First principle study of nanolasers: photon statistics and laser threshold

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Motivation for nanolasers

First-principles modeling approach

Examples of applications:

a) Laser threshold and thresholdless lasing

b) Single-photon sources and photon statistics

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

Why nano-emitter development?

① Save energy

Talk: Attojoule optoelectronics – why and how

David Miller, Stanford University
IEEE Photonics Summer Topicals 2013

Information communication and processing growth:

- Energy per bit has to reduce
- At limits for electrical approaches

Lasers: can still reduce required electrical energy by reducing volume

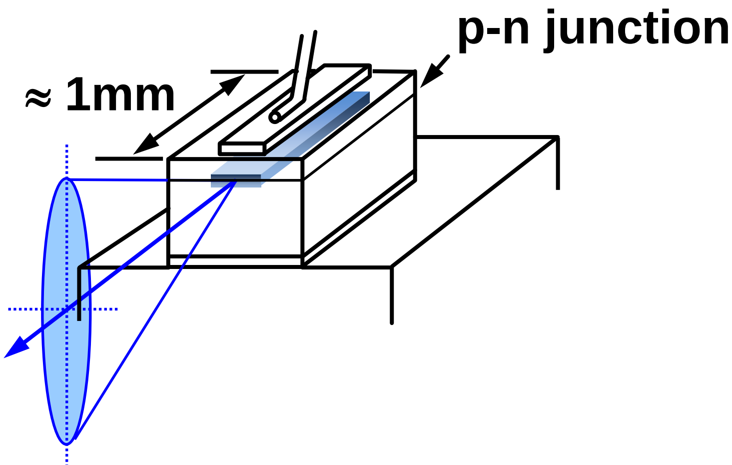
② Safe communication and quantum computing: Single-photon sources

Types of light

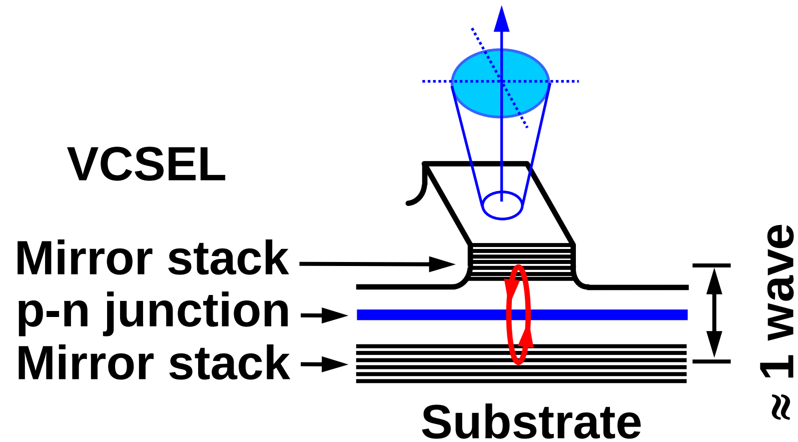
Laser (random) **Single-photon (antibunched)**

Towards smaller and smaller lasers

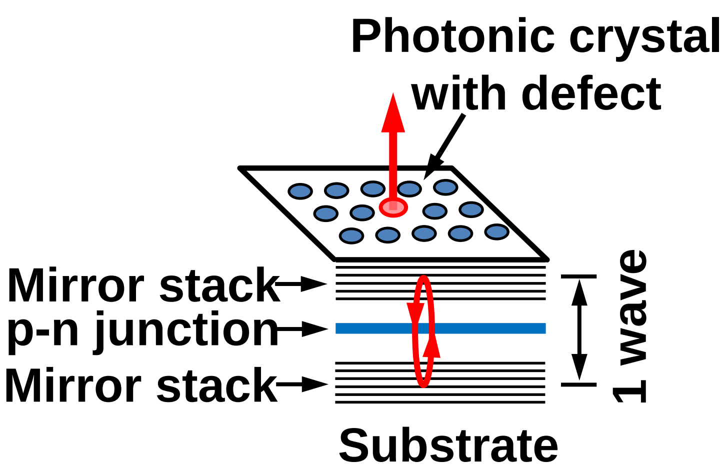
Edge - Emitting Laser

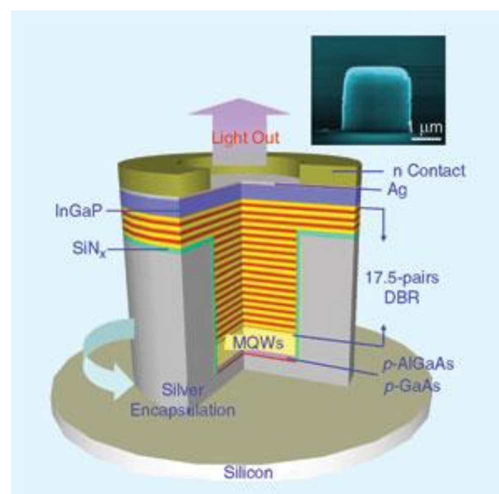


Vertical-Cavity Surface-Emitting Laser



Nanolasers



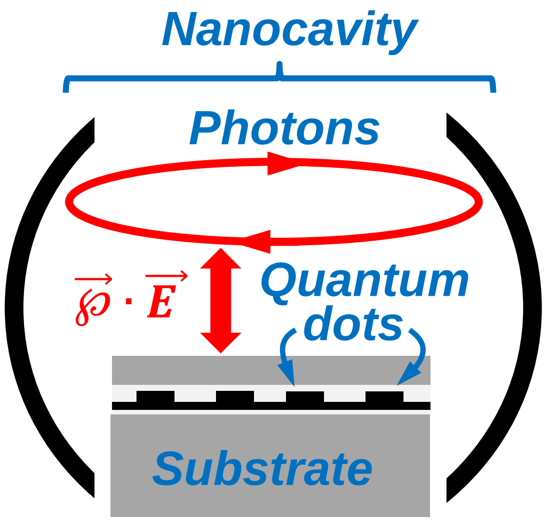


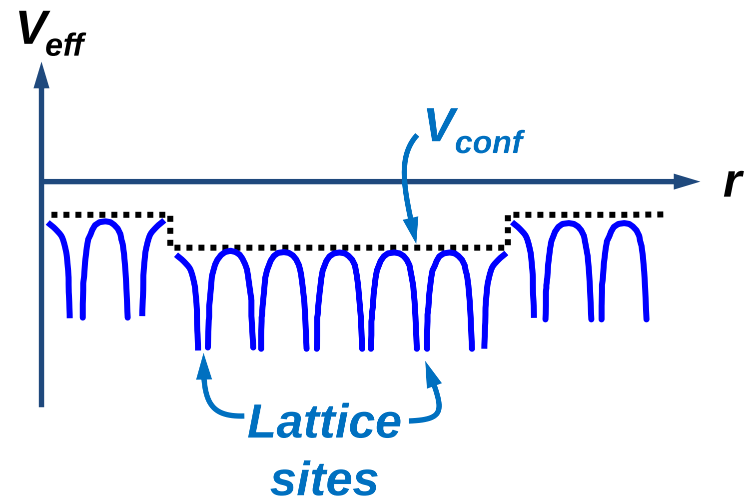
Combining semiconductors and metals … factor <u>100 smaller</u> than … VCSEL.

Adapted from a figure by Lu et al., UIUC.

Taken from D. Bimberg, IEEE Photonics Society Research Highlights

Hamiltonian





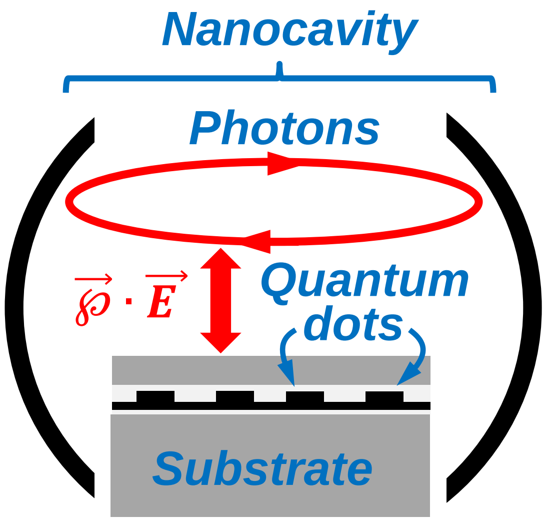
$$H = \sum_i \left[\frac{p_i^2}{2m_0} - \sum_j \frac{Ze^2}{4\pi\varepsilon_b |r_i - R_j|} + V_{conf}(r_i) + \sum_{j\neq i} \frac{e^2}{4\pi\varepsilon_b |r_i - r_j|} - \vec{\wp}_i \cdot \vec{E} \right]$$

Single-particle electronic structure & carrier-phonon interaction

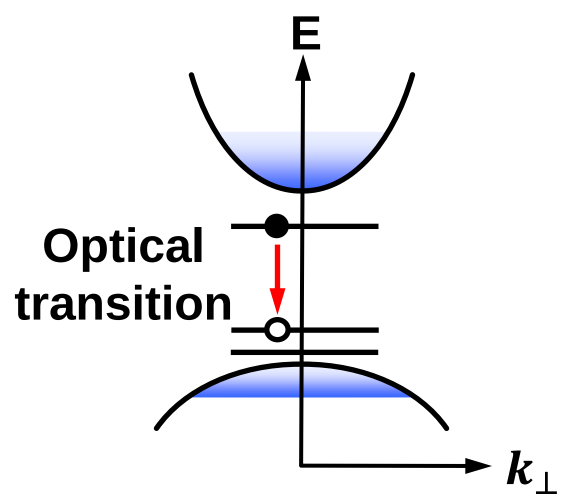
Many-body carrier-carrier interaction

Light-matter interaction (Dipole approx.)

