Designing High-Fidelity Gates for Dissipative Cat Qubits

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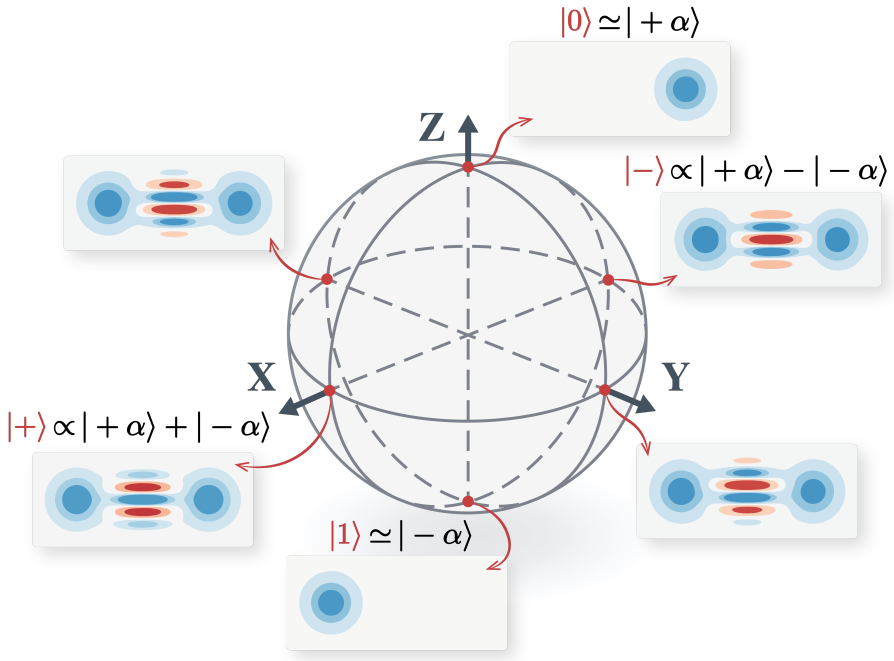
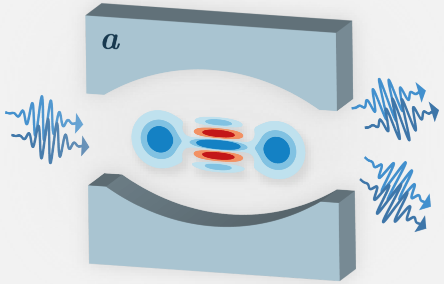
Dissipative Stabilization of Cat Qubits

Cat qubits can be stabilized with two-photon dissipation, often mediated by an **ancillary buffer mode**



Bloch Sphere Representation of a Cat Qubit

$$\frac{\mathrm{d}\boldsymbol{\rho}}{\mathrm{d}t} = \kappa_2 \mathcal{D}[\boldsymbol{a}^2 - \alpha^2]\boldsymbol{\rho}$$



Cochrane *et al.*, PRA (1999); Leghtas *et al.*, PRA (2013); Mirrahimi *et al.*, NJP (2014); Lescanne, Leghtas et al., Nat.Phy. (2019)

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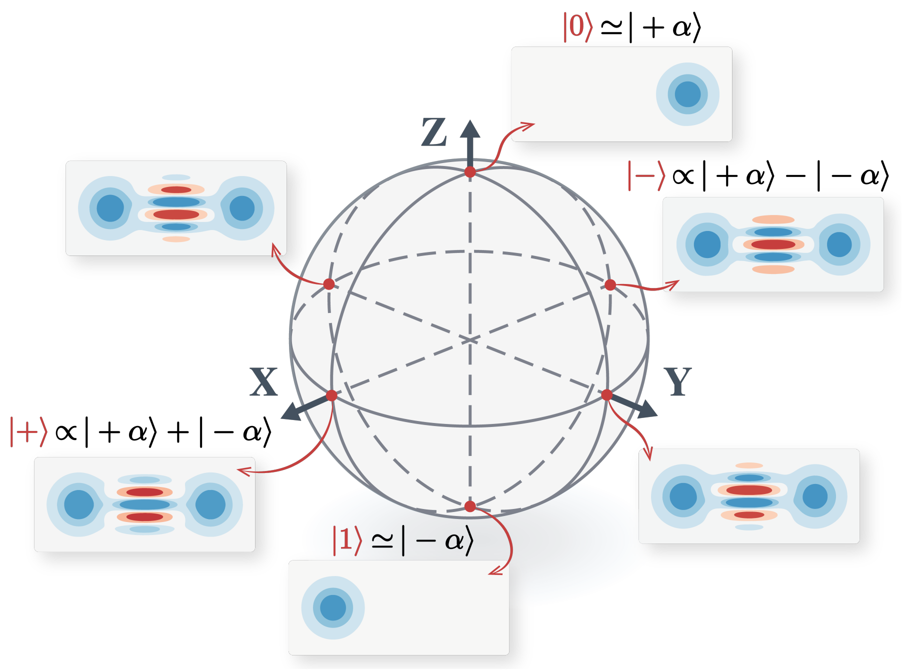

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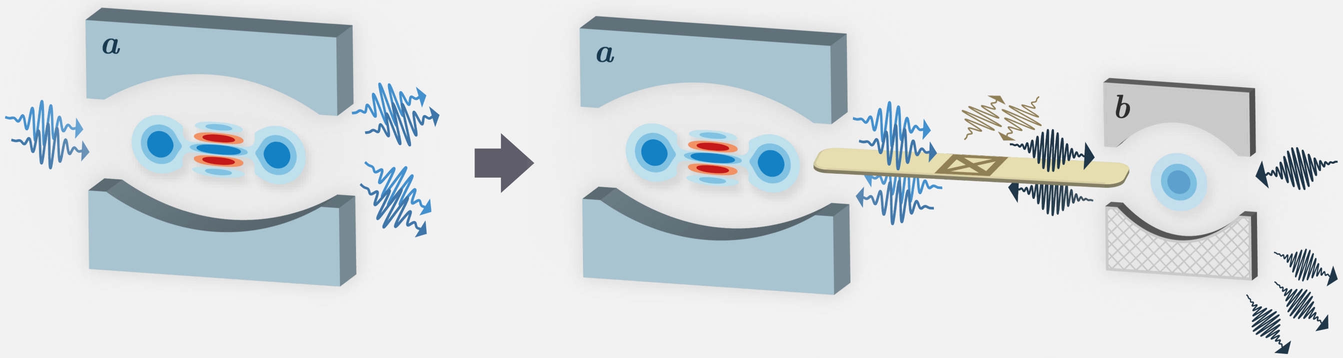
with $\boldsymbol{H}_{AB} = g_2(\boldsymbol{a}^2 - \alpha^2)\boldsymbol{b}^\dagger + \text{h.c.}$



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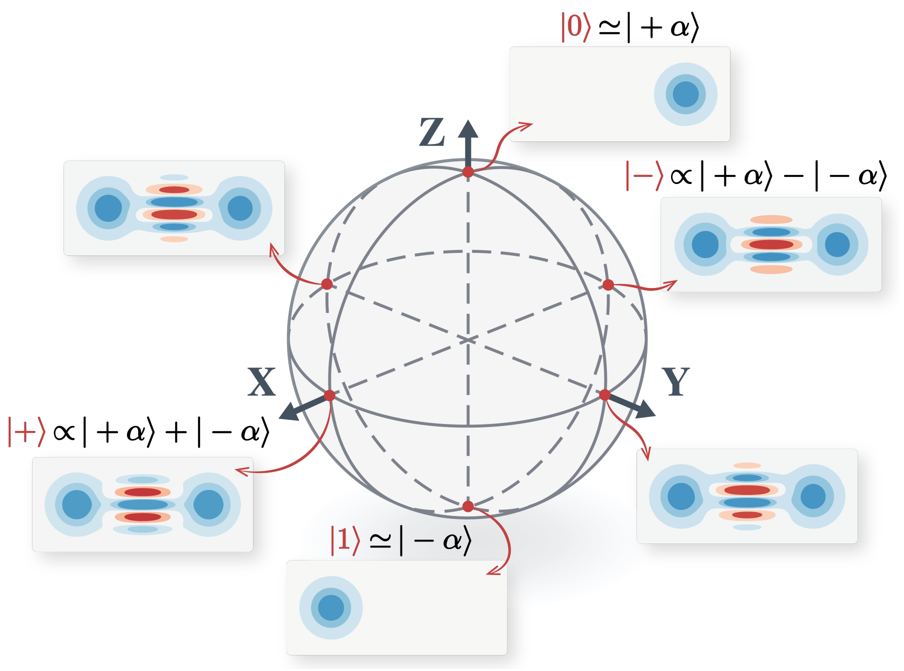

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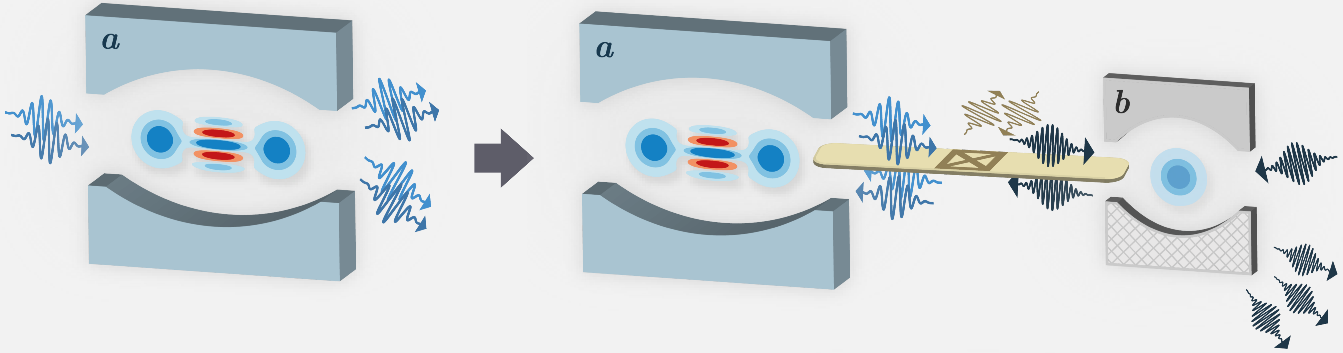

