Analytical support for SECANT emitter experiments

SAND2015-7252PE

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Single-photon sources

- **Quantum dots**
- **Nanocavities**
- **Single-quantum-dot sources**

Other QKD sources

- **Squeezed light**
- **Parametric down conversion**

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Experiment on growing highly-uniform quantum-dot samples

Questions:

- What does a perfect (homogeneously-broadened) quantum-dot sample look like?
- Is there a way to determine degree of nonuniformity (i.e. inhomogeneous broadening)?

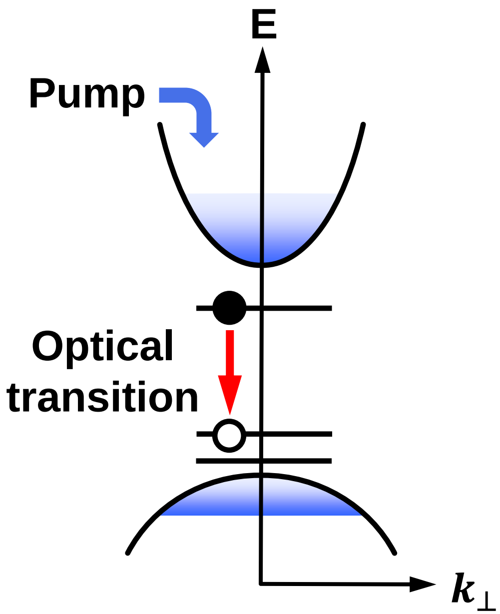
Answer: **Yes, by calculating optical response with rigorous description of dephasing (due to Coulomb correlations)**

↑

Usually treated as free parameter

Approach

Quantum-dot electronic structure



Single-particle — **Light-carrier**

$$H = \sum_{\alpha} \varepsilon^{e}_{\alpha}\, c^{\dagger}_{\alpha} c_{\alpha} + \sum_{\beta} \varepsilon^{h}_{\beta}\, b^{\dagger}_{\beta} b_{\beta} - \sum_{\alpha} \left(g_{\alpha} b^{\dagger}_{\alpha} c^{\dagger}_{\alpha} + g^{*}_{\alpha} c_{\alpha} b_{\alpha} \right) E$$

g_α: $\wp W(R_{QD}) \sum_{n} C_{\alpha}(R_n)\, V_{\alpha}(R_n)$

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

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

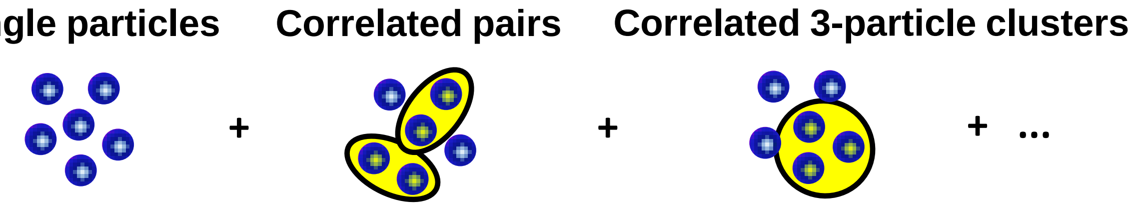
$$+ \hbar \sum_{\alpha\beta q} G_q \left(c^{\dagger}_{\alpha} c_{\beta} + b^{\dagger}_{\alpha} b_{\beta} \right) \left(d_q + d^{\dagger}_q \right)$$

Carrier-phonon

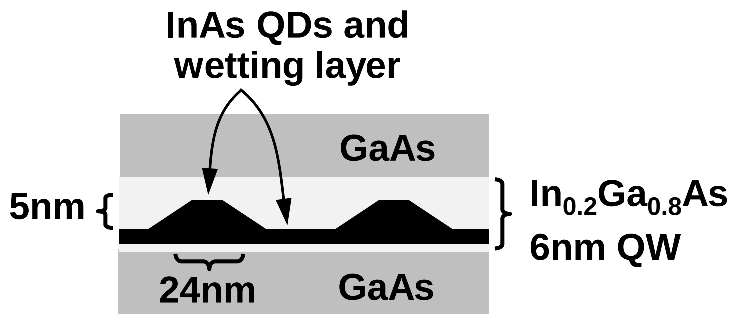
Heisenberg Picture $\quad \dfrac{\partial}{\partial t} A = -\dfrac{i}{\hbar} [A, H]$

Populations and correlations $\quad \langle c^{\dagger}_{\alpha} c_{\alpha} \rangle, \langle b^{\dagger}_{\alpha} b_{\alpha} \rangle, \langle c^{\dagger}_{\alpha} b^{\dagger}_{\alpha} \rangle, \left\langle c^{\dagger}_{\alpha} c^{\dagger}_{\beta} c_{\beta} c_{\alpha} \right\rangle, \left\langle b^{\dagger}_{\beta} c^{\dagger}_{\alpha} c_{\alpha} b_{\beta} \right\rangle, \ldots$

