Correlations and photon statistics in nanocavity emitters

SAND2015-3531PE

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Motivation for nanocavity emitters

Modeling approaches

Research:

- **a) β = 1 and thresholdless lasing**
- **b) Single-photon sources and photon statistics**

Thanks to:

Christopher Gies and Frank Jahnke, Bremen University

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

Why nano-emitter research?

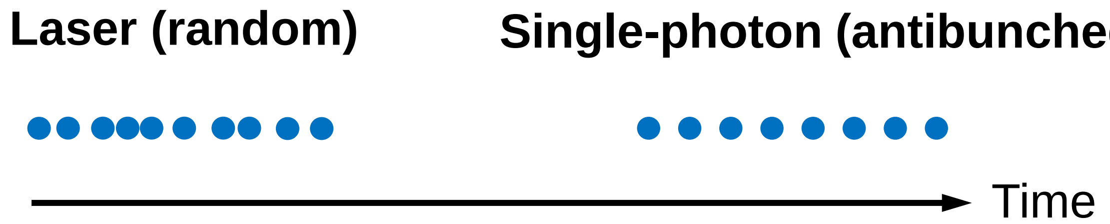
1 Save energy

Data centers and optical communication

- Reducing energy per bit
- At limits for electrical approaches
- Optical interconnects: laser energy consumption $\propto$ volume

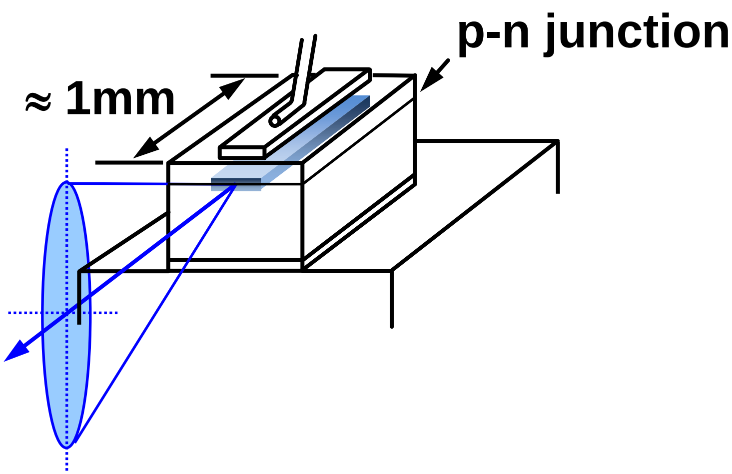
2 Safe communication

- Quantum key distribution (QKD)
- Single-photon sources
- Types of light

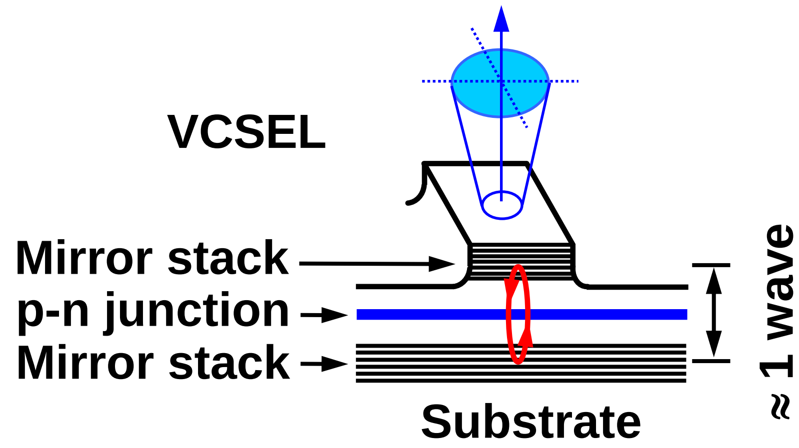


Towards smaller and smaller lasers

Edge - Emitting Laser

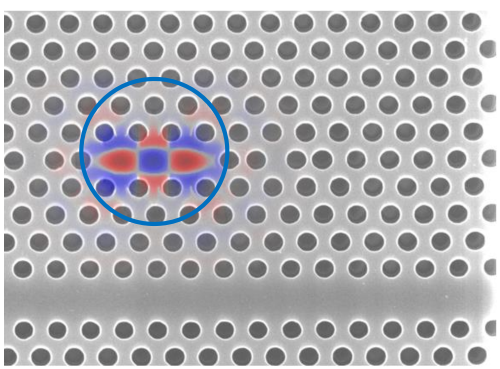


Vertical-Cavity Surface-Emitting Laser



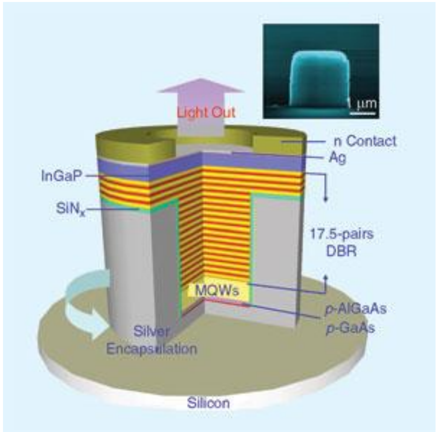
Nanolasers

Photonic crystal



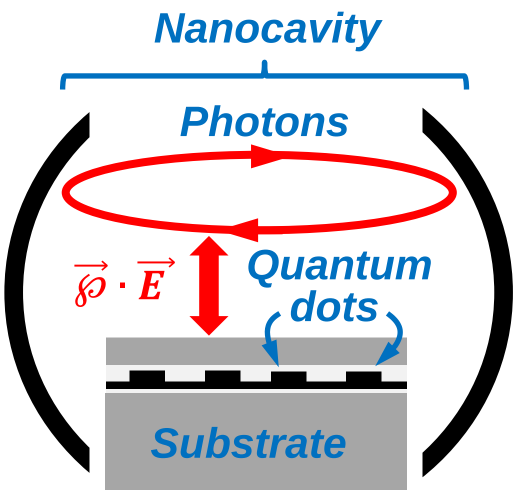
(Courtesy of Willie Luk, Sandia National Labs)

Nanocavity

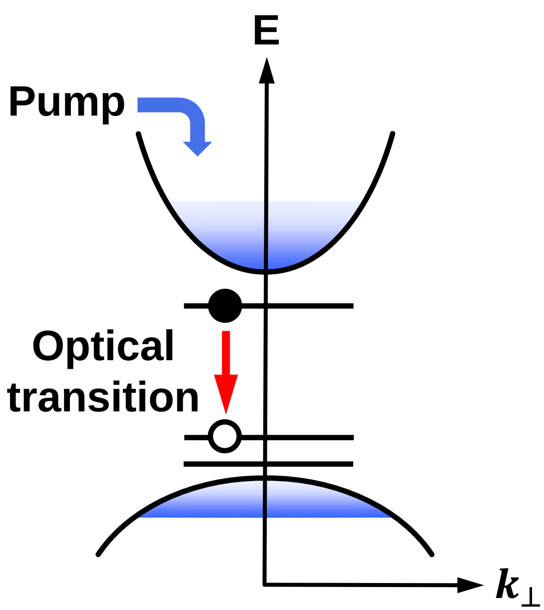


(Adapted from a figure by Lu et al., UIUC)

Hamiltonian: physics entering into the theory



Electronic structure



$$H = \sum_\alpha \varepsilon^e_\alpha c^\dagger_\alpha c_\alpha + \sum_\beta \varepsilon^h_\beta b^\dagger_\beta b_\beta + \hbar\omega\left(a^\dagger a + \frac{1}{2}\right)$$

Single-particle

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

Light-carrier interaction

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

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

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

Matrix element of

$$\frac{e^2}{4\pi\varepsilon_b|r - r'|}$$

Carrier-carrier

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

Carrier-phonon

Dynamical behavior of a quantum system

Schrödinger Picture

$$\frac{\partial}{\partial t}\varrho = -\frac{i}{\hbar}\,[H,\varrho]$$

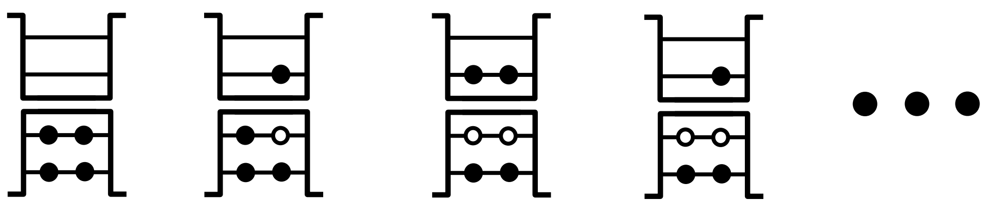
Density operator: $\sum_{\psi} P_{\psi}|\psi\rangle\langle\psi|$

Wave function: $\psi(r) \equiv \langle r|\psi\rangle$

Quantum-dot states (configurations)

Basis: $|j,n\rangle$

Photon number



$0X$ $1X_s$ $1X_{ss}$ $1X_s^+$

Expectation values: $\overbrace{\langle A\rangle}^{\text{Observable}} = Tr\{\varrho A\} = \sum_{n,j,n'j'} \langle n,j|\varrho|j',n'\rangle\langle n',j'|A|j,n\rangle$

Photon statistics: $P_n = \langle n,0X|\varrho|0X,n\rangle + \langle n,1X_s|\varrho|1X_s,n\rangle + \langle n,2X_{ss}|\varrho|2X_{ss},n\rangle + \ \ldots$

Dynamical behavior of a quantum system

Heisenberg Picture

System operator

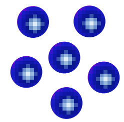
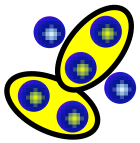
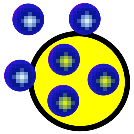
$$\frac{\partial}{\partial t} A = -\frac{i}{\hbar}\,[A, H]$$

Populations and correlations:

$$\langle c_\alpha^\dagger c_\alpha \rangle, \langle b_\alpha^\dagger b_\alpha \rangle, \langle c_\alpha^\dagger b_\alpha^\dagger a \rangle, \langle a^\dagger a \rangle$$

