SAND2012-2472P

Semiconductor quantum optics: Development of nonclassical-light sources

W. W. Chow, Sandia National Laboratories

Quantum optics (from AMO perspective)

How is it different with semiconductors

Strong coupling

Dephasing

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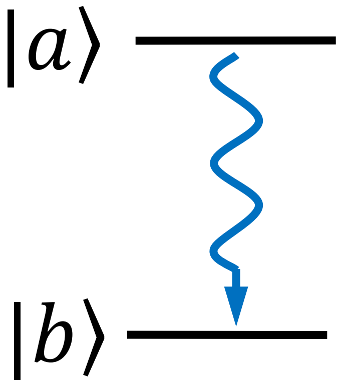
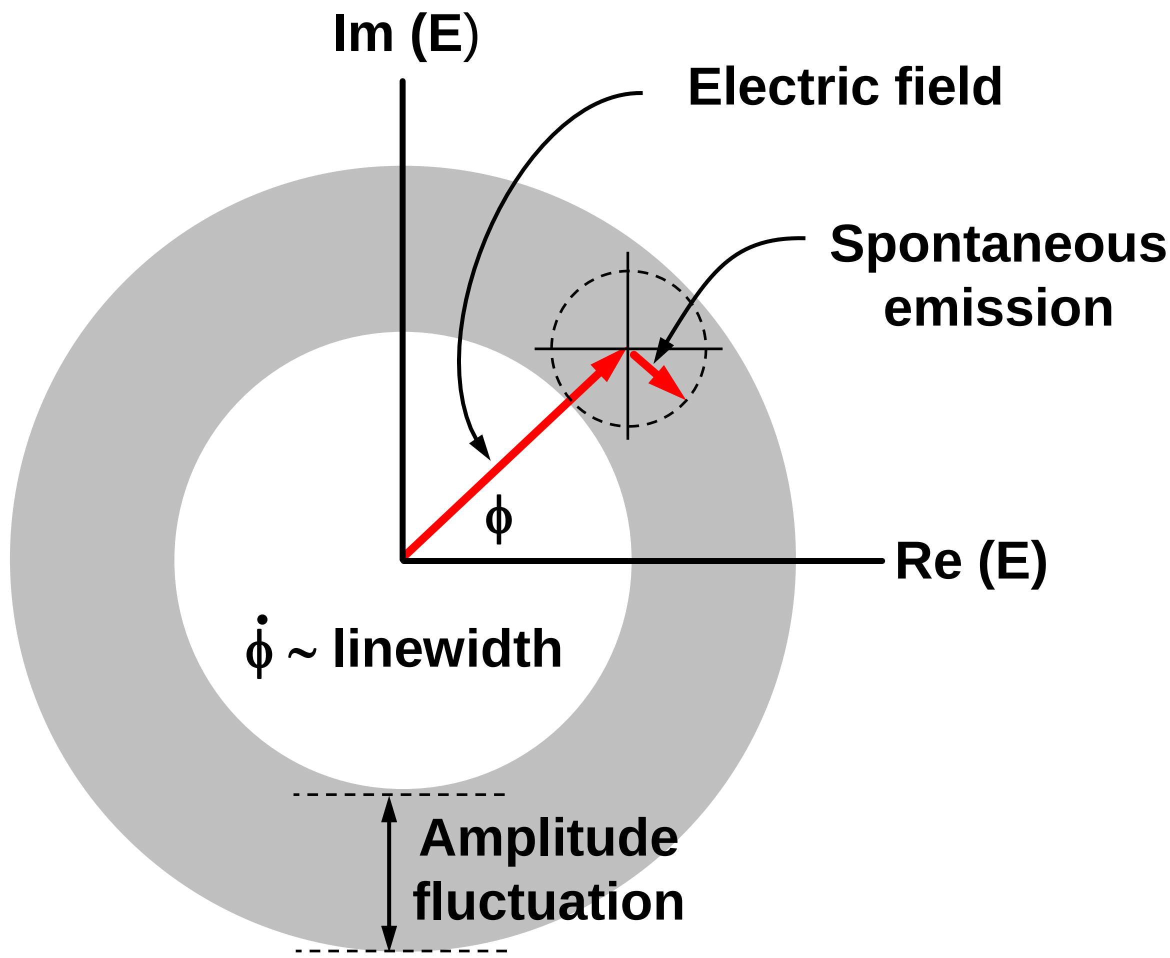
Rate equation description of light-matter interaction



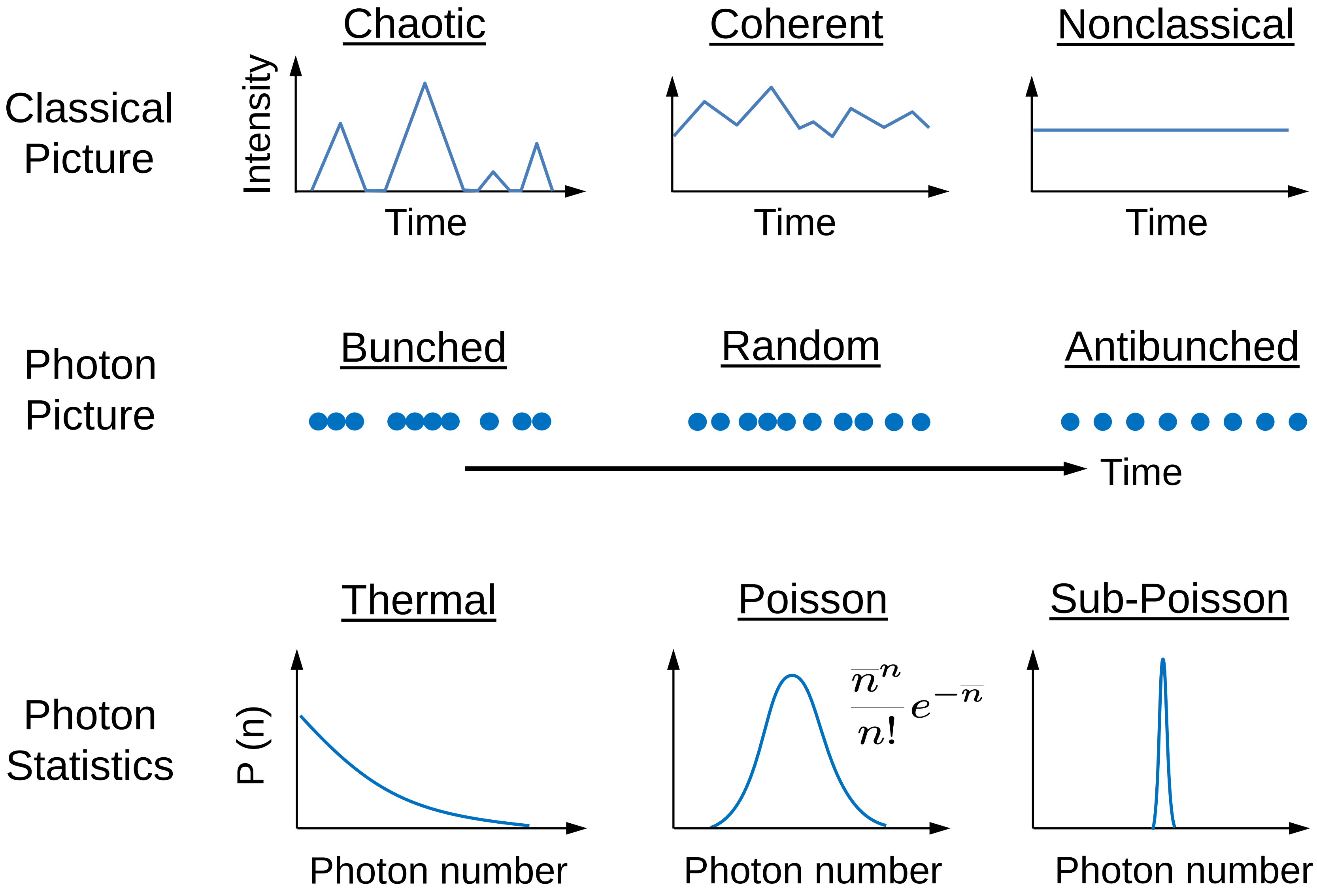
$$\frac{dn_a}{dt} = \underbrace{-\overset{\text{Einstein A}}{A}n_a}_{\substack{\text{Spontaneous}\\ \text{emission}}} - \underbrace{\overset{\text{Einstein B}}{B}\,\overset{\substack{\text{Light energy}\\ \text{density}}}{u(\omega)}(n_a - n_b)}_{\substack{\text{Absorption and}\\ \text{stimulated emission}}}$$

Equation is starting point of Einstein's derivation of Planck's blackbody radiation

Linewidth and photon statistics



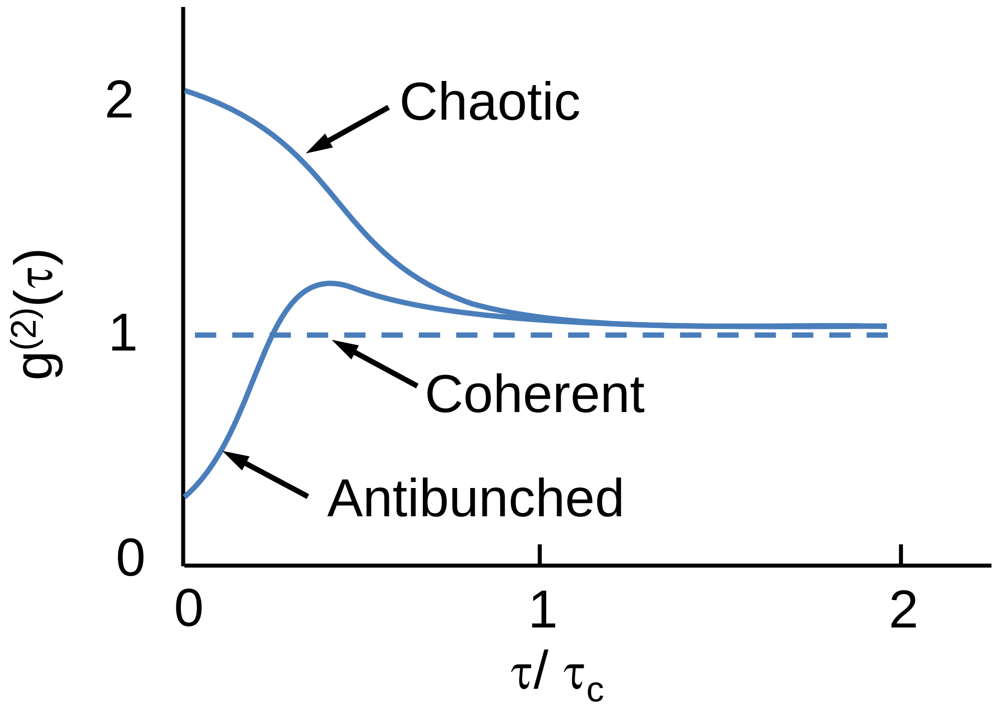
Types of light



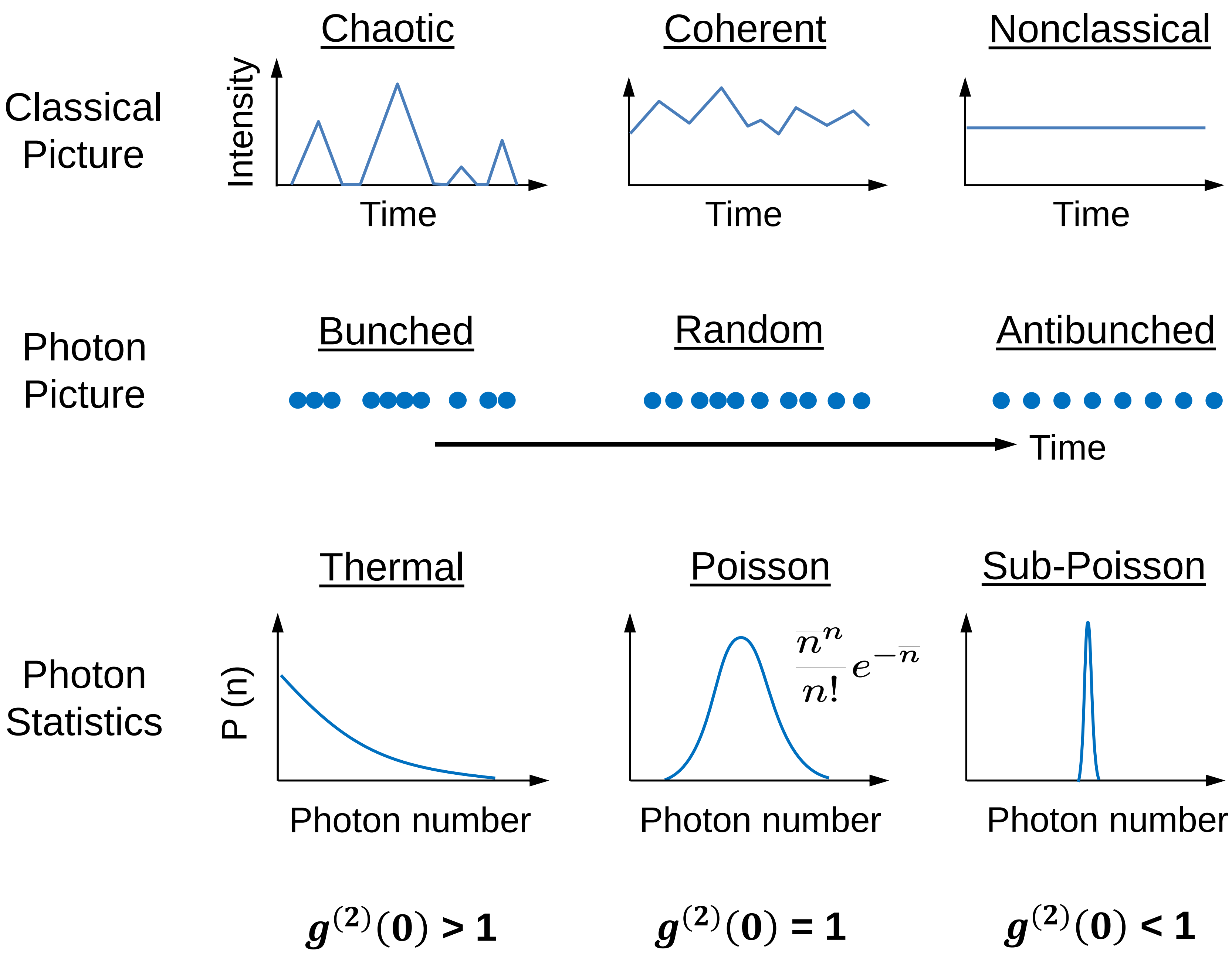
2nd-order correlation function

$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

$$= \frac{\left\langle c^\dagger(t)\, c^\dagger(t+\tau)\, c(t+\tau)\, c(t)\right\rangle}{\langle c^\dagger(t)\, c(t)\rangle \langle c^\dagger(t+\tau)\, c(t+\tau)\rangle}$$

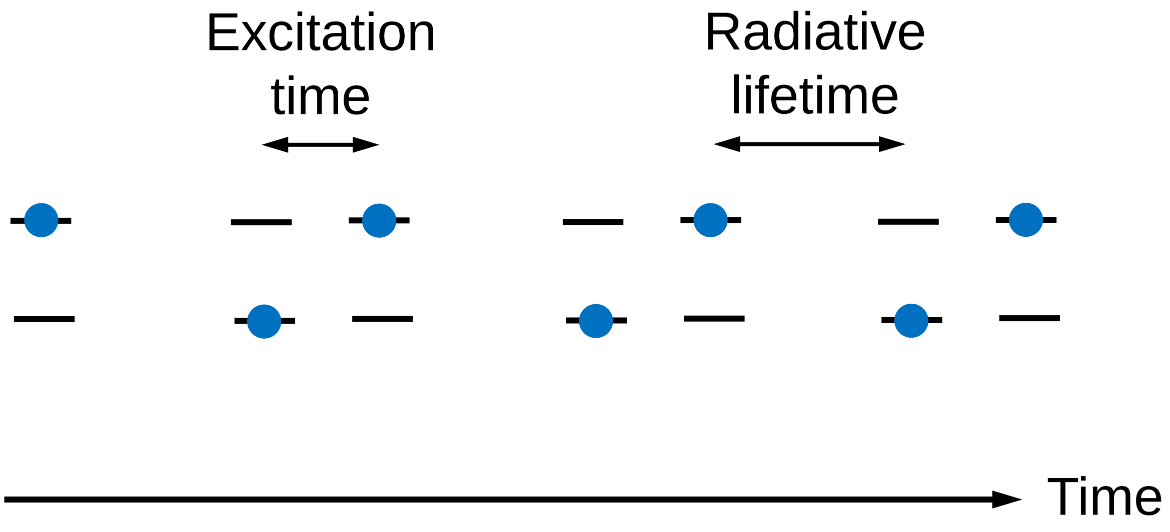


Types of light



How to generate nonclassical light

Single emitter: atom, molecule, quantum dot



Limitation of operating under rate equation condition

Steady state:

$$\frac{dn_a}{dt} = 0 \quad \Longrightarrow \quad n_a = \frac{Bu(\omega)n_b}{A + Bu(\omega)}$$

Intense excitation:

$$Bu(\omega) >> A \quad \Longrightarrow \quad n_a = n_b$$

Bleaching

(the best one can do)

Coherent transient in light-matter interaction

$$a(t)\,e^{-i\omega_a t}\left|a\right\rangle + b(t)\,e^{-i\omega_b t}\left|b\right\rangle$$

$$i\hbar\frac{d}{dt}\left|\psi(t)\right\rangle = H\left|\psi(t)\right\rangle$$

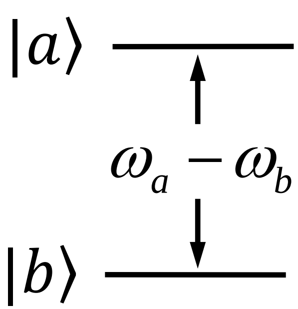
$$\frac{p^2}{2m} + V \underbrace{- \wp\cdot E_0\cos(\omega t)}_{\text{Electric dipole interaction}}$$

$$\frac{da}{dt} = -\frac{i}{\hbar}\wp E_0 b$$

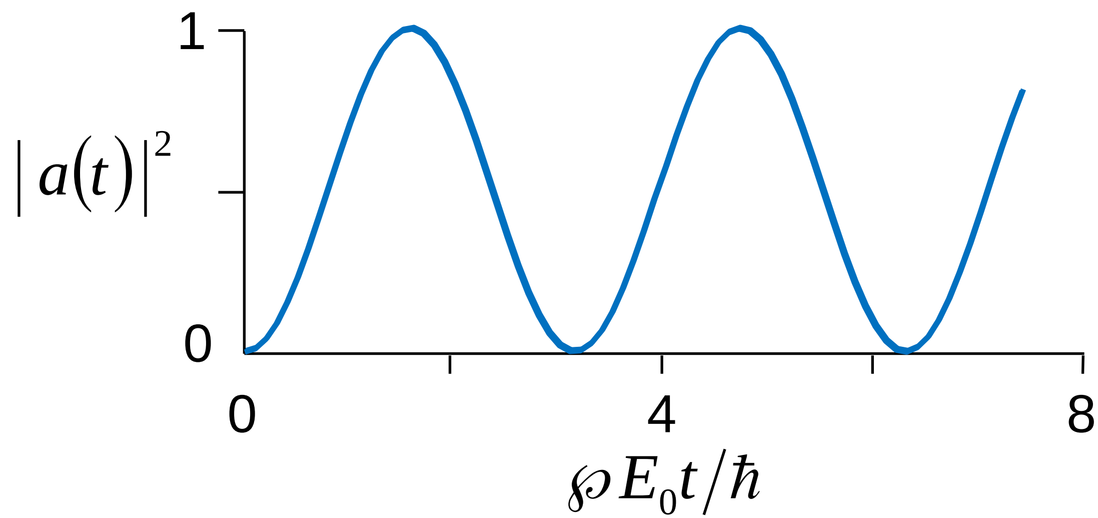
$$\frac{db}{dt} = -\frac{i}{\hbar}\wp E_0 a$$

$$a(t) = \sin\left(\frac{\wp E_0}{\hbar}t\right)$$

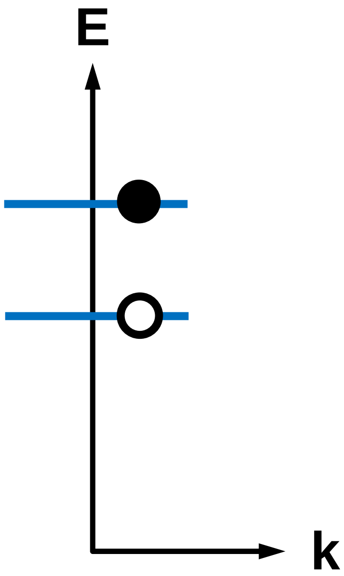
$$b(t) = \cos\left(\underbrace{\frac{\wp E_0}{\hbar}}_{\text{Rabi frequency}}t\right)$$

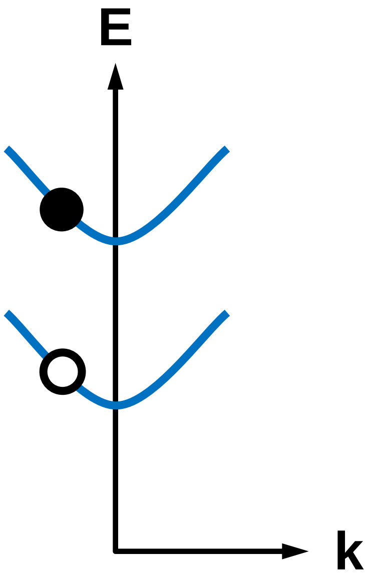


Rabi flopping



Quantum optics with semiconductors

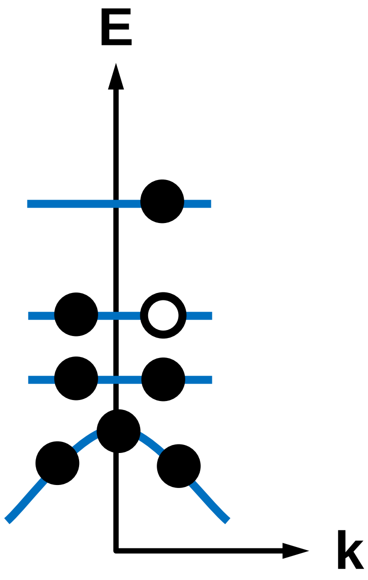


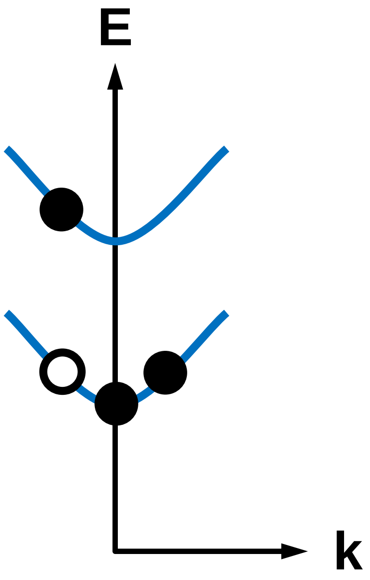


Quantum dot

Intersubband
(Quantum well)

