

Steering quantum properties in nanostructured semiconductor environments

Alexander Carmele*

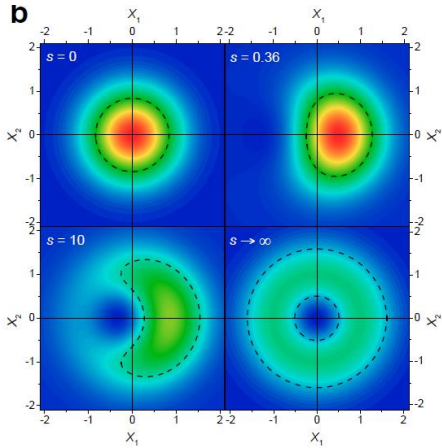


Technische Universität Berlin

*Collaborators: Alexander Thoma, Tobias Heindel, Julia Kabuss, Stephan Reitzenstein, and Andreas Knorr

Recent successes in semiconductor quantum optics

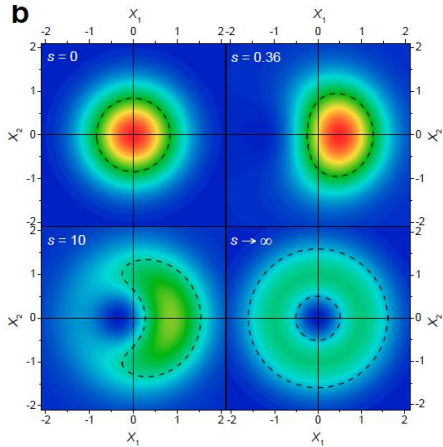
Schulte et al, Nature 525, 222 (2015)



Squeezed Photon
Emission from QD

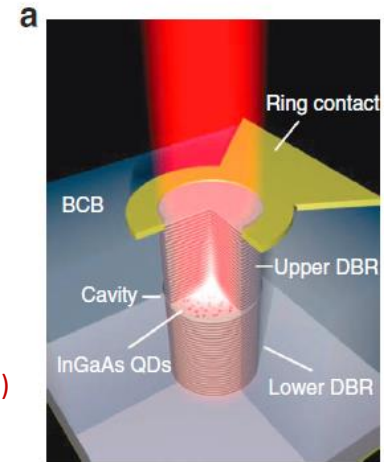
Recent successes in semiconductor quantum optics

Schulte et al, Nature 525, 222 (2015)

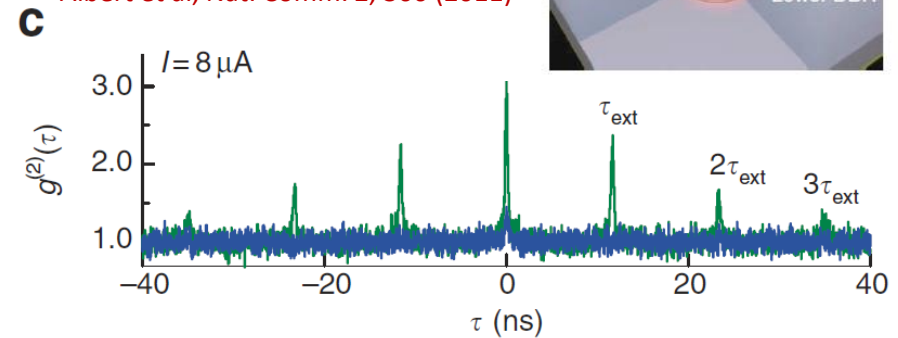


Squeezed Photon
Emission from QD

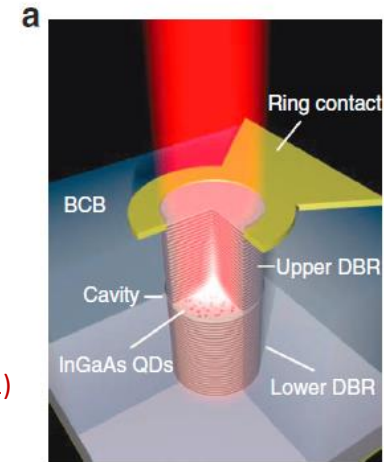
Quantum
Feedback



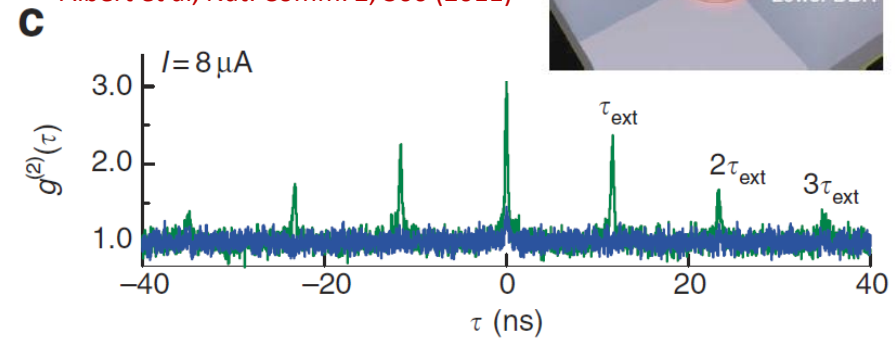
Albert et al, Nat. Comm. 2, 366 (2011)



Recent successes in semiconductor quantum optics

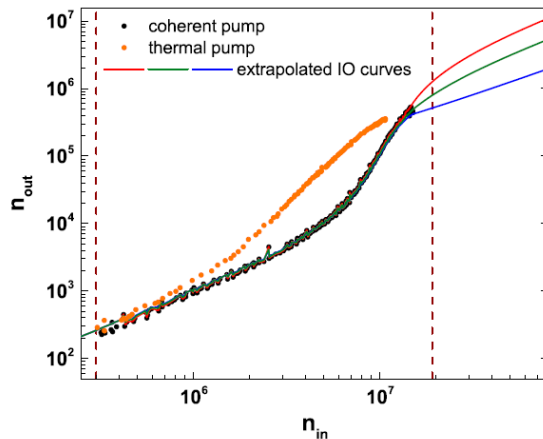
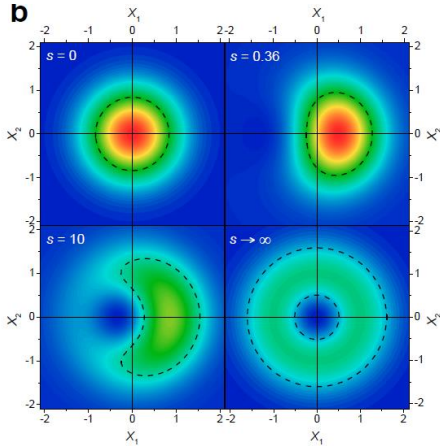