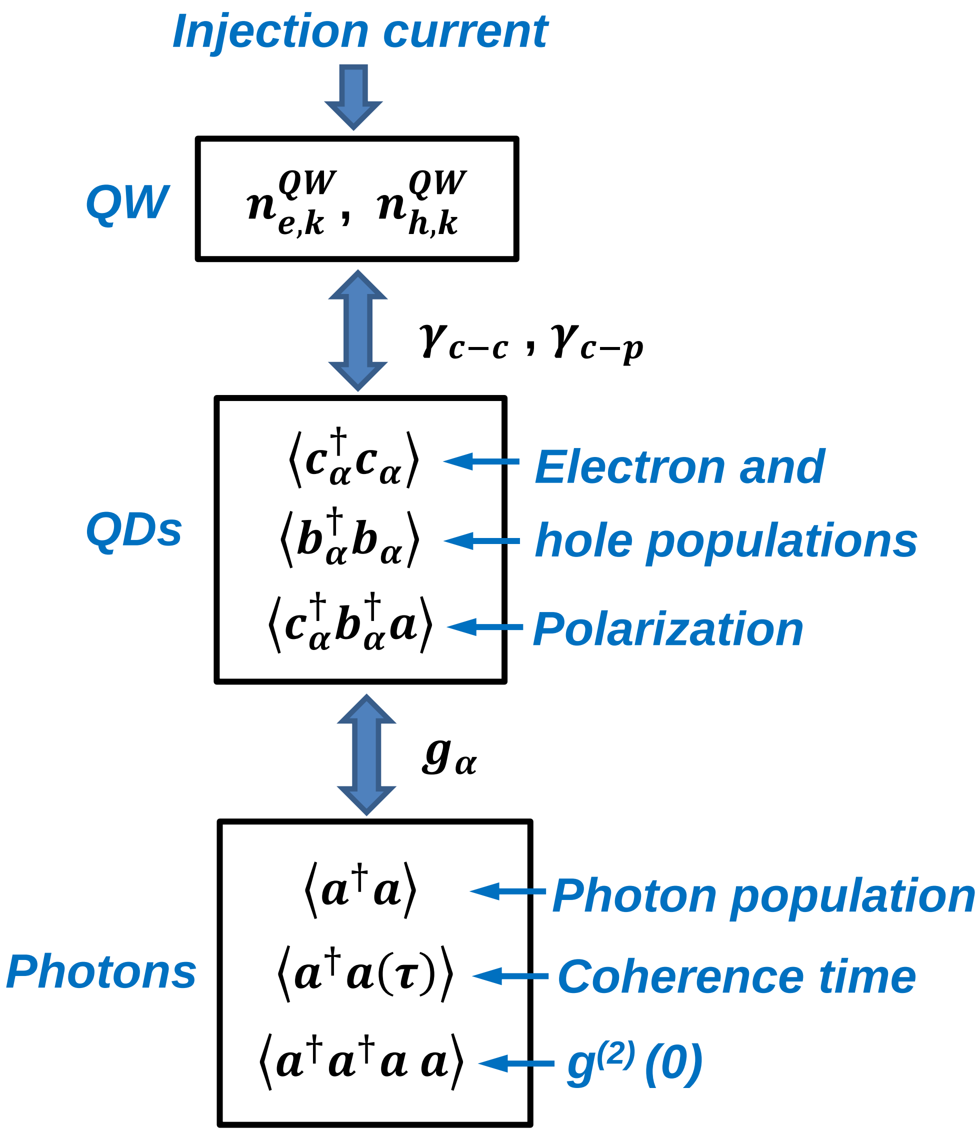
$$\langle a^\dagger a^\dagger a a \rangle, \langle c_\alpha^\dagger c_\sigma^\dagger c_\sigma c_\alpha \rangle, \langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle$$

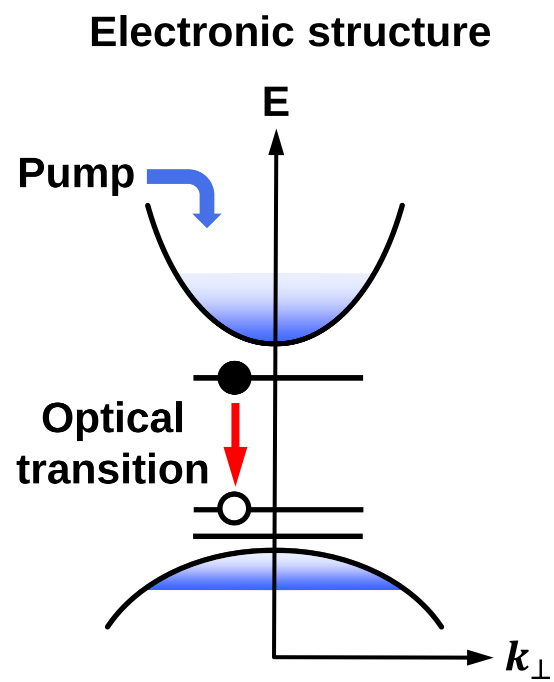
Single particles | Correlated pairs | Correlated 3-particle clusters

Cluster expansion: $\left\langle \hat{N} \right\rangle =$  +  +  + ...

Overview of both approaches: Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)

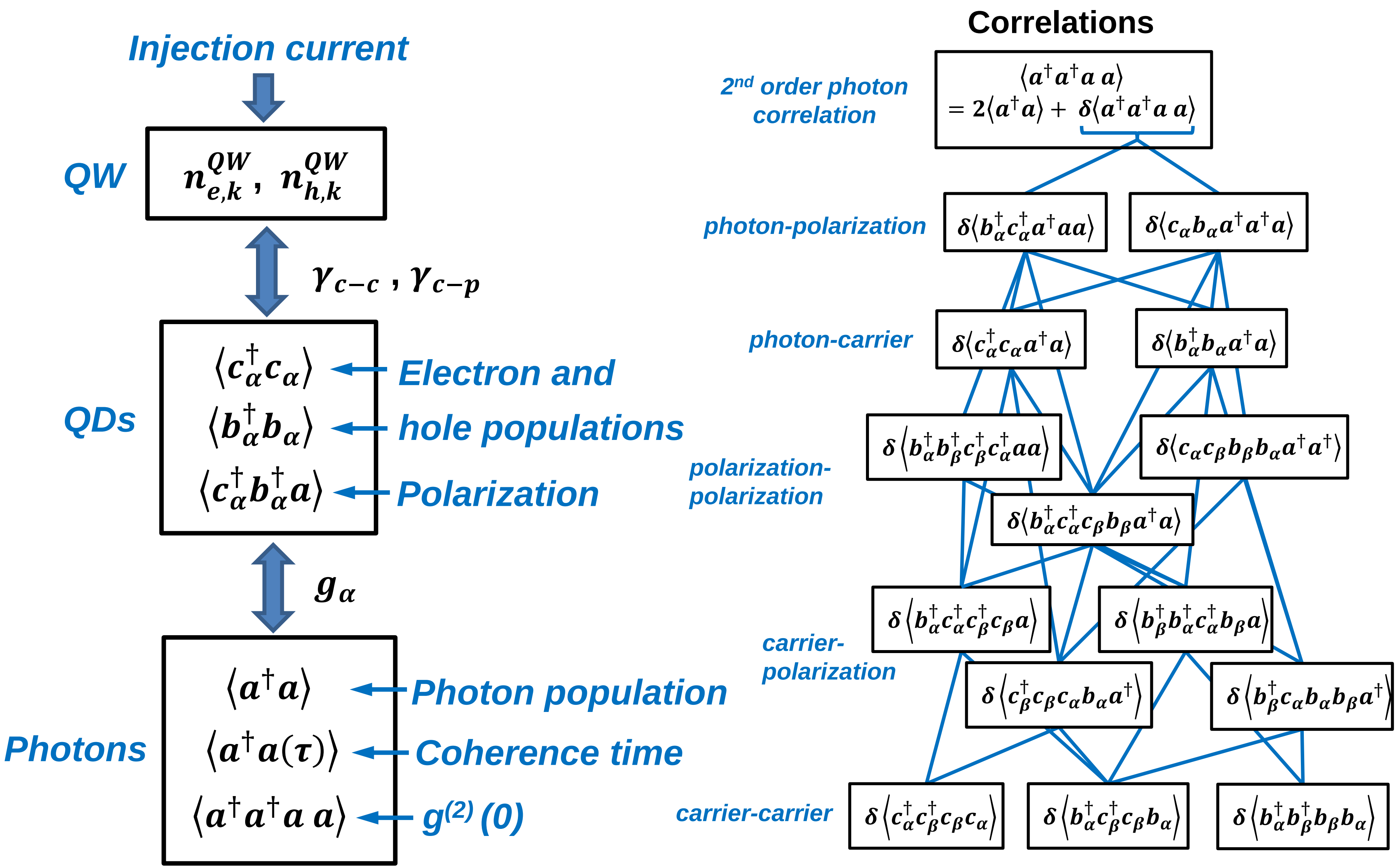
Nano-emitter model: population dynamics and correlations





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

Nano-emitter model: population dynamics and correlations

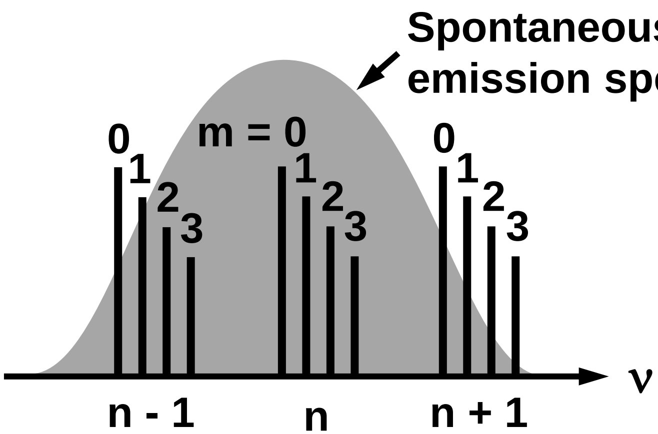


Emphasis now is on correlations involving light-matter interaction instead of Coulomb interaction

