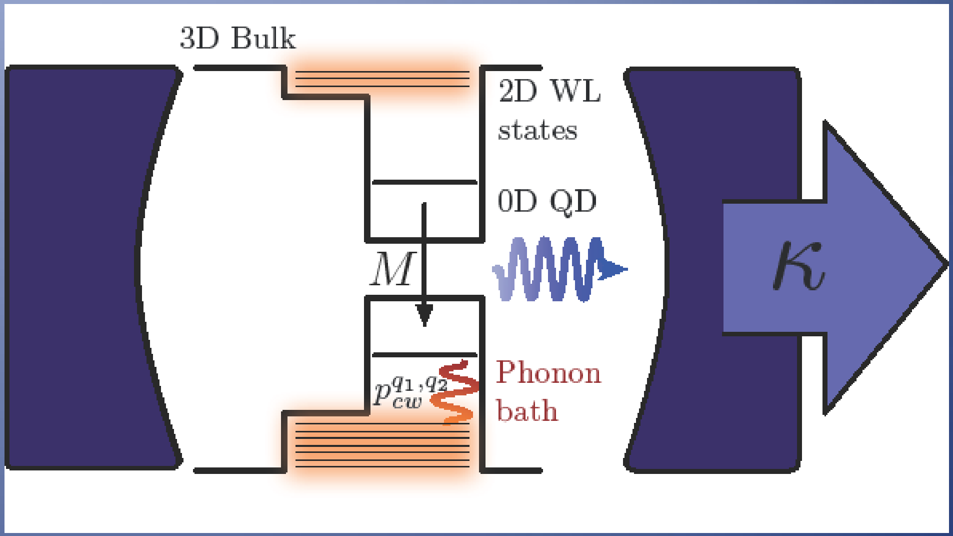
Quantum Light Emission From Cavity Enhanced LEDs

Alexander Carmele, Matthias-Rene Dachner, Julia Kabuss, Marten Richter, and Andreas Knorr

Outline: Three parts

Semiconductor Quantum Dot dynamics [1] :

- 3D bulk: Electron-phonon interaction:
  temperature dependent dephasing processes
- 2D WL: Electron-electron interaction
  carrier density dependent pumping rate
- 0D QD: Electron-photon interaction
  strong coupling for single-photon emission



1. Characterization of the system, e.g. via luminescence experiments
2. LO-phonon assisted carrier scattering from WL into QD states
3. Quantum emission dynamics of QD carriers strongly coupled to a cavity mode

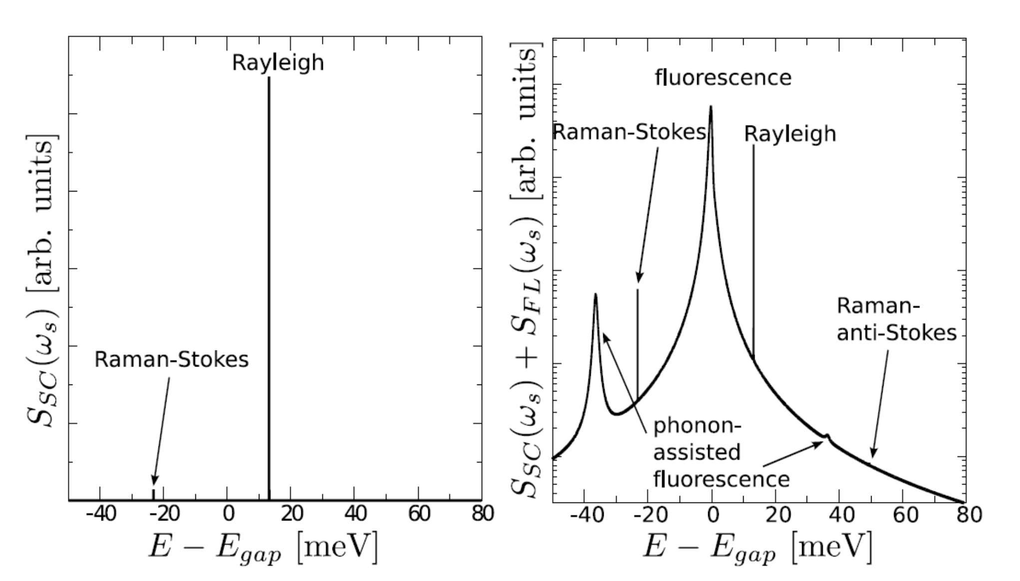
[1]PSSB **247**, 809 (2010)

Characterization of the QD system:

Contribution to Raman spectra:
- Fluorescence
- Rayleigh
- Stokes and Anti-Stokes
- LO - Fluorescence

→

Information:
- LO-Phonon frequency
- Bandgap frequency

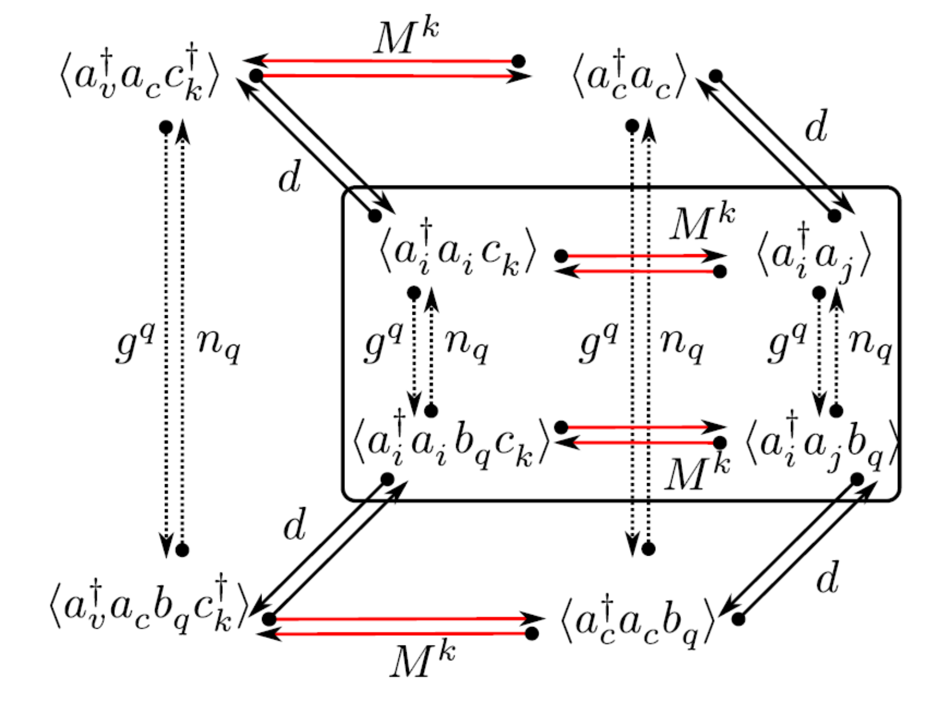


More information with time-resolved spectra:
1. Relaxation time-scales (T1)
2. Differentiation between fluorescence and raman signal on resonant excitation

