Non-Markovian quantum feedback control of photon statistics and quantum many body dynamics

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Semiconductor quantum optics

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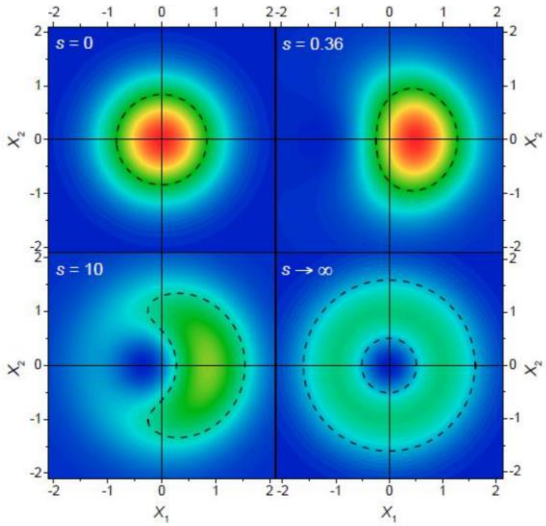
Walls and Zoller, PRL 47, 709 (1981)
Schulte et al, Nature 525, 222 (2015)



Laser-driven quantum dot exhibits squeezing in resonance fluorescence

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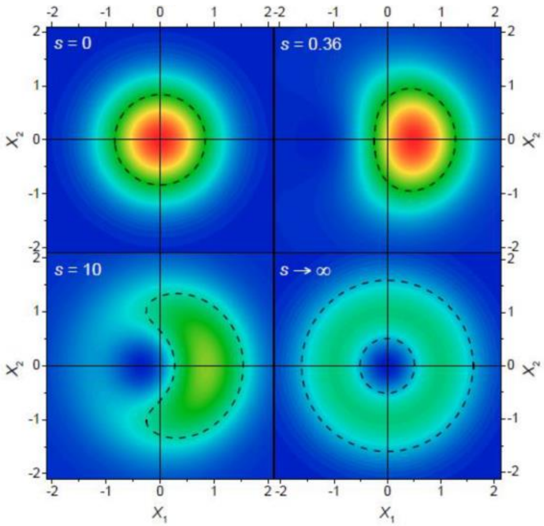

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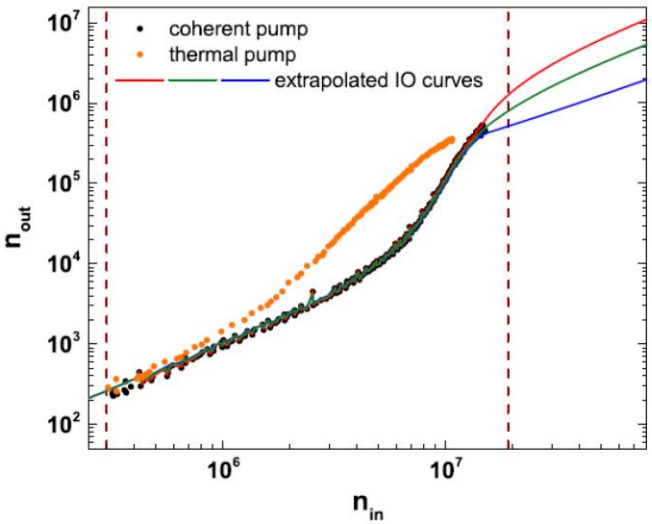
Quantum cascaded-driven laser systems exhibit qualitatively different thereshold behavior and input-output curve



Höfling et al, PRL 115, 027401 (2015)

Quantum optics of nanostructures in dissipative environments

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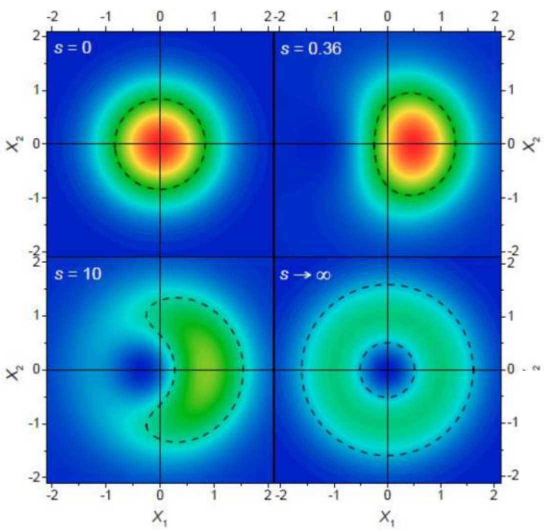

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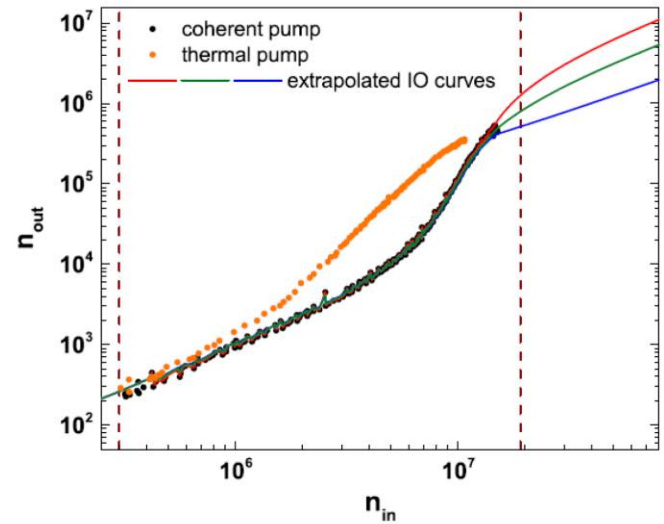

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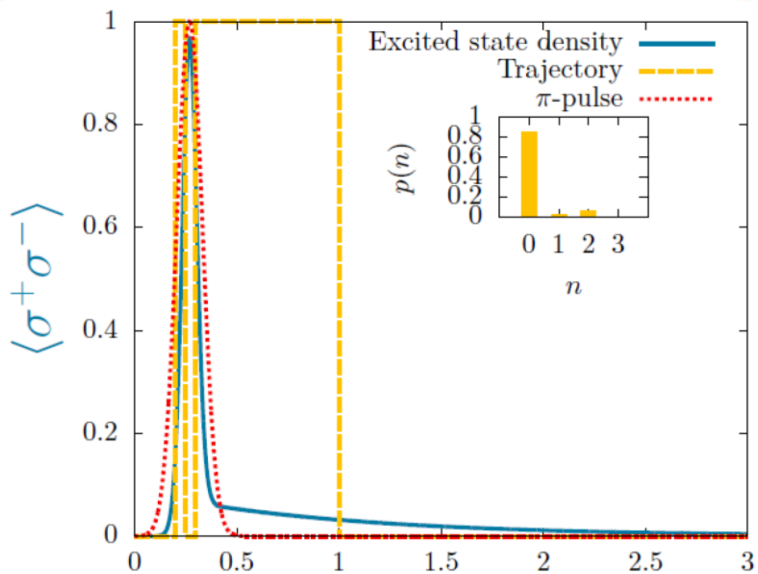

K. Fischer et al., Nat. Phys. 13, 649 (2017)

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

Example of Markovian quantum optical signals

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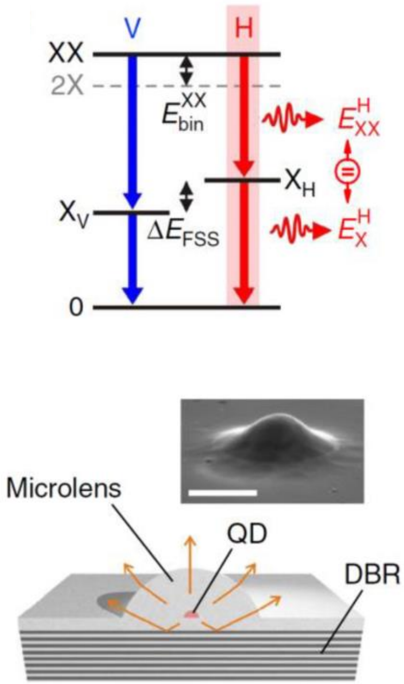
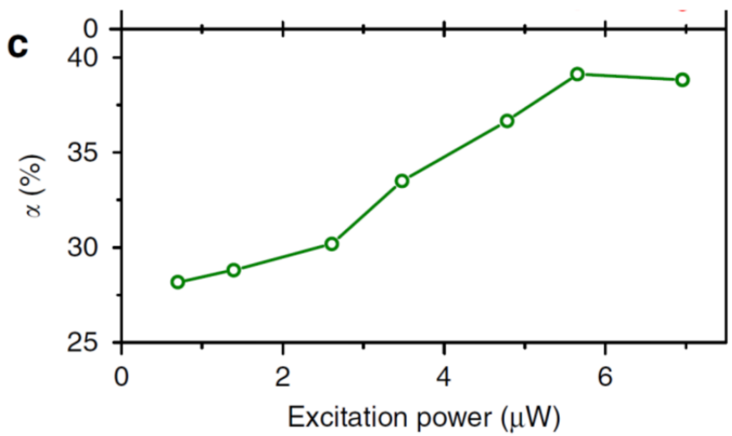


Ideal two-photon source of a quantum dot microlense with high brightness and fast repetition rate

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



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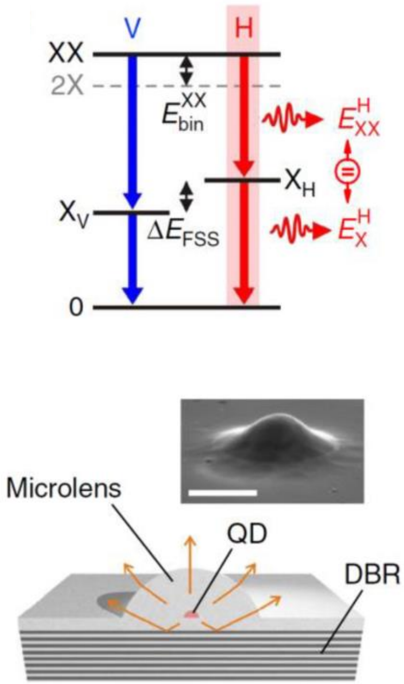

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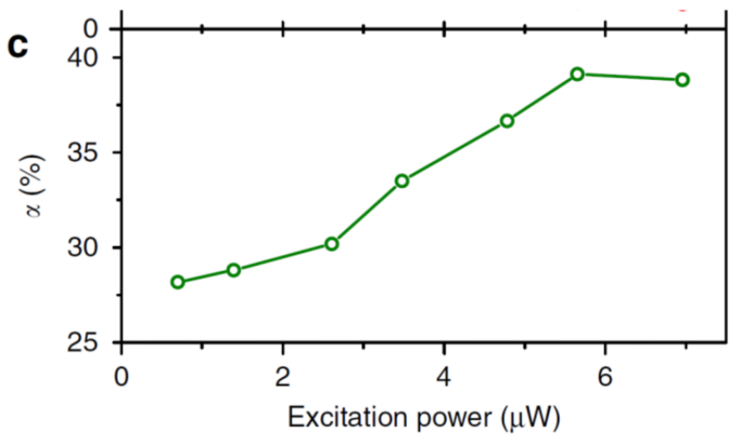
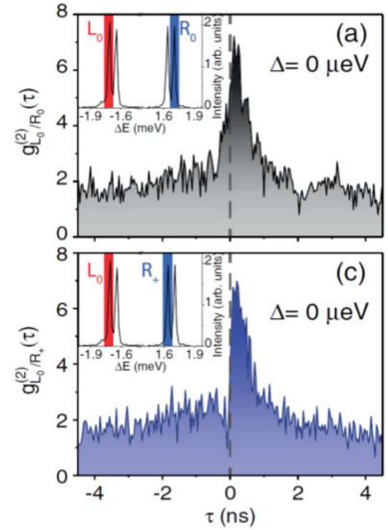


Time-reordered photon pairs of a biexciton driven at two-photon resonance

Bounouar, AC et al, PRL 118, 233601 (2017)



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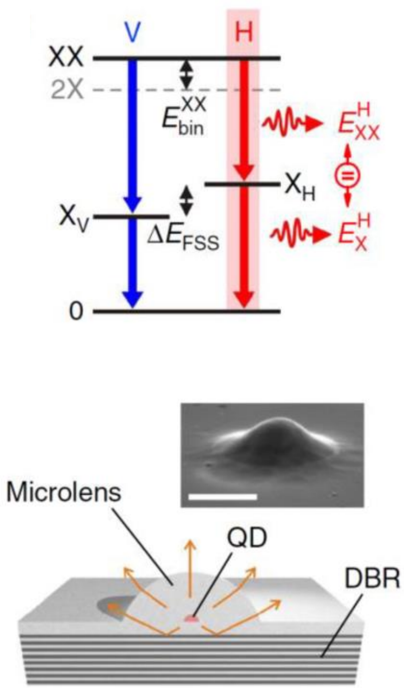

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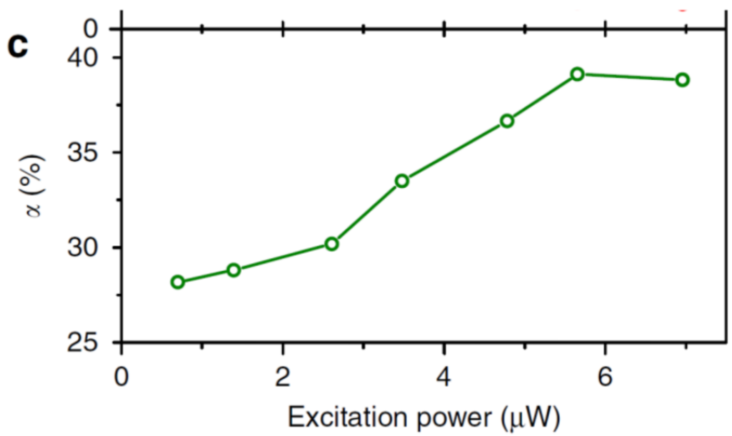

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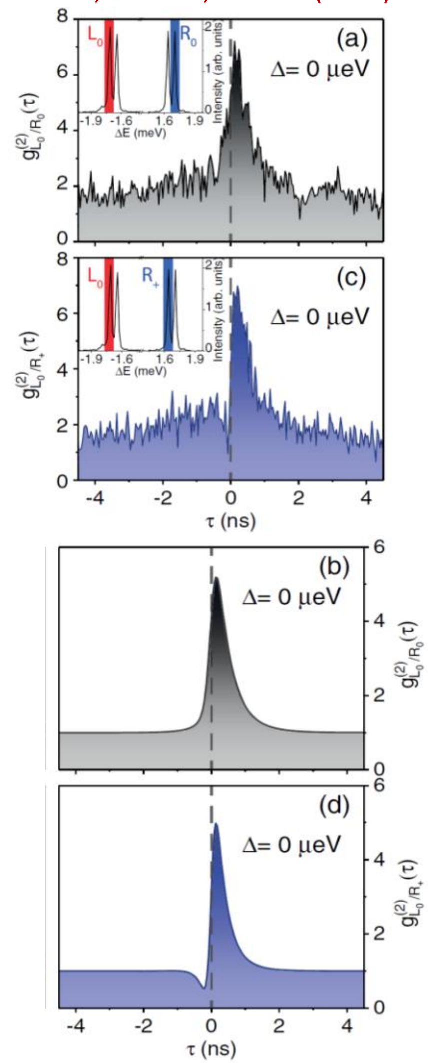

$$\partial_t\,\rho(t) = -\frac{i}{\hbar}\,[H(t),\,\rho(t)] + \sum_{\alpha} L[C_\alpha]\rho(t)$$

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

Schleibner, AC et al, arXiv:1710.03031

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

Example of non-Markovian quantum optical signals

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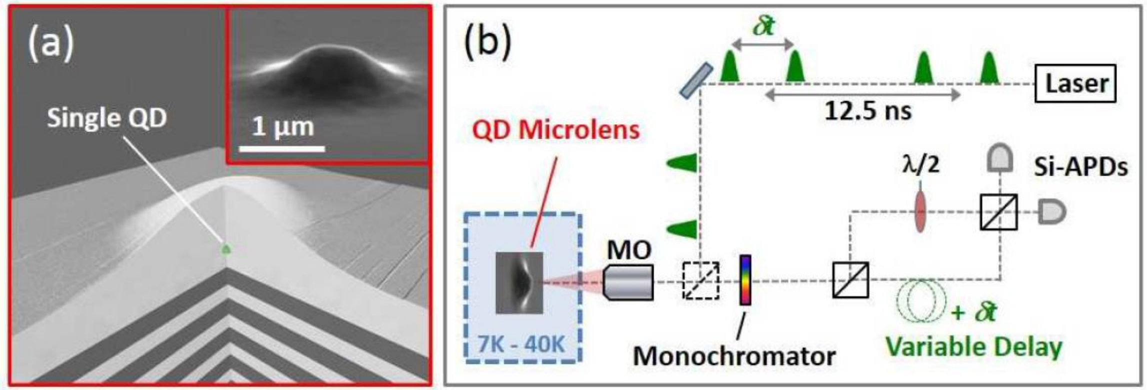
Pulsed Hong-Ou-Mandel experiments on single quantum dots allow to monitor the memory depth of environment fluctuations