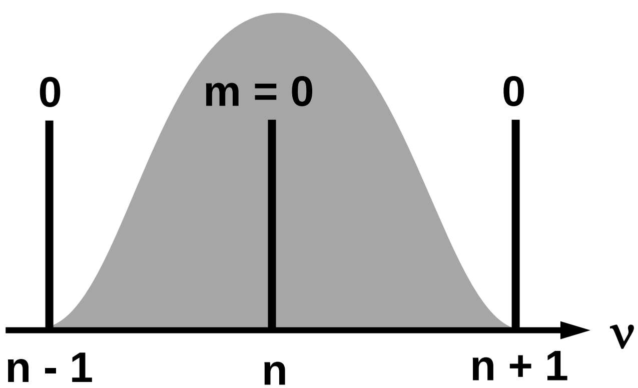
Interesting physics with nanolasers

Example 1: Laser threshold and thresholdless lasing

Most lasers $\beta << 1$



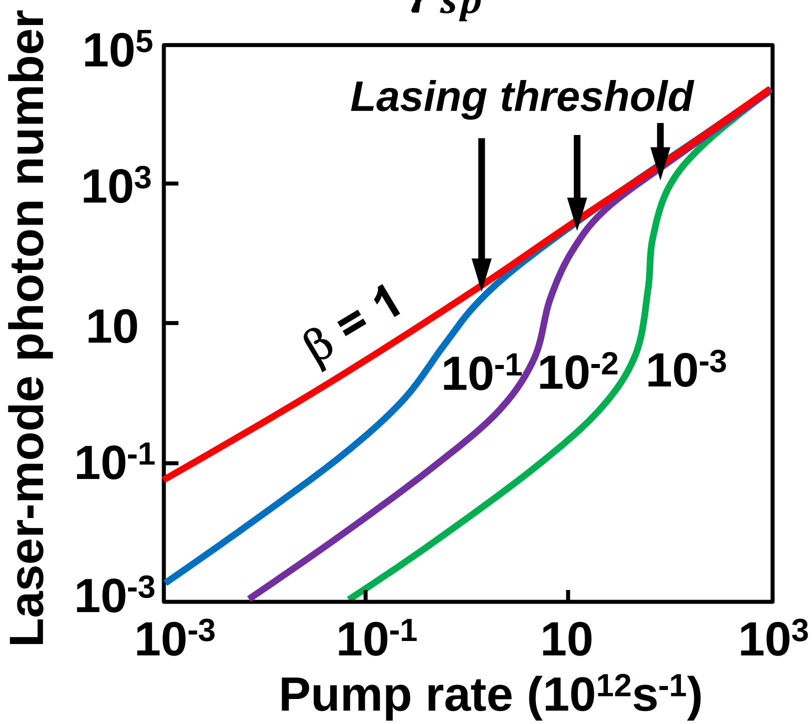
Some nanolasers $\beta = 1$



All emission into single resonator mode

Spontaneous emission factor

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



Questions:

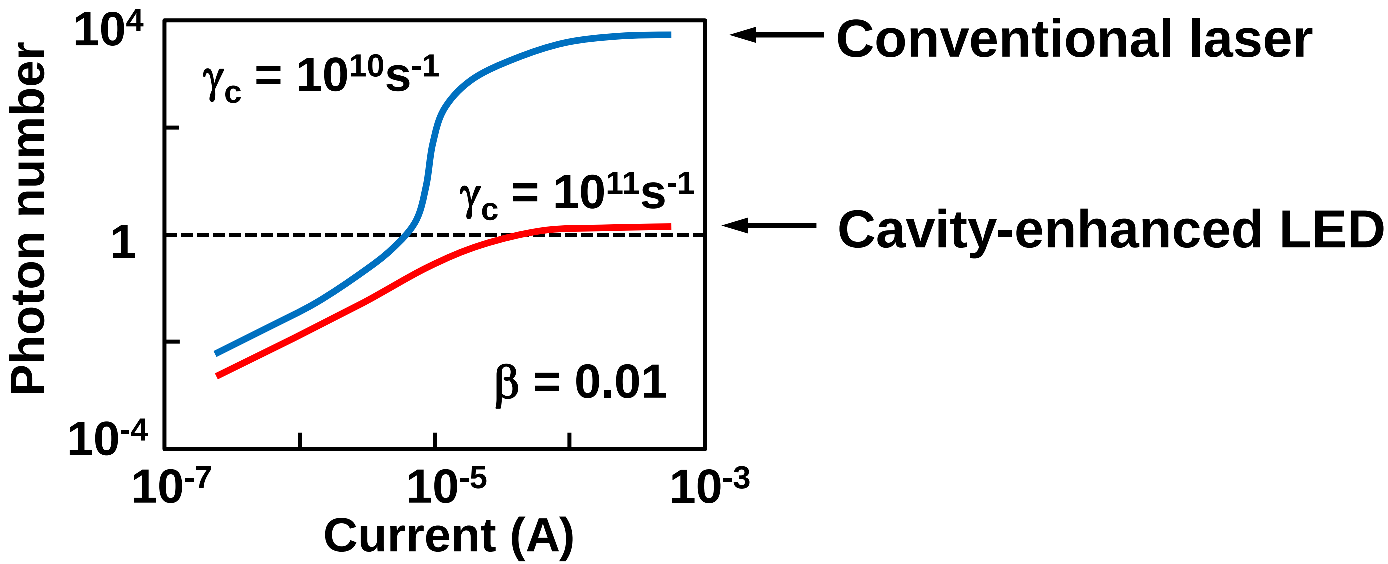
1) Is thresholdless lasing real?
2) What is lasing?

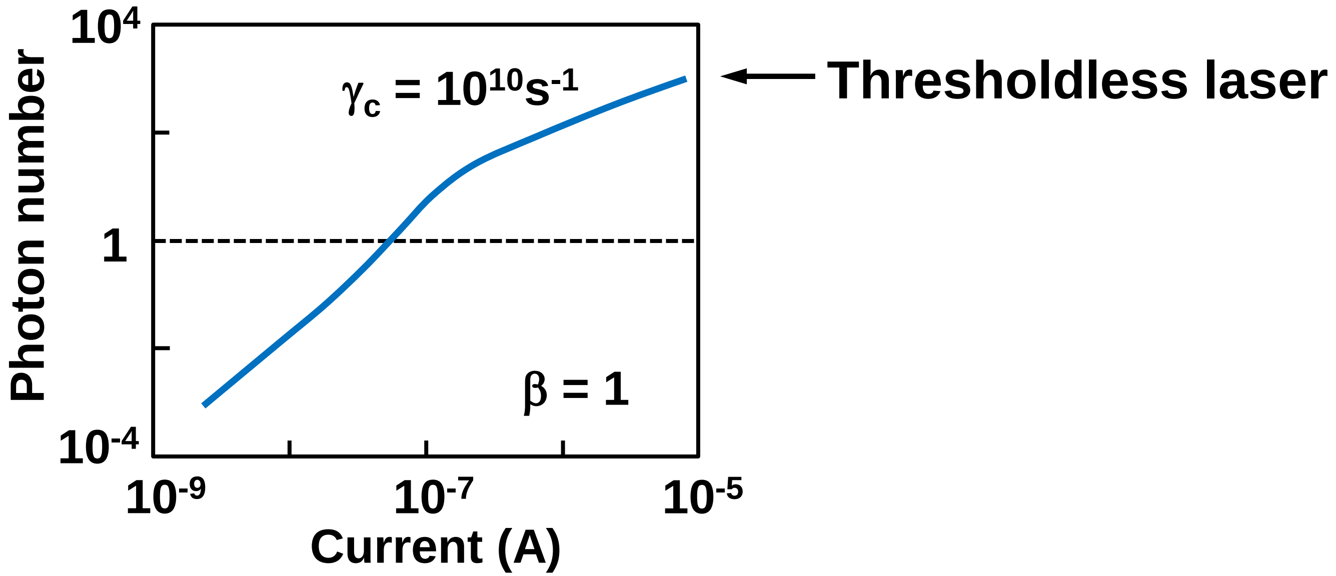
Early answer in Jin, Boggavarapu, Sargent, Meystre, Gibbs, Khitrova, Phy Rev A 49, 1994

Criterion for lasing

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

Input/Output





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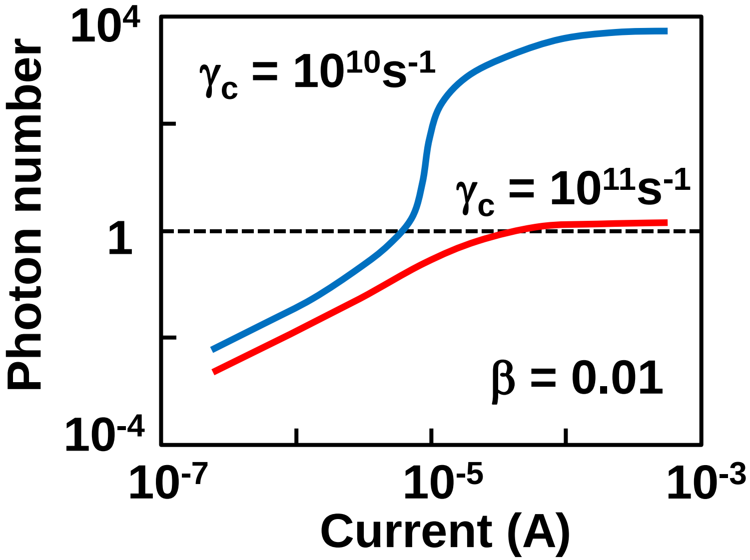
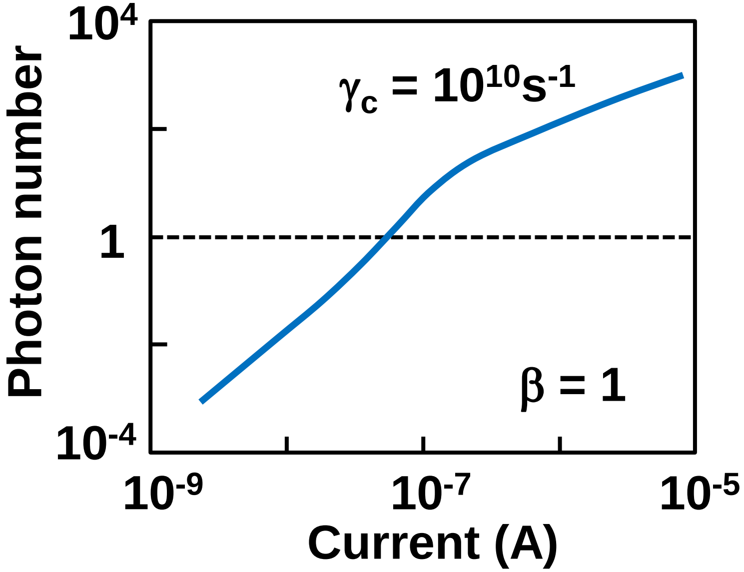
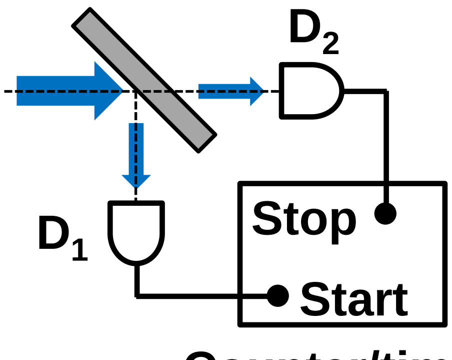