- Adiabatic elimination $\kappa_2 \equiv \dfrac{4g_2^2}{\kappa_b}$

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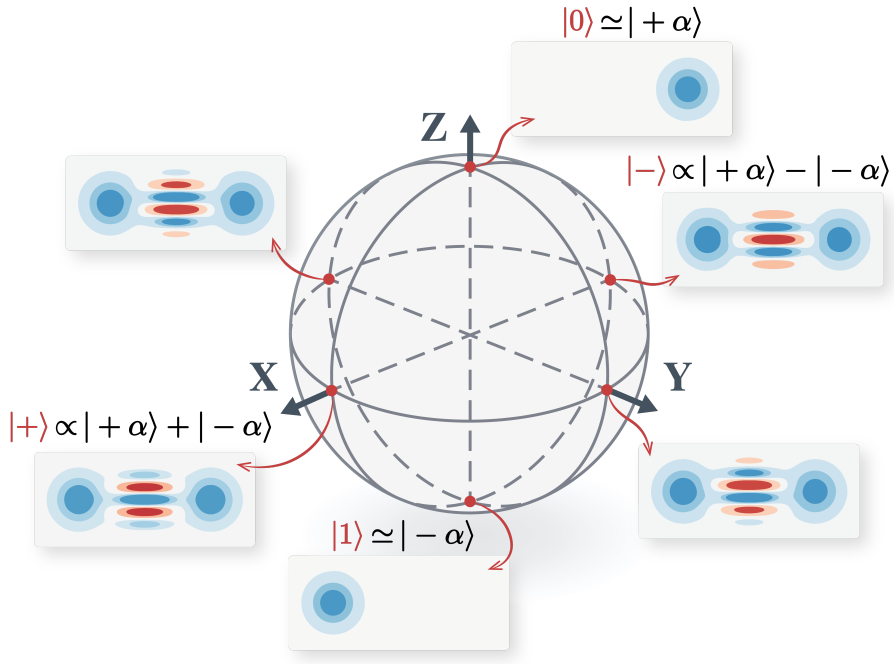

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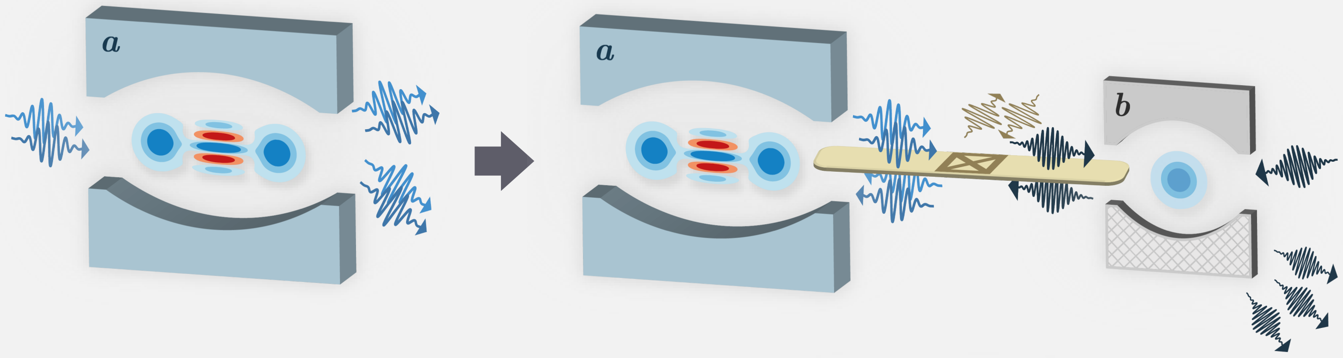
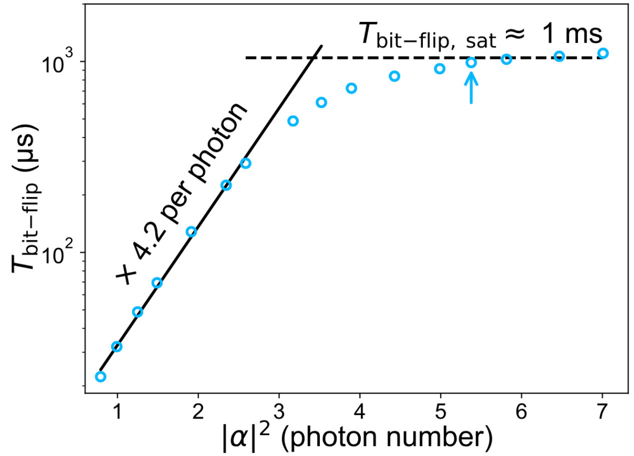


- Adiabatic elimination $\kappa_2 \equiv \frac{4g_2^2}{\kappa_b}$
- Exponentially noise-biased towards phase-flips



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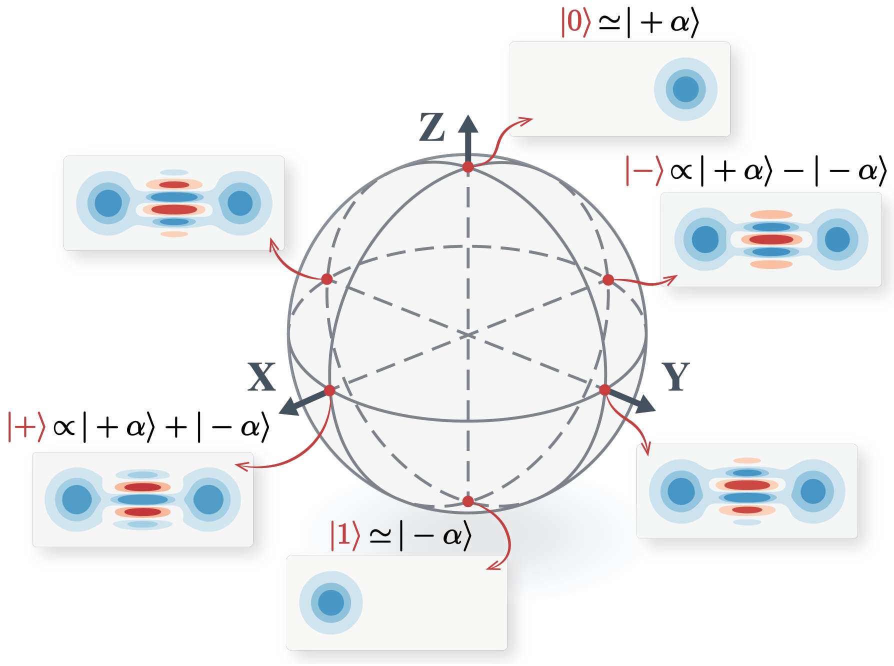

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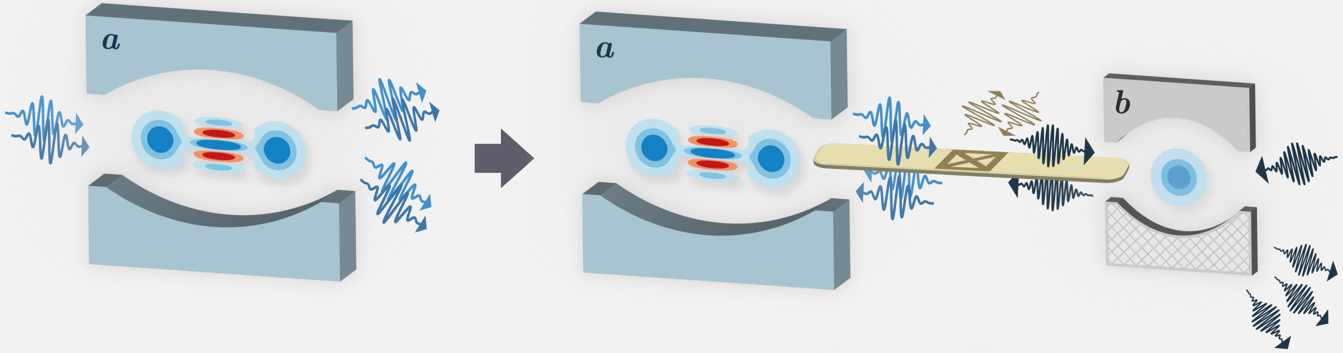

- Adiabatic elimination $\kappa_2 \equiv \frac{4g_2^2}{\kappa_b}$
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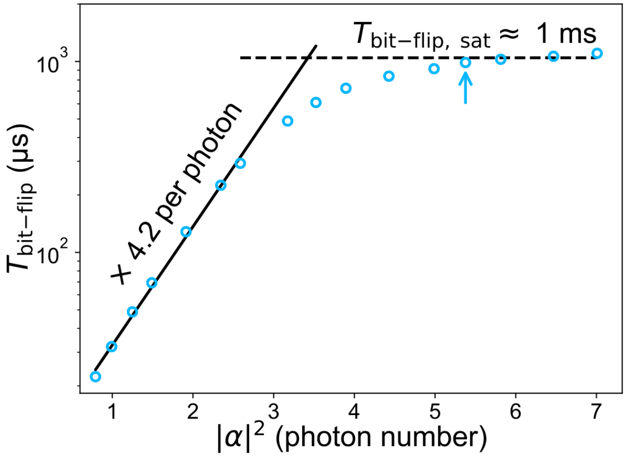
- The buffer mode provides **inertia** in the system



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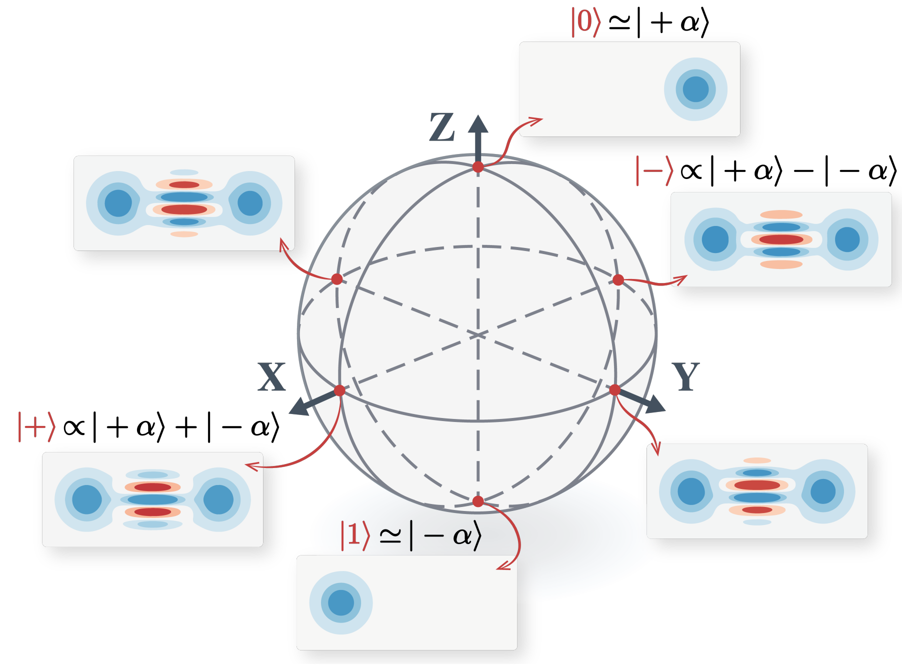