Quantum kinetics in equation of motion approach

Dynamics of photon coherences with full quantum kinetics in an equation of motion approach[1]:

$$\partial_t \langle c^\dagger_{k_1} c_{k_2}\rangle = i(\omega_{k_1} - \omega_{k_2})\langle c^\dagger_{k_1} c_{k_2}\rangle + \frac{i}{\hbar} M^{k_1}_{cv} \langle a^\dagger_c a_v c_{k_2}\rangle - \frac{i}{\hbar} M^{k_2 *}_{cv} \langle a^\dagger_v a_c c^\dagger_{k_1}\rangle$$



Fluorescence signal:
2nd & 4th order perturbation

Raman signal:
6th order perturbation

Time-resolution depends on the detector

[1]PRB **81**, 075314 (2010)

Time-resolved signal

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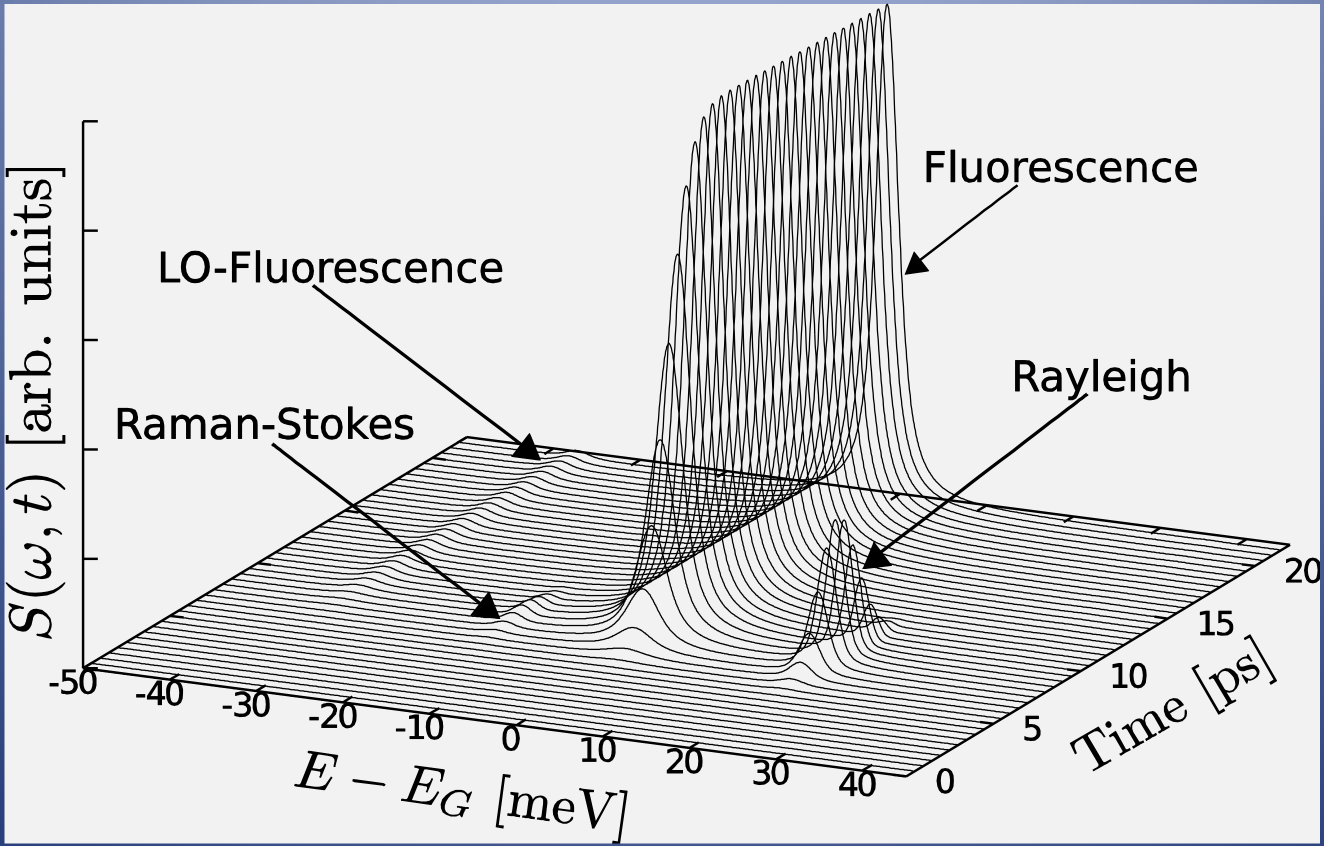
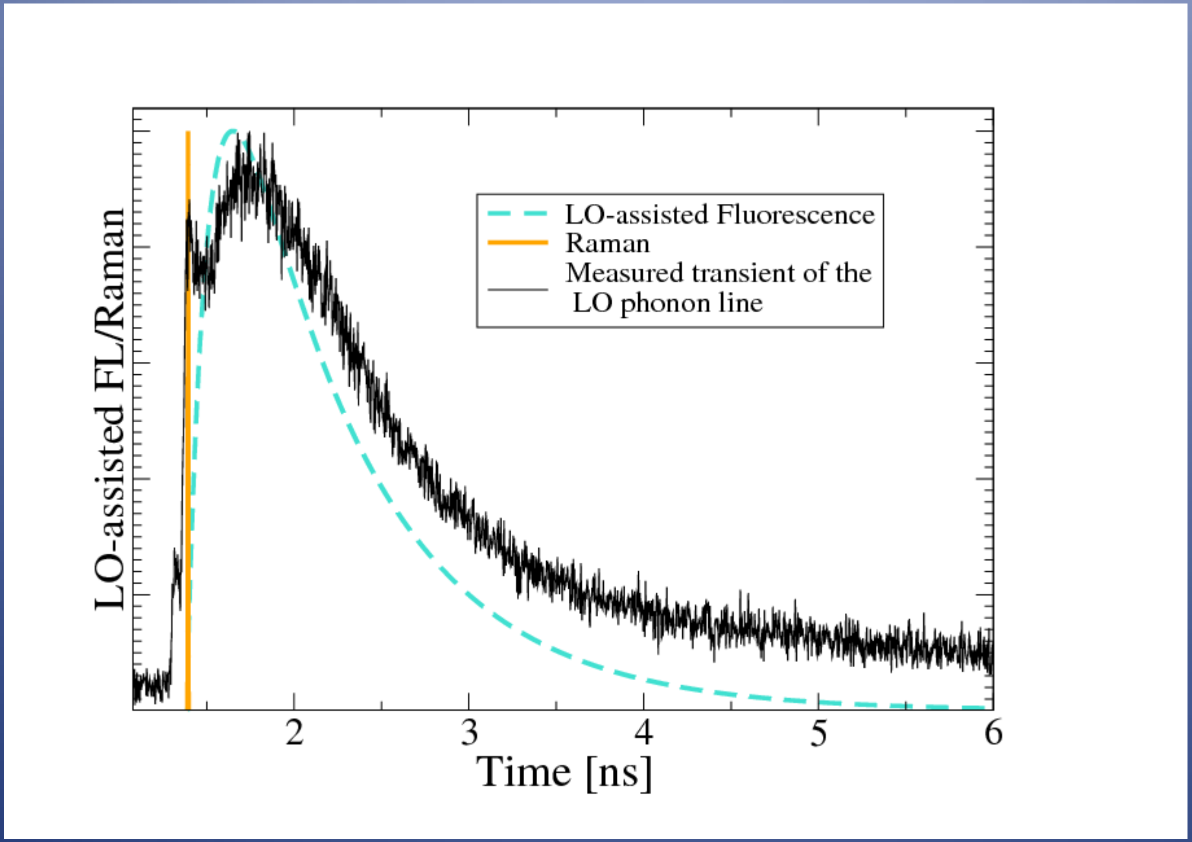


