Ronan Gautier

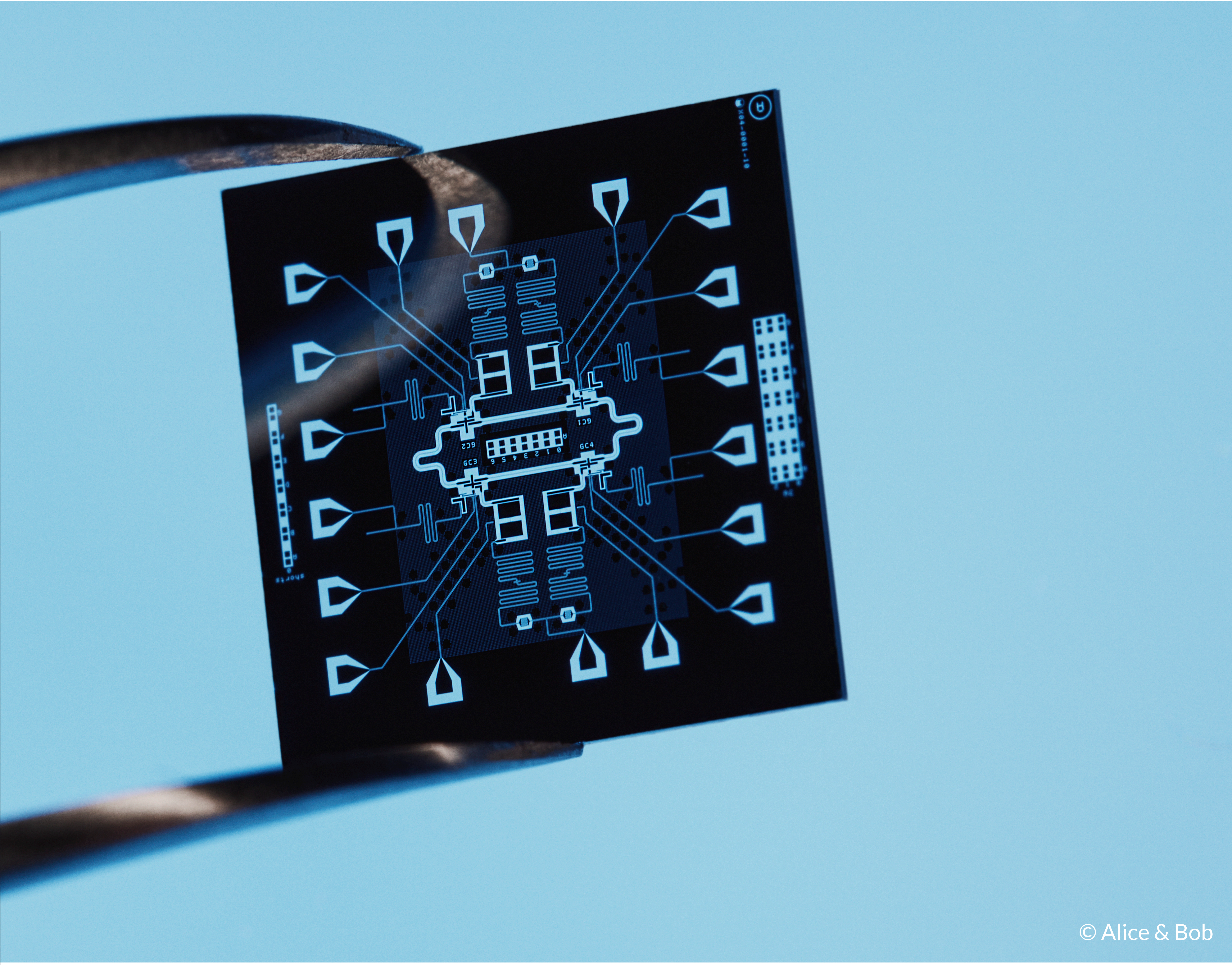
High-Fidelity Control and Stabilization of Cat Qubits

Director / Alain Sarlette

Reviewers / Liang Jiang
Clément Pellegrini

Examinators / Christiane Koch
Jean-Michel Raimond
Mario Sigalotti

Invited / Mazyar Mirrahimi
Alexandre Blais



PhD defence / 4th December 2023

Université de Sherbrooke
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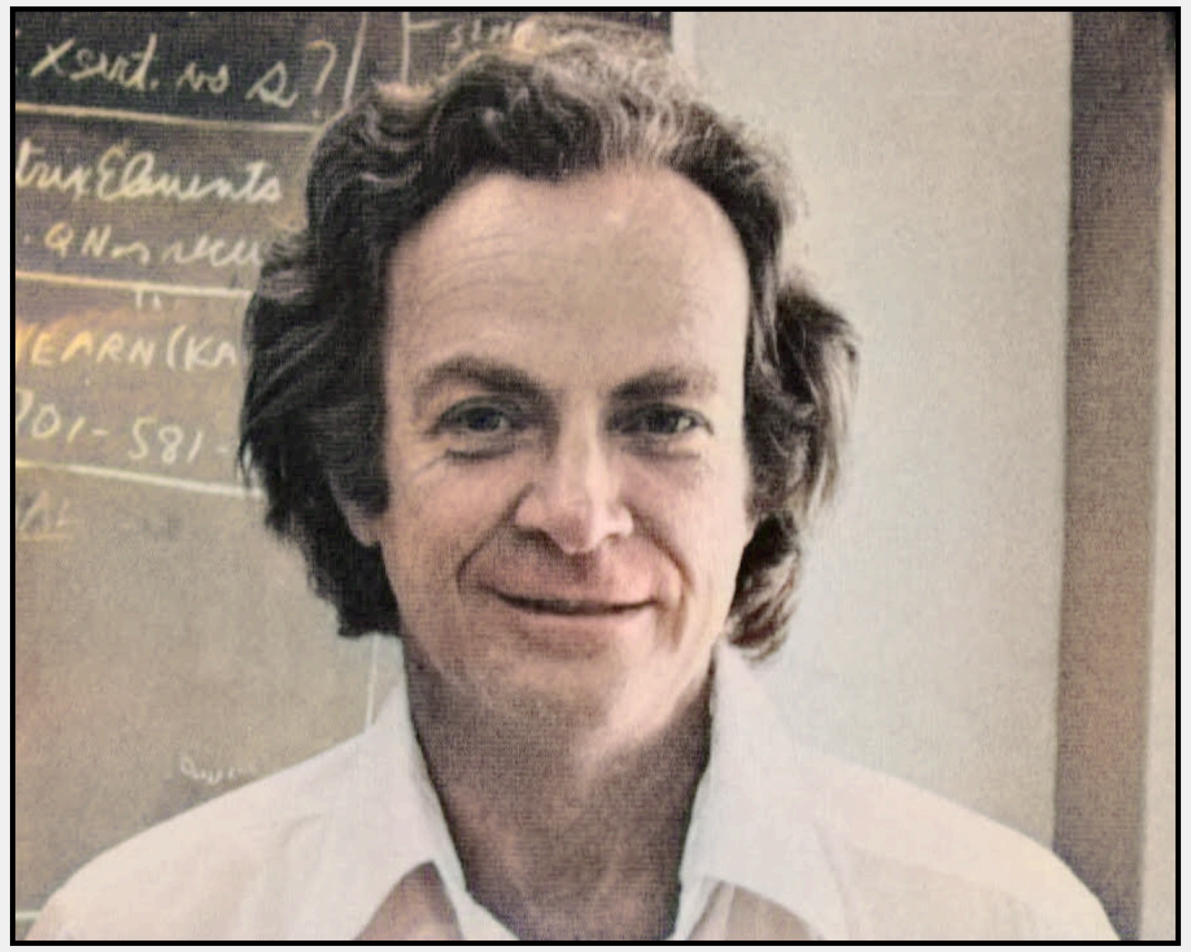
A quantum computer for simulating Nature

Feynman's 1981 talk

“ The full description of quantum mechanics […] *cannot be simulated with a normal computer*. ”



Richard Feynman at Caltech, circa 1980

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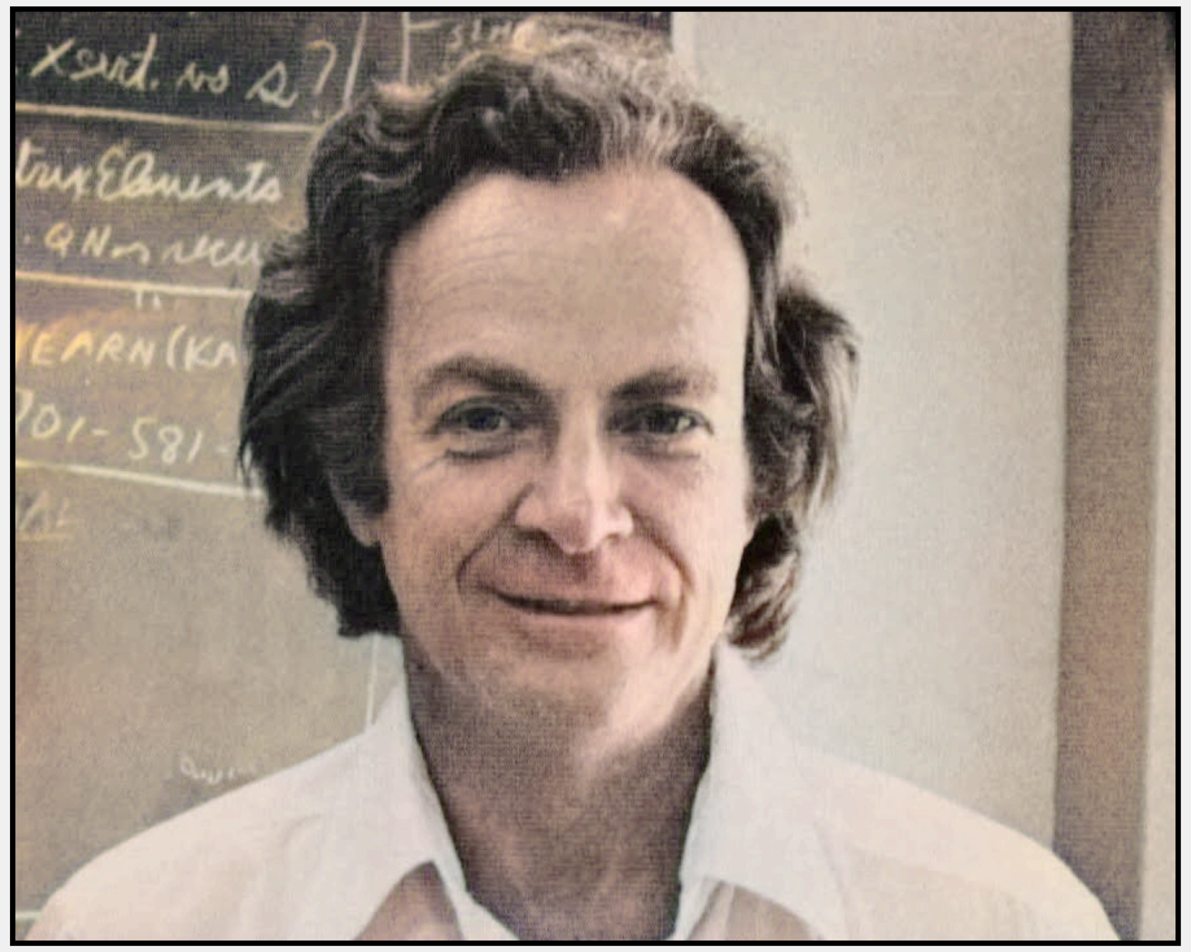

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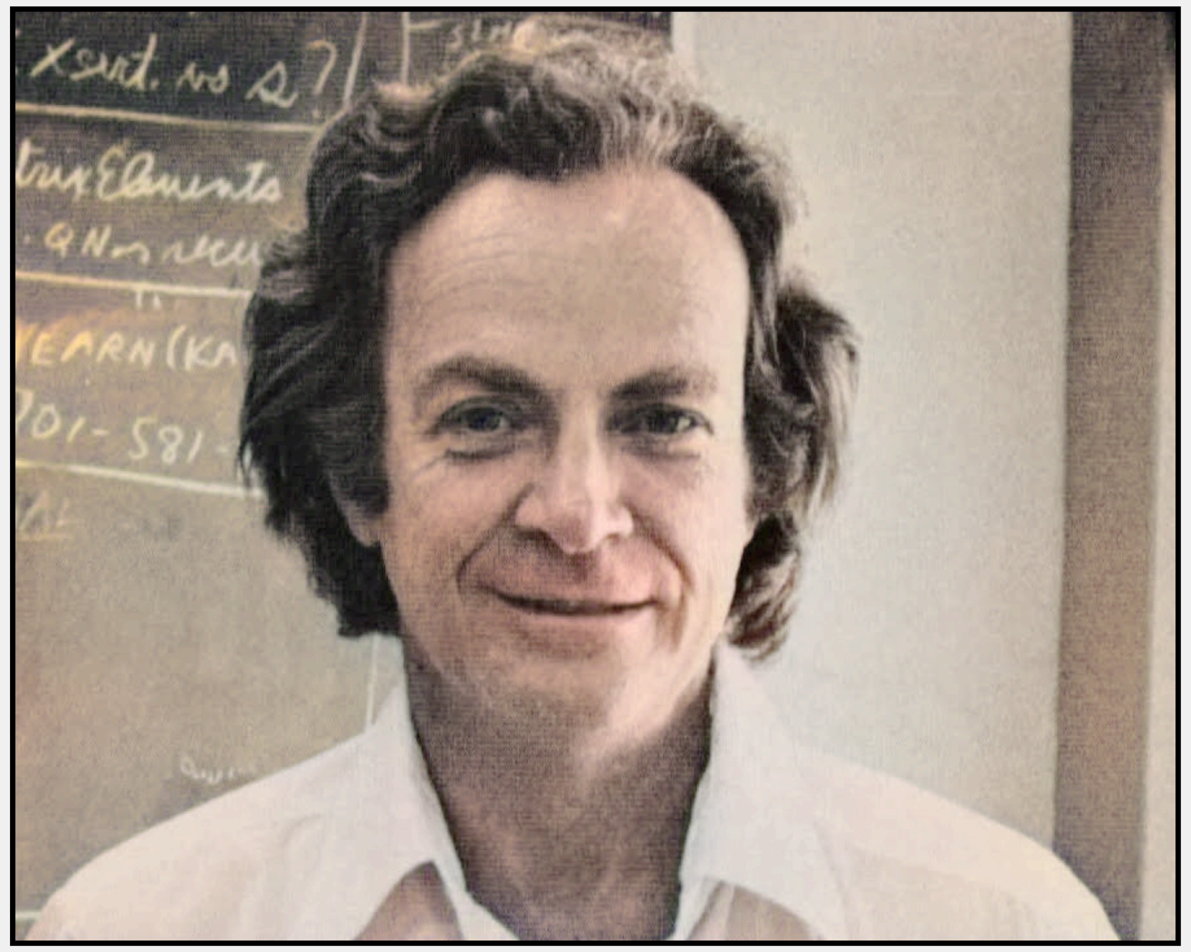

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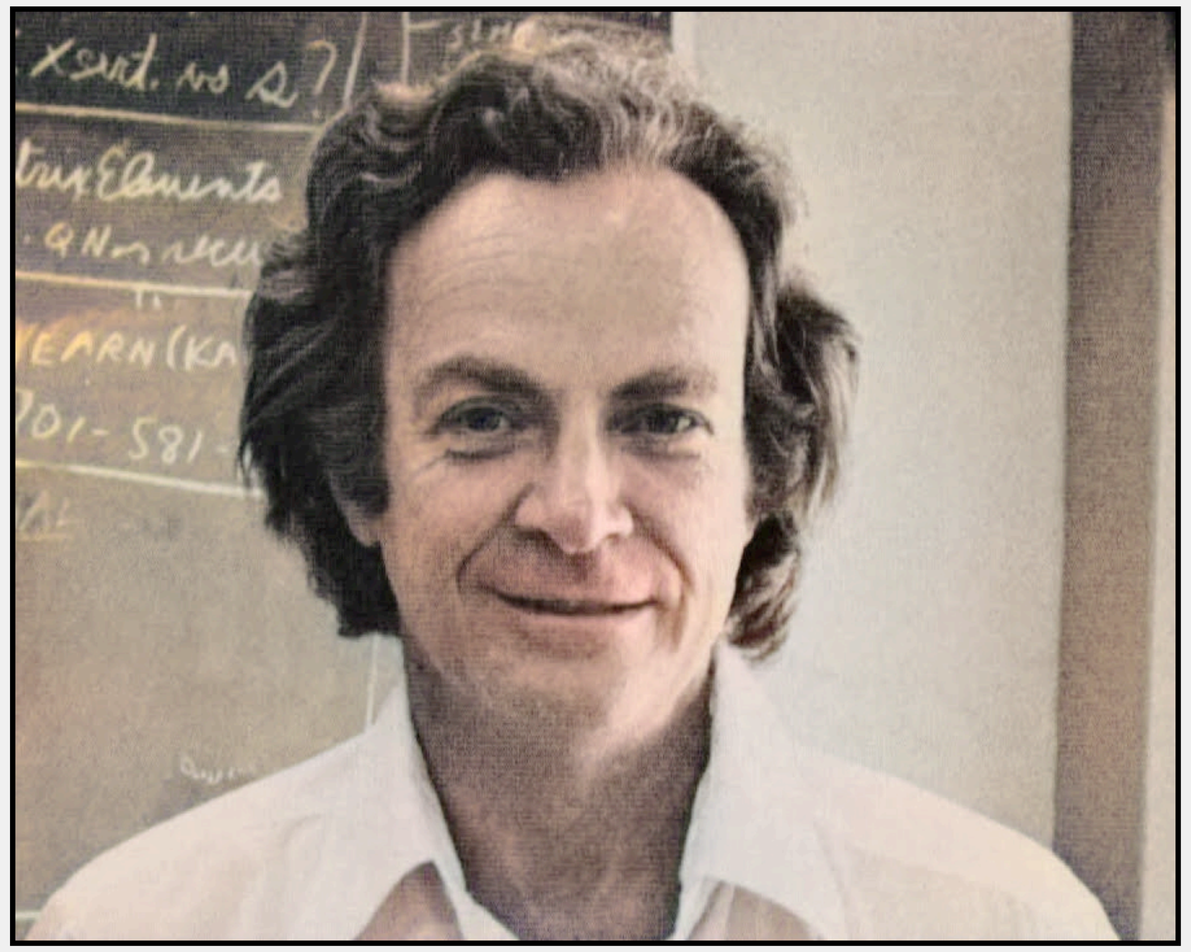

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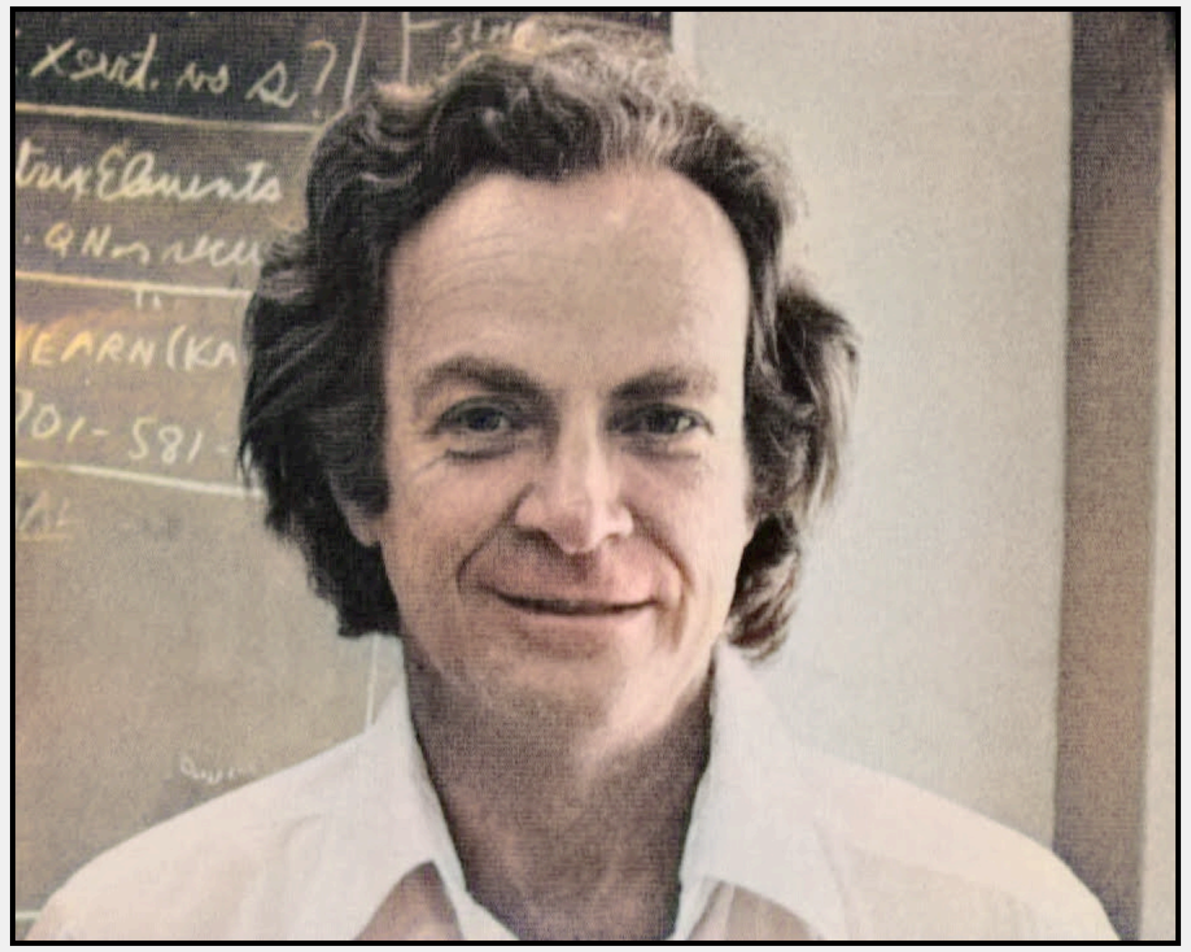

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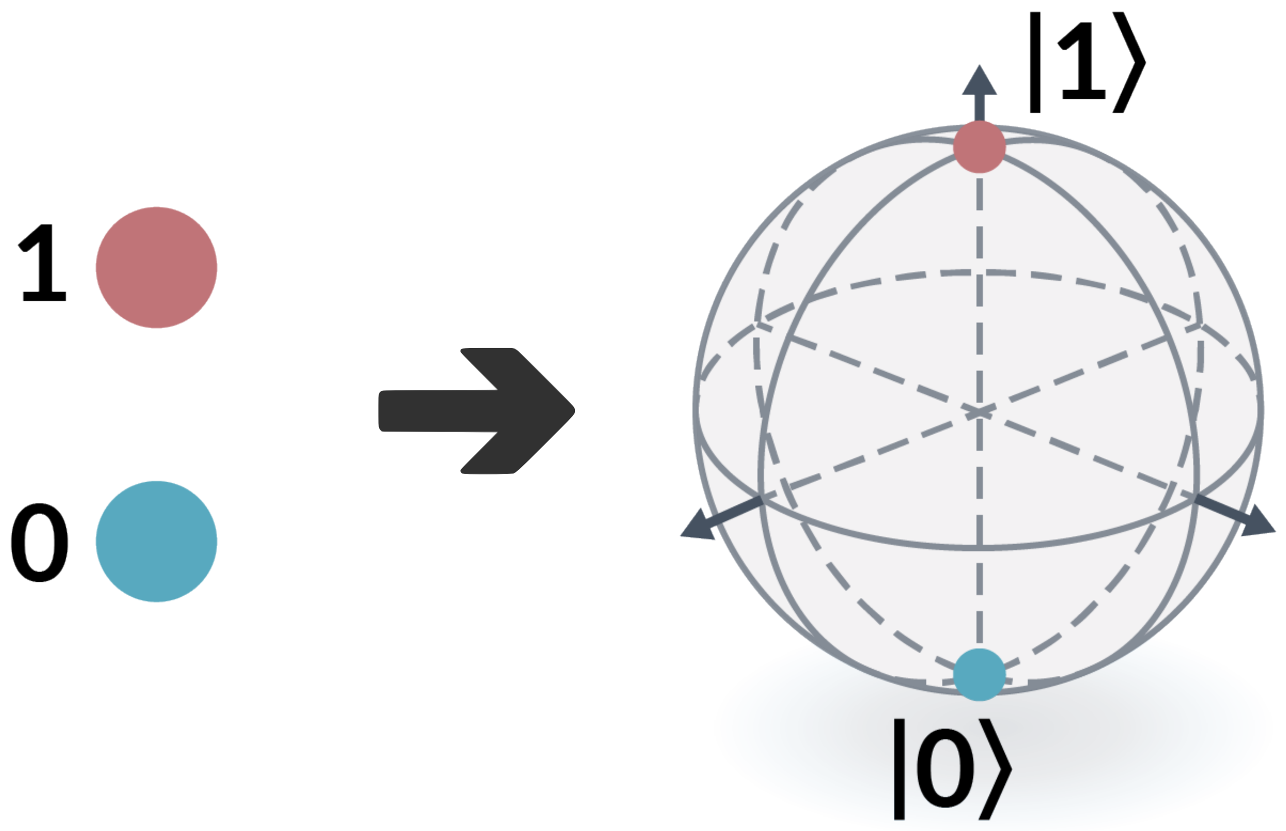
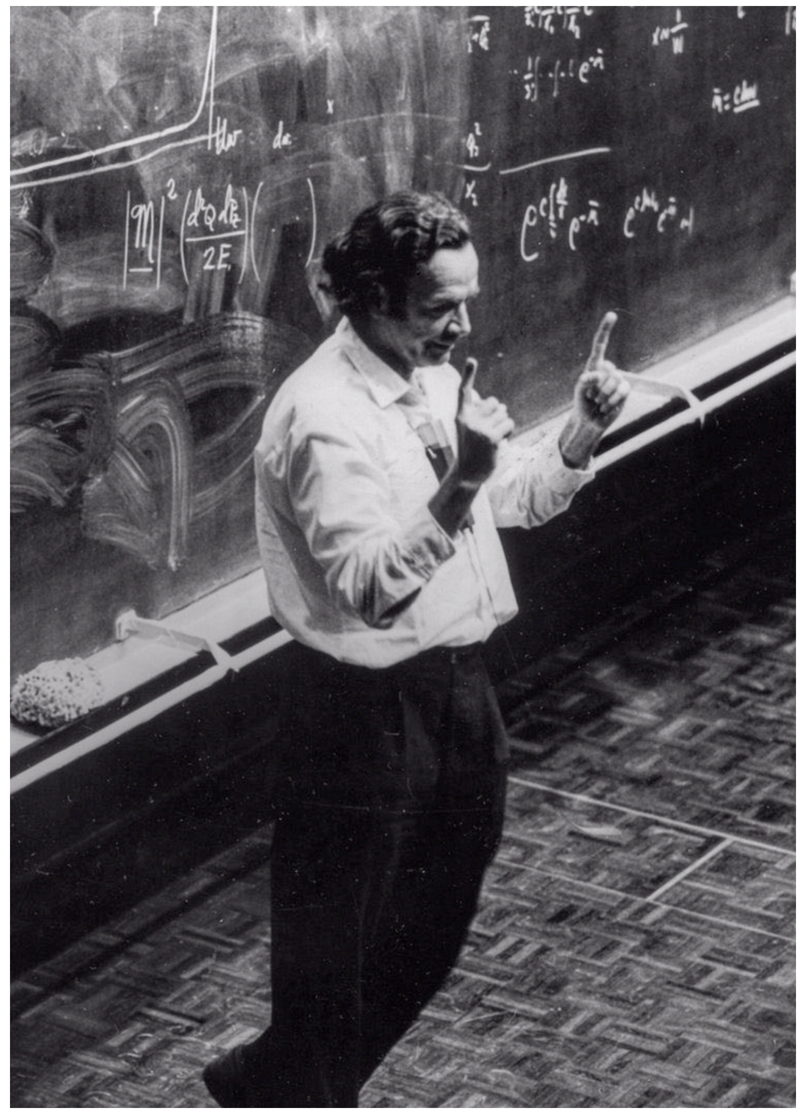
Classical bit



Quantum bit

The development of superconducting circuits

Feynman's talk on QC



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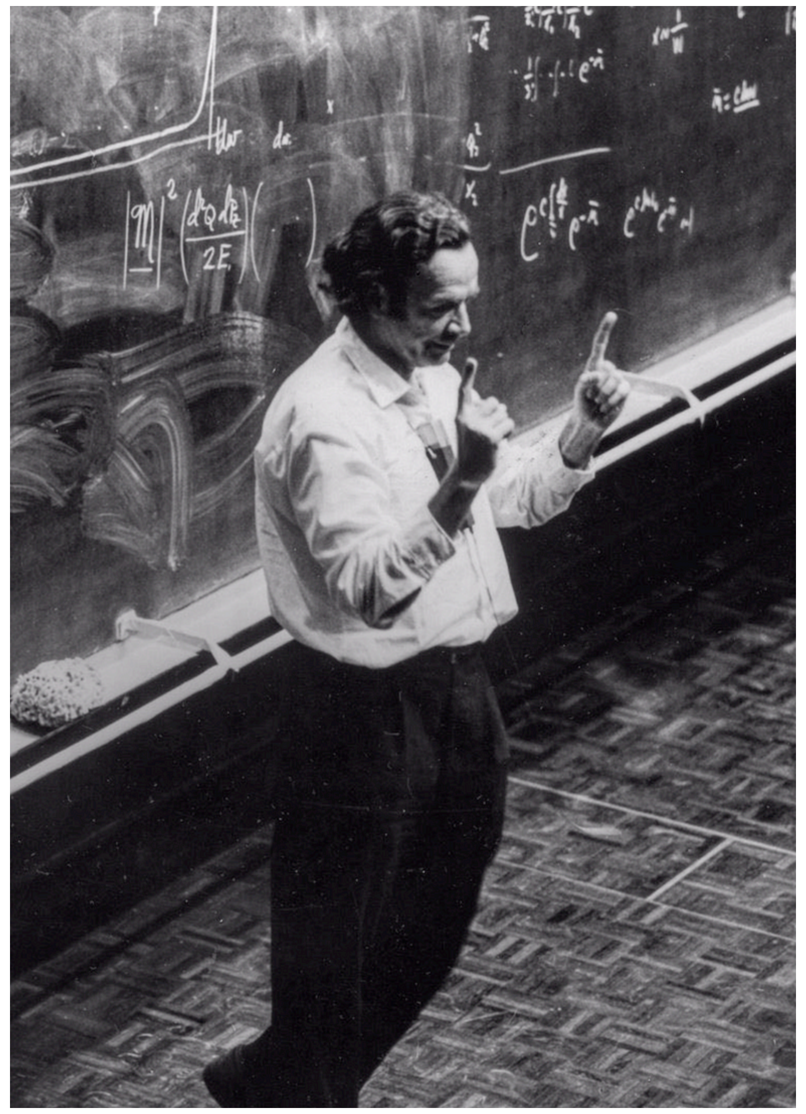
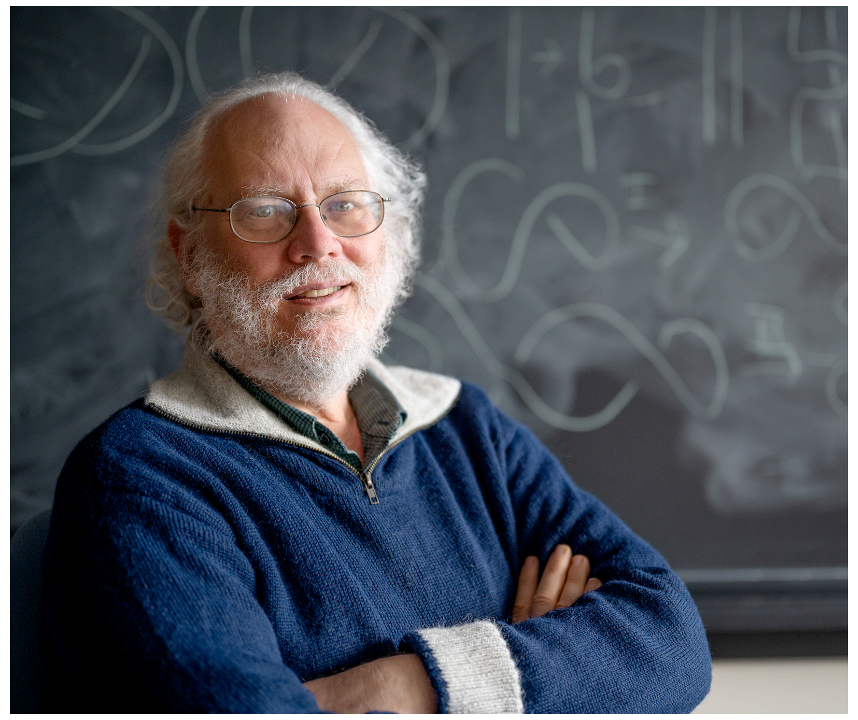


Shor’s algorithm



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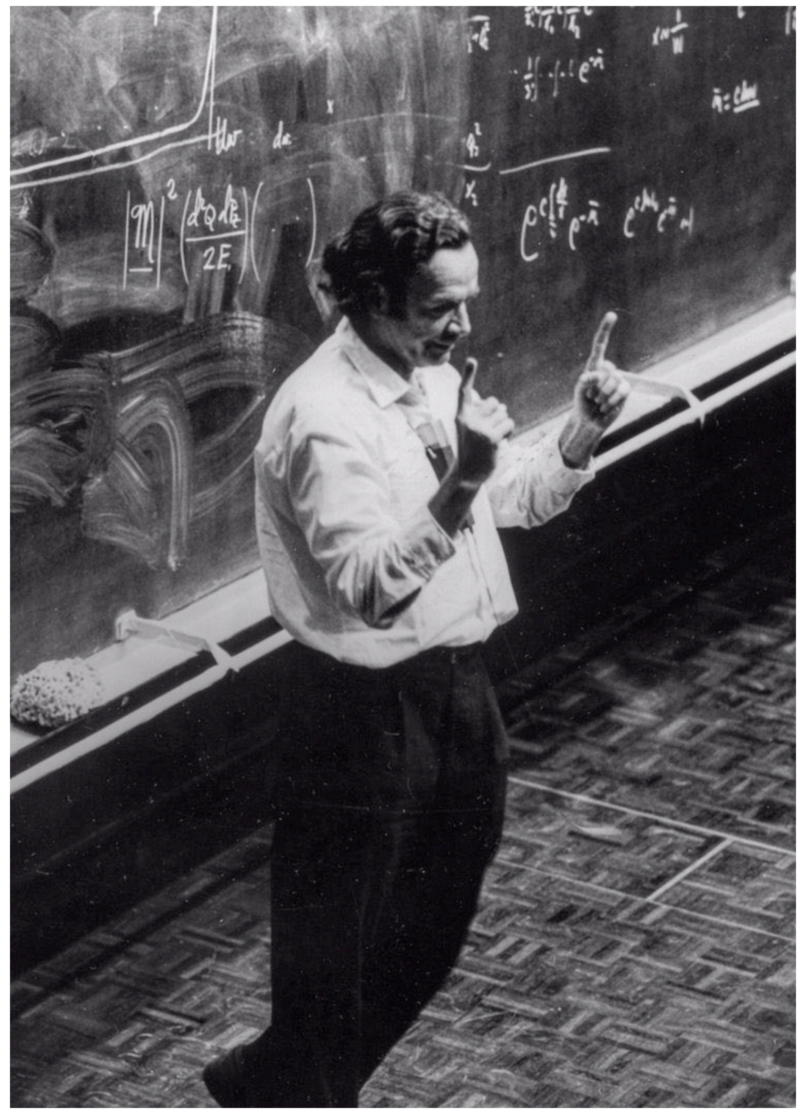

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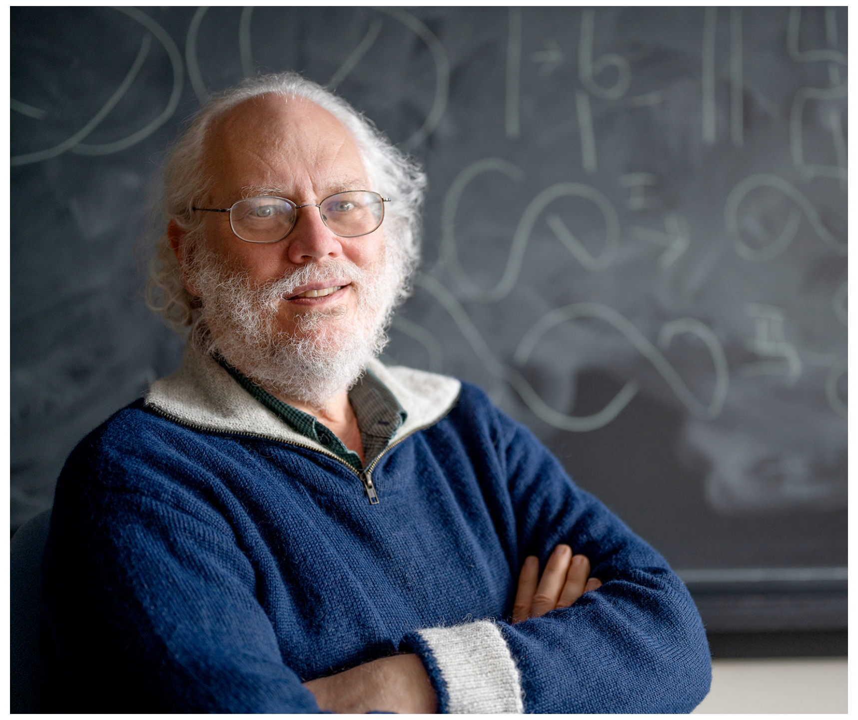

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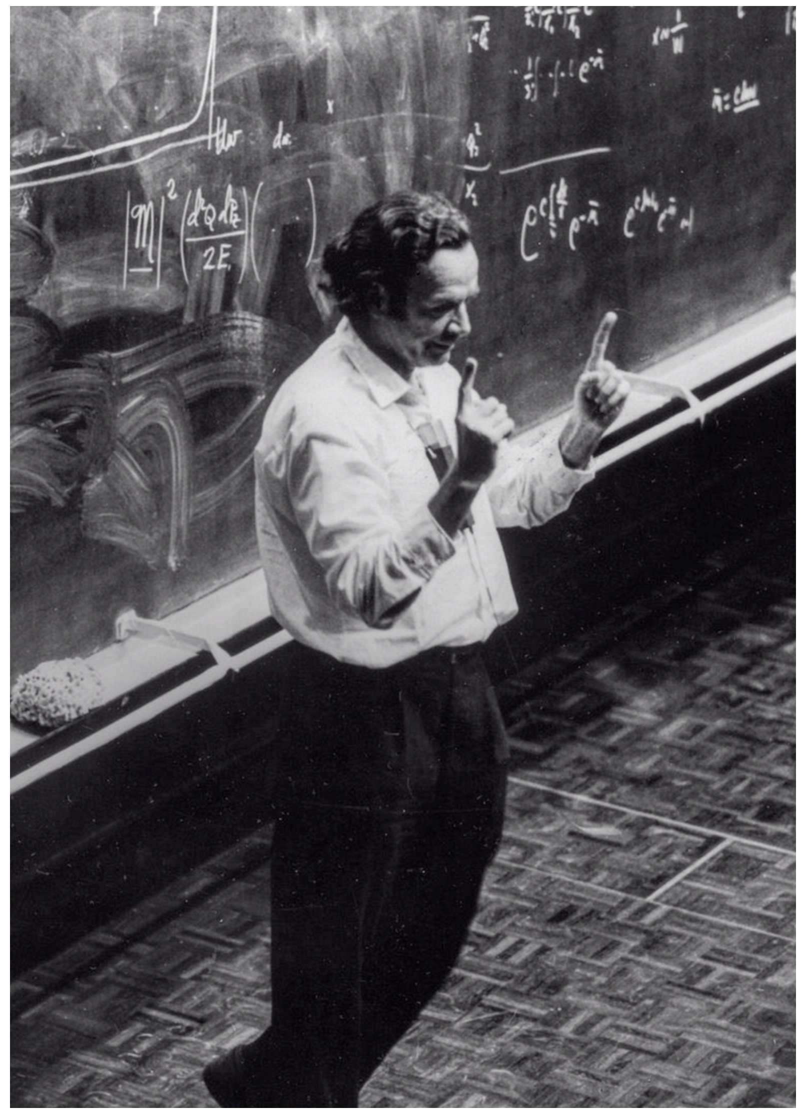

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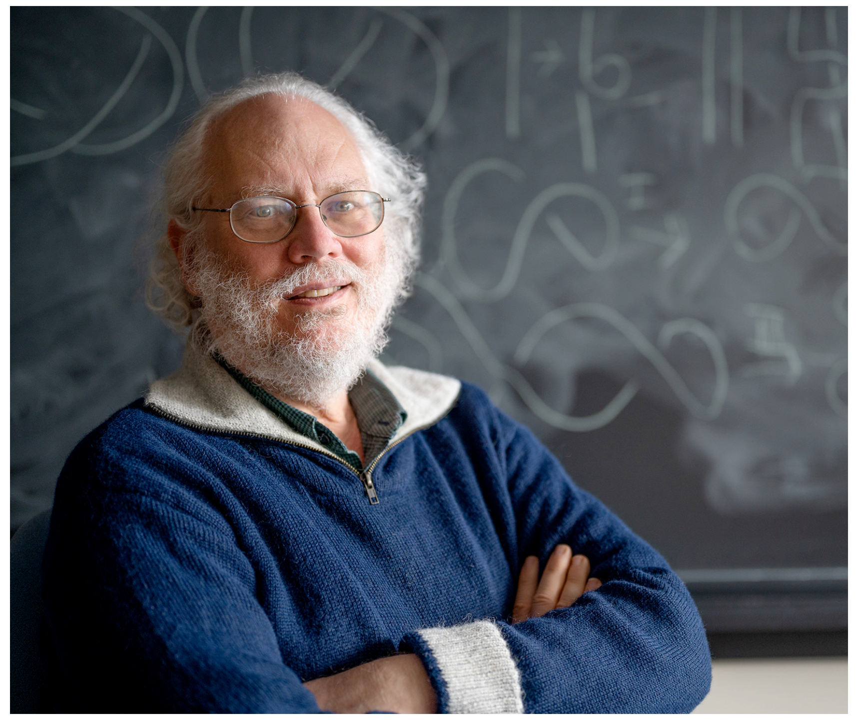

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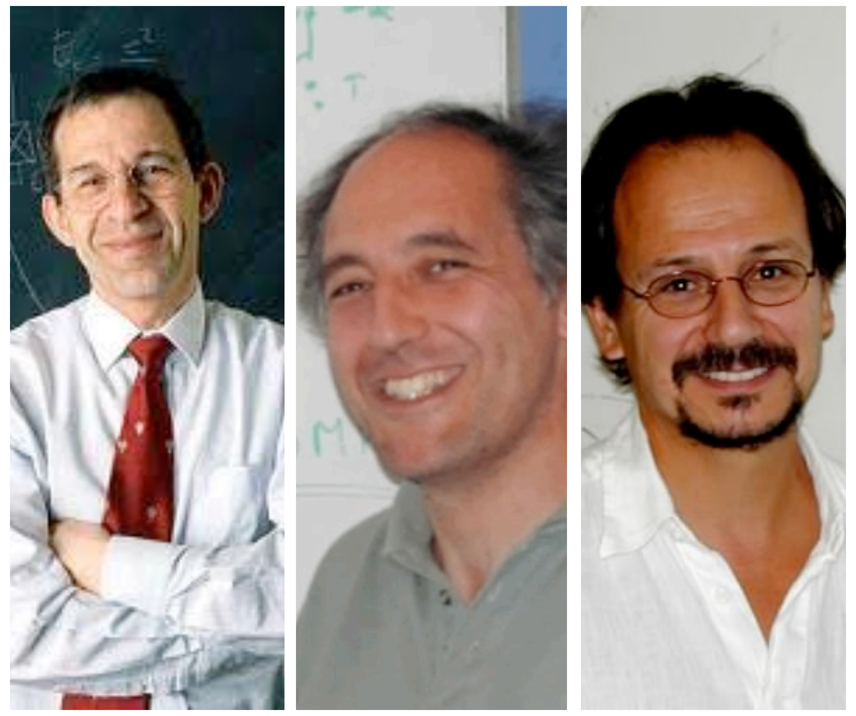

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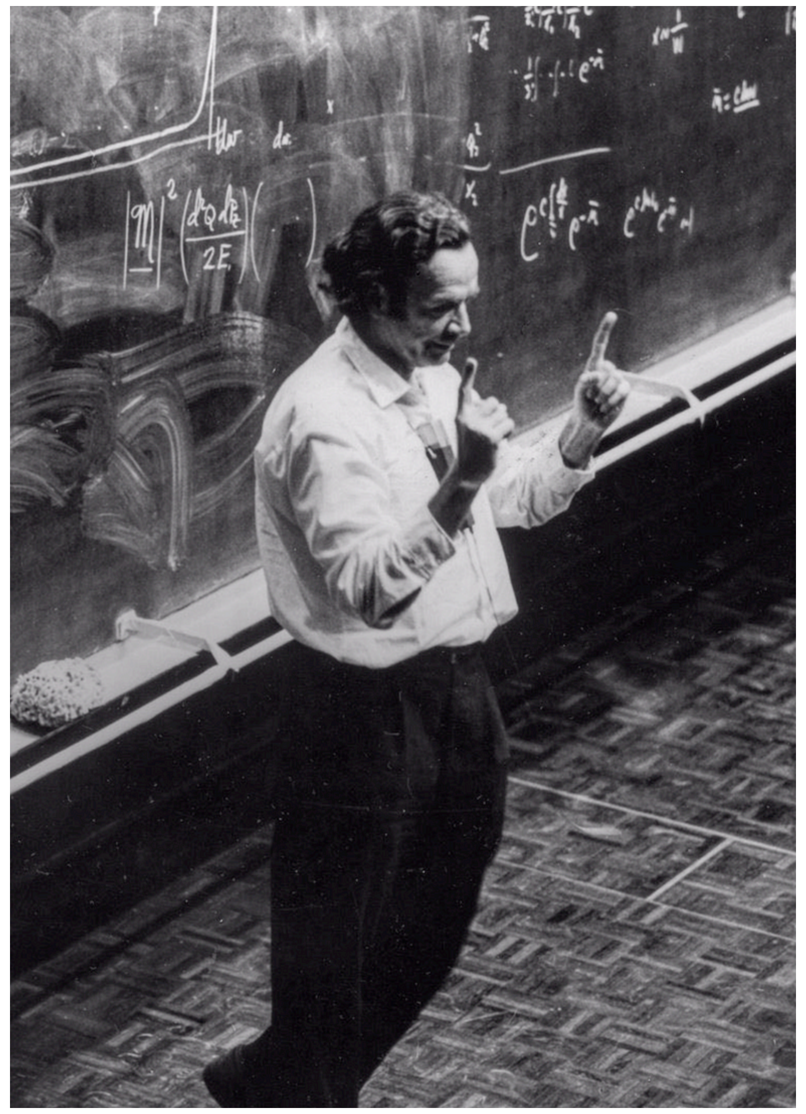

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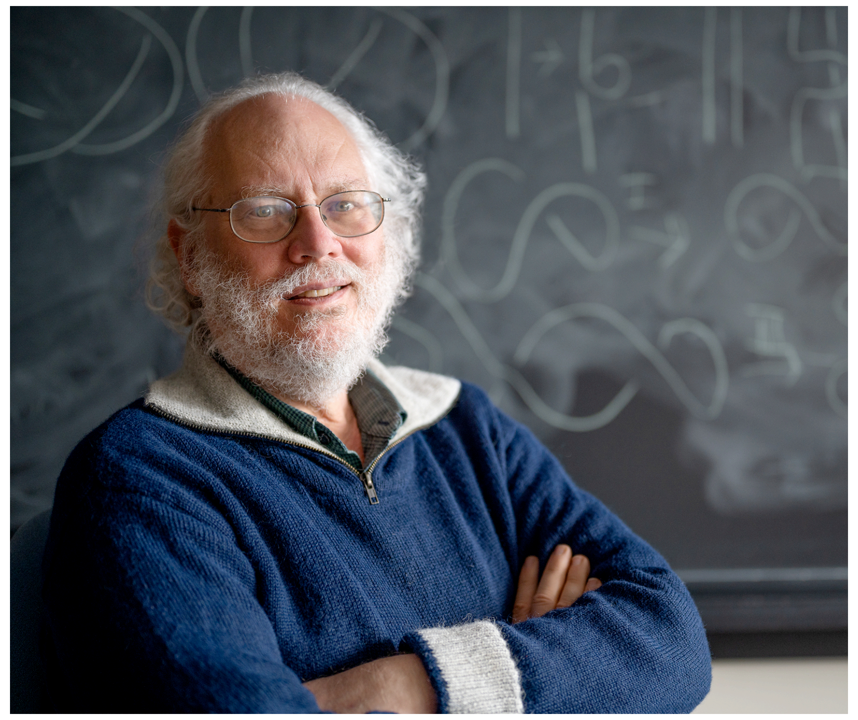