Albert et al, Nat. Comm. 2, 366 (2011)



Squeezed Photon
Emission from QD

Quantum
Feedback



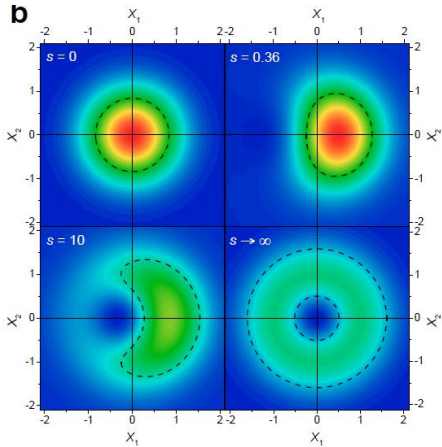
Höfling et al, PRL 115, 027401 (2015)

Strauß et al, PRB 93, 241306 (2016)

Quantum Light Excitation

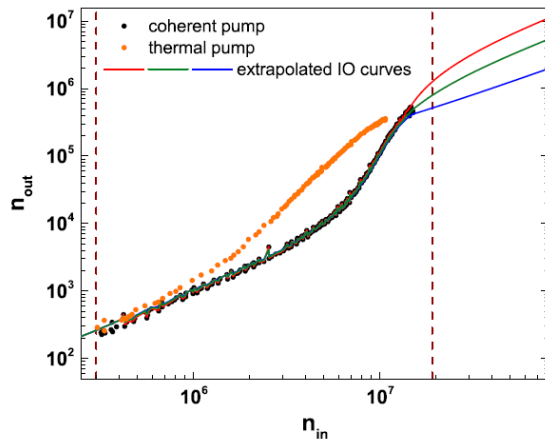
Recent successes in semiconductor quantum optics

Schulte et al, Nature 525, 222 (2015)



Squeezed Photon
Emission from QD

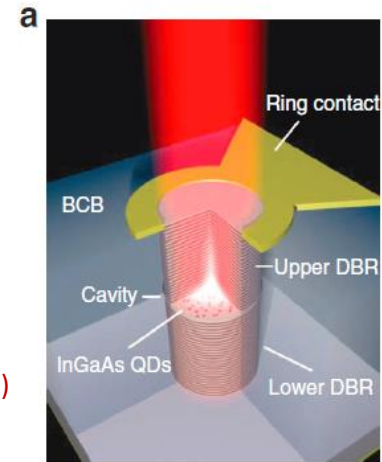
Quantum
Feedback



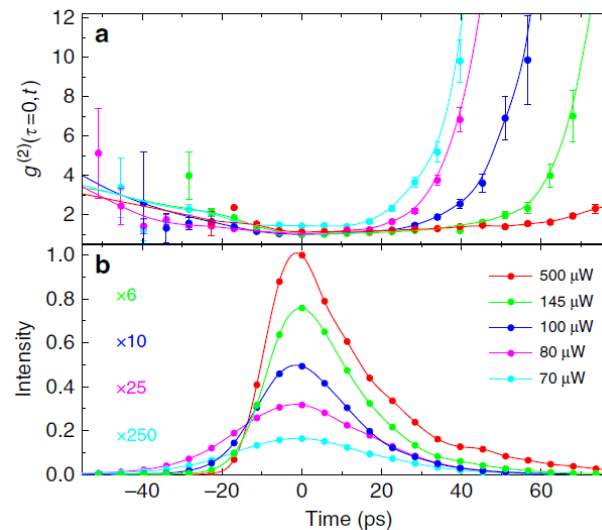
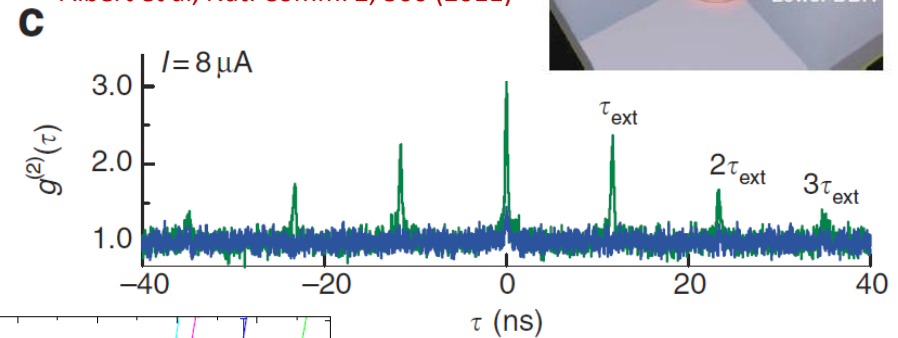
Höfling et al, PRL 115, 027401 (2015)

Strauß et al, PRB 93, 241306 (2016)

Quantum Light Excitation



Albert et al, Nat. Comm. 2, 366 (2011)

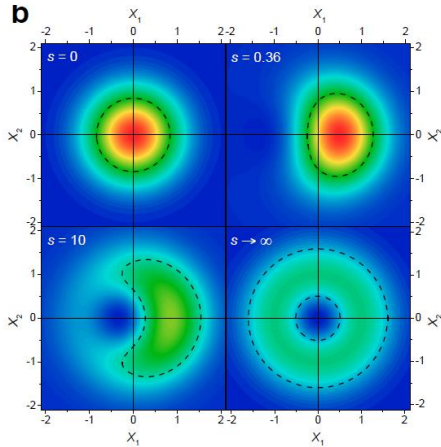


Giant Photon
bunching in QD
nanolasers

Jahnke et al, Nat. Comm. 7, 11540 (2016)

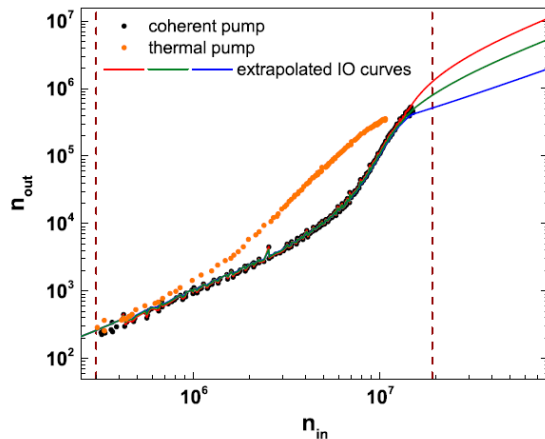
Recent successes in semiconductor quantum optics

Schulte et al, Nature 525, 222 (2015)



