Searching for lasing threshold in a thresholdless laser

SAND2014-16570PE

Weng Chow, Sandia National Laboratories
Christopher Gies and Frank Jahnke, Bremen University

Nanolasers and thresholdless lasing

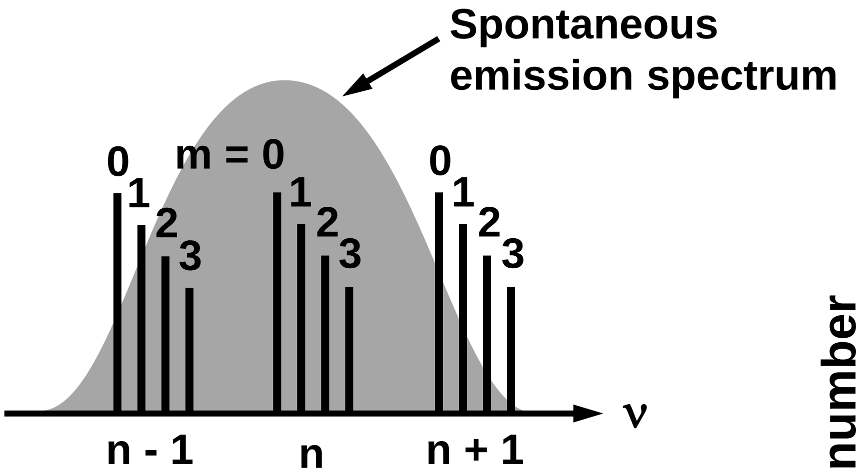
Criterial for lasing

β << 1 versus β = 1

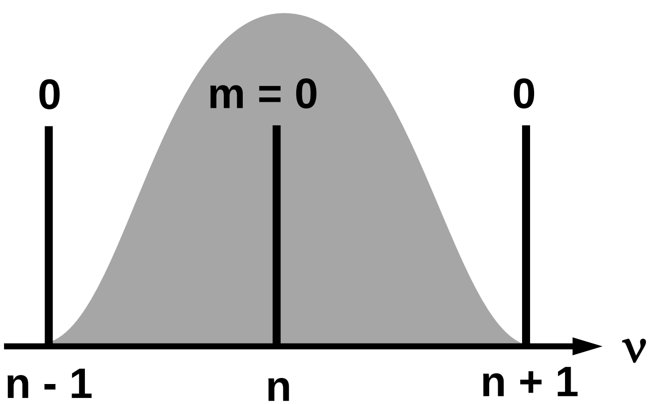
Thanks to:
Sandia's Laboratory Directed Research & Development (LDRD) Program

Motivation: Emission entirely into single mode

Most lasers β << 1

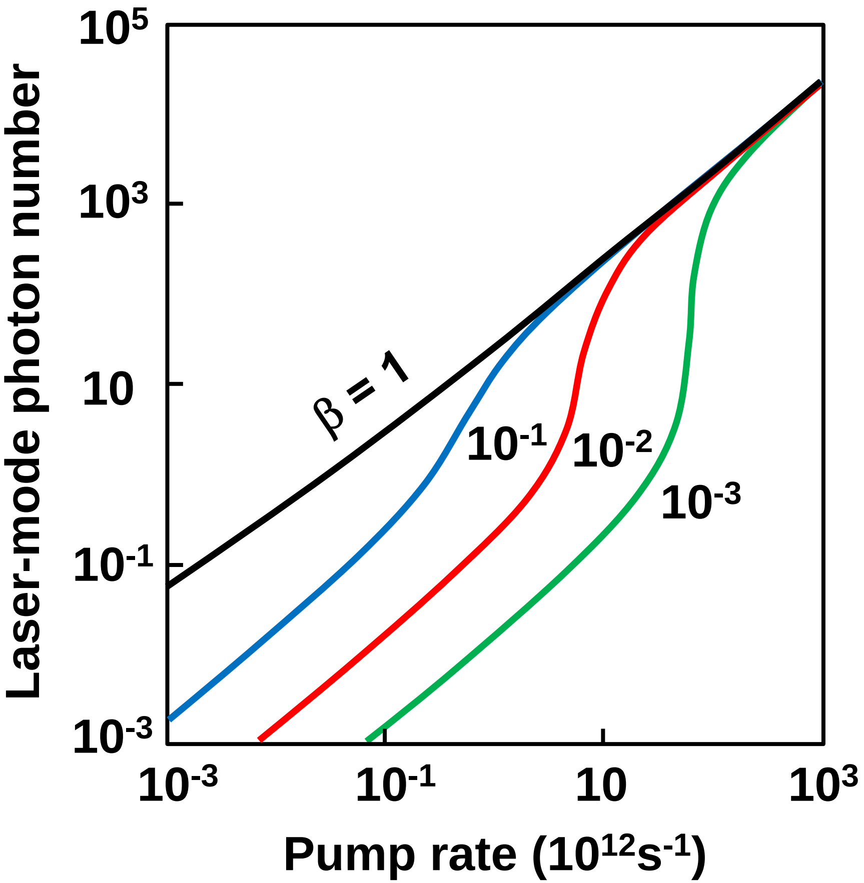


Nanolasers β = 1

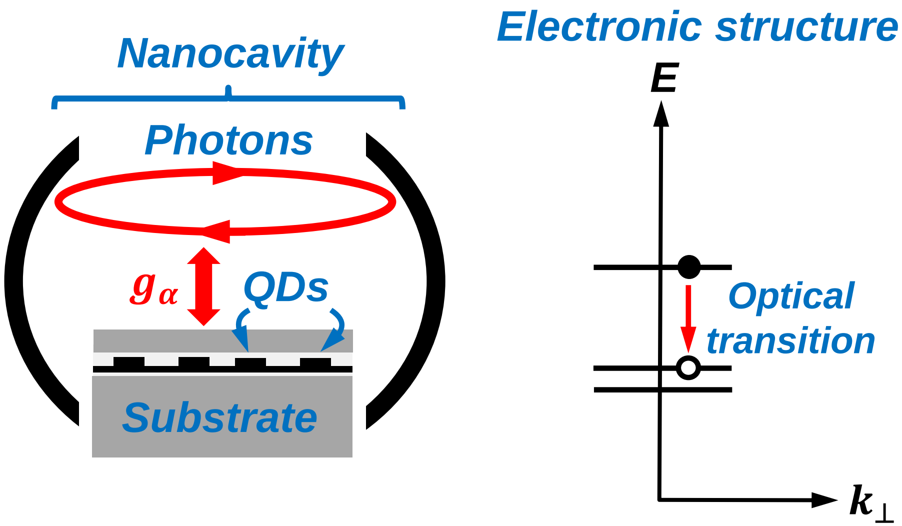


Spontaneous emission factor

$$\beta = \frac{\gamma_l}{\gamma_{sp}}$$



Nanolaser model



Hamiltonian

$$H = H_0$$ *Single-particle energies*

$$-\hbar \sum_{\alpha} \left(g_\alpha b_\alpha^\dagger c_\alpha^\dagger a - g_\alpha^* a^\dagger c_\alpha b_\alpha \right)$$ *Light-carrier*

$$g_\alpha = \wp \sqrt{\nu / \hbar \epsilon_b V}\; W(R_{QD}) \sum_n C_\alpha(R_n) V_\alpha(R_n)$$

$$+\hbar \sum_{\alpha\beta q} G_q \left(c_\alpha^\dagger c_\beta + b_\alpha^\dagger b_\beta \right) \left(d_q + d_q^\dagger \right)$$ *Carrier-phonon*

$$+\frac{1}{2} \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, c_\alpha^\dagger c_\beta^\dagger c_\eta c_\sigma + \frac{1}{2} \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger b_\beta^\dagger b_\eta b_\sigma$$

$$- \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger c_\beta^\dagger c_\eta b_\sigma$$

Carrier-carrier

Matrix element of $\dfrac{e^2}{4\pi\varepsilon_b |r - r'|}$

QDs

$\langle c_\alpha^\dagger c_\alpha \rangle$ ← *Electron and*

$\langle b_\alpha^\dagger b_\alpha \rangle$ ← *hole populations*

$\langle c_\alpha^\dagger b_\alpha^\dagger a \rangle$ ← *Polarization*

$\Updownarrow g_\alpha$

Photons

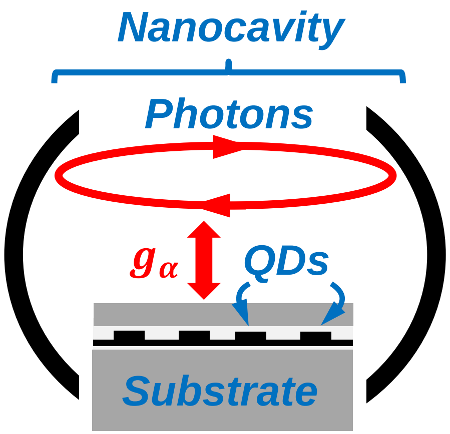
$\langle a^\dagger a \rangle$ ← *Photon population*

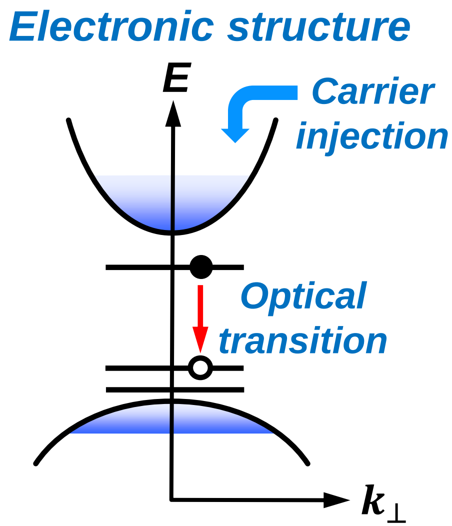
$\langle a^\dagger a(\tau) \rangle$ ← *Coherence time*