Nano-emitter model



Electronic structure



Second quantization

Radiation field

$$E(\mathbf{r}) = \hat{\epsilon}\sqrt{\frac{\hbar\nu}{2\epsilon_b V}}\,W(\mathbf{r})\left(a + a^\dagger\right)$$

Photon annihilation and creation operators

Carriers

$$\psi_e(\mathbf{r}) = C(\mathbf{r})\left\langle \mathbf{r}\middle|\tfrac{1}{2}, s_z\right\rangle c_e$$

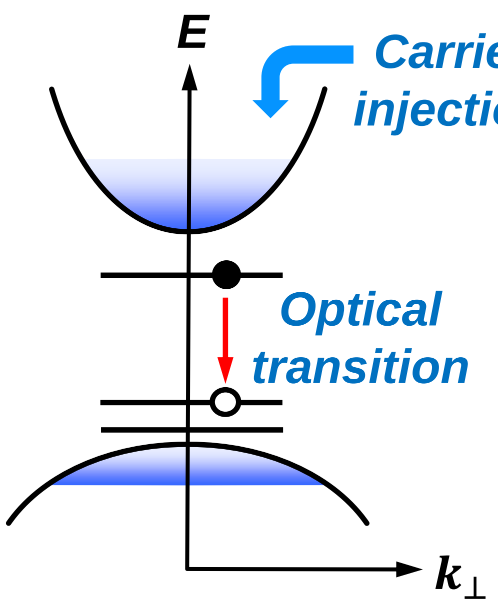
$$\psi_h(\mathbf{r}) = V(\mathbf{r})\langle \mathbf{r}|m\rangle\, c_h$$

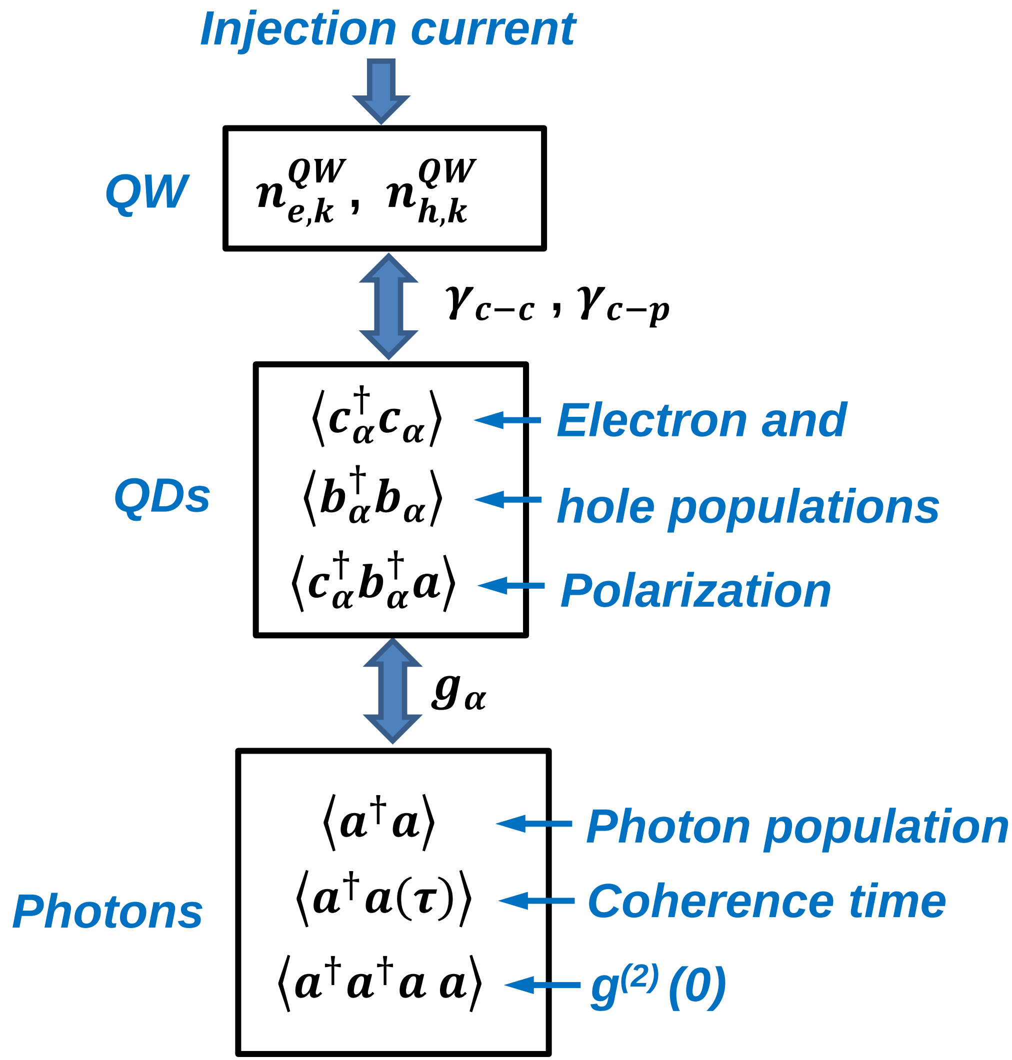
+ Adjoint

Hole and electron annihilation operators

Nano-emitter model

Electronic structure





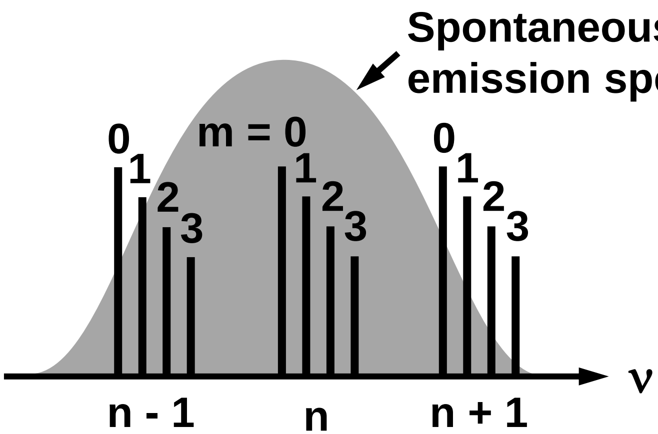
Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

Light: Science and Applications, online 29 August, 2014

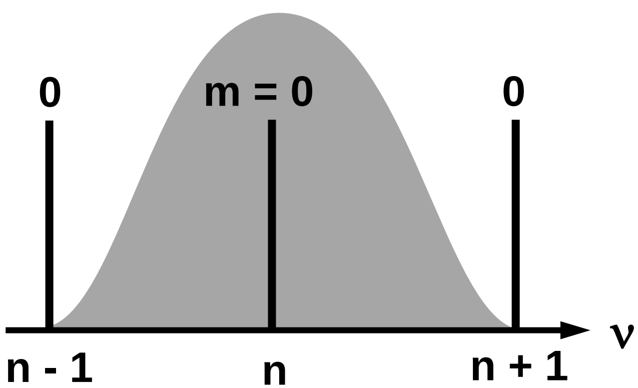
Interesting physics with nanolasers

Example 1: Laser threshold and thresholdless lasing

Most lasers $\beta \ll 1$



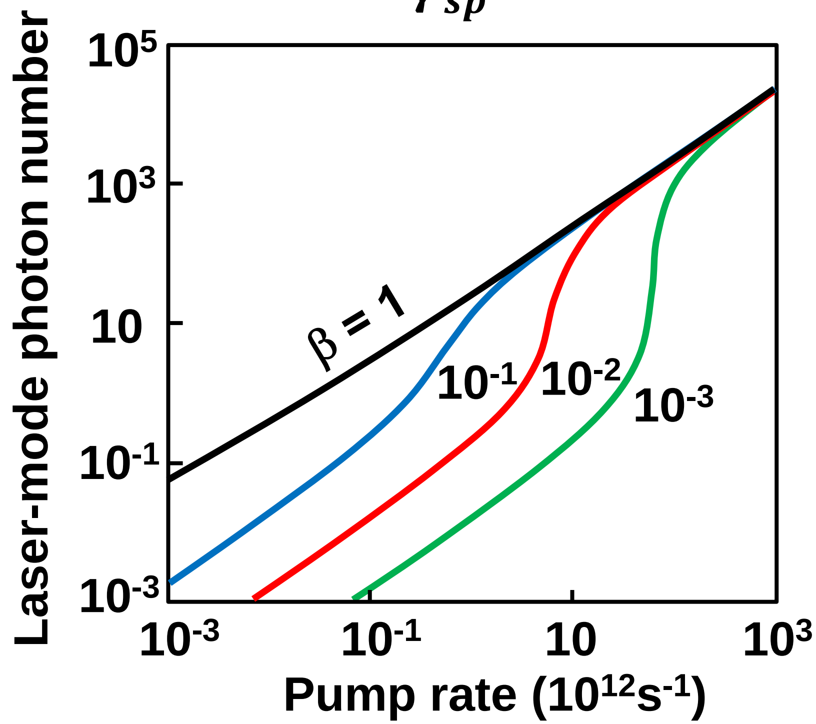
Some nanolasers $\beta = 1$



All emission into single resonator mode

Spontaneous emission factor

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



Questions:

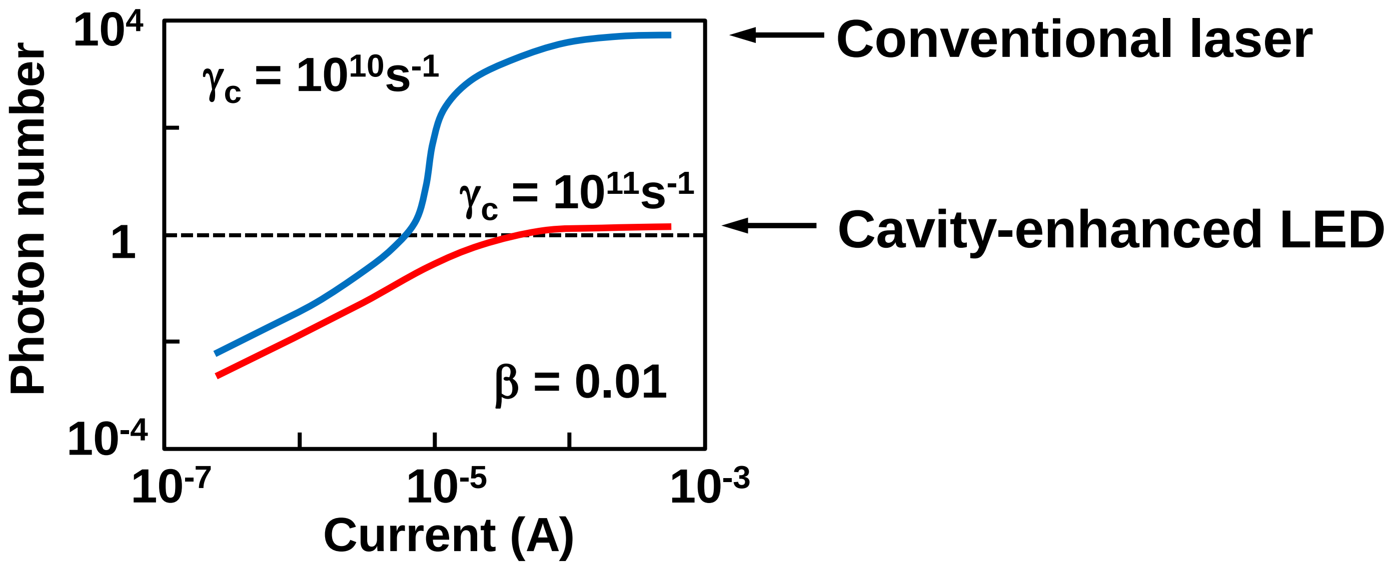
1) Is thresholdless lasing real?
2) What is lasing?

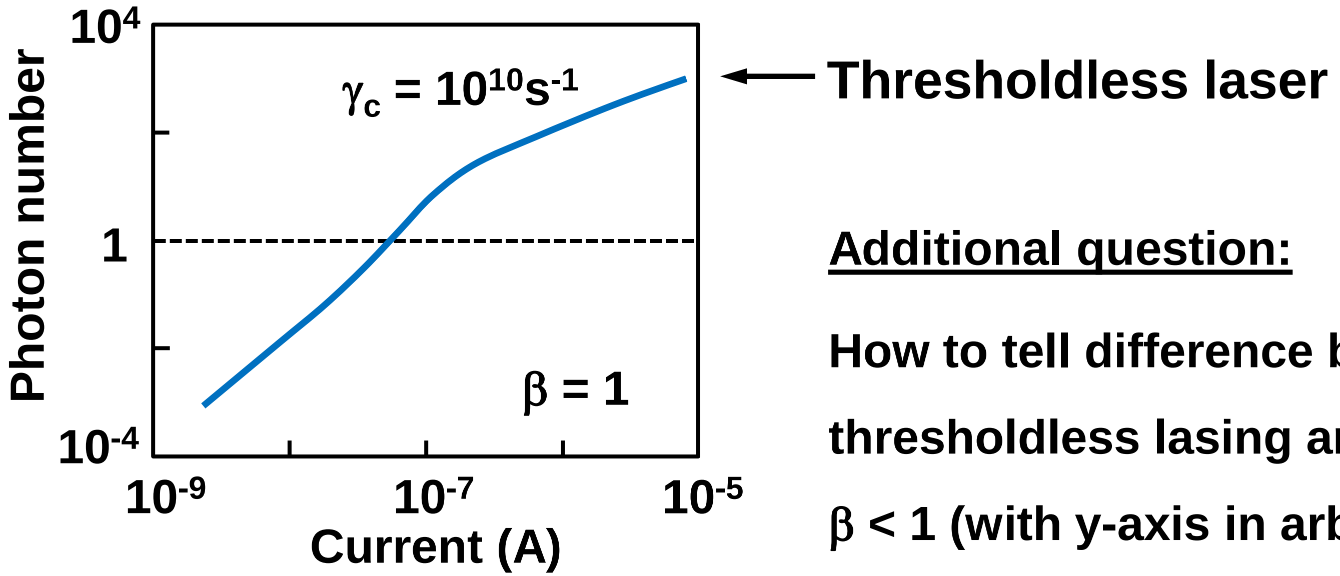
Early answer in Jin, Boggavarapu, Sargent, Meystre, Gibbs, Khitrova, Phy Rev A 49, 1994

Criterion for lasing

N_{QD} = 50, Δ_{inh} = 20meV

<u>**Input/Output**</u>





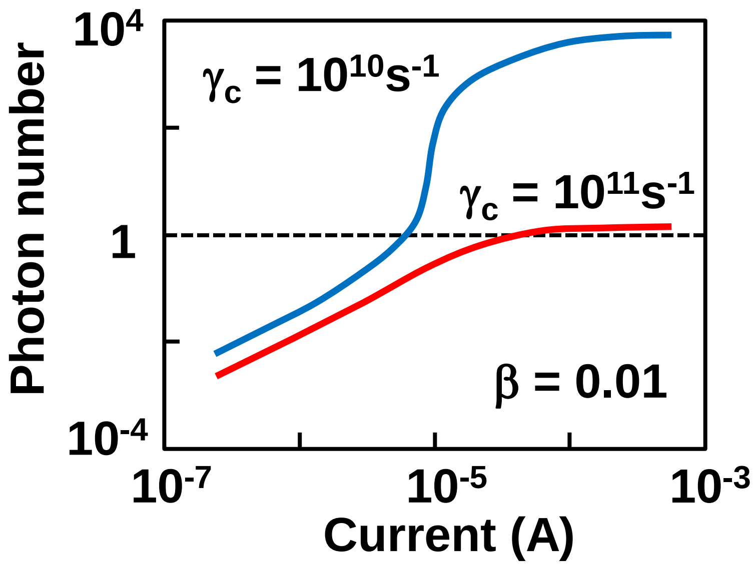
<u>**Additional question:**</u>

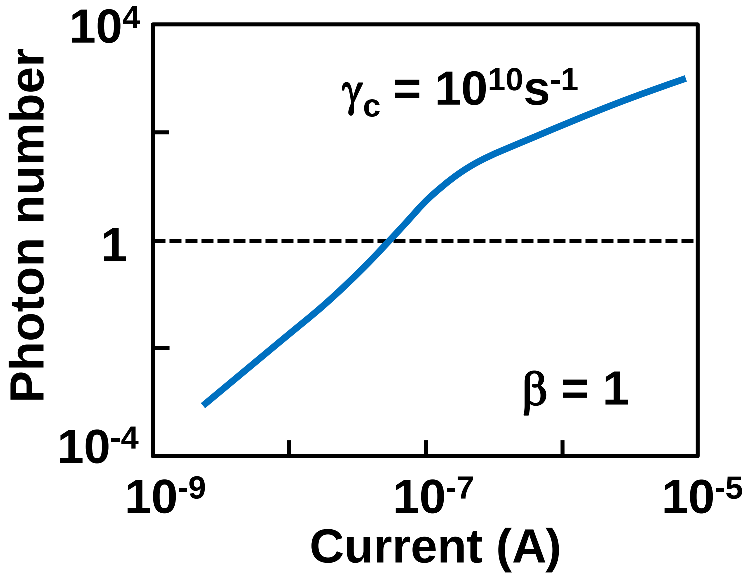
How to tell difference between thresholdless lasing and non-lasing with $\beta < 1$ (with y-axis in arbitrary units)?

