Aalto University

Strong-coupling effects in the relaxation dynamics and the steady state of a qubit

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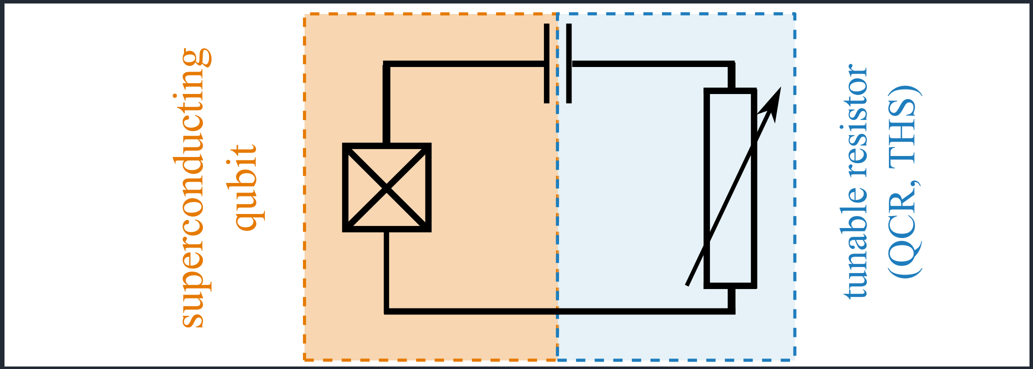
Jani Tuorila, Tapio Ala-Nissilä, Mikko Möttönen, QTF@Aalto
Jürgen Stockburger, Joachim Ankerhold, Ulm University

Outline

- Motivation
  - Fast, high-fidelity qubit reset
- Numerically exact method for dissipation
- Qubit dynamics under strong bath-coupling
  - Early time: universal decoherence
  - Steady state: entanglement & Lamb shift
- Conclusions

Motivation: Engineered environments for qubit initialization



Quantum-circuit refrigerator

K.Y. Tan et al. Nat. Commun. **8**, 15189 (2017).
M. Silveri et al. PRB **96**, 094524 (2017).
S. Masuda et al. Sci. Rep. **8**, 3966 (2018).

Tunable heat sink

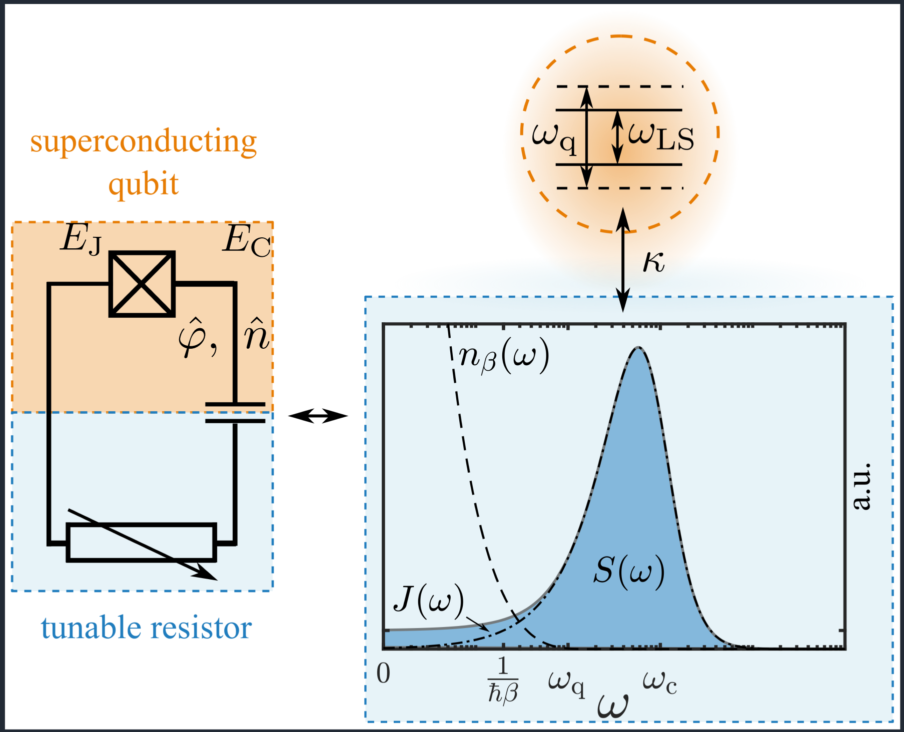
JT et al. npj Quant. Inf. **3**, 27 (2017).
M. Partanen et al. Sci. Rep. **8**, 6325 (2018).