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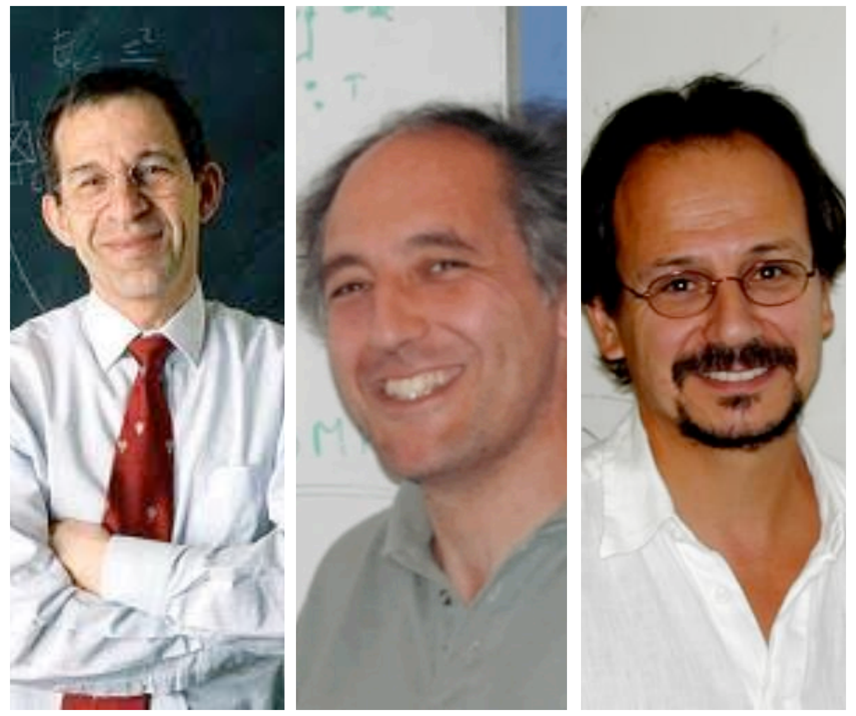

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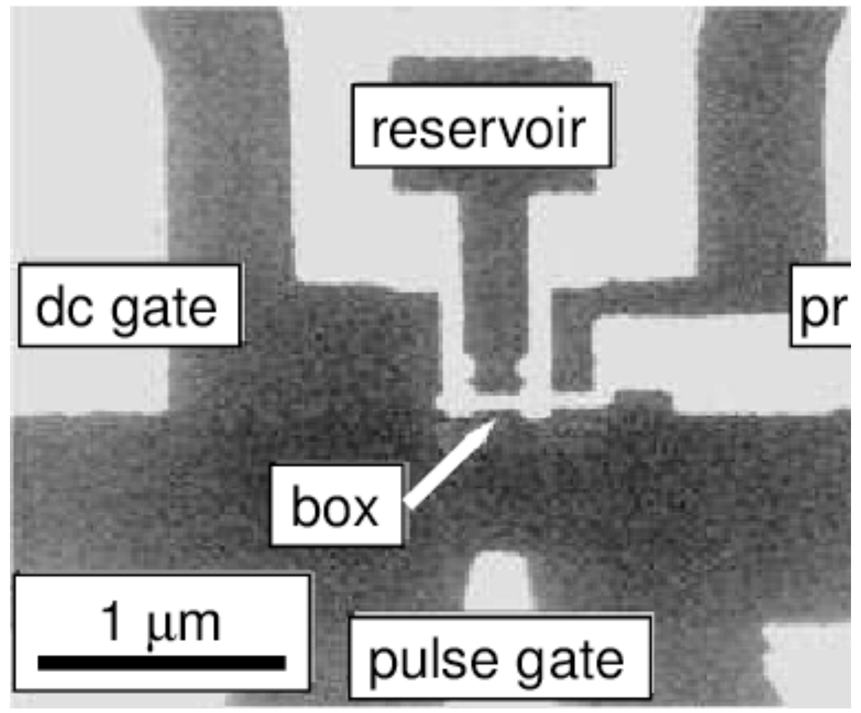
Cooper Pair Box



1999

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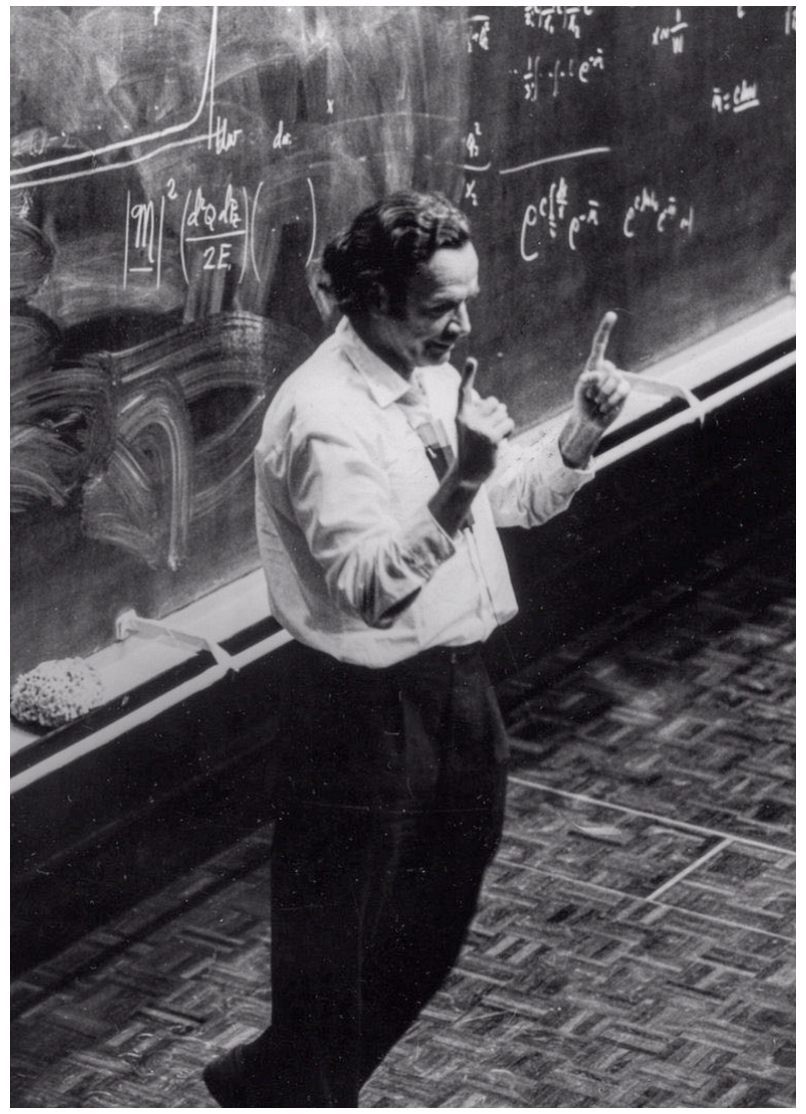

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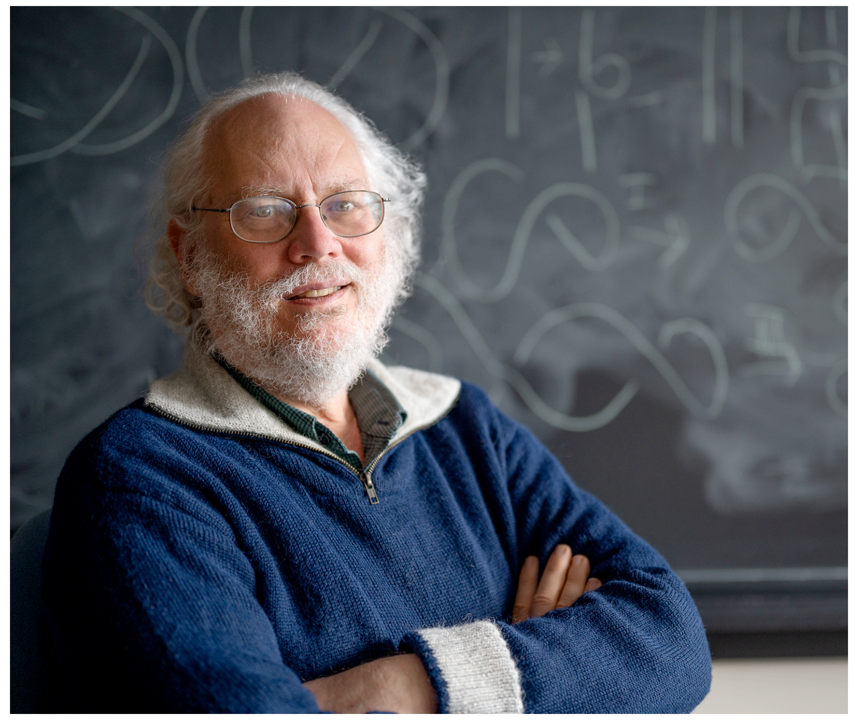

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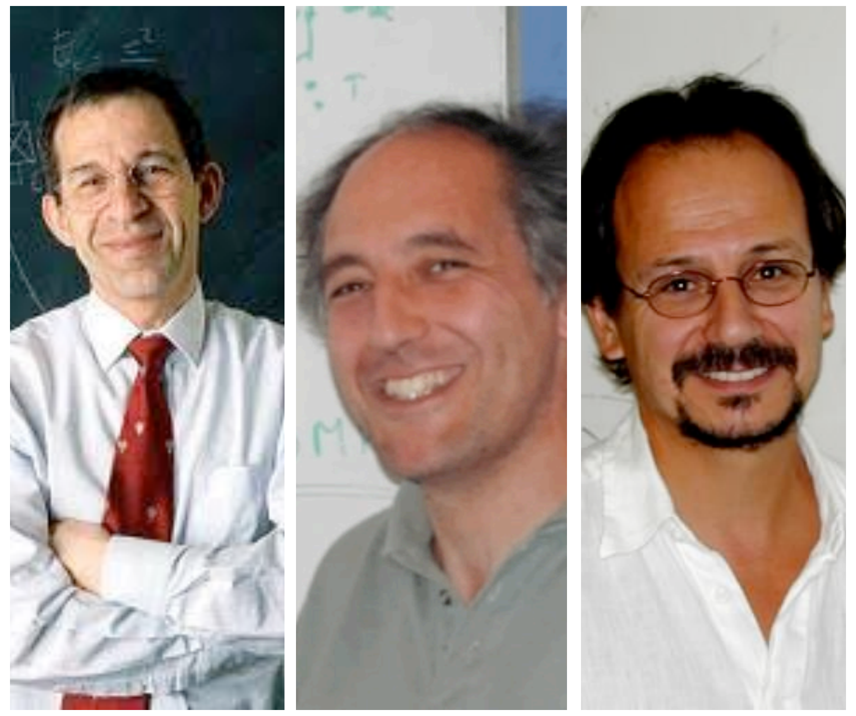

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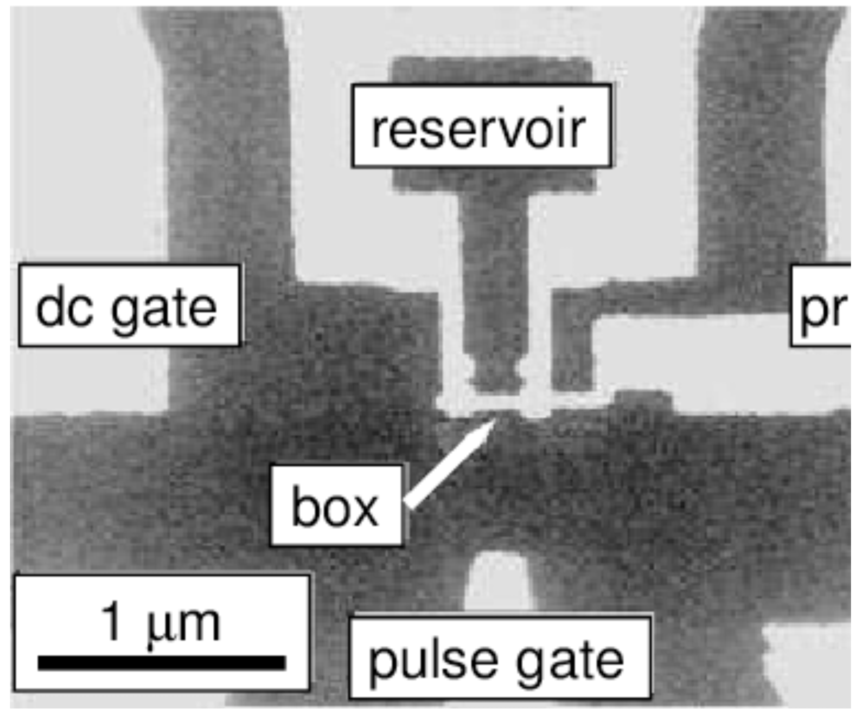

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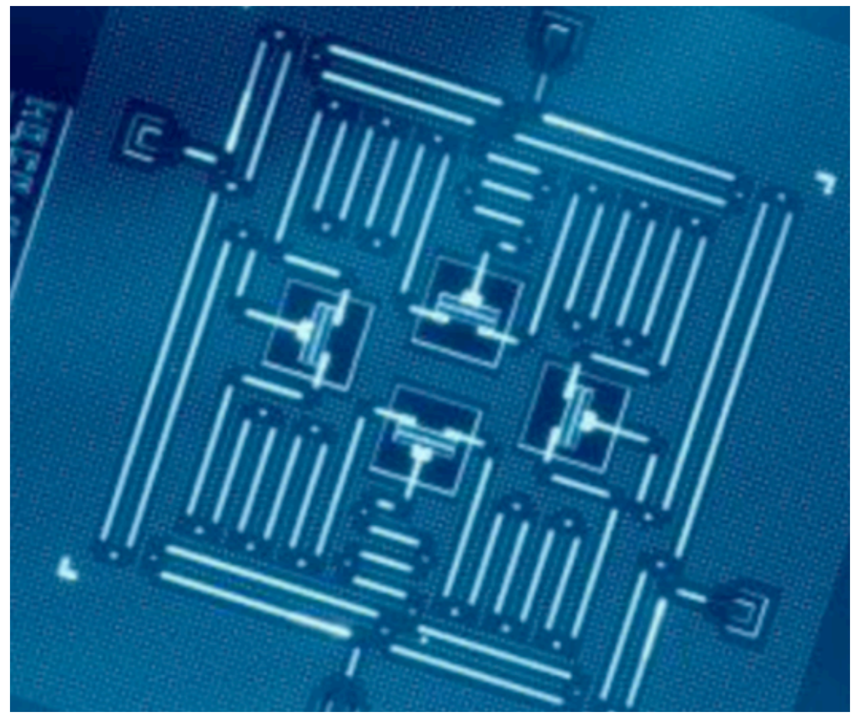
Transmon



2007

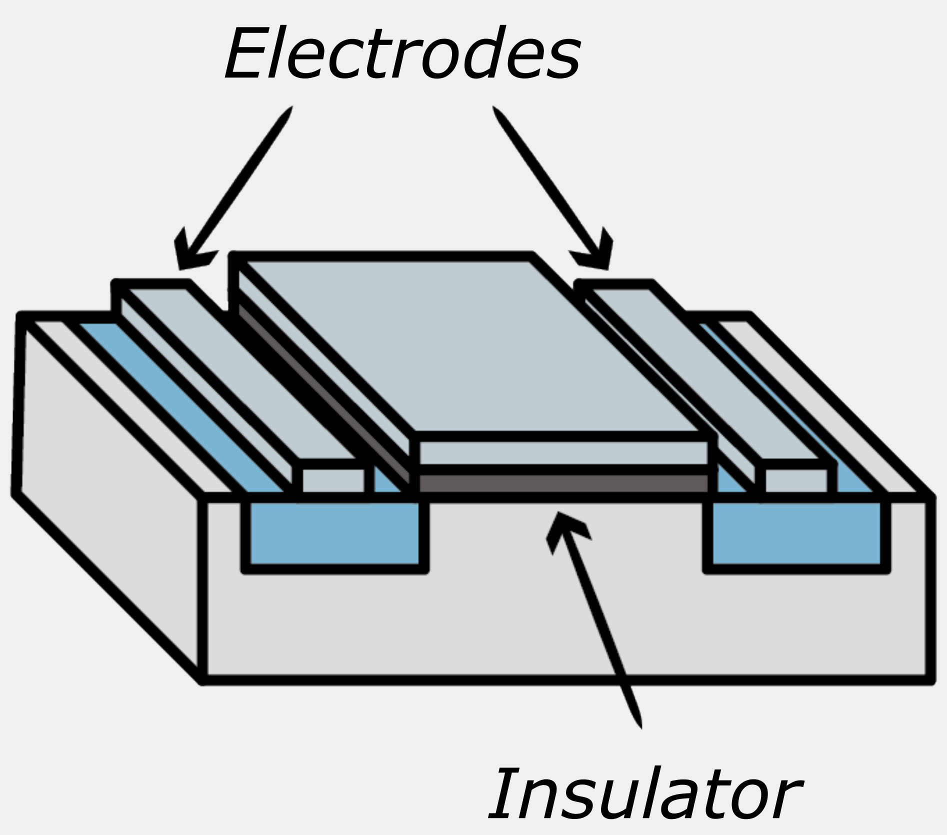
From transistors to transmons

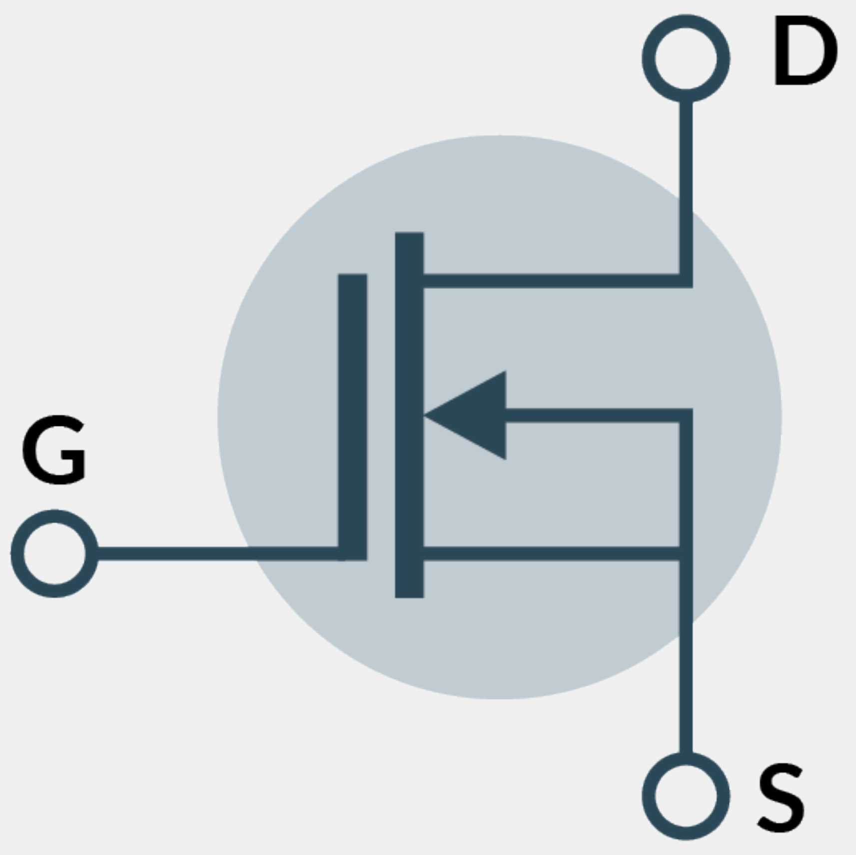
Transistor

1 ●

0 ●

Field-Effect Transistor





Error per operation

~10^{-20} — 10^{-22}

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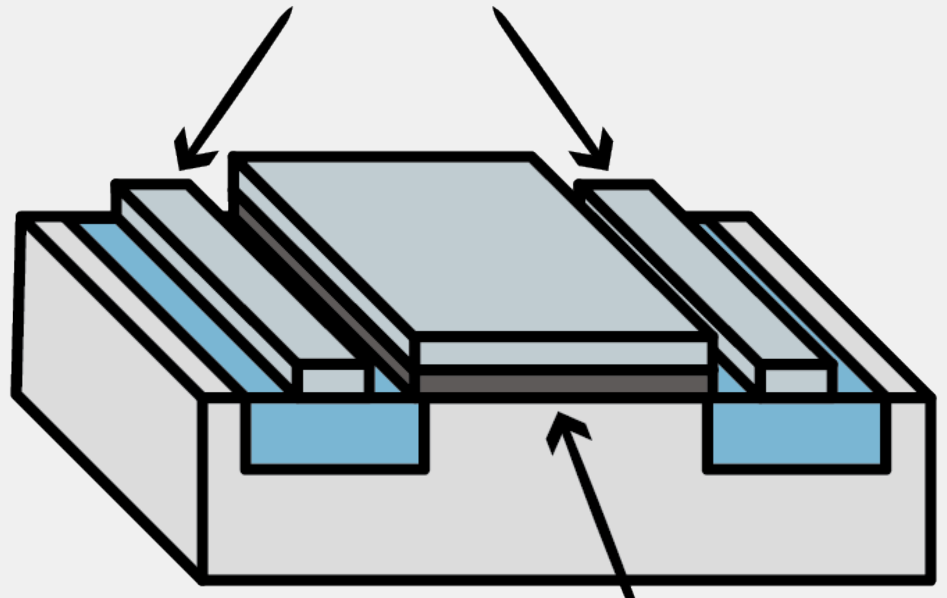

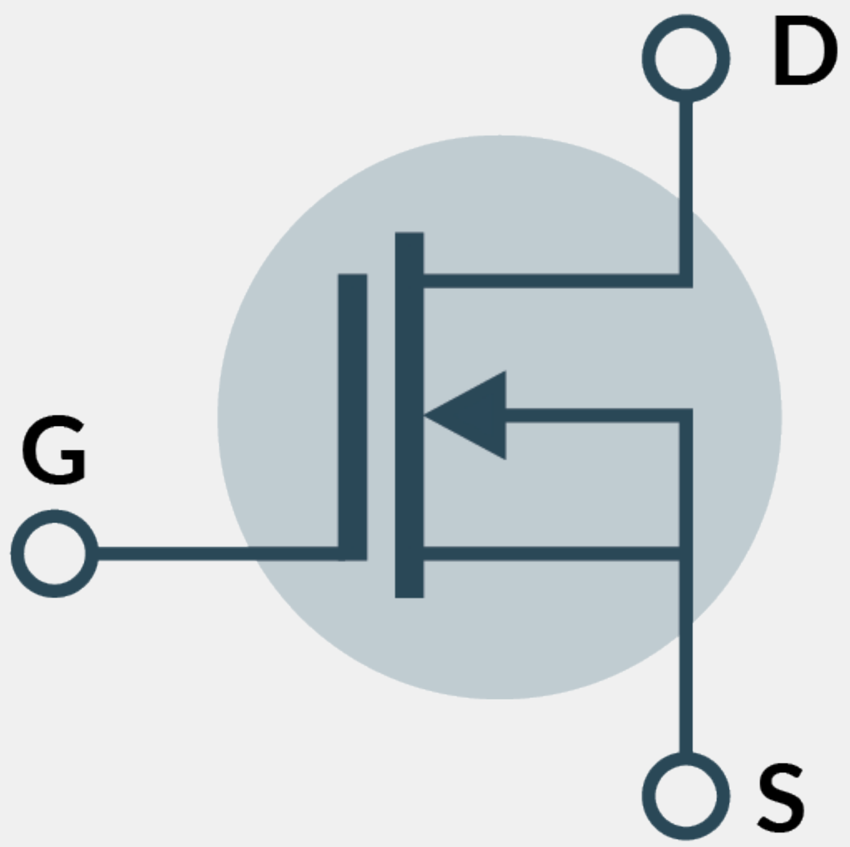

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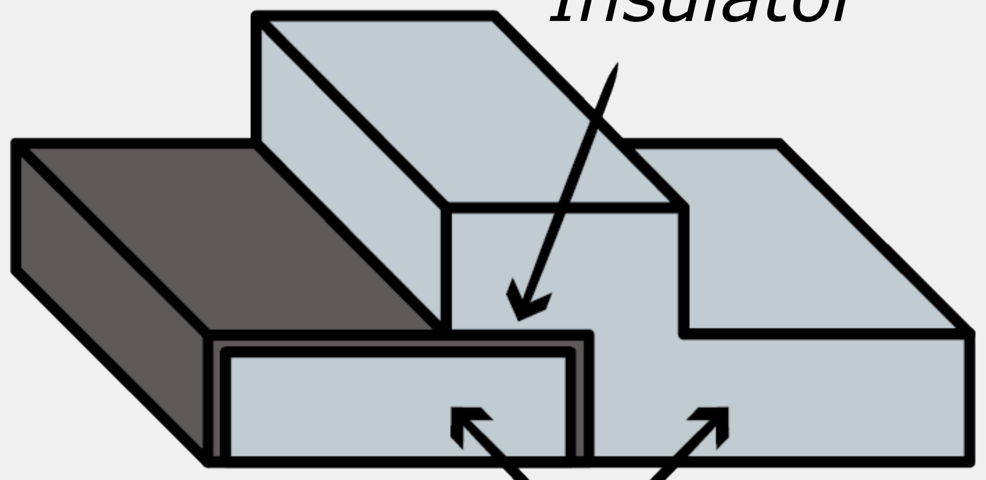
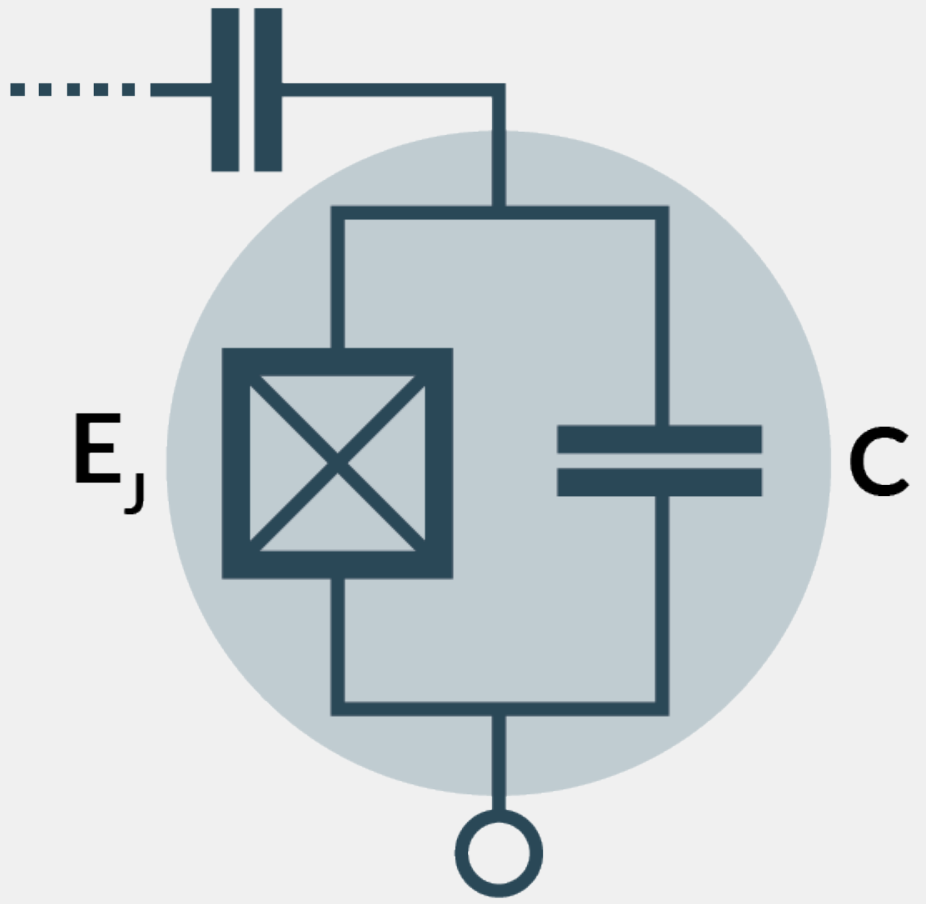


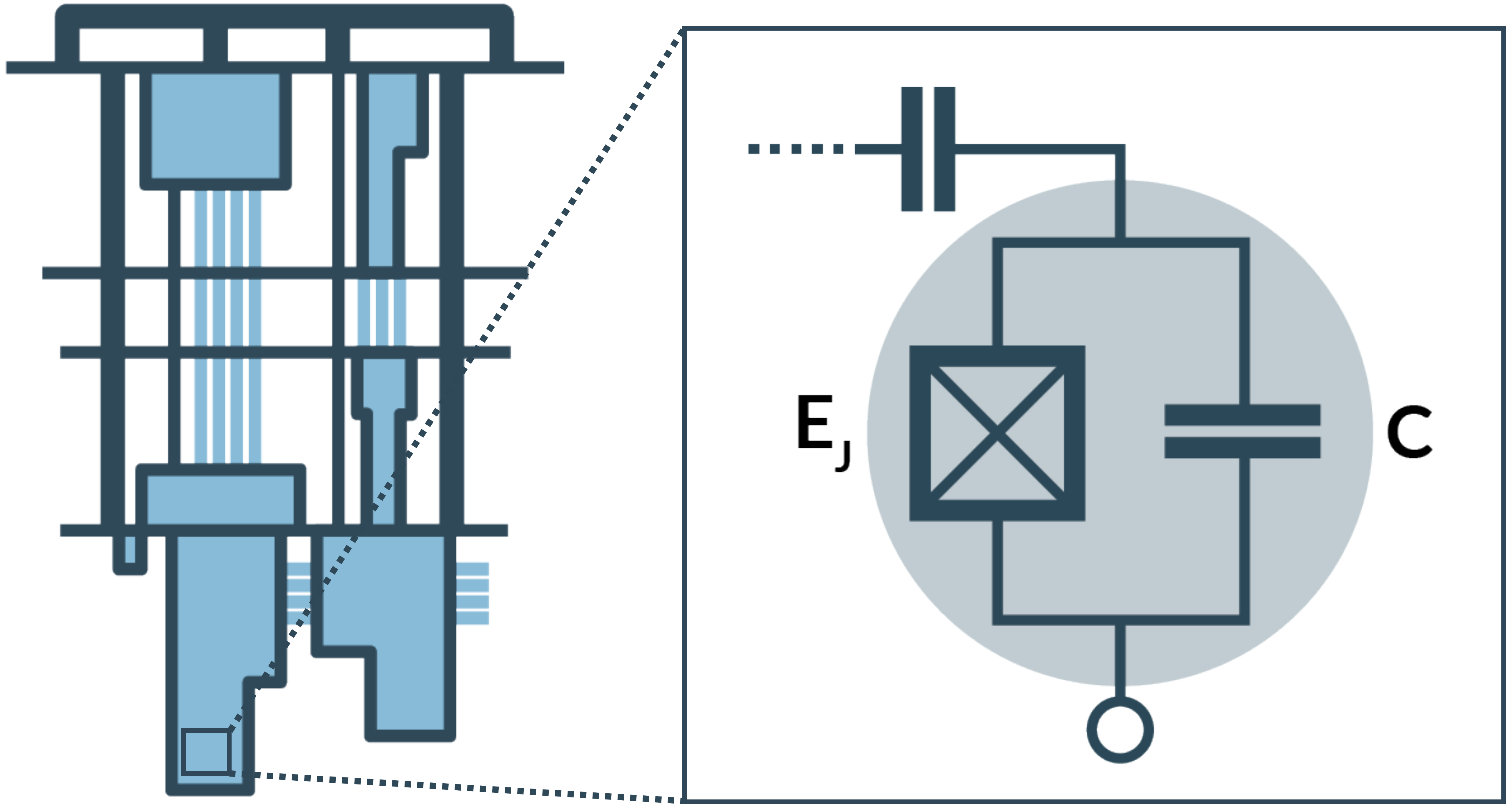


Error per operation

~10^{-2} — 10^{-4}

A fundamental predicament

High controllability ⟷ **Long lifetime**



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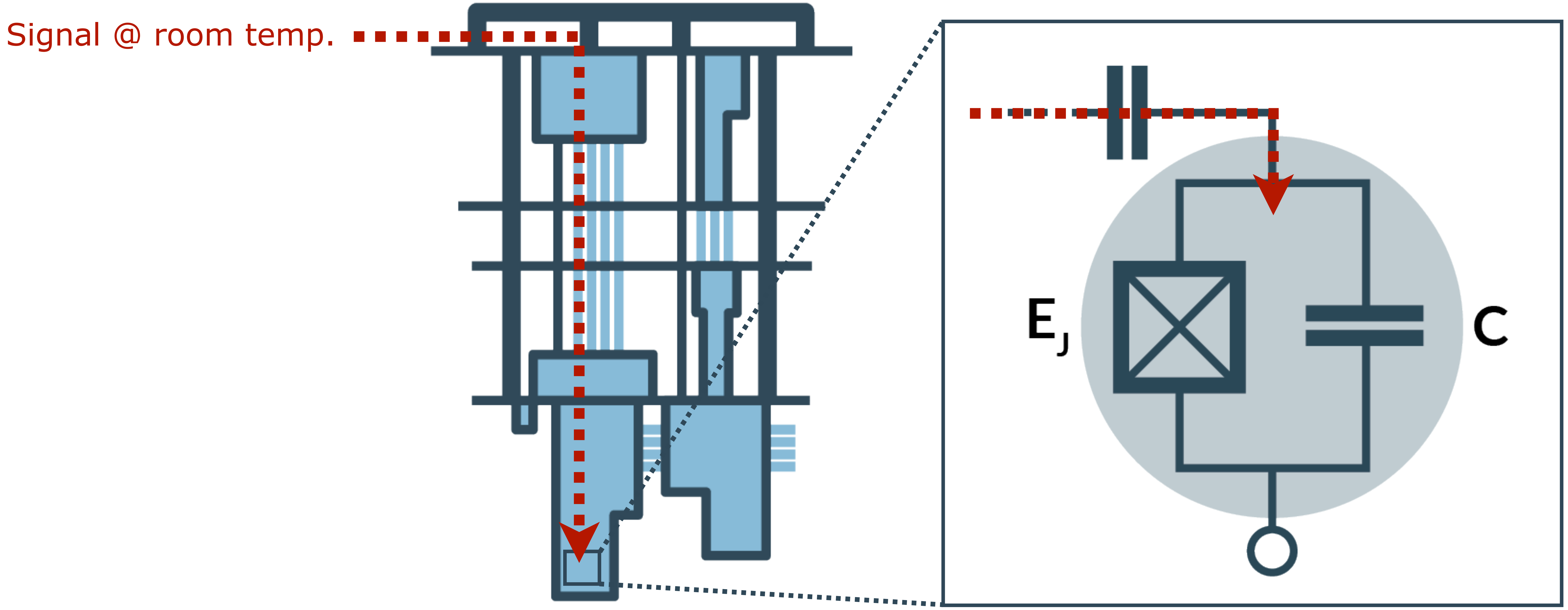

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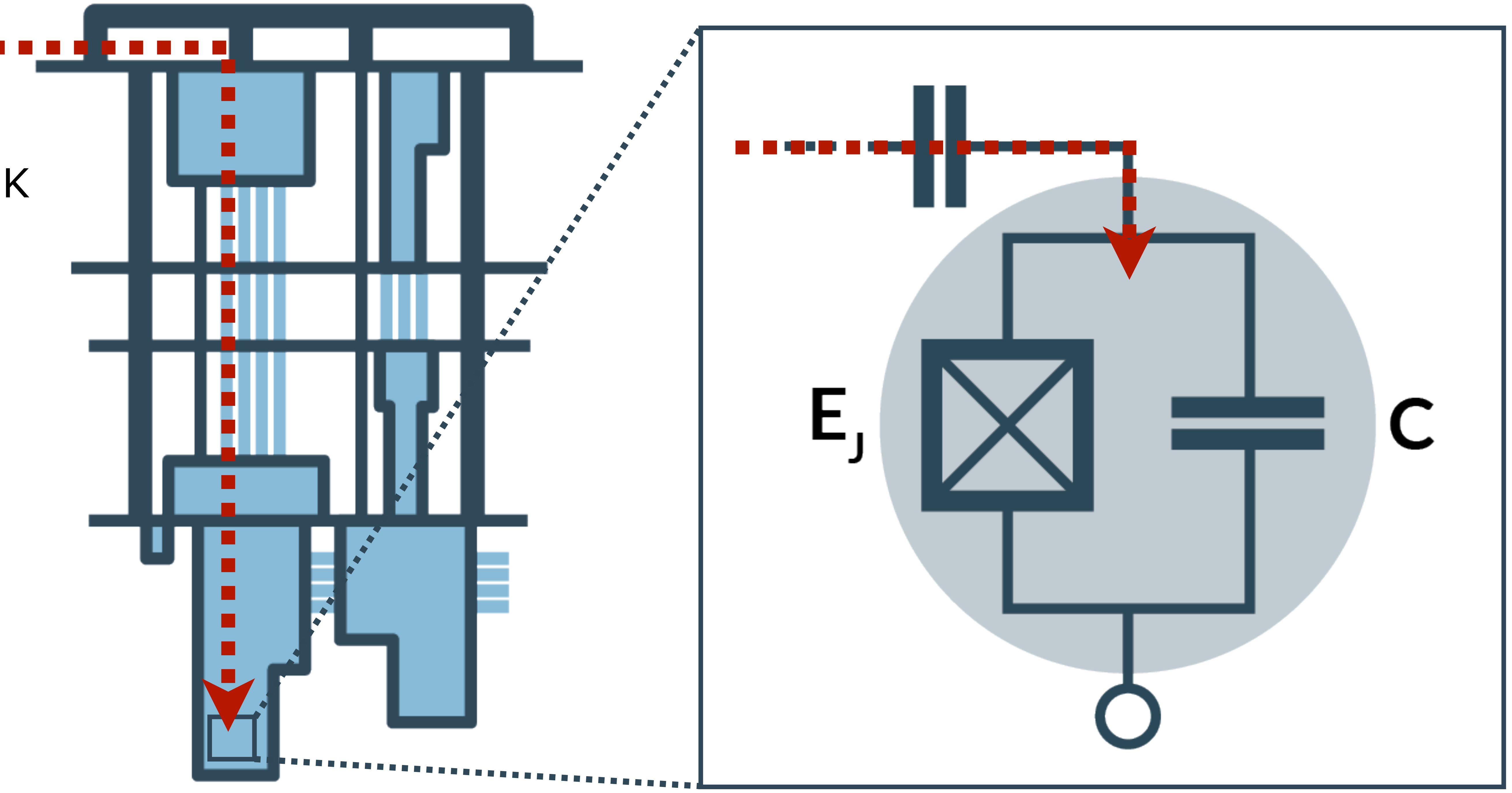
Signal @ room temp.

- Cooled down to ~20mK
- Frequency filtered



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Readout signal

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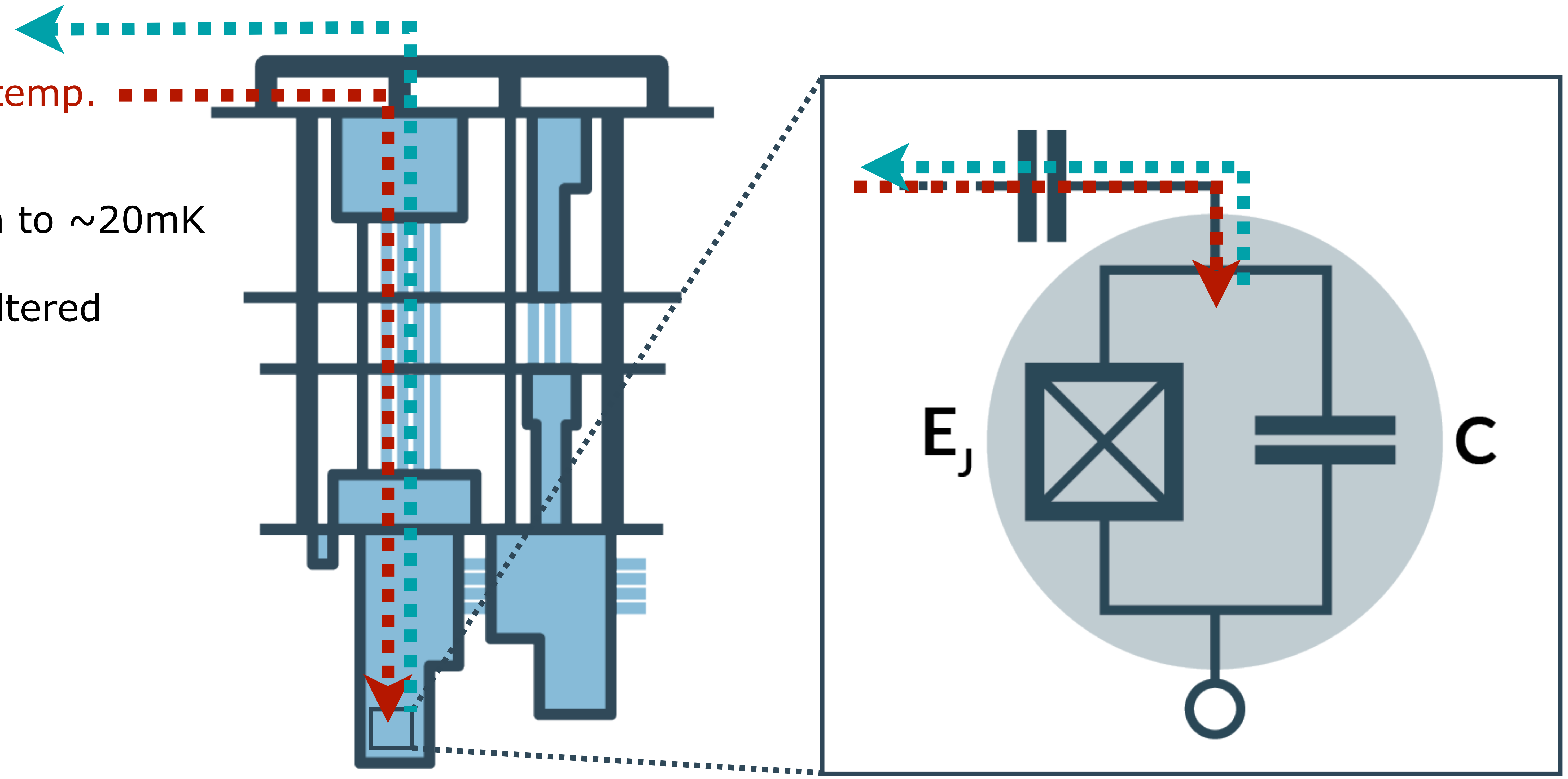

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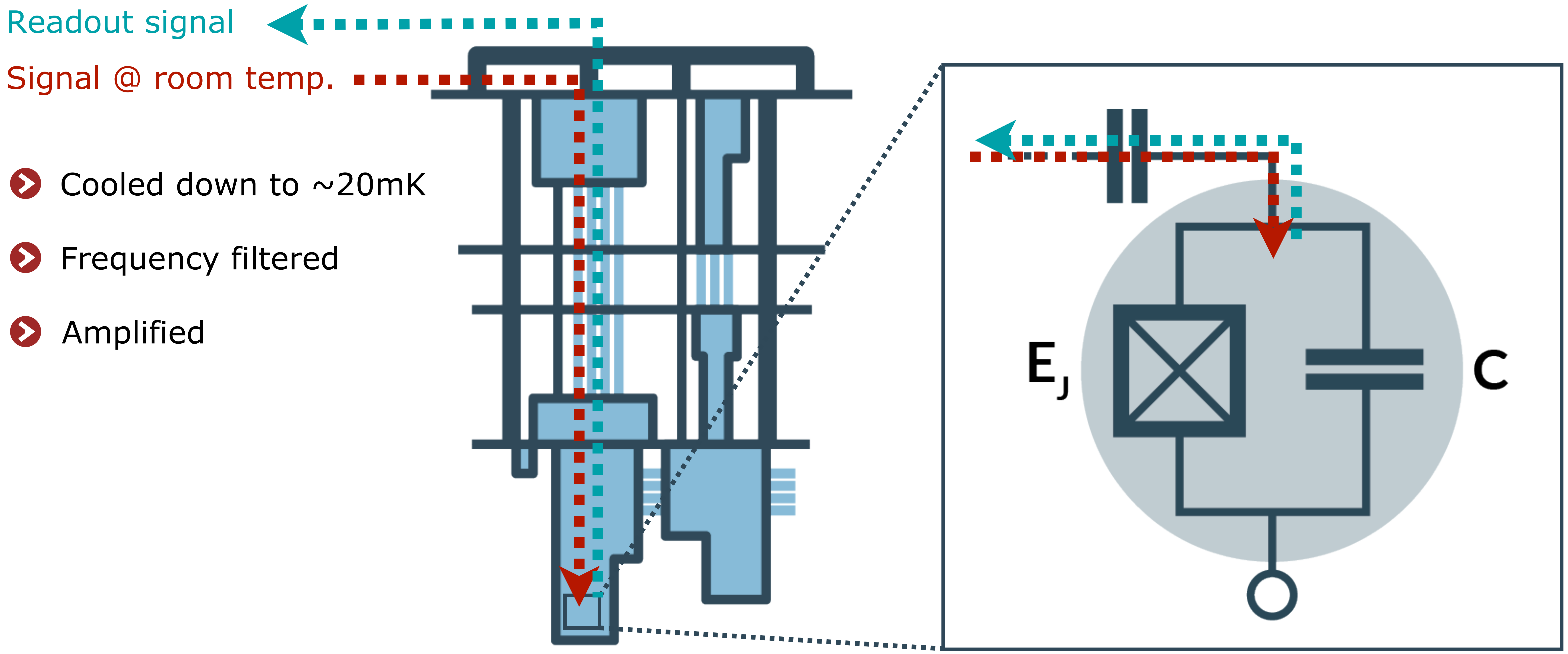

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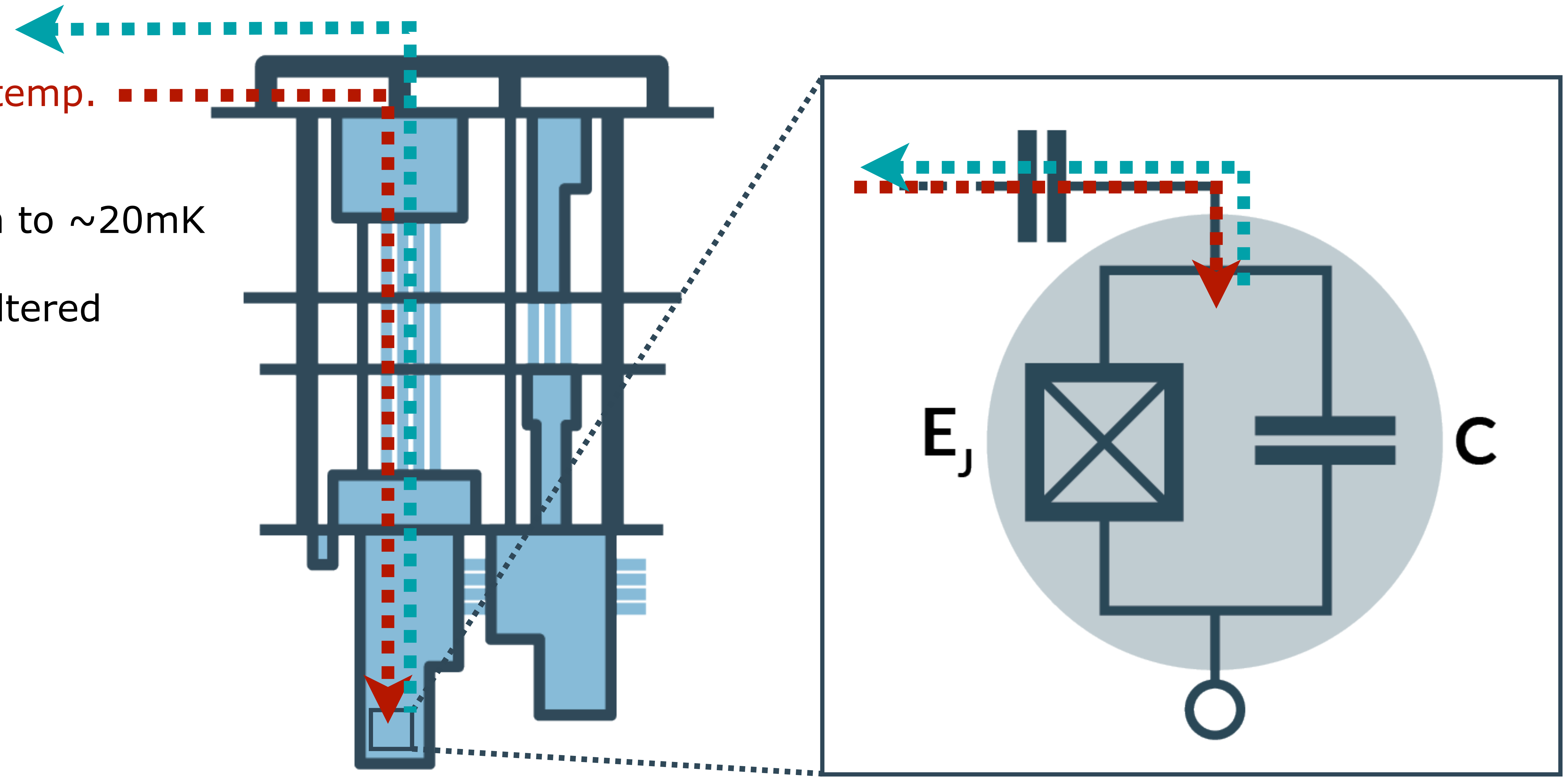
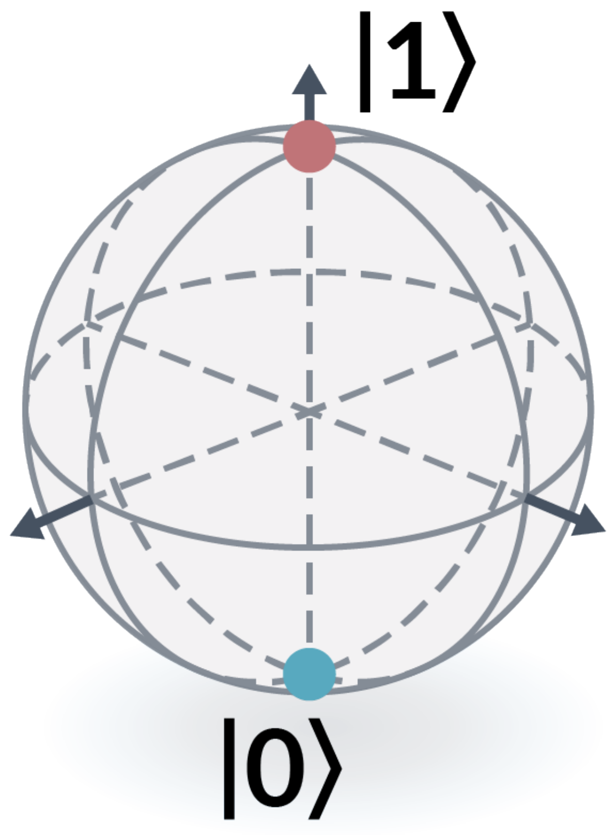