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



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

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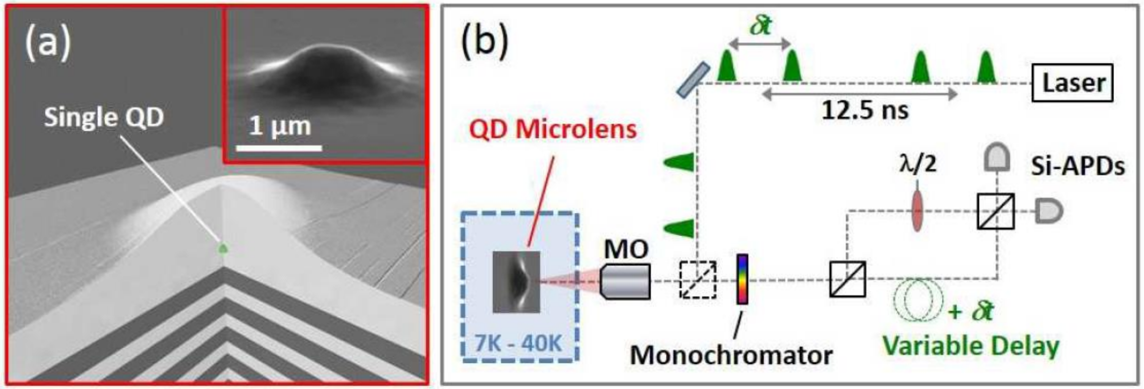

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Figure of merit: two-times correlation function (for perfect indistinguishability → 0)

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

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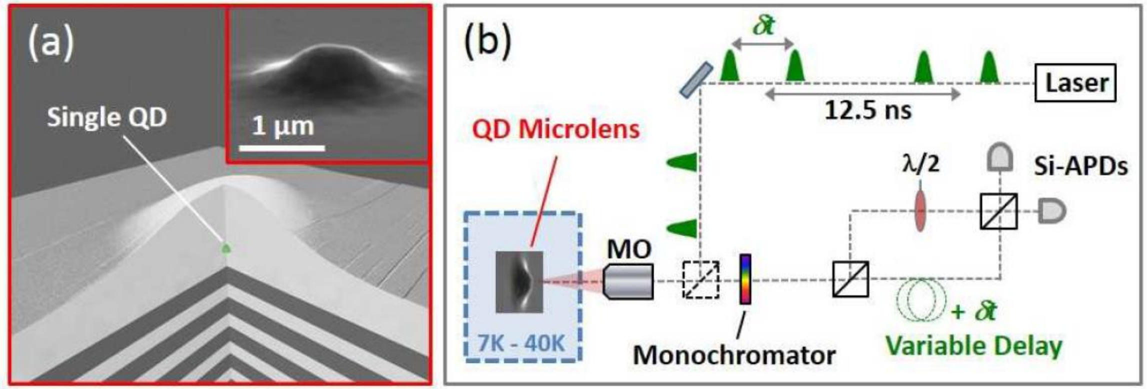

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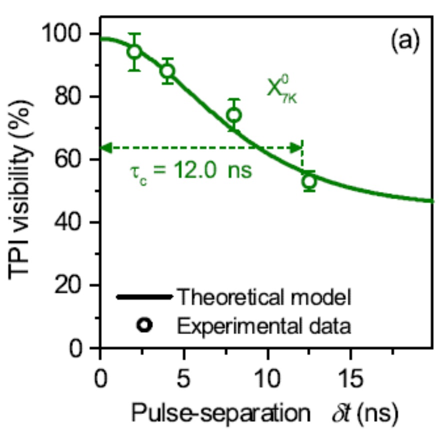
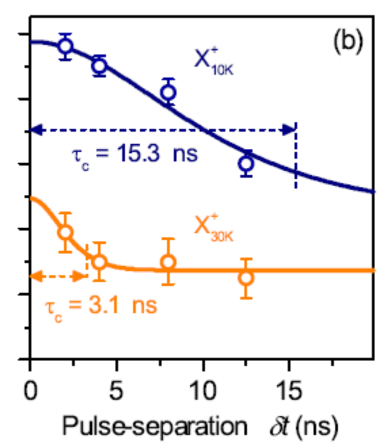


However, for non-Markovian environment noise-induced dephasing depends on the pulse separation → pulse separation allows to read-out material memory kernel



Non-Markovian quantum control

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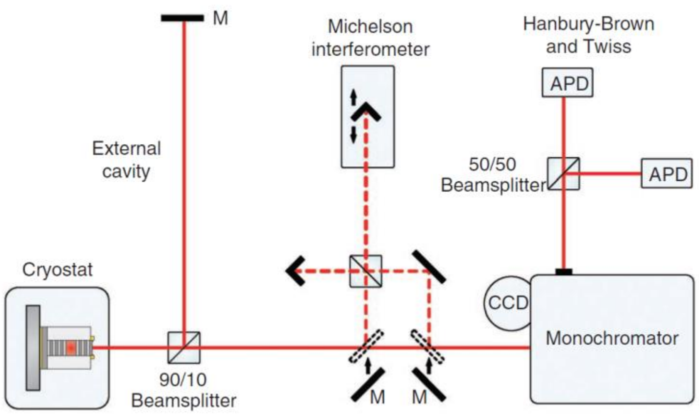
External mirror serves as control device



In principle (many photon, many emitter limit), to be modelled in a Lang-Kobayashi approach for the field amplitude

$$\mathcal{E} = \sqrt{N_{\mathrm{ph}}(t)}\, \mathrm{e}^{-\mathrm{i}\phi(t)}$$

Lang, Kobayashi, IEEE J. Quantum Electron. 16, 347 (1980)

Classical feedback control of semiconductor-based laser devices

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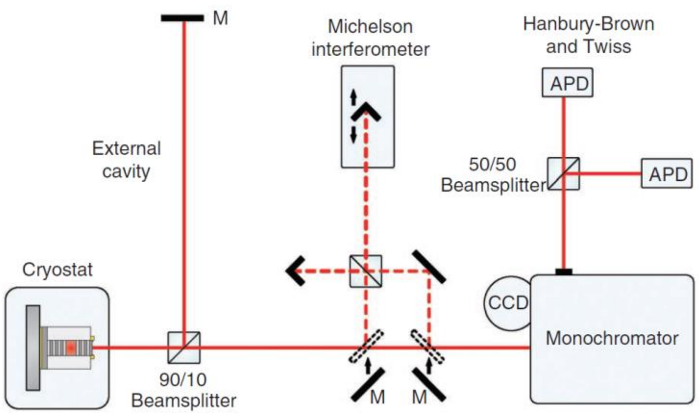
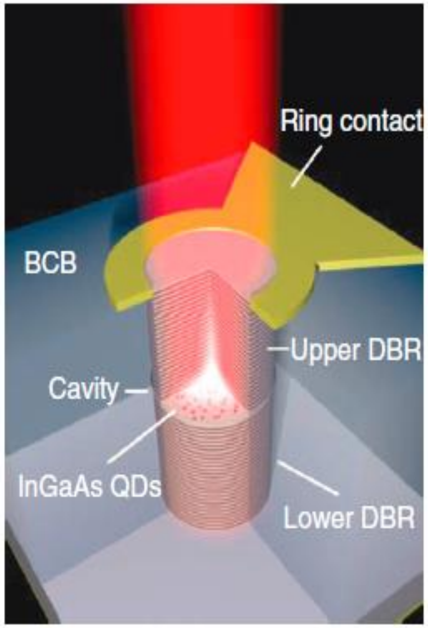


Feedback-induced nonlinear behavior in the output statistics of micropillar lasers



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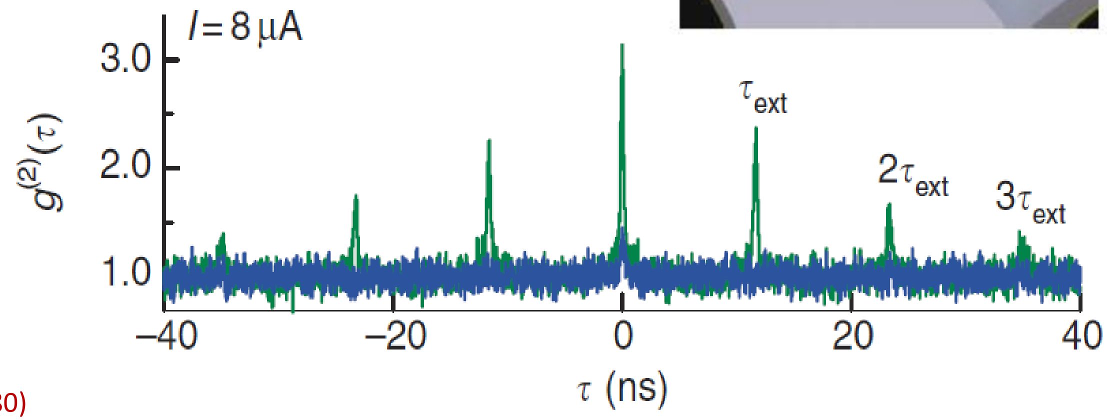

Albert et al, Nat. Comm. 2, 366 (2011)

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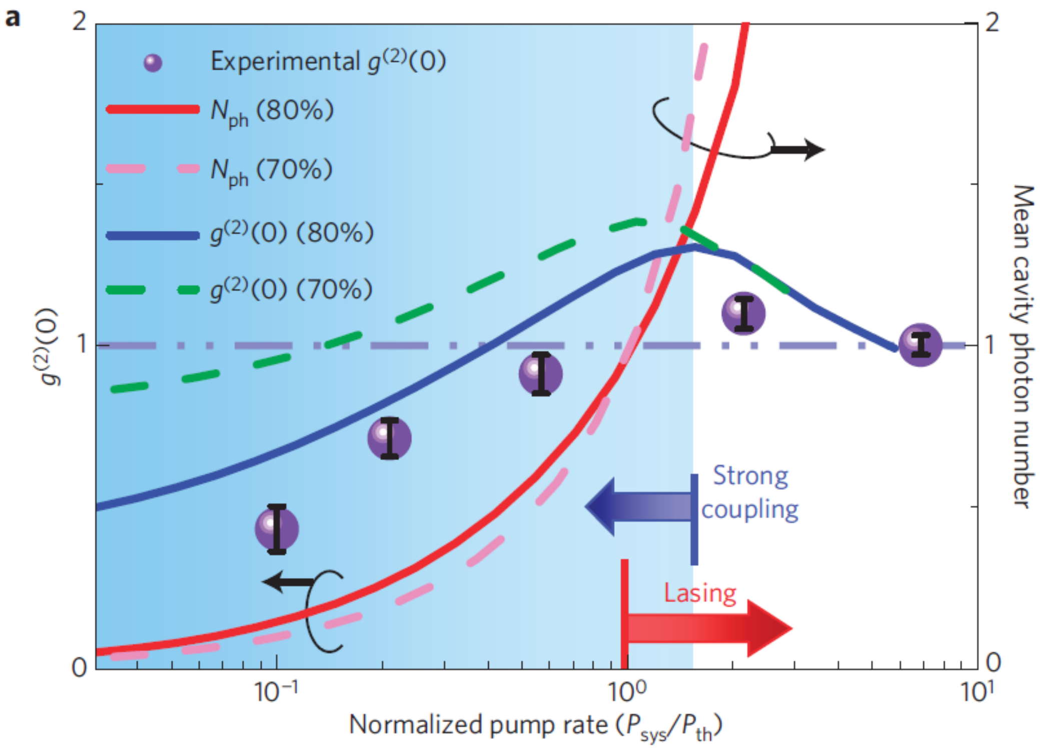
Lasing in the non-classical regime
(time-local correlation function):

Nomura et al, Nat. Phys. 6, 279 (2010)



An incoherently-pumped single quantum dot exhibits a strong non-classical output

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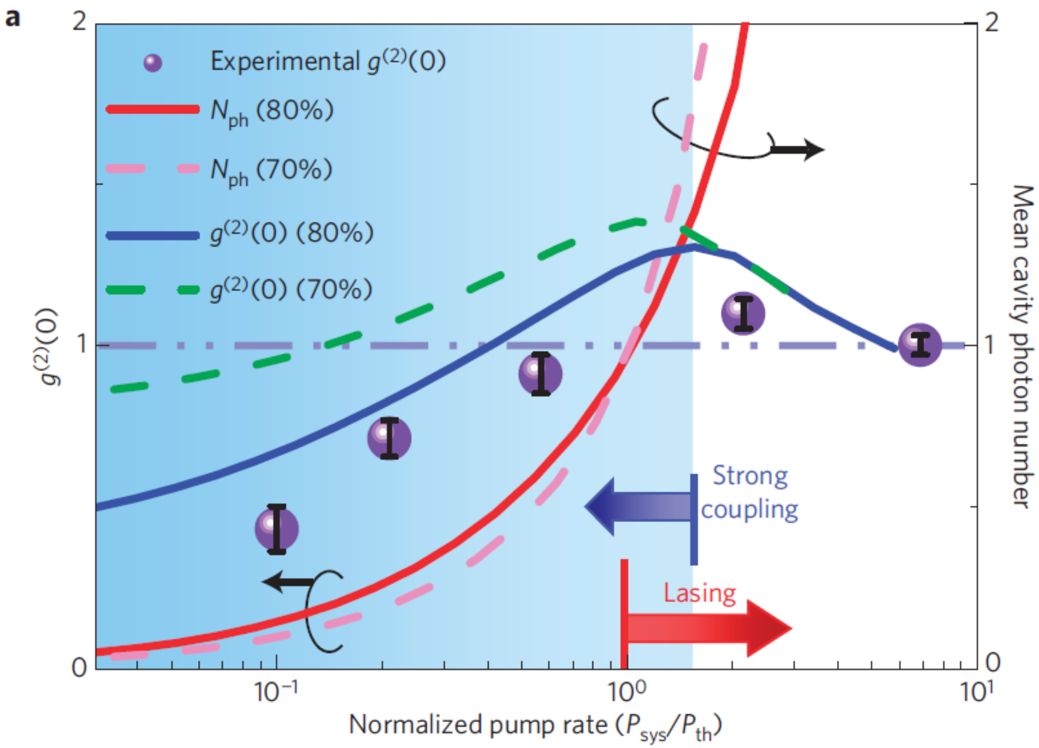
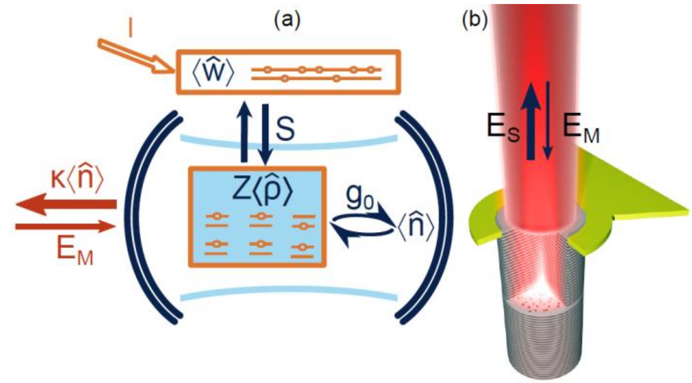
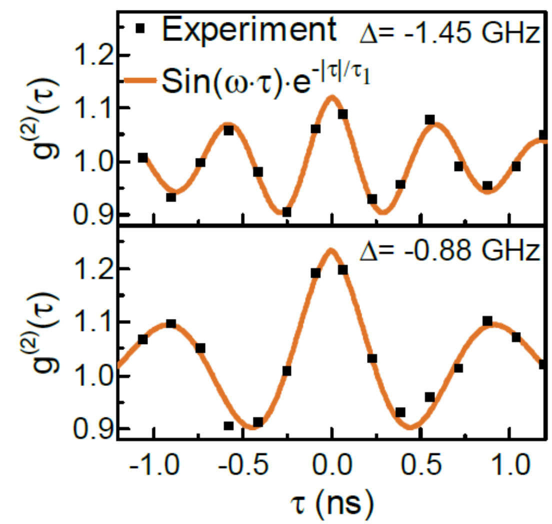




Schlottmann et al, Phys. Rev. Appl. 6, 44023 (2016)



$$\mathcal{E} = \sqrt{N_{ph}(t)}\, e^{-i\phi(t)}$$

An incoherently-pumped single quantum dot exhibits a strong non-classical output

Few-emitter dynamics, even driven with classical field amplitudes leads quantum

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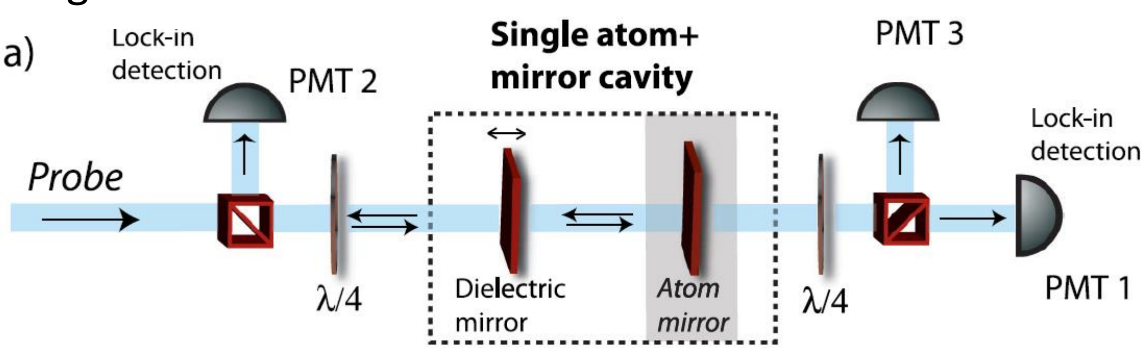
Experiments on the single quanta level feedback coupling:

- Experiments with cold atoms

Single atom-mirror:



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- Transmission controlled by the atom's position at length L
- Sinusoidal dependence