Cluster expansion $\quad \langle \hat{N} \rangle =$



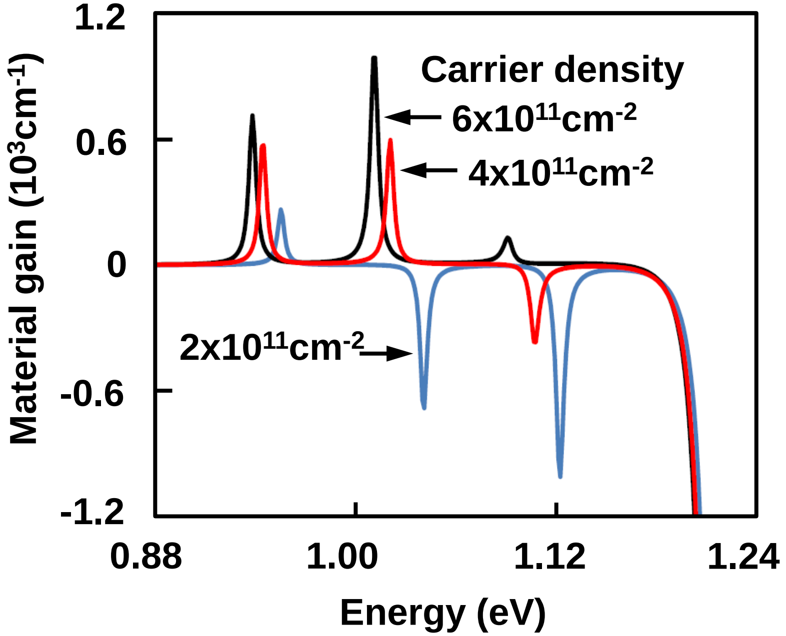
Calculated quantum-dot optical response



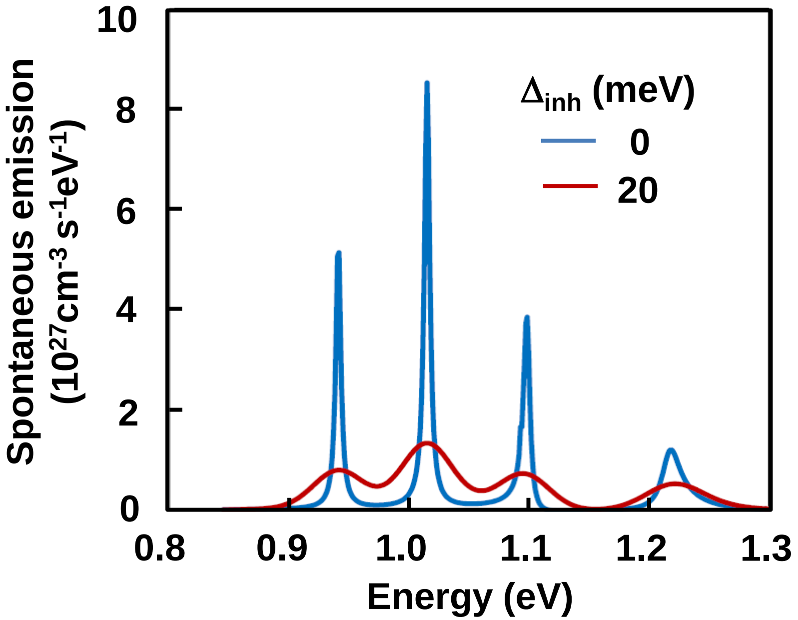
$N_{dot} = 5 \times 10^{10} cm^{-2}$

Perfect sample

Homogeneously-broadened absorption & gain



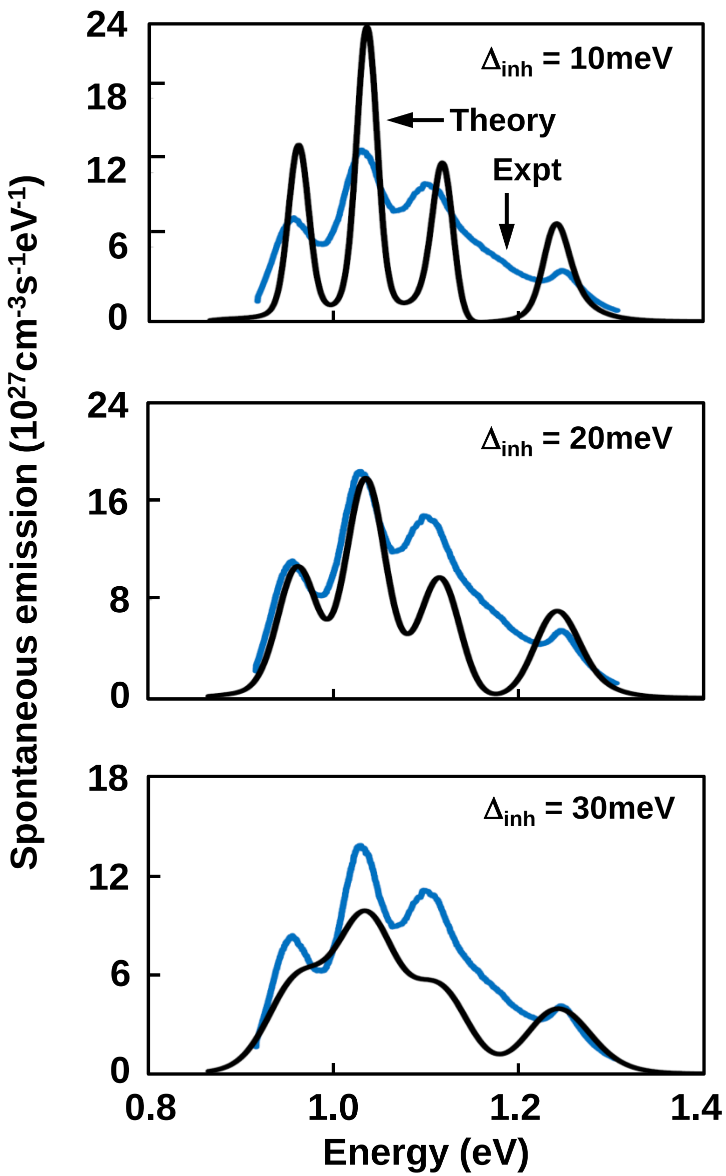
Spontaneous emission and effect of QD nonuniformity