Inevitable coupling to bath

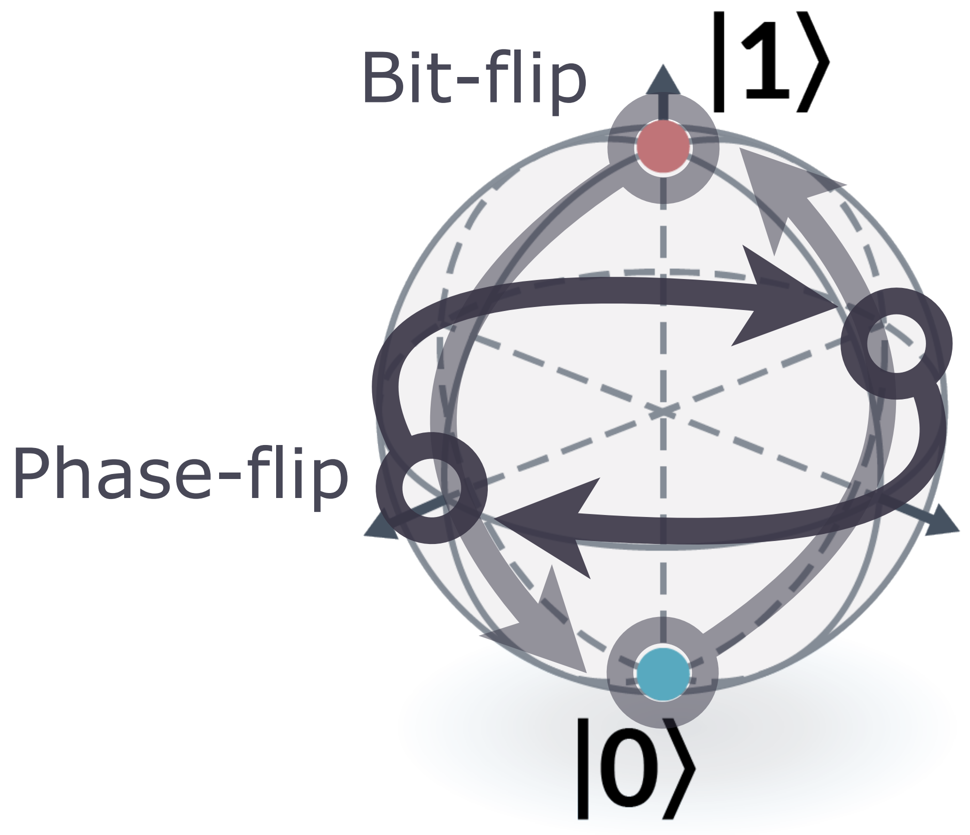
Quantum error correction



Error discretisation theorem

Correcting Pauli errors = correcting arbitrary errors

Quantum error correction



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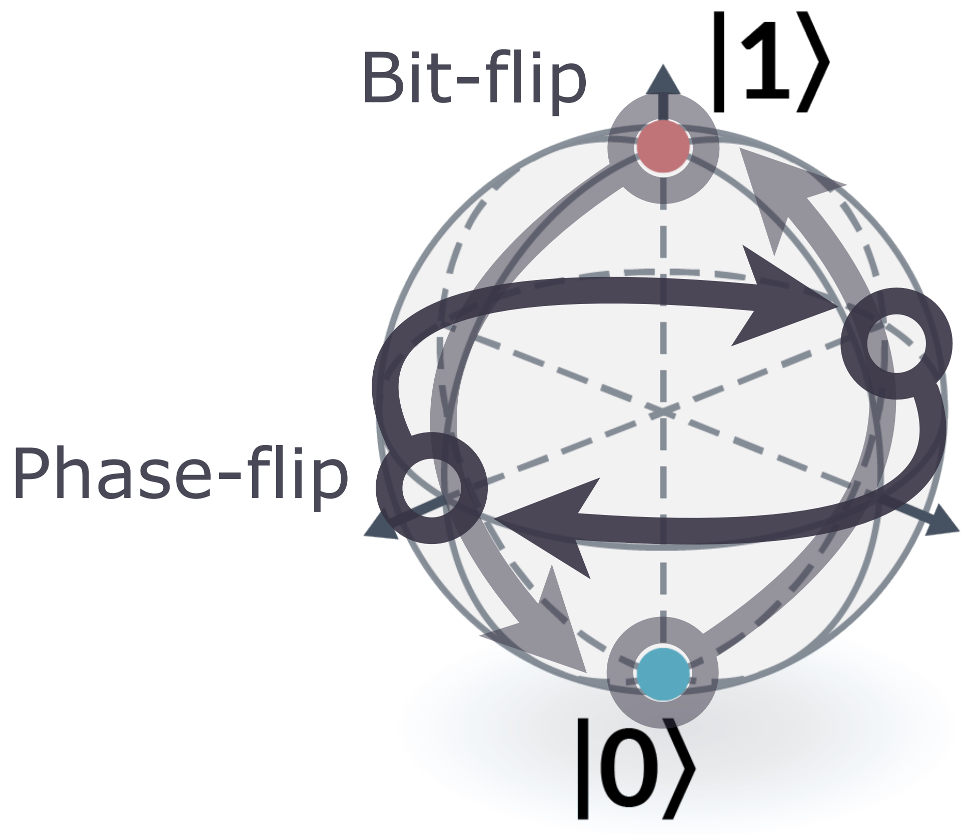

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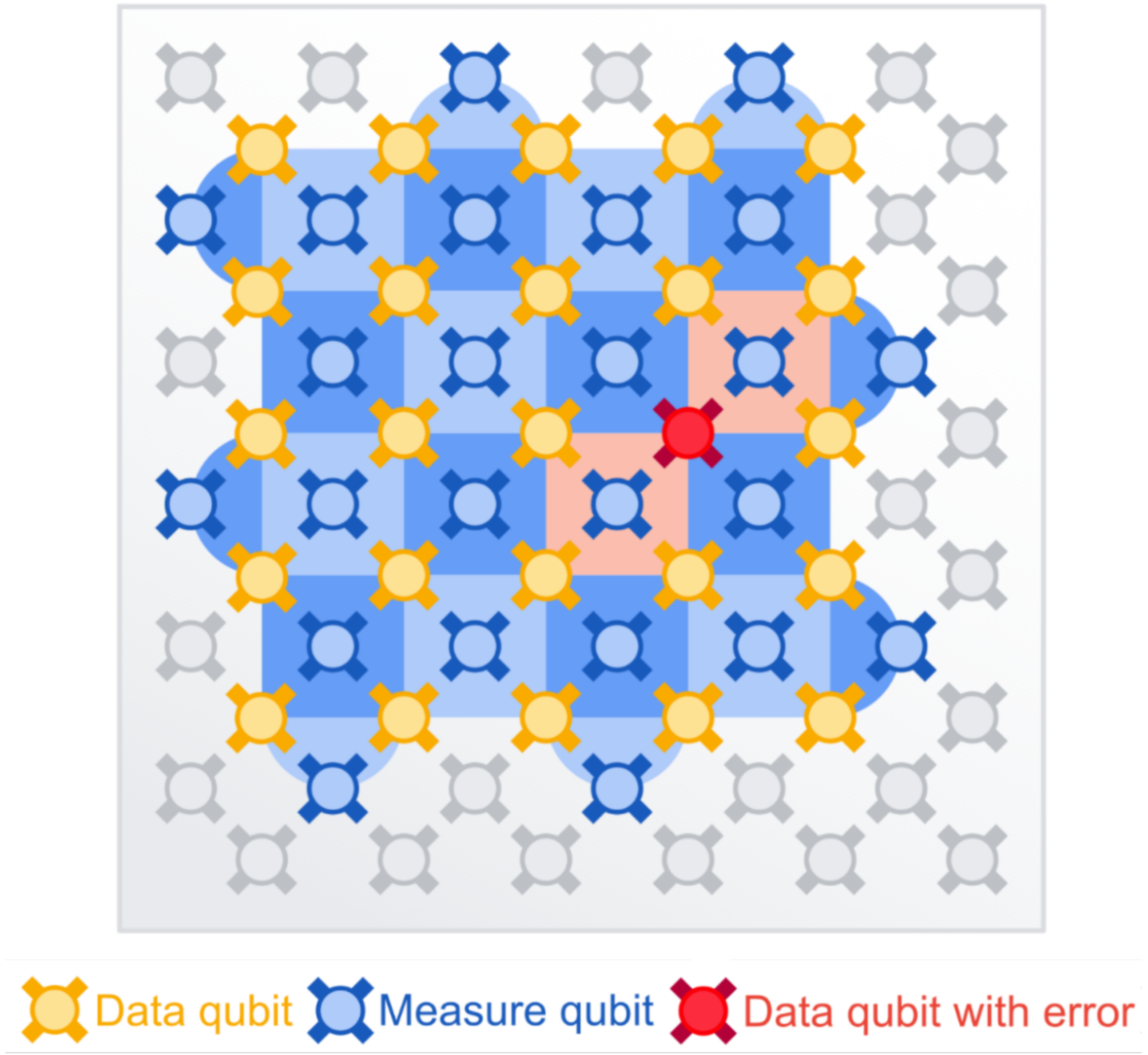
Discrete qubit codes



Google Quantum AI, Nature 2022

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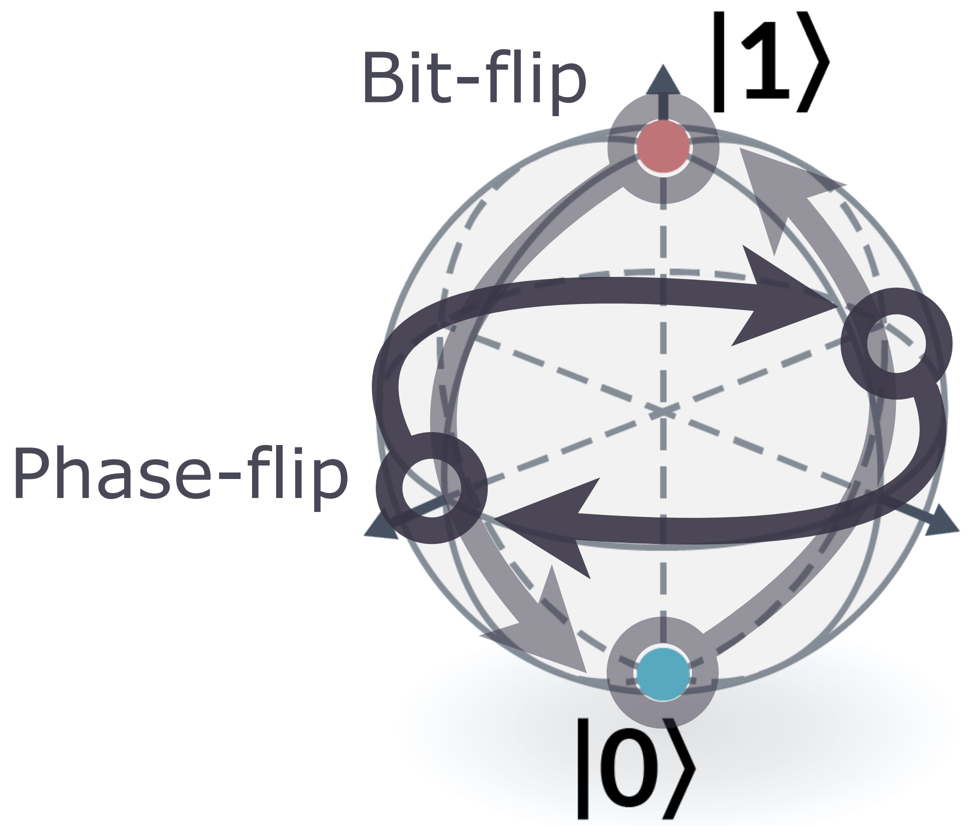

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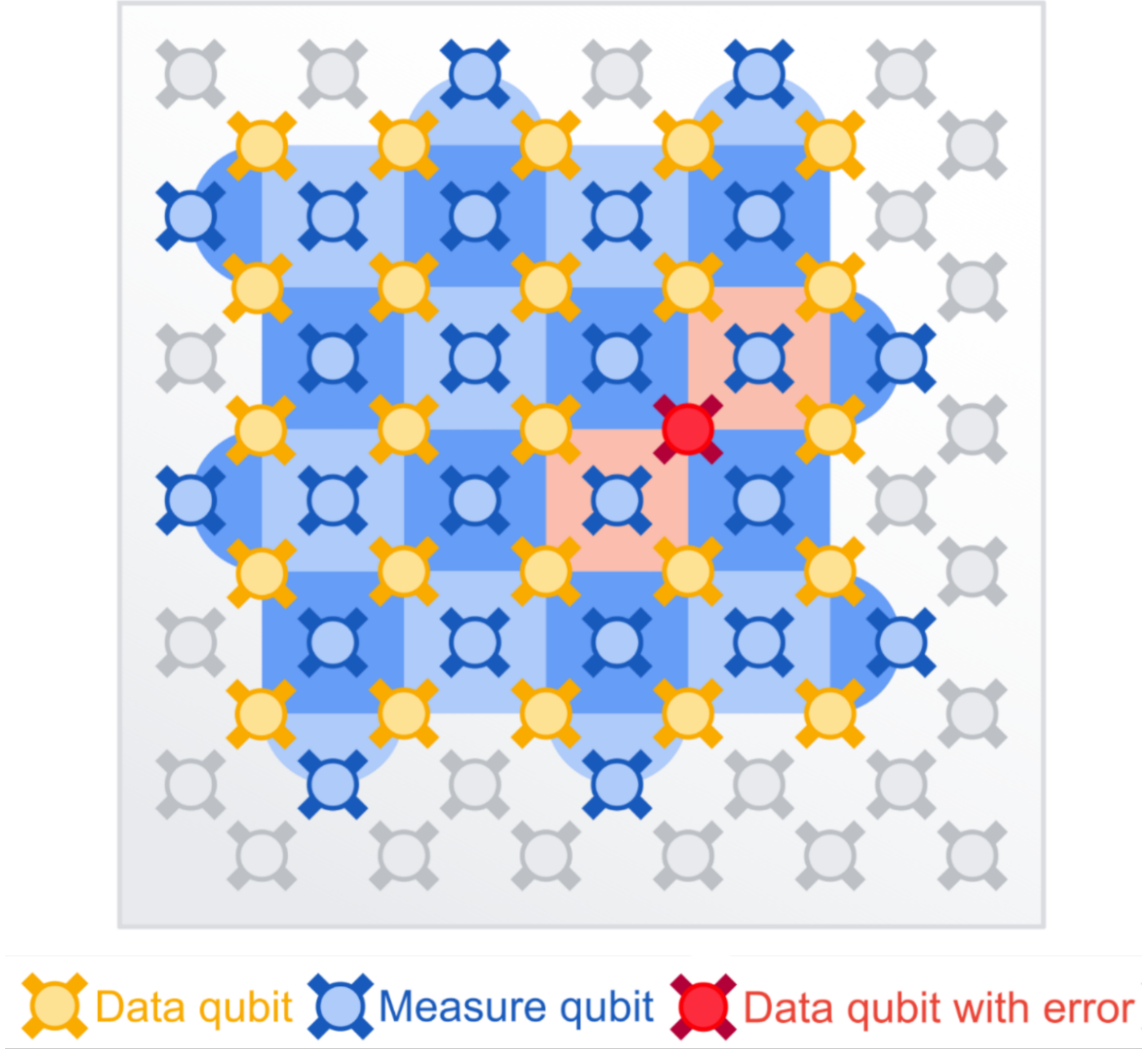

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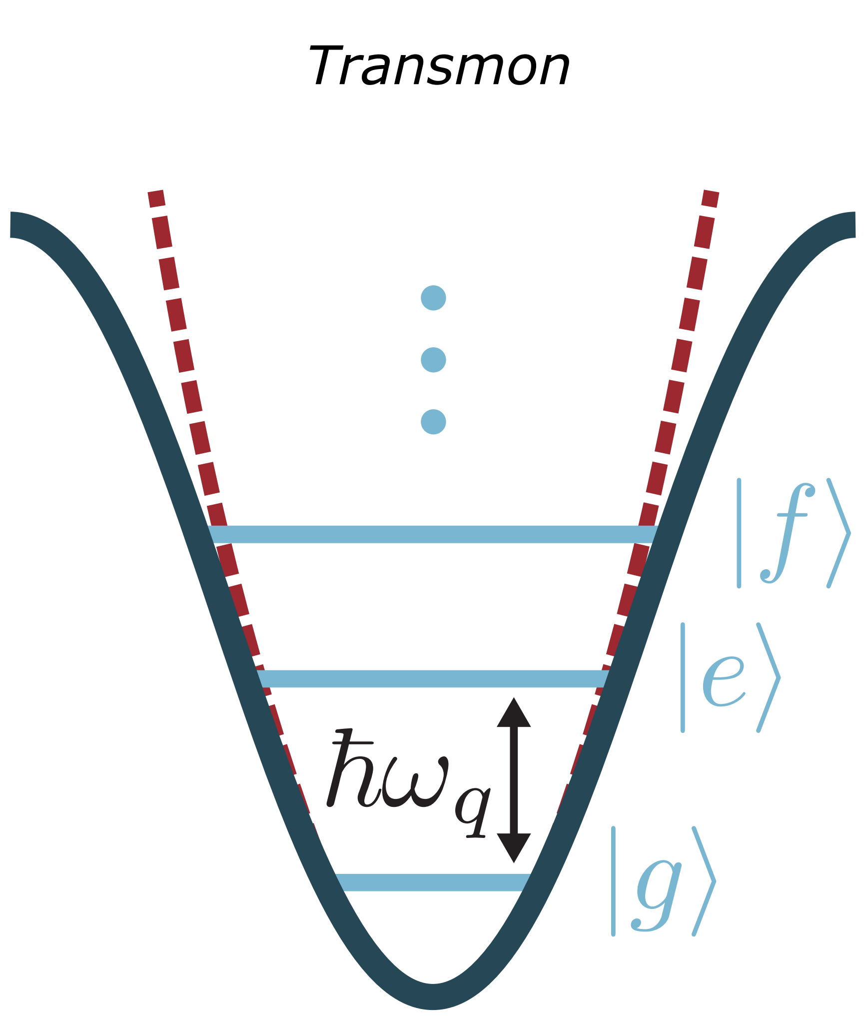

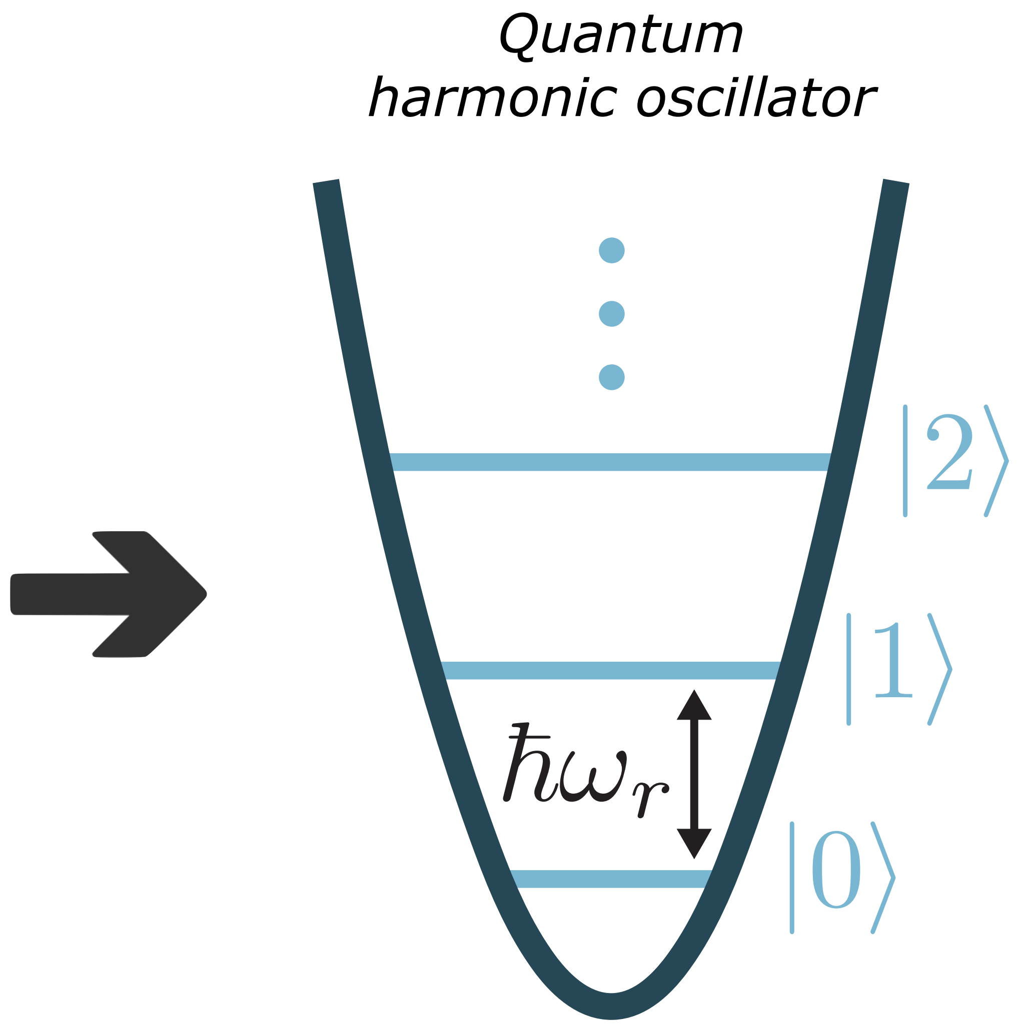

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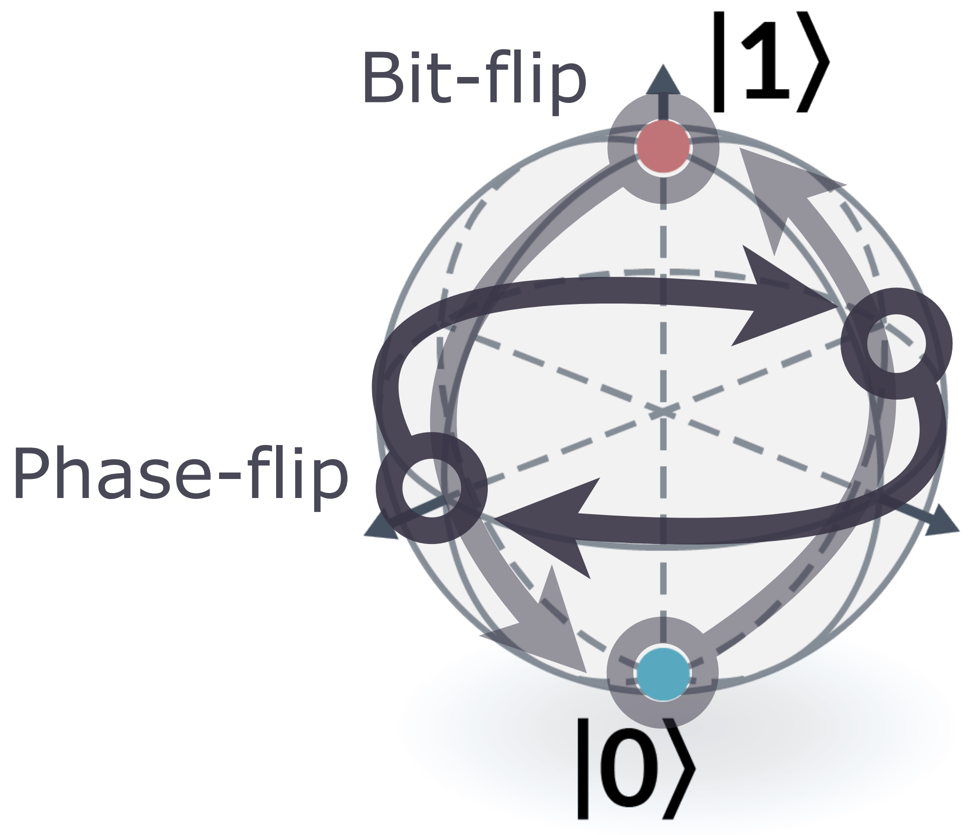

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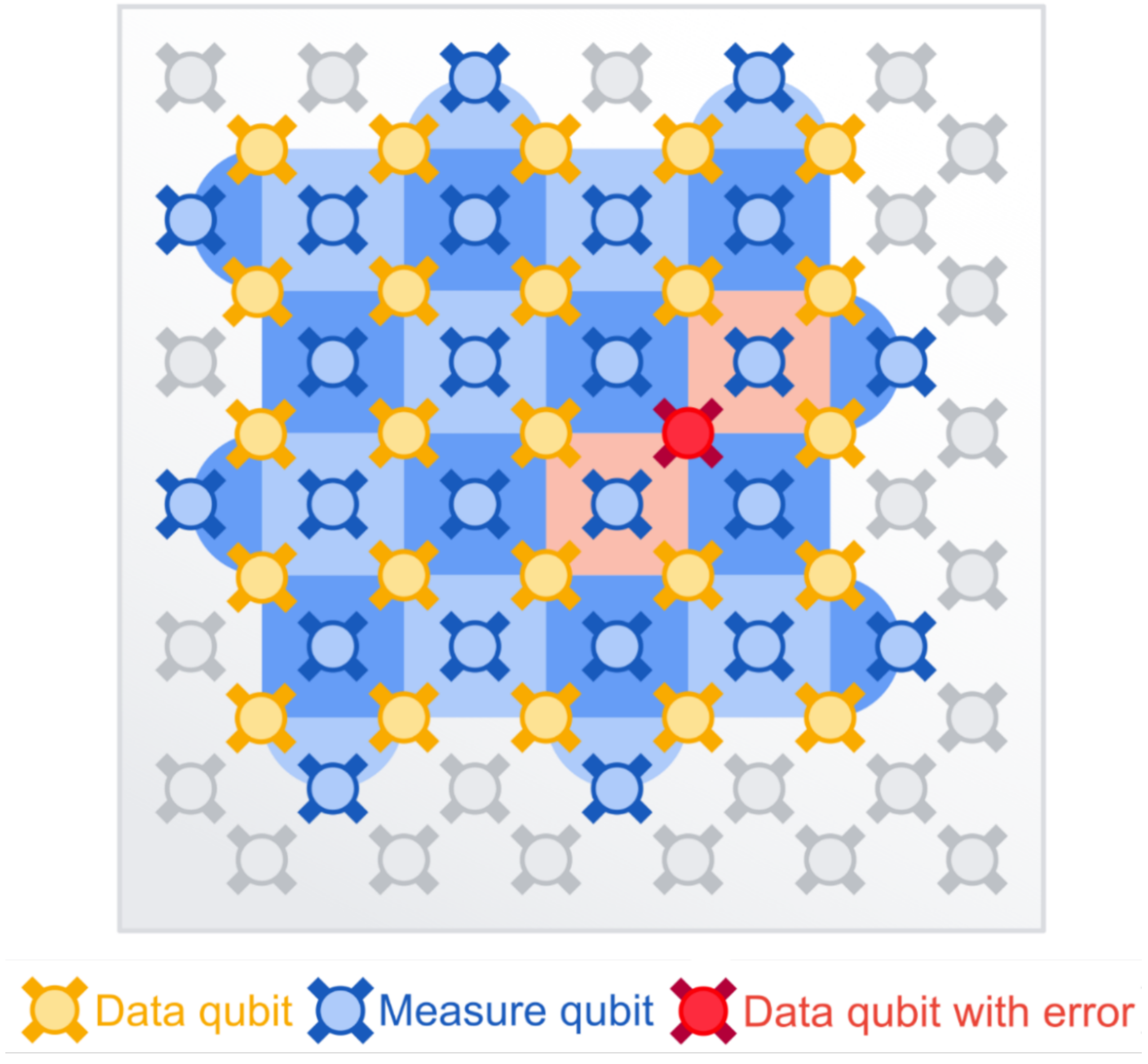

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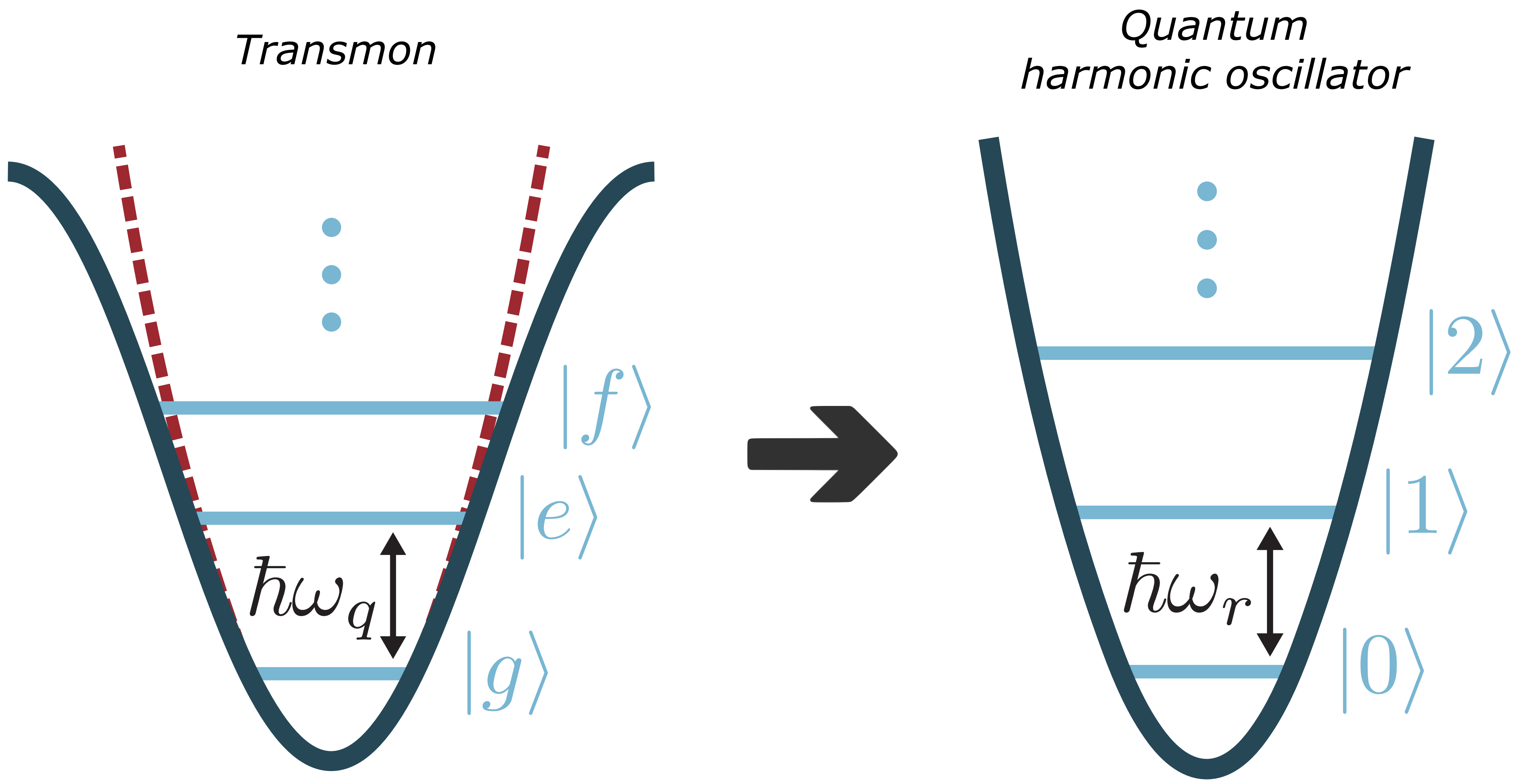

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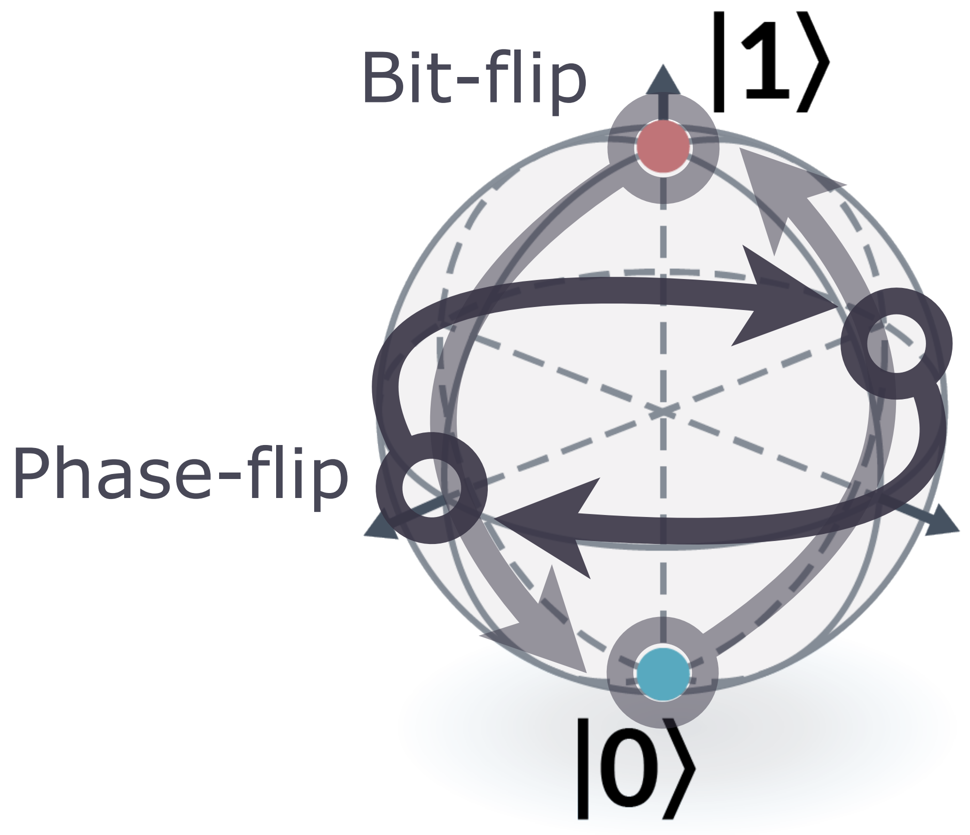

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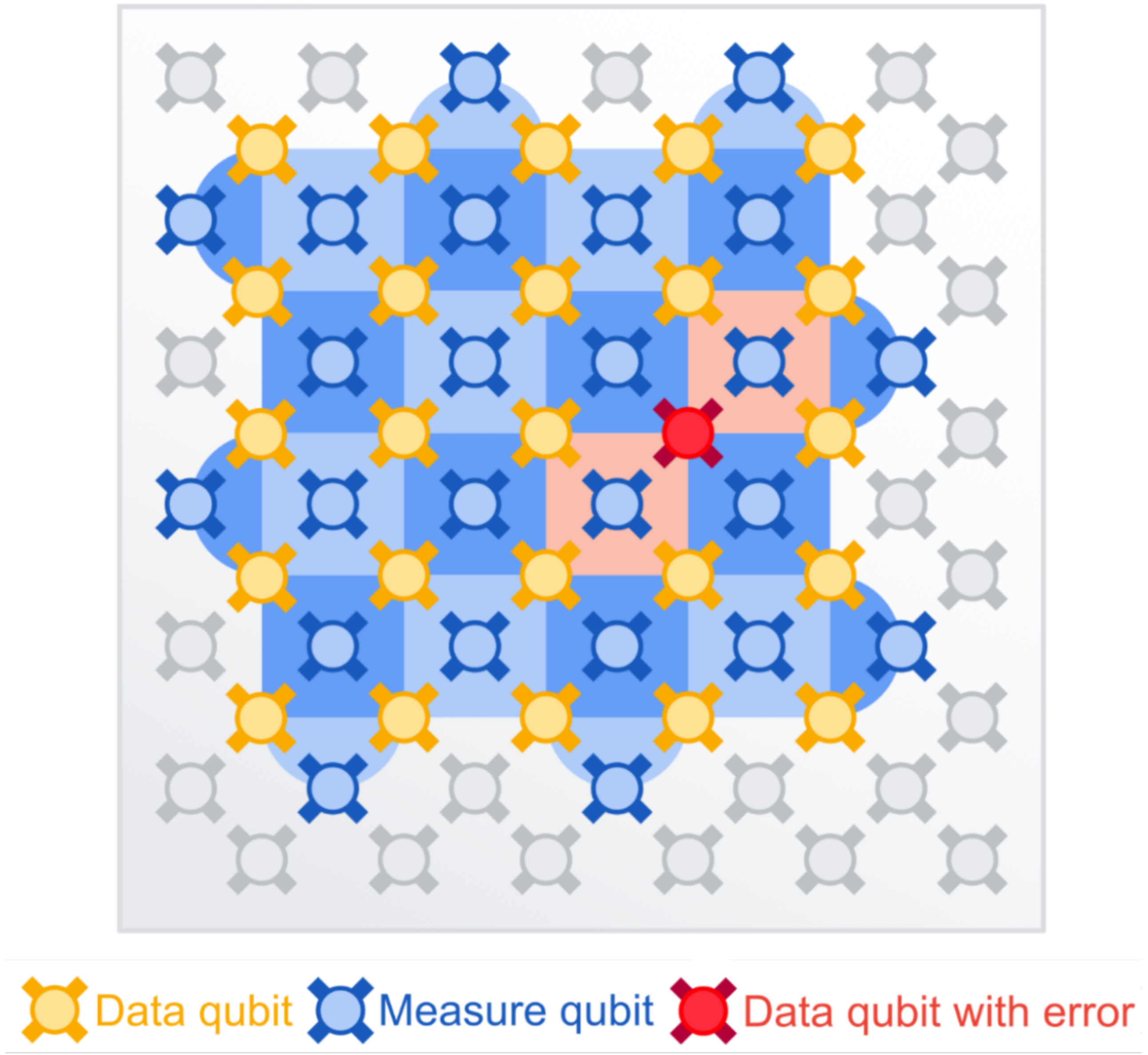

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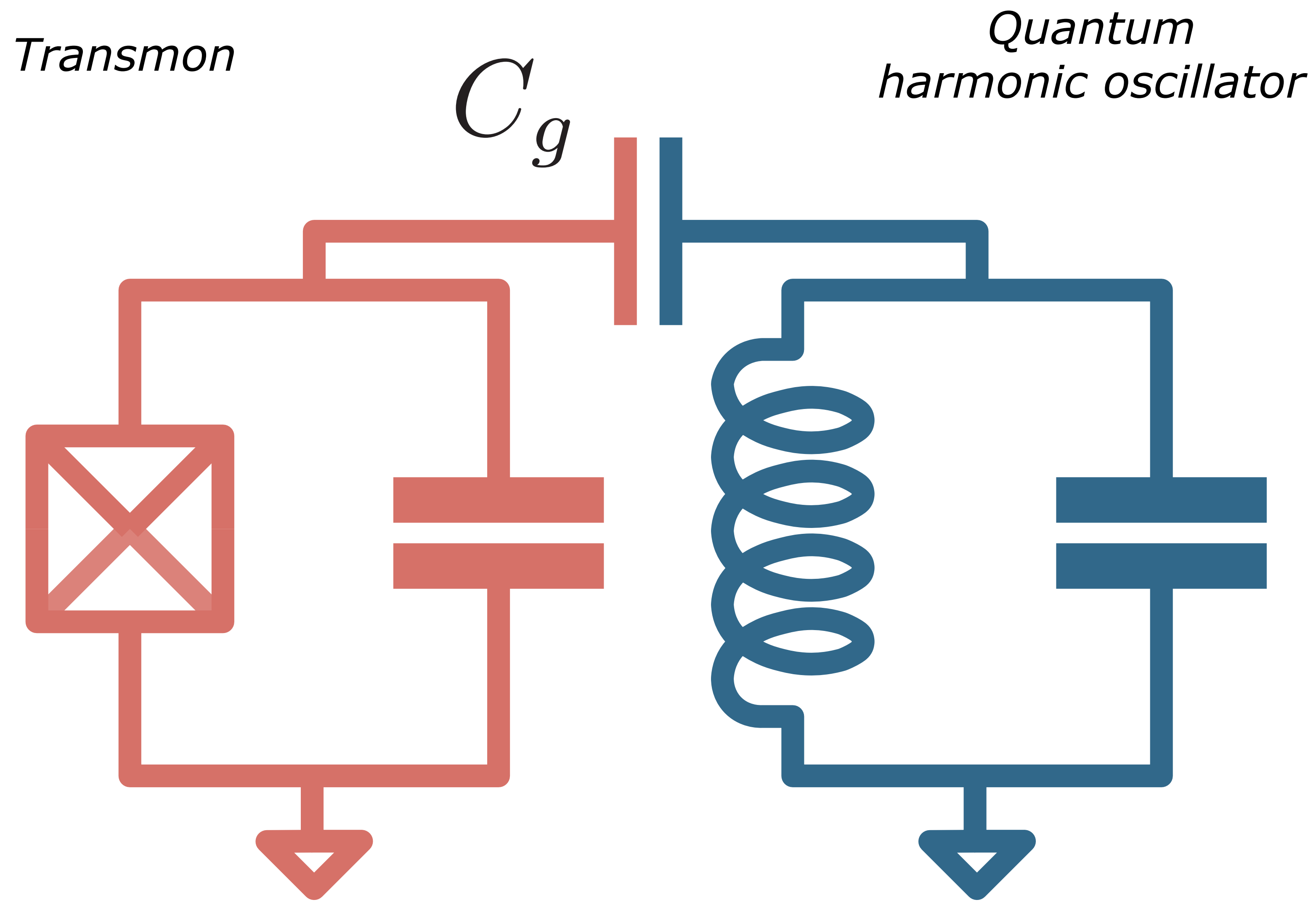
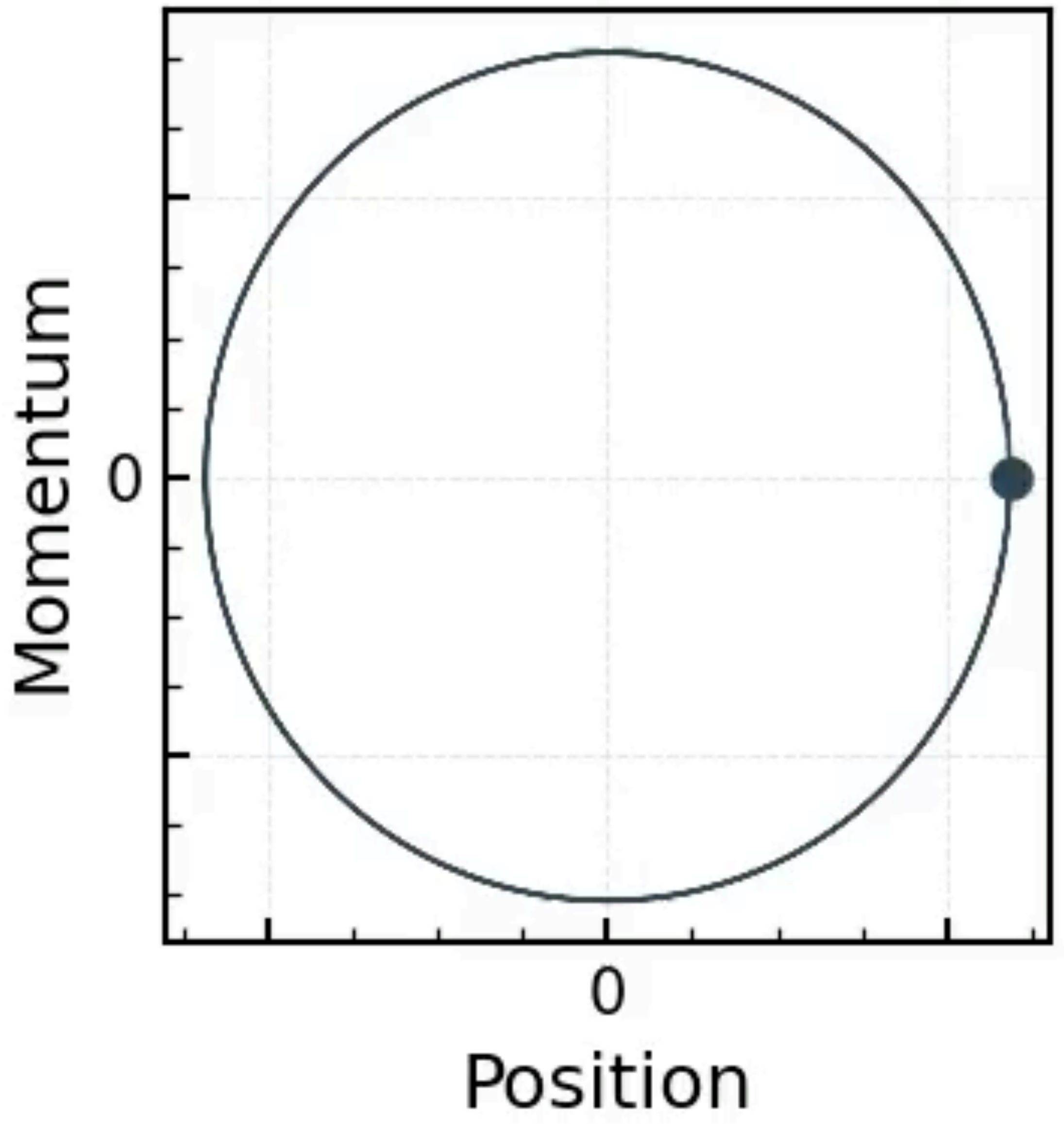


Encoding harmonic oscillators

How can we encode a harmonic oscillator?



