NON-MARKOVIAN QUANTUM FEEDBACK CONTROL OF PHOTON STATISTICS AND QUANTUM MANY BODY DYNAMICS

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

*in collaboration with
N. Nemet, L. Droenner, M. Strauß, S. Reitzenstein, S. Parkins, M. Heyl, and A. Knorr

- Non-Markovian signatures in Quantum Optics: Wigner delay
- Bypassing non-Markovian decoherence via quantum feedback
- Selective photon-probability control in the two-photon regime
- Stabilizing a discrete time crystal against dissipation

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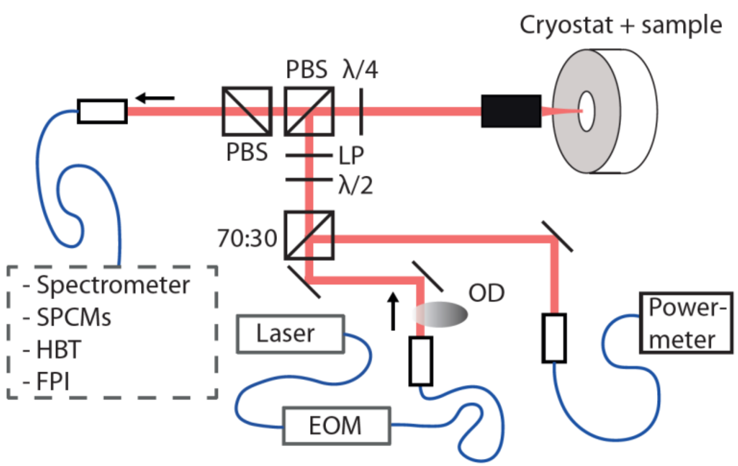
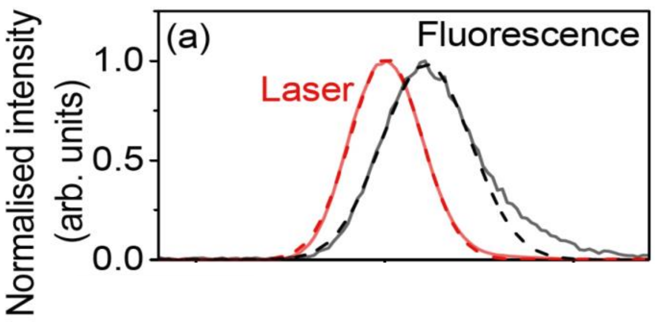


Wigner delay occurs between absorption and emission processes of a single quantum dot



Strauß, AC et al, PRL 122, 107401 (2019); arXiv: 1805.06357v1

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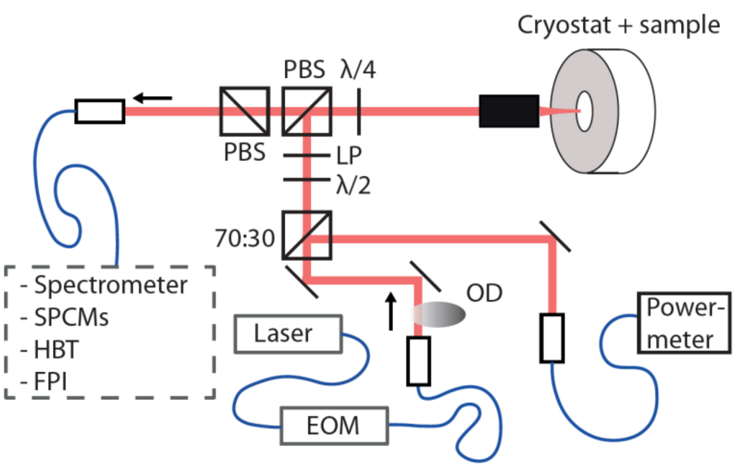

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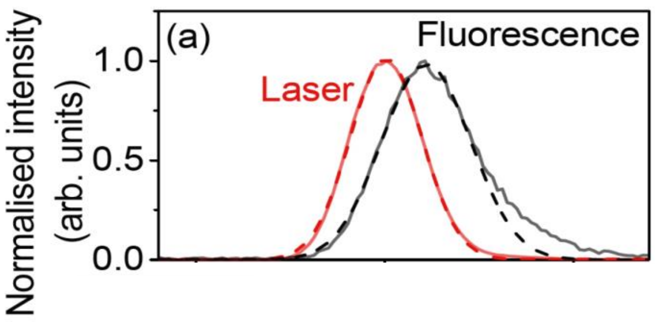

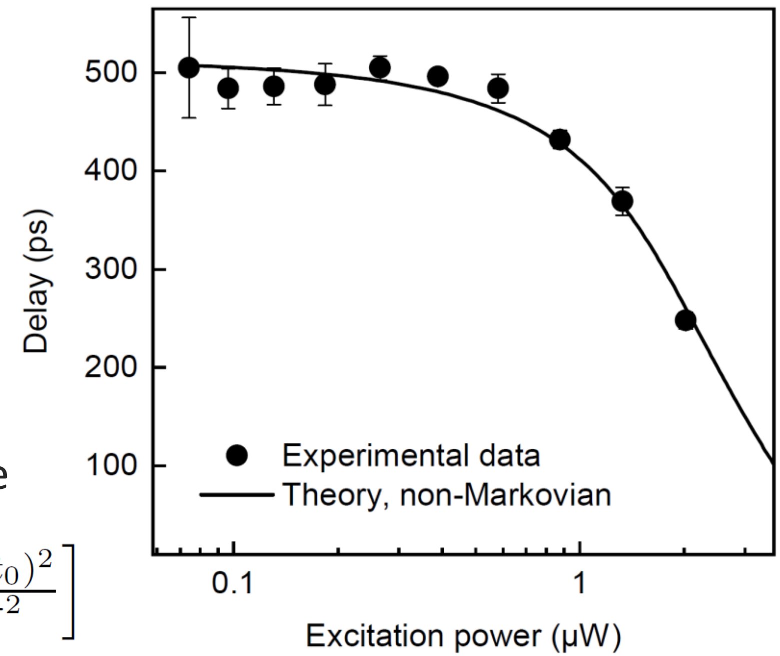

Wigner delay also strongly dependent on the excitation power **if not** in the Heitler regime

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

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Non-Markovian signatures in Wigner delays

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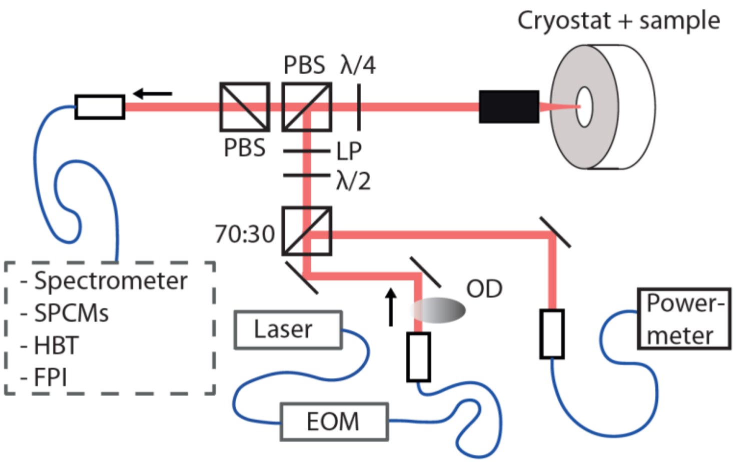

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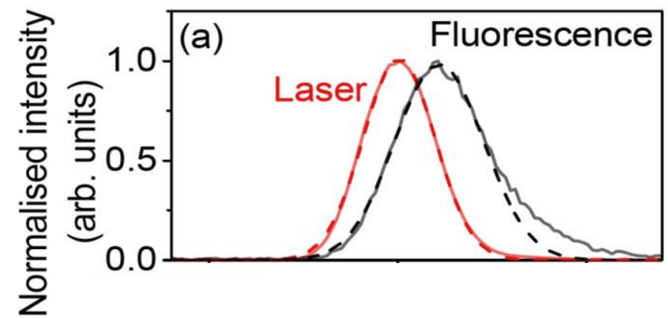

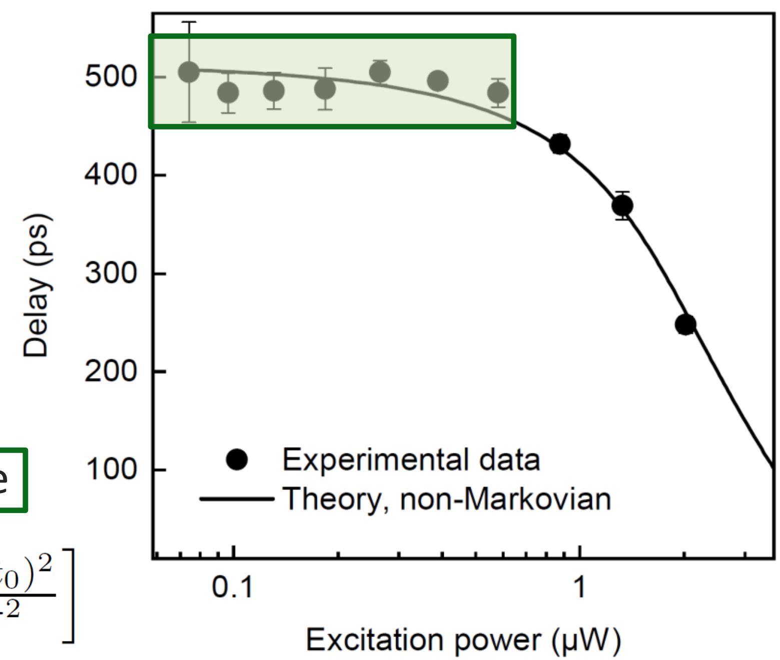

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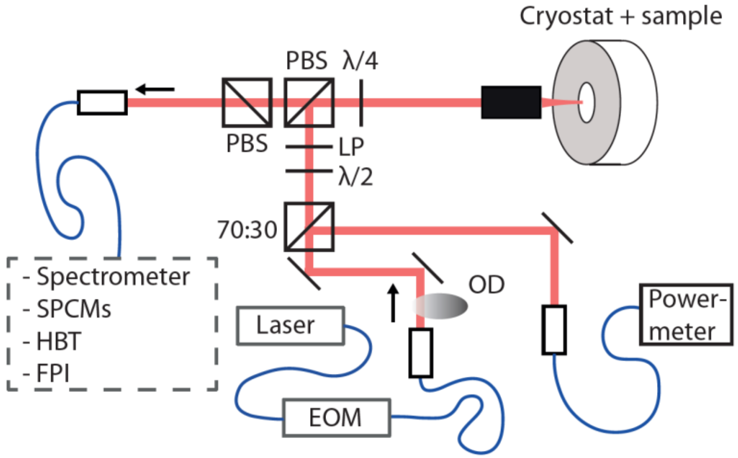

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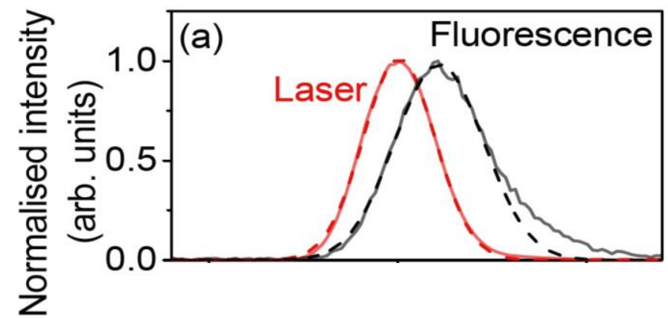

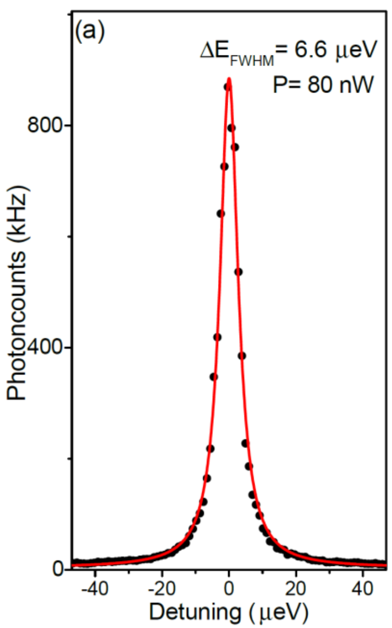

Wigner delay strongly dependent on the T1-time of the quantum dot, here T1 = (700 ± 100) ps

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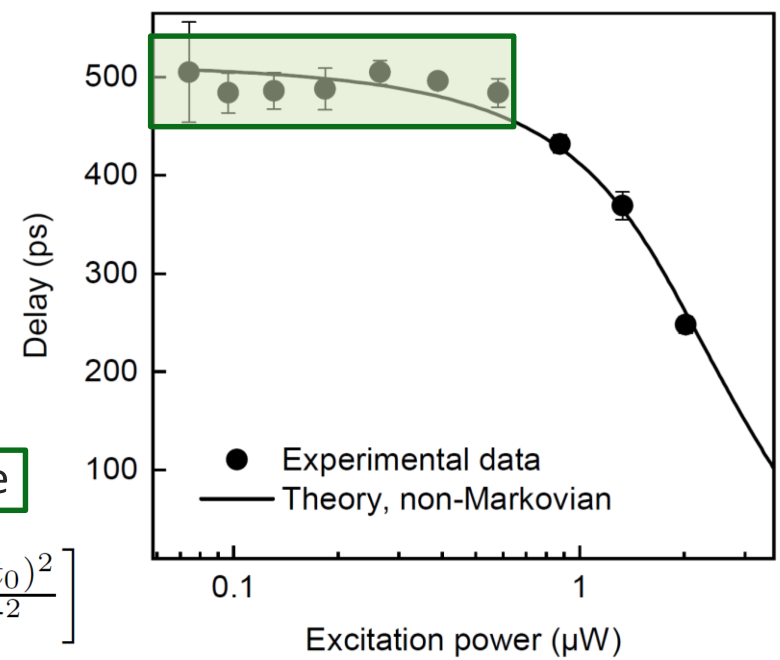

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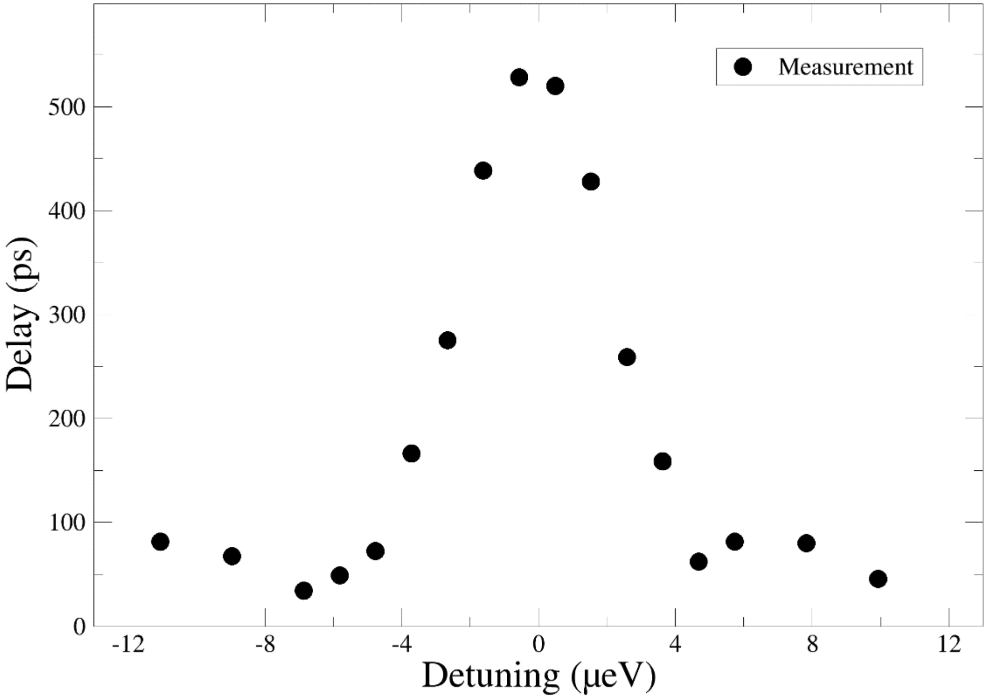
Wigner delay induced by a single quantum dot:

Markovian theory via Lindblad-type dephasing

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

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

$$\dot{\rho}_{12} = (i\Delta - \Gamma/2 - \gamma_p)\rho_{12} - i\Omega(t)(2\rho_{22} - 1)$$



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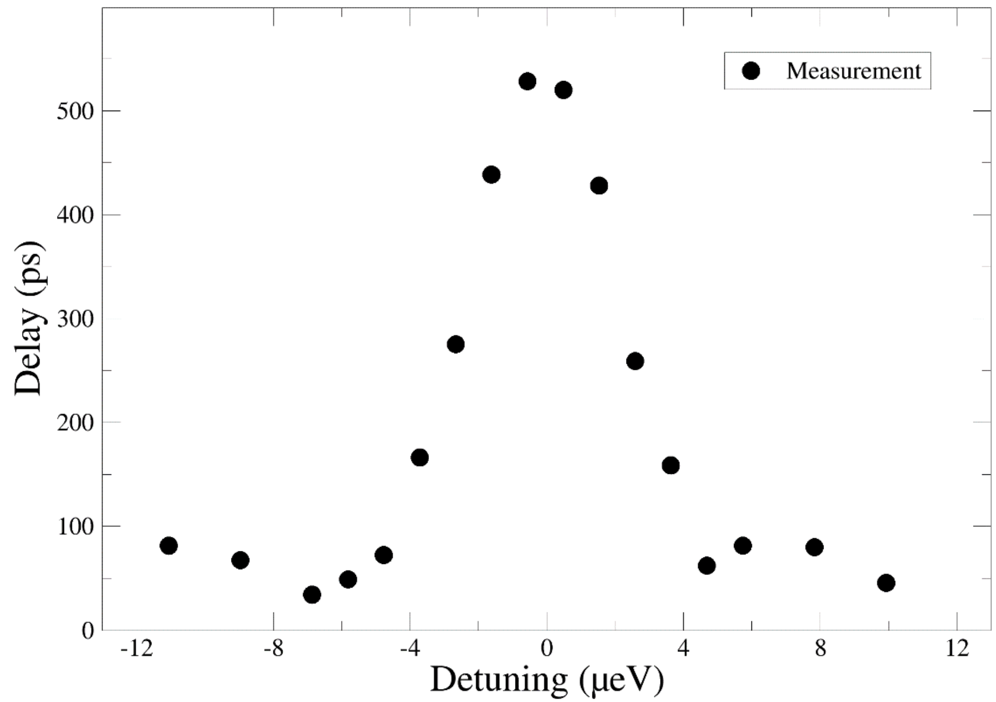

Bloch equations solved in the adiabatically limit

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

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

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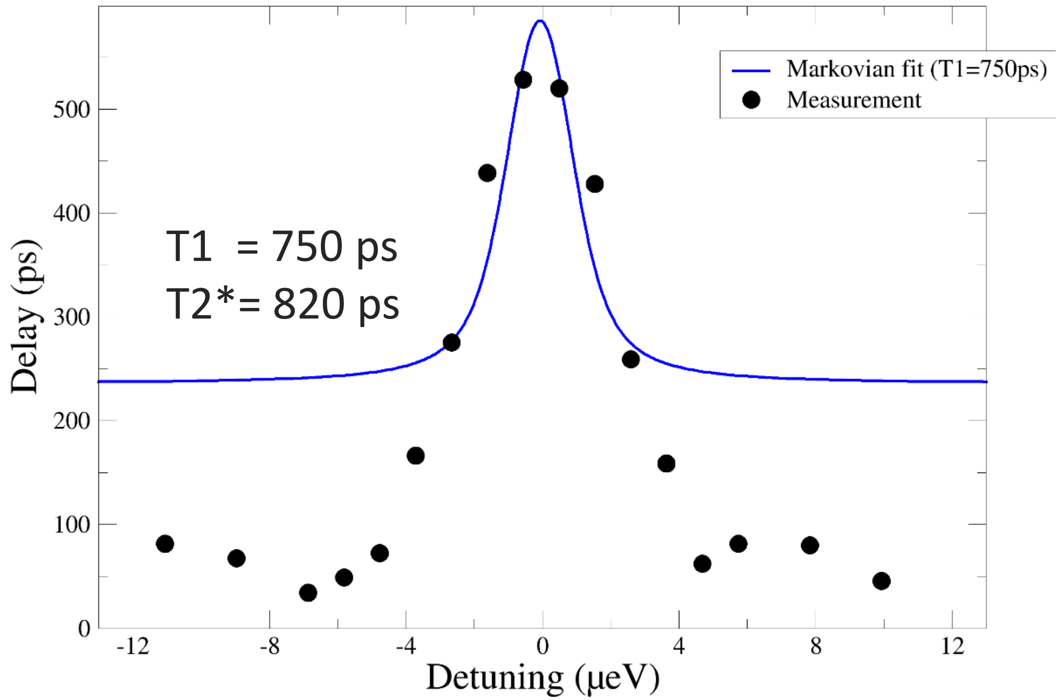

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Choose the pure dephasing to reproduce for a fixed radiative lifetime constant

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Non-Markovian signatures in Wigner delays

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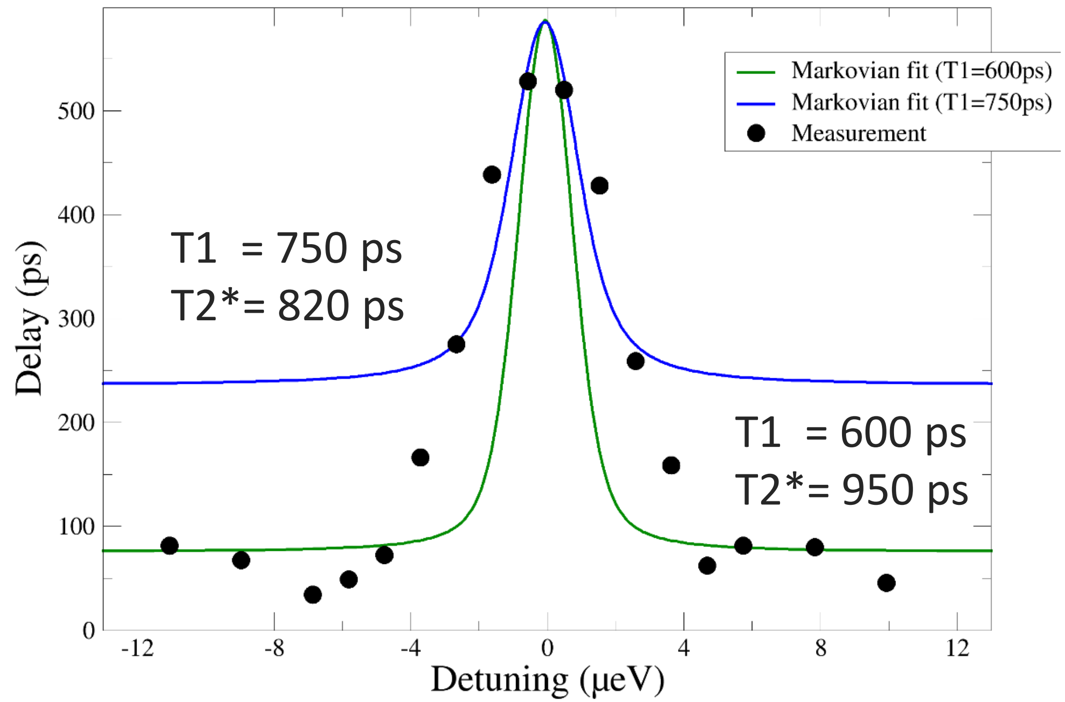

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⇨ Markovian theory fails to reproduce both limits and not the asymmetries between red- and blue-detuned Wigner delays

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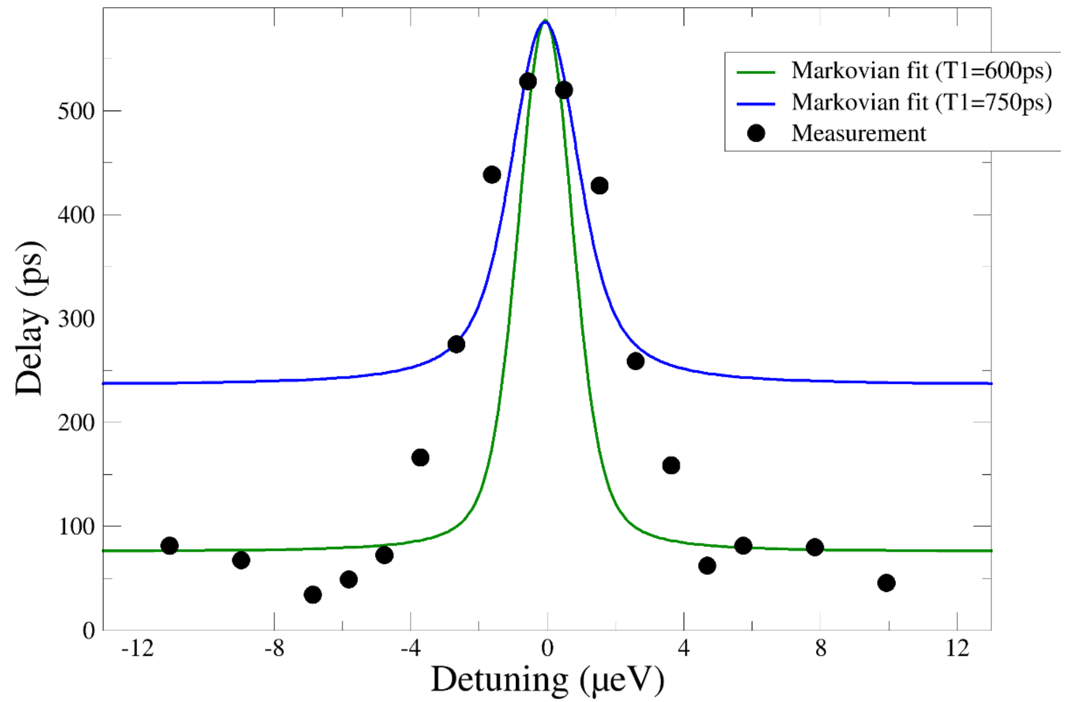
Wigner delay in the presence of electron-phonon interaction:

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

Non-Markovian theory via semiconductor Bloch equations

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

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



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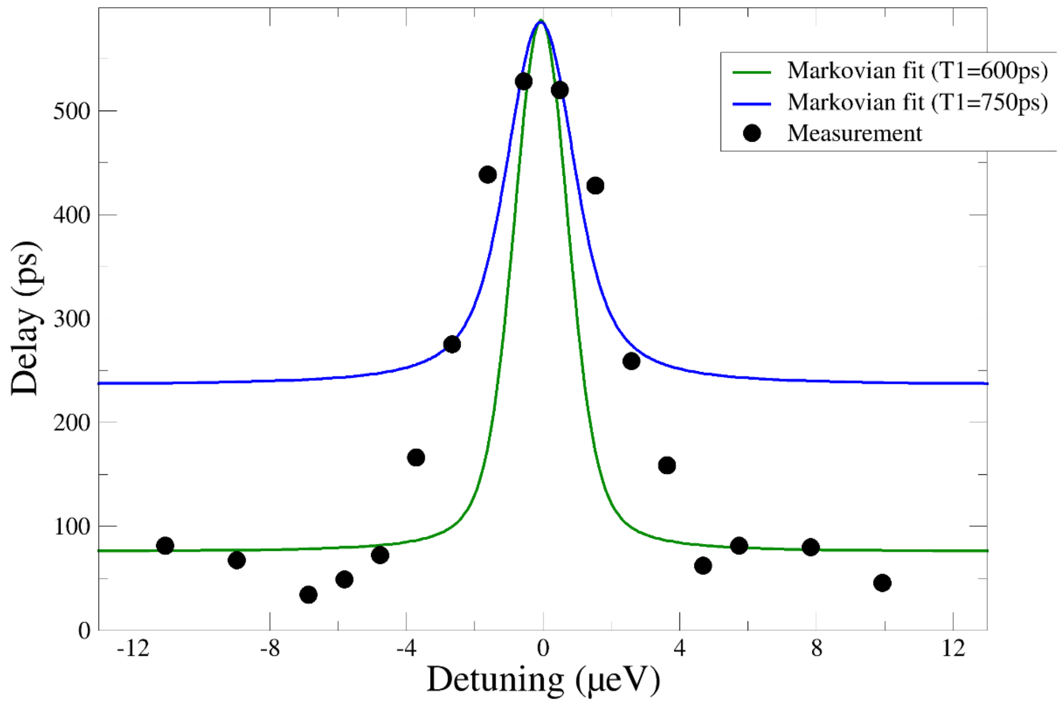

Bloch equations solved numerically in the second-order Born level

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

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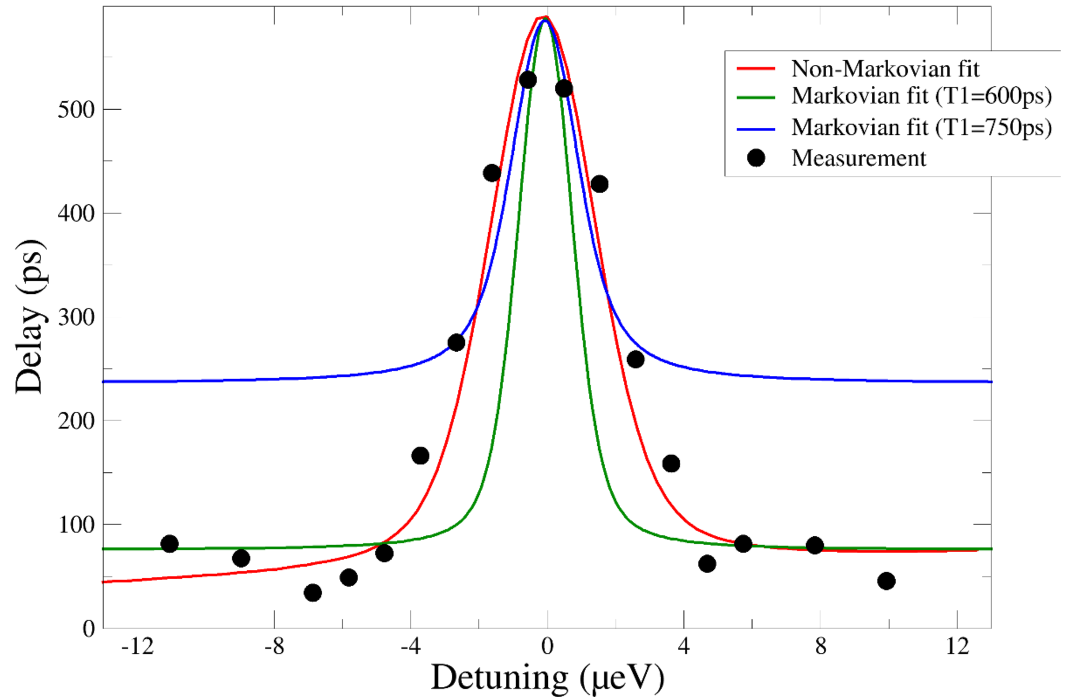

