Quantum-dot nanolasers

SAND2017-8379C

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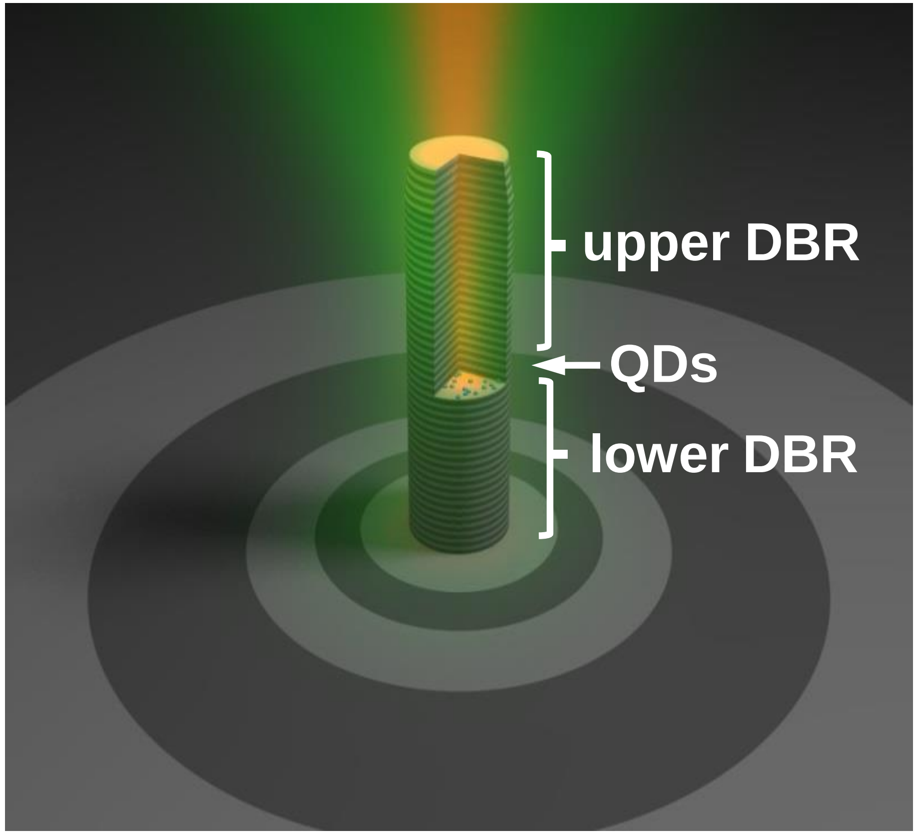

1) **Laser physics**
2) **Quantum optics**
3) **Device engineering**

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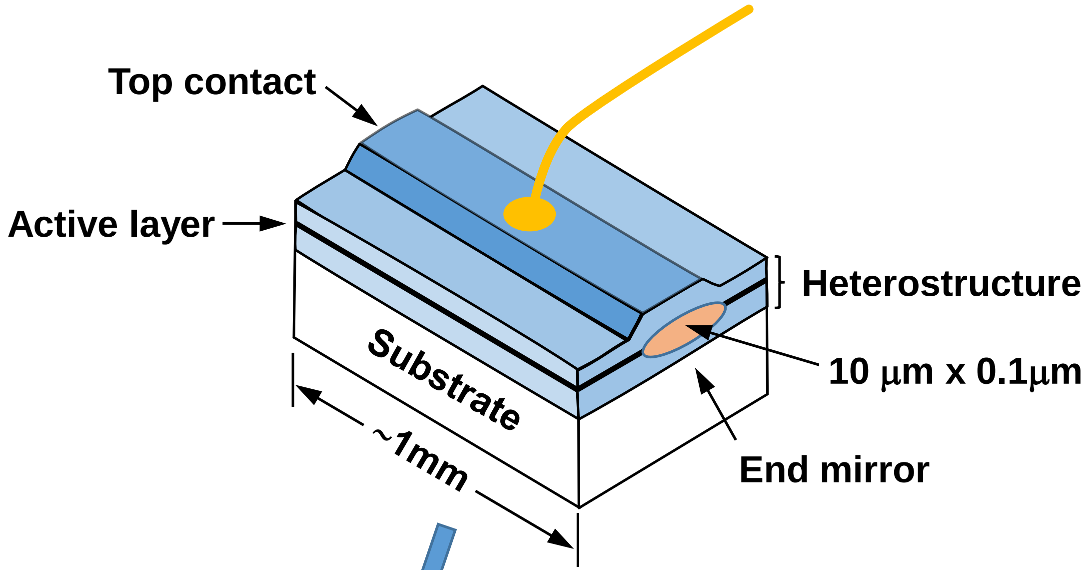
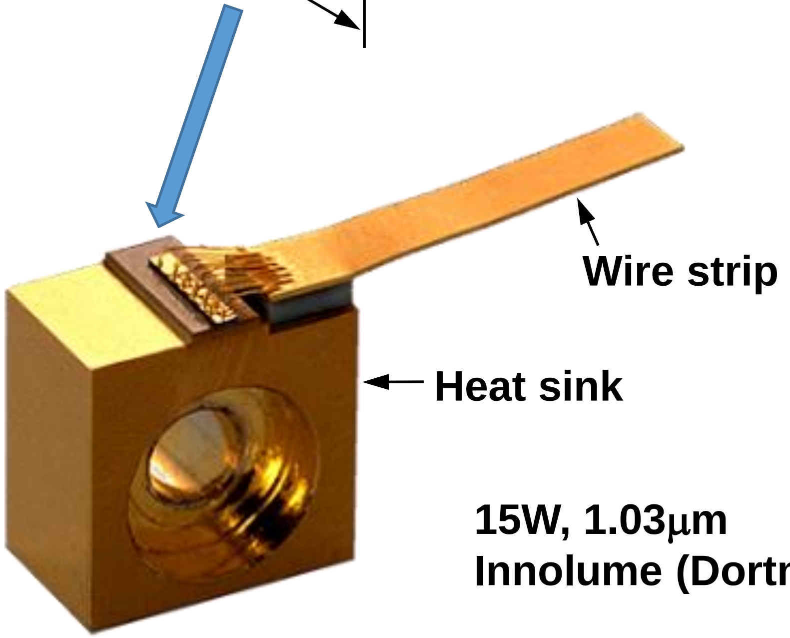
Different sizes of semiconductor lasers

Edge-emitting laser





15W, 1.03μm
Innolume (Dortmund)

Different sizes of semiconductor lasers

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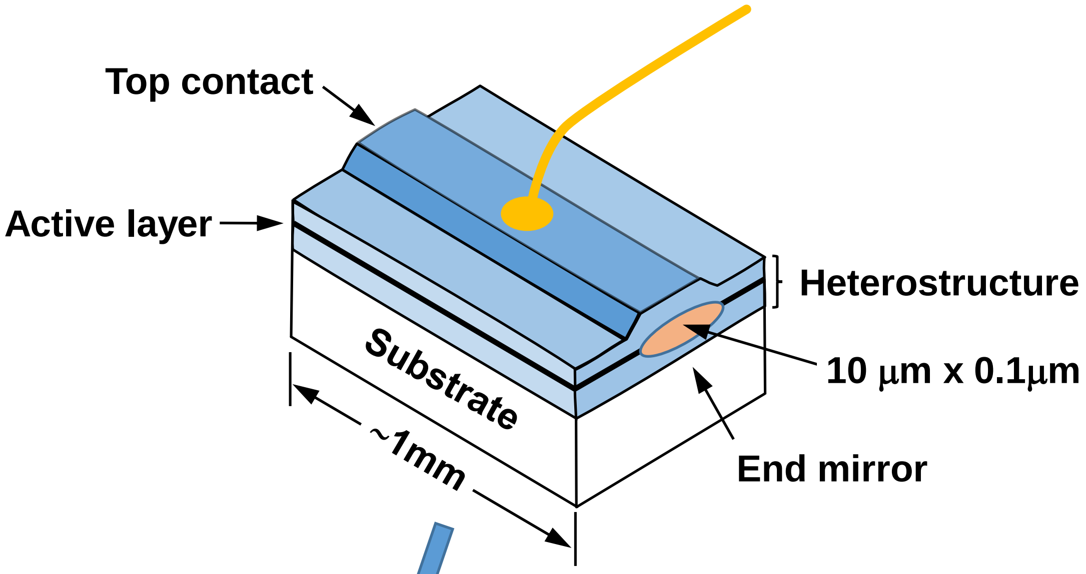

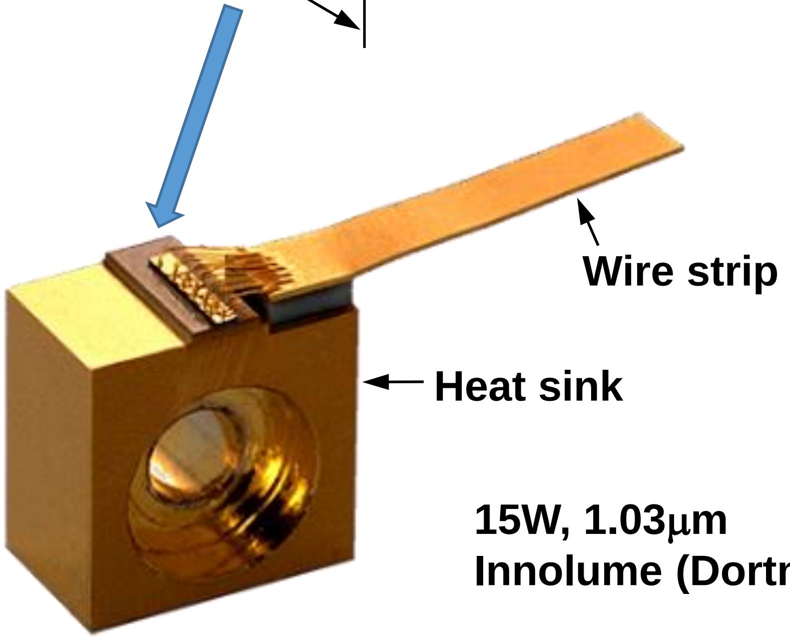

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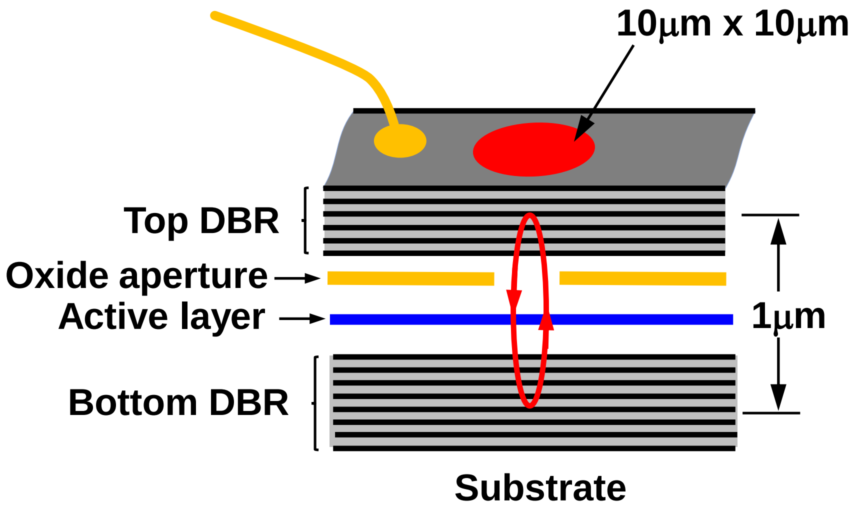
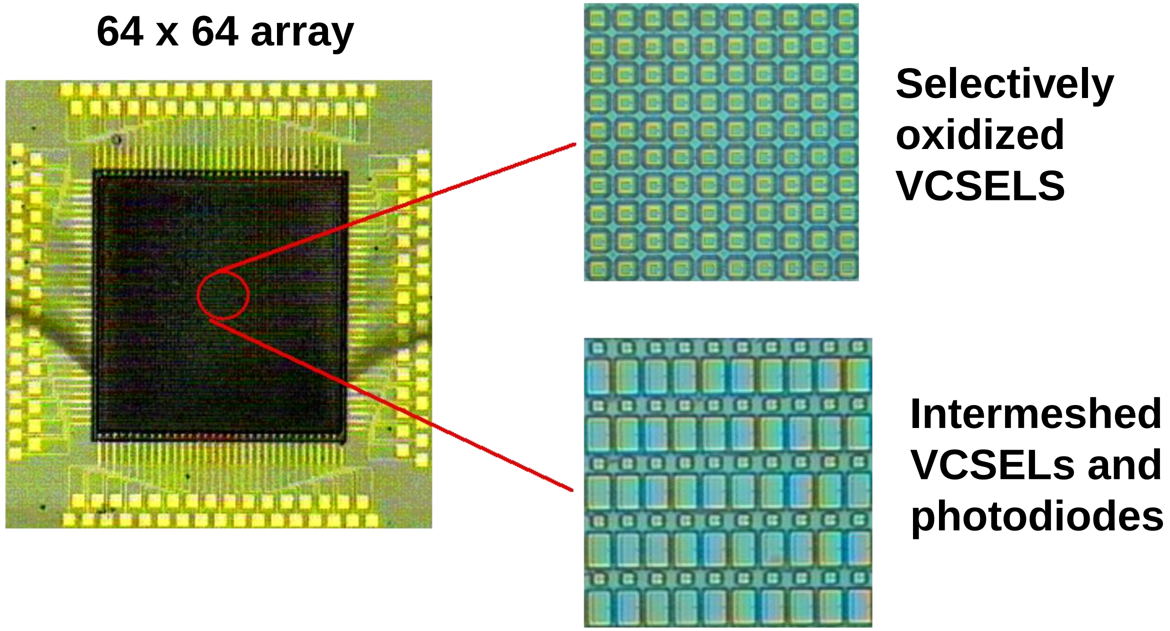
Vertical-cavity surface-emitting laser (VCSEL)



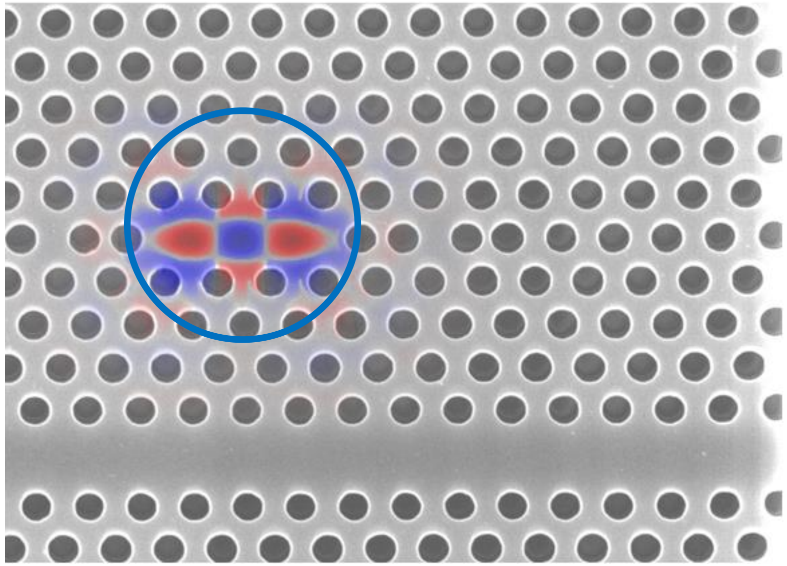
Matrix addressable
64 x 64 array



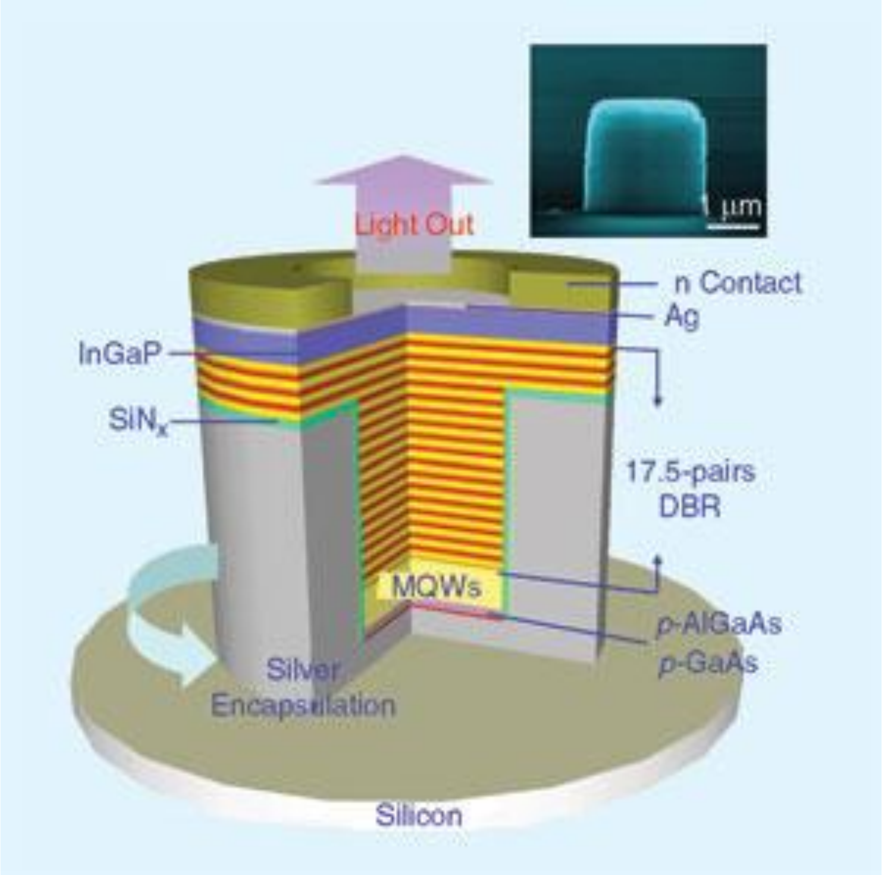
Nanolasers

Nano-pillar

Defect cavity in photonic crystal



(Courtesy of Willie Luk, Sandia National Labs)