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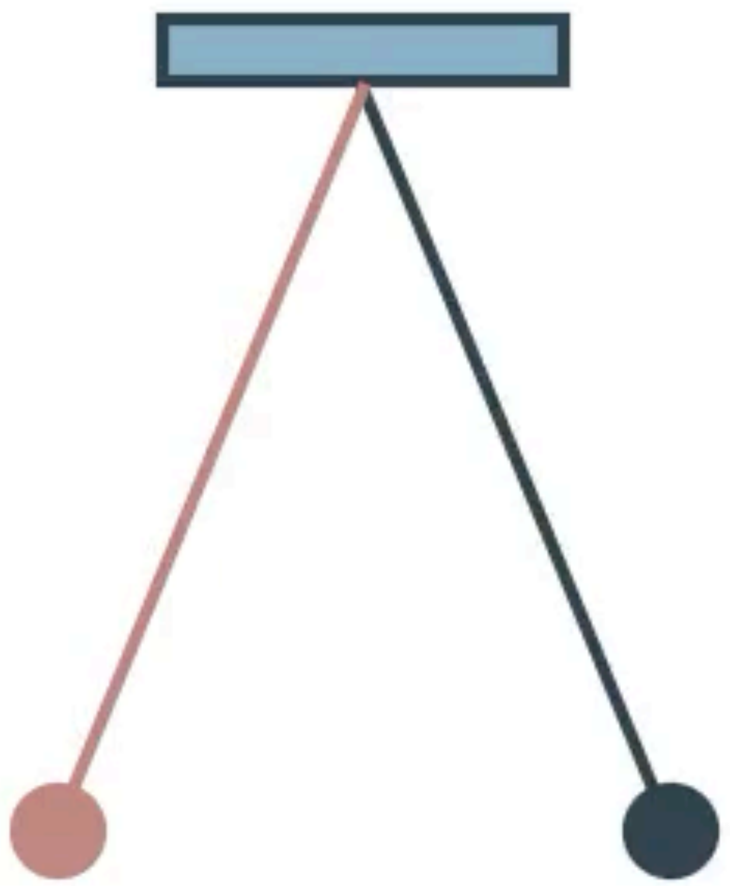

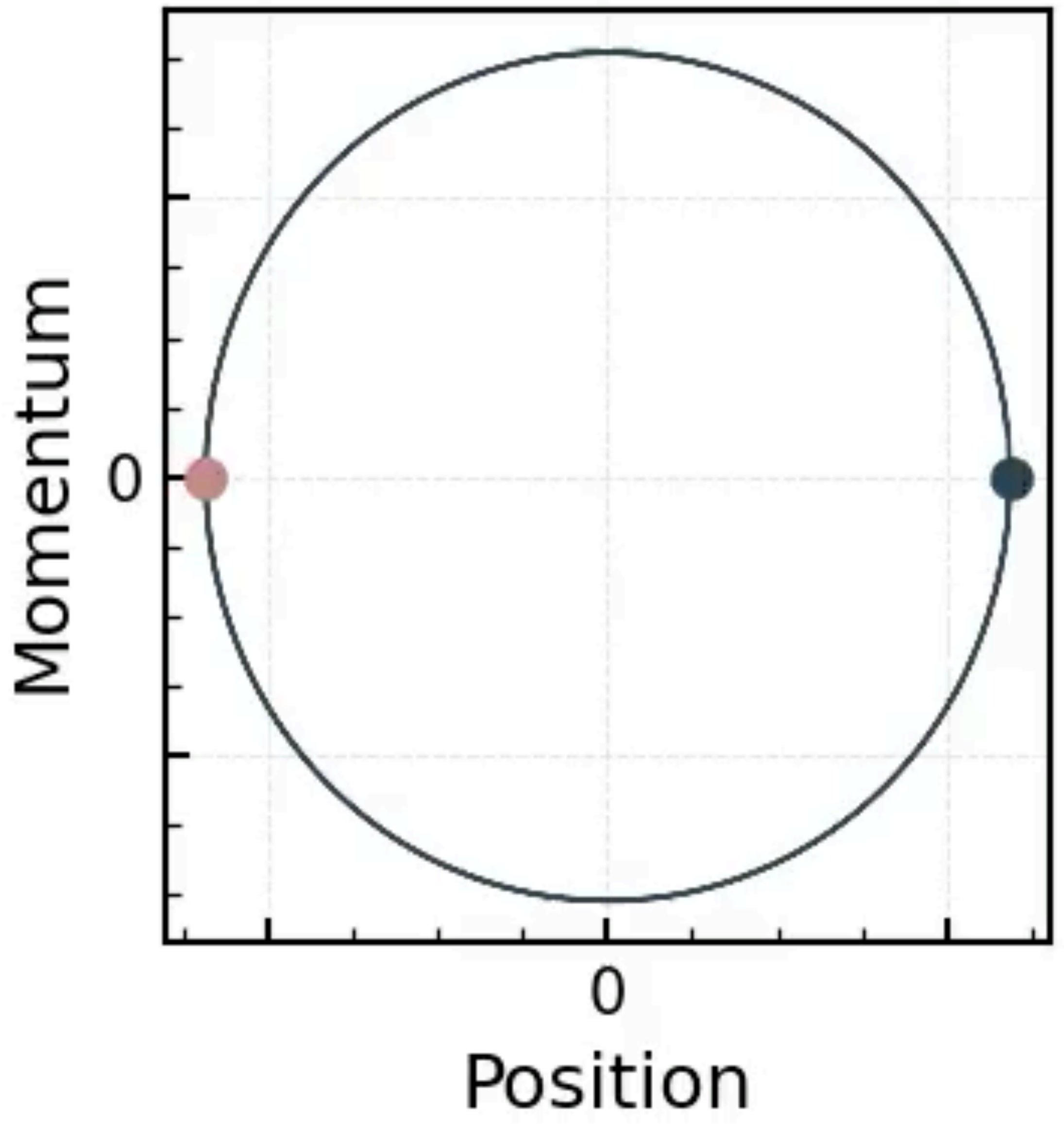

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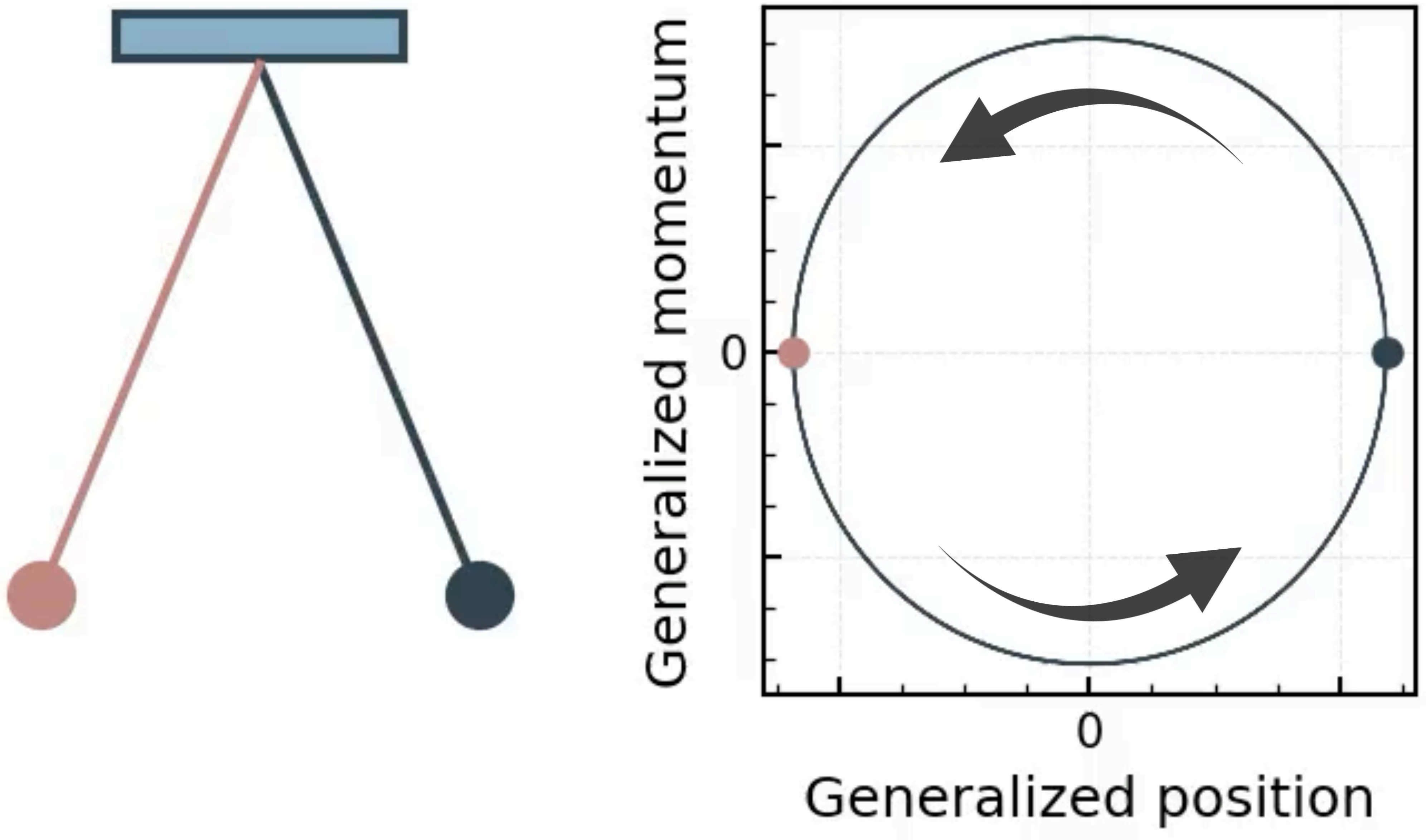

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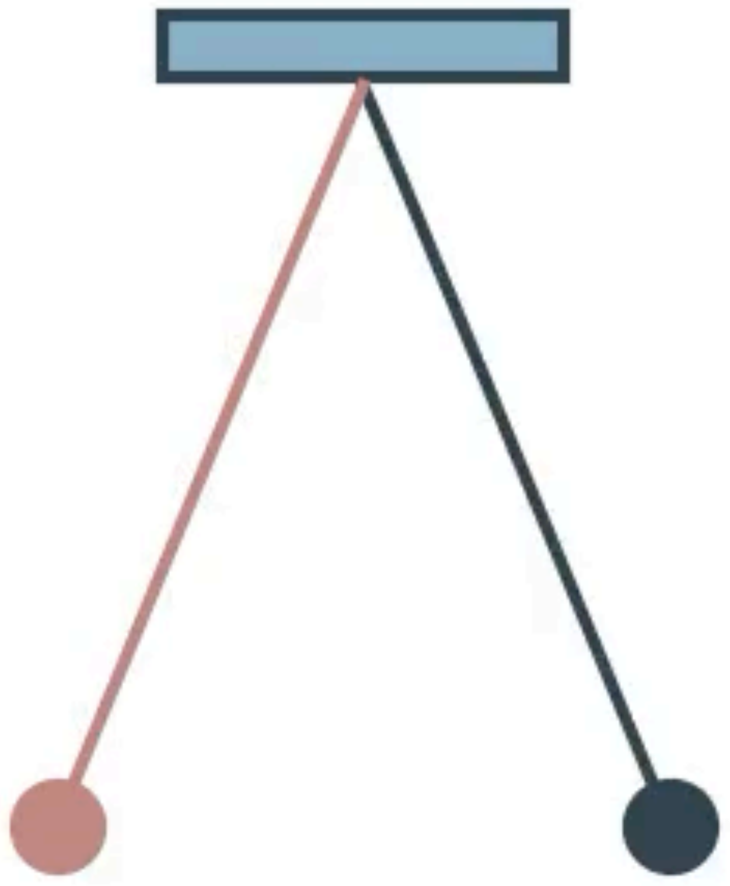

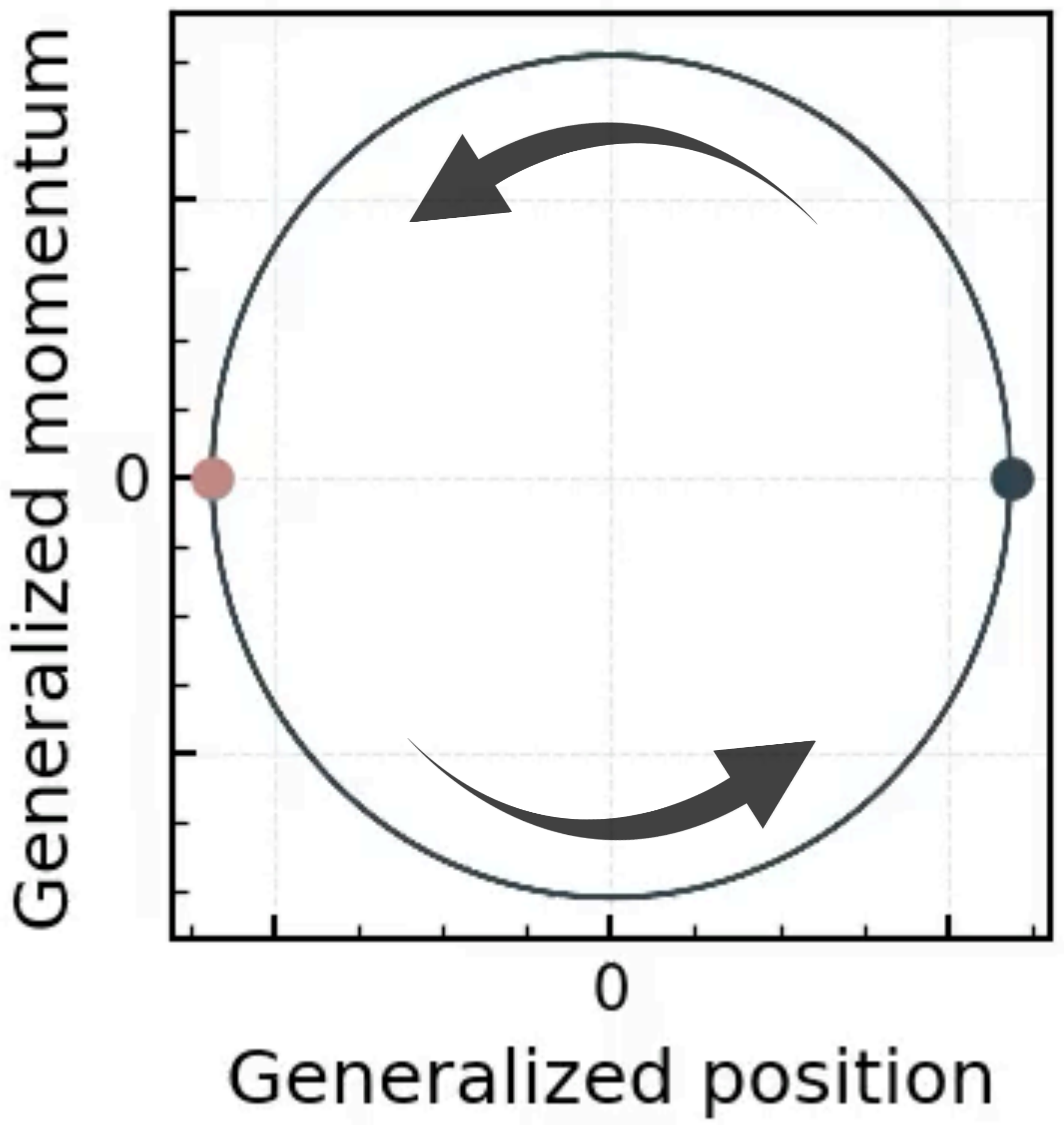

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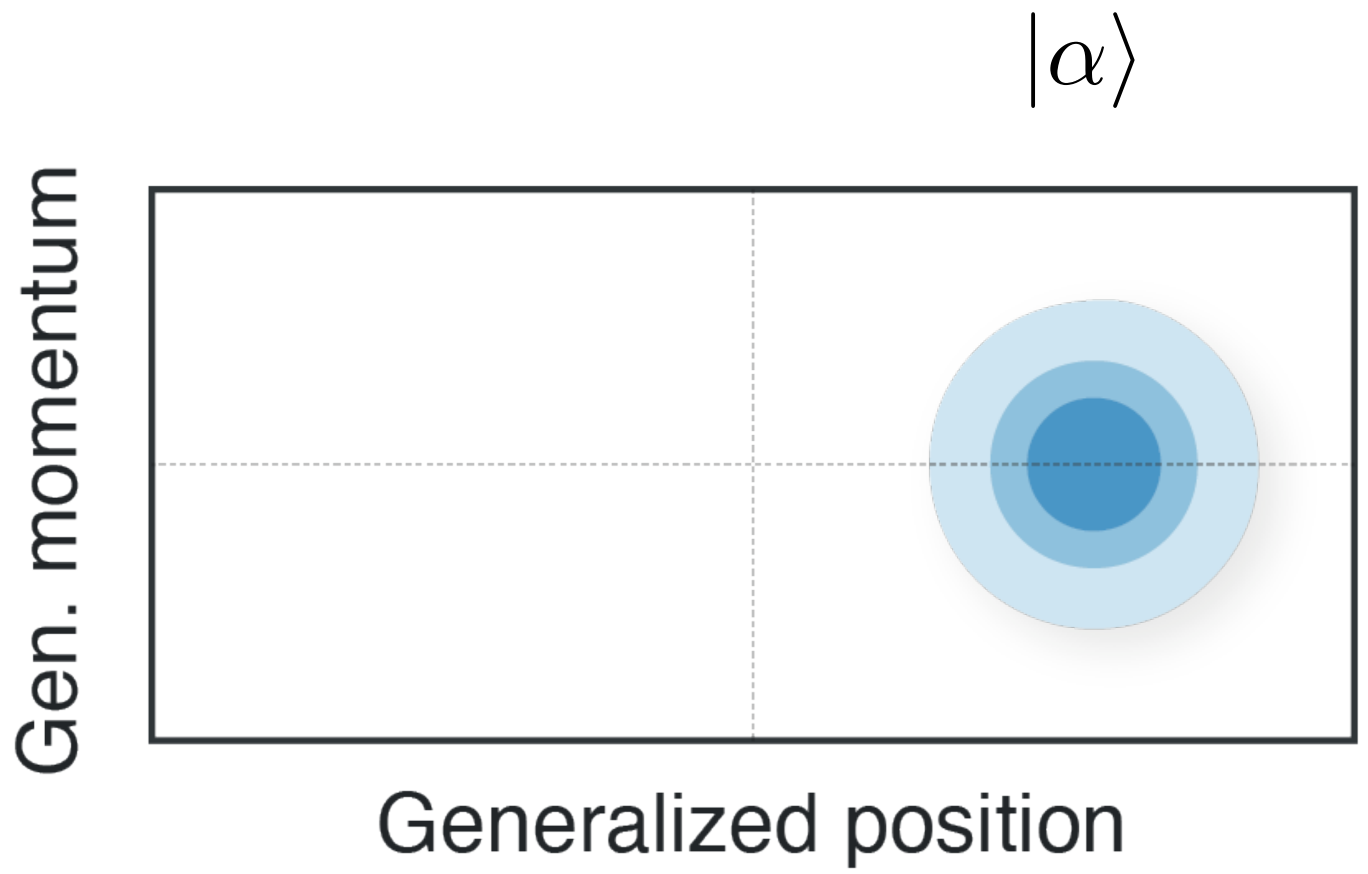

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with $\hat{a} = \hat{x} + i\hat{p}$

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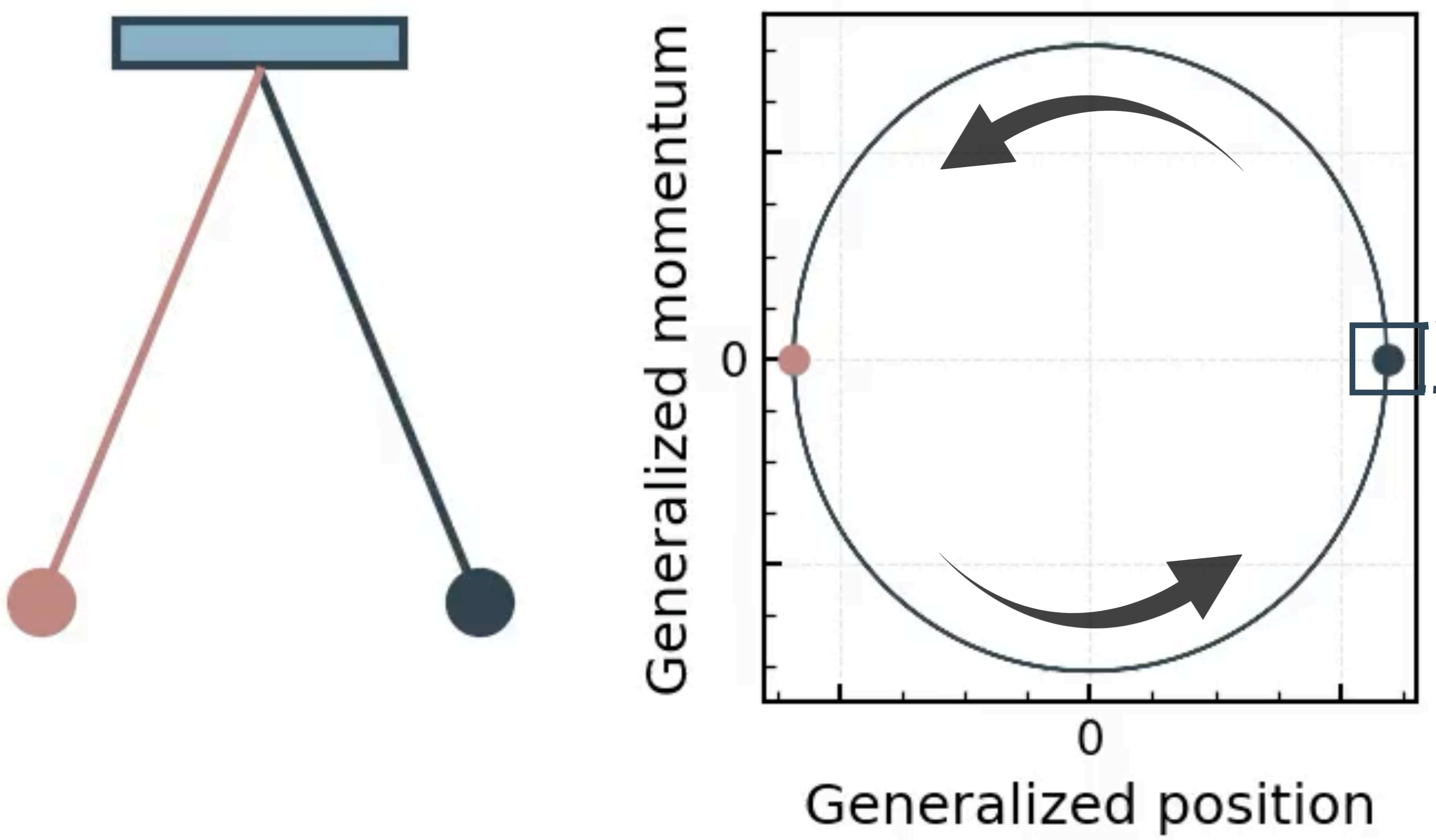

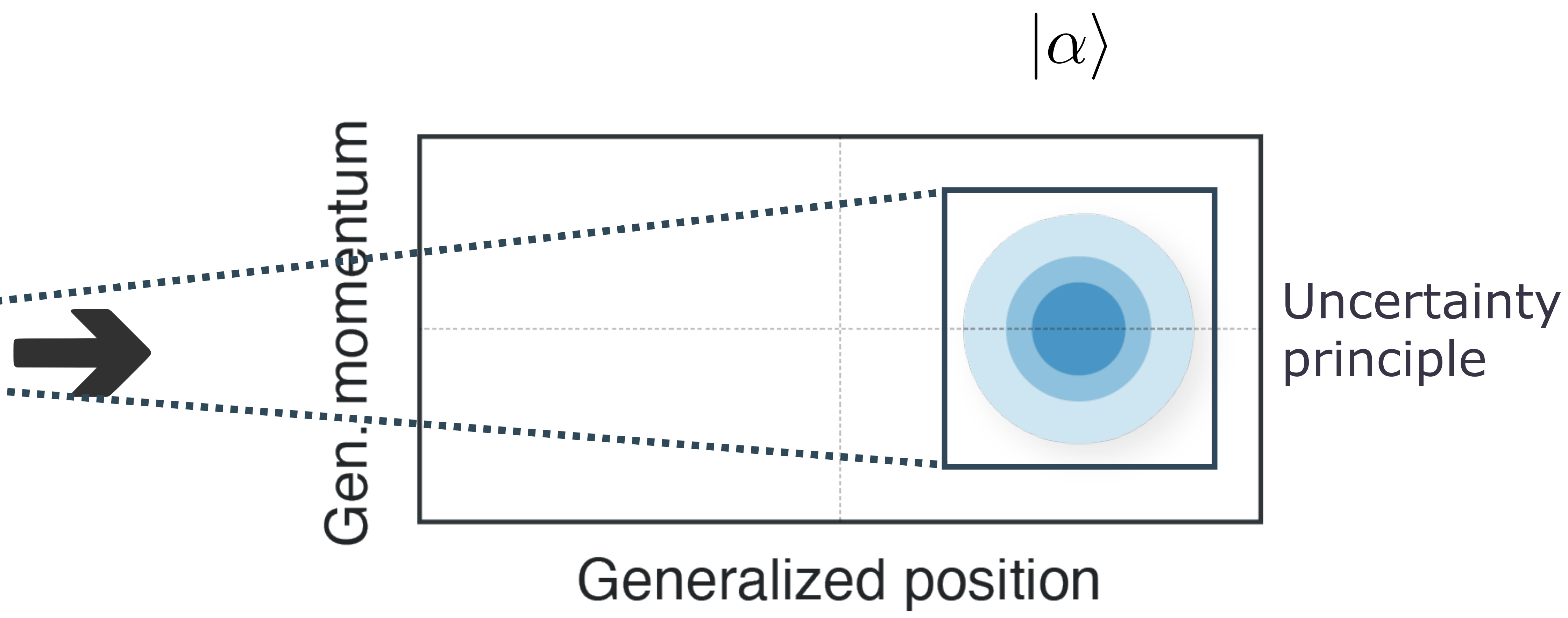

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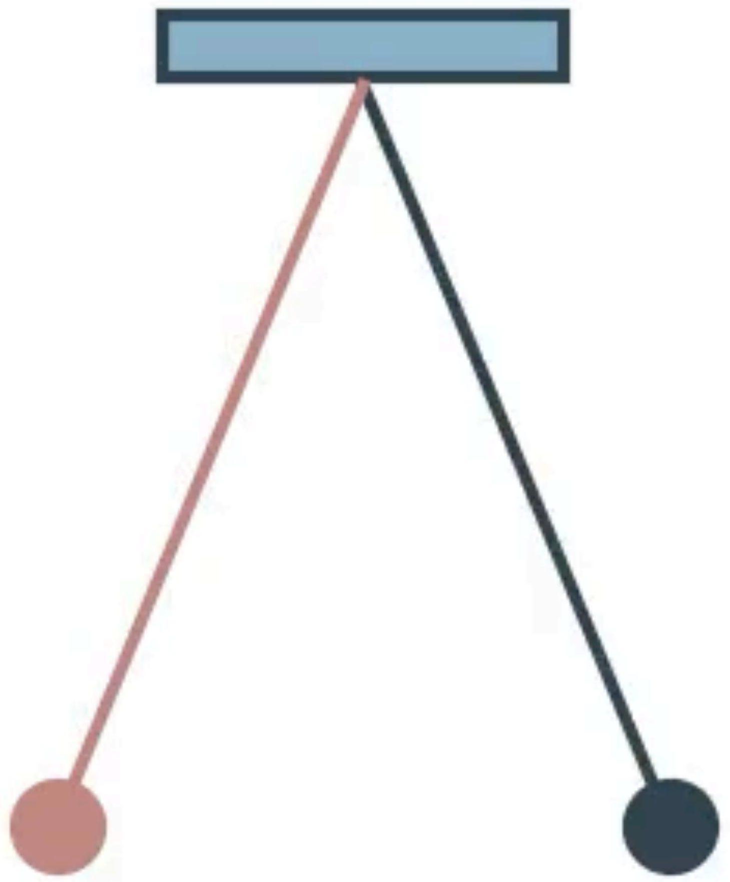

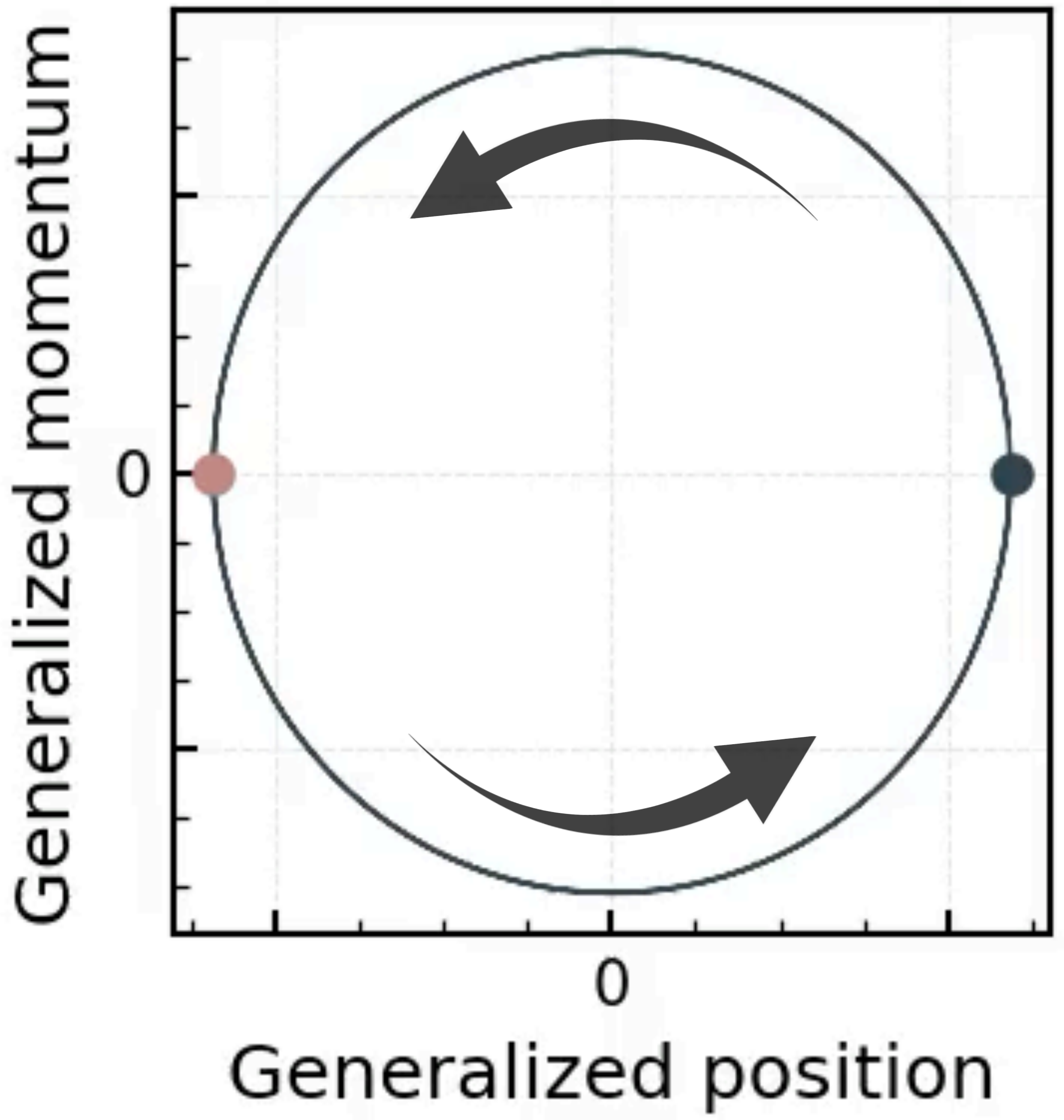

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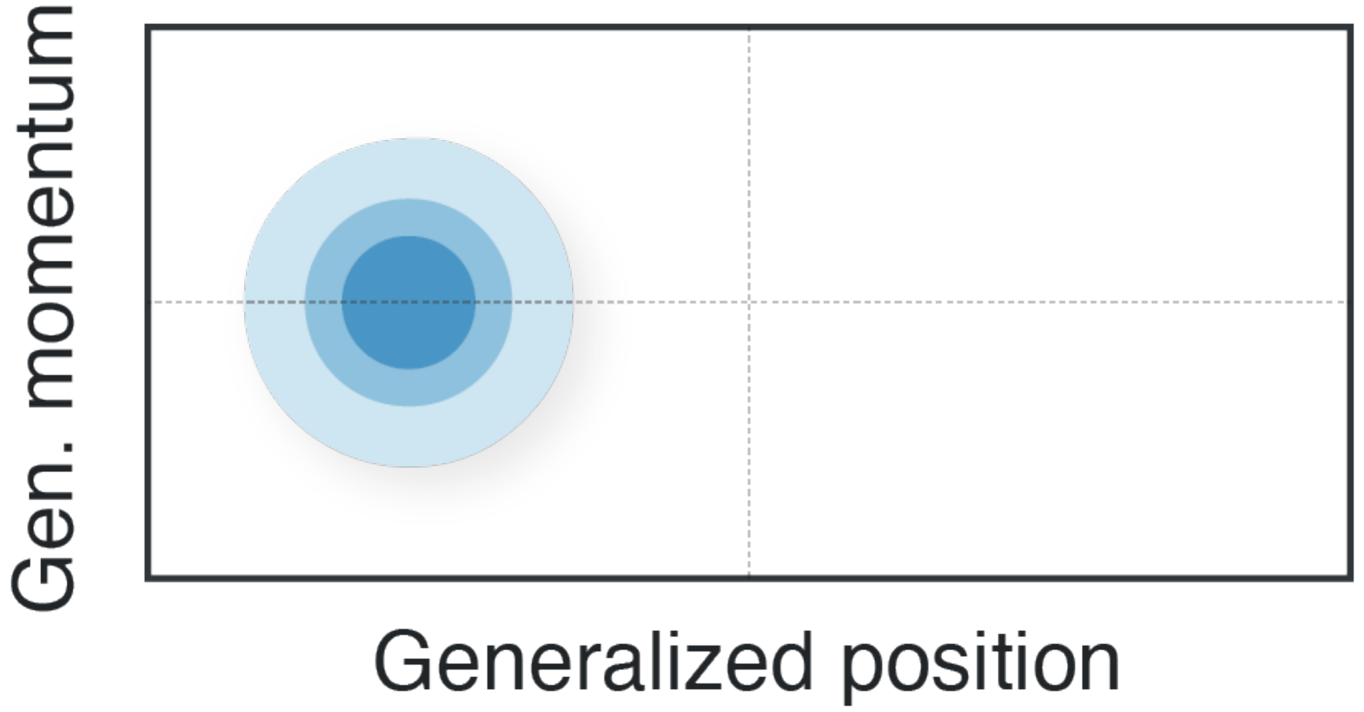

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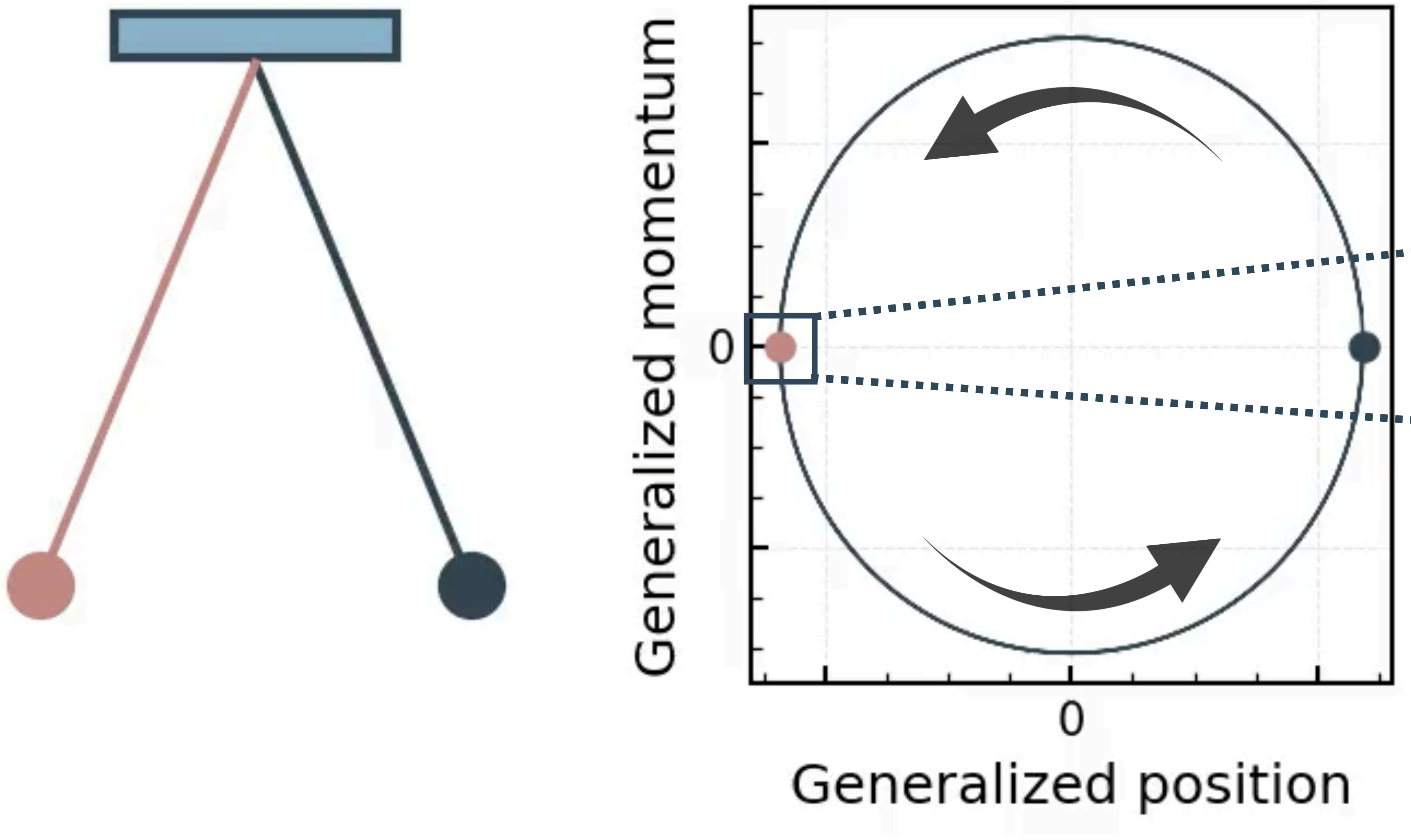
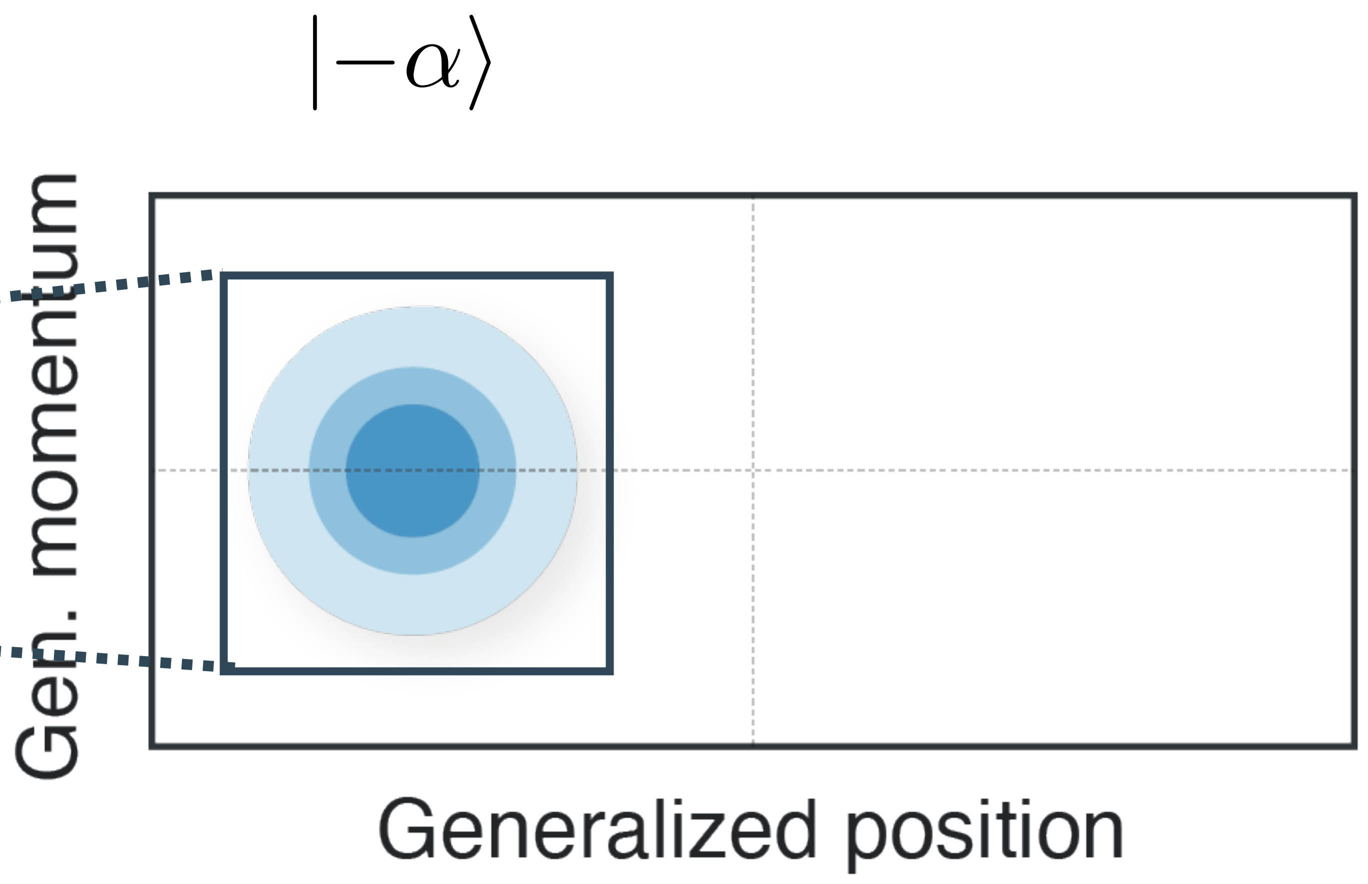


How can we encode a <u>quantum</u> harmonic oscillator?



where $\hat{a}|\pm\alpha\rangle = \pm|\pm\alpha\rangle$

with $\hat{a} = \hat{x} + i\hat{p}$

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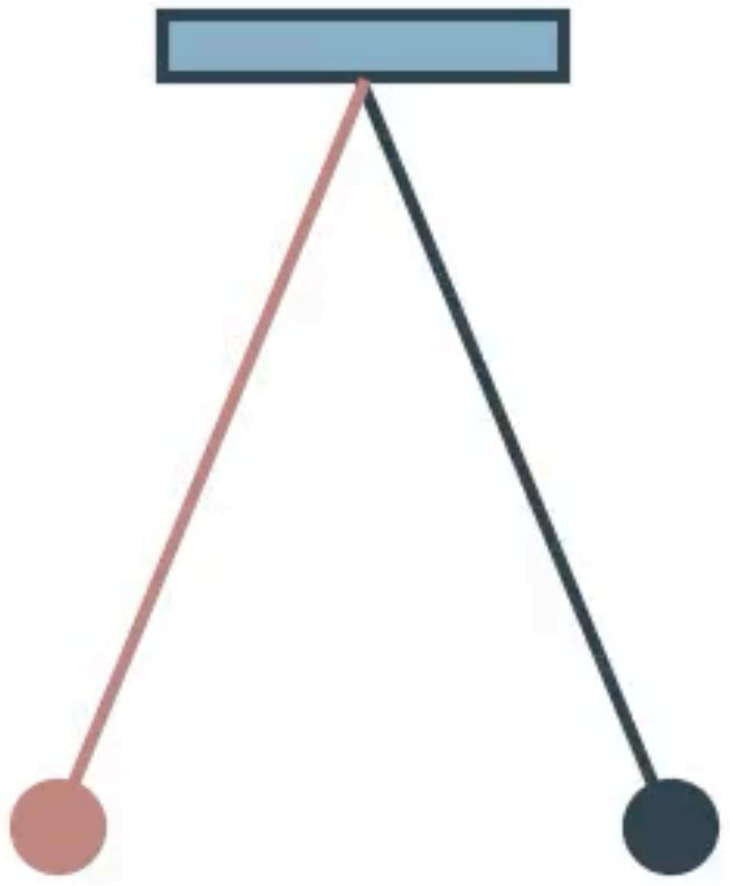

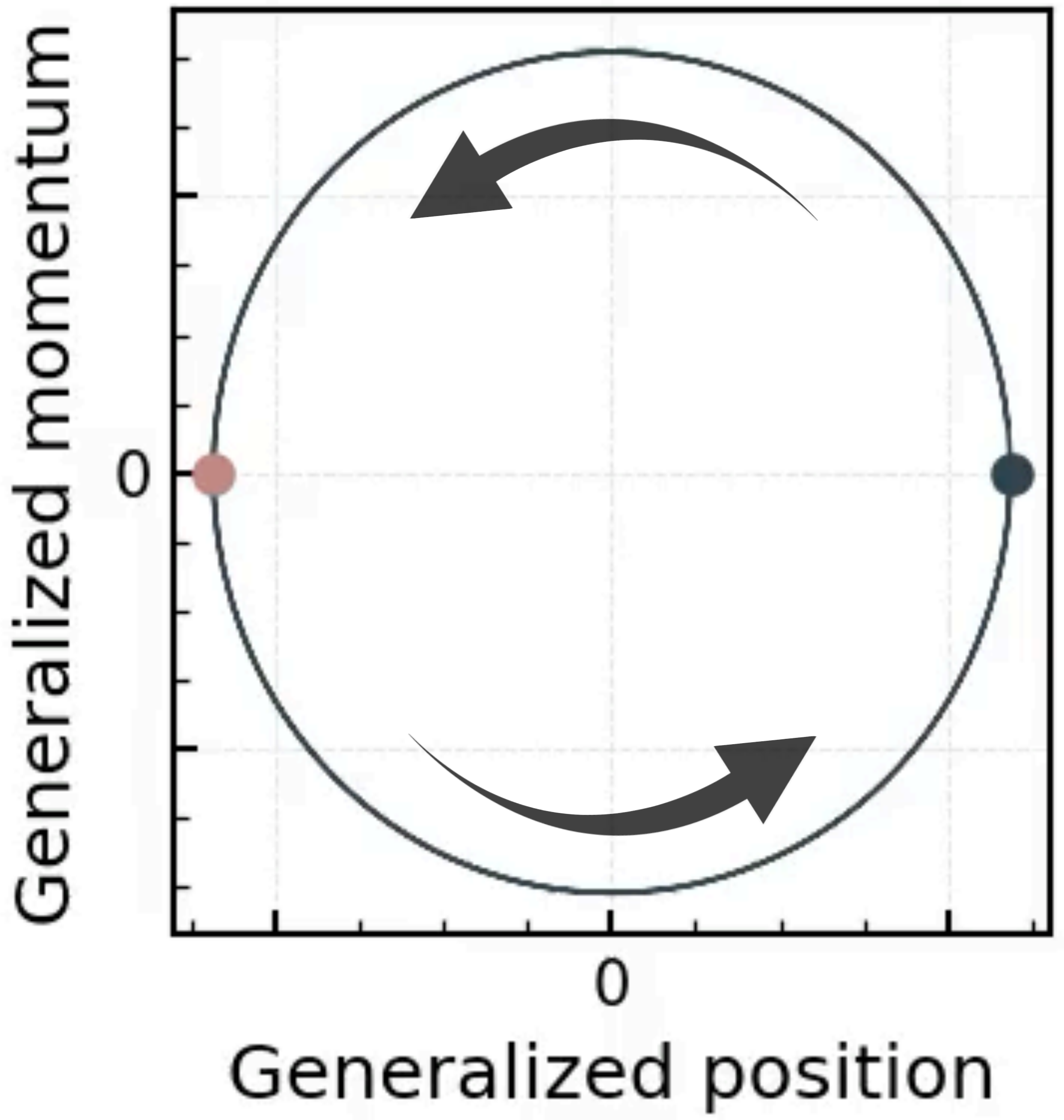

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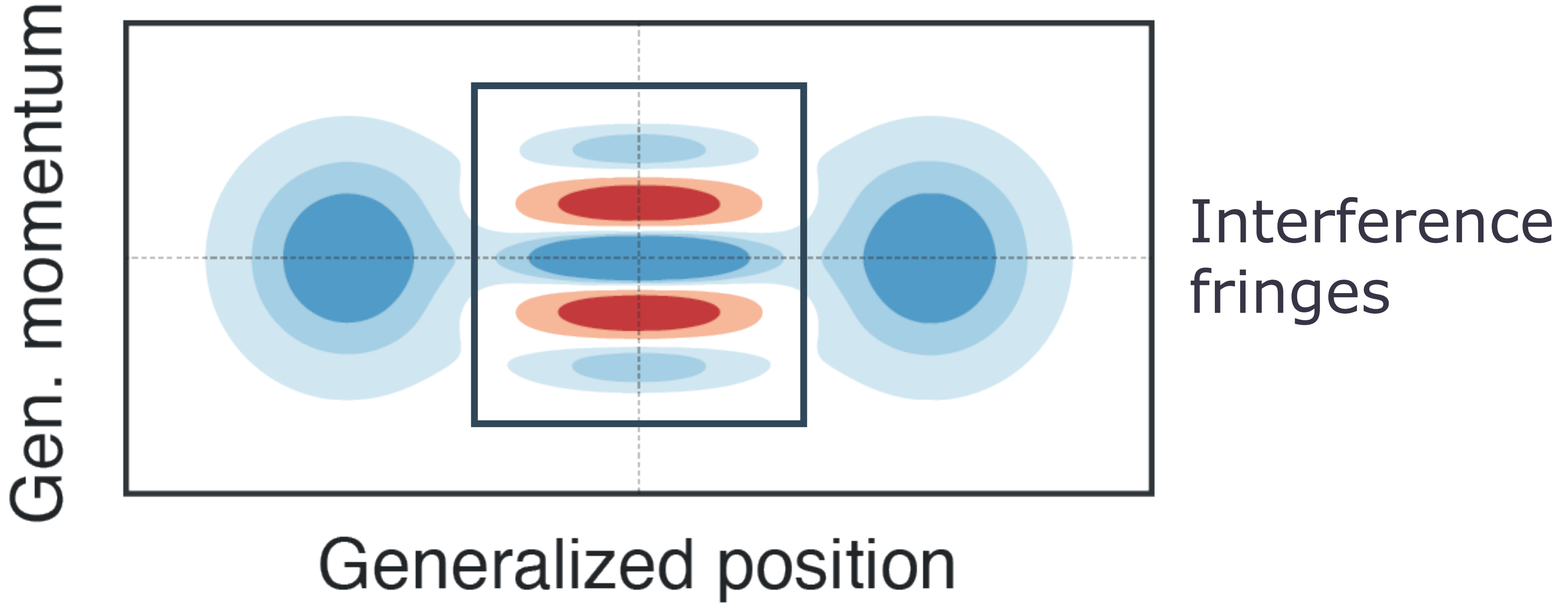
$|-\alpha\rangle \quad + \quad |\alpha\rangle$



