Extended quantum Maxwell demon acting over macroscopic distances

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A. V. Lebedev, G. B. Lesovik, V. M. Vinokur and G. Blatter, PRB 98, 214502 (2018)

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QSIT Quantum Science and Technology
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Quantum Maxwell Demon

S. Lloyd 1997

$$\Phi(\hat{1}) \neq \hat{1}$$

$$\mathrm{Tr}\left\{\hat{H}\,\Phi(\hat{\rho})\right\} = \mathrm{Tr}\left\{\hat{H}\,\hat{\rho}\right\}$$

QMD = a non-unital quantum channel which conserves system's energy

SWAP operation represents a QMD

mixed state

$$\mathrm{SWAP}(\hat{\rho}_A \otimes \hat{\rho}_B) = \hat{\rho}_B \otimes \hat{\rho}_A$$

$$\hat{\rho}_A = \begin{pmatrix} p_0 & 0 \\ 0 & p_1 \end{pmatrix}$$

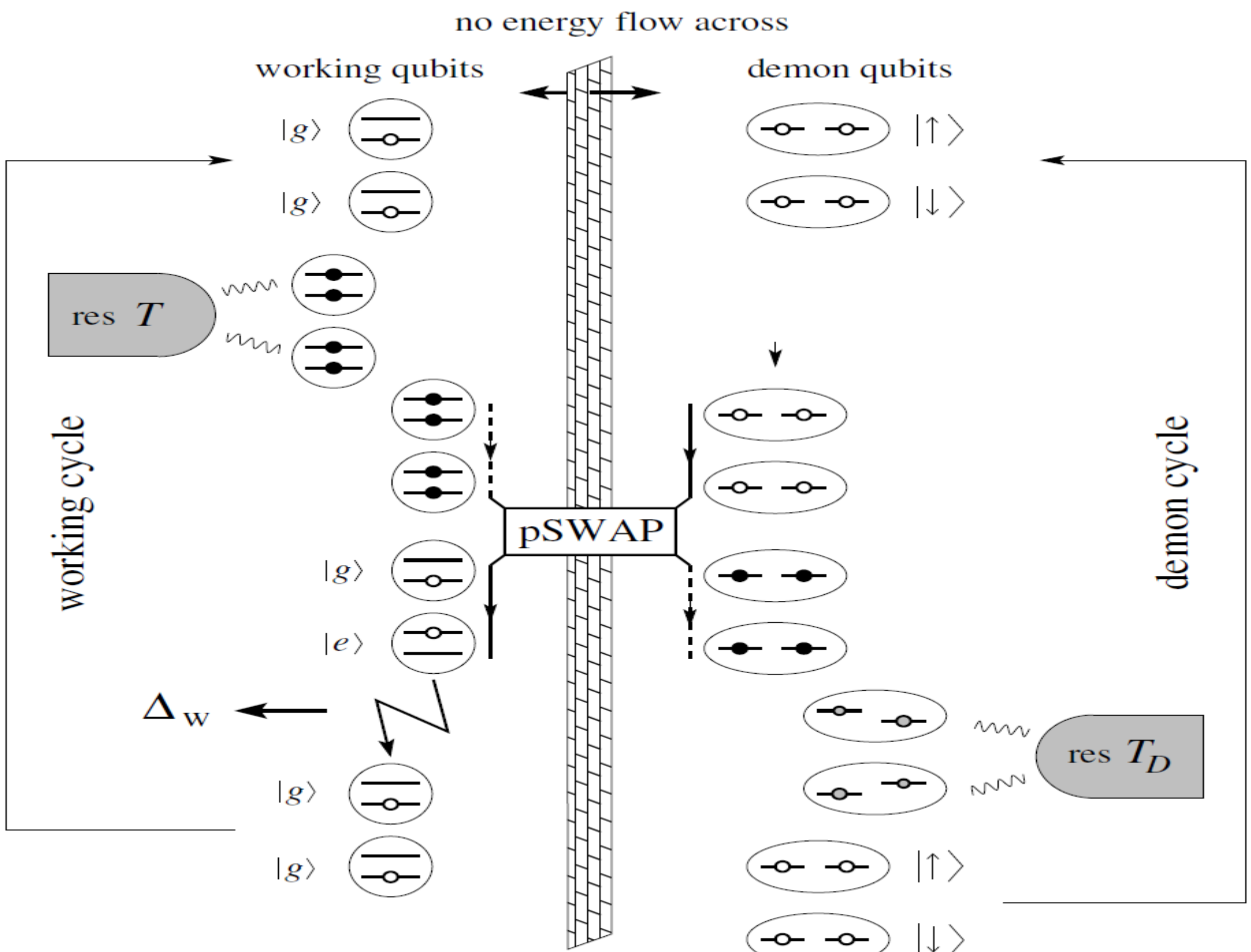
$$\hat{U}_{\mathrm{SWAP}} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\hat{\rho}_B = |\psi\rangle\langle\psi|$$