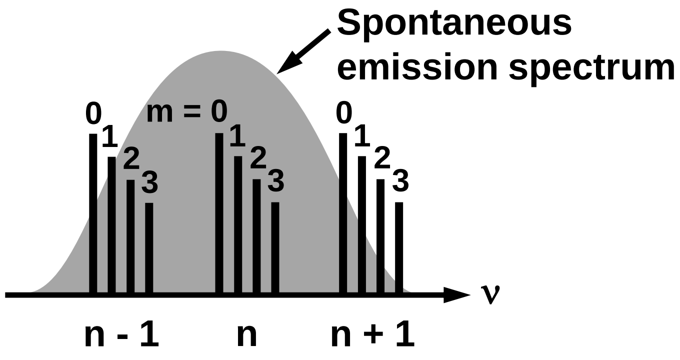
(Adapted from a figure by Lu et al., UIUC)

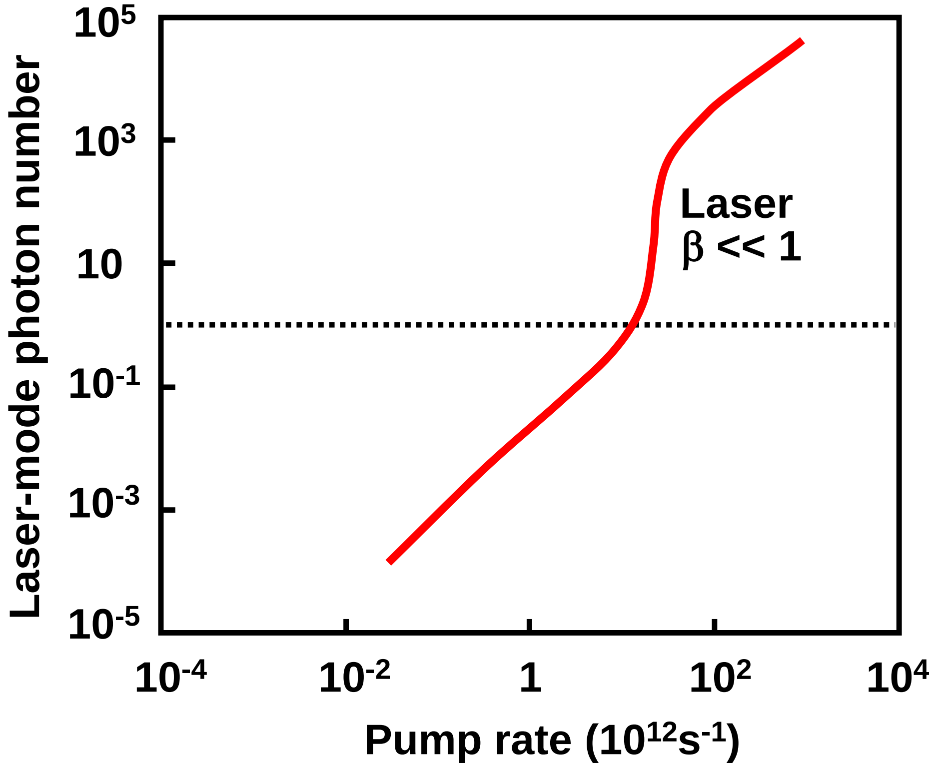
<1 μm x <1μm x <1μm

High β-factor lasers

Spontaneous emission factor: $\beta = \dfrac{\text{Spontaneous emission into lasing mode}}{\text{Total spontaneous emission}}$

<u>Most lasers</u> $\beta \ll 1$





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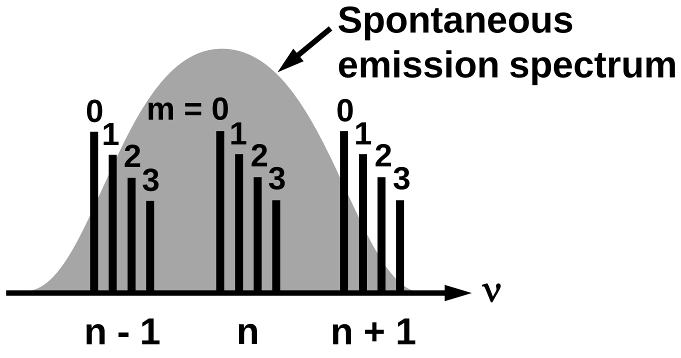
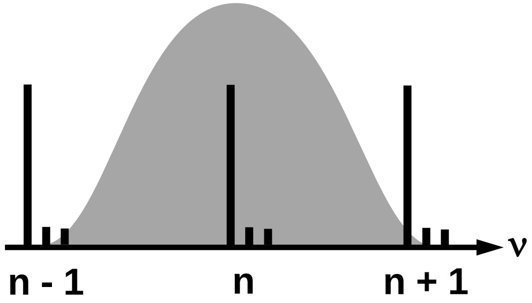
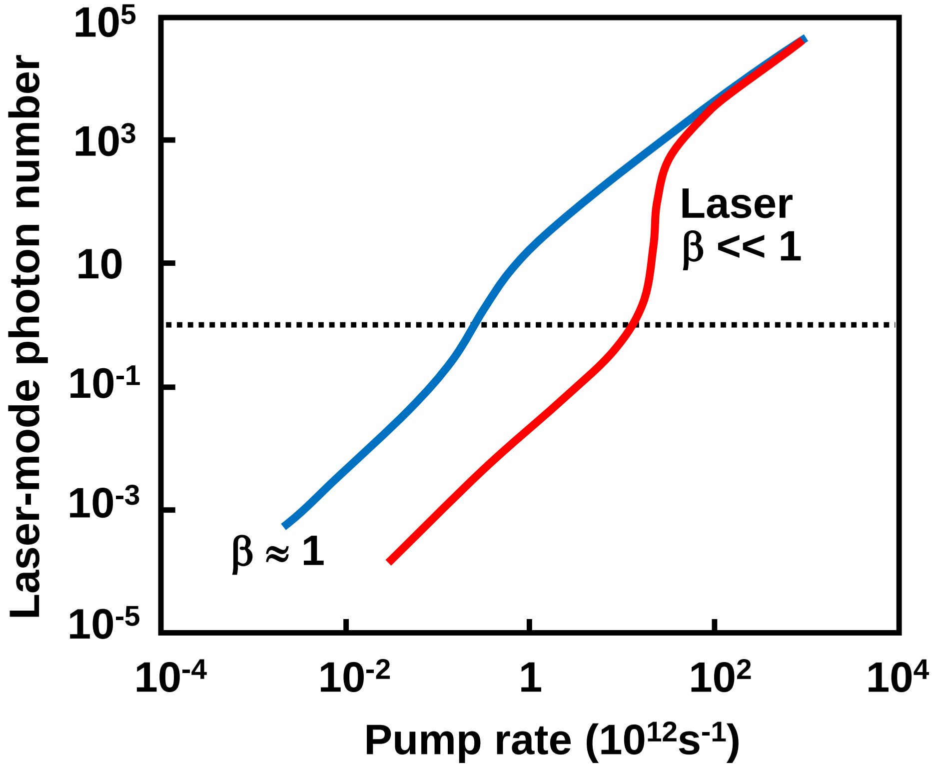


<u>High β-factor lasers</u> $\beta \lesssim 1$





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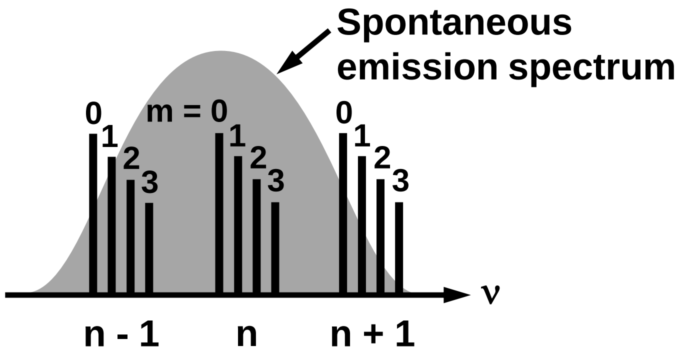

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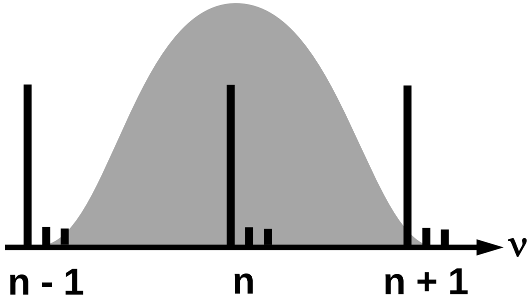
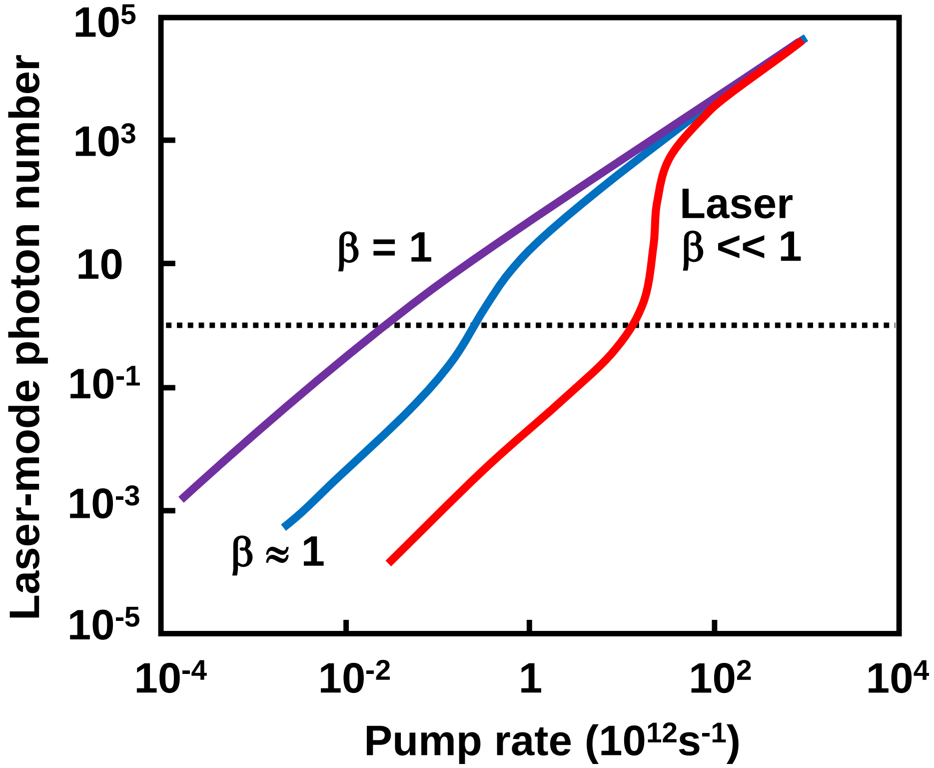


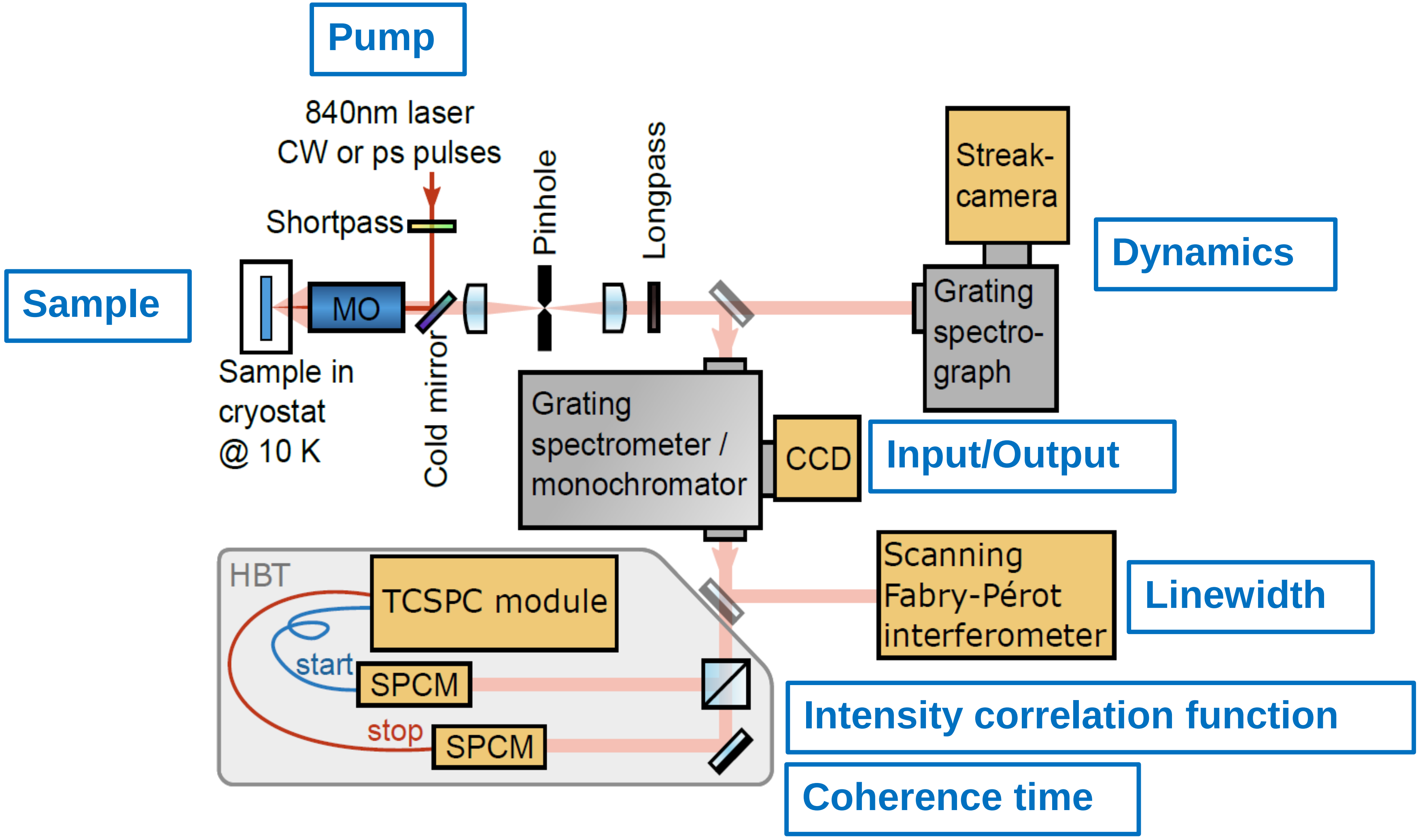
Limiting case: β = 1
All emission into single resonator mode



Question: How to verify lasing?