Second-order intensity correlation function

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

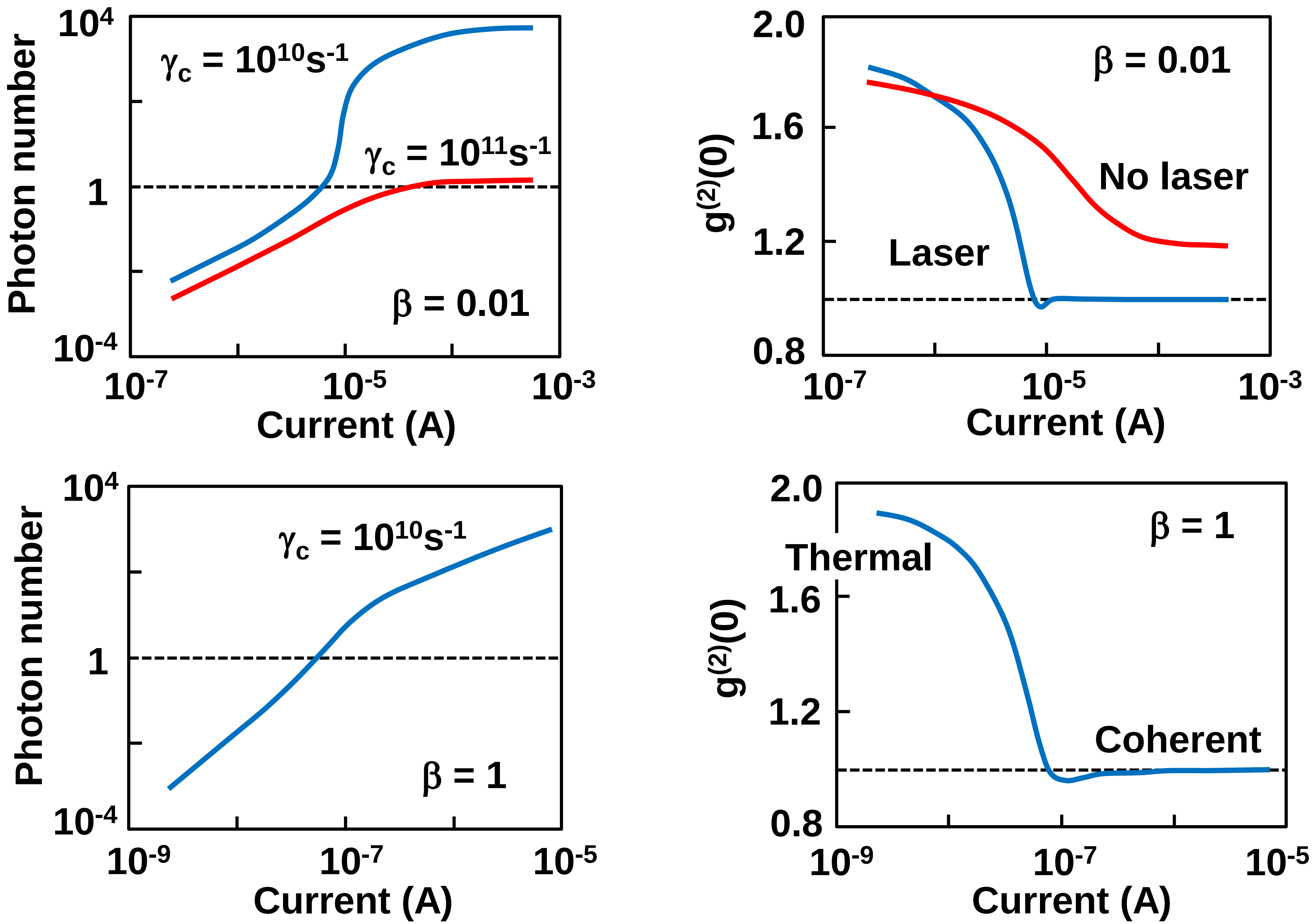
Hanbury-Brown-Twiss experiment



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

N_{QD} = 50, Δ_{inh} = 20meV

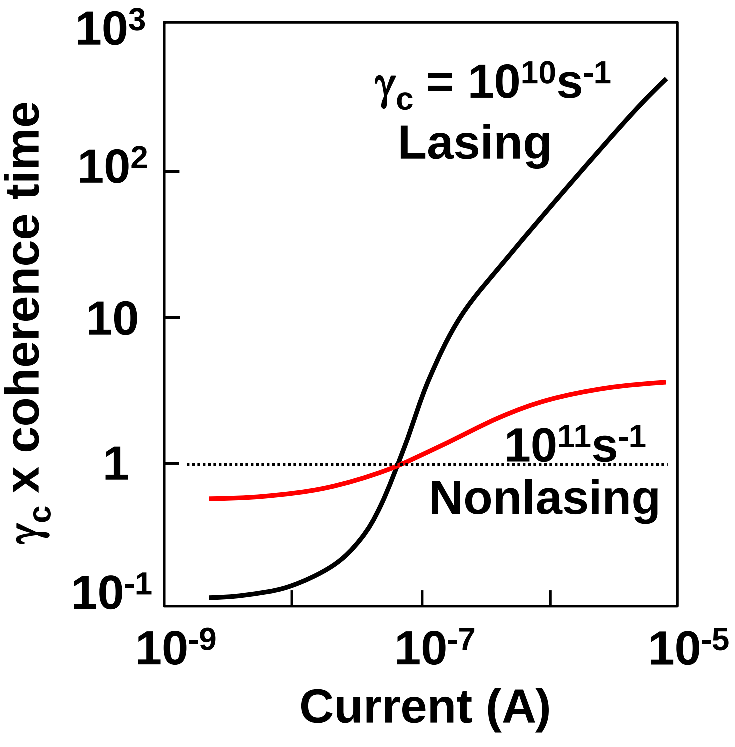
Input/Output | **Photon correlation**



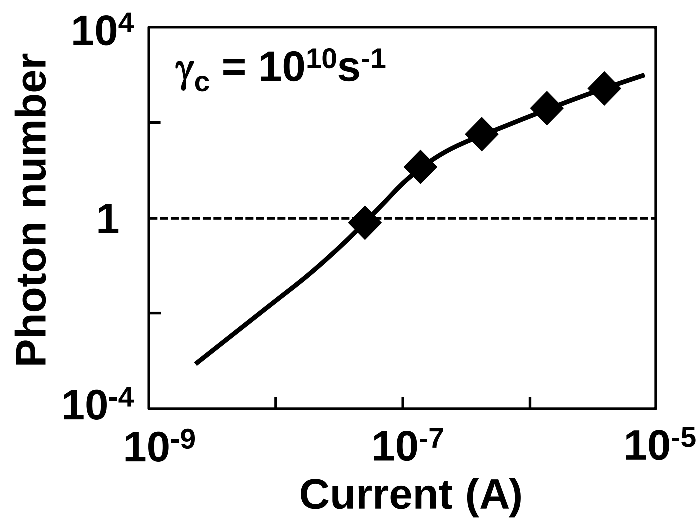
Other criteria for lasing

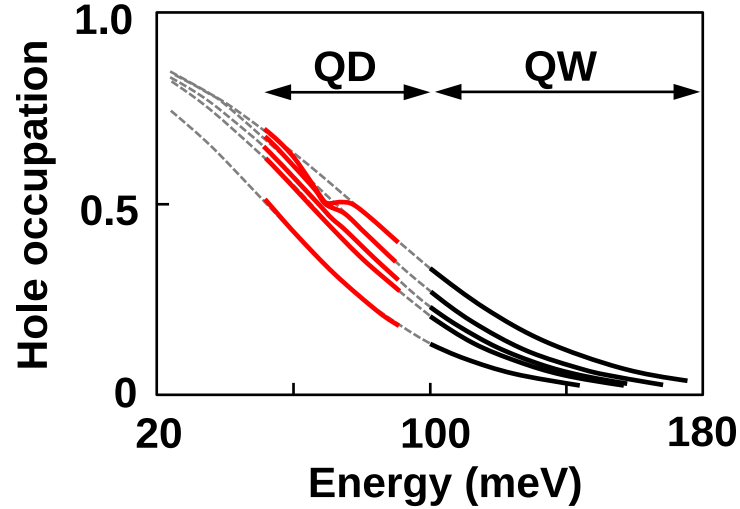
Coherence time

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



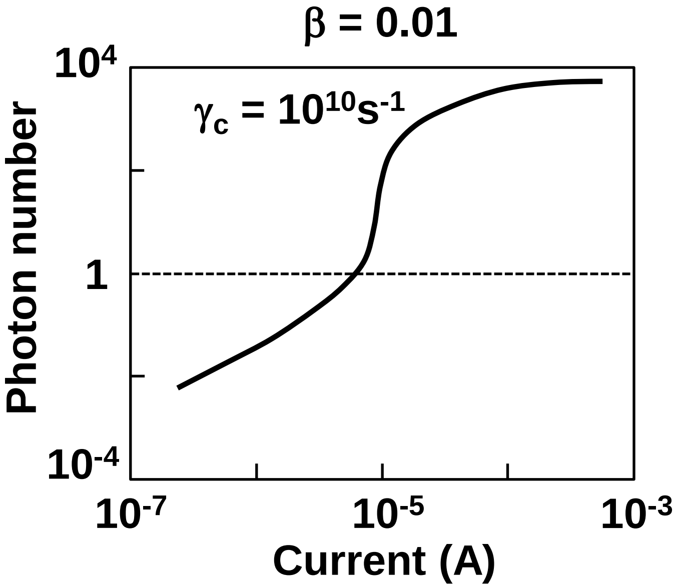
Population clamping and hole burning





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