Criterion for lasing

N_{QD} = 50, Δ_{inh} = 20meV

Input/Output

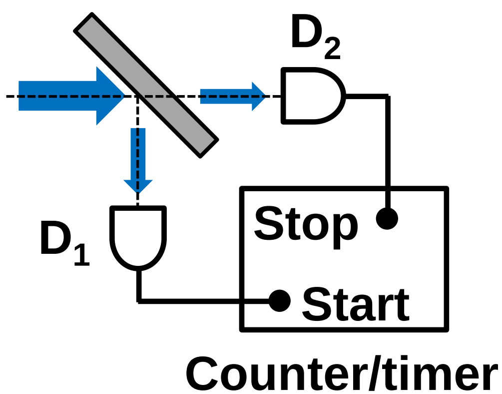


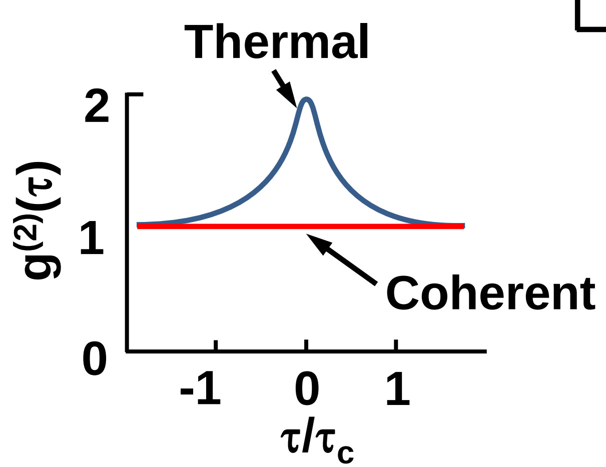


Second-order intensity correlation function

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

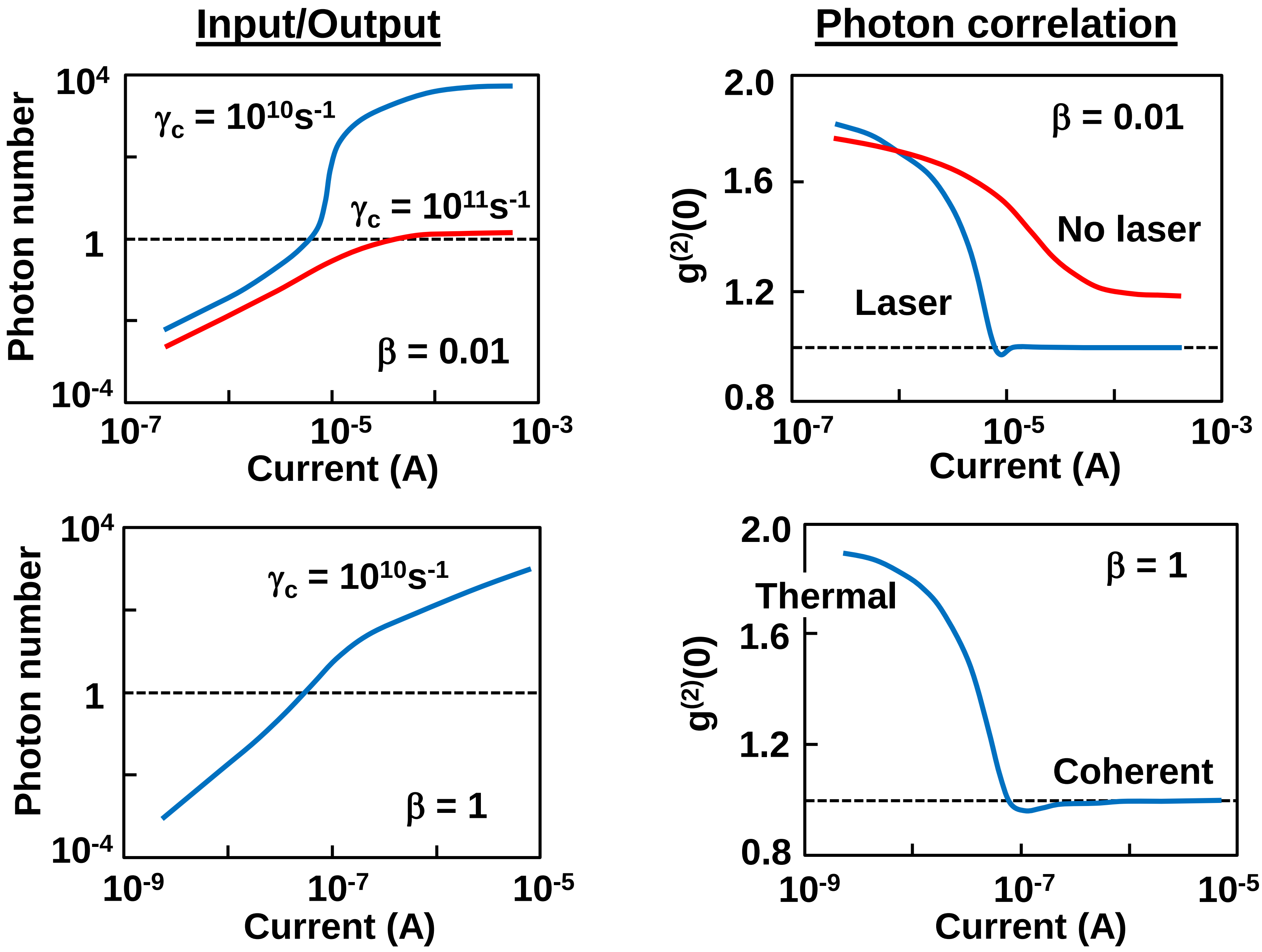
Hanbury-Brown-Twiss experiment





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

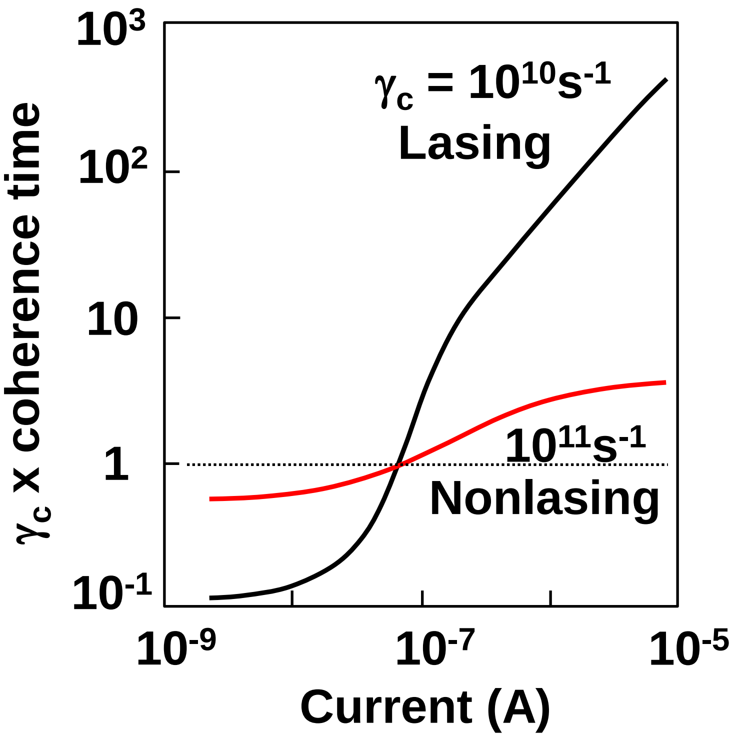
$N_{QD} = 50$, $\Delta_{inh} = 20$meV



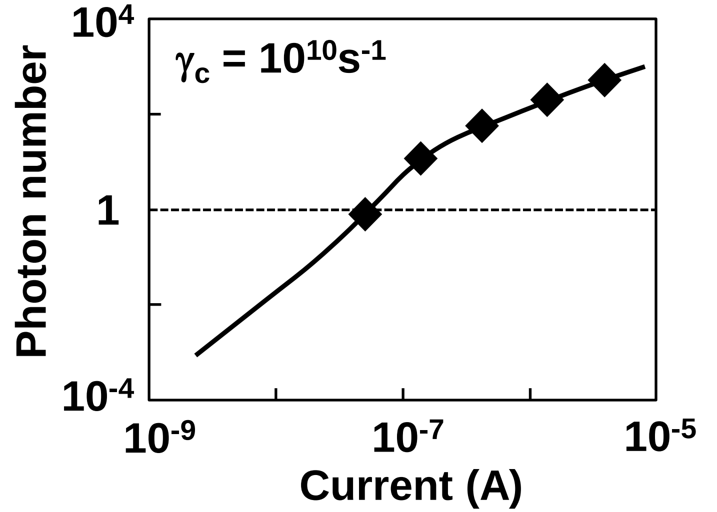
Other criteria for lasing