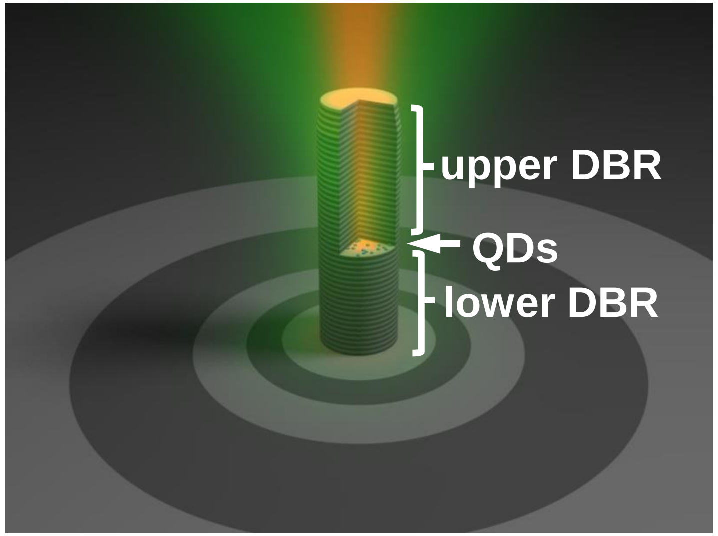
Jin, Boggavarapu, Sargent III, Meystre, Gibbs, Khitrova Phys. Rev. A 49, 4038 (1994)

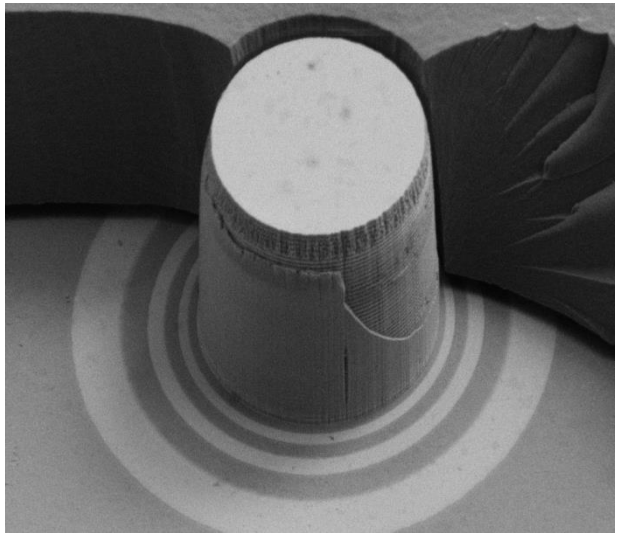
Experiment

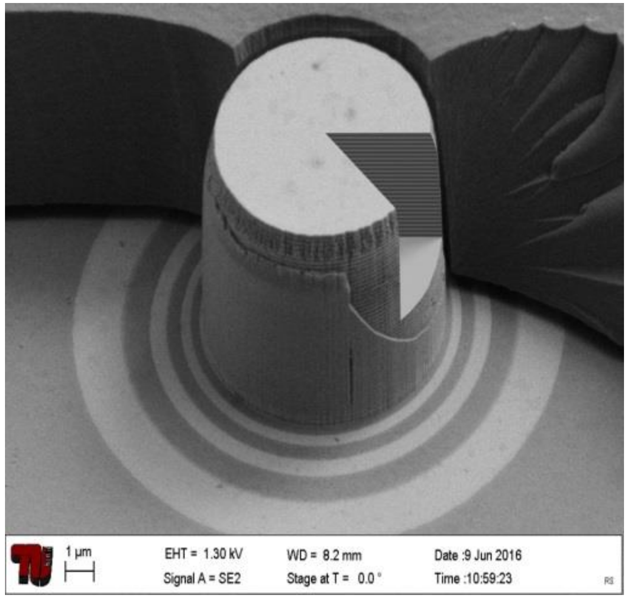


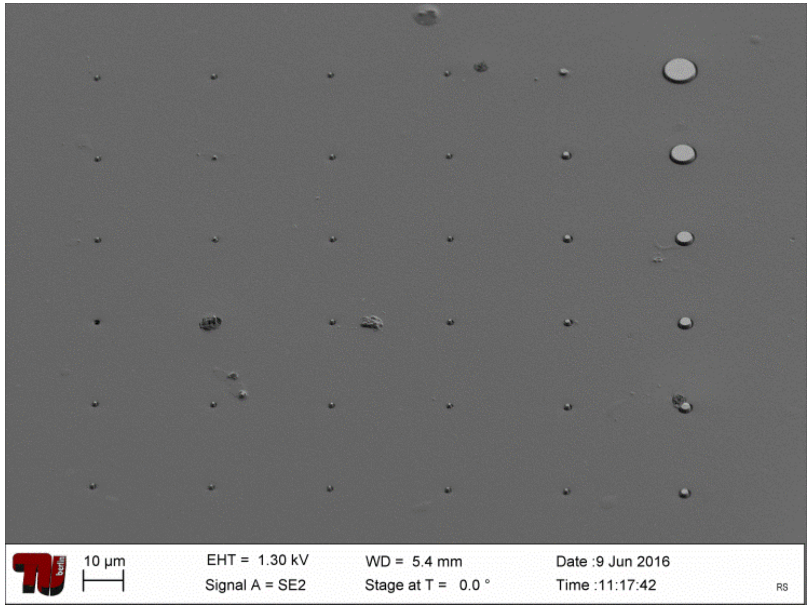
Setup: Stephan Rietzenstein' s laboratory, Technical University Berlin

Quantum-dot micropillars



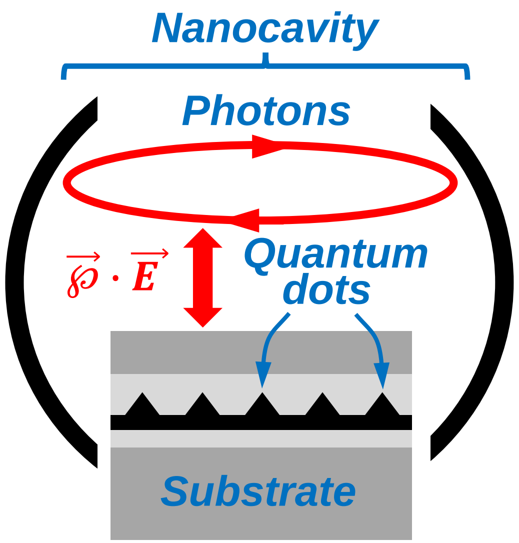




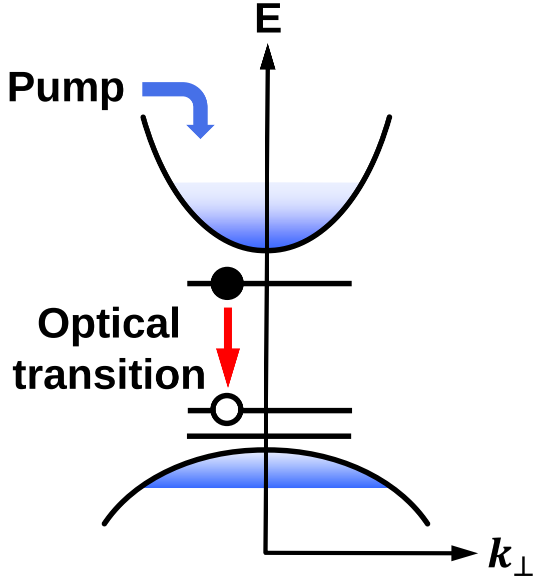


Sample growth: Universität Würzburg

Theory: Hamiltonian



Electronic structure



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

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

$$H = H_0 + H_{light-carrier} + H_{Coulomb}$$

$$\sum_\alpha \varepsilon_\alpha^e\, c_\alpha^\dagger c_\alpha + \sum_\beta \varepsilon_\beta^h\, b_\beta^\dagger b_\beta + \hbar\omega \left(a^\dagger a + \frac{1}{2} \right)$$

Inhomogeneous broadening

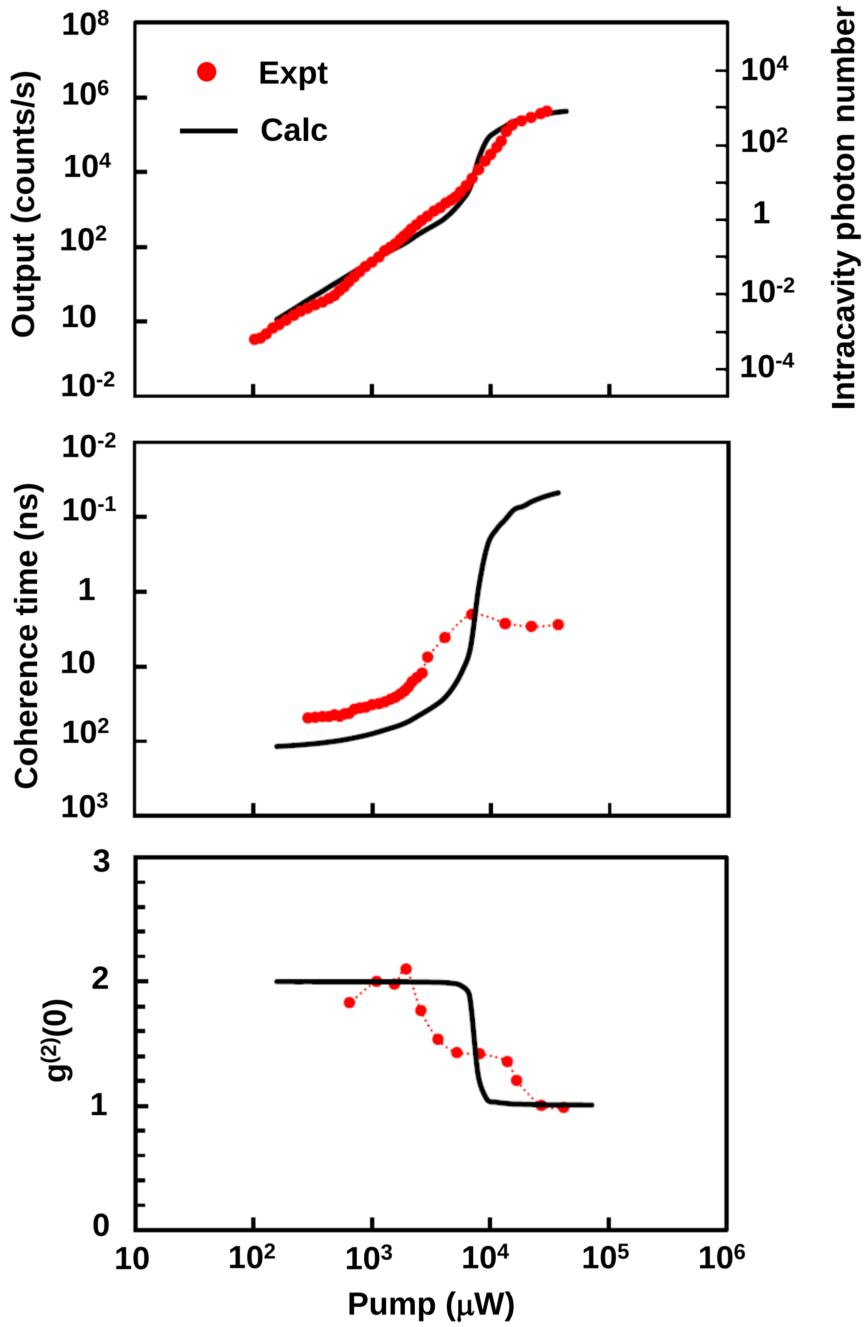
Carrier-phonon $\hbar \sum_{\alpha\beta q} G_q \left(c_\alpha^\dagger c_\beta + b_\alpha^\dagger b_\beta \right) \left(d_q + d_q^\dagger \right)$

Carrier-carrier $\frac{1}{2} \sum_{\alpha\beta\sigma\eta} \left[W_{\alpha\beta\sigma\eta}^{e} c_\alpha^\dagger c_\beta^\dagger c_\eta c_\sigma + W_{\alpha\beta\sigma\eta}^{h} b_\alpha^\dagger b_\beta^\dagger b_\eta b_\sigma - 2W_{\alpha\beta\sigma\eta}^{eh} b_\alpha^\dagger c_\beta^\dagger c_\eta b_\sigma \right]$

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

Quantum-dot micropillars: experiment & theory

	∅ (μm)	Q	β	N_{QD}	η	
D	2.5	22800	0.23	60	0.017	●



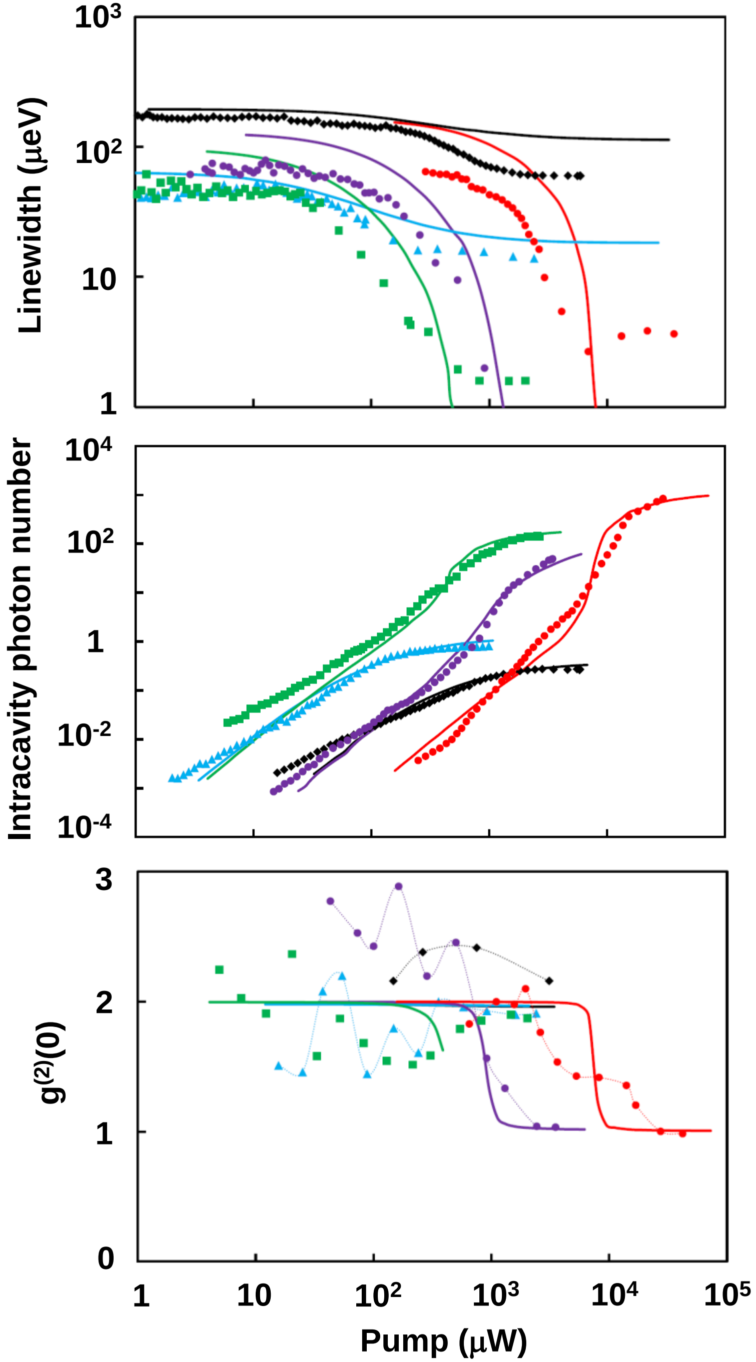
Quantum-dot micropillars: experiment & theory

