Accelerating qubit reset through the Mpemba effect

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1. Context

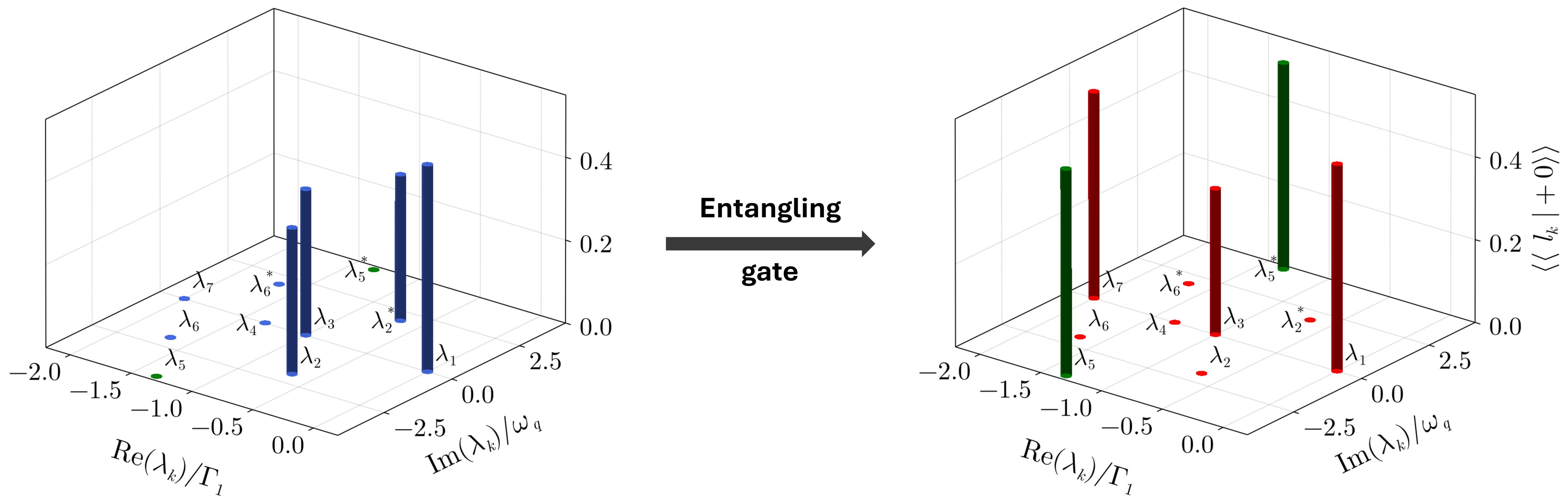
- Qubit reset is a key primitive for quantum computing, allowing execution of algorithms via e.g., Quantum Error Correction (QEC)
- **Passive reset:** Waiting a few T_1 for the qubit to relax to its ground state through natural dissipation (**slow**)
- **Active reset:** Measurement followed by a conditional NOT gate (**fast but imprecise**)
- **Mpemba effect:** Counterintuitive phenomenon in which configurations initially further from equilibrium can relax faster **[1]**
- **Our goal:** Exponentially accelerate **passive** qubit reset in the $T_1 < T_2$ case by leveraging the quantum **Mpemba** effect, through a simple **2-qubit gate [2]**

2. Liouvillian Spectral Theory

$$\mathcal{L}[\hat{\rho}] = -\mathrm{i}\omega_q[\hat{\sigma}_z^1 + \hat{\sigma}_z^2, \hat{\rho}] + \Gamma_1\left(\mathcal{D}_{\hat{\sigma}_-^1}[\hat{\rho}] + \mathcal{D}_{\hat{\sigma}_-^2}[\hat{\rho}]\right) + \frac{\Gamma_\phi}{2}\left(\mathcal{D}_{\hat{\sigma}_z^1}[\hat{\rho}] + \mathcal{D}_{\hat{\sigma}_z^2}[\hat{\rho}]\right)$$

$$\Gamma_2 = \frac{1}{T_2} = \frac{\Gamma_1}{2} + \Gamma_\phi \qquad \Gamma_1 = \frac{1}{T_1}$$

Vectorization [3] ⟶ $|\rho(t)\rangle\rangle = \mathrm{e}^{\hat{\mathcal{L}}t}|\rho_i\rangle\rangle = |\rho_{\mathrm{ss}}\rangle\rangle + \sum_{k=2} \mathrm{e}^{\lambda_k t}\langle\langle l_k|\rho_i\rangle\rangle|r_k\rangle\rangle$