Other criteria for laser: stimulated emission

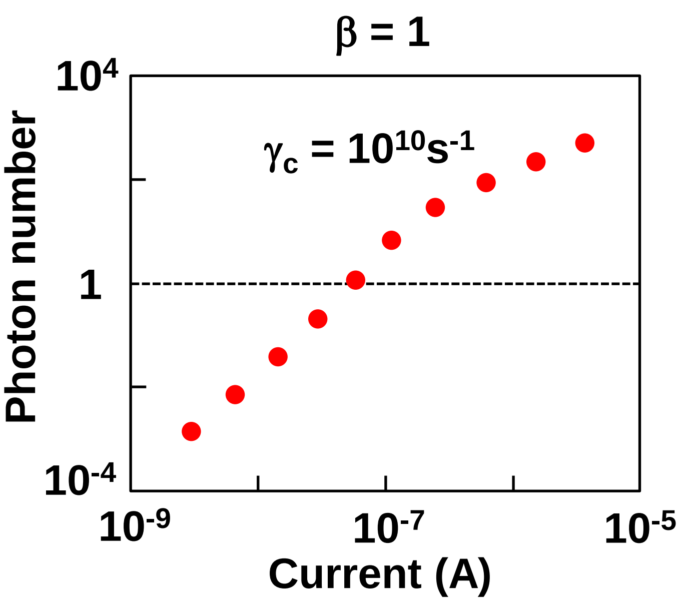


Light amplification by stimulated emission of radiation

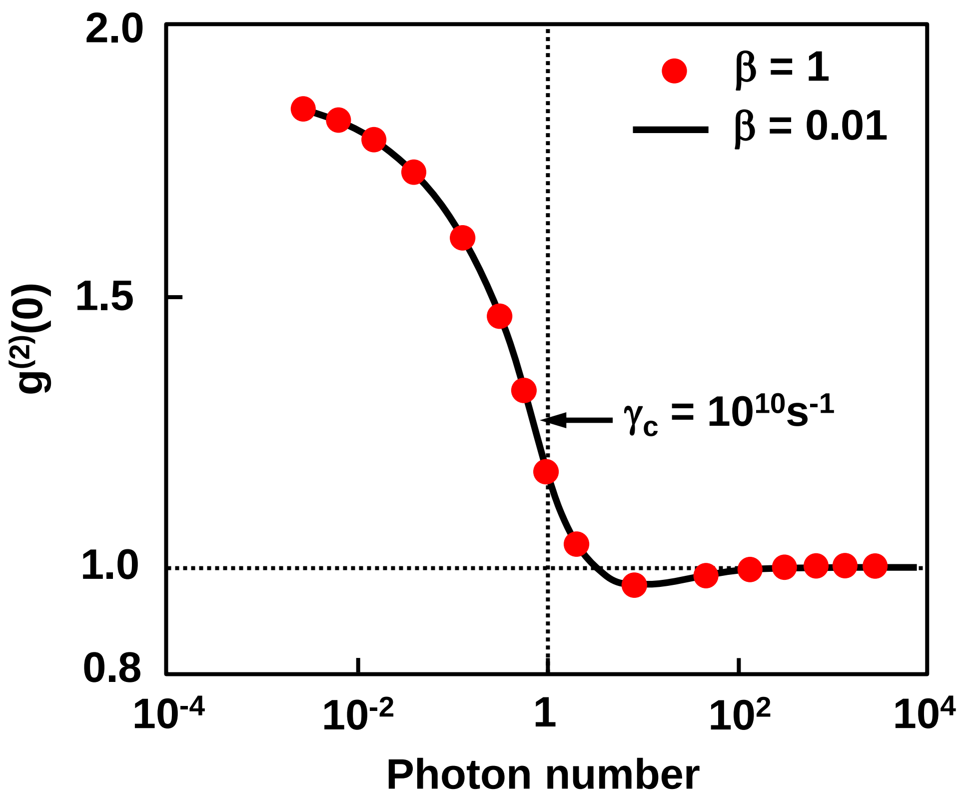
$$\frac{dP_a}{dt} = -\gamma_l(n+1)$$

Stimulated emission

Spontaneous emission

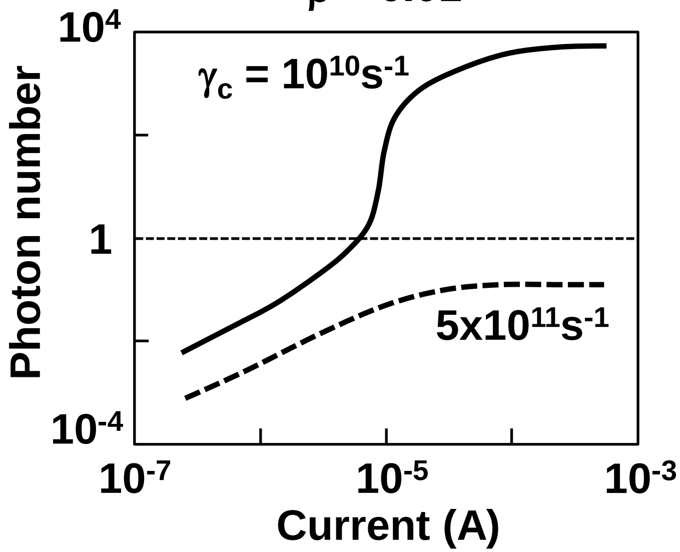


$N_{QD} = 50$, $\Delta_{inh} = 20$meV

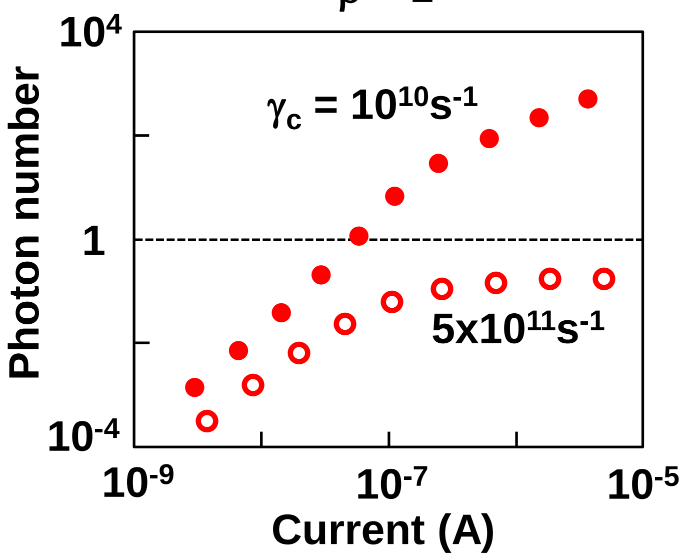


Other criteria for laser: stimulated emission

β = 0.01



β = 1

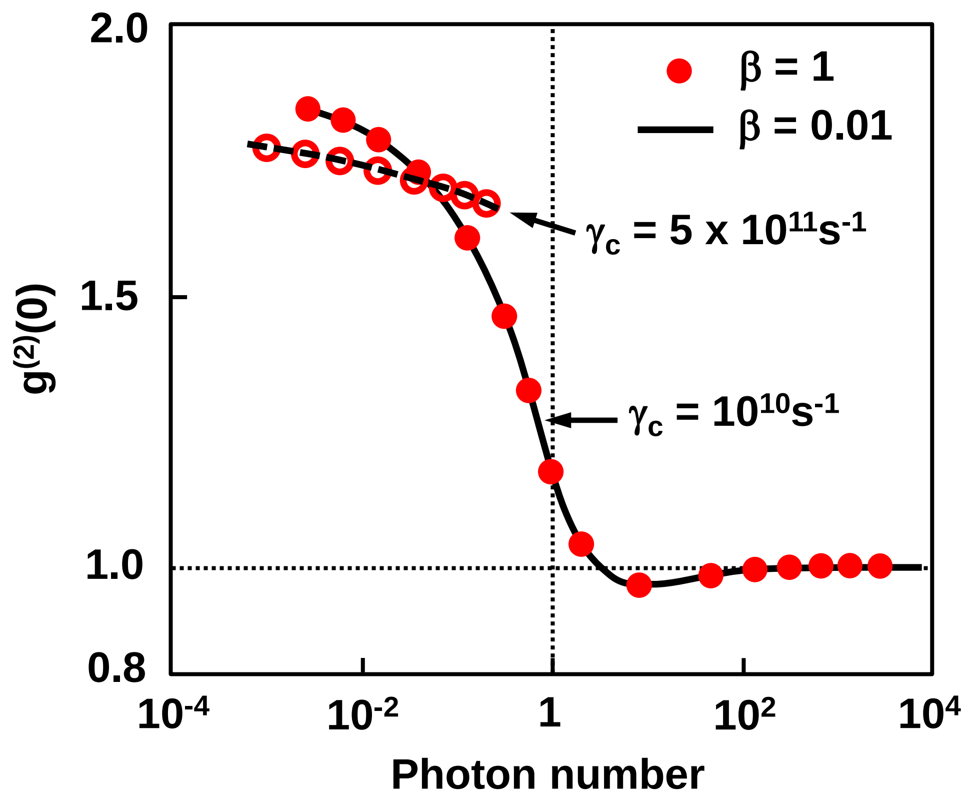


$N_{QD} = 50$, $\Delta_{inh} = 20meV$

Light amplification by stimulated emission of radiation

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

Stimulated emission (n) — Spontaneous emission (1)