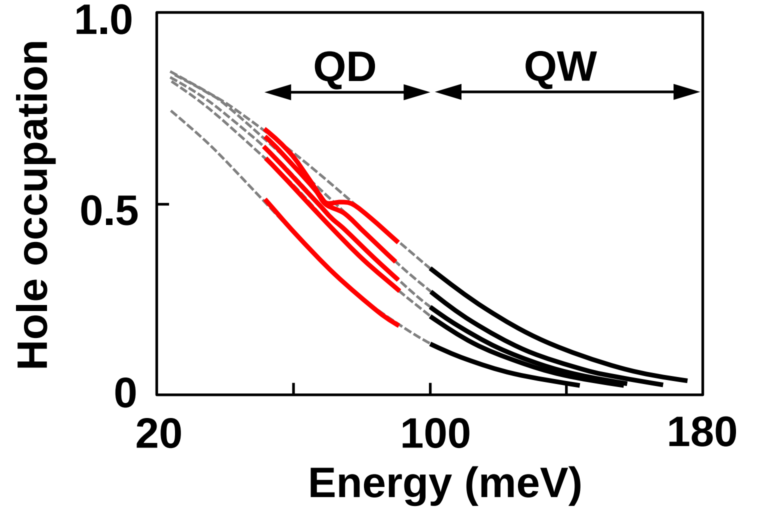
Coherence time

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



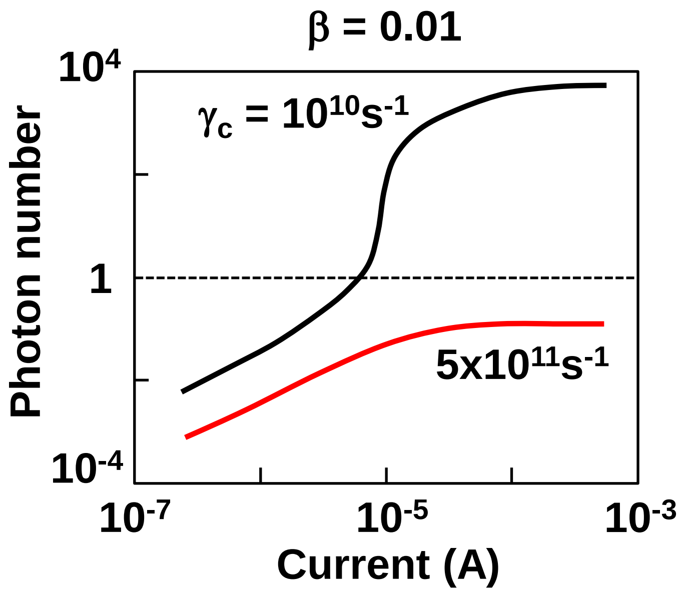
Population clamping and hole burning





$\beta = 1$, $N_{QD} = 50$, $\Delta_{inh} = 20meV$

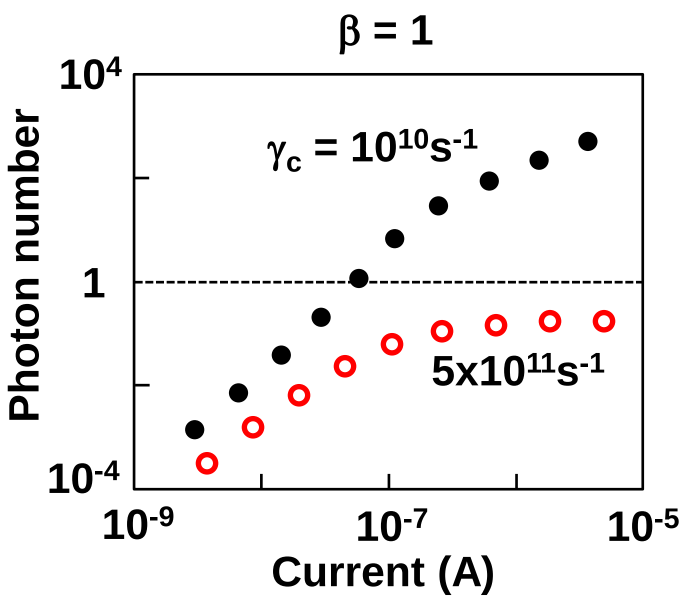
Other criteria for laser: stimulated emission

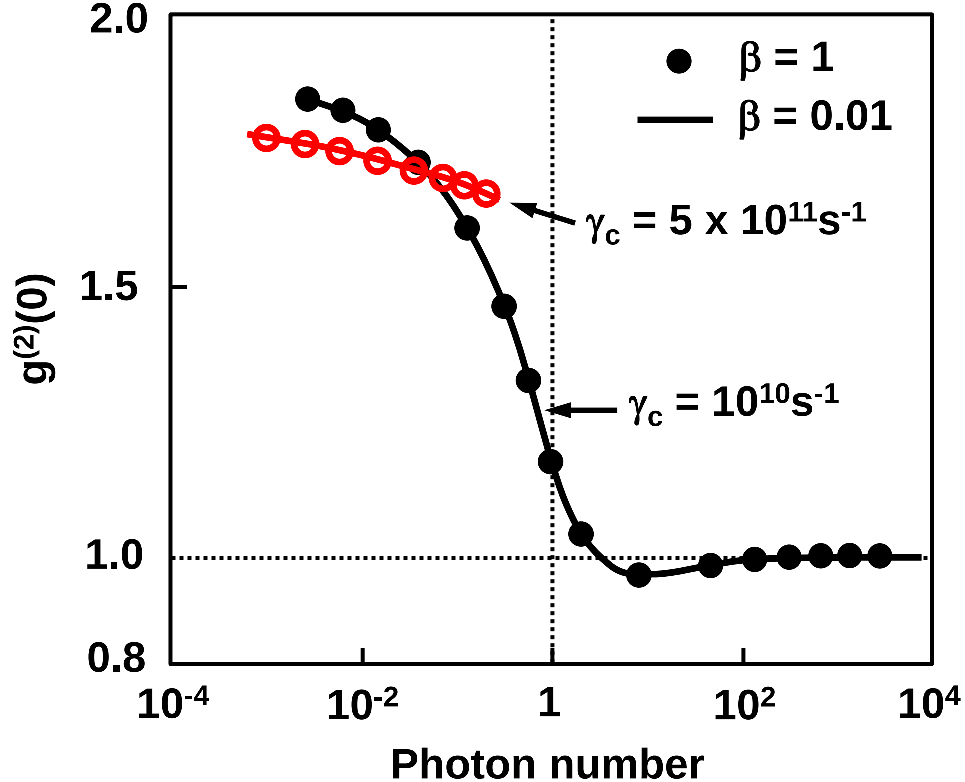


Light amplification by stimulated emission of radiation

$$\frac{dP_a}{dt} = -\gamma_l(n+1)$$

Stimulated emission (n) · Spontaneous emission (1)