Squeezed Photon
Emission from QD

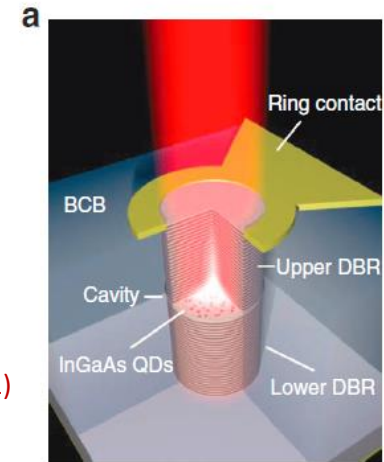
Quantum
Feedback



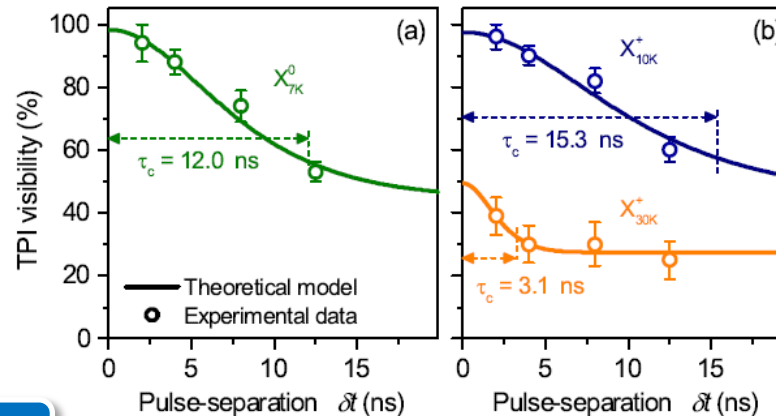
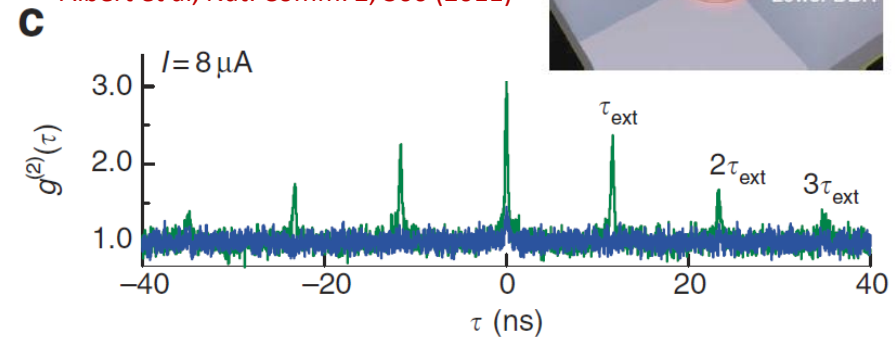
Höfling et al, PRL 115, 027401 (2015)

Strauß et al, PRB 93, 241306 (2016)

Quantum Light Excitation



Albert et al, Nat. Comm. 2, 366 (2011)



Thoma et al, PRL 116, 033601 (2016)

Two-Photon-
Interference with
96% visibility and
even higher

Ding et al, PRL 116, 020401 (2016)

Kim et al, Optica 3, 577 (2016)

Wang et al, PRL 116, 213601 (2016)

Outline

Steering quantum properties in nanostructured environments

- **Indistinguishable Photons from Semiconductor QDs**
 - Experiment by Thoma and Heindel: adjustable pulse sequences
 - Phenomenological model via stochastic forces
 - Noise correlation as indicator for interesting environment effects
- **Developing a microscopic model**
 - Deriving a general formalism in the Dirac picture
 - Method includes all kind of reservoirs and quantum noise effects
 - Applying this method to a pure dephasing mechanism

HOM effect

VOLUME 59, NUMBER 18

PHYSICAL REVIEW LETTERS

2 NOVEM

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)

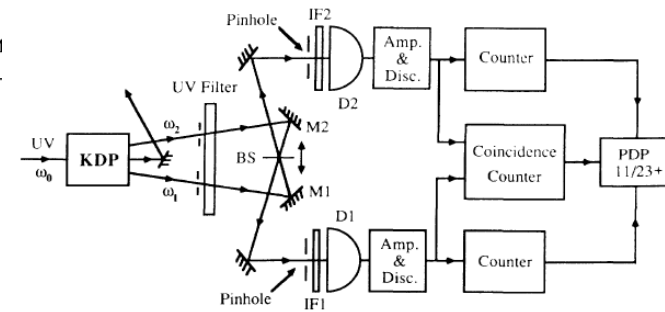


FIG. 1. Outline of the experimental setup.

Original Hong-Ou-Mandel Experiment

- Two-Photon-Source: Spontaneous parametric downconversion
- Send on a beam splitter and HBT setup
- No-coincidence, when beam splitter in middle of M1 and M2
- Explained by quantum mechanical treatment of beam splitter

HOM effect

VOLUME 59, NUMBER 18

PHYSICAL REVIEW LETTERS

2 NOVEM

Measurement of Subpicosecond Time Intervals between Two Photons by Interference

C. K. Hong, Z. Y. Ou, and L. Mandel

Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

(Received 10 July 1987)

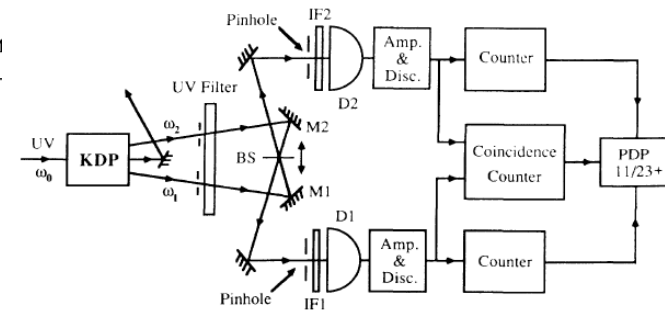
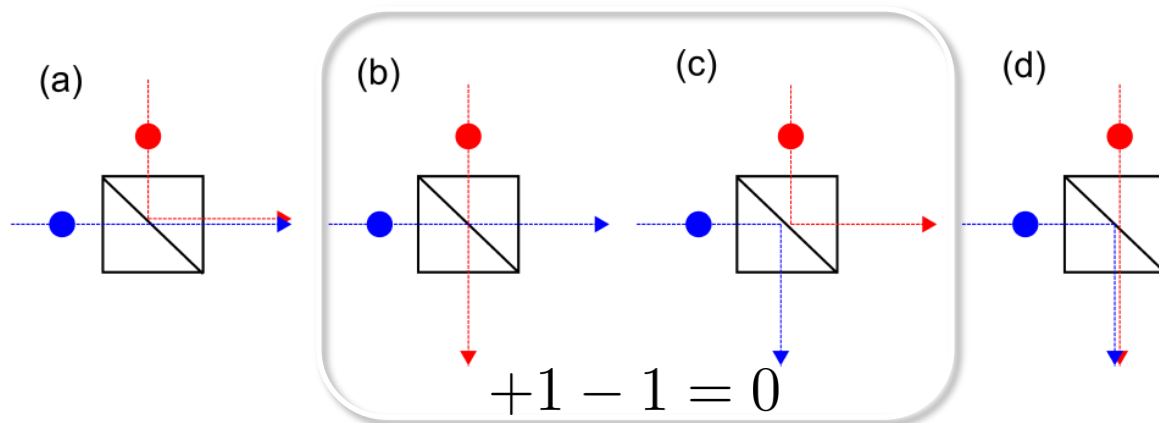


FIG. 1. Outline of the experimental setup.