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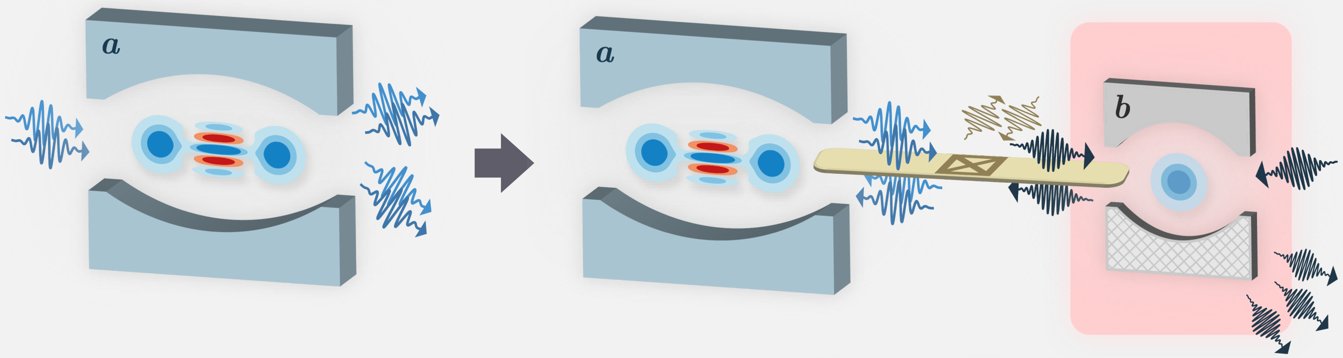

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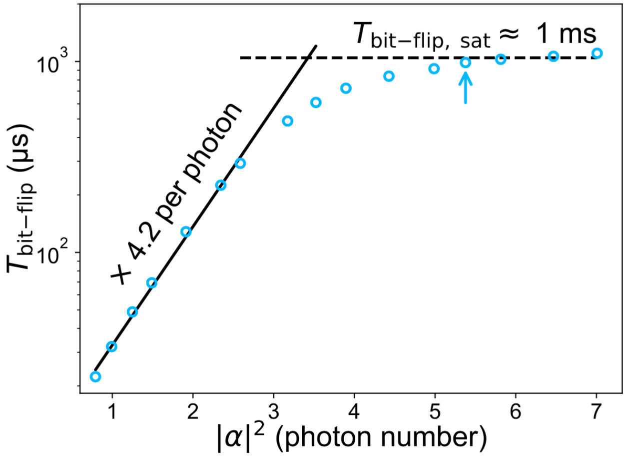
➡ **Gate engineering**



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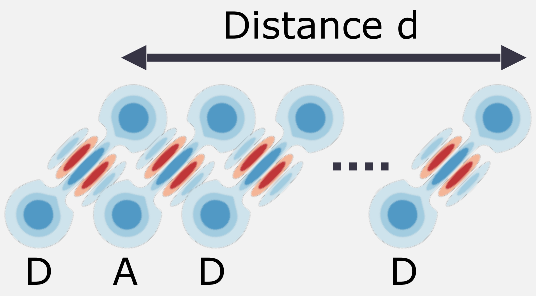
Repetition Cat Qubits

For fault-tolerant universal QC with repetition cat qubits, only four gates are required on top of preparation and measurement in $|\pm_L\rangle$



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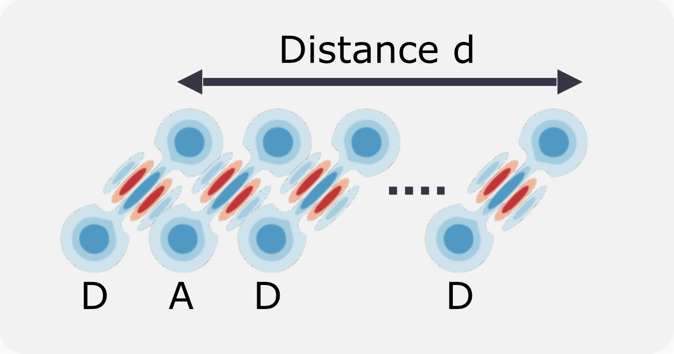

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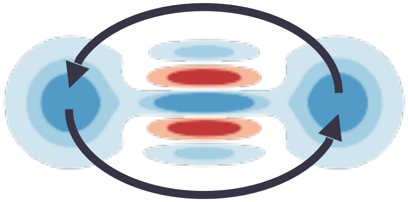
Pauli X



$$H = \Delta_X a^\dagger a$$

(~ error-less)

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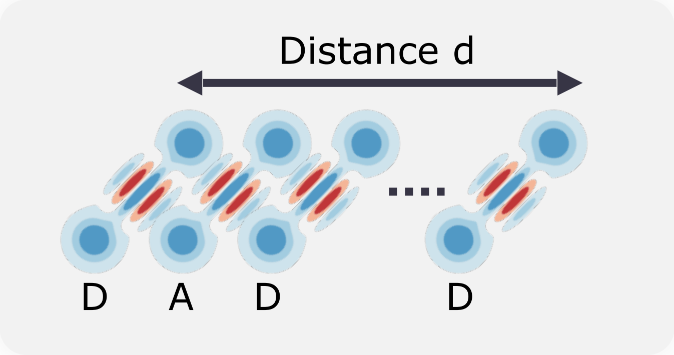

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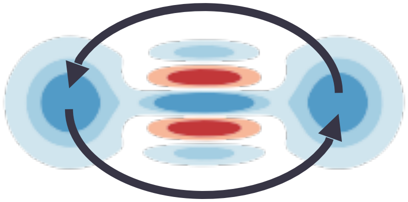

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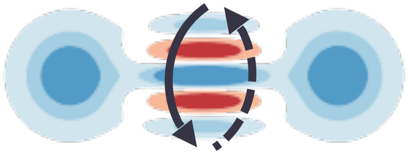
Z(θ) gate



$$H = \varepsilon_Z a^\dagger + \varepsilon_Z^* a$$

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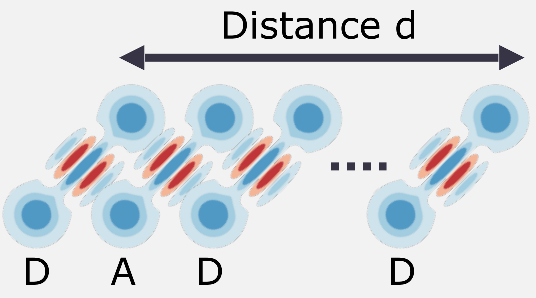

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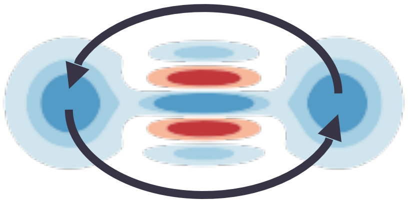

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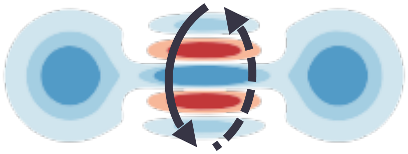

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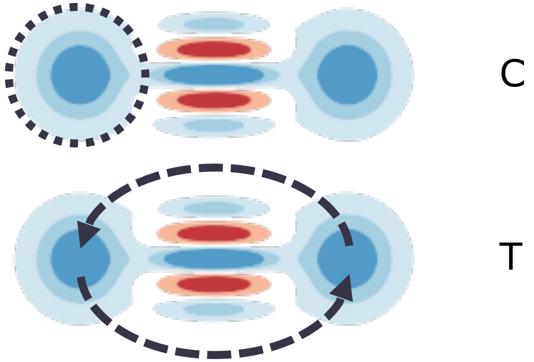
CNOT



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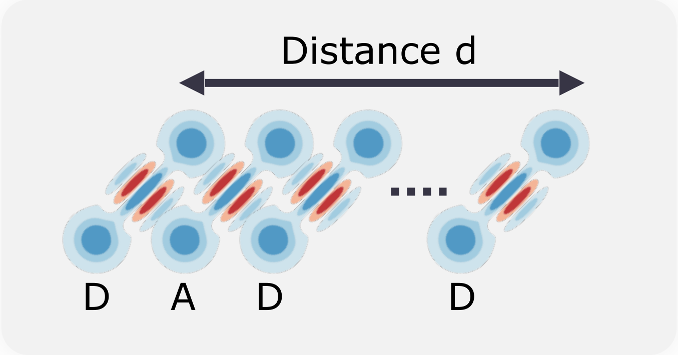

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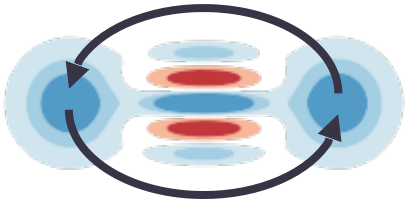

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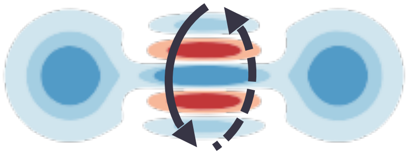

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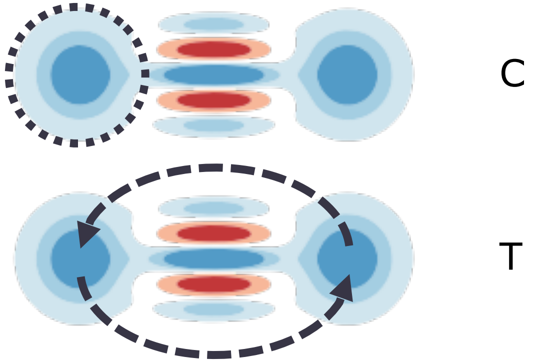

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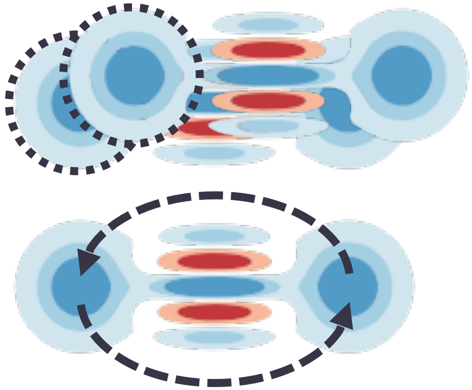
Toffoli



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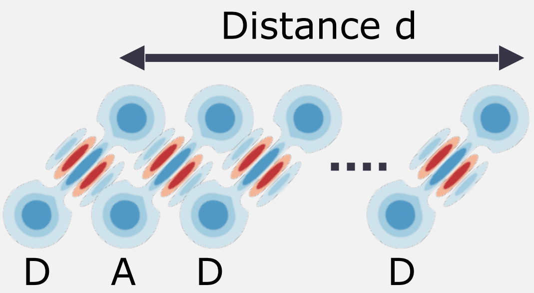

Pauli X

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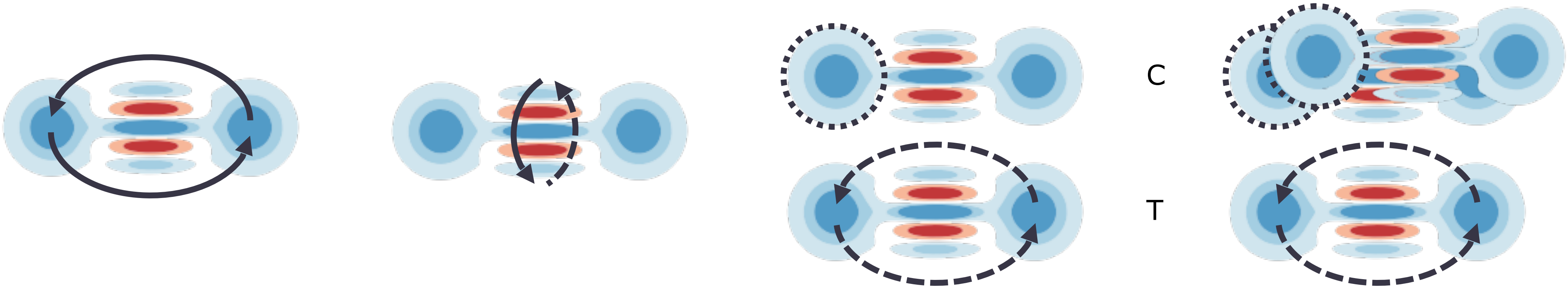