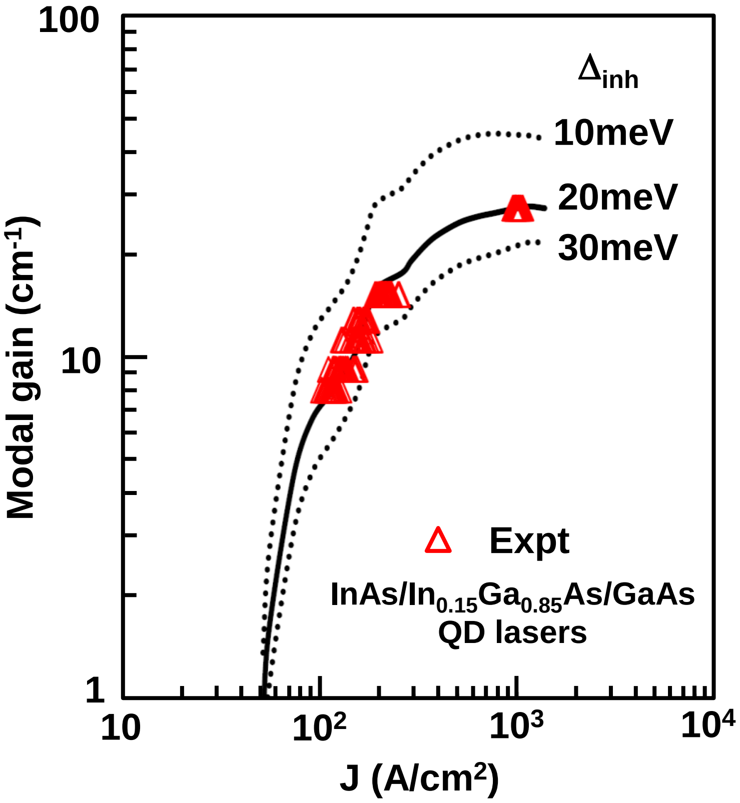
Overview: Chow & Jahnke, Progress in Quantum Electronics 37, 109 (2013)

Extraction of inhomogeneous broadening

From spontaneous emission



From lasers



Chow, Liu, Gossard and Bowers, ‘Extraction of inhomogeneous broadening and nonradiative losses in InAs quantum-dot lasers,’ (submitted APL)

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- Nanocavities ←
- Single-quantum-dot sources ←

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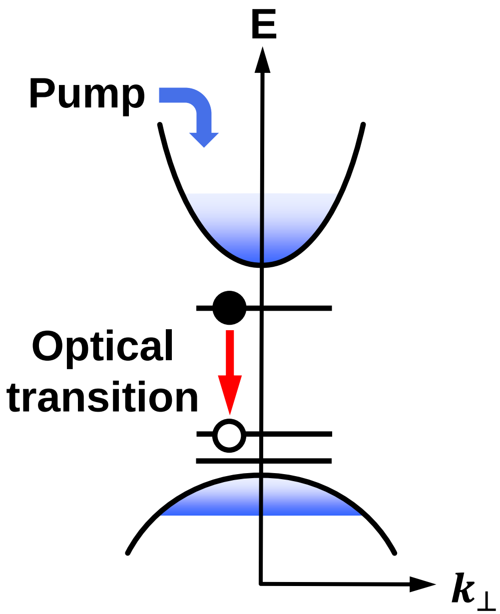
- Parametric down conversion

Approach (quantized electrons, classical optical field)

Quantum-dot electronic structure



Single-particle — **Light-carrier**

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g_{α}: $\wp W(R_{QD}) \sum_{n} C_{\alpha}(R_n)\, V_{\alpha}(R_n)$

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

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

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

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

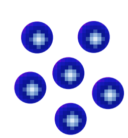
Carrier-phonon

Heisenberg Picture $\quad \dfrac{\partial}{\partial t} A = -\dfrac{i}{\hbar} [A, H]$

Populations and correlations $\quad \langle c^{\dagger}_{\alpha} c_{\alpha} \rangle, \langle b^{\dagger}_{\alpha} b_{\alpha} \rangle, \langle c^{\dagger}_{\alpha} b^{\dagger}_{\alpha} \rangle, \left\langle c^{\dagger}_{\alpha} c^{\dagger}_{\beta} c_{\beta} c_{\alpha} \right\rangle, \left\langle b^{\dagger}_{\beta} c^{\dagger}_{\alpha} c_{\alpha} b_{\beta} \right\rangle, \ldots$

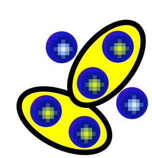
Cluster expansion $\quad \langle \hat{N} \rangle =$

Single particles



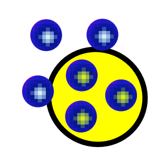
+

Correlated pairs



+

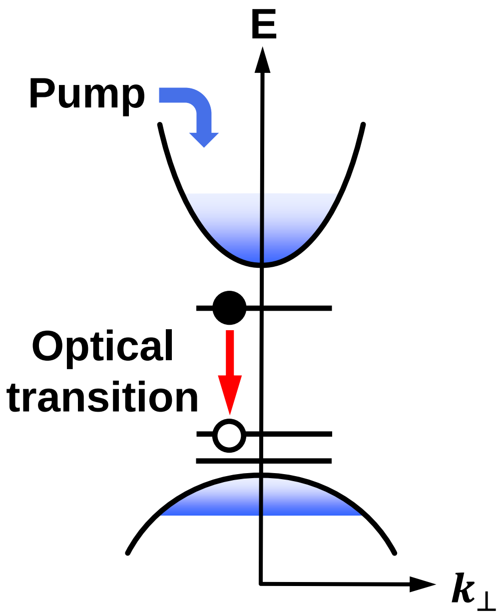
Correlated 3-particle clusters



+ ...

Approach (quantized electrons and optical field)

Quantum-dot 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**

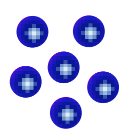
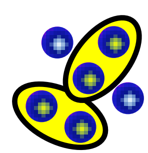
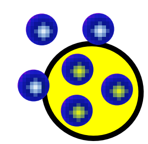
$$\wp\sqrt{\frac{\nu}{\hbar\epsilon_b V}}\,W(R_{QD})\sum_n C_\alpha(R_n)\,V_\alpha(R_n)$$

+ Carrier-carrier and carrier-phonon interactions

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

Populations and correlations $\langle c^\dagger_\alpha c_\alpha\rangle, \langle b^\dagger_\alpha b_\alpha\rangle, \langle c^\dagger_\alpha b^\dagger_\alpha a\rangle, \langle a^\dagger a\rangle, \langle a^\dagger a^\dagger a a\rangle, \langle c^\dagger_\alpha c_\alpha a^\dagger a\rangle$, + ...