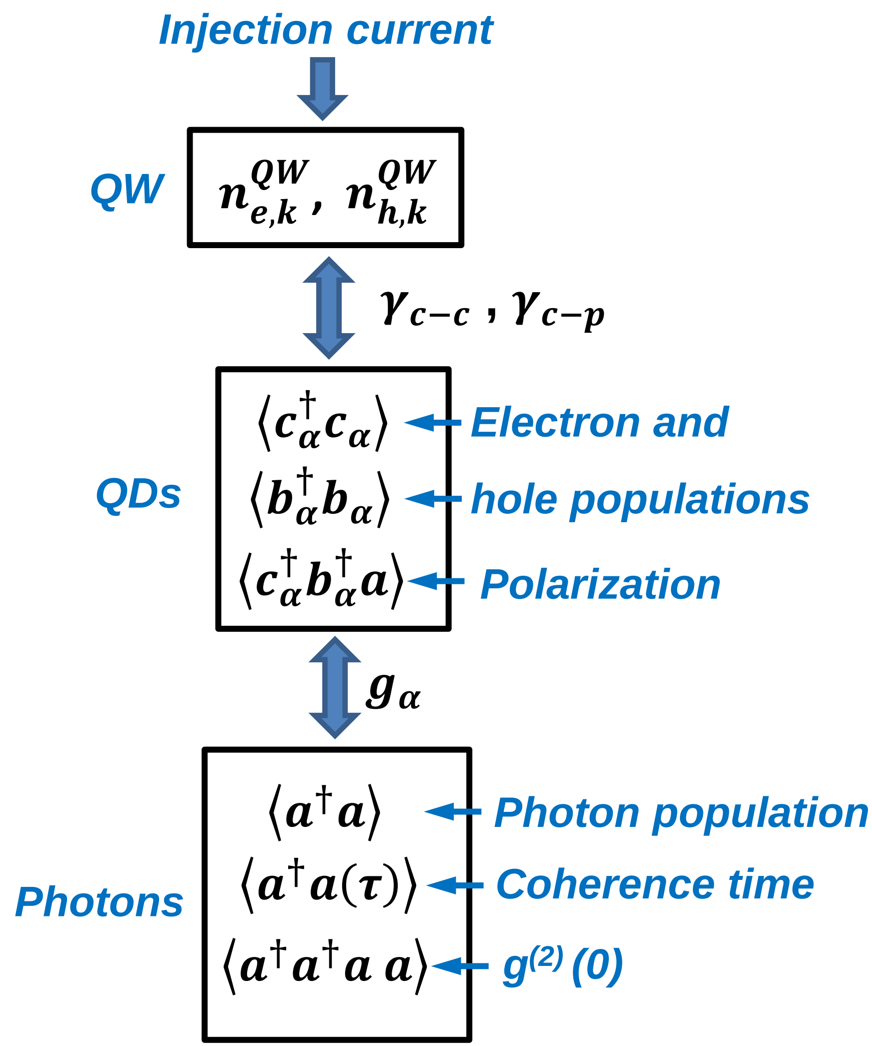
$\langle a^\dagger a^\dagger a\, a \rangle$ ← $g^{(2)}(0)$

Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

Nanolaser model







Hamiltonian

$$H = H_0$$ **Single-particle energies**

$$-\hbar\sum_{\alpha}\left(g_\alpha b^\dagger_\alpha c^\dagger_\alpha a - g^*_\alpha a^\dagger c_\alpha b_\alpha\right)$$ **Light-carrier**

$$g_\alpha = \wp\sqrt{\nu/\hbar\epsilon_b V}\; W(R_{QD})\sum_n C_\alpha(R_n)V_\alpha(R_n)$$

$$+\hbar\sum_{\alpha\beta q} G_q\left(c^\dagger_\alpha c_\beta + b^\dagger_\alpha b_\beta\right)\left(d_q + d^\dagger_q\right)$$ **Carrier-phonon**

$$+\frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, c^\dagger_\alpha c^\dagger_\beta c_\eta c_\sigma + \frac{1}{2}\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^\dagger_\alpha b^\dagger_\beta b_\eta b_\sigma$$

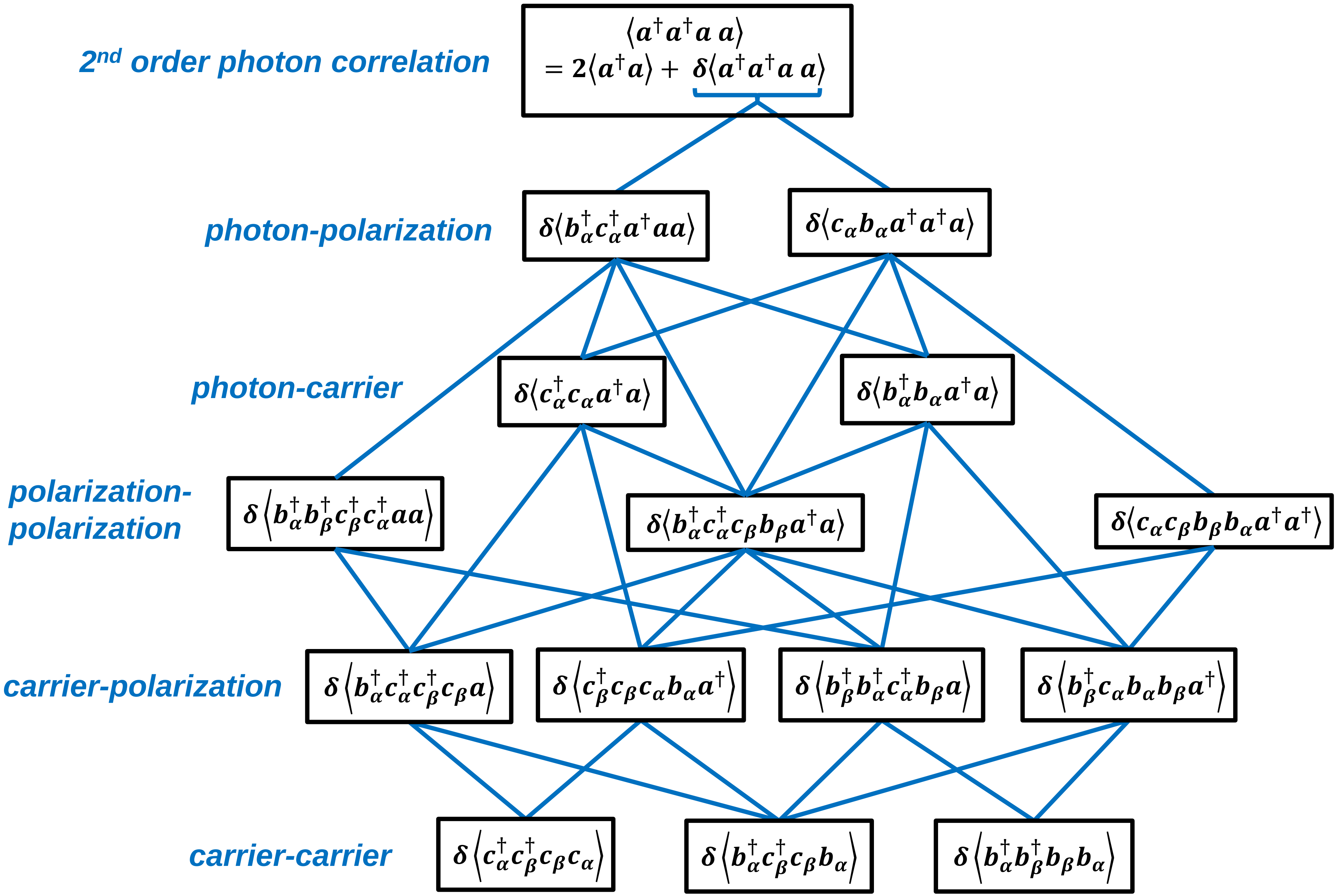
$$-\sum_{\alpha\beta\sigma\eta} W^{\alpha\beta}_{\sigma\eta}\, b^\dagger_\alpha c^\dagger_\beta c_\eta b_\sigma$$

Carrier-carrier

$W^{\alpha\beta}_{\sigma\eta}$: Matrix element of $\dfrac{e^2}{4\pi\varepsilon_b|r-r'|}$

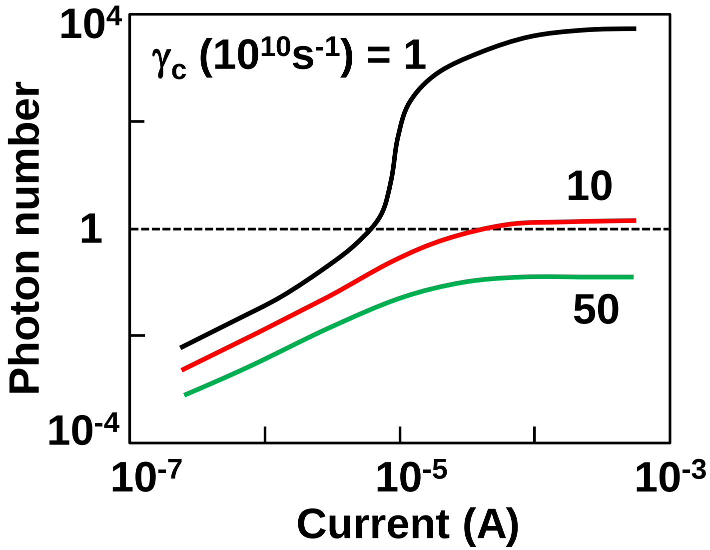
Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