Original Hong-Ou-Mandel Experiment

- Two-Photon-Source: Spontaneous parametric downconversion
- Send on a beam splitter and HBT setup
- No-coincidence, when beam splitter in middle of M1 and M2
- Explained by quantum mechanical treatment of beam splitter



HOM - SC QDs

letters to nature

Indistinguishable photons from a single-photon device

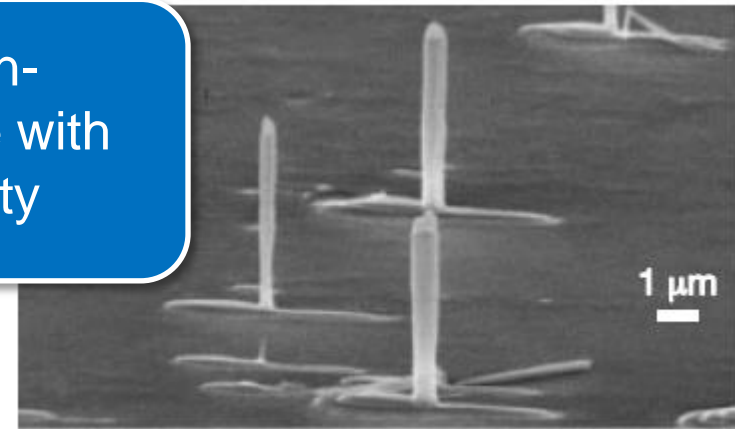
Charles Santori*, David Fattal*, Jelena Vučković*, Glenn S. Solomon*† & Yoshihisa Yamamoto*‡

* Quantum Entanglement Project, ICORP, JST, E. L. Ginzton Laboratory, Stanford University, Stanford, California 94305-4088, USA

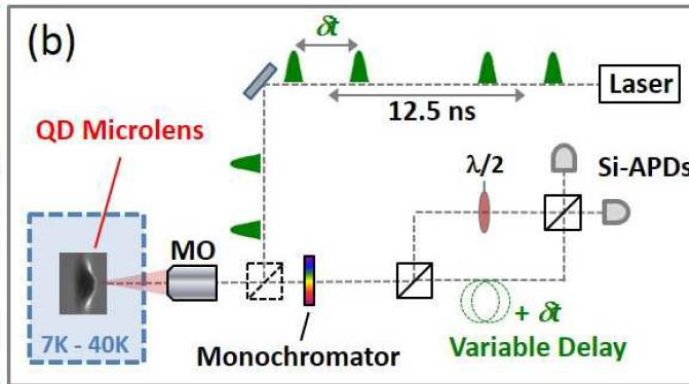
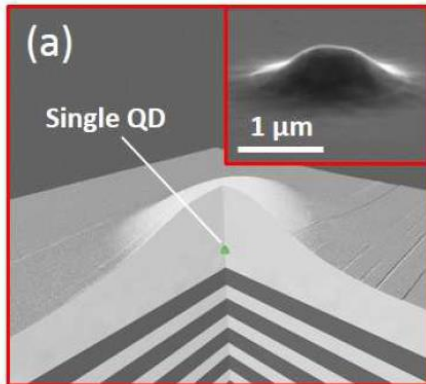
† Solid-State Photonics Laboratory, Stanford University, Stanford, California 94305-4085, USA

‡ NTT Basic Research Laboratories, Atsugi, Kanagawa, 243-0198, Japan

Two-Photon-Interference with 81% visibility



Santori et al, Nature 419, 594 (2002)



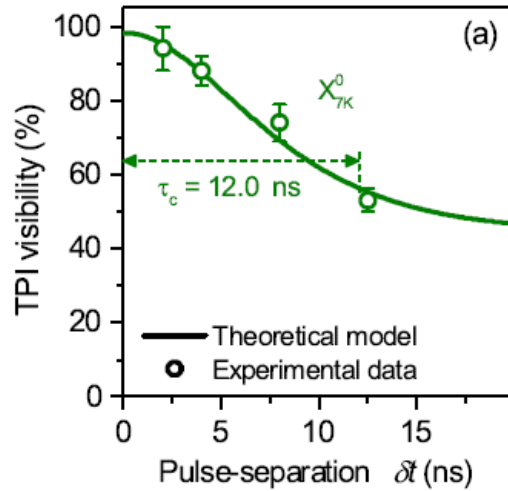
Two-Photon-Interference with 96+/-4% visibility

Thoma et al, PRL 116, 033601 (2016)

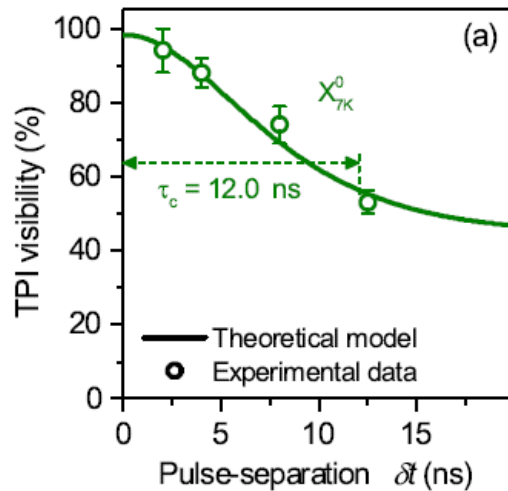
Pulsed Hong-Ou-Mandel Experiment

- Recent HOM experiments in SC are pulsed
- Probing environmental dynamics possible

