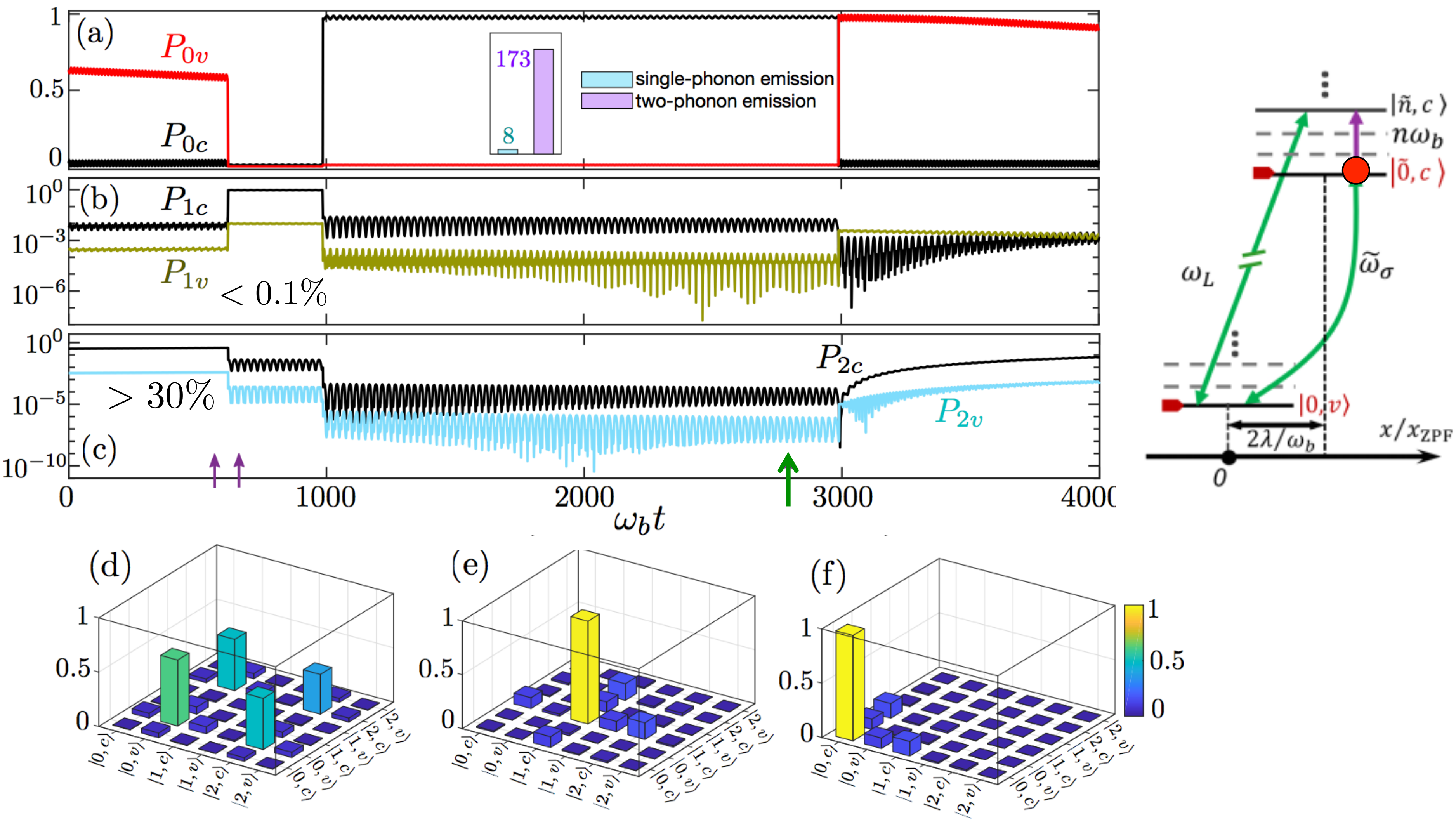
Cascade emission of Fock states in a short time window