Correlations

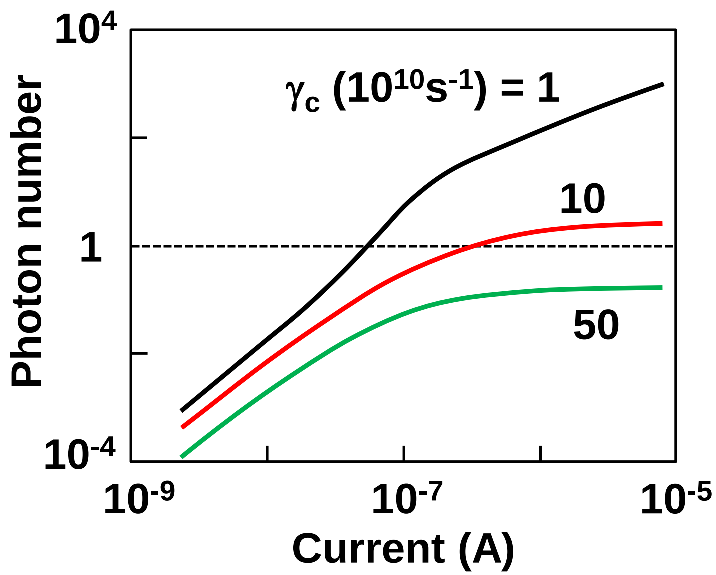


Criterial for lasing: Input/Output

β = 0.01



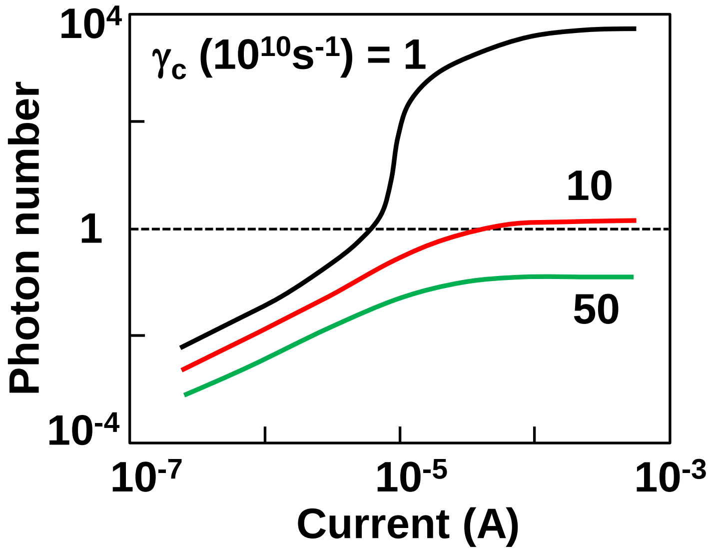
β = 1

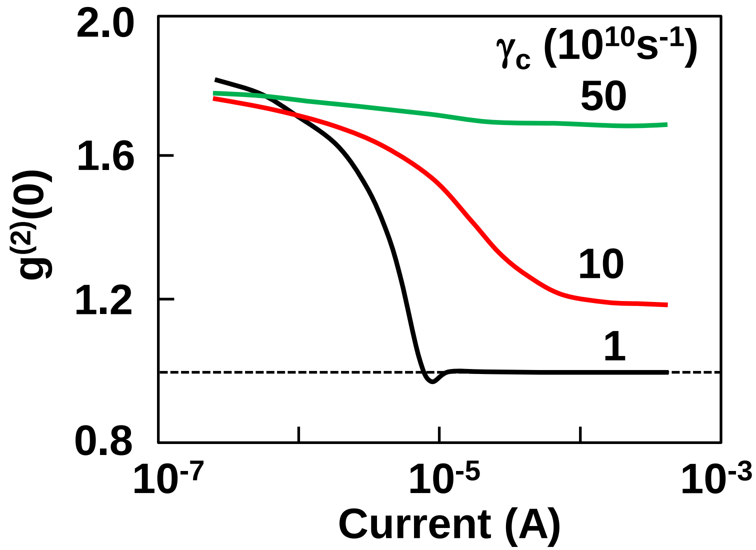


N_{QD} = 50, Δ_{inh} = 20meV

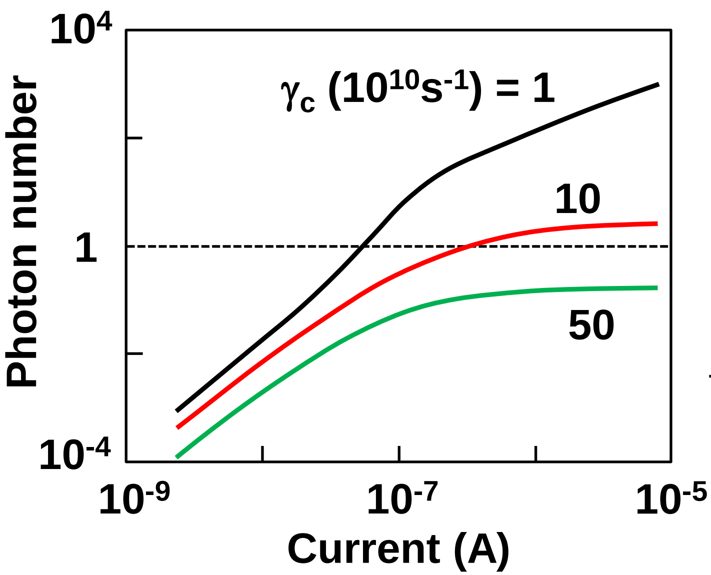
Criterial for lasing: $g^{(2)}(0)$

$\beta = 0.01$





$\beta = 1$

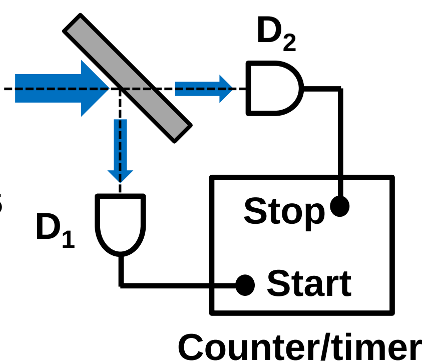


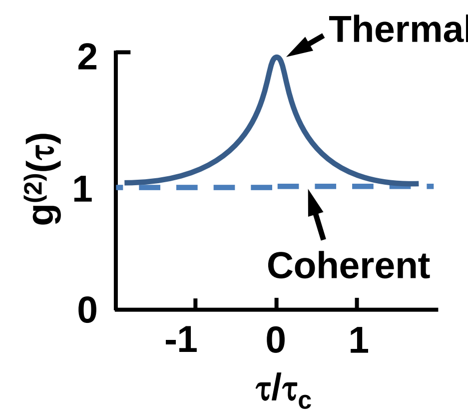
N_{QD} = 50, Δ_{inh} = 20meV

Second-order photon correlation function

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

Hanbury-Brown-Twiss experiment

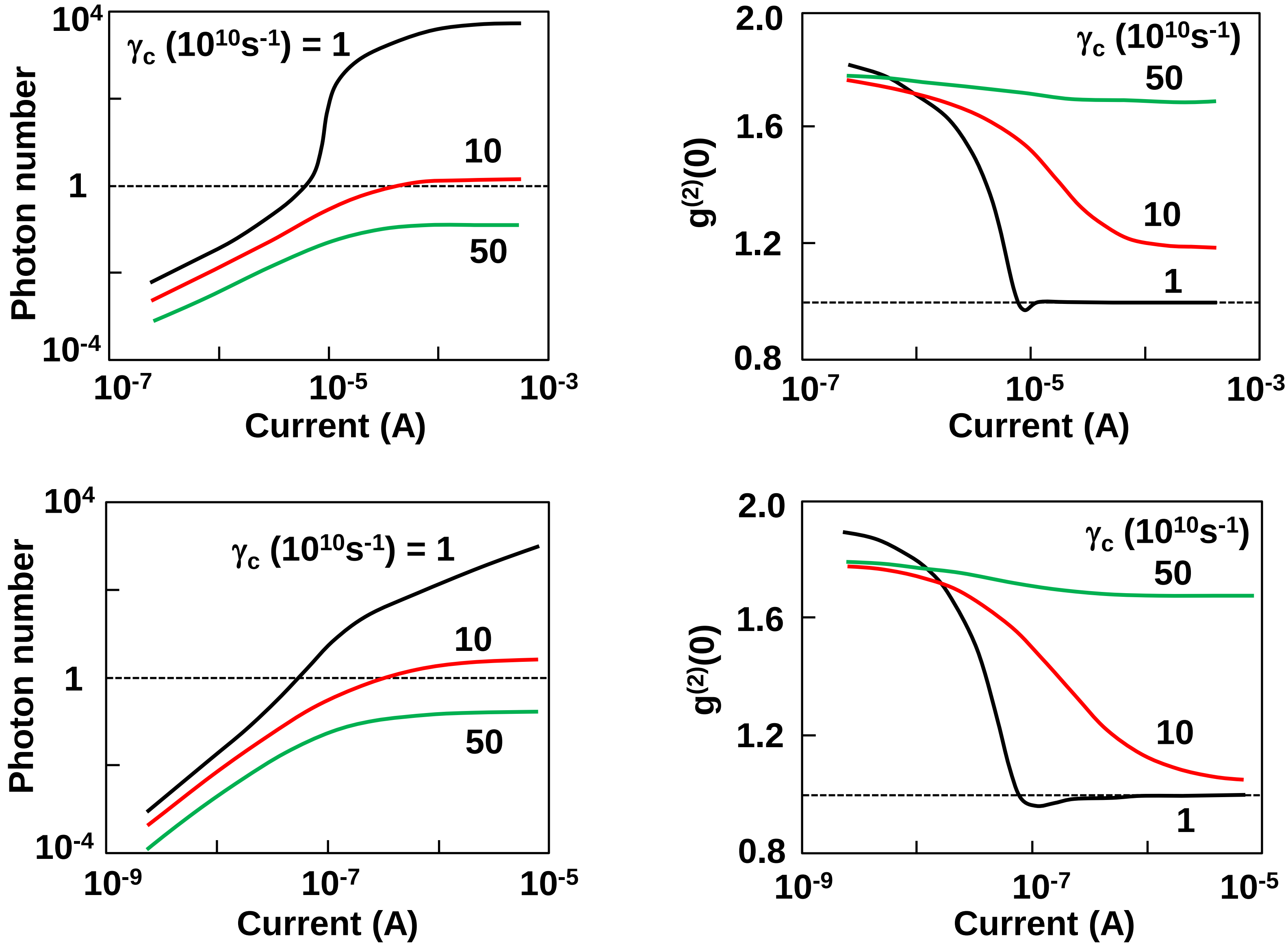




Criterial for lasing: $g^{(2)}(0)$

$\beta = 0.01$

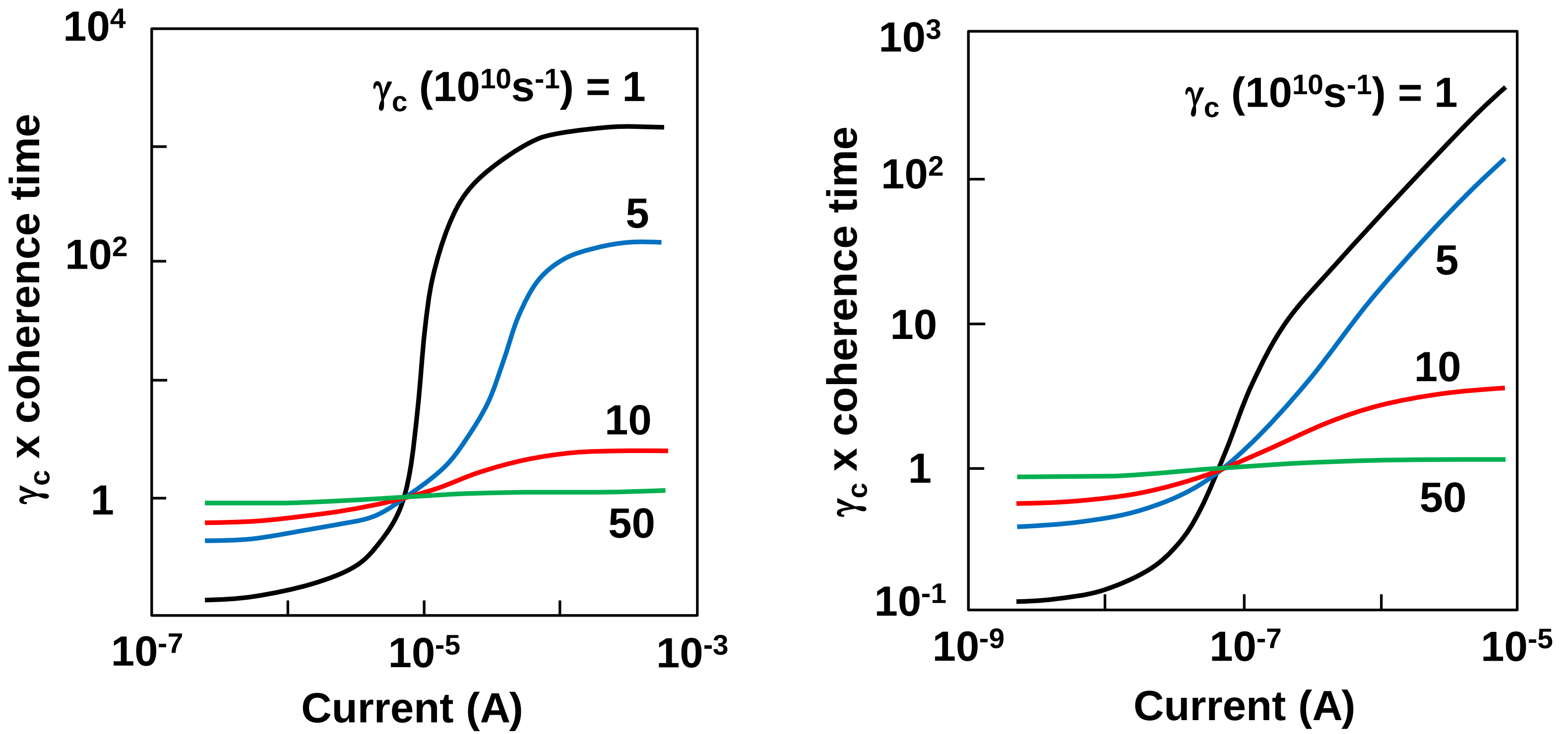
$\beta = 1$