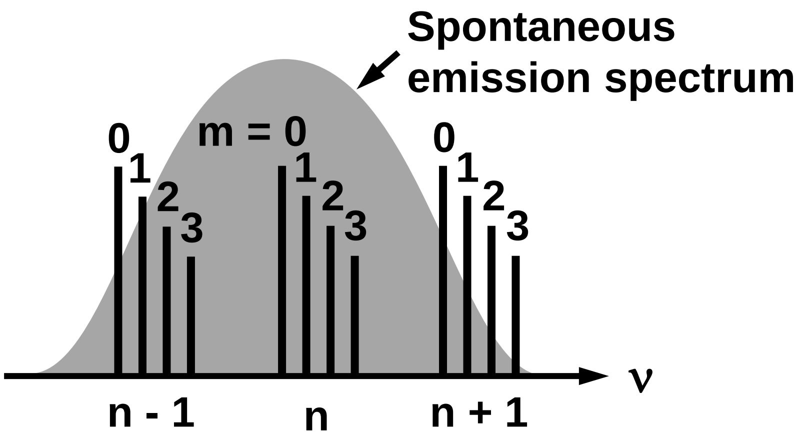


Light: Science and Applications, online 29 August, 2014

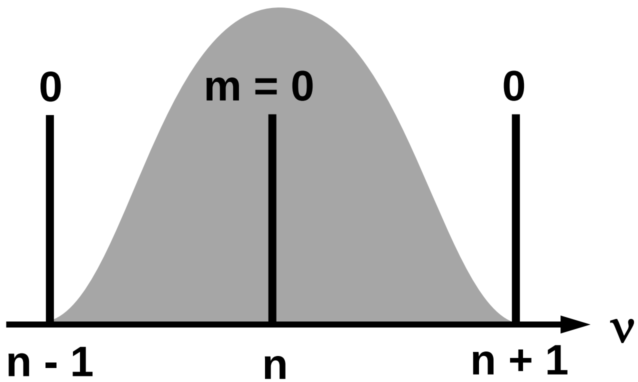
Interesting physics with nanolasers

Example 1
Thresholdless lasing

Most lasers $\beta \ll 1$



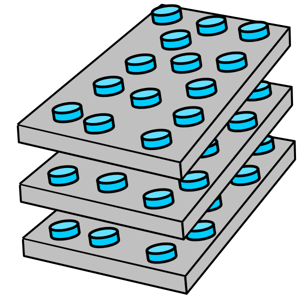
Some nanolasers $\beta = 1$



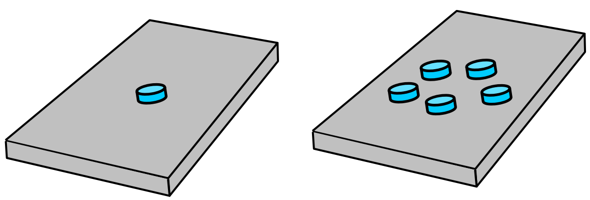
All emission into single resonator mode

Example 2
Single-photon generation

Most QD-laser active regions

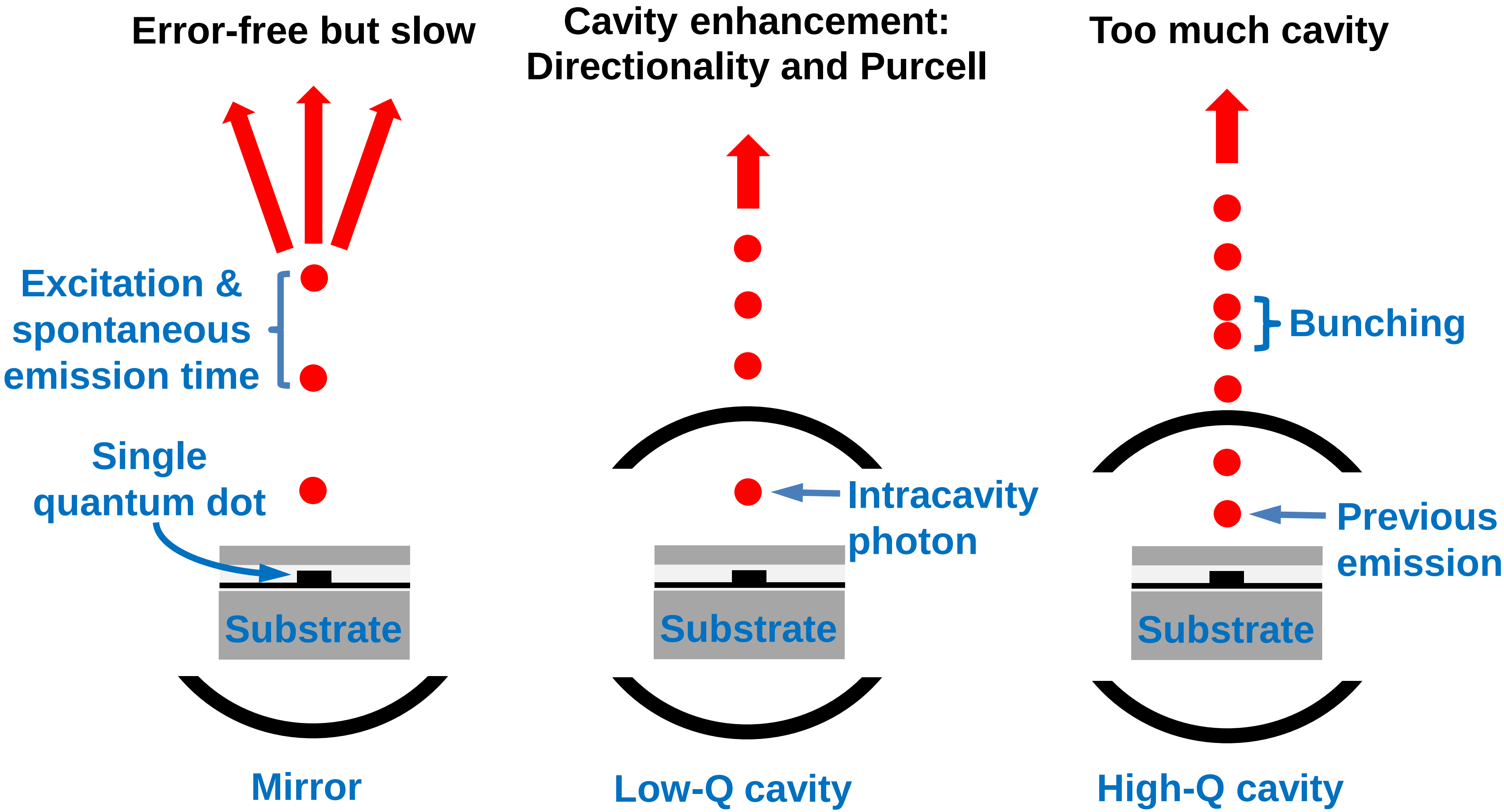


Few- QD active regions



Nonclassical light

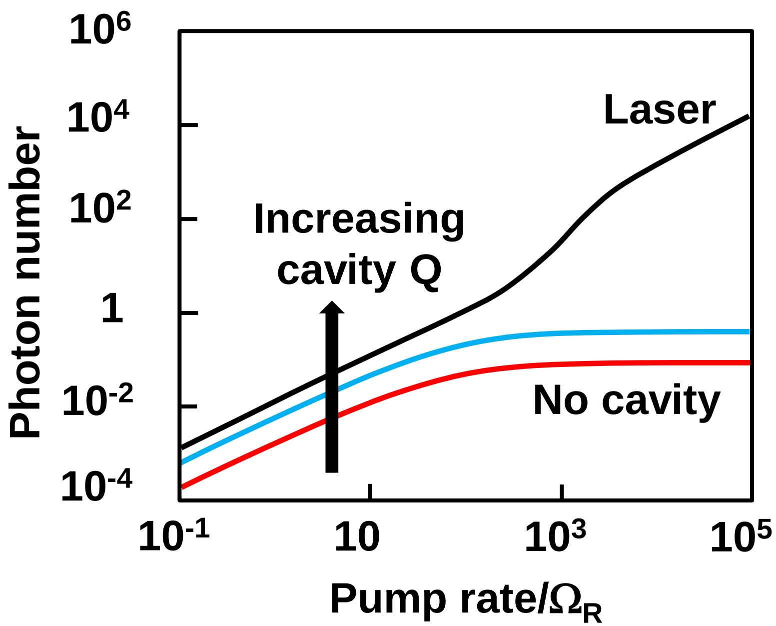
Single-photon source

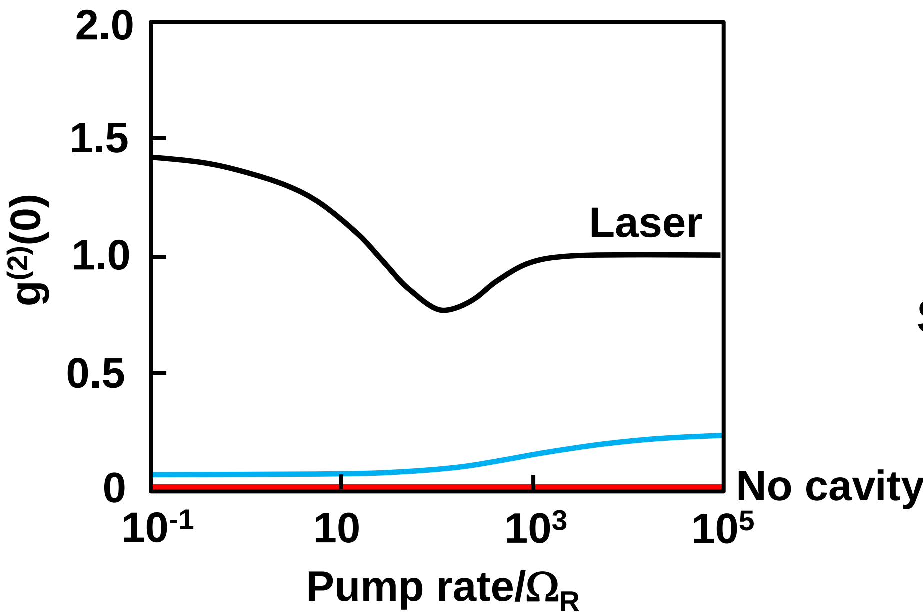


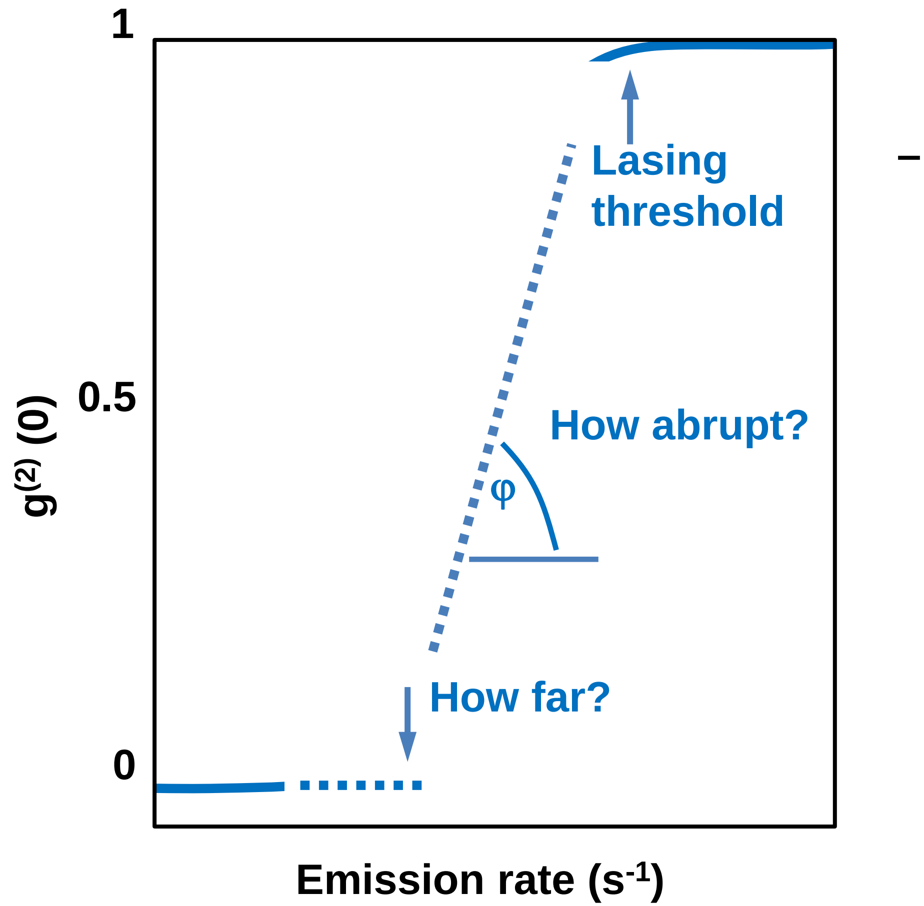
What is the right Q?

Fundamental limit to efficiency, rate and error?