	∅ (μm)	Q	β	N_{QD}	η	
A	1.7	8300	0.40	10	0.36	◆
B	2.0	32100	0.37	6	0.36	▲
C	2.0	32100	0.37	15	0.18	■
D	2.5	22800	0.23	60	0.017	●
E	2.5	24900	0.72	40	0.36	●

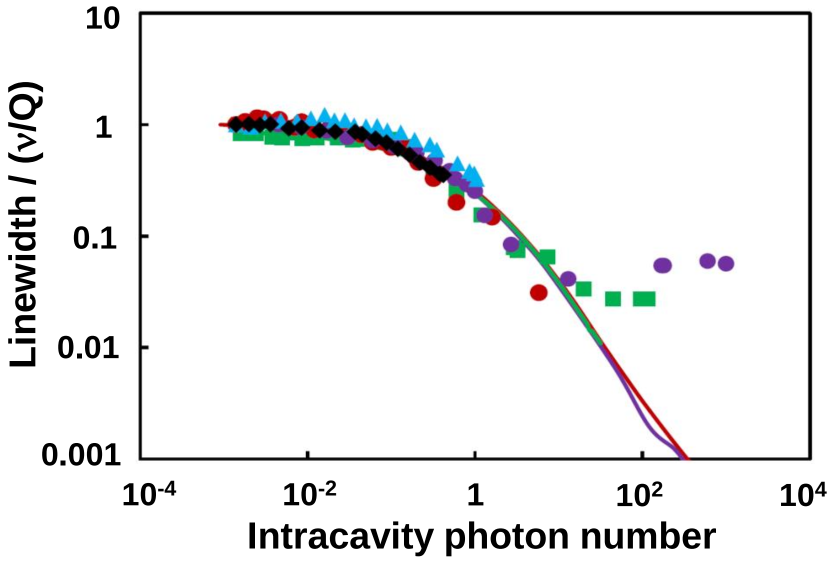
LEDs (A, B)

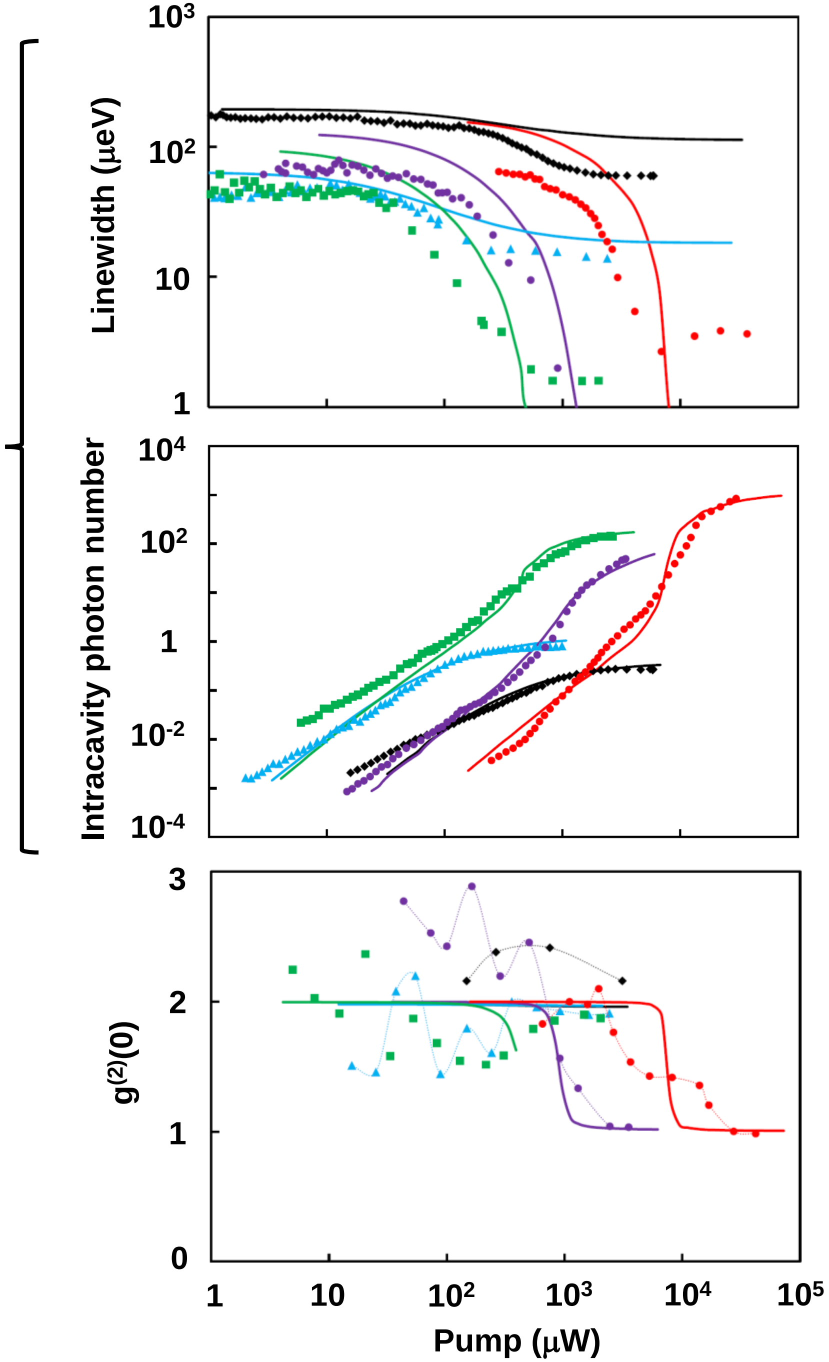
?

Lasers (D, E)



Consolidation of data





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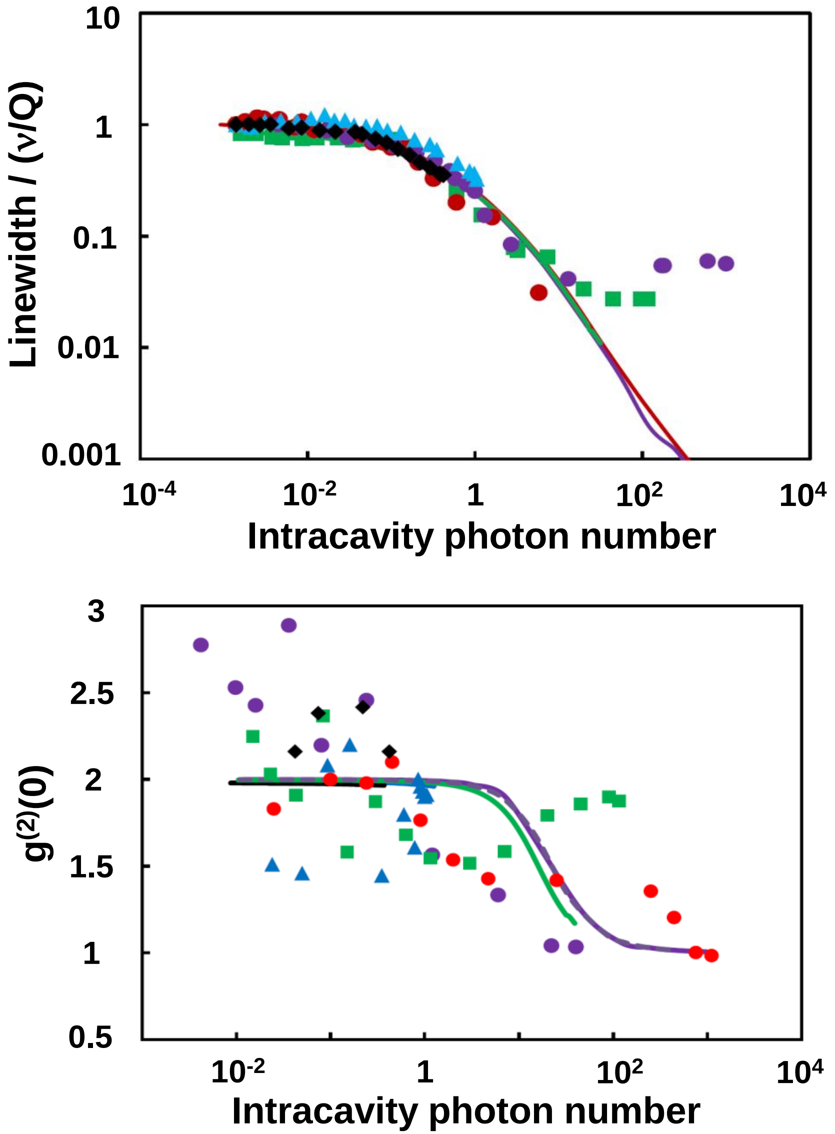
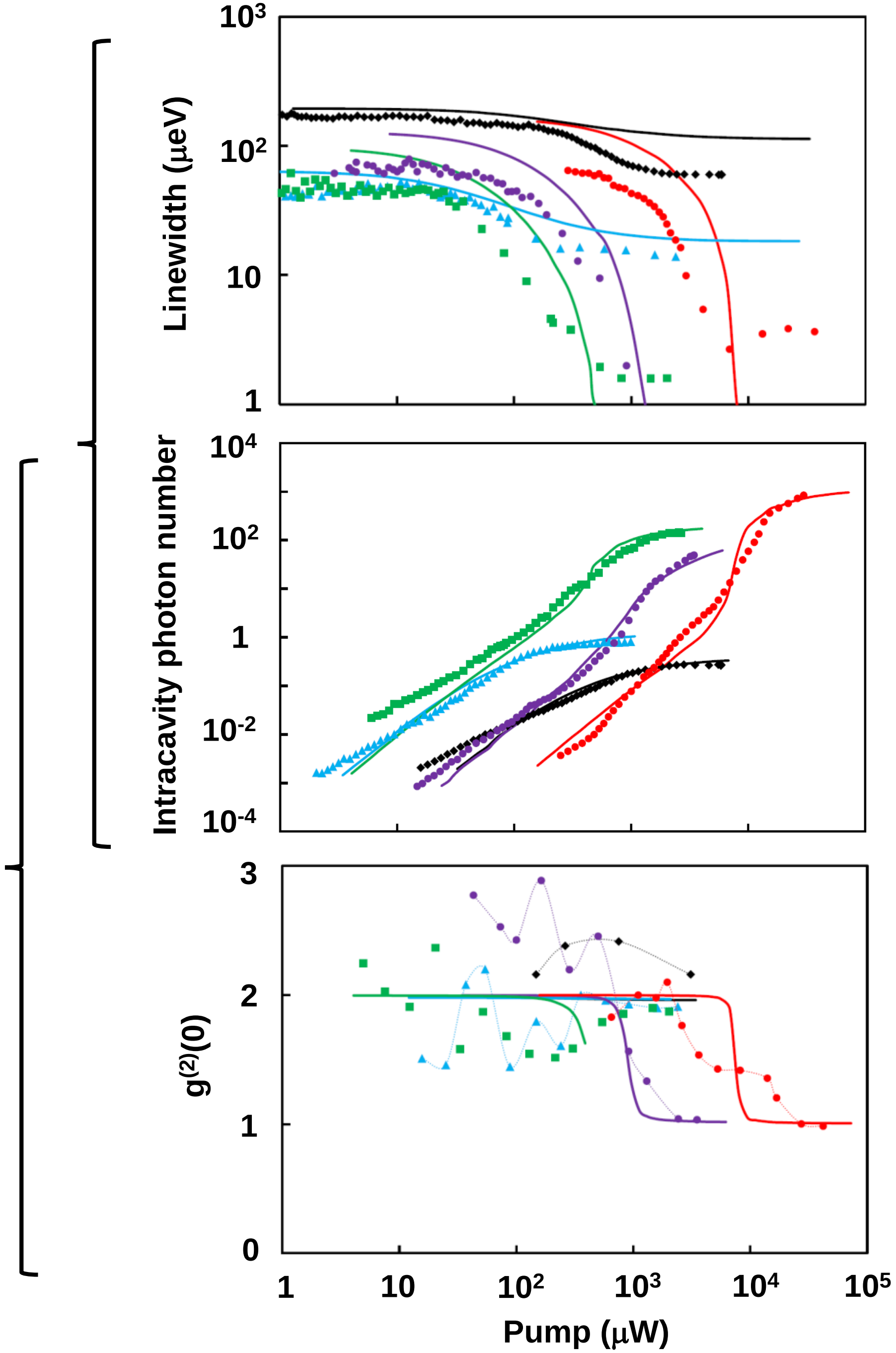
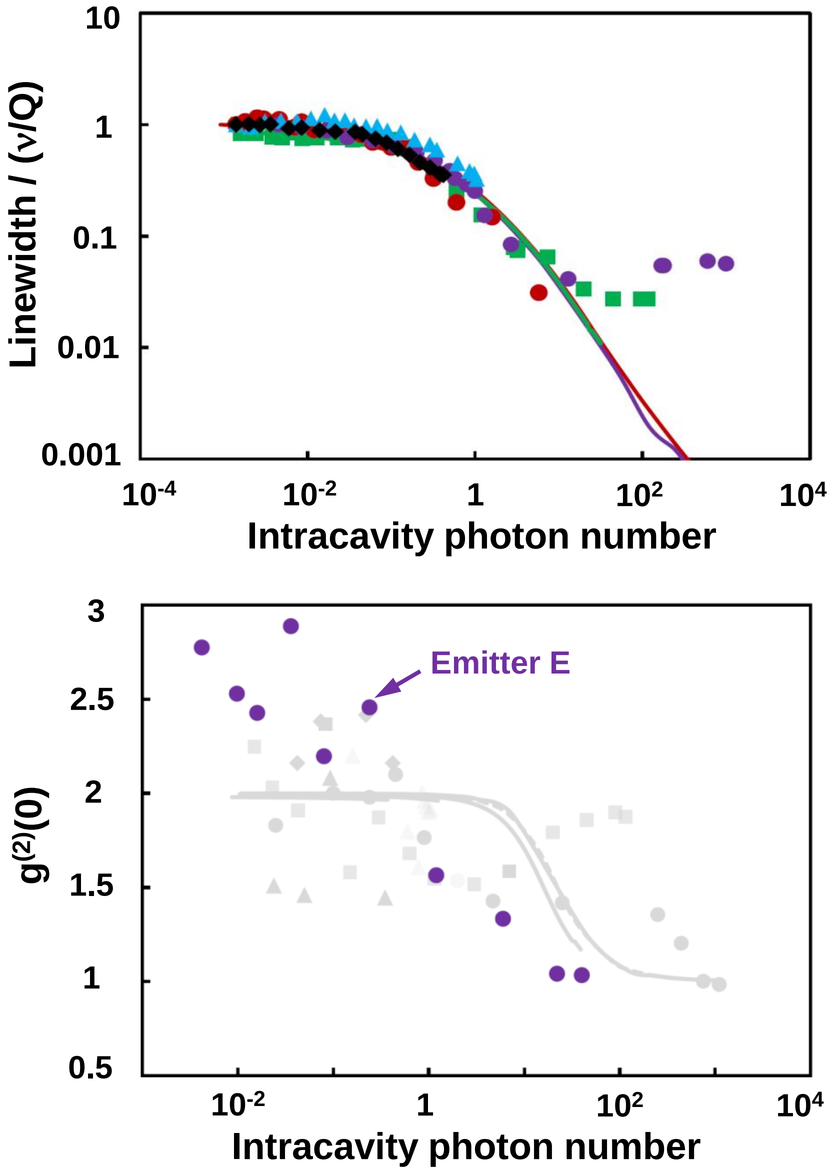