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➡ Gate-induced errors are only on **control** qubits

$$p_Z = \underbrace{\frac{\pi^2}{16|\alpha|^4 \kappa_2 T}}_{\text{Gate errors}} + \underbrace{\kappa_1 |\alpha|^2 T}_{\text{Cavity lifetime}}$$

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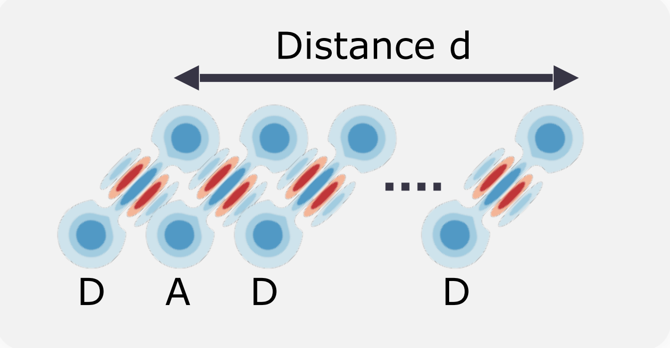

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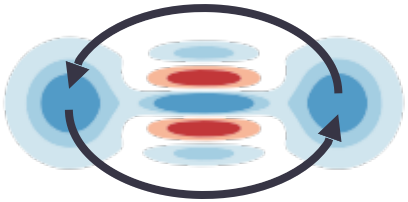

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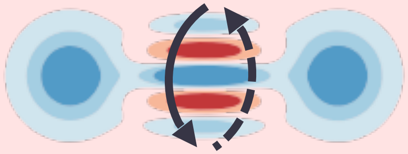

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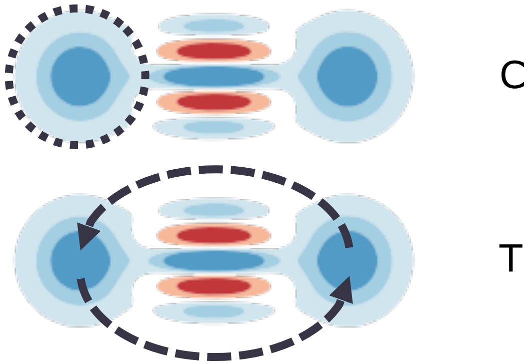

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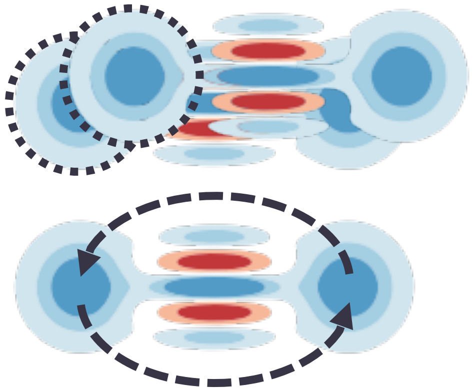

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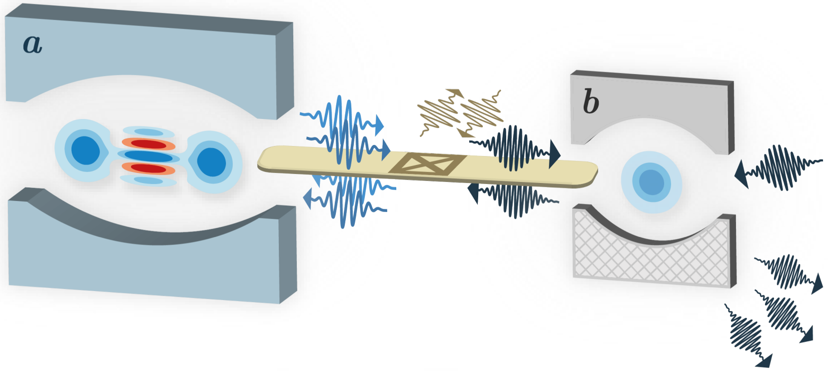
Gate errors Cavity lifetime

Guillaud *et al.*, PRX (2019); Chamberland *et al.*, PRX Q (2021)

On the Origin of Gate Errors



Consider the Z gate Hamiltonian with a buffer mode,

$$\boldsymbol{H} = g_2(\boldsymbol{a}^2 - \alpha^2)\boldsymbol{b}^\dagger + \varepsilon_Z \boldsymbol{a} + \mathrm{h.c.}$$

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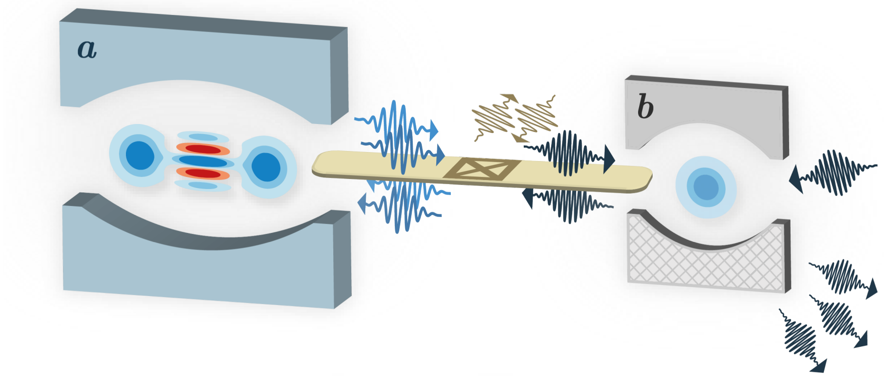

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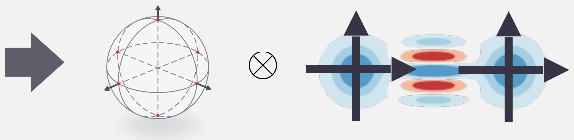
Introduce the Shifted Fock Basis

$$\boldsymbol{a} \rightarrow \underbrace{\boldsymbol{\sigma}_z}_{\text{qubit}} \otimes \underbrace{(\tilde{\boldsymbol{a}} + \alpha)}_{\text{gauge}}$$



$$\boldsymbol{H} = g_2(\tilde{\boldsymbol{a}}^2 + 2\alpha\tilde{\boldsymbol{a}})\boldsymbol{b}^\dagger + \varepsilon_Z \boldsymbol{\sigma}_z(\tilde{\boldsymbol{a}} + \alpha) + \mathrm{h.c.}$$

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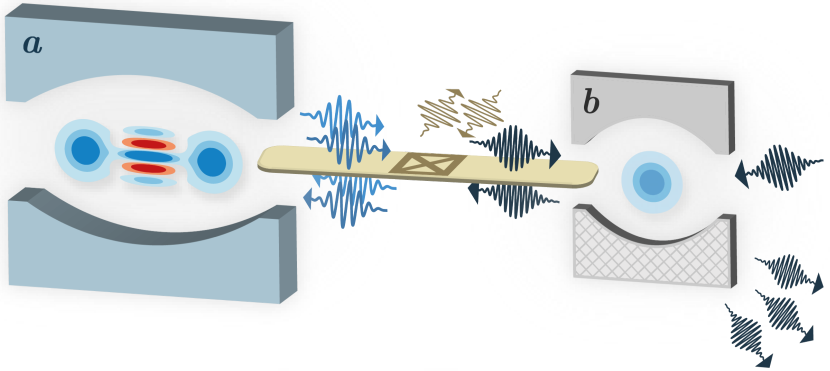

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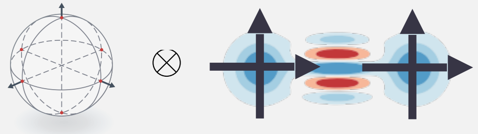
Introduce the Shifted Fock Basis

$$\boldsymbol{a} \to \underset{\text{qubit}}{\boldsymbol{\sigma}_z} \otimes \underset{\text{gauge}}{(\tilde{\boldsymbol{a}} + \alpha)}$$



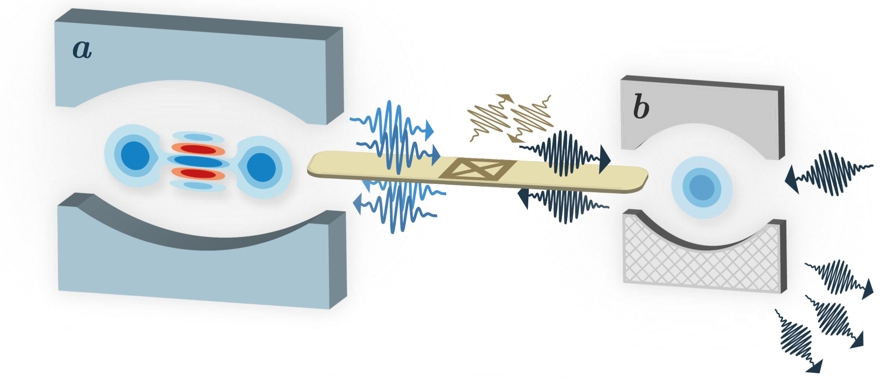
$$\boldsymbol{H} = g_2(\tilde{\boldsymbol{a}}^2 + 2\alpha\tilde{\boldsymbol{a}})\boldsymbol{b}^\dagger + \varepsilon_Z \boldsymbol{\sigma}_z(\tilde{\boldsymbol{a}} + \alpha) + \text{h.c.}$$

Write master equation in Heisenberg picture

$$\dot{\tilde{\boldsymbol{a}}} = -2i\alpha g_2 \boldsymbol{b} - i\varepsilon_Z \boldsymbol{\sigma}_z$$
$$\dot{\boldsymbol{b}} = -2i\alpha g_2 \tilde{\boldsymbol{a}} - \kappa_b \boldsymbol{b}/2$$

Gautier *et al.*, arXiv (2023); Chamberland *et al.*, PRX Q (2021)

On the Origin of Gate Errors



Consider the Z gate Hamiltonian with a buffer mode,

$$H = g_2(a^2 - \alpha^2)b^\dagger + \varepsilon_Z a + \text{h.c.}$$

Introduce the Shifted Fock Basis

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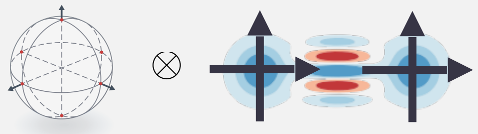

$$H = g_2(\tilde{a}^2 + 2\alpha\tilde{a})b^\dagger + \varepsilon_Z \sigma_z(\tilde{a} + \alpha) + \text{h.c.}$$