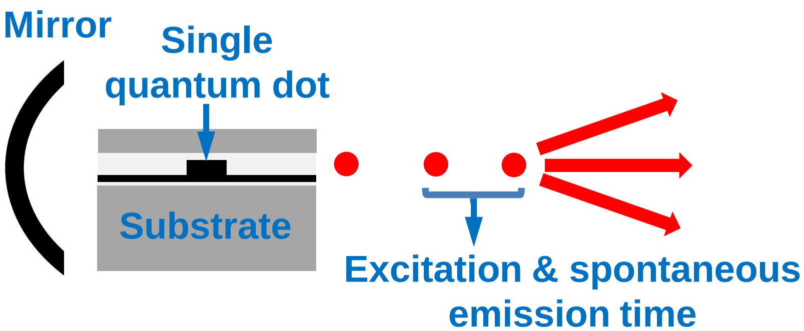
Cluster expansion $\langle\hat{N}\rangle =$

Single particles  + Correlated pairs  + Correlated 3-particle clusters  + ...

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

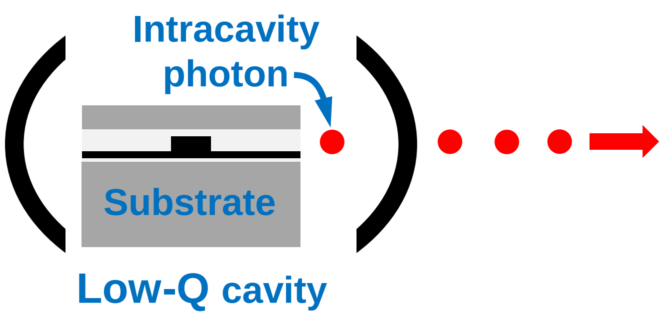
Single-photon source

Error-free but slow

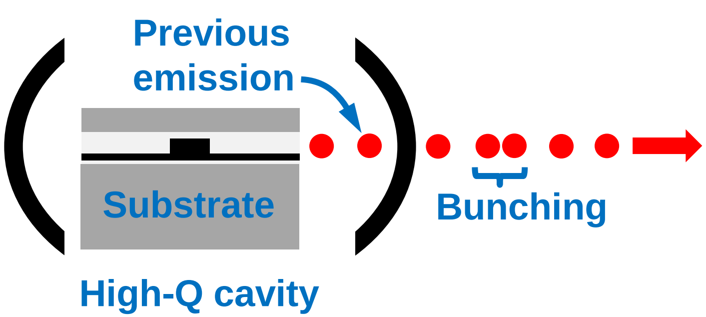


Cavity enhancement

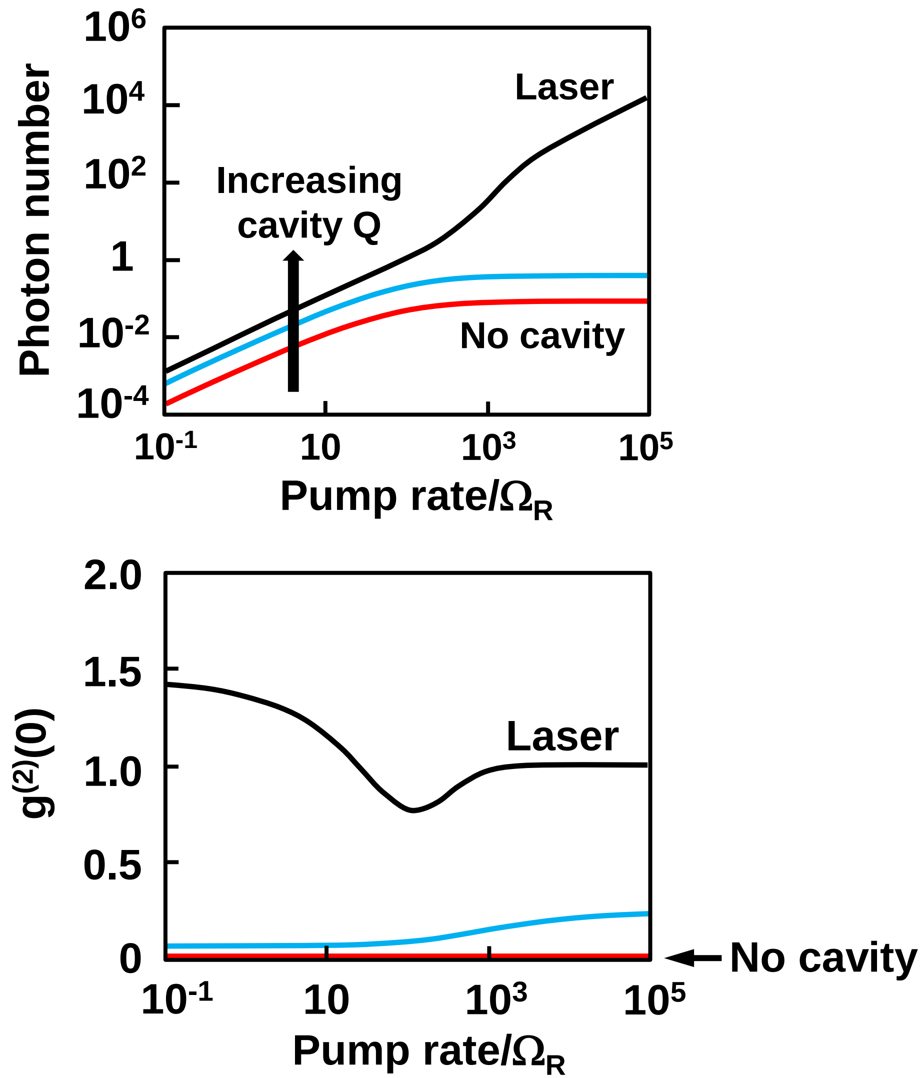
Directionality and Purcell



Too much cavity



From cavity-QED model

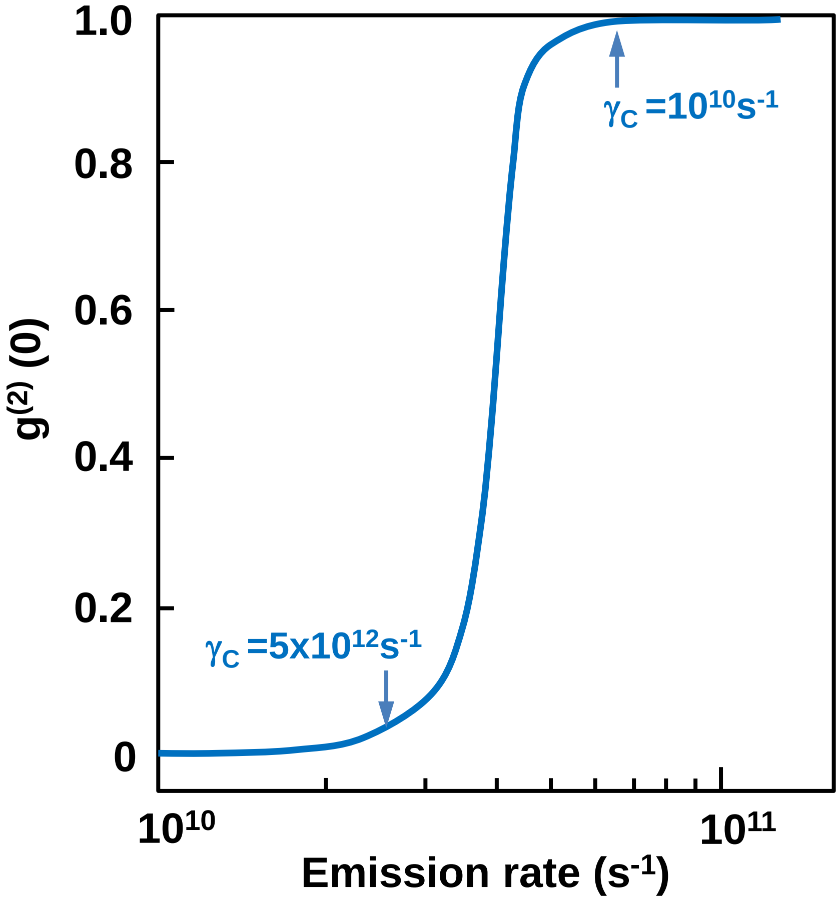