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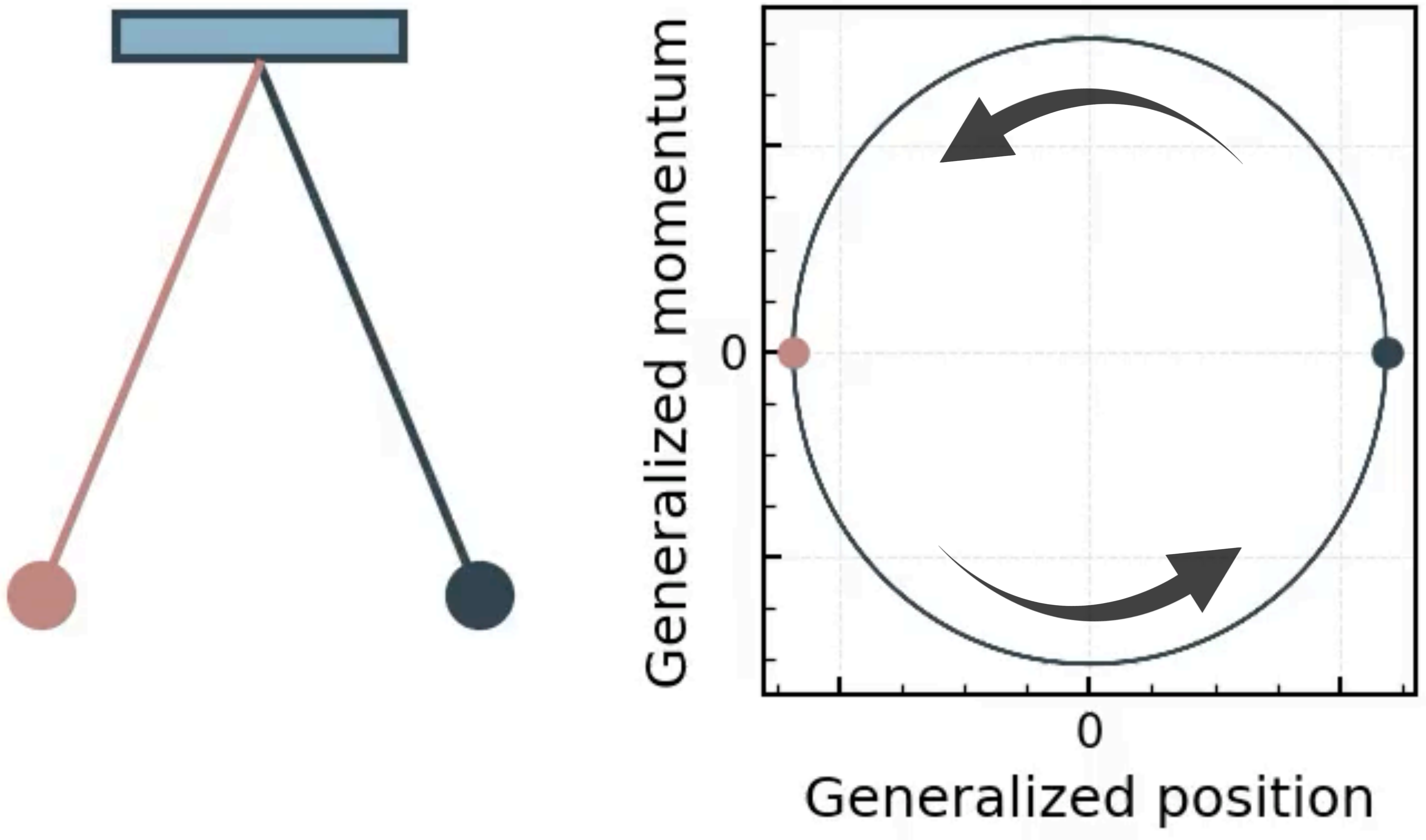

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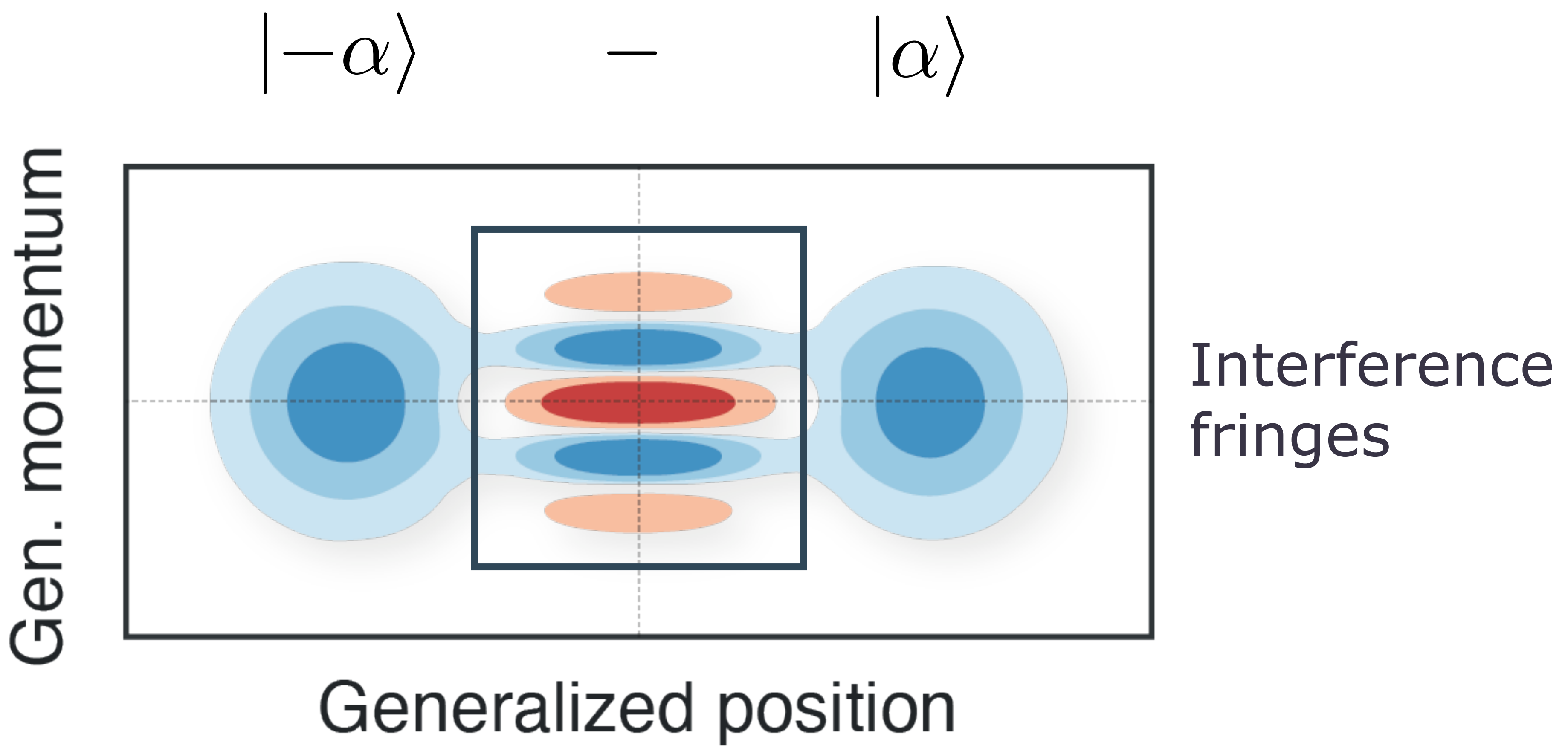

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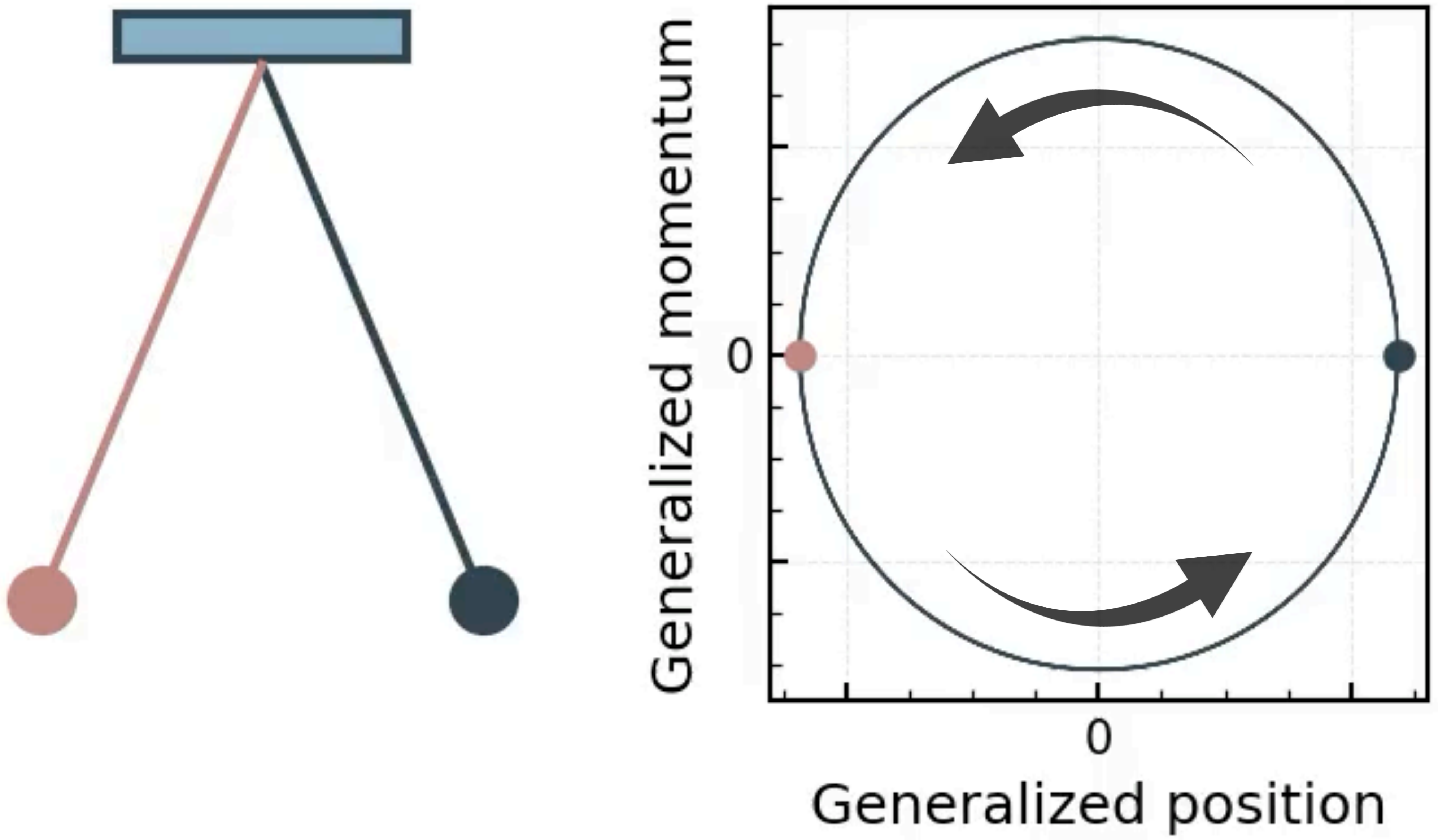

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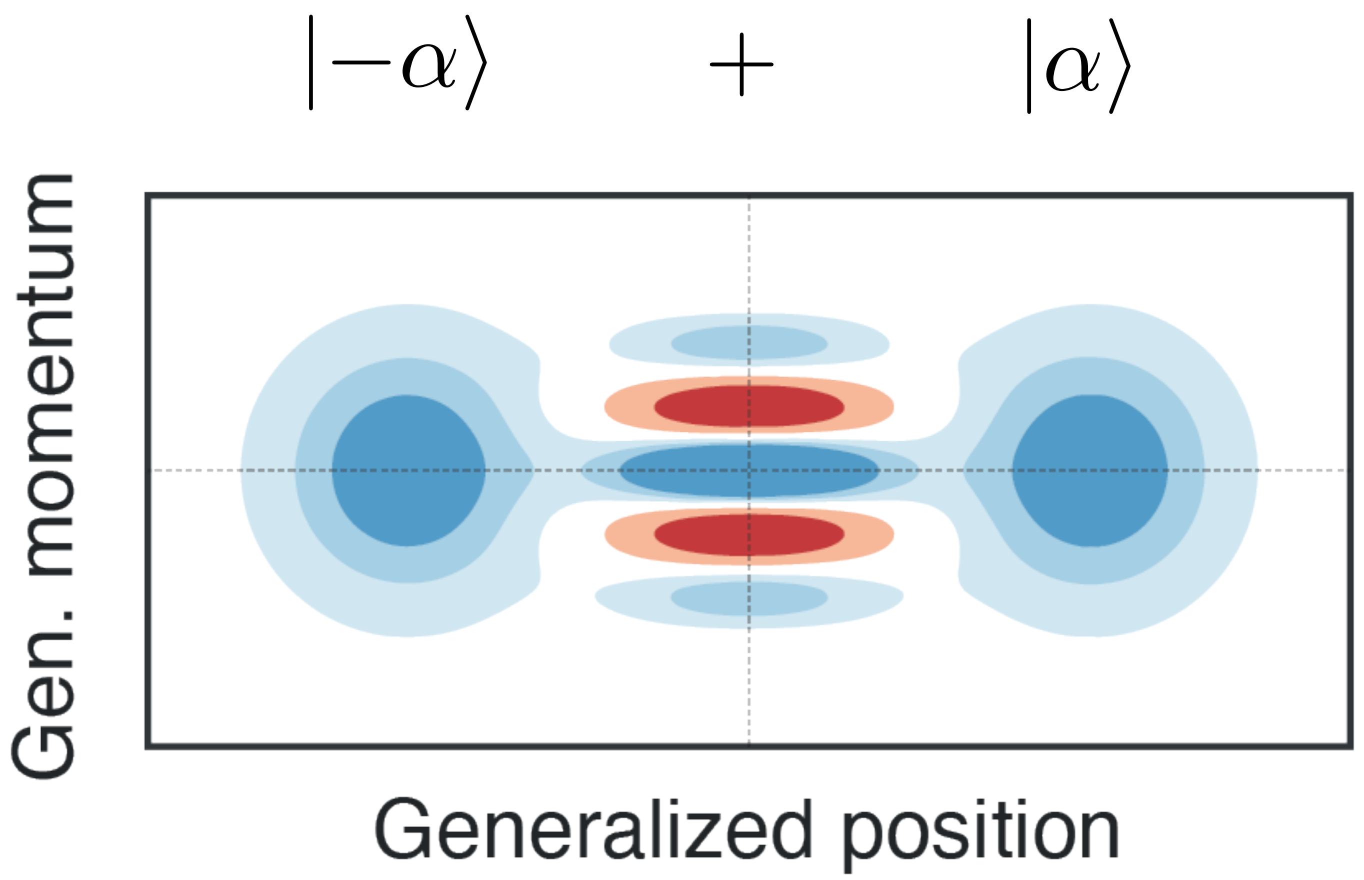

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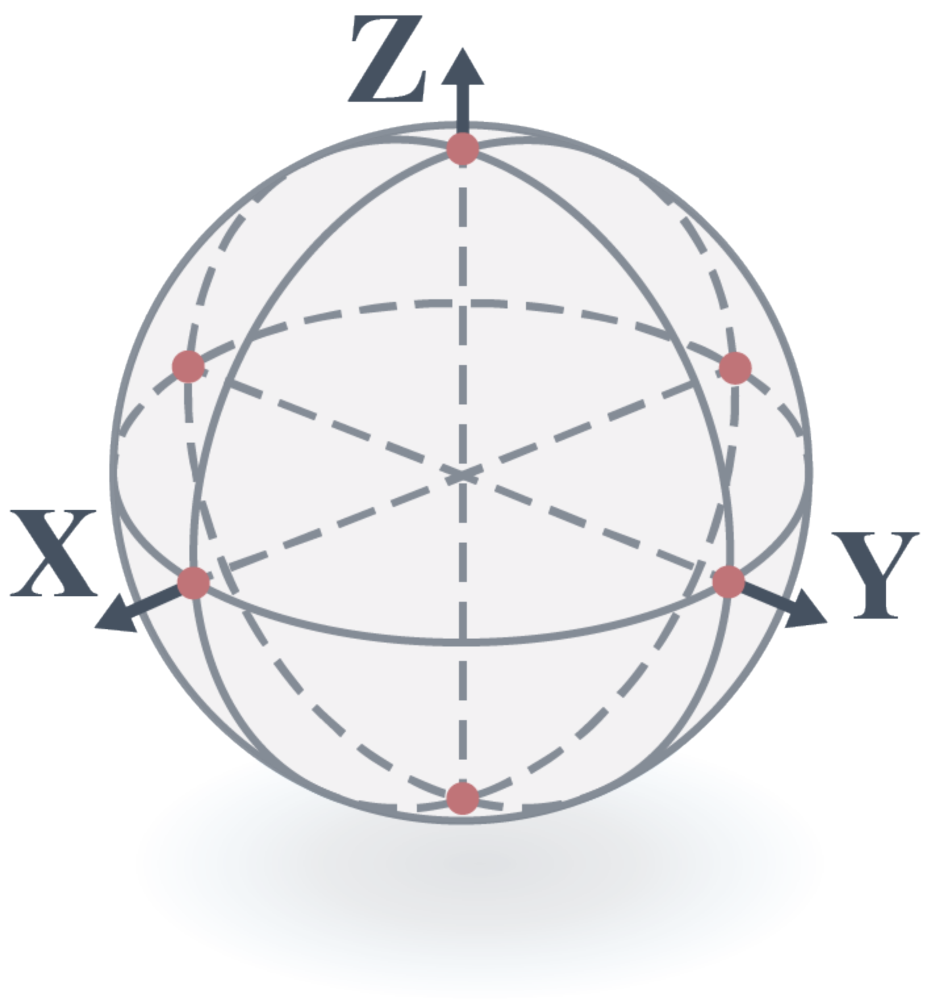
Cat qubits



Mirrahimi et al., NJP (2014); Guillaud et al., PRX (2019); Lescanne et al., Nat. Phy. (2019)

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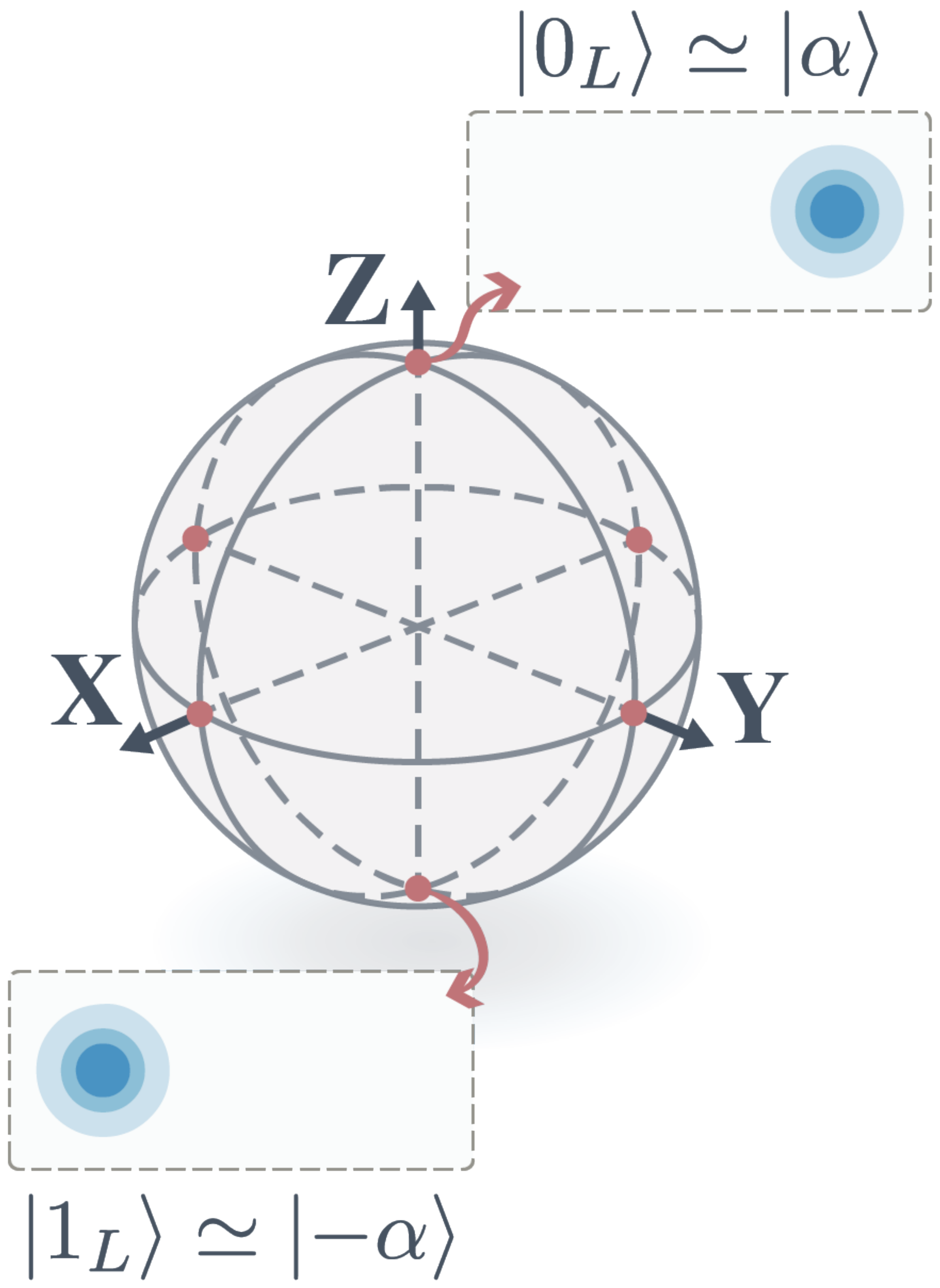

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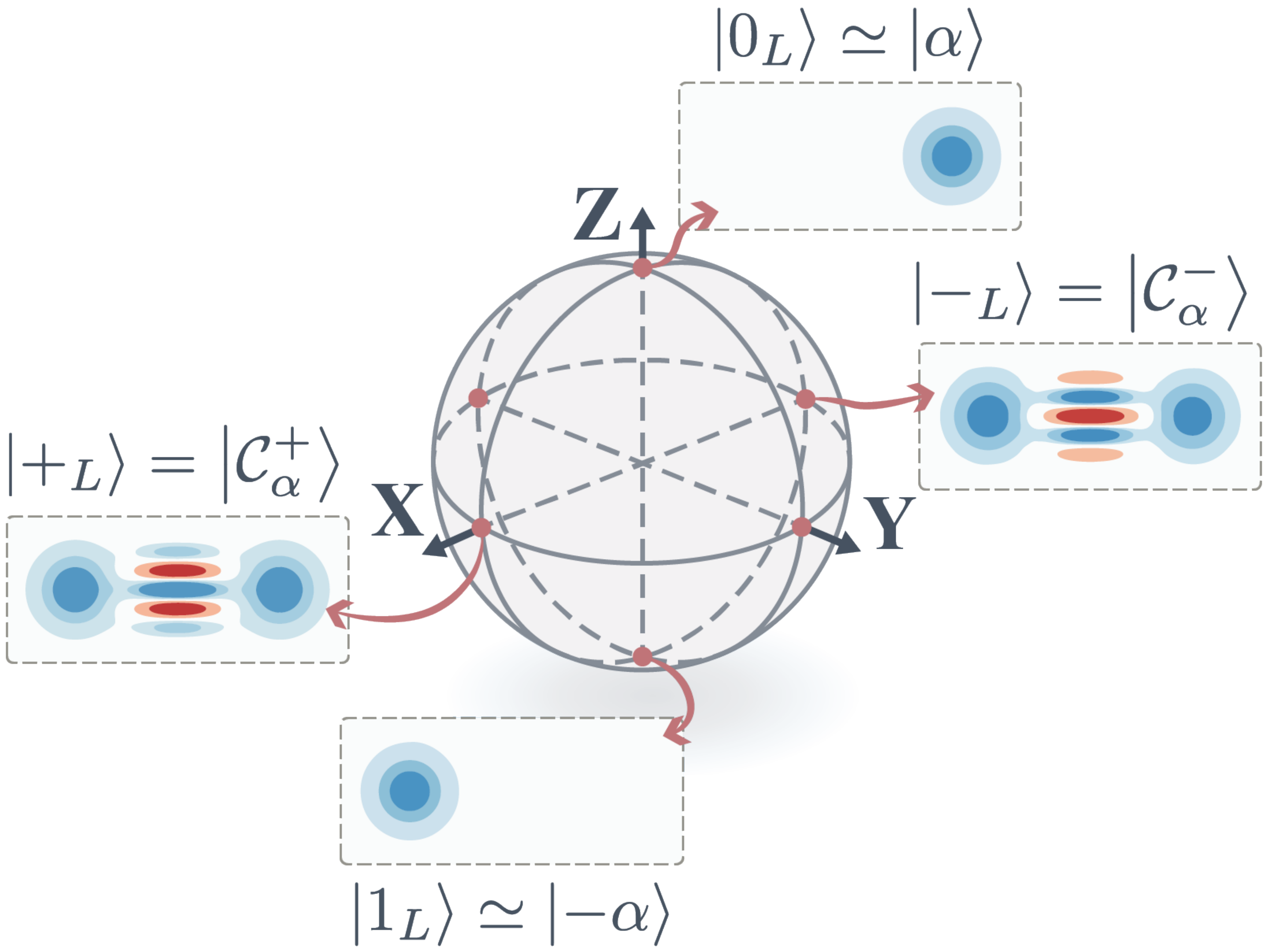

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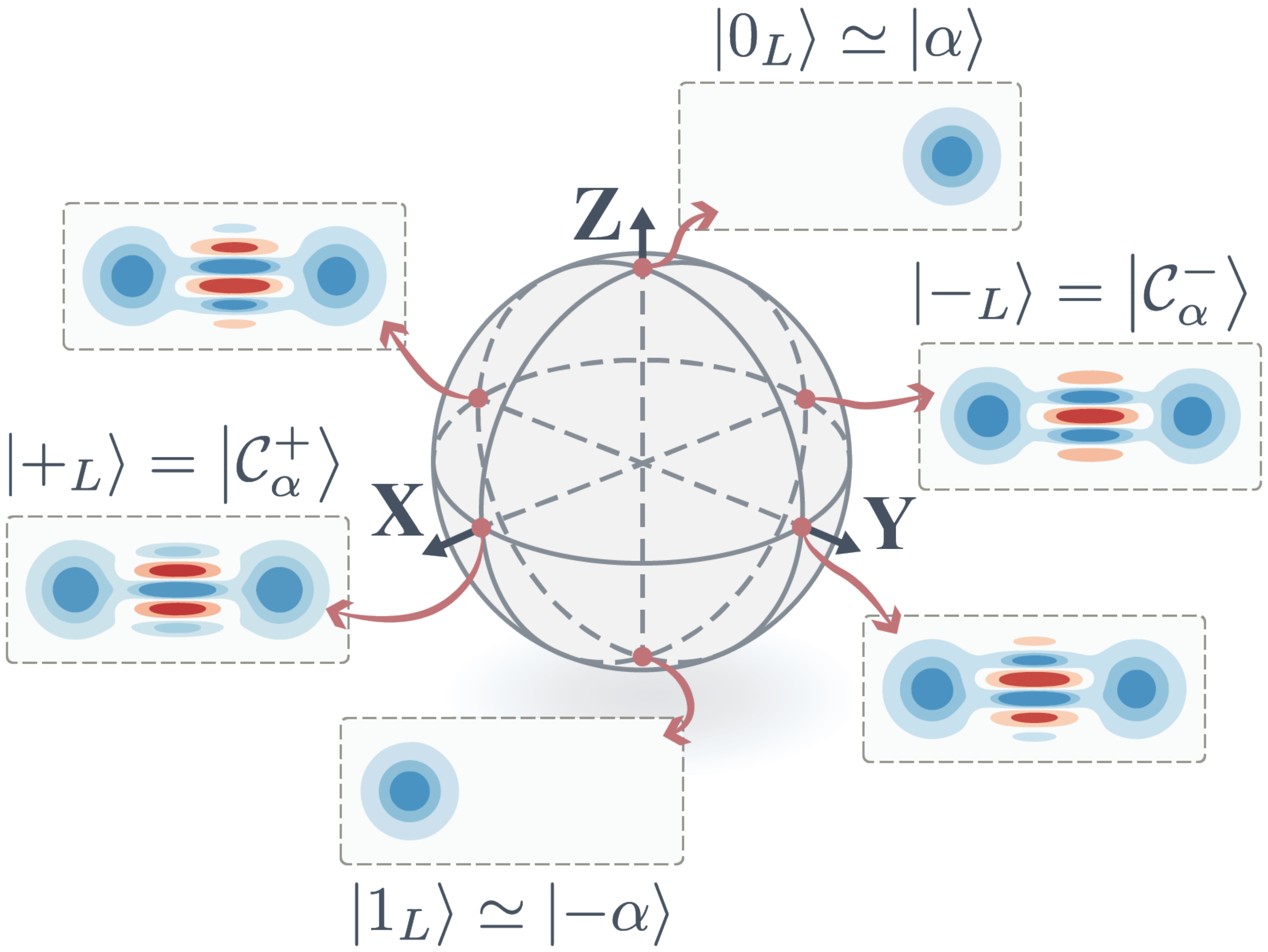

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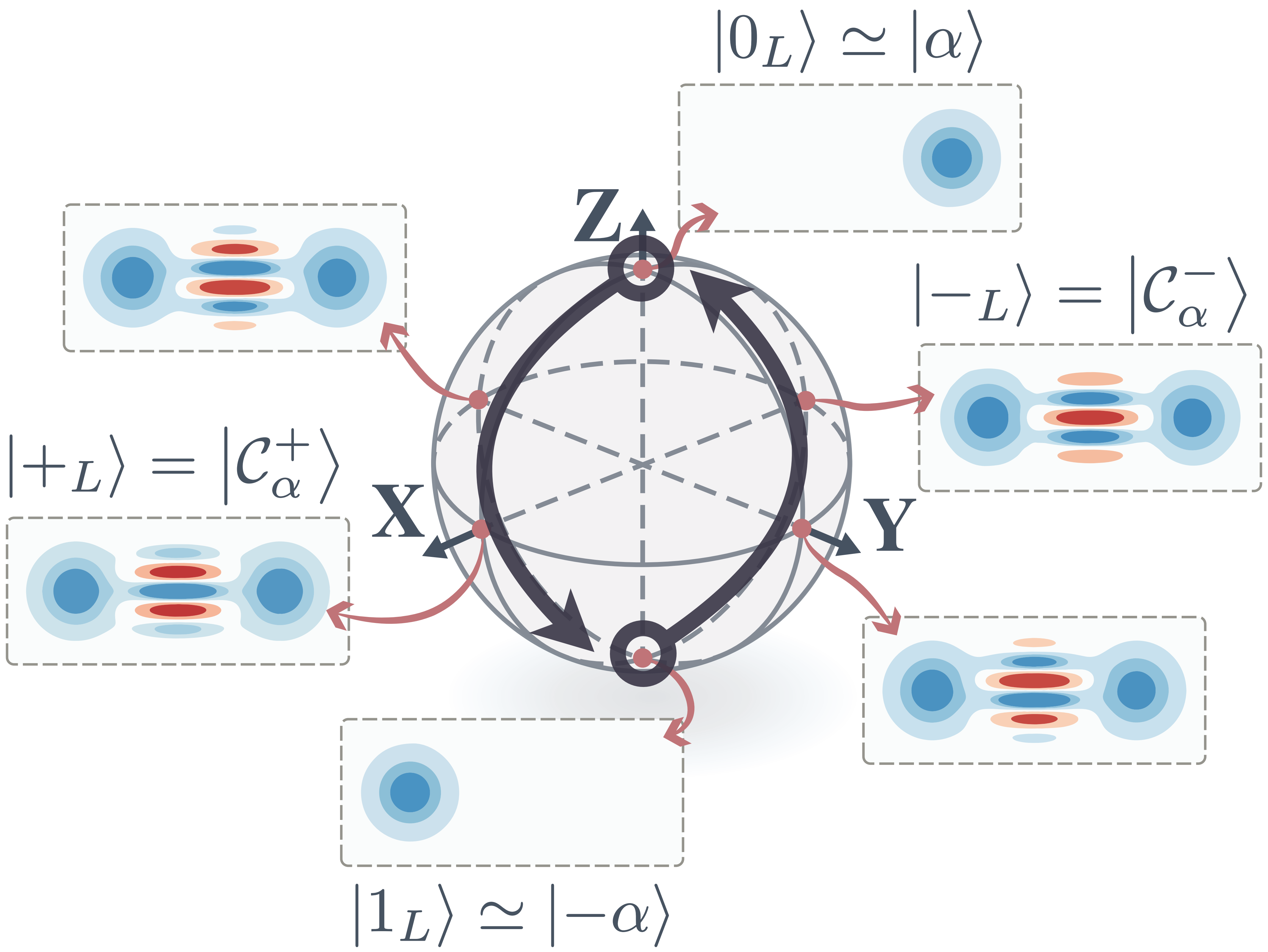
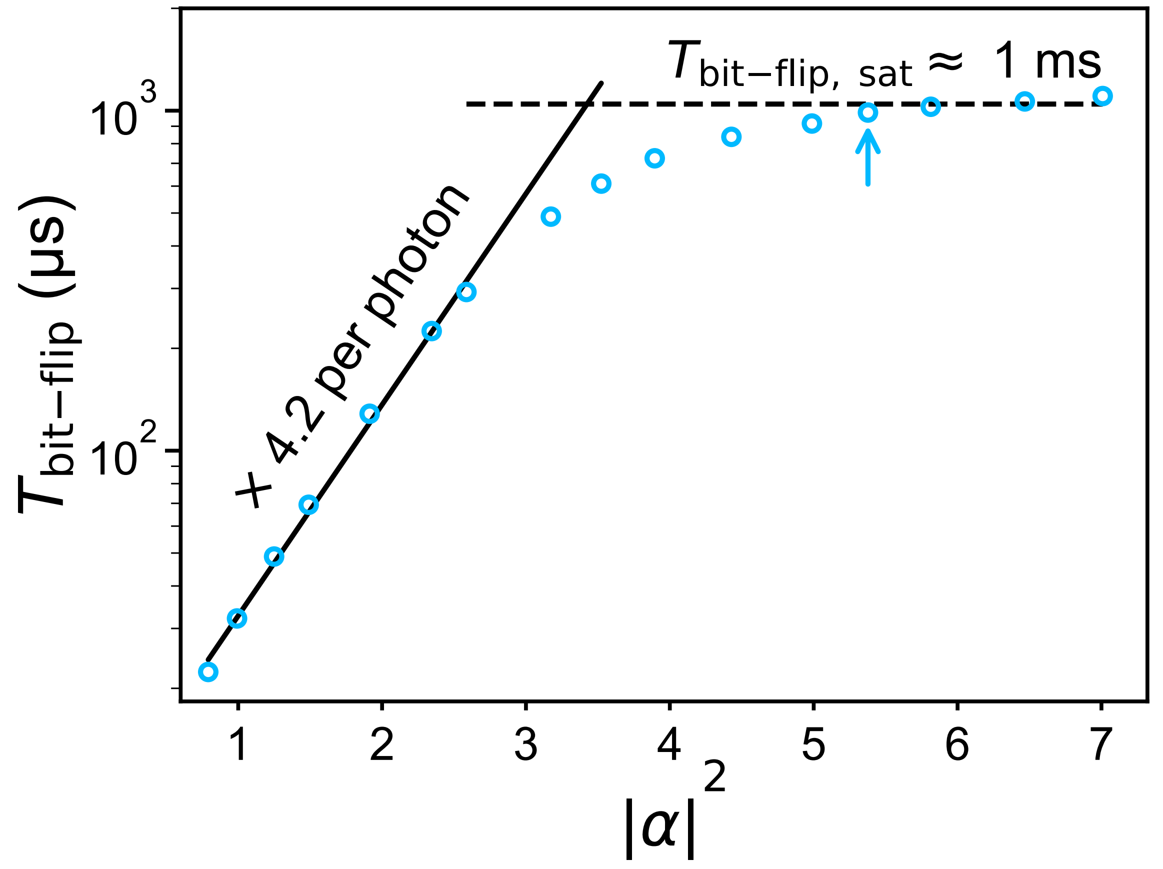


- Cat qubits are **exponentially** biased against bit-flip errors



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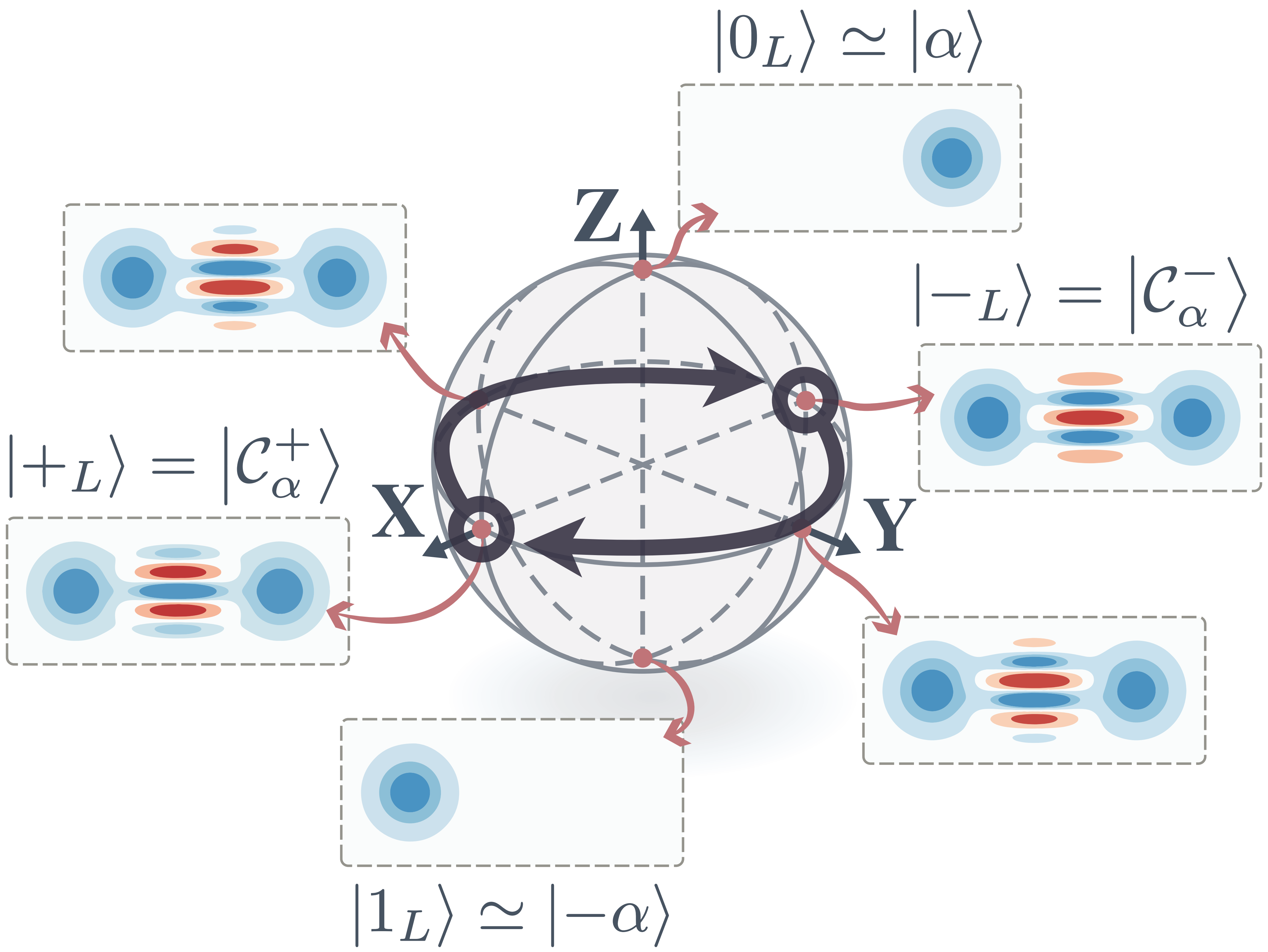

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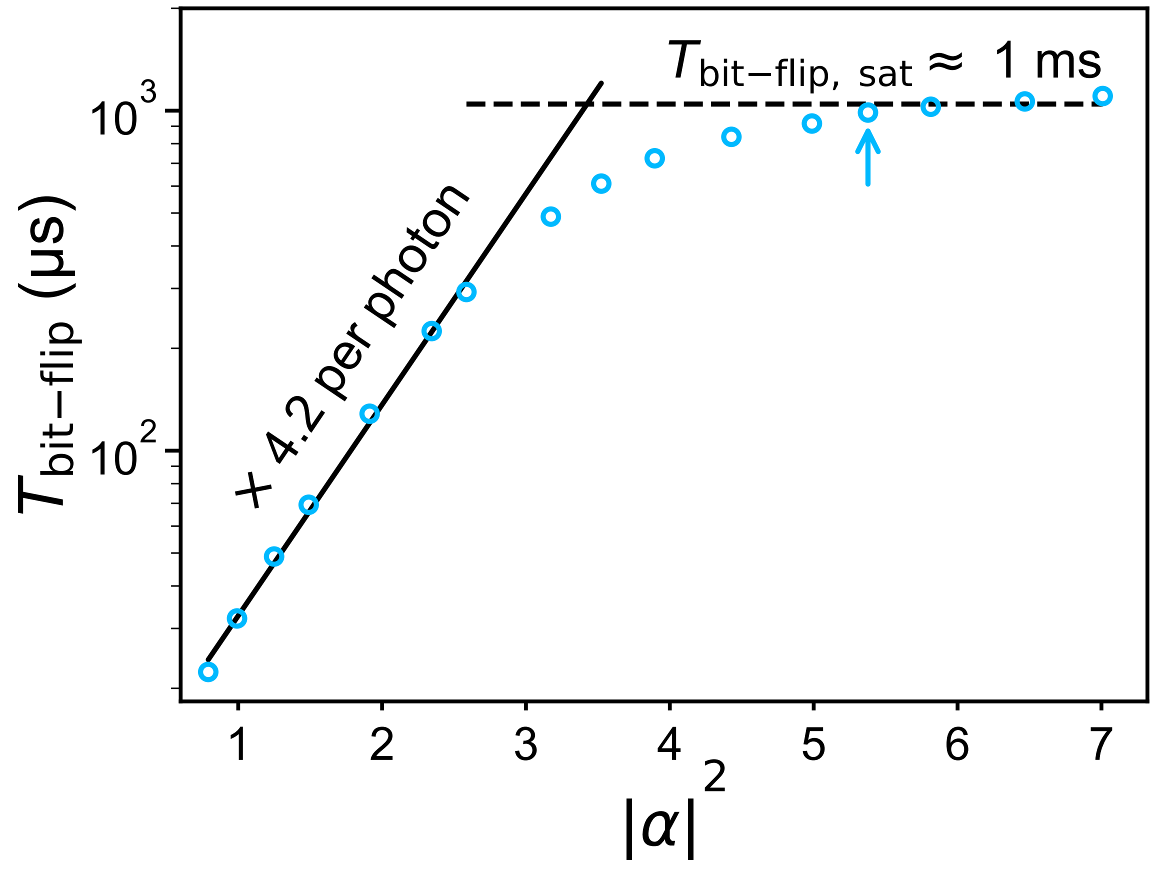
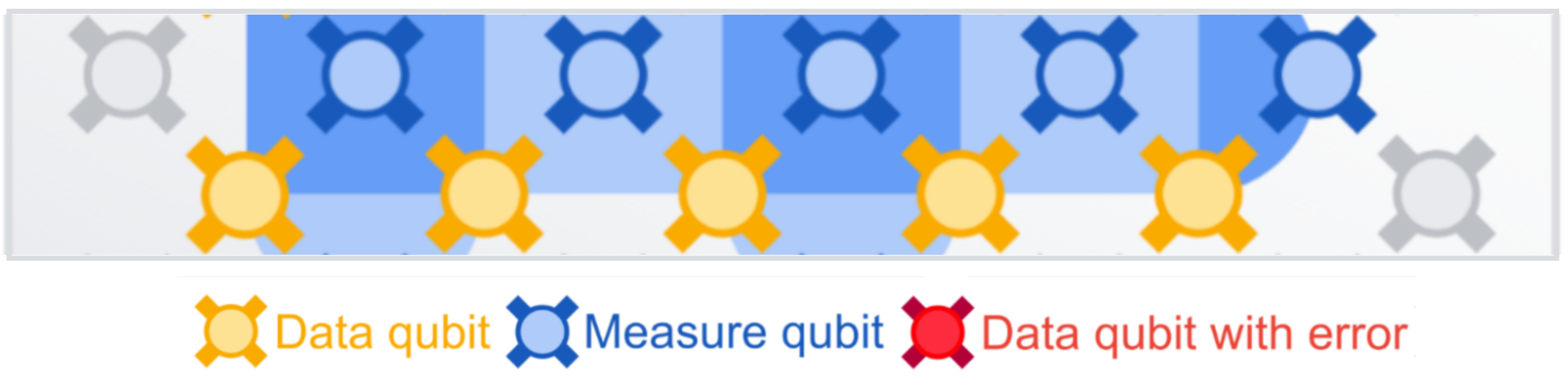


- A repetition code takes care of <u>phase-flip</u> errors



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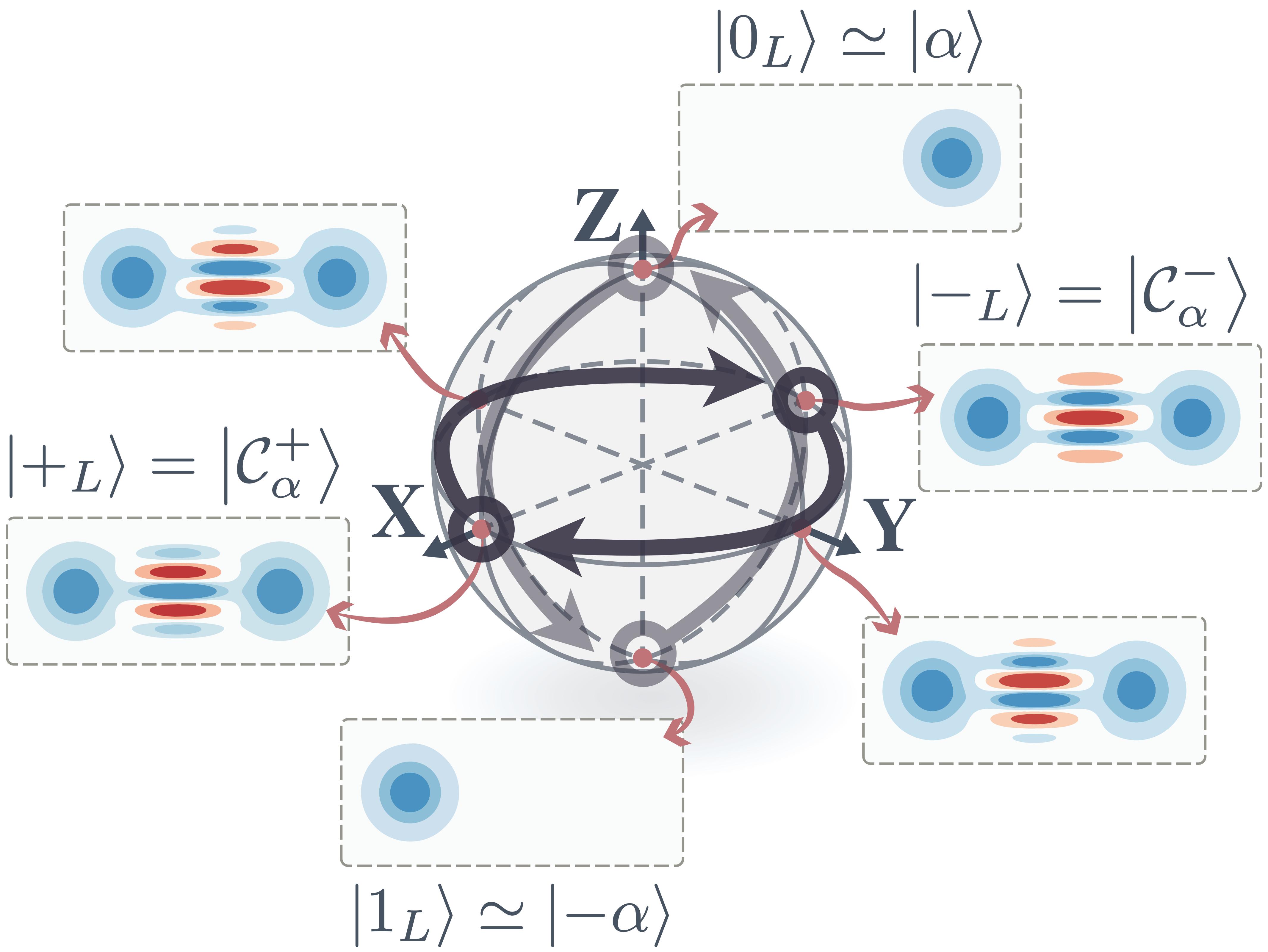