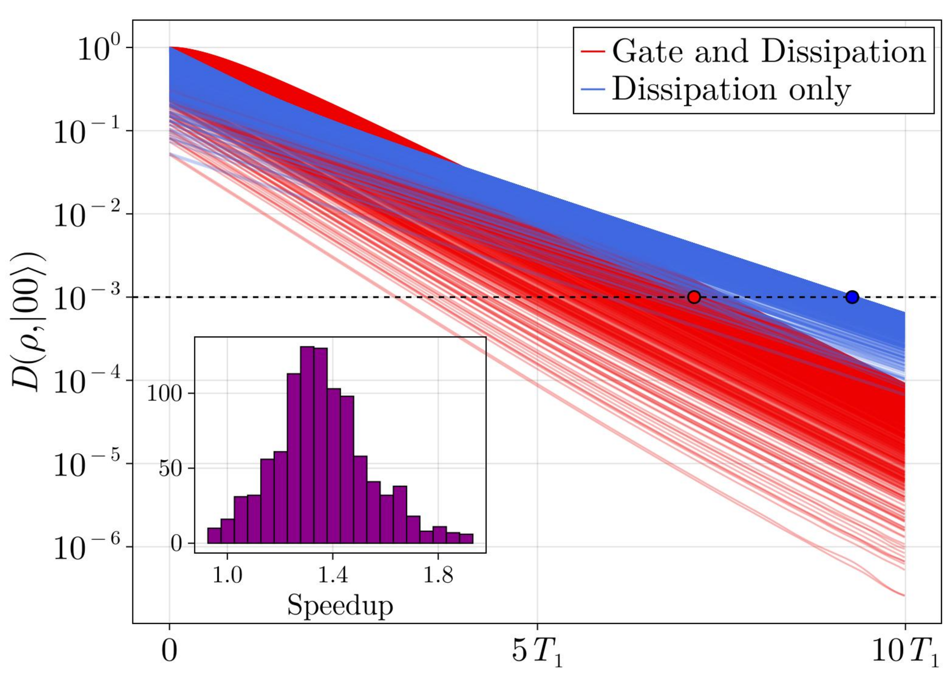
3. Results

3.1 Gate application and speedups

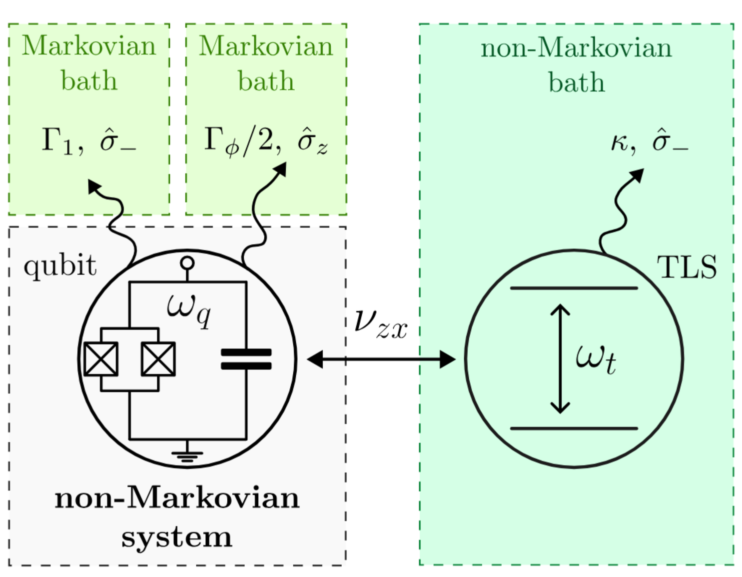
$$q_1: \begin{pmatrix} p_0 & c \\ c^* & p_1 \end{pmatrix} \otimes q_2: \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} = \begin{pmatrix} p_0 & 0 & c & 0 \\ 0 & 0 & 0 & 0 \\ c^* & 0 & p_1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix} \xrightarrow{\text{CNOT-type gate with } R_y(\pi)} \begin{pmatrix} p_0 & 0 & 0 & c \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ c^* & 0 & 0 & p_1 \end{pmatrix}$$