$c_1|0,\nu\rangle + c_2|n,c\rangle \Rightarrow |n_i\rangle\ (0 \leq n_i \leq n)$

Phonon

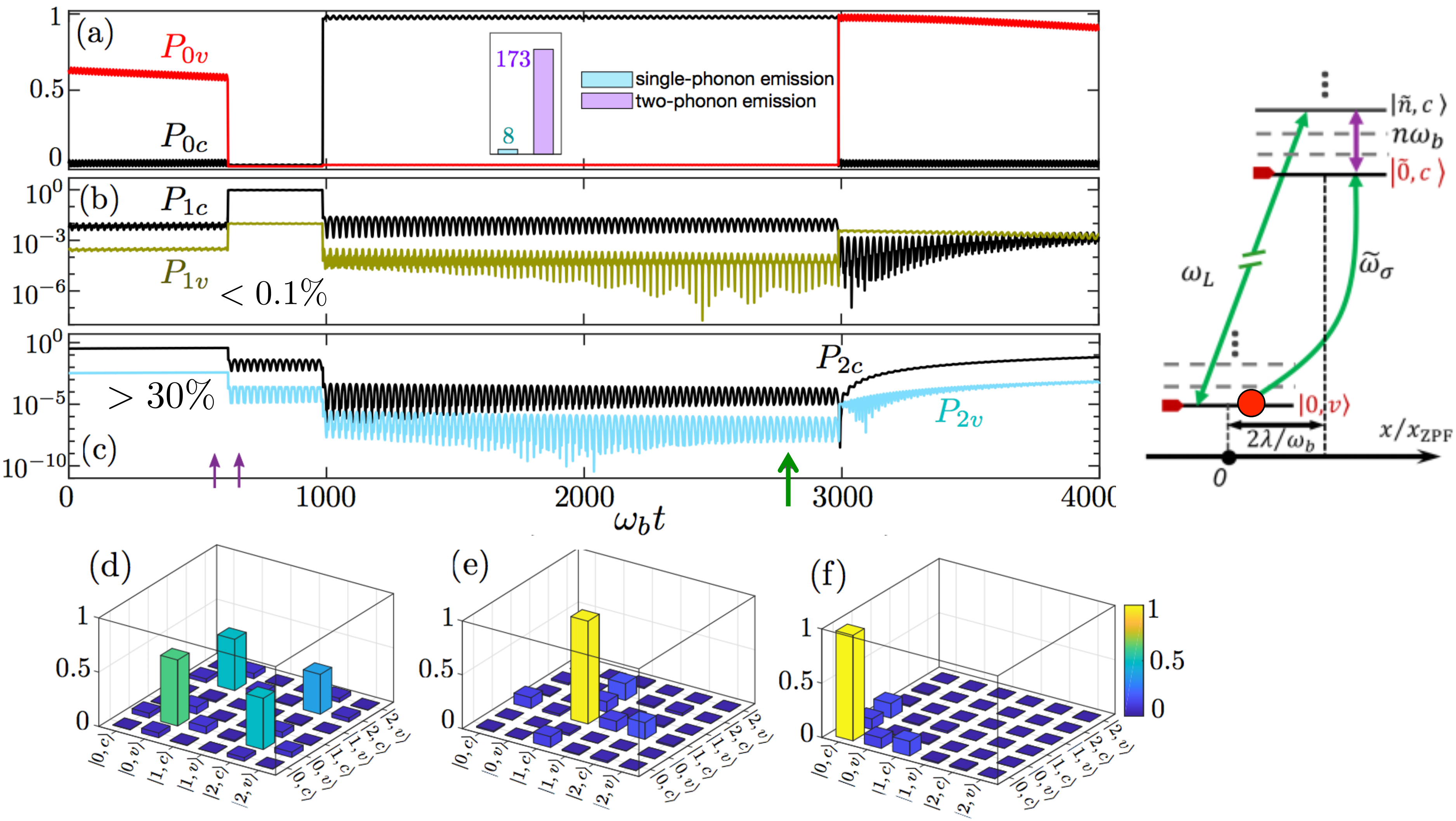
Cascade emission of Fock states in a short time window



$c_1|0,\nu\rangle + c_2|n,c\rangle$ ⇨ $|n_i\rangle\ (0 \le n_i \le n)$ ⇨ $|0,c\rangle$

Phonon Phonon

Cascade emission of Fock states in a short time window



$c_1|0,\nu\rangle + c_2|n,c\rangle \Rightarrow |n_i\rangle\ (0 \le n_i \le n) \Rightarrow |0,c\rangle \Rightarrow |0,\nu\rangle$