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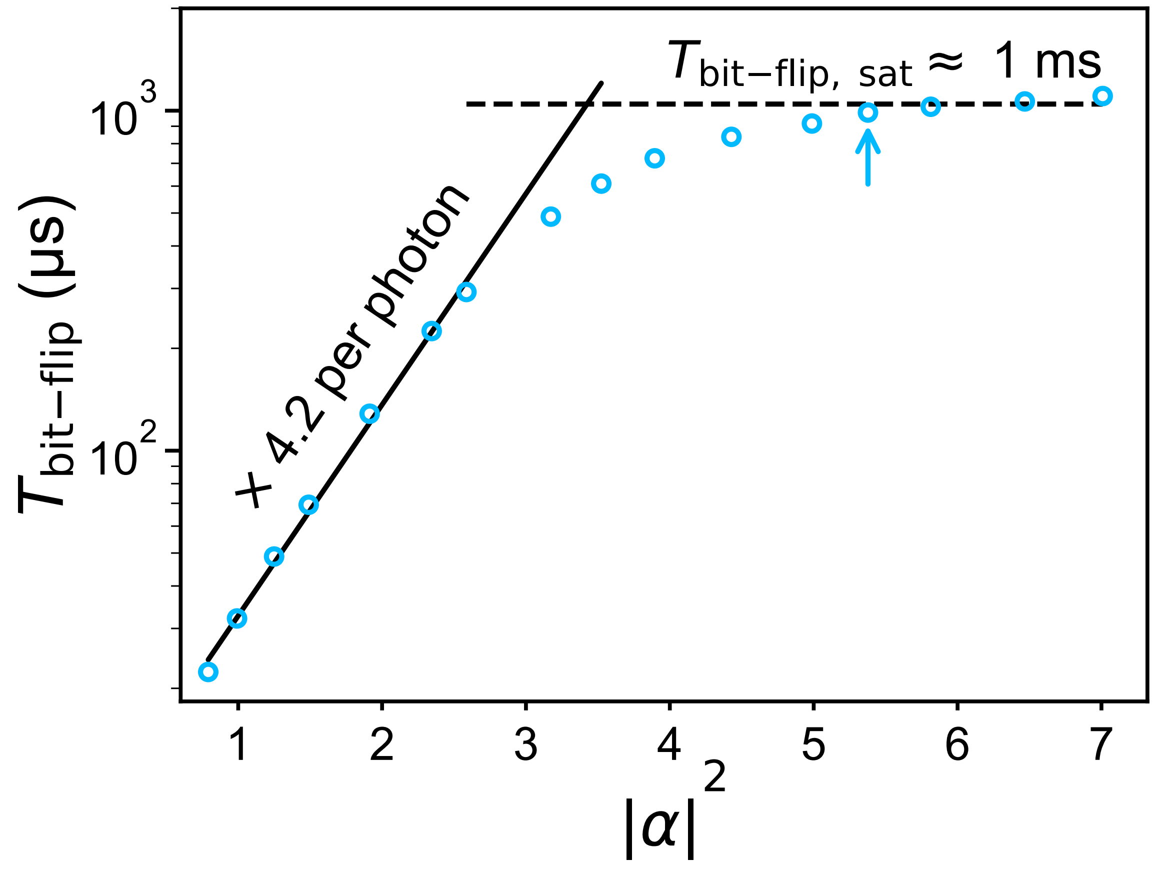

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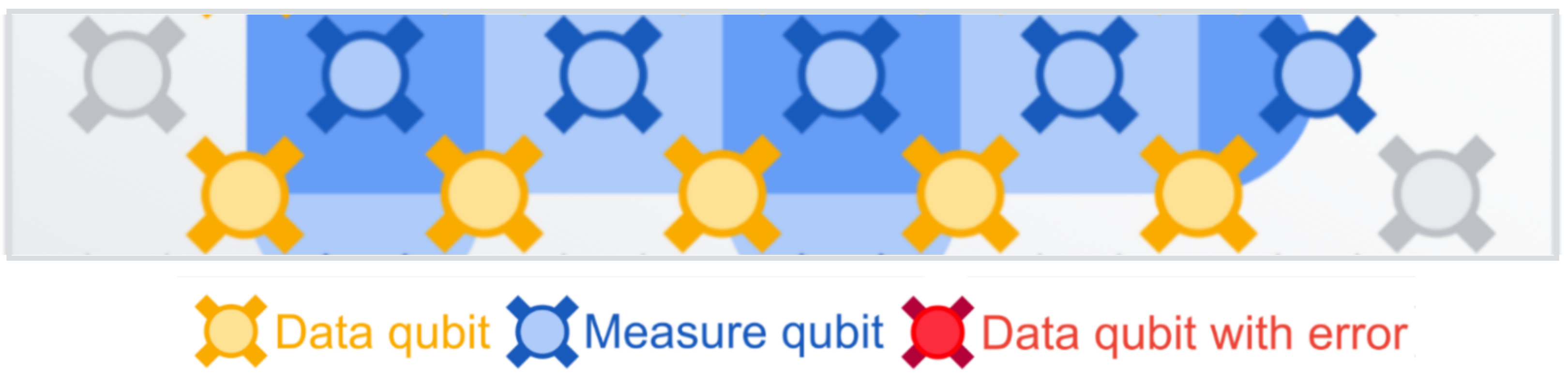

- Inner: cat qubits (bit-flips)
  Outer: repetition code (phase-flips)

Mirrahimi et al., NJP (2014); Guillaud et al., PRX (2019); Lescanne et al., Nat. Phy. (2019)

Protecting cat qubits

Kerr cat qubits

- Hamiltonian confinement

$$H = -K(a^{\dagger 2} - \alpha^{*2})(a^2 - \alpha^2)$$

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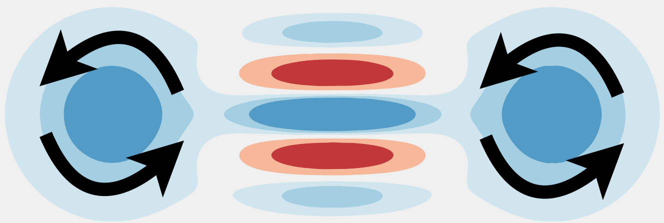
- 

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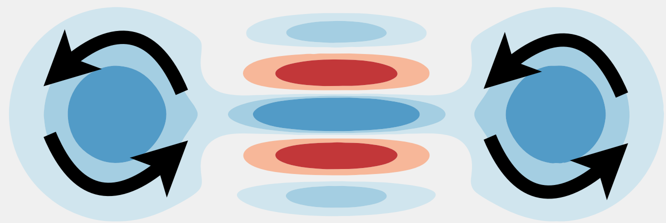
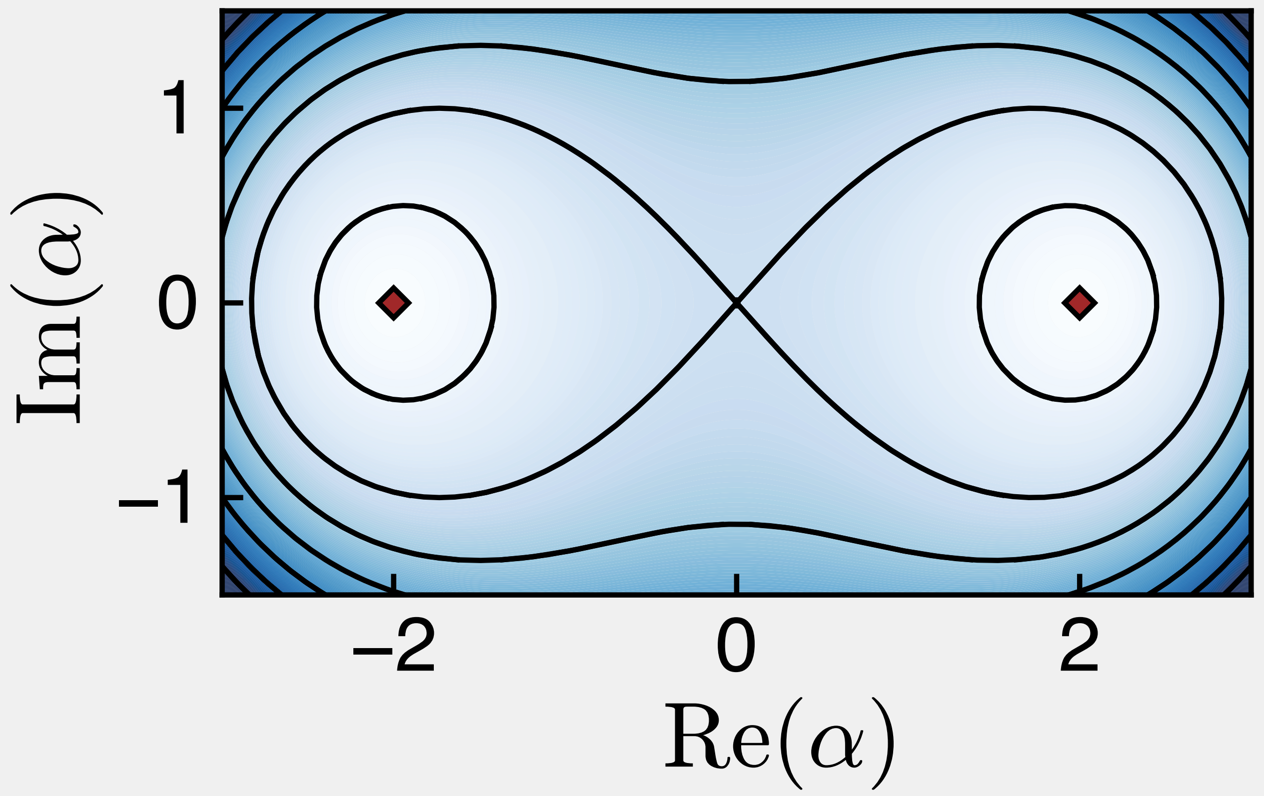
- 

Semiclassical potential



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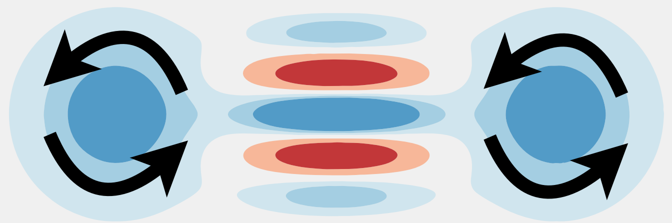
- 

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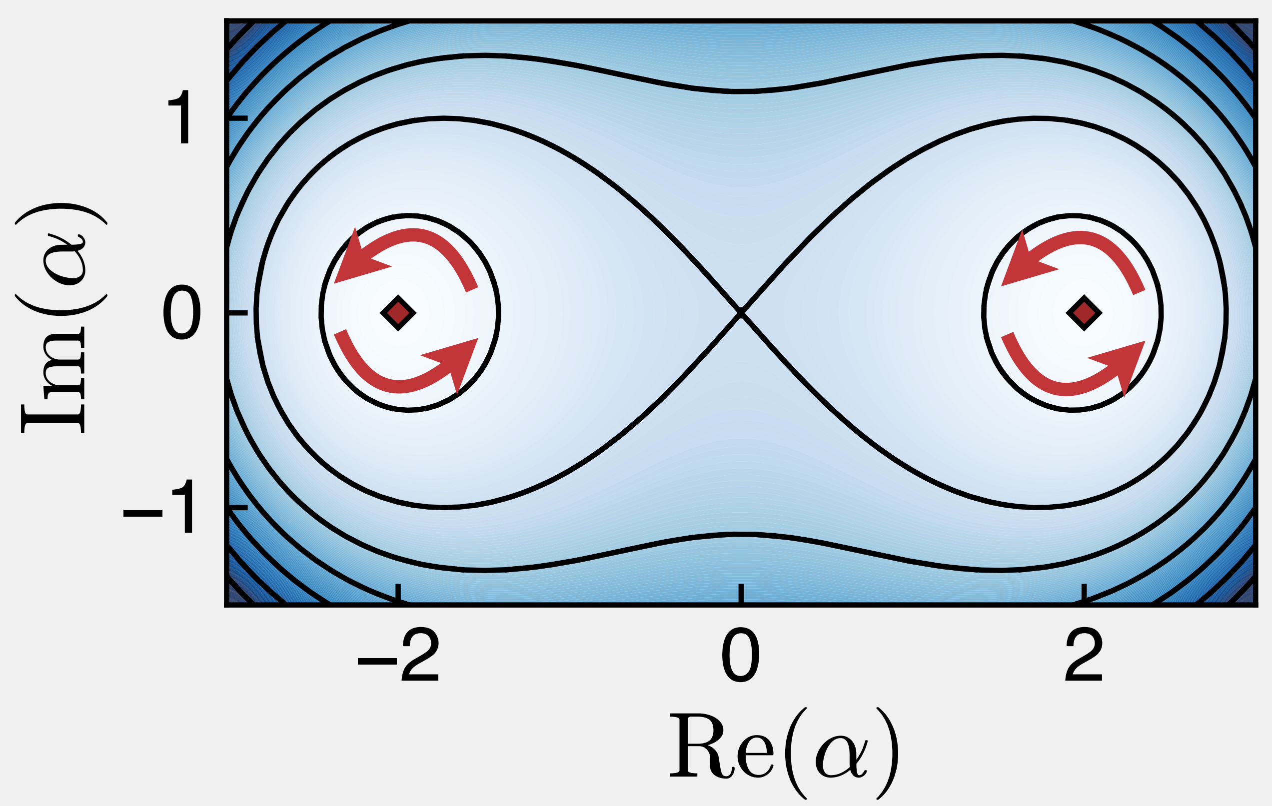

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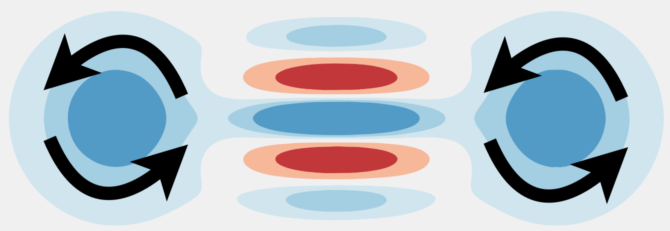
- 

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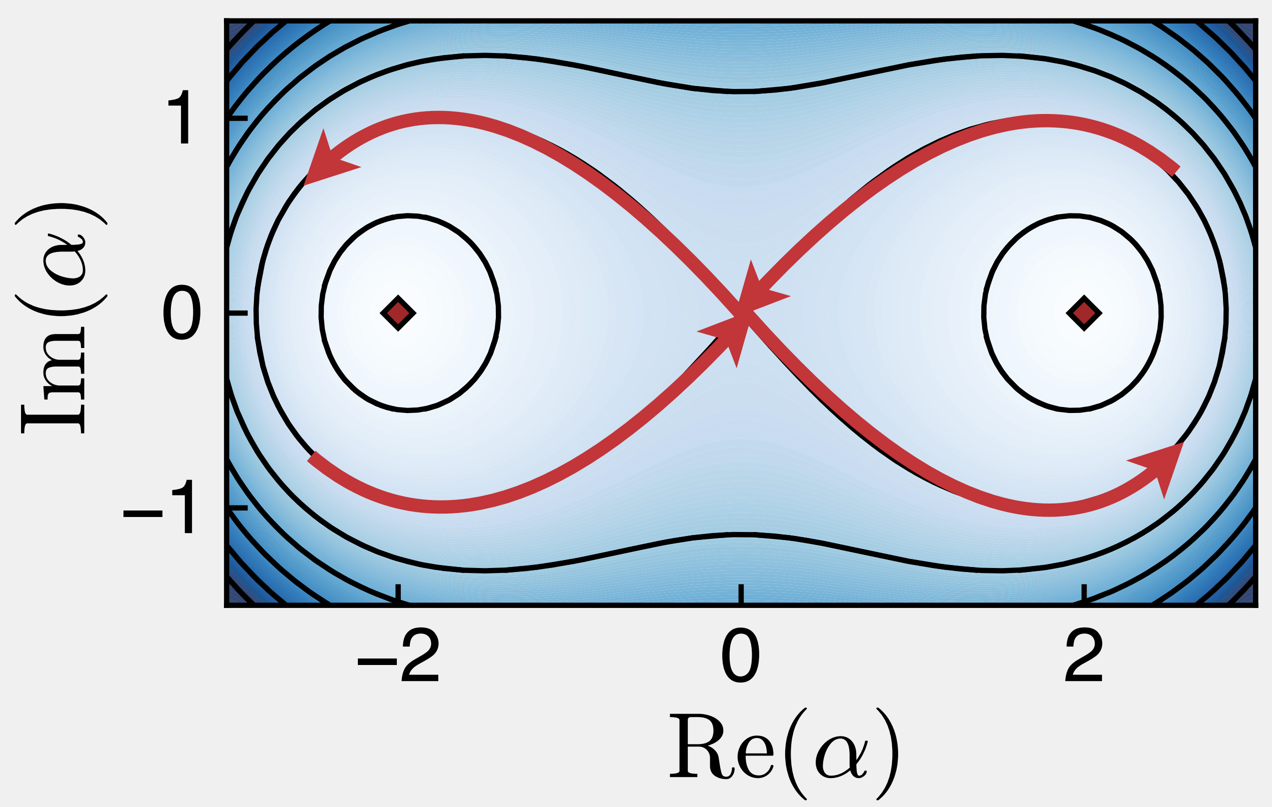

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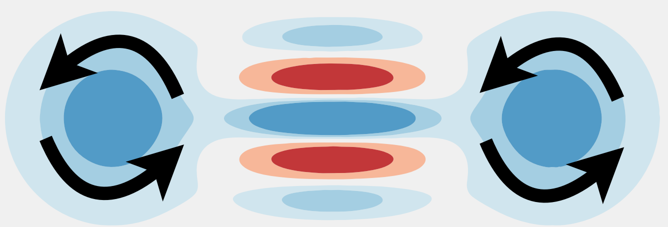
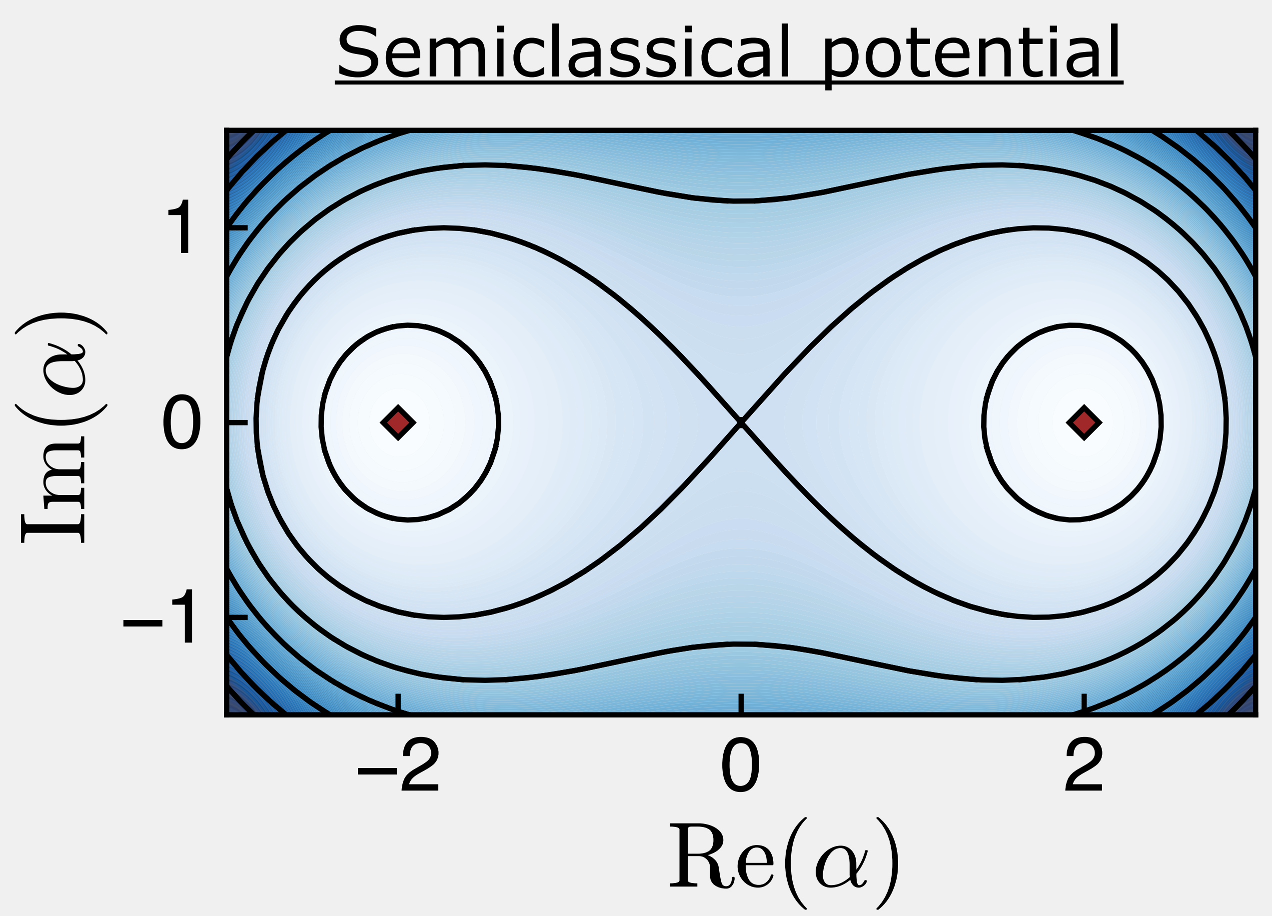
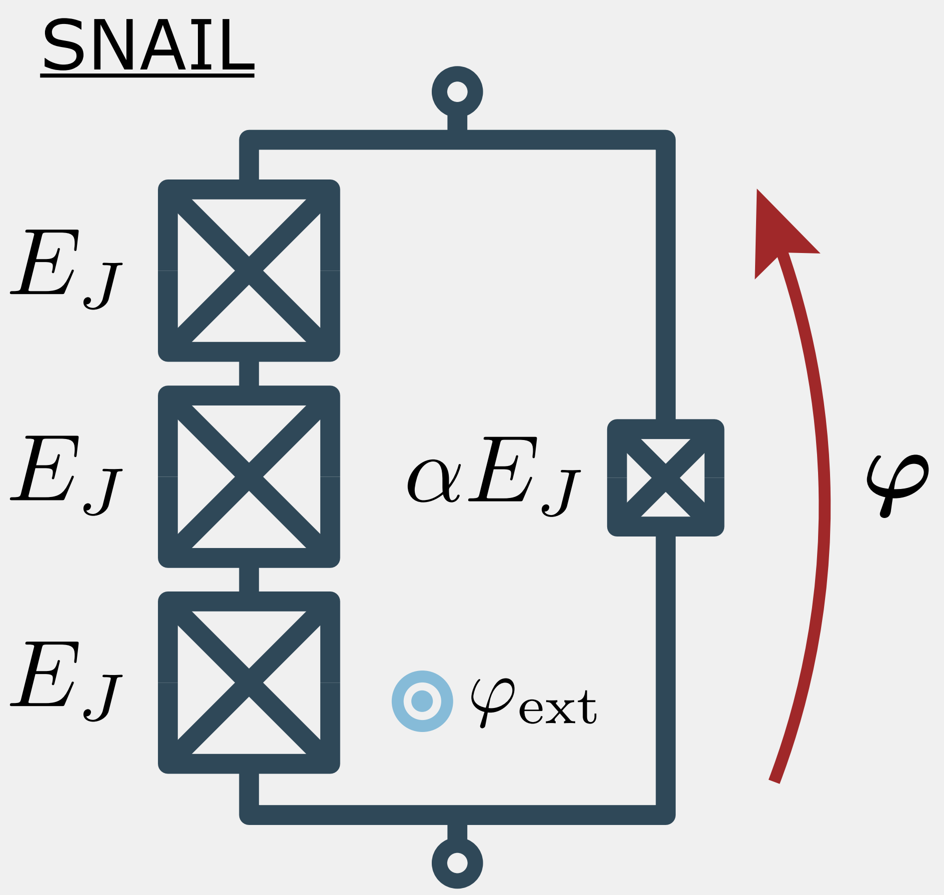
- 





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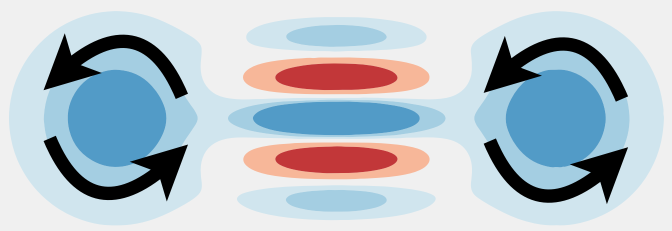
- 

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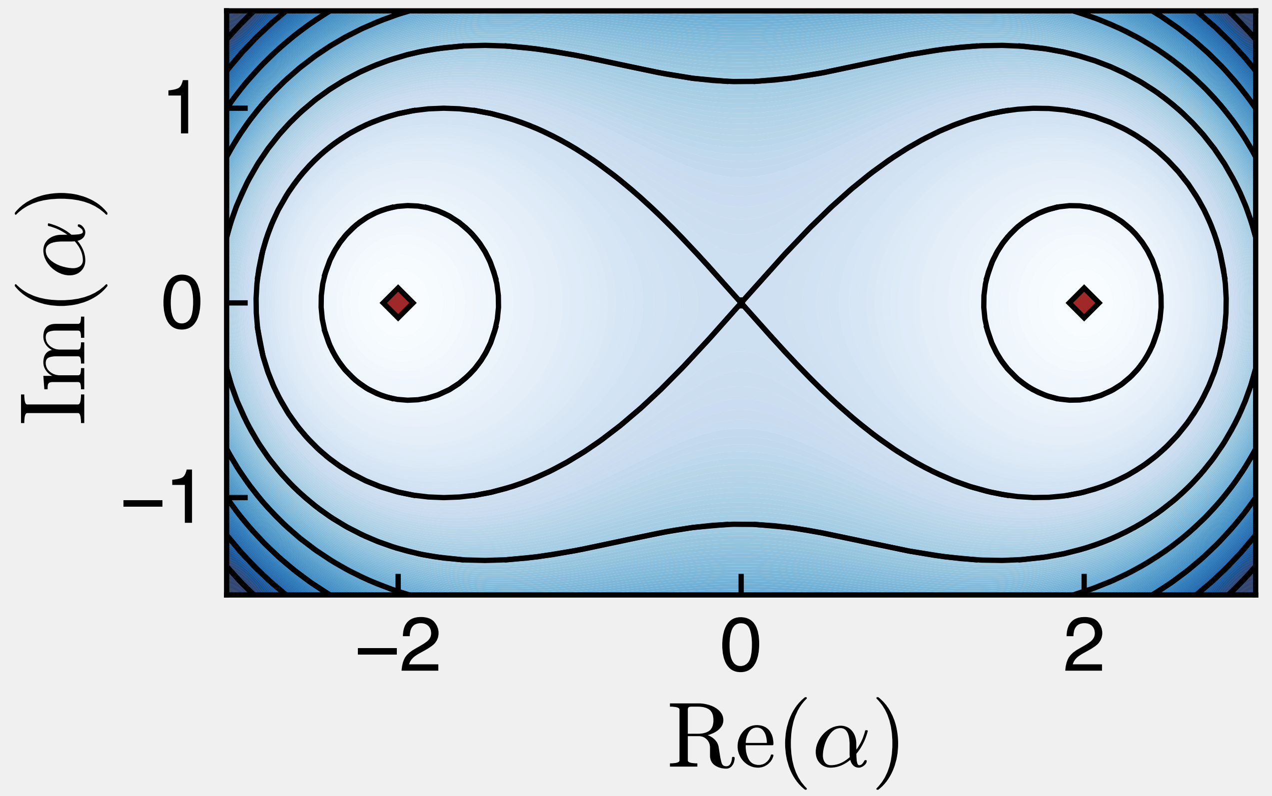
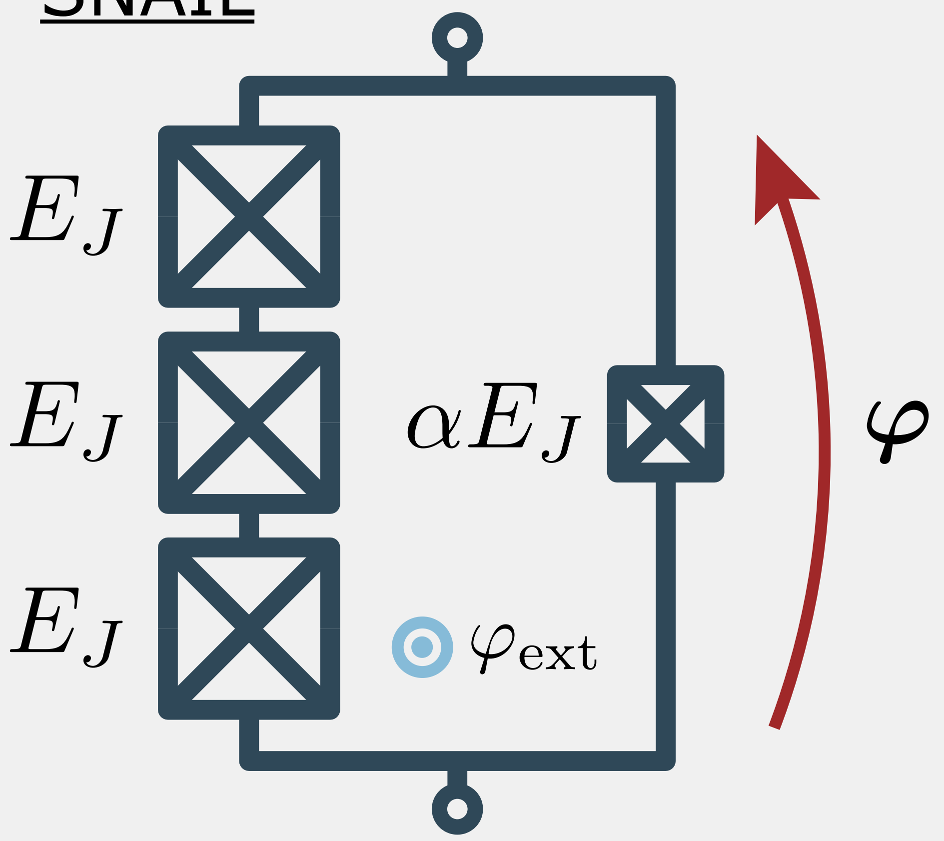


SNAIL



Dissipative cat qubits

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$$\kappa_2 \mathcal{D}[a^2 - \alpha^2]$$

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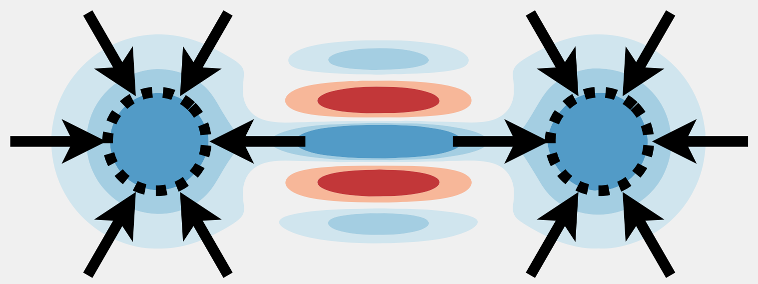
- 

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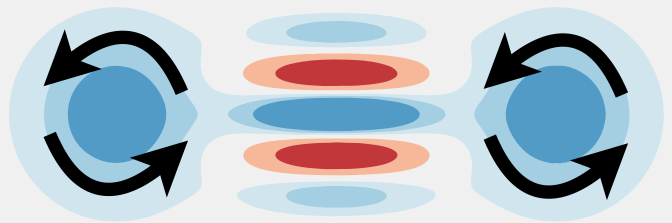

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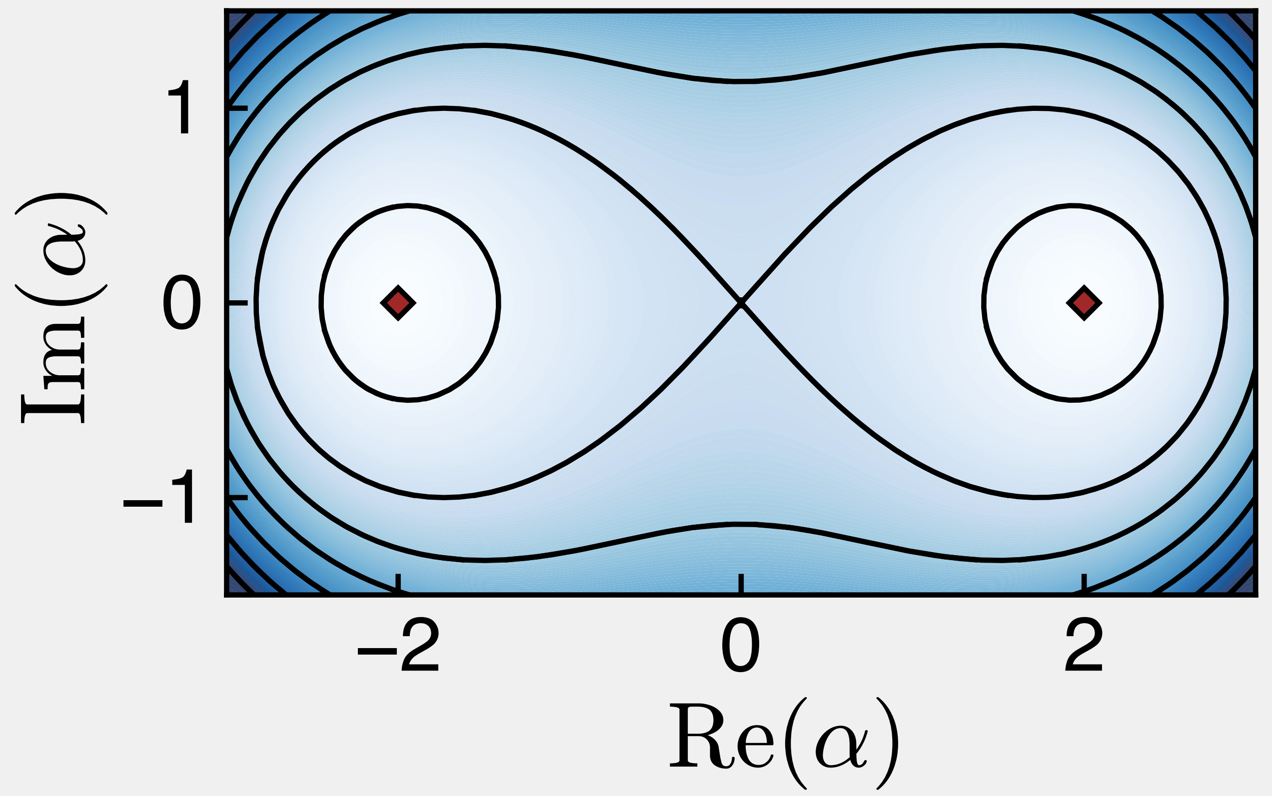

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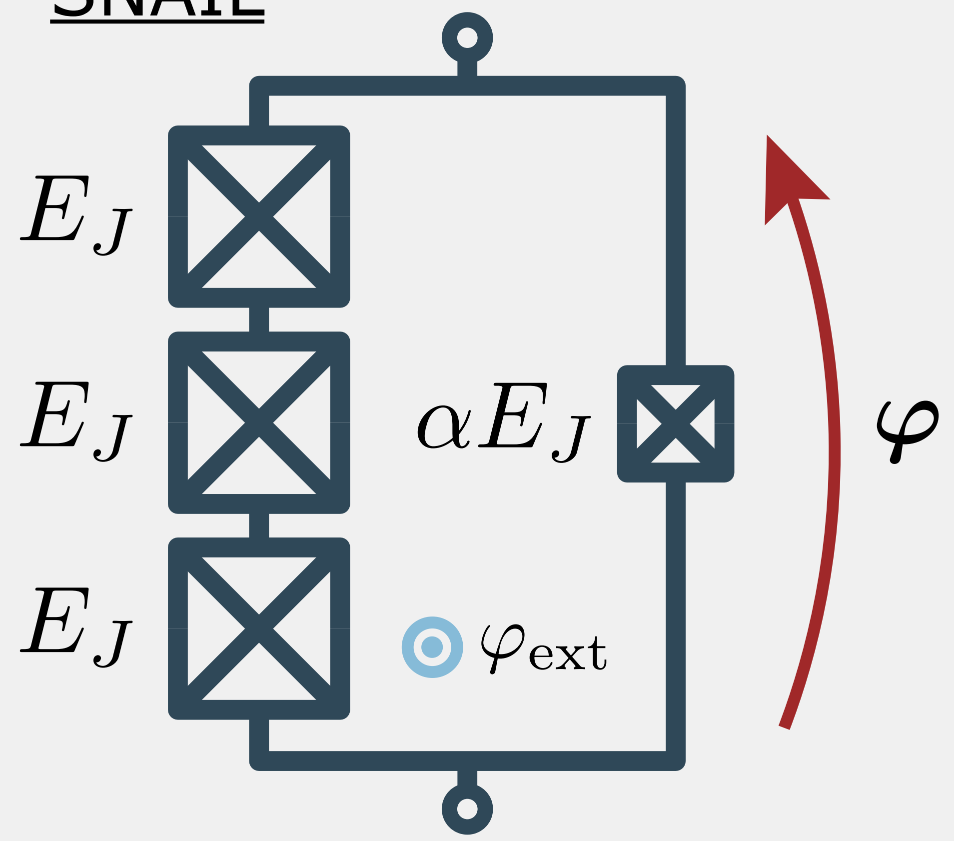

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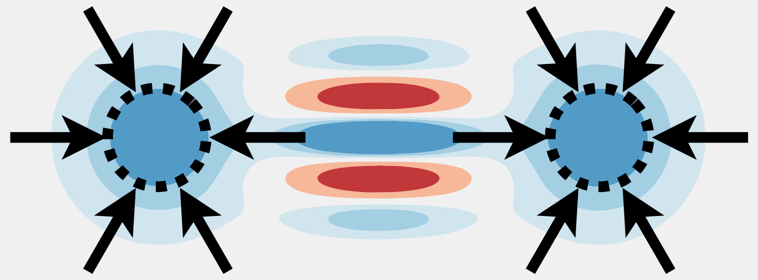

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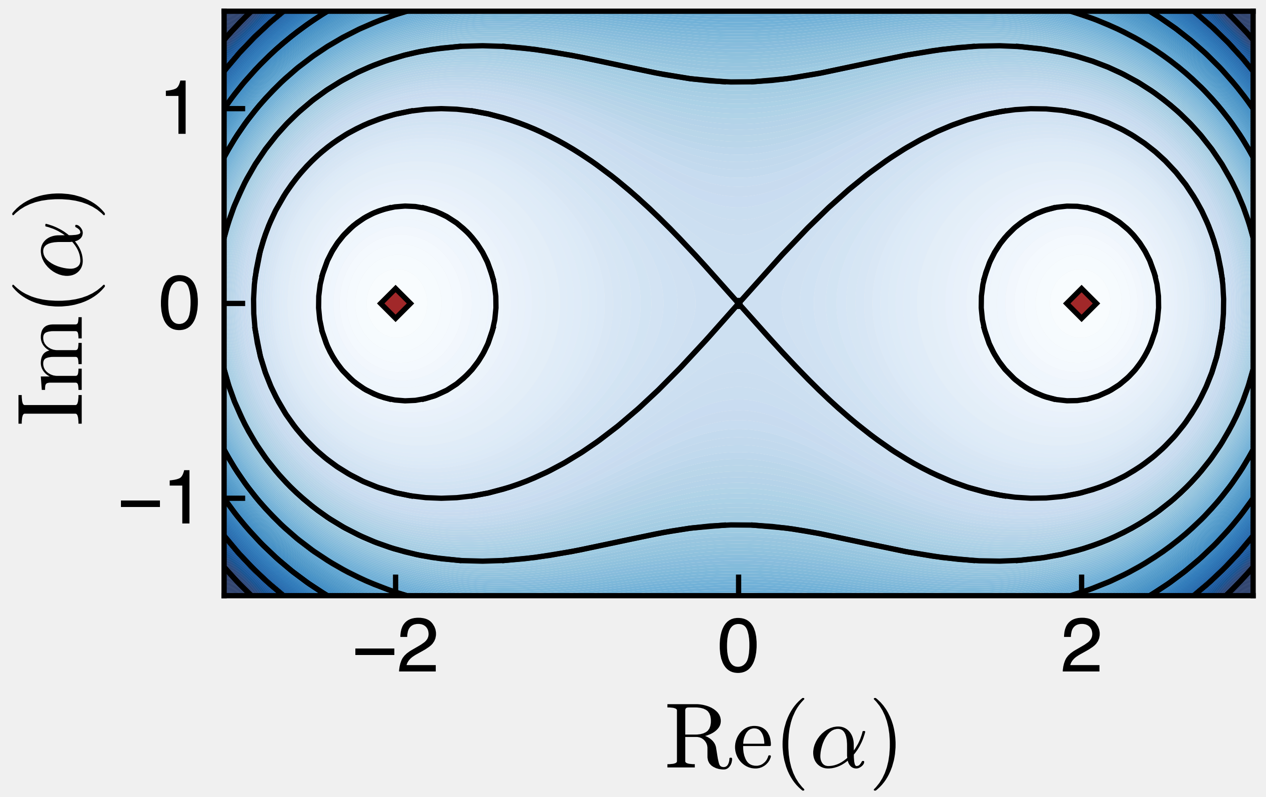

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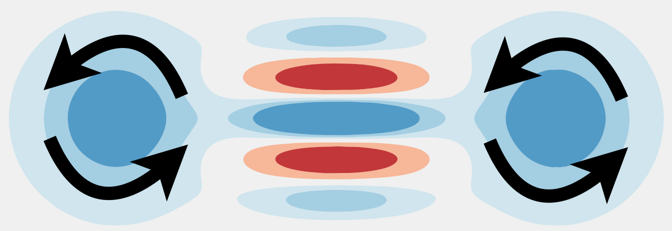

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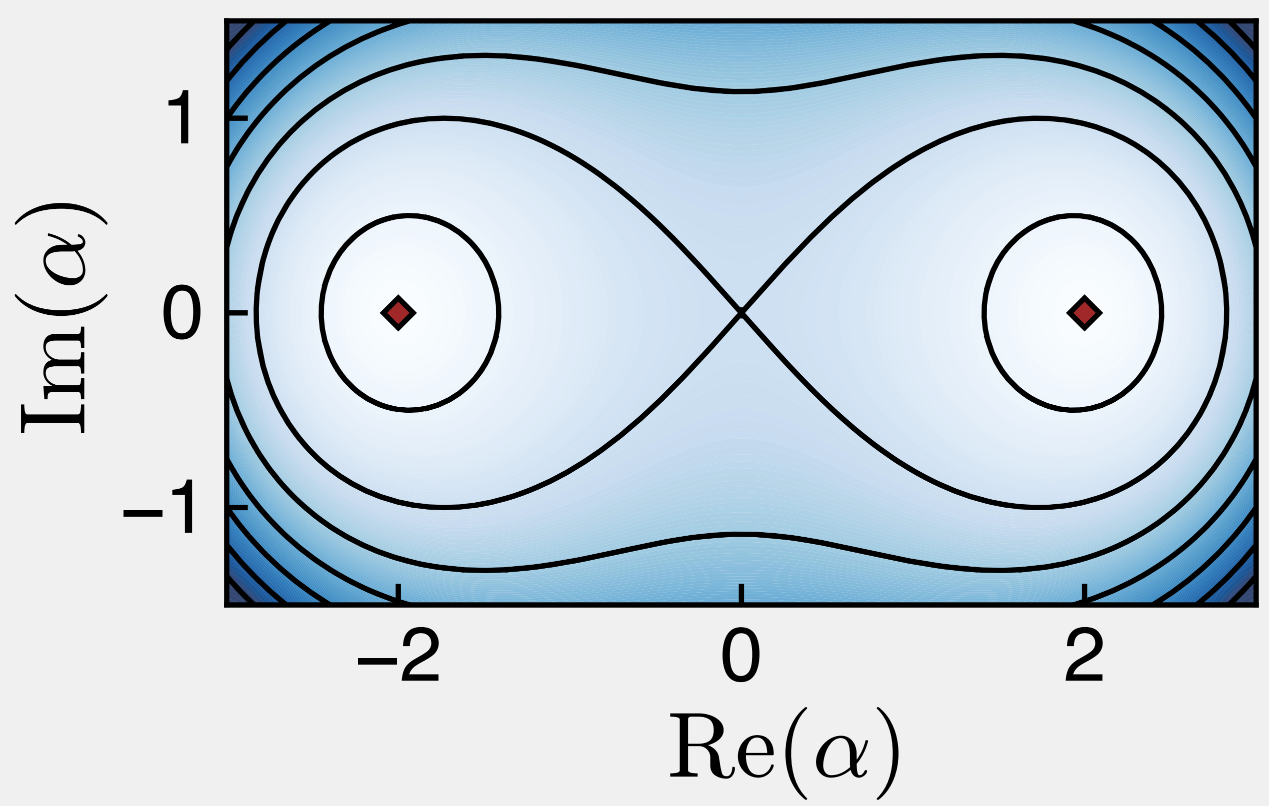

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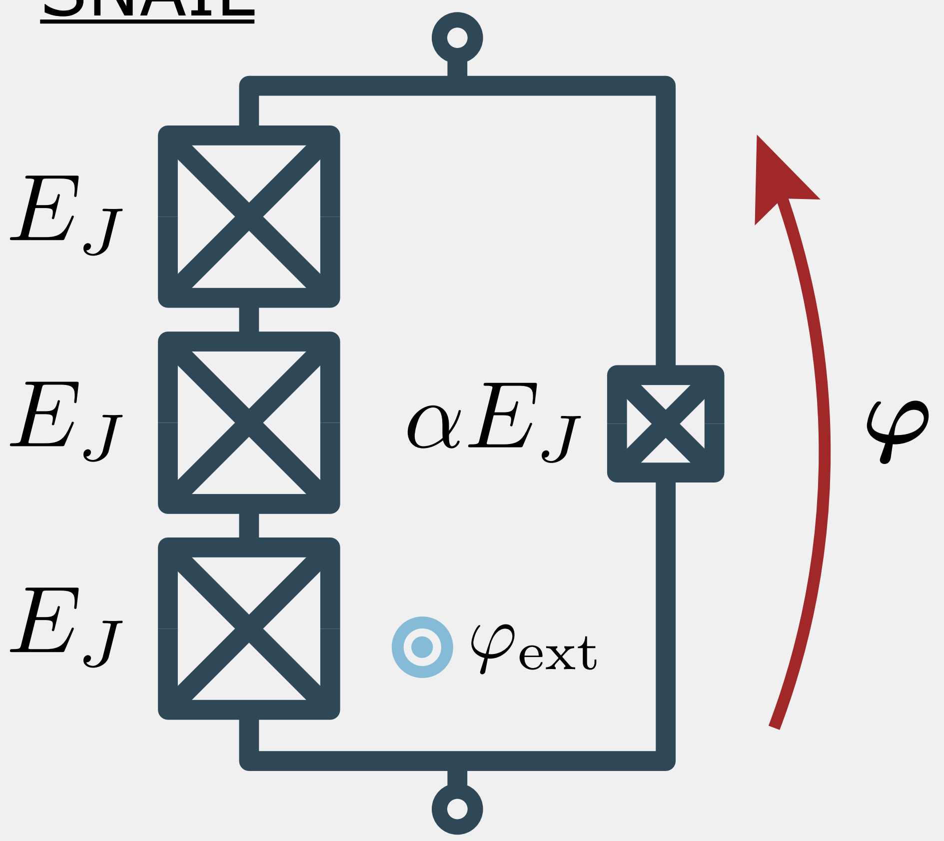

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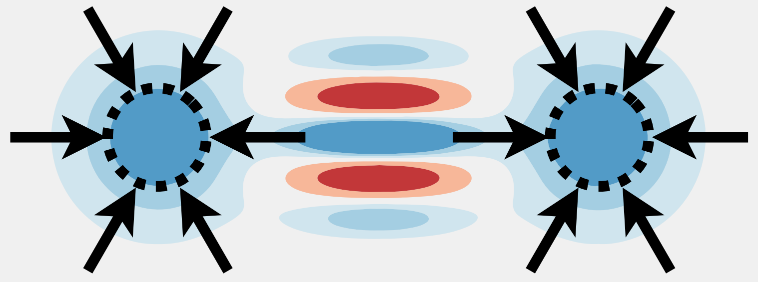

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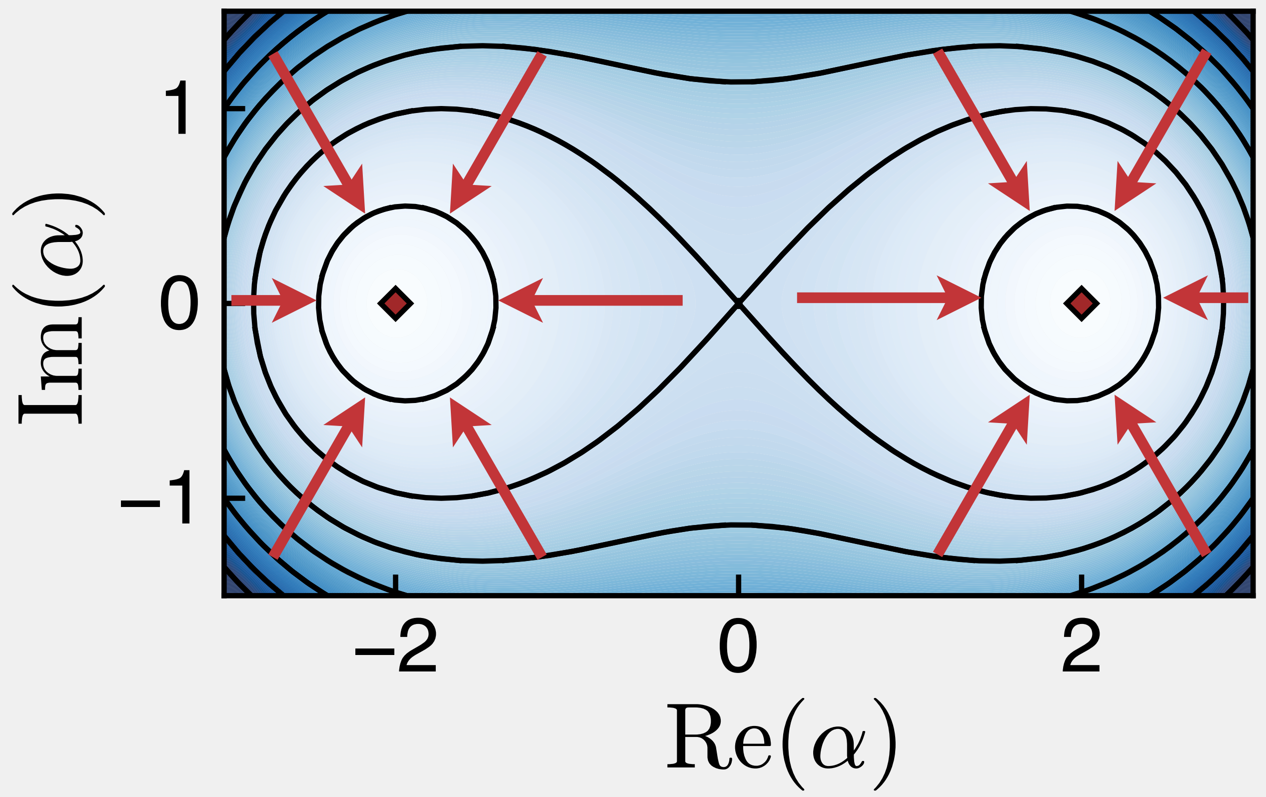