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Coupling element input parameter from material theory of InAs/GaAs (bulk phonons)

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

Strauß, AC et al, PRL 122, 107401 (2019); arXiv: 1805.06357v1

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Feedback in the quantum regime

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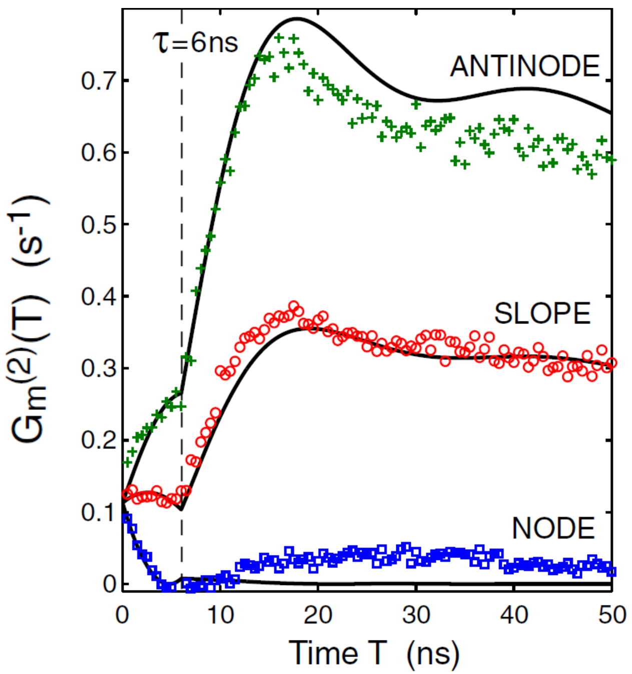
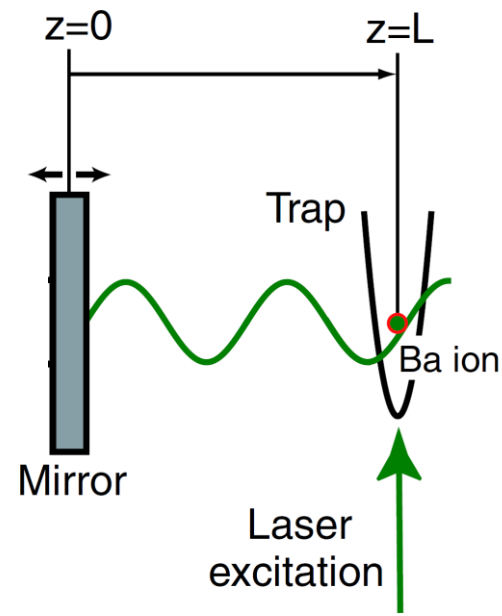
Experiments on the single quanta level feedback coupling:

- Experiments with cold atoms



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



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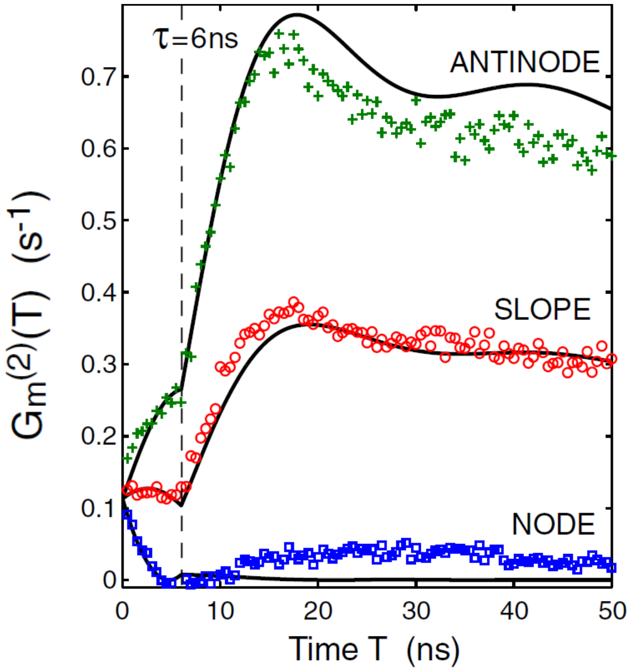

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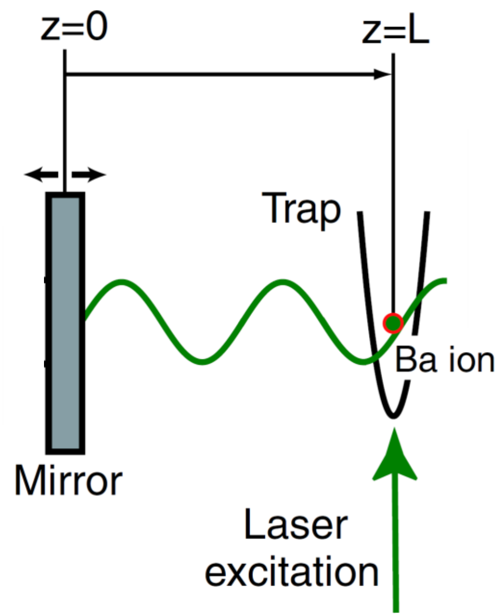

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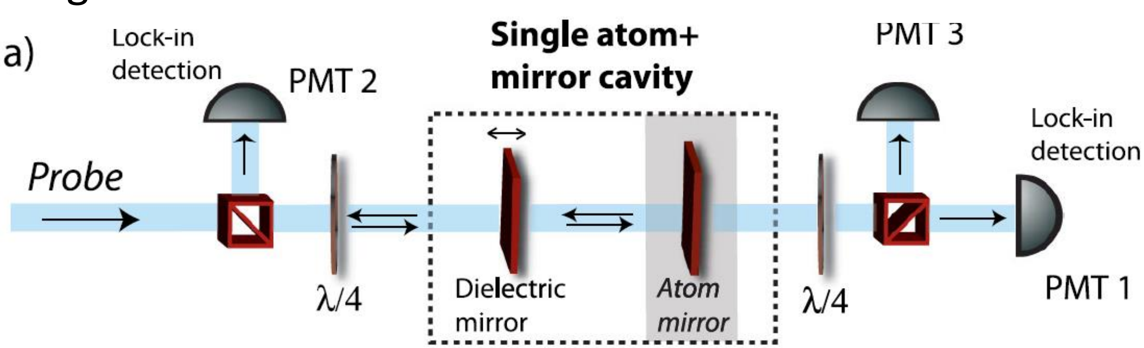
- Transmission controlled by the atom's position at length L

Single atom-mirror:



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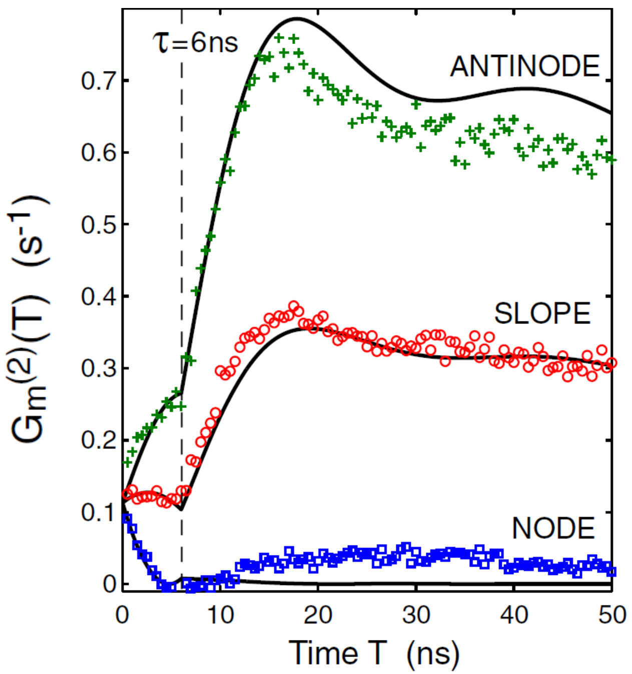

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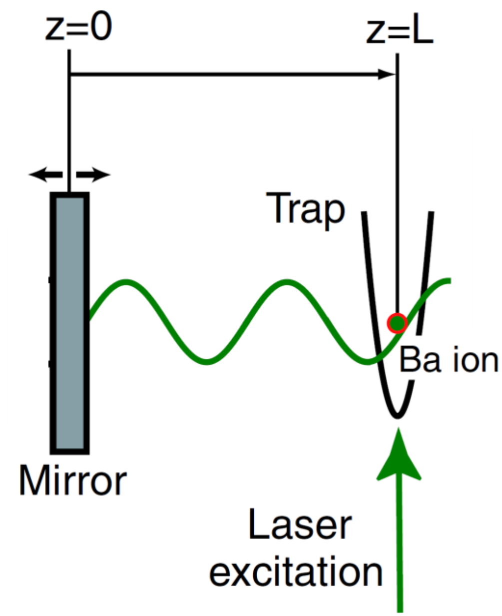

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- Transmission controlled by the atom's position at length L
- **Sinusoidal dependence**

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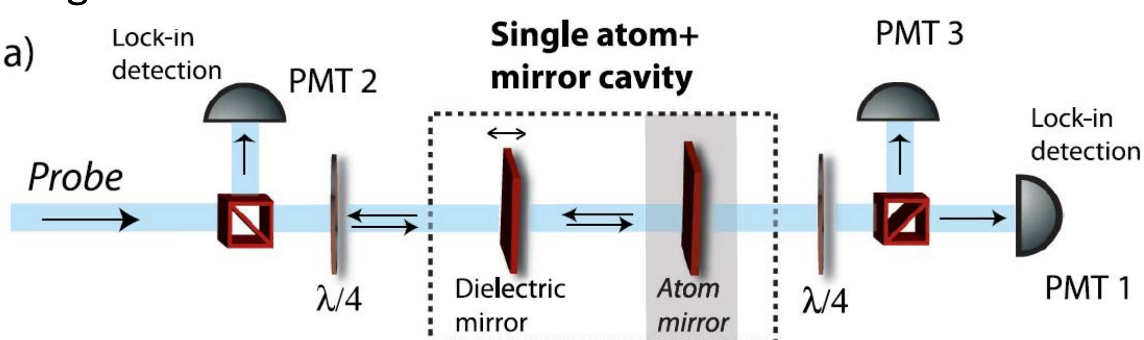

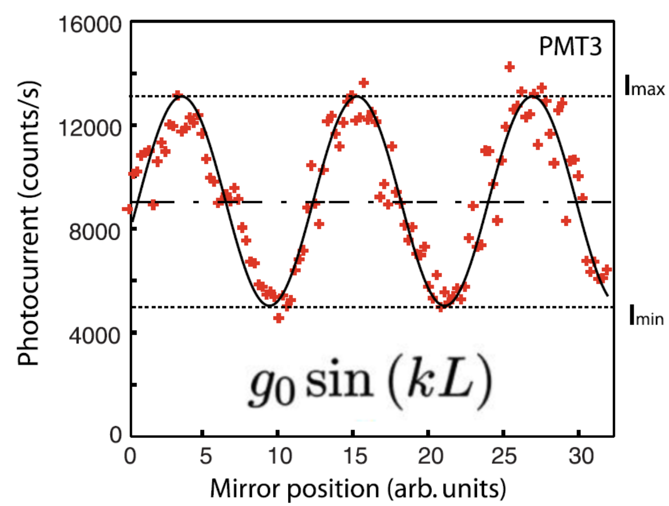

G. Hetet et al, Phys. Rev. Lett. 107, 133002 (2011).

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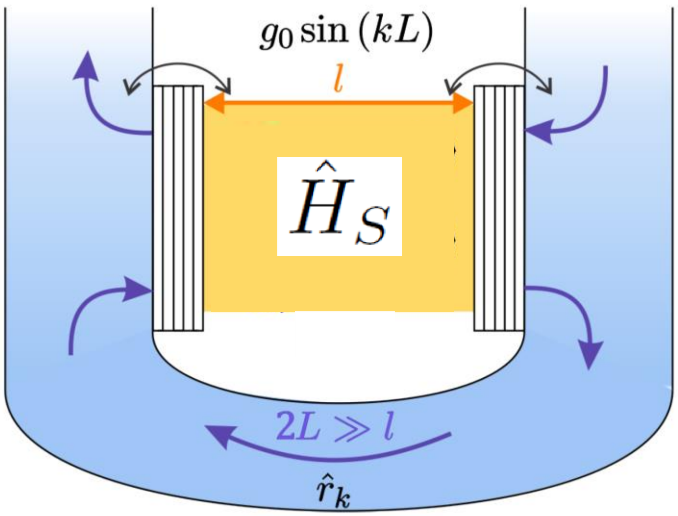

Whalen et al, Quant. Sci. and Tech. 44008 (2017)

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

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

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

Nemet, AC et al, arXIv: 1902.08328

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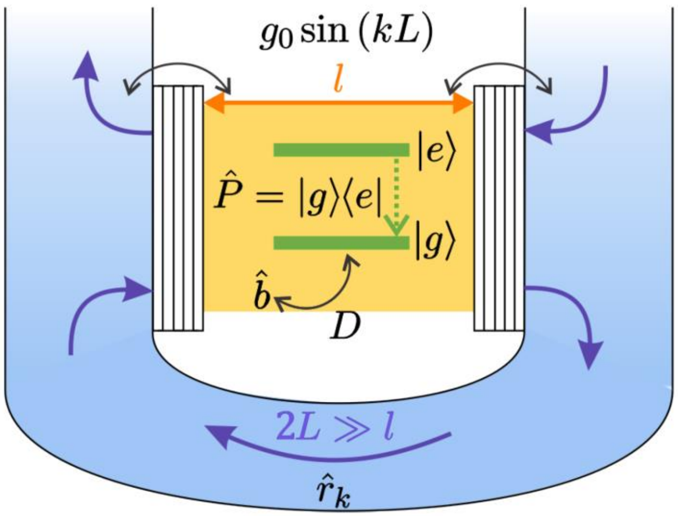

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Bypassing decoherence via quantum feedback