What is the right Q?

Fundamental limit to efficiency, rate and error?

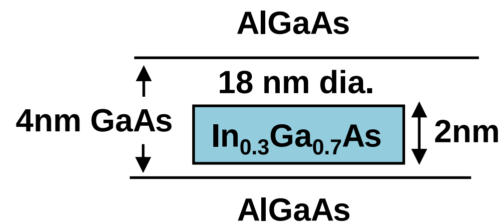
Single-photon purity and emission rate

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



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

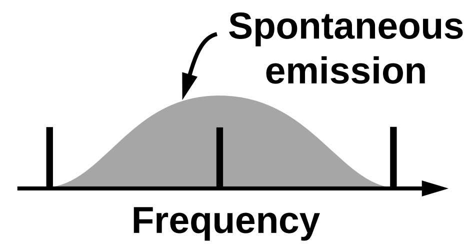
① Shallow quantum dot



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

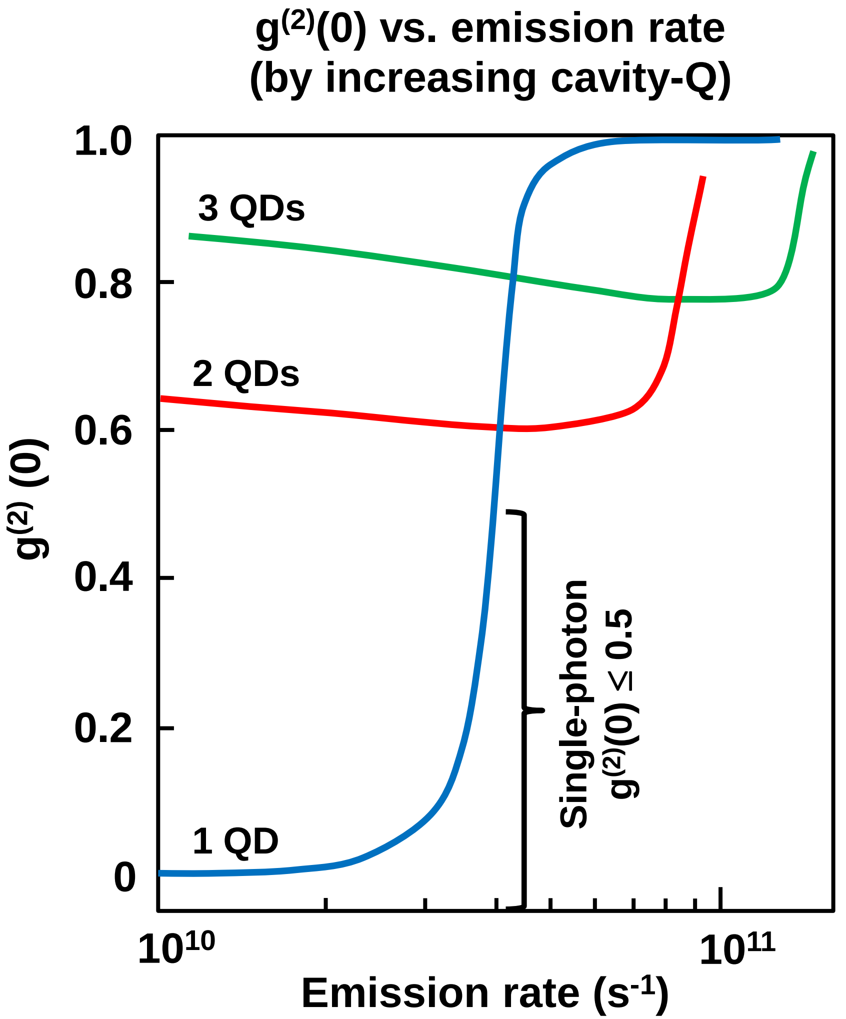
$$\wp \sqrt{\frac{\nu}{\hbar \epsilon_b V}}\, W(R_{QD}) \sum_n C(R_n)\, V(R_n)$$