[1]PRB **81**, 075314 (2010)

Time-resolved signal

Agreement with measurements done by S. Werner and A. Hoffmann [1]:

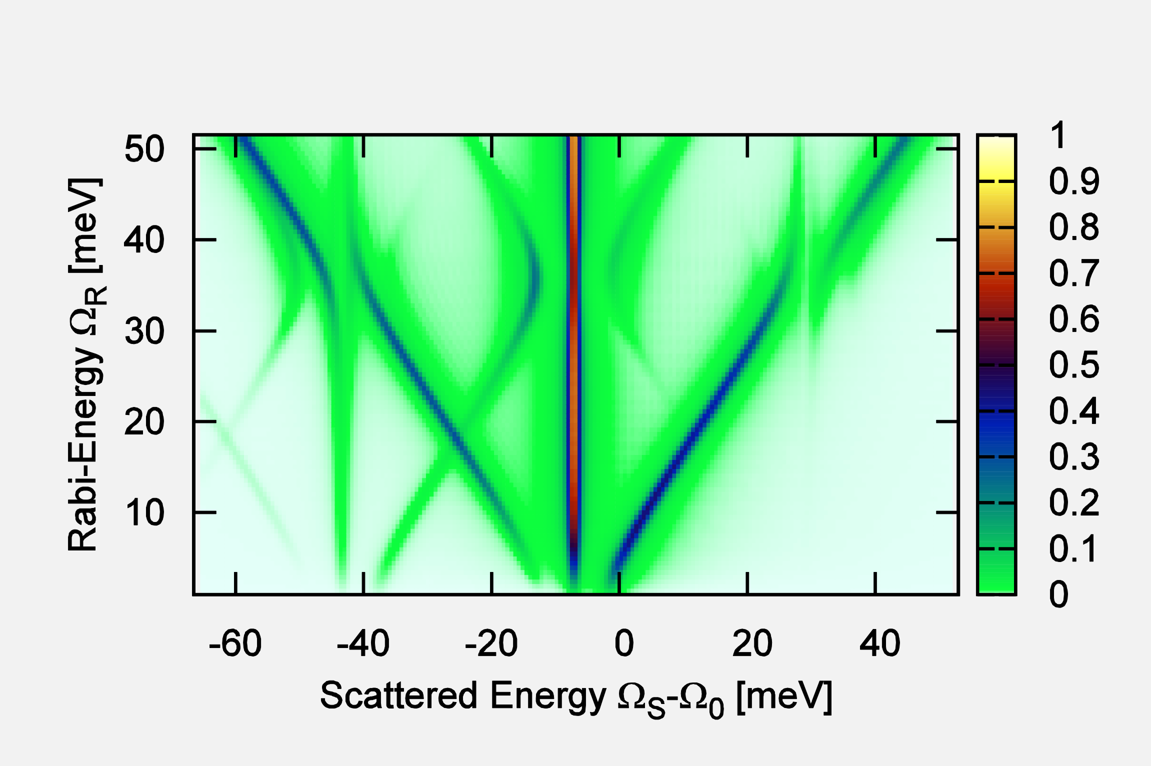


Microscopic theory identifies contributions in spectrum

[1] S. Werner, in preparation (2010)

Equation of motion approach allows exact solution (e.g. induction method [1]):

Multi-phonon-assisted quantum emission in the high driving field limit [2]:



[1] PRL **104**, 156801 (2010)
[2] Kabuss, in preparation, (2010)

Semiconductor Quantum Dot:

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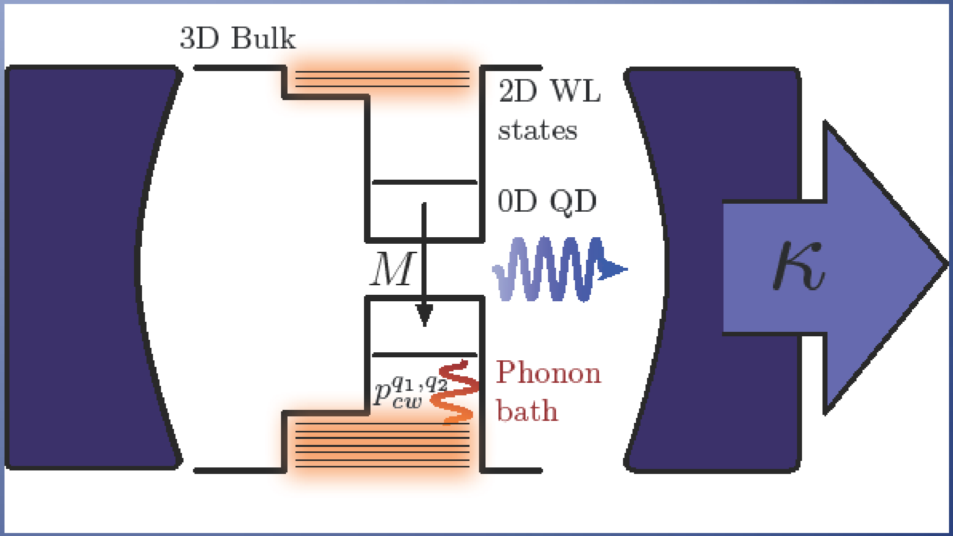

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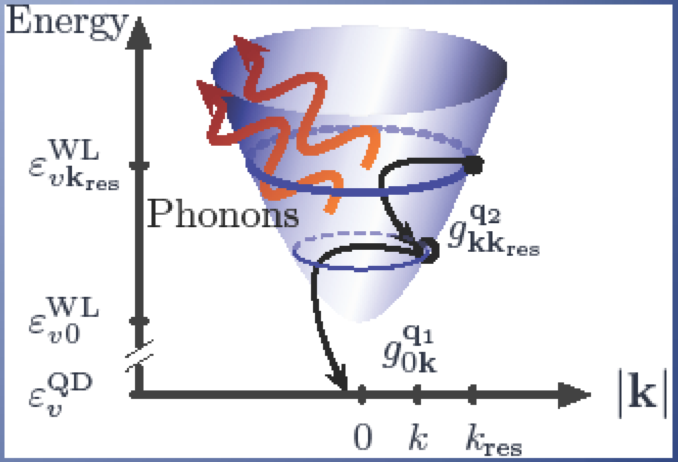
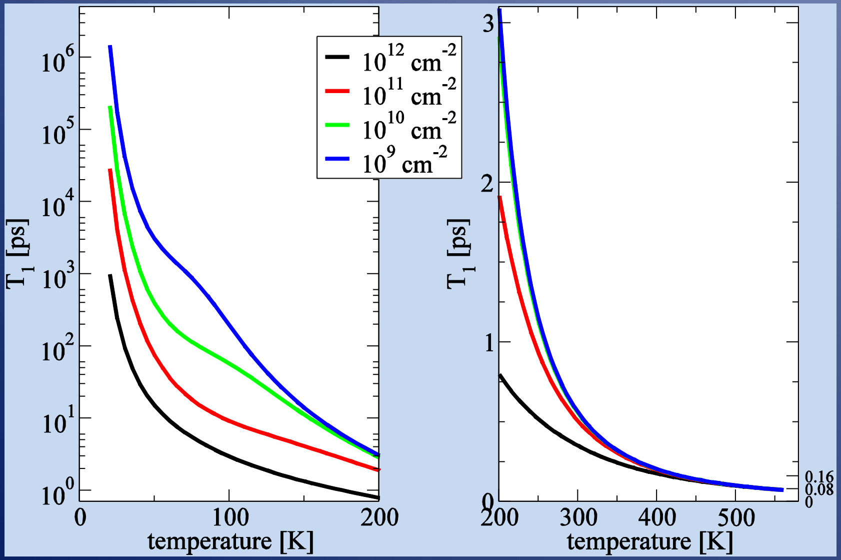
[1]PRB **80**, 245401 (2010)

LO-phonon scattering rates: effective Hamiltonian

- In an effective Hamiltonian approach a higher order Markovian process is assumed
- Probability of a subprocess depends on how strong the subprocess violetes the energy conservation



Relaxation rates[1] in the weak density limit:



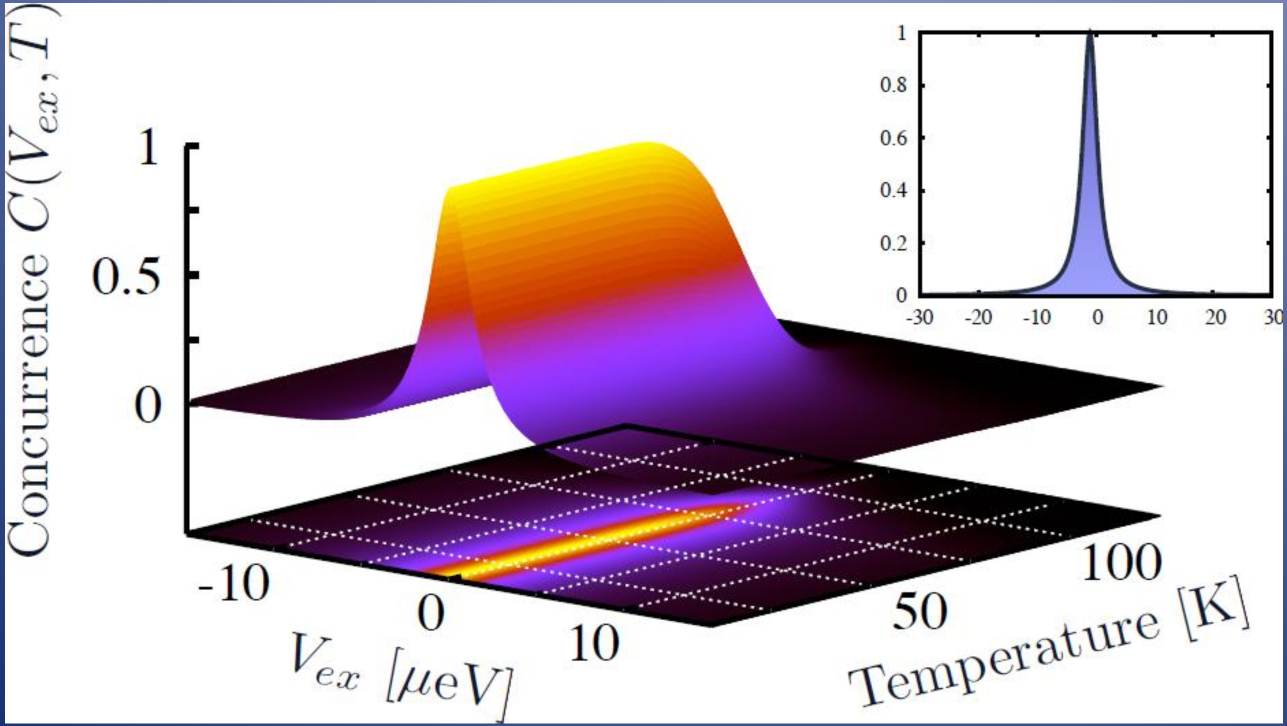
- The relaxation rates depend on the temperature of the bulk material
- Dependence corresponds to a square of the Bose-Einstein-distribution function
- The higher the temperature, the shorter the T1 - Time