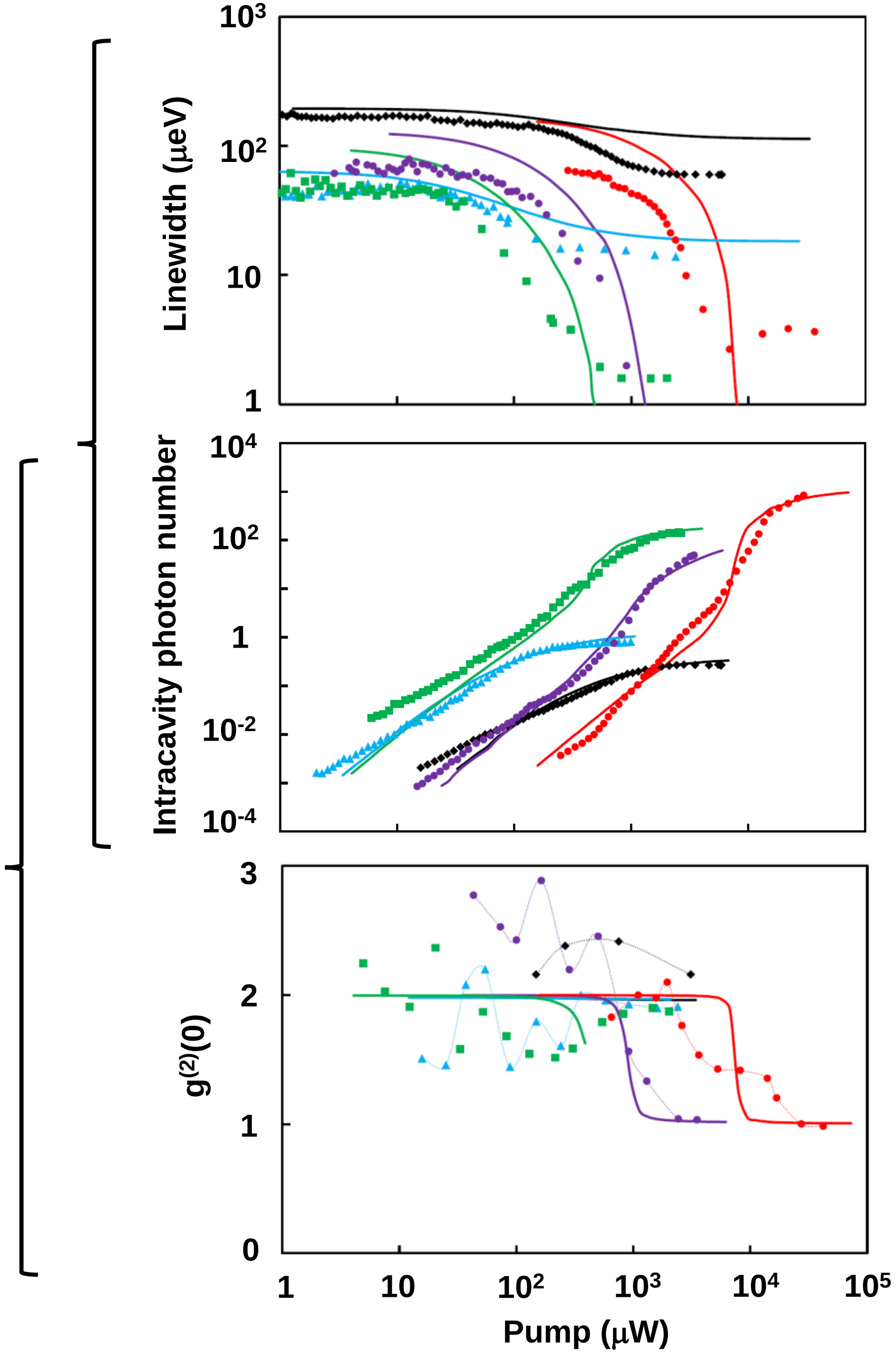


Lasing (or not lasing) depends solely on intracavity photon number

$8300 < Q < 32000$, $6 < N_{QD} < 60$ $0.03 < \eta < 0.36$, $0.23 < \beta < 0.72$

Consolidation of data





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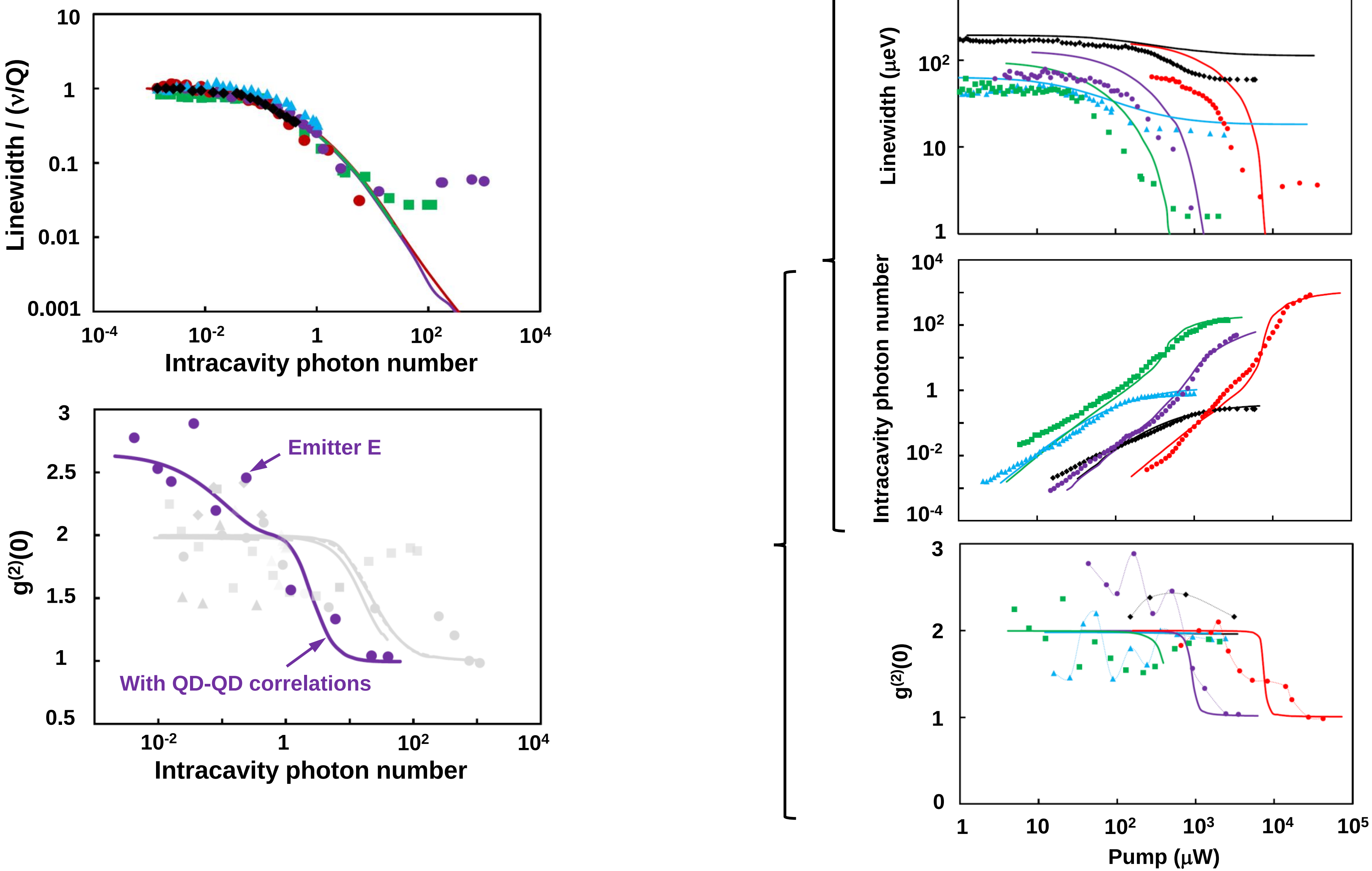


Equations of motion: population dynamics and correlations

$$\frac{\partial \hat{O}}{\partial t} = -\frac{i}{\hbar}\left[\hat{O}, H\right]$$

Carrier populations $\langle c_\alpha^\dagger c_\alpha \rangle$ $\left\langle b_\beta^\dagger b_\beta \right\rangle$

Polarization $\left\langle c_\alpha^\dagger b_\beta^\dagger a \right\rangle$

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

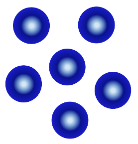
Coherence time $\langle a^\dagger a(\tau) \rangle$

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

<u>**Approximation**</u>

Cluster expansion: $\langle \hat{O} \rangle =$

Single particles



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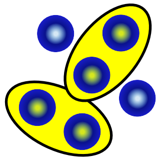
Correlated pairs



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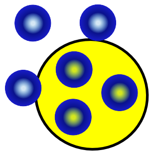
Correlated 3-particle clusters



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Inter-QD correlations leading to subradiance, superradiance and giant bunching

Single-particle: $p_\alpha = \langle b_\alpha^\dagger c_\alpha^\dagger a \rangle$ $\quad n_e^\alpha = \langle c_\alpha^\dagger c_\alpha \rangle$ $\quad n_h^\alpha = \langle b_\alpha^\dagger b_\alpha \rangle$ $\quad n_p = \langle a^\dagger a \rangle$

Inter QD correlation: $\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho \rangle = \langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho \rangle - \delta_{\alpha,\varrho} n_e^\alpha n_h^\alpha$

$$\frac{d}{dt}\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta b_\beta \rangle = [-2\gamma + i(\omega_\alpha - \omega_\beta)]\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta b_\beta \rangle + g_\beta p_\alpha \left(n_e^\beta + n_e^\beta - 1\right) + g_\alpha^* p_\beta^* (n_e^\alpha + n_e^\alpha - 1)$$

$$+ g_\beta \left[\delta \left\langle b_\beta^\dagger b_\alpha^\dagger c_\alpha^\dagger b_\beta a \right\rangle + \delta \left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a \right\rangle\right] + g_\alpha^* [\delta\langle c_\alpha^\dagger c_\alpha c_\beta b_\beta a^\dagger \rangle + \delta\langle b_\alpha^\dagger c_\beta b_\beta b_\alpha a^\dagger \rangle]$$

Electron-hole polarization:

$$\frac{dp_\alpha}{dt} = [-(\gamma + \gamma_c) + i(\omega_\alpha - \nu)]p_\alpha + g_\alpha^*[n_e^\alpha n_h^\alpha + n_p(n_e^\alpha + n_h^\alpha - 1)] + g_\alpha^*[\delta\langle c_\alpha^\dagger c_\alpha a^\dagger a \rangle + \delta\langle b_\alpha^\dagger b_\alpha a^\dagger a \rangle] + \underline{\sum_\varrho g_\varrho^* \, \delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho \rangle}$$

Inter-QD correlations leading to subradiance, superradiance and giant bunching

Single-particle: $p_\alpha = \langle b_\alpha^\dagger c_\alpha^\dagger a \rangle \qquad n_e^\alpha = \langle c_\alpha^\dagger c_\alpha \rangle \qquad n_h^\alpha = \langle b_\alpha^\dagger b_\alpha \rangle \qquad n_p = \langle a^\dagger a \rangle$

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Necessary for strong coupling with Fermions

Inter-QD correlation

$$\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho\rangle = \langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho\rangle - \delta_{\alpha,\varrho} n_e^\alpha n_h^\alpha$$

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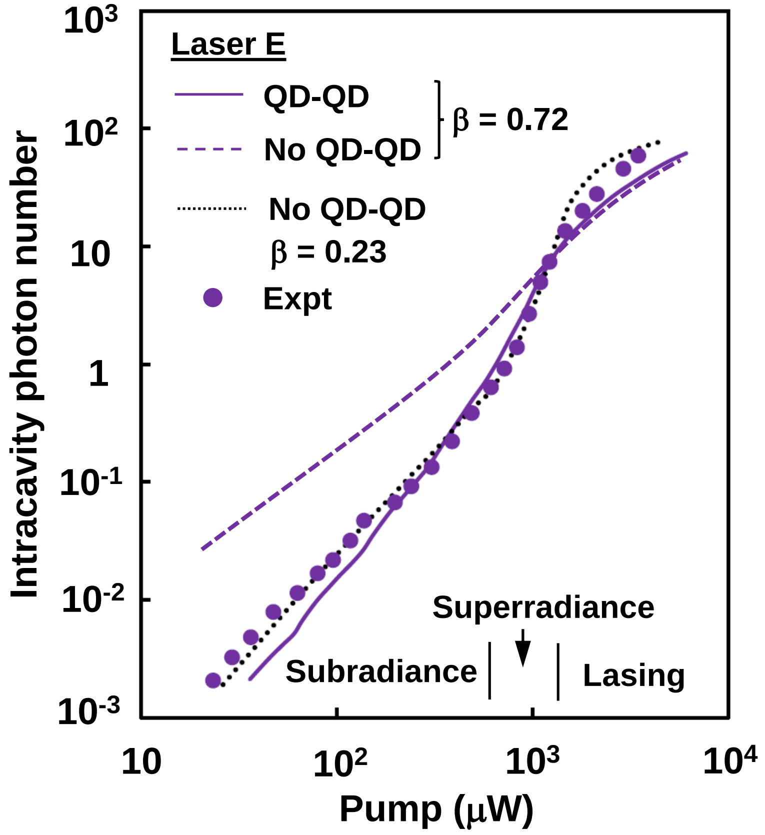


Connecting inter-QD correlation to $g^{(2)}(0)$

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

$$\frac{d}{dt}\delta\langle a^\dagger a^\dagger a a\rangle = -4\gamma_c\delta\langle a^\dagger a^\dagger a a\rangle + 4\sum_{\varrho} Re[g_\varrho \underbrace{\delta\langle b_\varrho^\dagger c_\varrho^\dagger a^\dagger a a\rangle}_{\text{2pl}}]$$

2pl

$$\frac{d}{dt}\delta\langle b_\alpha^\dagger c_\alpha^\dagger a^\dagger a a\rangle = [-(\gamma+3\gamma_c)+i(\omega_\alpha-\nu)]\delta\langle b_\alpha^\dagger c_\alpha^\dagger a^\dagger a a\rangle + 2g_\alpha^*[(n_p+n_h^\alpha)\delta\langle c_\alpha^\dagger c_\alpha a^\dagger a\rangle + (n_p+n_e^\alpha)\delta\langle b_\alpha^\dagger b_\alpha a^\dagger a\rangle - p_\alpha^2]$$
$$+g_\alpha^*(n_e^\alpha+n_e^\alpha-1)\delta\langle a^\dagger a^\dagger a a\rangle + \sum_\varrho [g_\varrho \underbrace{\delta\langle b_\alpha^\dagger b_\varrho^\dagger c_\varrho^\dagger c_\alpha^\dagger a a\rangle}_{\text{2pp}} + 2g_\varrho^* \underbrace{\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho a^\dagger a\rangle}_{\text{2pp}^*}]$$

2pp

$$\frac{d}{dt}\delta\left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger c_\alpha a a\right\rangle = [-2(\gamma+\gamma_c)+i(\omega_\alpha+\omega_\beta-2\nu)]\delta\left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger c_\alpha a a\right\rangle$$
$$+2g_\alpha^*\left[(n_p+n_e^\alpha)\delta\left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger b_\alpha a\right\rangle + (n_p+n_h^\alpha)\delta\left\langle b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a\right\rangle\right] + g_\alpha^*(n_e^\alpha+n_e^\alpha-1)\delta\left\langle b_\beta^\dagger c_\beta^\dagger a^\dagger a a\right\rangle$$
$$+2g_\beta^*\left[\left(n_p+n_e^\beta\right)\delta \underbrace{\left\langle b_\beta^\dagger b_\alpha^\dagger c_\alpha^\dagger b_\beta a\right\rangle}_{\text{2ep}} + \left(n_p+n_h^\beta\right)\delta \underbrace{\left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a\right\rangle}_{\text{2ep}}\right] + g_\beta^*\left(n_e^\beta+n_e^\beta-1\right)\delta\left\langle b_\alpha^\dagger c_\alpha^\dagger a^\dagger a a\right\rangle$$