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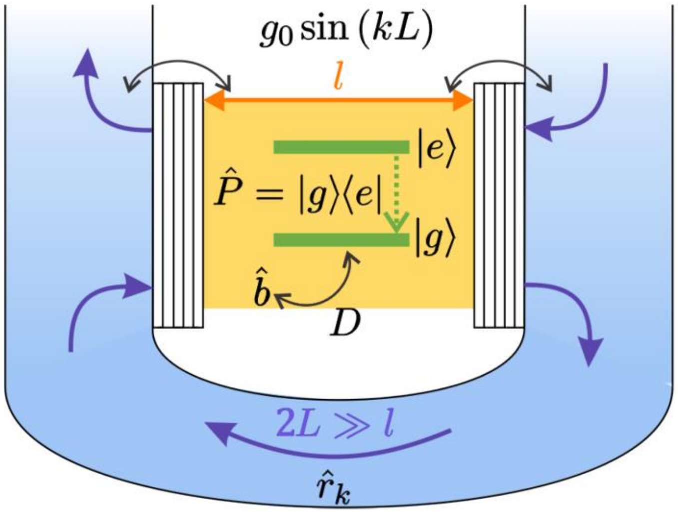

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$$\hat{H}_{LB}(t) = \hbar D[\hat{b}(t) + \hat{b}^\dagger(t)]\hat{P}^\dagger(t)\hat{P}(t)$$

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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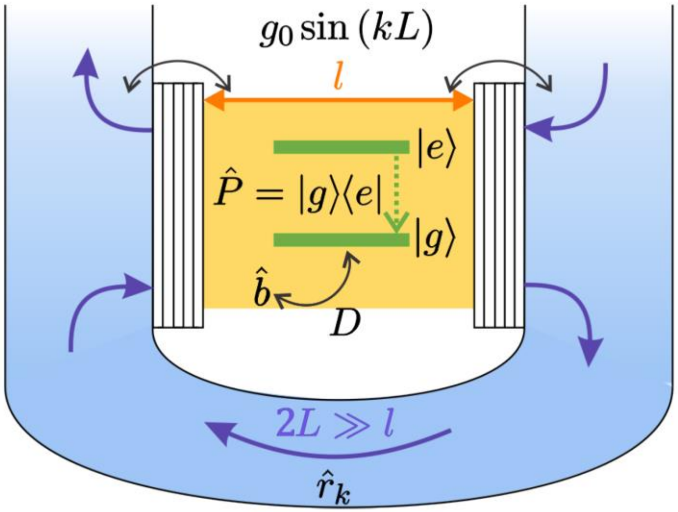

Goal: Stabilize an initial given coherence even in the presence of a reservoir at finite temperature

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

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

$$\hat{H}_{LB}(t) = \hbar D[\hat{b}(t) + \hat{b}^\dagger(t)]\hat{P}^\dagger(t)\hat{P}(t)$$

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

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

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-Trotter expansion

Nemet, AC et al, arXIv: 1902.08328

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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

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

Nemet, AC et al, arXlv: 1805.2317

Bypassing decoherence via quantum feedback

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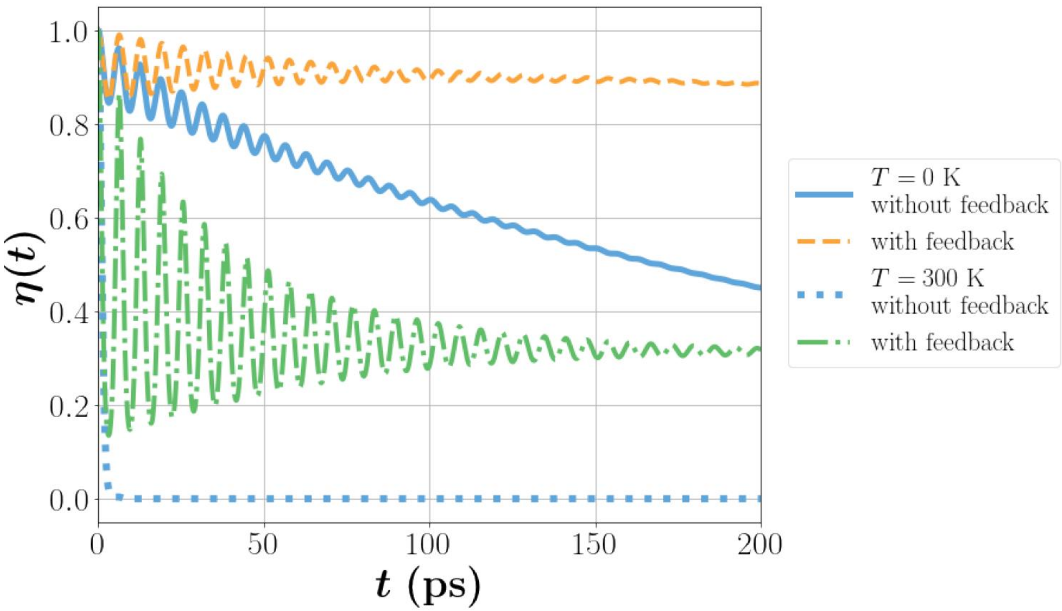

Feedback stops via quantum interference the decoherence process – a synchronisation between the oscillators take place

Nemet, AC et al, arXIv: 1805.2317

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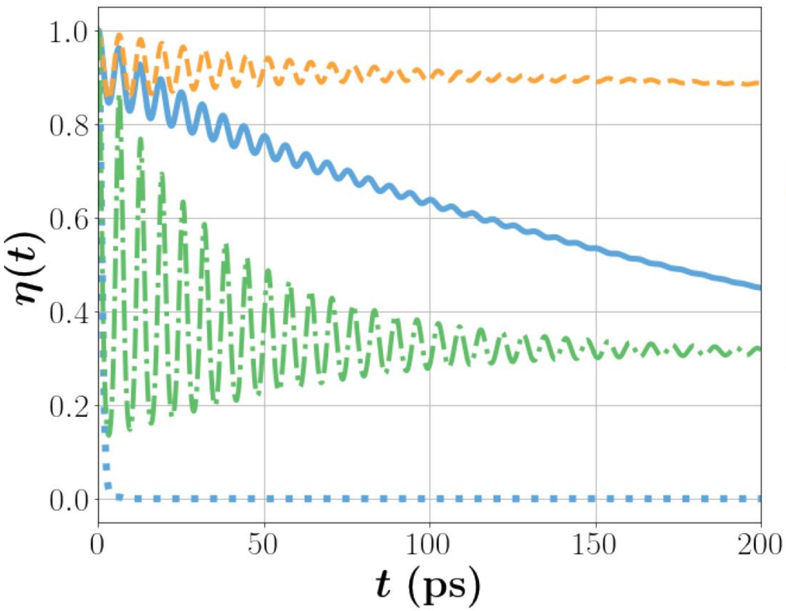

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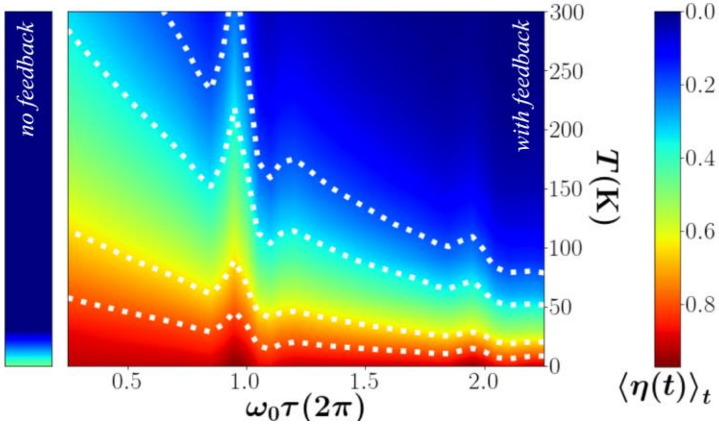

Delay time and phase-matching allow very long coherence times initial coherence at room temperature up to 200ps

Nemet, AC et al, arXIv: 1805.2317

- Non-Markovian signatures in Quantum Optics: Wigner delay
- Bypassing non-Markovian decoherence via quantum feedback
- **Selective photon-probability control in the two-photon regime***
- Stabilizing a discrete time crystal against dissipation

*with Leon Droenner, Nicolas Naumann, and Andreas Knorr

Quantum feedback in the nonlinear or many photon regime

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)

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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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and solve stroboscopically

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

Pichler, Zoller PRL 116, 93601 (2016)

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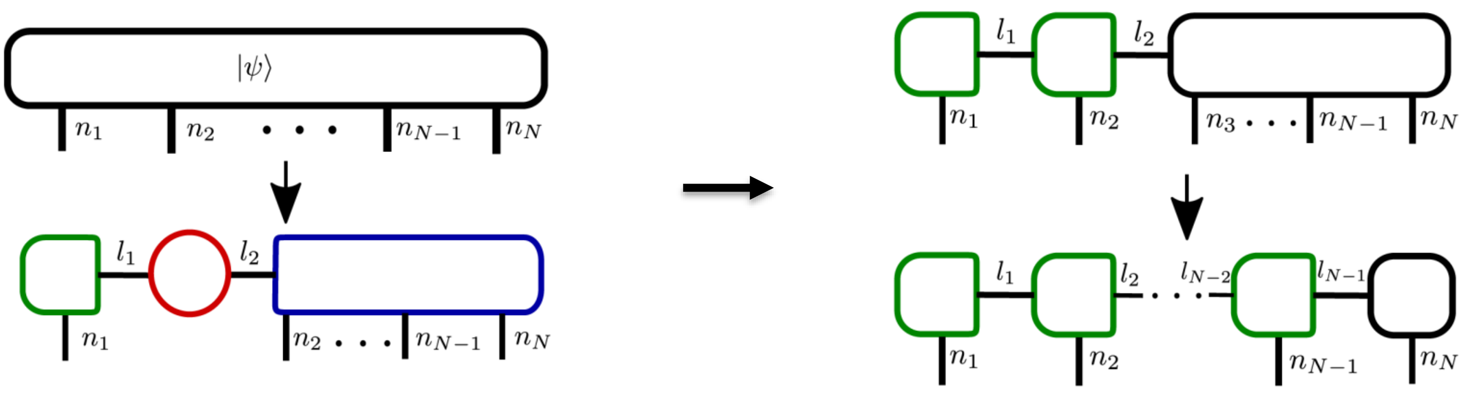

after SVD, yielding an MPS form $|\Psi\rangle = \sum_{i_1 \dots i_N} A^{[1]}_{i_1} \dots A^{[N]}_{i_N} |i_1\rangle \dots |i_N\rangle = \sum_{\mathbf{i}} A_{\mathbf{i}} |\mathbf{i}\rangle$

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

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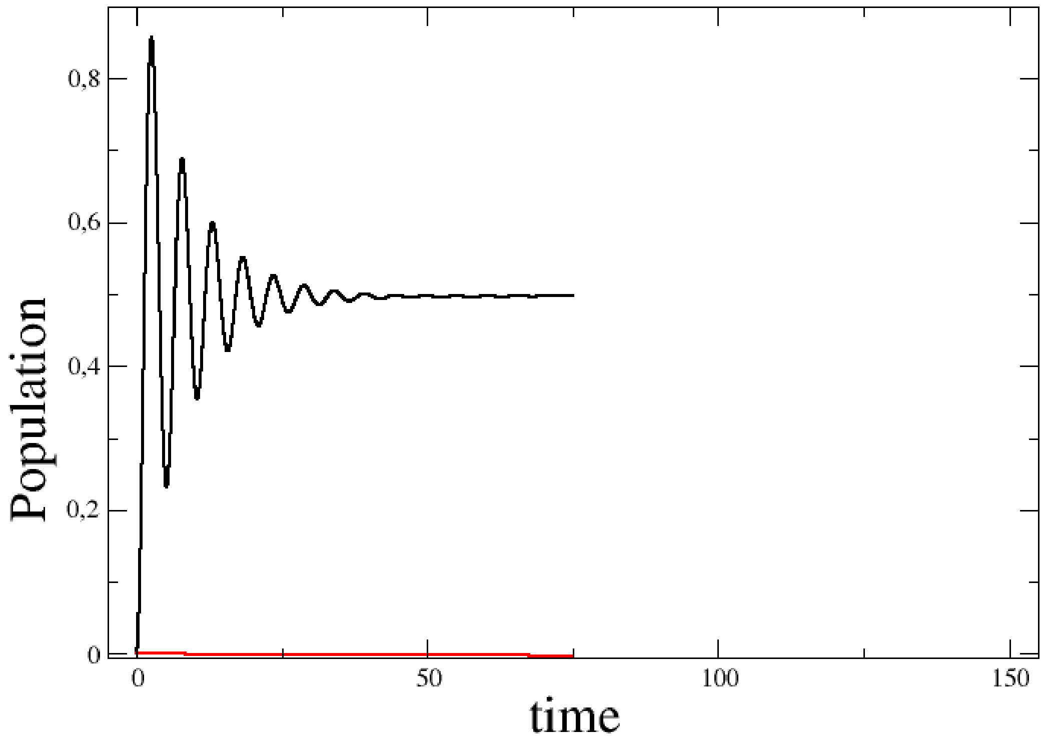
Schrödinger equation yields reversible dynamics.
Example: Driven and decaying two-level system.

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



Pichler, Zoller PRL 116, 93601 (2016)
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Quantum feedback in the nonlinear or many photon regime

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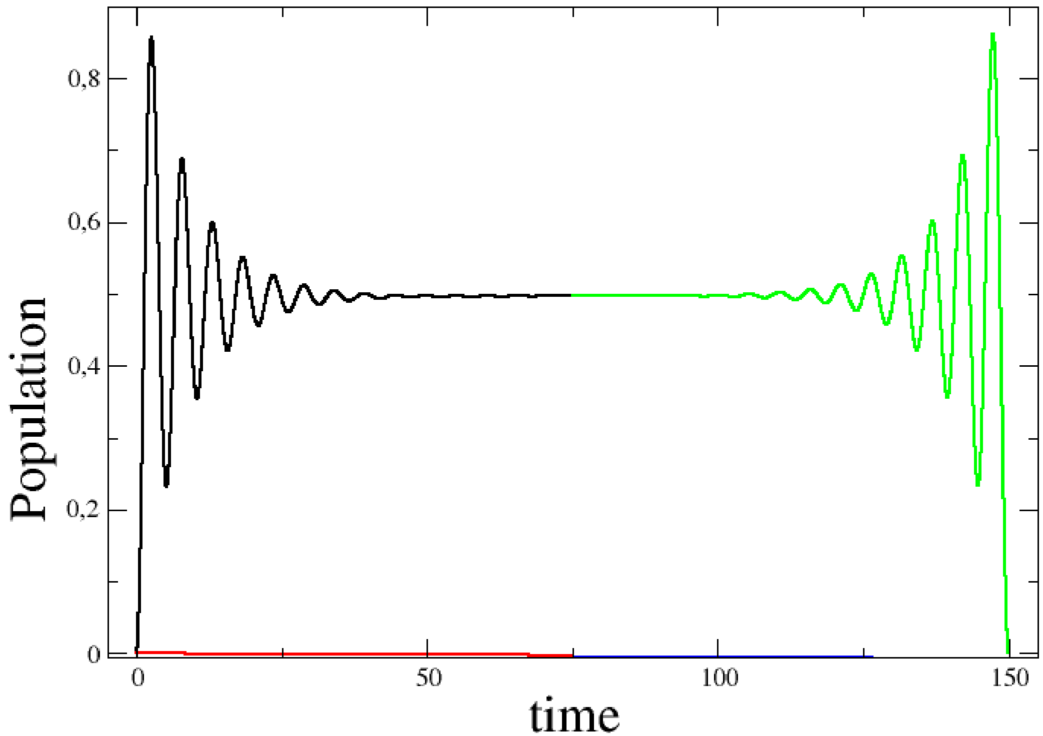

Time-reversal yields initial state. Full information of the reservoir in state. Numerical exact solution and dissipatively driven-correlation included.