[1]PSSB **247**, 809 (2010)

Wetting layer contributions lead to an additional dephasing:

$$\Gamma = \Gamma_{rad} + \Gamma_{WL}$$

Multiphonon processes attack the generation of polarization entangled photons [1]:



[1]PRB **81**, 195319 (2010)

LO-phonon scattering rates: carrier density dependence

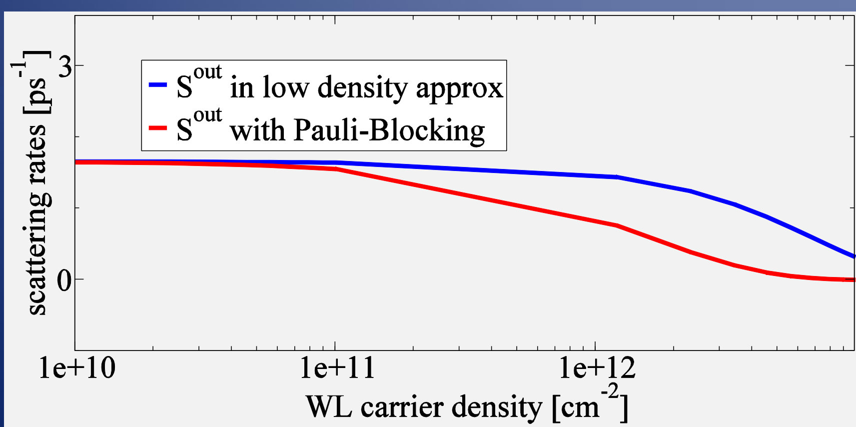
LO-phonon assisted carrier scattering rates depend on carrier density:

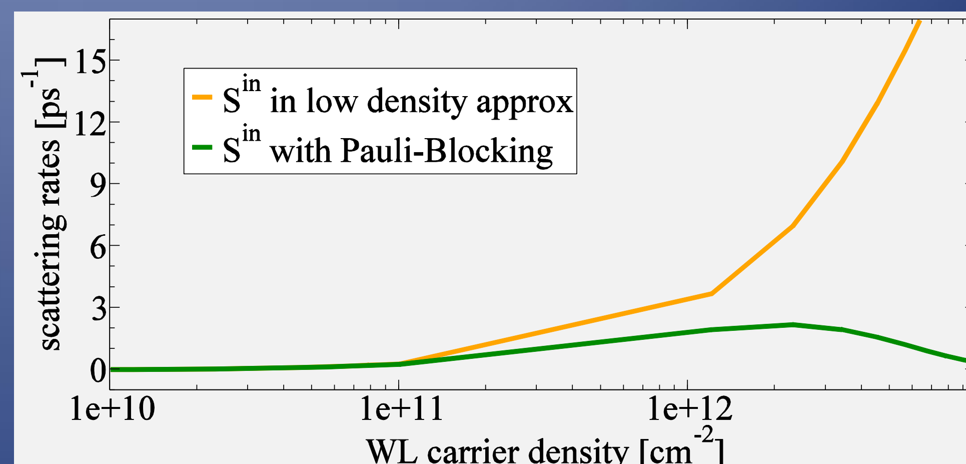
Effective Hamiltonian coupling element:

$$g_{r0}^{q'q''} = -\tilde{\sum_i} \frac{g_{ri}^{q'} g_{i0}^{q''} (1-f_i)}{(\epsilon_i - \epsilon_0 - \hbar\omega_{\mathrm{LO}})}$$

Pauli-blocking enters in the total T1-time [1]:

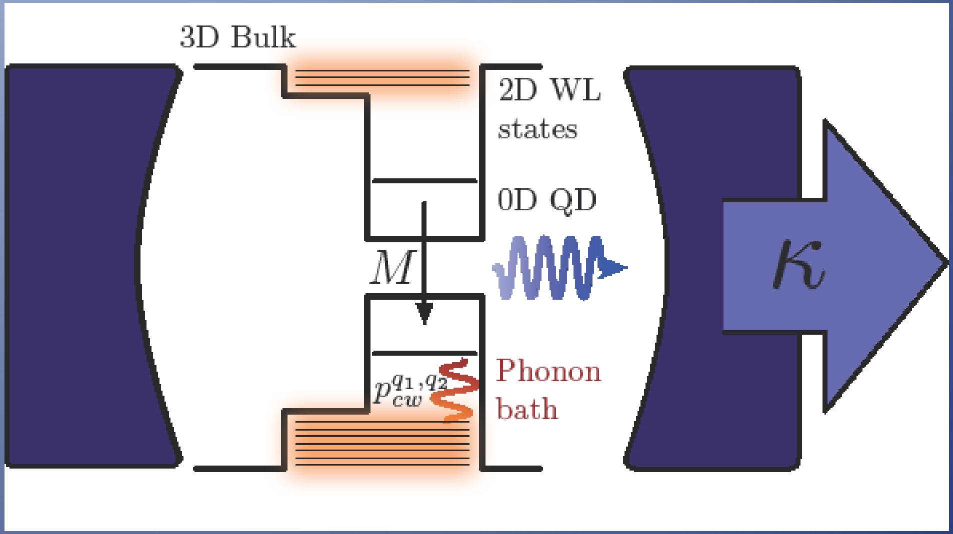
$$T_1 = \frac{1}{\Gamma} \frac{1}{n^2(1-f_r) + (n+1)^2 f_r}$$





[1] Proc. SPIE, **7597**, 7597P (2010)