2ep

$$\frac{d}{dt}\delta\left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a\right\rangle = [-(\gamma+\gamma_c+\gamma_e)+i(\omega_\alpha-\nu)]\delta\left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a\right\rangle - g_\beta^*[n_p\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta b_\beta\rangle + \delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta b_\beta a^\dagger a\rangle] - g_\beta\delta\left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger a a\right\rangle$$
$$+g_\alpha^*\left[(n_e^\alpha+n_e^\alpha-1)\delta\left\langle c_\beta^\dagger c_\beta a^\dagger a\right\rangle + (n_p+n_e^\alpha)\delta \underbrace{\left\langle b_\alpha^\dagger c_\beta^\dagger c_\beta b_\alpha\right\rangle}_{\text{2eh}} + (n_p+n_h^\alpha)\delta \underbrace{\left\langle c_\alpha^\dagger c_\beta^\dagger c_\beta c_\alpha\right\rangle}_{\text{2p'p'}}\right]$$

QD-QD coupling

2eh

$$\frac{d}{dt}\delta\left\langle b_\alpha^\dagger c_\beta^\dagger c_\beta b_\alpha\right\rangle = -(\gamma_e+\gamma_h+\gamma_{cc}^{ph})\delta\left\langle b_\alpha^\dagger c_\beta^\dagger c_\beta b_\alpha\right\rangle - Re\left[g_\alpha\delta\left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a\right\rangle + g_\beta\delta\left\langle b_\alpha^\dagger b_\beta^\dagger c_\beta^\dagger b_\alpha a\right\rangle\right]$$

2p'p'

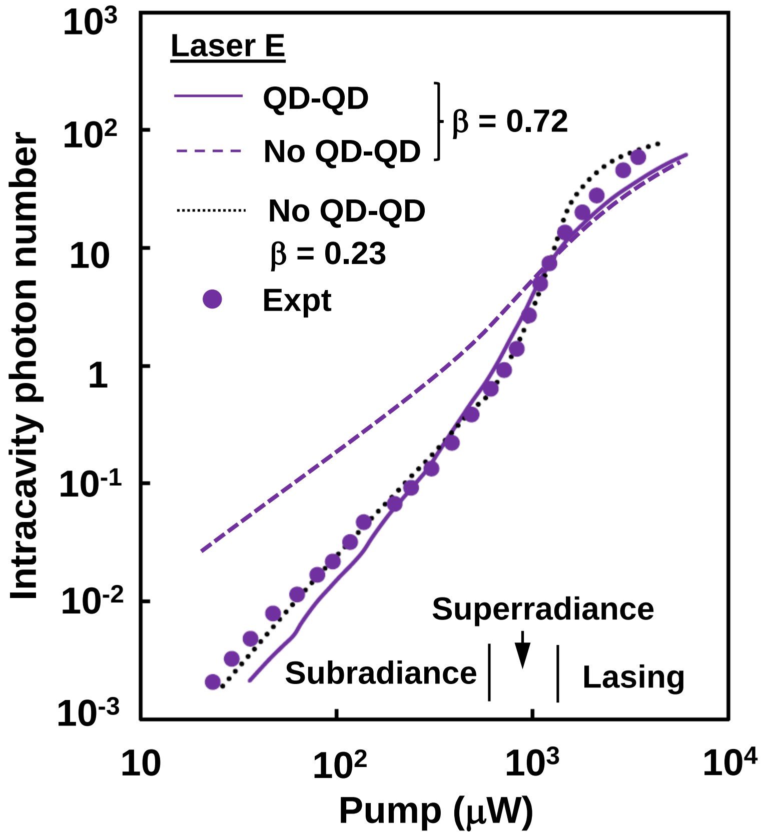
$$\frac{d}{dt}\delta\left\langle c_\alpha^\dagger c_\beta^\dagger c_\beta c_\alpha\right\rangle = -(2\gamma_e+\gamma_{cc}^{ph})\delta\left\langle c_\alpha^\dagger c_\beta^\dagger c_\beta c_\alpha\right\rangle - 2Re\left[g_\alpha\delta\left\langle b_\alpha^\dagger c_\alpha^\dagger c_\beta^\dagger c_\beta a\right\rangle + g_\beta\delta\left\langle b_\beta^\dagger c_\beta^\dagger c_\alpha^\dagger c_\alpha a\right\rangle\right]$$

Inter-QD correlation

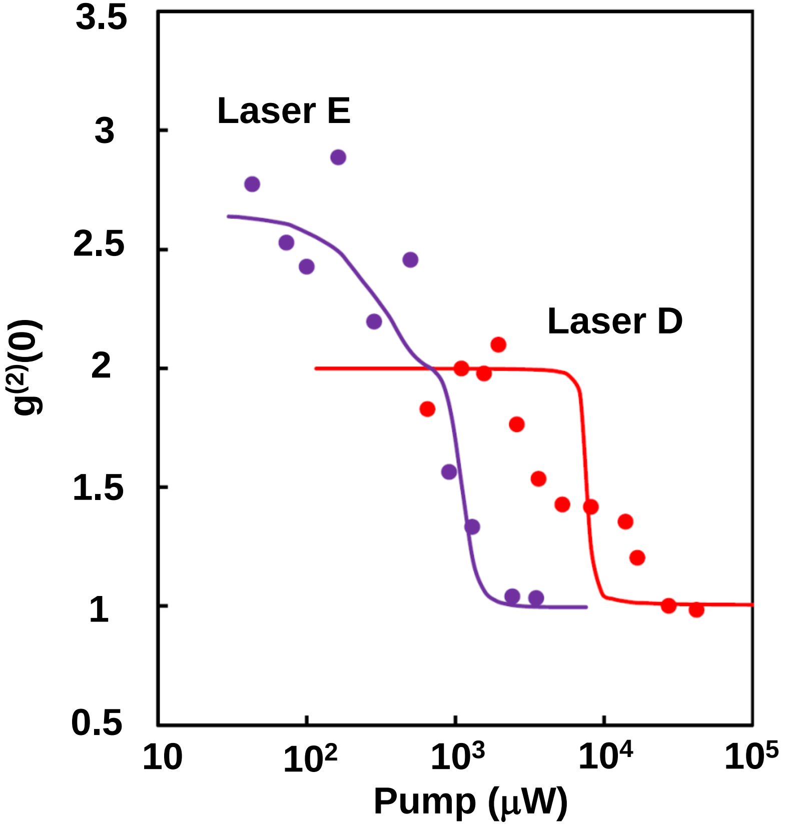
$$\delta\langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho\rangle = \langle b_\alpha^\dagger c_\alpha^\dagger c_\varrho b_\varrho\rangle - \delta_{\alpha,\varrho} n_e^\alpha n_h^\alpha$$

	∅ (μm)	Q	β	N_{QD}	η	
A	1.7	8300	0.40	10	0.36	◆
B	2.0	32100	0.37	6	0.36	▲
C	2.0	32100	0.37	15	0.18	■
D	2.5	22800	0.23	60	0.017	●
E	2.5	24900	0.72	40	0.36	●

Subradiance & superradiance



Super-thermal bunching



Inter-QD correlation

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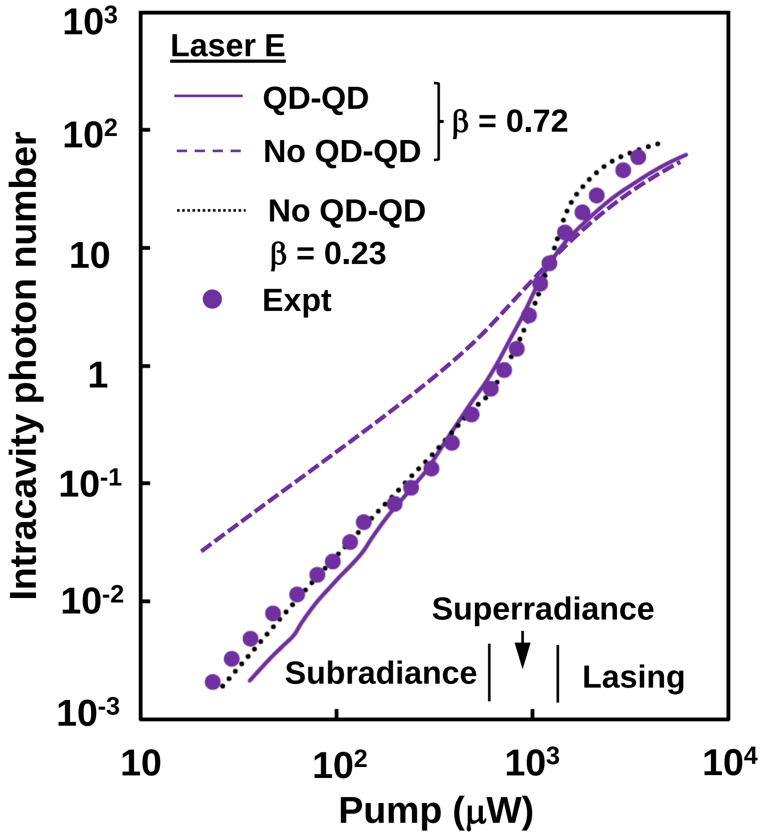
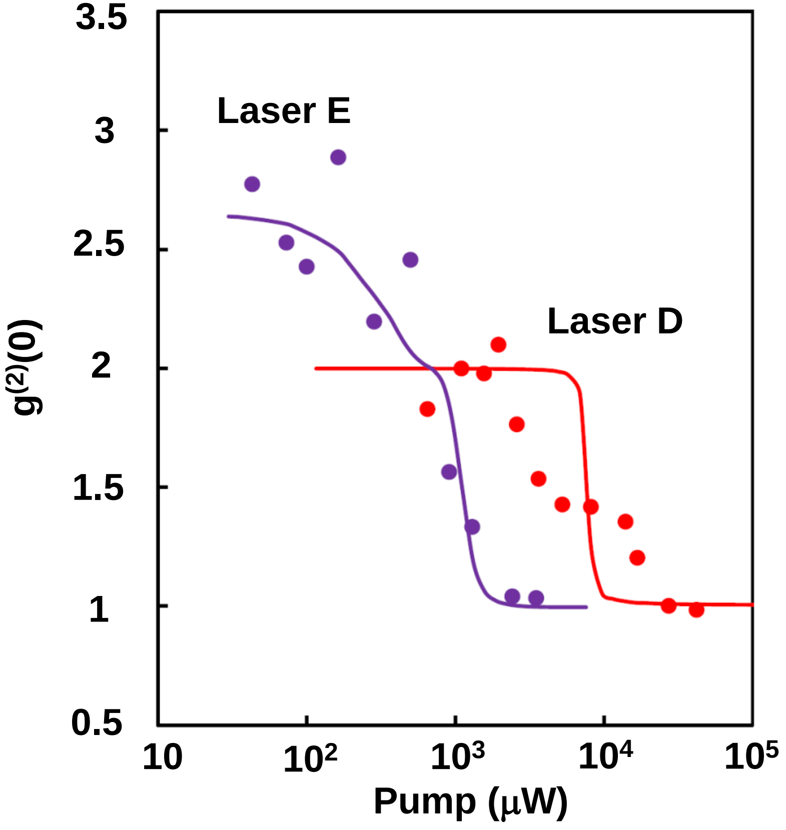
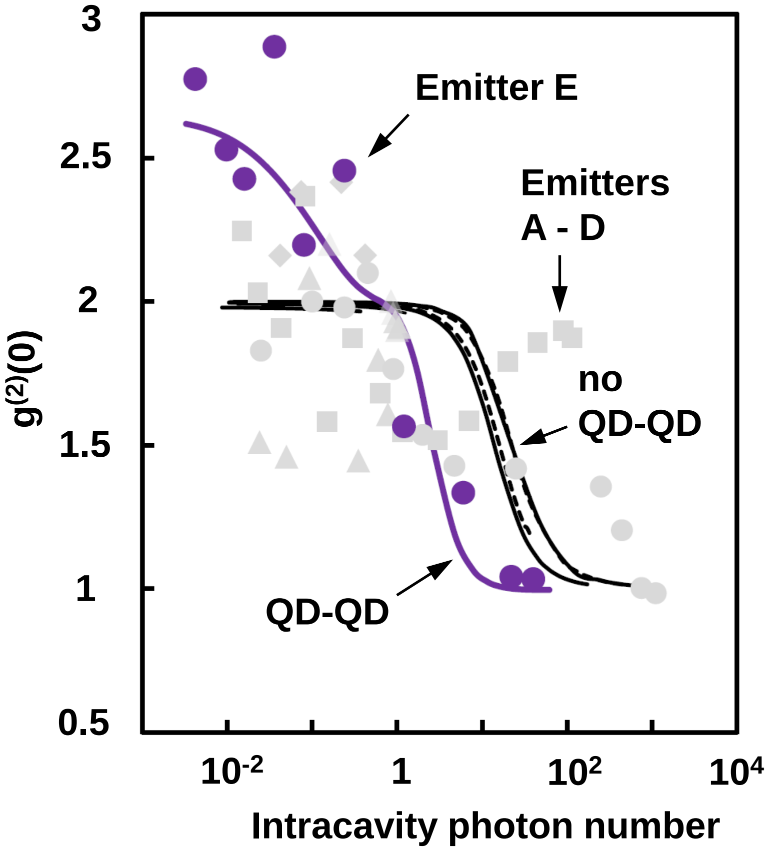