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$$\dot{b} = -2i\alpha g_2 \tilde{a} - \kappa_b b/2$$

Decouple these equations

$$\ddot{b} + \kappa\dot{b} + \omega_0^2 b = -\omega_0\varepsilon_Z\sigma_z \quad \Rightarrow \quad b_{eq} = -\varepsilon_Z/\omega_0\sigma_z$$

with $\kappa = \kappa_b/2$ and $\omega_0 = 2\alpha g_2$

Gautier *et al.*, arXiv (2023); Chamberland *et al.*, PRX Q (2021)

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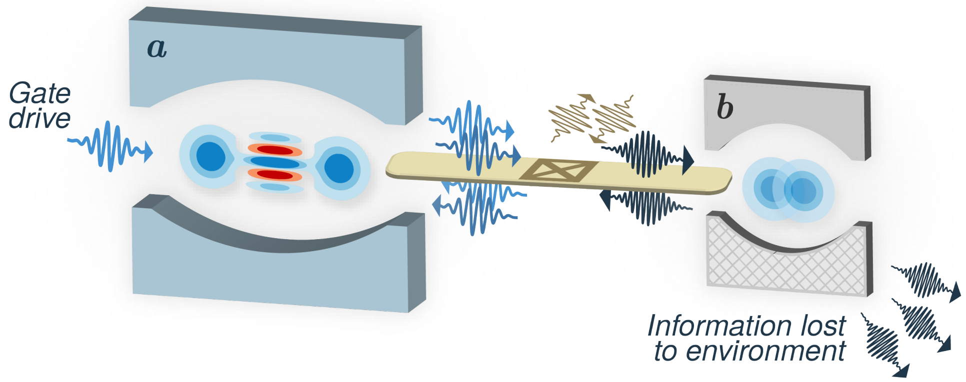

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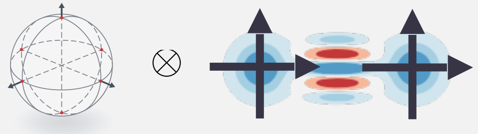
qubit gauge



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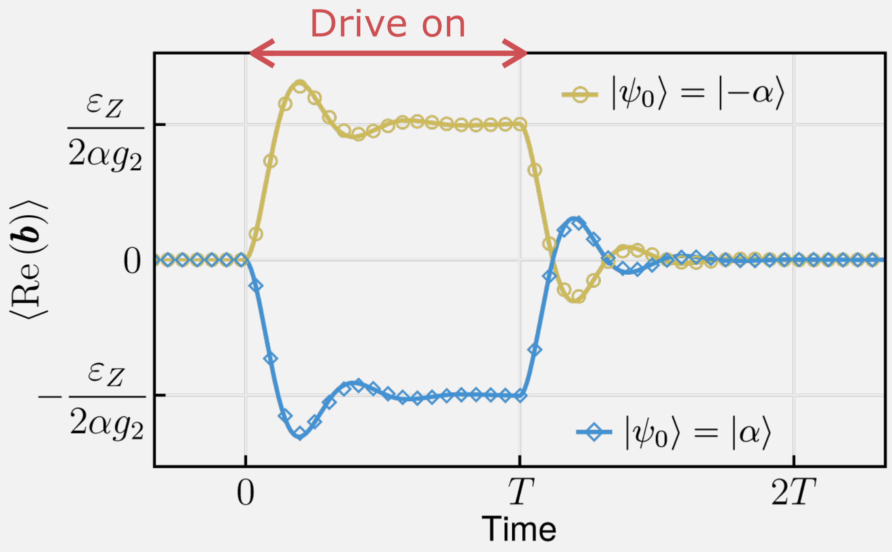
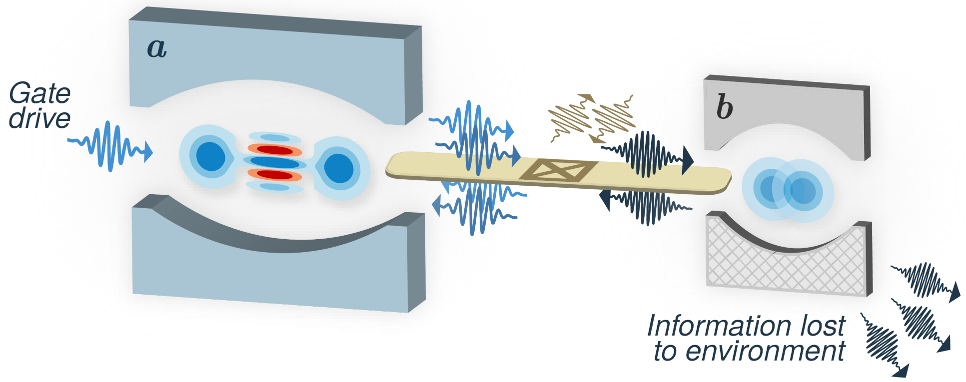


Gautier *et al.*, arXiv (2023); Chamberland *et al.*, PRX Q (2021)

On the Origin of Gate Errors



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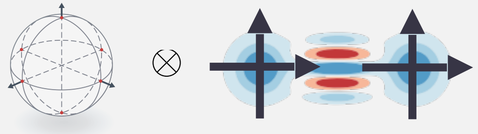

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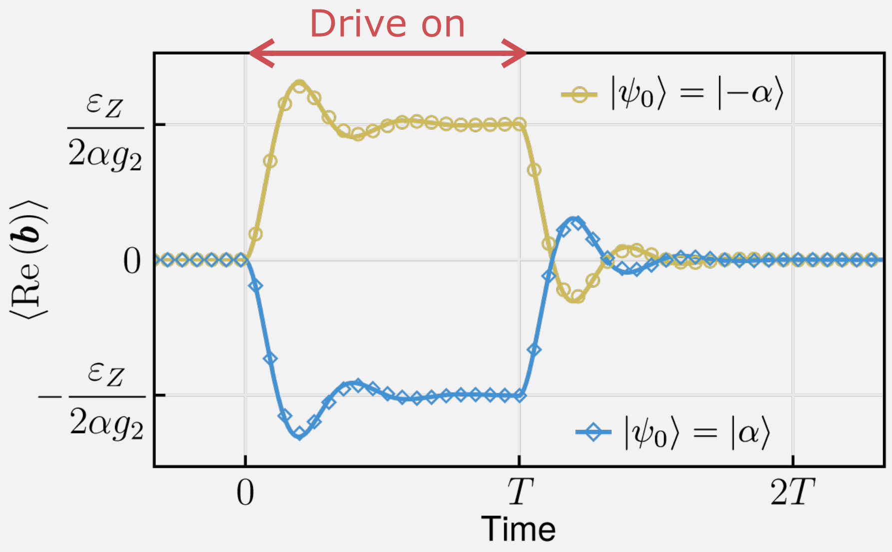
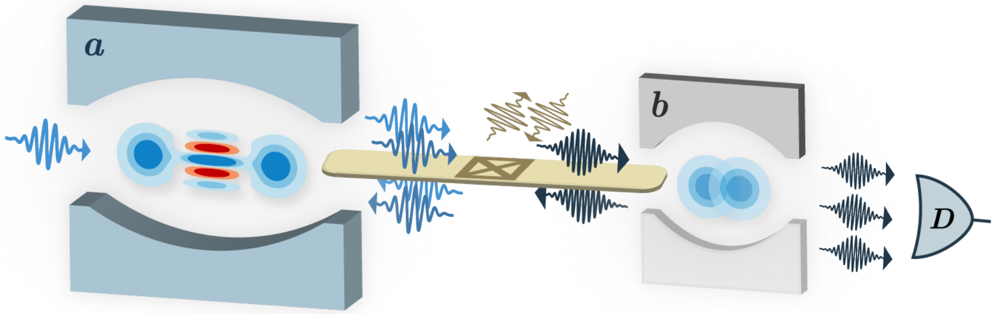


Can re-derive Zeno gate errors

$$\mathcal{D}[\boldsymbol{b}] \approx \mathcal{D}[\boldsymbol{b}_{\text{eq}}] = \frac{\varepsilon_Z^2}{\omega_0^2}\mathcal{D}[\boldsymbol{\sigma}_z] \Rightarrow p_Z = \frac{\pi^2}{16|\alpha|^2 T}\frac{\kappa_b}{4g_2^2}$$

Gautier *et al.*, arXiv (2023); Chamberland *et al.*, PRX Q (2021)

Buffer Photodetection – Rabi oscillations



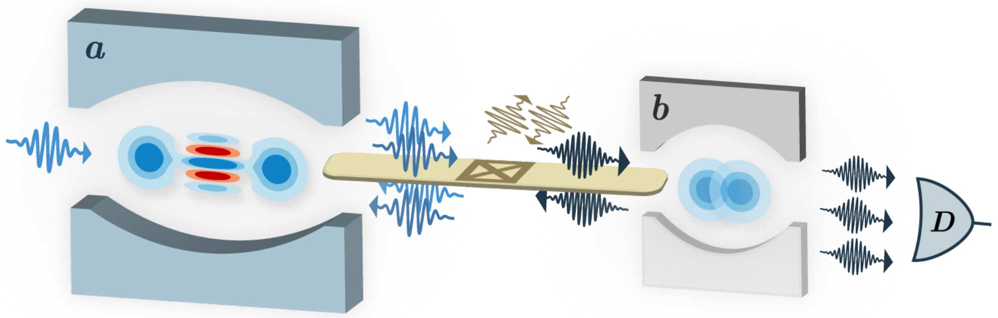
Information is lost through the buffer mode
→ **measure the buffer output** to retrieve it

$$\mathrm{d}\boldsymbol{\rho} = -i[\boldsymbol{H}, \boldsymbol{\rho}]\mathrm{d}t + \kappa_b\big(\underbrace{\mathcal{D}_\eta[\boldsymbol{b}]\boldsymbol{\rho}\,\mathrm{d}t}_{\text{no-jump}} + \underbrace{\mathcal{J}[\boldsymbol{b}]\boldsymbol{\rho}\,\mathrm{d}N_\eta}_{\text{jump}}\big)$$

with $0 \leq \eta \leq 1$ (detection efficiency)

Gautier *et al.*, arXiv (2023)