Theoretical model: Stochastic forces



Theoretical model: Stochastic forces



Pulsed Hong-Ou-Mandel Experiment

- Observable is the coincidence rate
- Fit data to a noise correlation length parameter
- Hamiltonian with a stochastic force

$$\mathcal{V} = 1 - \bar{g}^{(2)}$$

$$\mathcal{H}/\hbar = (\mathcal{H}_0 + \mathcal{H}_W + \mathcal{H}_A)/\hbar = (\omega_e + F(t)) \sigma_{ee} + \Omega(t) \left(e^{-i\omega_{pt}} \sigma_{eg} + e^{+i\omega_{pt}} \sigma_{ge} \right) + \int_0^\infty d\omega \left(\omega c_\omega^\dagger c_\omega + g_\omega c_\omega^\dagger \sigma_{ge} + g_\omega^* \sigma_{eg} c_\omega \right).$$

$$\phi_{t_1} = \int_{t_1}^t dt' F(t')$$

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

Theoretical model: Stochastic forces

Two-photon state includes excitation times

- Stochastic forces have different initial times

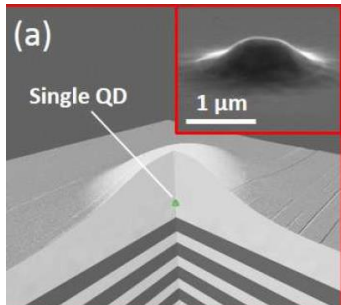
$$|\Psi(t)\rangle = |\Psi(t)\rangle_{\delta t} \otimes |\Psi(t)\rangle_0 = \left[-ig \int_0^\infty d\omega_S \int_{\delta t}^t dt_S e^{i(\omega_S - \omega_e)t_S - i\phi_{\delta t}(t_S) - \Gamma t_S} c_{\omega_S}^\dagger |0_{\omega_S}\rangle \right] \\ \otimes \left[-ig \int_0^\infty d\omega_L \int_0^t dt_L e^{i(\omega_L - \omega_e)t_L - i\phi_0(t_L) - \Gamma t_L} c_{\omega_L}^\dagger |0_{\omega_L}\rangle \right]$$

Evaluation of coincidence counting

- Stochastic forces need additional averaging

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

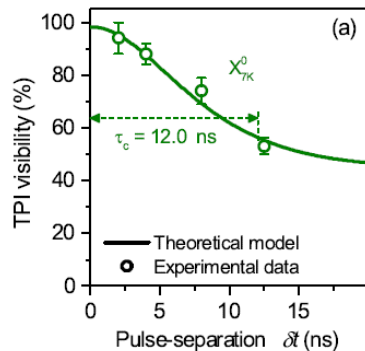
Theoretical model: Stochastic forces



Determination of noise correlations

- Colored noise related to telegraph noise

$$\langle \phi_{t_1}(t_2) \phi_{t_3}(t_4) \rangle = \int_{t_1}^{t_2} dt \int_{t_3}^{t_4} dt' \langle F(t) F(t') \rangle = e^{-\frac{(t_1 - t_3)^2}{\tau_c^2}} (\min[t_2, t_4] - \max[t_1, t_3])$$



Evaluate via Cumulant Expansion

- different integration times leads to the desired dephasing mechanism

$$\gamma' = \Gamma'_0 \left(1 - \exp[-(\delta t / \tau_c)^2] \right) + \gamma$$

$$G^{(2)}(t_D, \tau) = g^4 \pi^4 e^{-2\Gamma t_D} \left[\mathcal{T}^2 e^{-\Gamma|\tau|} + \mathcal{R}^2 e^{-\Gamma|\tau|} - 2\mathcal{R}\mathcal{T} e^{-(\gamma' + \Gamma)|\tau|} \right]$$

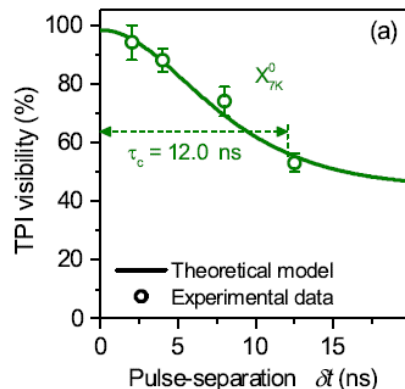
Theoretical model: Quantum Noise

Phenomenological vs. quantum mechanical model

- Stochastic force allows a direct link and fit to the experimental data
- However, the stochastic force is an effective model of underlying processes, and
- Possible feasible properties of the underlying mechanism stays hidden

$$H|_{\text{noise}} = F(t) P^\dagger P \rightarrow$$

$$P \equiv \sigma_{ge}$$



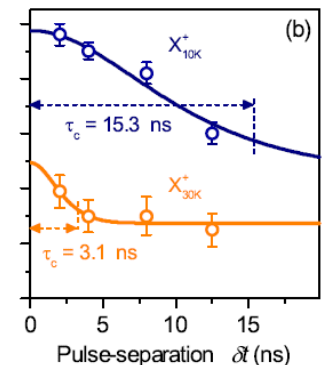
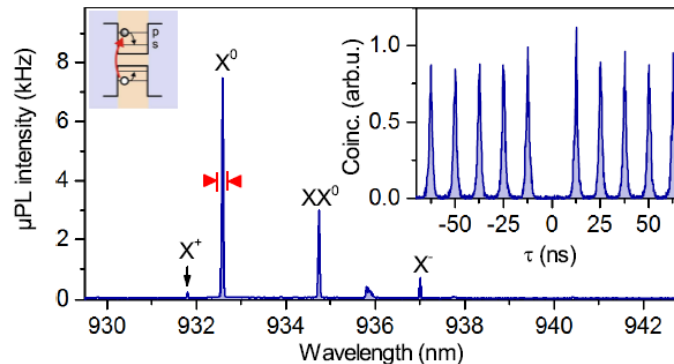
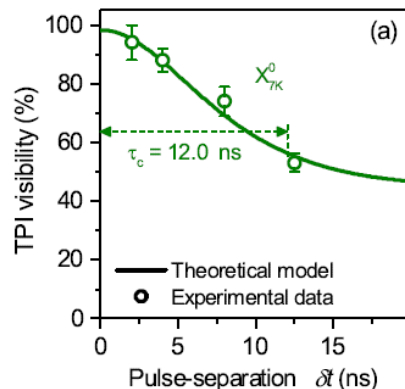
Theoretical model: Quantum Noise