Quantum optics with semiconductors





<u>Quantum dot</u>

<u>Intersubband</u>
(Quantum well)

Many-body effects in semiconductors

<u>Quantum statistics</u>

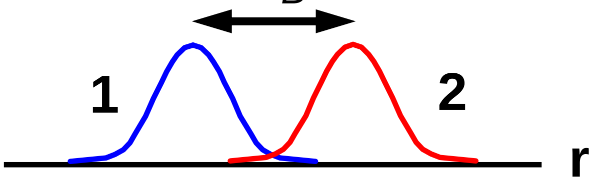
Identical particles, antisymmetric wavefunctions and the exclusion principle

2 Fermions: $\boldsymbol{\psi(r_1, r_2) = \phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2)}$

<u>Coulomb interaction</u>

$$\frac{e^2}{4\pi\varepsilon_B r}$$

Determines separation



Many-body effects in semiconductors

Quantum statistics

Identical particles, antisymmetric wavefunctions and the exclusion principle

2 Fermions: $\psi(r_1, r_2) = \phi_a(r_1)\phi_b(r_2) - \phi_b(r_1)\phi_a(r_2)$

Determines separation

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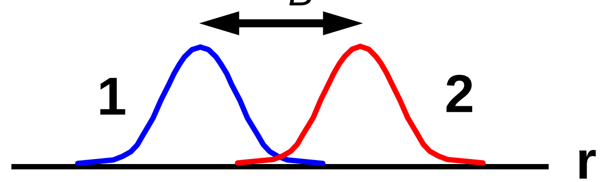


n Fermions (Slater determinant)

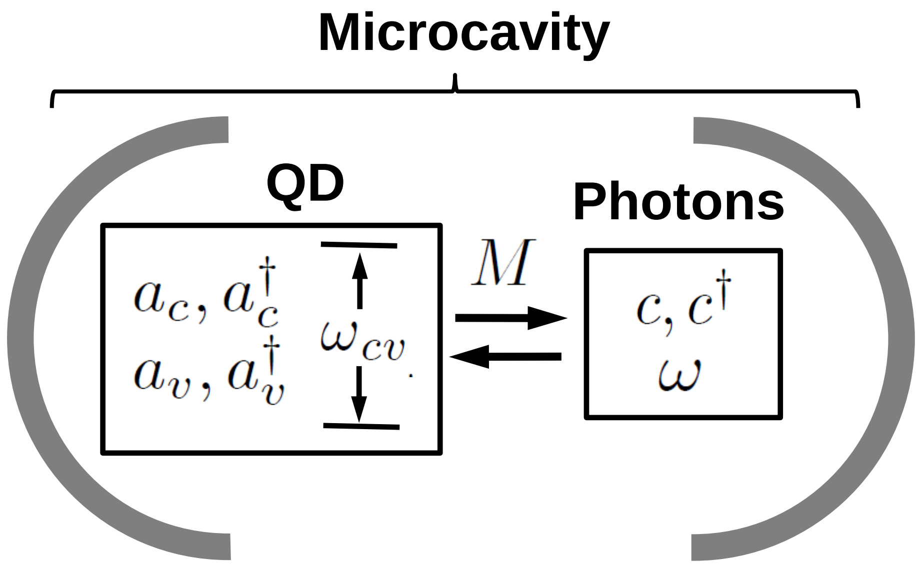
$$\psi(r_1, r_2, \ldots r_n) = \begin{vmatrix} \phi_a(r_1) & \phi_a(r_2) & \ldots & \phi_a(r_n) \\ \phi_b(r_1) & \phi_b(r_2) & \ldots & \phi_b(r_n) \\ \ldots & \ldots & \ldots & \ldots \\ \phi_g(r_1) & \phi_g(r_2) & \ldots & \phi_g(r_n) \end{vmatrix}$$

2nd quantization for easier bookkeeping

Anticommutation relation: $\left\{a_i, a_j^\dagger\right\} = a_i a_j^\dagger + a_j^\dagger a_i = \delta_{i,j}$

Electron annihilation and creation operators

Quantum optics with semiconductors



Hamiltonian

$$H = \hbar\omega_c a_c^\dagger a_c + \hbar_v a_v^\dagger a_v + \hbar\omega(c^\dagger c + 1/2) - \hbar M(a_v^\dagger a_c c^\dagger + c a_c^\dagger a_v)$$

+ Coulomb interaction

Polarization

$$\frac{d\left\langle a_v^\dagger a_c c^\dagger \right\rangle}{dt} = -i\left(\omega - \omega_c - \omega_v\right)\left\langle a_v^\dagger a_c c^\dagger \right\rangle$$
$$-iM\left\langle \left(a_c^\dagger a_c - a_v^\dagger a_v\right) c^\dagger c + a_c^\dagger a_c \left(1 - a_v^\dagger a_v\right)\right\rangle + \ldots$$

Mean Field Approximation

$$\frac{d\left\langle b_m^\dagger c_{ck}^\dagger c_{ak}\right\rangle}{dt} = \frac{i}{\hbar}\left(\hbar\omega_m - \varepsilon_{ak} - \varepsilon_{ck}\right)\left\langle b_m^\dagger c_{ck}^\dagger c_{ak}\right\rangle$$

$$+\frac{g_{km}}{\hbar}\left(\left\langle c_{ak}^\dagger c_{ak}\right\rangle - \left\langle c_{ck}^\dagger c_{ck}\right\rangle\right)\langle b_m^\dagger b_m\rangle \Longrightarrow \textbf{Stimulated emission}$$

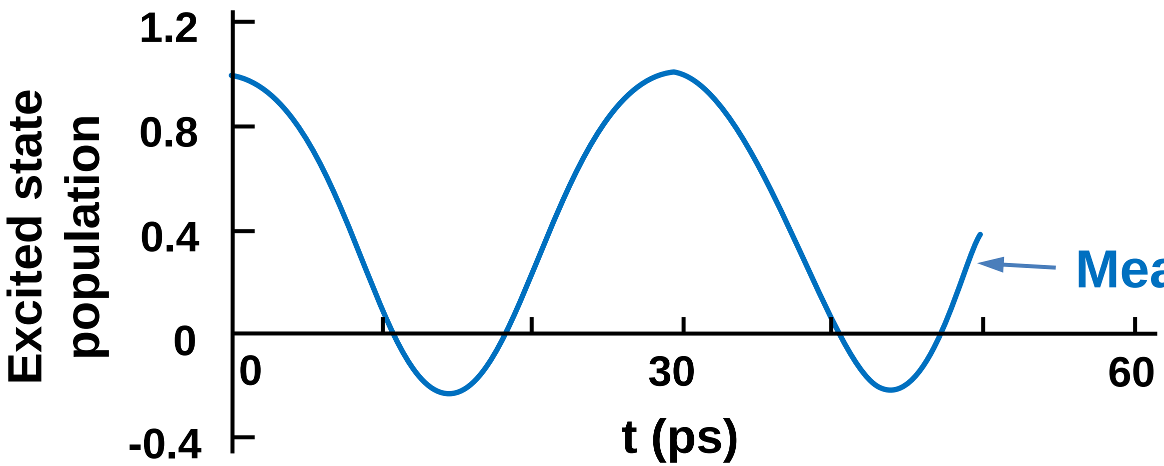
$$+\frac{g_{km}}{\hbar}\left\langle c_{ak}^\dagger c_{ak}\right\rangle\left(1 - \left\langle c_{ck}^\dagger c_{ck}\right\rangle\right) \Longrightarrow \textbf{Spontaneous emission}$$

Mean Field Approximation

$$\frac{d\left\langle b_m^\dagger c_{ck}^\dagger c_{ak}\right\rangle}{dt} = \frac{i}{\hbar}\left(\hbar\omega_m - \varepsilon_{ak} - \varepsilon_{ck}\right)\left\langle b_m^\dagger c_{ck}^\dagger c_{ak}\right\rangle$$

$$+\frac{g_{km}}{\hbar}\left(\left\langle c_{ak}^\dagger c_{ak}\right\rangle - \left\langle c_{ck}^\dagger c_{ck}\right\rangle\right)\left\langle b_m^\dagger b_m\right\rangle$$

$$+\frac{g_{km}}{\hbar}\left\langle c_{ak}^\dagger c_{ak}\right\rangle\left(1 - \left\langle c_{ck}^\dagger c_{ck}\right\rangle\right) \longrightarrow BN_eN_h \longrightarrow BN^2$$

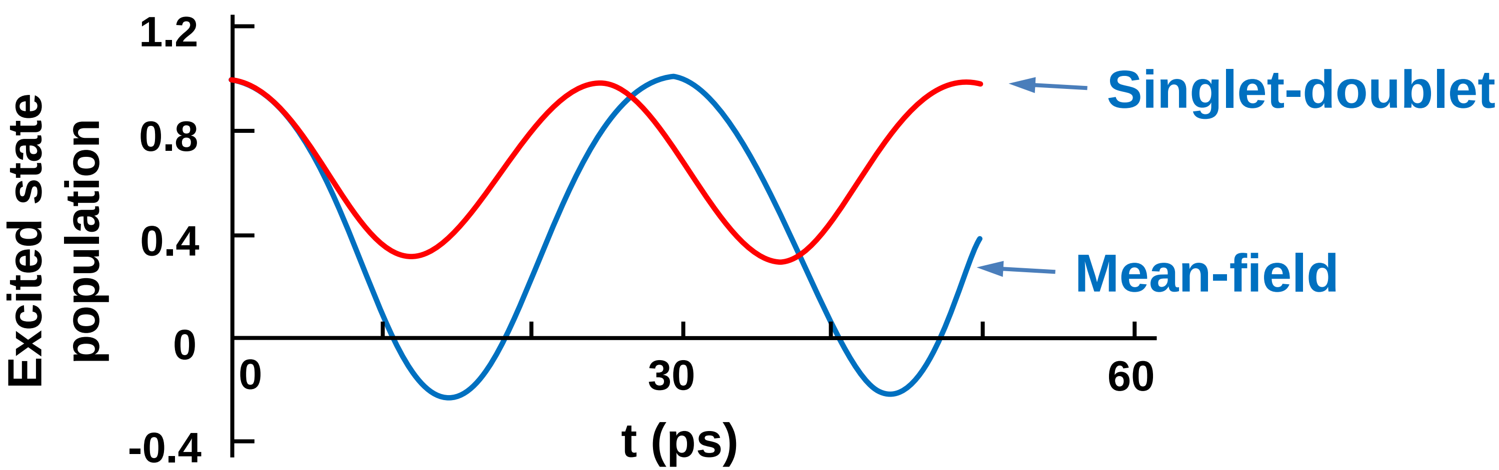


Beyond Mean Field Approximation

Baer, Gies, Wiersig and Jahnke, Eur. Phys. J. B **50**, 411 (2006)

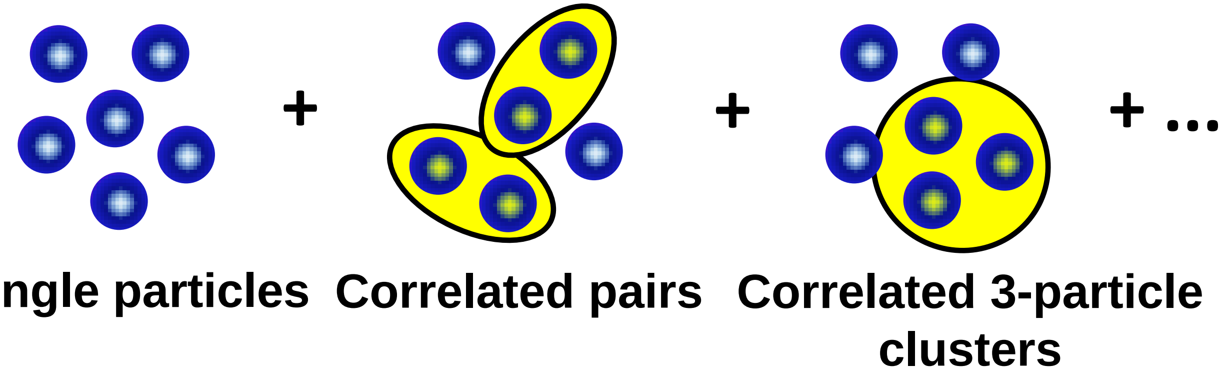
$$\frac{d\left\langle b^\dagger_m c^\dagger_{ck} c_{ak}\right\rangle}{dt} = \frac{i}{\hbar}\left(\hbar\omega_m - \varepsilon_{ak} - \varepsilon_{ck}\right)\left\langle b^\dagger_m c^\dagger_{ck} c_{ak}\right\rangle$$
$$+\frac{g_{km}}{\hbar}\left(\left\langle c^\dagger_{ak} c_{ak}\right\rangle - \left\langle c^\dagger_{ck} c_{ck}\right\rangle\right)\left\langle b^\dagger_m b_m\right\rangle$$
$$+\frac{g_{km}}{\hbar}\left\langle c^\dagger_{ak} c_{ak}\right\rangle\left(1 - \left\langle c^\dagger_{ck} c_{ck}\right\rangle\right)\boxed{+\frac{g_{km}}{\hbar}C^x_k + \frac{g_{km}}{\hbar}C^y_{km}}$$

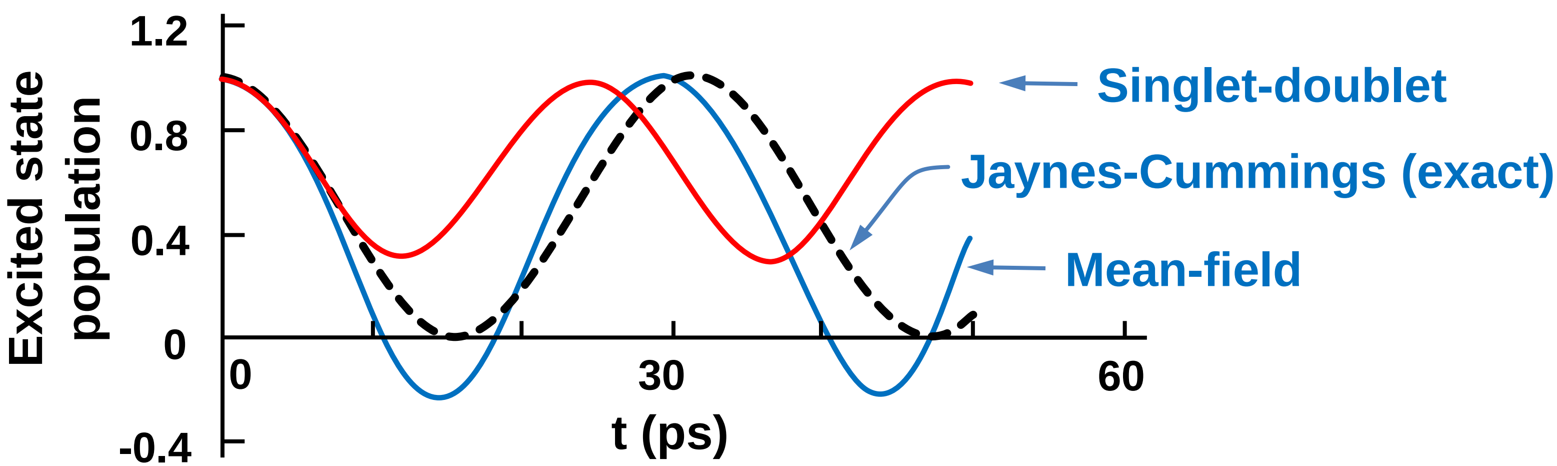
$$\frac{dC^x_k}{dt} = \sum_m \left(\frac{g^*_{km}}{\hbar}\left\langle b^\dagger c^\dagger_c c_a\right\rangle + \frac{g_{km}}{\hbar}\left\langle c^\dagger_{ak} c_{ck} b_m\right\rangle\right)\left(\left\langle c^\dagger_{ak} c_{ak}\right\rangle - \left\langle c^\dagger_{ck} c_{ck}\right\rangle\right)$$
$$\frac{dC^y_{km}}{dt} = -\left(\frac{g^*_{km}}{\hbar}\left\langle b^\dagger c^\dagger_c c_a\right\rangle + \frac{g_{km}}{\hbar}\left\langle c^\dagger_{ak} c_{ck} b_m\right\rangle\right)\left[\left\langle c^\dagger_{ak} c_{ak}\right\rangle - \left\langle c^\dagger_{ck} c_{ck}\right\rangle + 2\left\langle b^\dagger_m b_m\right\rangle\right]$$



Cluster expansion

$$\langle \widehat{N} \rangle =$$





Semiconductor luminescence theory

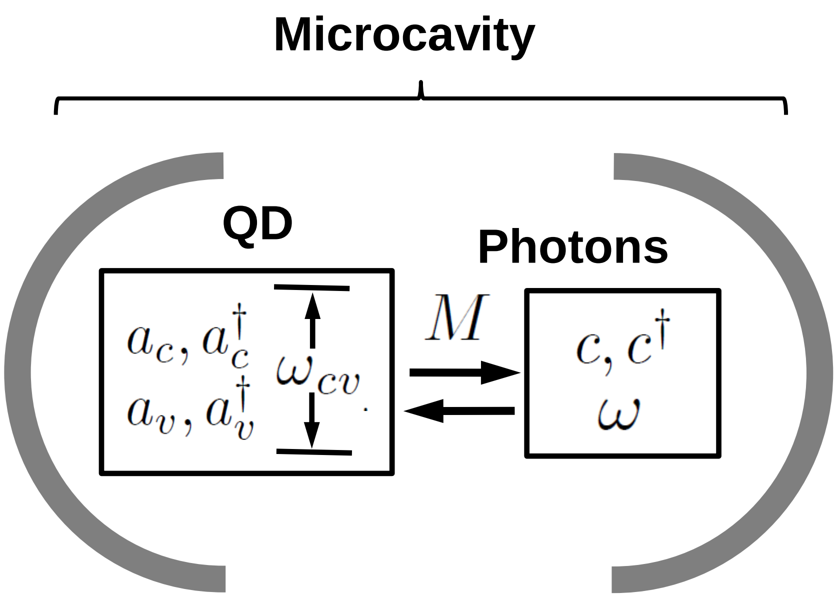
Semiconductor microcavity-QED

What about higher order correlations?
- **How to get them**
- **How high is needed**

Berlin/Sandia:

Single-transition in quantum dot + photon mode

Quantum-dot cavity-quantum-electrodynamics (QD-CQED)



Complete problem description with dressed (photon-assisted) electronic operator combinations

$$G^{p,s} = \langle a_v^\dagger a_v c^{\dagger p} c^s \rangle$$

$$E^{p,s} = \langle a_c^\dagger a_c c^{\dagger p} c^s \rangle$$

$$T^{p,s} = \langle a_v^\dagger a_c c^{\dagger p} c^s \rangle$$

$$G_{n,m}^{p,s} = \left\langle a_v^\dagger a_v c^{\dagger p} c^s b^{\dagger n} b^m \right\rangle$$

$$E_{n,m}^{p,s} = \left\langle a_c^\dagger a_c c^{\dagger p} c^s b^{\dagger n} b^m \right\rangle$$

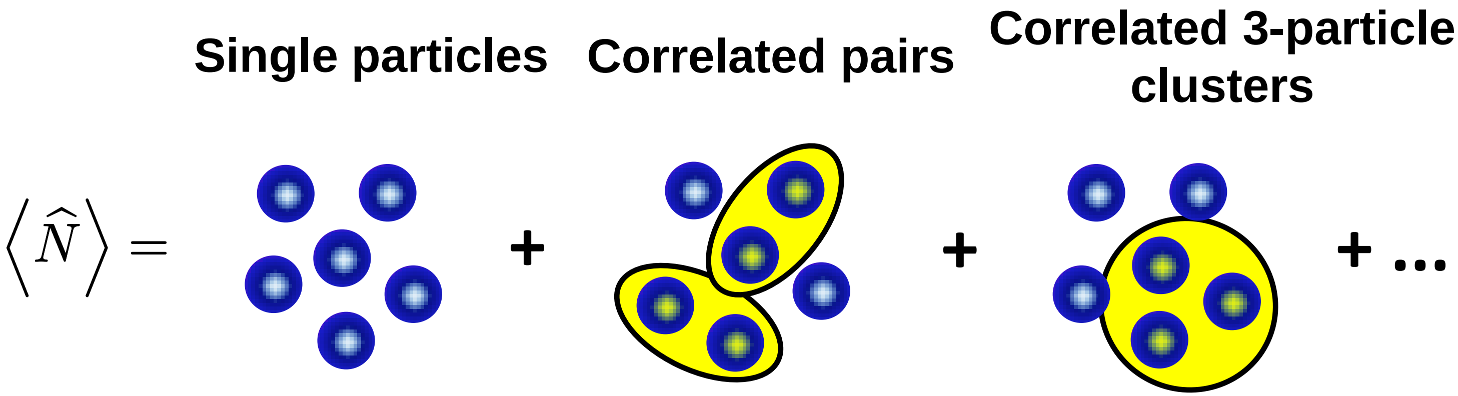
$$T_{n,m}^{p,s} = \left\langle a_v^\dagger a_c c^{\dagger p} c^s b^{\dagger n} b^m \right\rangle$$