Phonon   Phonon   Photon

Single cascade-emission process of two-phonon

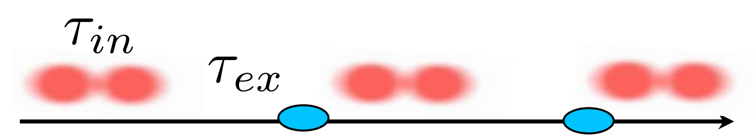
Initially: $P_2 > 30\%, P_1 < 0.1\%$

$\tau_{in} < 1/\kappa < \tau_{ex} \approx 1/\gamma$

Emit a first phonon: $P_1 \approx 1$

$\tau_{in} < 1/\kappa$

Emit the second phonon: $P_{0c} \approx 1$

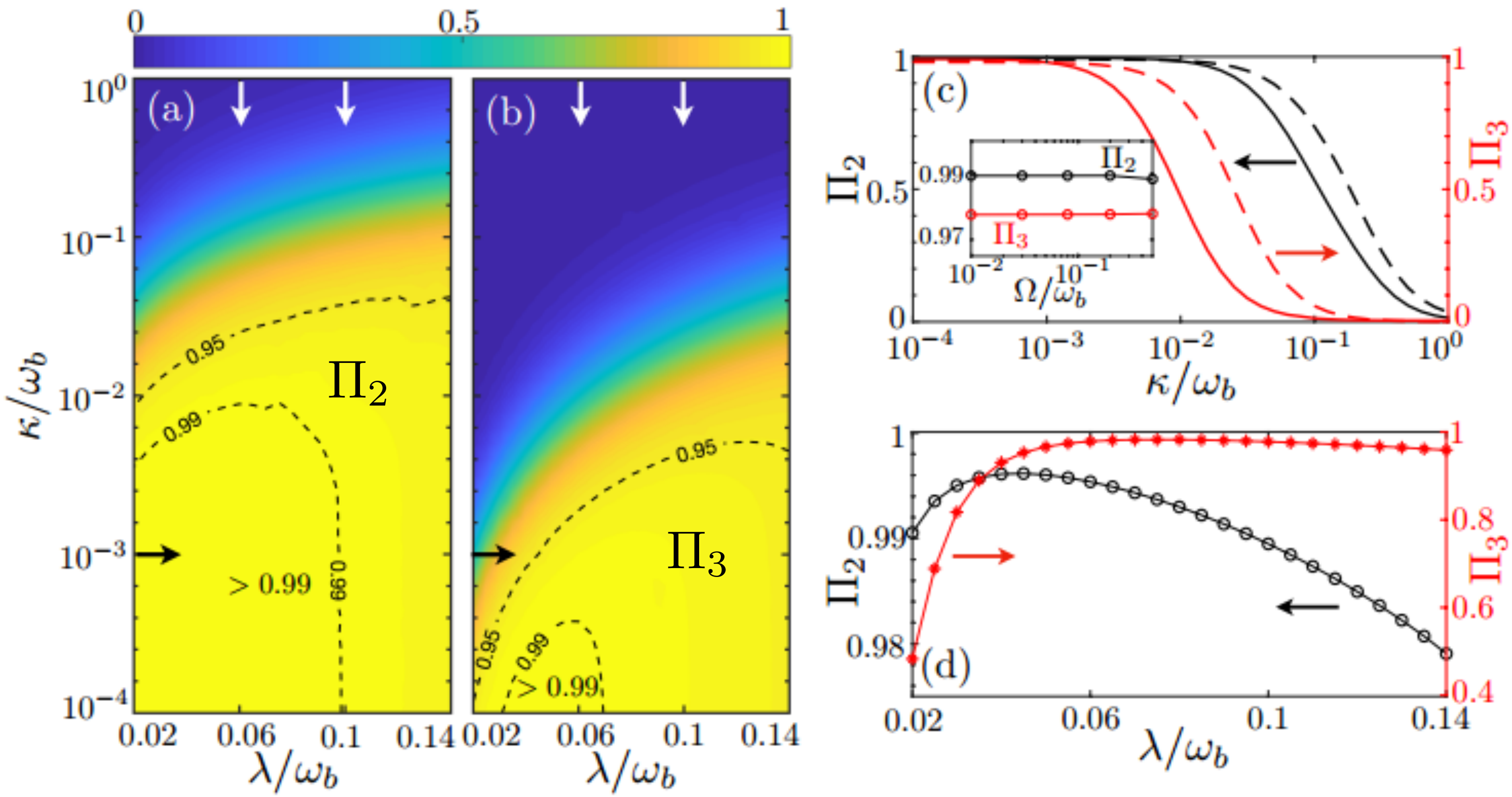


