Thermodynamics of fidelity in quantum gates

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Yukawa Institute for Theoretical Physics, Kyoto U

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with Tomotaka Kuwahara (RIKEN) and Keiji Saito (Kyoto U)

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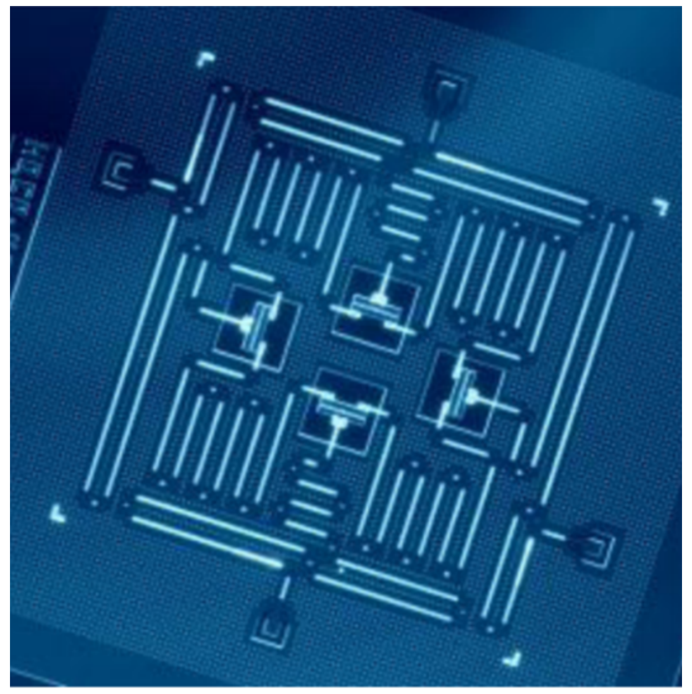
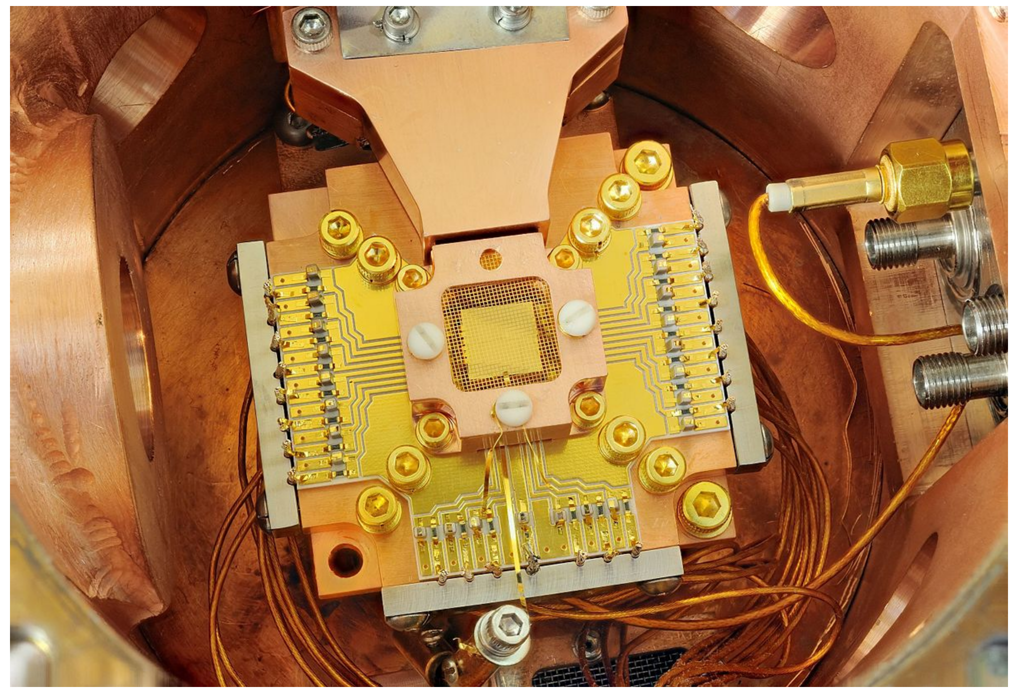
Outline

- Background and motivation
- Setup and main results
- Numerical demonstration

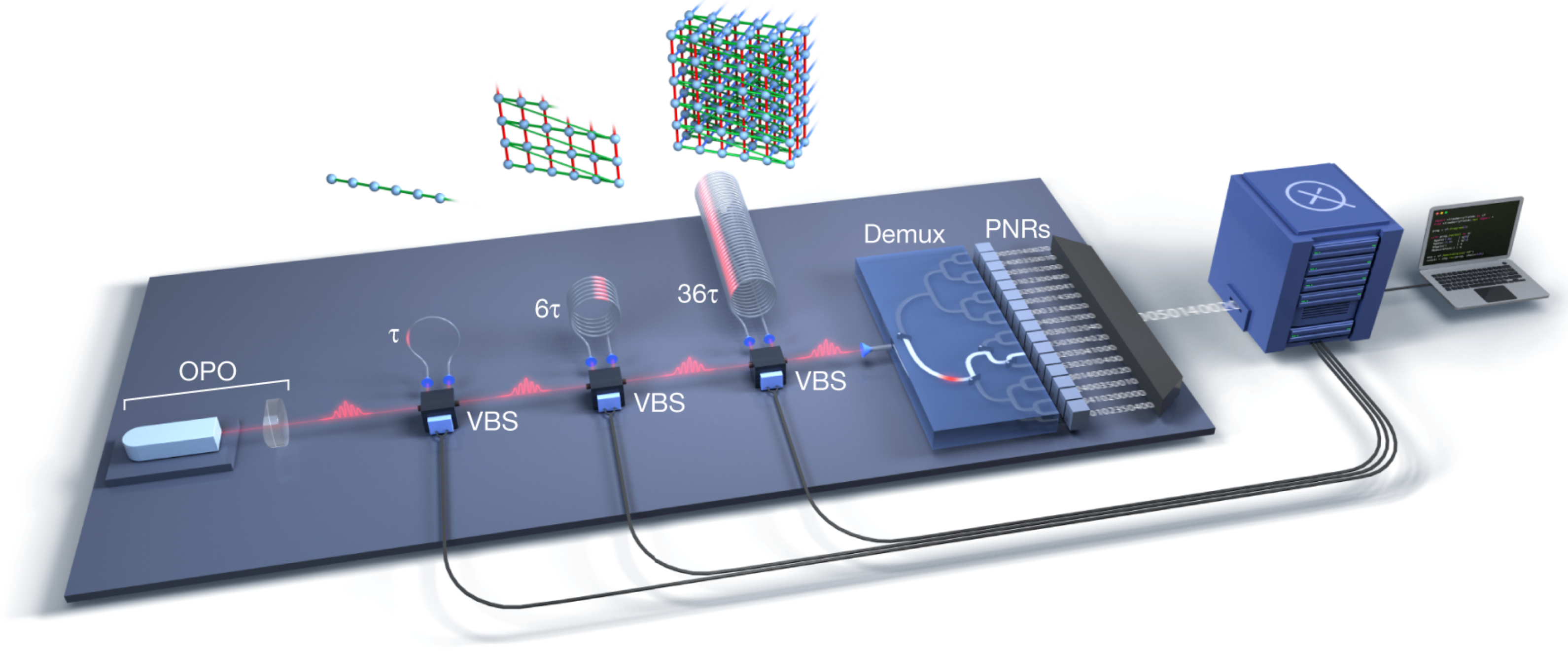
Quantum gates



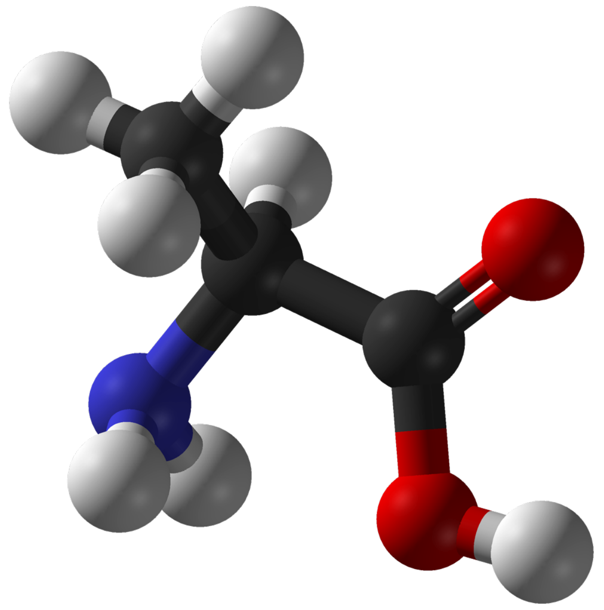
superconducting (wiki)



trapped ions (wiki)

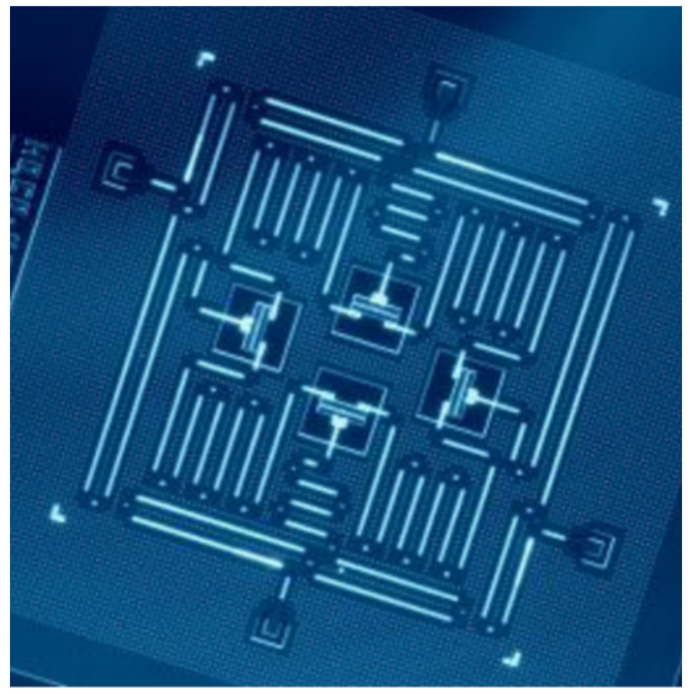


photonic (Madsen+, Nature 2022)



NMR (wiki)

Quantum gates



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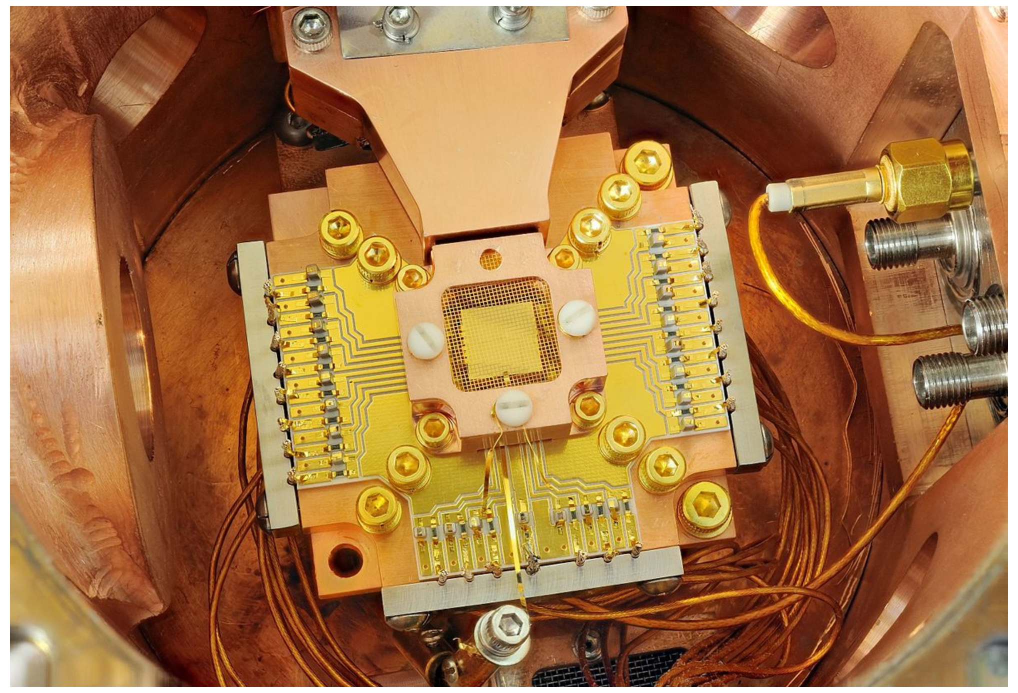

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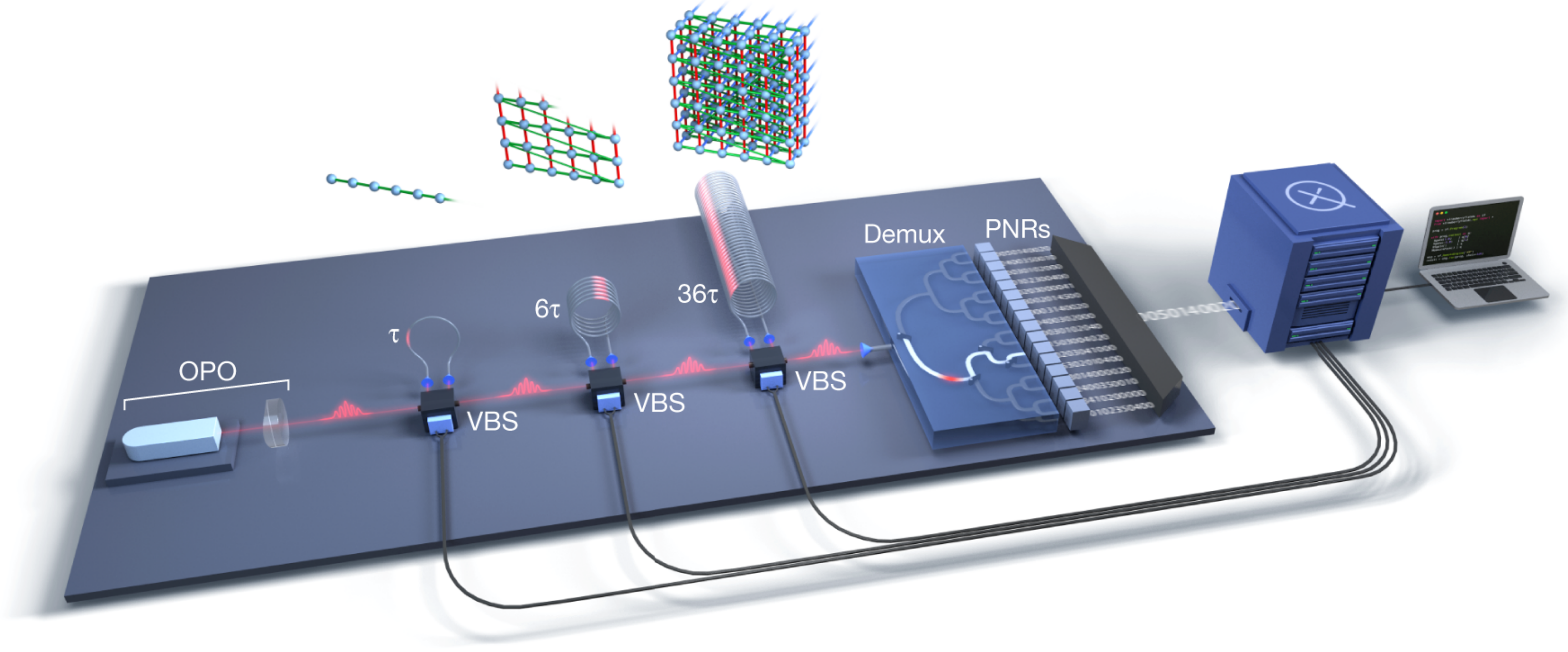

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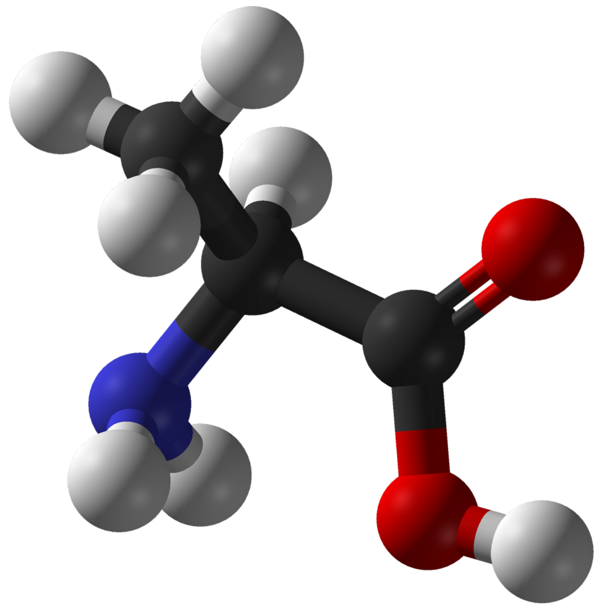

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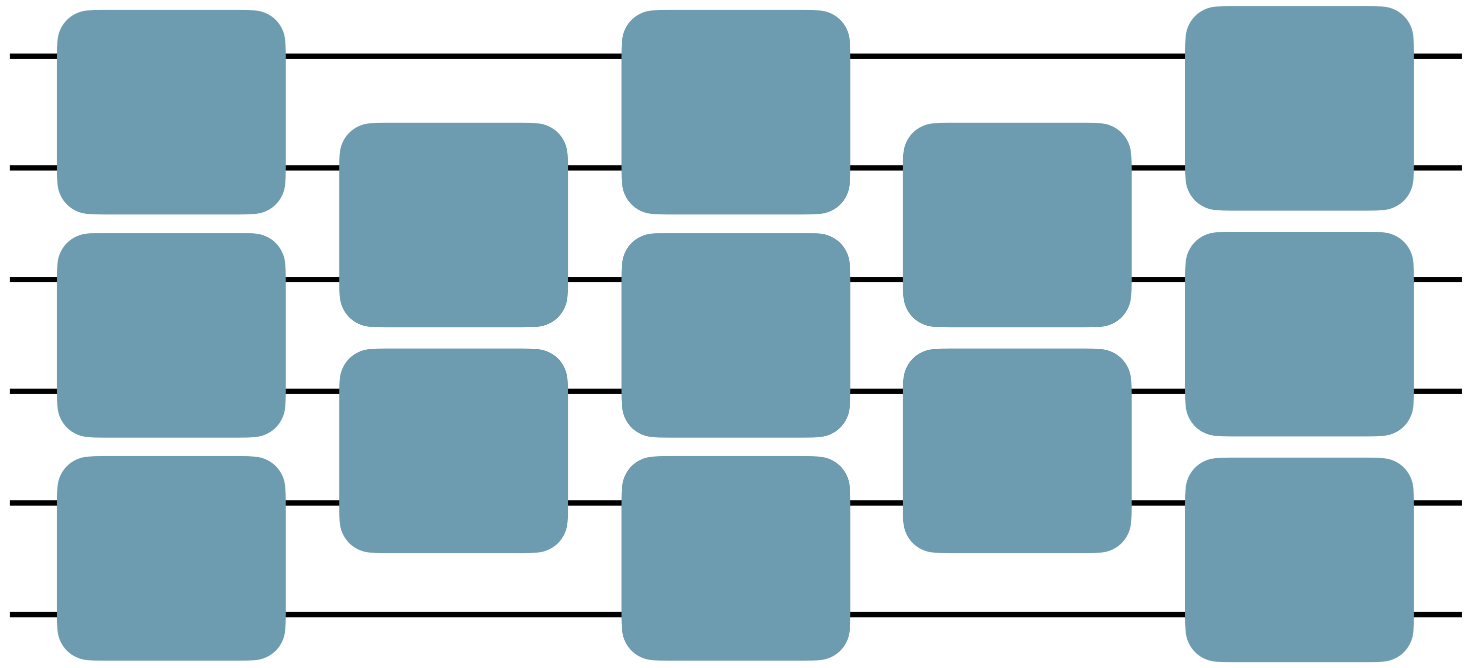

Quantum gates: Hadamard, CNOT, CZ, Toffoli, etc.