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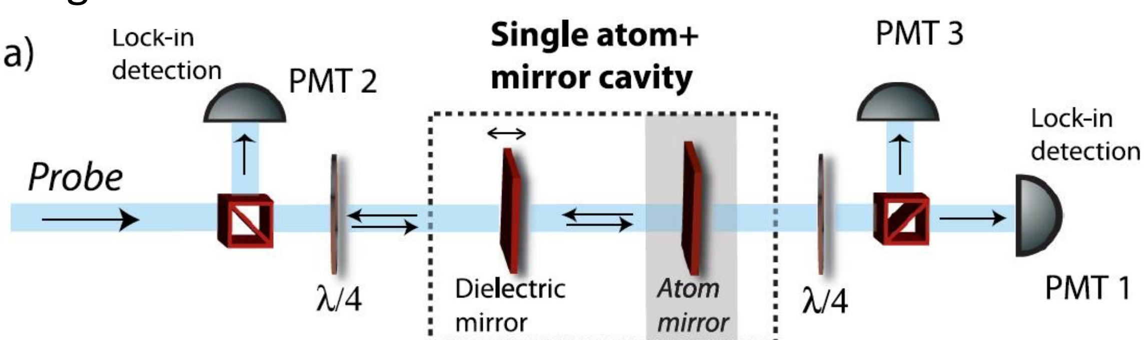

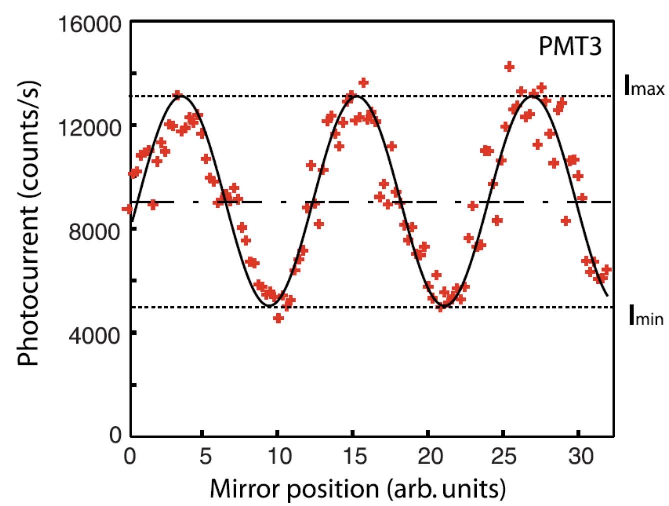

G. Hetet et al, Phys. Rev. Lett. 107, 133002 (2011).

Feedback in the quantum regime

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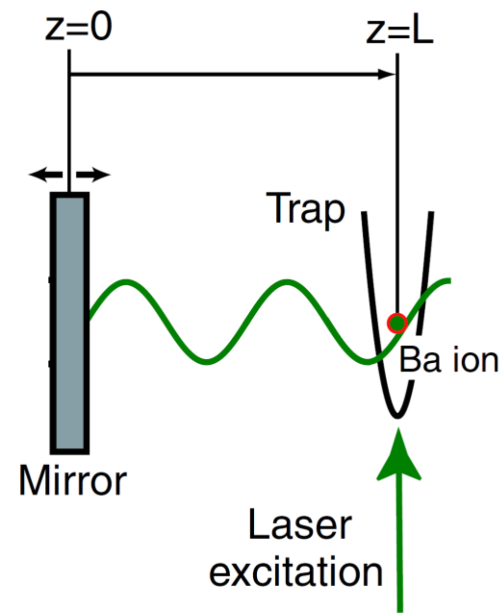
Experiments on the single quanta level feedback coupling:

- Experiments with cold atoms

- Dissipative dynamics of a laser-driven emitter, position dependent



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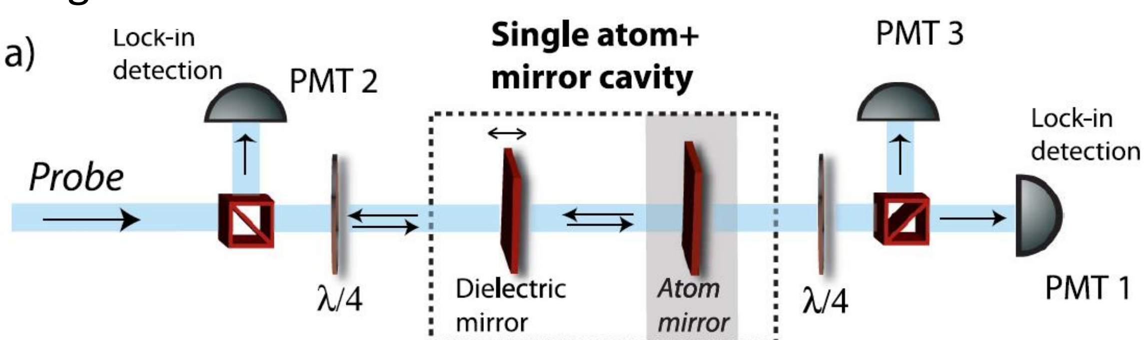

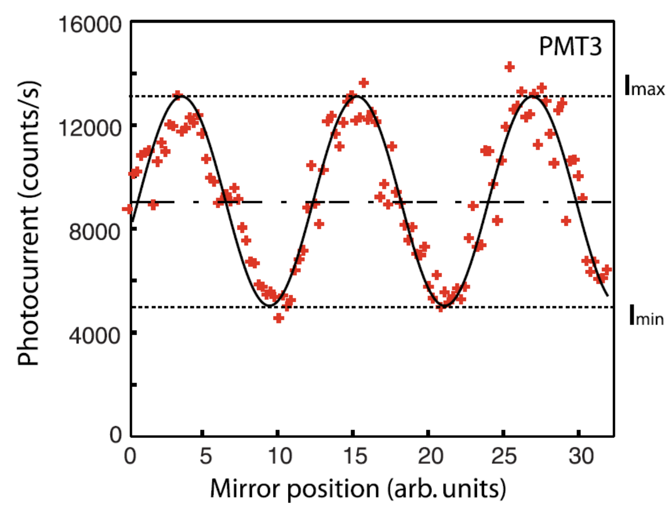

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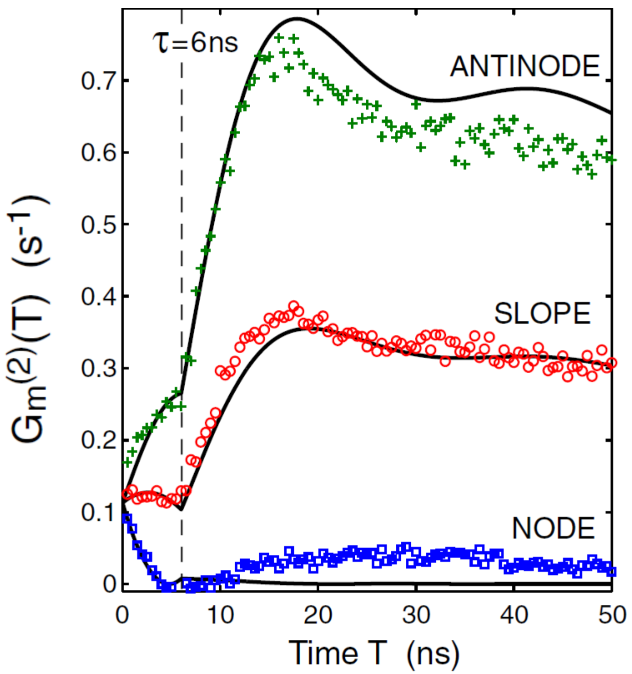
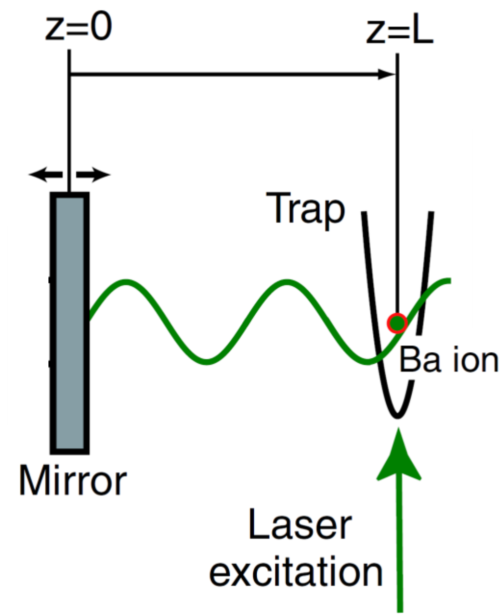


- Dissipative dynamics of a laser-driven emitter, position dependent
- Note kink in signal



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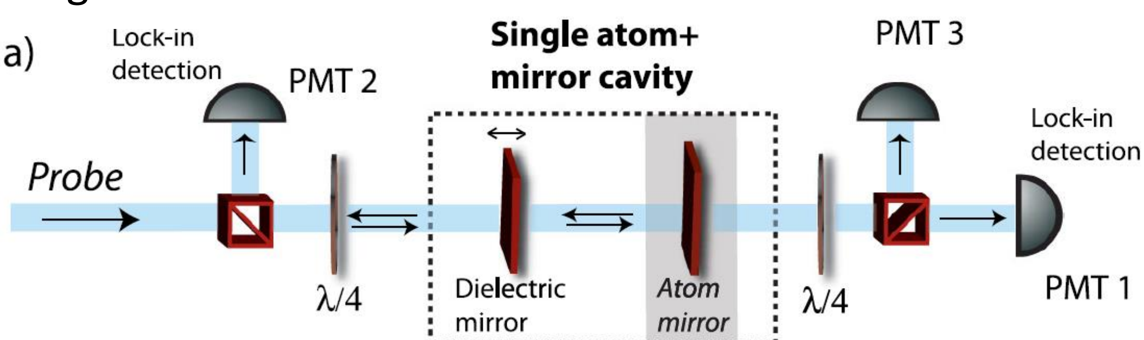

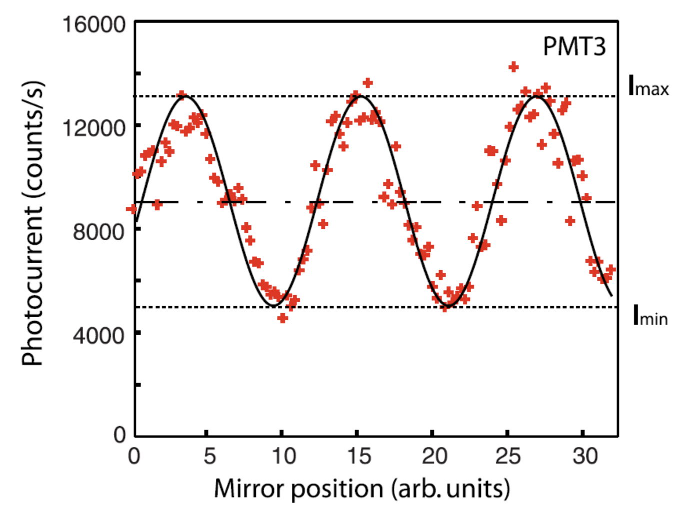

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Coherent quantum feedback model

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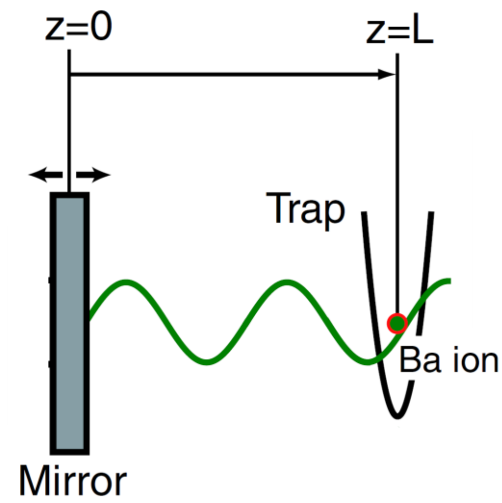
Theoretical modelling of quantum feedback:



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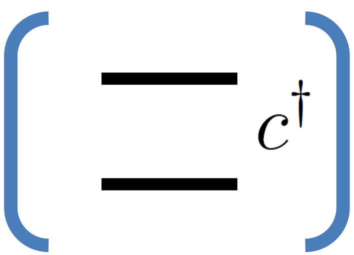
Assume a system which couples to an ensemble of two-level emitters via a structured reservoir



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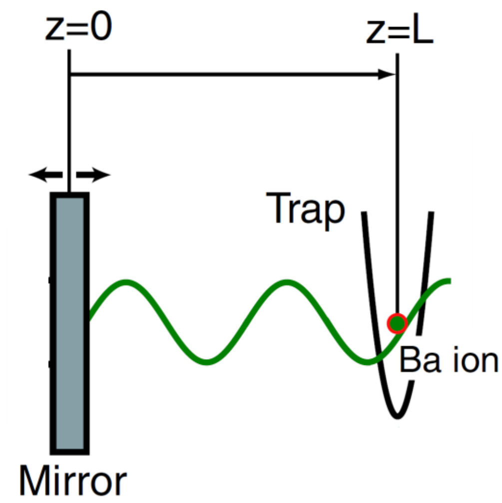

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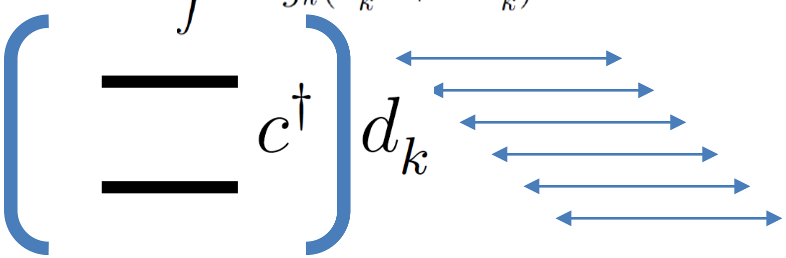
$$\int dk\ \tilde{g}_k (d_k^\dagger c + c^\dagger d_k)$$



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Theoretical modelling of quantum feedback:

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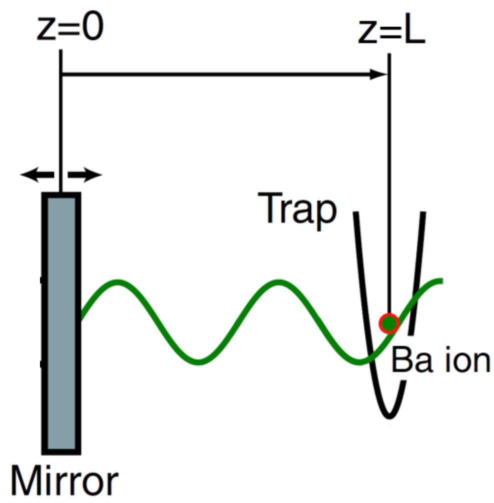

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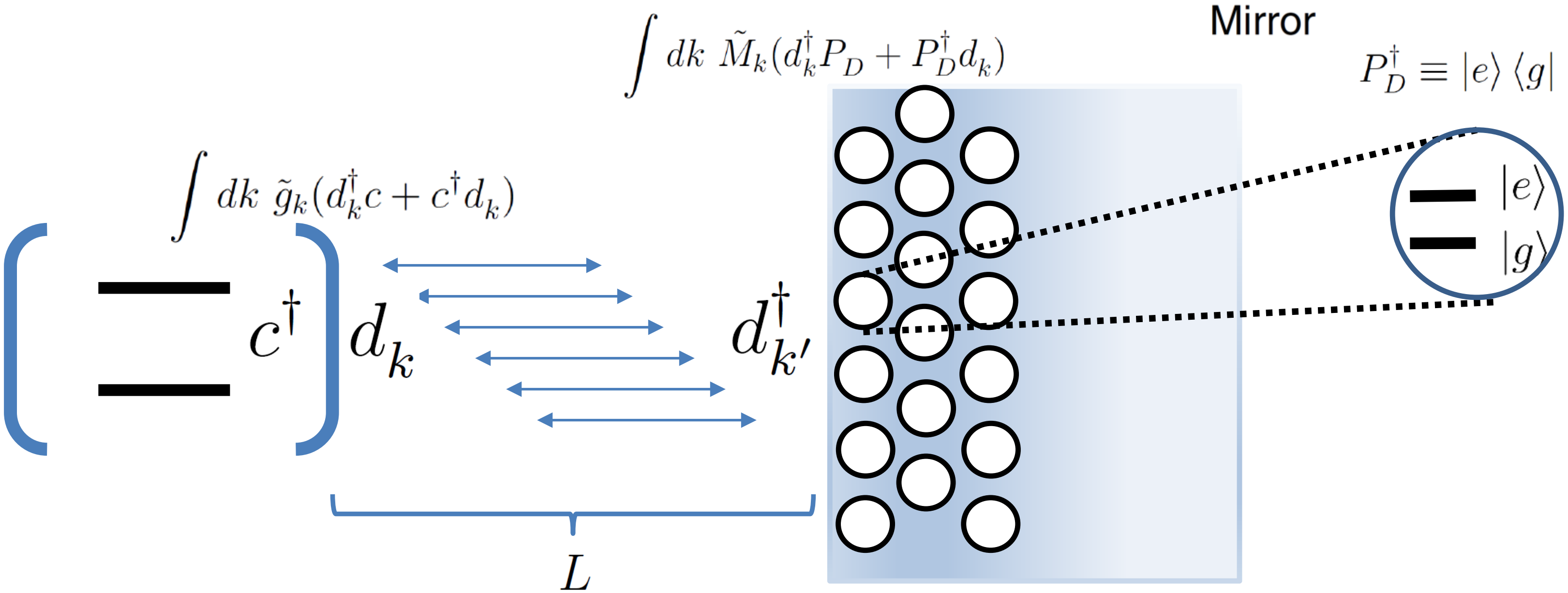