Photon emission QD flip $|0, c\rangle \rightarrow |0, \nu\rangle$

Optical heralded two-phonon bundle emission

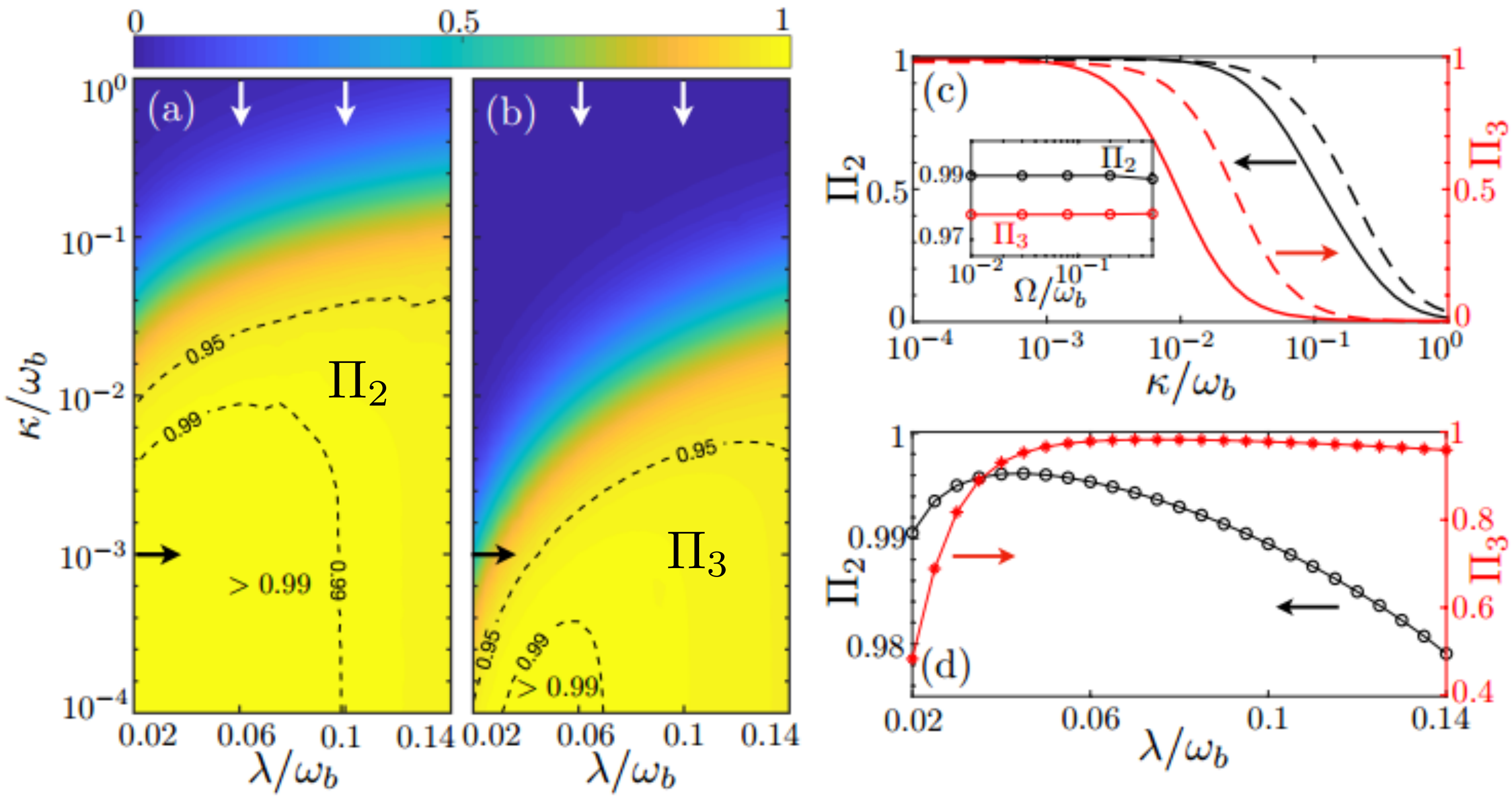
Two-phonon emission rates $\approx 1.8 \times 10^9/s$

The purity of *n*-phonon emission



Definition: $\Pi_n = n\tilde{P}_n / \sum_{n_i=1}^{n} n_i \tilde{P}_{n_i}$ → *n*-phonon state population in the time-span *T*