$N_{QD} = 50,\ \Delta_{inh} = 20\text{meV}$

Criterial for lasing: coherence time

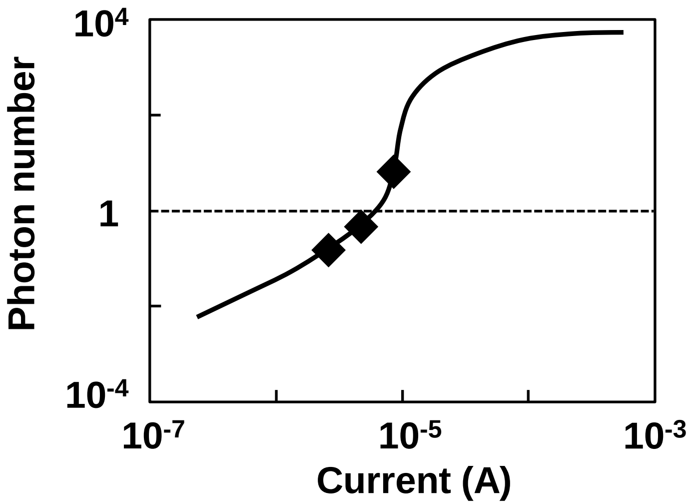
$$\tau_c = 2\int_{-\infty}^{\infty} d\tau \left|\frac{\langle a^\dagger a(\tau)\rangle_{ss}}{\langle a^\dagger a\rangle_{ss}}\right|^2$$

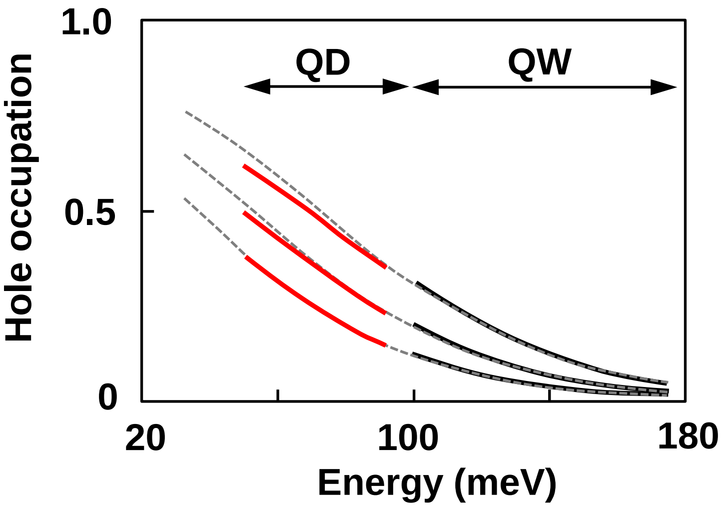


$N_{QD} = 50$, $\Delta_{inh} = 20$meV

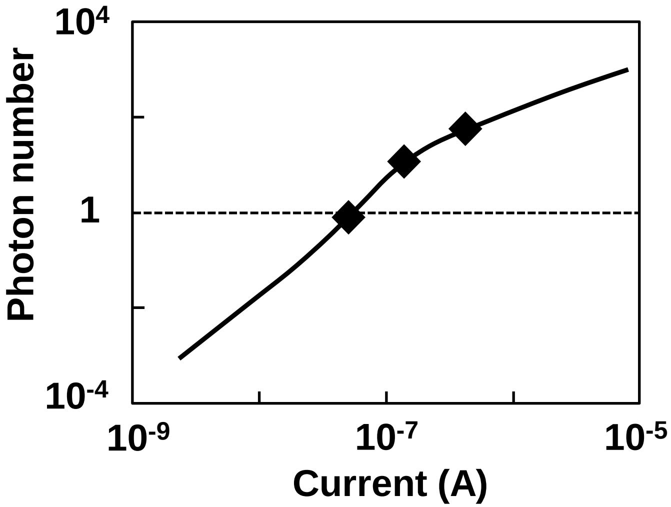
Criterial for lasing: Population clamping and hole burning

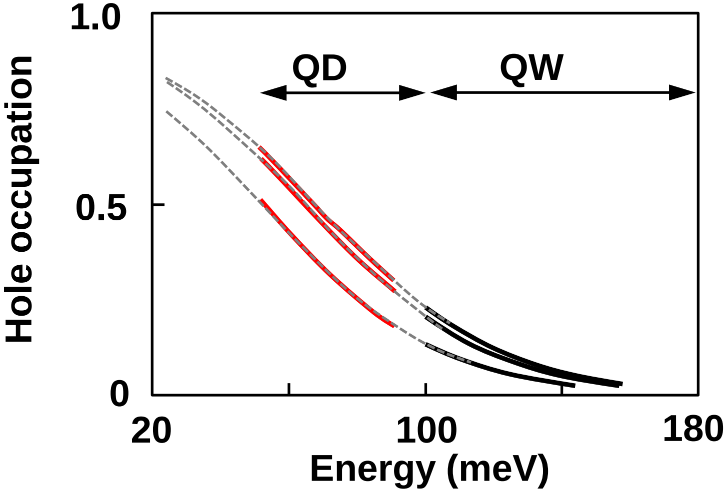
$\beta = 0.01$





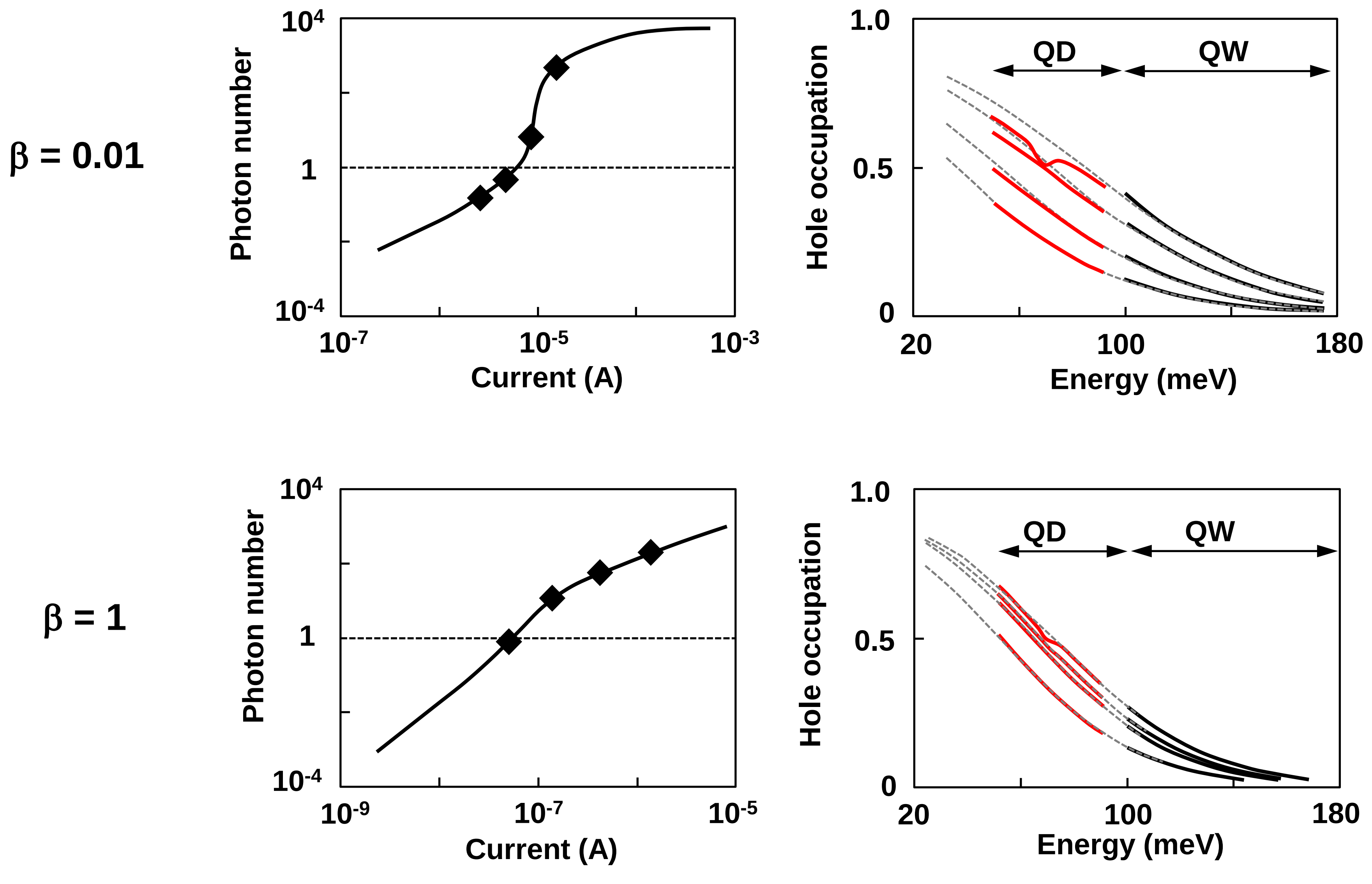
$\beta = 1$





$N_{QD} = 50$, $\Delta_{inh} = 20meV$, $\gamma_c = 10^{10} s^{-1}$

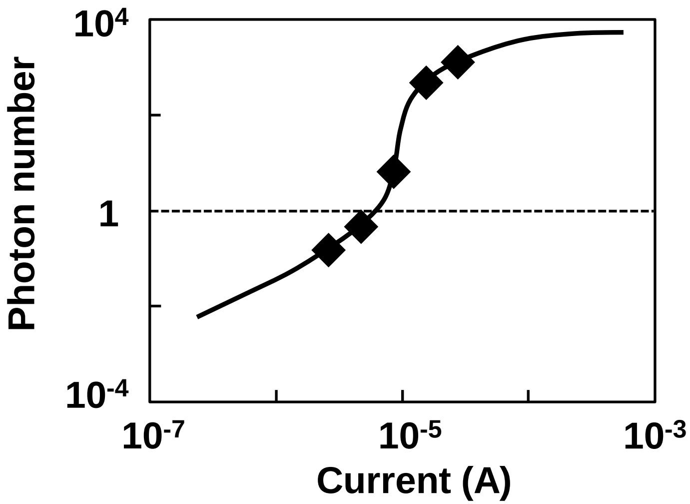
Criterial for lasing: Population clamping and hole burning