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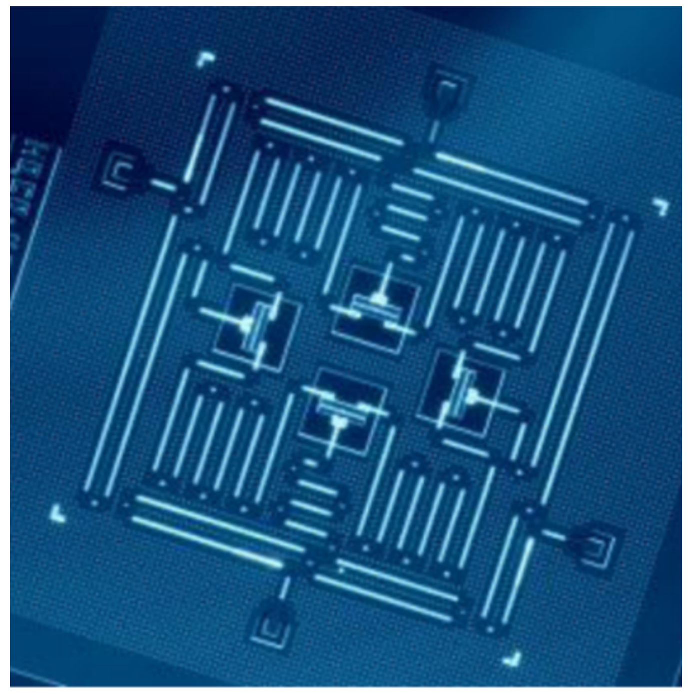

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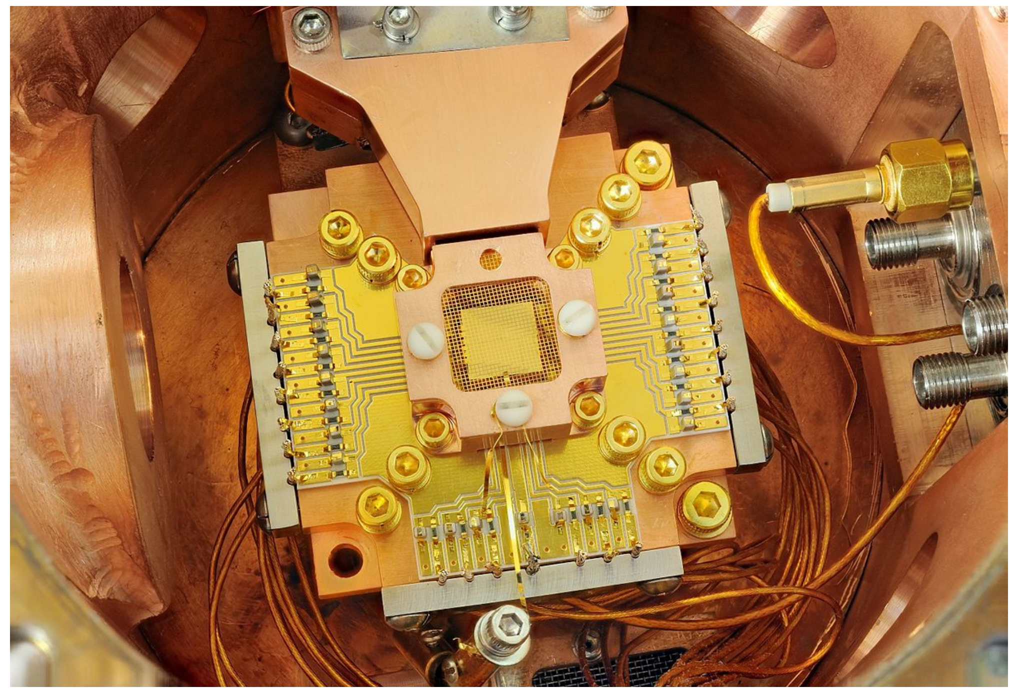

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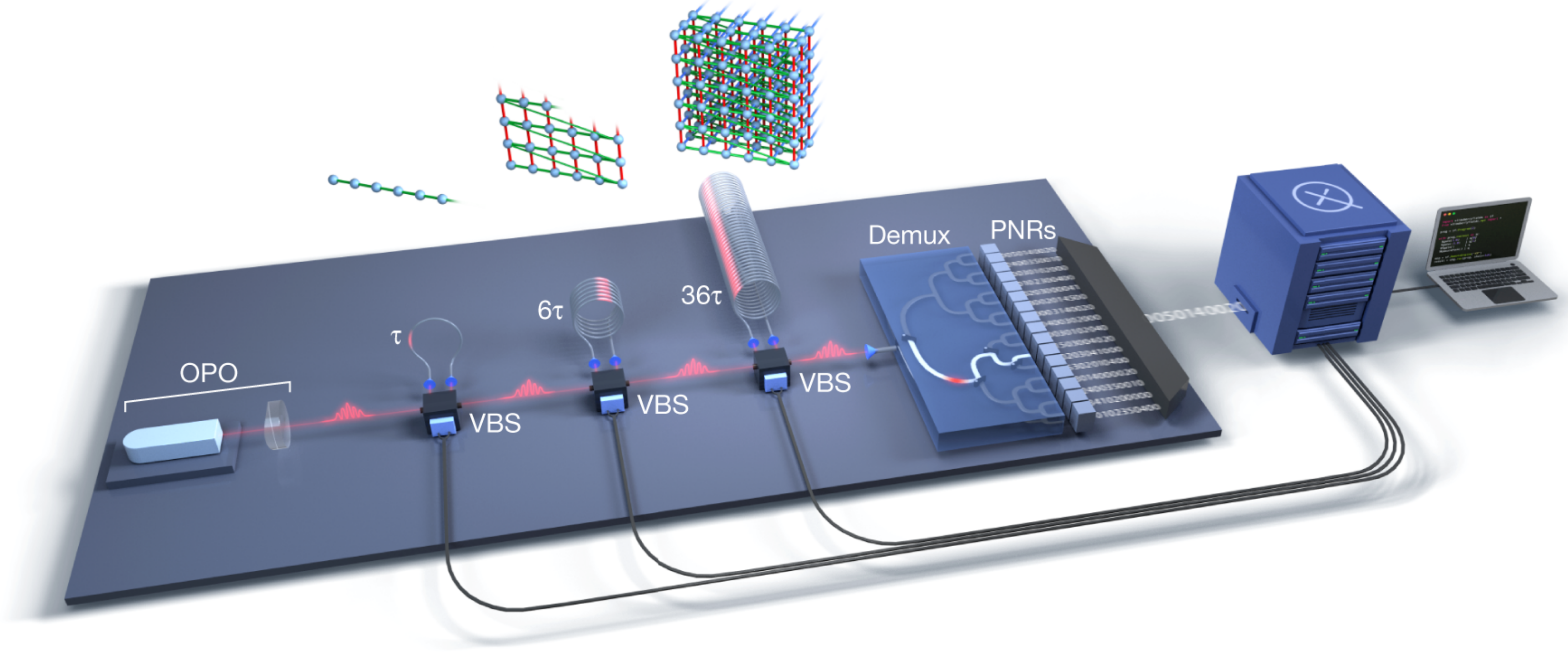

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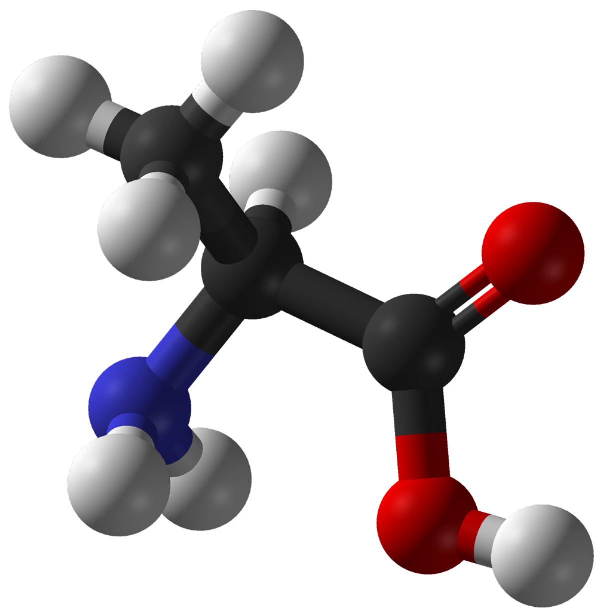

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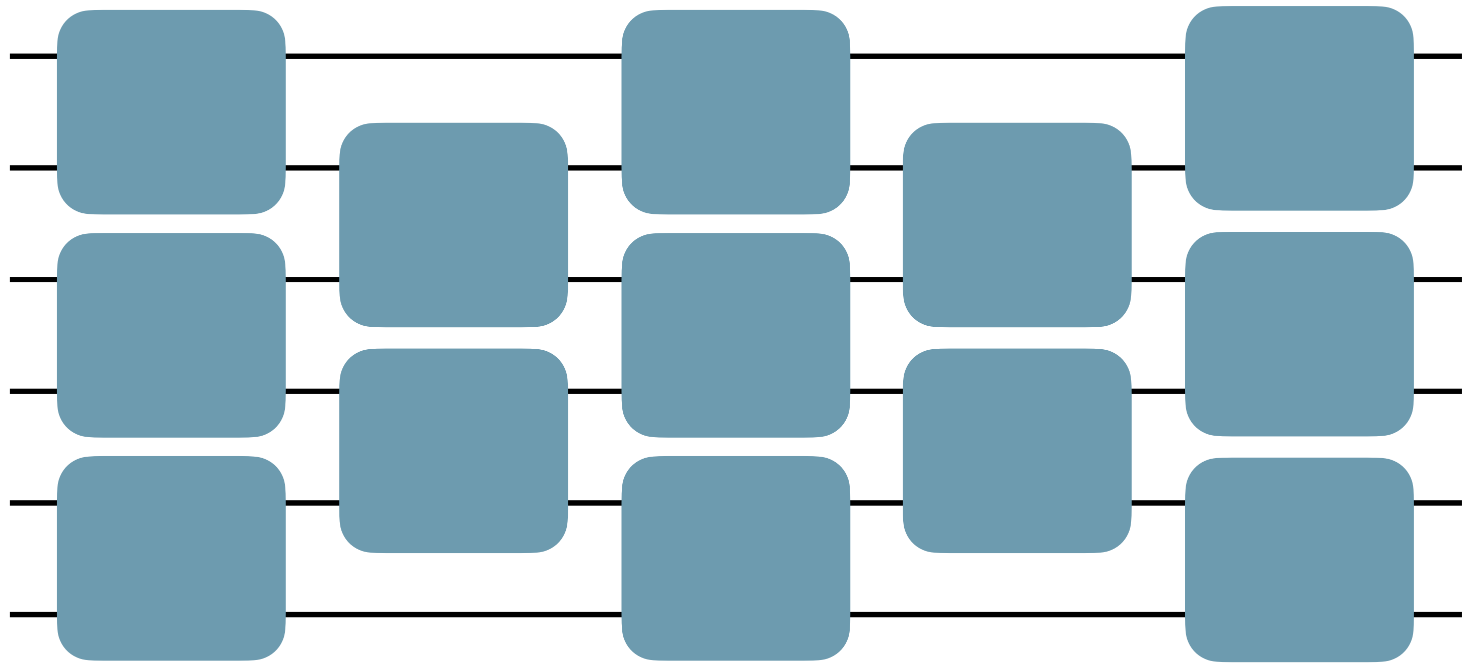

- Implementation of fast and high-fidelity quantum gates

  trapped-ion qubit: Ballance+, PRL (2016)
  solid-state spin: Huang+, PRL (2019)
  two-qubit gate: Hegde+, PRL (2022)
  CNOT gate: Xie+, PRL (2023)

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Noises and thermodynamic effects

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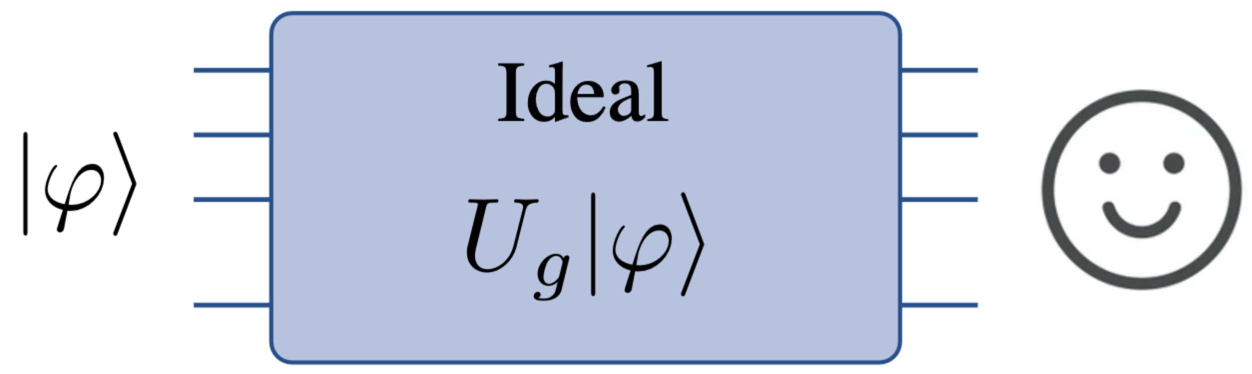