F. Faulstich, AC et al, J. Mod. Opt. (2018)

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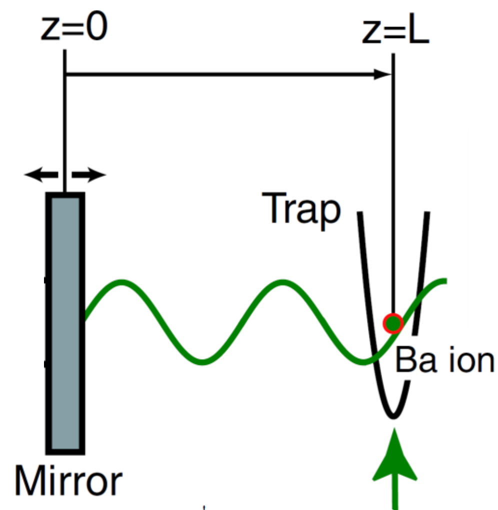

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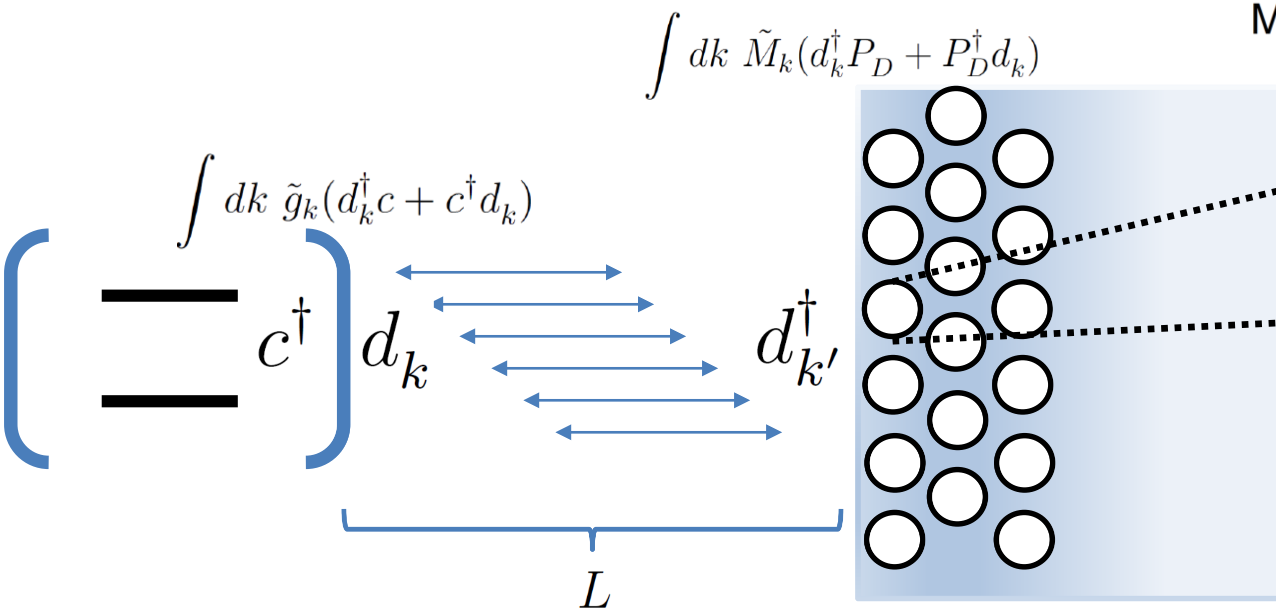

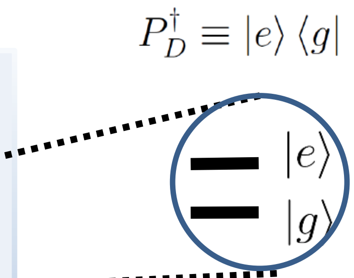

Eliminate the two-level systems and the reservoir to yield an effective equation of motion of Pyragas type

$$\dot{c} = -(i\omega_c + \Gamma)\ c(t) - iM\,P + \Gamma_\tau c(t-\tau)\Theta(t-\tau) - i\Delta B(t)$$

→ Effective Hamiltonian

F. Faulstich, AC et al, J. Mod. Opt. (2018)

Coherent quantum feedback model

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email: alex@itp.tu-berlin.de

F. Faulstich, AC et al, J. Mod. Opt. (2018)
Dorner, Zoller, PRA 66, 23816 (2002)

Equation of motion reproduced via:

$$H/\hbar = \omega_0 c^\dagger c + \int dk\ \omega_k\ d_k^\dagger d_k + \int dk\ g_k \sin(kL)(d_k^\dagger c + c^\dagger d_k)$$

and employing Heisenberg equation of motion $-i\hbar \frac{\mathrm{d}O}{\mathrm{dt}} = [H, O]$

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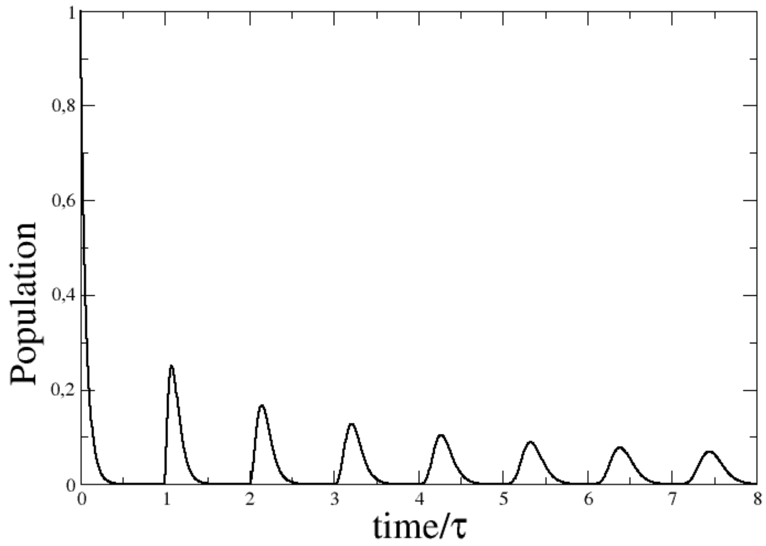

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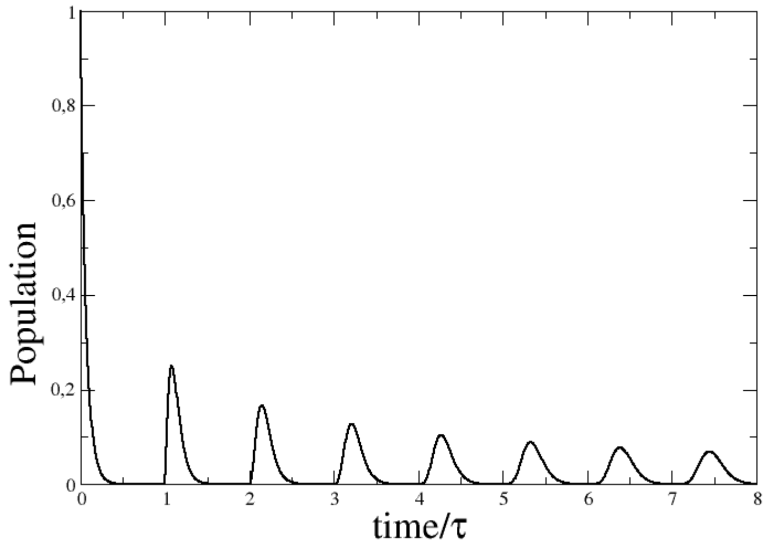

Feedback strength (depends on the interaction element system-bath coupling in the Hamiltonian)

Feedback strength dependence

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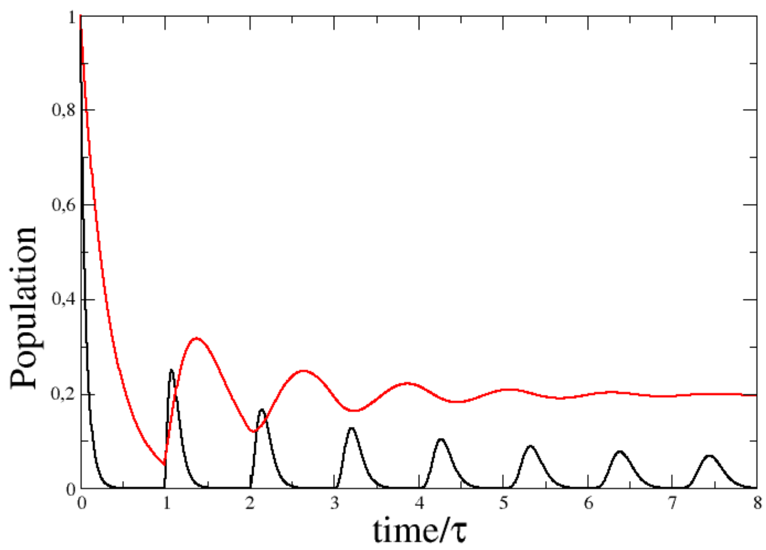

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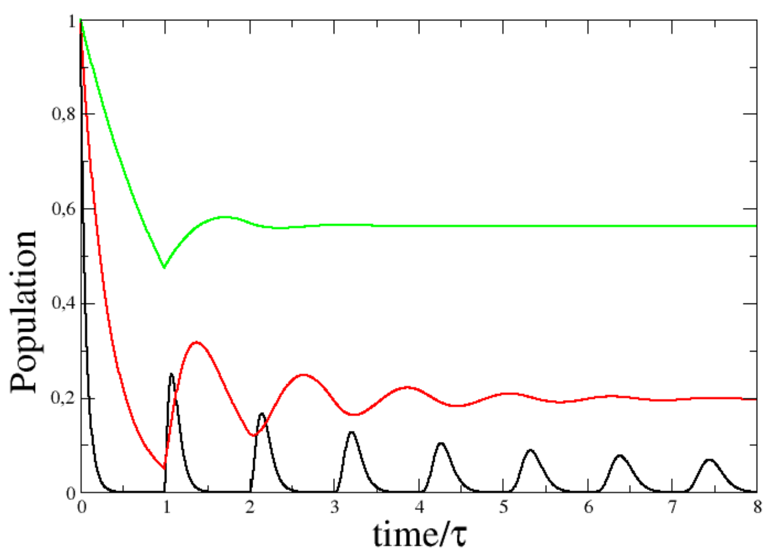

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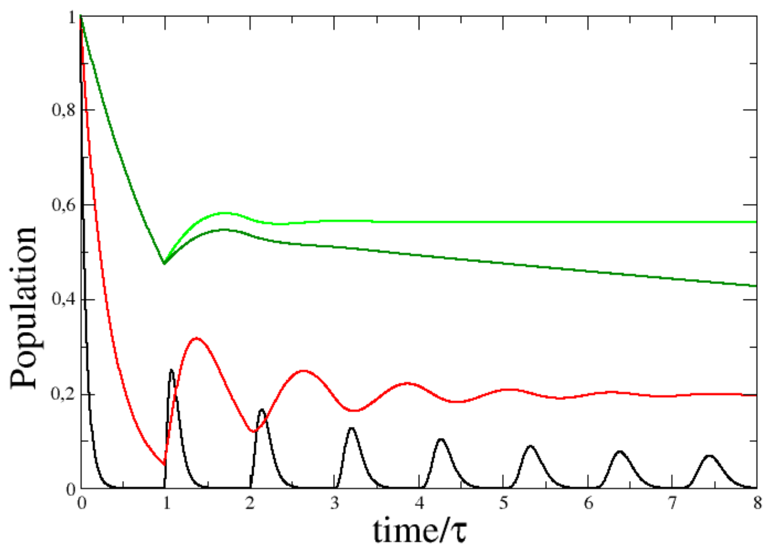

Feedback strength (depends on the interaction element system-bath coupling in the Hamiltonian)

Phase of feedback signal (depends on the round trip time and the transition frequency of the system operator)

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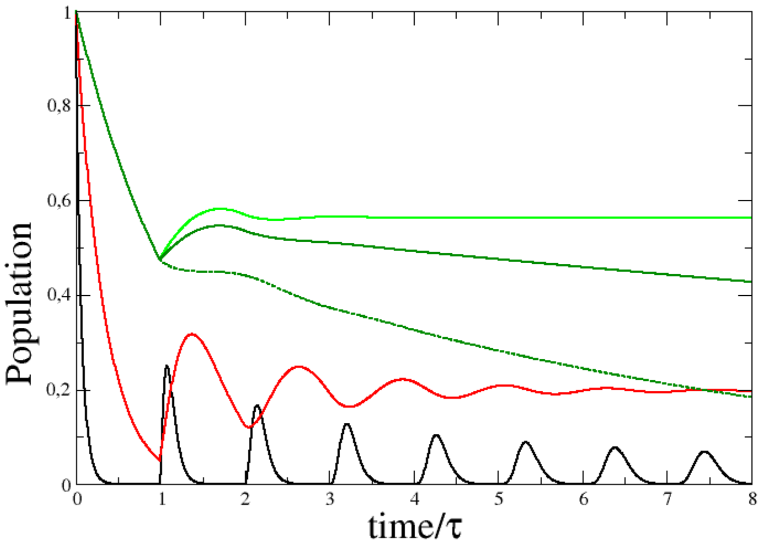

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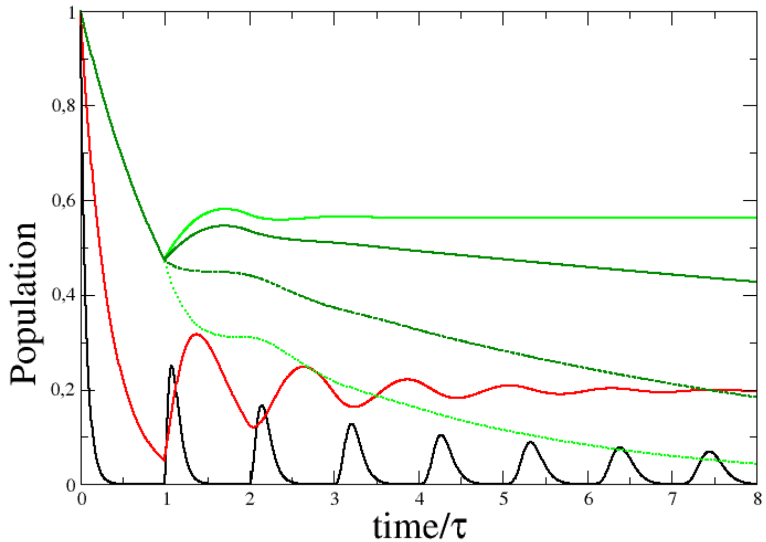

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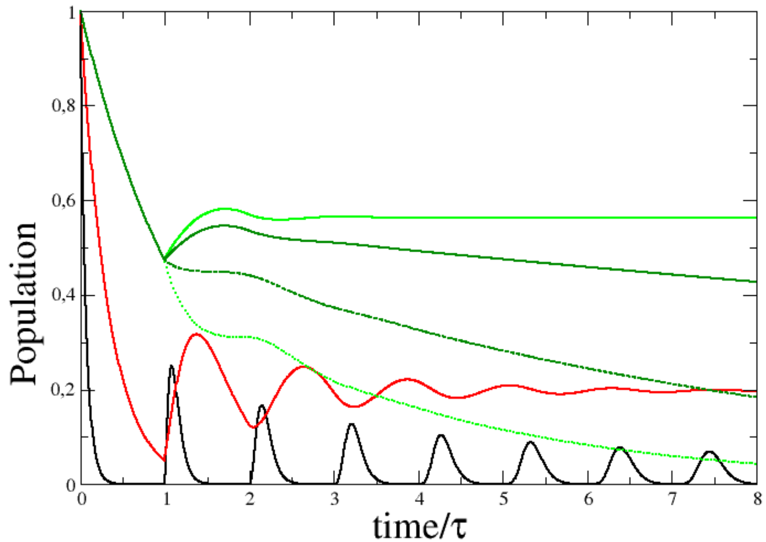

Feedback strength (depends on the interaction element system-bath coupling in the Hamiltonian)

Phase of feedback signal (depends on the round trip time and the transition frequency of the system operator)

Suppression of decoherence via quantum feedback-stabilized acoustic cavities

Motivation (ii): Good model to investigate non-Markovian dynamics

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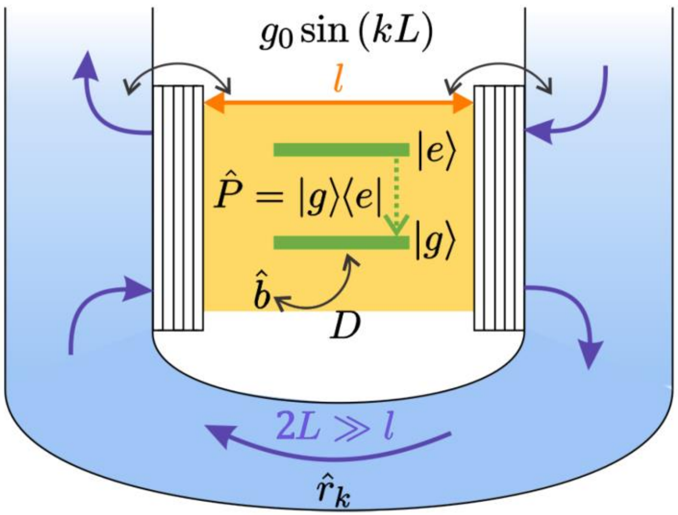

Goal: Stabilize an initial given coherence even in the presence of a reservoir at finite temperature