Mode volume

Confinement factor

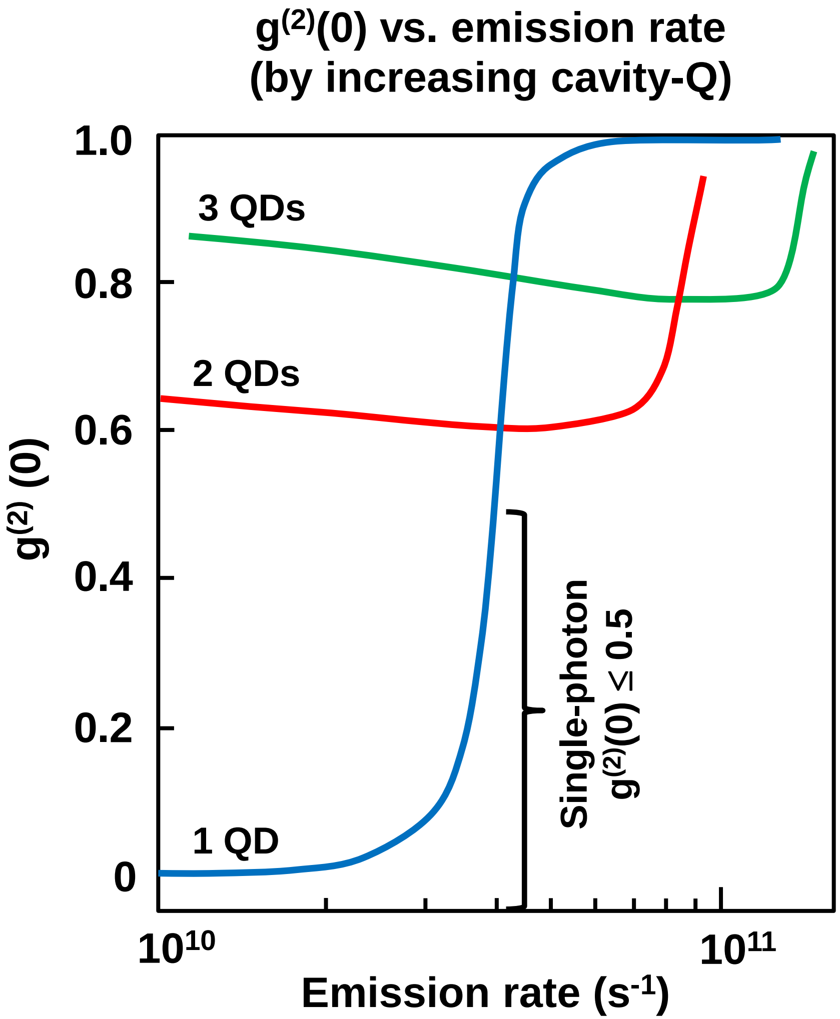
Electron-hole envelope overlap

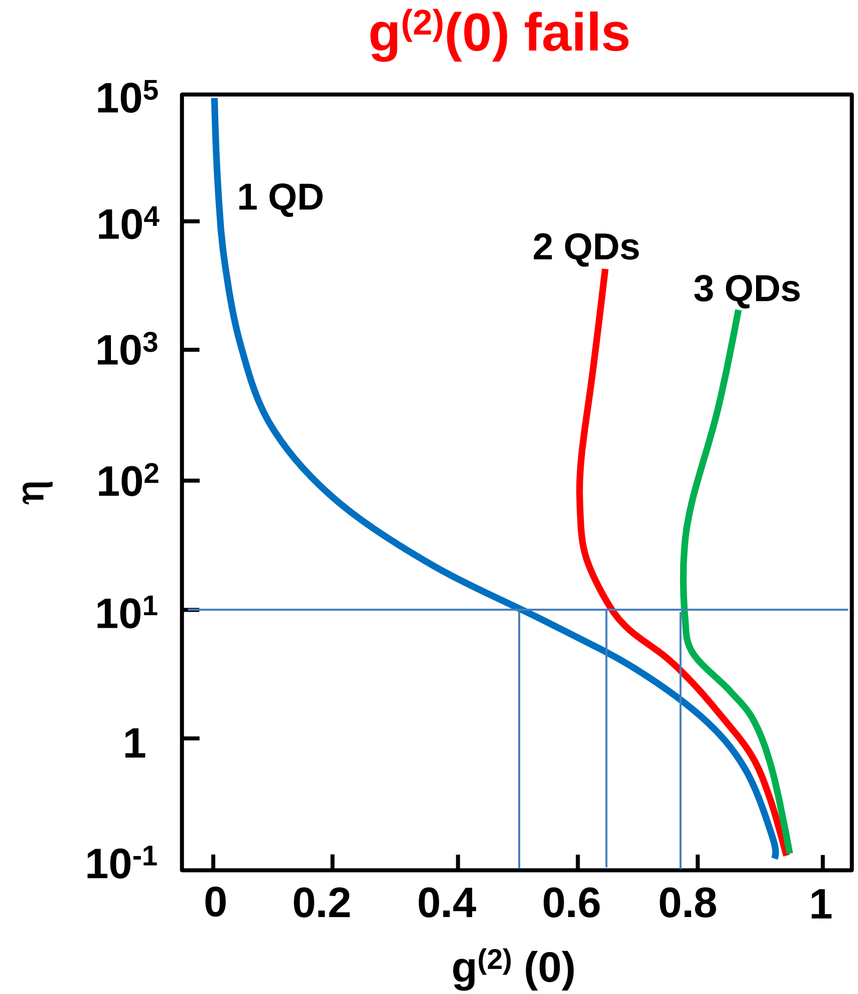
Concern: Extraneous quantum dots



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

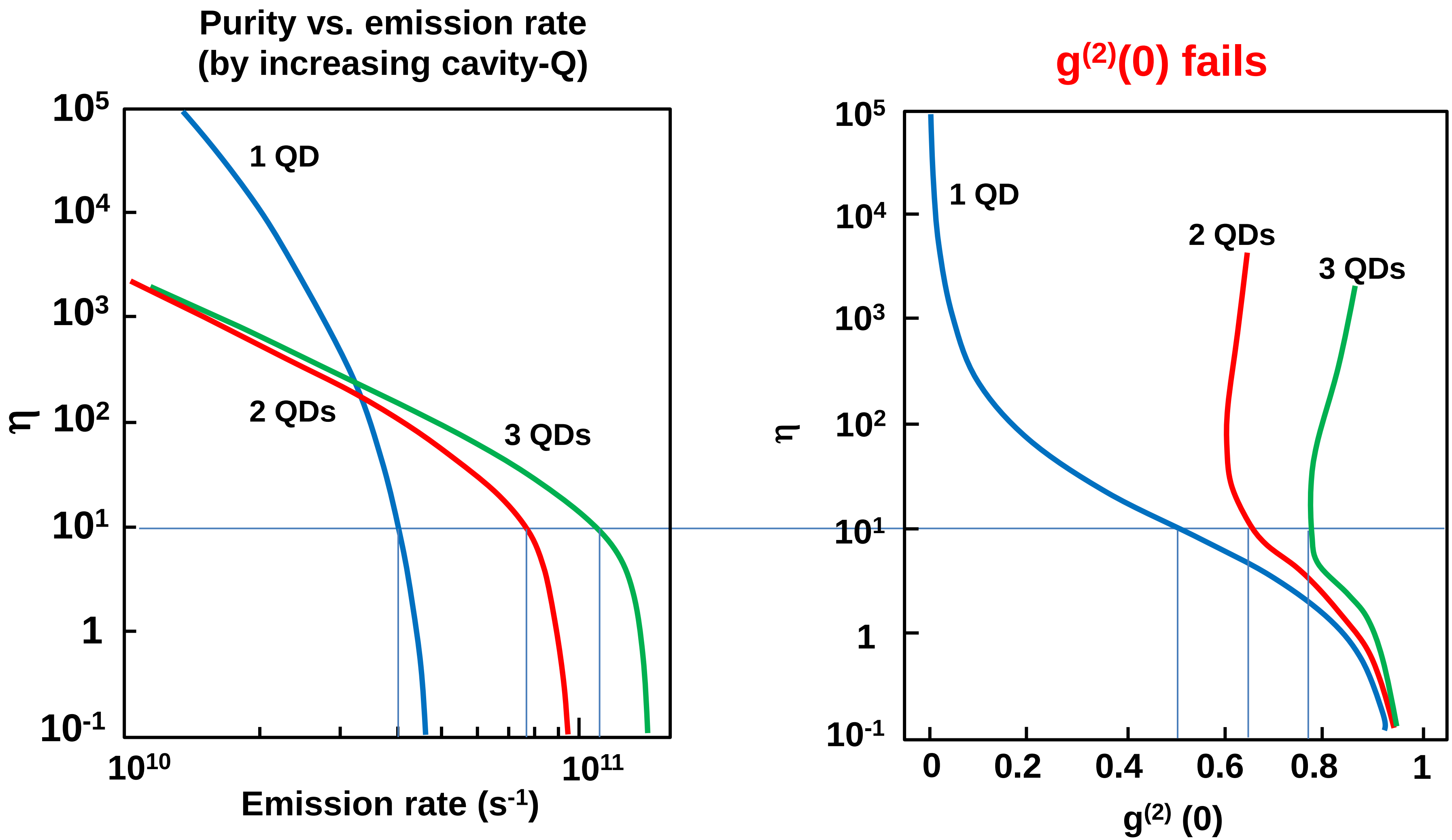
Single-photon purity: $\eta = \dfrac{\text{Single-photon emission probability}}{\text{Multi-photon emission probability}}$





Full photon statistics vs. $g^{(2)}(0)$

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



Gies, Jahnke, Chow, 'Photon antibunching from few quantum dots in a cavity,' PRA 91, 061804 (R) (2015)

Analytical support for SECANT emitter experiments