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

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

Selective photon-probability control

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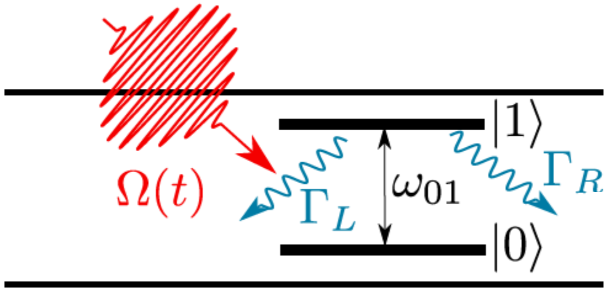
Pulsed and decaying two-level system.



Nearly perfect single photon emission for π-pulse

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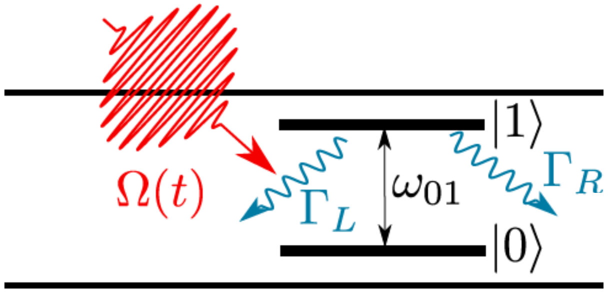

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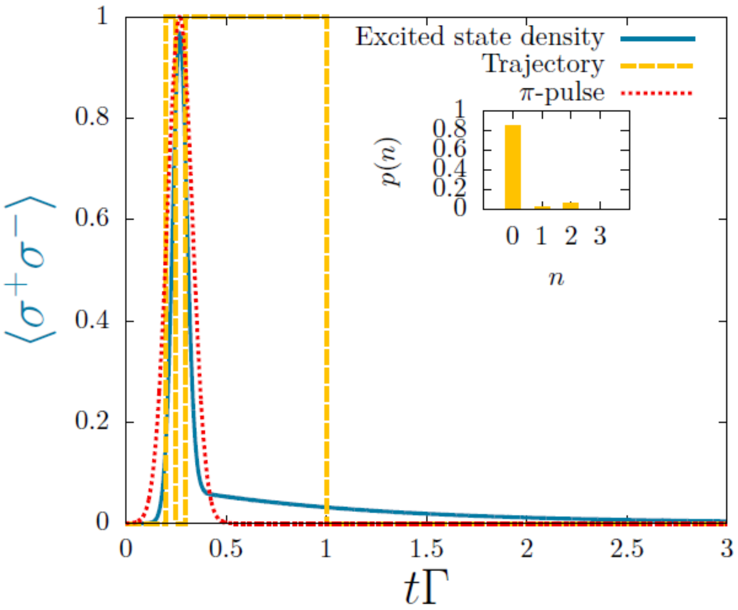

K. Fischer et al., Nat. Phys. 13, 649 (2017)

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

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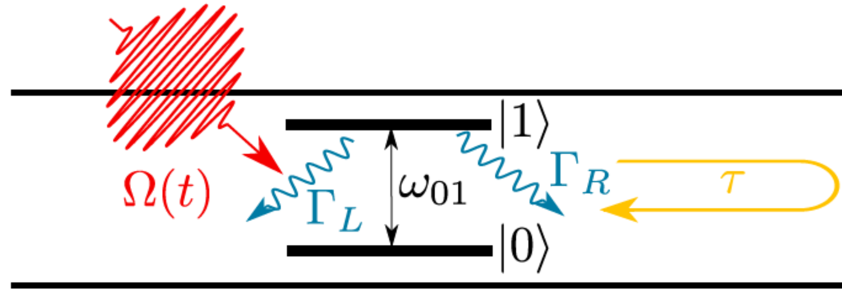

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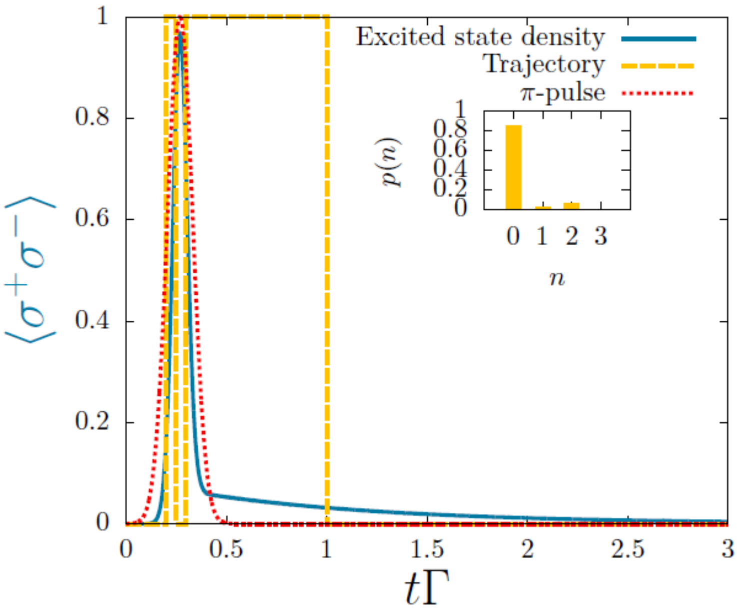

K. Fischer et al., Nat. Phys. 13, 649 (2017)

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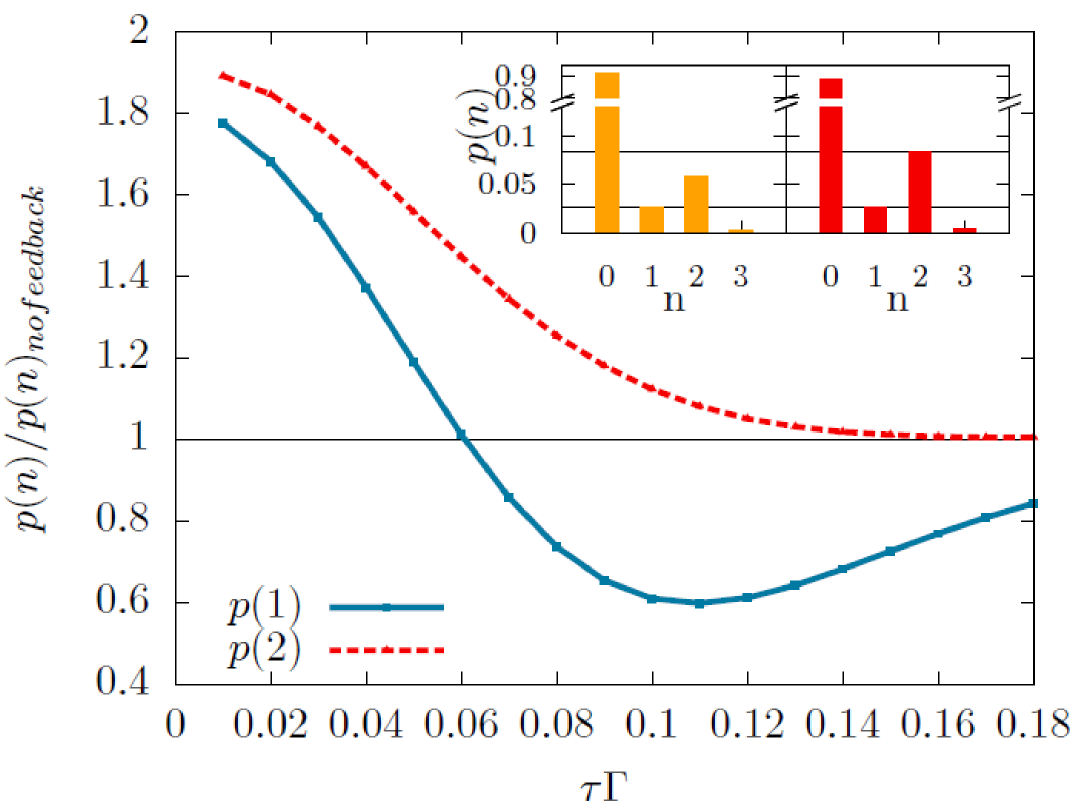
Purified two-photon state



Droenner, AC et al, PRA 99, 23840 (2019); arXiv:1801.03342v2

- Non-Markovian signatures in Quantum Optics: Wigner delay
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*with Leon Droenner, and Markus Heyl

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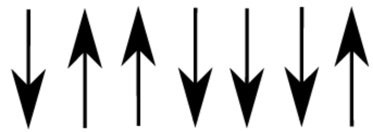
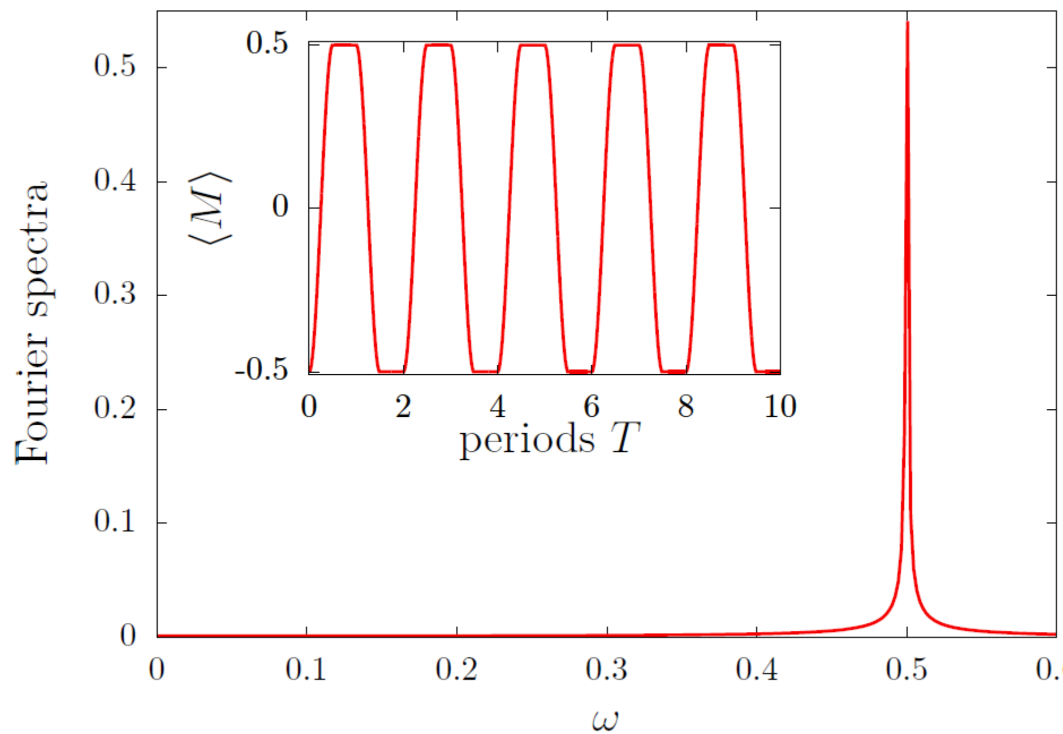
Illustration of a discrete time-crystal



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

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

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



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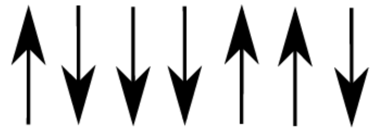

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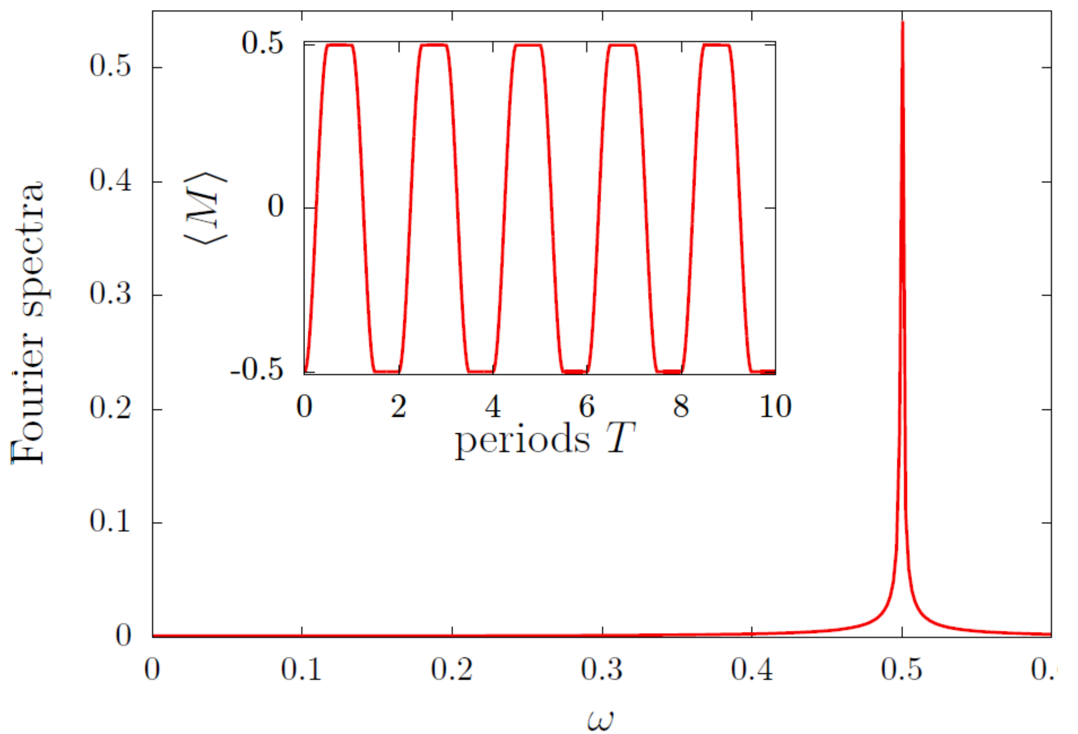

Discrete Time Crystal

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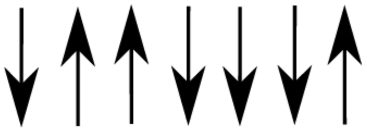