The purity of n-phonon emission



Wide range $\Pi_{2,3} > 95\%$

Π_n is robust with Ω

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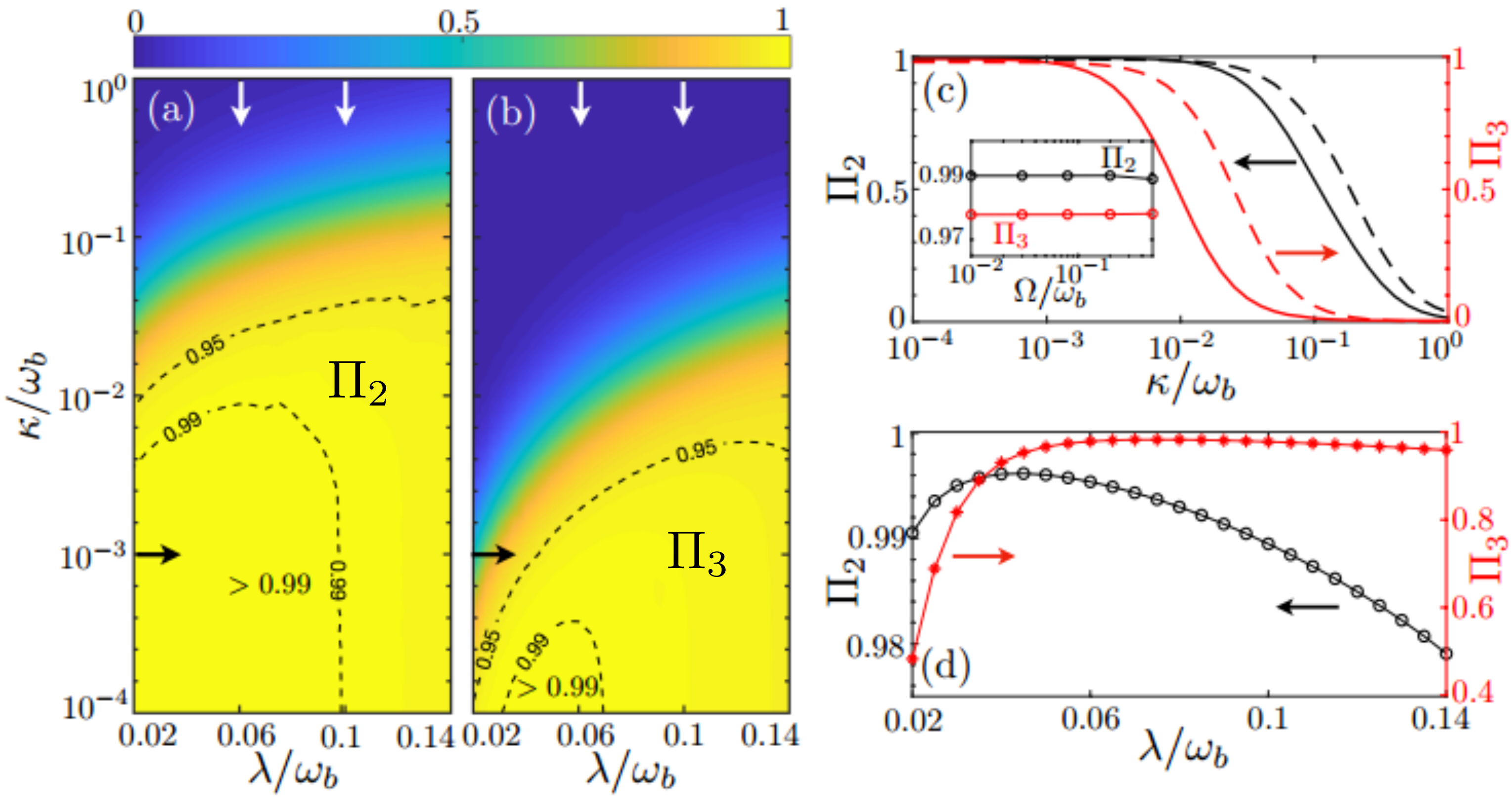