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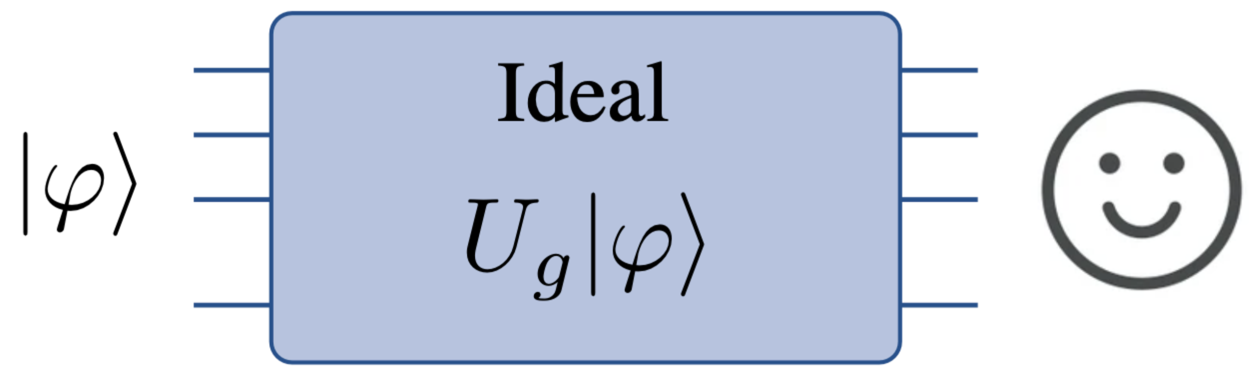
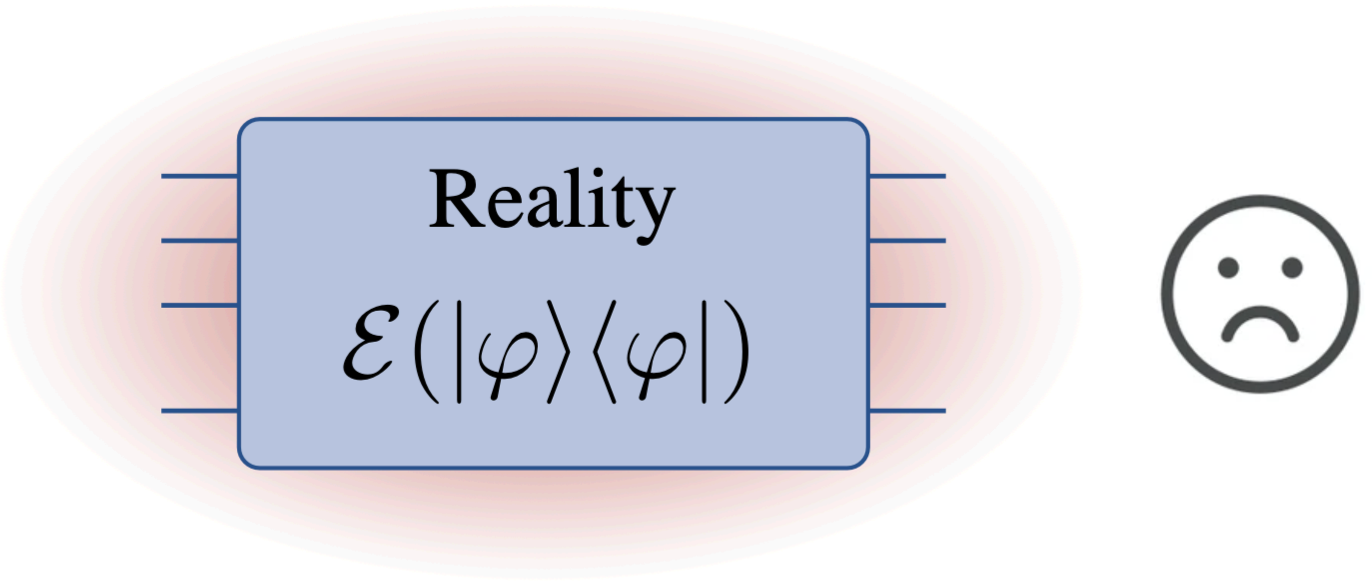
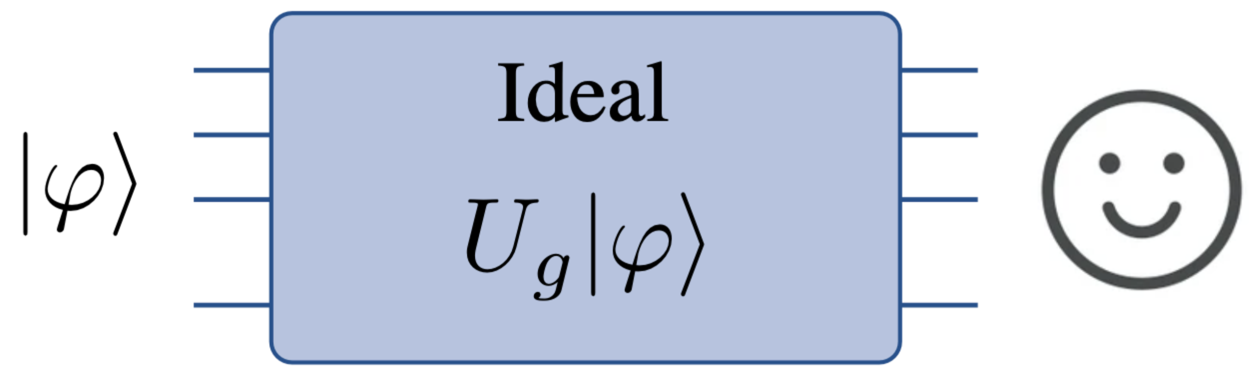


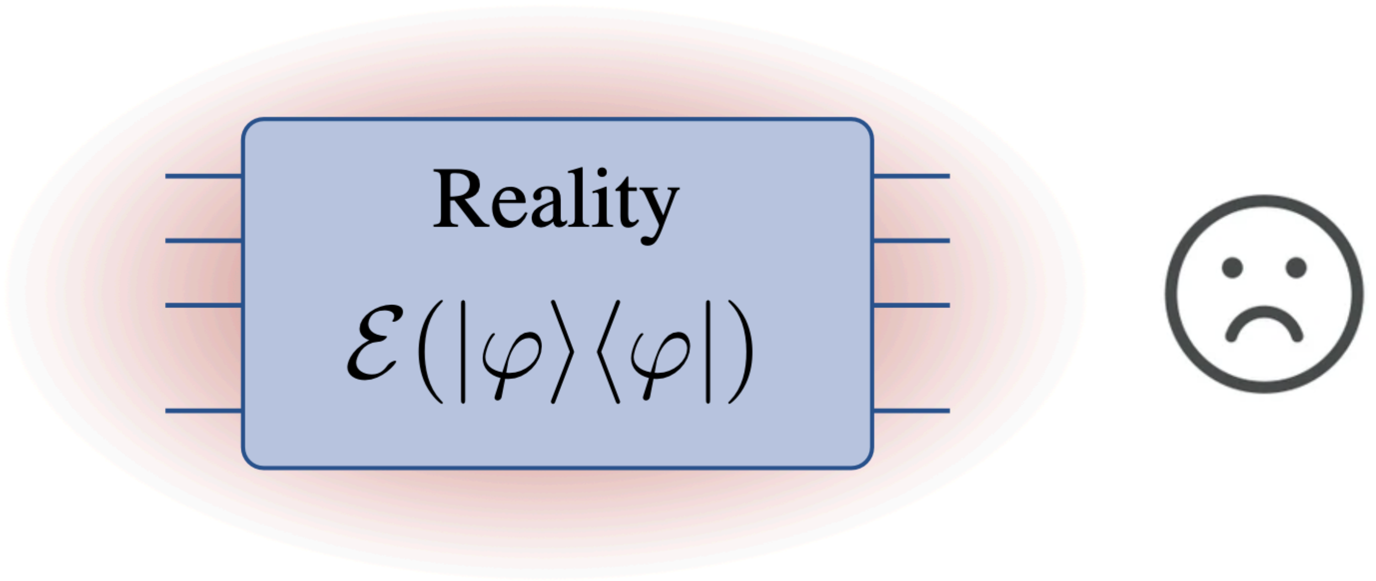


Bit flip, phase flip (Pauli channels)
Amplitude damping, phase damping, etc.

Noises and thermodynamic effects

- Quantum gates are unavoidably affected by noises





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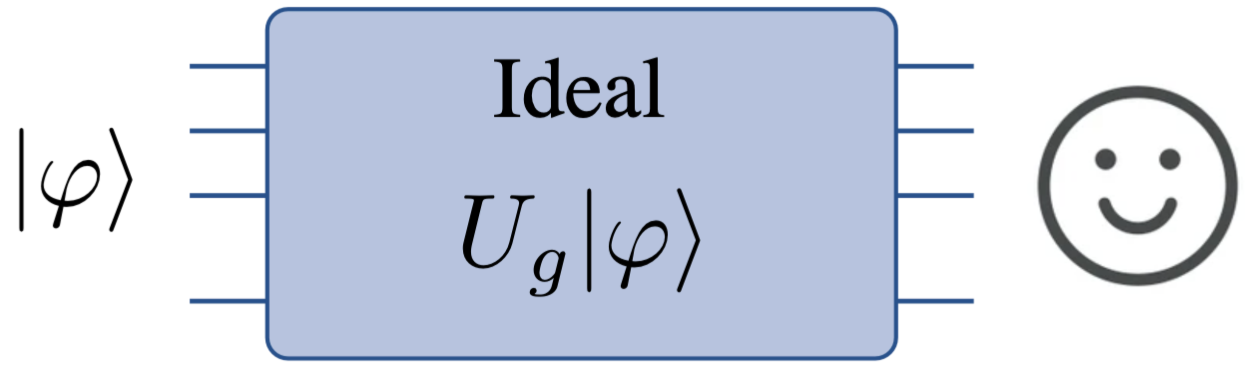

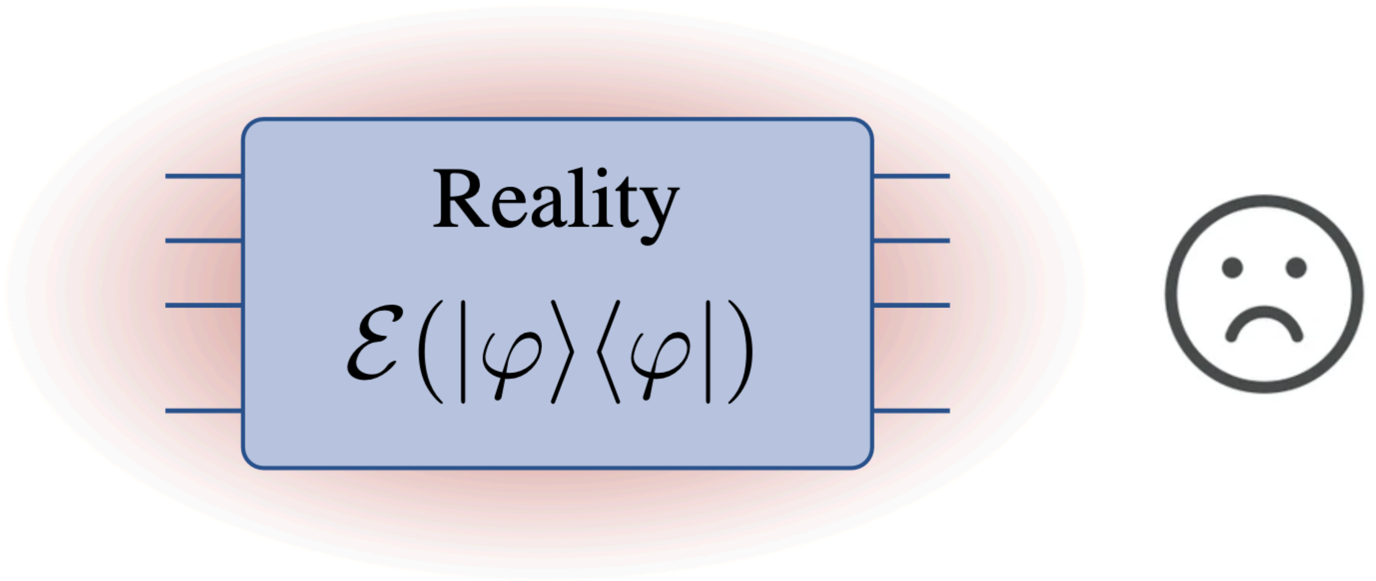

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- Analysis of gate fidelity
  - conservative laws — Ozawa, PRL (2002)
  - short operational times — Abad+, PRL (2022)
  - imperfect timekeeping — Xuereb+, PRL (2023)
  - fluctuations of external control — Jiang+, PRA (2023)

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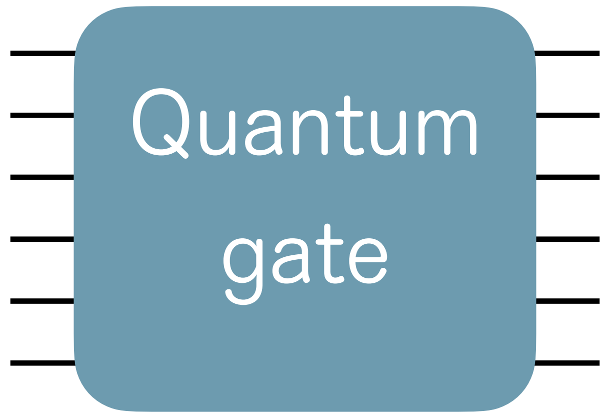
- <u>Motivation</u>: Elucidate thermodynamic effects on fidelity of quantum gates

Setup



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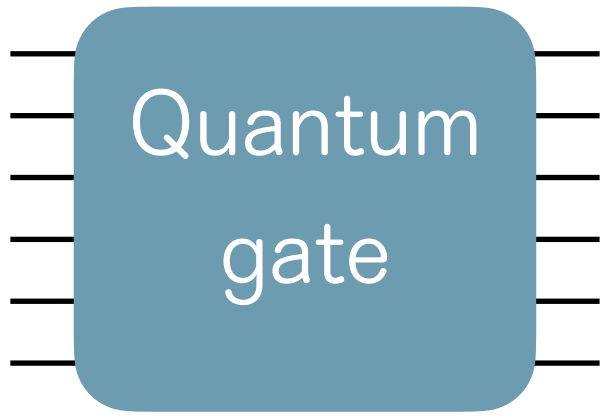

- Ideal dynamics $\varrho_\tau = U_g \varrho_0 U_g^\dagger$

$$\dot{\varrho}_t = -i[H_t, \varrho_t] \qquad U_g = \overrightarrow{\mathbb{T}} \exp\left(-i\int_0^\tau dt\, H_t\right)$$

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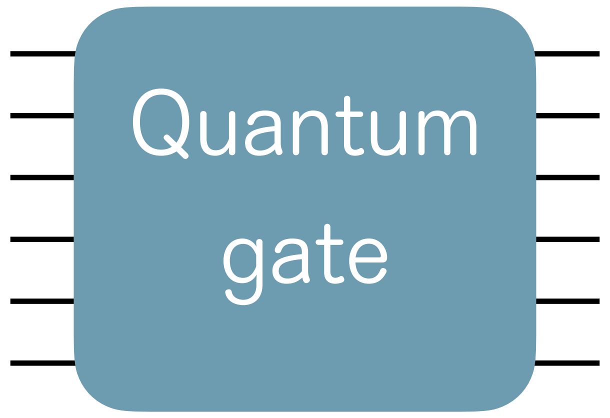

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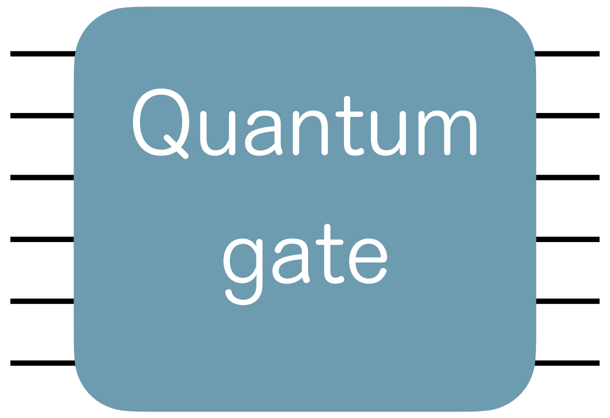

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Lindblad, Commun. Math. Phys. (1976)
Gorini+, J. Math. Phys. (1976)

$\mathscr{D}[L]\varrho = L\varrho L^\dagger - \{L^\dagger L, \varrho\}/2$: dissipator

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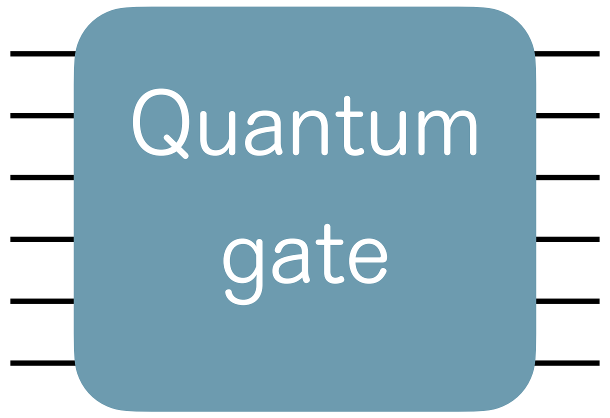

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- Dissipative jump operators → local detailed balance $L_c(t) = e^{s_c(t)/2} L_{c'}(t)^\dagger$

e.g., energy relaxation

Horowitz+, New J. Phys. (2013)

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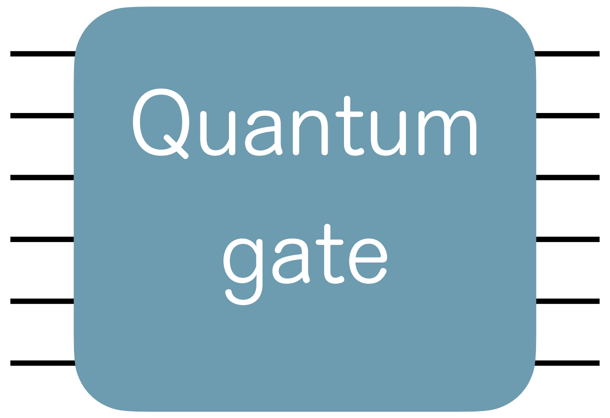

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- Non-dissipative jump operators → self-adjoint $L_c(t) = L_c(t)^\dagger$

  e.g., phase damping

  i.e., $s_c(t) = 0$ & $c' = c$

Fidelity and dissipation

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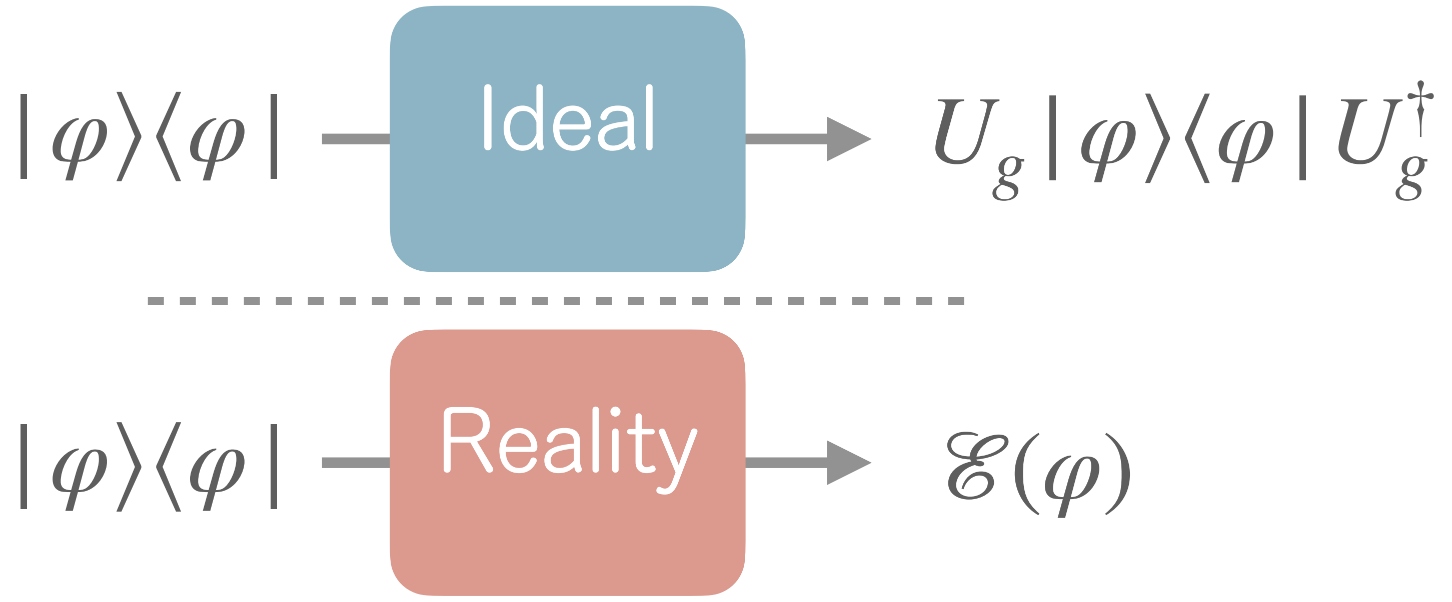