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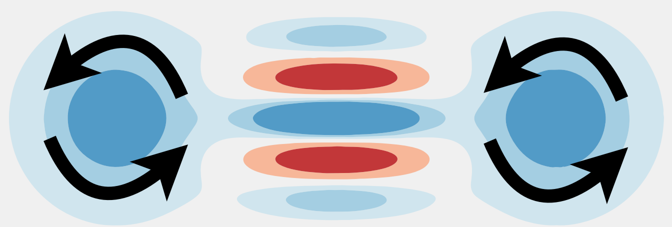
- 

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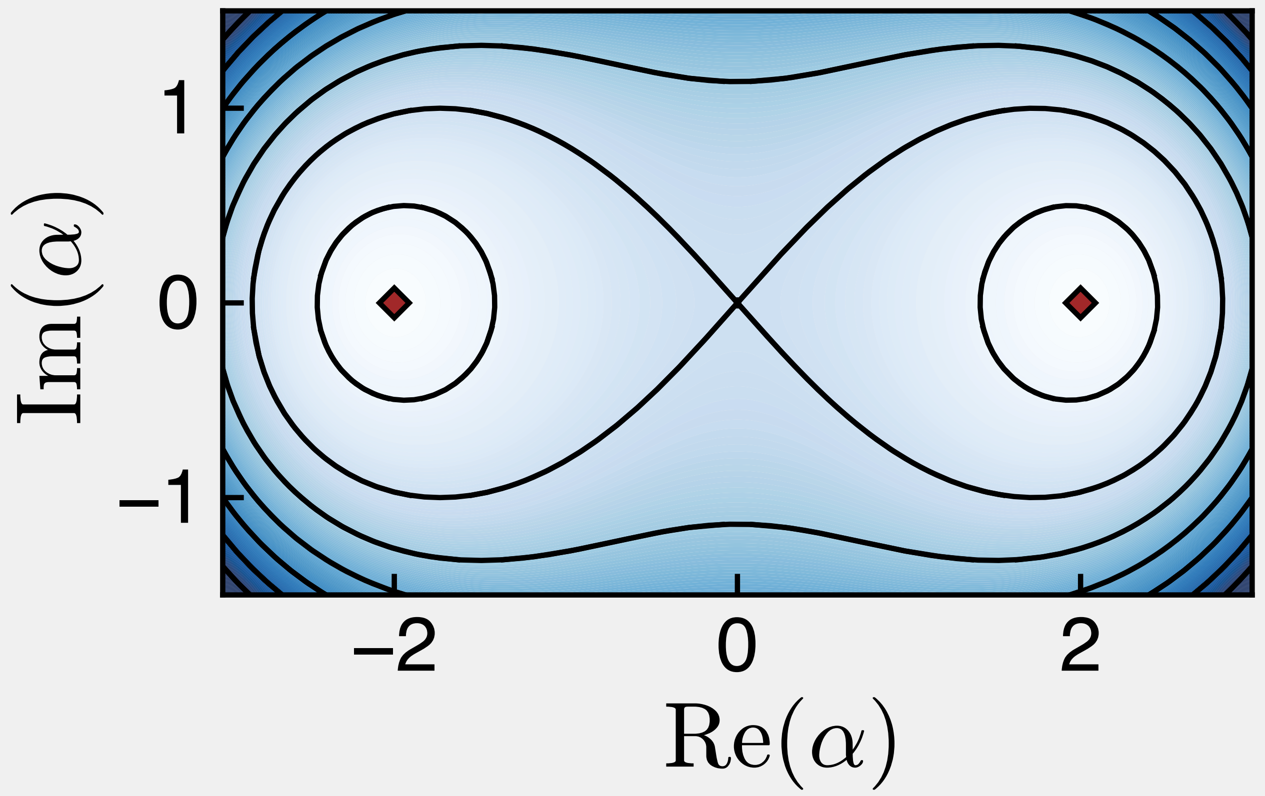

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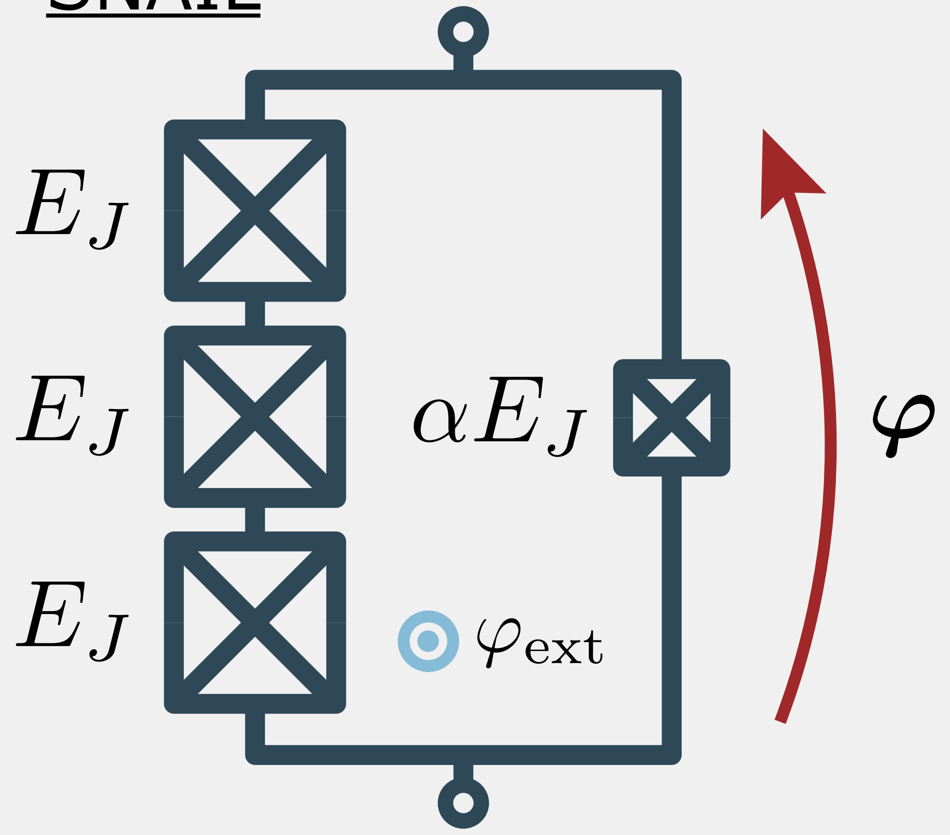

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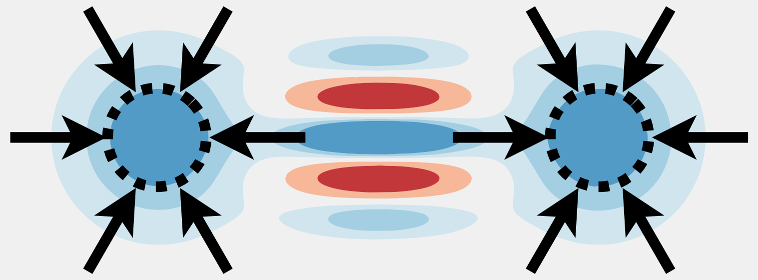
- 

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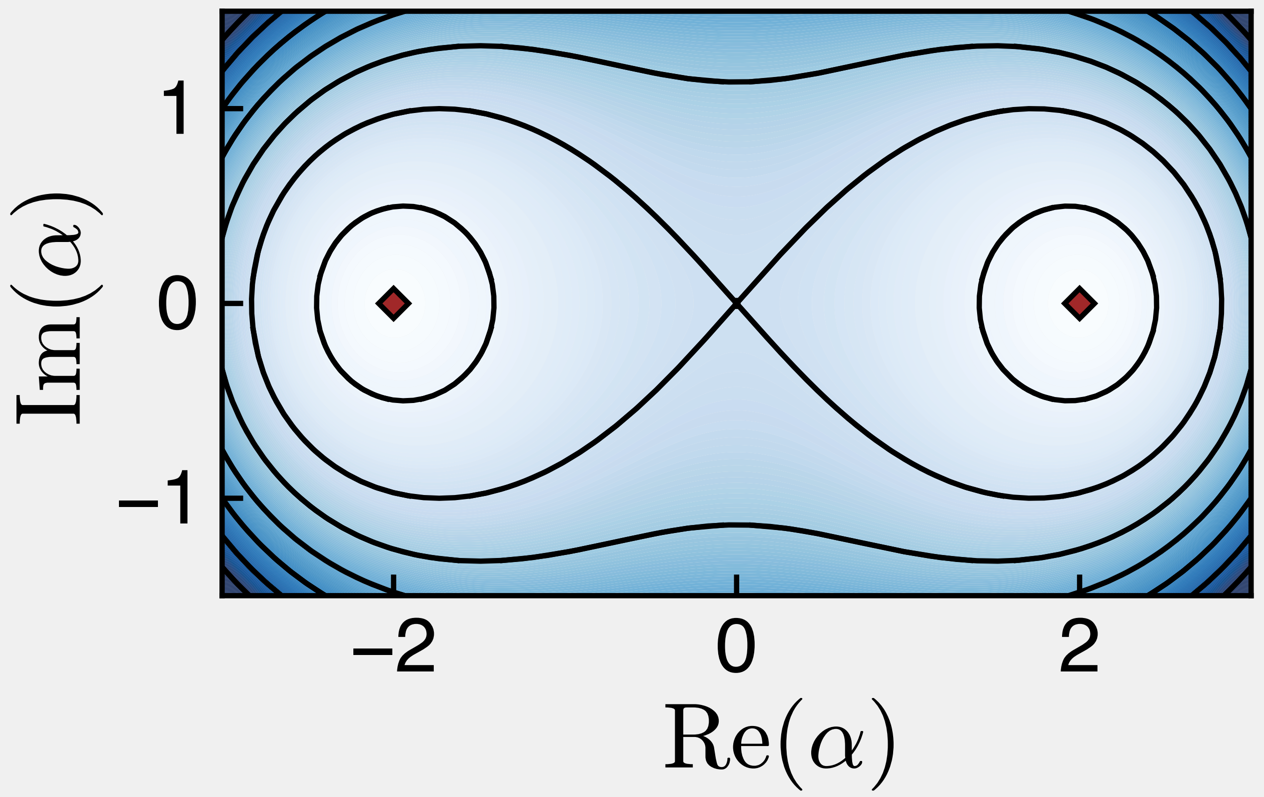
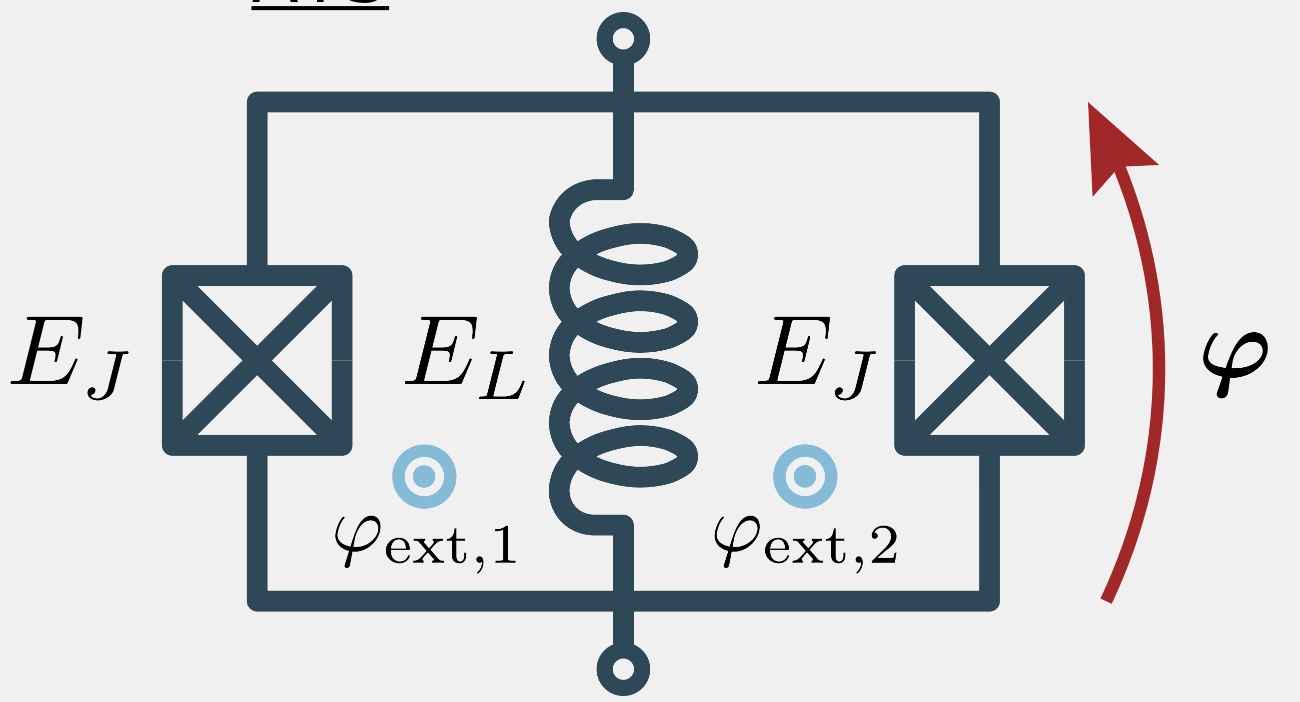


ATS



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Fault-tolerant universal QC

Guillaud et al. (2019)

- Preparation (X)
- Measurement (X)
- Bias-preserving gates

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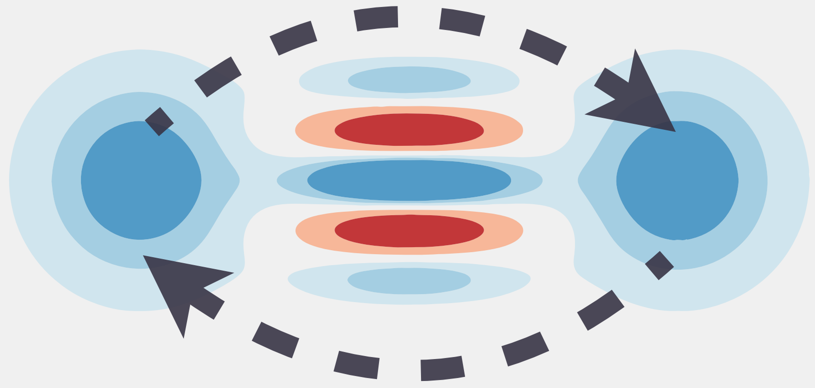
Pauli X



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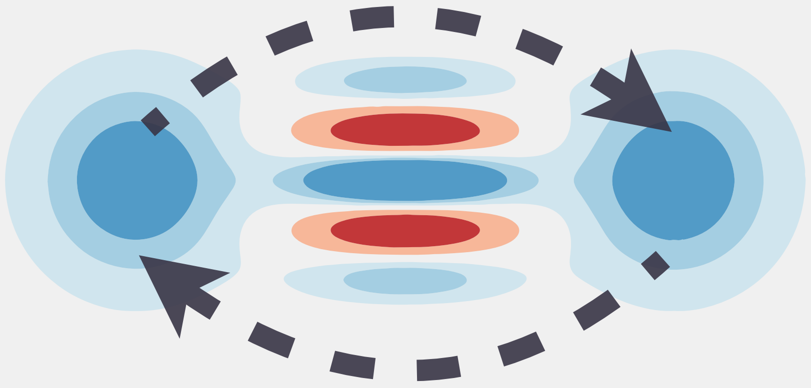

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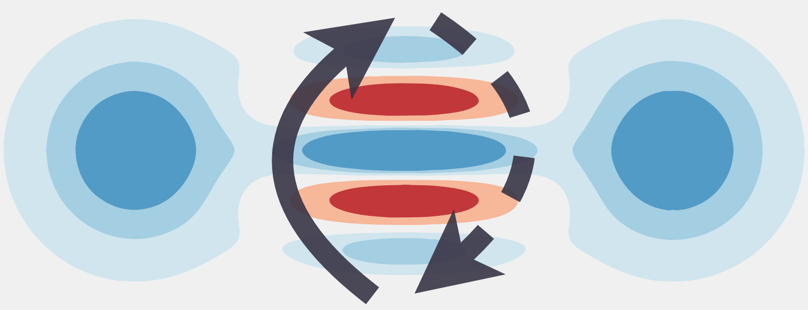
Z rotation



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

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- Bias-preserving gates

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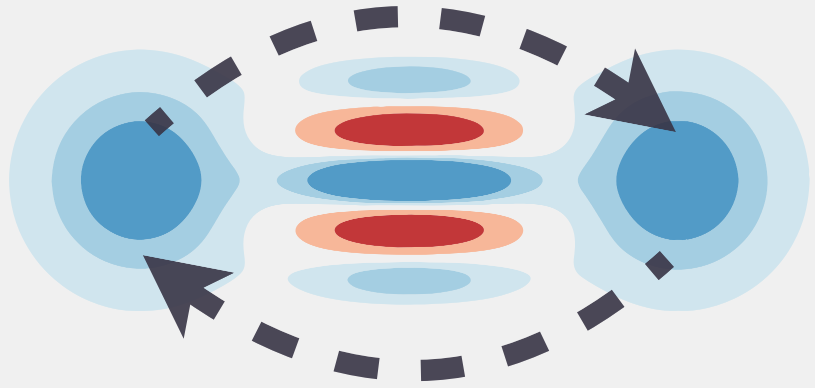
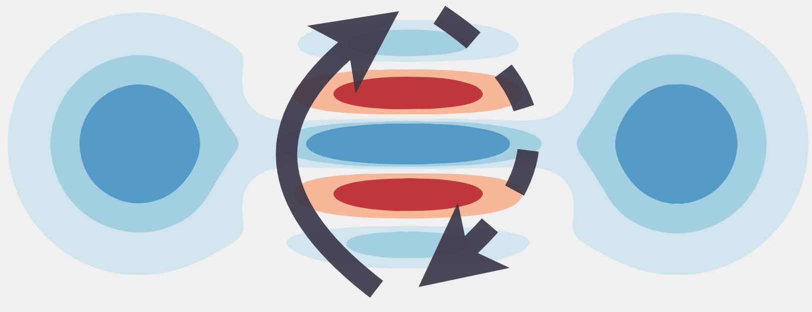


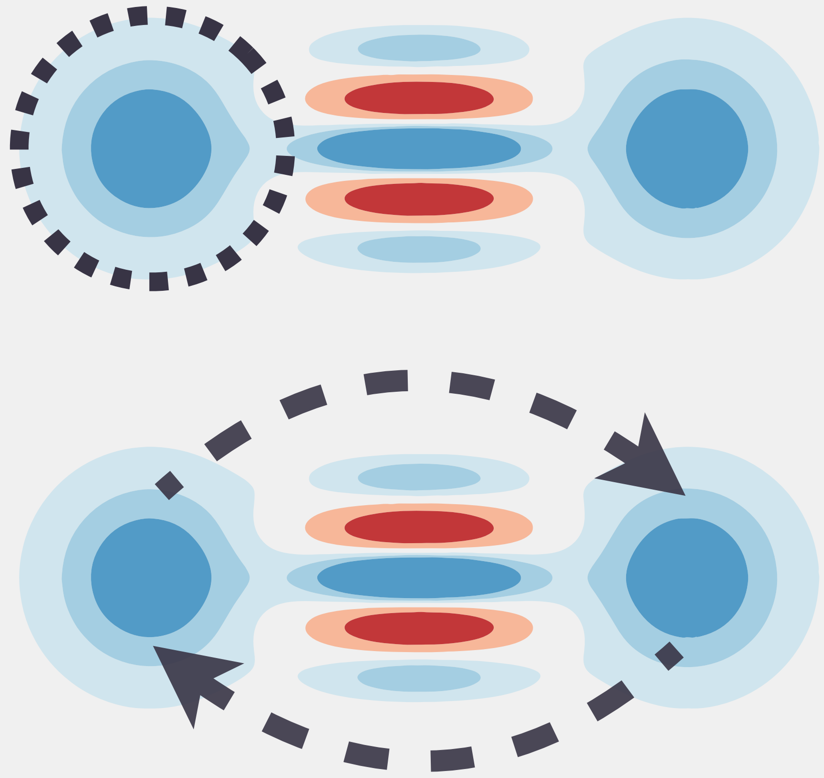
$$H = \Delta_X a^\dagger a$$

Z rotation



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

CNOT



$$H = \varepsilon_{CX}(a_C^\dagger + a_C - 2\alpha) \otimes (a_T^\dagger a_T - |\alpha|^2)$$

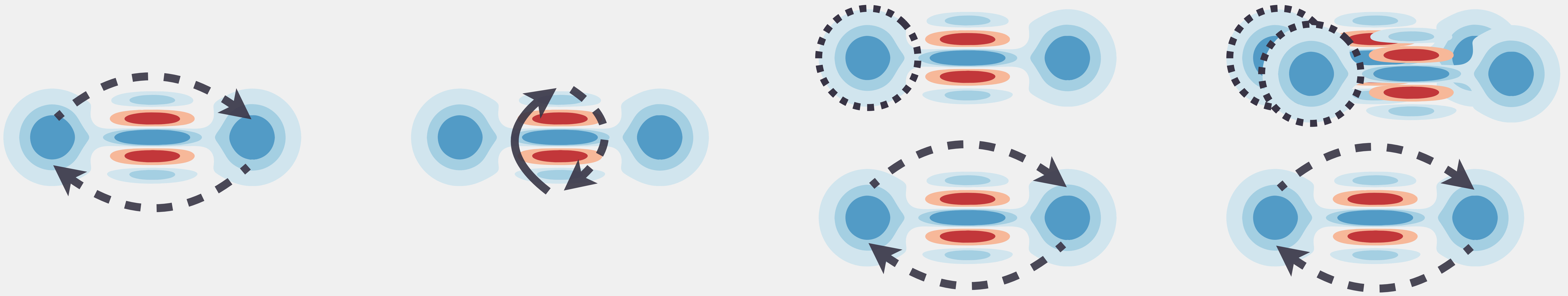
Guillaud et al., PRX (2019); Xu et al., PRR (2012)

Fault-tolerant universal QC

Guillaud et al. (2019)

- Preparation (X)
- Measurement (X)
- Bias-preserving gates

Pauli X | **Z rotation** | **CNOT** | **Toffoli**



Pauli X: $H = \Delta_X a^\dagger a$

Z rotation: $H = \varepsilon_Z a^\dagger + \varepsilon_Z a$

CNOT: $H = \varepsilon_{CX}(a_C^\dagger + a_C - 2\alpha) \otimes (a_T^\dagger a_T - |\alpha|^2)$

Toffoli: $H = \varepsilon_{CX}(a_{C,1}^\dagger + a_{C,1} - 2\alpha) \otimes (a_{C,2}^\dagger + a_{C,2} - 2\alpha) \otimes (a_T^\dagger a_T - |\alpha|^2)$

Guillaud et al., PRX (2019); Xu et al., PRR (2012)

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- Preparation (X)
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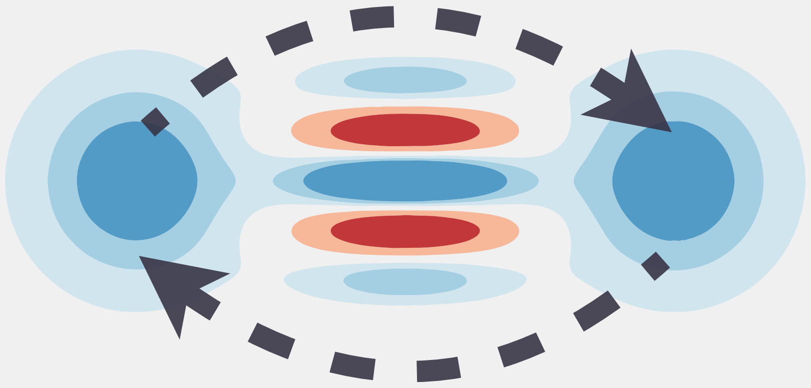

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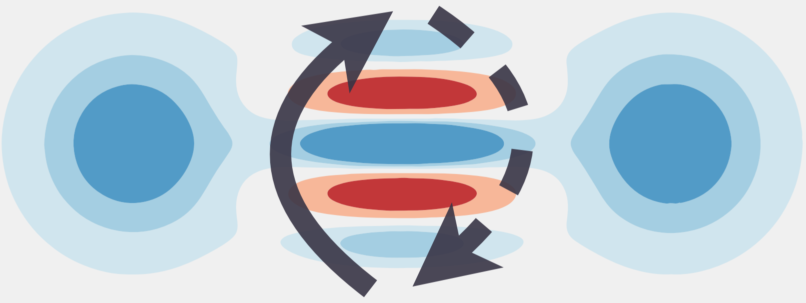

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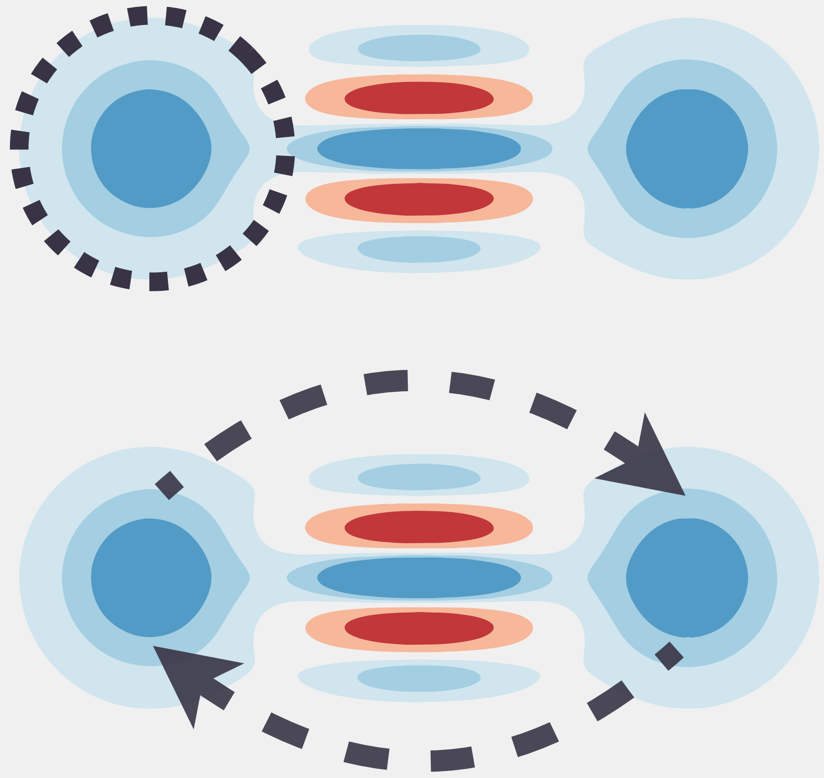

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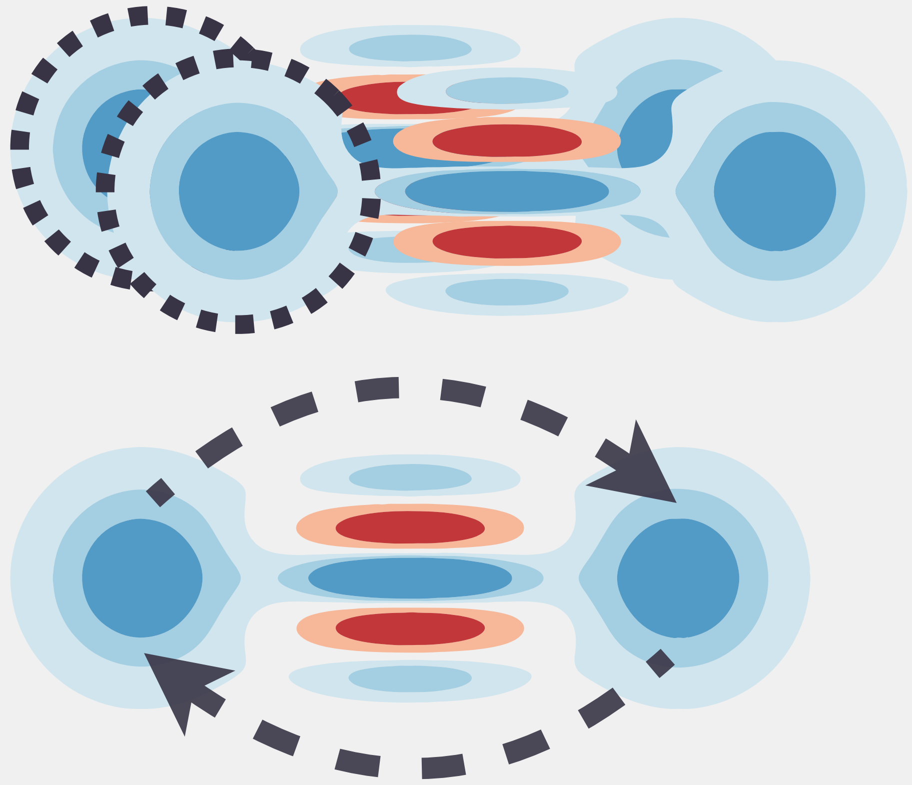
Toffoli



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- For Kerr cat qubits ➔ $1 - F \propto \exp(-\gamma T_{\text{gate}})$ (adiabatic theorem)
- For dissipative cat qubits ➔ $1 - F \propto 1/T_{\text{gate}}$ (Zeno effect)

Guillaud et al., PRX (2019); Xu et al., PRR (2012)

Summary of PhD contributions

Work on cat qubits

- **RG**, A. Sarlette, M. Mirrahimi, *Combined dissipative and Hamiltonian confinement of cat qubits*, PRX Quantum (2021)
- D. Ruiz, **RG**, J. Guillaud, M. Mirrahimi, *Two-photon driven Kerr quantum oscillator with multiple spectral degeneracies*, Phys. Rev. A (2022)
- **RG**, M. Mirrahimi, A. Sarlette, *Designing high-fidelity Zeno gates for dissipative cat qubits*, PRX Quantum (2022)
- U. Réglade, A. Bocquet, **RG**, *et al.*, *Quantum control of a cat-qubit with bit-flip times exceeding ten seconds*, arXiv (2023)

Work on optimal control of open quantum systems

- **RG**, É. Genois, A. Blais, *Optimal readout and reset of a transmon*, in preparation
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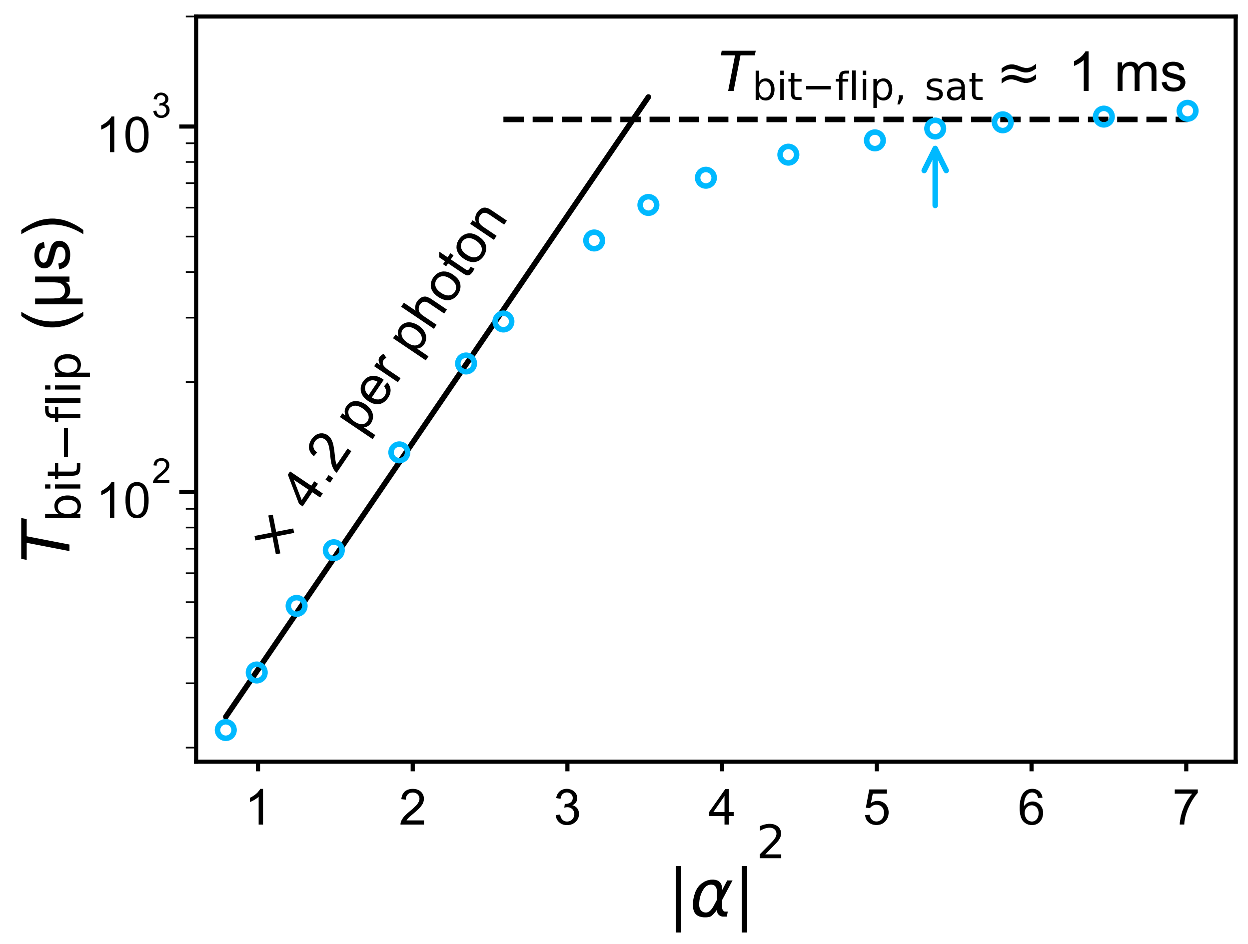
Bit-flip lifetime of cat qubits

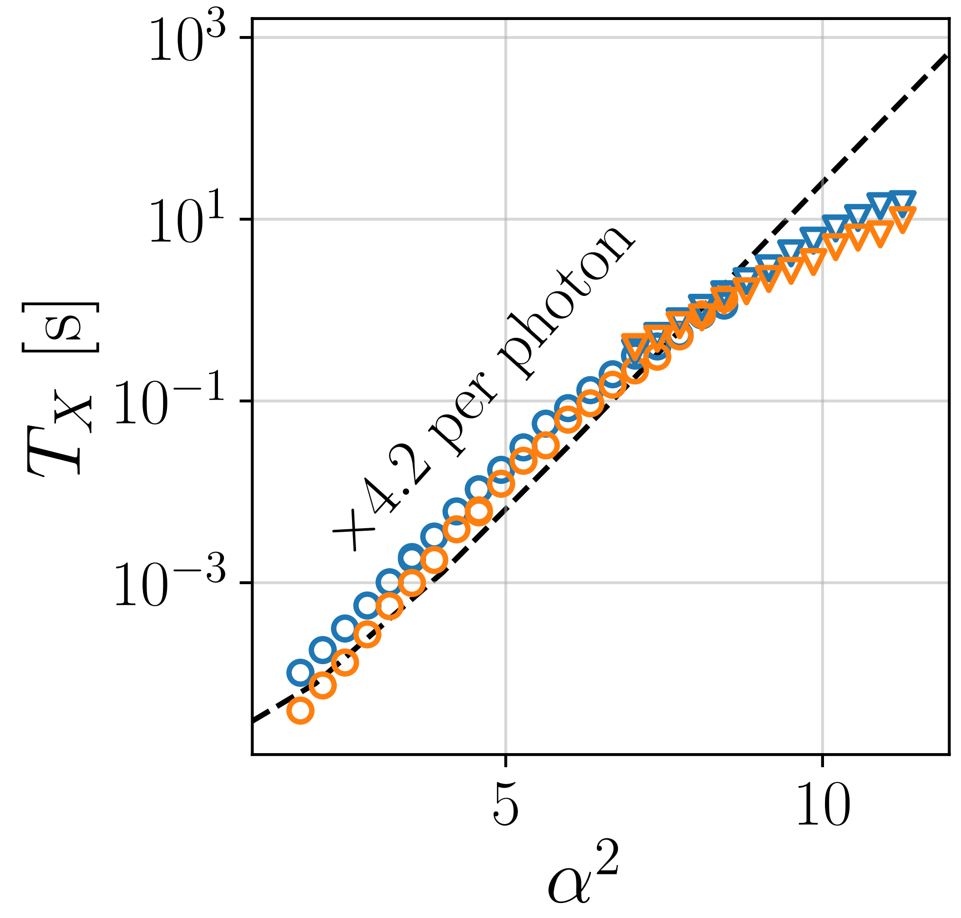
Dissipative cat qubits

- ~1ms in 2019
- >10s in 2023
- Exponential ➔ Saturation

2019: Lescanne *et al.*



2023: Reglade, Bocquet *et al.*



Bit-flip lifetime of cat qubits

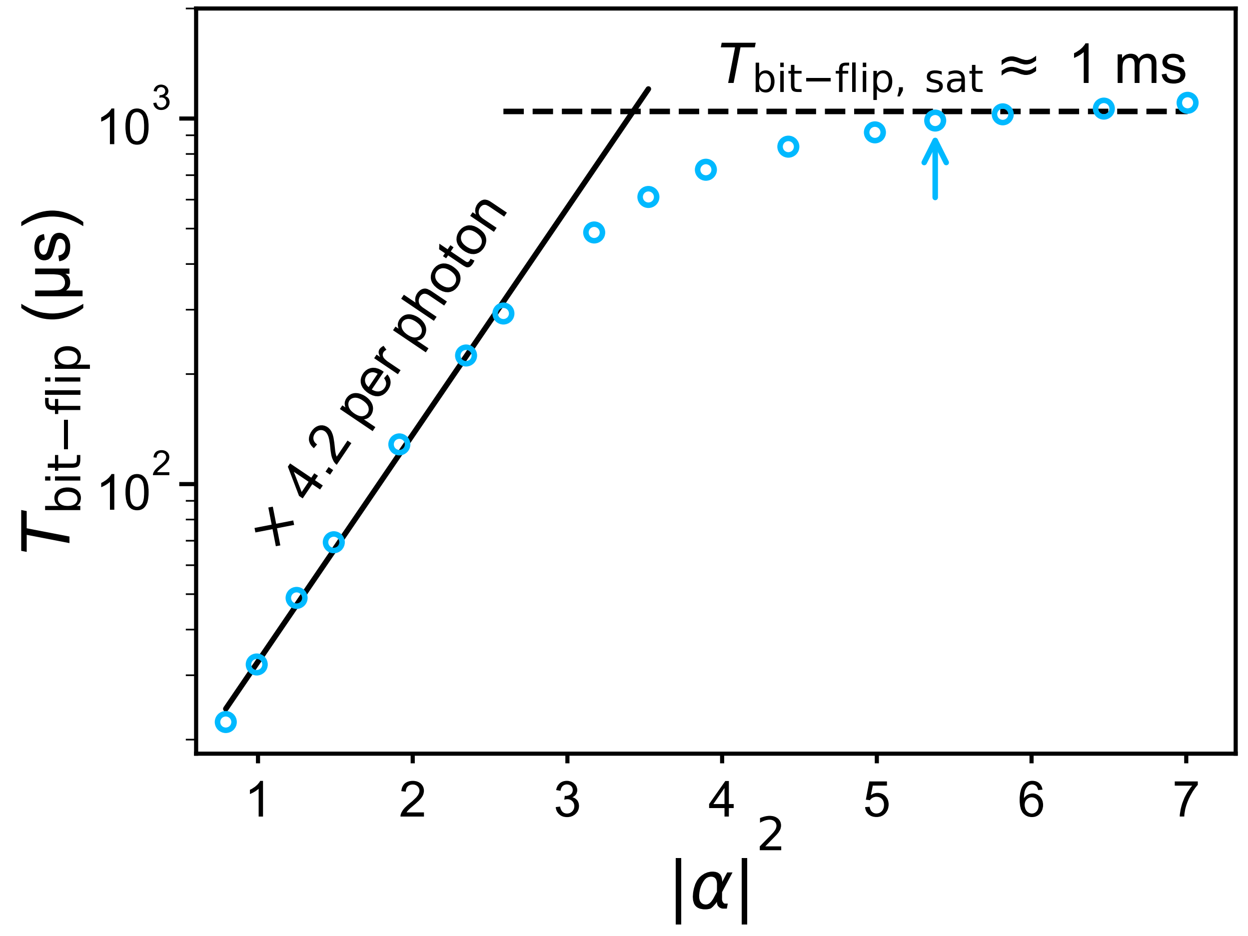
Dissipative cat qubits

- ~1ms in 2019
- >10s in 2023
- Exponential ➔ Saturation

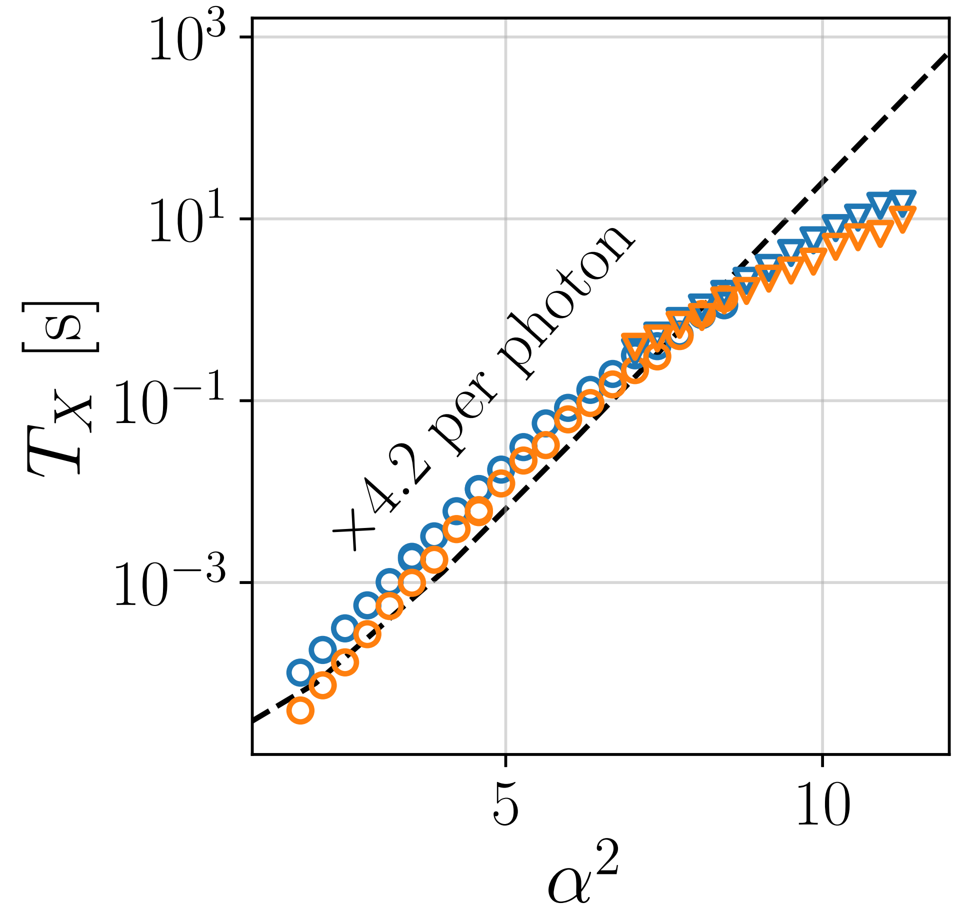
Kerr cat qubits

- ~500us in 2022
- Exponential ➔ Plateaus
- Saturation predicted in 2021 by Putterman et al.
- **Why plateaus?**