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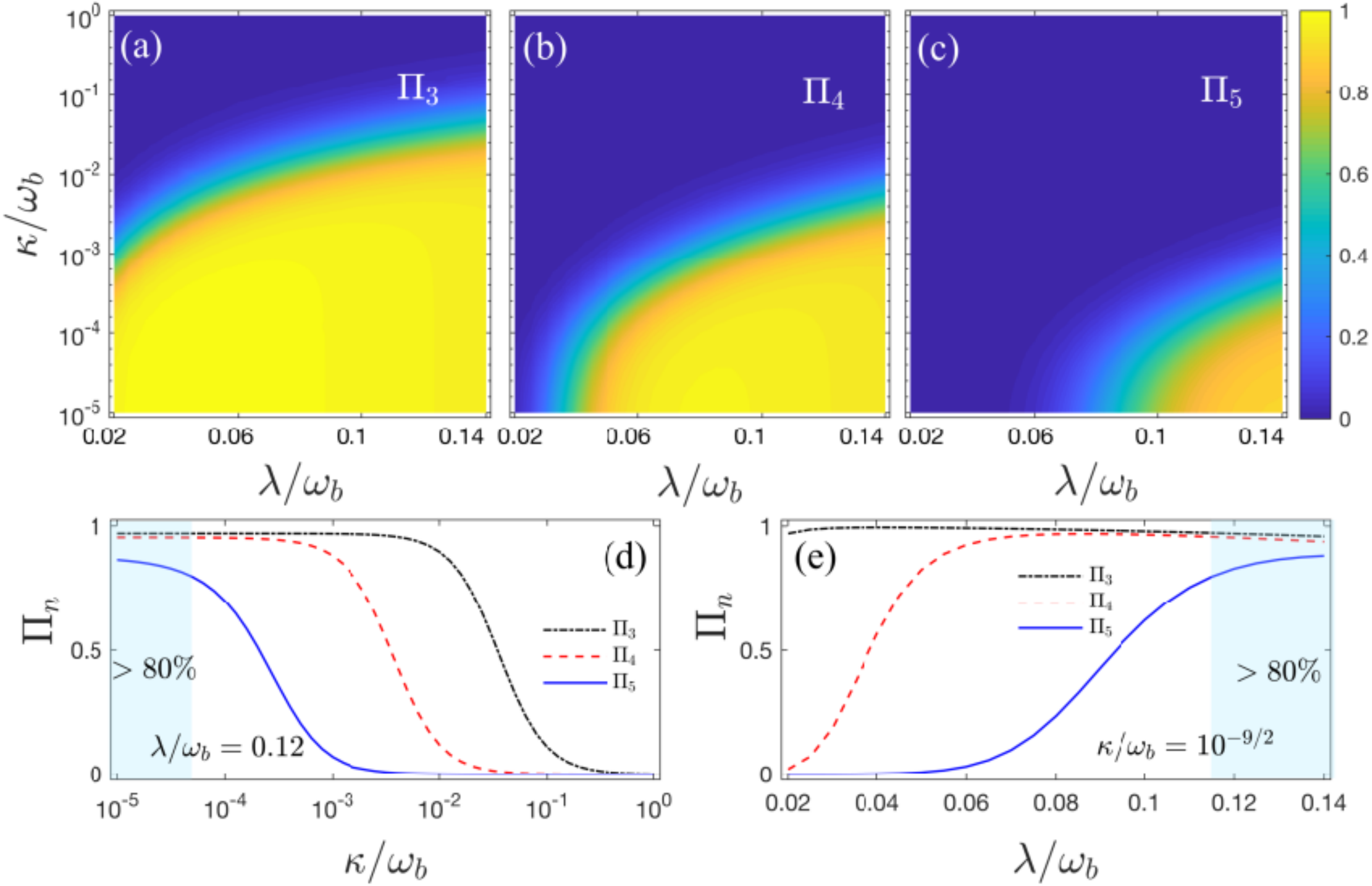
Increasing λ can enhance (decrease) the Π_3 (Π_2) by enhancing the high-order phonon sideband processes.