Semiconductor Quantum Dot:



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1. Characterization of the system, e.g. via luminescence experiments
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[1]PRL **103**, 087407 (2009)

Heisenberg equation of motion approach to treat more interactions

$$-i\hbar\partial_t\langle O\rangle = \langle[H_0 + H_{el-pt}, O]\rangle$$

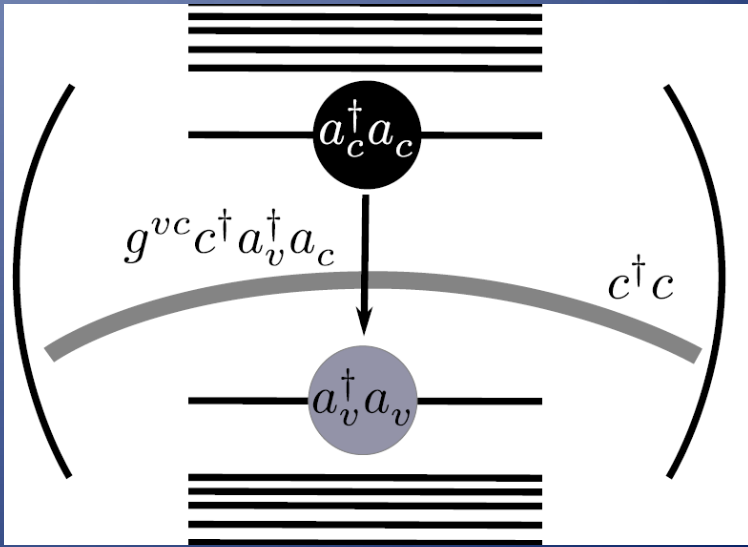
To reproduce the Jaynes-Cummings model,
we introduce a factorization approach for strongly correlated systems:
the photon probability cluster expansion (PPCE).[1]

$$p_n = \langle|n\rangle\langle n|\rangle$$

$$f_n^h = p_n - \langle|n\rangle\langle n|a_v^\dagger a_v\rangle$$

$$\langle c^\dagger c\rangle = \sum_{n=1}^{\infty} n\, p_n$$

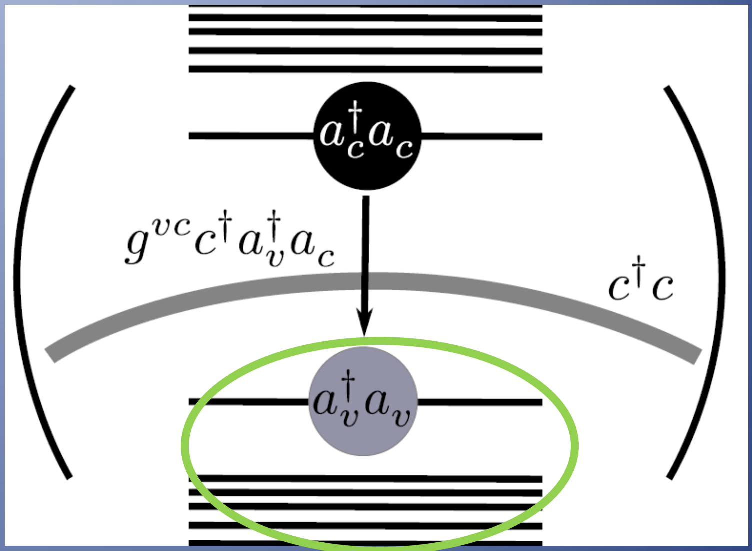
$$f_n^e = \langle|n\rangle\langle n|a_c^\dagger a_c\rangle$$



[1]PRL **103**, 087407 (2009)

Modified Hartree-Fock factorization

Due to the quantum dot-wetting layer interaction, the one-electron assumption is not valid anymore.



$$\langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4 \rangle \neq 0$$

This many-particle contribution is taken into account via the Hartree – Fock approximation

$$\langle a_1^\dagger a_2^\dagger a_3 a_4 \rangle \approx \langle a_1^\dagger a_4 \rangle \langle a_2^\dagger a_3 \rangle - \langle a_1^\dagger a_3 \rangle \langle a_2^\dagger a_4 \rangle$$

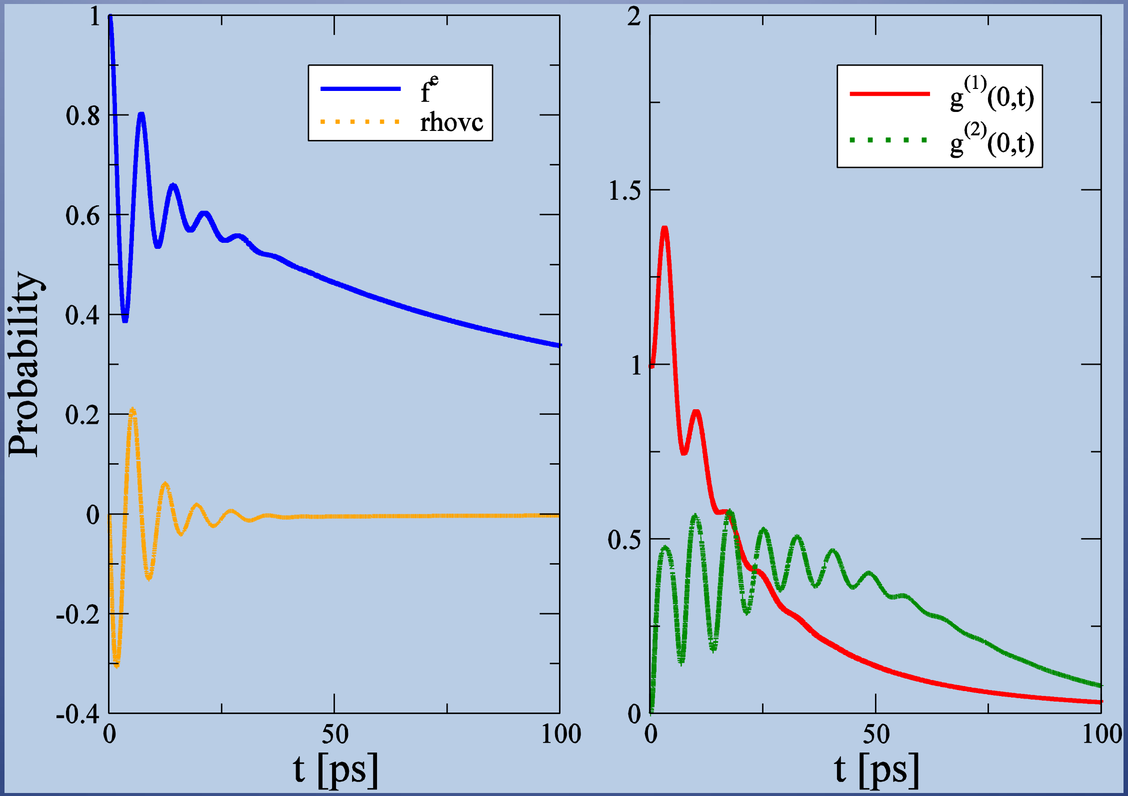
Here, we introduce a modified the Hartree – Fock approximation[1]:

$$\begin{aligned} \langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4 \rangle &\approx p_n \left\{ \langle \frac{|n\rangle\langle n|}{p_n} a_1^\dagger a_4 \rangle \langle \frac{|n\rangle\langle n|}{p_n} a_2^\dagger a_3 \rangle - \langle \frac{|n\rangle\langle n|}{p_n} a_1^\dagger a_3 \rangle \langle \frac{|n\rangle\langle n|}{p_n} a_2^\dagger a_4 \rangle \right\} \\ &\approx \frac{1}{p_n} \left\{ \langle |n\rangle\langle n| a_1^\dagger a_4 \rangle \langle |n\rangle\langle n| a_2^\dagger a_3 \rangle - \langle |n\rangle\langle n| a_1^\dagger a_3 \rangle \langle |n\rangle\langle n| a_2^\dagger a_4 \rangle \right\} \end{aligned}$$

[1]Proc. SPIE, **7597**, 7597P (2010)

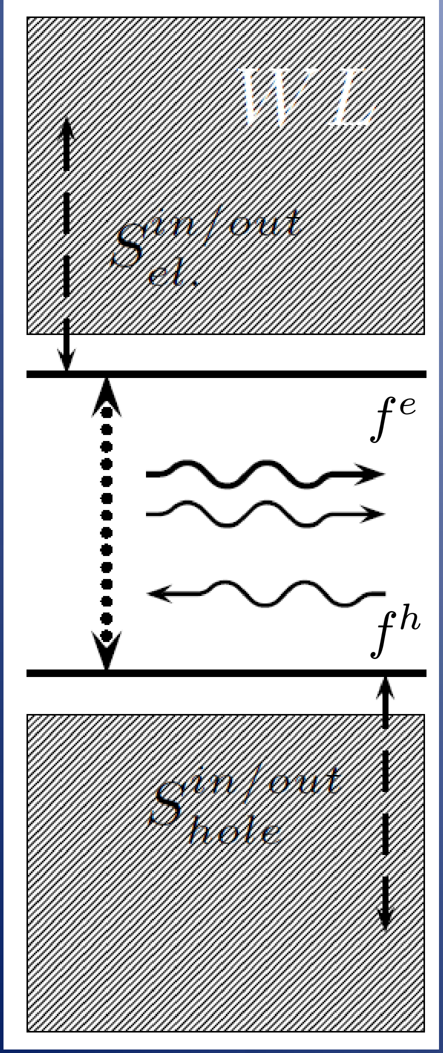
Dynamics without pump mechanism:

Rabi-oscillation as strong coupling signature:



without pump mechanism, photon density and electron density decays

Pump mechanism:



Electrically driven QD is a source for single-photons on demand

Electrons scatter into the QD via LO-phonon assisted scattering

$$\partial_t f^e_n|_{pump} = S^{in}_e (p_n - f^e_n) - S^{out}_e f^e_n$$

$$\partial_t f^h_n|_{pump} = S^{in}_h (p_n - f^h_n) - S^{out}_h f^h_n$$

$$\partial_t \langle |n+1\rangle\langle n| a^\dagger_v a_c \rangle|_{pump} = -\left(\frac{S^{in}_e}{2} + \frac{S^{in}_e}{2} + \frac{S^{out}_e}{2} + \frac{S^{out}_h}{2} \right) \langle |n+1\rangle\langle n| a^\dagger_v a_c \rangle$$

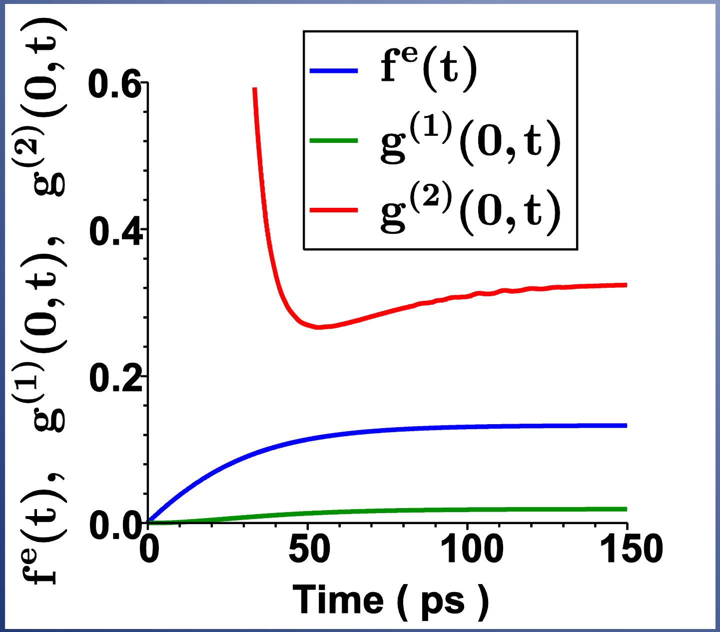
Derived via effective Hamiltonian approach