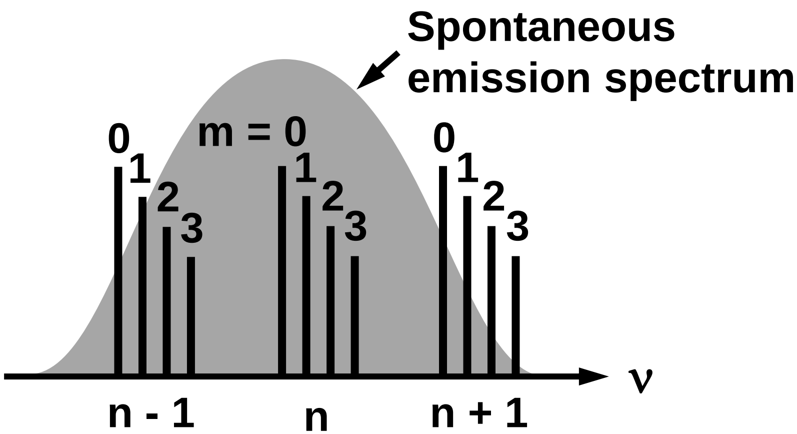


$N_{QD} = 50$, $\Delta_{inh} = 20$meV

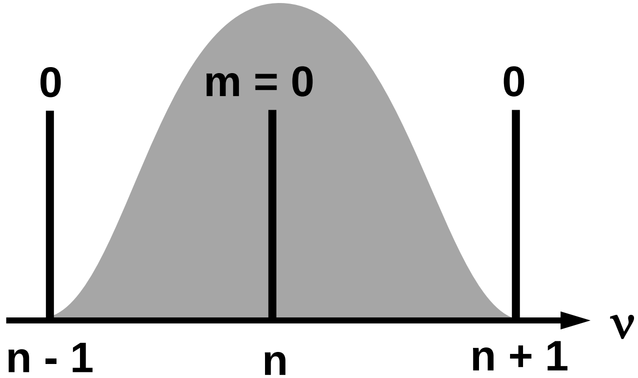
Interesting physics with nanolasers

Example 1
Thresholdless lasing

Most lasers β << 1



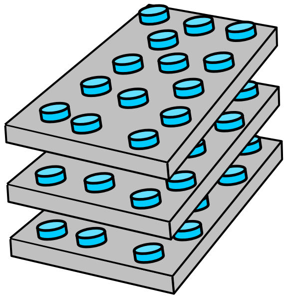
Some nanolasers β = 1



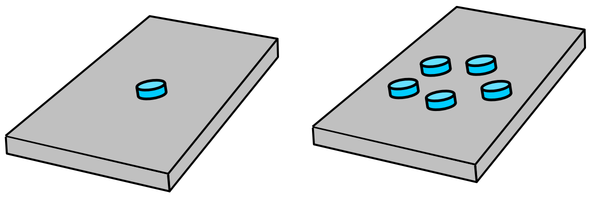
All emission into single resonator mode

Example 2
Single-photon generation

Most QD-laser active regions

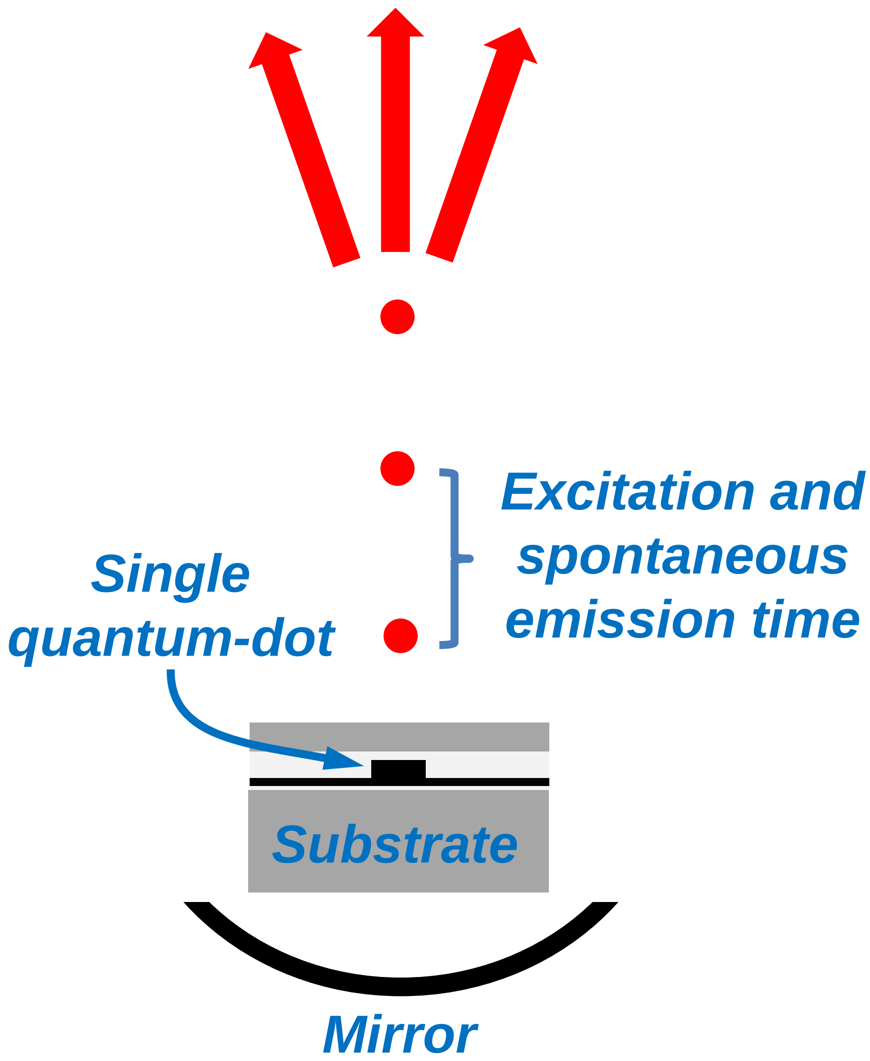


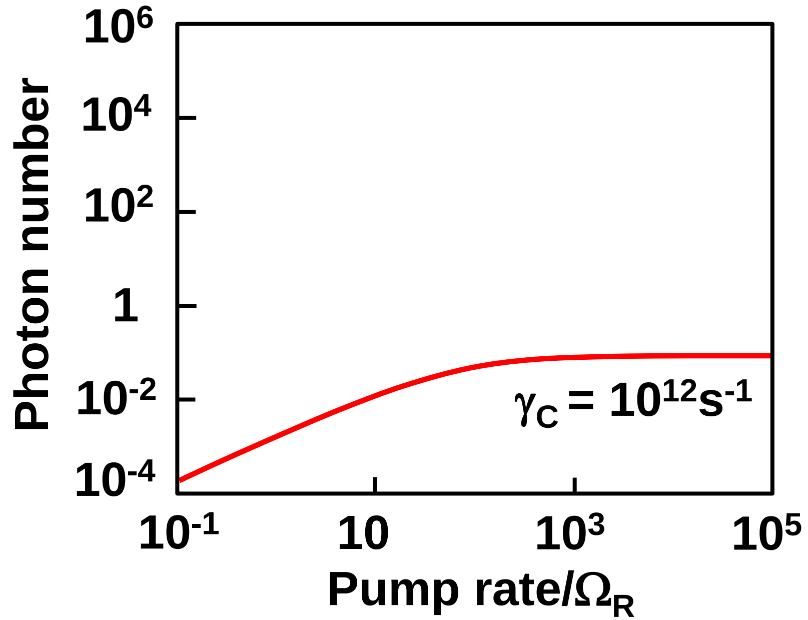