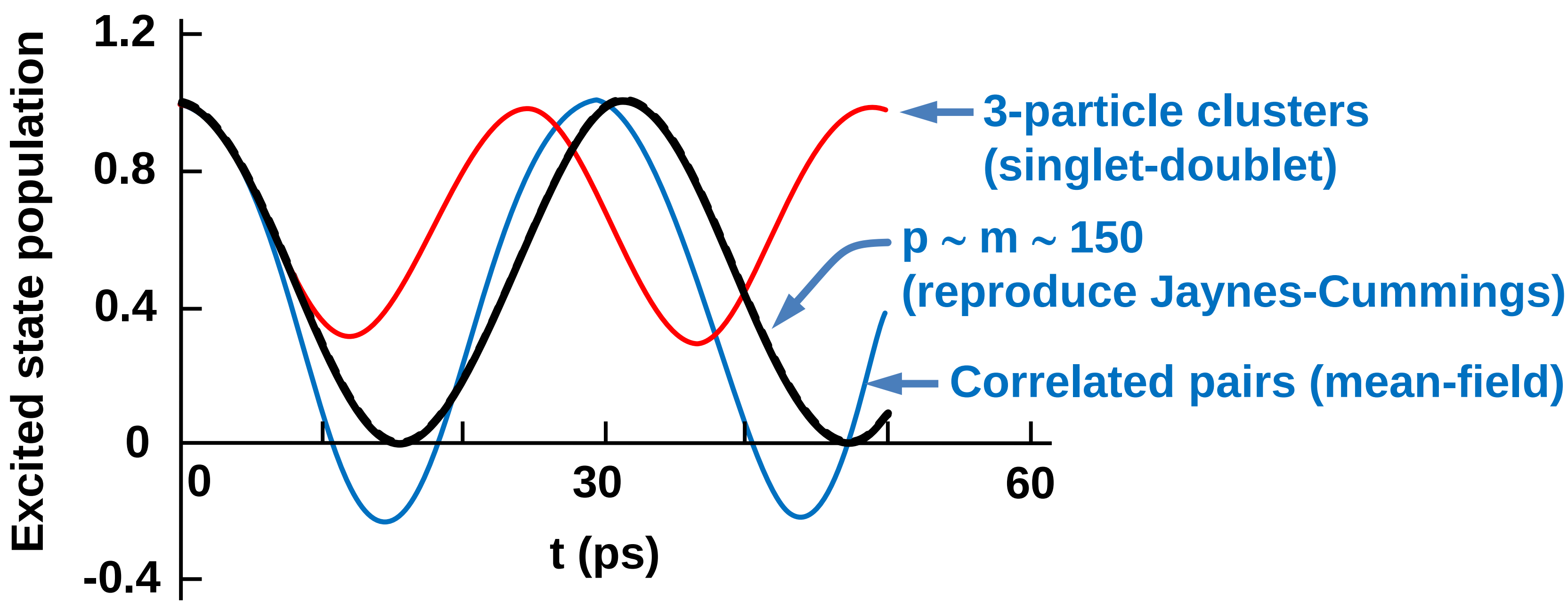
$$\begin{aligned} \partial_t G_{n,m}^{p,s} &= -\left[i(m-n)\omega_{LO} + i(p-s)\omega - (p+s)\kappa \right] G_{n,m}^{p,s} \\ &\quad + iMT_{n,m}^{p+1,s} - iM\left(T_{m,n}^{s+1,p}\right)^* + isMT_{n,m}^{p,s-1} \\ &\quad - ipM^*\left(T_{m,n}^{s,p-1}\right)^* \end{aligned}$$

$$\begin{aligned} \partial_t T_{n,m}^{p,s} &= -i\left[\omega_{cv} - (p-s)\omega + (m-n)\omega_{LO}\right] T_{n,m}^{p,s} \\ &\quad -(p+s)\kappa T_{n,m}^{p,s} - iT_{n,m+1}^{p,s} - iT_{n+1,m}^{p,s} \\ &\quad -iM^*(pE_{n,m}^{p-1,s} + E_{n,m}^{p,s+1} - G_{n,m}^{p,s+1}) \end{aligned}$$

$$\begin{aligned} \partial_t E_{n,m}^{p,s} &= -\left[i(m-n)\omega_{LO} + i(p-s)\omega + (p+s)\kappa \right] E_{n,m}^{p,s} \\ &\quad -i\ MT_{n,m}^{p+1,s} + i\ M\left(T_{m,n}^{s+1,p}\right)^* \end{aligned}$$

Cluster expansion



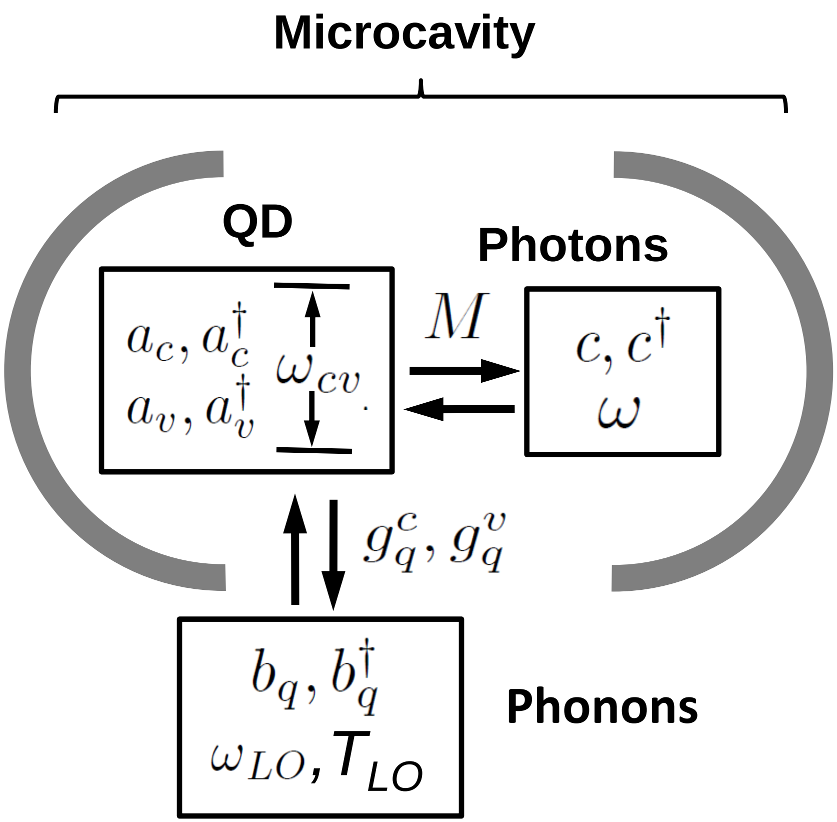


Berlin/Sandia:

Single-transition in quantum dot + photon mode + phonon bath

$\underbrace{\text{Single-transition in quantum dot + photon mode}}$

Quantum-dot cavity-quantum-electrodynamics (QD-CQED)



Complete problem description with dressed (photon- and phonon-assisted) electronic operator combinations

$$G^{p,s}_{n,m} = \langle a_v^\dagger a_v c^{\dagger p} c^s \underline{b^{\dagger n} b^m} \rangle$$

$$E^{p,s}_{n,m} = \langle a_c^\dagger a_c c^{\dagger p} c^s \underline{b^{\dagger n} b^m} \rangle$$

$$T^{p,s}_{n,m} = \langle a_v^\dagger a_c c^{\dagger p} c^s \underline{b^{\dagger n} b^m} \rangle$$

$$\sum_q (g_q^c - g_q^v) b_q$$

(Beyond typical 2nd Born approx. reservoir theory)

Carmele, Kabuss, Richter, Richter, Knorr & Chow and Knorr, J. Modern Optics 58, 1951 (2011)

$$G^{p,s}_{n,m} = \left\langle a_v^\dagger a_v c^{\dagger p} c^s b^{\dagger n} b^m \right\rangle$$

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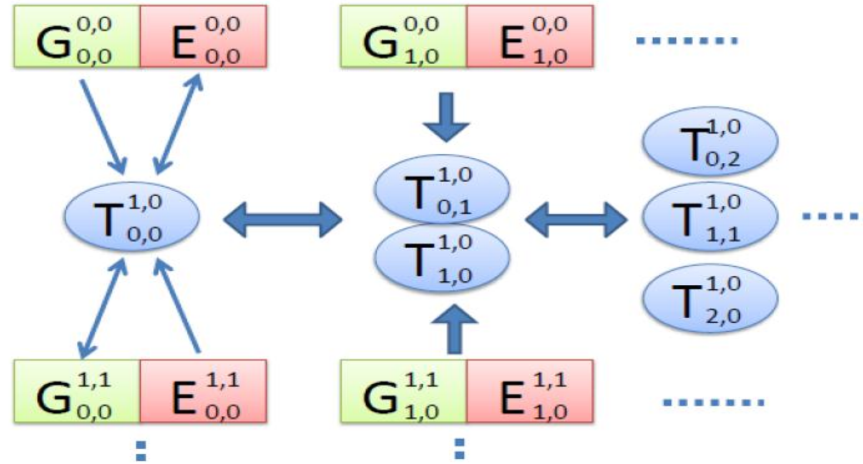
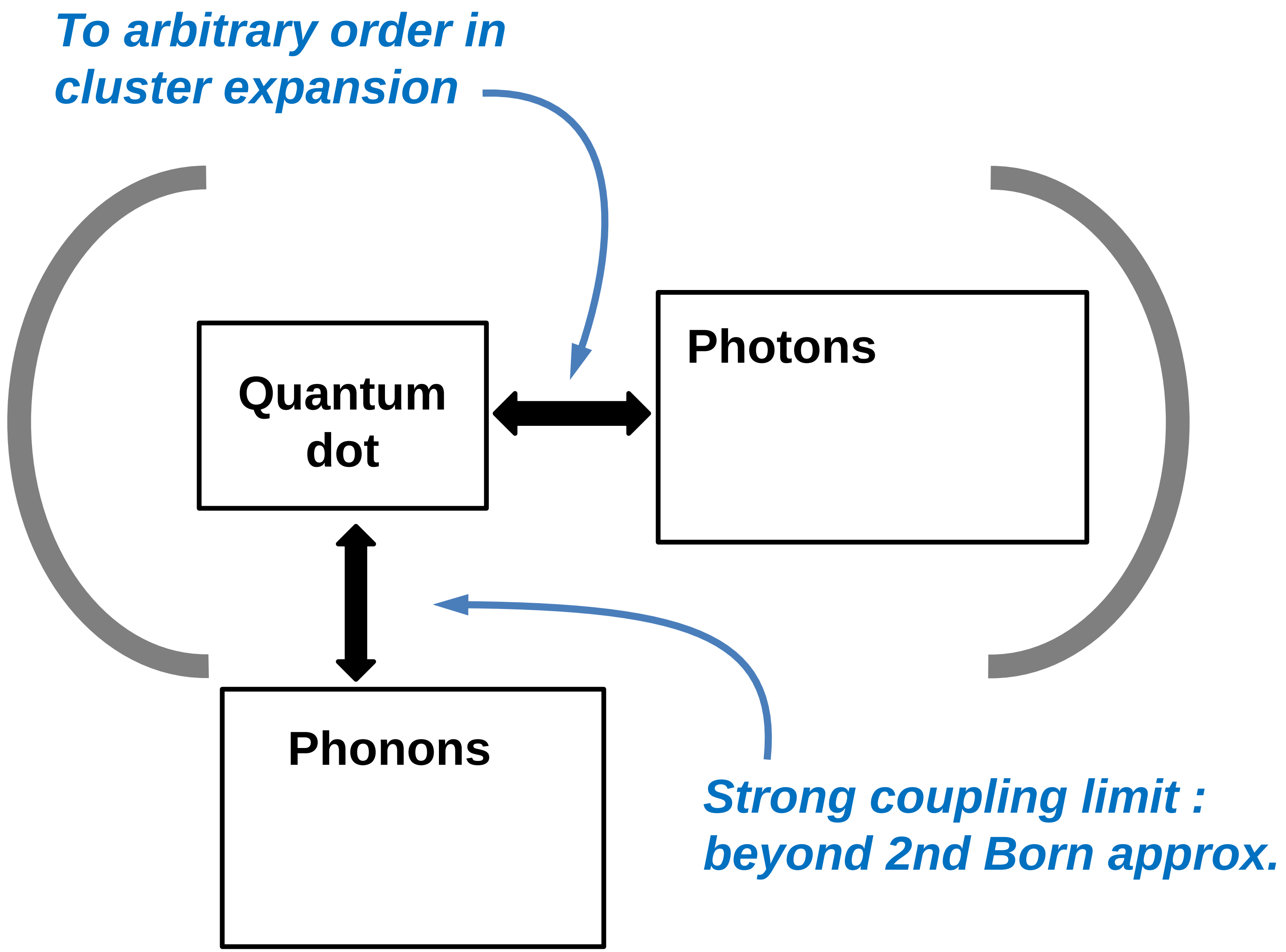


$$\begin{aligned}
\partial_t G^{p,s}_{n,m} &= -\left[i(m-n)\omega_{LO} + i(p-s)\omega - (p+s)\kappa\right] G^{p,s}_{n,m} \\
&\quad + iMT^{p+1,s}_{n,m} - iM\left(T^{s+1,p}_{m,n}\right)^* + isMT^{p,s-1}_{n,m} \\
&\quad - ipM^*\left(T^{s,p-1}_{m,n}\right)^* \boxed{+ ing_v G^{p,s}_{n-1,m} - img_v^* G^{p,s}_{n,m}}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

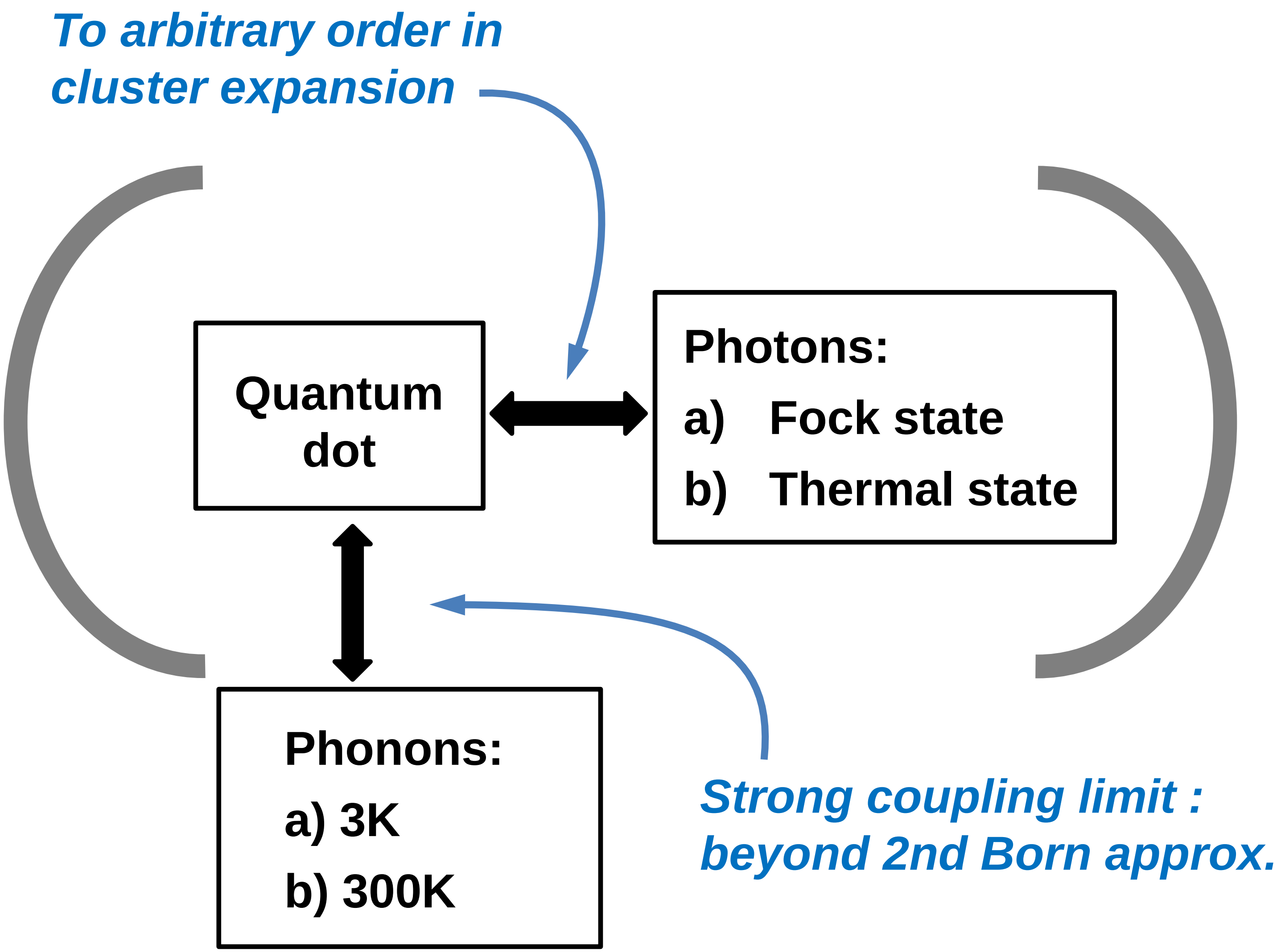
$$\begin{aligned}
\partial_t T^{p,s}_{n,m} &= -i\left[\omega_{cv} - (p-s)\omega + (m-n)\omega_{LO}\right] T^{p,s}_{n,m} \\
&\quad -(p+s)\kappa T^{p,s}_{n,m} - iT^{p,s}_{n,m+1} - iT^{p,s}_{n+1,m} \\
&\quad -iM^*(pE^{p-1,s}_{n,m} + E^{p,s+1}_{n,m} - G^{p,s+1}_{n,m}) \\
&\quad \boxed{+ing^v T^{p,s}_{n-1,m} - img_c^* T^{p,s}_{n,m-1}}
\end{aligned}$$

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

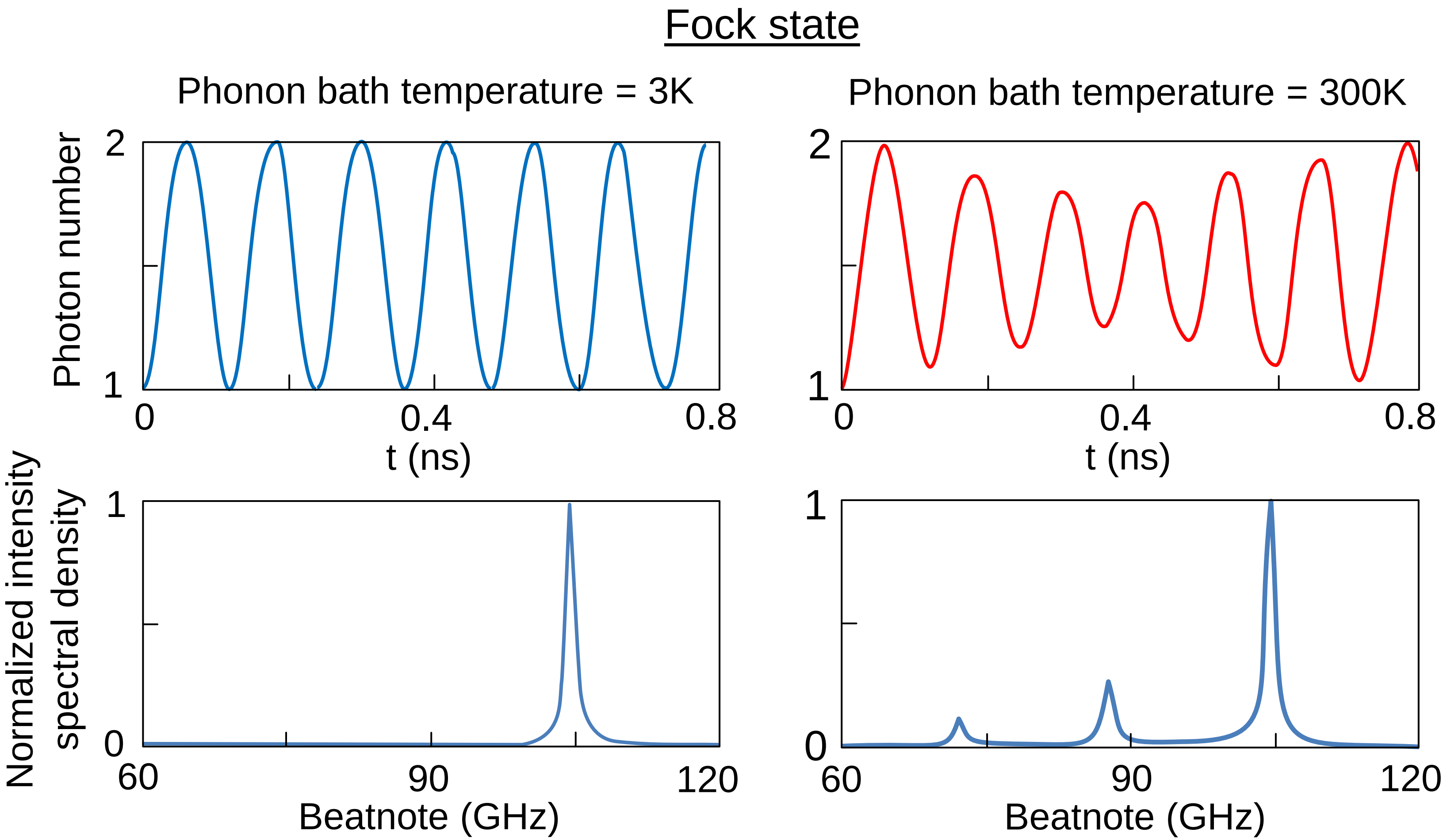
Exercise #1: Strongly interacting quantum-dot/photon/phonon-bath



Exercise #1: Strongly interacting quantum-dot/photon/phonon-bath



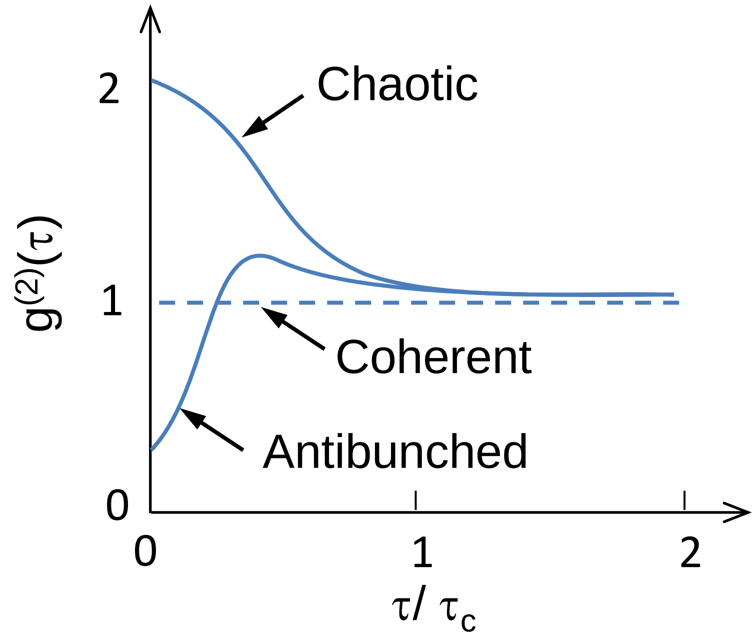
Look at photon statistics


Fock state
Phonon bath temperature = 3K
Phonon bath temperature = 300K
Photon number
2
1
0
0.4
0.8
t (ns)
Normalized intensity spectral density
1
0
60
90
120
Beatnote (GHz)