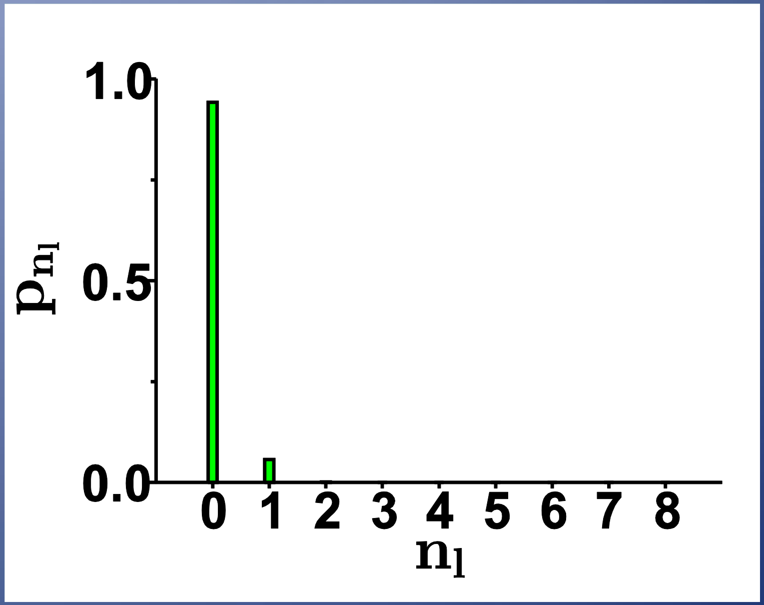
Pump mechanism and losses balance into a stationary state[1]

[1]RRL, accepted (2010)

Dynamics with pump mechanism:

Weak pumping regime: a single-photon source operates in stationary state

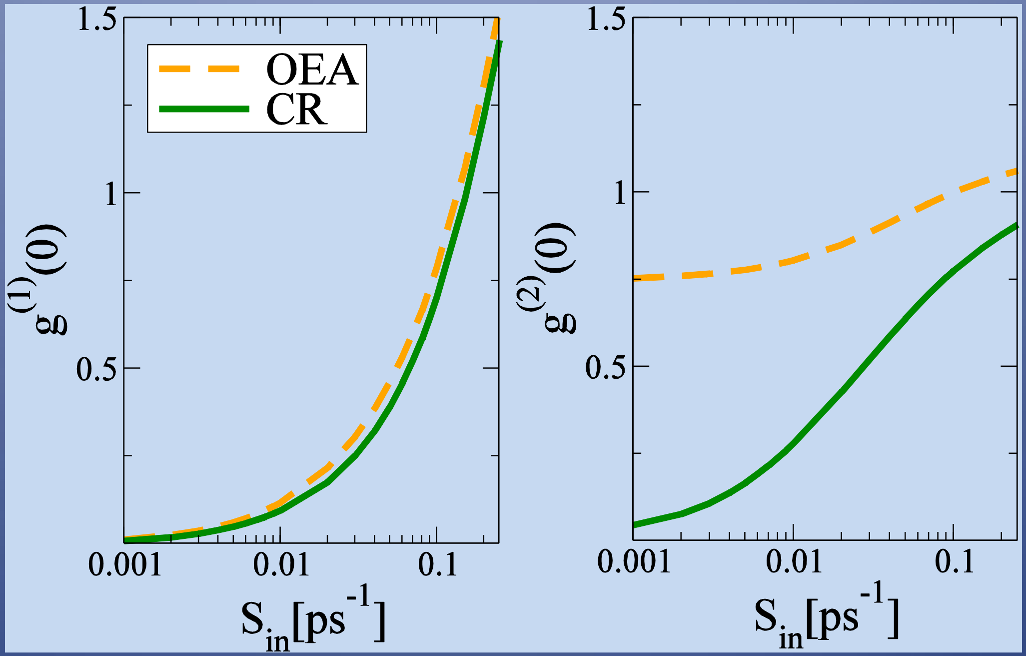




Microscopic model includes the different time-scale consistently, and the detailed description of the quantum light correlations via photon-probablities

Microscopic model reveals: Why QD are very promising single-photon sources

Comparison with one-electron approximation (OEA):



Due to the WL, Pauli-blocking in the QD states occur
Advantageous for single-photon emission in a wide pump interval

Summary:

- Characterization of the system via Raman spectroscopy (Julia Kabuss), predicted anti-crossing between Mollow-triplett and LO-phonon peak

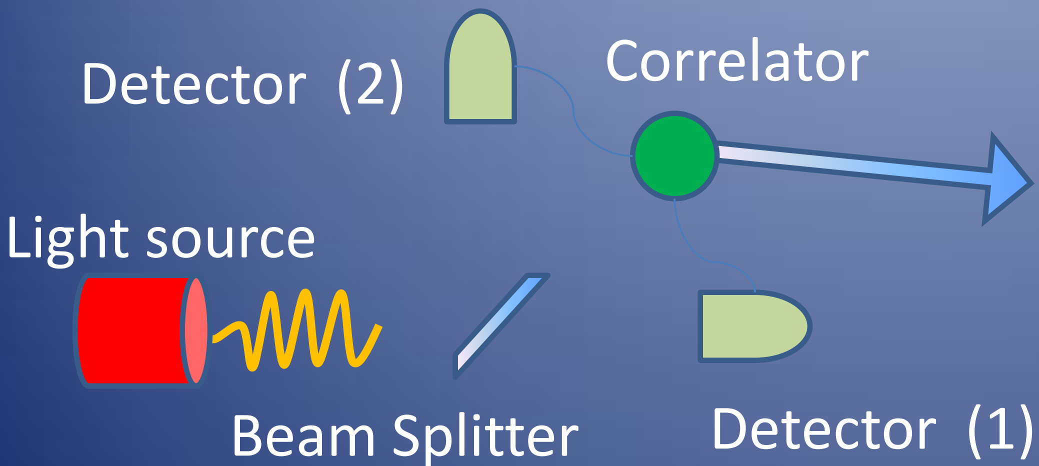
- LO-phonon assisted carrier scattering rates (Matthias-Rene Dachner), decreased T1-time due to Pauli-blocking

- Few photon model for quantum light emission (Alexander Carmele), modified Hartree-Fock factorization

- Electrically driven single-photon emitter (Yumian Su), advantageous Pauli-blocking in semiconductor single-photon sources

thank you!!

Hanbury Brown – Twiss Experiment: Intensity correlation



$$g^{(2)} = \frac{\langle c^\dagger c^\dagger c c \rangle}{\langle c^\dagger c \rangle^2}$$

$$= \frac{\langle (\Delta n)^2 \rangle - \langle n \rangle}{\langle n \rangle^2} + 1$$

- Does the probability to measure a photon at Detector (1) change the probability to measure a photon at Detector (2) and vice versa?