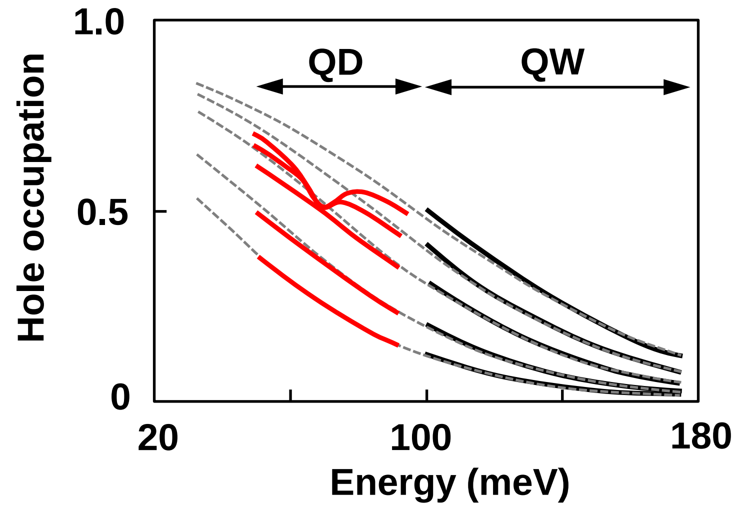


$N_{QD} = 50$, $\Delta_{inh} = 20\text{meV}$, $\gamma_c = 10^{10}\text{s}^{-1}$

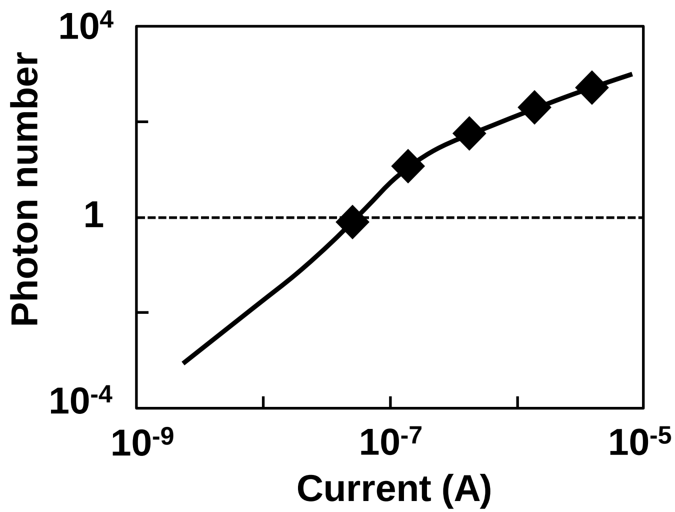
Criterial for lasing: Population clamping and hole burning

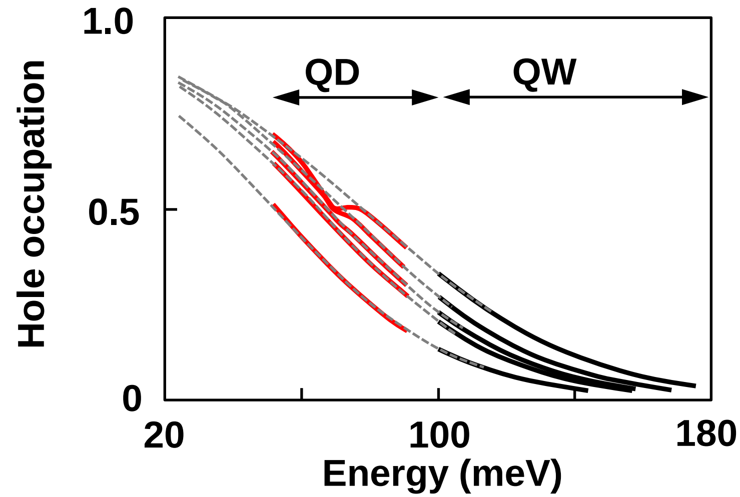
$\beta = 0.01$





$\beta = 1$





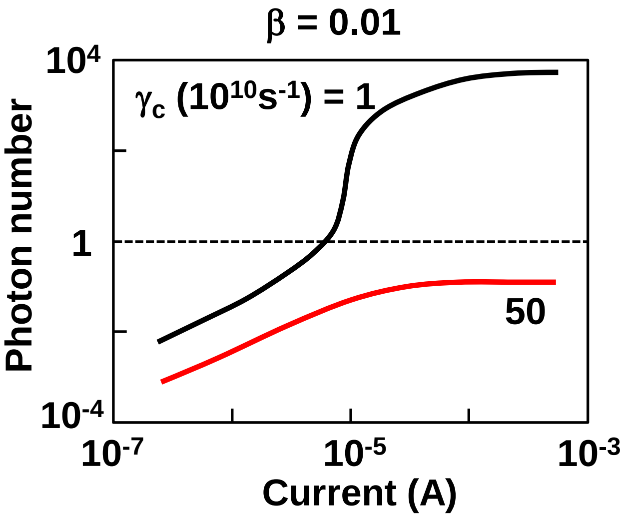
$N_{QD} = 50$, $\Delta_{inh} = 20\text{meV}$, $\gamma_c = 10^{10}\text{s}^{-1}$

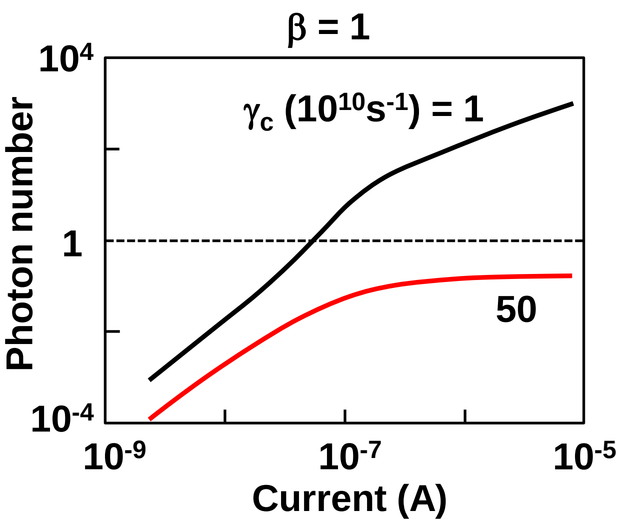
Criterial for lasing: Stimulated emission

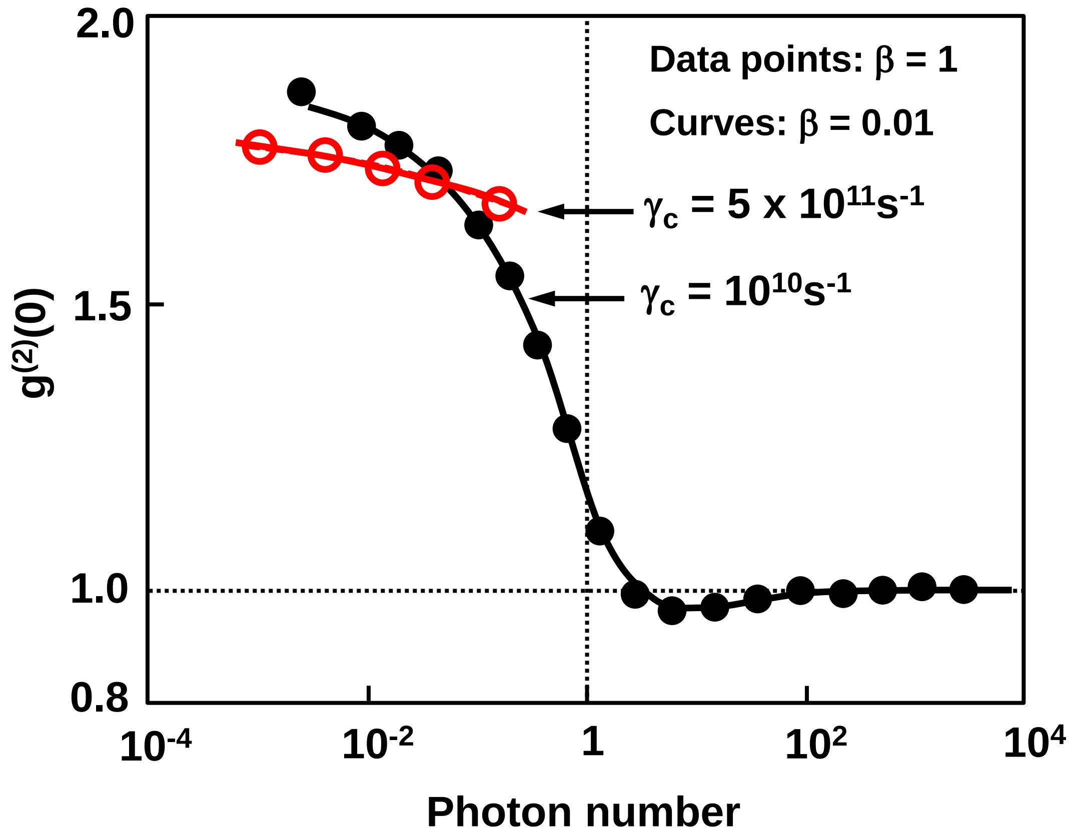
$$\frac{dn}{dt} = -2\gamma_c n + \gamma_l (n+1) N$$

Stimulated emission

Spontaneous emission

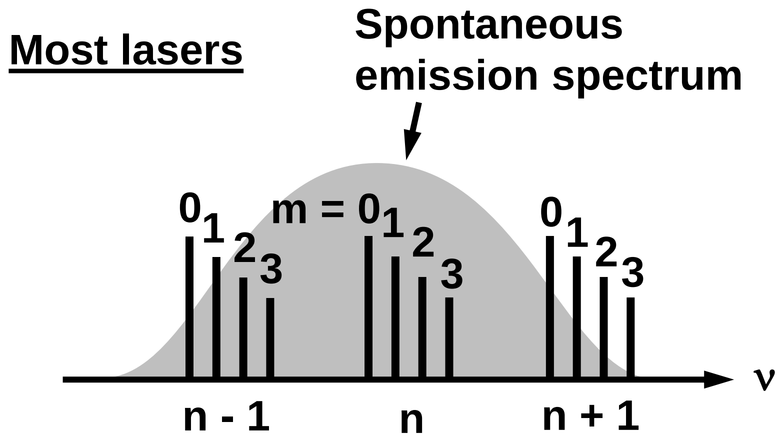


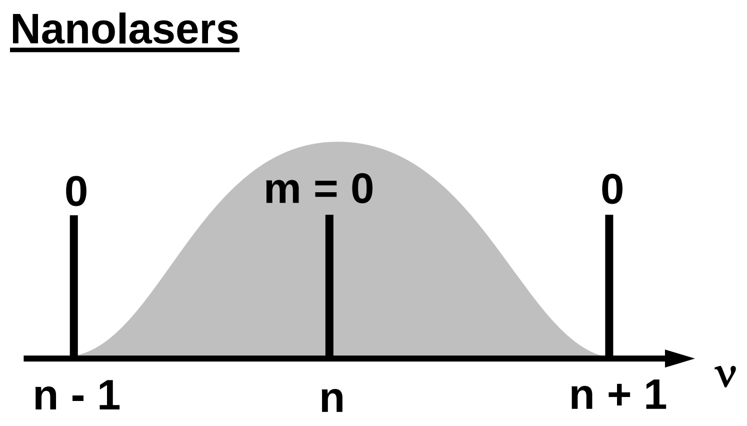




$N_{QD} = 50$, $\Delta_{inh} = 20\text{meV}$

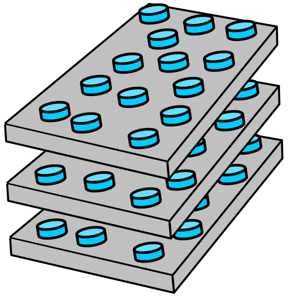
Why work on nanolasers?



