# Characterizing and bypassing decoherence in semiconductor quantum dot-based light-matter interfaces

**Alexander Carmele***
Technische Universität Berlin, Institut für Theoretische Physik, Germany

*Collaborators: Max Strauß, Alexander Thoma, Tobias Heindel, Stephan Reitzenstein, Nikolett Nemet, Scott Parkins, and Andreas Knorr

- Recent successes in semiconductor quantum optics, e.g. quadrature squeezing, quantum excitation, twin-photon source
- Characterizing non-Markovianity via detuning-dependent Wigner delay induced by a single quantum dot
- Bypassing non-Markovian decoherence via quantum feedback

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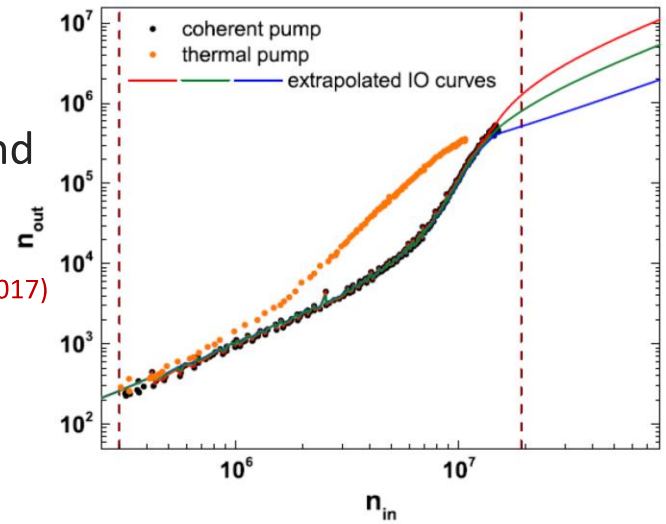
Quantum cascaded-driven laser systems exhibit qualitatively different thereshold behavior and input-output curve

Azizabadi, AC et al, PRA 96, 02381 (2017)

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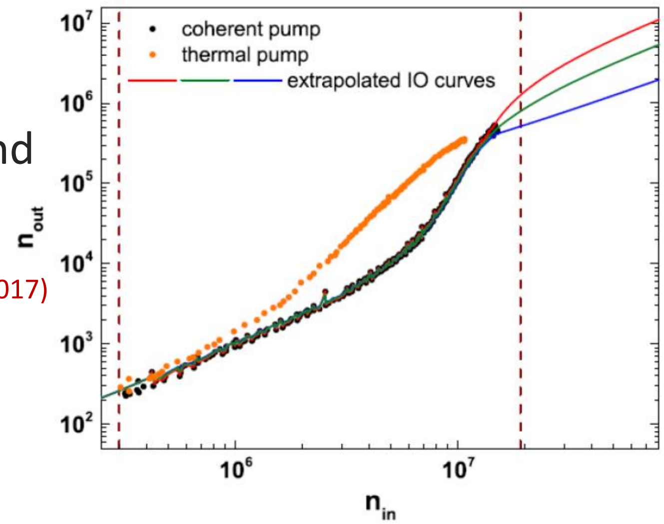


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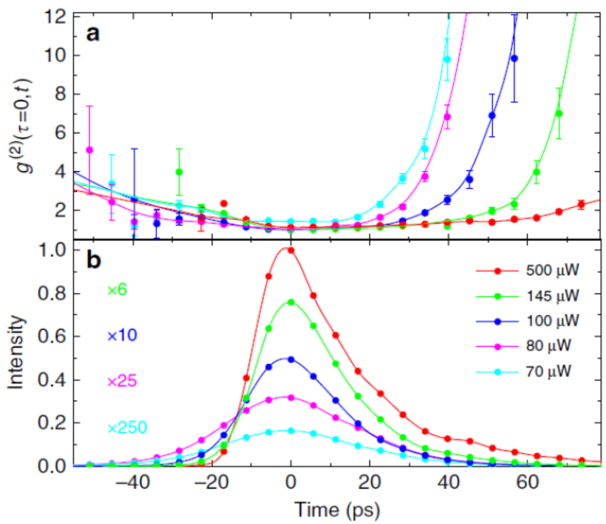


Superradiant-induced giant bunching in QD ensembles

Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de



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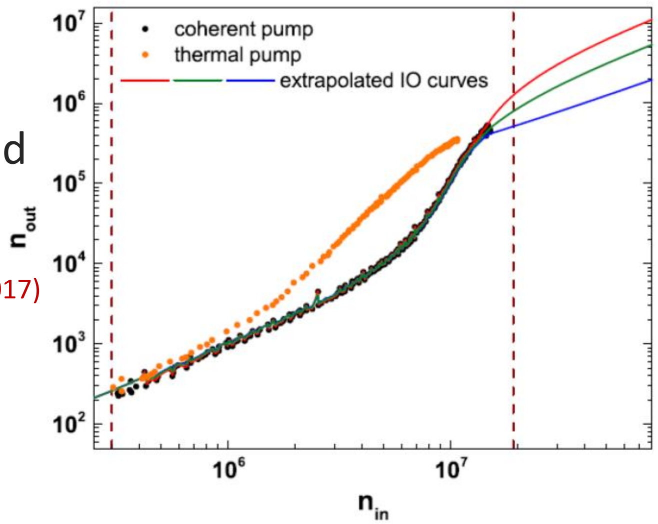


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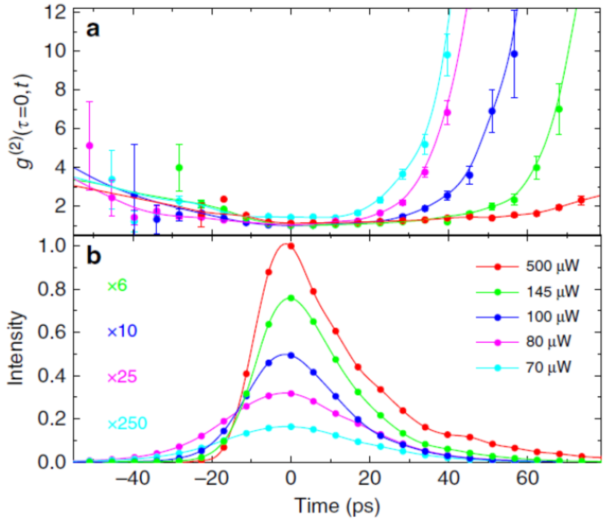


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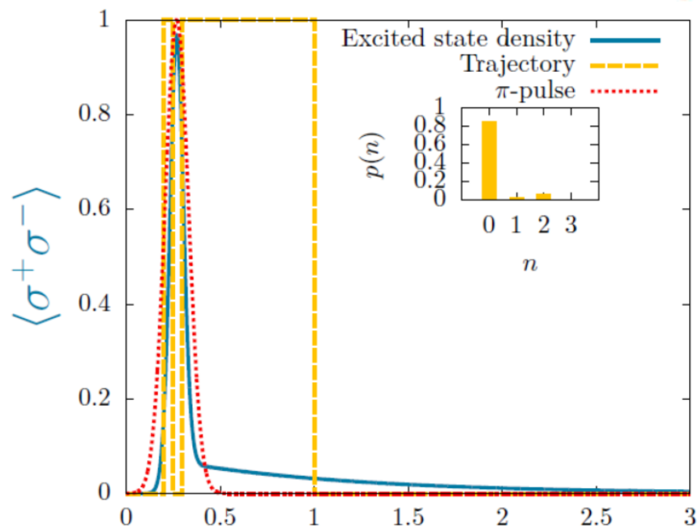


Single laser-pulsed quantum performs as a dynamical tunable two-photon source

K. Fischer et al., Nat. Phys. 13, 649 (2017)

Technische Universität Berlin
Alexander Carmele (09.01.2019)
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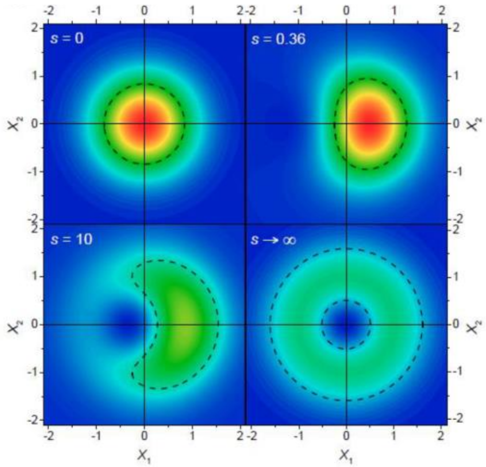
PQE-2019

Walls and Zoller, PRL 47, 709 (1981)
Schulte et al, Nature 525, 222 (2015)