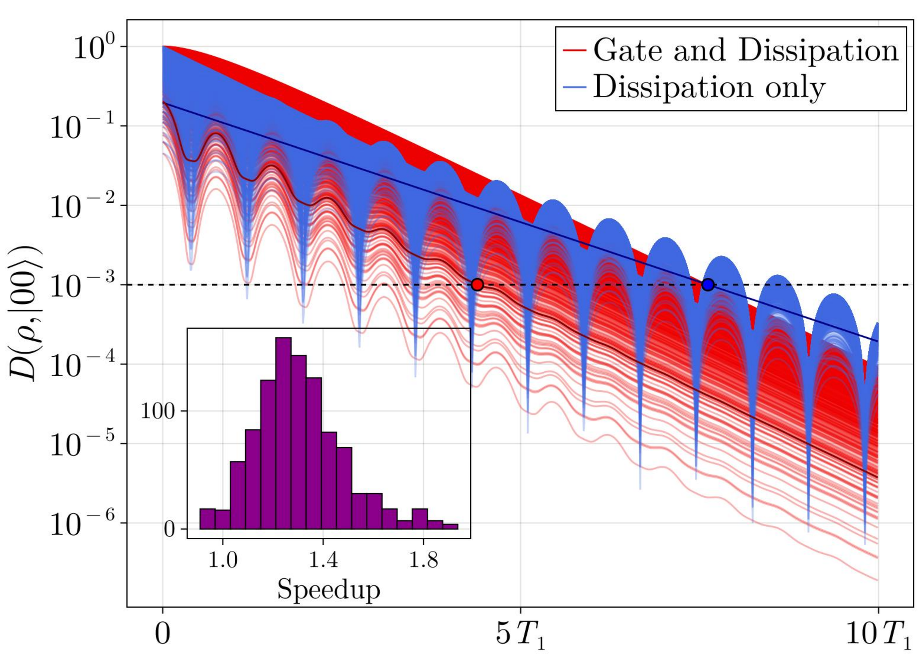
Speedup $S = \frac{|\mathrm{Re}(\lambda_3)|}{|\mathrm{Re}(\lambda_2)|}$