Simulations





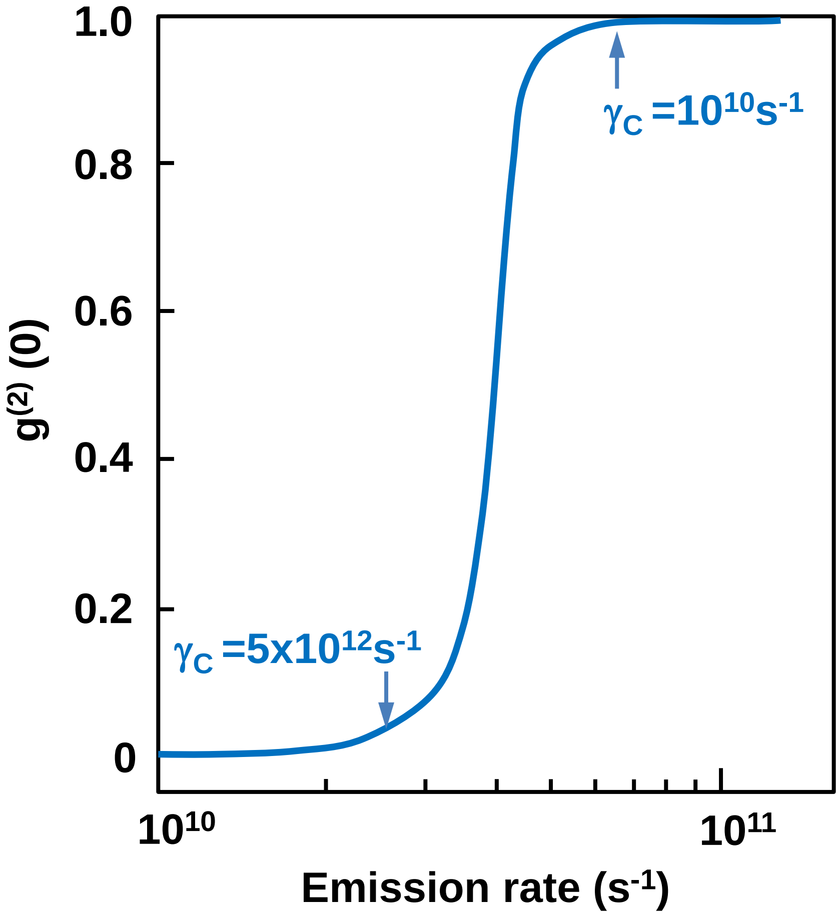


Second-order intensity correlation

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

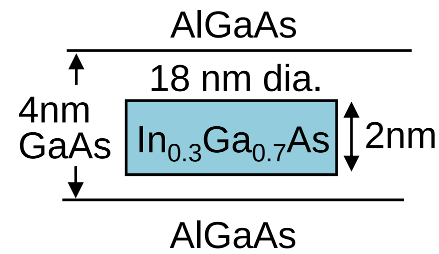
Single-photon purity and emission rate

$g^{(2)}(0)$ vs. emission rate
(by increasing cavity-Q)



Cavity-enhanced rate ~ $10^9 s^{-1}$ (expt)

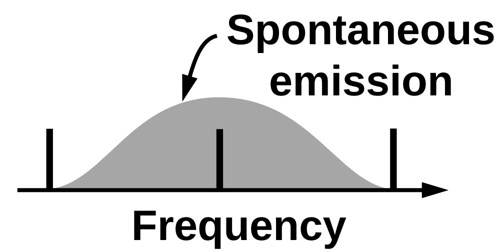
1 Shallow quantum dot



Only s-shell transition

2 Nanocavity

$$\beta = \frac{\gamma_l}{\gamma_{sp}} = 1$$



All emission into single resonator mode

3 Scaling with electron-light coupling

$$\wp \sqrt{\frac{\nu}{\hbar \epsilon_b V}}\, W(R_{QD}) \underbrace{\sum_n C(R_n)\, V(R_n)}_{\text{Electron-hole envelope overlap}}$$

Mode volume

Confinement factor

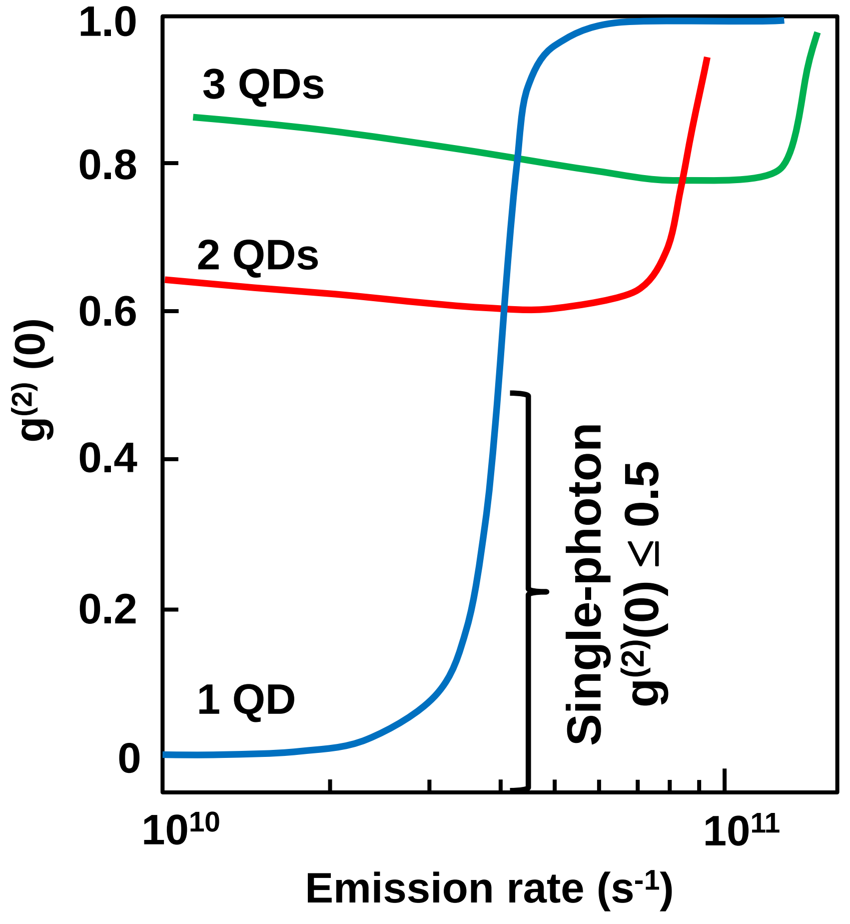
Electron-hole envelope overlap

Concern: $g^{(2)}(0)$ as measure of error

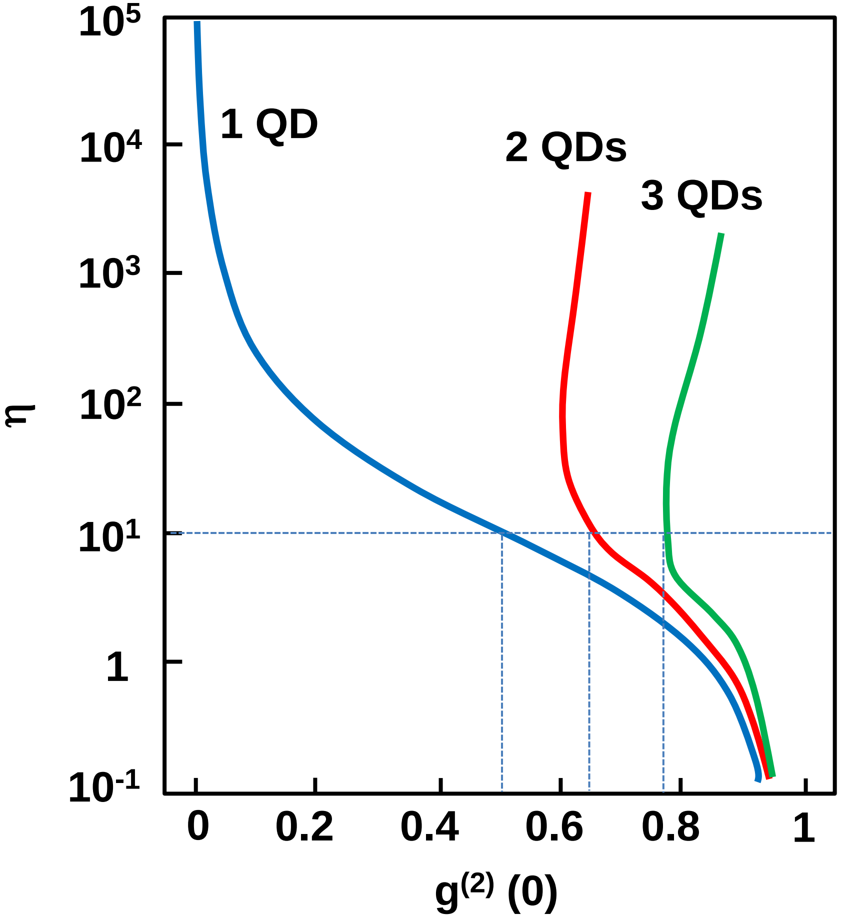
Single-photon purity: $\eta = \dfrac{\text{Single-photon emission probability}}{\text{Multi-photon emission probability}}$

$g^{(2)}(0)$ vs. emission rate

(by increasing cavity-Q)



$g^{(2)}(0)$ fails



From calculating photon statistics
Gies, Jahnke, Chow (submitted)

Concern: $g^{(2)}(0)$ as measure of error

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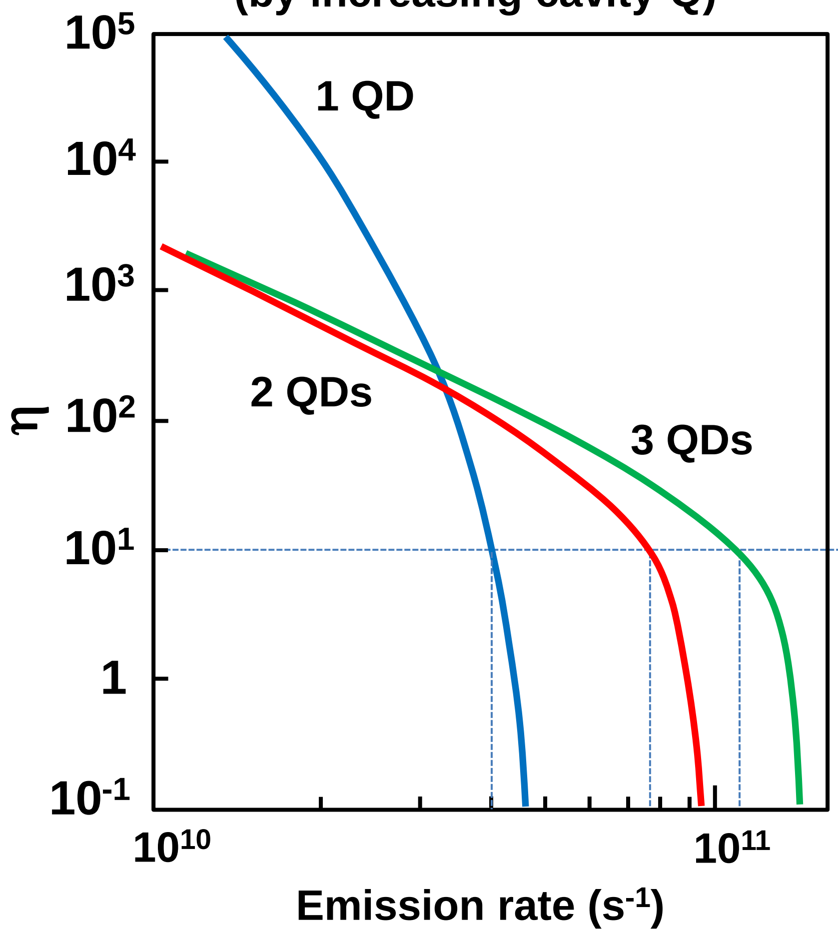
Purity vs. emission rate