Laser-driven quantum dot exhibits squeezing in resonance fluorescence

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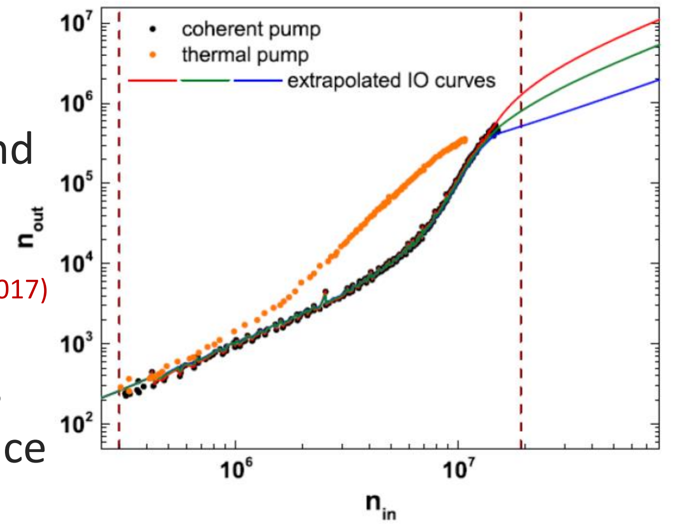


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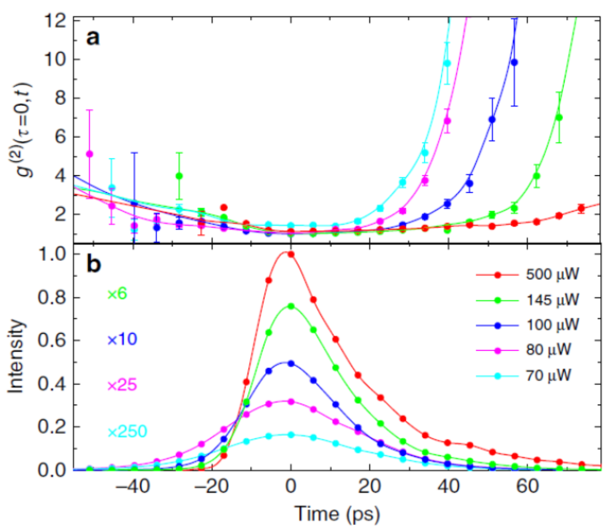


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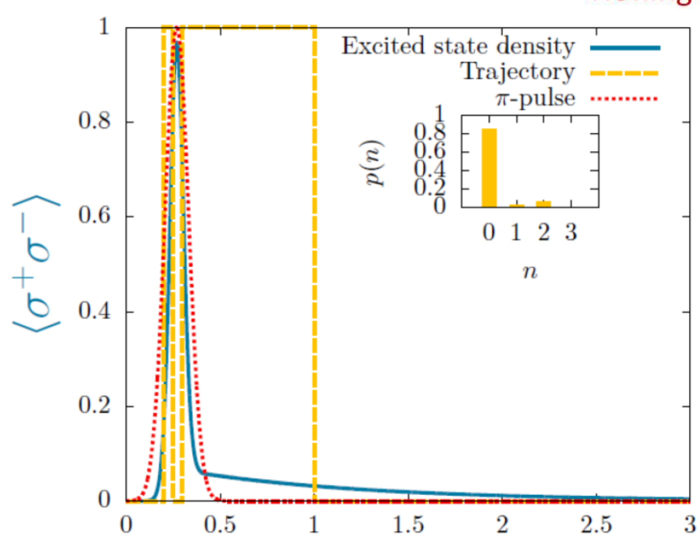


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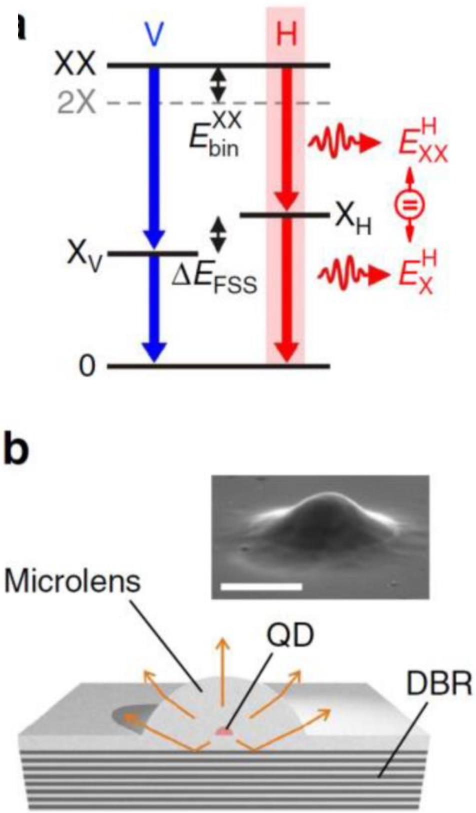

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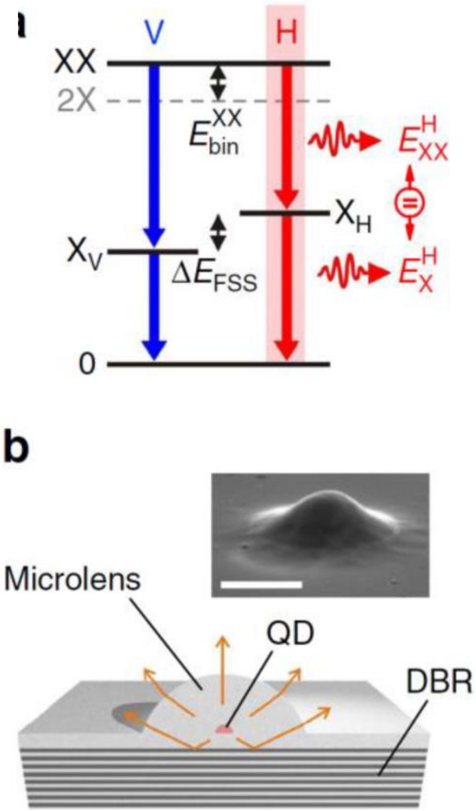
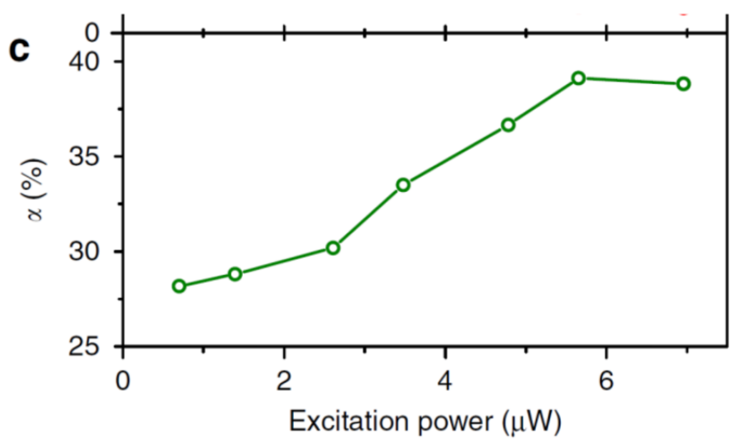
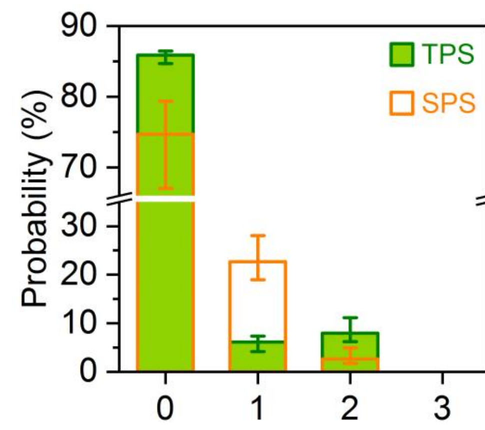



Ideal two-photon source of a quantum dot microlense with high brightness and fast repetition rate

Heindel, AC et al, Nat. Comm. 8, 14870 (2017)




Twin-photon source

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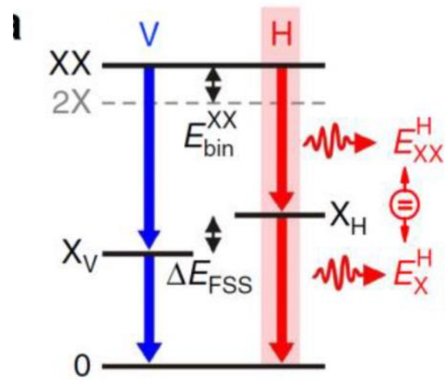


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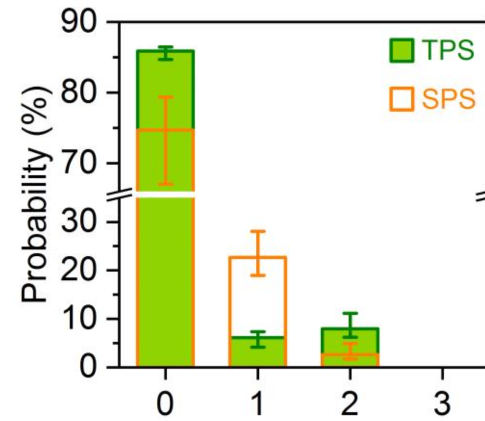