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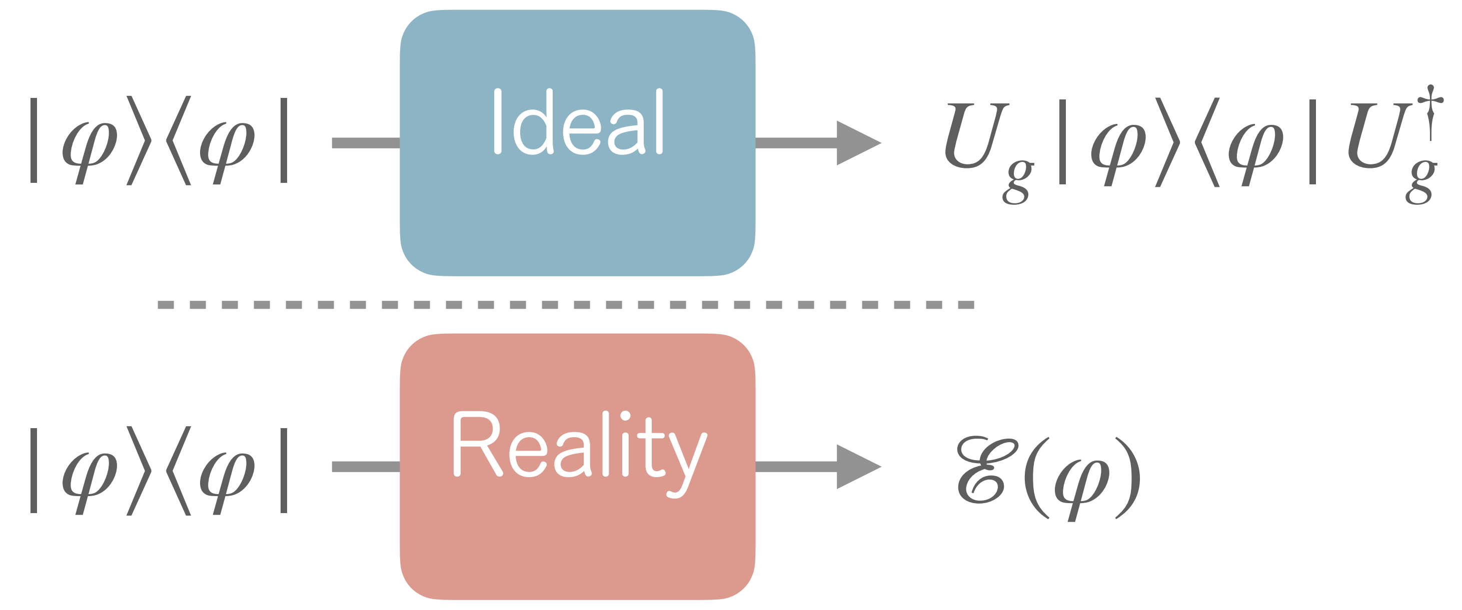


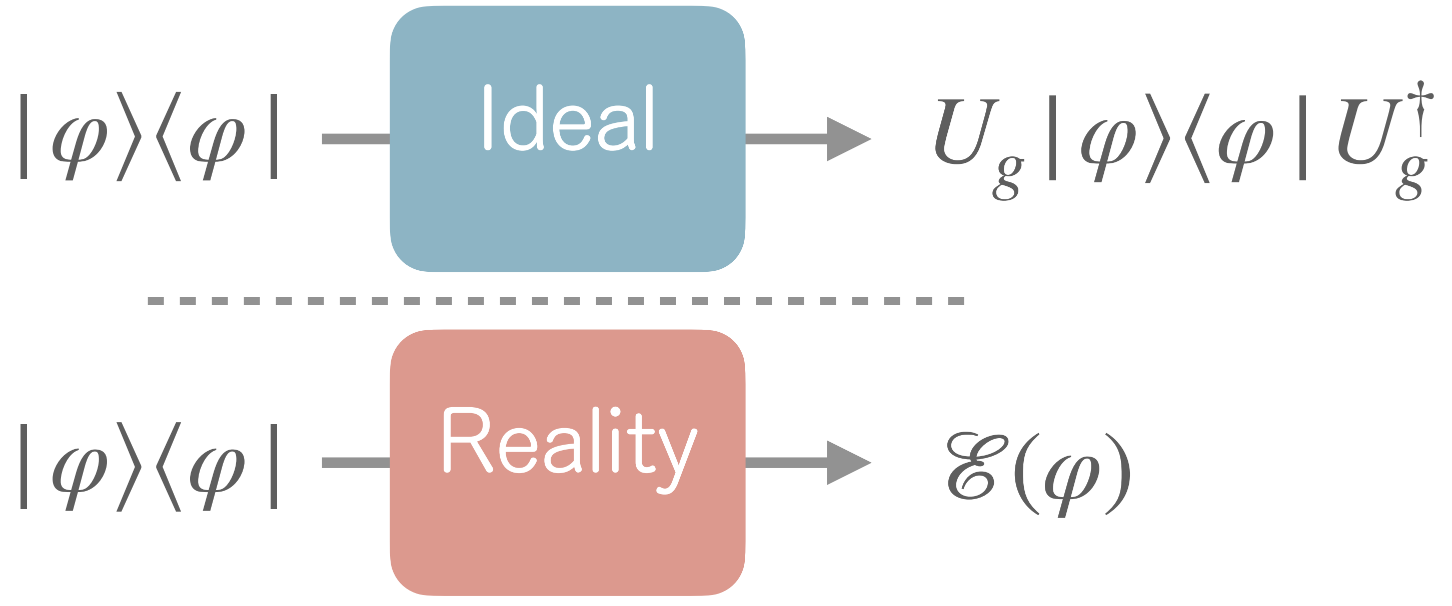
$$F(U_g|\varphi\rangle\langle\varphi|U_g^\dagger, \mathcal{E}(\varphi)) = \langle\varphi|U_g^\dagger\mathcal{E}(\varphi)U_g|\varphi\rangle$$

Fidelity and dissipation

- Average fidelity

$$\mathscr{F} := \int d\varphi \, \langle \varphi | U_g^\dagger \mathscr{E}(\varphi) U_g | \varphi \rangle \leq 1$$

Nielsen, Phys. Lett. A (2002)



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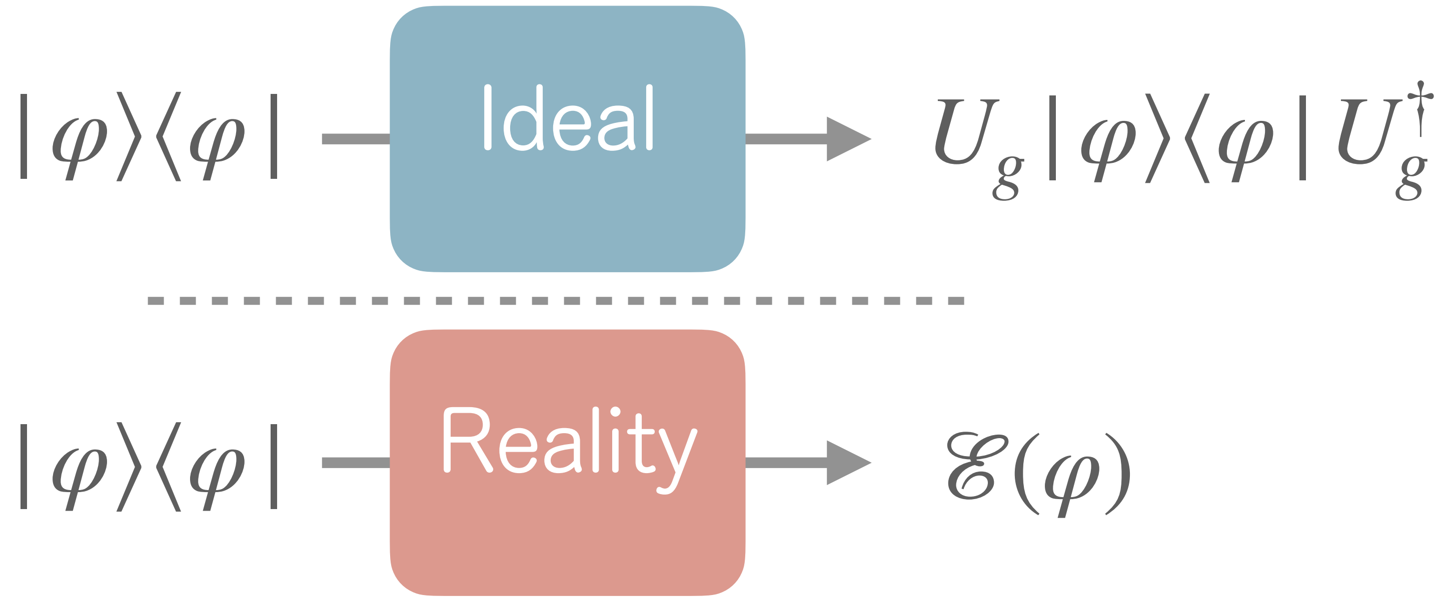

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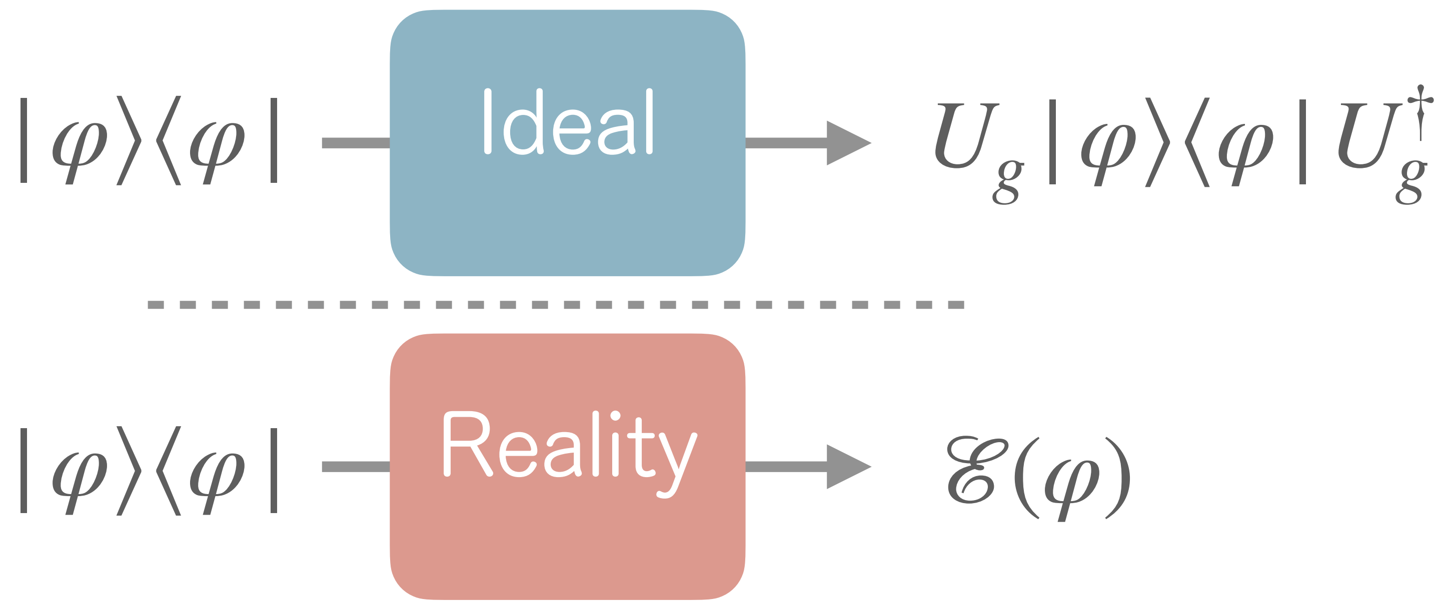

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$\Sigma_\varphi^{\mathrm{env}}(\tau) := \int_0^\tau dt \sum_c \mathrm{tr}\{L_c(t)\varrho_t L_c(t)^\dagger\} s_c(t)$: environmental entropy change

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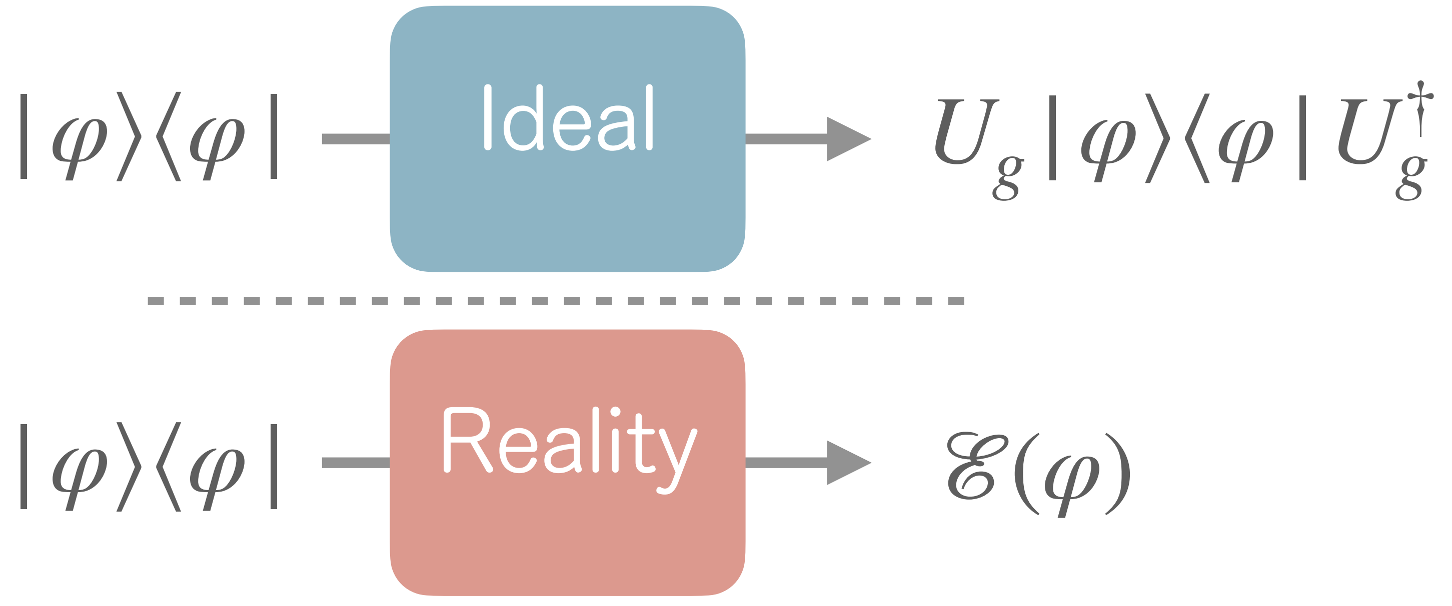

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- Average dissipation

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Result Ⅰ

Result I

- Relation between fidelity and entropy production

$$\mathcal{F} + \sqrt{\gamma\Sigma/2} \geq 1$$

$$\gamma := \int_0^\tau dt \sum_c [\Delta L_c(t)]^2$$

$$[\Delta L]^2 := \frac{(d\,\mathrm{tr}\{L^\dagger L\} - |\,\mathrm{tr}\{L\}\,|^2)}{d(d+1)} \geq 0$$

$d = 2^N$: Hilbert space's dimension

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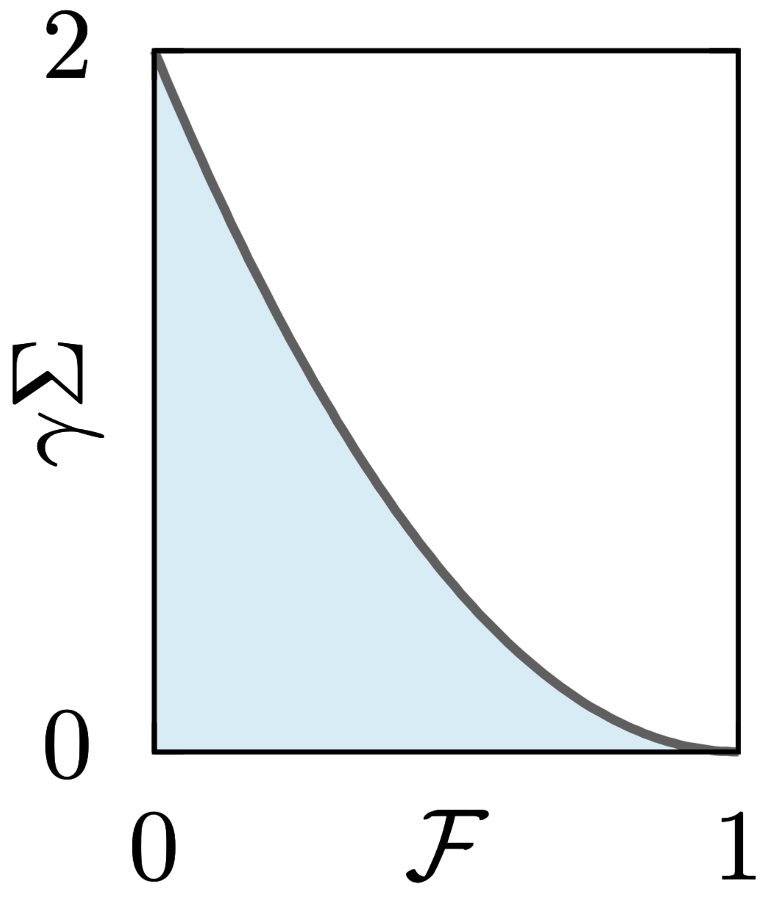