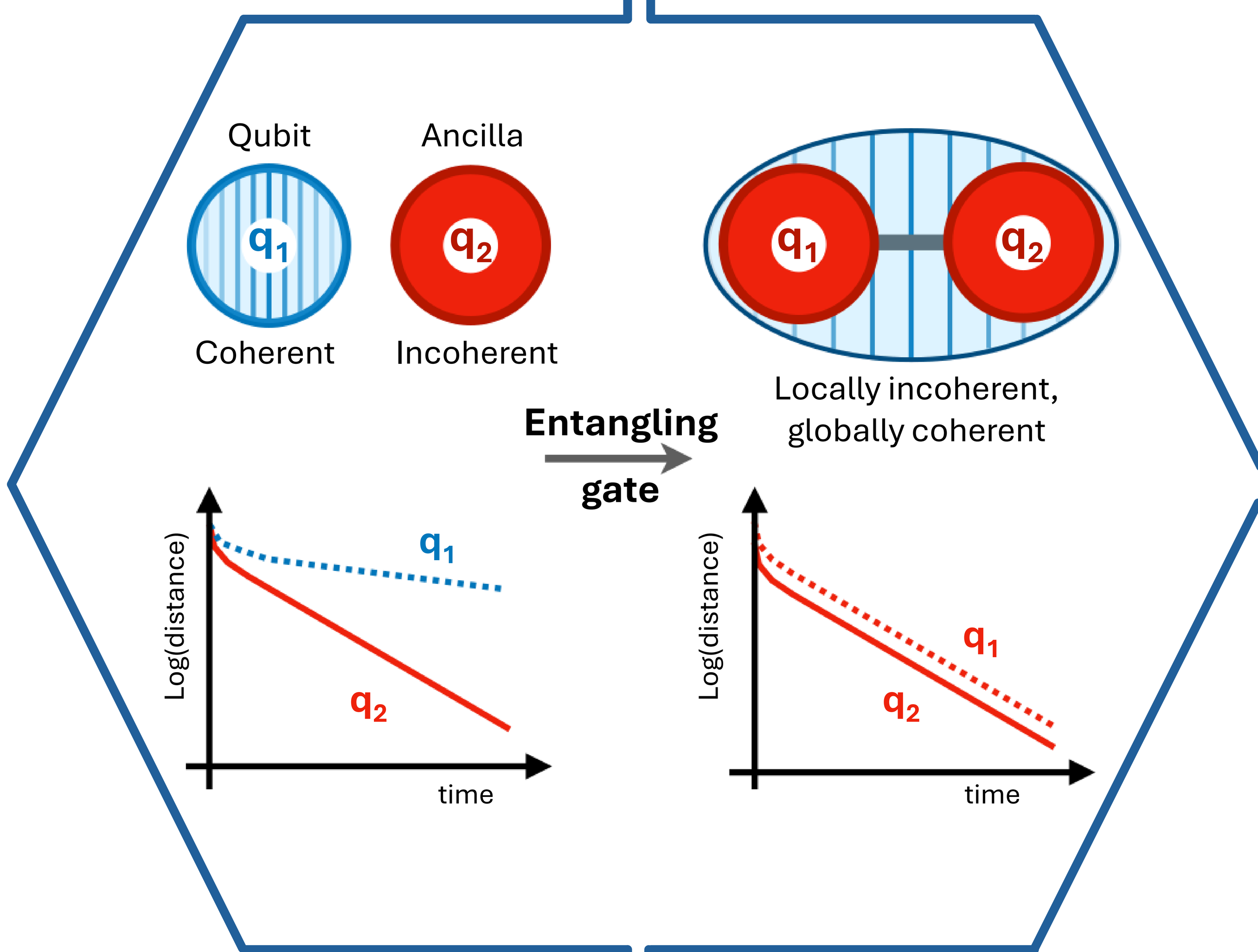
Markovian case



Non-Markovian case

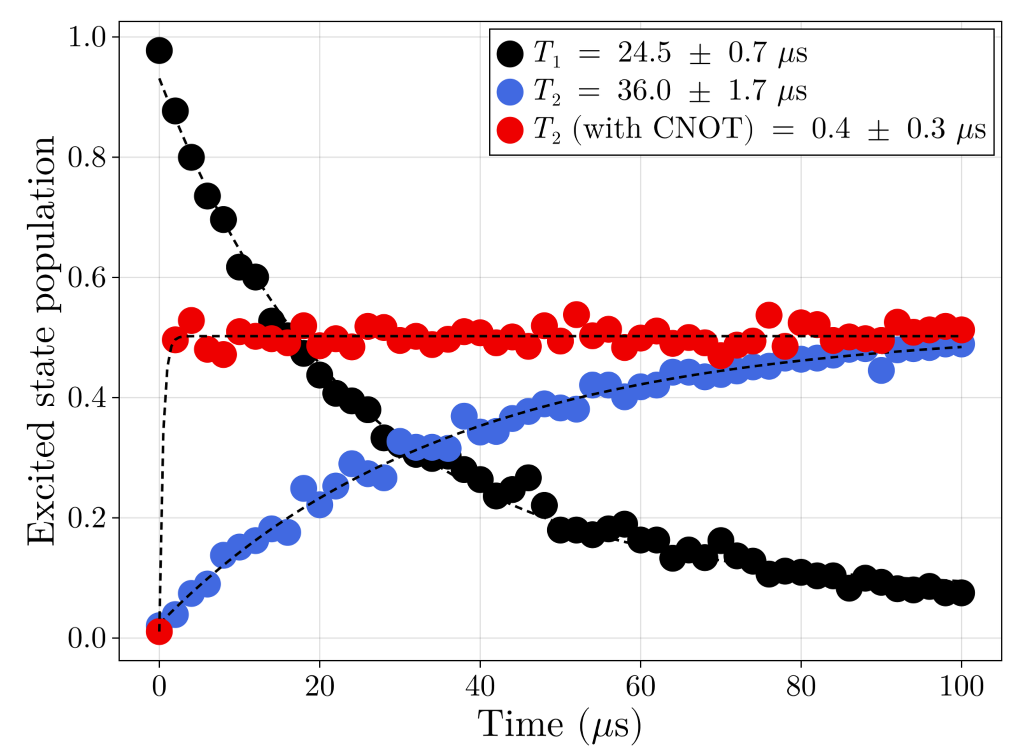




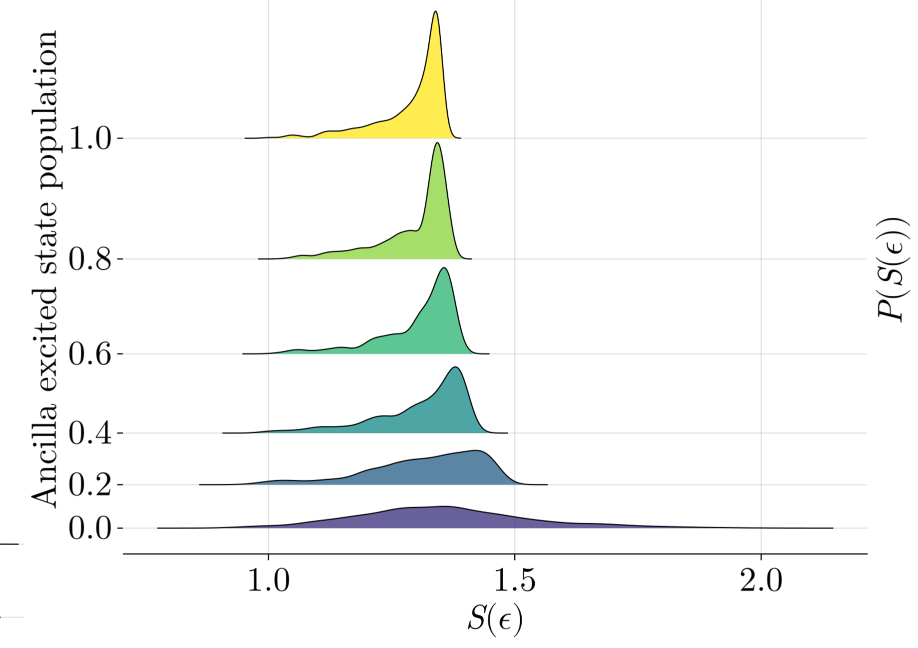


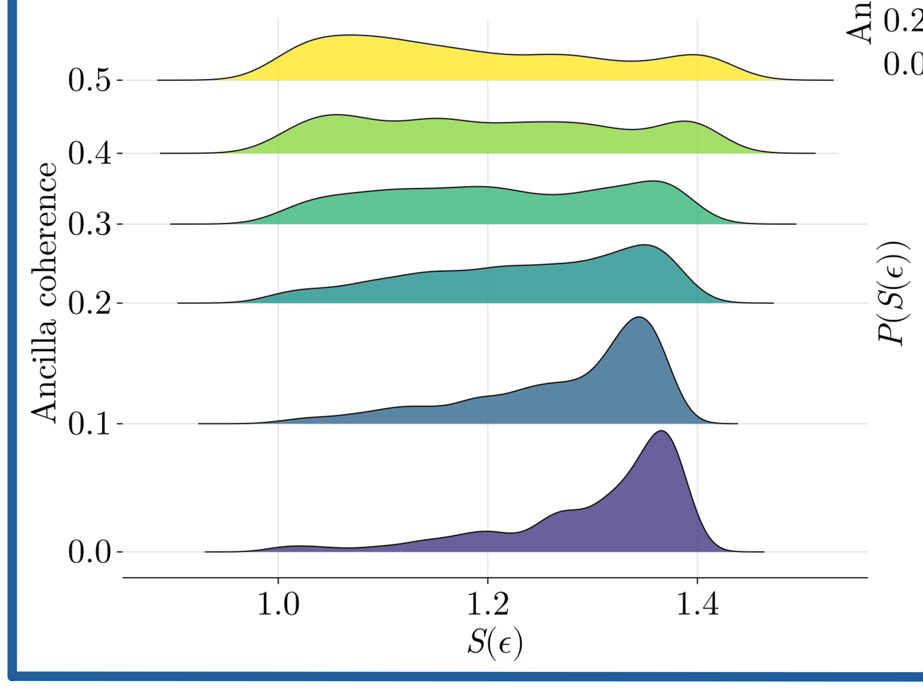
3.2 Experimental implementation

Performed on **IQM** Garnet superconducting quantum processor



3.3 Ancilla imperfections





The protocol is **resilient** to ancilla imperfections !

4. Conclusion

- We have demonstrated how the quantum Mpemba effect can be harnessed to accelerate passive qubit reset
- Our protocol is conceptually simple and compatible with existing superconducting-qubit architectures
- A single entangling gate converts local coherences into fast-decaying global two-qubit coherences, yielding a median speedup of approximately T_2 / T_1
- In quantum algorithms, the measured (incoherent) qubits are a readily available resource to accelerate the reset of qubits

5. References

[1] Z. Lu and O. Raz, " *Nonequilibrium thermodynamics of the Markovian Mpemba effect and its inverse*", PNAS **114** (20), 5083 (2017).
[2] T. Lejeune **et al.**, **"*Accelerating qubit reset through the Mpemba effect*", *arXiv*:2602.03765 (2026).**
[3] F. Carollo et al., "*Exponentially Accelerated Approach to Stationarity in Markovian Open Quantum Systems through the Mpemba Effect*", PRL **127**, 060401 (2021).

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