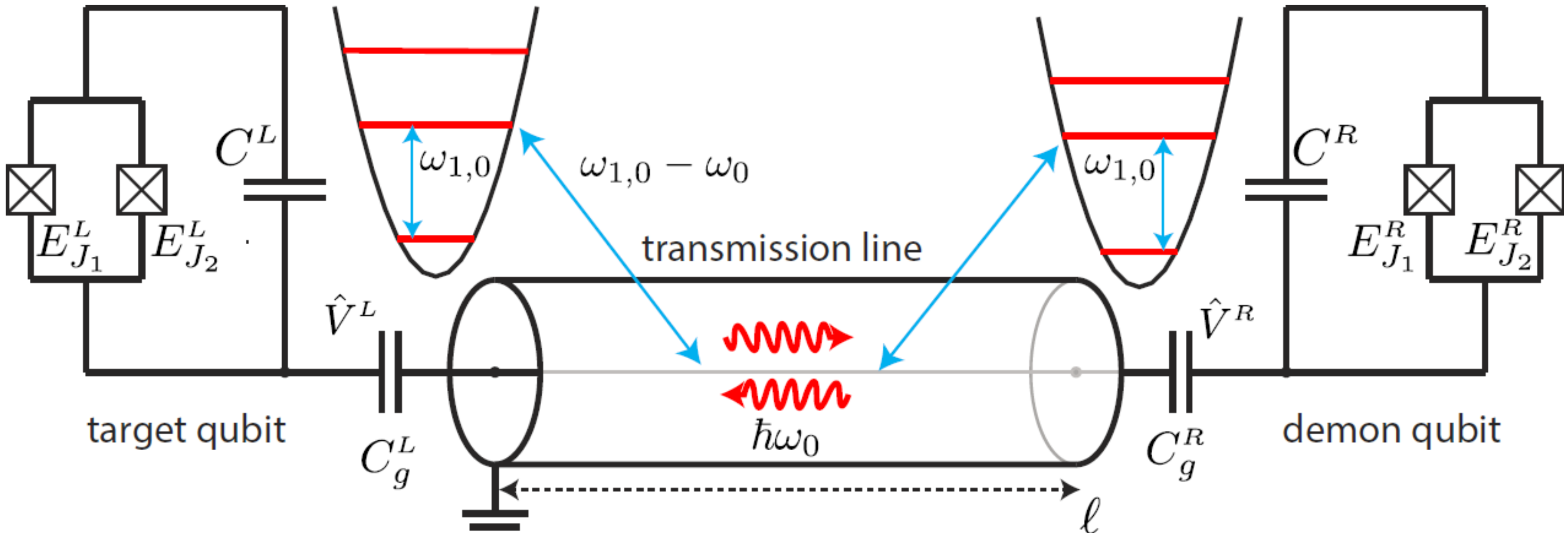
$$|\psi\rangle = \sqrt{p_0}|0\rangle + \sqrt{p_1}|1\rangle$$

Four-qubit quantum engine

A. V. Lebedev, D. Oehri, G. B. Lesovik,
B. G. Blatter, PRA 2016



Can one separate the working and demon qubits through a classical environment?