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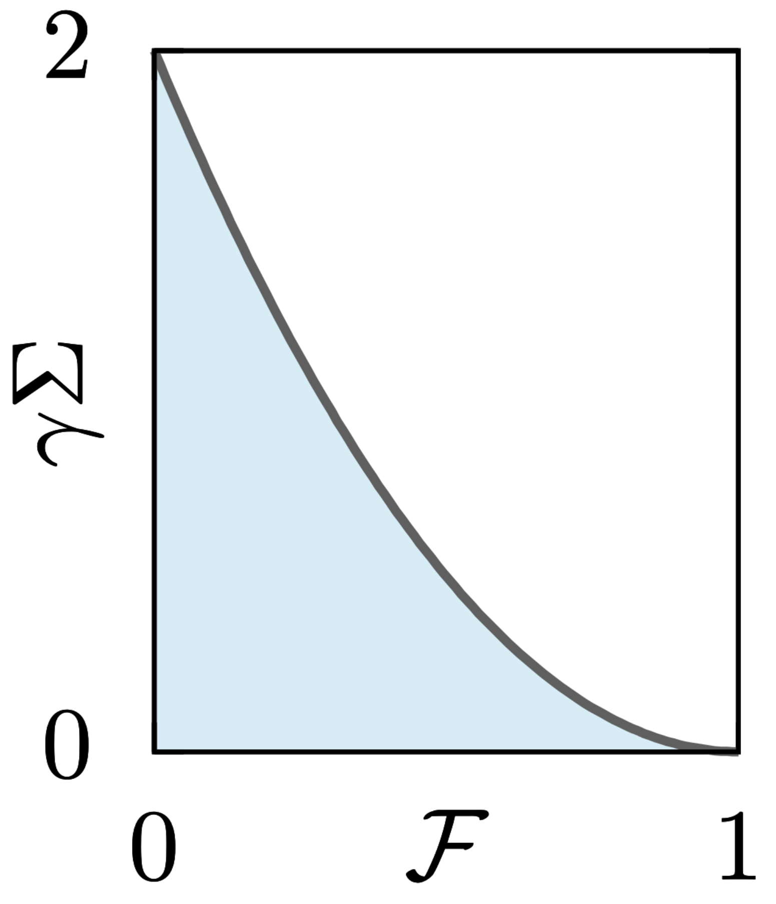

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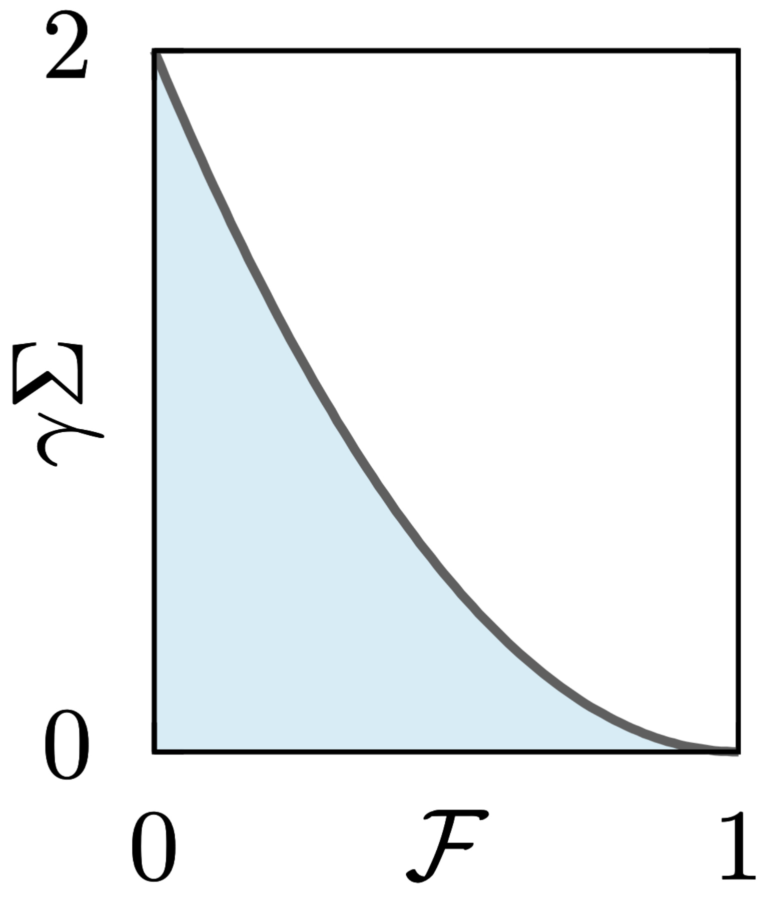

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✓ Valid for arbitrary times and protocols

✓ Thermodynamic upper bound on error

$$\underline{1 - \mathscr{F}} \leq \underline{\sqrt{\gamma\Sigma/2}}$$

Remarks

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$\Rightarrow$

$$\Sigma \geq \frac{2d}{d+1}\Gamma\tau + O(\Gamma^2\tau^2)$$

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⇒

$$\Sigma \geq \frac{2d}{d+1}\Gamma\tau + O(\Gamma^2\tau^2)$$

✓ dephasing rate Γ is estimable in experiments

Harper+, Nat. Phys. (2020)

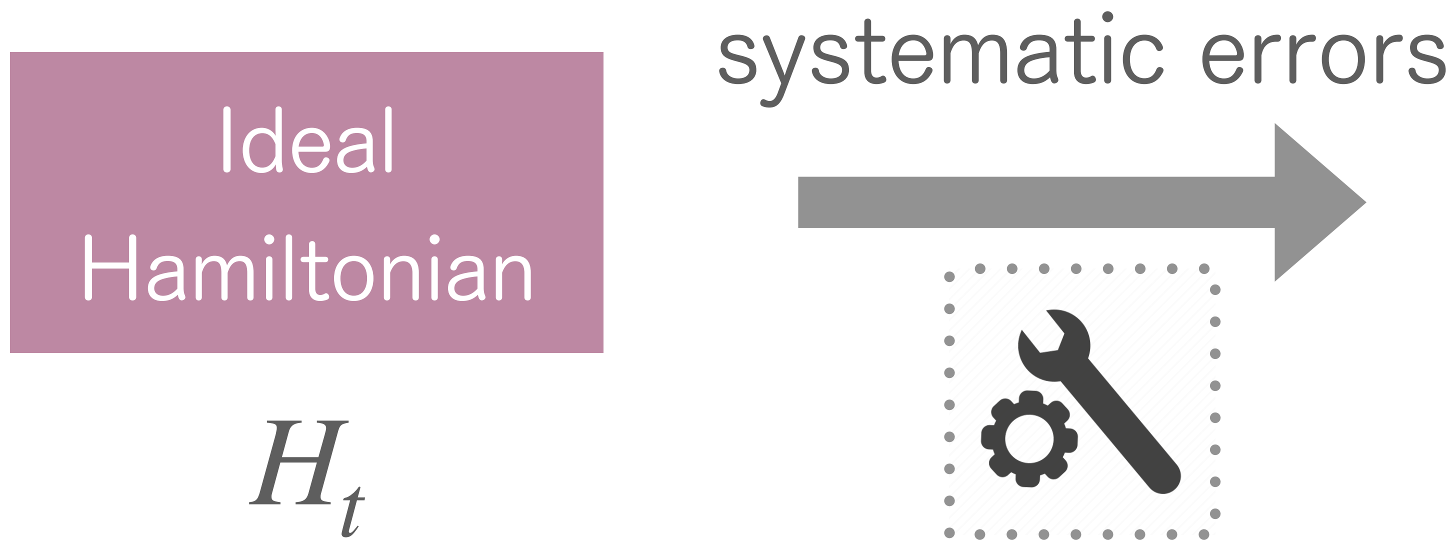
Flammia+, Quantum (2021)

Remarks

Ideal
Hamiltonian

H_t

Remarks



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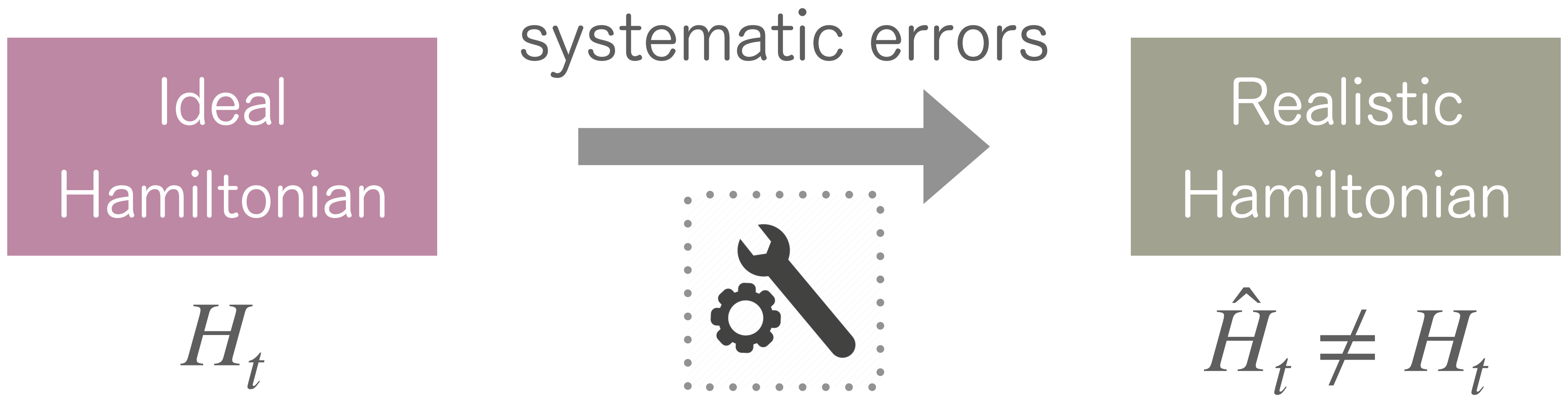
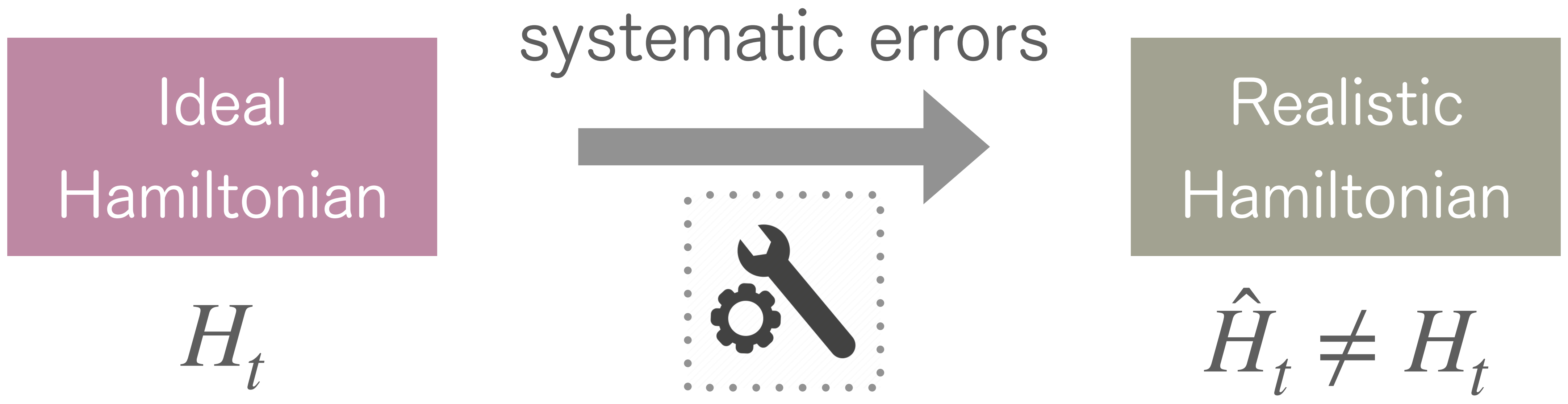

Ideal
Hamiltonian
H_t
systematic errors
Realistic
Hamiltonian
$\hat{H}_t \neq H_t$

Remarks

- Further generalization

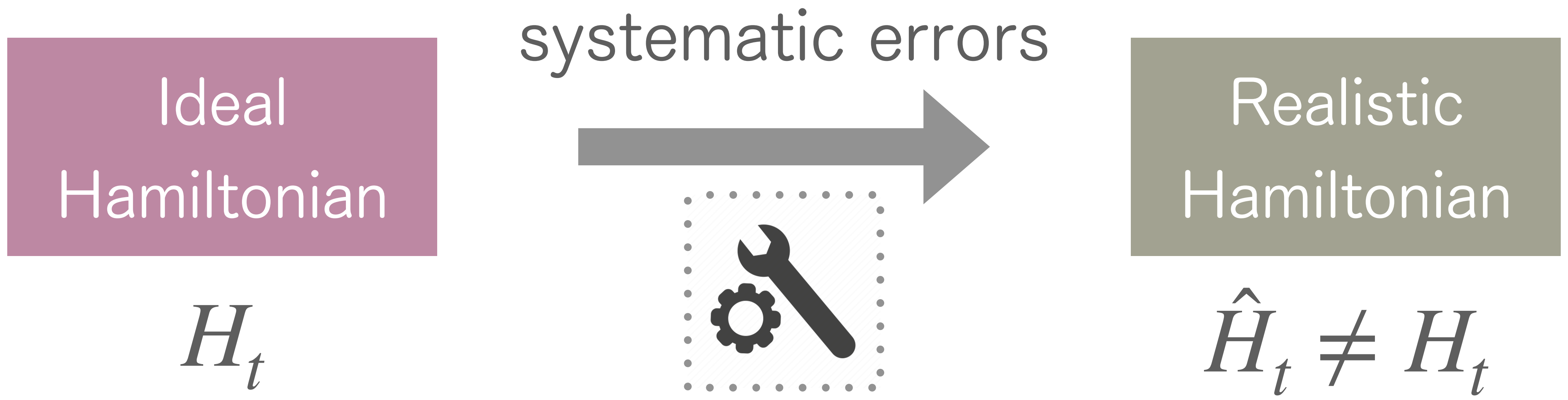
$$\mathscr{F} + \sqrt{\gamma\Sigma/2} \geq \frac{|\mathrm{tr}\{\hat{U}_\tau^\dagger U_g\}|^2 + d}{d(d+1)}$$



$$\hat{U}_\tau := \overrightarrow{\mathbb{T}} \exp\left(-i \int_0^\tau dt\, \hat{H}_t \right)$$

Remarks

- Further generalization



H_t $\qquad$ $\hat{H}_t \neq H_t$

$$\hat{U}_\tau := \overrightarrow{\mathbb{T}} \exp\left(-i \int_0^\tau dt\, \hat{H}_t \right)$$

$$\mathscr{F} + \sqrt{\gamma\Sigma/2} \geq \frac{|\mathrm{tr}\{\hat{U}_\tau^\dagger U_g\}|^2 + d}{d(d+1)}$$

✓ Recover original relation for perfect implementation of Hamiltonian

$$\hat{H}_t = H_t \to \mathrm{tr}\{\hat{U}_\tau^\dagger U_g\} = d \to \mathscr{F} + \sqrt{\gamma\Sigma/2} \geq 1$$

Result 2

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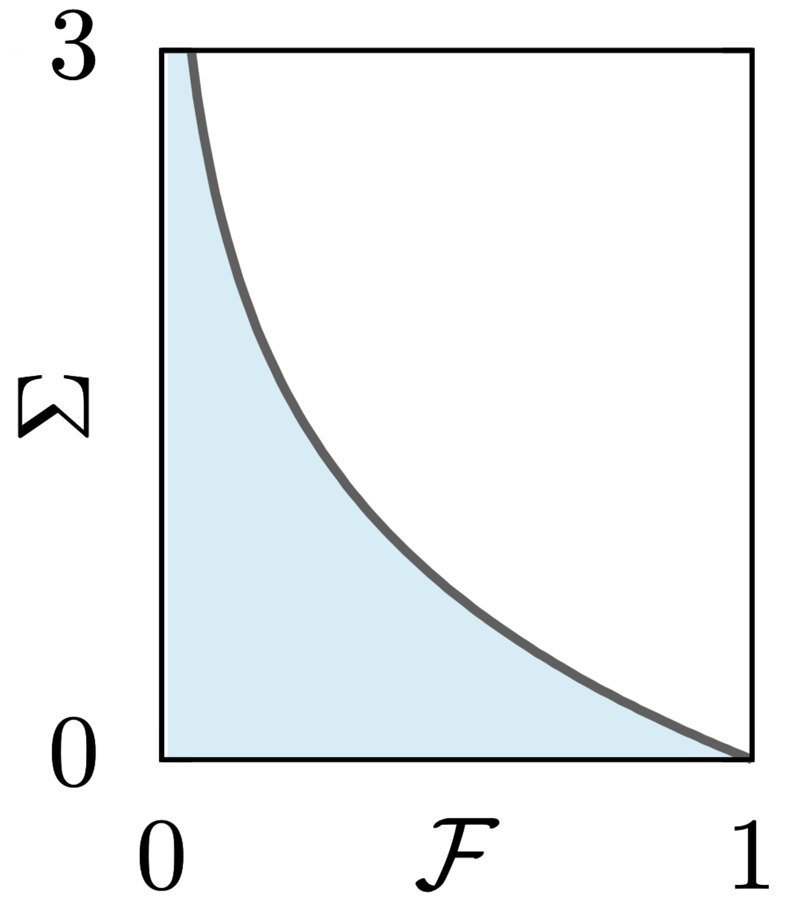