2^{nd}-order correlation function

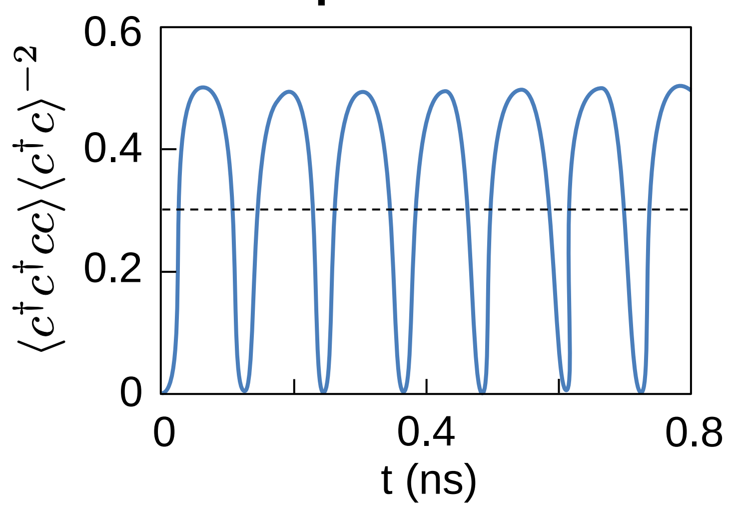
$$g^{(2)}(\tau) = \frac{\langle I(t)\, I(t+\tau)\rangle}{\langle I(t)\rangle^2}$$

$$= \frac{\langle c^\dagger(t)\, c^\dagger(t+\tau)\, c(t+\tau)\, c(t)\rangle}{\langle c^\dagger(t)\, c(t)\rangle \langle c^\dagger(t+\tau)\, c(t+\tau)\rangle}$$

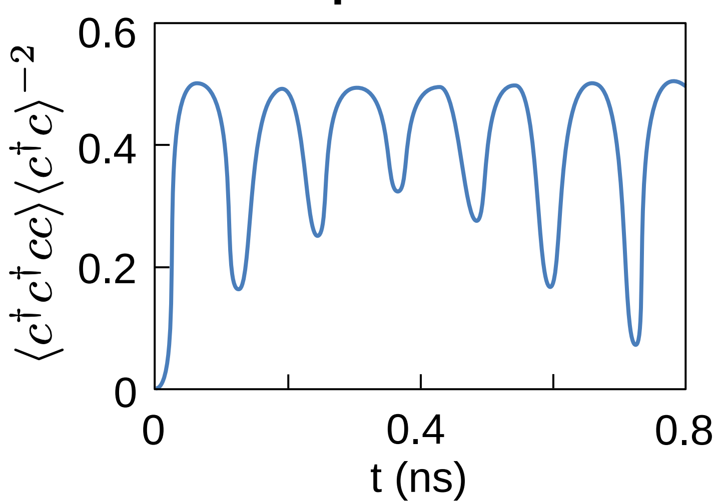


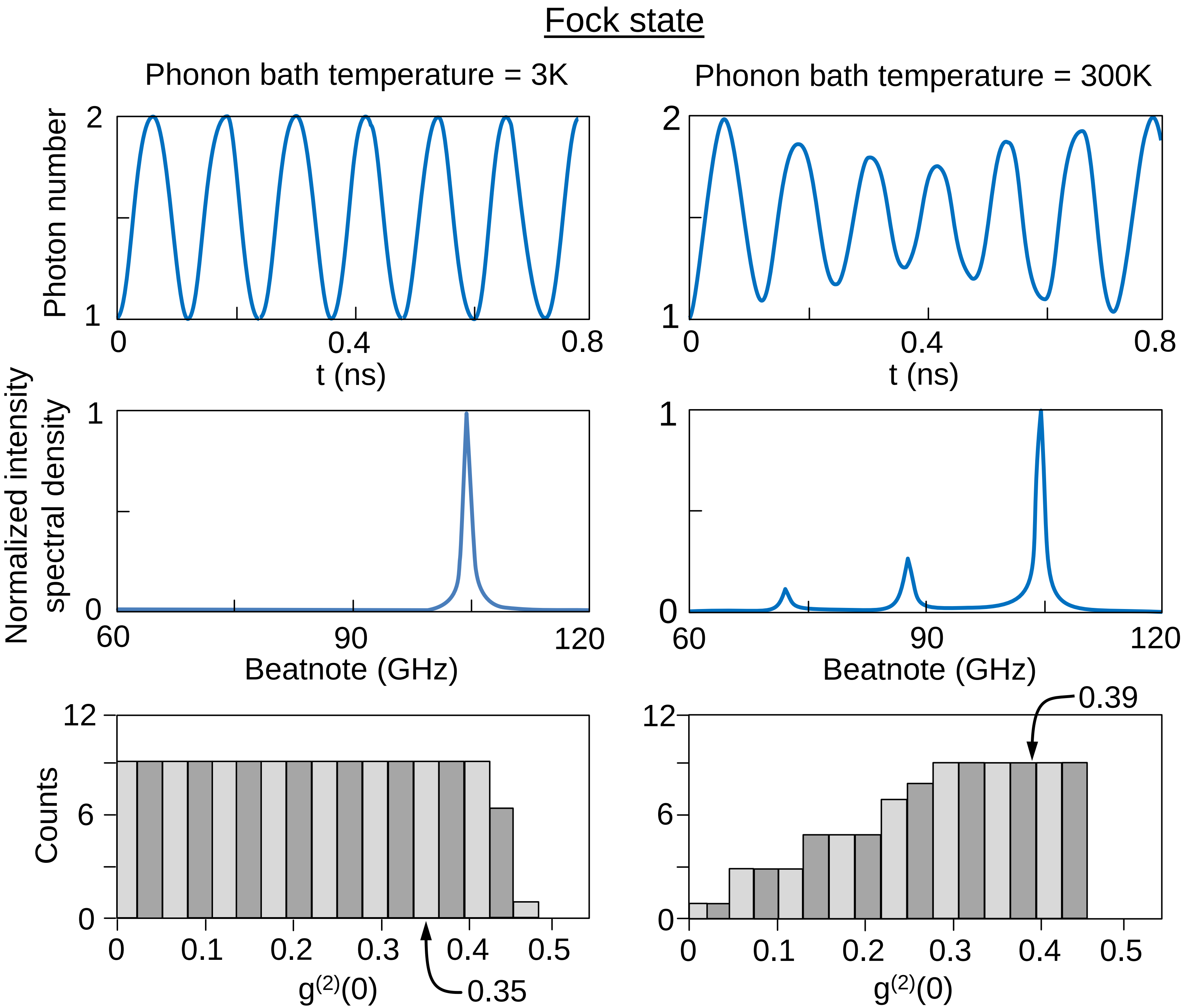
Fock state

3K phonon bath

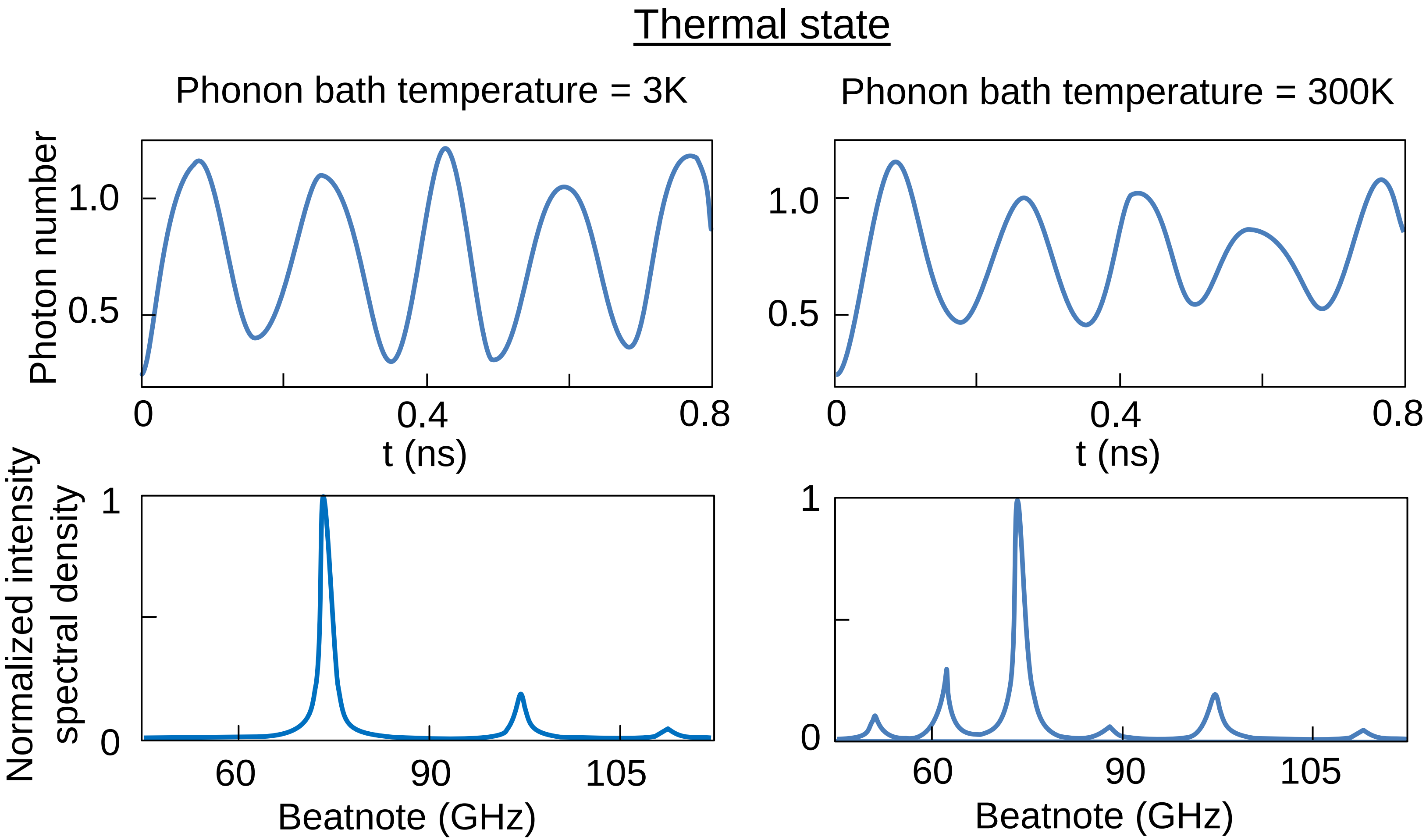


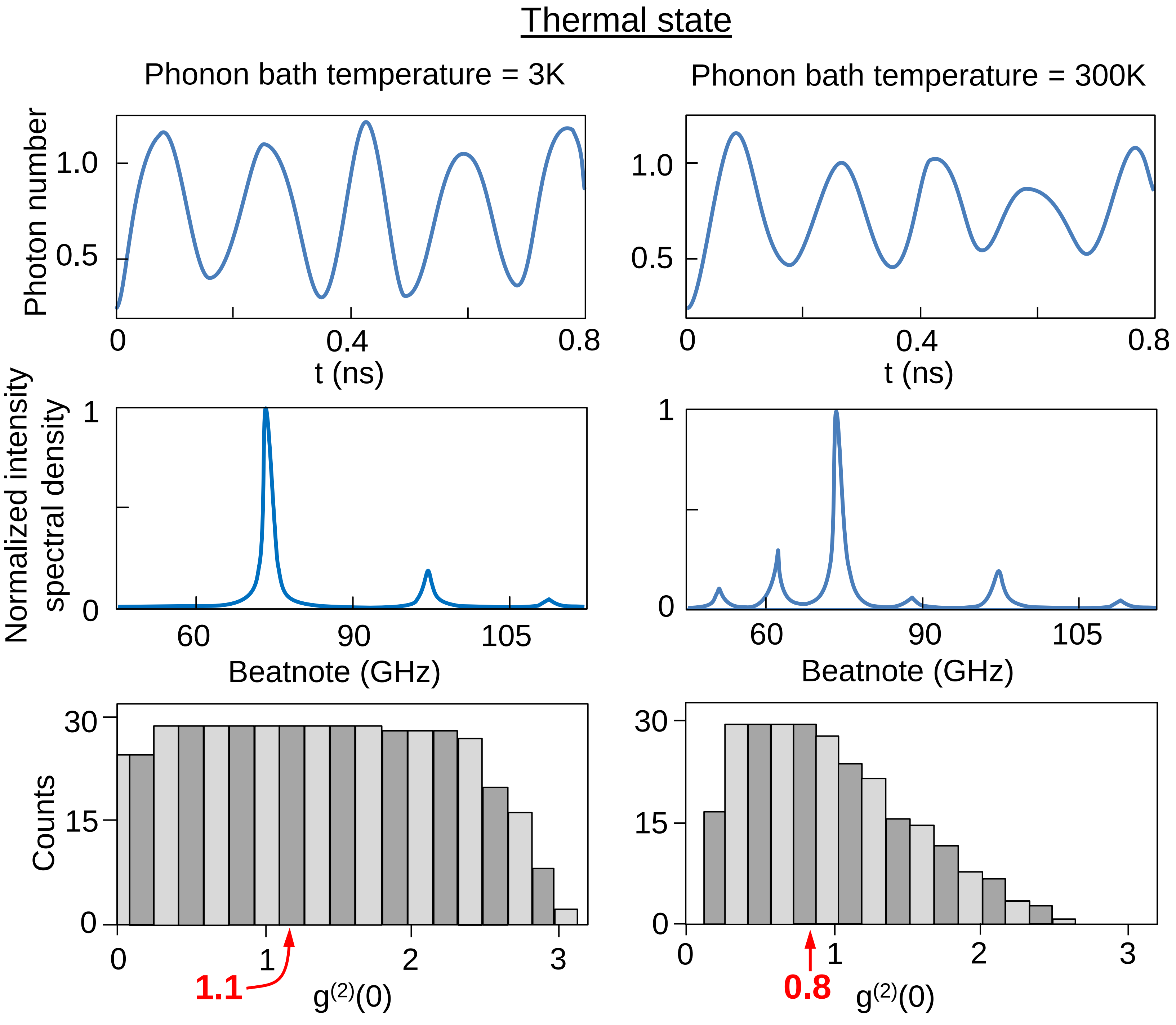
300K phonon bath



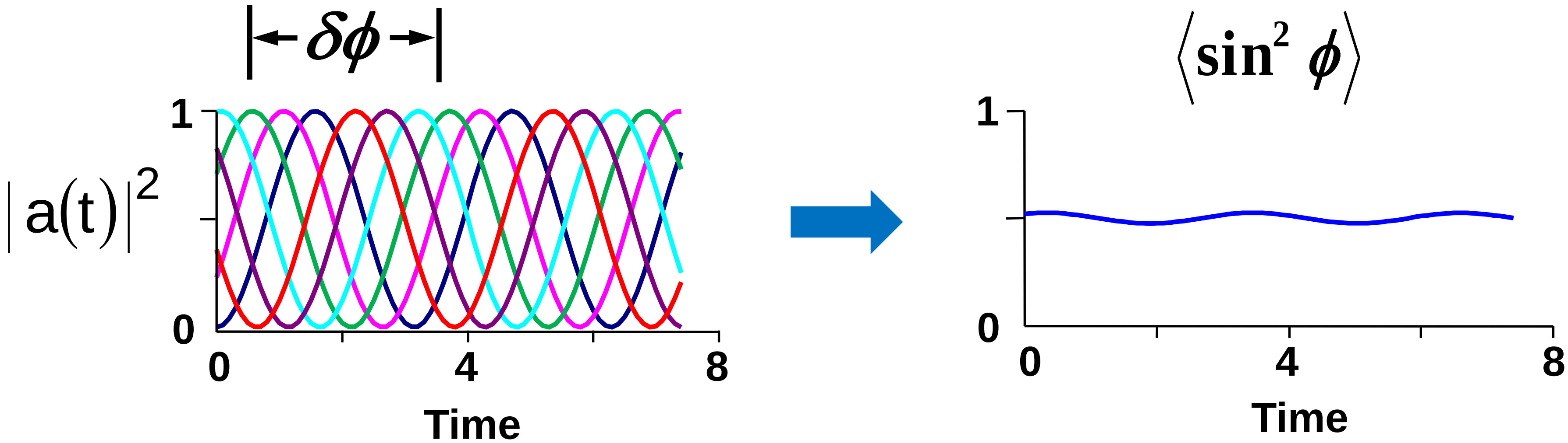


Fock state
Phonon bath temperature = 3K
Phonon bath temperature = 300K
Photon number
2
1
0
0.4
0.8
t (ns)
Normalized intensity spectral density
1
0
60
90
120
Beatnote (GHz)
Counts
12
6
0
0.1
0.2
0.3
0.4
0.5
g(2)(0)
0.35
0.39

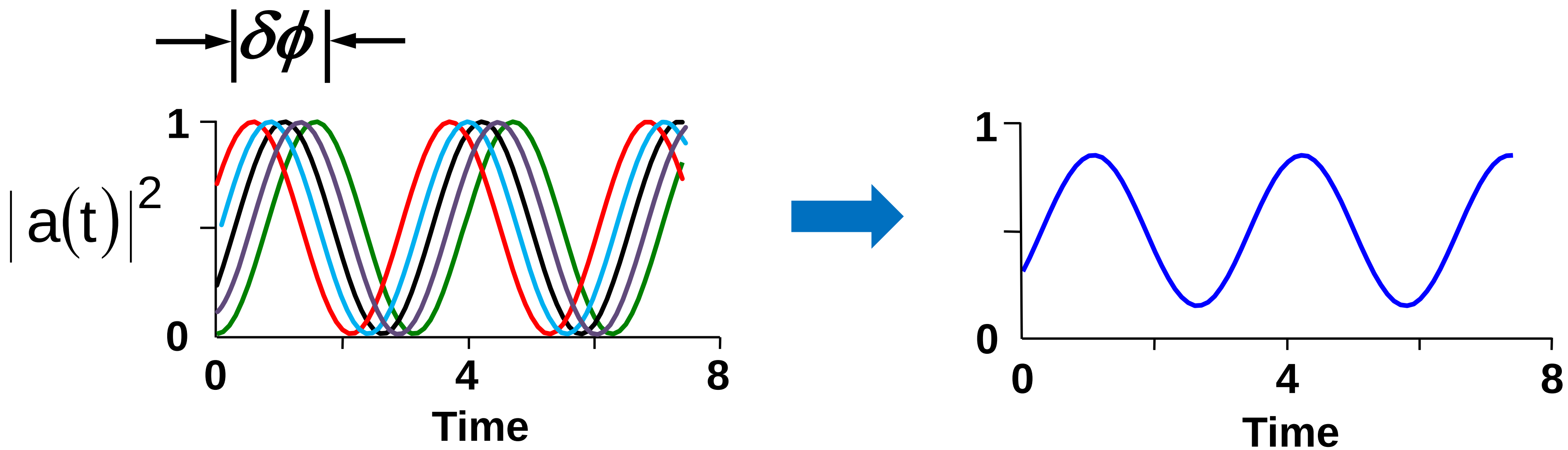

Thermal state
Phonon bath temperature = 3K
Phonon bath temperature = 300K
Photon number
1.0
0.5
0
0.4
0.8
t (ns)
1.0
0.5
0
0.4
0.8
t (ns)
Normalized intensity
spectral density
1
0
60
90
105
Beatnote (GHz)
1
0
60
90
105
Beatnote (GHz)


Thermal state
Phonon bath temperature = 3K
Phonon bath temperature = 300K
Photon number
1.0
0.5
0
0.4
0.8
t (ns)
Normalized intensity
spectral density
1
0
60
90
105
Beatnote (GHz)
Counts
30
15
0
1
2
3
g(2)(0)
1.1
0.8

Dephasing rate > Rabi frequency -- Rate equation limit



Dephasing rate < Rabi frequency -- Strong coupling limit

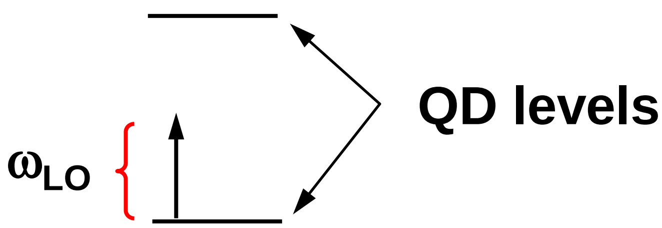


Warning sign that QW techniques may not work for QD laser theory

Rate for carrier-phonon scattering (2nd Born approx.)