On-demand dissipation: switching between quantum-operation mode and reset mode

Motivation: Relaxation and steady state beyond weak coupling

- Relaxation dynamics
  - Exponential decay with rate κ
- Steady state
  - Boltzmann distribution $\propto e^{-\hbar\beta\omega_i}$
- Neglects quantum correlations
  - Universal decoherence, entanglement, Lamb shift

Strong coupling with the bath



$$\hat{H}_\mathrm{S} = 4E_\mathrm{C}\hat{n}^2 - E_\mathrm{J}\cos\hat{\varphi}$$

$$\hat{H}_\mathrm{S}|n\rangle = \hbar\omega_n|n\rangle$$

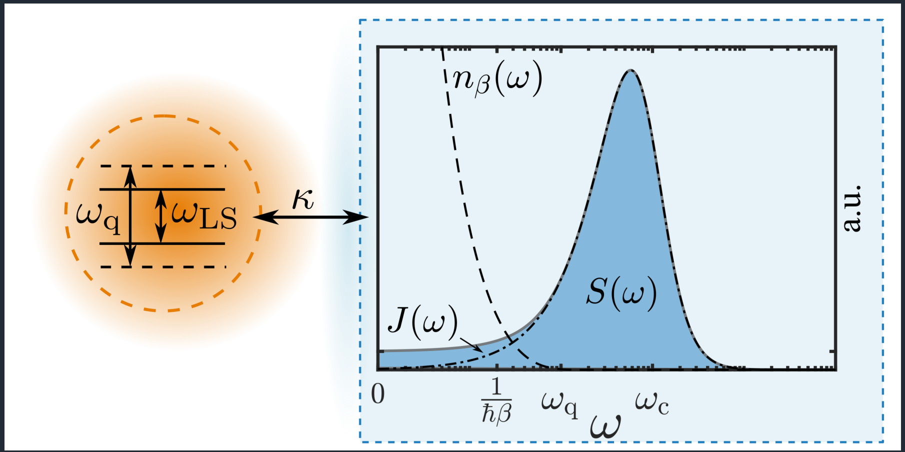
$$\hat{q} = \sum_{k,m}\langle k|\hat{n}|m\rangle|k\rangle\langle m|$$

$$\omega_\mathrm{q} = \omega_1 - \omega_0$$

$$\hat{H} = \hbar\sum_{n=0}^{N-1}\omega_n|n\rangle\langle n| + \hbar\sum_k \Omega_k \hat{a}_k^\dagger \hat{a}_k + \hbar\hat{q}\sum_k g_k(\hat{a}_k^\dagger + \hat{a}_k)$$

Numerically exact dissipation

- Exact dynamics of the qubit: Feynman-Vernon path-integral formalism
- Ohmic bath with high cut-off: stochastic Liouville equation with dissipation (SLED)