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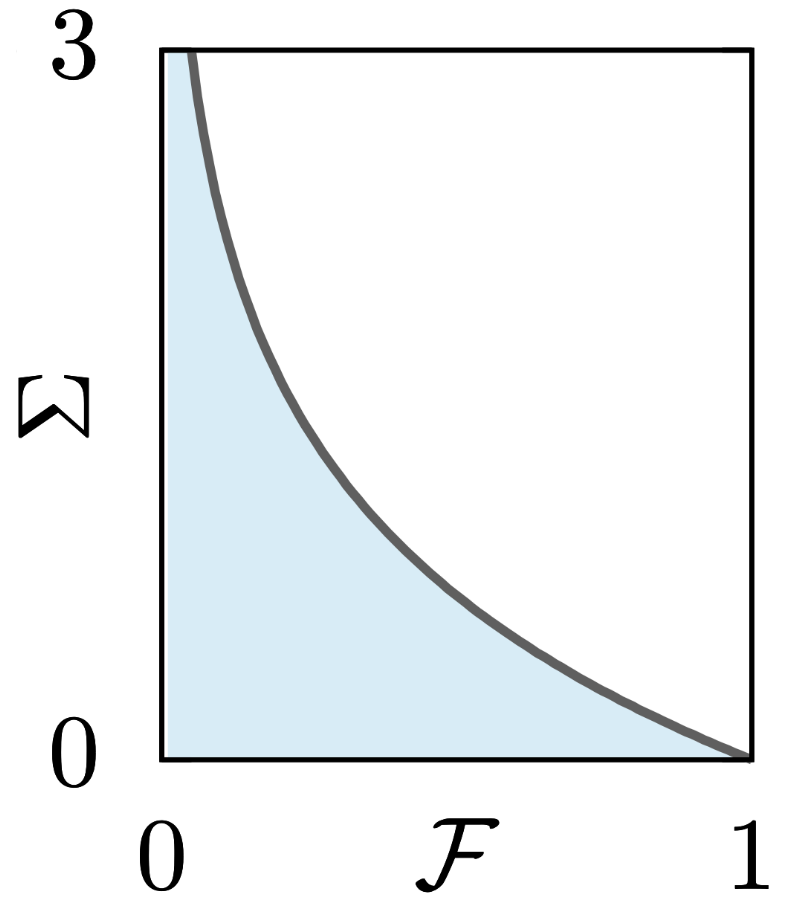

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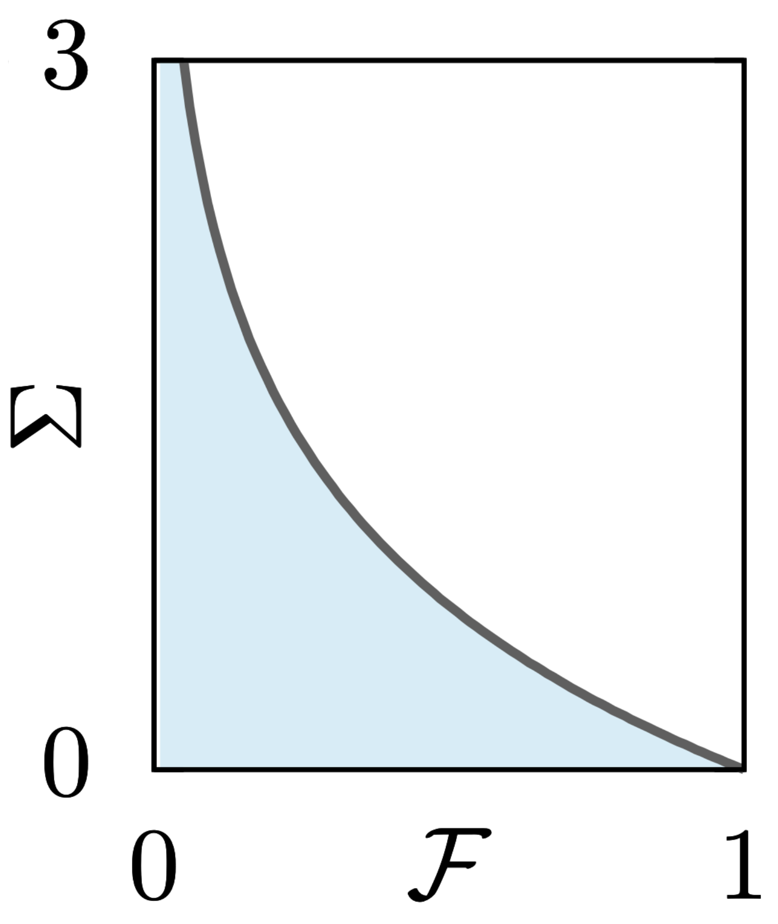

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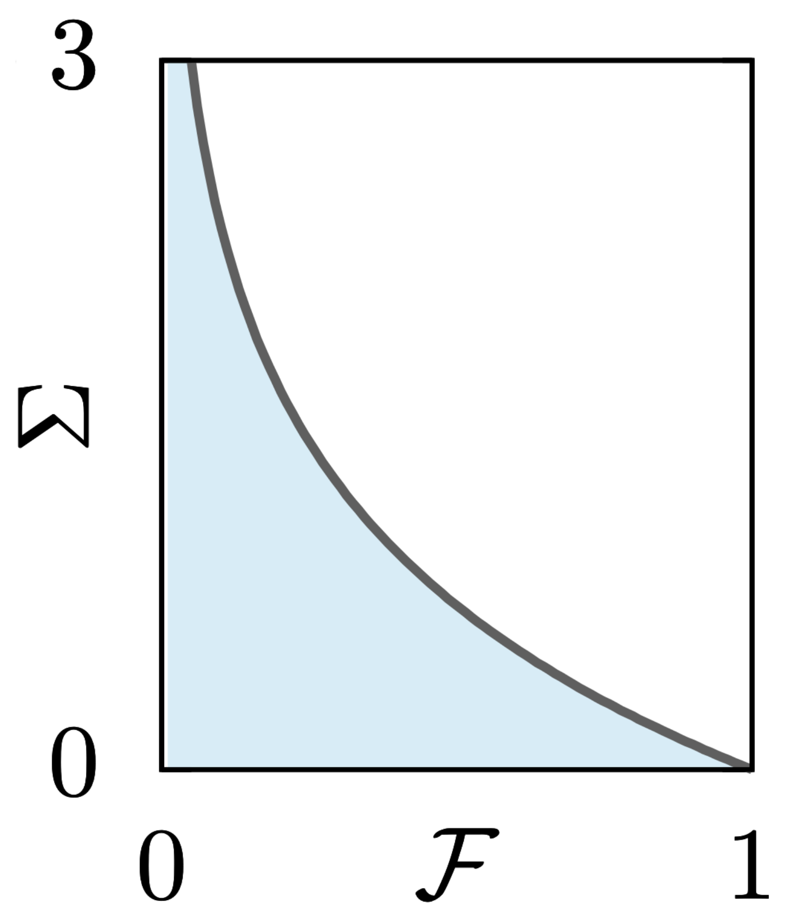

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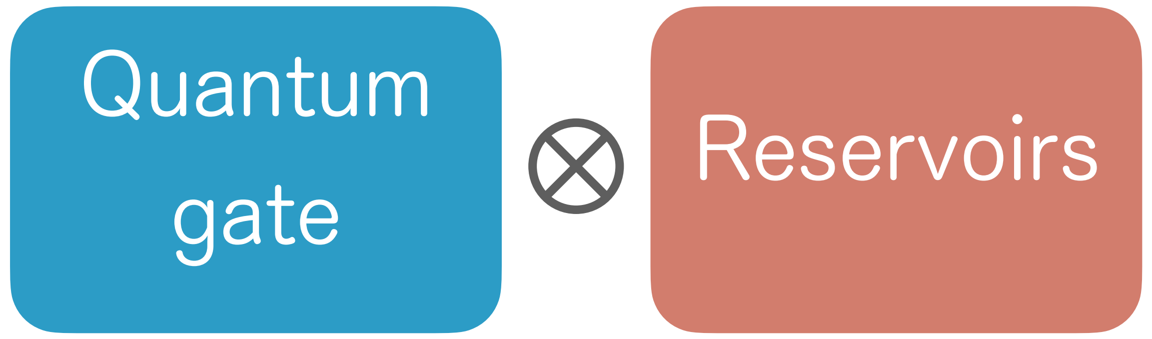
✓ Simple estimation for dissipation

$$\Sigma \geq -\ln \mathscr{F}$$

Beyond Markovian environments

- Generic quantum gate coupled to arbitrary reservoirs



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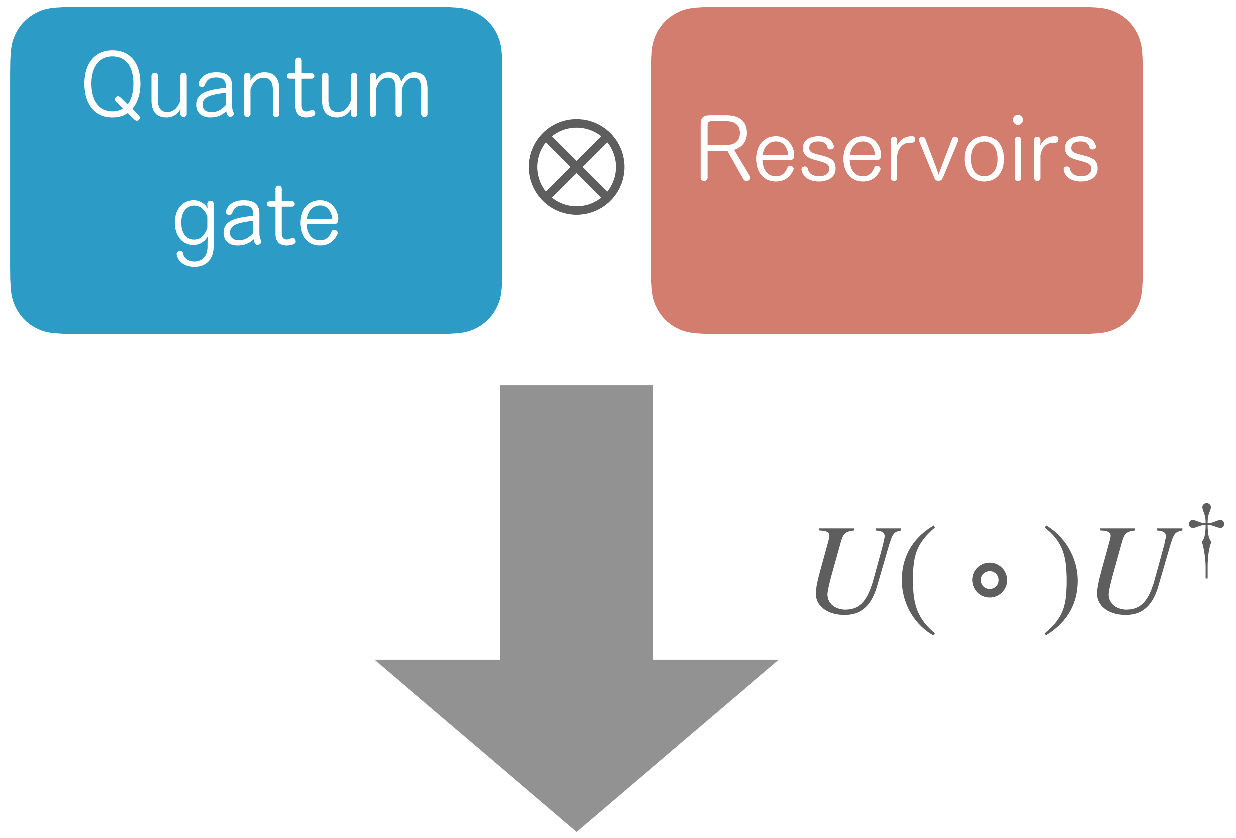

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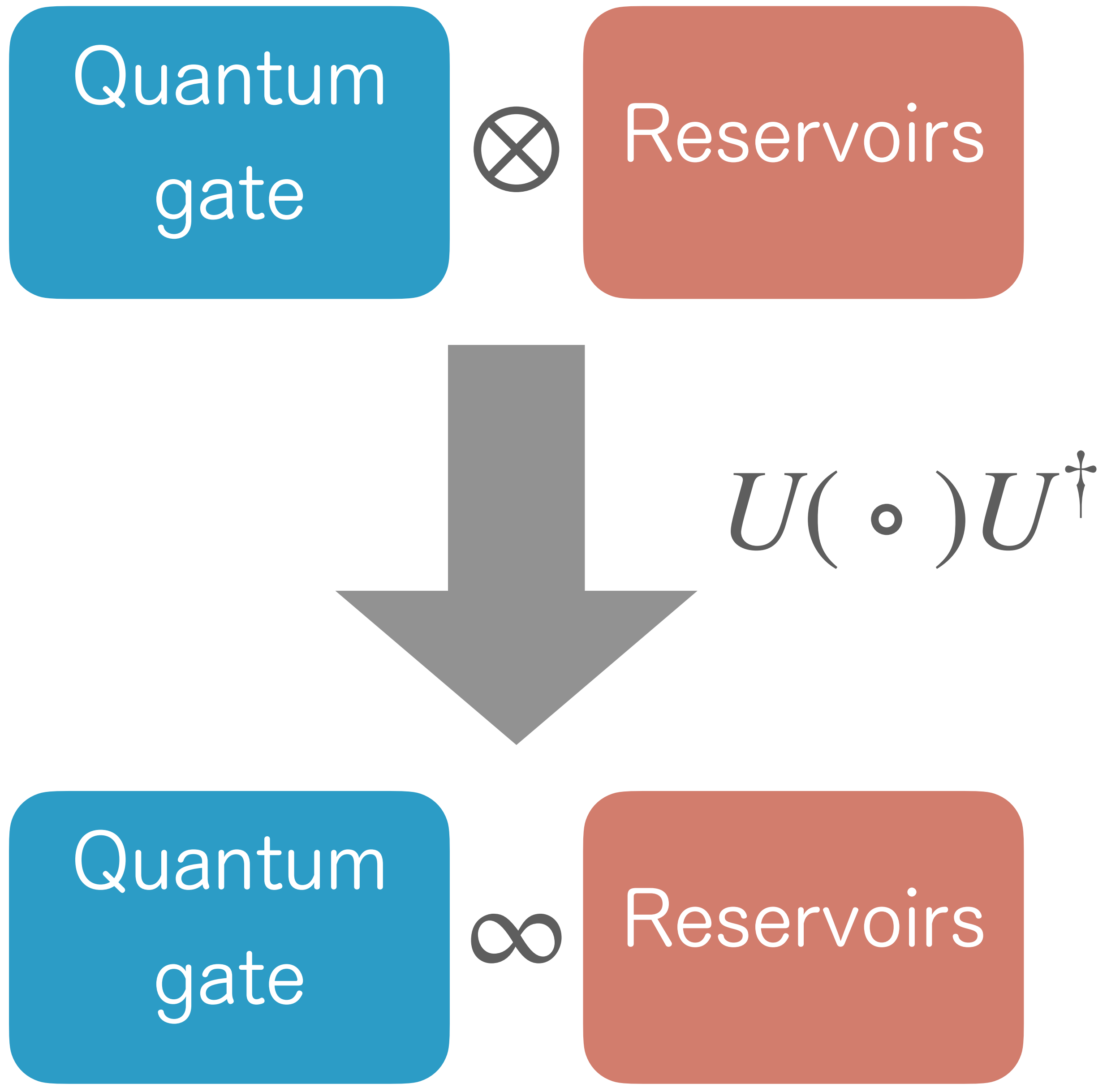

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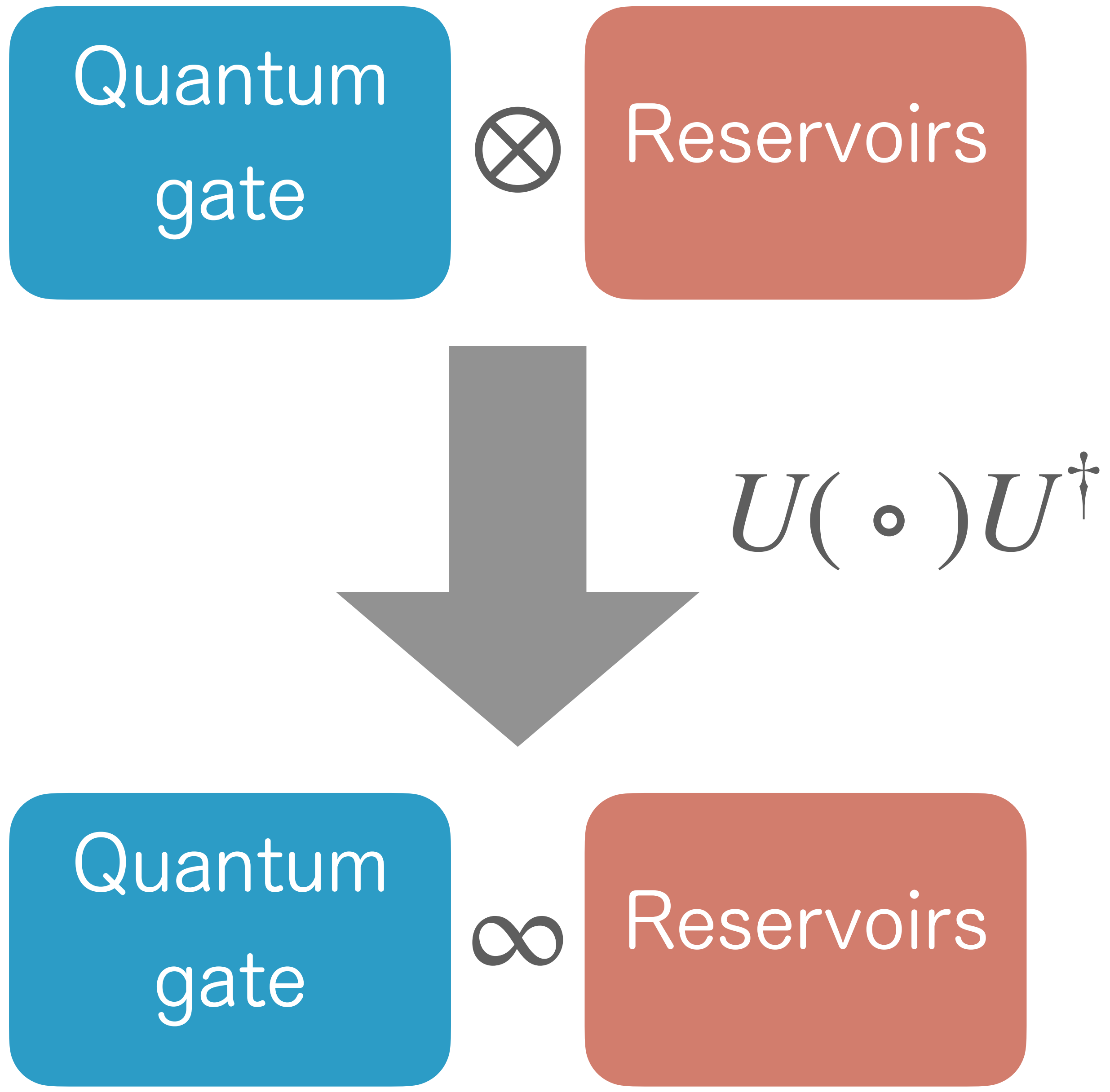
ϱ_E : initial state of reservoirs