Buffer Photodetection – Rabi oscillations



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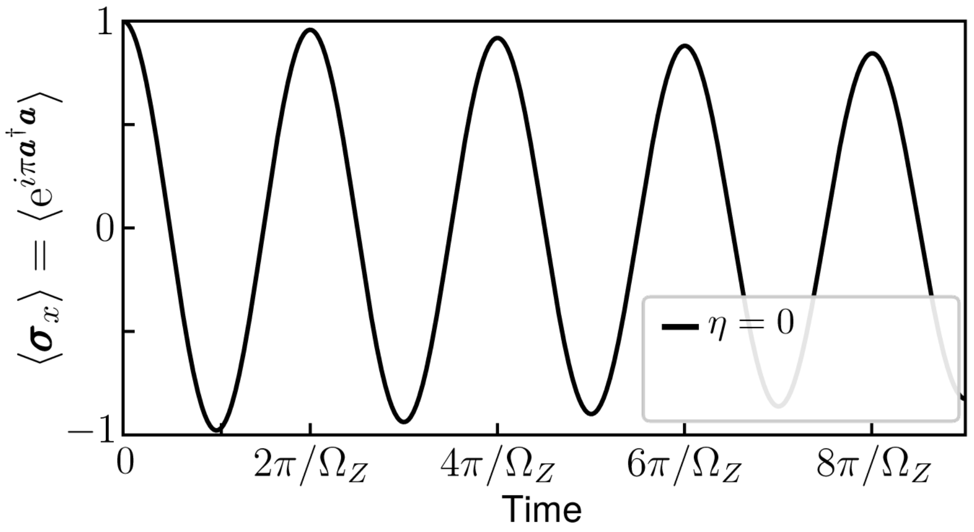

Gautier *et al.*, arXiv (2023)

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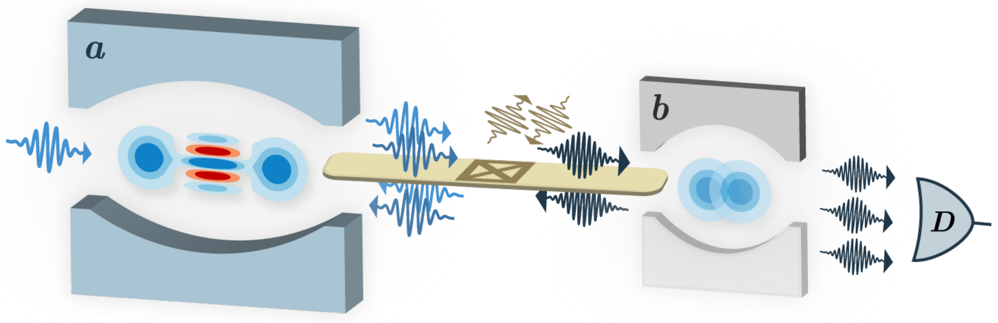

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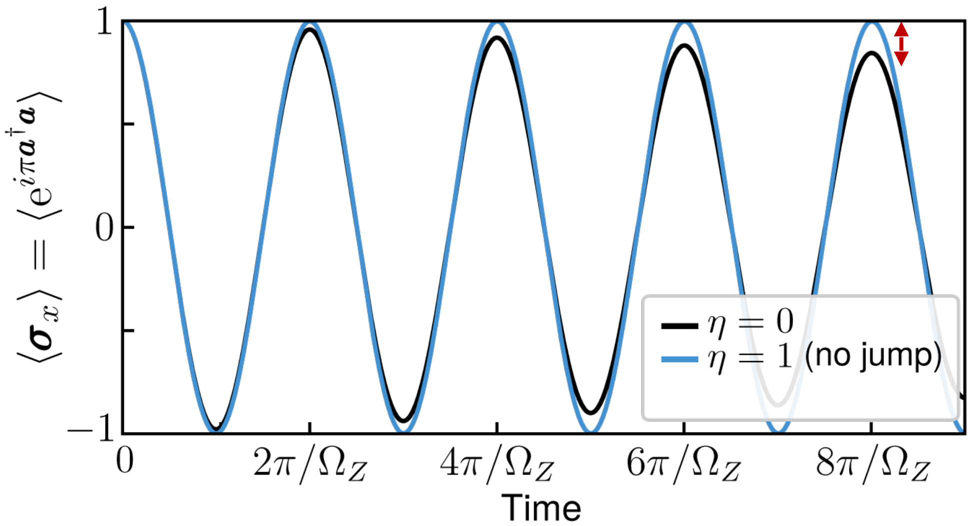


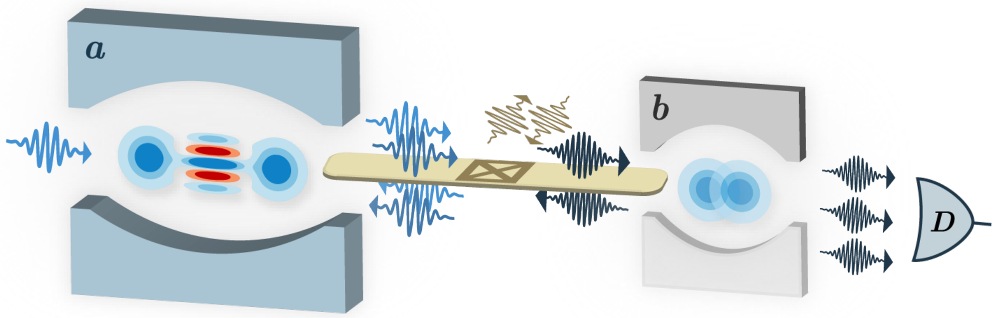
No parity damping

Assuming $\eta = 1$

- Preserves purity (no information lost)

Gautier *et al.*, arXiv (2023)

Buffer Photodetection – Rabi oscillations



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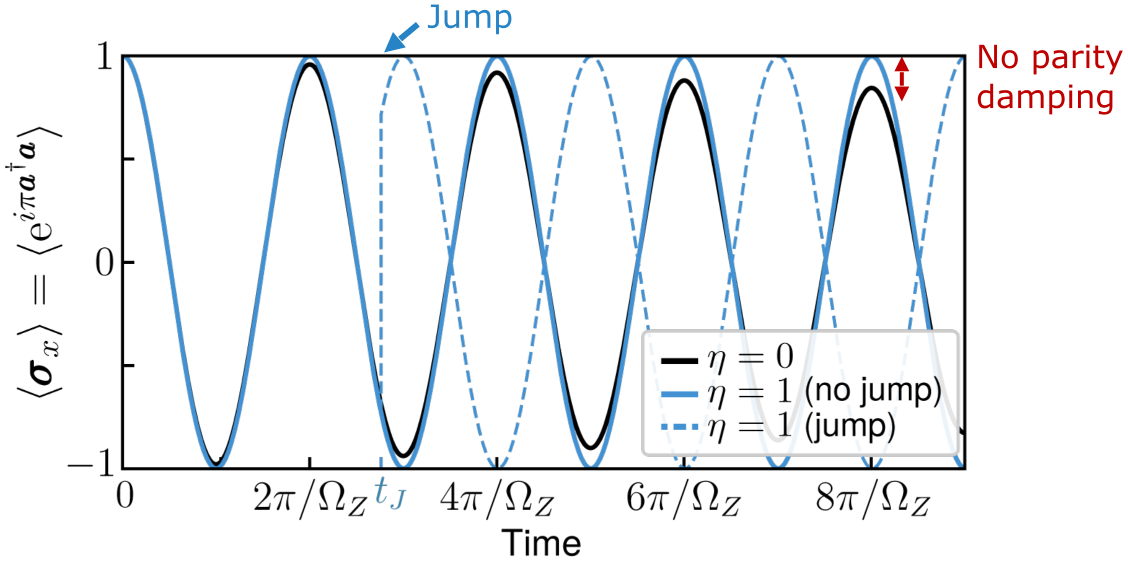
no-jump jump

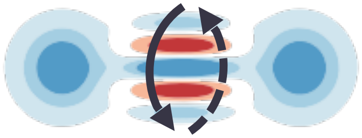
with $0 \leq \eta \leq 1$ (detection efficiency)



Assuming $\eta = 1$

- Preserves purity (no information lost)
- Jump detected = parity swap

➡ $\boldsymbol{b} \propto \boldsymbol{\sigma}_z$



Gautier *et al.*, arXiv (2023)

Buffer Photodetection – Gates and buffer relaxation

Information is lost through the buffer mode

- ➡ measure the buffer output to retrieve it + **classical feedback**

$$\mathrm{d}\boldsymbol{\rho} = -i[\boldsymbol{H},\boldsymbol{\rho}]\mathrm{d}t + \kappa_b\big(\underset{\text{no-jump}}{\mathcal{D}_\eta[\boldsymbol{b}]\boldsymbol{\rho}\,\mathrm{d}t} + \underset{\text{jump}}{\mathcal{J}[\boldsymbol{b}]\boldsymbol{\rho}\,\mathrm{d}N_\eta}\big)$$

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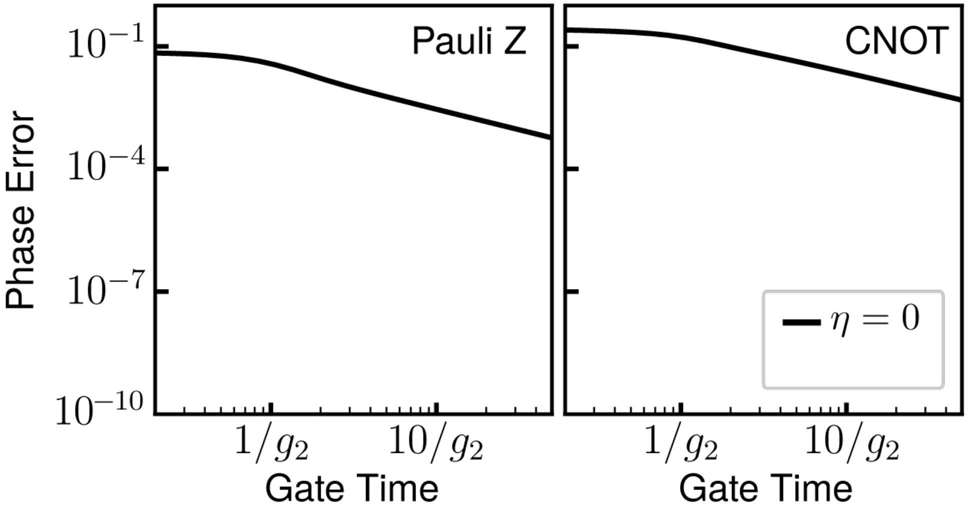

➡ Zeno scaling in 1/T

Gautier *et al.*, arXiv (2023)

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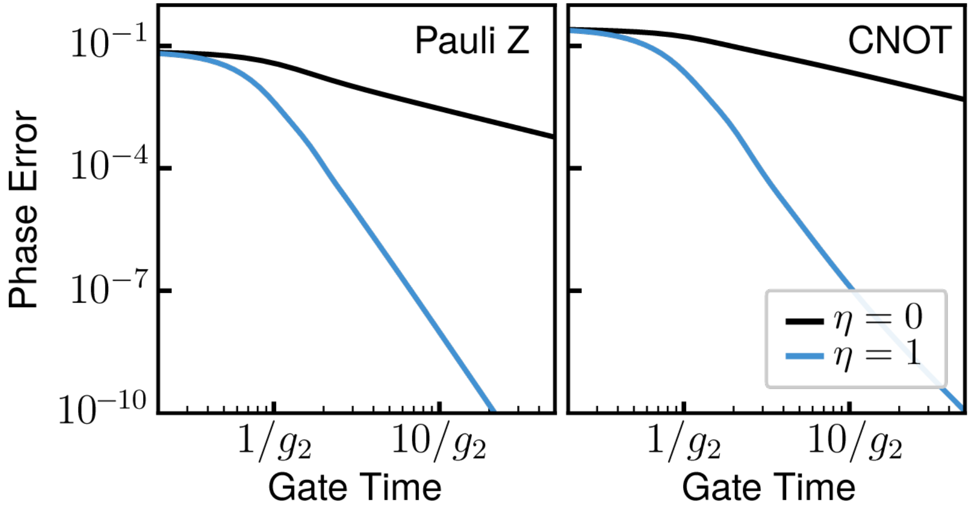