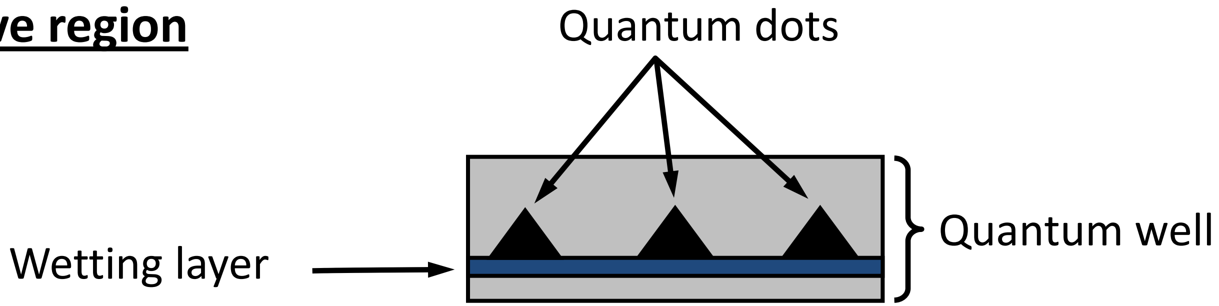
$$\Lambda^{c-p}_{\alpha\beta q} = \frac{1}{\hbar} G_q^2 \left\{ \left[(1-n_\alpha)\, n_q^{ph} + n_\alpha \left(1 + n_q^{ph}\right) \right] \frac{1}{\gamma - i\left(\varepsilon_\alpha - \varepsilon_\beta \mp \hbar\omega_{LO}\right)} + ... \right\}$$

Phonon bottleneck problem

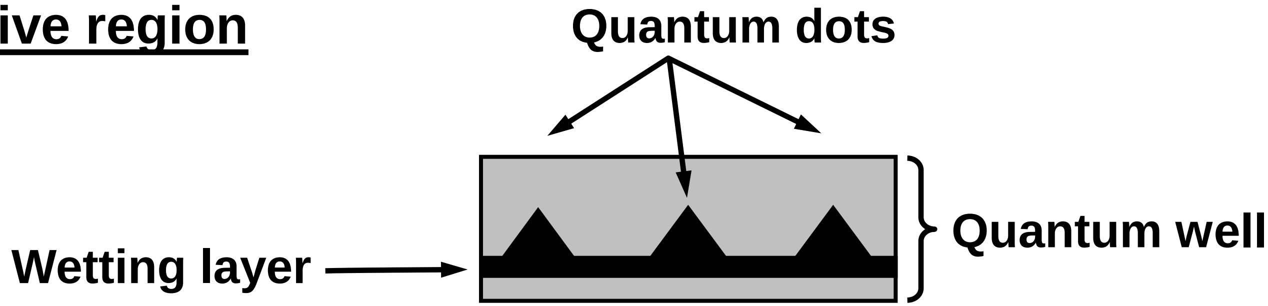


But indications of phonon bottleneck were not found in present devices

Active region



Active region



Dot-Well Hamiltonian

discrete for QD
continuous for QW

$$H = \sum_n \varepsilon_n a_n^\dagger a_n + \sum_m \varepsilon_m b_m^\dagger b_m$$

Single-particle

$$- \sum_{n,m} \left(\mu_{nm} a_n^\dagger b_m^\dagger + \mu_{nm}^* b_m a_n \right) E\left(z,t\right)$$

Light-matter interaction

$$+ \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger a_s^\dagger a_m a_n + \frac{1}{2} \sum_{n,m,r,s} W_{nm}^{rs} b_r^\dagger b_s^\dagger b_m b_n - \sum_{n,m,r,s} W_{nm}^{rs} a_r^\dagger b_s^\dagger b_m a_n$$

$$+ \sum_{n,q} \hbar G_q a_{n+q}^\dagger a_n \left(b_q + b_{-q}^\dagger \right)$$

Carrier - phonon

Carrier - carrier

Coulomb matrix element

$$W_{nk}^{rk'} = \int d^3 r\, d^3 r'\, \phi_r^* \left(\mathbf{r}\right) \phi_{k'}^* \left(\mathbf{r}'\right) \frac{e^2}{4\pi\varepsilon_b \left|\mathbf{r} - \mathbf{r}'\right|} \phi_k \left(\mathbf{r}'\right) \phi_n \left(\mathbf{r}\right)$$

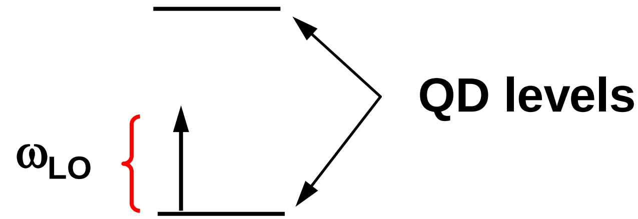
Polarization equation of motion

$$\frac{dp_\alpha}{dt} = -i\omega_\alpha p_\alpha - i\Omega_\alpha \left(n_{e\alpha} + n_{h\alpha} - 1\right)$$
$$+S_\alpha^{c-c} + S_\alpha^{c-p}$$

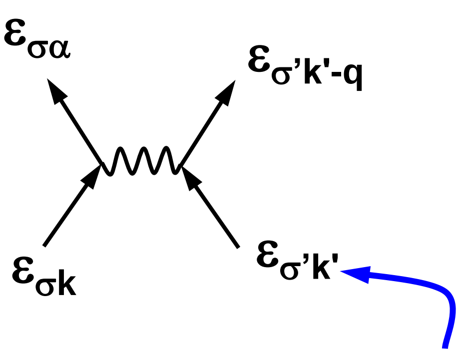
Extra care with quantum dots

$$\frac{dp_\alpha}{dt} = -i\omega_\alpha p_\alpha - i\Omega_\alpha \left(n_{e\alpha} + n_{h\alpha} - 1\right)$$
$$+S_\alpha^{c-c} + S_\alpha^{c-p}$$

(1) Phonon bottleneck problem



(2) Carrier-carrier scattering



Must use renormalized energies
Memory effects important

(Schneider, et al, PRB **70**, 235308, 2004)

Perturbative (2nd Born) treatment overestimates problem

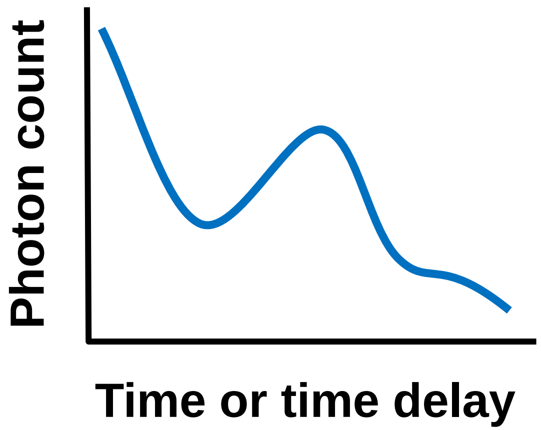
Corrected with polaron (nonperturbative) description

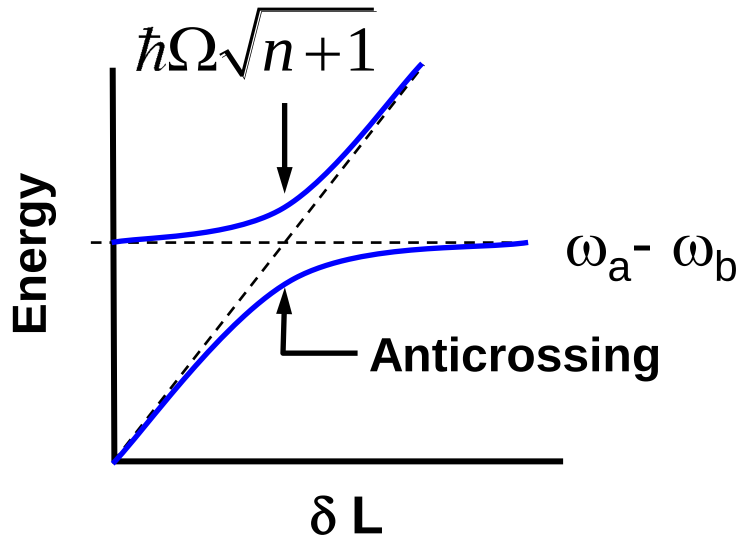
(Inoshita, Sakaki, PRB 56,4355, 1997; Seebeck et al, PRB **71**, 125327, 2005)

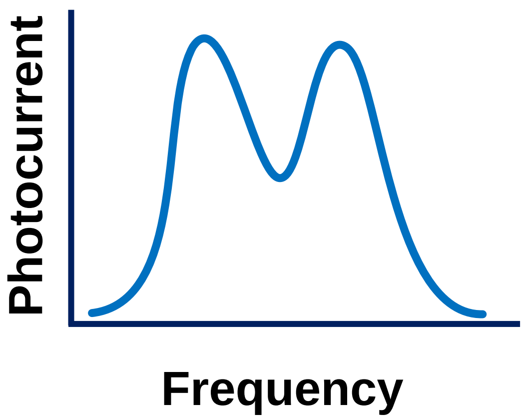
$$-p_\alpha \int_0^\infty dt' \sum_{\mathbf{k}} \left|\frac{M_{\alpha k}}{\hbar}\right|^2 \sum_{\sigma=e,h} G_{k_\sigma}(t')\, G_{\alpha_\sigma}(t')\, e^{i(\varepsilon_{\alpha\sigma}-\varepsilon_{k\sigma})t'/\hbar}$$
$$\times \Big\{ (1-n_{k\sigma}) \left[n_{LO} e^{i\omega_{LO}t'} + (n_{LO}+1)\, e^{-i\omega_{LO}t'} \right]$$
$$+ n_{k\sigma} \left[(n_{LO}+1)\, e^{i\omega_{LO}t'} + n_{LO} e^{-i\omega_{LO}t'} \right] \Big\}$$

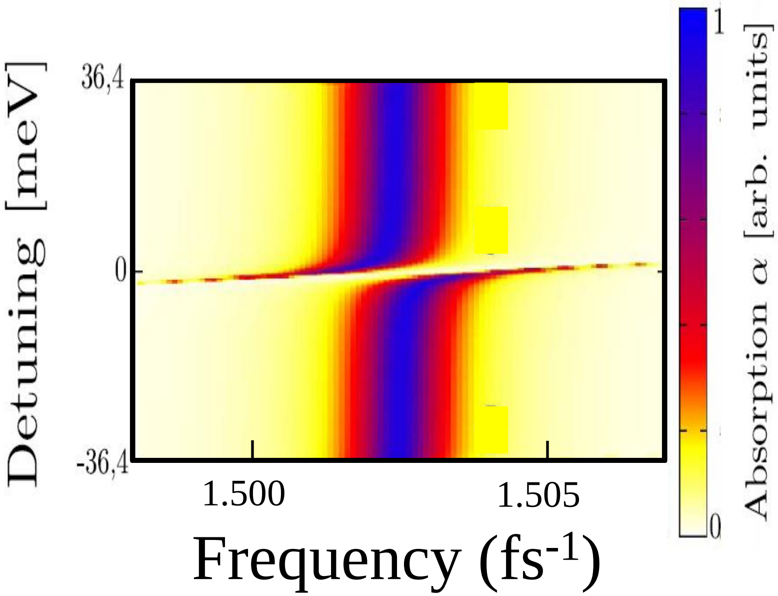
$$\frac{dG_{\alpha_\sigma}(t)}{dt} = -\int_0^t dt' \left[(n_{LO}+1)\, e^{-i\omega_{LO}t'} + n_{LO} e^{i\omega_{LO}t'} \right]$$
$$\times G_{\alpha_\sigma}(t-t') \sum_{\beta_{\sigma'}} \frac{\left|M_{\alpha_\sigma,\beta_{\sigma'}}\right|^2}{\hbar^2} G_{\beta_{\sigma'}}(t') \exp\left[i \frac{\varepsilon_{\alpha_\sigma} - \varepsilon_{\beta_{\sigma'}}}{\hbar} t' \right]$$

Rabi oscillations with dephasing



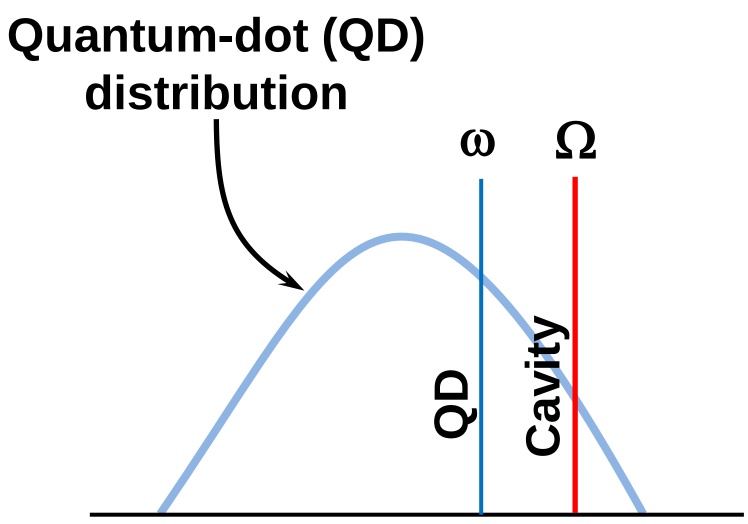






Detuned Rabi oscillation in a strongly-interacting QD-photon-phonon system

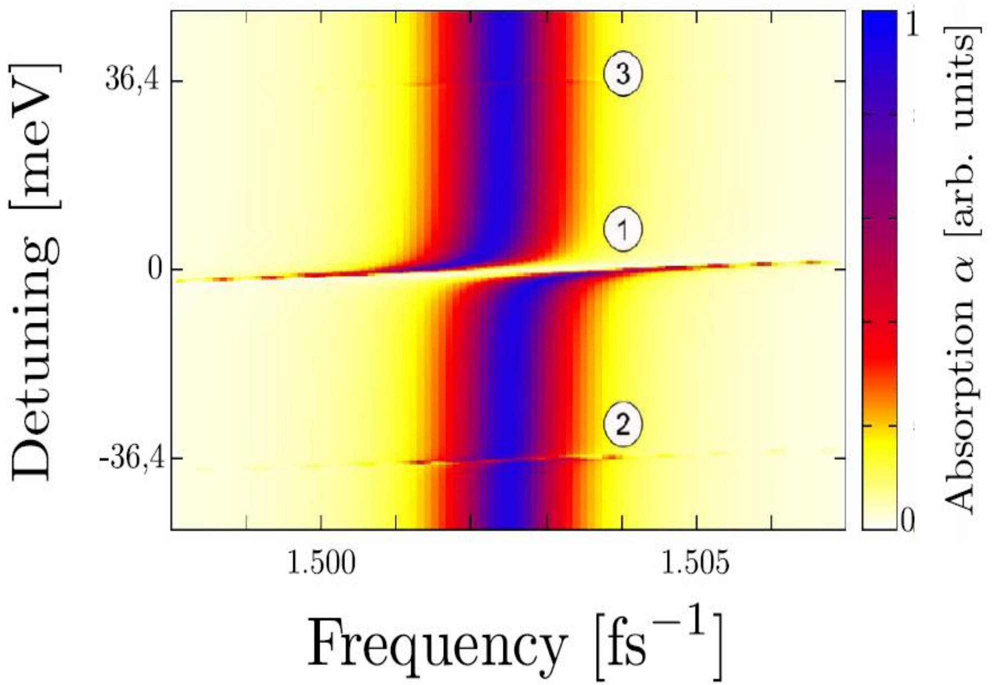
Conventional quantum optics



$$\Omega_R' = \sqrt{\left(\wp E_p/\hbar\right)^2 + (\Omega - \omega)^2}$$

Only on-resonant anticrossing

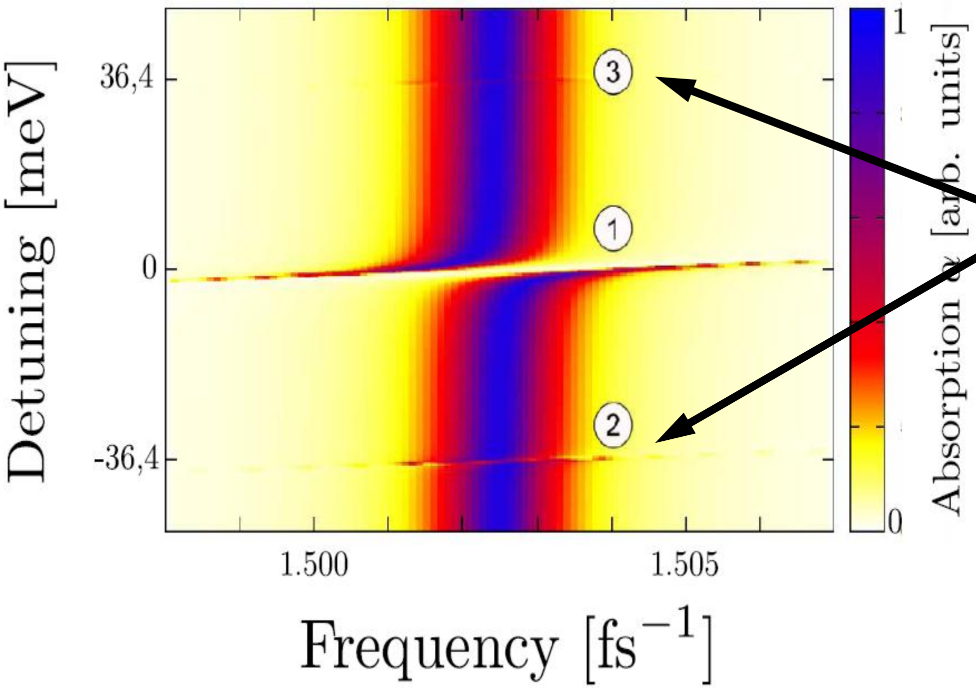
Semiconductor quantum optics



Phonon-assisted strong light-matter coupling

Carmele, Kabuss and Chow
submitted to Optics Express

Phonon statistics



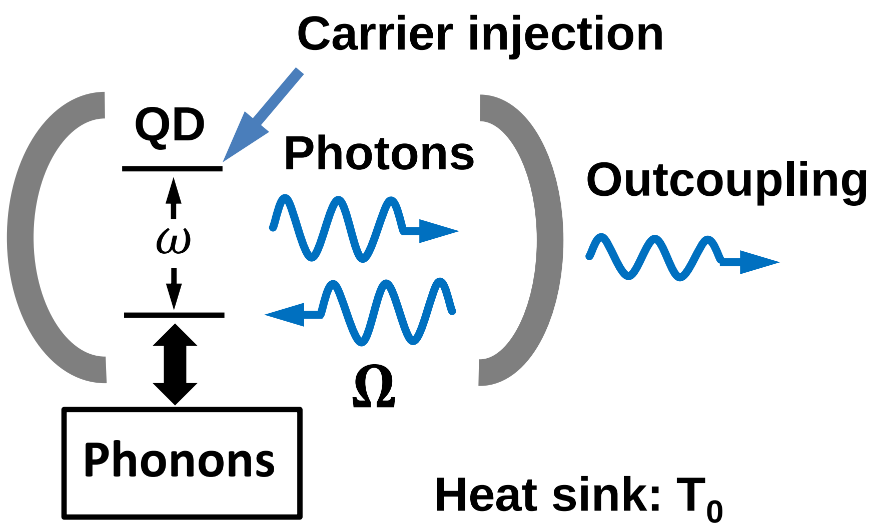
Anticrossings at +/- LO-phonon energy detuning

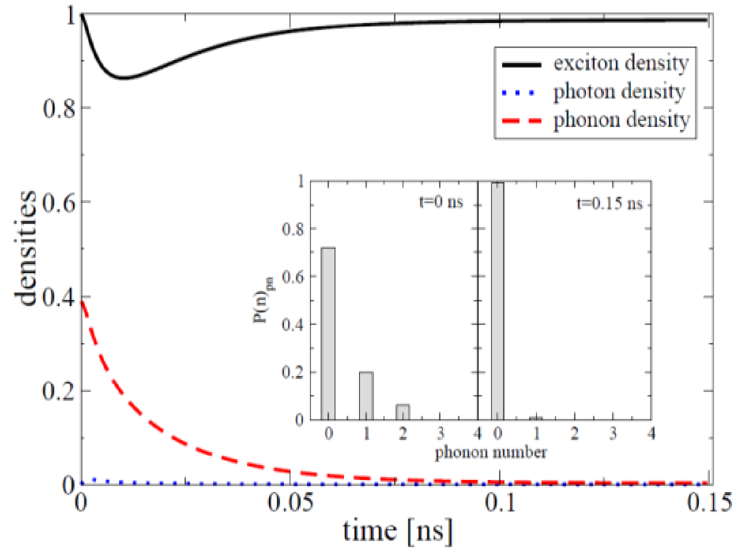
Phonon-assisted strong-coupling can change phonon population and statistics

Substrate temperature

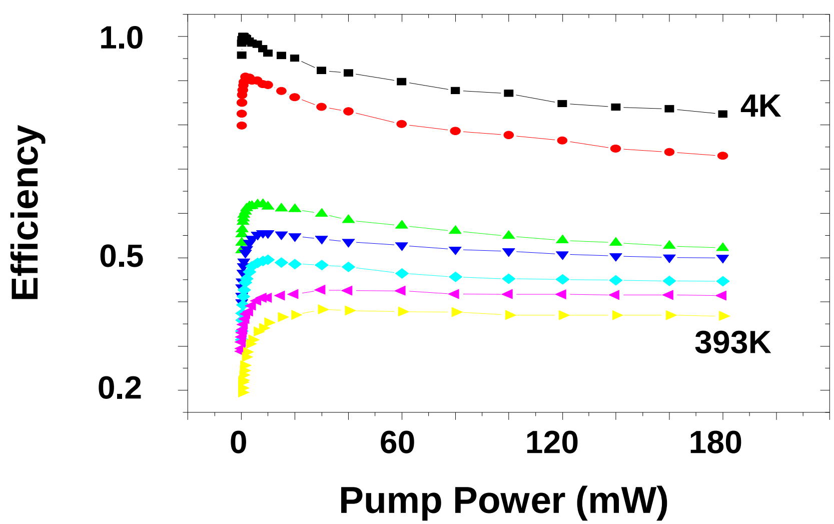
Self-cooled optoelectronics

Self-cooling by anti-Stokes ($\omega > \Omega$) phonon-assisted strong coupling

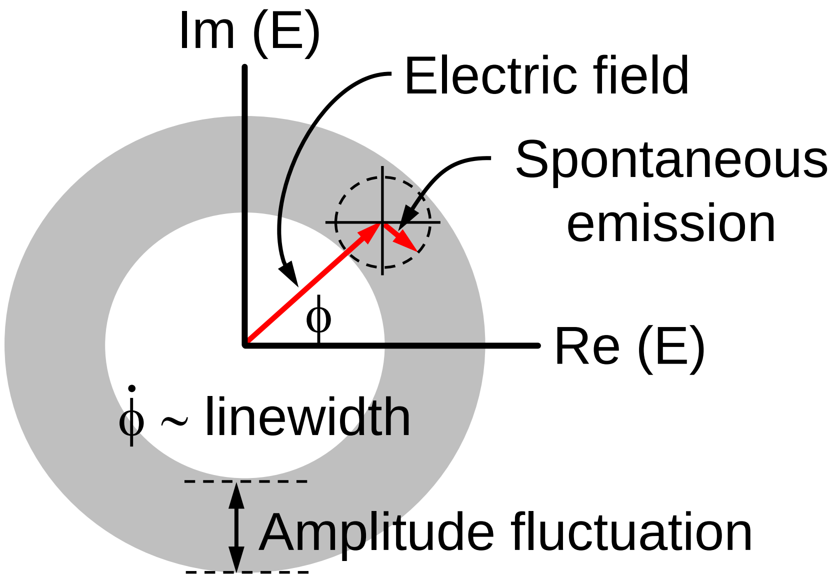


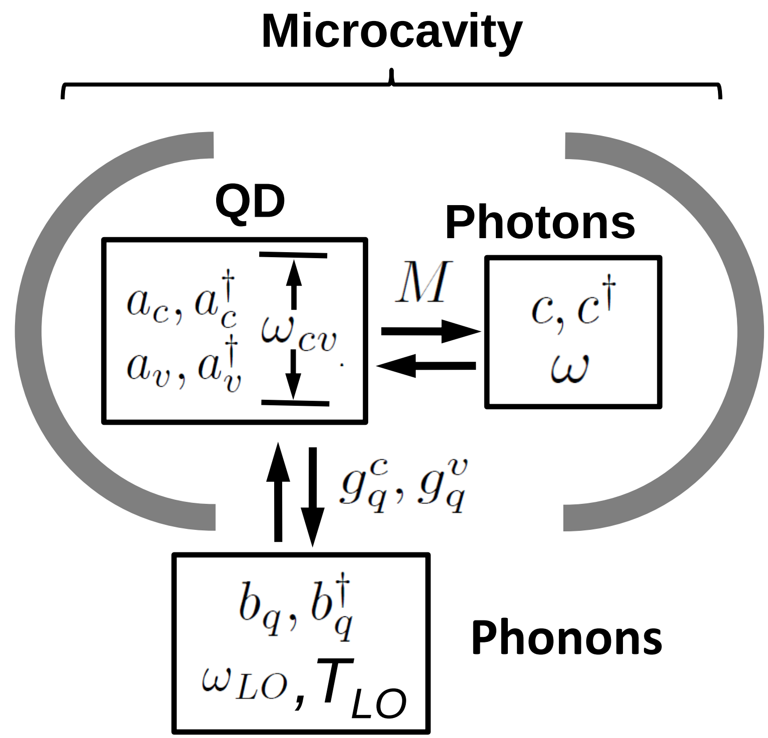


Temperature dependence of LED efficiency



Summary





Complete problem description with dressed (photon- and phonon-assisted) electronic operator combinations