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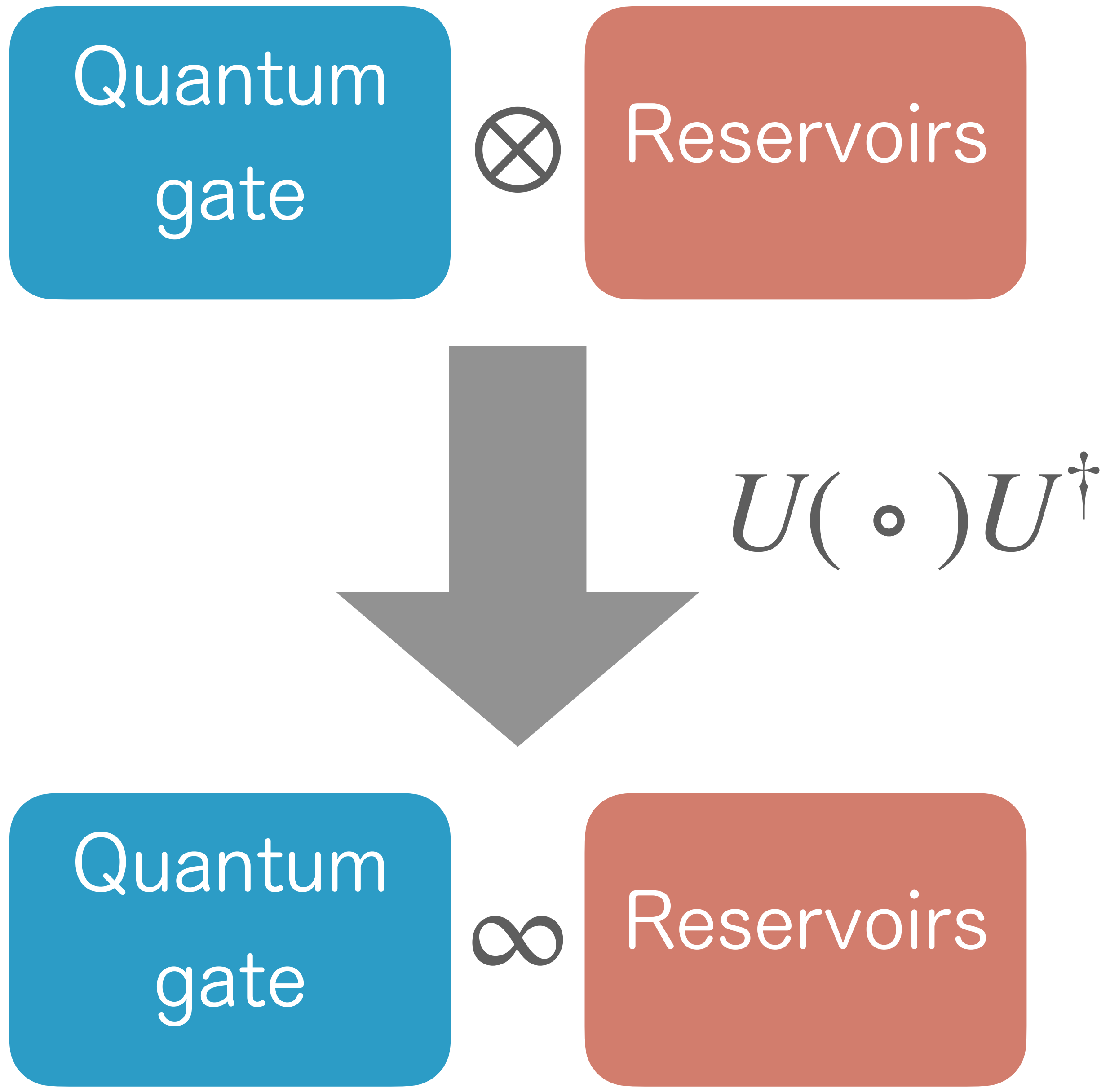

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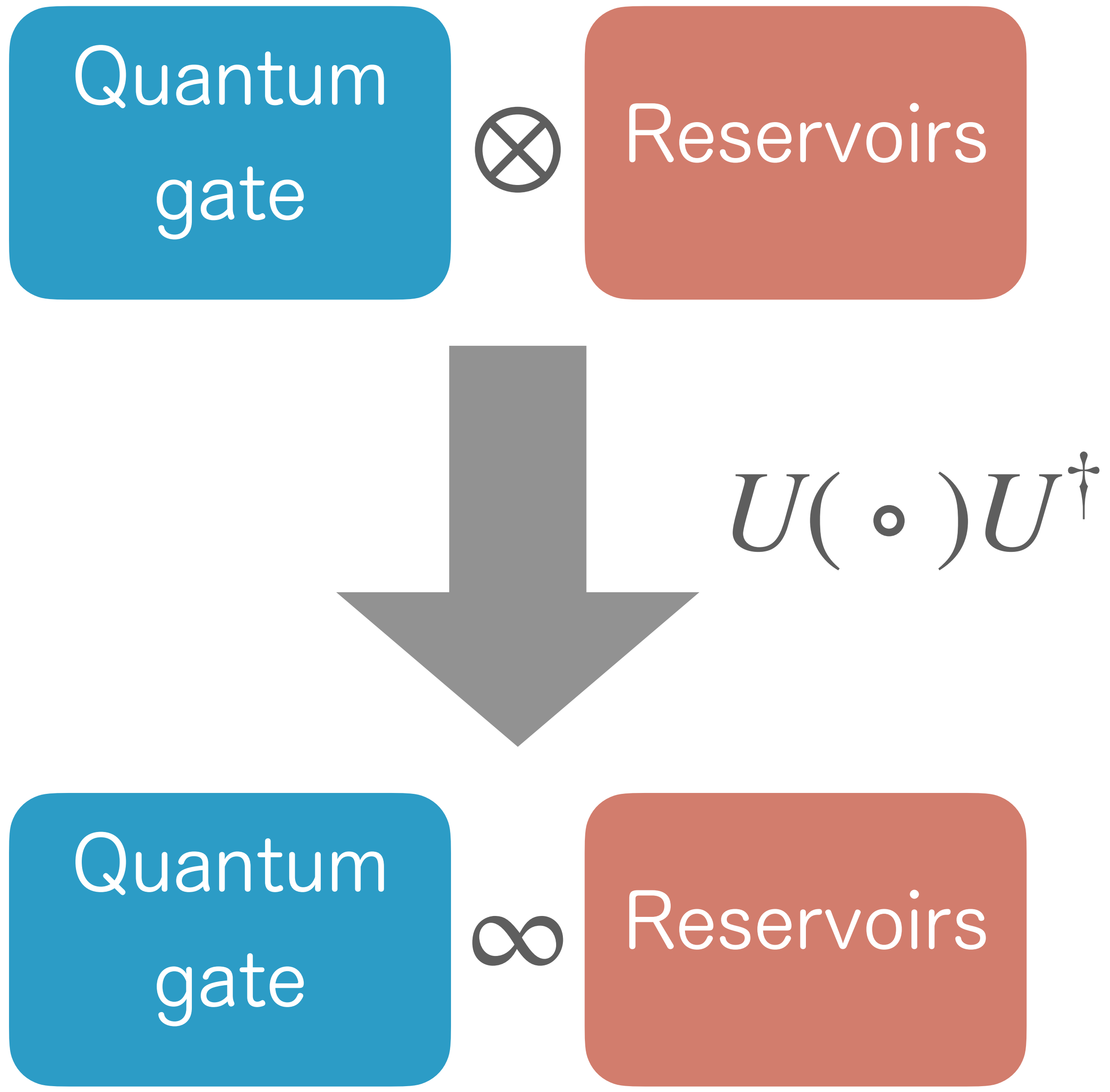

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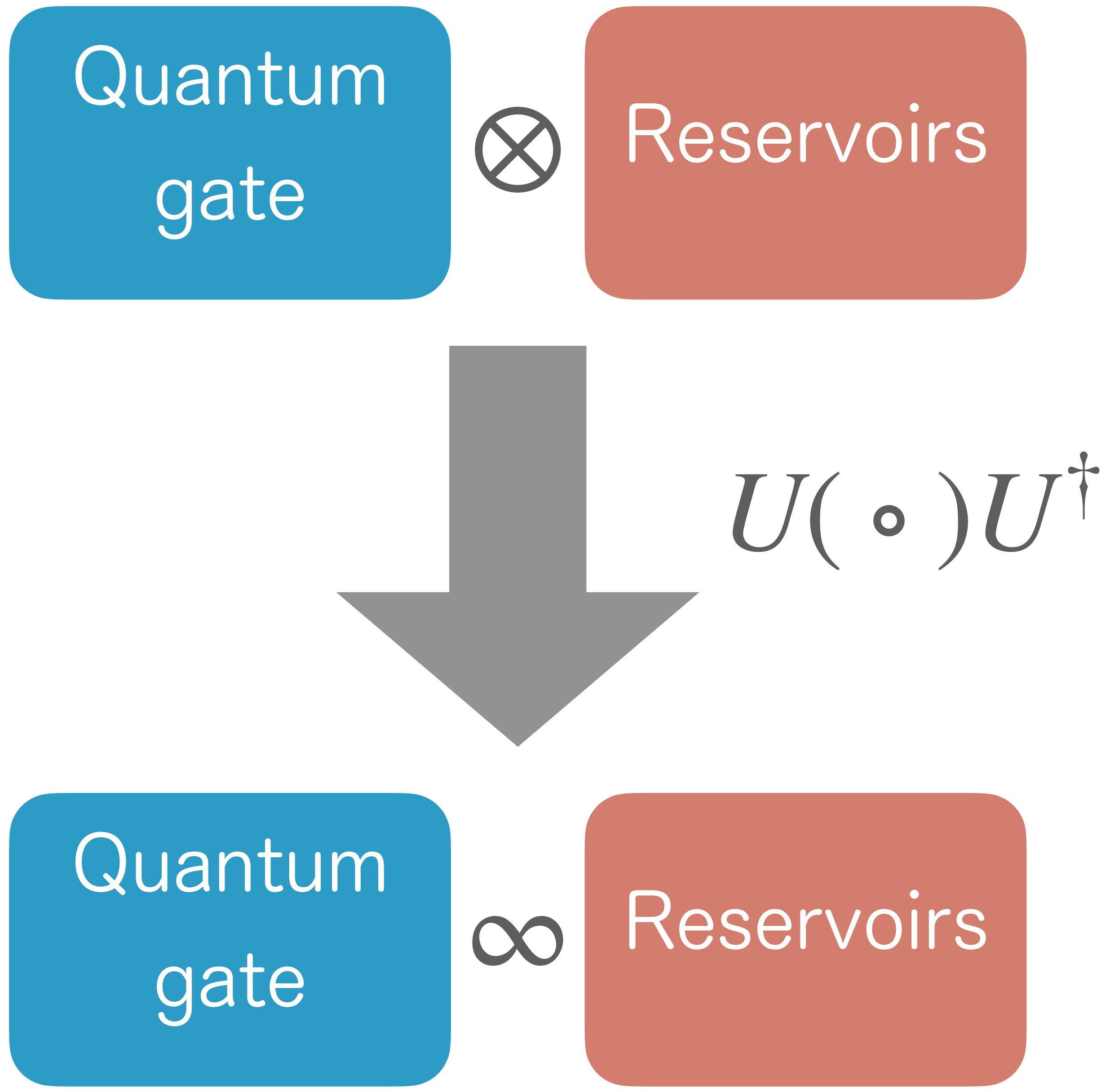

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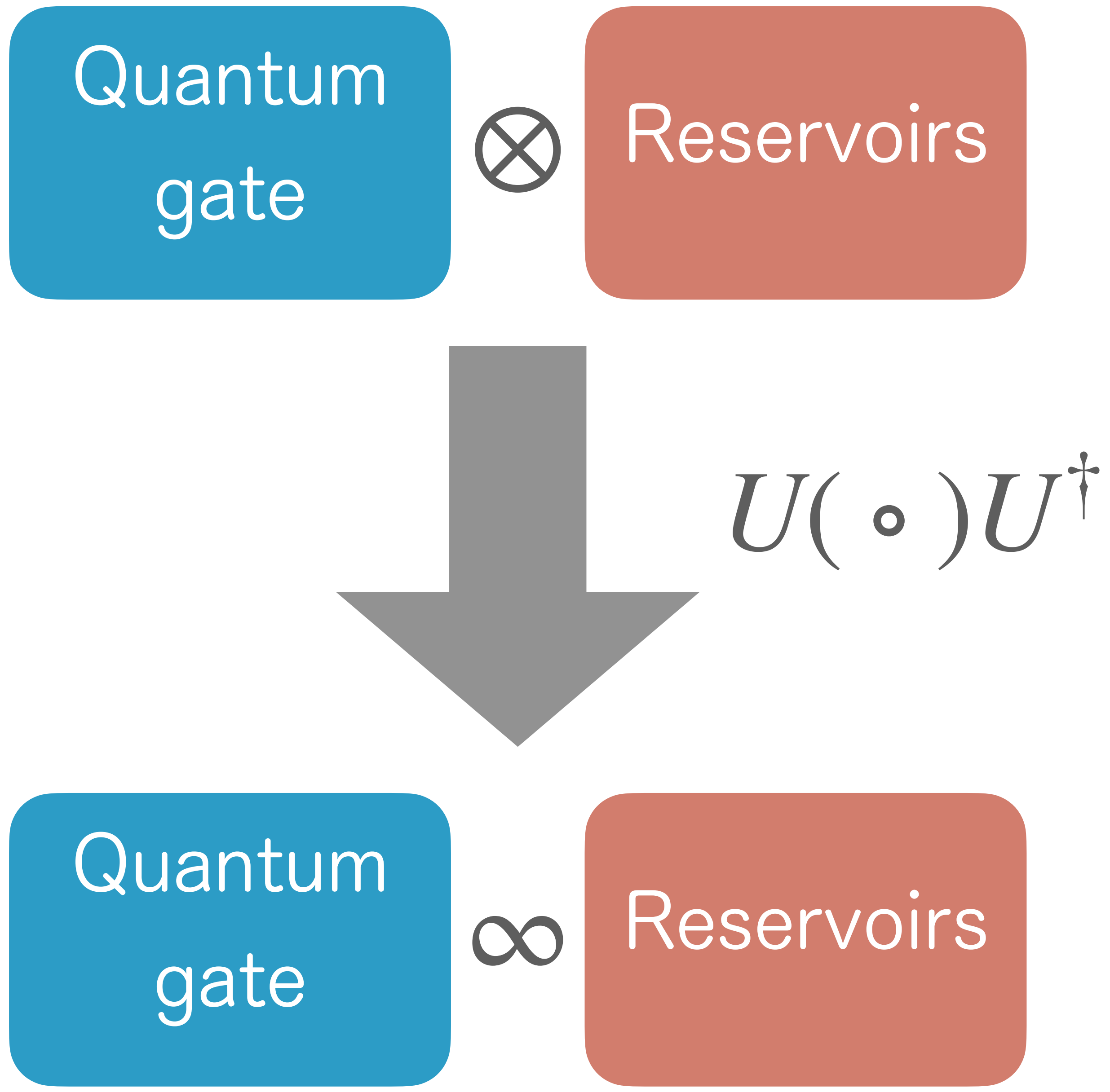
  - U conserves total energy → $\mathscr{Q}$ equals heat dissipation to environment