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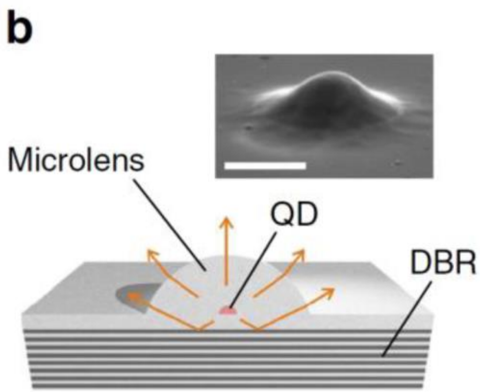


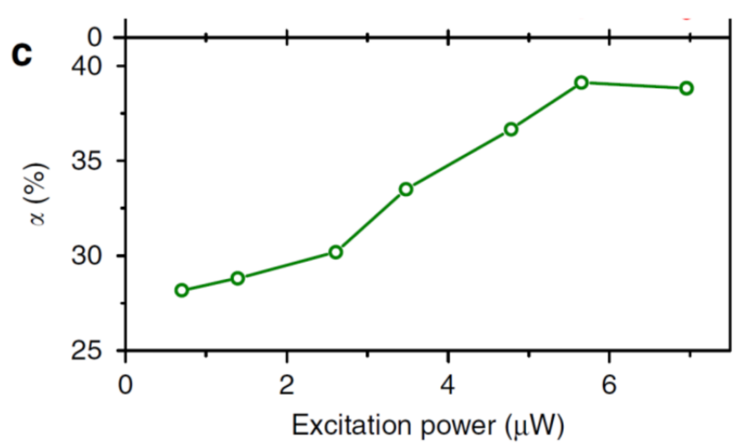


$$\partial_t\, \rho(t) = -\frac{i}{\hbar}\,[H(t),\, \rho(t)] + \sum_{\alpha} L[C_\alpha]\rho(t)$$

$$L[C] = C\rho C^\dagger - \frac{1}{2}C^\dagger C\rho + \frac{1}{2}\rho C^\dagger C$$

Experimental data satisfactorily and analytically explained by Markovian, Lindblad master equation

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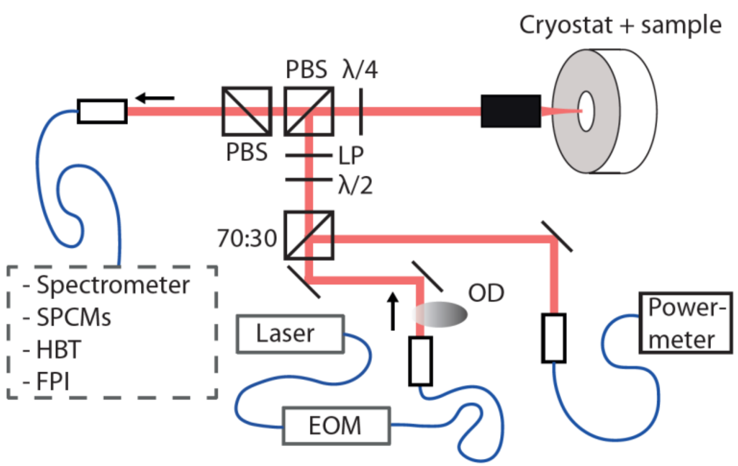
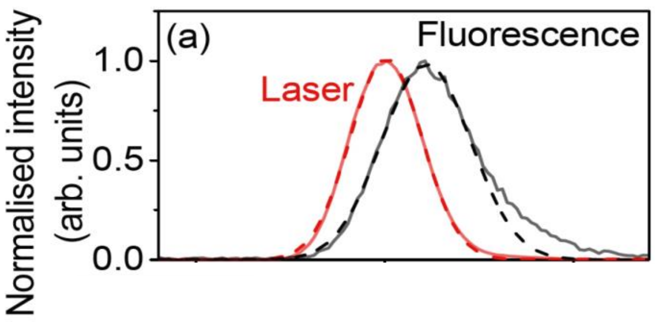
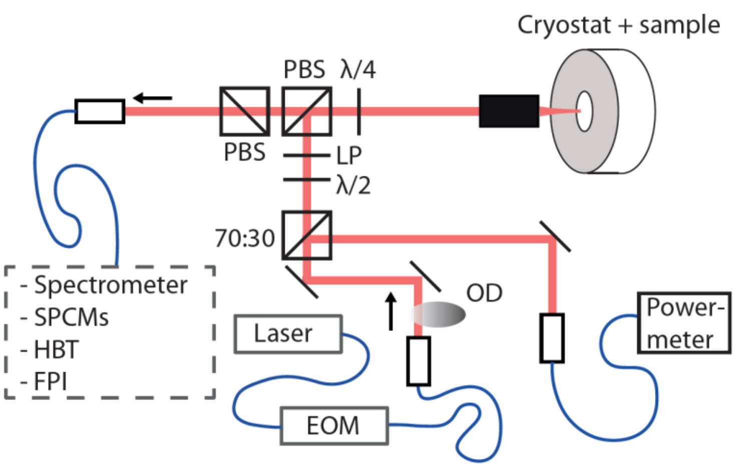



Wigner delay occurs between absorption and emission processes of a single quantum dot



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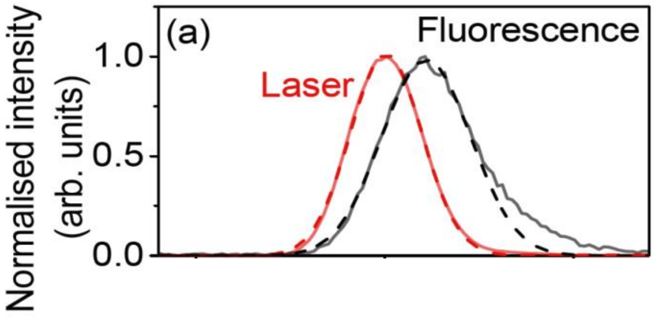


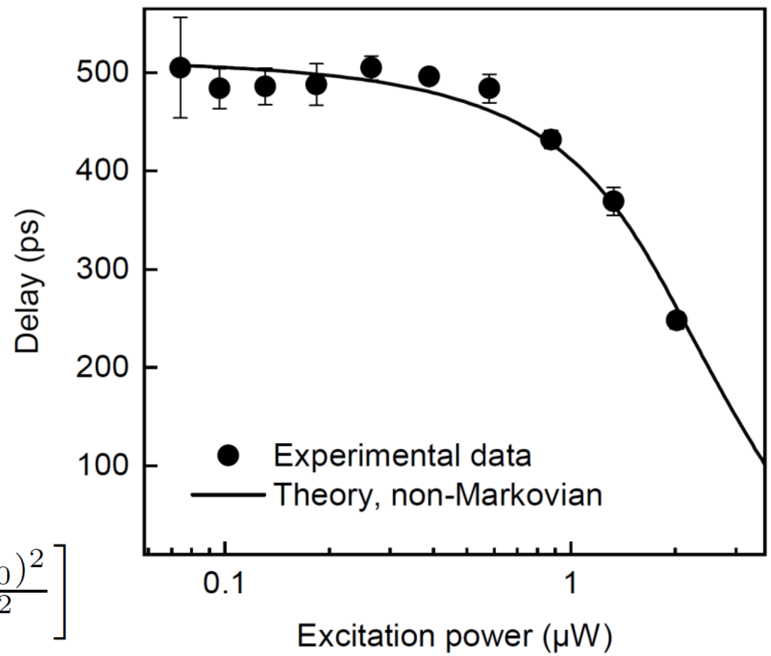


Wigner delay also strongly dependent on the excitation power **if not** in the Heitler regime

$$\Omega(t) = \Omega_L \sqrt{\frac{\pi}{(2\tau^2)}} \exp\left[-\frac{(t-t_0)^2}{2\tau^2}\right]$$

Strauß, AC et al, arXiv: 1805.06357v1

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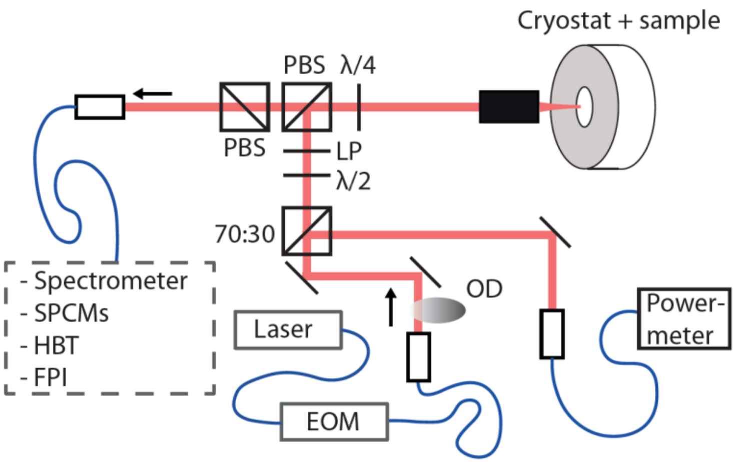