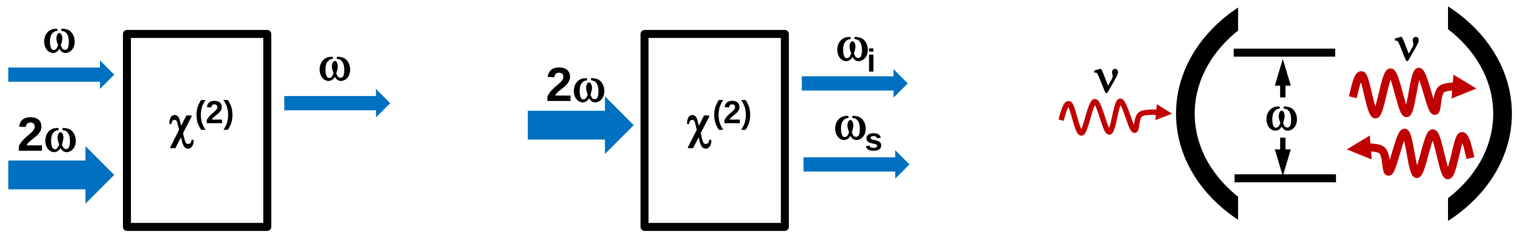
Single-photon sources

- Quantum dots
- Nanocavities
- Single-quantum-dot sources

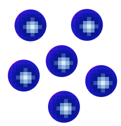
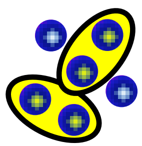
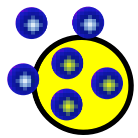
Other QKD sources ←

- Squeezed light
- Parametric down conversion

On-going



Single particles | Correlated pairs | Correlated 3-particle clusters

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

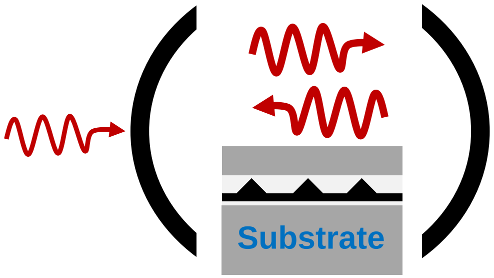
Before :
$$\langle c_\alpha^\dagger c_\alpha \rangle, \langle b_\alpha^\dagger b_\alpha \rangle$$
$$\langle a^\dagger a \rangle, \langle c_\alpha^\dagger b_\alpha^\dagger a \rangle$$