$$\hat{H} = \sum_{\alpha=L,R} \sum_{i=0}^{\infty} \epsilon_i^\alpha |i\rangle\langle i|_\alpha + q^\alpha_{i+1,i} \hat{V}_\alpha(x_\alpha) |i+1\rangle\langle i|_\alpha + \hat{H}_{\rm line}$$

$$\hat{H}_{\rm line} = \frac{1}{2} \int dx \Big\{ \mathcal{C}\, \hat{V}^2(x) + \mathcal{L}\, \hat{I}^2(x) \Big\}$$

Off –resonance regime (dispersive coupling) $\omega_k \ll \omega_{01}$

Effective Hamiltonian:

$$\hat{H}_{\text{int}} = \sum_{ij} J_{ij} |i+1\rangle\rangle i| \otimes |j\rangle\langle j+1|_R + H.c.$$

$$J_{ij} = \frac{q^{\text{L}}_{i+1,i} q^{\text{R}}_{j,j+1}}{2\mathcal{C}\ell} \int d\omega \left[\frac{\omega^{\text{L}}_{i+1,i}}{\left(\omega^{\text{L}}_{i+1,i} - \omega\right)^2} + \frac{\omega^{\text{R}}_{j+1,j}}{\left(\omega^{\text{R}}_{j+1,j} - \omega\right)^2} \right]$$

Qubit regime:

Heisenberg XY coupling

$$\hat{H} = \frac{1}{2}\hbar\omega_{01}\left(\hat{\sigma}_z^L + \hat{\sigma}_z^R\right) + \frac{J}{2}\left(\hat{\sigma}_x^L \otimes \hat{\sigma}_x^R + \hat{\sigma}_y^L \otimes \hat{\sigma}_y^R\right)$$

$$J = \kappa^{\text{L}} \kappa^{\text{R}} \frac{\Delta\omega\, \omega_{1,0}}{(\omega_{1,0} - \omega_0)^2} \frac{hv}{\ell} \qquad \kappa^{\alpha} = \beta^{\alpha} \left(\frac{E_J^{\alpha}}{2E_C^{\alpha}} \right)^{1/4} \sqrt{\frac{Z_0}{R_Q}}$$

$$\kappa \sim 0.01$$

iSWAP vs SWAP Quantum Maxwell Demon

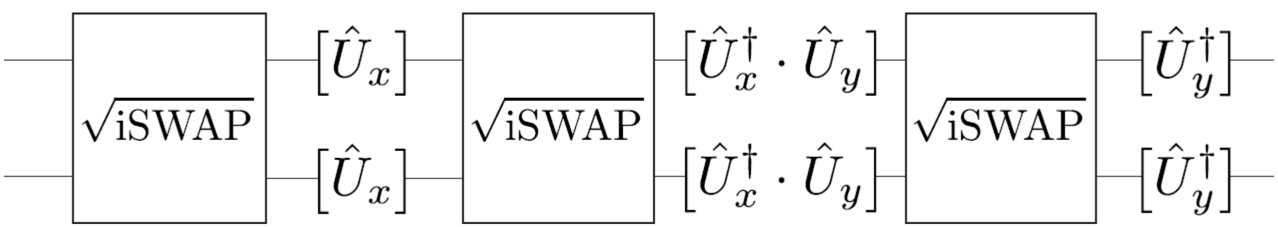
iSWAP gate

$$\hat{H}_{XY} = \frac{J}{2}\left(\hat{\sigma}_x \otimes \hat{\sigma}_x + \hat{\sigma}_y \otimes \hat{\sigma}_y\right) \quad \Longrightarrow \quad \exp\left(-i\hat{H}_{XY}\,\frac{h}{4J}\right) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & i & 0 \\ 0 & i & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