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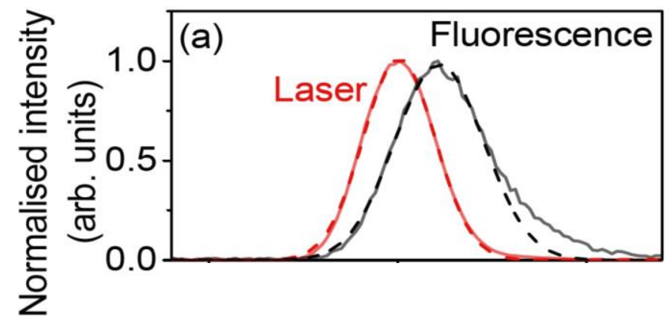


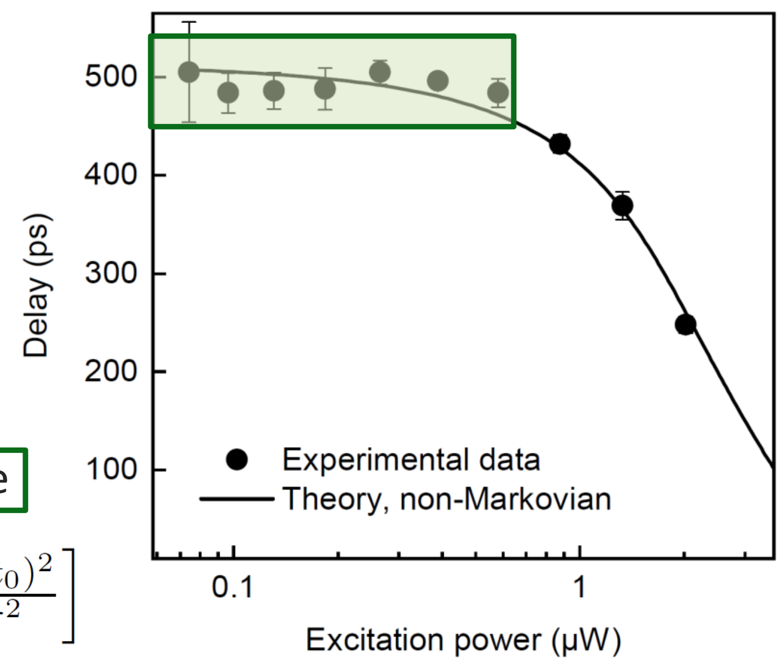


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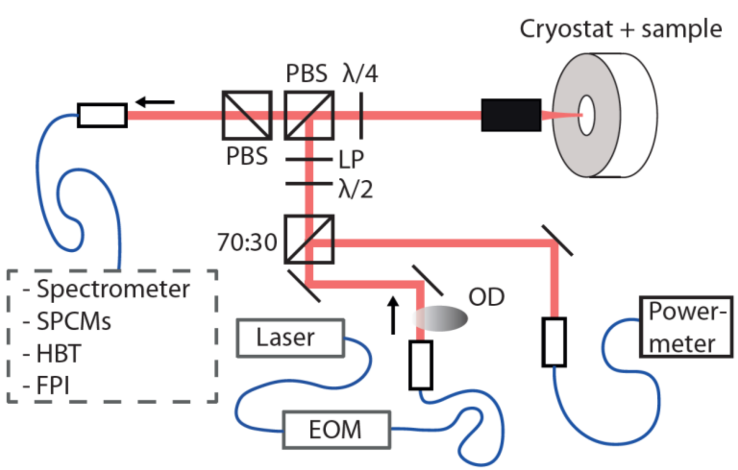


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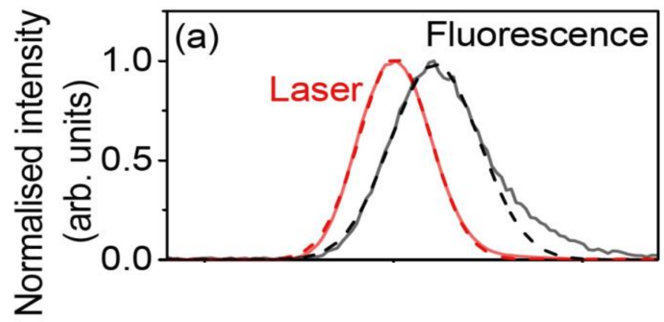


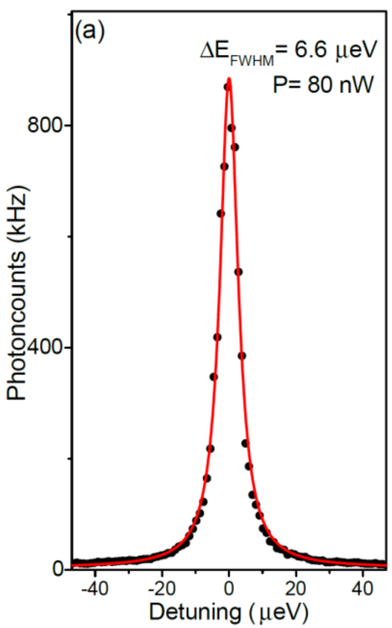


Wigner delay strongly dependent on the T1-time of the quantum dot, here T1 = (700 ± 100) ps

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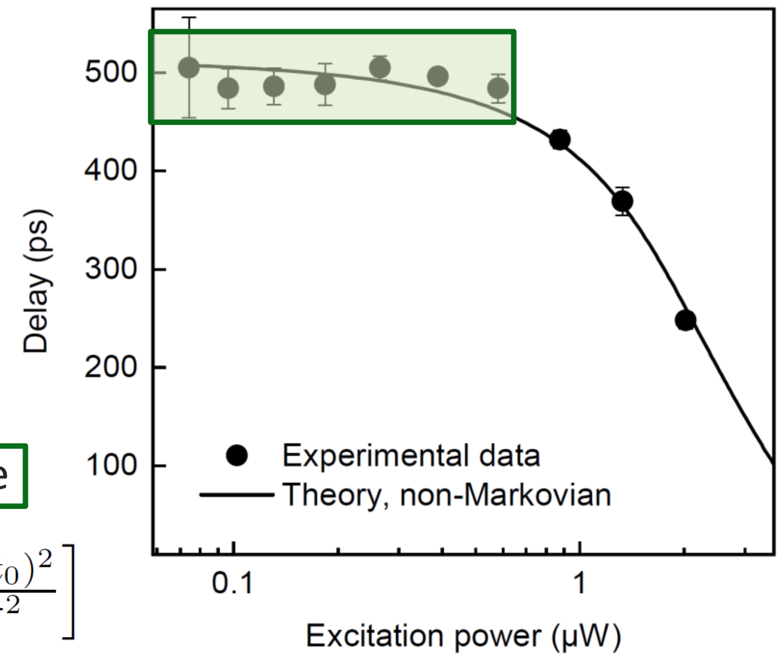


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# Wigner delay induced by a single quantum dot:

Markovian theory via Lindblad-type dephasing

$$\dot{\rho} = -\frac{i}{\hbar}[H(t),\rho] + \frac{\Gamma}{2}\mathcal{D}[\sigma_{12}]\rho + \frac{\gamma_p}{2}\mathcal{D}[\sigma_{22}]\rho$$

$$\dot{\rho}_{22} = -\Gamma\rho_{22} + 2\mathrm{Im}[\Omega(t)\rho_{12}]$$

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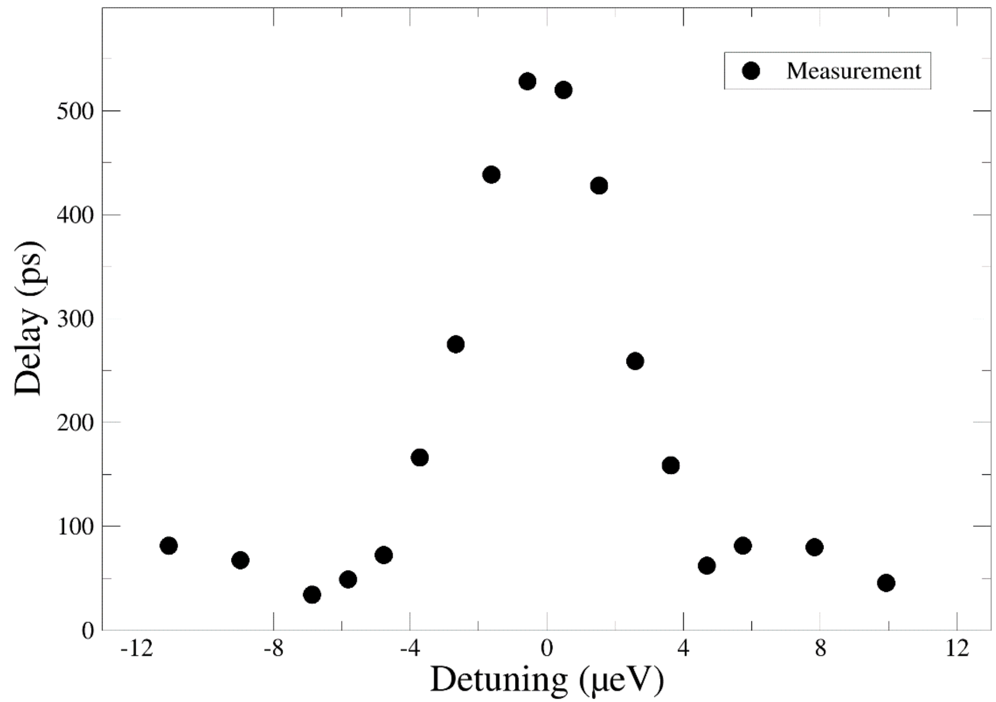