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

Before : $$\langle a^\dagger a^\dagger a\, a \rangle = 2\langle a^\dagger a \rangle \langle a^\dagger a \rangle + \delta \langle a^\dagger a^\dagger a\, a \rangle$$

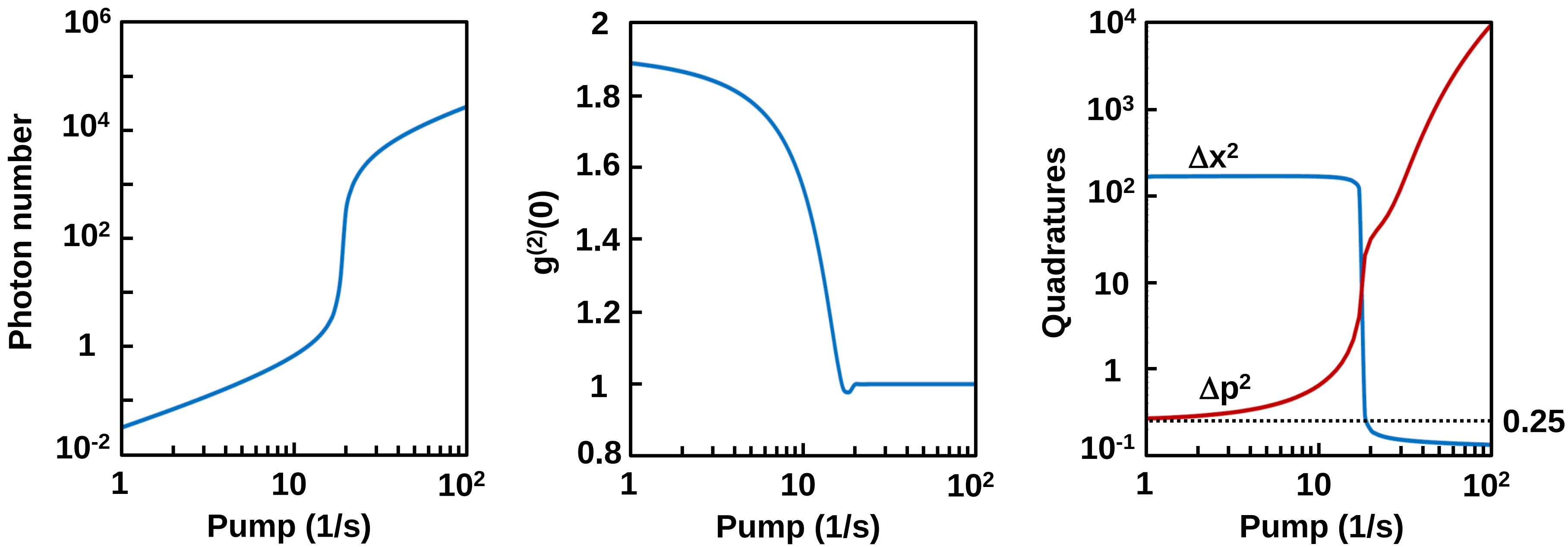
Now : $$\langle a^\dagger a^\dagger a\, a \rangle = \langle a^\dagger \rangle^2 \langle a \rangle^2 + 4\langle a^\dagger \rangle \langle a \rangle \delta \langle a^\dagger a \rangle + \langle a^\dagger \rangle^2 \delta \langle a a \rangle + \langle a \rangle^2 \delta \langle a^\dagger a^\dagger \rangle$$
$$+2\delta \langle a^\dagger a \rangle \delta \langle a^\dagger a \rangle + \delta \langle a^\dagger a^\dagger \rangle \delta \langle a a \rangle$$

Preliminary result



$$\Delta x^2 = \frac{1}{4}\left[1 + 2\delta\left\langle a^\dagger a\right\rangle + 2\,\mathrm{Re}\left(\delta\left\langle a^2\right\rangle\right)\right]$$

$$\Delta p^2 = \frac{1}{4}\left[1 + 2\delta\left\langle a^\dagger a\right\rangle - 2\,\mathrm{Re}\left(\delta\left\langle a^2\right\rangle\right)\right]$$



SECANT related publications

Single-photon (quantum dots, nanocavities and single-QD sources)

Chow, Jahnke 'On the physics of semiconductor quantum dots for applications in lasers and quantum optics,' PROGRESS IN QUANTUM ELECTRONICS **37** 109-184 (2013)

Chow, Jahnke, Gies 'Emission properties of nanolasers during the transition to lasing' LIGHT-SCIENCE & APPLICATIONS **3** e201 (2014)

Gies, Jahnke, Chow 'Photon antibunching from few quantum dots in a cavity' PHYSICAL REVIEW A **91** 061804(R) (2015)

Chow 'Are Nonclassical Light Sources Lasers?' IEEE JOURNAL OF SELECTED TOPICS IN QUANTUM ELECTRONICS **19** 1503402 (2013)

Chow, Liu, Gossard and Bowers 'Extraction of inhomogeneous broadening and nonradiative losses in InAs quantum-dot lasers' (submitted APPLIED PHYSICS LETTERS)

TA13282 'Higher photon-flux in single-photon emission using a few emitter system*'* (2014)

Beyond single-photon sources (squeeze-light, parametric down conversion)

Lingnau, Chow, Scholl, Ludge 'Feedback and injection locking instabilities in quantum-dot lasers: a microscopically based bifurcation analysis,' NEW JOURNAL OF PHYSICS **15** 093031 (2013)

Michael, Chow, Schneider 'Group-velocity slowdown in a double quantum dot molecule' PHYSICAL REVIEW B **88** 125305 (2013)

Michael, Chow, Schneider, 'Microscopic model for intersubband gain from electrically pumped quantum-dot structures,' PHYSICAL REVIEW B **90** 165302 (2014)

Chow, Straatsma, Anderson, 'Numerical model for atomtronic circuit analysis,' PHYSICAL REVIEW A **92** 013621 (2015)