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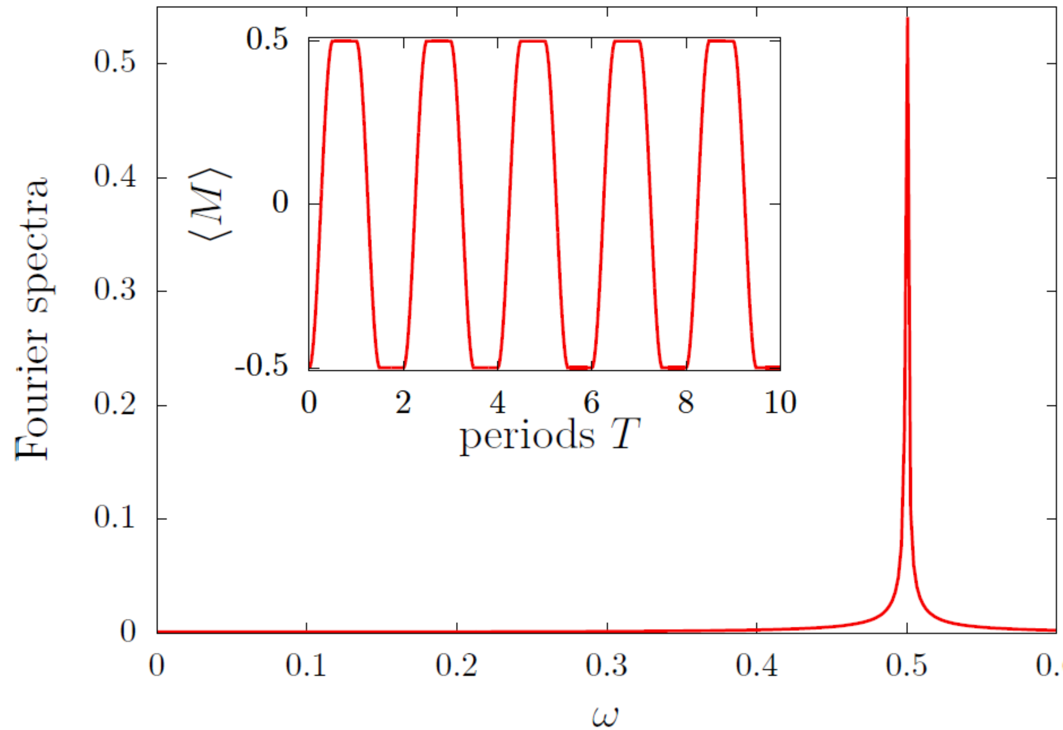

Discrete Time Crystal

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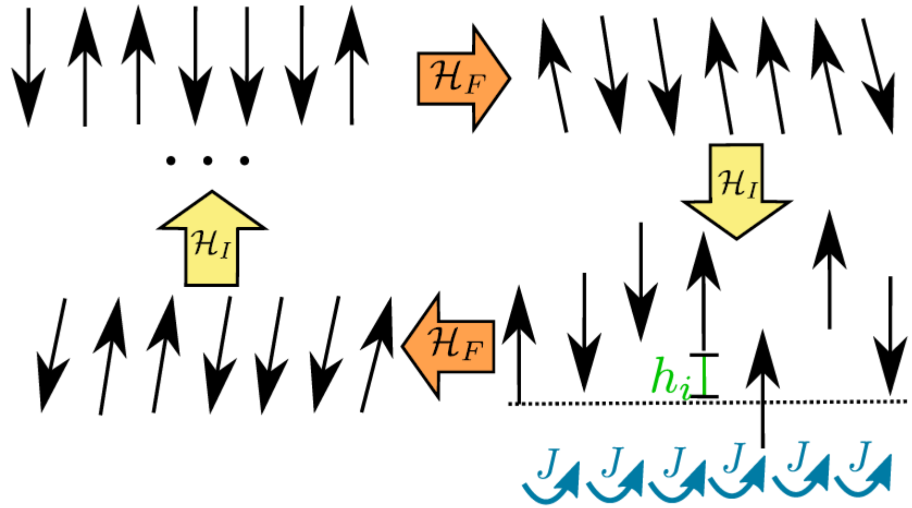
Illustration of a discrete time-crystal

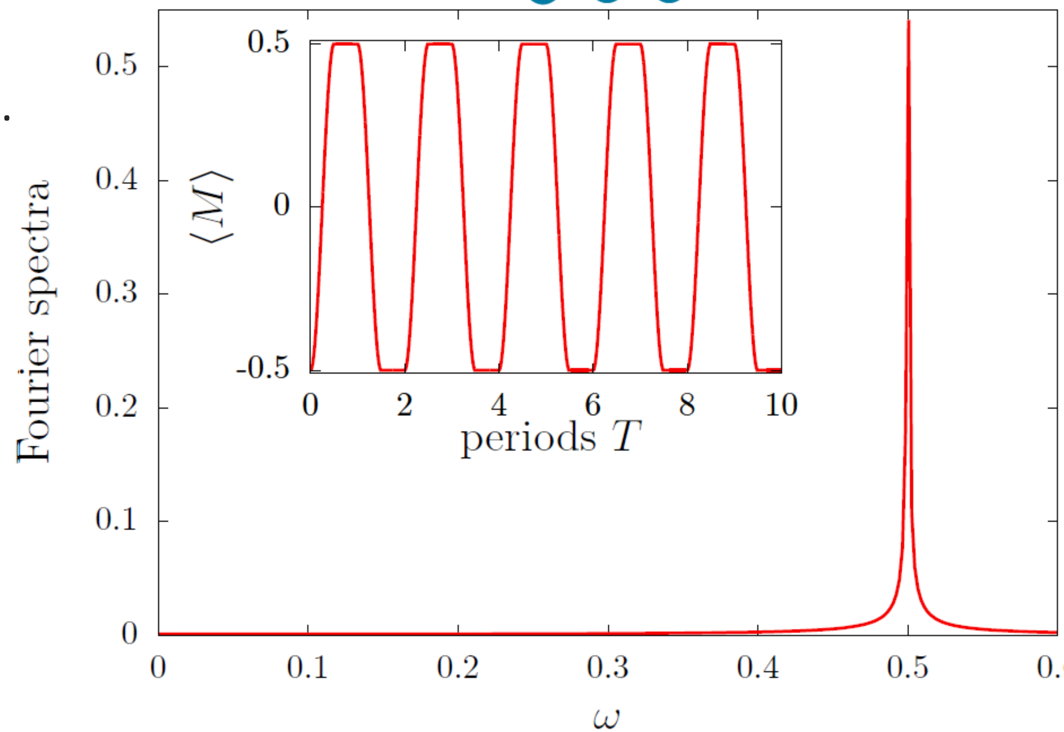
$$\mathcal{H}_F = (\Omega - \epsilon) \sum_{i=1}^{N} \sigma_i^x$$



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)

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



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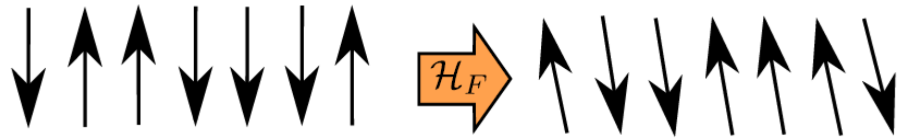

$$\mathcal{H}_F = (\Omega - \epsilon) \sum_{i=1}^{N} \sigma_i^x$$

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

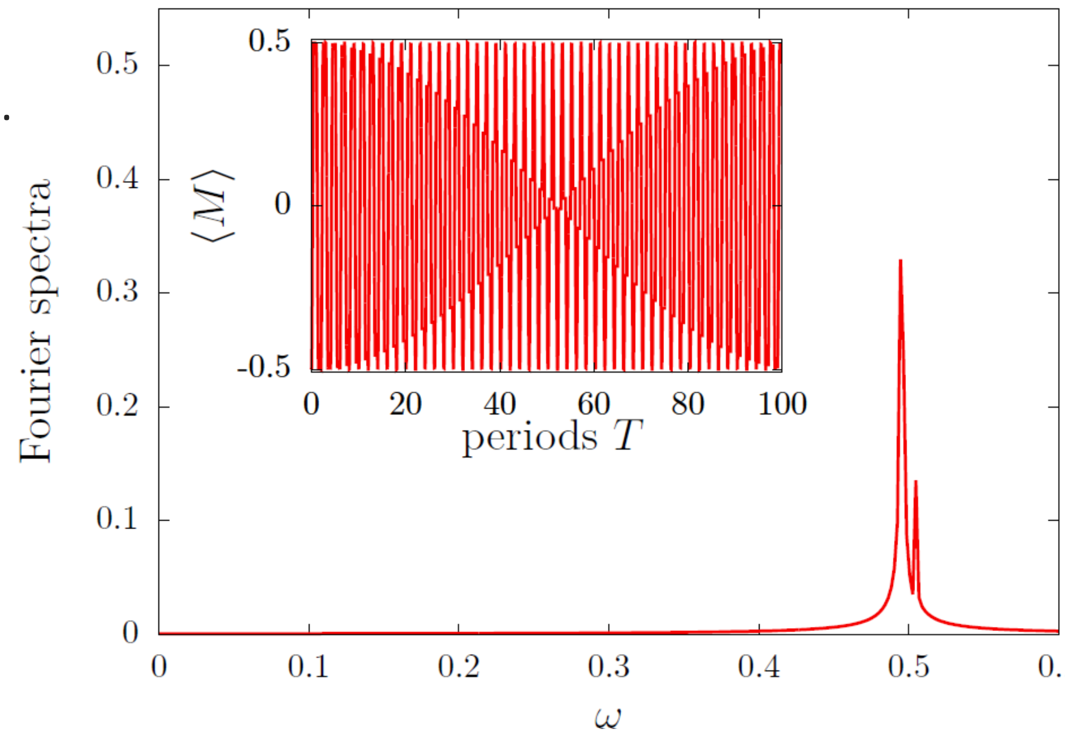

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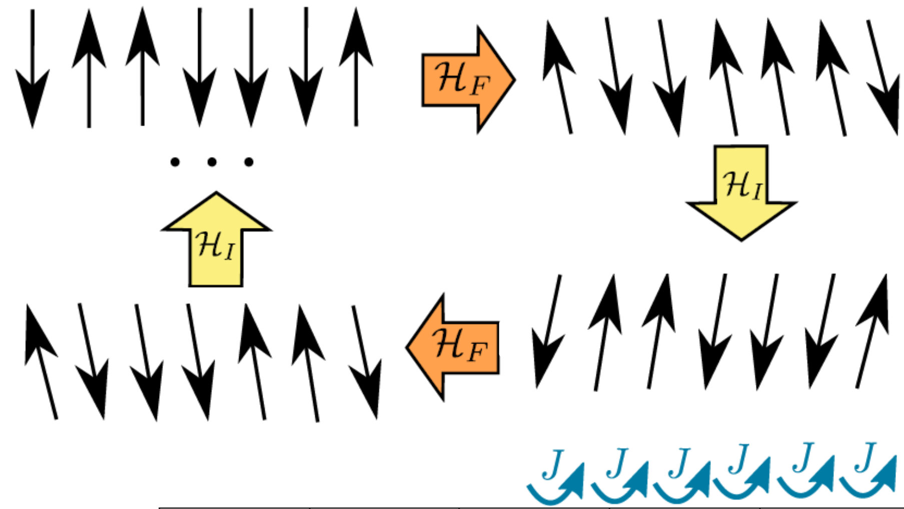
Illustration of a discrete time-crystal

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

$$\mathcal{H}_I = \sum_{i=1}^{N-1} J \sigma_i^z \sigma_{i+1}^z$$



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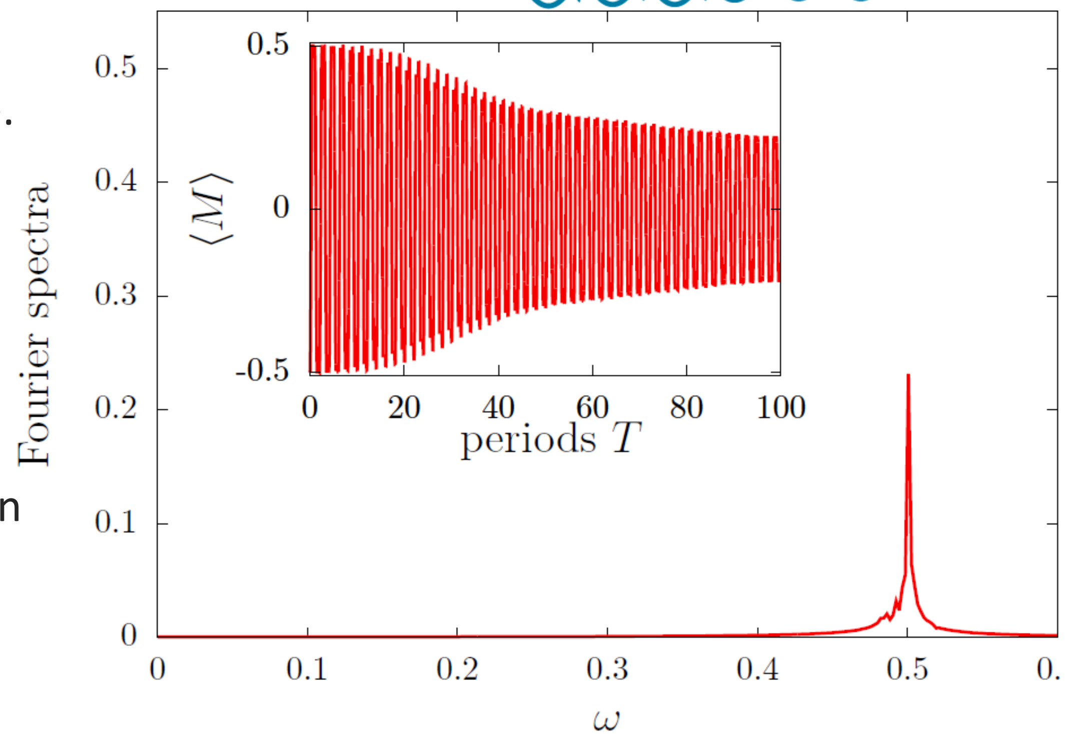
$$\langle M \rangle = \frac{1}{N} \sum_{i=1}^{N} (-1)^i \frac{\langle \sigma_i^z \rangle}{2}$$

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



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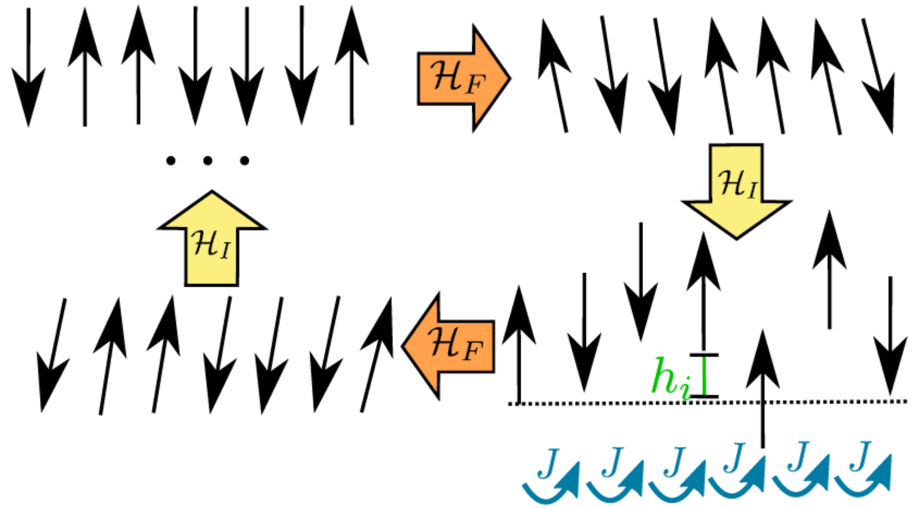

$$\mathcal{H}_F = (\Omega - \epsilon)\sum_{i=1}^{N} \sigma_i^x$$

$$\mathcal{H}_I = \sum_{i=1}^{N-1} J\sigma_i^z \sigma_{i+1}^z + \sum_{i=1}^{N} h_i \sigma_i^z$$