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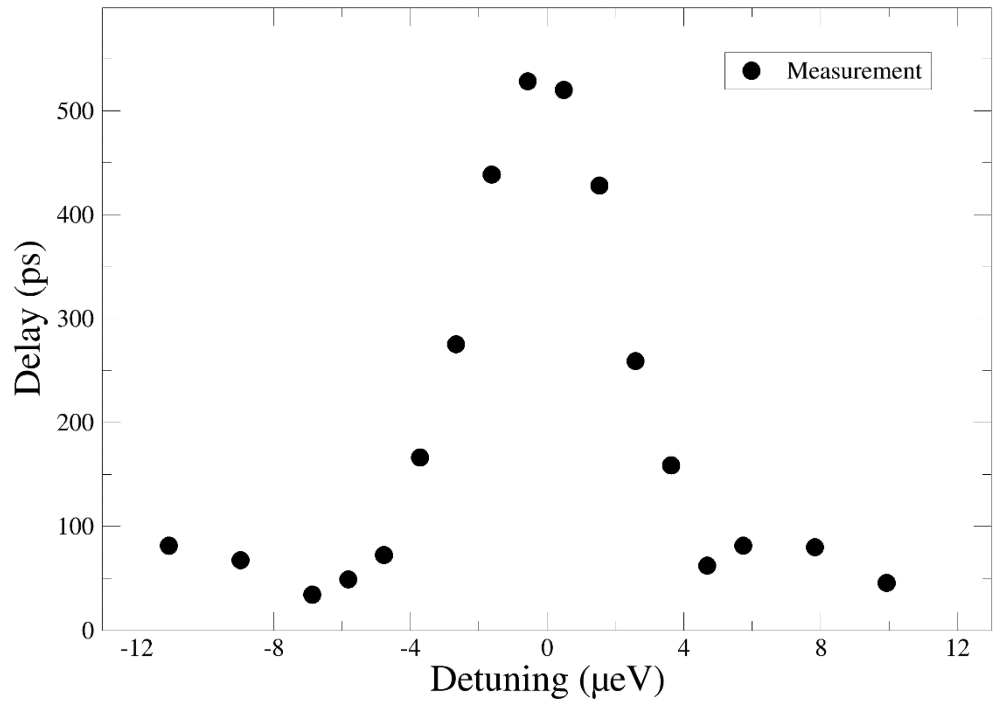


Markovian theory via Lindblad-type dephasing

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Bloch equations solved in the adiabatically limit

$$\tau_W = \frac{d\phi}{d\omega} = \frac{1}{\gamma + \Delta^2/\gamma}$$

$$\gamma = \Gamma/2 + \gamma_p$$

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SFB 910
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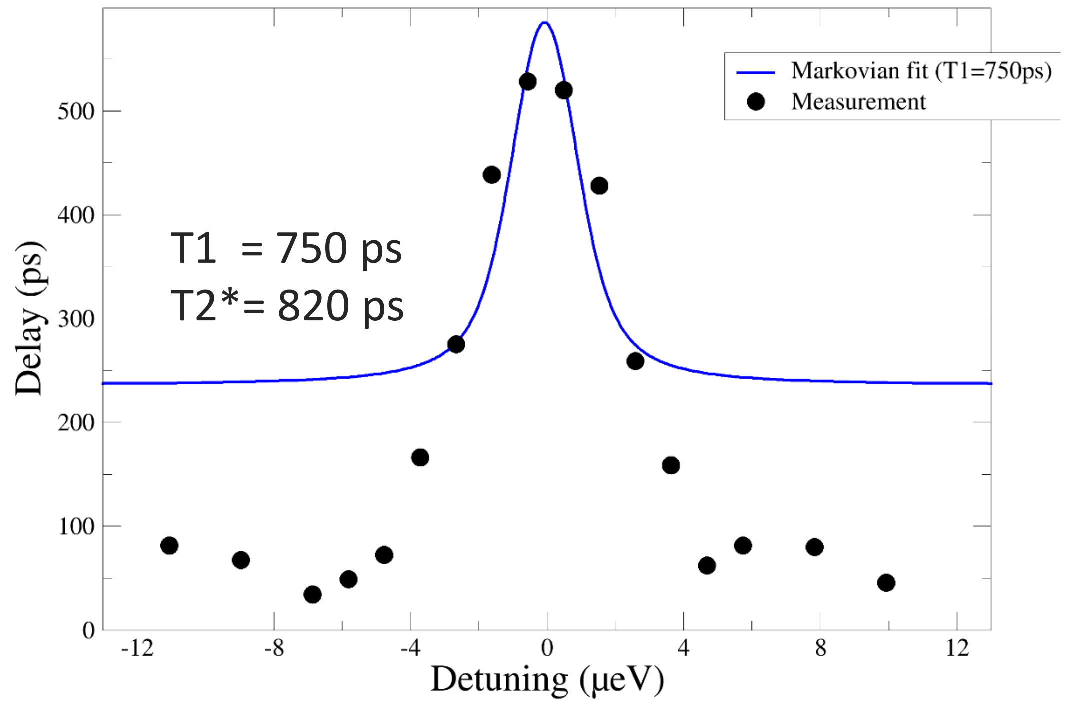


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Choose the pure dephasing to reproduce for a fixed radiative lifetime constant

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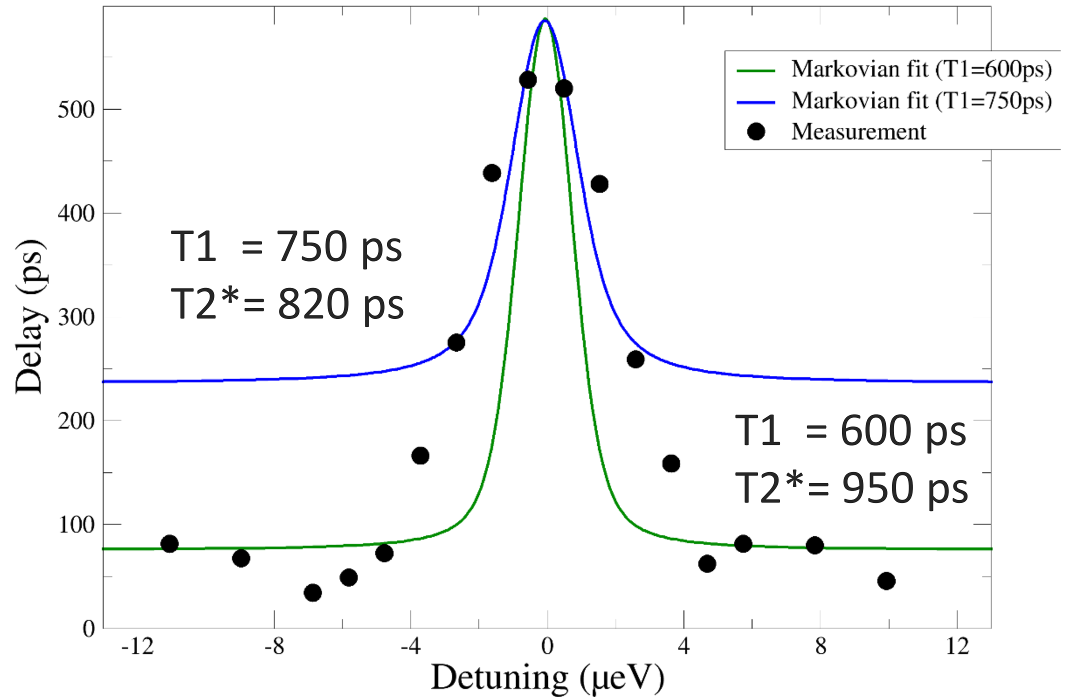


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⇒ Markovian theory fails to reproduce both limits and not the asymmetries between red- and blue-detuned Wigner delays