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

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

$$T^{p,s}_{n,m} = \langle a_v^\dagger a_c c^{\dagger p} c^s b^{\dagger n} b^m \rangle$$

Summary

Dephasing in semiconductors

Reservoir theory

$$\frac{\Delta\rho}{\Delta t} = -\gamma\rho$$

Carrier-carrier scattering

$$\frac{\Delta\rho_k}{\Delta t} = -\gamma\rho_k + \sum_{k\prime}\gamma^{nd}\rho_{k\prime}$$

Summary

Dephasing in semiconductors

Reservoir theory $$\frac{\Delta\rho}{\Delta t} = -\gamma\rho$$

Carrier-carrier scattering $$\frac{\Delta\rho_k}{\Delta t} = -\gamma\rho_k + \sum_{k'} \gamma^{nd}\rho_{k'}$$

Quantum dots Memory and beyond 2nd Born approximation

QD cavity-QED Memory, beyond 2nd Born approximation and polaritons

LO phonon-assisted strong coupling

High-temperature photon antibunching

Tracking of phonon statistics

Substrate cooling with light emission

Summary

Dephasing in semiconductors

Reservoir theory $$\frac{\Delta\rho}{\Delta t} = -\gamma\rho$$

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Quantum dots Memory and beyond 2nd Born approximation

QD cavity-QED Memory, beyond 2nd Born approximation and polaritons

LO phonon-assisted strong coupling

High-temperature photon antibunching

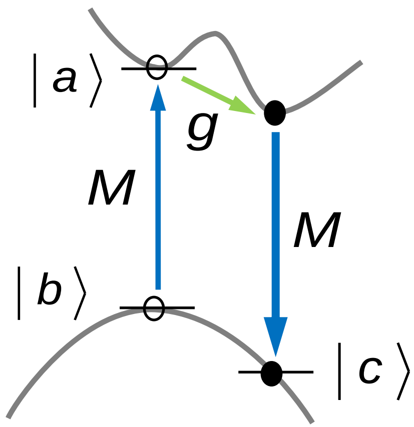
Tracking of phonon statistics

Substrate cooling with light emission

The future: ‘put in the continuum?

e.g.: Si quantum optics and coherences

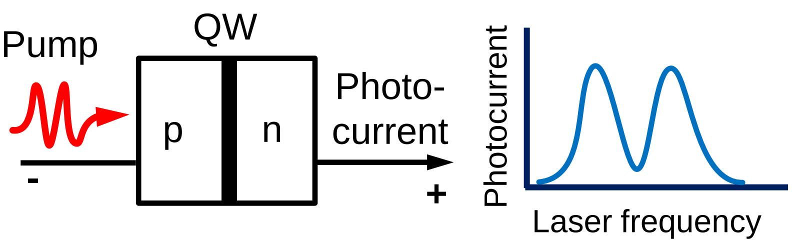
Effective phonon assisted light-matter coupling $\Big\}$ $\frac{Mg}{\omega_{LO}}$



Experiments to date

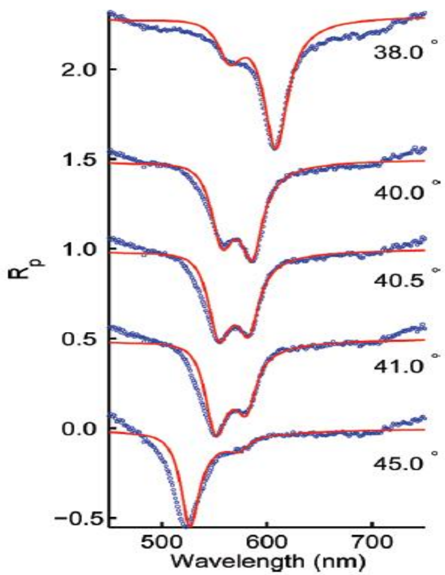
Optically pump

Early expts



Reithmaier et al., Nature **432**, 197 (2004) and others

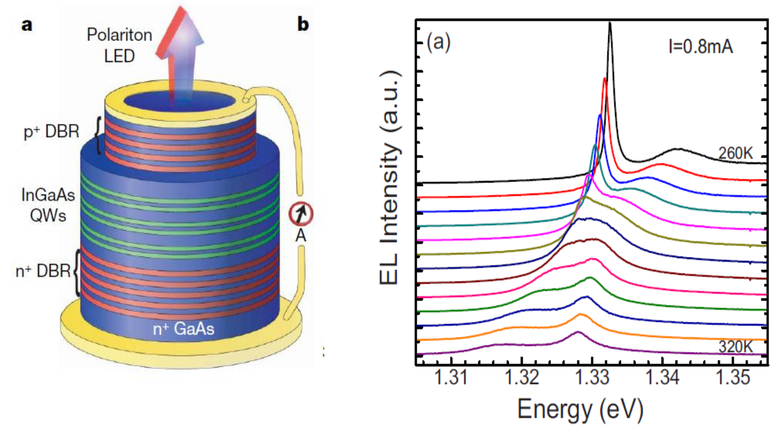
Plasmon mediated



Gomez et al., Nano Lett. **10**, 274 (2010)

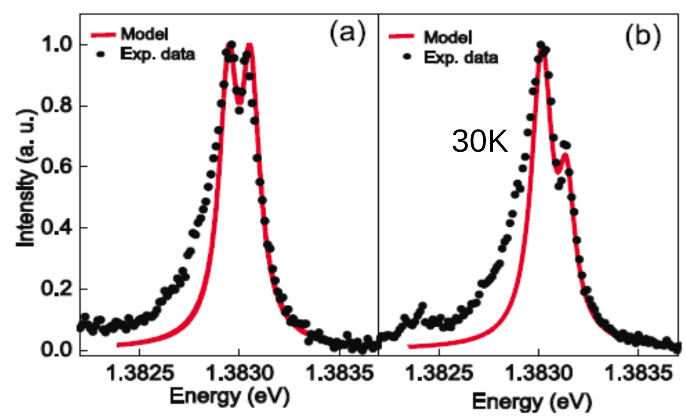
Electrically pump

QW, 300K



Tsintzos et al., Nature Lett. 453 373 (2008)
APL 94, 071109 (2009)

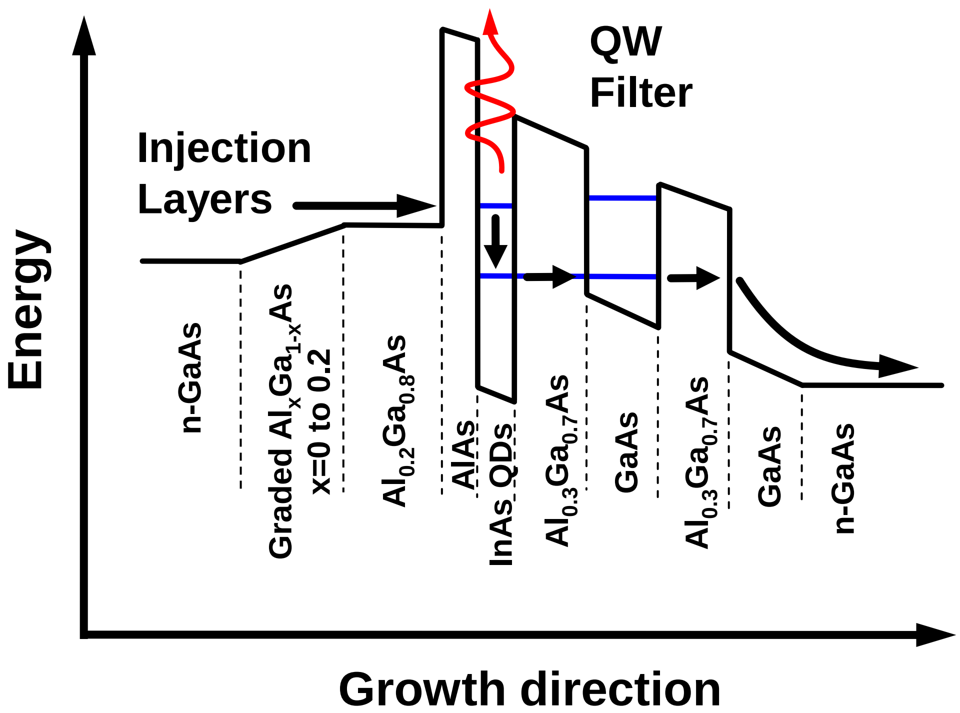
Quantum dots



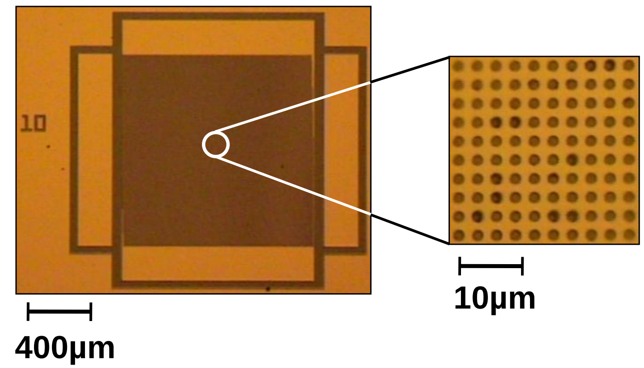
Kistner et al., APL 96, 221102 (2010)

Mid-IR emitter using inter-conduction-state transition in InAs quantum dots

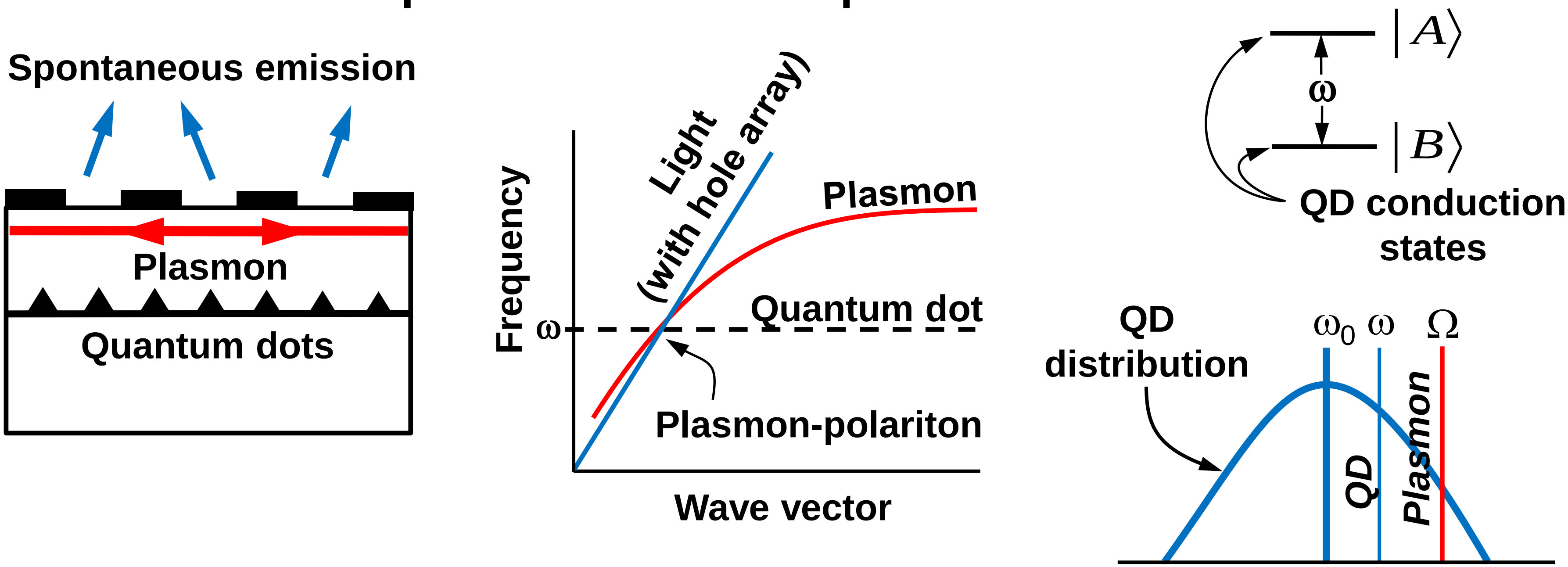
Confinement potential



Hole array and electrical contact



Spontaneous emission from quantum-dot ensemble in presence of field in plasmon mode



Schrödinger Equation

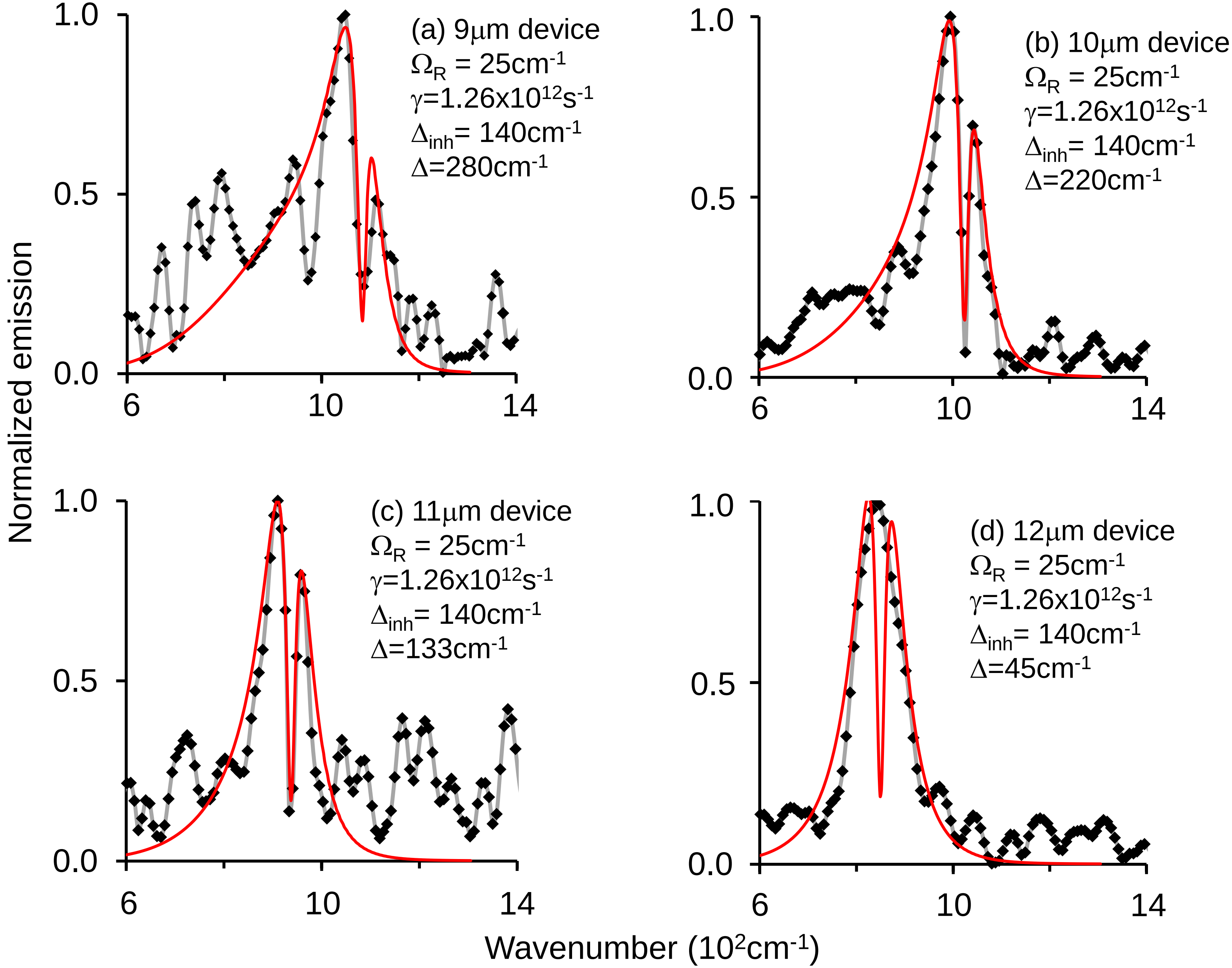
$$i\hbar\frac{d}{dt}\left|\psi_\omega(t)\right\rangle = \Big(\underbrace{H_0 + H_{QD-Plasmon}} + \underbrace{H_{QD-photon}}\Big)\left|\psi_\omega(t)\right\rangle$$

Solve exactly

$$\overbrace{\sum_\omega \hbar\omega\left|a_\omega\right\rangle\left\langle a_\omega\right| + \sum_\nu \hbar\nu c_\nu^\dagger c_\nu - E_p(t)\,u_p(z)\sum_\omega \mu\left(\left|a_\omega\right\rangle\left\langle b_\omega\right| + \left|b_\omega\right\rangle\left\langle a_\omega\right|\right)}$$

Include to 1st order

$$\overbrace{-\sum_{\omega,\nu} u_\nu(z)\,\mu\sqrt{\frac{\hbar\nu}{A\varepsilon}}\left(\left|a_\omega\right\rangle\left\langle b_\omega\right| c_\nu + c_\nu^\dagger\left|b_\omega\right\rangle\left\langle a_\omega\right|\right)}$$



(a) 9μm device
Ω_R = 25cm^{-1}
γ=1.26x10^{12}s^{-1}
Δ_{inh}= 140cm^{-1}
Δ=280cm^{-1}
(b) 10μm device
Ω_R = 25cm^{-1}
γ=1.26x10^{12}s^{-1}
Δ_{inh}= 140cm^{-1}
Δ=220cm^{-1}
(c) 11μm device
Ω_R = 25cm^{-1}
γ=1.26x10^{12}s^{-1}
Δ_{inh}= 140cm^{-1}
Δ=133cm^{-1}
(d) 12μm device
Ω_R = 25cm^{-1}
γ=1.26x10^{12}s^{-1}
Δ_{inh}= 140cm^{-1}
Δ=45cm^{-1}
Normalized emission
Wavenumber (10^{2}cm^{-1})
1.0
0.5
0.0
6
10
14

Experimentally demonstrated and theoretically verified:
Strong-light-matter interaction in electrically-excited,
inter-conduction-state quantum-dot transitions

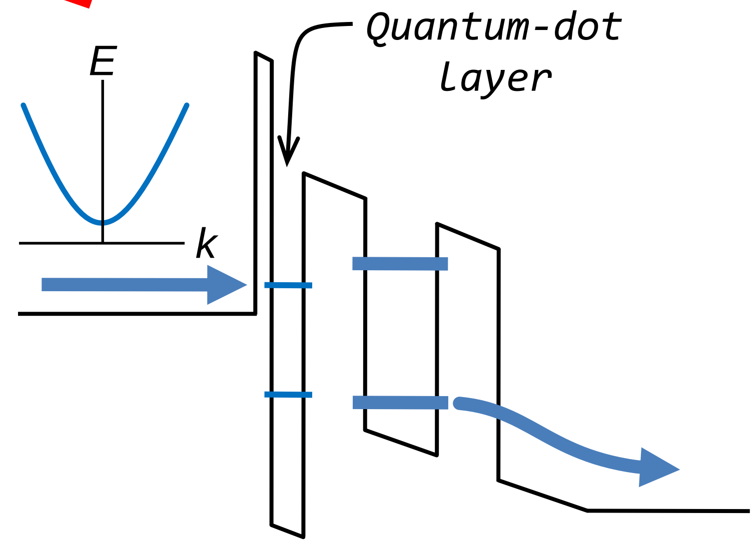
Advantage of intersubband/level platform for coherent transient and quantum coherence phenomena

	Interband	Intersubband or level
☺ $\wp$/e	<1nm	10nm
T_1 , T_2	$10^9 s^{-1}$, $10^{13} s^{-1}$	$10^{13} s^{-1}$, $10^{13} s^{-1}$

☹ *for quantum-coherence devices*

☹ *for population-based devices*

Quantum-coherent electrical excitation!