Phenomenological vs. quantum mechanical model

- Stochastic force allows a direct link and fit to the experimental data
- However, the stochastic force is an effective model of underlying processes, and
- Possible feasible properties of the underlying mechanism stays hidden

$$H|_{\text{noise}} = F(t) P^\dagger P \rightarrow$$

$$P \equiv \sigma_{ge}$$

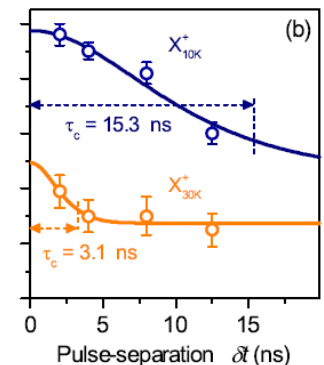
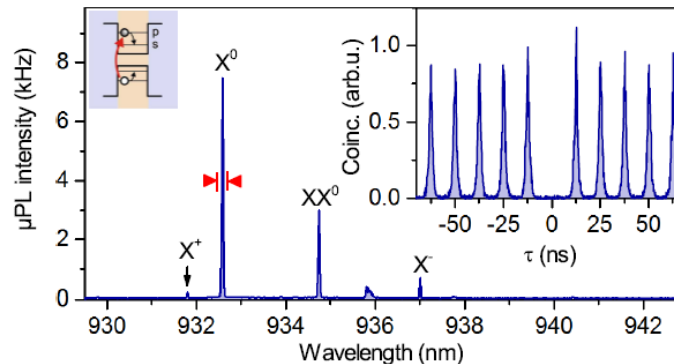
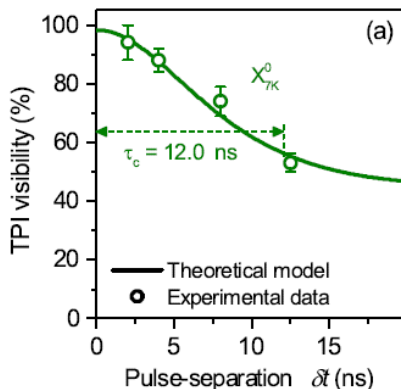


Theoretical model: Quantum Noise

Phenomenological vs. quantum mechanical model

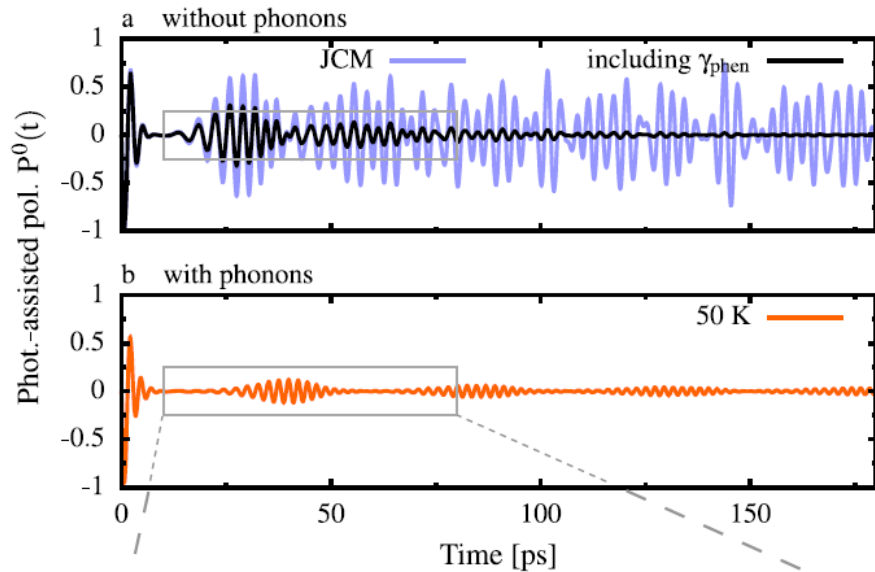
- Stochastic force allows a direct link and fit to the experimental data
- However, the stochastic force is an effective model of underlying processes, and
- Possible feasible properties of the underlying mechanism stays hidden

$$H|_{\text{noise}} = F(t) P^\dagger P \rightarrow H|_{\text{noise}} = P^\dagger P \sum_q g_q b_q^\dagger + g_q^* b_q \quad P \equiv \sigma_{ge}$$

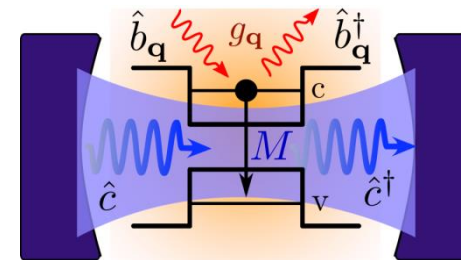


Theoretical proposals based on phonons

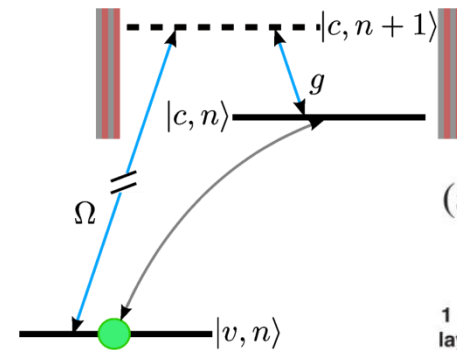
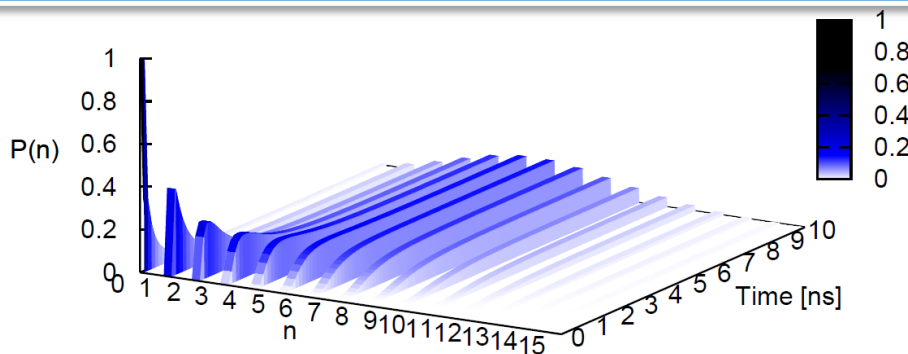
Carmelet et al, NJP 15, 105024 (2013)



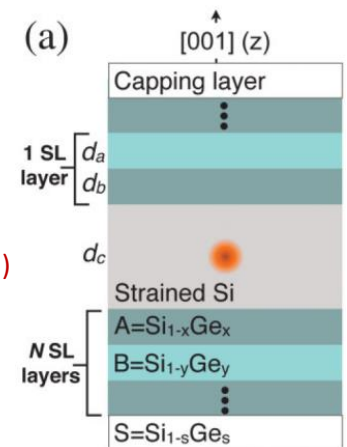
Phonon-induced
coherence in QD-cQED



Phonon stimulated emission allows
for mechanical lasing



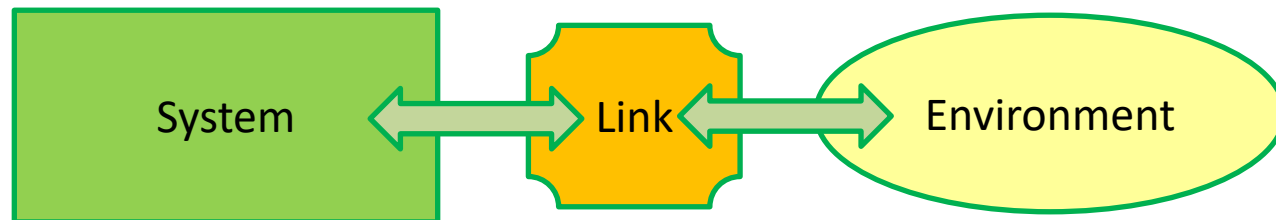
Kabuss et al, PRL 109, 54301 (2012)