Strauß, AC et al, arXiv: 1805.06357v1

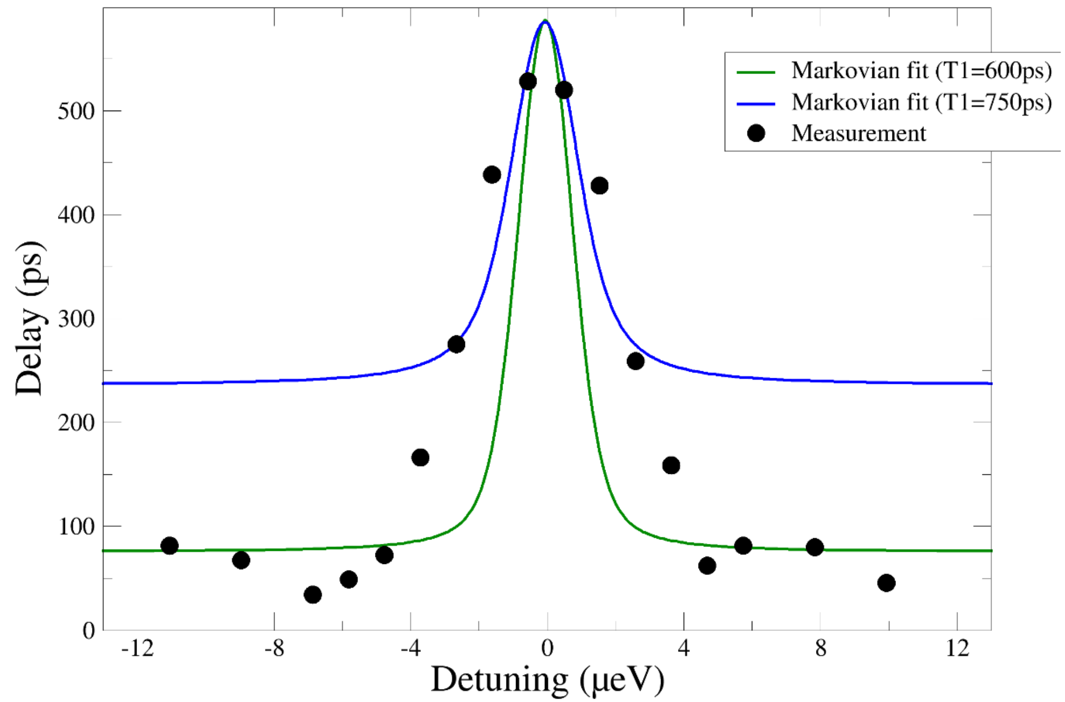
# Wigner delay in the presence of electron-phonon interaction:

$$H_{\mathrm{dec}} = \sigma_{22} \sum_q g_{12}^q \left[ b_q^\dagger(t) + b_q(t) \right]$$

Non-Markovian theory via semiconductor Bloch equations

$$\partial_t \langle \sigma_{22} \rangle = -2\Gamma \langle \sigma_{22} \rangle + 2\mathrm{Im}\left[ \Omega(t) \langle \sigma_{12} \rangle \right],$$

$$\partial_t \langle \sigma_{12} \rangle = -(\Gamma + i\Delta) \langle \sigma_{12} \rangle - i\Omega(t) \left( 2\langle \sigma_{22} \rangle - 1 \right) - i \sum_{\mathbf{q}} g_{12}^{\mathbf{q}} \langle b_{\mathbf{q}} \sigma_{12} \rangle + g_{12}^{\mathbf{q}*} \langle b_{\mathbf{q}}^\dagger \sigma_{12} \rangle$$

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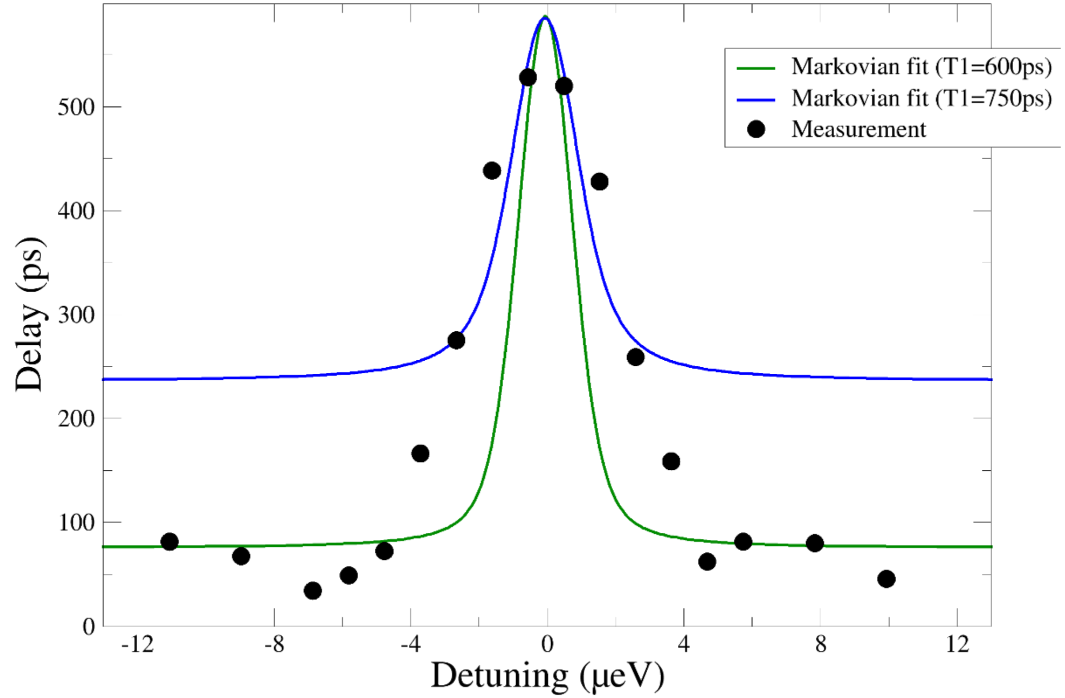


Bloch equations solved numerically in the second-order Born level

$$\partial_t\langle b_{\mathbf{q}}\sigma_{12}\rangle = -(\Gamma + i\Delta + i\omega_q)\langle b_{\mathbf{q}}\sigma_{22}\rangle - i\Omega(t)\left(2\langle b_{\mathbf{q}}\sigma_{22}\rangle - \langle b_{\mathbf{q}}\rangle\right) - ig_{12}^{\mathbf{q}*}\langle b_{\mathbf{q}}^\dagger b_{\mathbf{q}}\rangle\langle\sigma_{12}\rangle$$

$$\partial_t\langle b_{\mathbf{q}}\sigma_{22}\rangle = -(2\Gamma + i\omega_q)\langle b_{\mathbf{q}}\sigma_{22}\rangle - i\Omega(t)\left(\langle b_{\mathbf{q}}\sigma_{12}\rangle - \langle b_{\mathbf{q}}^\dagger\sigma_{12}\rangle^*\right) + ig_{vc}^{\mathbf{q}*}\langle b_{\mathbf{q}}^\dagger b_{\mathbf{q}}\rangle\langle\sigma_{22}\rangle$$

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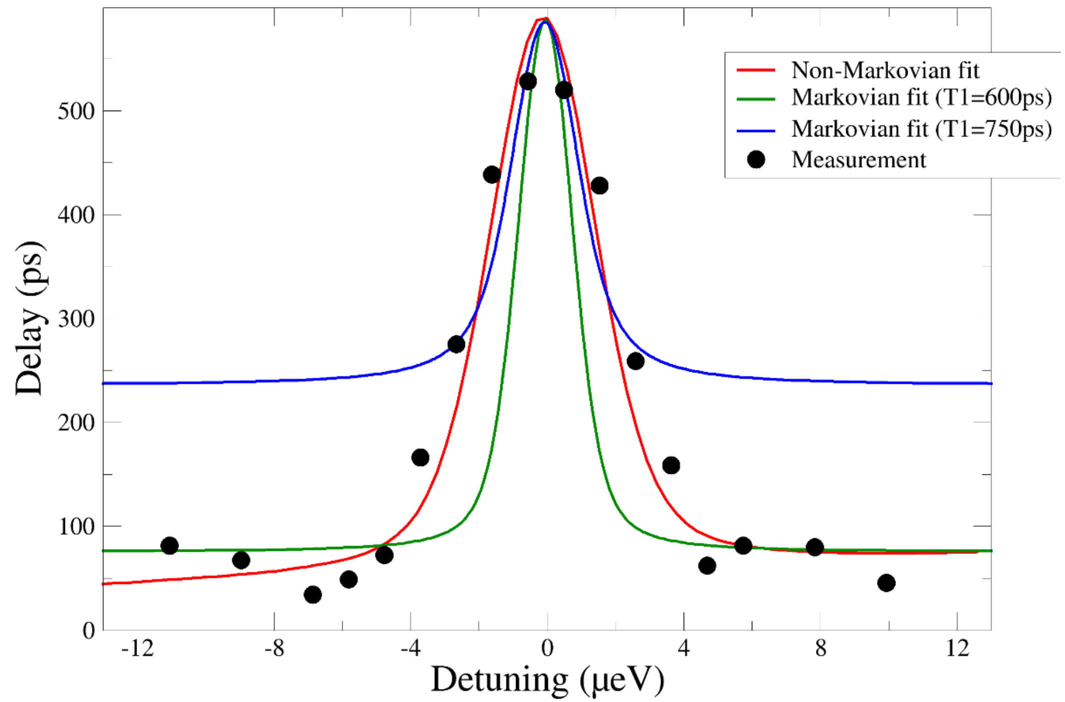