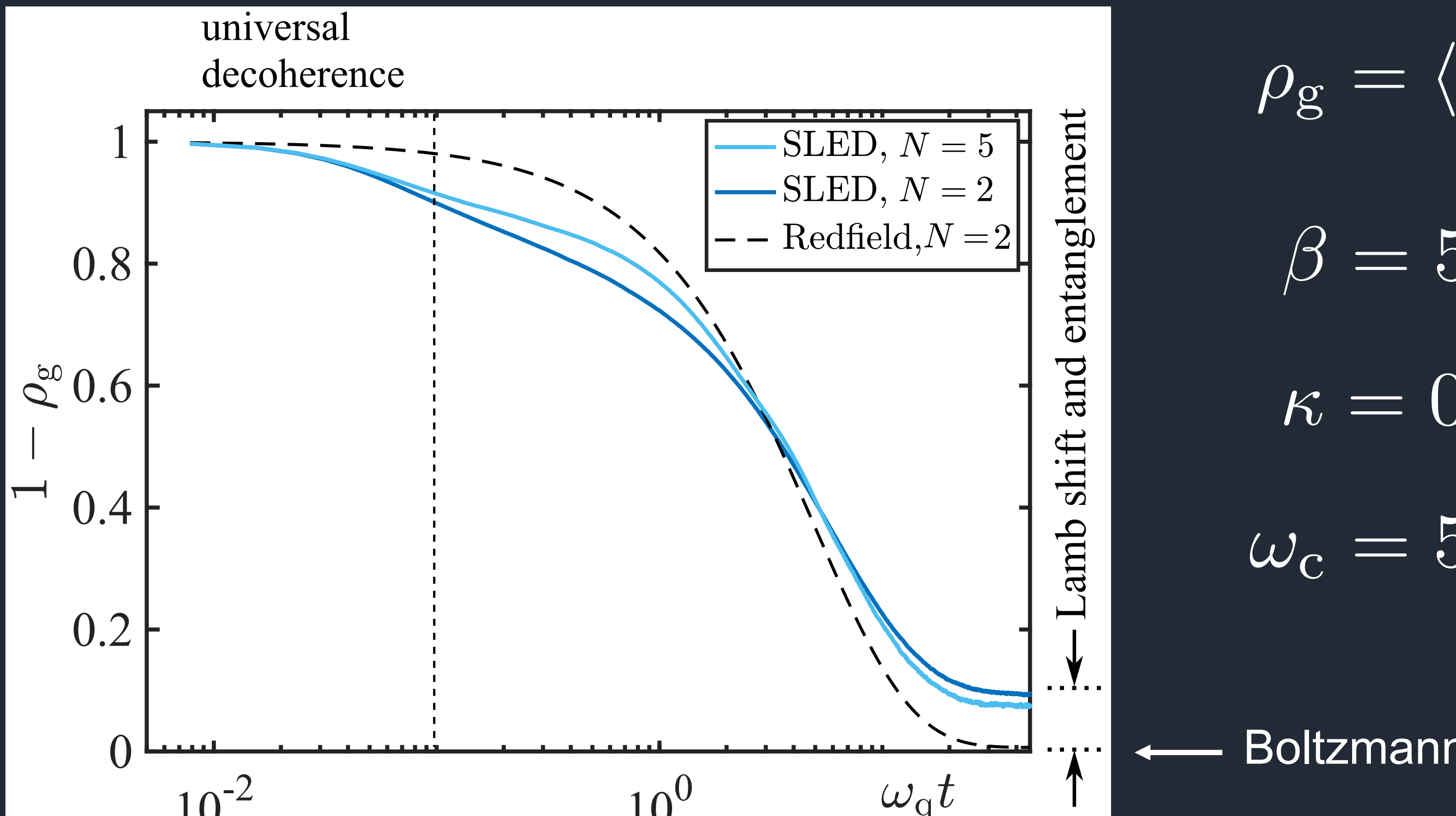
$$S(\omega) = J(\omega)[n_\beta(\omega) + 1]$$

$$J(\omega) \propto \frac{\omega}{(1 + \omega^2/\omega_c^2)^2}$$

κ = zero-temperature dissipation rate

J. Stockburger et al. PRL **88**, 170407 (2002).
J. Stockburger et al. J. Chem. Phys. **110**, 4983 (1999).
JT et al. arXiv:1901.06209