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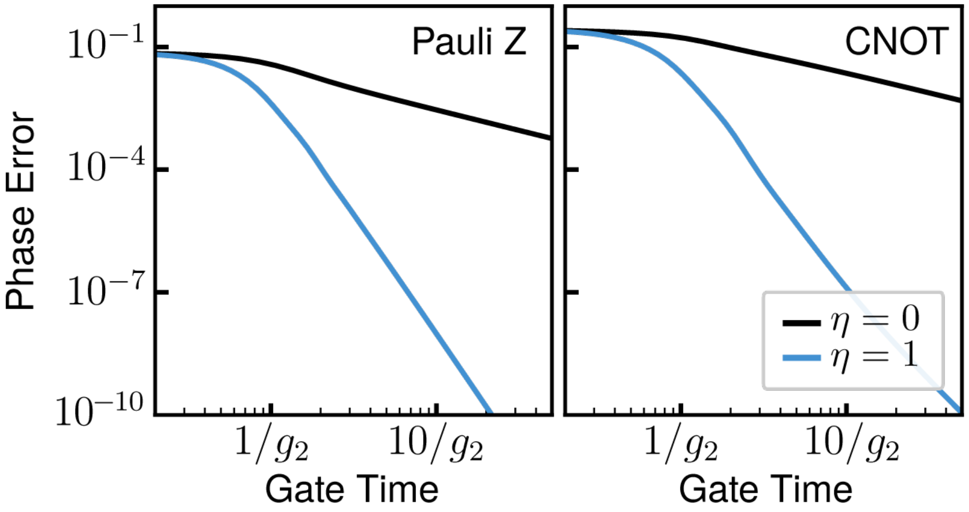

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- Detection of buffer photons ➡ Erasure errors or classical feedback

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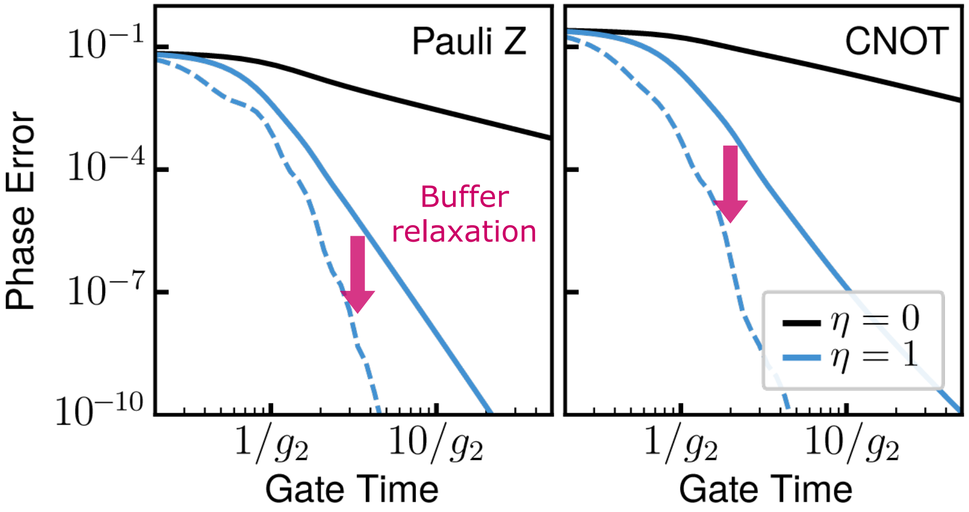

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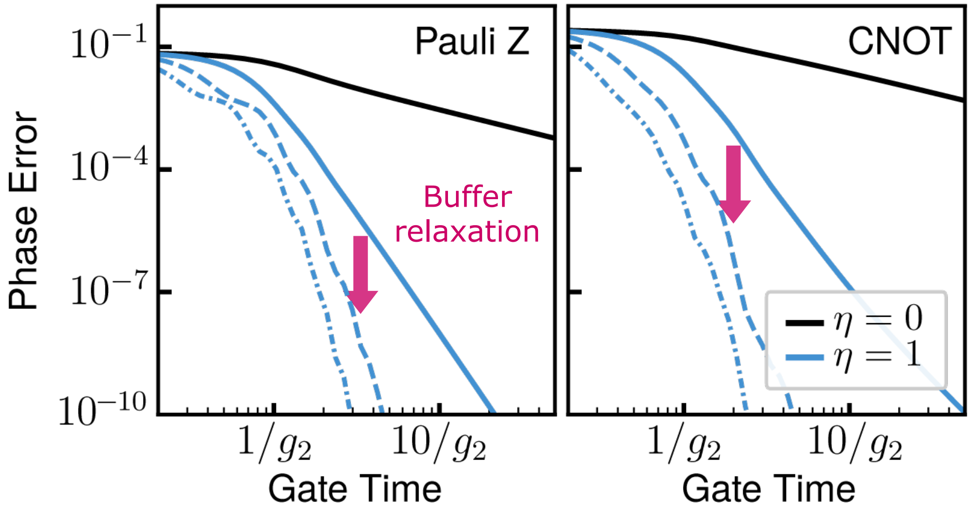

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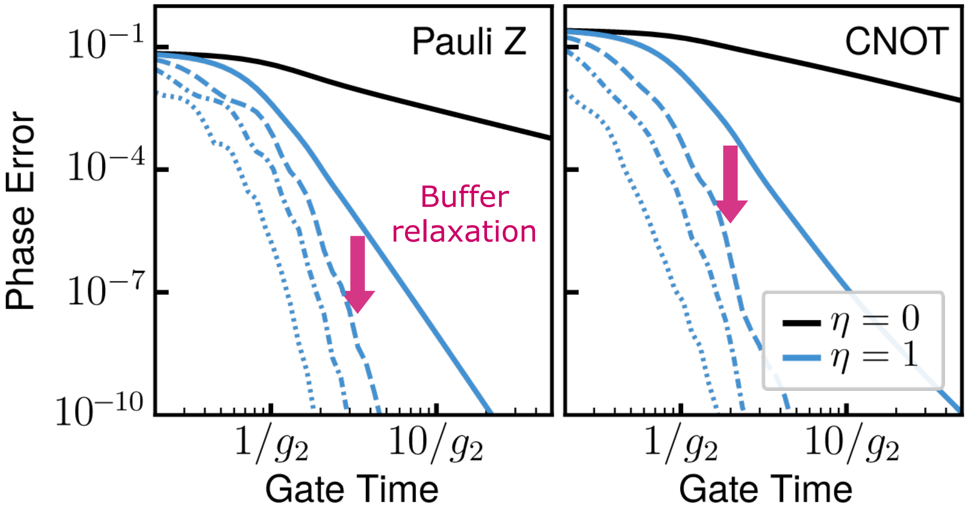

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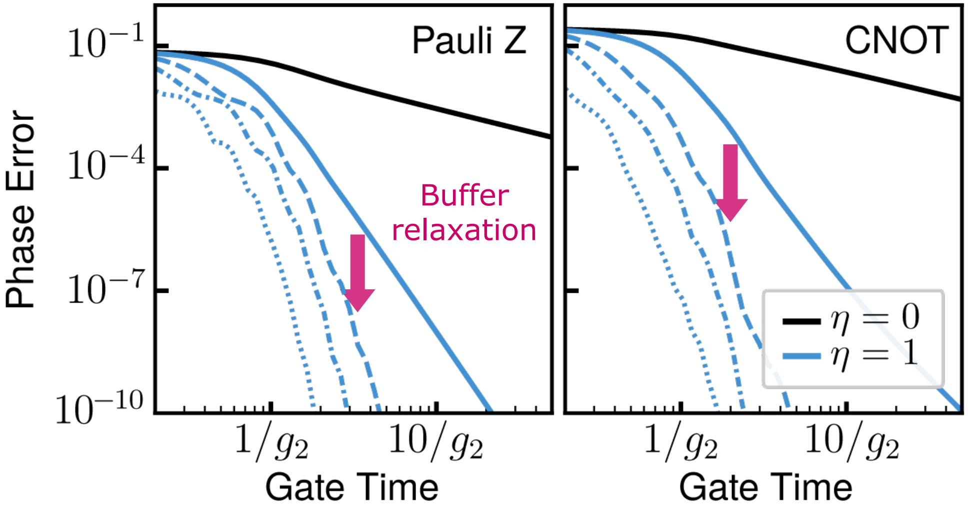

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- Can apply N gates with a single relaxation per QEC cycle

Gautier *et al.*, arXiv (2023)

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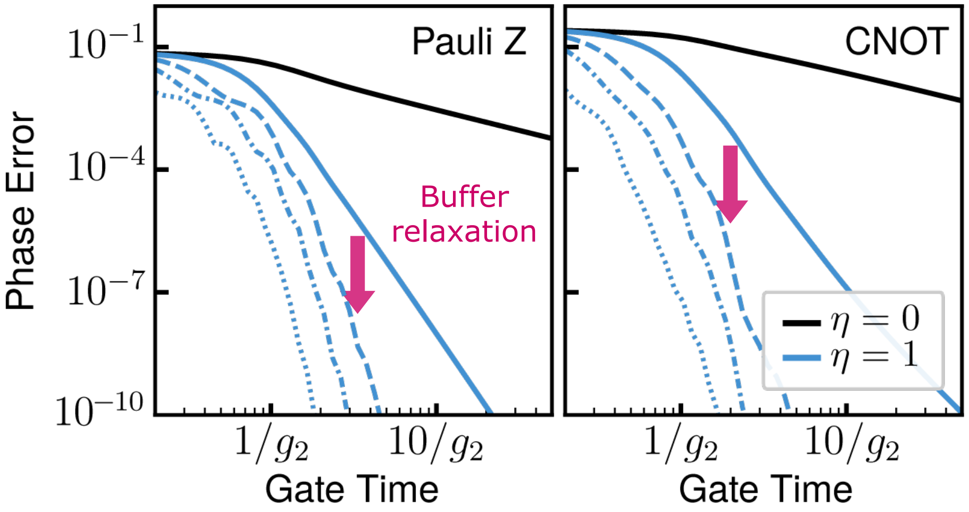

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- Detection of buffer photons ➡ Erasure errors or classical feedback
- Can apply N gates with a single relaxation per QEC cycle
- Gate fidelity limited by detection efficiency ➡ **Autonomous feedback**

Gautier *et al.*, arXiv (2023)