Few- QD active regions

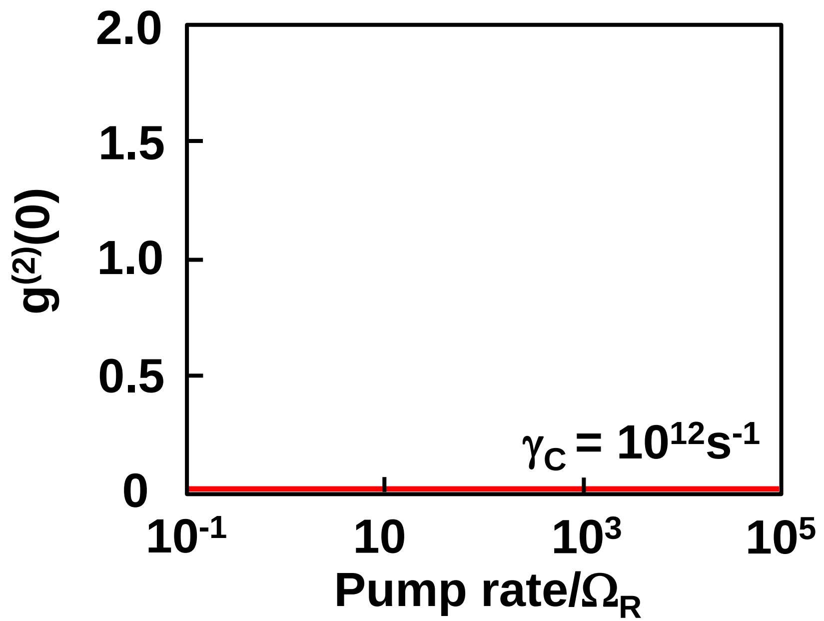


Nonclassical light

Example 2: Single-photon sources and photon statistics

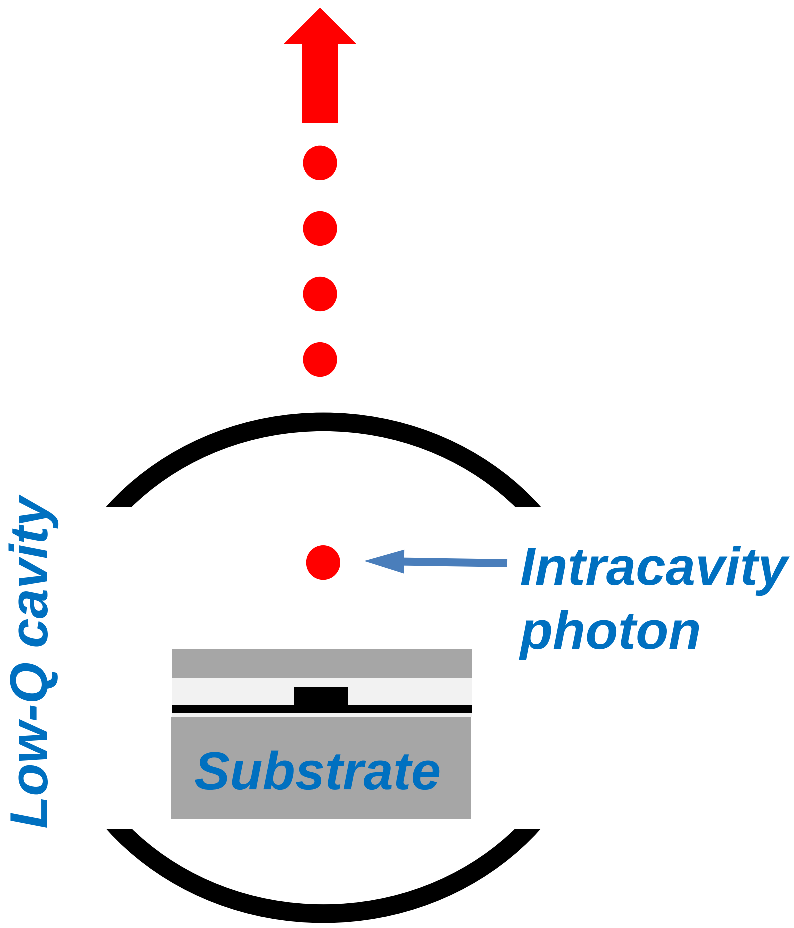


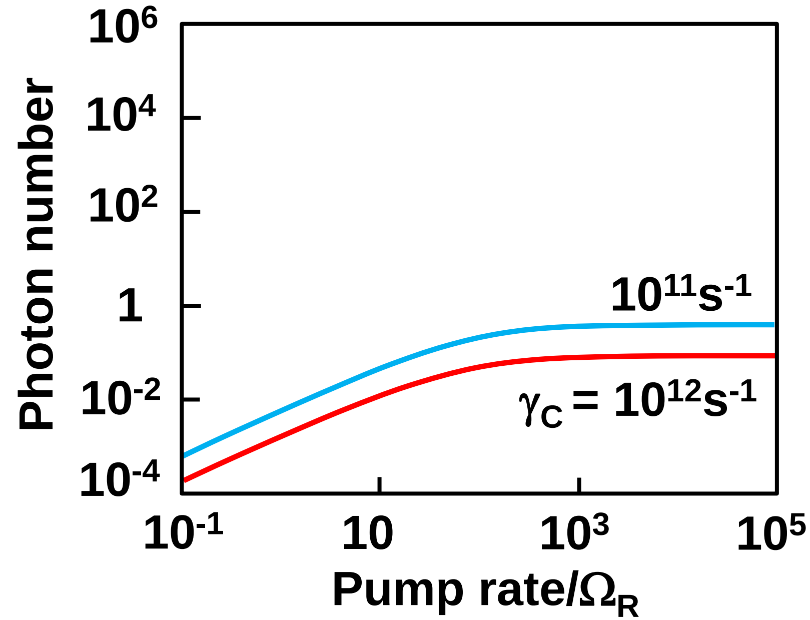


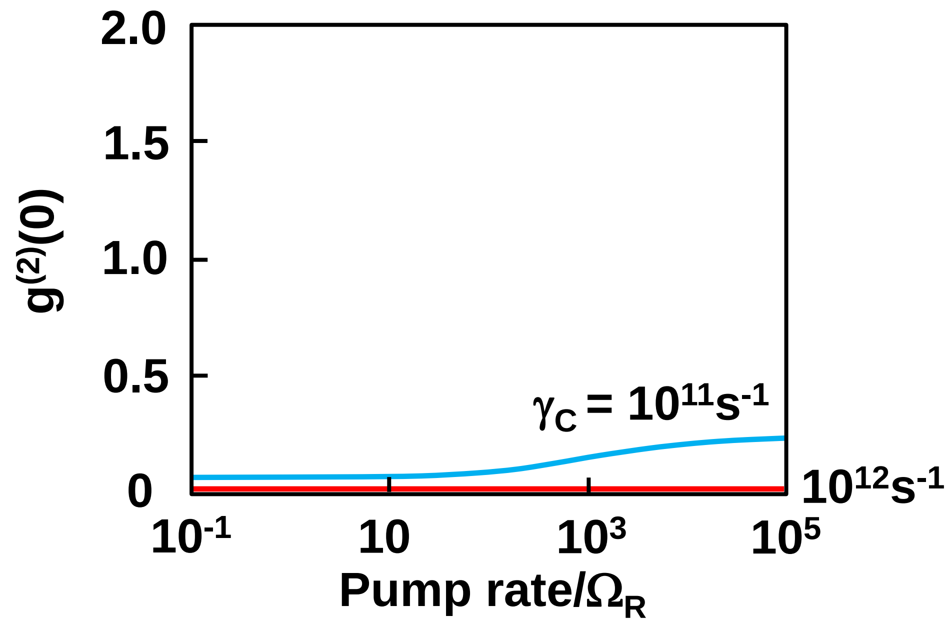


Example 2: Single-photon purity and emission rate

Cavity enhancement: Purcell and directionality







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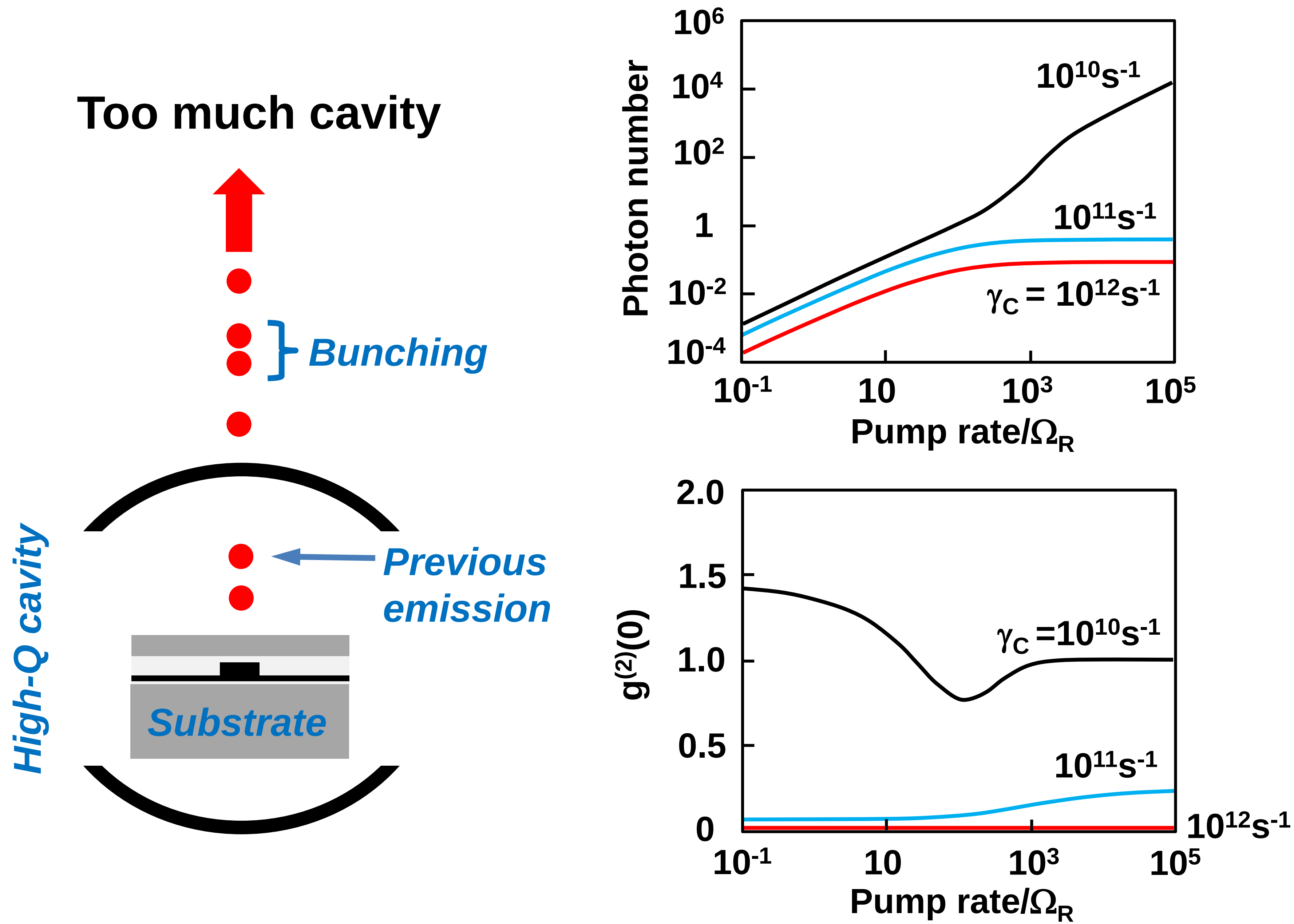