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

Nemet, AC et al, arXIv: 1805.2317

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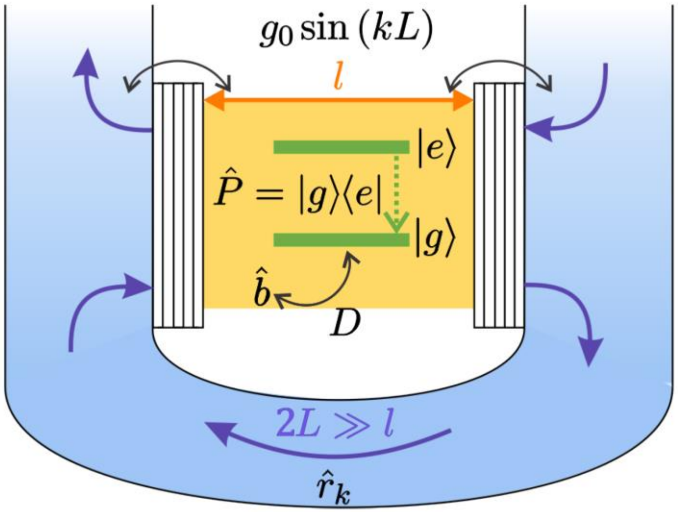

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$$\hat{H}_R/\hbar = \omega_0 \hat{b}^\dagger \hat{b} + \int \left[\omega_k \hat{r}_k^\dagger \hat{r}_k + g_k(\hat{r}_k^\dagger \hat{b} + \hat{b}^\dagger \hat{r}_k)\right] dk$$

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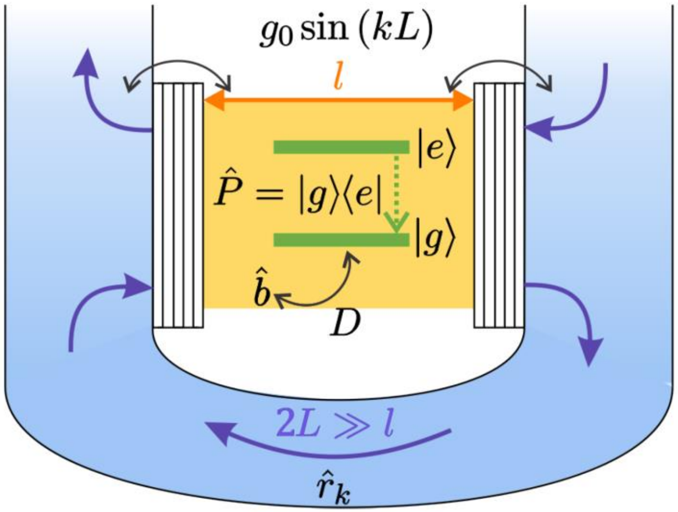

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We assume a reservoir at T>0 with non-Ohmic spectral density with delay

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

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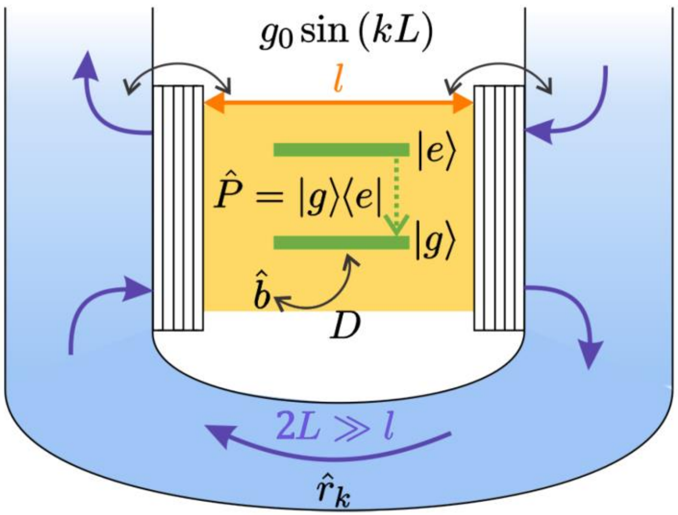

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$$J(\omega_k) = \sin^2\left(\frac{\omega_k \tau}{2}\right) e^{-i\omega_k(t-t')}$$

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

$$\hat{\rho}_P(t) = \exp\left\{ \left(-i \int_0^t \hat{\mathcal{B}}(t_1) dt_1 - \frac{1}{2} \int_0^t \int_0^{t_1} [\hat{\mathcal{B}}(t_1), \hat{\mathcal{B}}(t_2)] dt_2 dt_1 \right) \hat{P}^\dagger(0) \hat{P}(0) \right\} \hat{\rho}_P(0)$$

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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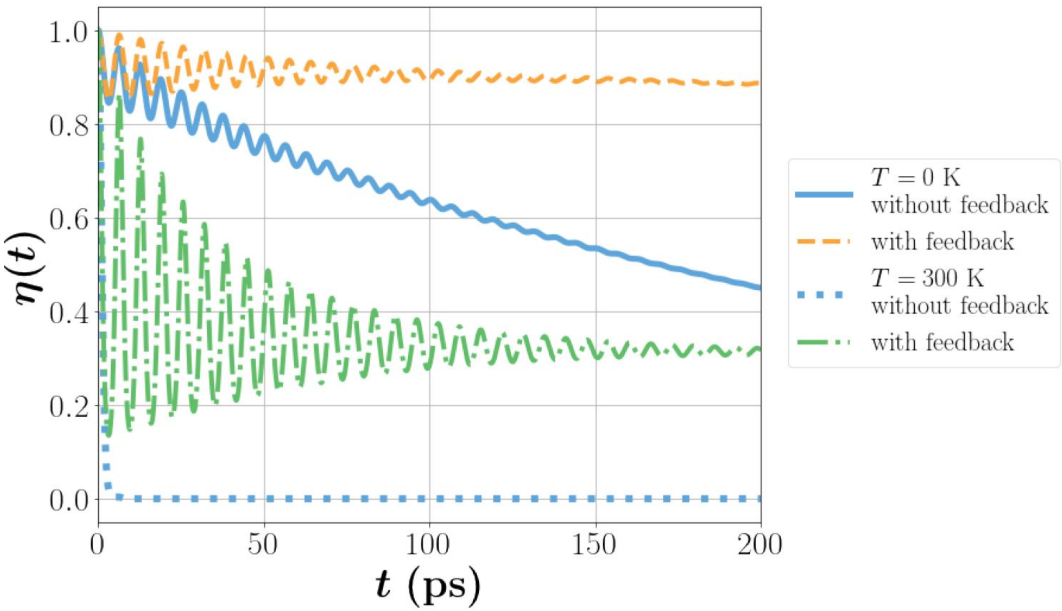

Feedback stops via quantum interference the decoherence process – a synchronisation between the oscillators take place

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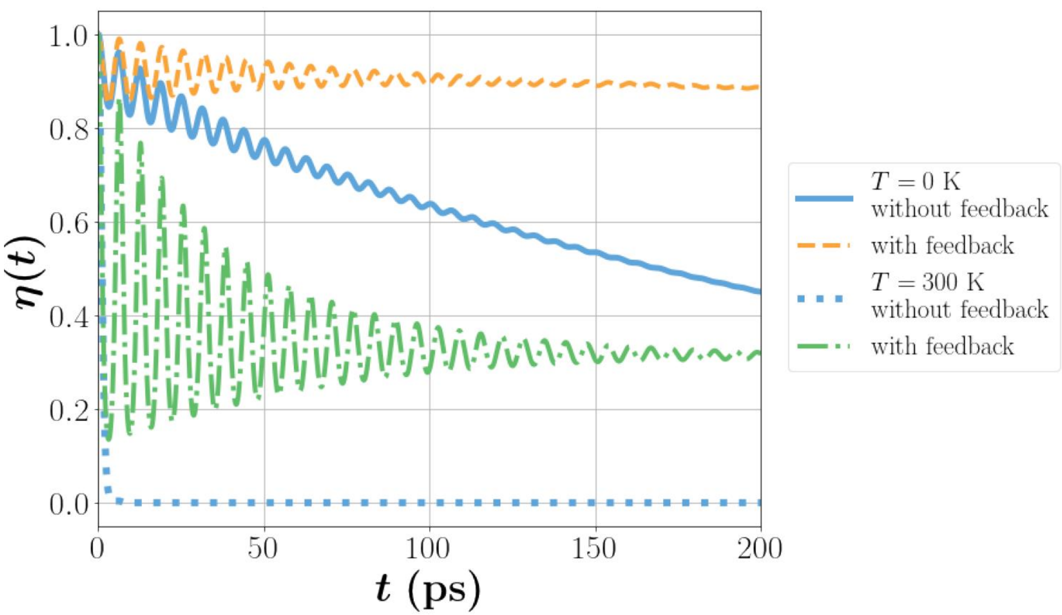

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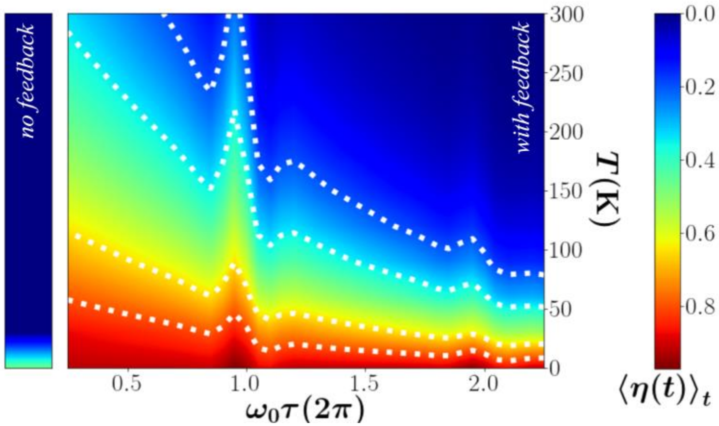

Delay time and phase-matching allow very long coherence times initial coherence at room temperature up to 200ps

Nemet, AC et al, arXlv: 1805.2317

Quantum Pyragas control –
Two-photon purification of quantum light emission

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However, for open quantum system case dynamics, the model is too detailed in the bath description:

$$H/\hbar = \omega_0 c^\dagger c + \int dk\ \omega_k\ d_k^\dagger d_k + \int dk\ g_k \sin(kL)(d_k^\dagger c + c^\dagger d_k)$$

within the interaction picture

$$H_I(t) = -i\hbar g_0 \left(c^\dagger \left[\int dk (1 - e^{i2kL})\ d_k\ e^{-i(\omega_k - \omega_0)t} \right] - \text{h.c.} \right)$$

Pichler, Zoller PRL 116, 93601 (2016)   Lu, AC et al, PRA 63, 63840 (2017)

Circumvent the limitations of the model

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Integrate Schrödinger equation $$|\psi(t)\rangle_I = \mathcal{T} \left\{ \exp\left[-\frac{i}{\hbar} \int_0^t H_I(t')dt' \right] |\psi(0)\rangle_I \right\}$$

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$$|\psi(\Delta t)\rangle_I = \exp\left[-\frac{g_0}{2} c \left(\Delta R(\Delta t) + e^{i\omega_0 \tau} \Delta R(\Delta t - \tau) \right) + \text{h.c.} \right] |\psi(0)\rangle_I$$

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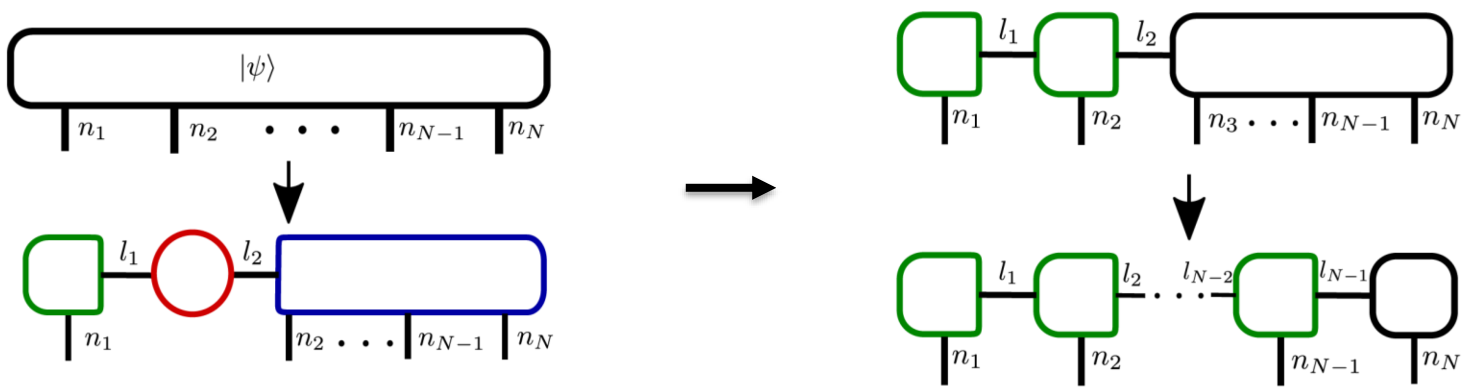
within the interaction picture $H_I(t) = -i\hbar g_0 \left(c^\dagger \left[\int dk (1 - e^{i2kL})\ d_k\ e^{-i(\omega_k - \omega_0)t} \right] - \text{h.c.} \right)$

Integrate Schrödinger equation $|\psi(t)\rangle_I = \mathcal{T} \left\{ \exp\left[-\frac{i}{\hbar} \int_0^t H_I(t')dt' \right] |\psi(0)\rangle_I \right\}$



after SVD, yielding an MPS form $|\Psi\rangle = \sum_{i_1 \ldots i_N} A_{i_1}^{[1]} \ldots A_{i_N}^{[N]} |i_1\rangle \ldots |i_N\rangle = \sum_{\mathbf{i}} A_{\mathbf{i}} |\mathbf{i}\rangle$

Pichler, Zoller PRL 116, 93601 (2016) Lu, AC et al, PRA 63, 63840 (2017)

Limits of the MPS model

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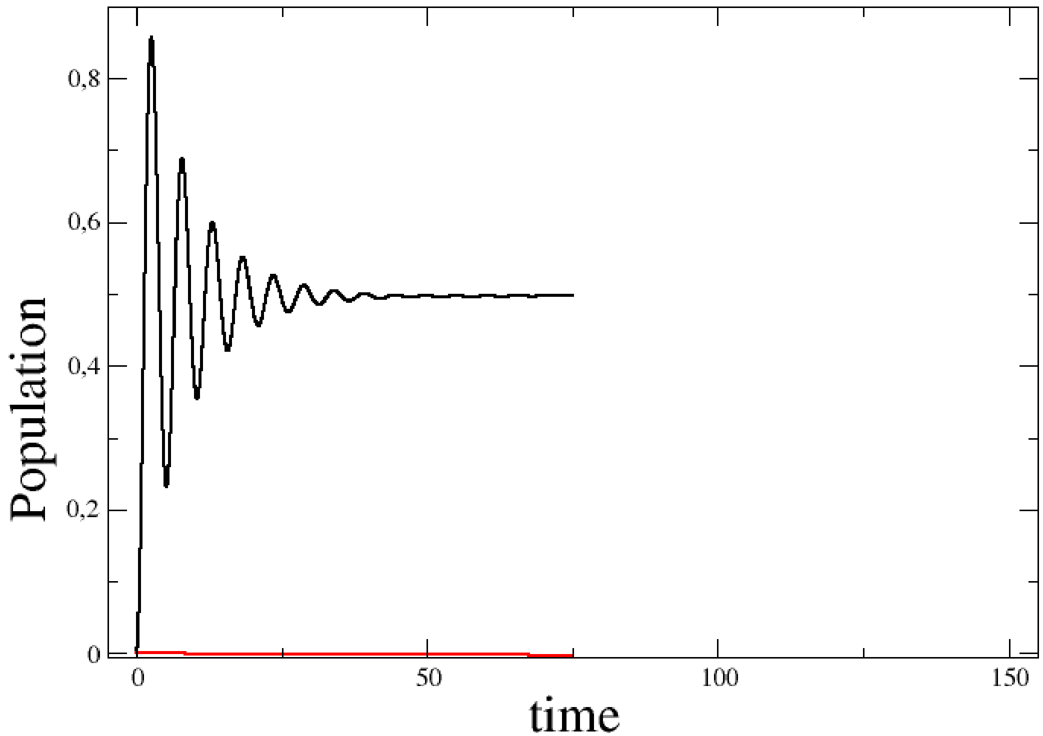
Schrödinger equation yields reversible dynamics.
Example: Driven and decaying two-level system.

$$|\psi(n+1)\rangle = \exp\left[-i\Delta t\Omega_L\left(\sigma^+ + \sigma^-\right) - \sqrt{\Gamma\Delta t}\sigma_-\Delta R^\dagger(n)\right]|\psi(n)\rangle$$