Autonomous Feedback

Information is lost through the buffer mode

➡ **Feedback buffer detection autonomously**

$$\frac{\mathrm{d}\boldsymbol{\rho}}{\mathrm{d}t} = -i[\boldsymbol{H}_{AB} + \boldsymbol{H}_Z, \boldsymbol{\rho}] + \kappa_{ab}\mathcal{D}[\boldsymbol{ab}]\boldsymbol{\rho}$$

➡ Correlate buffer photon losses with cat parity-swaps

Gautier *et al.*, arXiv (2023)

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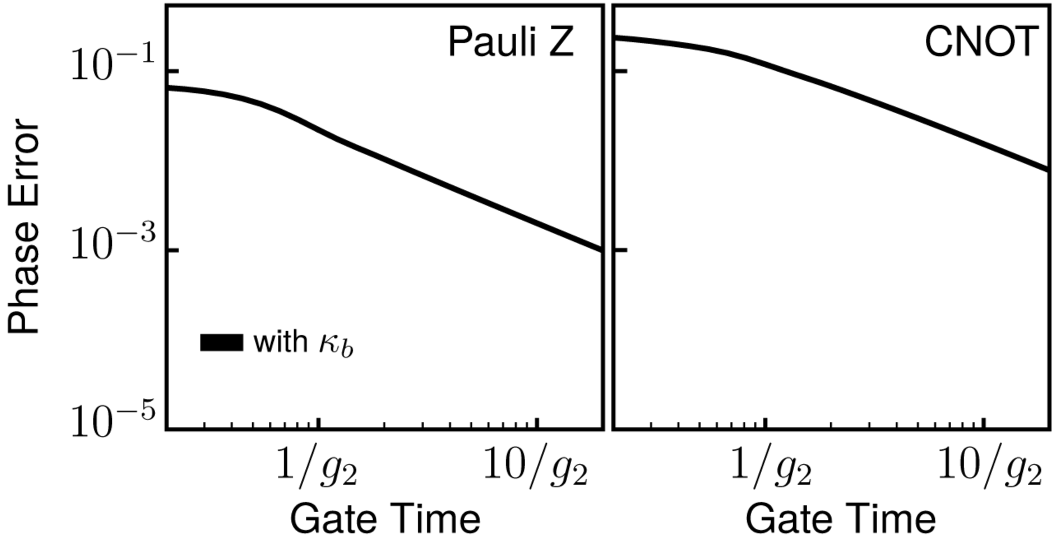

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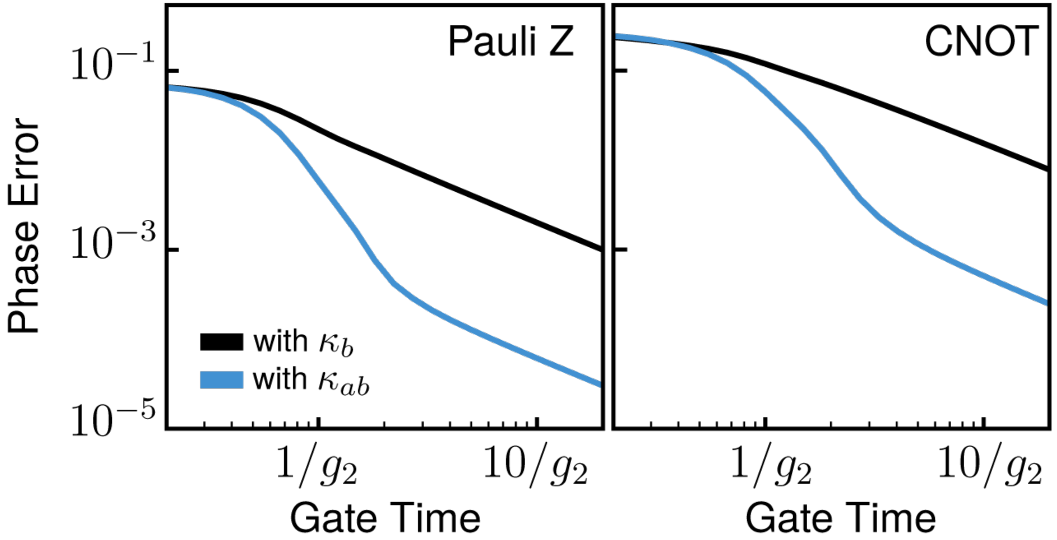

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$

Gautier *et al.*, arXiv (2023); Xu, Jiang *et al.*, arXiv (2022)

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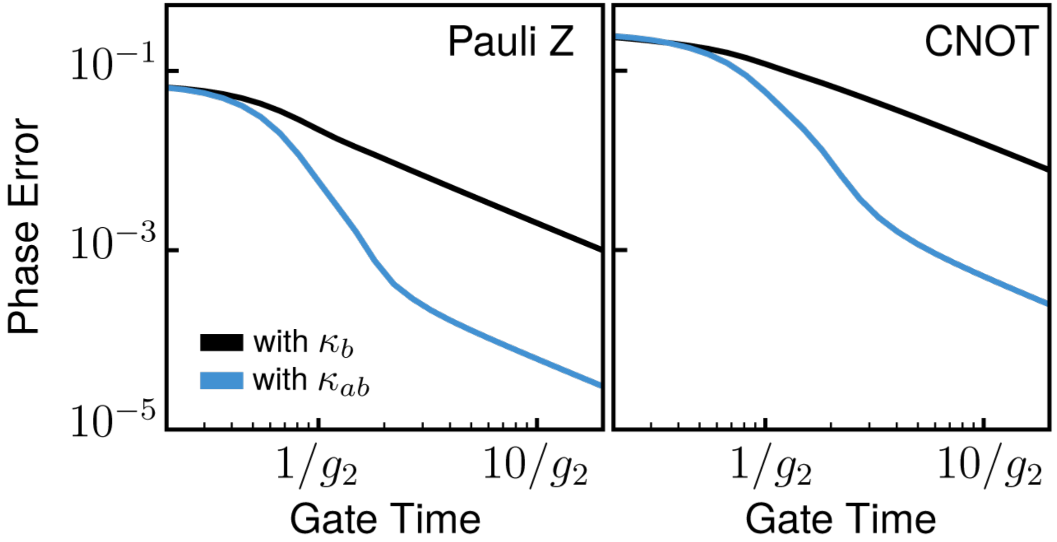

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^{n}X gate with no additional experimental overhead

Gautier *et al.*, arXiv (2023); Xu, Jiang *et al.*, arXiv (2022)

Autonomous Feedback

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➡ **Feedback buffer detection autonomously**

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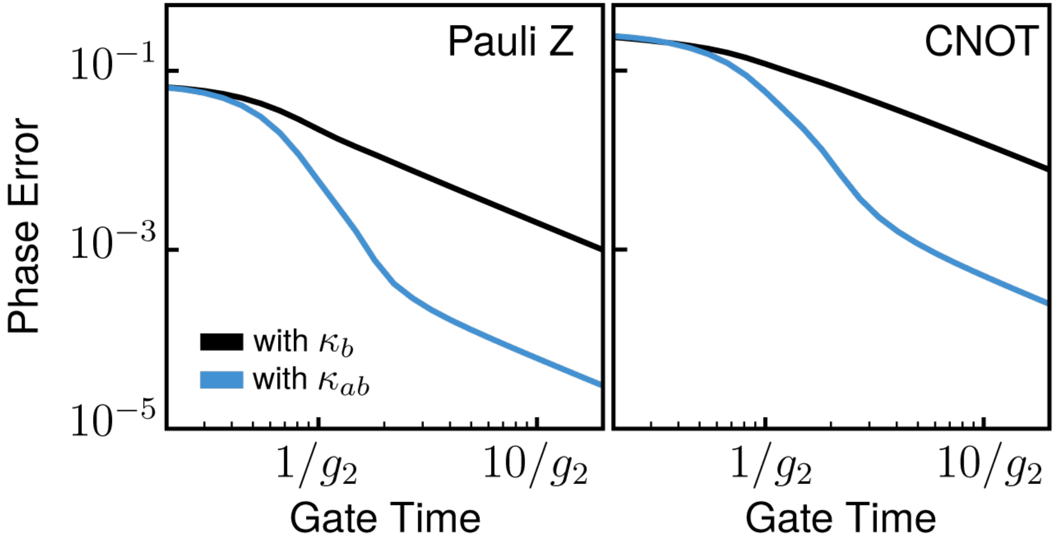
➡ Correlate buffer photon losses with cat parity-swaps



- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^nX gate with no additional experimental overhead
- Autonomous correction of cavity losses with **squeezed** cats

Gautier *et al.*, arXiv (2023); Xu, Jiang *et al.*, arXiv (2022)

Autonomous Feedback

Information is lost through the buffer mode

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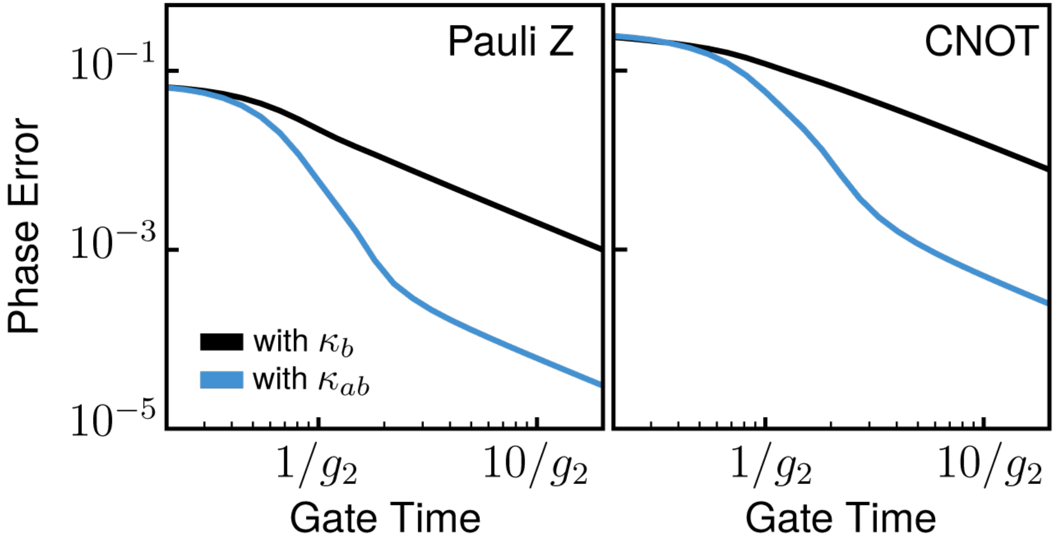

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^{n}X gate with no additional experimental overhead
- Autonomous correction of cavity losses with **squeezed** cats
- Can tune dissipation in situ

Gautier *et al.*, arXiv (2023); Xu, Jiang *et al.*, arXiv (2022)

Designing High-Fidelity Gates for Dissipative Cat Qubits

- Buffer mode useful for more than dissipation engineering
- Information retrieval through photodetection: interesting conceptually but limited in practice
- Devised a scheme for autonomous correction of gate errors
- Check out **arXiv:2303.00760** for more details