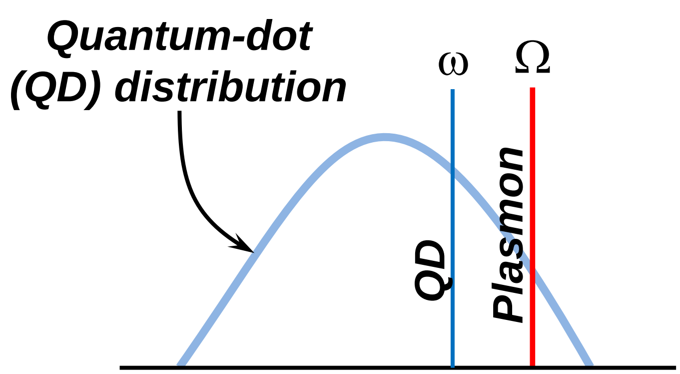
when random will lead to a mixed state ☹

$$|\psi\rangle = a|a\rangle + be^{i\phi}|b\rangle$$

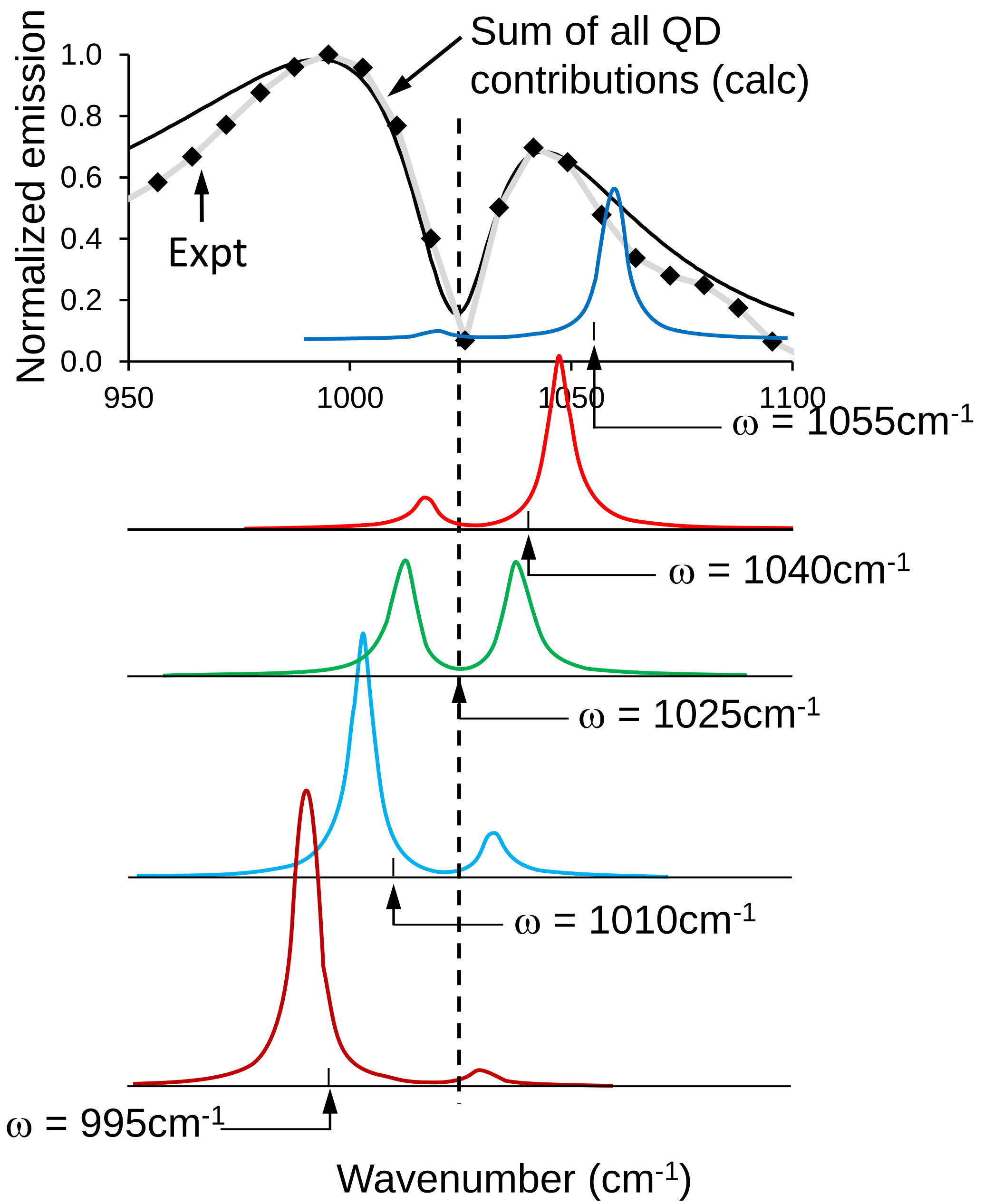
2-d to 0-d excitation gives robust pure state ☺

$$|\psi\rangle = a|a\rangle$$

Quantum dot contributions to electroluminescence



$$\Omega'_R = \sqrt{\left(\wp E_p/\hbar\right)^2 + (\Omega - \omega)^2}$$



Solution

$$|\psi_\omega(t)\rangle = A_\omega(t)\, e^{-i\omega t}\, |\overset{\text{QD}}{a_\omega}\, \overset{\text{vacuum}}{\{0\}}\rangle + B_\omega(t)\, |b_\omega \{0, \dots, \overset{\text{Spontaneous emission}}{1_\nu}, 0, \dots\}\rangle$$

$$\frac{g_\omega \Omega_R}{\Omega'_R}\left[\frac{e^{-[\gamma+i(\Delta-\Omega'_R)]t/2}}{\gamma+i(\Delta-\Omega'_R)} - \frac{e^{-[\gamma+i(\Delta+\Omega'_R)]t/2}}{\gamma+i(\Delta+\Omega'_R)}\right]$$

Intensity spectrum

$$S(\nu) = \int dt\, e^{i\nu t} \langle E(t+\tau) E(t)\rangle$$

$$\frac{1}{T}\int_0^T dt\, \langle \psi_\omega(t+\tau) | c_\omega^\dagger e^{iH\tau/\hbar} c_\omega | \psi_\omega(t)\rangle$$

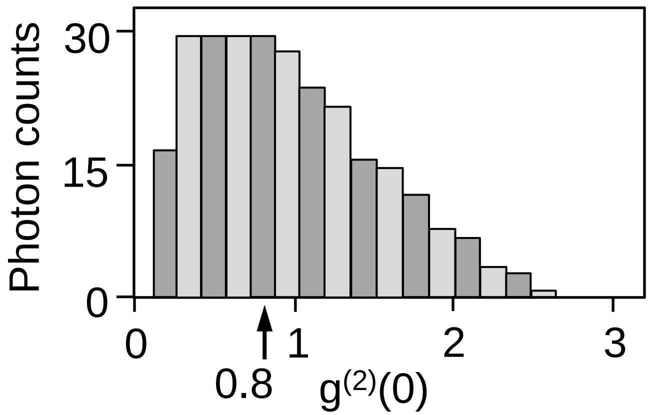
$$\boxed{\int_0^\infty d\omega\, P(\omega) \left(\frac{g_\omega \Omega_\mathrm{R}}{\Omega'_\mathrm{R}}\right)^2 \gamma \left\{\frac{\eta(\Omega'_\mathrm{R})}{\gamma + i(2\upsilon - \Omega - \omega + \Omega'_\mathrm{R})} + \frac{\eta(-\Omega'_\mathrm{R})}{\gamma + i(2\upsilon - \Omega - \omega + \Omega'_\mathrm{R})}\right\} + c.c.}$$

$$\eta(\Omega'_\mathrm{R}) = \frac{1}{\gamma^2 + (\Delta - \Omega'_\mathrm{R})^2} - \frac{1}{[\gamma - i(\Delta - \Omega'_\mathrm{R})][\gamma + i(\Delta + \Omega'_\mathrm{R})][\gamma + i\Omega'_\mathrm{R}]}$$

Summary of past results

1) Photon antibunching in strongly-coupled QD-photon-phonon system

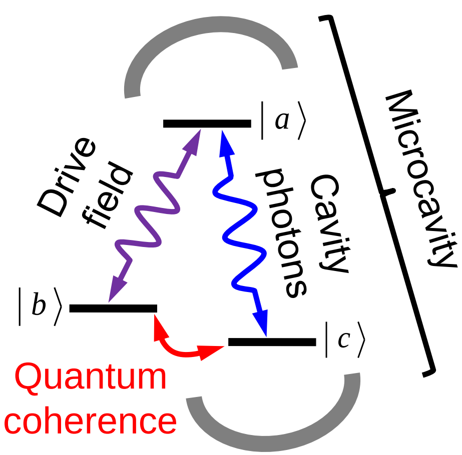
Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)



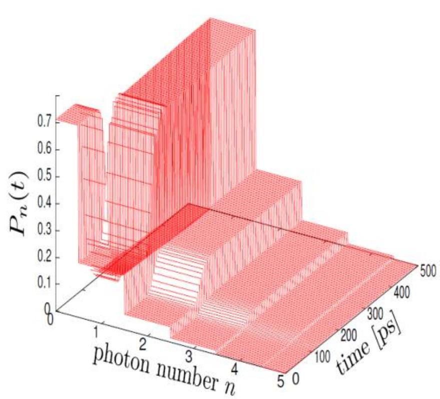
- Nonclassical (better than laser) intensity correlation
- Potential Application : Room temperature single-photon sources

2) Using quantum coherence to control of strong coupling

Kabuss, Carmele, Richter, Chow and Knorr, physica status solidi B 248, 872 (2011)



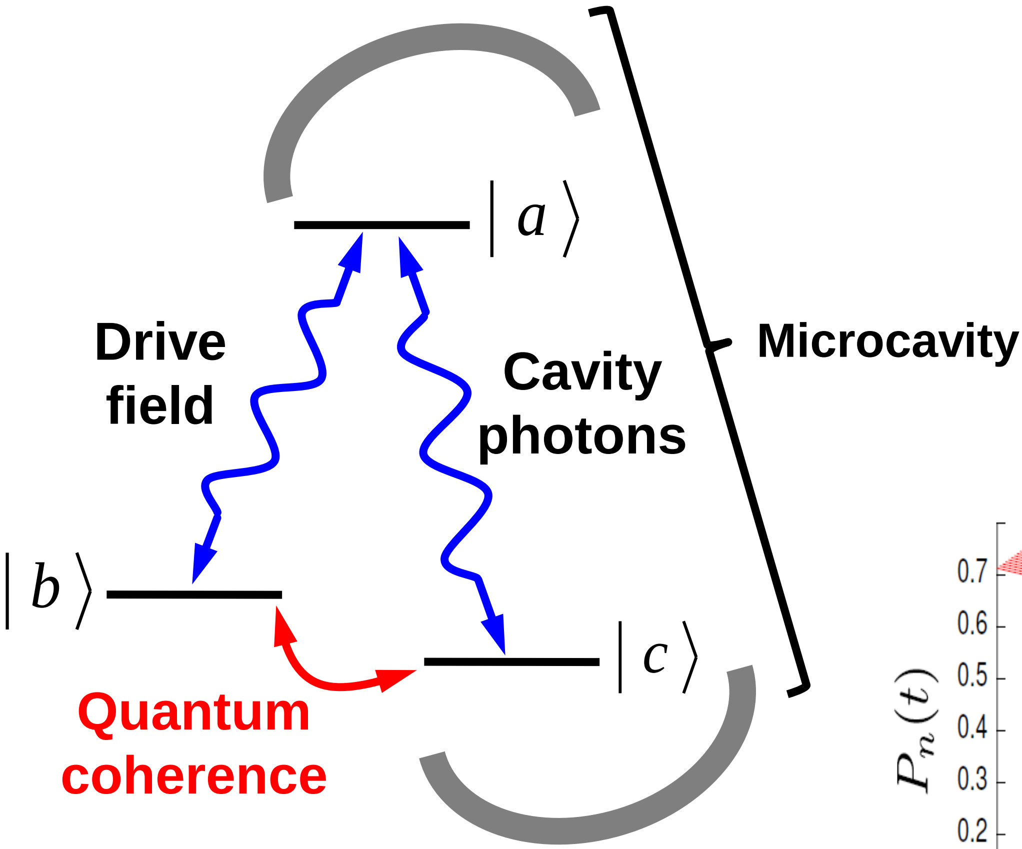
Photon statistics change by drive pulse

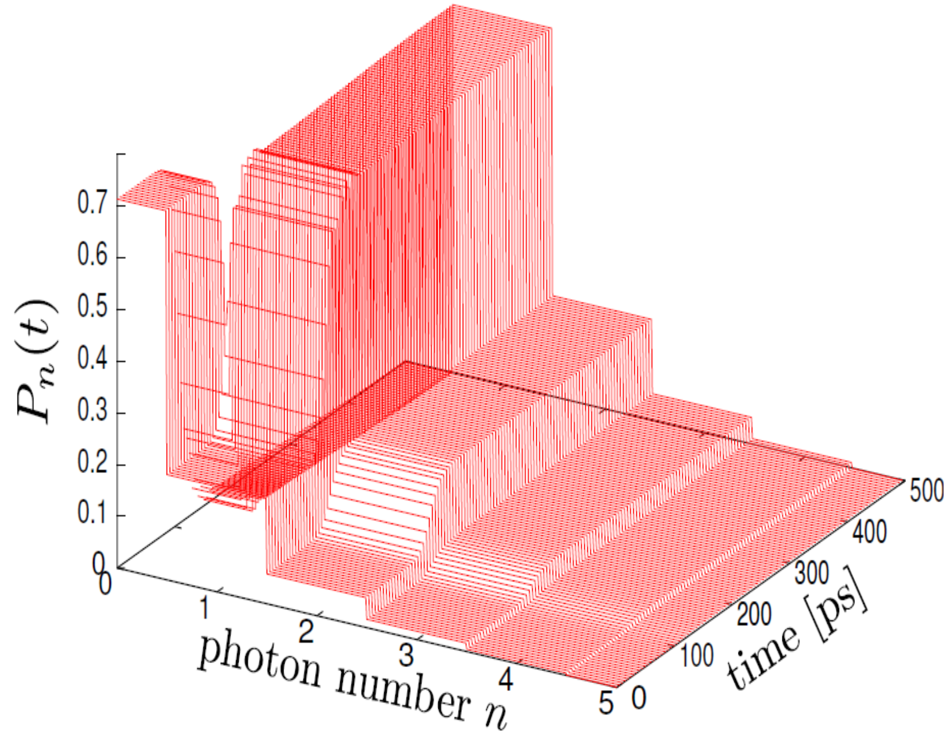


Potential Applications

- Photon-on-demand sources
- Fundamental efficiency limit of PVCs

Exercise #2: Coherence induced control of spontaneous emssion

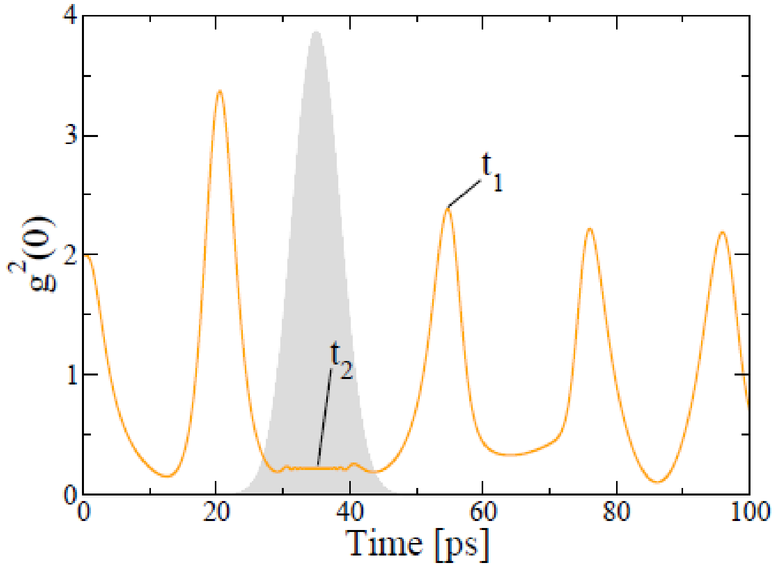




Exercise #2: Coherence induced control of spontaneous emssion

Control of photon statistics

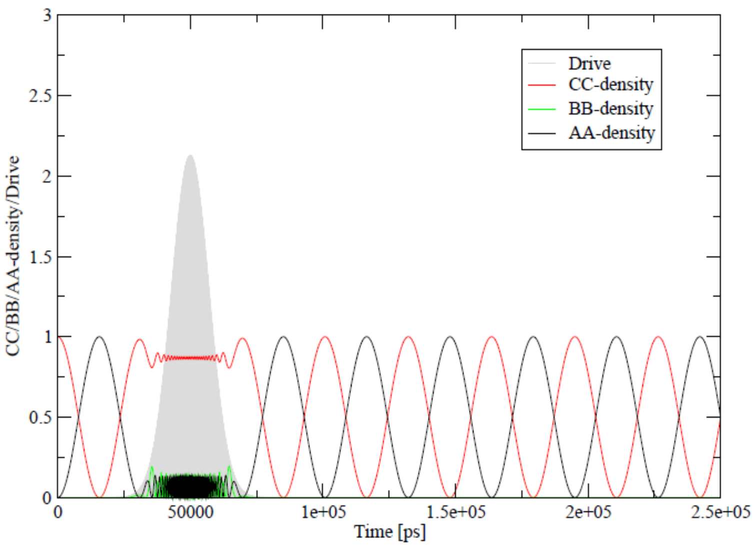
Low noise light sources



Contol of carrier populations

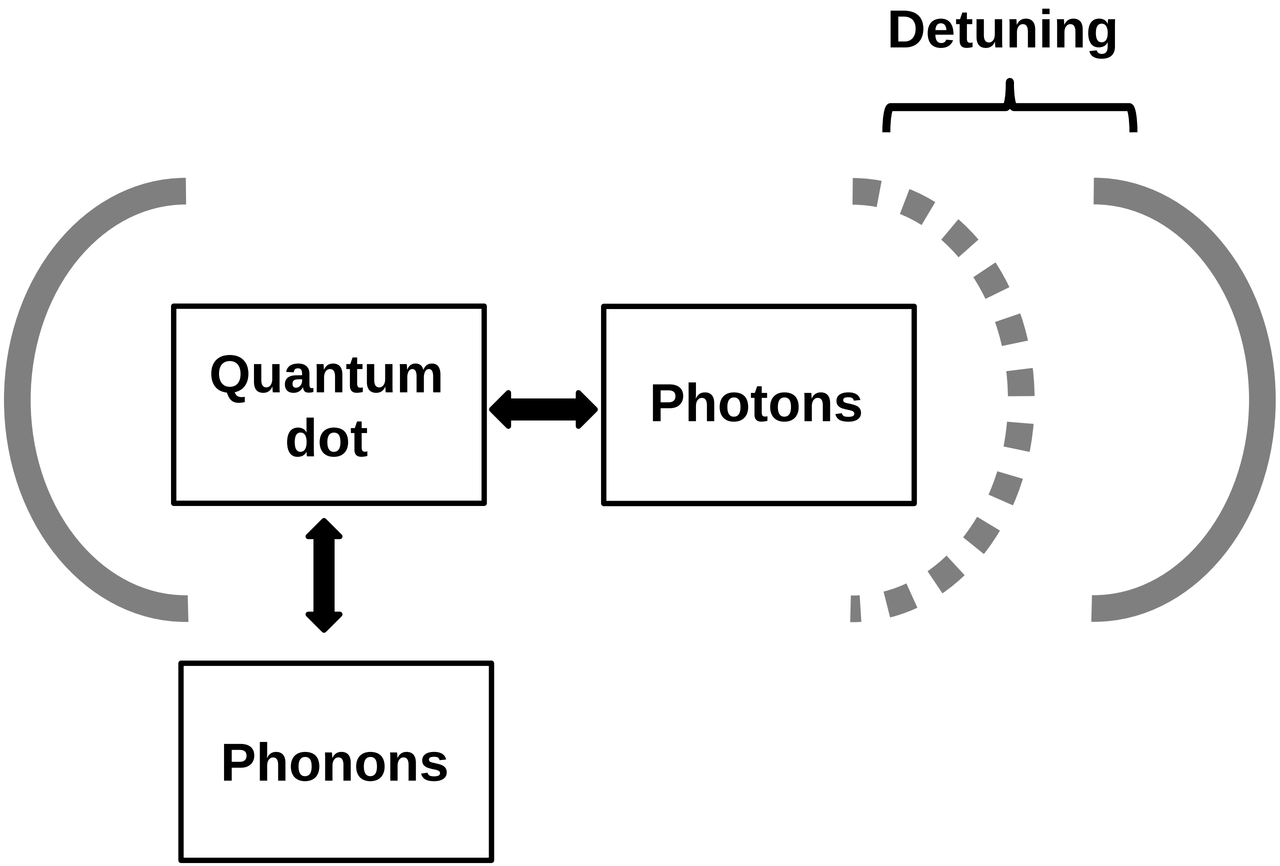
Efficient photovoltaic cells

(inspired by M.O. Scully)



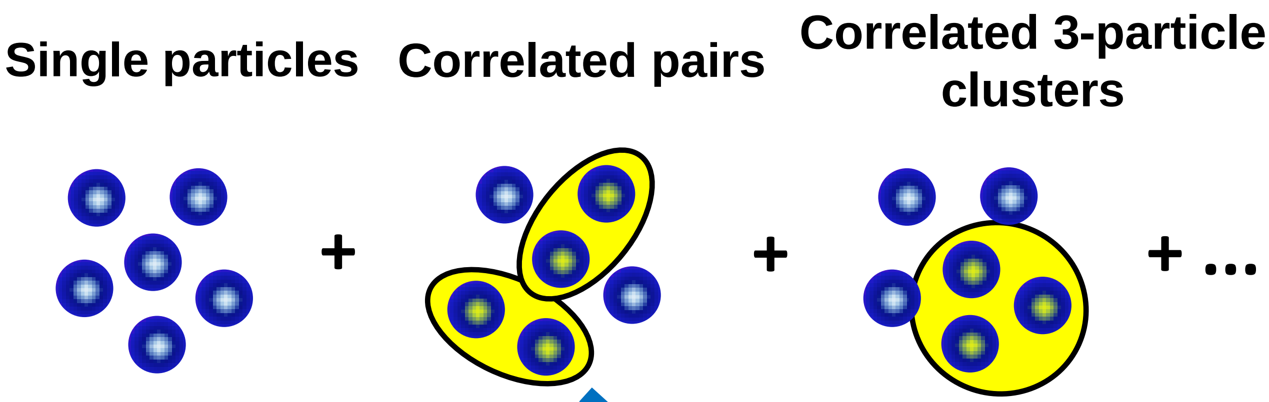
Kabuss, Carmele, Richter, Chow and Knorr, physica status solidi B 248, 872, 2011