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

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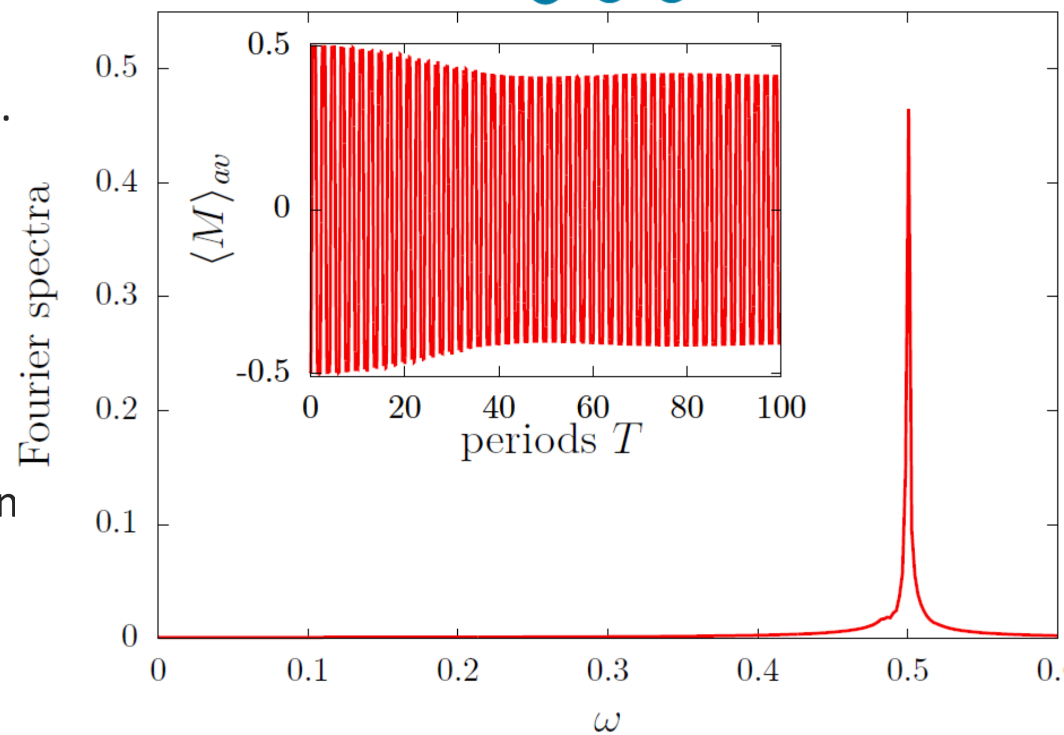

If driving is imperfect ε>0, and interaction switched and disorder is present, thermalization is prevented. Periodicity even for large N.

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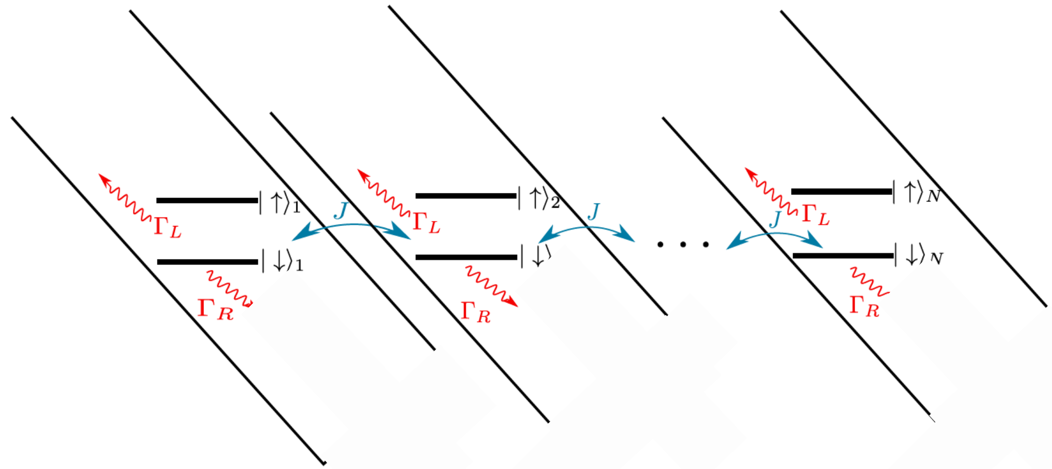
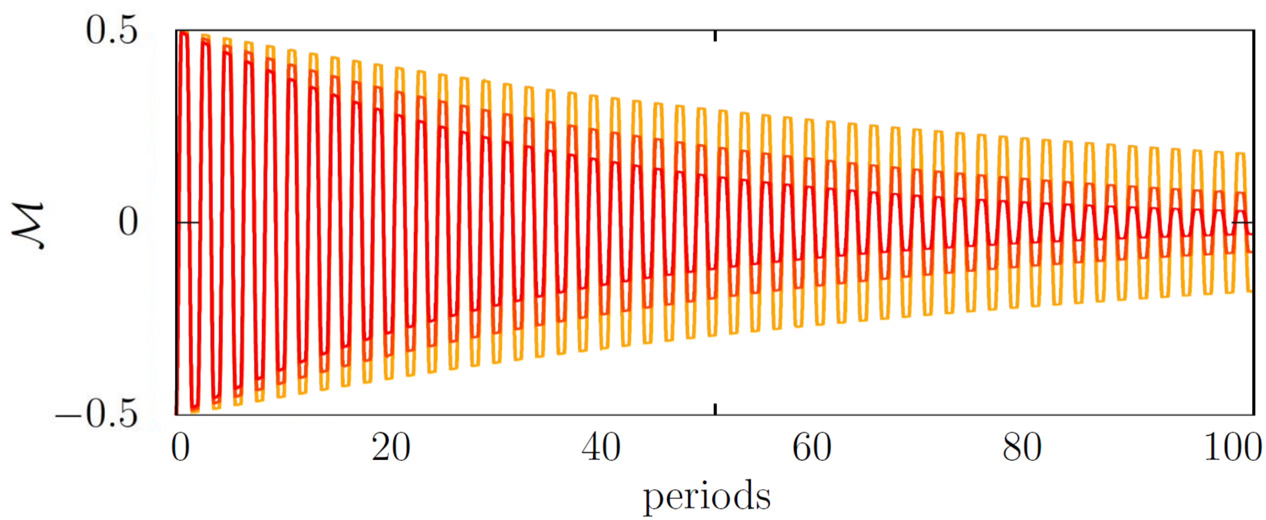
Time-crystal in the presence of losses

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



Discrete Time Crystal stabilized against dissipation

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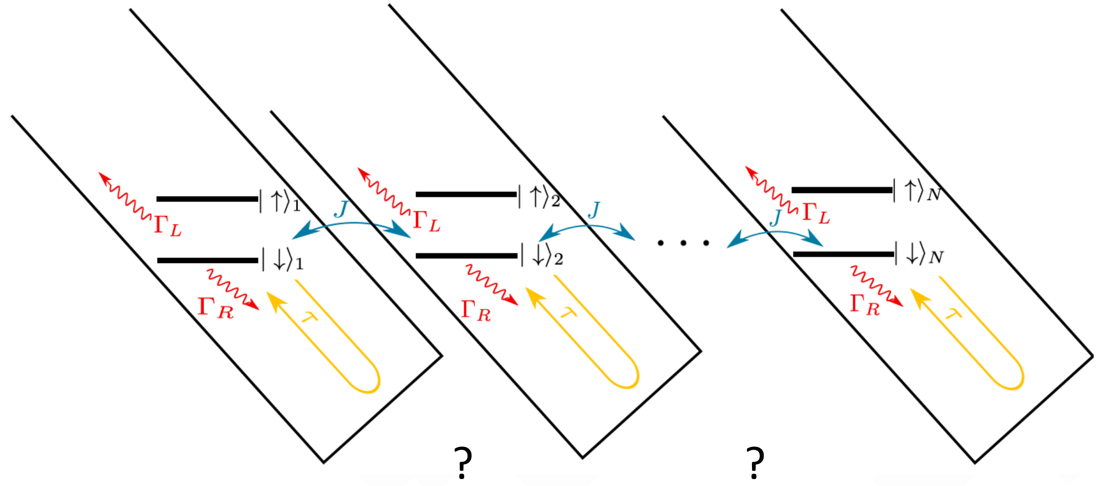

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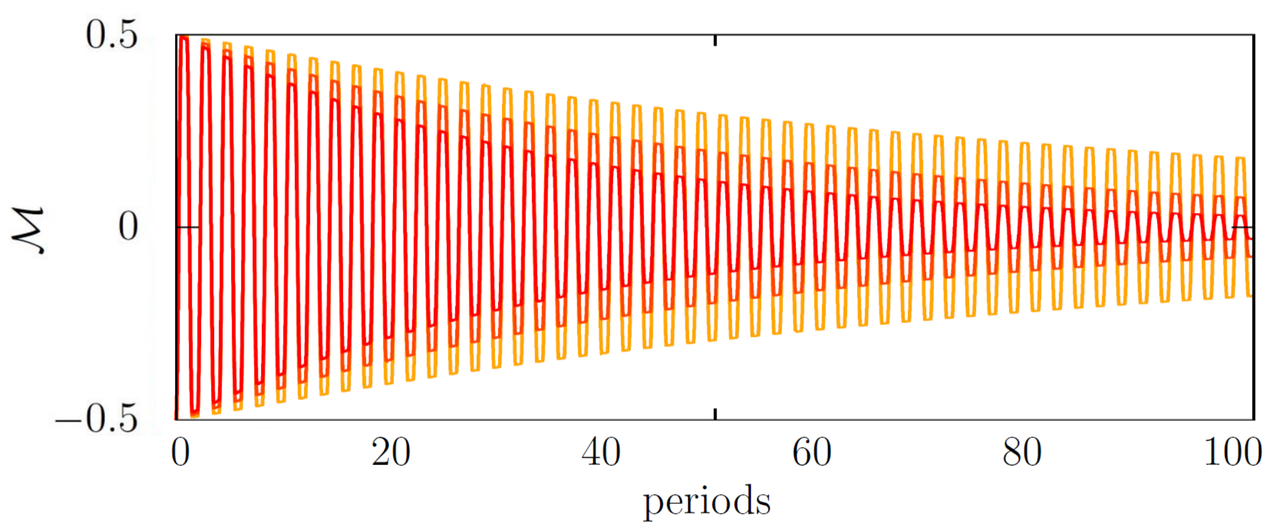

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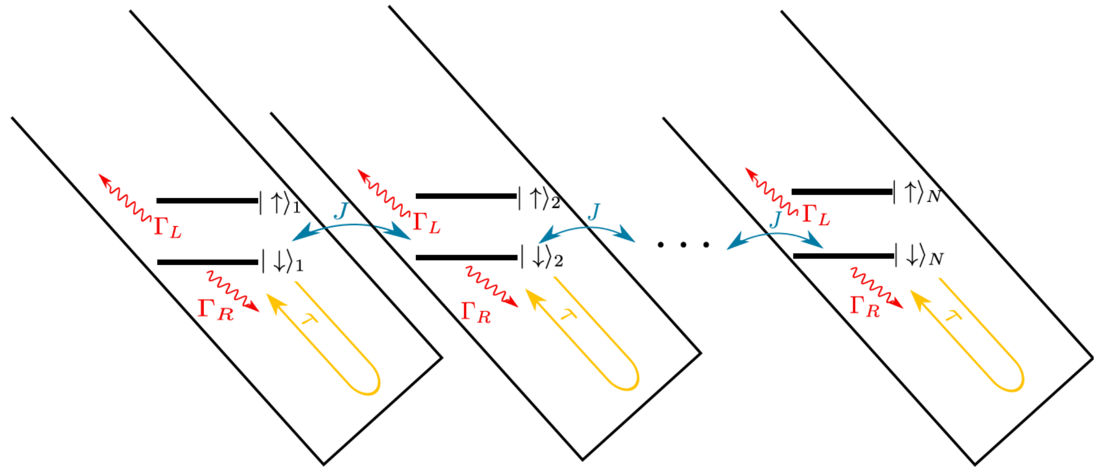

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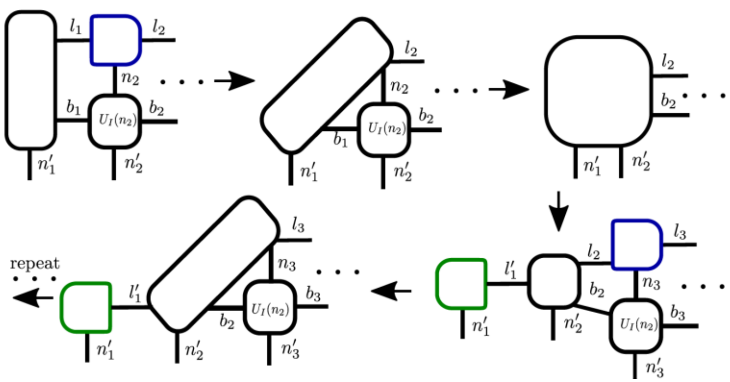
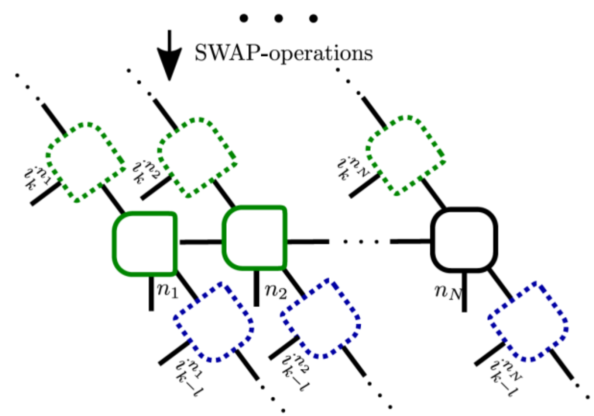
Droenner, AC et al, arXiv:1902.0498v1





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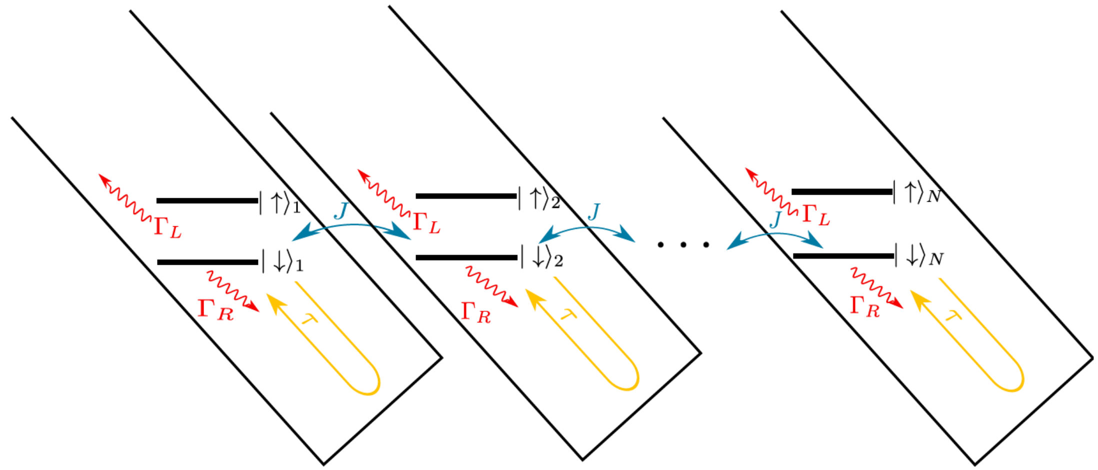