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Coupling element input parameter from material theory of InAs/GaAs (bulk phonons)

⇨ Non-Markovian theory reproduces well both limits and the asymmetries

Strauß, AC et al, arXiv: 1805.06357v1

- Recent successes in semiconductor quantum optics, e.g. quadrature squeezing, quantum excitation, twin-photon source
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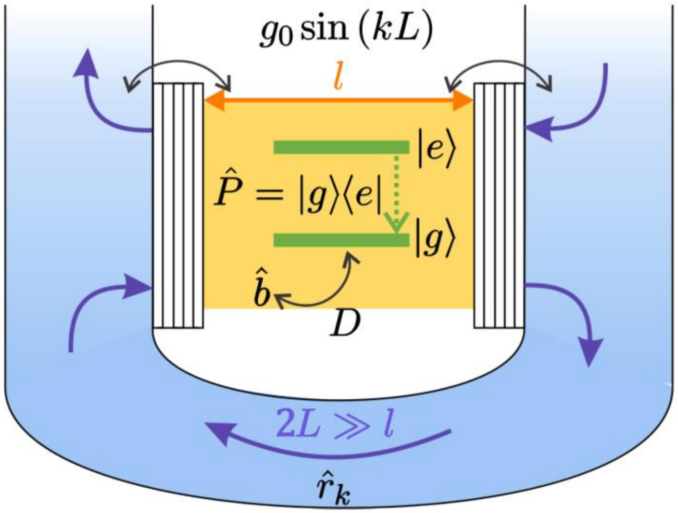
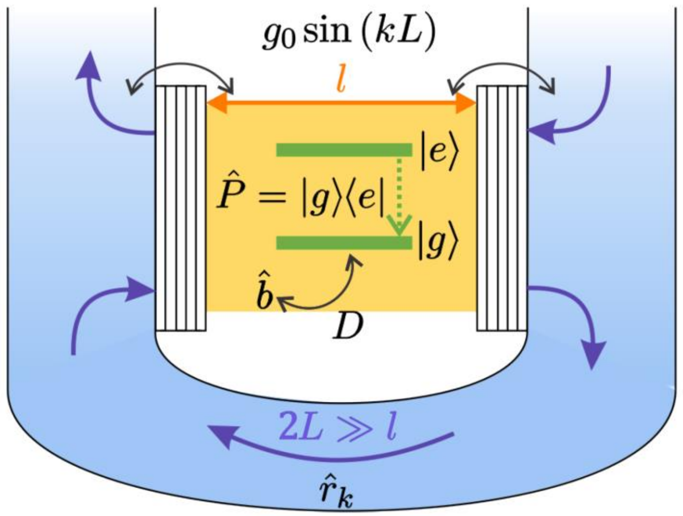



Goal: Stabilize an initial given coherence even in the presence of a reservoir at finite temperature

$$\hat{H} = \hat{H}_S + \hat{H}_R + \hat{H}_{LB}\left(\hat{b}, \hat{b}^\dagger, \hat{P}_i, \hat{P}_i^\dagger\right)$$

Nemet, AC et al, arXlv: 1805.2317




Goal: Stabilize an initial given coherence even in the presence of a reservoir at finite temperature

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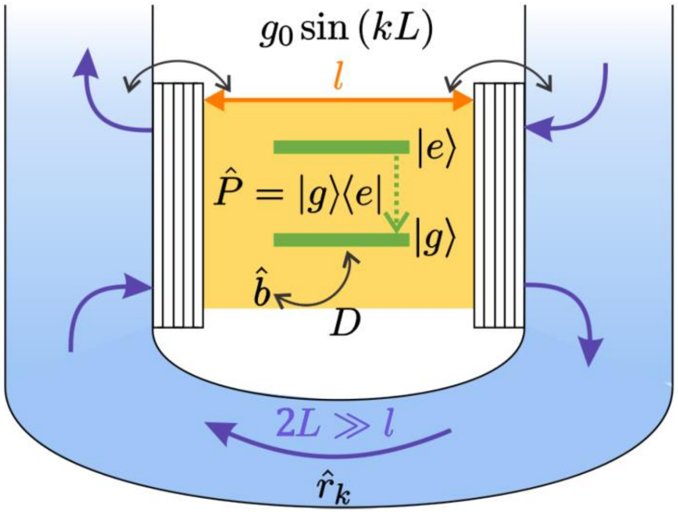
Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de



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We assume a reservoir at T>0 with non-Ohmic spectral density with delay

$$J(\omega_k) = \sin^2\left(\frac{\omega_k \mathcal{T}}{2}\right) e^{-i\omega_k(t-t')}$$

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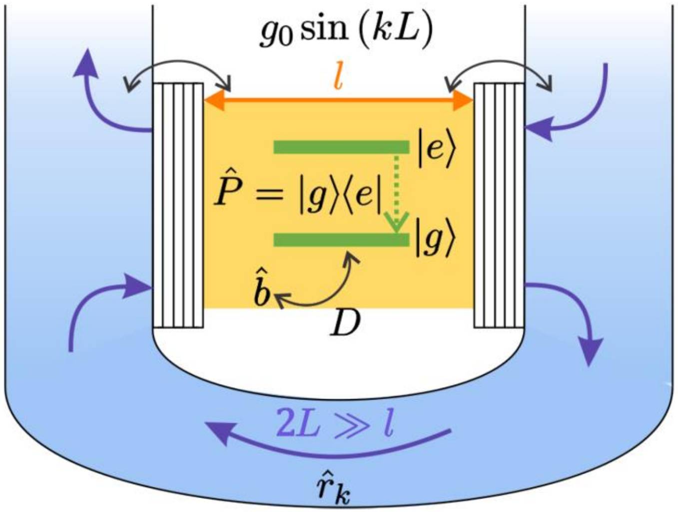


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Due to the lineaer coupling between the acoustic cavity mode and the reservoir, an exact solution exist

$$\hat{b}(t) = F(t)\hat{b}(0) + \int G_k(t)\hat{r}_k(0) dk$$

In the linear regime, the system dynamics can be exactly evaluated via a Feynman-Vernon influence functional or Suzuki-Trotta expansion

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With given initial conditions, the dynamics can be evaluated

$$\hat{\rho}_P(t) = \exp\left\{\left(-i\int_0^t \hat{\mathcal{B}}(t_1)dt_1 - \frac{1}{2}\int_0^t\int_0^{t_1}[\hat{\mathcal{B}}(t_1),\hat{\mathcal{B}}(t_2)]dt_2dt_1\right)\hat{P}^\dagger(0)\hat{P}(0)\right\}\hat{\rho}_P(0)$$

Our figure of merit is the survival time of an initial introduced coherence, e.g. via an delta pulse

$$\eta(t) = \frac{|\langle\hat{P}(t)\rangle|^2}{|\langle\hat{P}(0)\rangle|^2}$$

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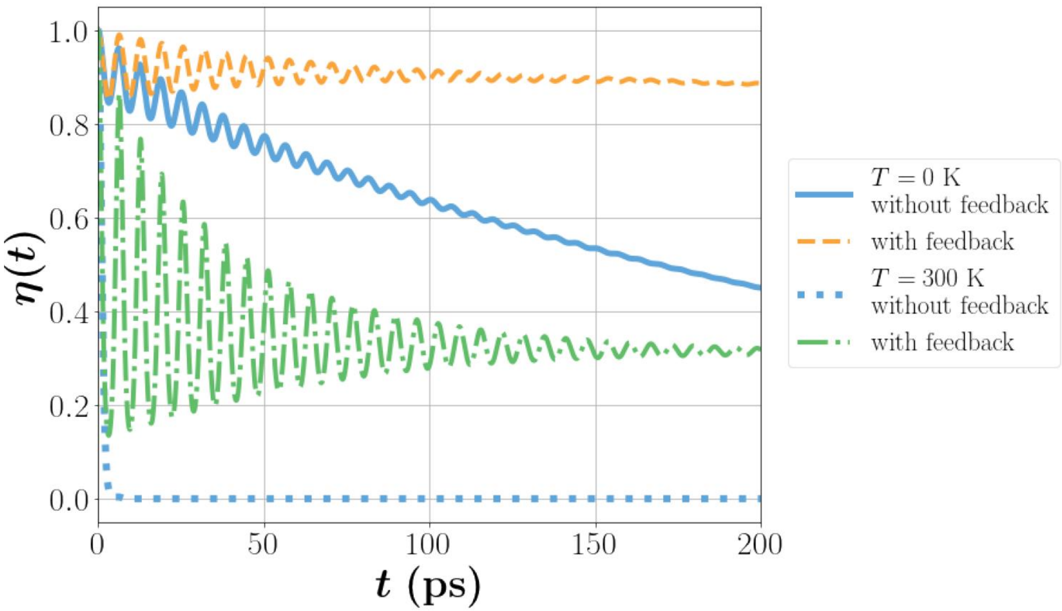