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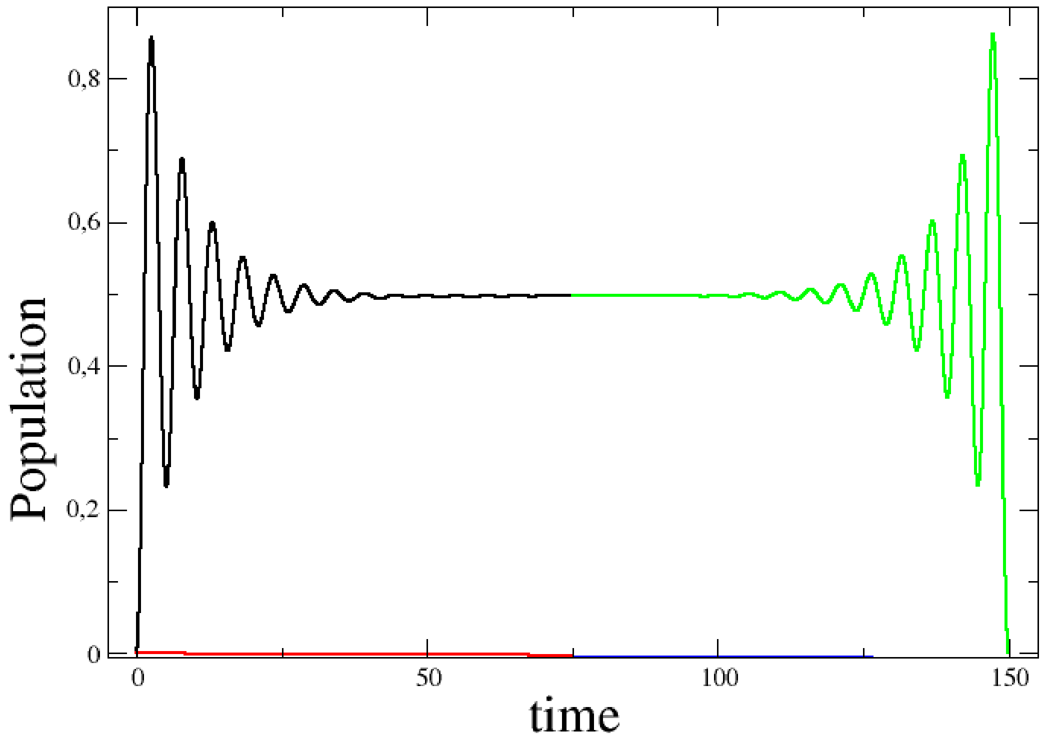

Time-reversal yields initial state. Full information of the reservoir in state. Numerical exact solution and dissipatively driven-correlation included.

$$\langle\psi(n-1)| = \langle\psi(n)|\exp\left[i\Delta t\Omega_L\left(\sigma^+ + \sigma^-\right) - \sqrt{\Gamma\Delta t}\sigma_-\Delta R\ (n)\right]$$

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Examples: (i) Two-photon purification

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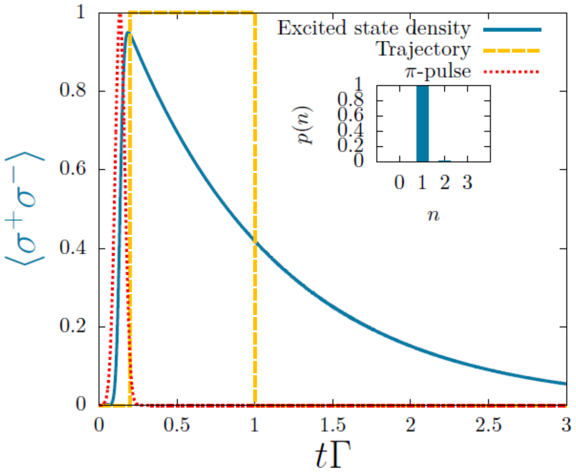
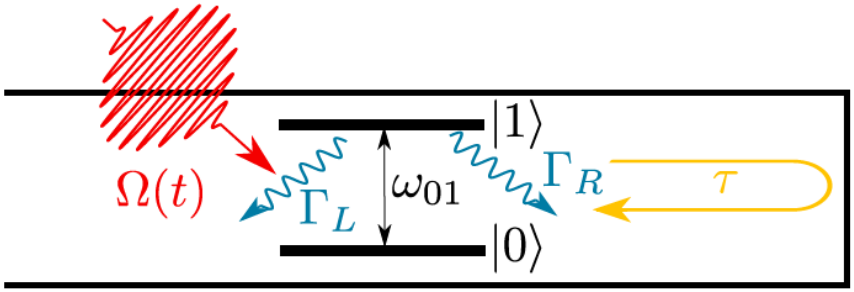
Pulsed and decaying two-level system.

Nearly perfect single photon emission for π-pulse





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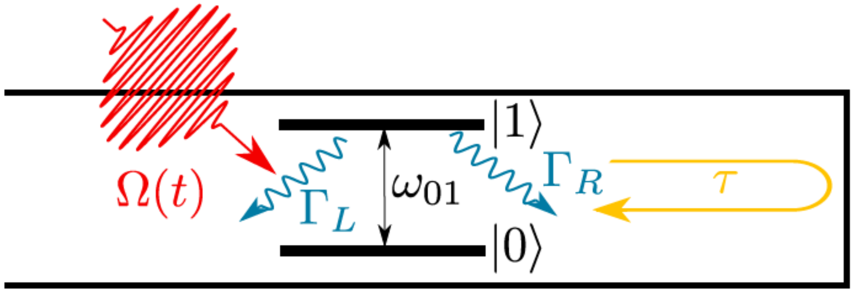

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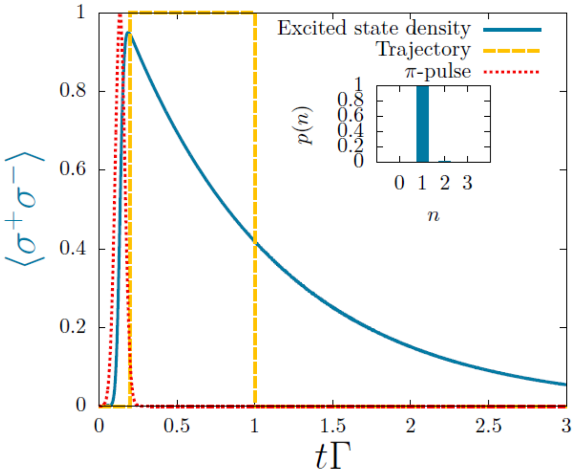
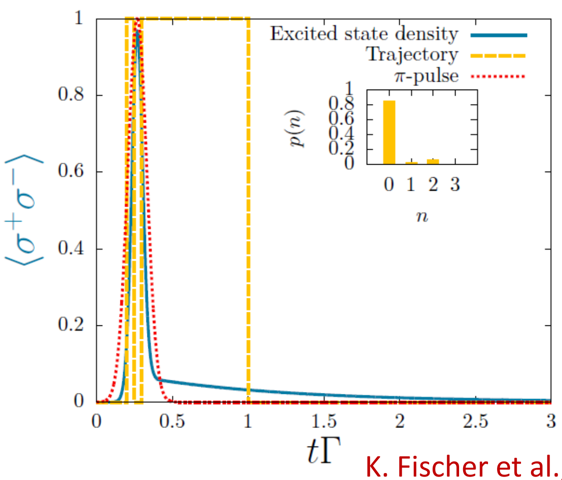


Two-photon emission events are favored for 2π-pulses.



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

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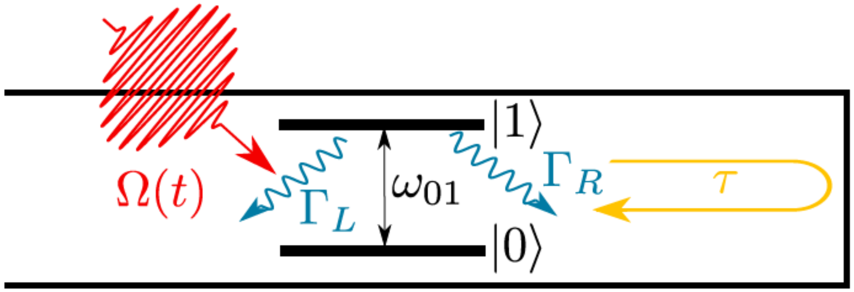

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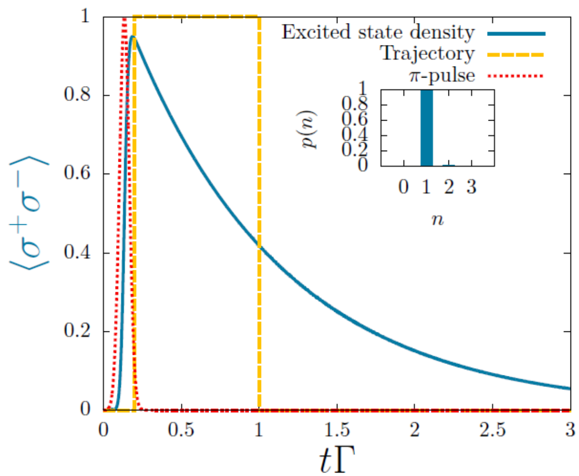
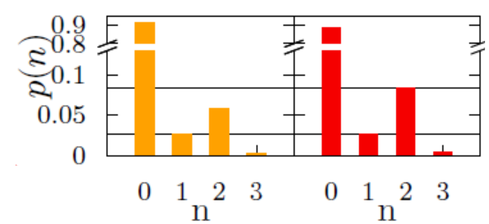


Quantum feedback allows to steer between purified two-photon and single photon emission, selectively.



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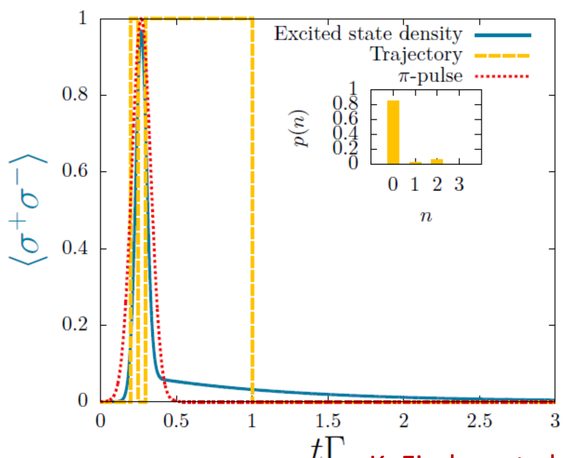

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Droenner, AC, et al, arXiv:1801.03342v2

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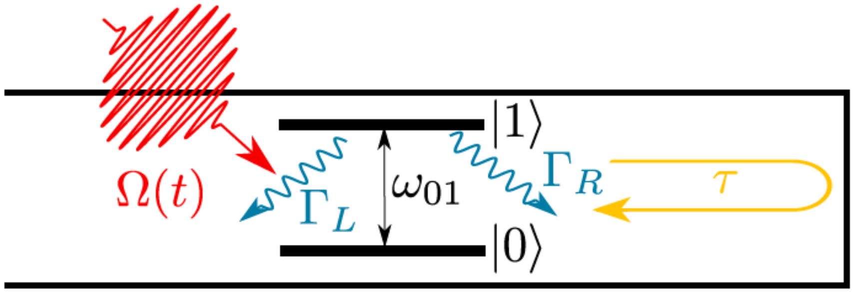

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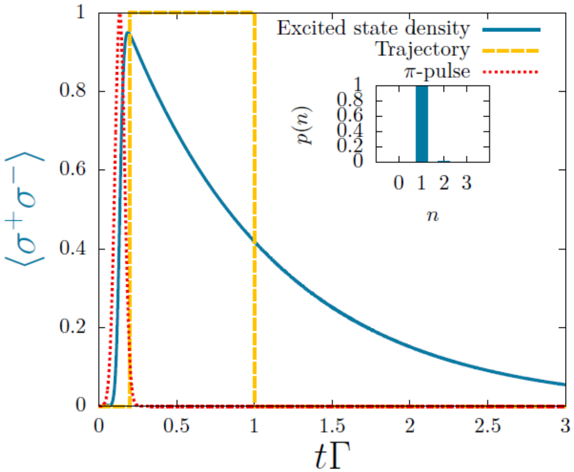

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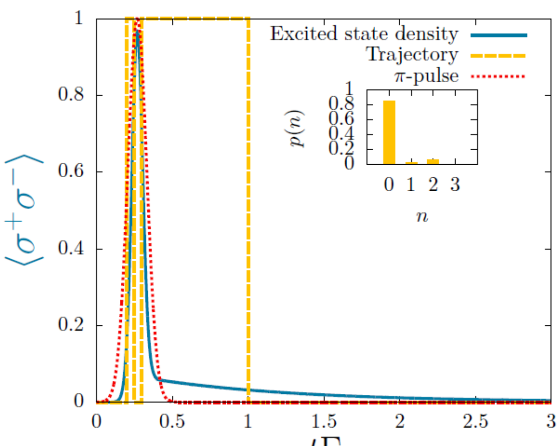

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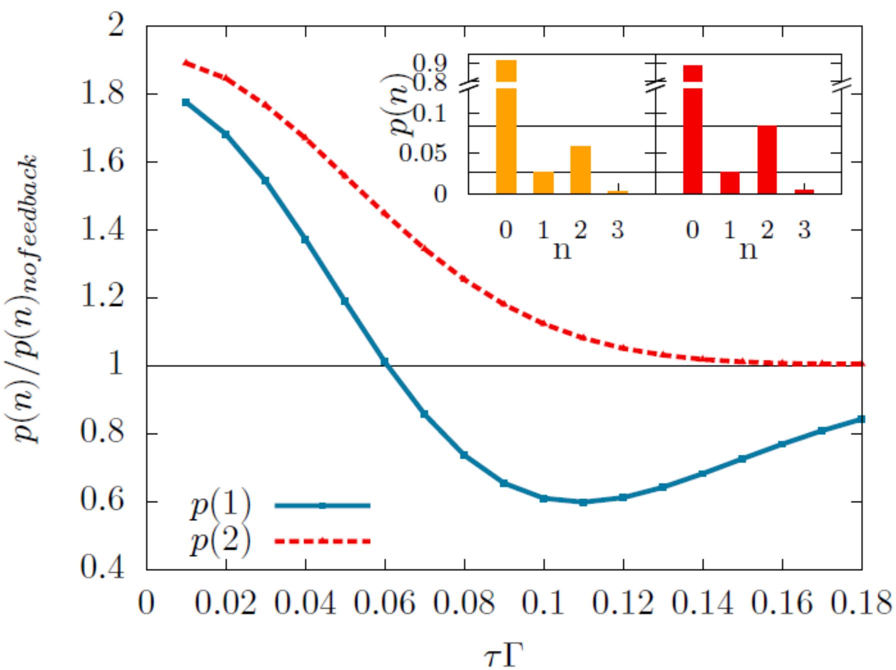

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Feedback-stabilized discrete time crystal dynamics

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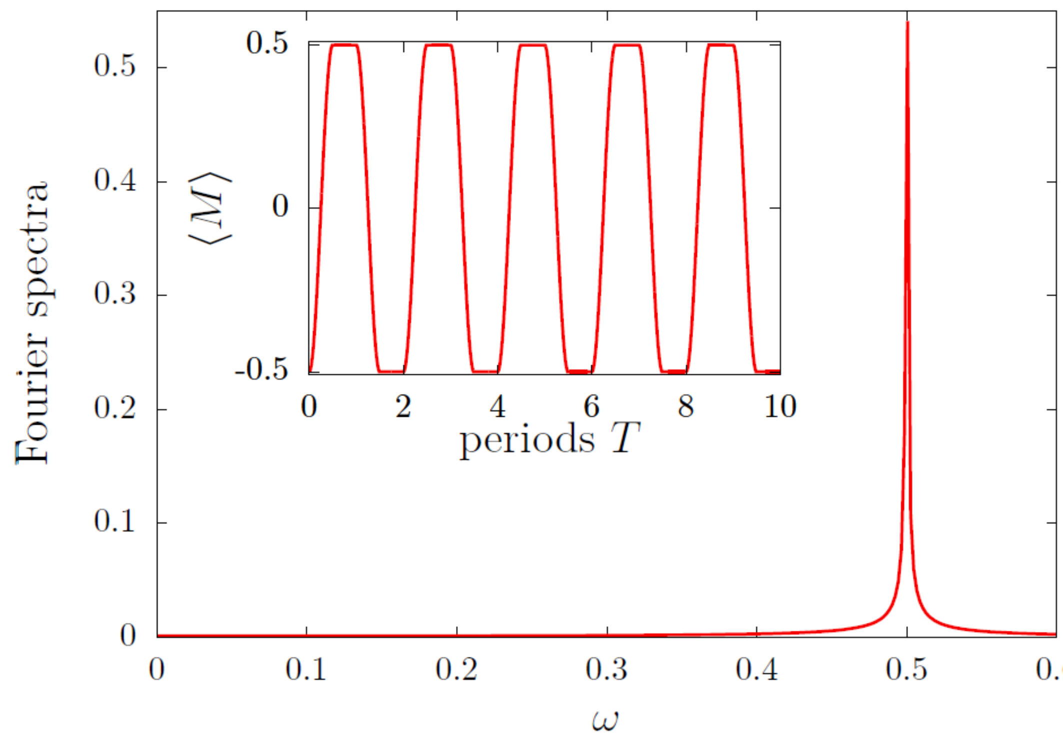
Illustration of a discrete time-crystal

$$\mathcal{H}_F = (\Omega \qquad) \sum_{i=1}^{N} \sigma_i^x$$

$$\langle M \rangle = \frac{1}{N} \sum_{i=1}^{N} (-1)^i \frac{\langle \sigma_i^z \rangle}{2}$$

If driving is perfect ε=0, the magnetization shows a single peak in the Fourier spectra. Perfect periodicity.