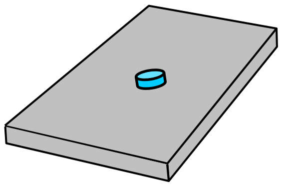


All emission into single resonator mode

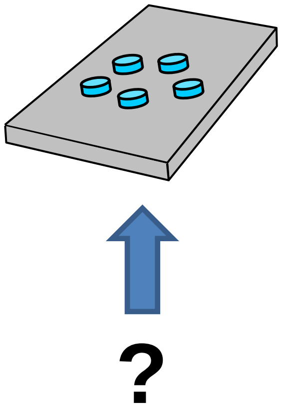
Typical QD-laser
active region



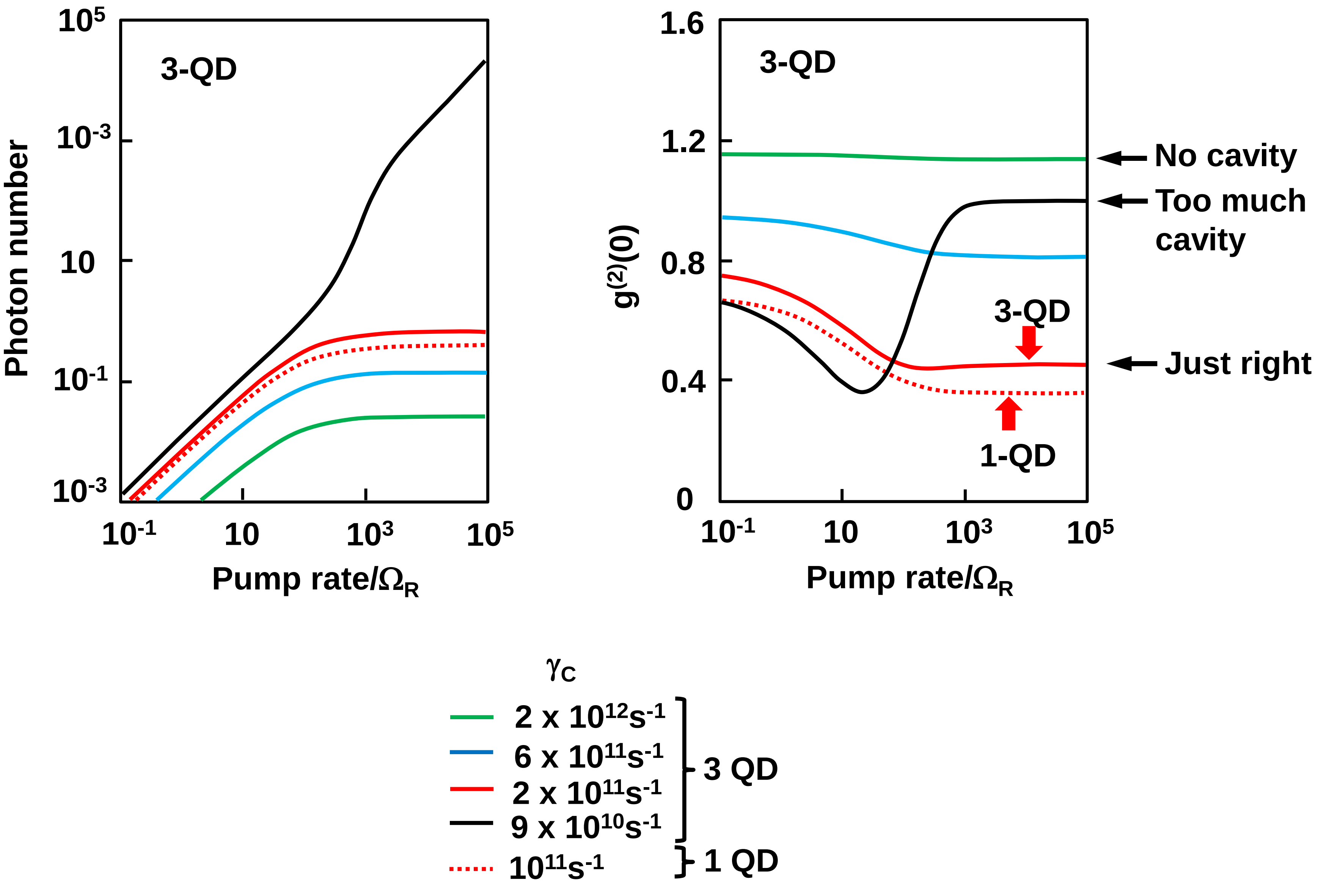
Single-photon
source active region



Few-QD active region

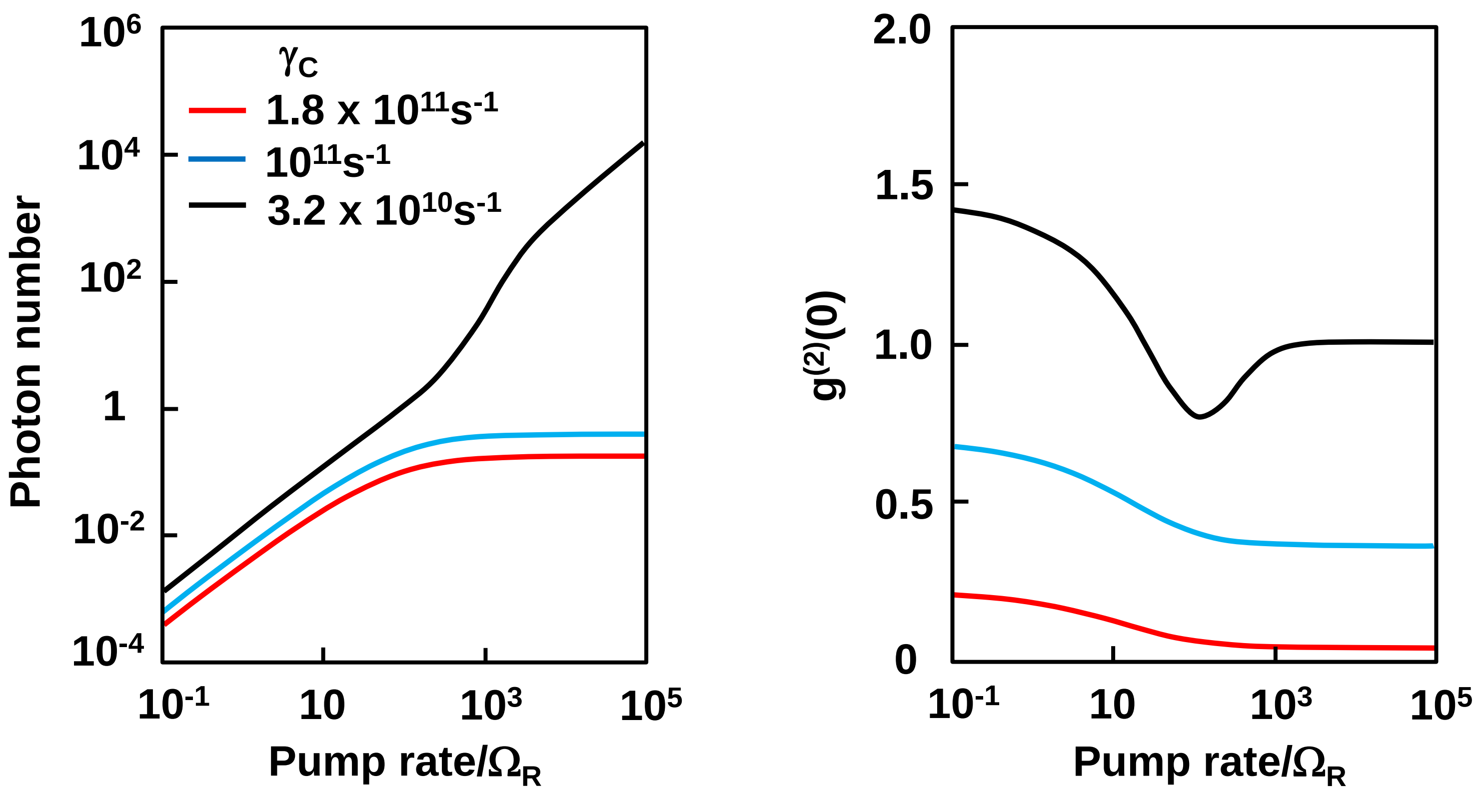


Higher single-photon production rate with few-QD active region



Single-quantum-dot active region

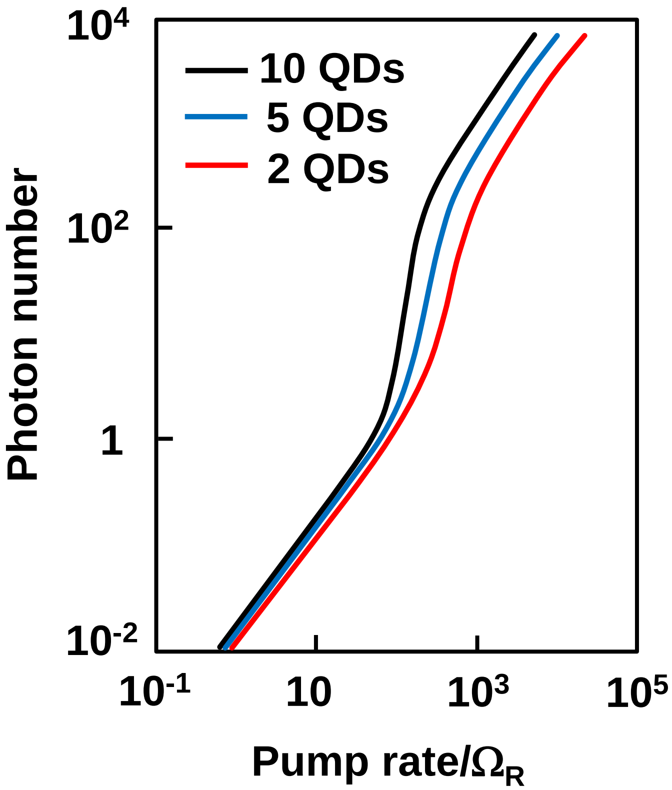
Single-photon source ➡ Nonclassical-light source ➡ Laser