Feedback stops via quantum interference the decoherence process – a synchronisation between the oscillators take place

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Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de



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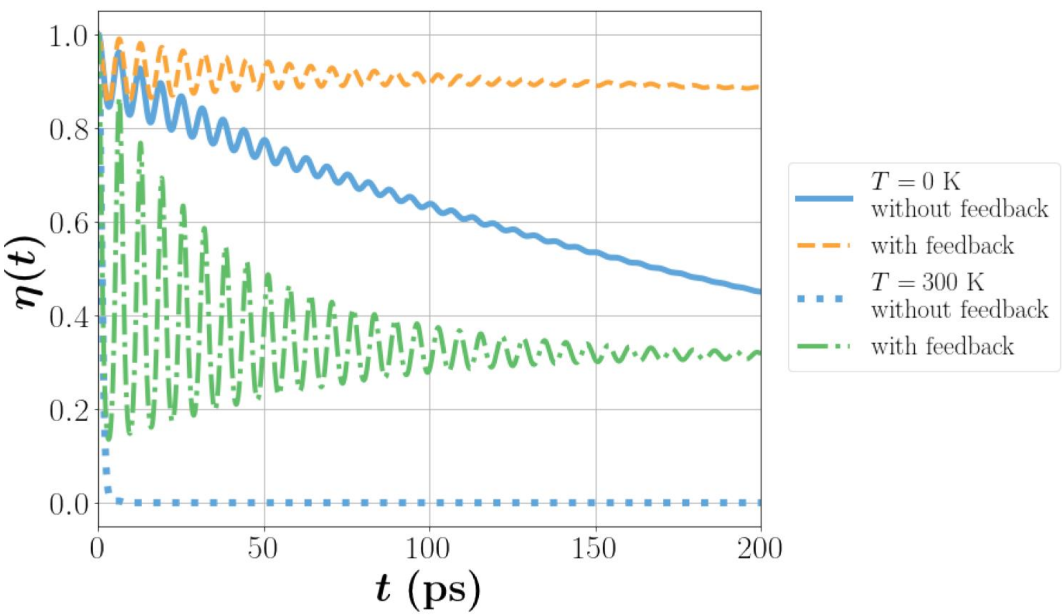


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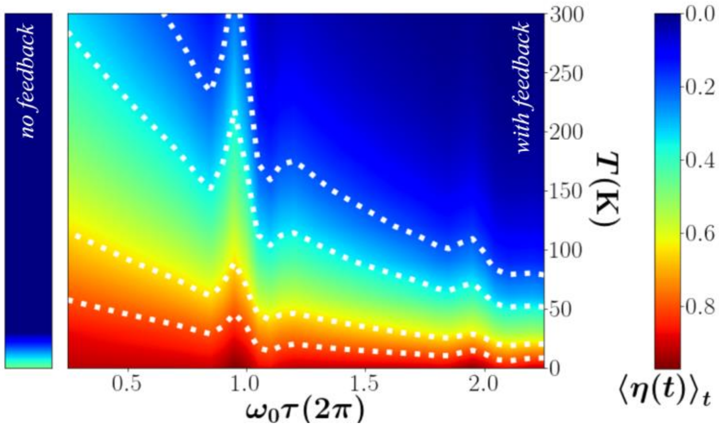


Delay time and phase-matching allow very long coherence times initial coherence at room temperature up to 200ps

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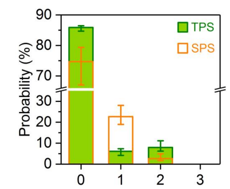
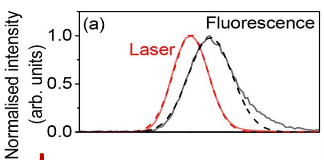
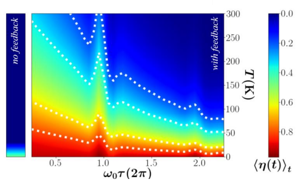
Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de



- Recent successes in semiconductor quantum optics, e.g. quadrature squeezing, quantum excitation, twin-photon source
- Characterizing non-Markovianity via detuning-dependent Wigner delay induced by a single quantum dot
- Bypassing non-Markovian decoherence via quantum feedback




Heindel, AC et al, Nat. Comm. 8, 14870 (2017)

Strauß, AC et al, arXiv: 1805.06357v1

Nemet, AC et al, arXIv: 1805.2317

Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de

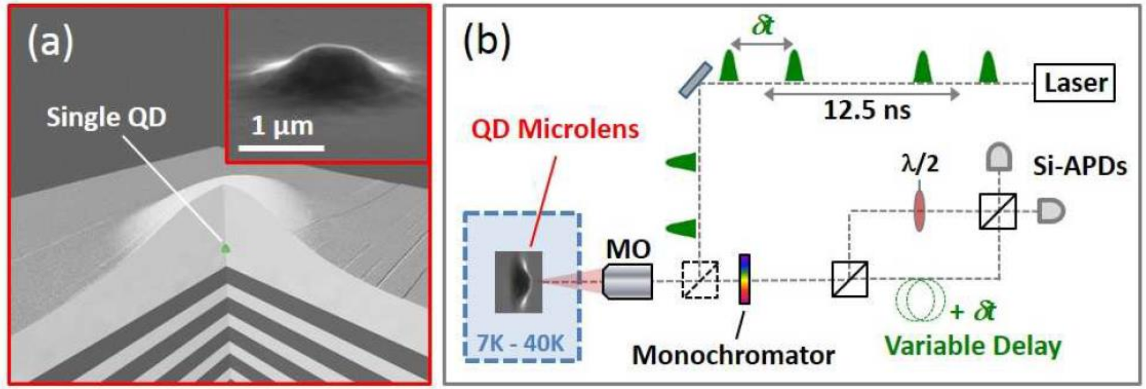

Thank you for the attention!

Technische Universität Berlin
Alexander Carmele (09.01.2019)
email: alex@itp.tu-berlin.de



Pulsed Hong-Ou-Mandel experiments on single quantum dots monitor the memory depth of environment fluctuations

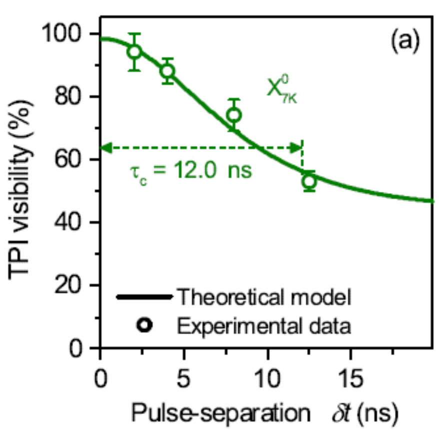
Thoma, AC et al, PRL 116, 033601 (2016)




$$\mathcal{H}_\mathrm{I} = \Omega(t)(\sigma_\mathrm{eg} + \sigma_\mathrm{ge}) + g \int d\omega\ e^{i(\omega-\omega_e)t - i\phi_0(t)} c_\omega \sigma_\mathrm{ge} + e^{-i(\omega-\omega_e)t + i\phi_0(t)} \sigma_\mathrm{eg} c_\omega$$

Figure of merit: two-times correlation function (for perfect indistinguishability → 0)

$$G^{(2)}(t_\mathrm{D},\tau) = g^4 \pi^4 e^{-\Gamma(2t_\mathrm{D}+\tau)} \cdot \left[\mathcal{T}^2 + \mathcal{R}^2 - 2\mathcal{R}\mathcal{T}\ \mathrm{Re}\left[\left\langle e^{-i\phi(t_\mathrm{D}+\tau) - i\phi_{\delta t}(t_\mathrm{D}) + i\phi_{\delta t}(t_\mathrm{D}+\tau) + i\phi(t_\mathrm{D})} \right\rangle\right]\right]$$




$$V(\delta t) = 1 - \int_0^\infty \int_0^\infty \mathrm{d}\tau \mathrm{d}t \frac{G^{(2)}(t,\tau)}{(\pi/2)^2}$$

However, for non-Markovian environment noise-induced dephasing depends on the pulse separation → pulse separation allows to read-out material memory kernel