Examples: (ii) Stabilized time-crystal

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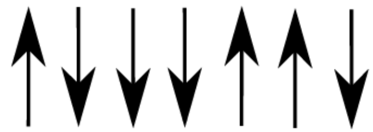

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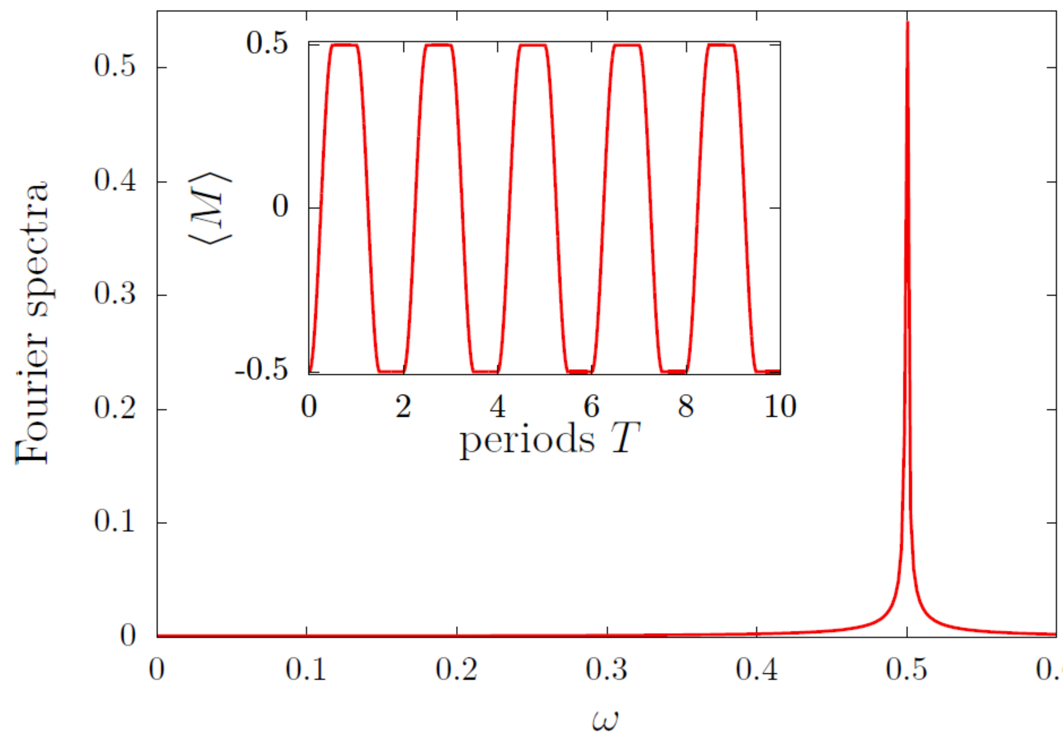

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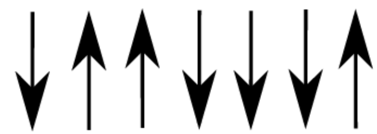

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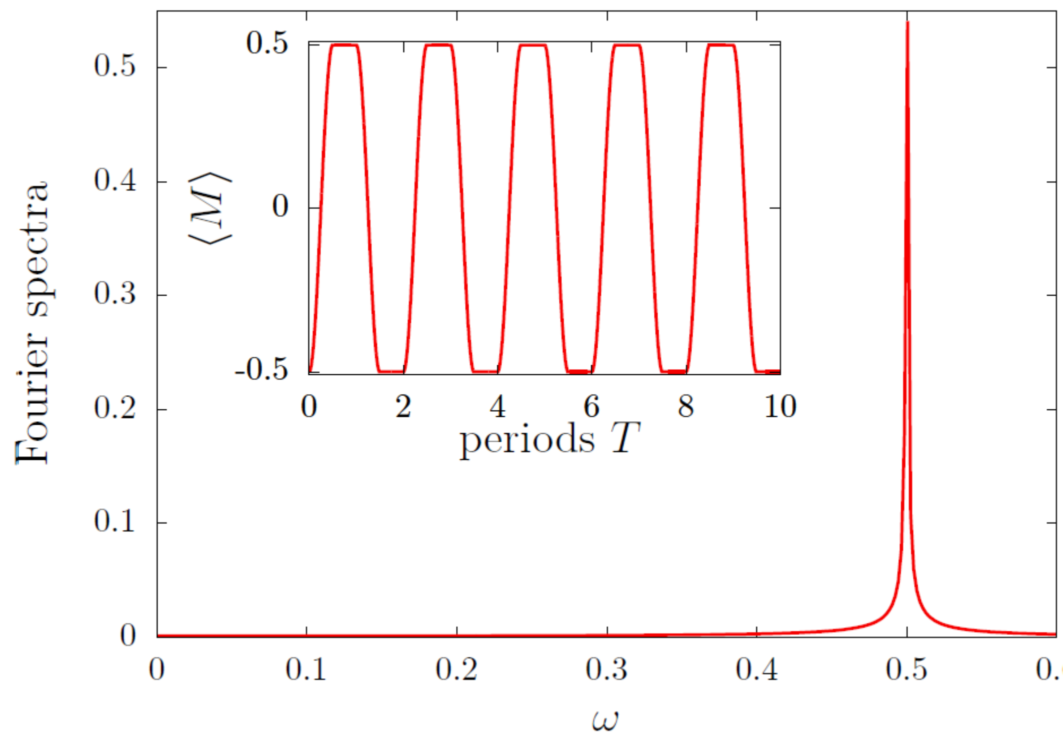

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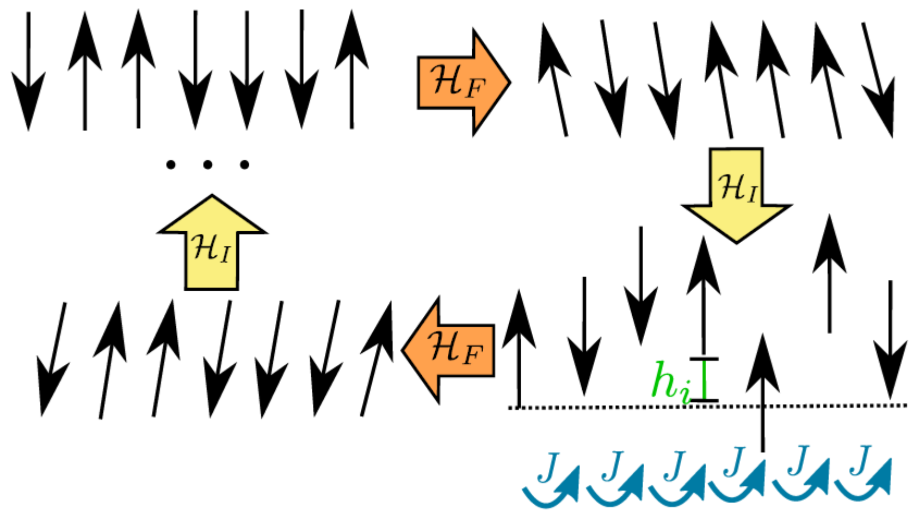
Illustration of a discrete time-crystal

$$\mathcal{H}_F = (\Omega - \epsilon) \sum_{i=1}^{N} \sigma_i^x$$



The spin chain of N spins returns despite **imperfect** rotation back to its initial state. Figure of merit and observable (staggered magnetization):

Yao et al, Phys. Rev. Lett. 118, 030401 (2017)

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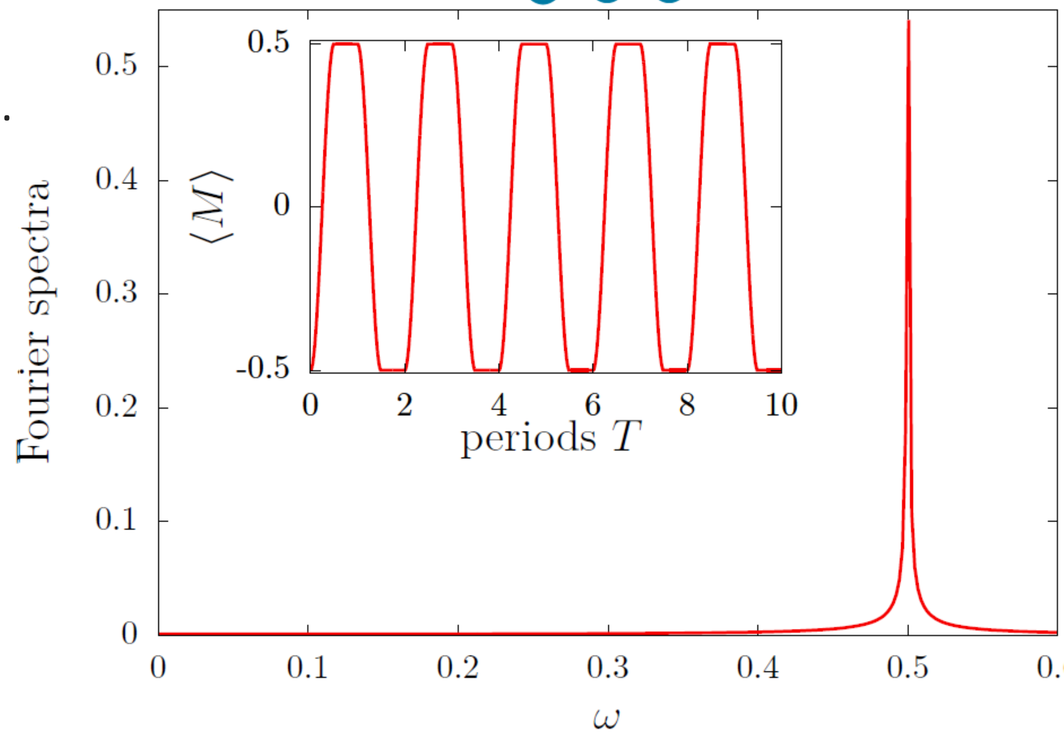

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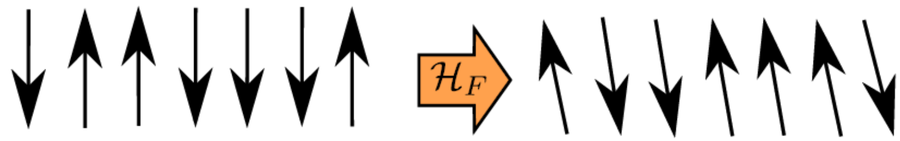

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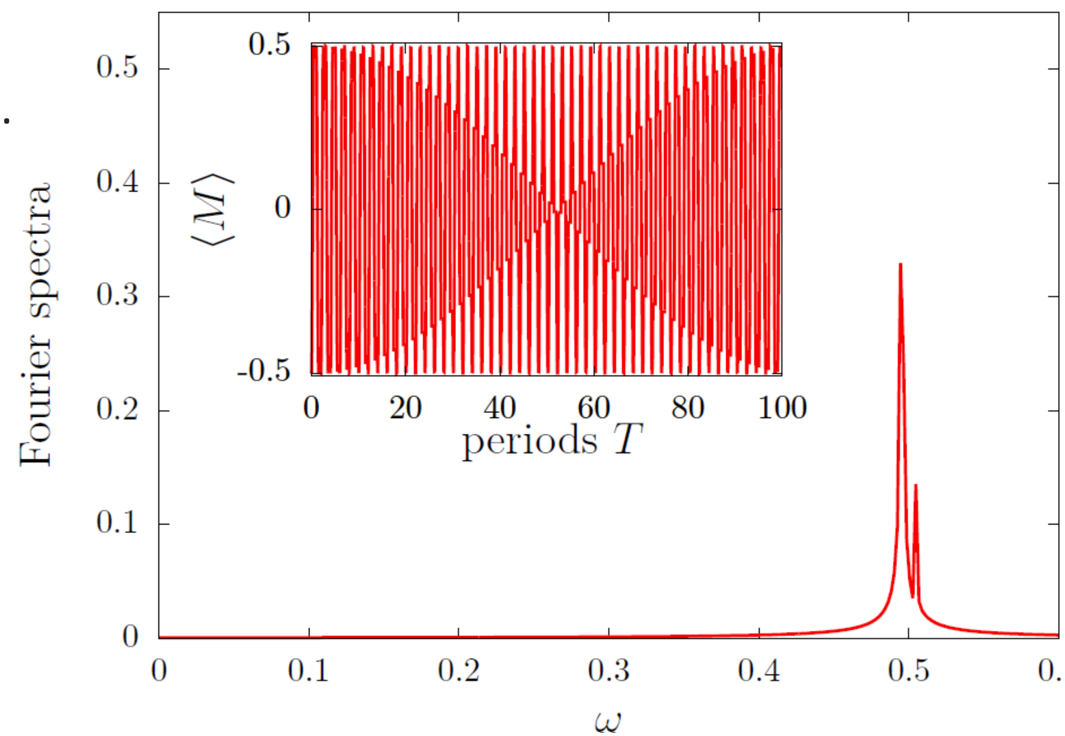
If driving is imperfect ε>0, the magnetization dynamics shows an envelope. Imperfect periodicity.



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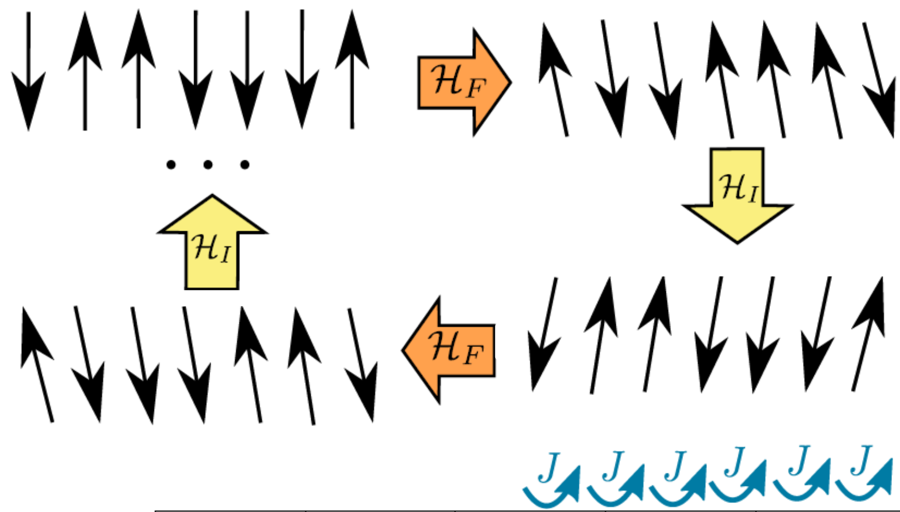

$$\mathcal{H}_F = (\Omega - \epsilon)\sum_{i=1}^{N} \sigma_i^x$$

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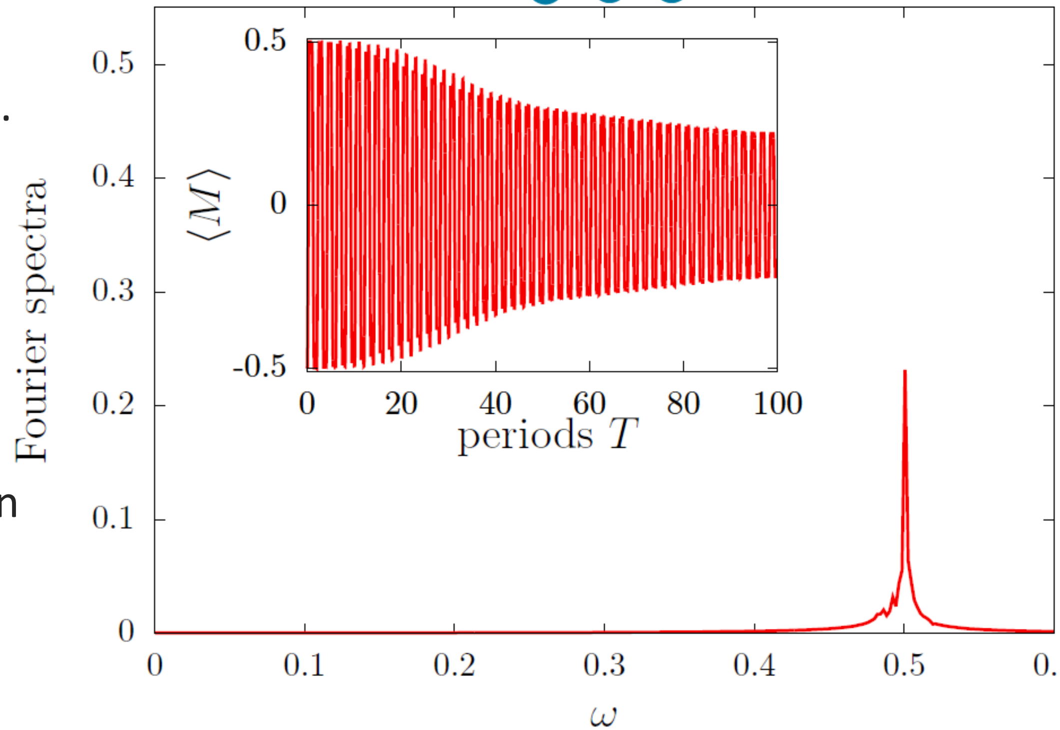

If driving is imperfect ε>0, and interaction switched on, single peak appears but is damped due to thermalization within chain. Vanishing periodicity for large N.