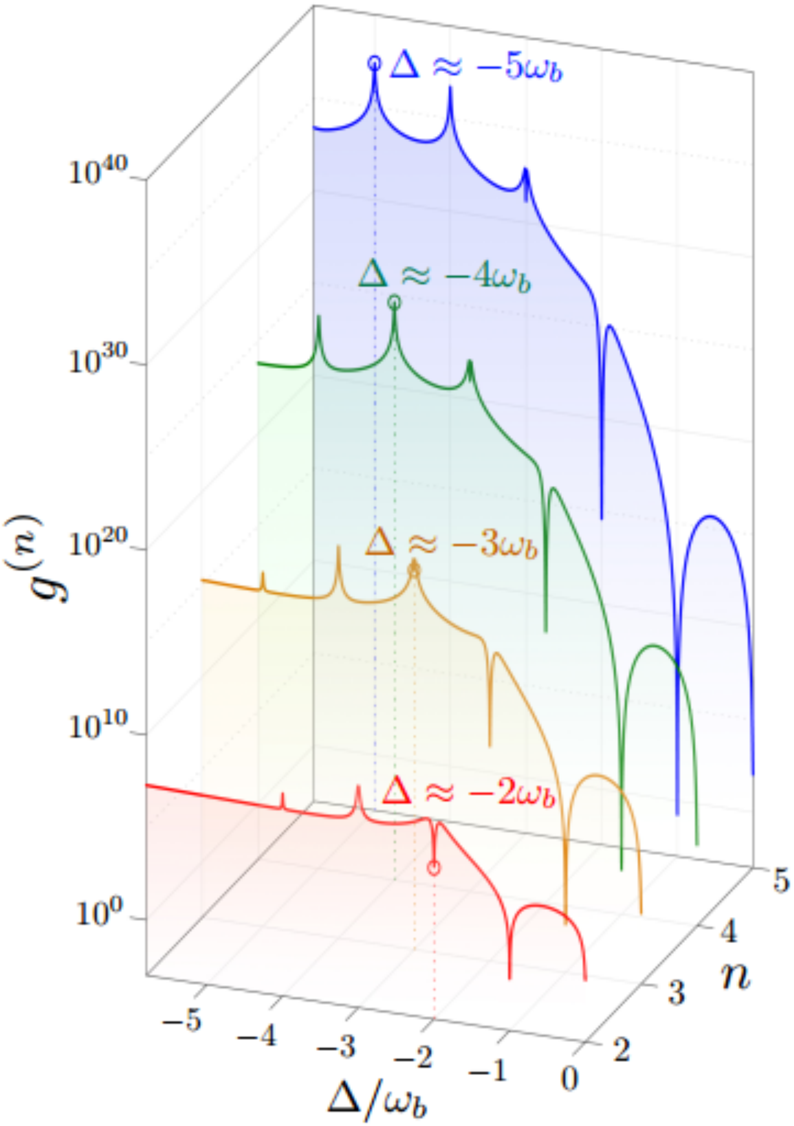
The purity of n-phonon emission



The purity is less robust for larger n

$\Pi_4 > 95\%$, $\Pi_5 > 80\%$ with feasible experimental parameter

The mechanism deciding high purity for large n



Electron-phonon coupling

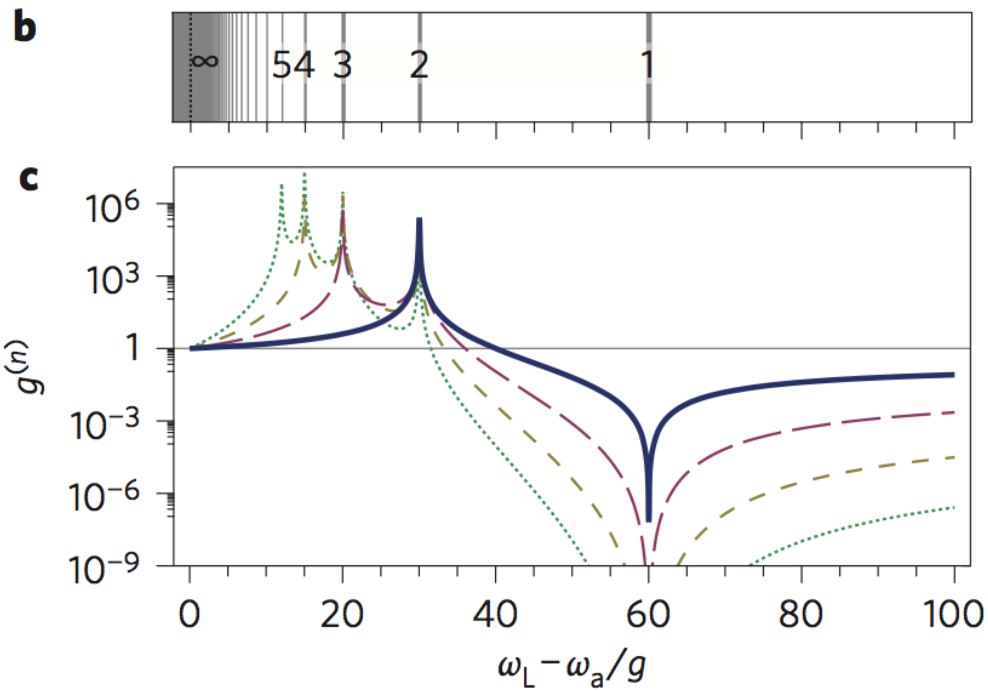
Anti-Stokes resonances

Frequency differences between the n and (n+1)-phonon resonances are almost independent of n

Even for large n, the optimum pumping frequency can be well resolved when $\omega_b \gg \kappa, \gamma$