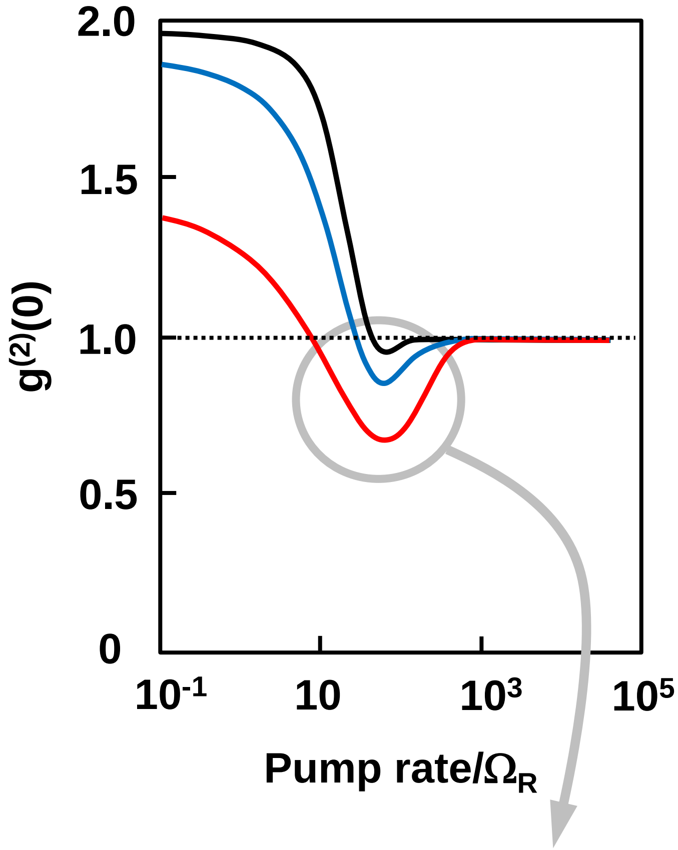


Vacuum Rabi frequency: $\Omega_R = 2.7 \times 10^{11} s^{-1}$

Few-quantum-dot active region

Question: Can we increase single-photon production rate?

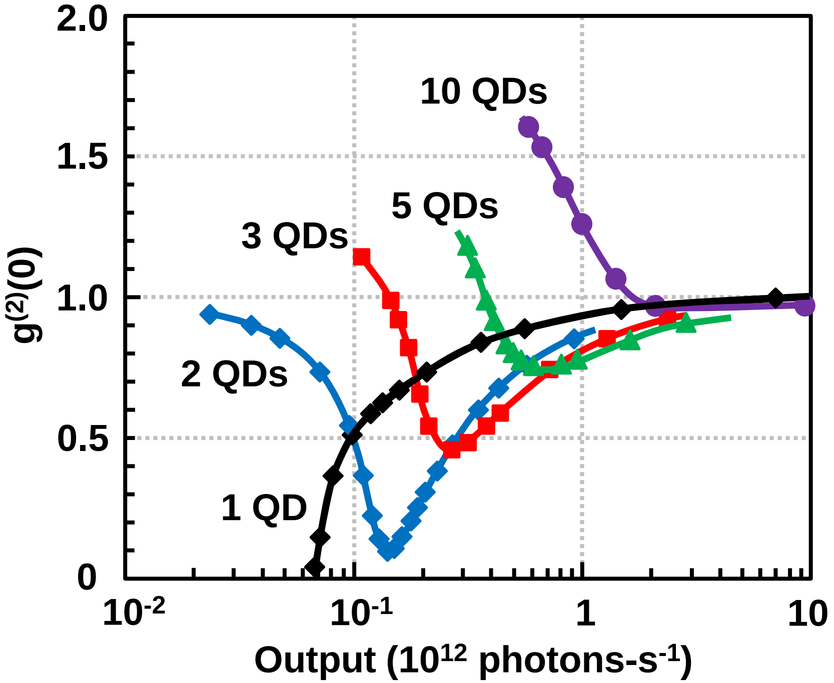


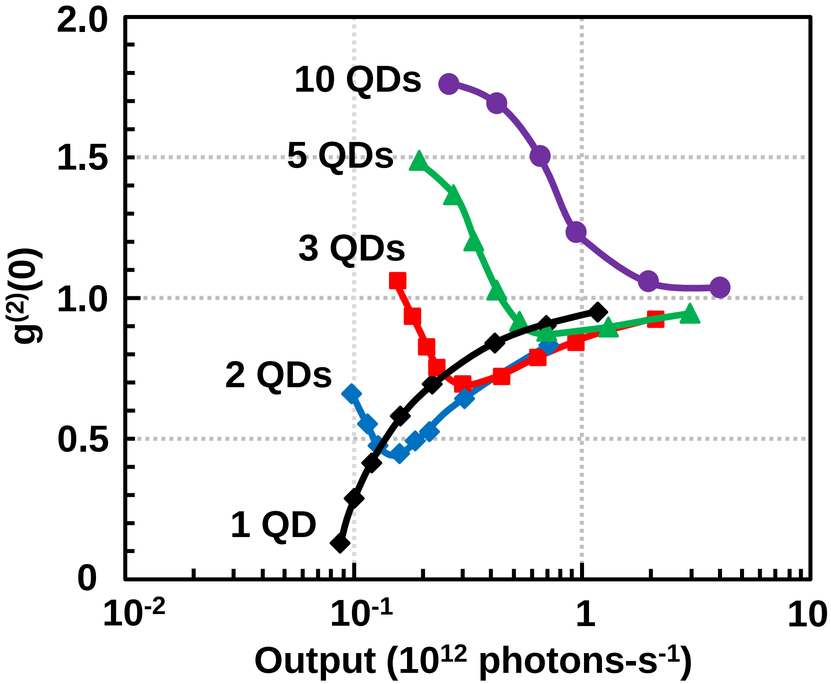


QD	γ_C
10	$2 \times 10^{11} s^{-1}$
5	$10^{11} s^{-1}$
2	$6 \times 10^{10} s^{-1}$

Light-carrier correlation
Leading terms:
$\delta\langle c^\dagger c a^\dagger a\rangle, \delta\langle b^\dagger b a^\dagger a\rangle,$
$\delta\langle b^\dagger c^\dagger a^\dagger a a\rangle$

Increasing single-photon production rate with few-emitter active region





Concerns and next refinements

Present model

Injection current

QW

$$n_{e,k}^{QW}\ ,\ n_{h,k}^{QW}$$

$\gamma_{c-c}\ ,\ \gamma_{c-p}$

More rigorous treatment of excitation necessary for few-QD situations

QDs

$$\langle c_n^\dagger c_n \rangle$$
$$\langle b_n^\dagger b_n \rangle$$
$$\langle c_n^\dagger b_n^\dagger a \rangle$$

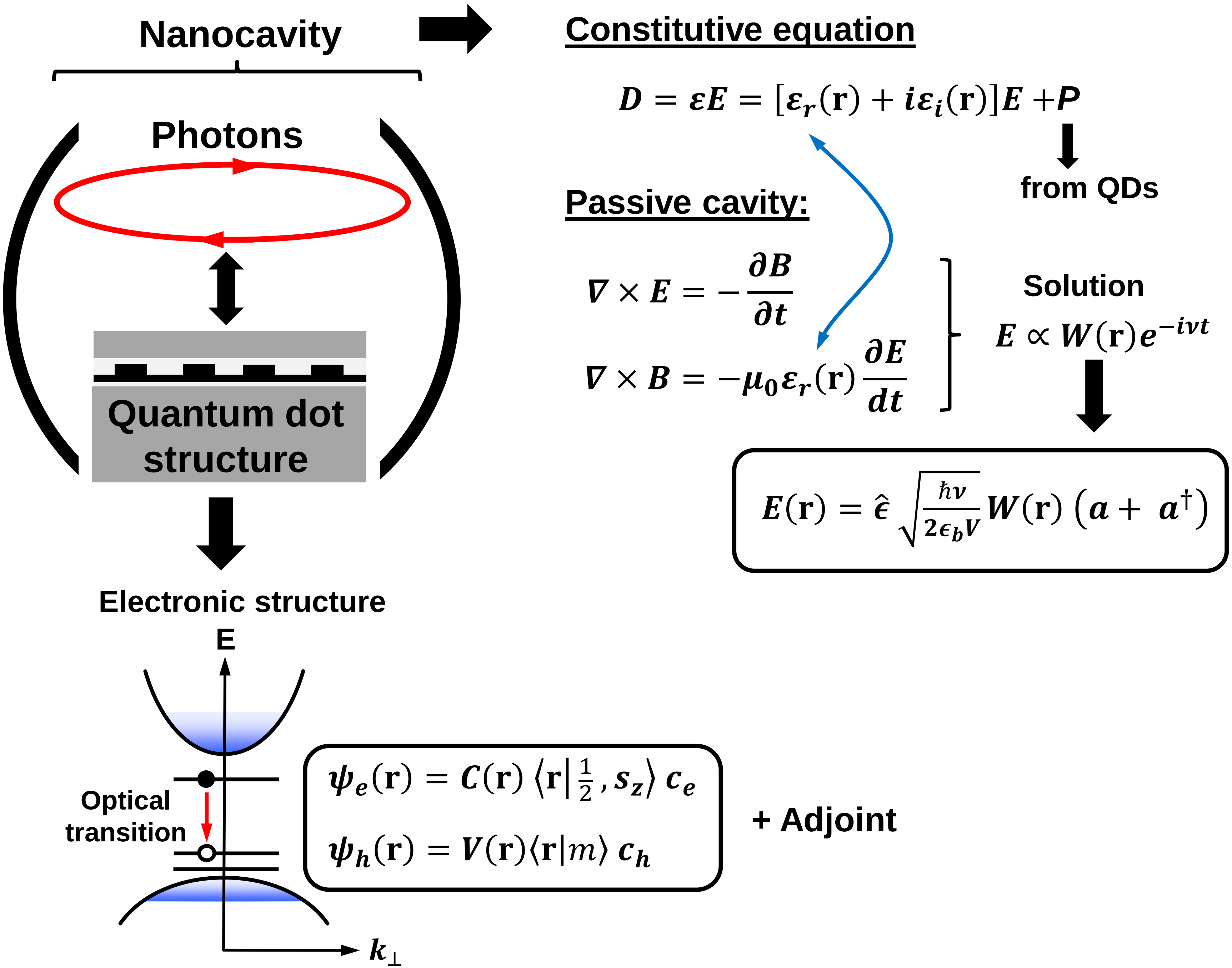
ω_n

g

Photons

$$\langle a^\dagger a \rangle \qquad \langle a^\dagger a(\tau) \rangle$$
$$\langle a^\dagger a^\dagger a\ a \rangle \quad \langle a^\dagger a^\dagger a\ b_n c_n \rangle$$
$$\langle a^\dagger a\ c_n^\dagger c_n \rangle \quad \langle a^\dagger a\ b_n^\dagger b_n \rangle$$