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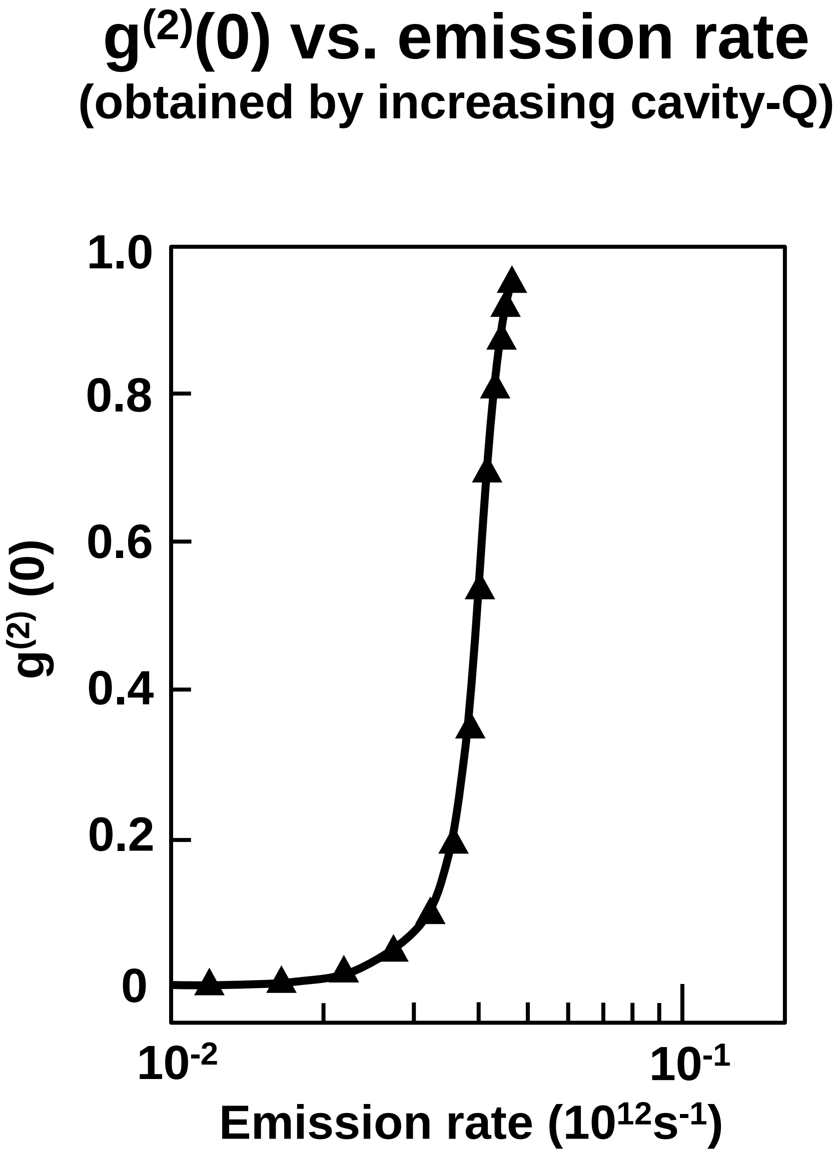
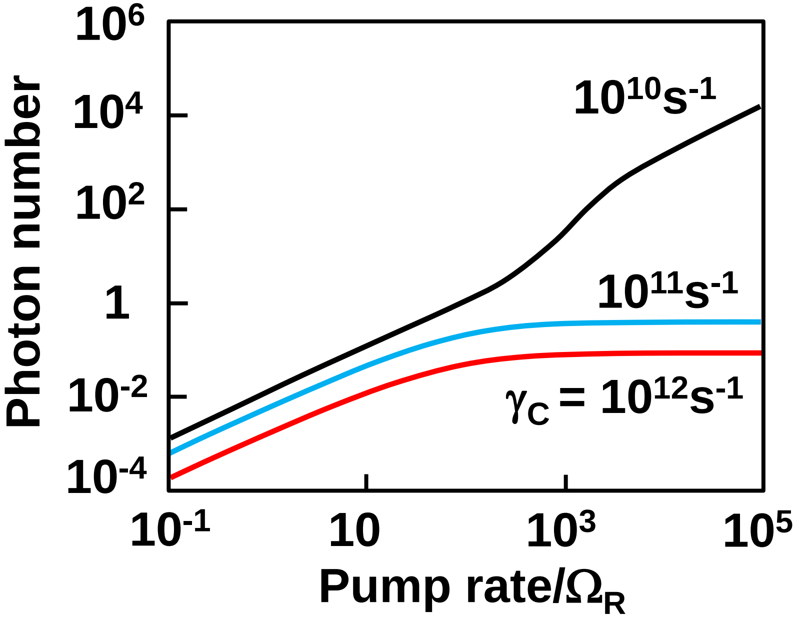
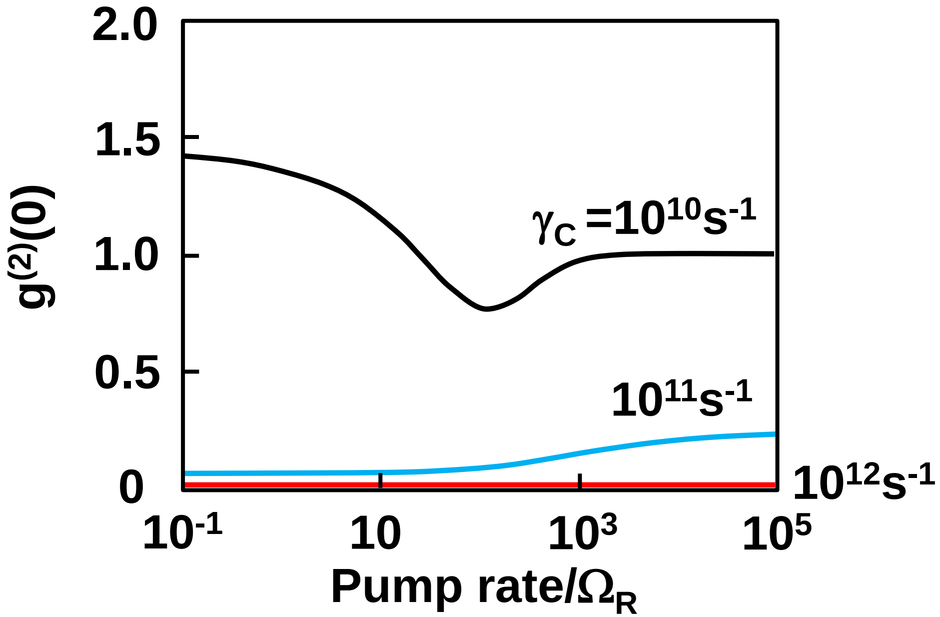
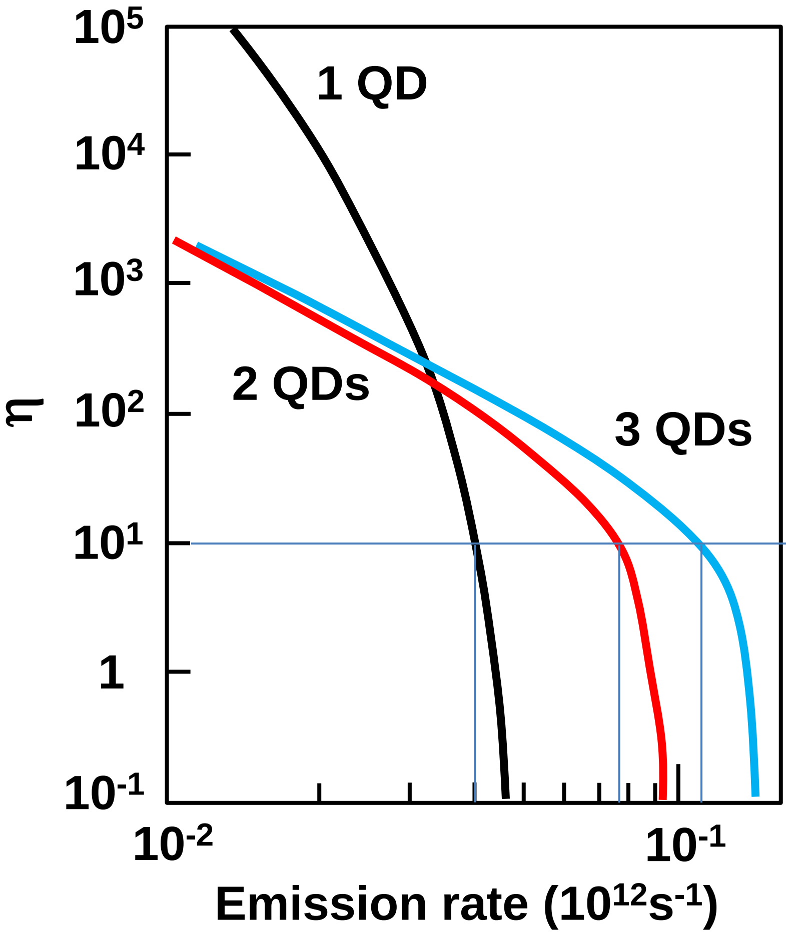






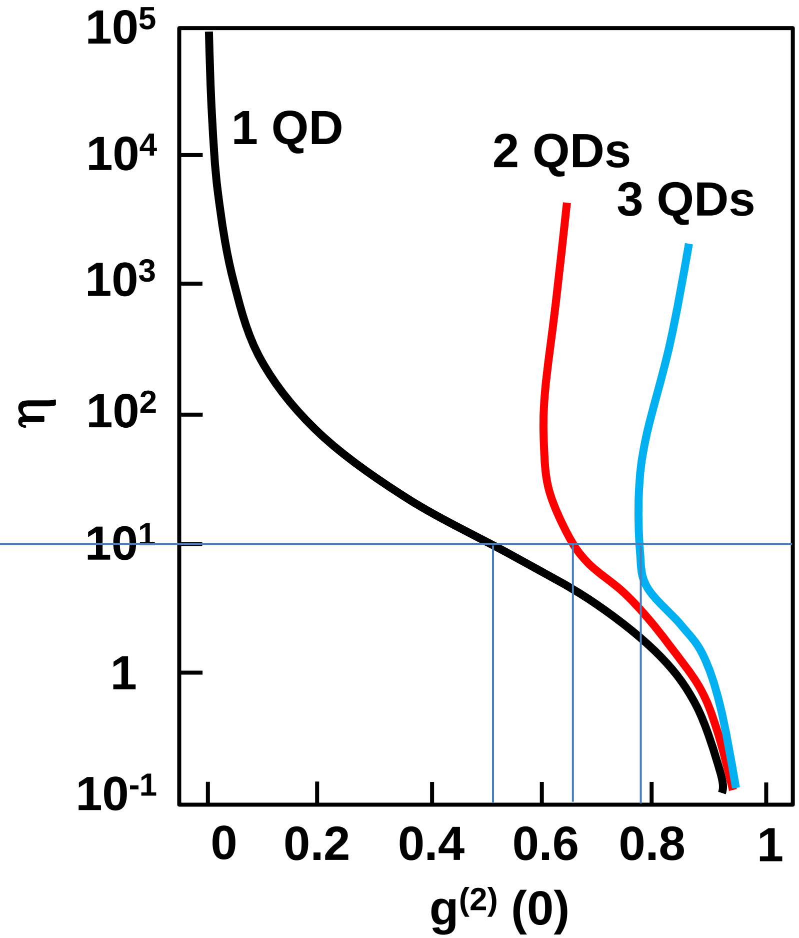
Extraneous emitters

η vs. emission rate



Single-photon purity

$$\eta = \frac{\text{Single-photon emission probability}}{\text{Multi-photon emission probability}}$$



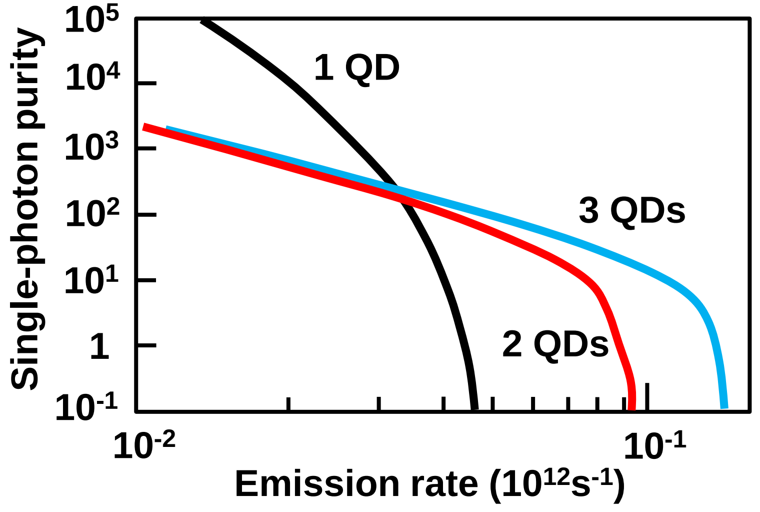
First principle study of nanolasers: photon statistics and laser threshold

First-principles: Quantized light and carriers

Consistent account of light-carrier correlations

Photon statistics:

1) Single-photon sources
2) Emission rate vs. single-photon purity
3) > one quantum dot – good or bad?
4) $g^{(2)}(0)$ adequate for N-emitter systems?
5) How would a dimmed laser compare?



Laser threshold:

1) Combination of intensity & $g^{(2)}(0)$ gives definitive description of lasing
2) There is no thresholdless lasing