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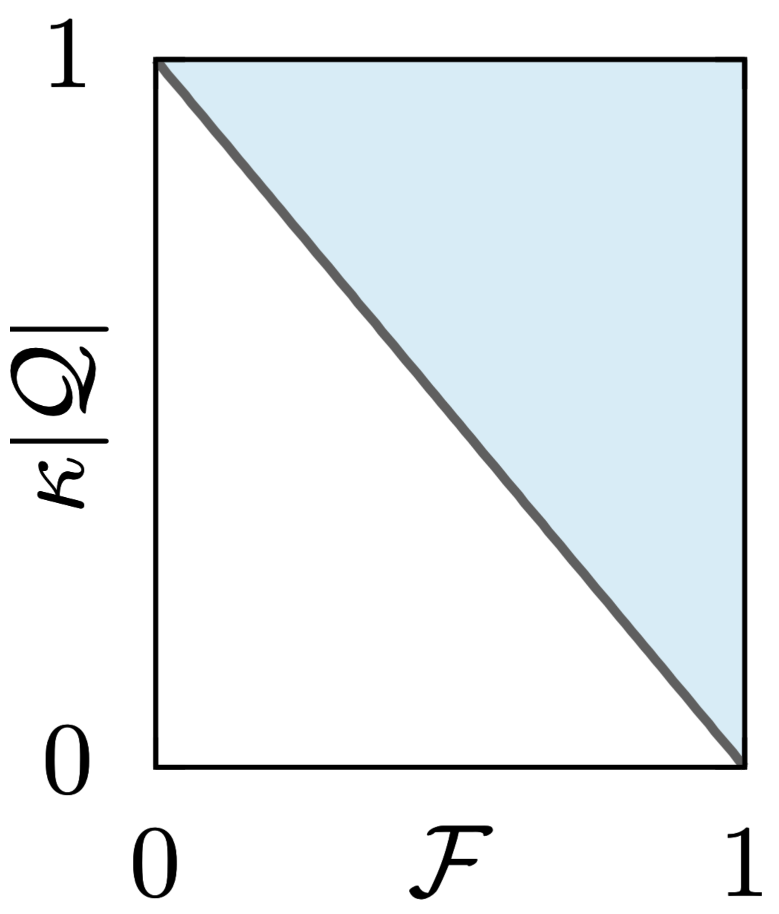

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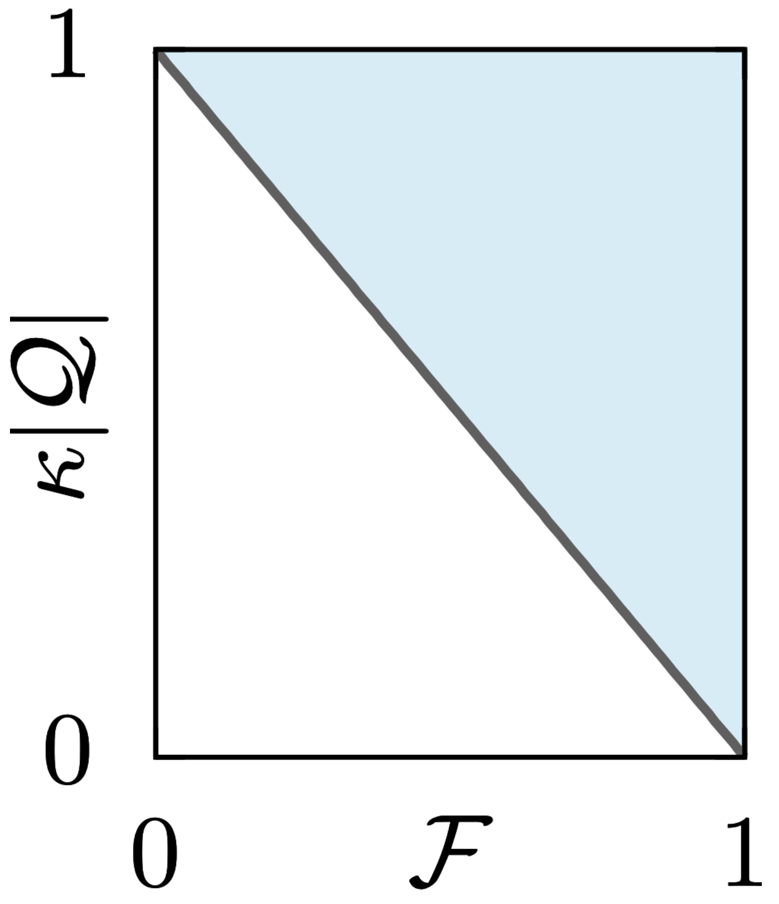

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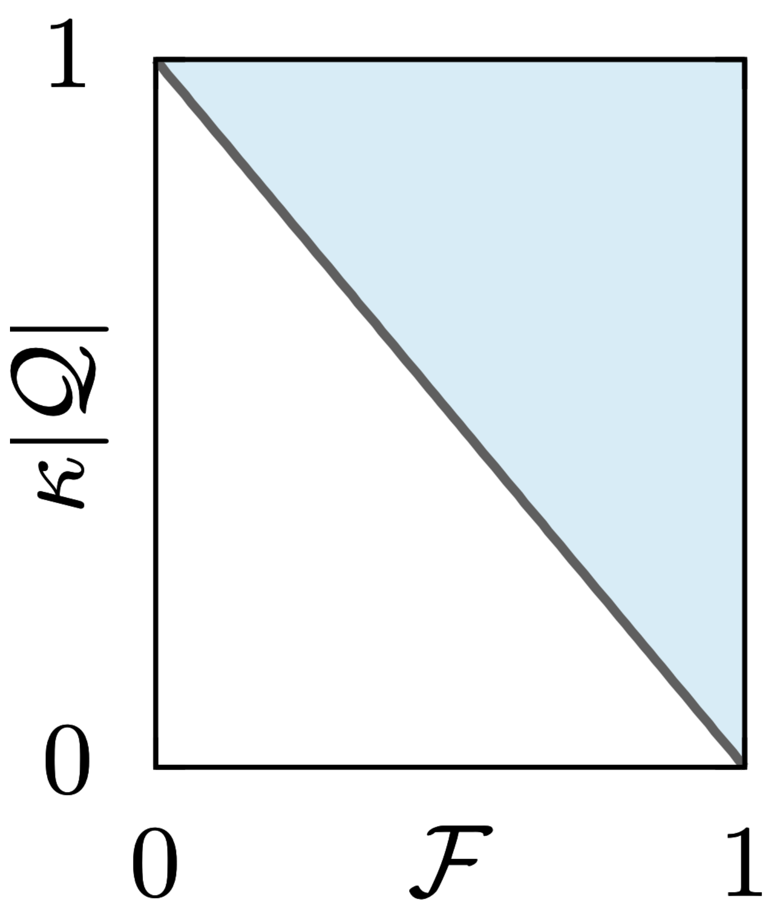

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Demonstration

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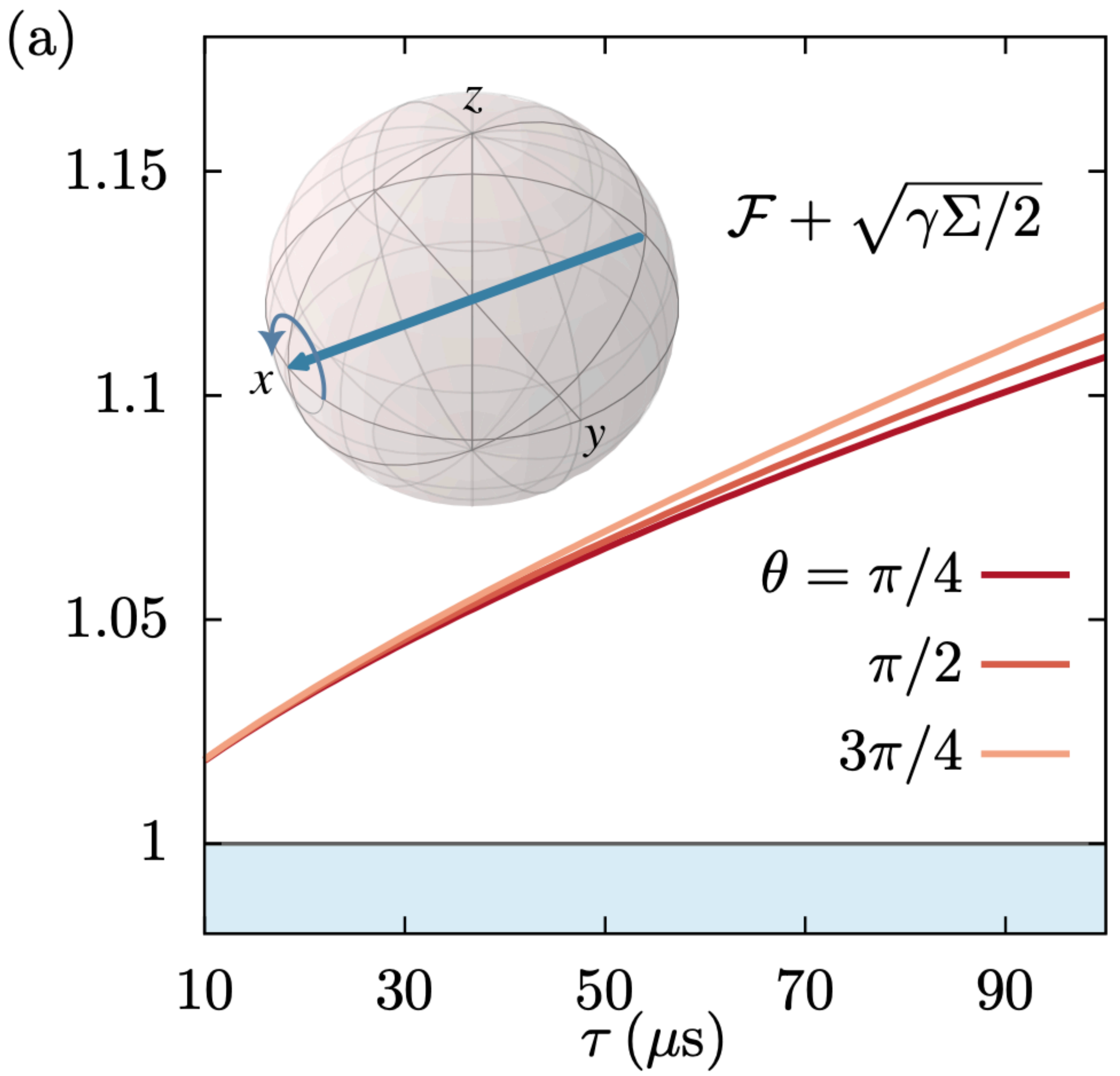
X_θ gate



$$H_t = \omega_t(\sigma_x \cos\phi_t + \sigma_y \sin\phi_t)/2$$

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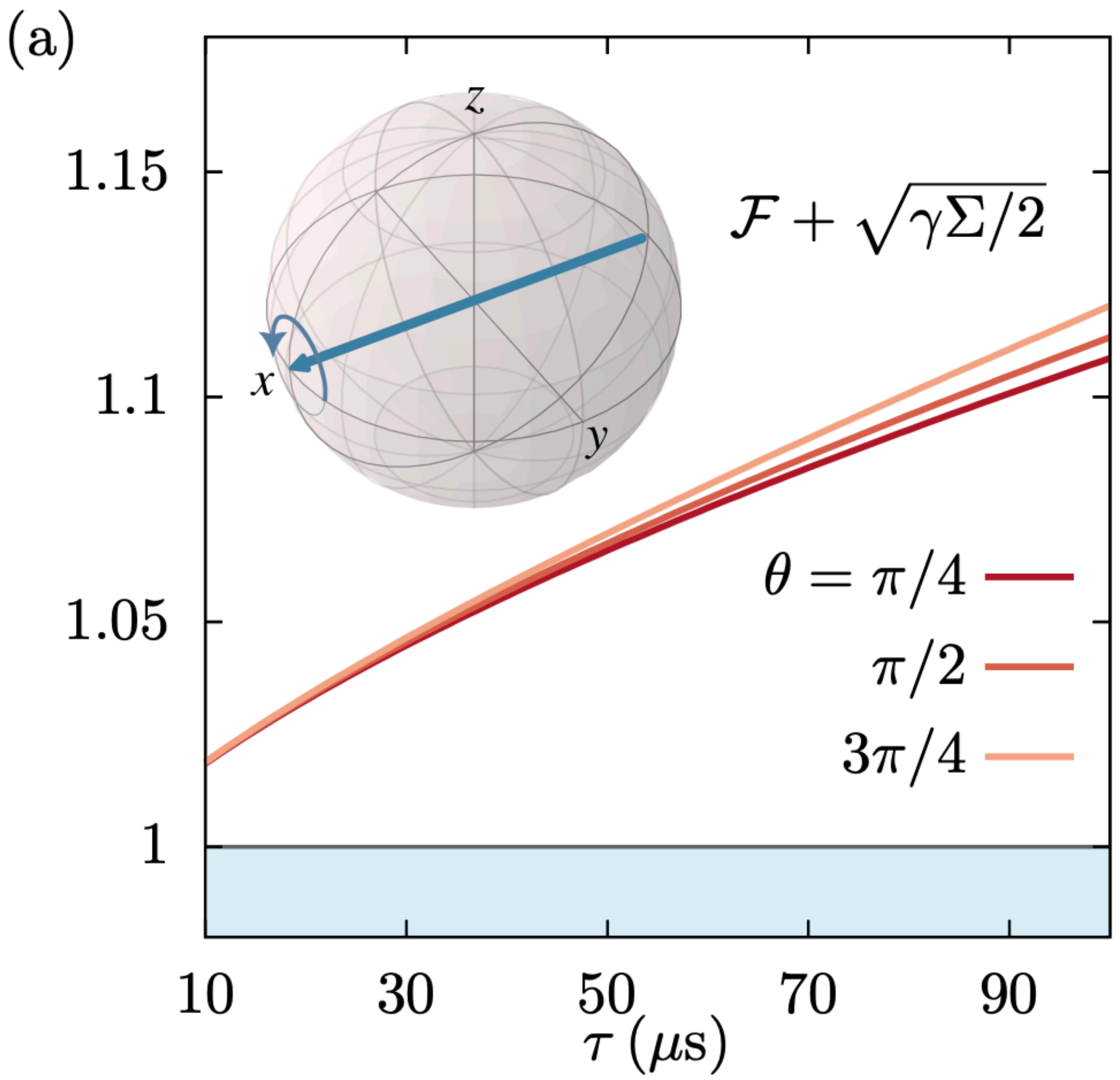

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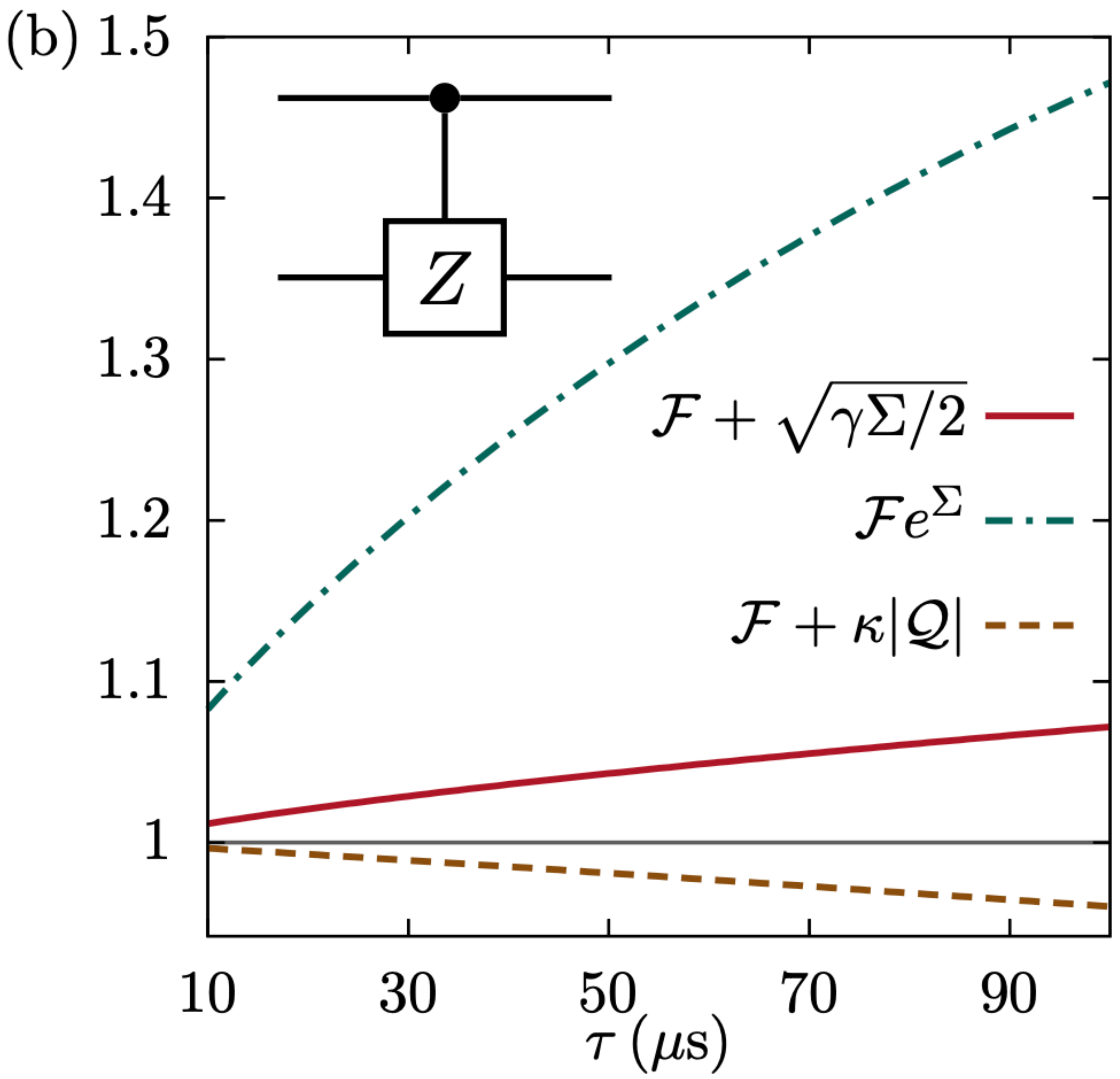
CZ gate



$$H = (\omega/2)(\sigma_z \otimes 1 + 1 \otimes \sigma_z - \sigma_z \otimes \sigma_z)$$

$$L_1 \propto \sigma_- \otimes \sigma_-, \; L_2 \propto \sigma_+ \otimes \sigma_+$$

$$L_3 \propto \sigma_z \otimes 1, \; L_4 \propto 1 \otimes \sigma_z$$

Summary

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✓ Role of thermodynamics in dissipative quantum computation Verstraete+, Nat. Phys. (2009)
✓ Thermodynamics of quantum error correction

Landi+, PRA (2020)
Danageozian+, PRX Quantum (2022)

Thank you for your attention!