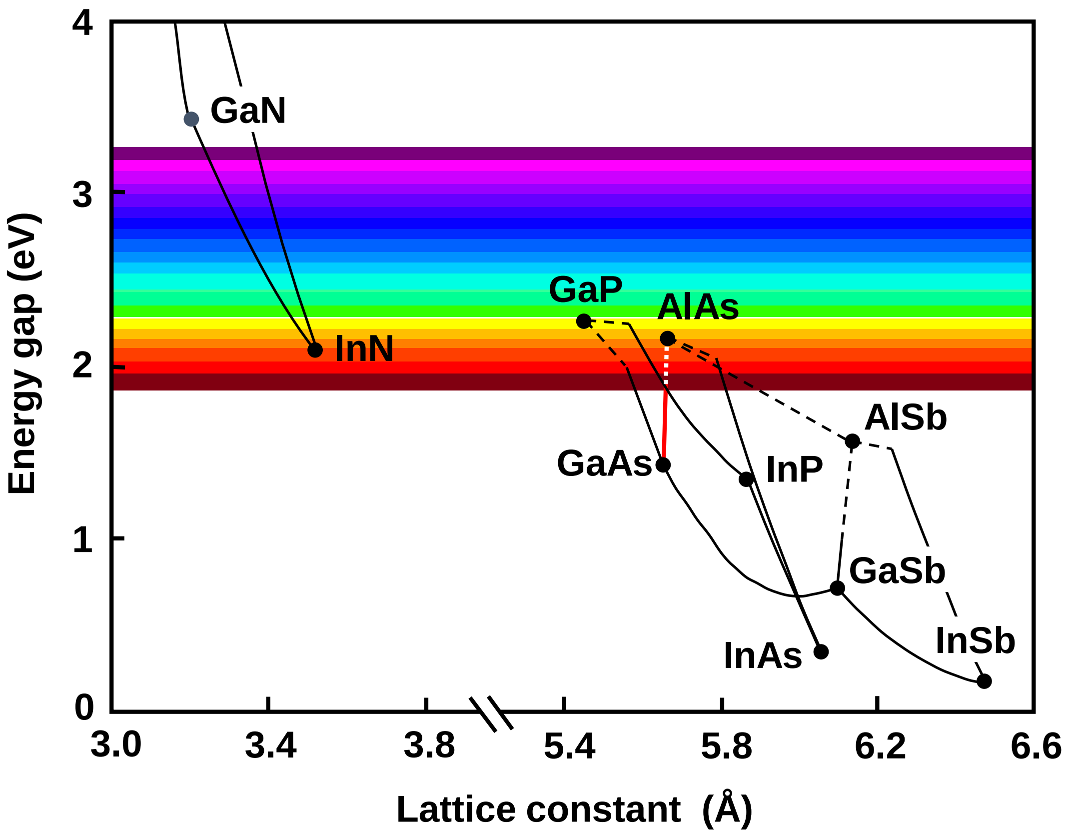
Super-thermal bunching



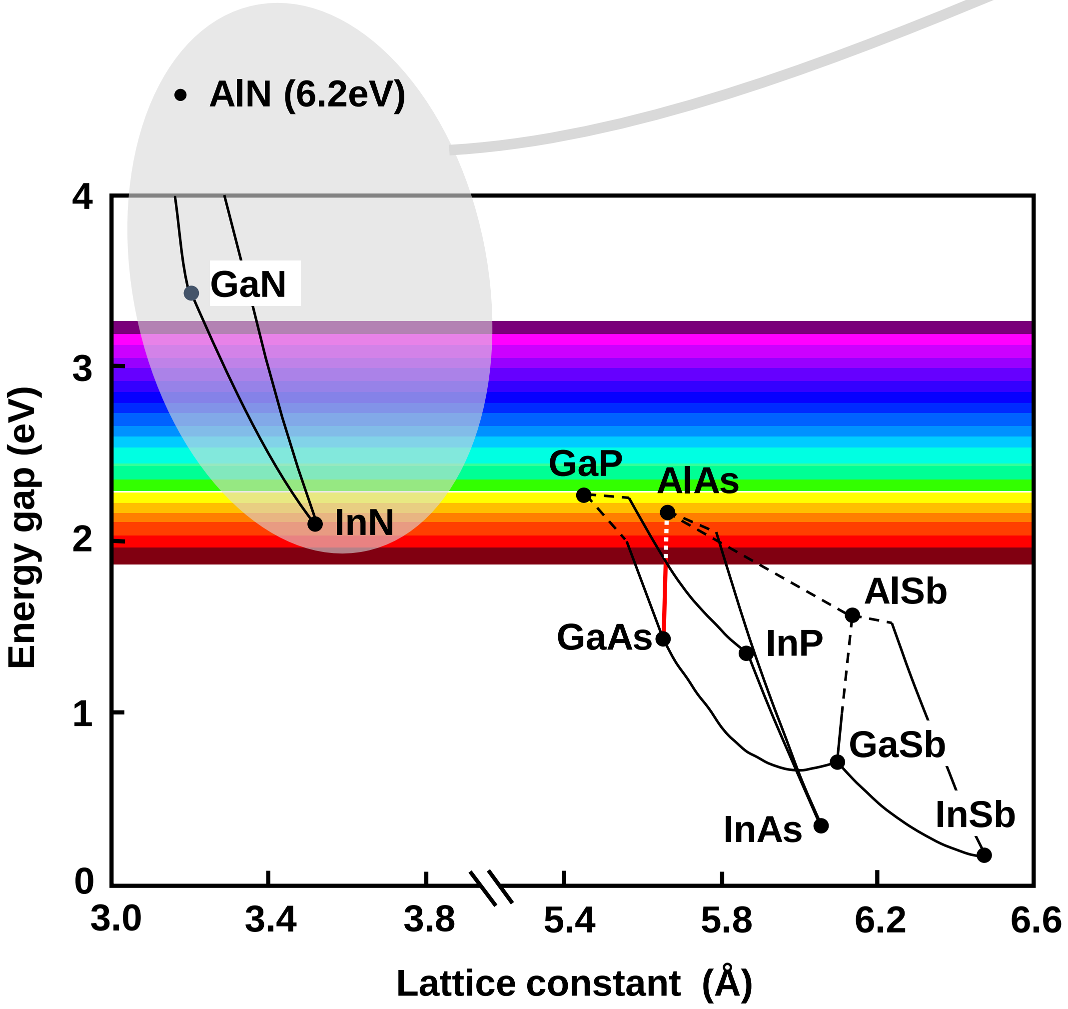


Laser and LED material systems

- AlN (6.2eV)



Laser and LED material systems

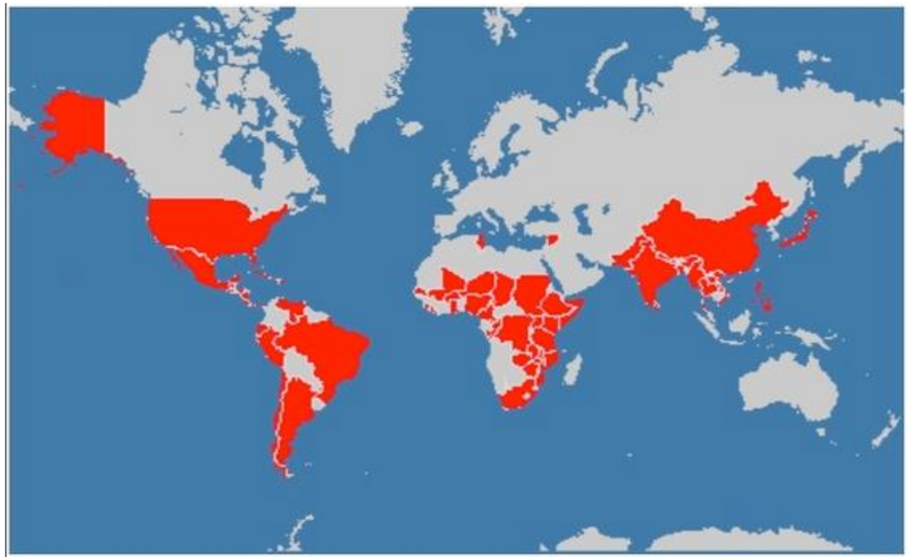


Semiconductor lighting

Problem
1.5 billion people rely on (cancer causing) kerosene for light

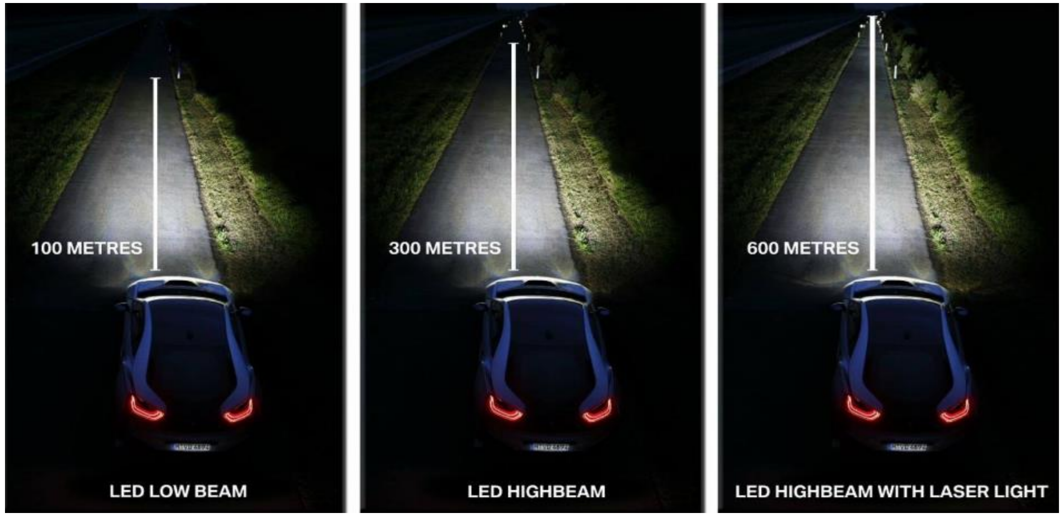
Solution: Solar-powered LEDs

80,000 lights distributed to over 64 countries



Nanolasers for lighting

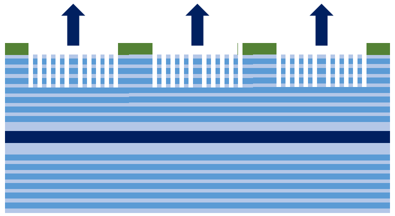
Laser headlights



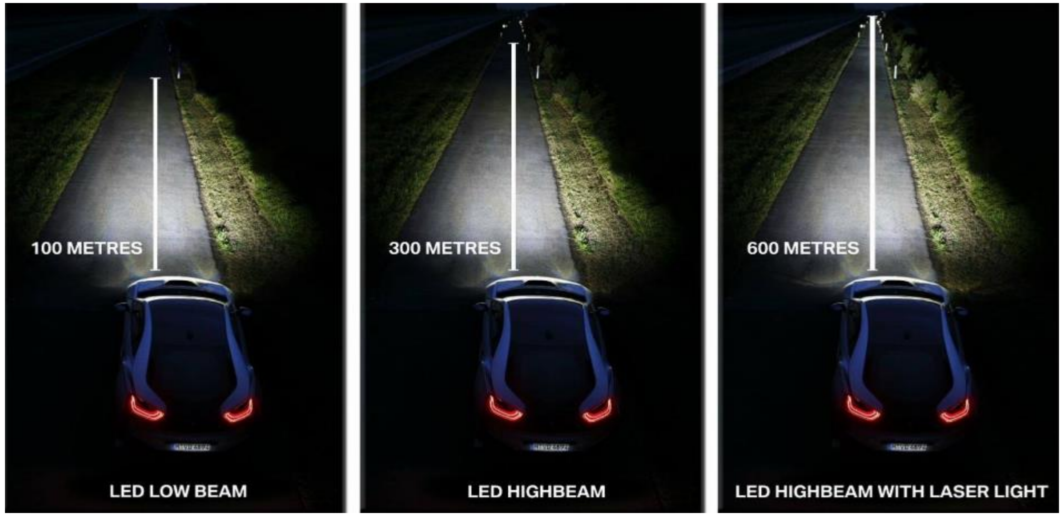
BMW i8 & 7 series, Audi R8 LMX

Car Tech: ‘How BMW’s new laser headlights will work and not kill you.’

Nanolasers for lighting



Laser headlights



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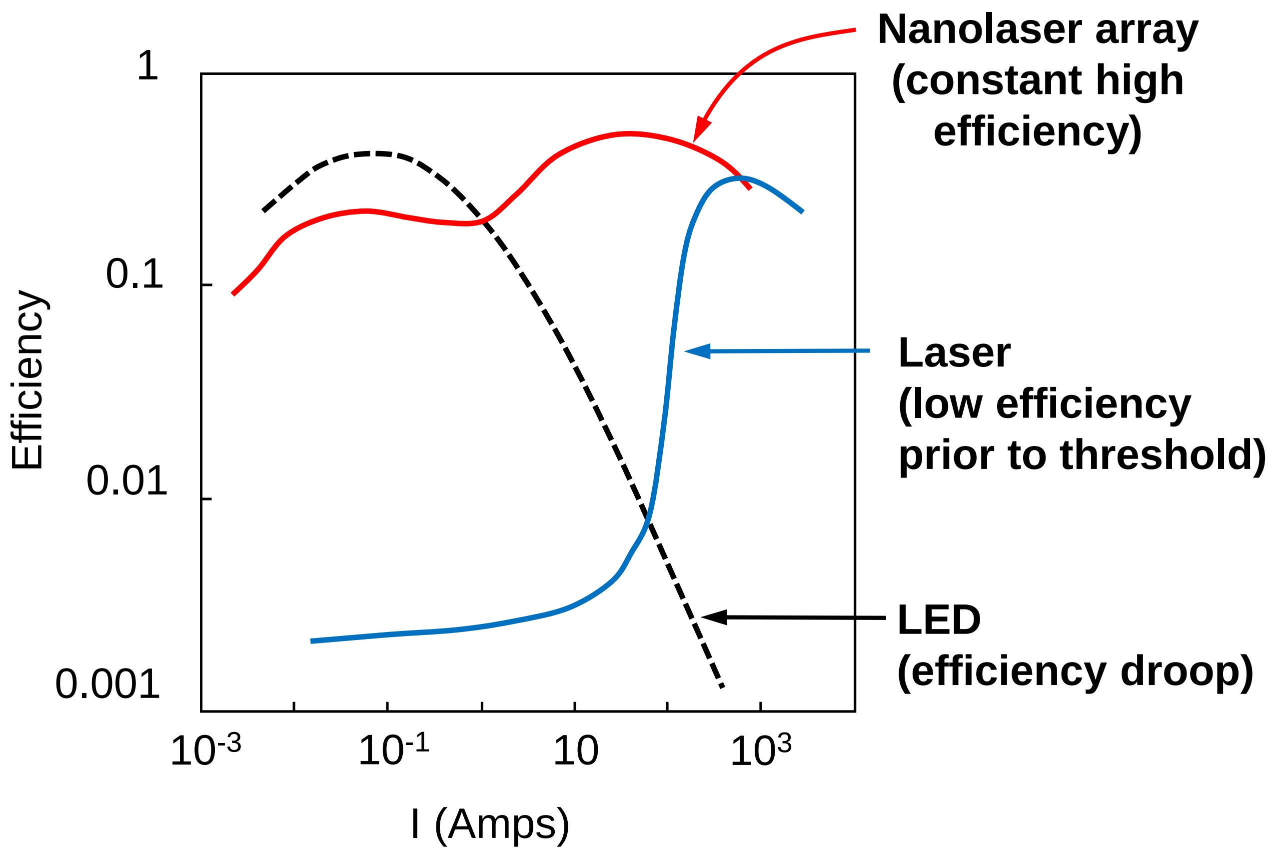
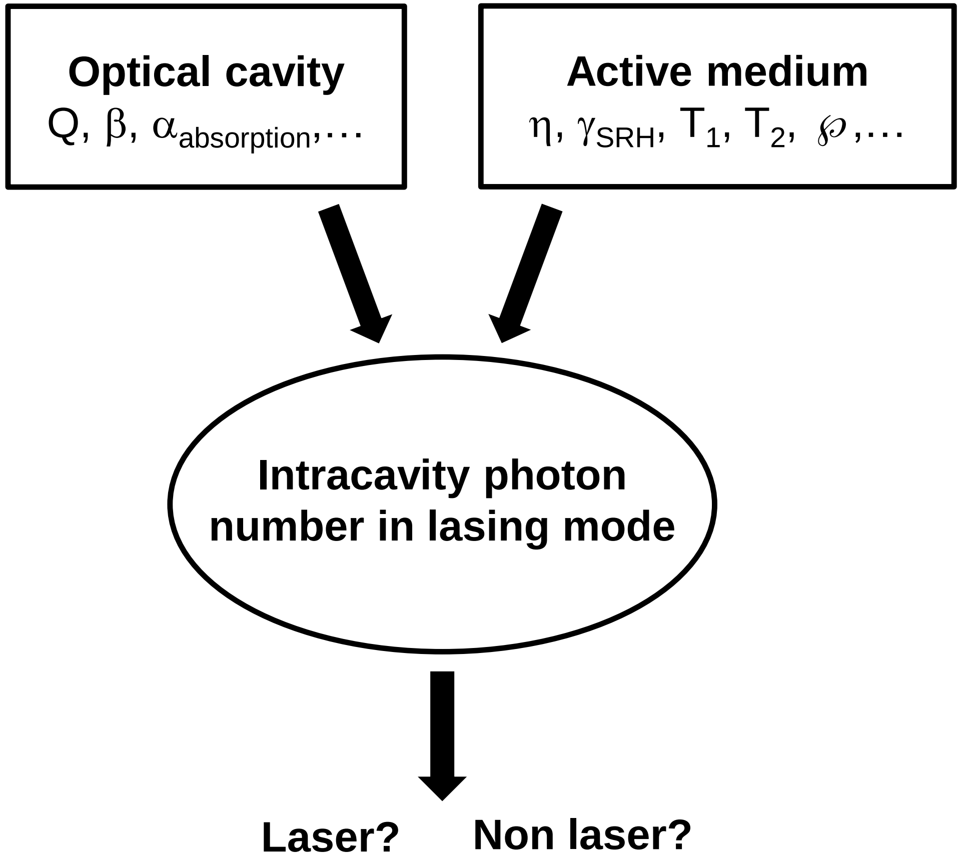


Appl. Phys. Lett. **107**, 141107 (2015)
Nanolasers for Solid-State Lighting patent application filed 3/21/2016
Reported in Research Review, Compound Semiconductor Magazine, Dec. 2015