(by increasing cavity-Q)



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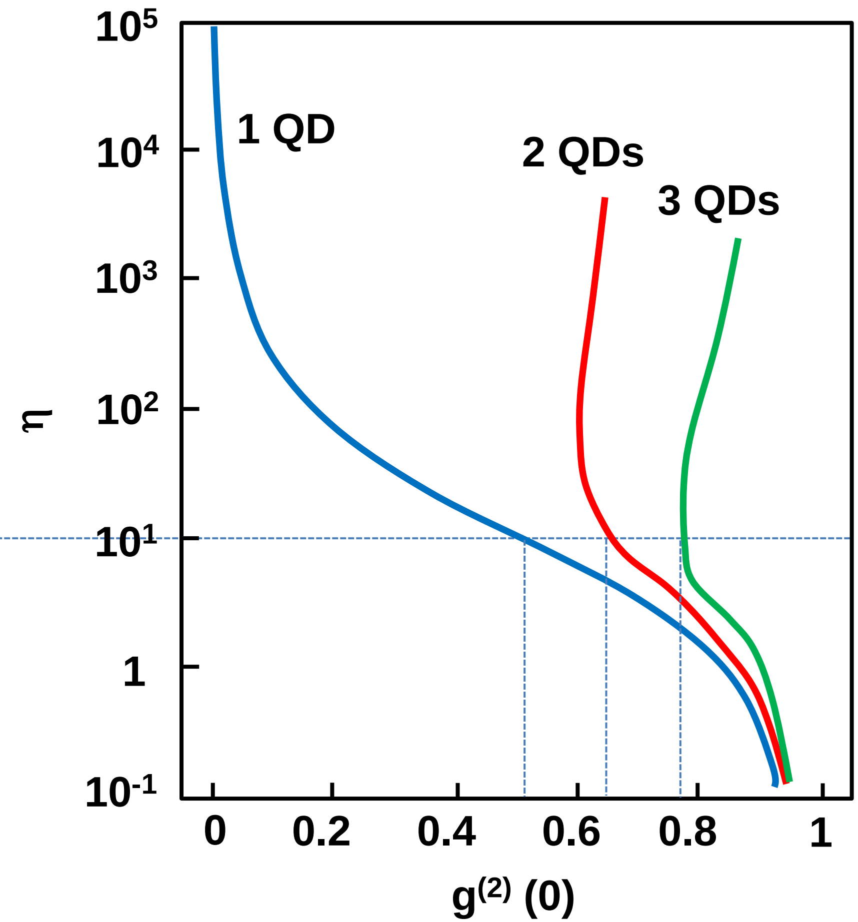

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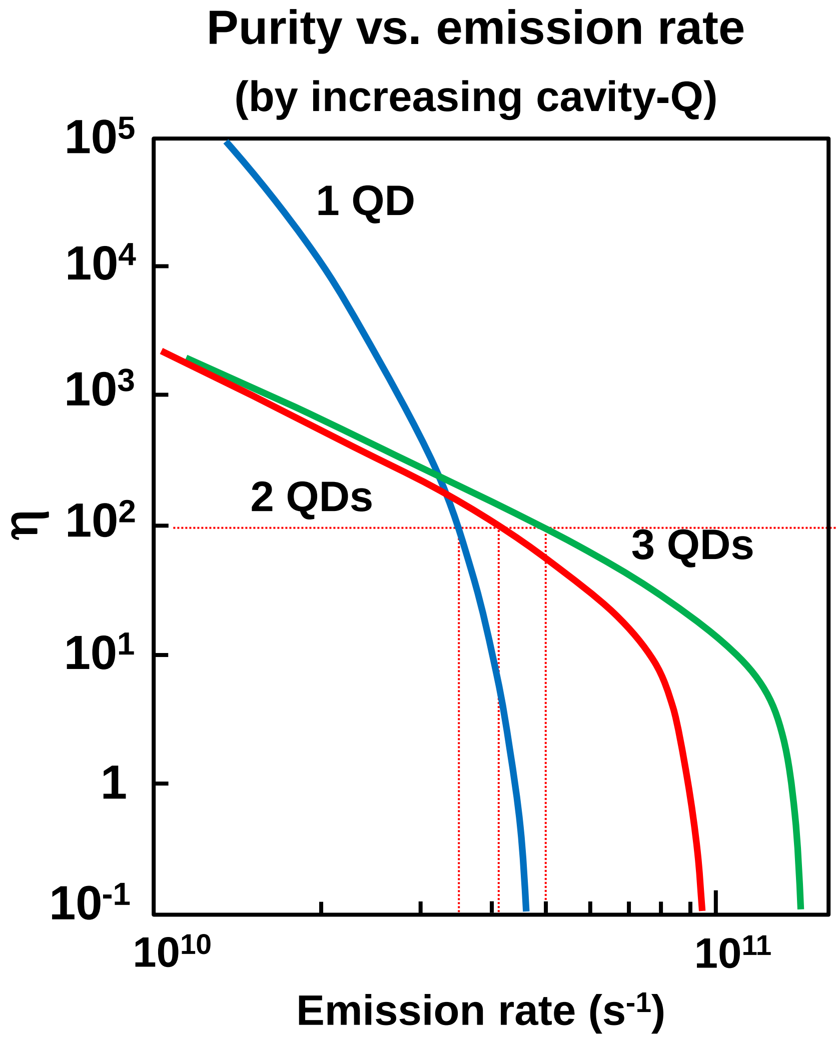

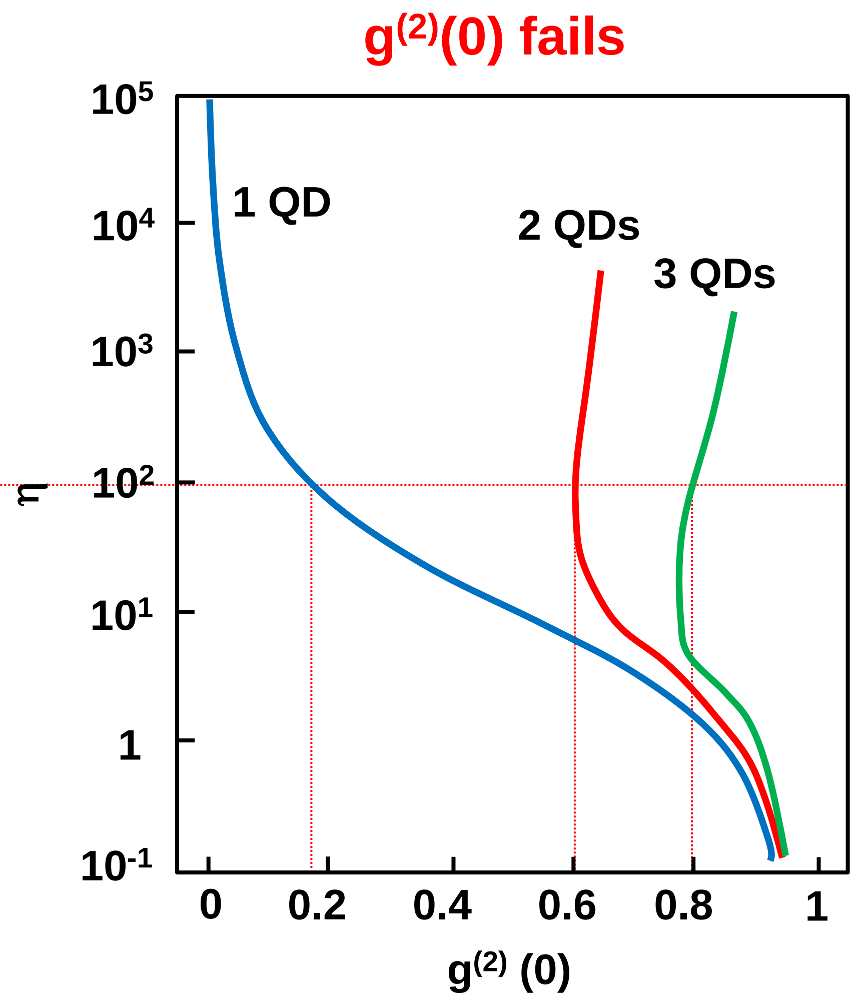

From calculating photon statistics
Gies, Jahnke, Chow (submitted)

Correlations and photon statistics in nanocavity emitters

Approach
- Quantized light and carriers
- Consistent account of light-carrier correlations

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

Single-photon sources

Quantum communications

Disconnect:

	Ideal	Applications
	Single-photon	Dimmed laser
	$\|n\rangle$	$e^{-\frac{\|\alpha\|^2}{2}} \sum_n \frac{\alpha^n}{\sqrt{n!}} \|n\rangle \,, \quad \|\alpha\|^2 \ll 1$

Bridge: tradeoff among efficiency, rate and error
- Challenges in fabrication and modeling
- Questions concerning present measure of performance

Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)

Chow, Gies & Jahnke, Light: Science and Applications, online 29 August, 2014

Other applications of modeling approach

Gain medium engineering

Chow, Lorke & Jahnke, 'Will Quantum Dots Replace Quantum Wells As the Active Medium of Choice in Future Semiconductor Lasers?' IEEE J. Selected Topics in Quantum Electron. **17**, 1349 (2011).

Frank Jahnke, Bremen University

Liu, Chow, Gossard, Bowers, "Extraction of inhomogeneous broadening and nonradiative losses in InAs quantum-dot lasers,' (in preparation)

John Bowers, UC Santa Barbara

Solid state lighting

Chow, *Novel LED Model Offers New Insights,* Compound Semiconductor Magazine, July, 2014.

EFRC

Quantum optomechanics

Carmele, Kabuss & Chow, 'Highly detuned Rabi oscillations for a quantum dot in a microcavity,' Physical Review B **87**, Rapid Communication, 041305 (2013).

Andreas Knorr: TU-Berlin

BEC and Atomtronics

Chow, Straatsma & Anderson, 'An engineering design tool for atomtronic circuits' (submitted PRA).

Dana Anderson, U Colorado and JILA

Stephan Koch, Philipps University, Marburg