The mechanism of previous work

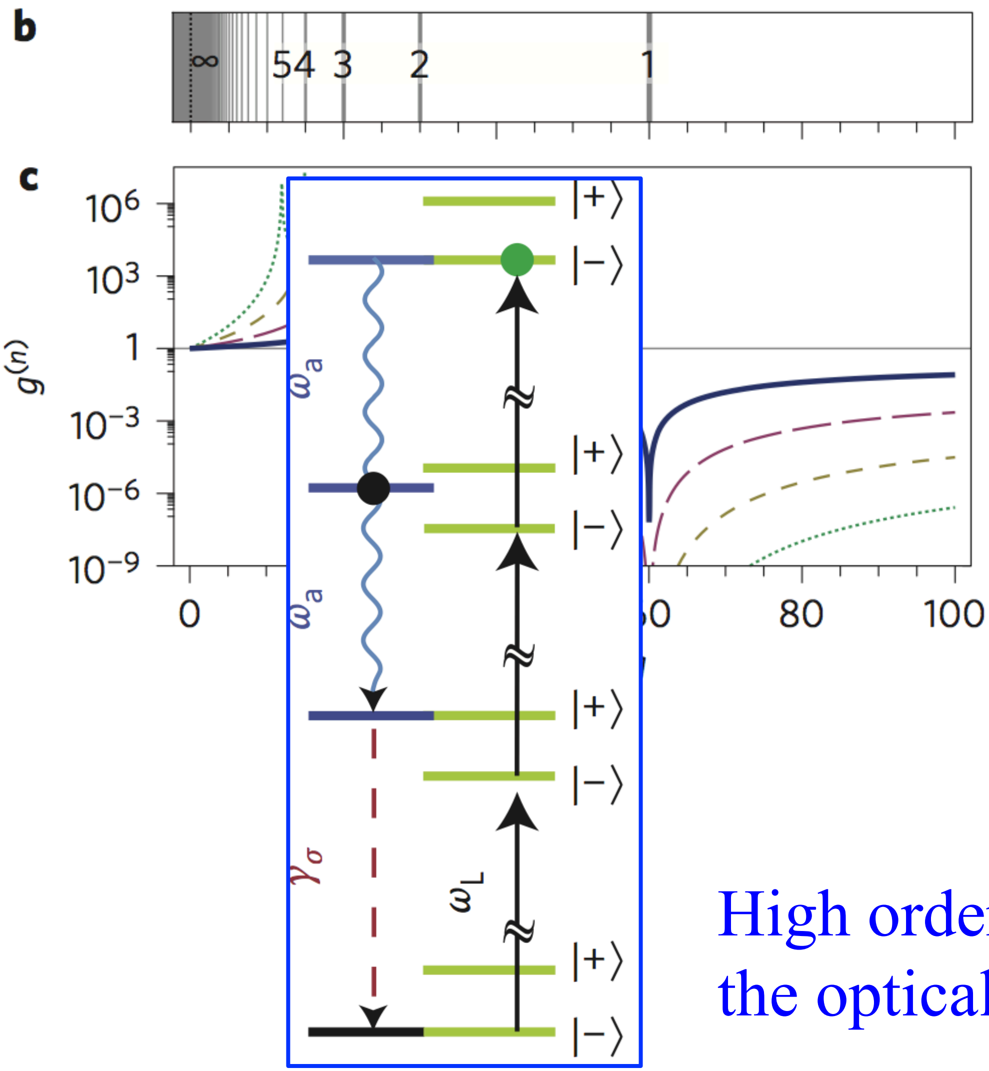
JC coupling



Frequency differences between the *n* and (*n*+1) photon resonances becomes small as increasing *n*

The mechanism of previous work

JC coupling



Frequency differences between the *n* and (*n*+1) photon resonances becomes small as increasing *n*

High order process for the optical driving

Advantages and applications of our work

The mechanism of anti-Stokes processes

↓

Expands the theory of *n*-quanta bundle emission

Broadens the family of anti-Stokes processes

Advantages and applications of our work

The mechanism of anti-Stokes processes

⇩

Expands the theory of *n*-quanta bundle emission

Broadens the family of anti-Stokes processes

Mixed phonon-photon emission

⇩

Optical heralded phonon laser/guns

On chip quantum communications and metrology

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Quantum Toolbox in Python

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RIKEN-AIST Challenge
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Conclusions

- We introduced the basic knowledge of *n*-photon bundle emission.
- We proposed *n*-phonon bundle emission via anti-Stokes process.
- We discussed the purity of *n*-phonon bundle emission and the corresponding applications.

Thanks for your attention!