Beyond doublet


Nanocavity
Photons
Quantum dot structure
Electronic structure
E
$k_\perp$
Optical transition
$\psi_e(\mathbf{r}) = C(\mathbf{r})\left\langle \mathbf{r} \middle| \frac{1}{2}, s_z \right\rangle c_e$
$\psi_h(\mathbf{r}) = V(\mathbf{r})\langle \mathbf{r} | m\rangle\, c_h$
+ Adjoint
Constitutive equation
$D = \varepsilon E = [\varepsilon_r(\mathbf{r}) + i\varepsilon_i(\mathbf{r})]E + P$
from QDs
Passive cavity:
$\nabla \times E = -\frac{\partial B}{\partial t}$
$\nabla \times B = -\mu_0 \varepsilon_r(\mathbf{r}) \frac{\partial E}{dt}$
Solution
$E \propto W(\mathbf{r}) e^{-i\nu t}$
$E(\mathbf{r}) = \hat{\epsilon}\sqrt{\frac{\hbar\nu}{2\epsilon_b V}}\, W(\mathbf{r})\,(a + a^\dagger)$

Nano-emitter model

$H = H_0$ *Single-particle energies*

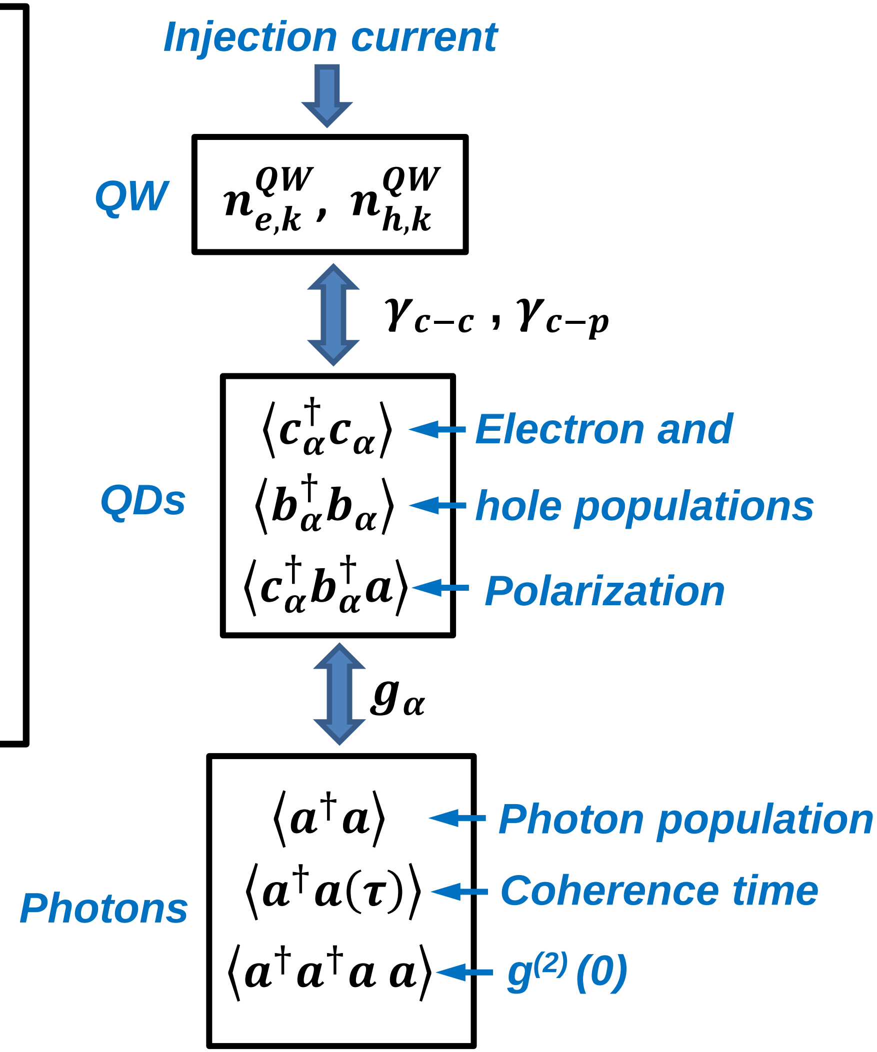
$-\hbar \sum_{\alpha} \left(g_\alpha b_\alpha^\dagger c_\alpha^\dagger a - g_\alpha^* a^\dagger c_\alpha b_\alpha \right)$ *Light-carrier*

$\wp \sqrt{\nu / \hbar \epsilon_b V}\; W(R_{QD}) \sum_n C_\alpha(R_n) V_\alpha(R_n)$

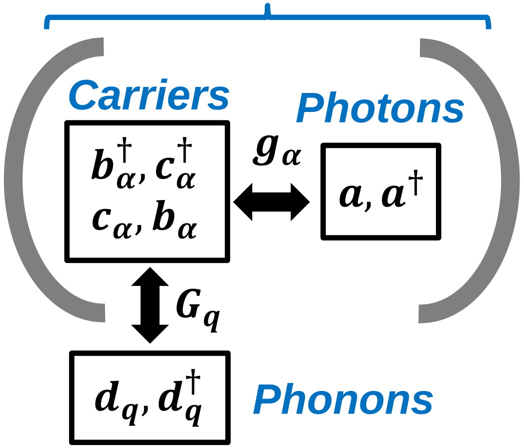
$+\hbar \sum_{\alpha\beta q} G_q \left(c_\alpha^\dagger c_\beta + b_\alpha^\dagger b_\beta \right) \left(d_q + d_q^\dagger \right)$ *Carrier-phonon*

$$\left.\begin{array}{l} + \frac{1}{2} \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, c_\alpha^\dagger c_\beta^\dagger c_\eta c_\sigma + \frac{1}{2} \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger b_\beta^\dagger b_\eta b_\sigma \\ - \sum_{\alpha\beta\sigma\eta} W_{\sigma\eta}^{\alpha\beta}\, b_\alpha^\dagger c_\beta^\dagger c_\eta b_\sigma \end{array}\right\} \text{Carrier-carrier}$$

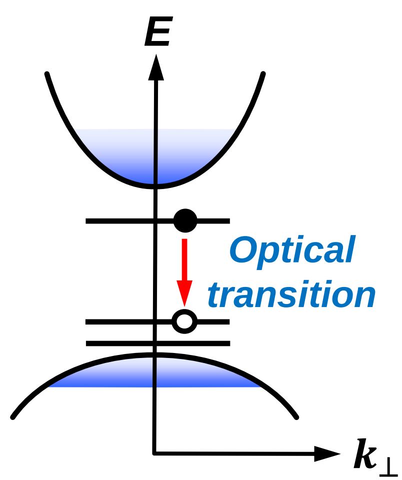
Matrix element of $\dfrac{e^2}{4\pi\varepsilon_b |r - r'|}$



Nanocavity



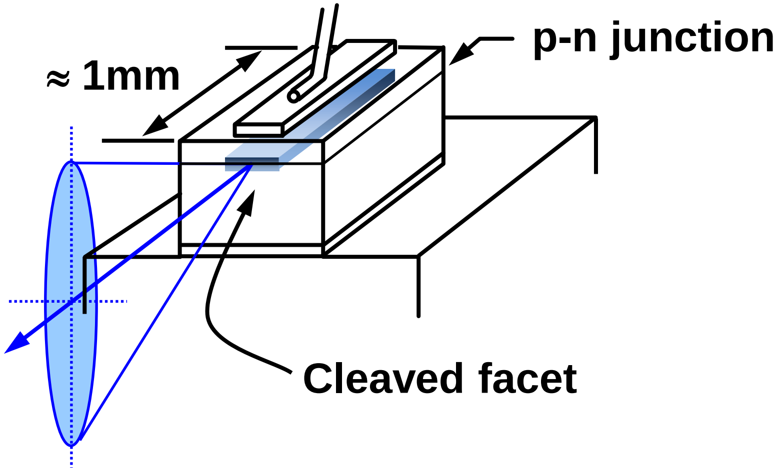
Electronic structure



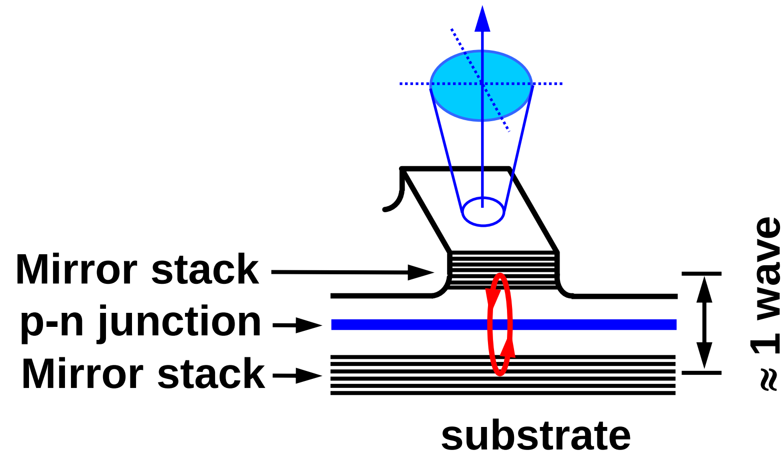
Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

Towards smaller and smaller lasers

Edge - Emitting Laser



Vertical-Cavity Surface-Emitting Laser (VCSEL)



Nanolasers

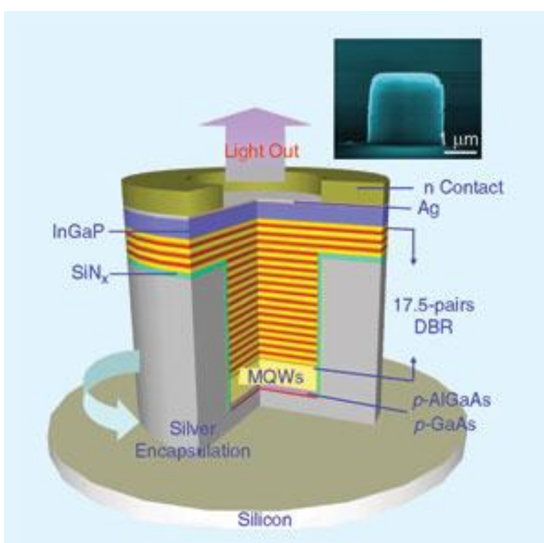


Figure 6. Combining semiconductors and metals enables nanolasers having a footprint roughly a factor <u>100 smaller</u> than that of a classical VCSEL. Adapted from a figure originally created by C. Y. Lu et al., UIUC.

Taken from D. Bimberg, IEEE Photonics Society Research Highlights