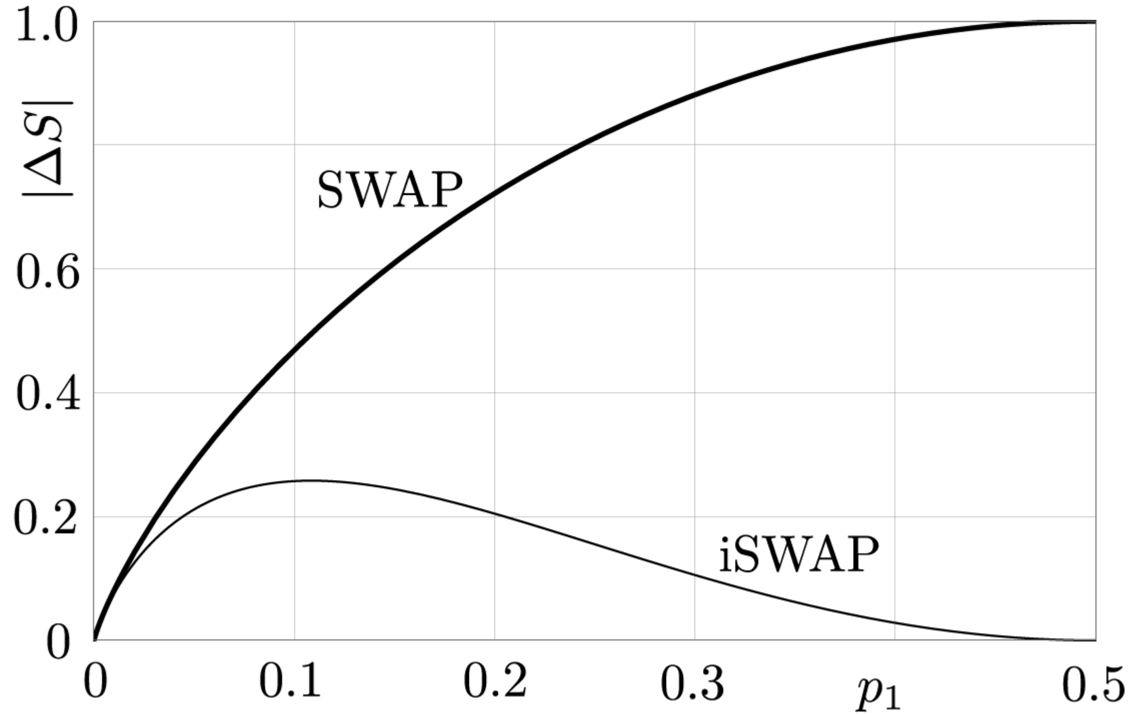
SWAP gate

$$\hat{H}_{XYZ} = \frac{J}{2}\left(\hat{\sigma}_x \otimes \hat{\sigma}_x + \hat{\sigma}_y \otimes \hat{\sigma}_y + \hat{\sigma}_z \otimes \hat{\sigma}_z\right) \quad \Longrightarrow \quad \exp\left(-i\hat{H}_{XYZ}\,\frac{h}{4J}\right) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Optimal SWAP generation through iSWAP gates:



$$\tau_{\mathbf{SWAP}} = \frac{3}{2}\,\tau_{\mathbf{iSWAP}}$$



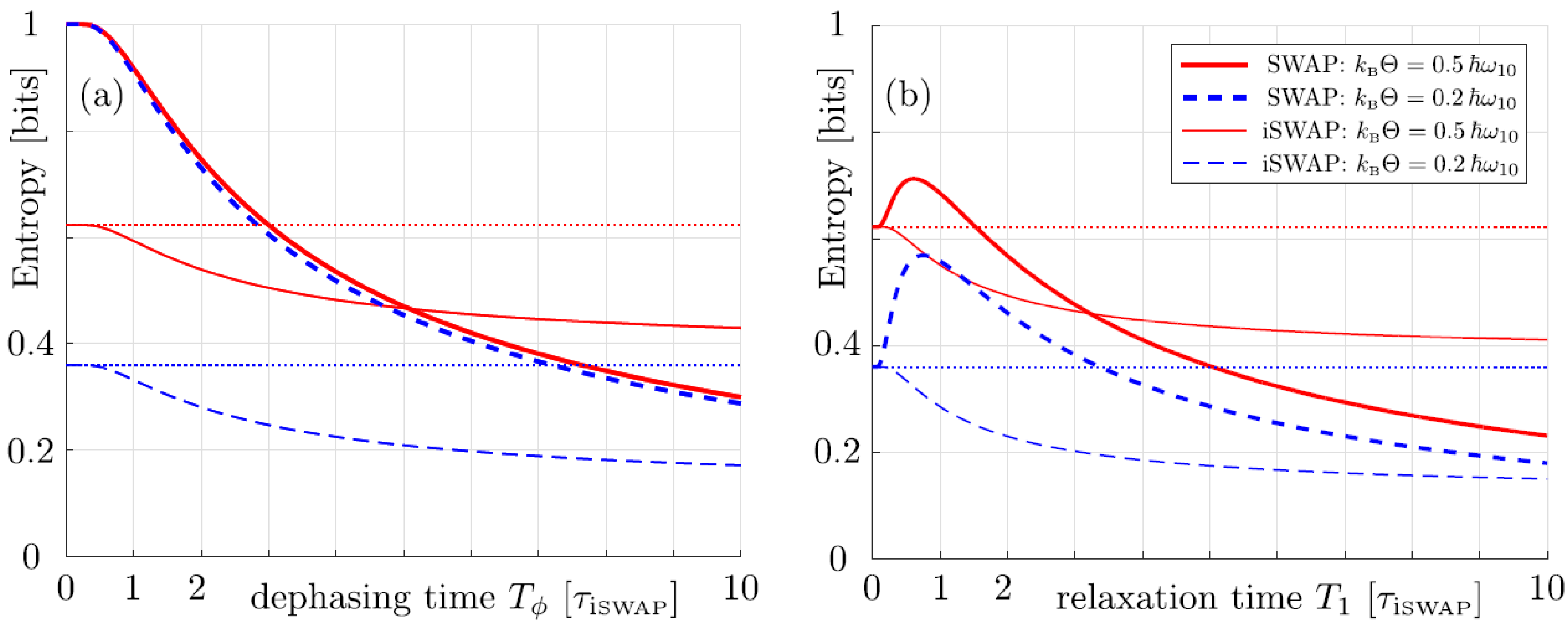
$$\hat{\rho}_A = \begin{pmatrix} p_0 & 0 \\ 0 & p_1 \end{pmatrix}$$

$$\hat{\rho}_B = |\psi\rangle\langle\psi|$$

$$|\psi\rangle = \sqrt{p_0}|0\rangle + \sqrt{p_1}|1\rangle$$

iSWAP is entangling gate !

Operation at finite relaxation and dephasing



Operation requirement: $\tau_{\mathbf{iSWAP}} \equiv \frac{h}{4J} \sim T_2$

$T_2 \in [50, 250]\mu s$

Transmission line frequency band

$$\ell \leq (vT_2)\, 8\kappa^2\, \frac{\Delta\omega}{\omega_0}$$

$\ell \sim 1.0 - 5.0\, m$

$\omega_{01} = 2\omega_0$

Dephasing due to hot transmission line

bosonic modes of the transmission line

Dispersive shift interaction Hamiltonian:

$$\hat{H}_{\text{deph}} = \hat{\sigma}_z \otimes \sum_{nm} \beta_{nm}\, \hat{a}_n^\dagger \hat{a}_m$$

Corresponding dephasing rates:

$$\gamma = 32\pi\kappa^4 N_0(1+N_0)\Delta\omega \left[\frac{\omega_{an}\omega_0}{(\omega_{01}-\omega_0)(\omega_{12}-\omega_0)}\right]^2$$

$$\gamma \propto \kappa^4 \qquad J \propto \kappa^2/\ell$$

$$\ell \sim 1.0 - 5.0\, m \quad \Rightarrow \quad T_{\text{line}} \sim 3.5 - 7.5\, K$$

THE END

Quantum Maxwell Demon can operate at macroscopic distances

The interaction mediated environment can be more classical than the demon