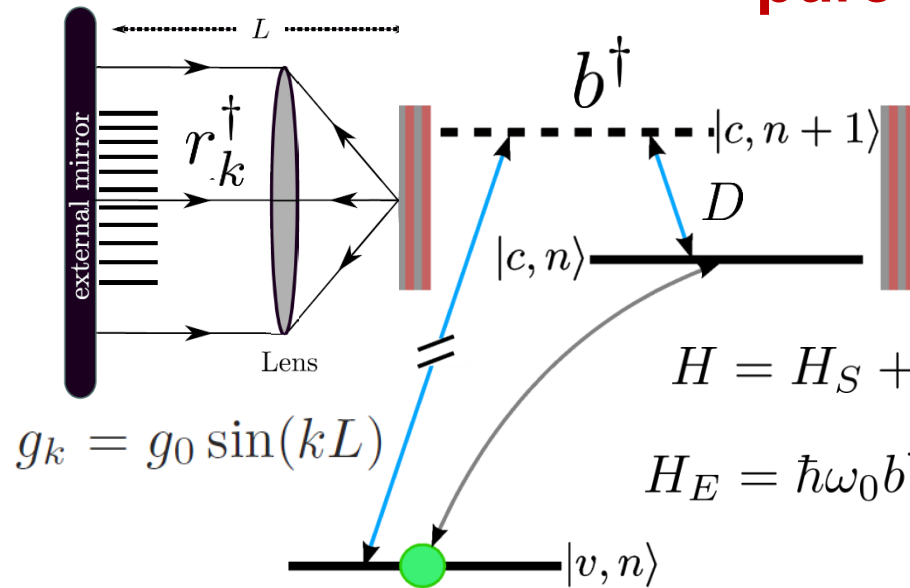
Deriving a quantum model: A sketch

Full quantum treatment of the environment

- System of interest (e.g. dipole density)
- Include a link-boson between system and environment
- Leave the environment as general as possible but as bosons with or without structure
- Trace out the environment, now completely included in link-boson dynamics



Feedback controlled pure dephasing



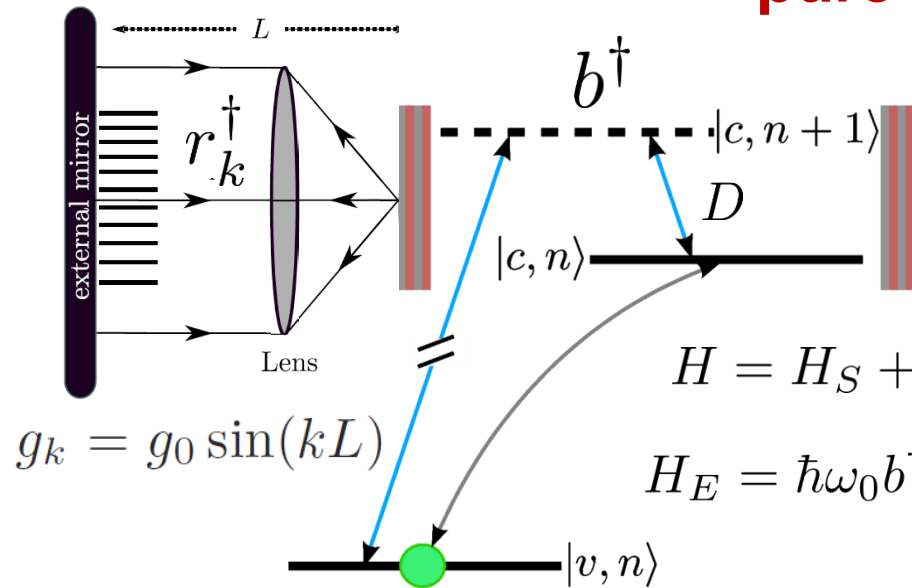
Environment controlled
phonon cavity dynamics

$$H = H_S + H_E$$

$$H_S = \hbar [\omega_e + D(b^\dagger + b)] P^\dagger P$$

$$H_E = \hbar \omega_0 b^\dagger b + \int dk \omega_k r_k^\dagger r_k + \int dk g_k (r_k^\dagger b + b^\dagger r_k)$$

Feedback controlled pure dephasing



Environment controlled
phonon cavity dynamics

$$H = H_S + H_E$$

$$H_S = \hbar [\omega_e + D(b^\dagger + b)] P^\dagger P$$

$$H_E = \hbar \omega_0 b^\dagger b + \int dk \omega_k r_k^\dagger r_k + \int dk g_k (r_k^\dagger b + b^\dagger r_k)$$

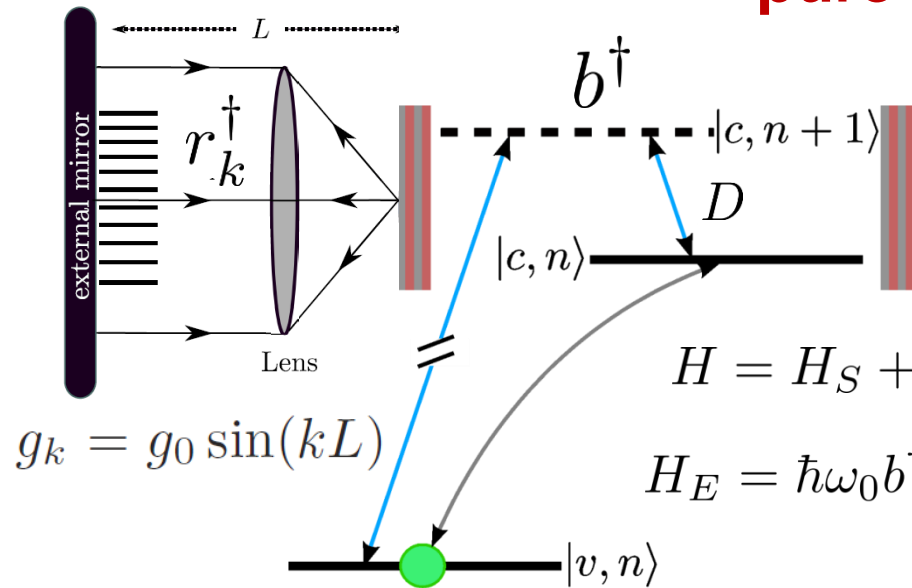
Choose interaction picture

$$U = \exp \left[\frac{i}{\hbar} H_E t \right]$$

Solution includes the full
dynamics of the reservoir

$$U b(0) U^{-1} = f(t) b(0) + \int dk g(k, t) r_k(0) = b(t)$$

Feedback controlled pure dephasing



Environment controlled
phonon cavity dynamics

$$H = H_S + H_E$$

$$H_S = \hbar [\omega_e + D(b^\dagger + b)] P^\dagger P$$

$$H_E = \hbar \omega_0 b^\dagger b + \int dk \omega_k r_k^\dagger r_k + \int dk g_k (r_k^\dagger b + b^\dagger r_k)$$