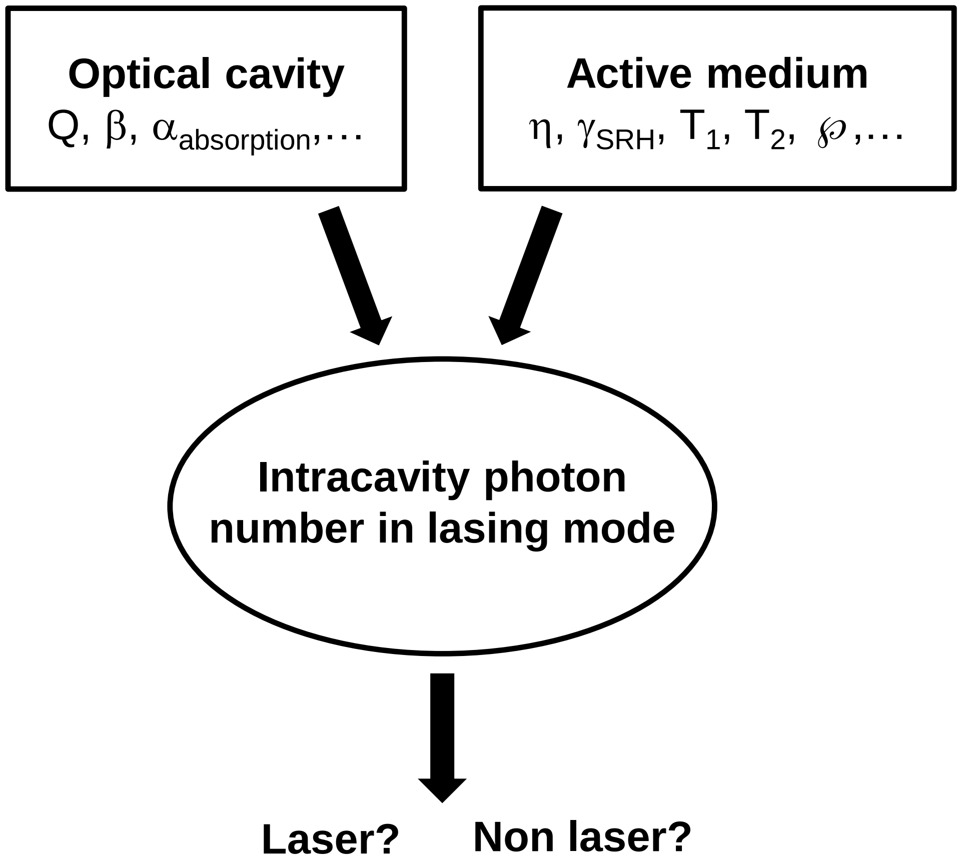
Summary

What determines lasing

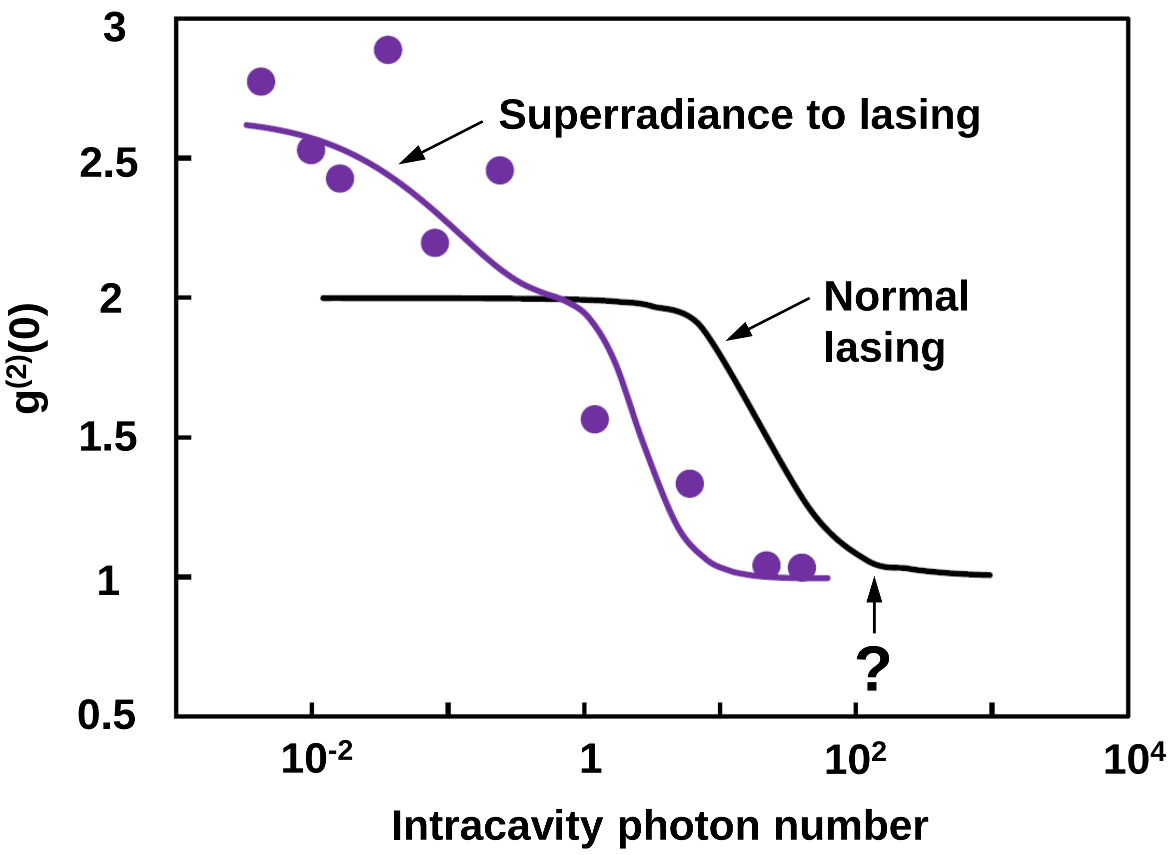


Summary

What determines lasing

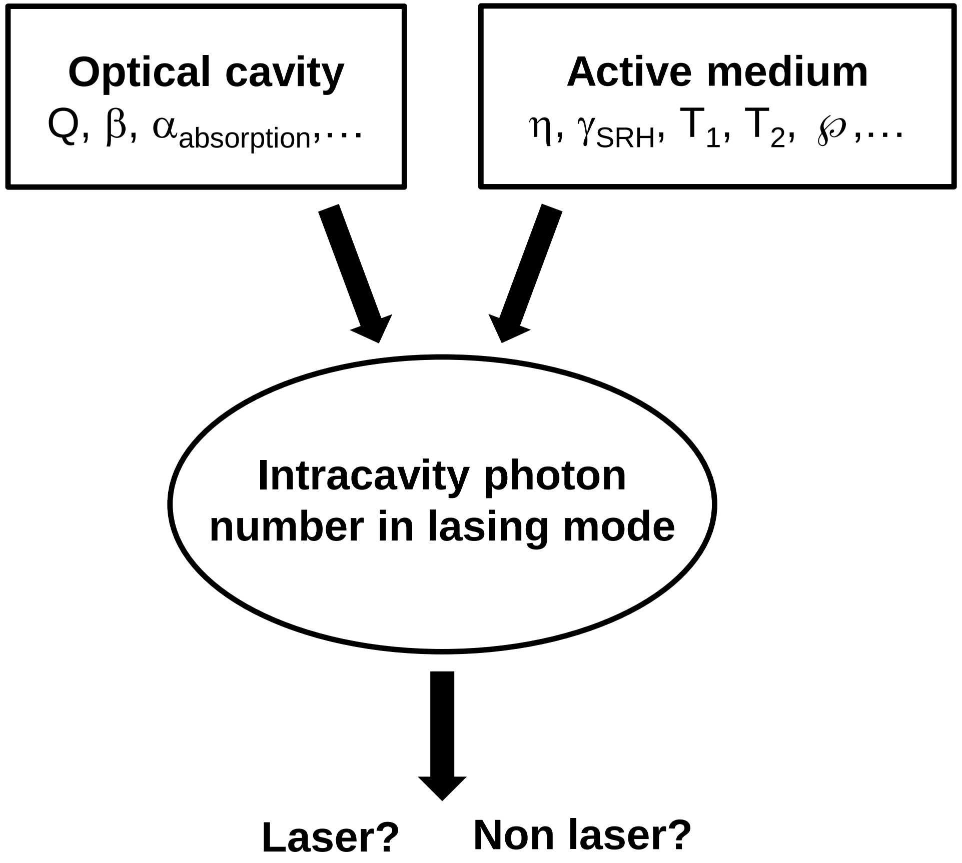


Why look at $g^{(2)}(0)$



Summary

What determines lasing



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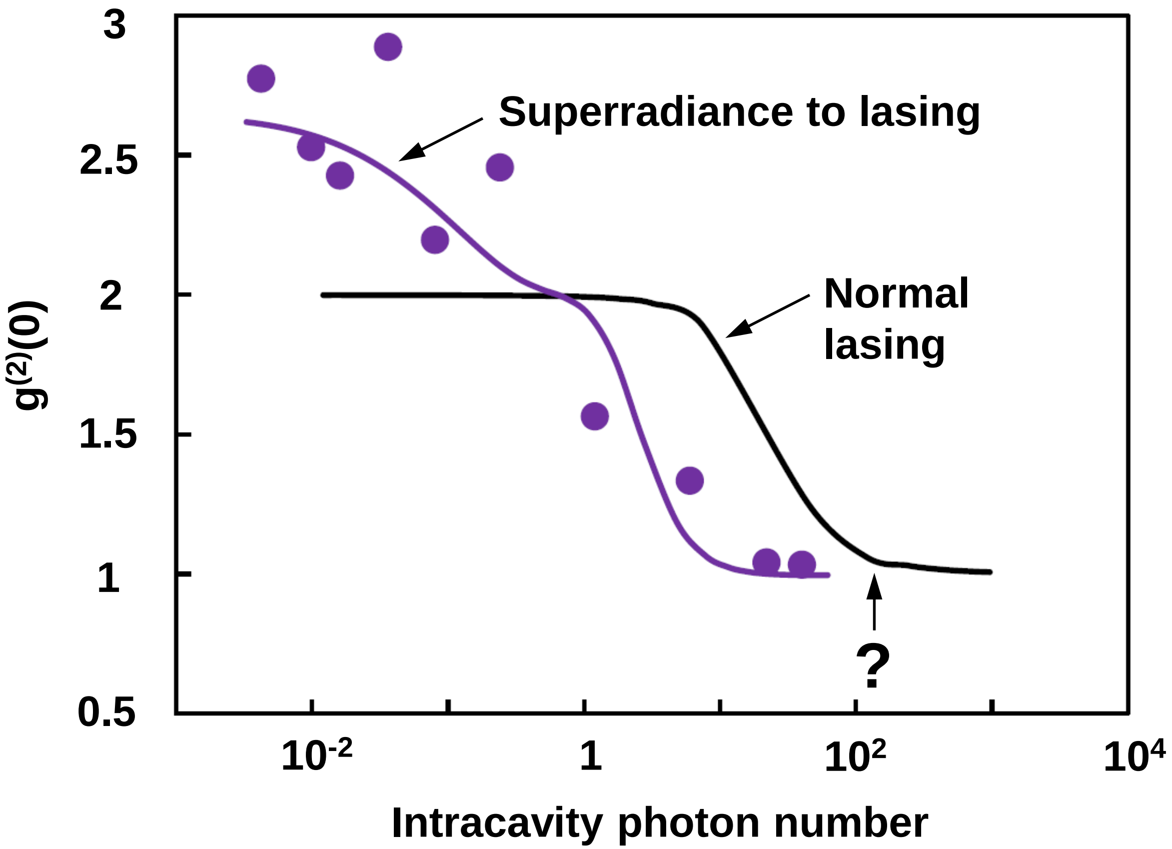

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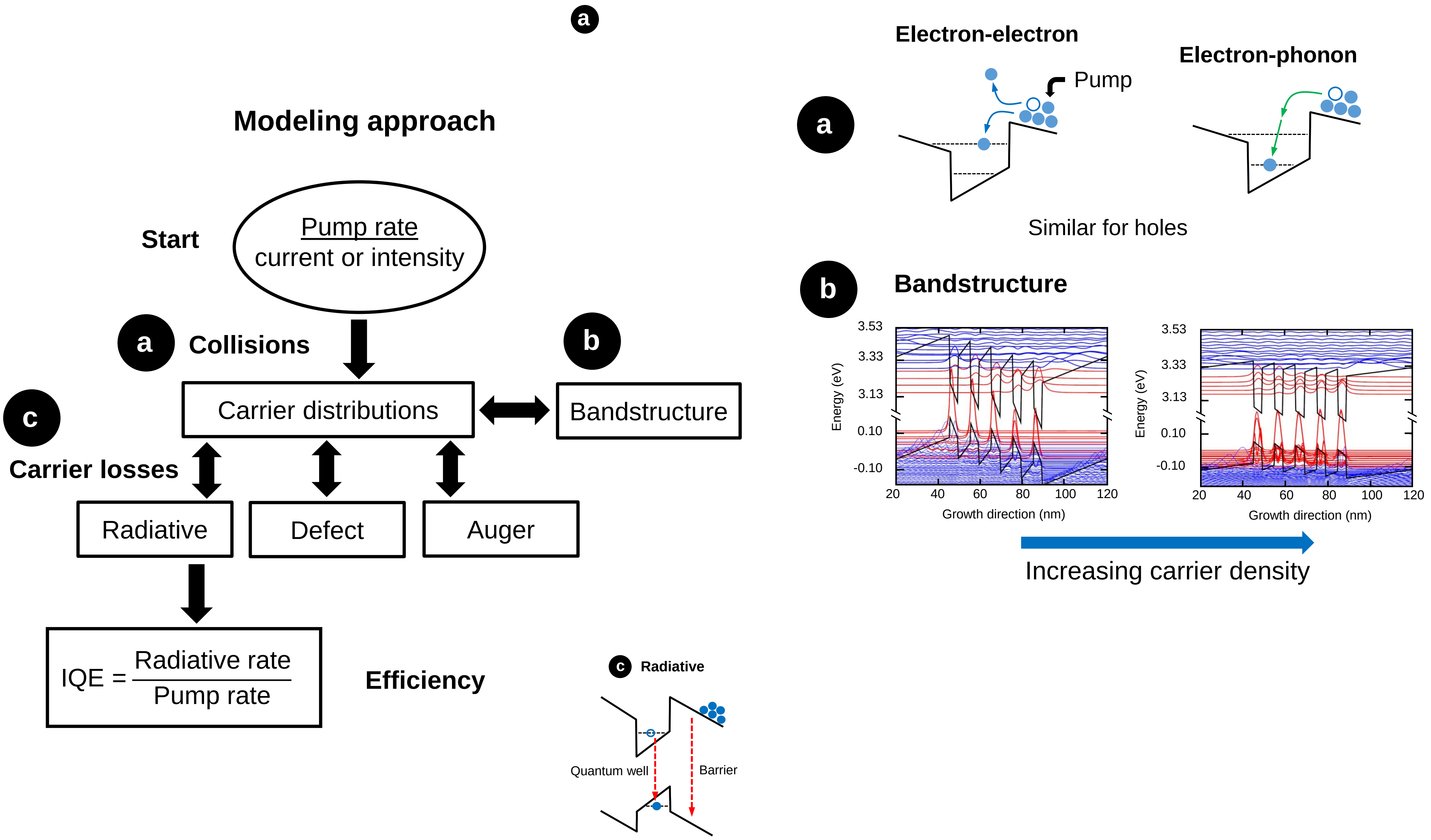
Sven Höfling	Janik Wolters	Frank Jahnke	
	Stephan Reitzenstein		

Details: "Emission from quantum-dot high-β microcavities: transition from spontaneous emission to lasing and the effects of superradiant emitter coupling,' Light: Science and Applications (2017) 6, e17030.



a
Modeling approach
Start
Pump rate
current or intensity
a
Collisions
b
Carrier distributions
Bandstructure
c
Carrier losses
Radiative
Defect
Auger
IQE = Radiative rate / Pump rate
Efficiency
c
Radiative
Quantum well
Barrier
a
Electron-electron
Pump
Electron-phonon
Similar for holes
b
Bandstructure
3.53
3.33
3.13
0.10
-0.10
Energy (eV)
20
40
60
80
100
120
Growth direction (nm)
Increasing carrier density