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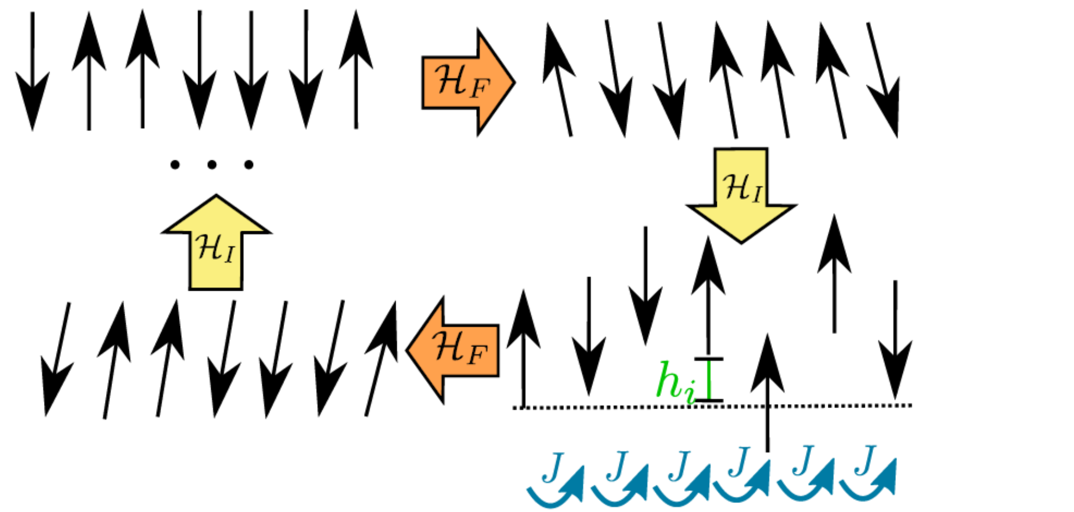

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The spin chain of N spins returns despite imperfect rotation back to its initial state. Figure of merit and observable (staggered magnetization):

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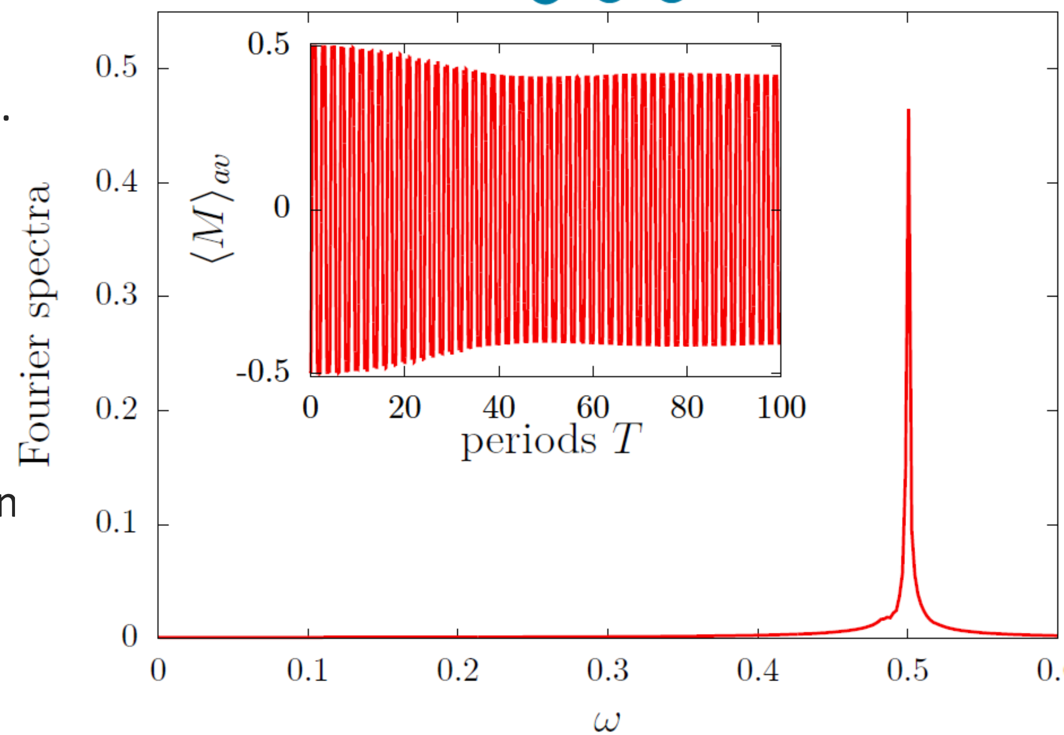
$$\langle M \rangle = \frac{1}{N} \sum_{i=1}^{N} (-1)^i \frac{\langle \sigma_i^z \rangle}{2}$$

If driving is imperfect ε>0, and interaction switched and disorder is present, thermalization is prevented. Periodicity even for large N.



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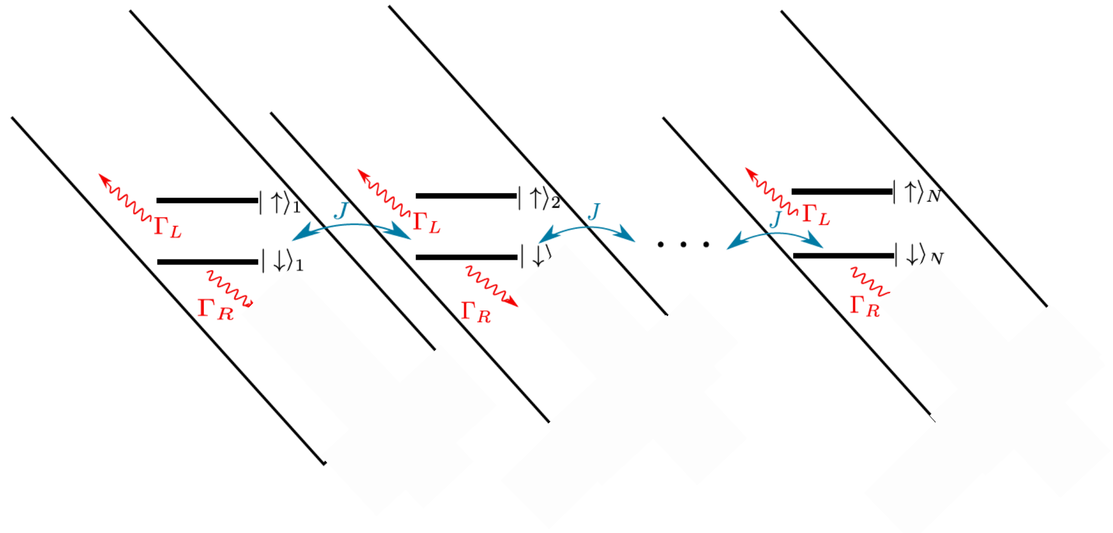
Time-crystal in the presence of losses

Lazarides and Moessner, Phys. Rev. B 95, 195135 (2017)



Periodicity is lost when Markovian reservoir (bath) is coupled to the chain. Thermalization within chain is prevented due to many-body localization but thermalization with bath is inevitable

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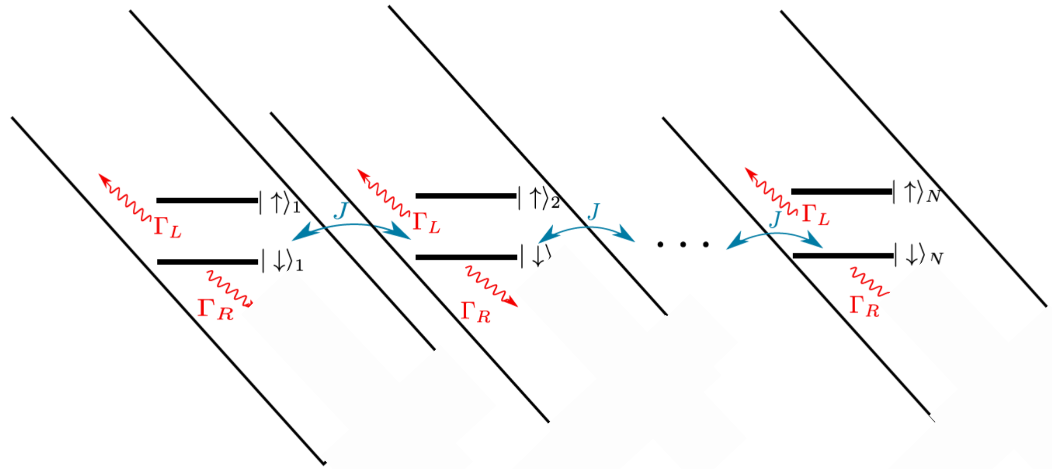

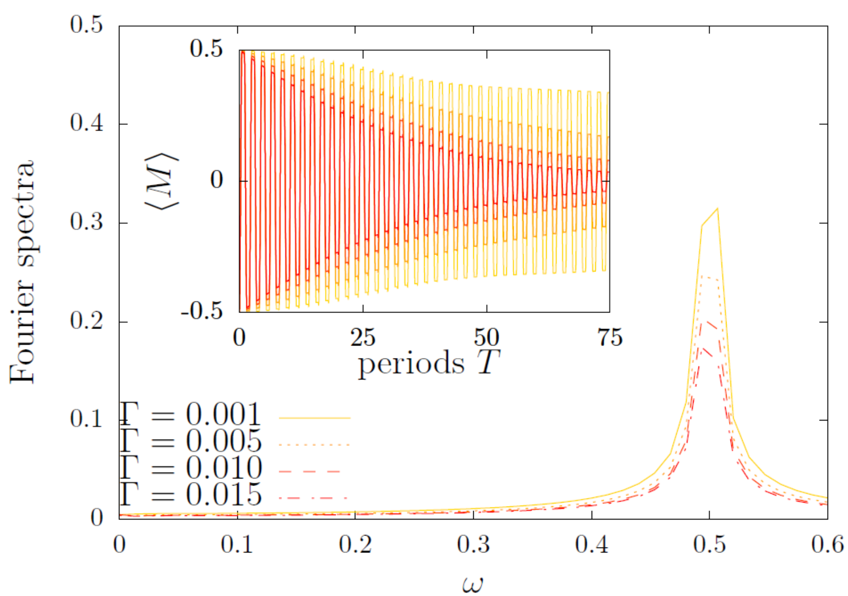

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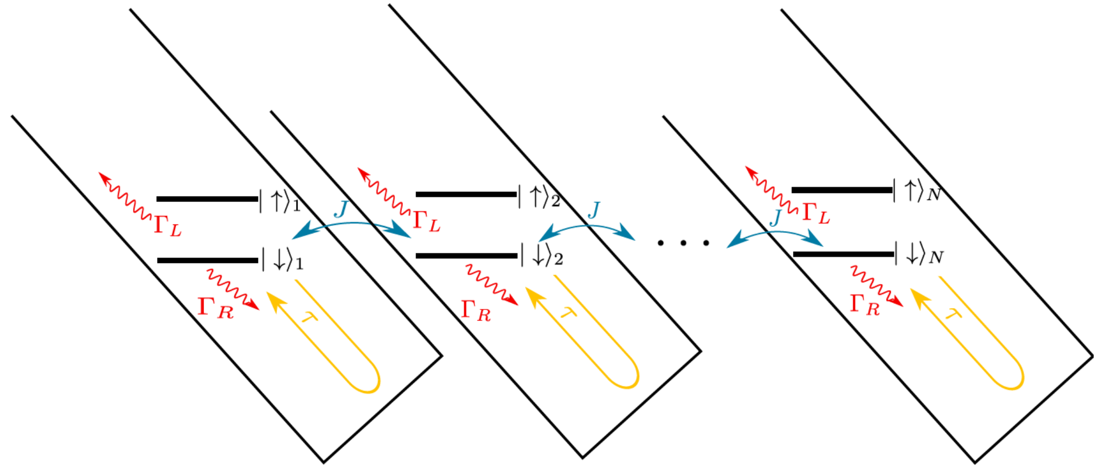
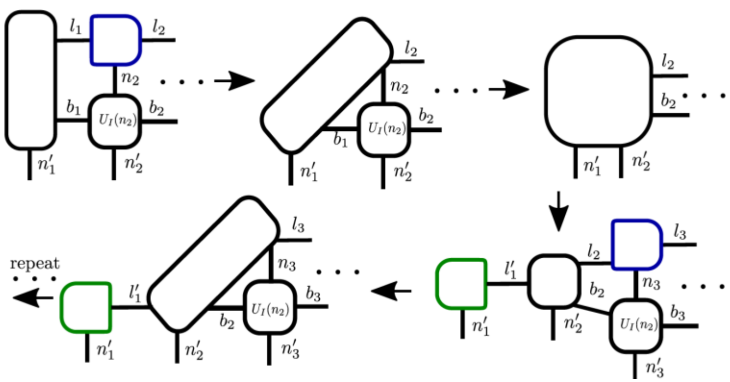
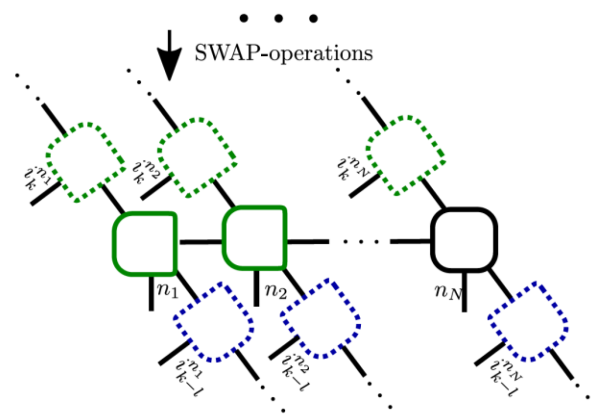


But non-Markovian dissipation, such as quantum feedback interaction allows self-stabilizing system-reservoir dynamics and prevents again thermalization.

Droenner, AC in preparation (2018)





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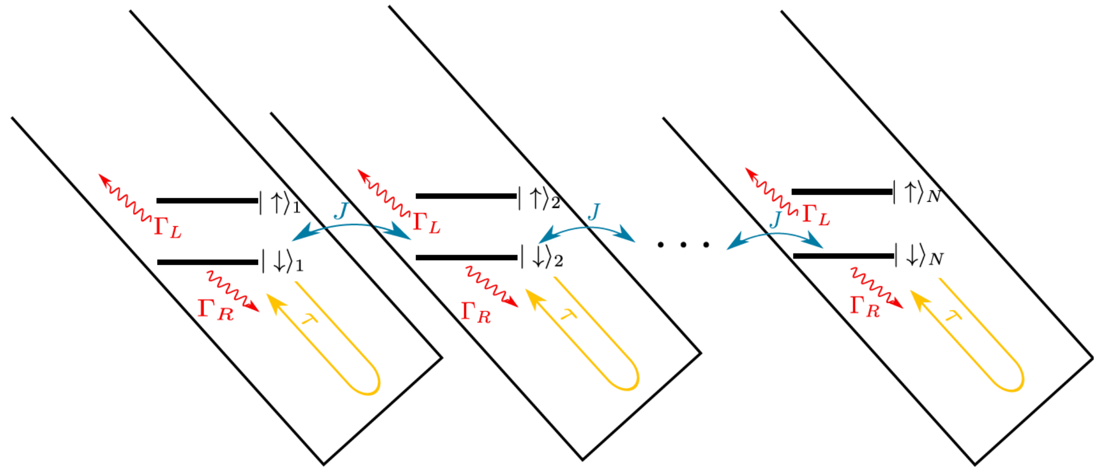

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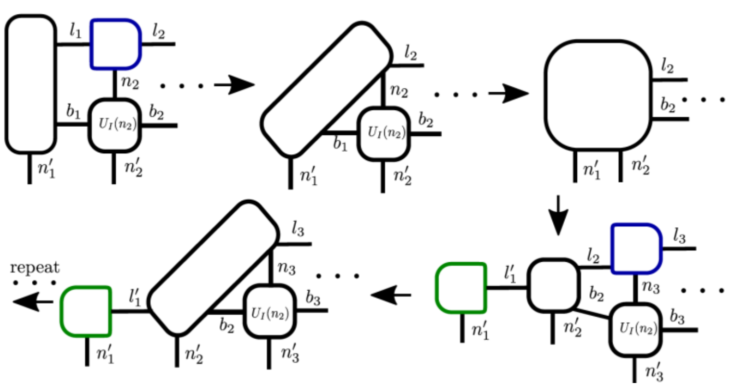

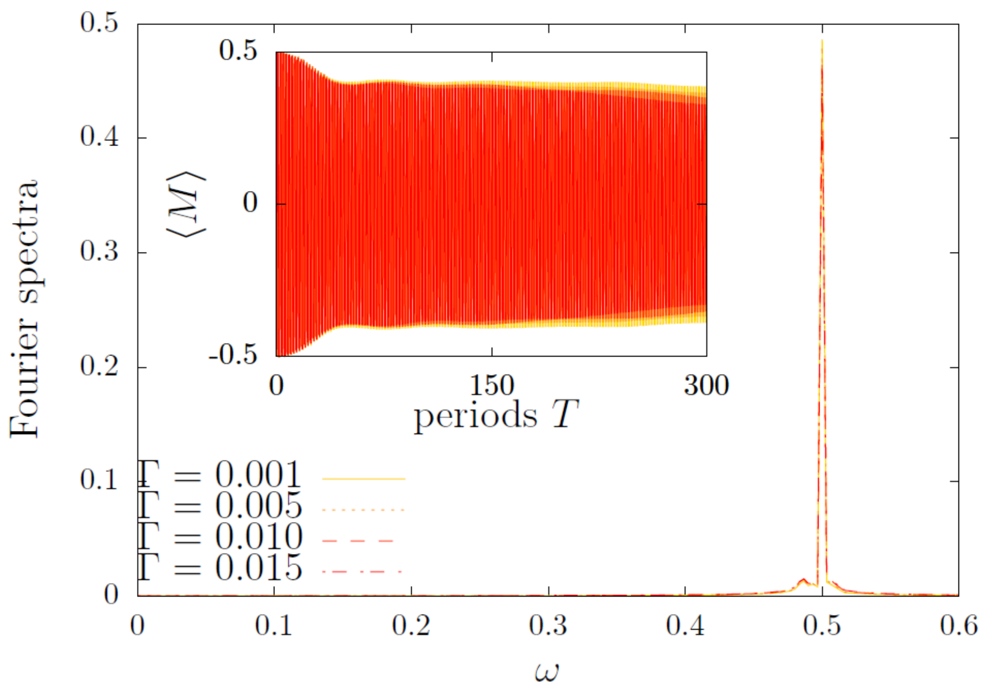

Thank you for the attention!