Strong coupling with the bath



$$\rho_g = \langle 0|\hat{\rho}|0\rangle$$

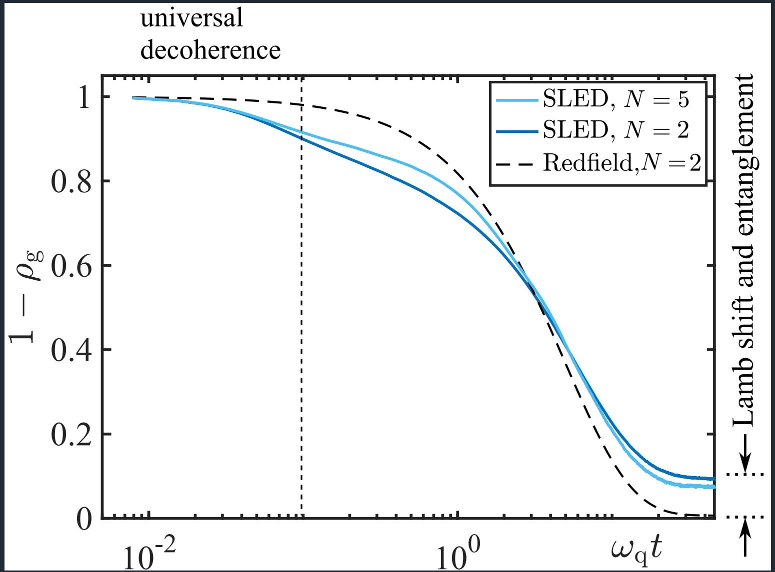
$$\beta = 5/(\hbar\omega_q)$$

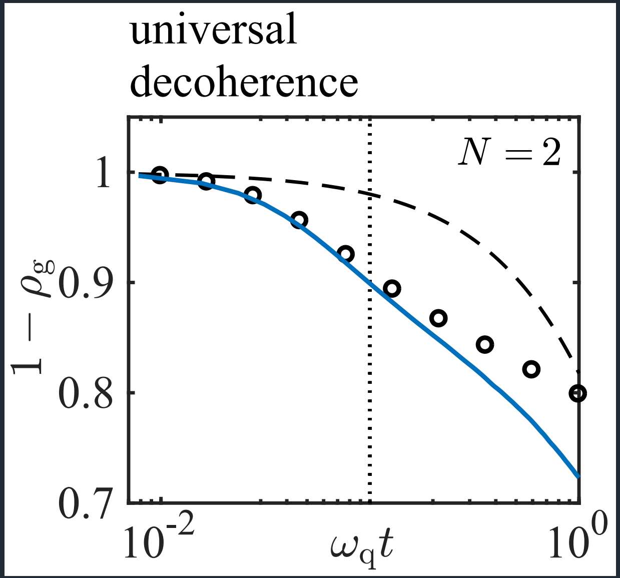
$$\kappa = 0.2 \times \omega_q$$

$$\omega_c = 50 \times \omega_q$$

JT et al, arXiv:1901.06209

Early times: Universal decoherence





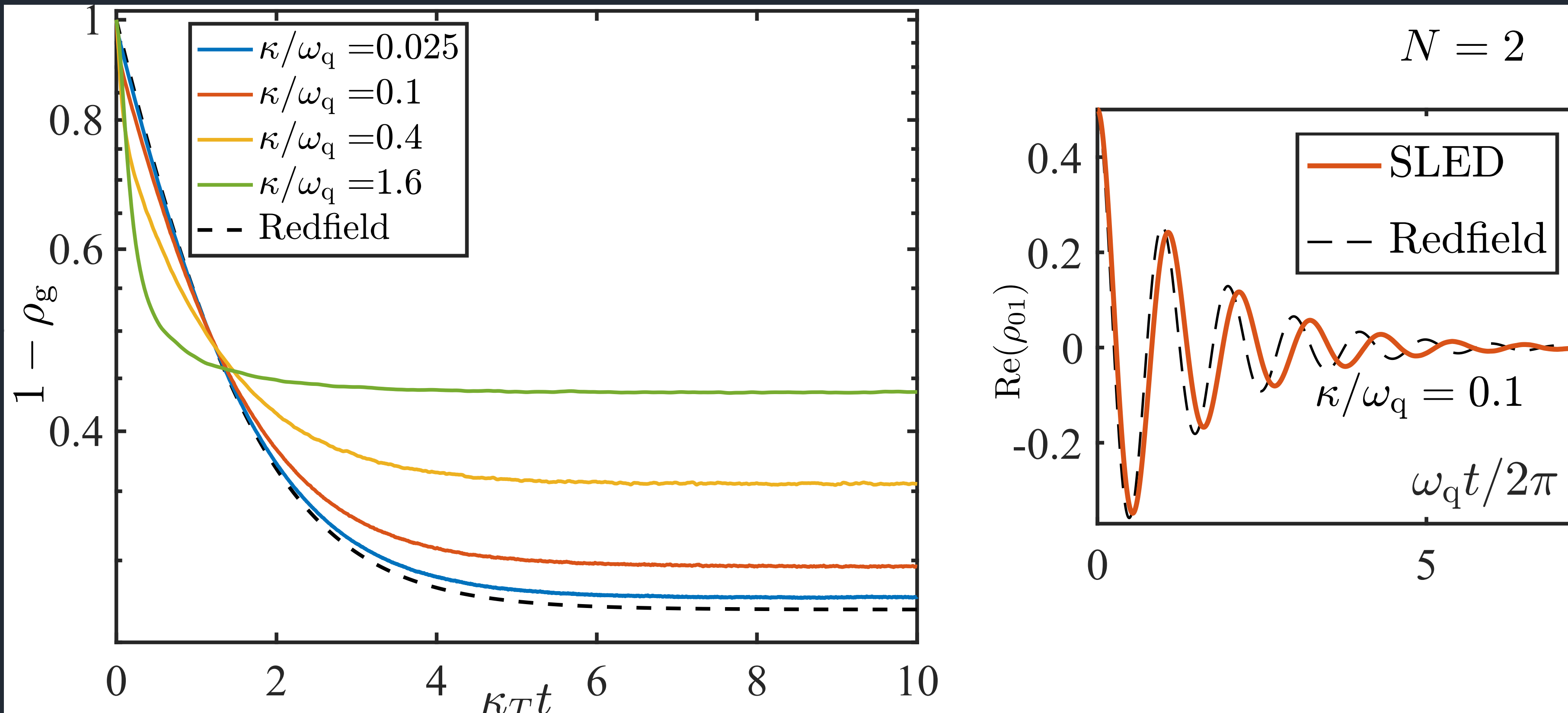
- $\omega_q t \ll 1$: neglect system dynamics
- $\omega_c t \ll 1$: superexponential decay