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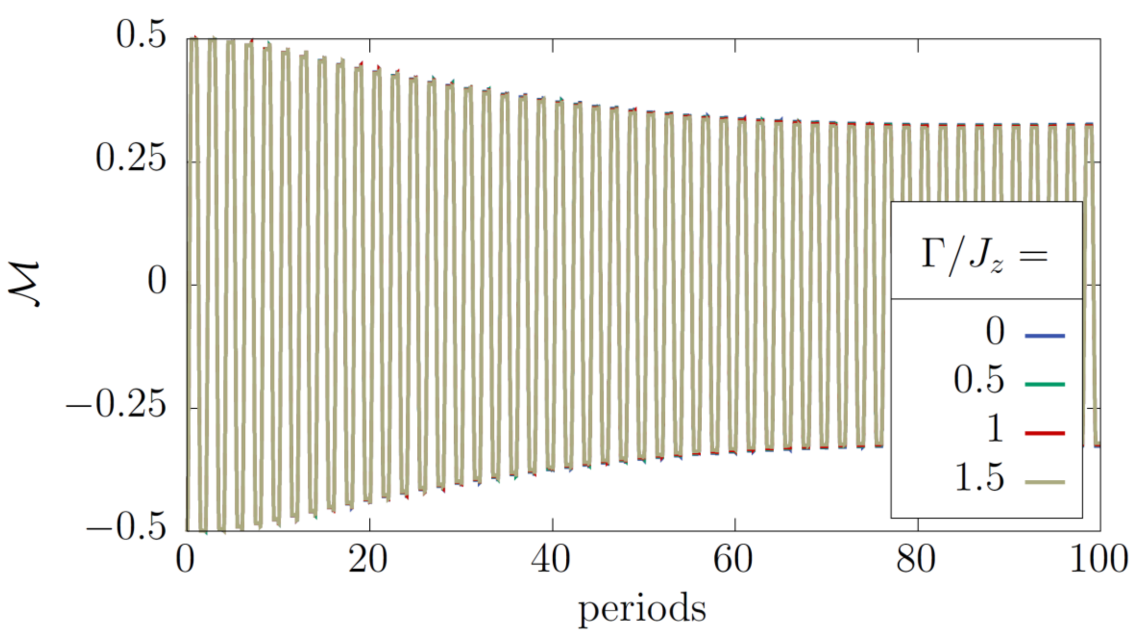

N=40 spins for different dissipative strengths and imperfect driving

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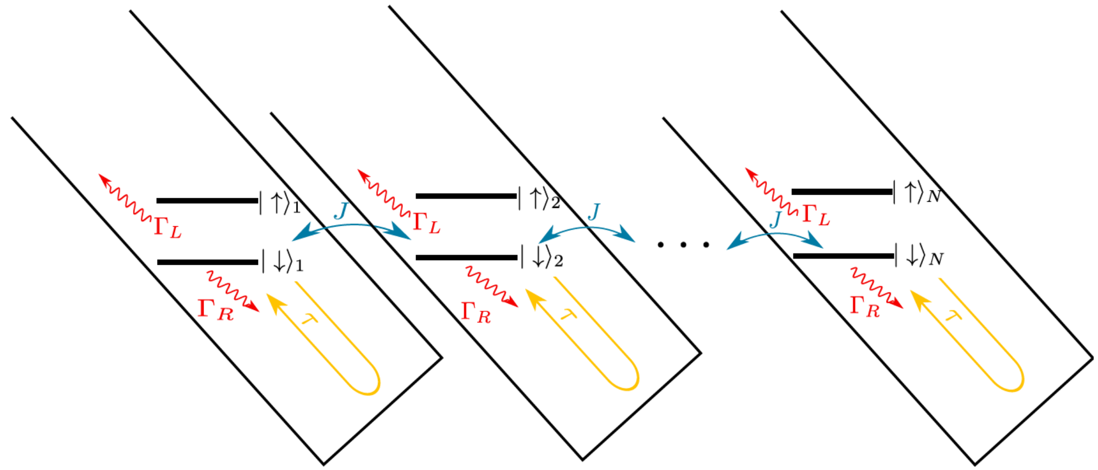

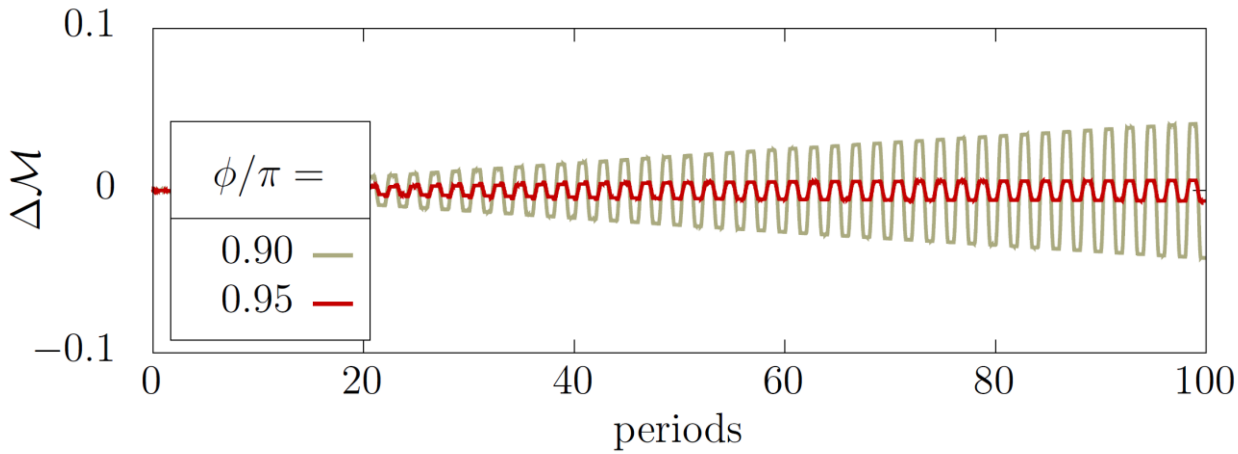

Even stable against imperfect quantum feedback phase

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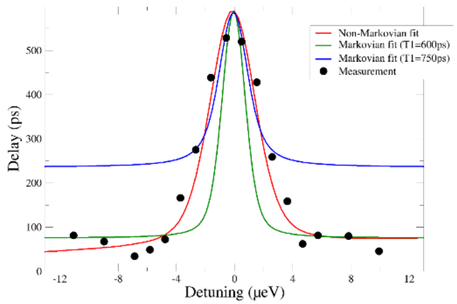

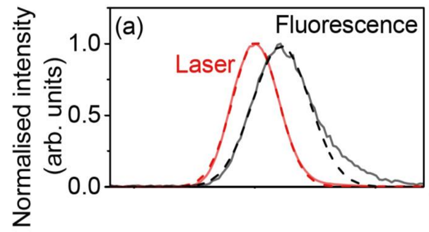

- Non-Markovian signatures in Quantum Optics: Wigner delay
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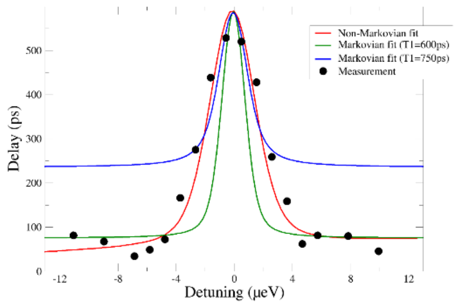

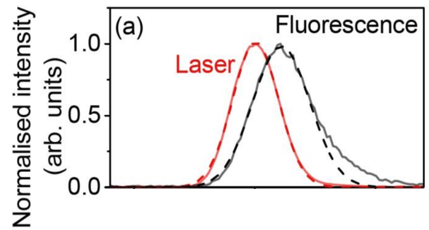

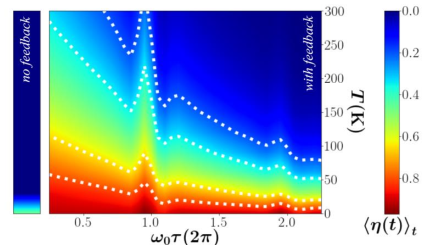

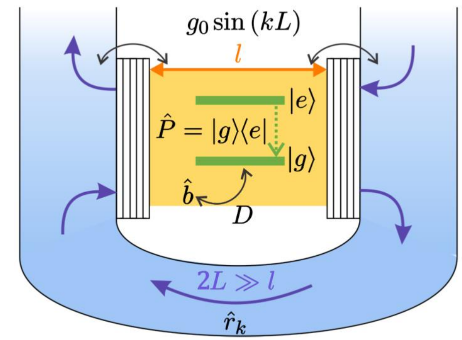

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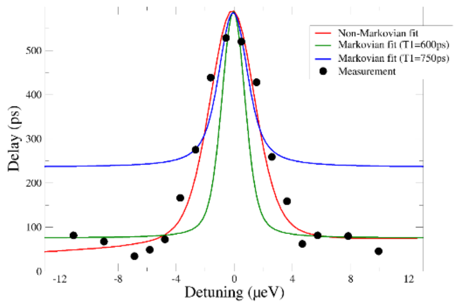

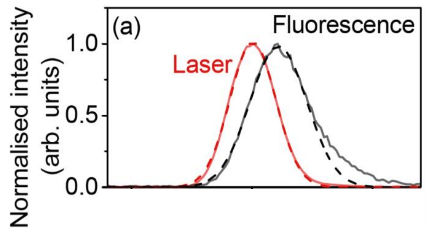

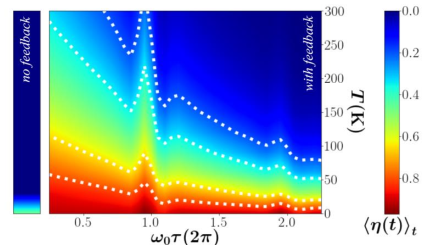

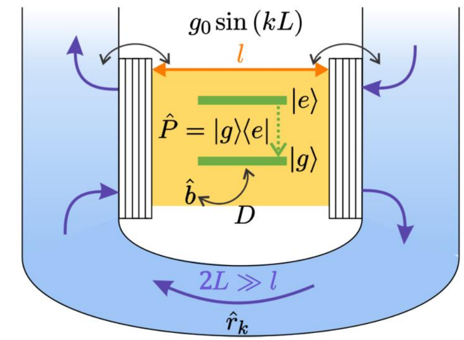

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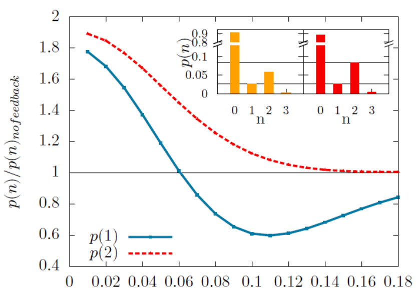

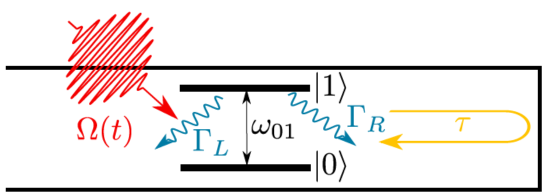

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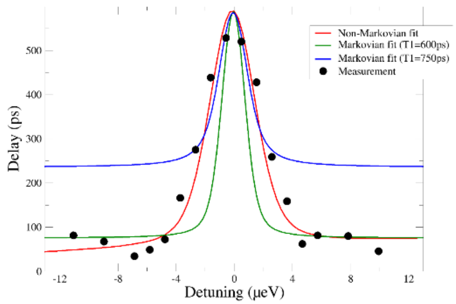

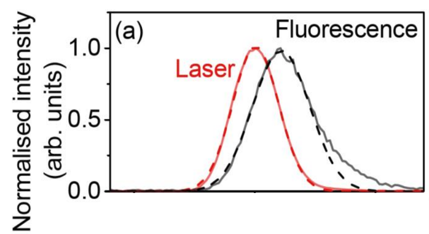

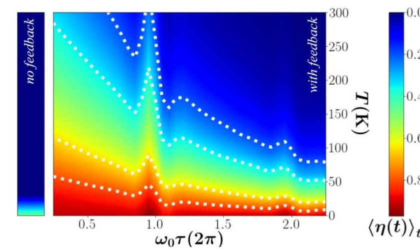

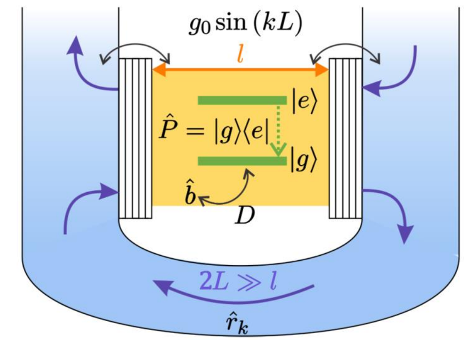

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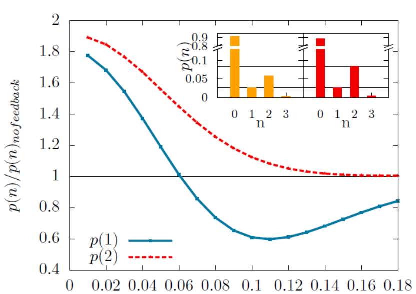

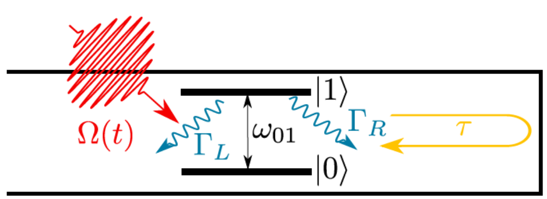

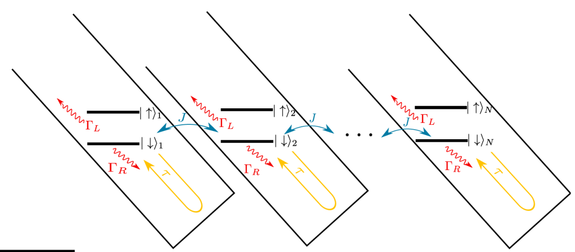

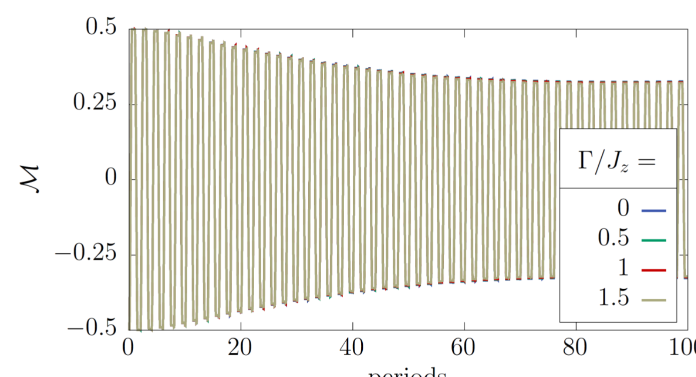

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Thank you for the attention!

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