Choose interaction picture

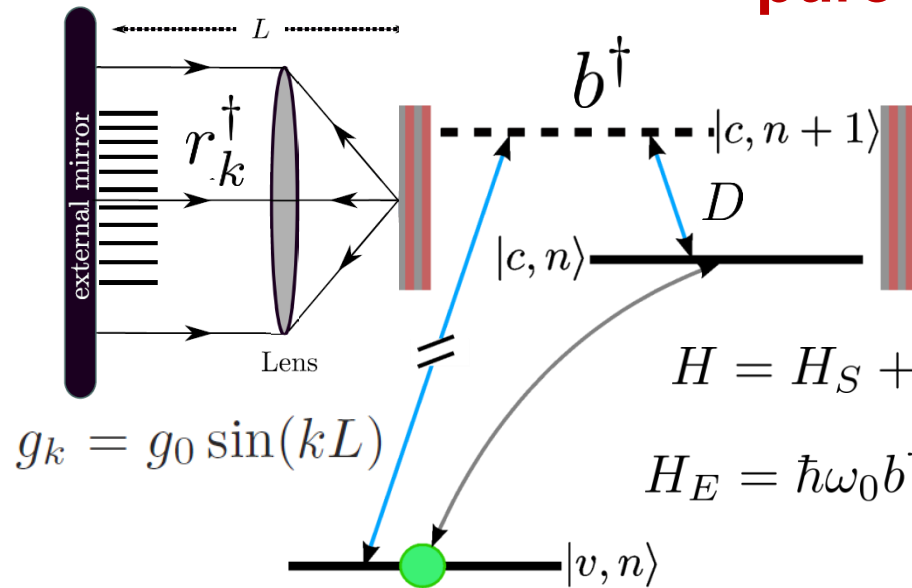
$$U = \exp \left[\frac{i}{\hbar} H_E t \right]$$

Solution includes the full
dynamics of the reservoir

$$U b(0) U^{-1} = f(t) b(0) + \int dk g(k, t) r_k(0) = b(t)$$

$$H_I = U H U^{-1} - (i/\hbar) U \partial_t U^{-1} = \hbar [\omega_e + D(b^\dagger(t) + b(t))] P^\dagger P$$

Feedback controlled pure dephasing



Environment controlled
phonon cavity dynamics

$$H = H_S + H_E$$

$$H_S = \hbar [\omega_e + D(b^\dagger + b)] P^\dagger P$$

$$H_E = \hbar \omega_0 b^\dagger b + \int dk \omega_k r_k^\dagger r_k + \int dk g_k (r_k^\dagger b + b^\dagger r_k)$$

Choose interaction picture

$$U = \exp \left[\frac{i}{\hbar} H_E t \right]$$

Solution includes the full
dynamics of the reservoir

$$U b(0) U^{-1} = f(t) b(0) + \int dk g(k, t) r_k(0) = b(t)$$

Quantum noise
without quantum
kinetics!

$$H_I = U H U^{-1} - (i/\hbar) U \partial_t U^{-1} = \hbar [\omega_e + D(b^\dagger(t) + b(t))] P^\dagger P$$

$$F(t) \rightarrow D [b(t) + b^\dagger(t)]$$

Feedback controlled pure dephasing

$$\dot{\rho}_I(t) = \frac{i}{\hbar} [H_I(t), \rho_I(t)] = \mathcal{L}_I(t) \rho_I(t)$$

$$\rho_I(t) = \hat{T} \exp \left(\frac{i}{\hbar} \int_0^t \mathcal{L}_I(t) \right) \rho_I(0)$$

Dirac picture simplifies the
Hamiltonian w/ quantum
noise and temperatures

Feedback controlled pure dephasing

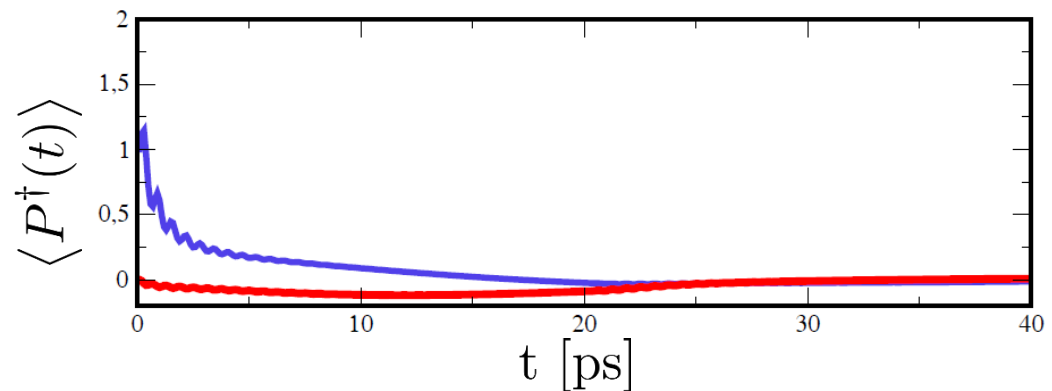
$$\dot{\rho}_I(t) = \frac{i}{\hbar} [H_I(t), \rho_I(t)] = \mathcal{L}_I(t) \rho_I(t)$$

$$\rho_I(t) = \hat{T} \exp \left(\frac{i}{\hbar} \int_0^t \mathcal{L}_I(t) \right) \rho_I(0)$$

$$\langle P^\dagger(t) \rangle = \exp \left[F(t) + \int dk (n_k + 1) G_k(t) + n_k G_k^*(t) \right]$$

Dirac picture simplifies the
Hamiltonian w/ quantum
noise and temperatures

With tractable parameters
interesting dephasing
dynamics can be explained



Quantum control model

- Exploit the linear interaction between the link-boson and the environment to control system parameters of interest

Conclusion

- Recent progress in the nanofabrication of quantum emitters
- Interesting dephasing effects in Hong-Ou-Mandel experiments
- Dephasing explained by a phenomenological model
- Method to connect such a stochastic force model to microscopic parameters
- Method applied to a pure dephasing model with feedback, including thermal, squeezed and single quantum contributions

Thank you for your attention!