$$1-\rho_g(t) = \{1+\exp[-\kappa\omega_c^2 t^2/(2\pi\omega_q)]\}/2$$

D. Braun et al. PRL **86**, 2913 (2001).

JT et al, arXiv:1901.06209

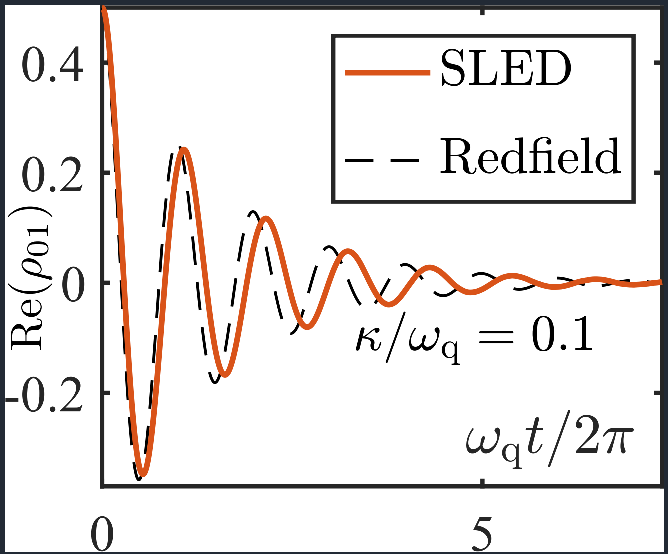
Steady state



$\omega_c = 50 \times \omega_q$ $\quad\beta = 1/(\hbar\omega_q)$ $\quad\kappa_T = \kappa \coth(\hbar\beta\omega_q/2)$

Lamb shift and entanglement

- Start from pointer state $\langle \hat{\sigma}_{\mathrm{x}} \rangle = 1$
- Larmor frequency decreased
  → Lamb shift
- Deviation from analytic weak damping result ≈ 2%