Exercise #3: Phonon-assisted strong light-matter coupling



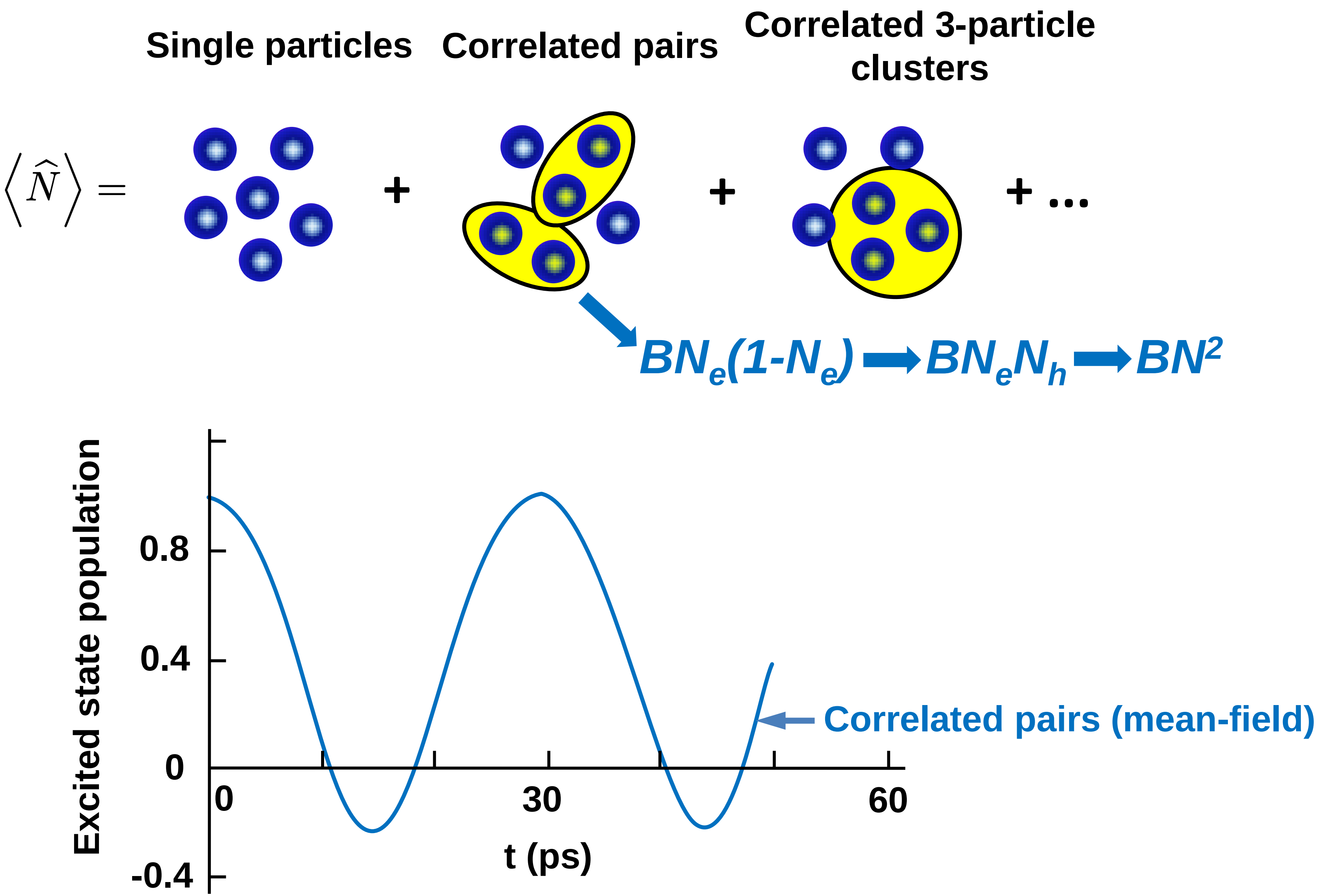
Cluster expansion

$\langle \hat{N} \rangle =$

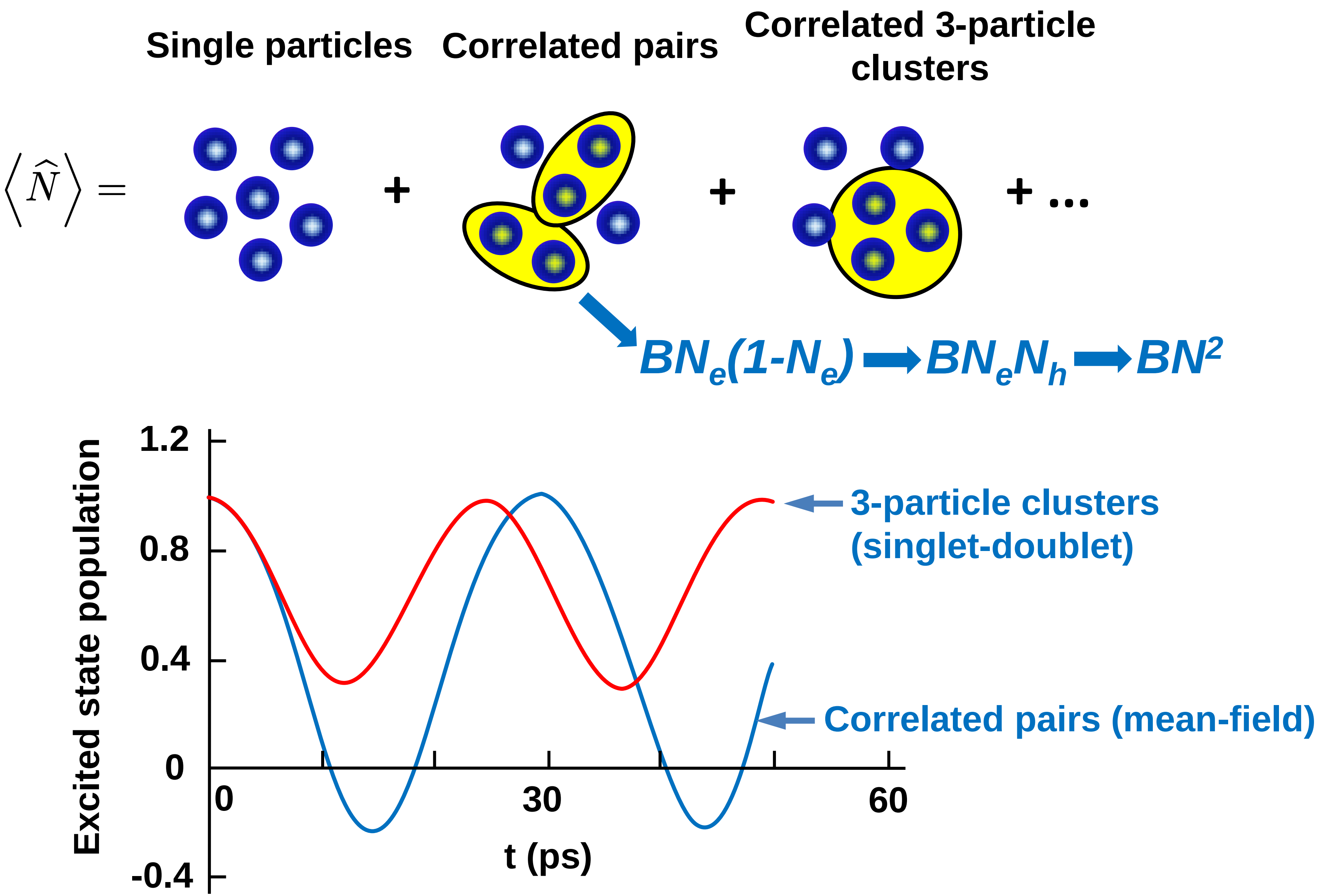


$BN_e(1-N_e) \rightarrow BN_eN_h \rightarrow BN^2$

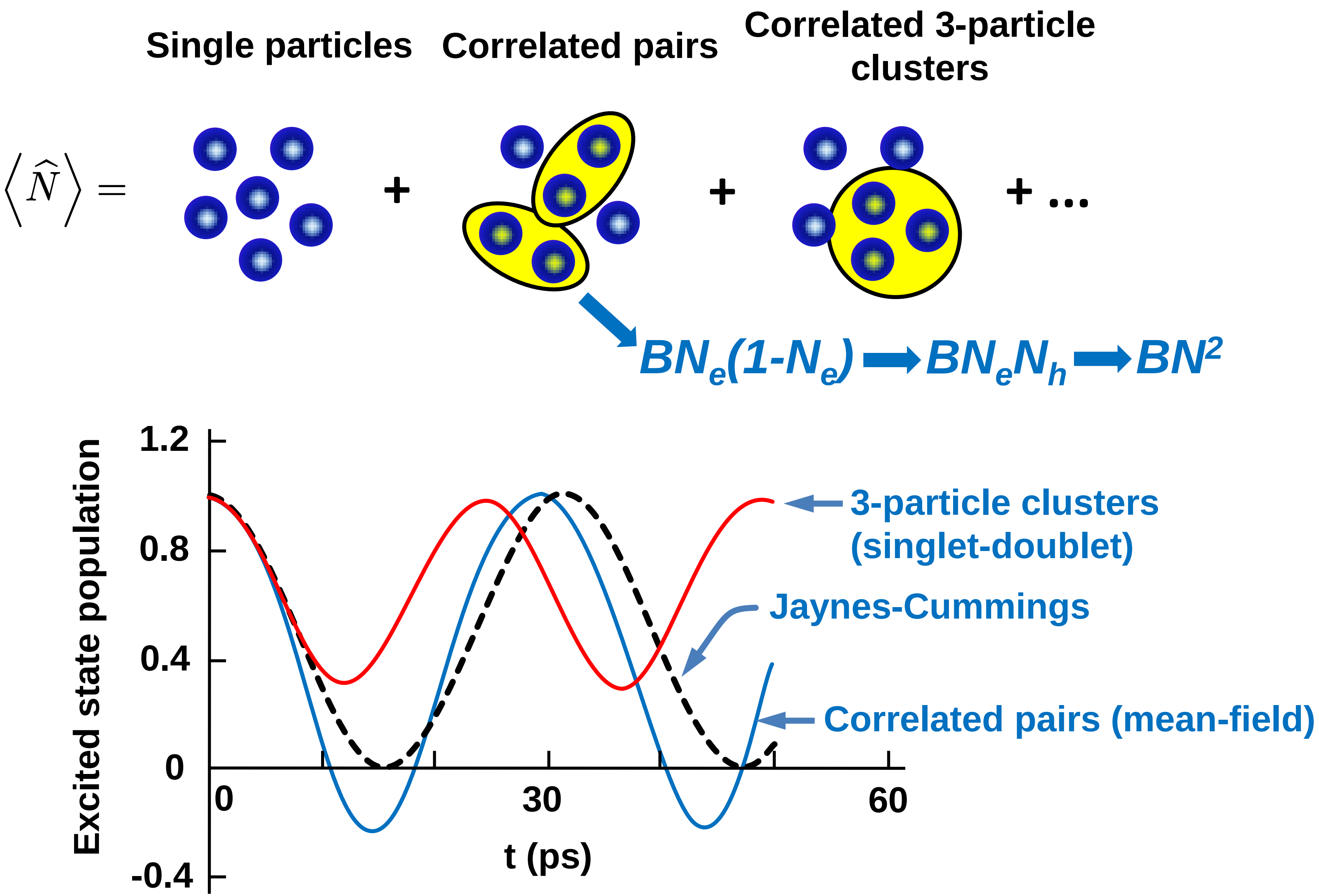
Cluster expansion



Cluster expansion



Cluster expansion



Quantum-dot cavity-quantum-electrodynamics (QD-CQED)

Approach to solving to arbitrary accuracy, quantum dot under strong photon-electron and phonon-electron coupling conditions

Antibunching of thermal radiation by room-temperature phonon bath

Collaborators

Technical University, Berlin: Alexander Carmele, Martin Richter and Andreas Knorr

For more information

Carmele, Richter, Chow and Knorr, PRL **104**, 156801 (2010)

Control of spontaneous emission

Solution

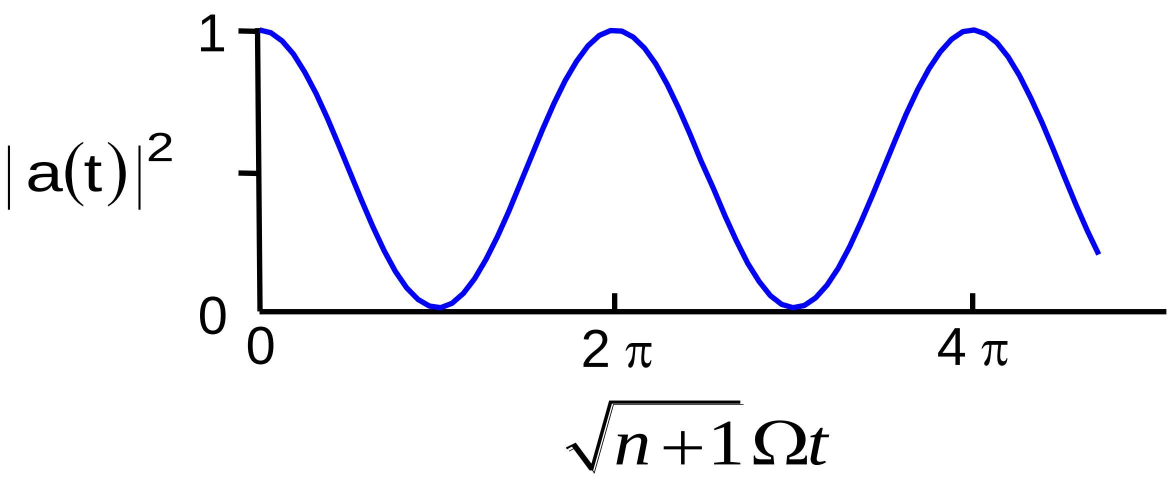
Photon number

$$|\psi(t)\rangle = a(t)|a\rangle|n\rangle + b(t)|b\rangle|n+1\rangle$$

$$= e^{i\omega(n+1/2)t}\left[\cos\left(\frac{\Omega\sqrt{n+1}}{2}t\right)|a\rangle|n\rangle + i\sin\left(\frac{\Omega\sqrt{n+1}}{2}t\right)|b\rangle|n+1\rangle\right]$$

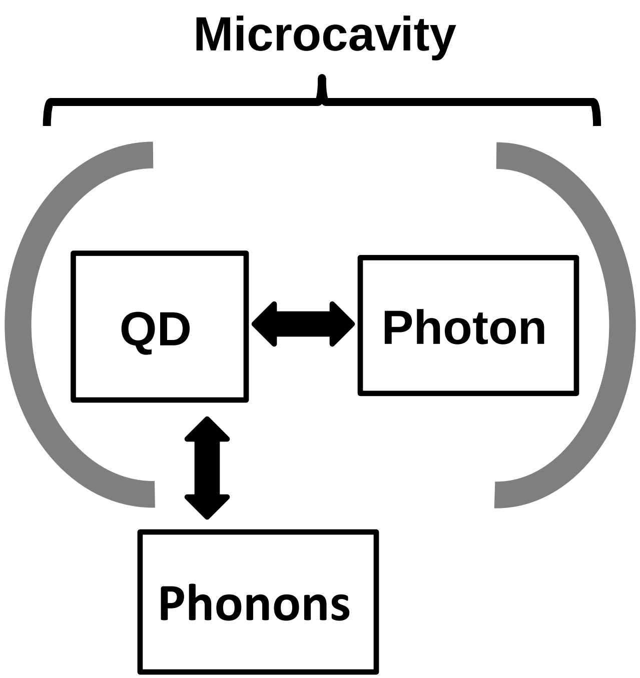
Rabi flopping

$$|a(t)|^2 = \cos^2\left(\frac{\wp}{2}\sqrt{\frac{\omega(n+1)}{\hbar\varepsilon V}}t\right)$$



SUMMARY

QD-CQED



1) **Strong QD-photon coupling**
2) **Strong QD-phonon coupling**
3) **Electronic-photon-phonon correlations to arbitrary order**

Photon antibunching with 300K phonon bath

- Ph.D. dissertation: Alexander Carmele, TU-Berlin, 2010
- PRL **104**, 156801 (2010): Carmele, Richter, Chow, Knorr,
- Submitted J. Modern Optics: Carmele, Kabuss, Richter, Knorr, Chow
- **single-photon, multi-QD problem (dot-dot correlations)**
- ***the continuum***

Coherence-induced control of photon statistics and electronic populations

- physica status solidi B **248**, 872, 2011: Kabuss, Carmele, Richter, Chow, Knorr
- **Ph.D. dissertation: Julia Kabuss, TU- Berlin, <1 year**

Phonon-assisted strong light-matter coupling

- Submitted Optics Express: Carmele, Kabuss, and Chow
- **Indirect gap quantum optics (Si, Ge)**

QD physics

- Accepted IEEE Select.Topics Quant. Electron. Chow & Jahnke
- **Invited review article, Progress in Quantum Electronics: Chow and Jahnke, 'On the physics of semiconductor quantum dots for applications in lasers and quantum optics.'**

Deutsche Forschungsgemeinschaft (DFG)
Deutsche Sonderforschungbereich (SFB 787)
(WWC travel expenses)

Observation of Rabi Splitting from Surface <u>Plasmon</u> Coupled <u>Conduction State Transitions</u> in <u>Electrically Excited</u> InAs <u>Quantum Dots</u>

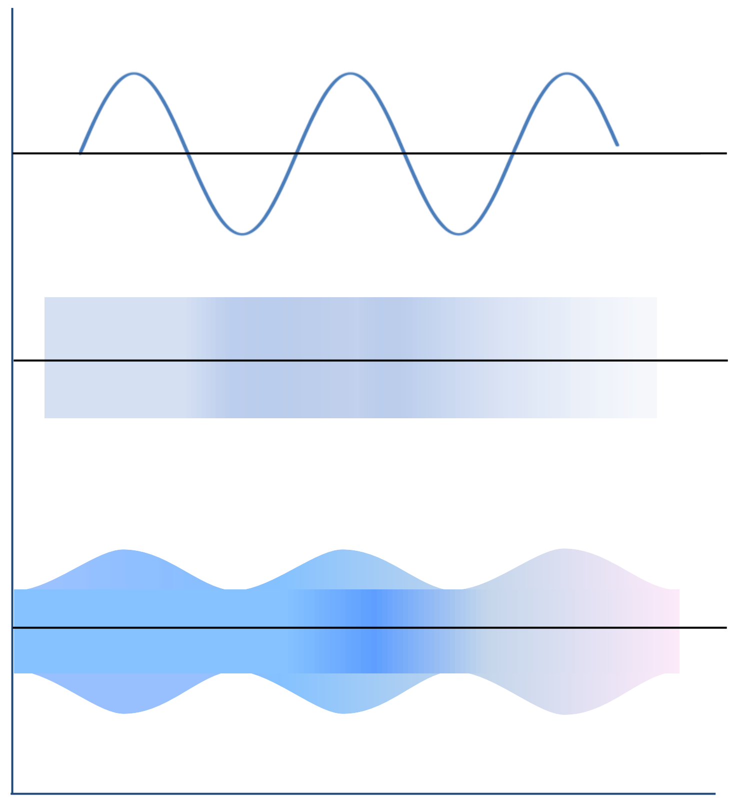
<u>Mid-IR emitter</u>

Numerical device model: current in → light out

<u>Strong field → strong coupling</u>

Physics of transition from semiclassical to fully quantum regime

Multi-QD/single-photon source (typical: single-QD/single-photon source)



ω_{LO}

Berlin /Sandia collaboration

Technical University, Berlin (SFB 787 funding)

Alexander Carmele – Student/Posdoc

Ph.D. dissertation (2010) research related to EFRC strong coupling task

Carl-Ramsauer Prize for outstanding physics Ph.D. dissertation

Julia Kabuss – Student

Ph.D. expected completion Fall, 2012

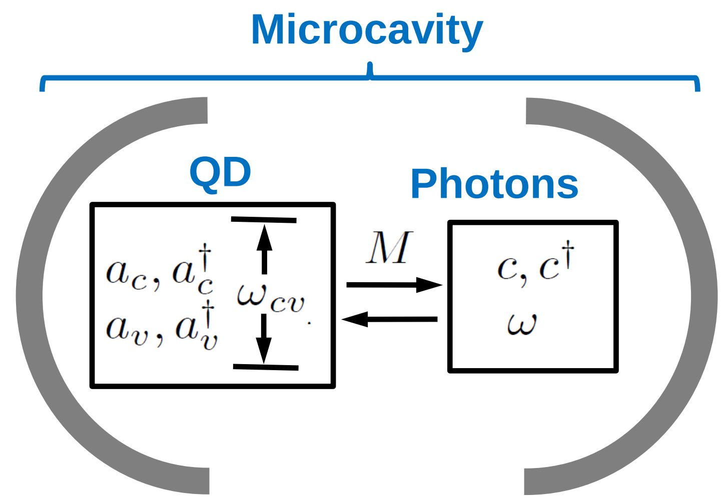
Research on quantum coherence and phonon physics in strongly coupled systems

Andreas Knorr – Professor of Theoretical Physics

Collaborator since 1990

Collaborated on first GaN gain theory paper (APL, 1995)

Sandia National Labs
(EFRC strong-coupling subtask)



Constrain: Single-transition in QD

Complete description with dressed (photon-assisted) electronic operator combinations

$$E^{p,s} = \left\langle a_c^\dagger a_c c^{\dagger p} c^s \right\rangle$$

$$G^{p,s} = \left\langle a_v^\dagger a_v c^{\dagger p} c^s \right\rangle$$

$$T^{p,s} = \left\langle a_v^\dagger a_c c^{\dagger p} c^s \right\rangle$$

Carmele, Kabuss, Richter, Knorr, Chow (J. Modern Optics 58, 1951 (2011))

Atomic, molecular, and optical physics is the study of matter-matter and light-matter interactions on the scale of single atoms or structures containing a few atoms.

Fundamental Optical Processes in Semiconductors (FOPS)

Aug. 1-5, 2011 – Lake Junaluska, North Carolina

Sessions:

Quantum dots I, II & III

Graphene and Carbon

Spins I & II

Excitons and Polaritons I, II & III

Photonic Resonators

Novel Light Sources

Tutorial: Photonic metamaterials and transformation optics

AMO physics

Atomic, molecular and optical

Replace with electrons in semiconductor

Semiconductor quantum optics

Strong-field interaction

Classical field

$$|\psi(t)\rangle = \sin(\Omega_R t)e^{-i\omega_a t}|a\rangle + \cos(\Omega_R t)e^{-i\omega_b t}|b\rangle \qquad \Omega_R = \frac{\wp E_0}{\hbar}$$

$$\begin{aligned}|\psi(t)\rangle &= \sin(\Omega_R t)e^{-i\omega_a t}|a\rangle|\alpha\rangle + \cos(\Omega_R t)e^{-i\omega_b t}|b\rangle|\alpha\rangle \\ &= \left[\sin(\Omega_R t)e^{-i\omega_a t}|a\rangle + \cos(\Omega_R t)e^{-i\omega_b t}|b\rangle\right]|\alpha\rangle\end{aligned}$$

Factorizable

Coherent state: $\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}e^{|\alpha|^2/2}|n\rangle$

Strong coupling

Polariton state: $|\psi(t)\rangle = \sin(\underbrace{\Omega_R}_{\wp\underbrace{\left(\nu/\hbar V\varepsilon_0\right)}_{\text{‘Electric field per photon’}}^{1/2}\sqrt{n}} t)e^{-i\omega_a t}|a\rangle|n-1\rangle + \cos(\Omega_R t)e^{-i\omega_b t}|b\rangle\underbrace{|n\rangle}_{\text{Photon number state}}$