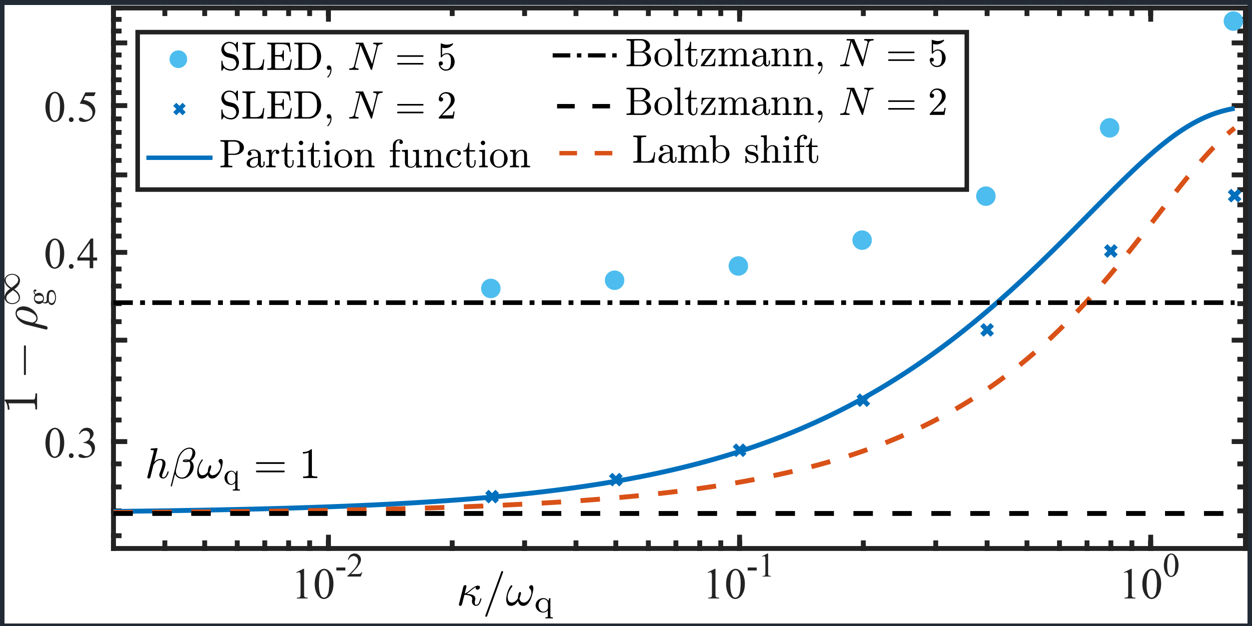


$$\beta = 1/(\hbar\omega_{\mathrm{q}})$$

$$\omega_{\mathrm{c}} = 50 \times \omega_{\mathrm{q}}$$

U. Weiss: *Quantum dissipative systems*
Recent exp.: M. Silveri et al. Nat. Phys. **15**, 533 (2019)

Lamb shift and entanglement



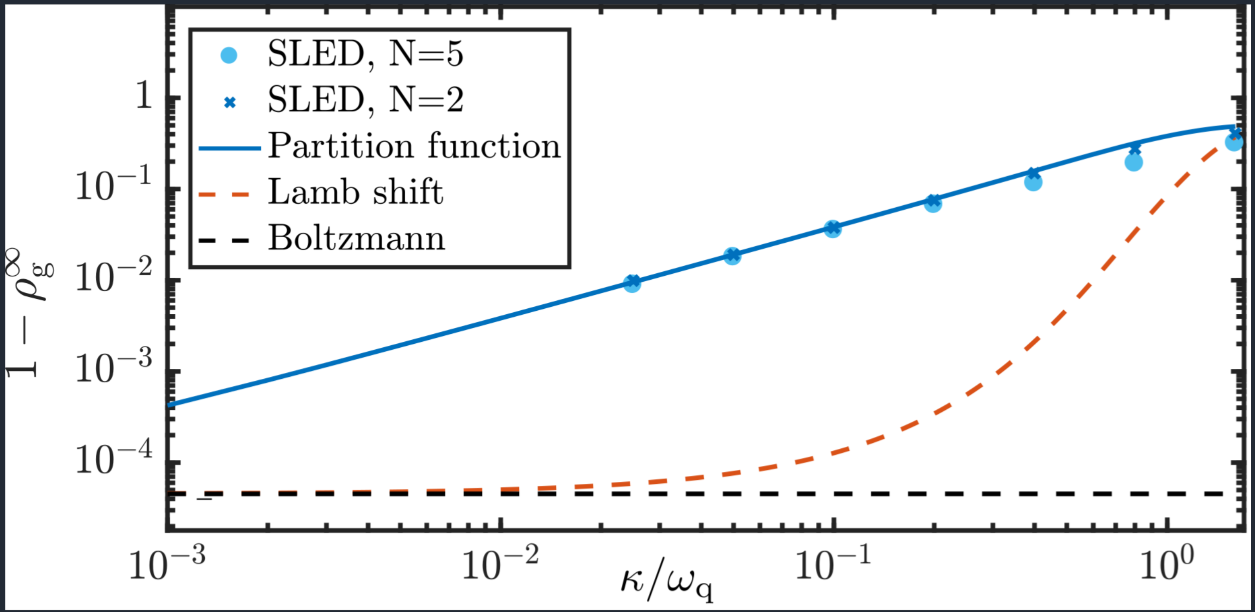
$$\beta = 1/(\hbar\omega_q)$$

$$\rho_g^\infty = \rho_g(t \to \infty)$$

- Deviation from bare Boltzmann distribution not explained solely by Lamb shift! → entanglement

JT et al, arXiv:1901.06209

Lamb shift and entanglement



$$\beta = 10/(\hbar\omega_q)$$

JT et al, arXiv:1901.06209

- Zero-*T* reset error: Entanglement in the uncoupled basis

$$1-\rho_g^\infty = \frac{\kappa}{2\pi\omega_q}\left[-\frac{3}{2}+\ln(\omega_c/\omega_q)\right]$$

- Trade-off between fidelity and speed!

Conclusions

- Numerically exact open quantum system dynamics can be calculated with stochastic Liouville equation with dissipation (SLED).

- Strong coupling affects the relaxation dynamics (universal decoherence) and steady state (Lamb shift and entanglement) of a qubit.

- Future: Quantitative validity regions for BM master equations for one and two qubit systems.