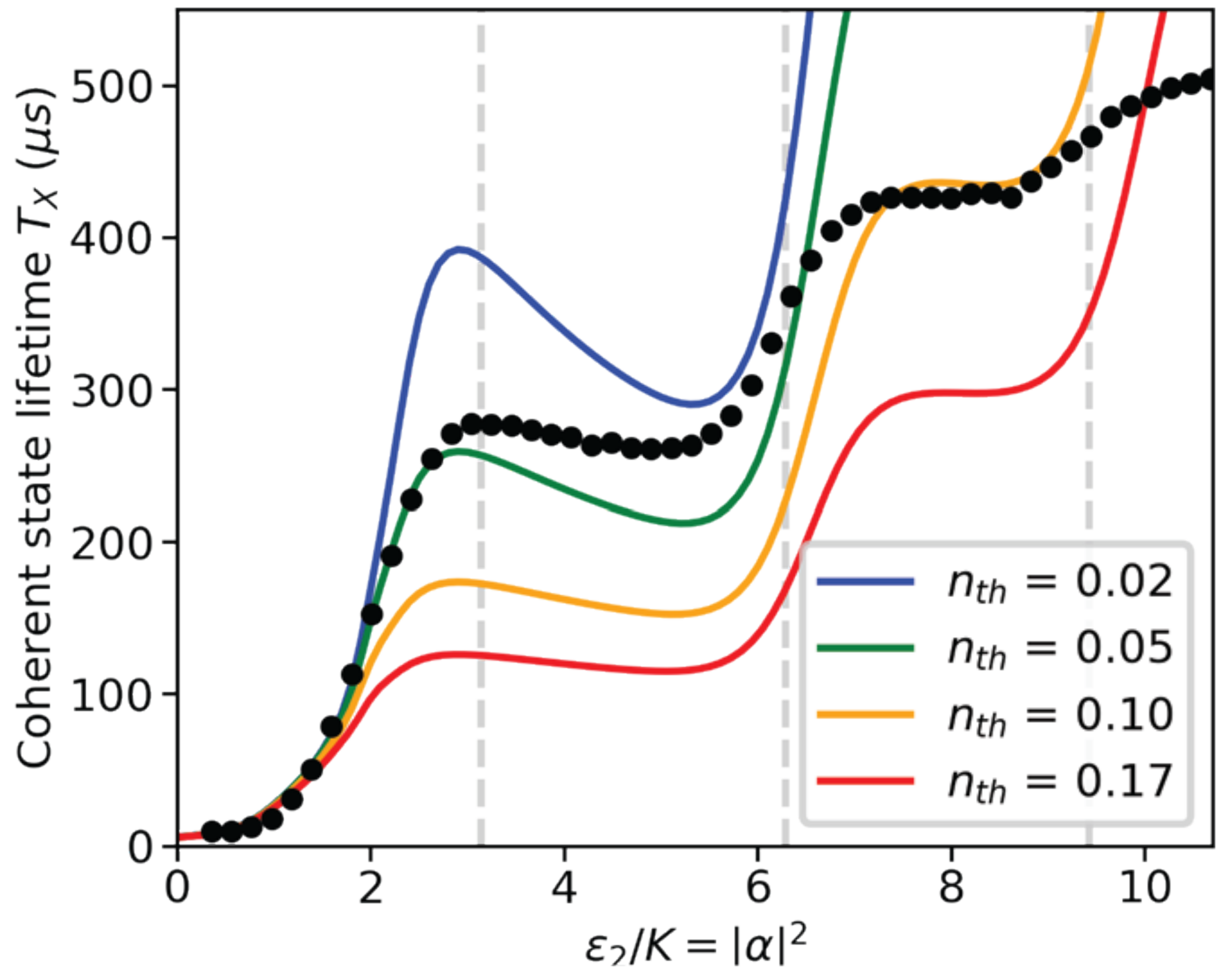
2019: Lescanne *et al.*



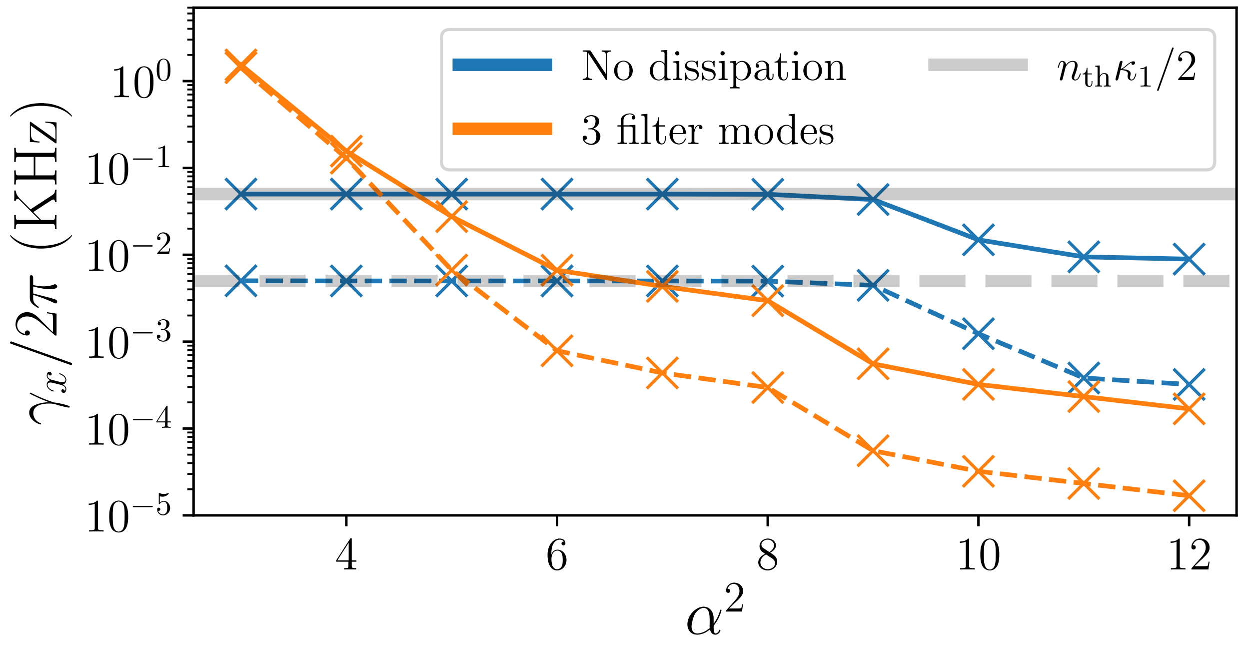
2023: Reglade, Bocquet *et al.*



Sep. 2022: Frattini *et al.*

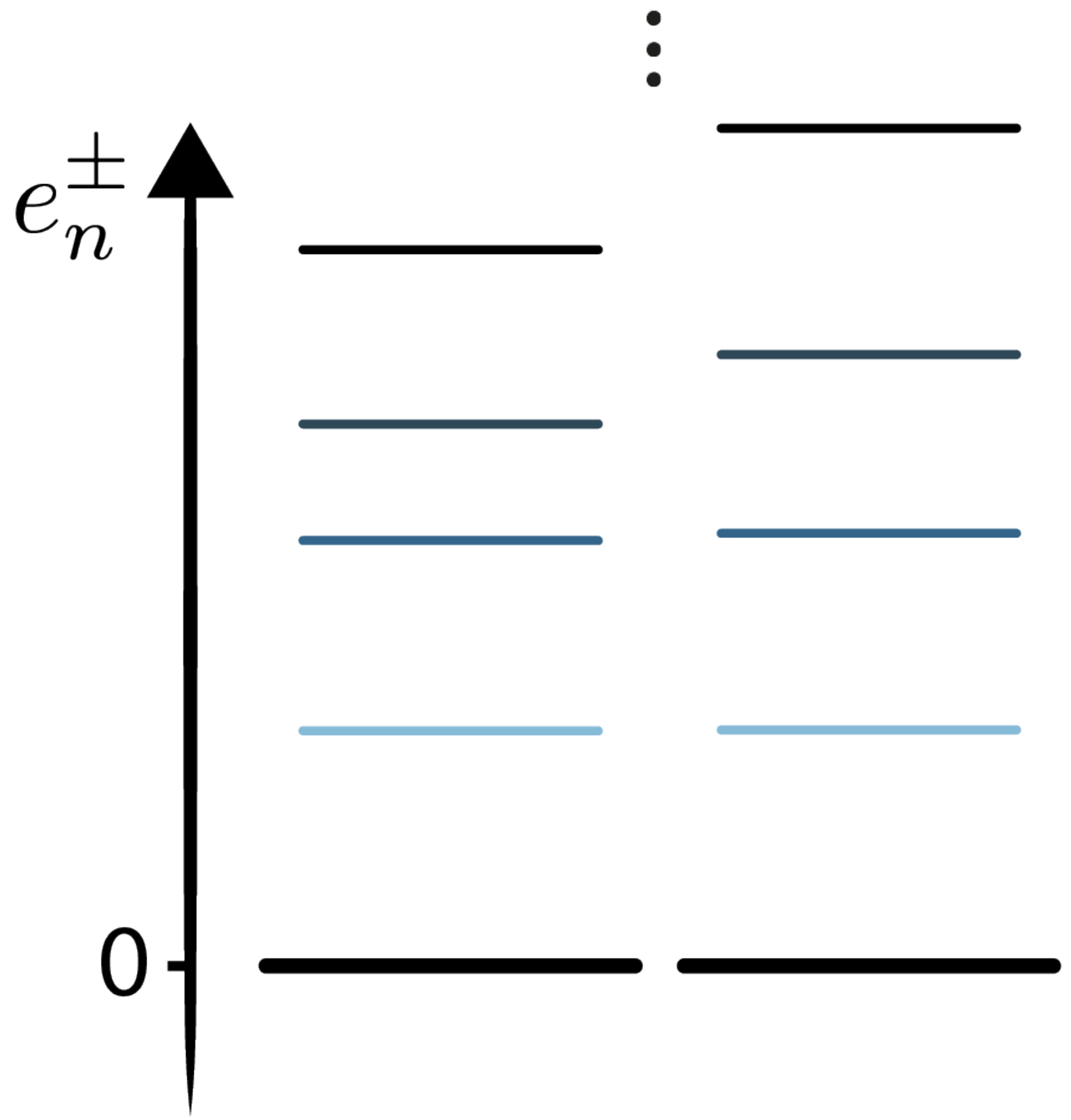


July 2021: Putterman *et al.*



The spectrum of Kerr cat qubits

$$H = -K(a^{\dagger 2} - \alpha^{*2})(a^2 - \alpha^2)$$



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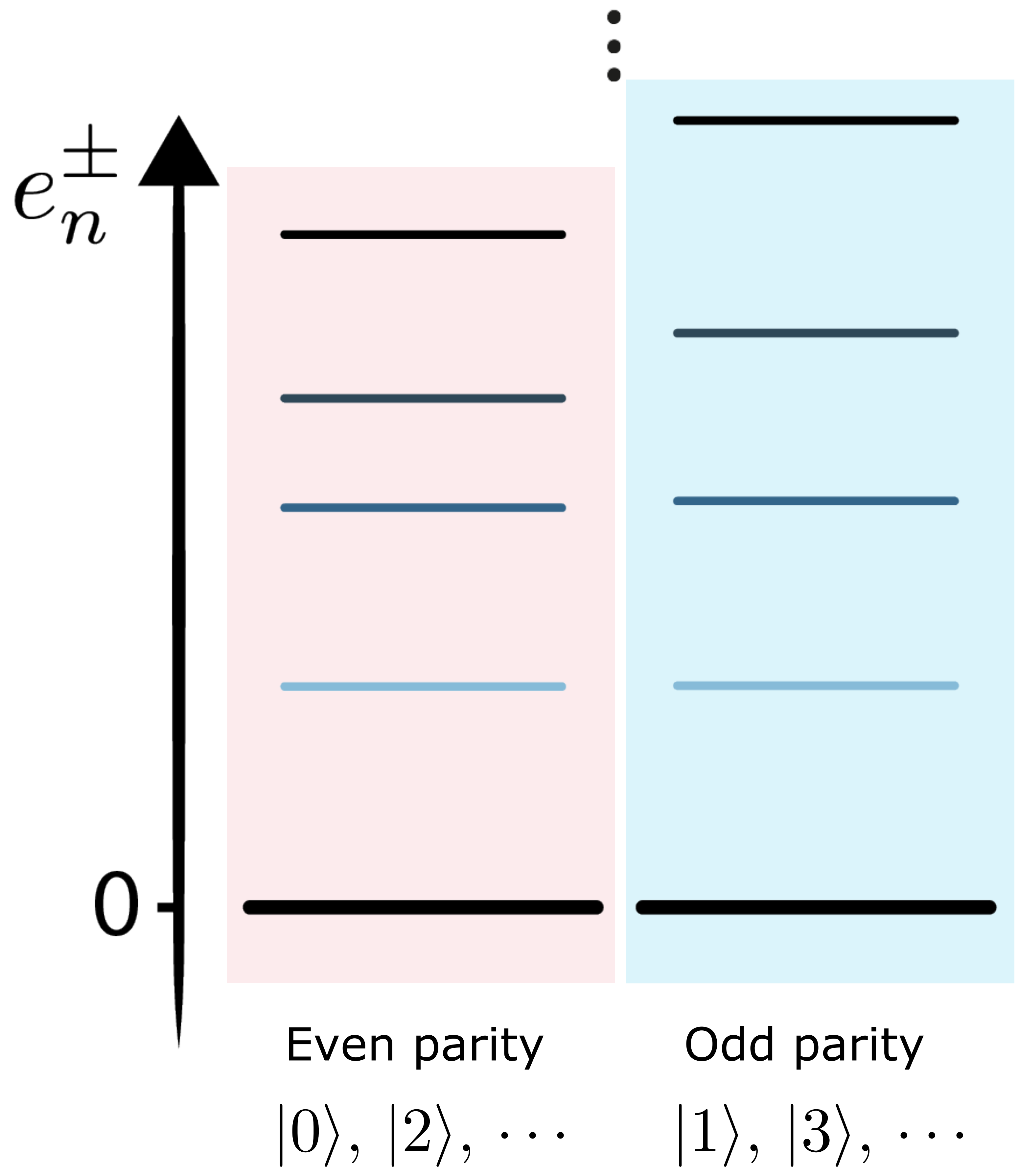

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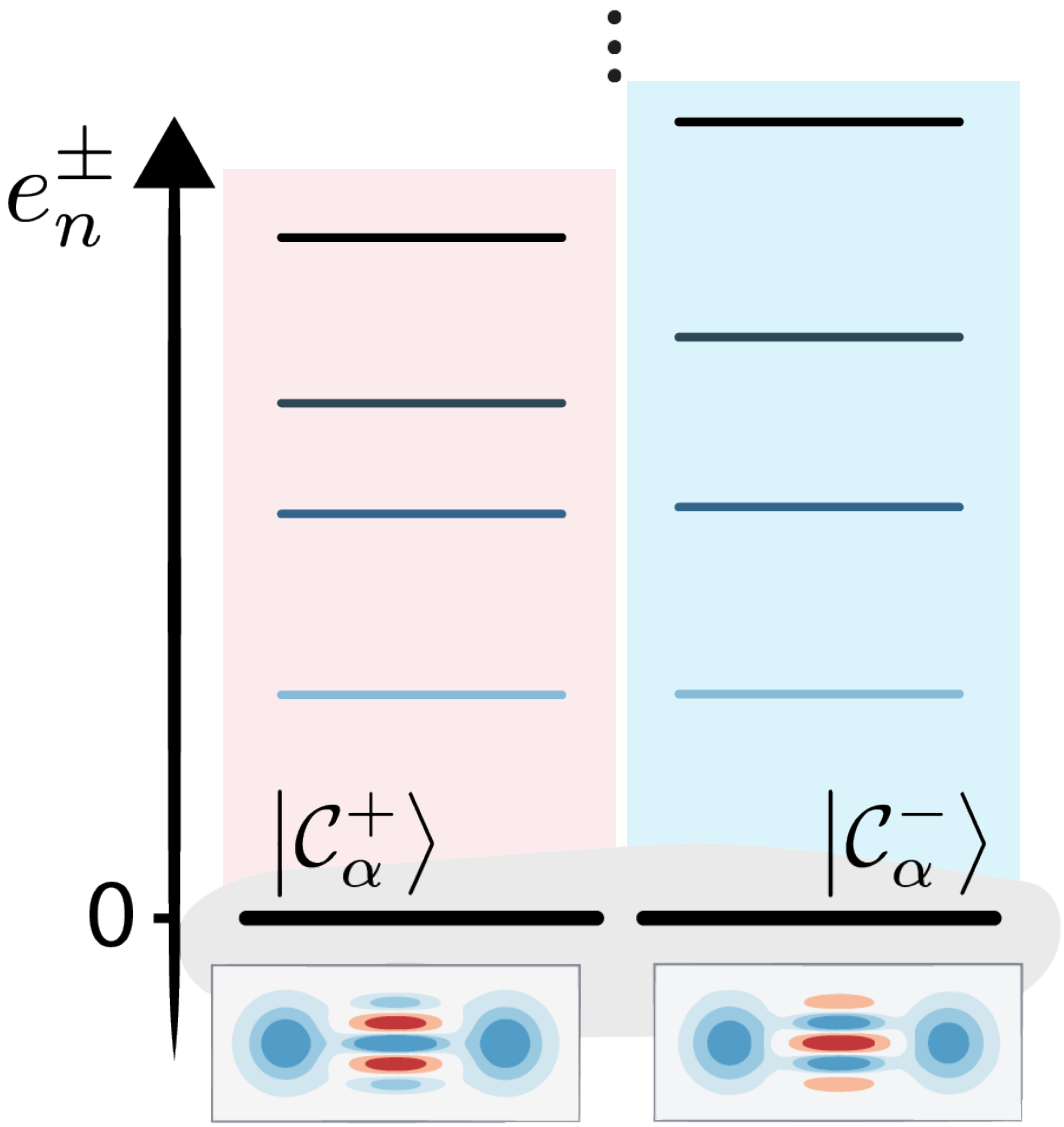

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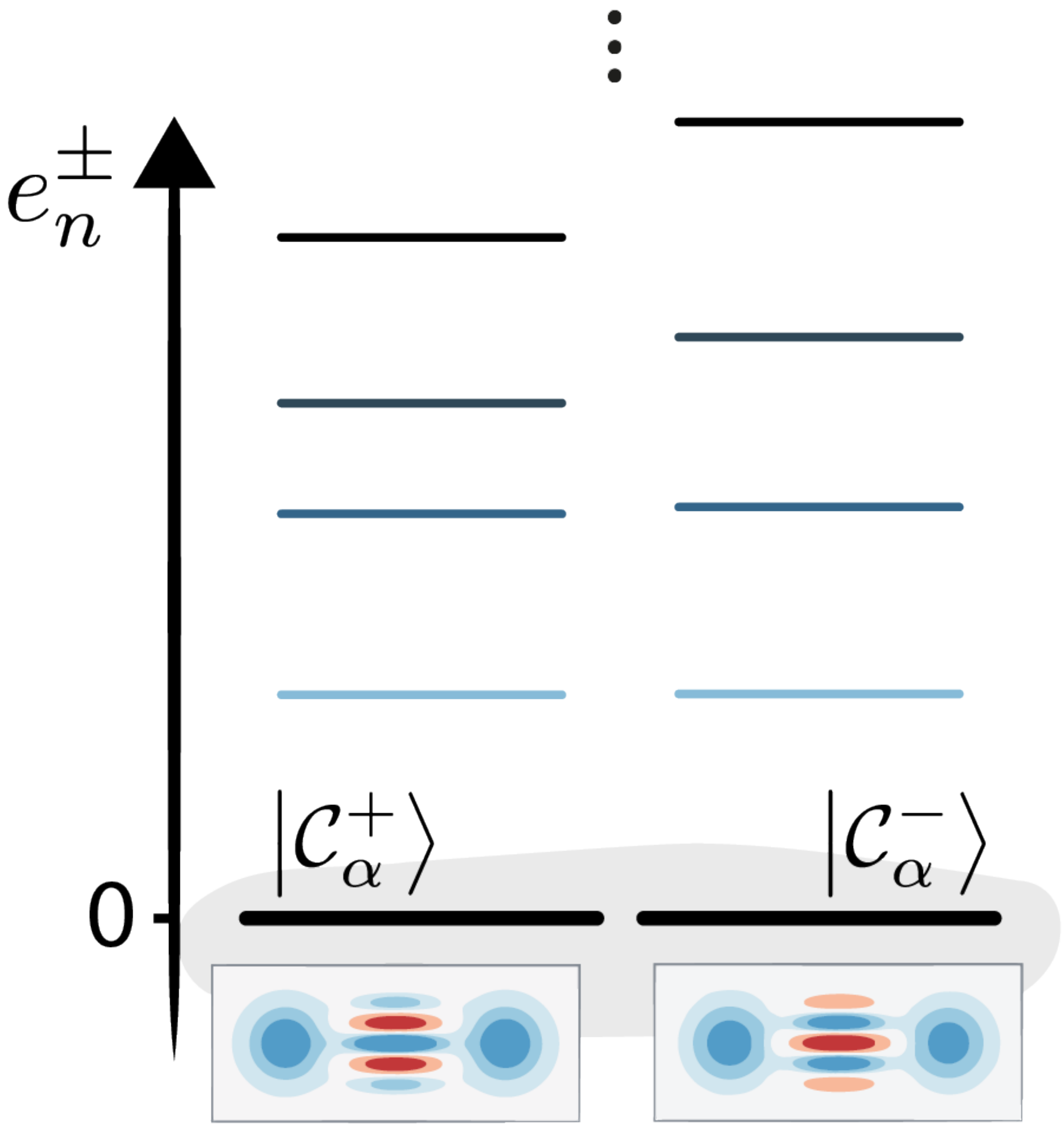

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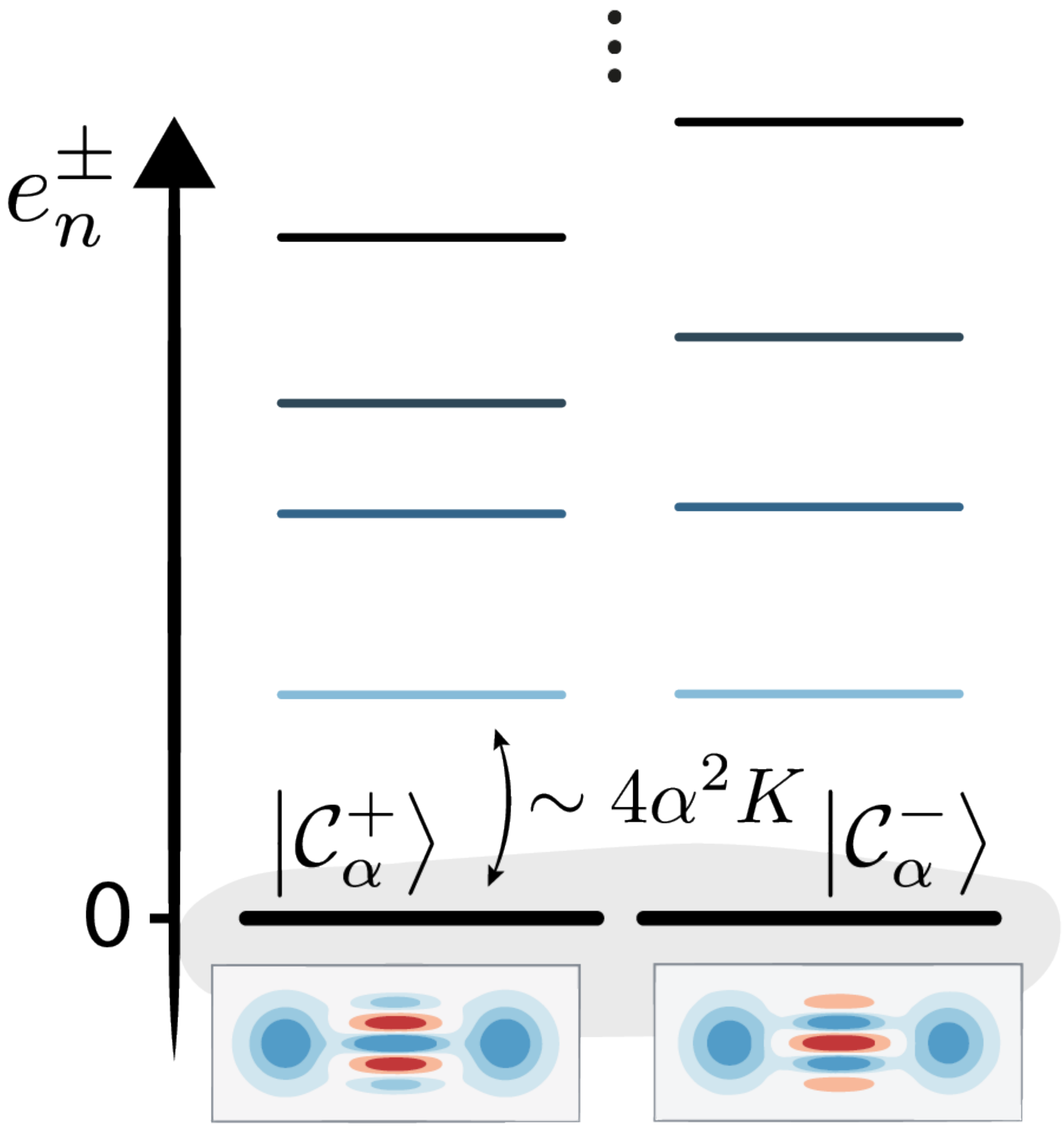
- Gapped spectrum



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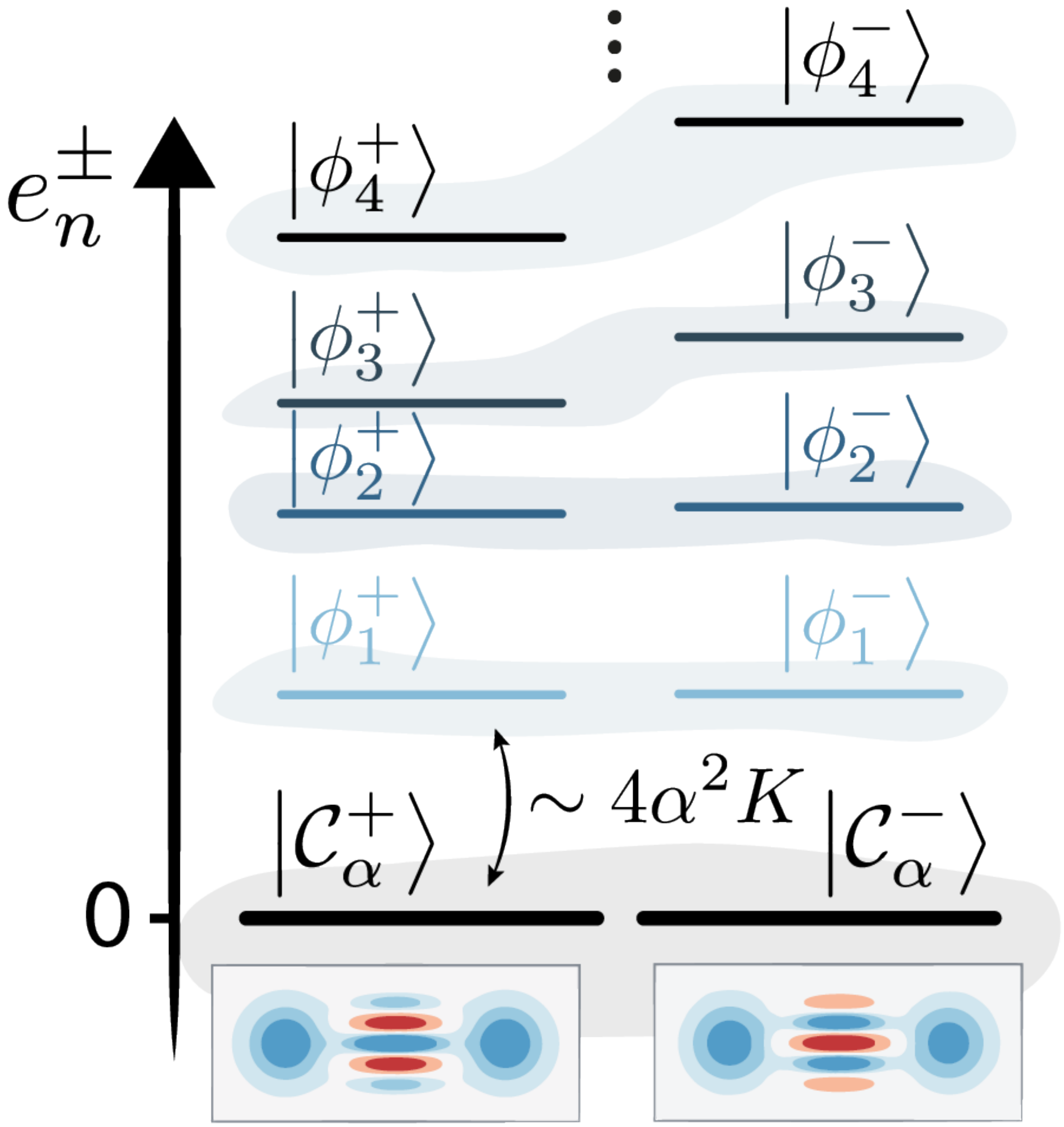

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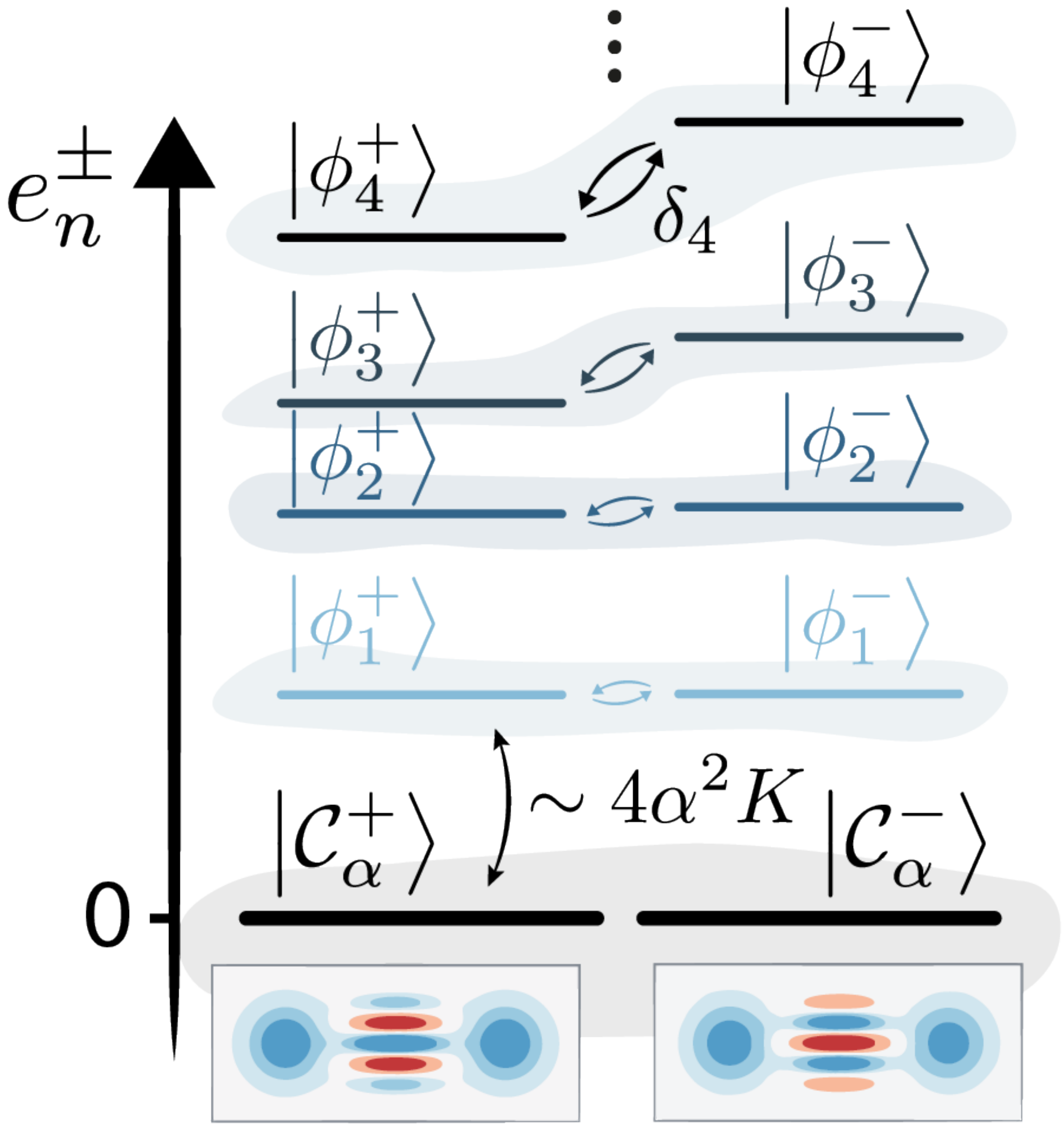
- Gapped spectrum
- Standard Tunneling Model

<u>phase basis</u>

$$\begin{pmatrix} e_n + \delta_n/2 & 0 \\ 0 & e_n - \delta_n/2 \end{pmatrix}$$



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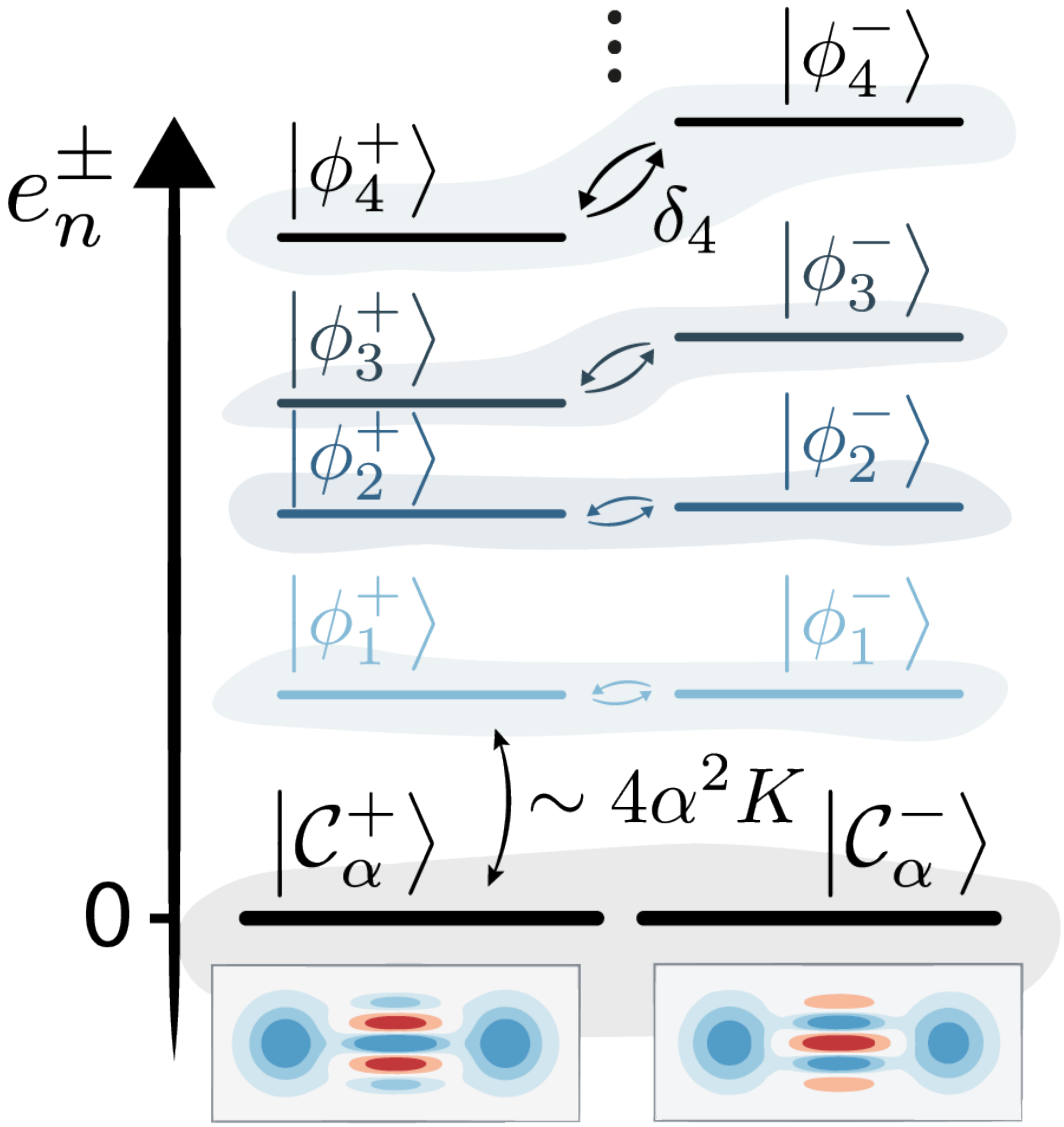
<u>bit basis</u> ← <u>phase basis</u>

$$\begin{pmatrix} e_n & \delta_n/2 \\ \delta_n/2 & e_n \end{pmatrix} \leftarrow \begin{pmatrix} e_n + \delta_n/2 & 0 \\ 0 & e_n - \delta_n/2 \end{pmatrix}$$



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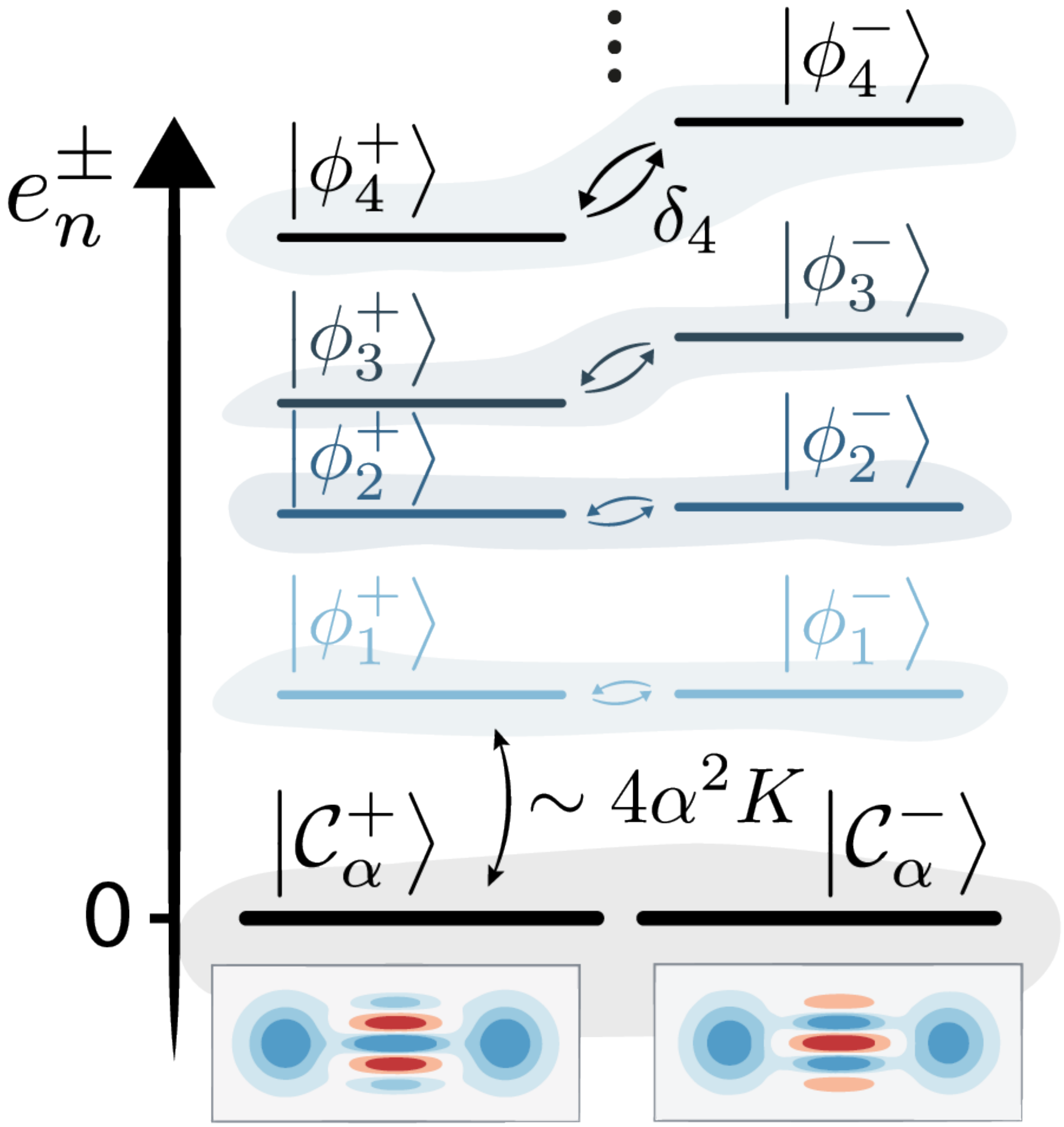
Tunneling matrix element



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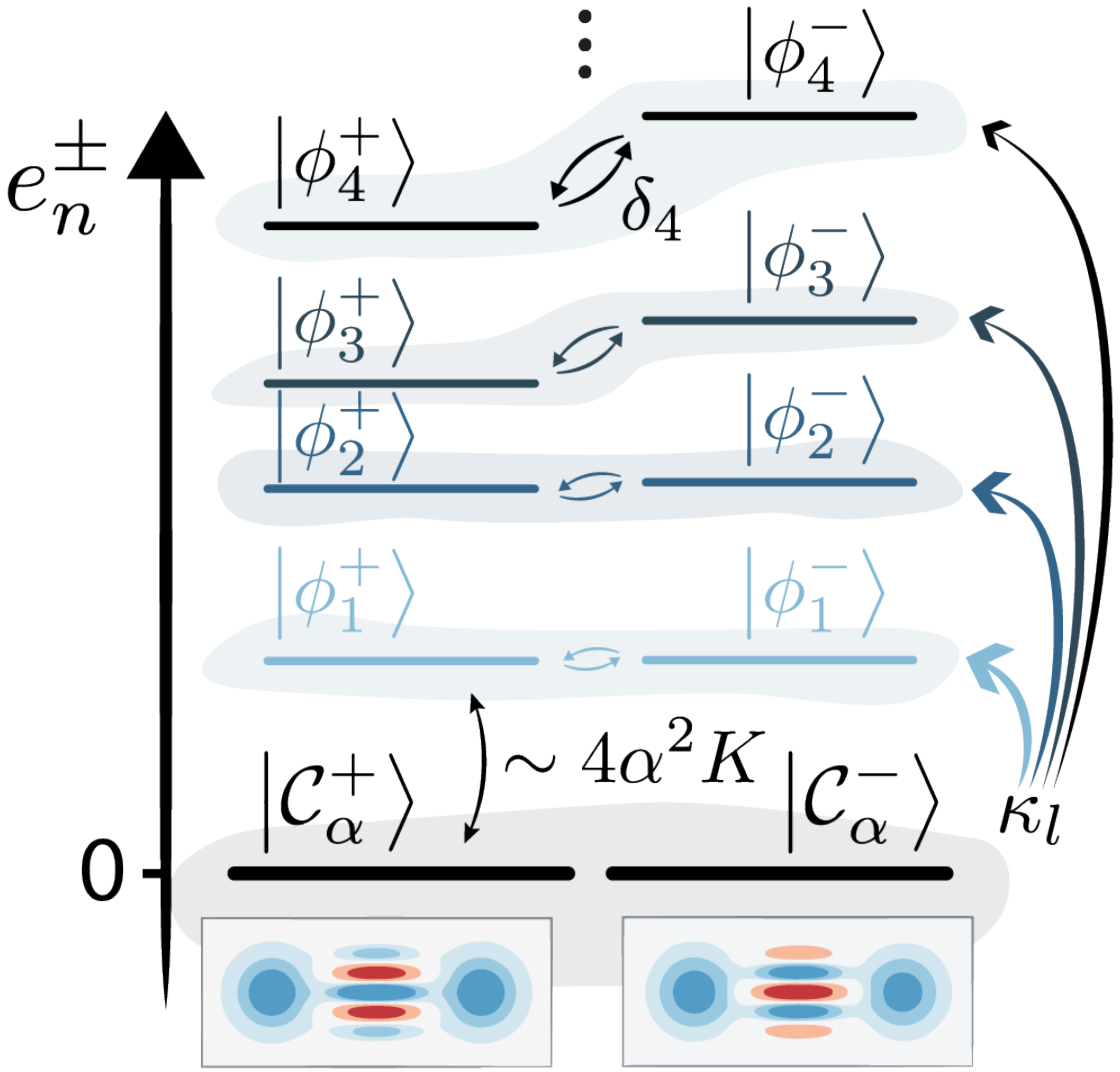
- Incoherent leakage
  - ➔ Thermal photons
  - ➔ Pure dephasing



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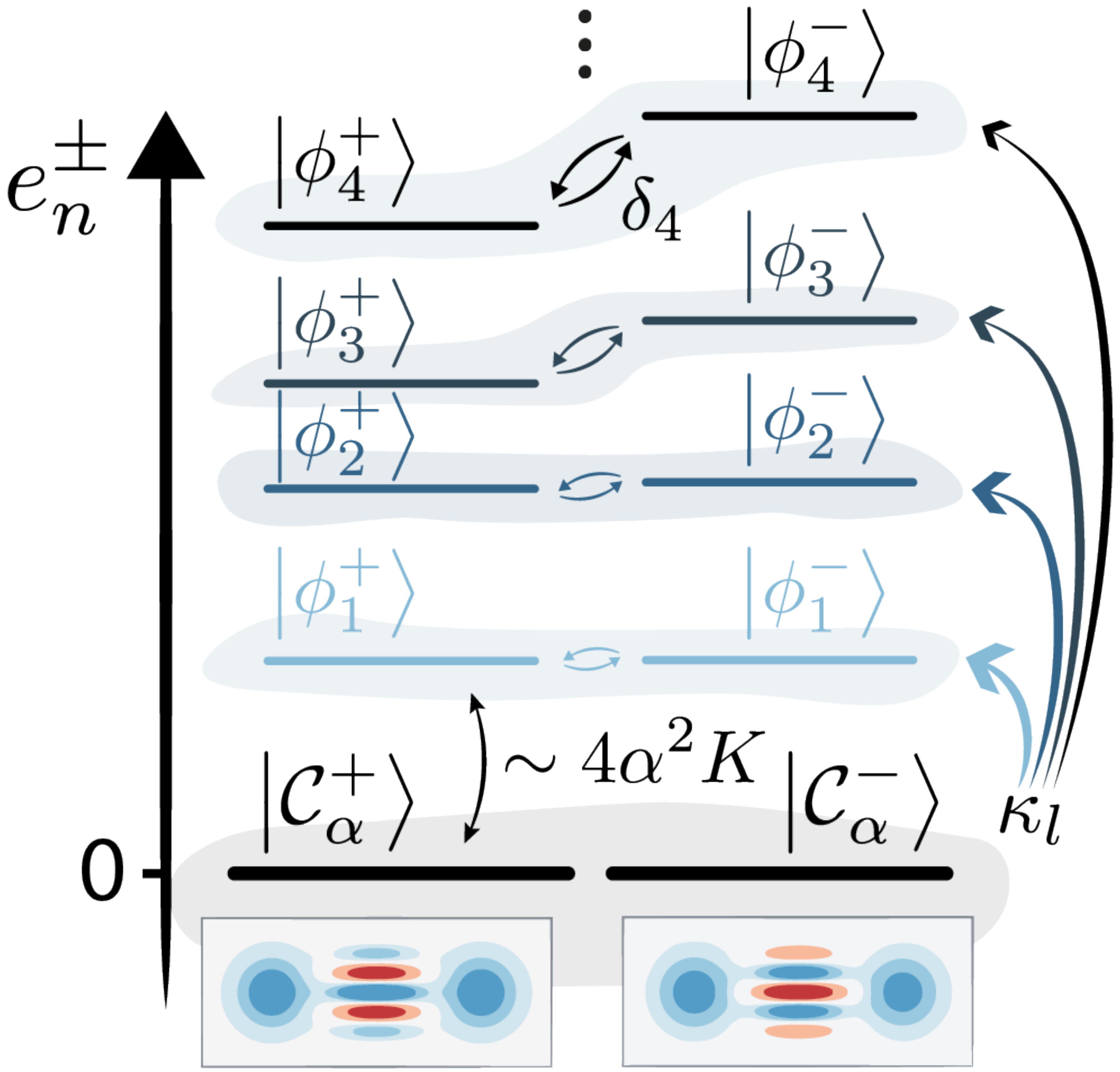
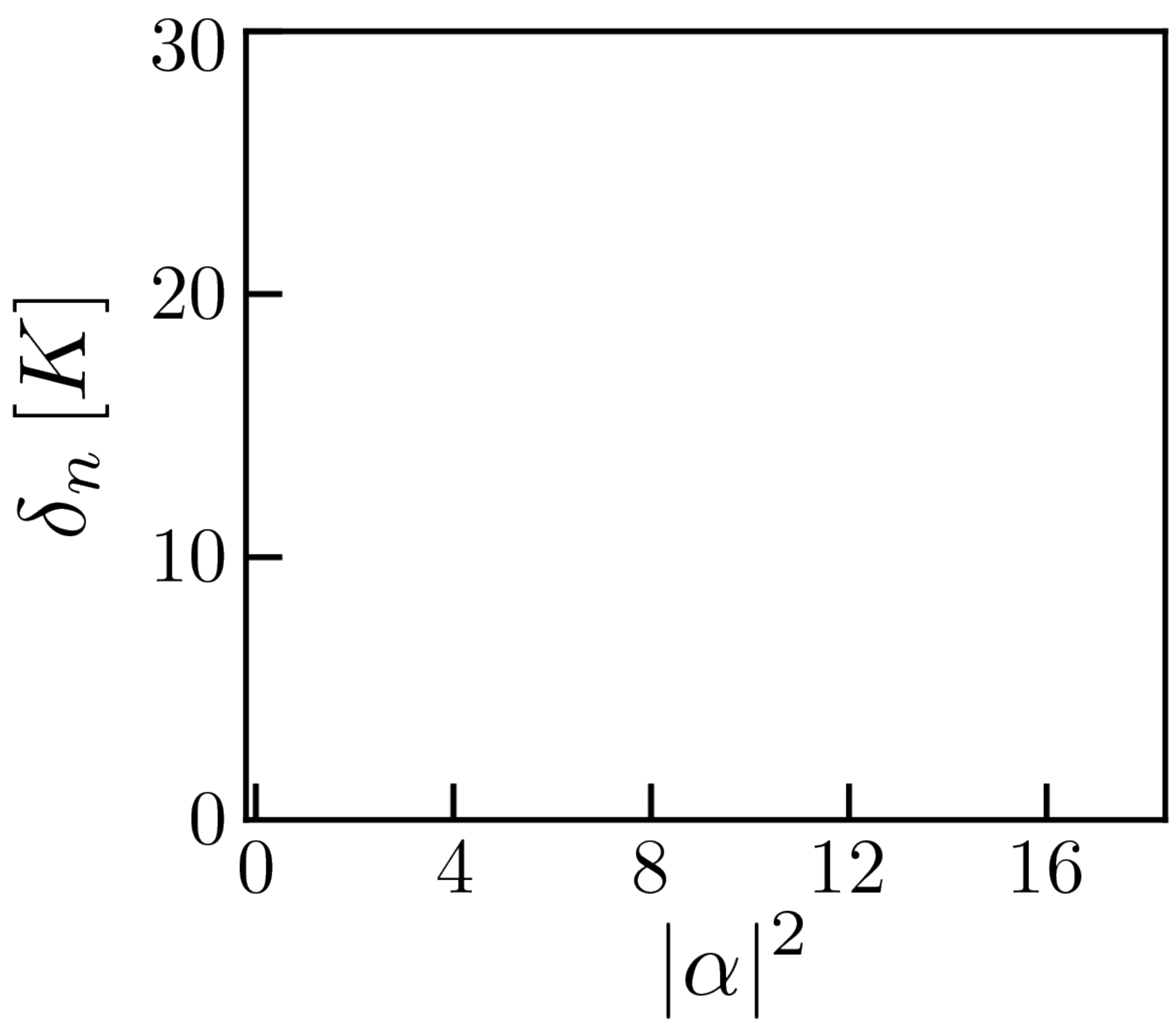
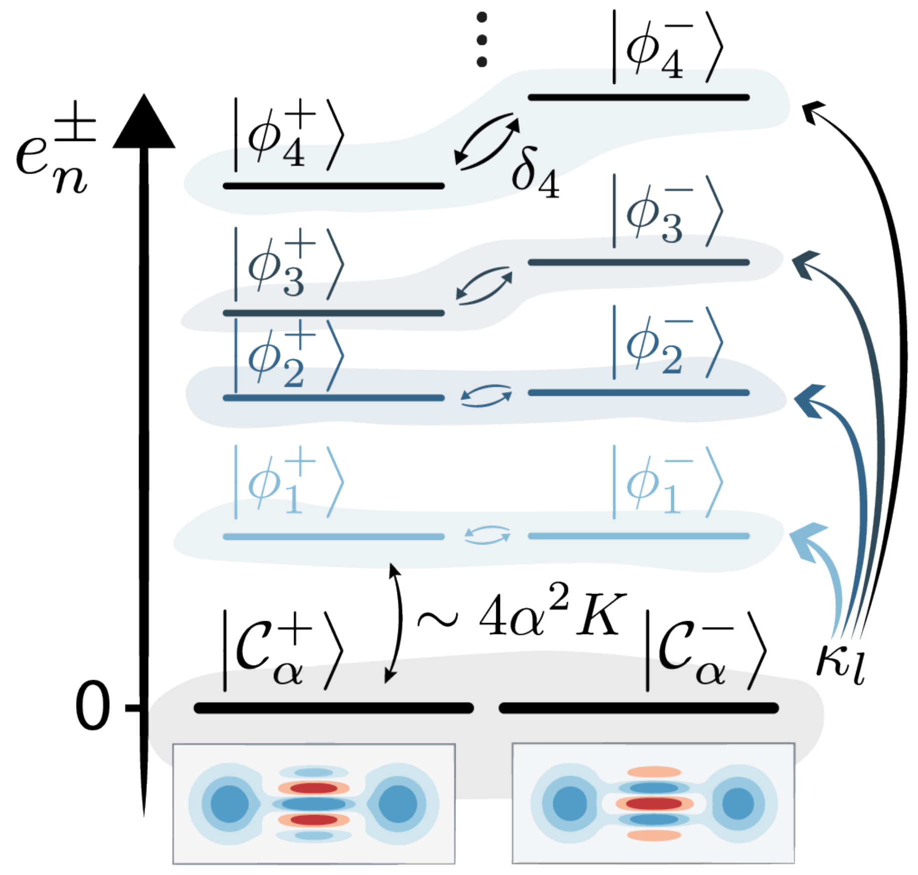


Bit-flip induced by incoherent leakage

Bit-flip plateaus





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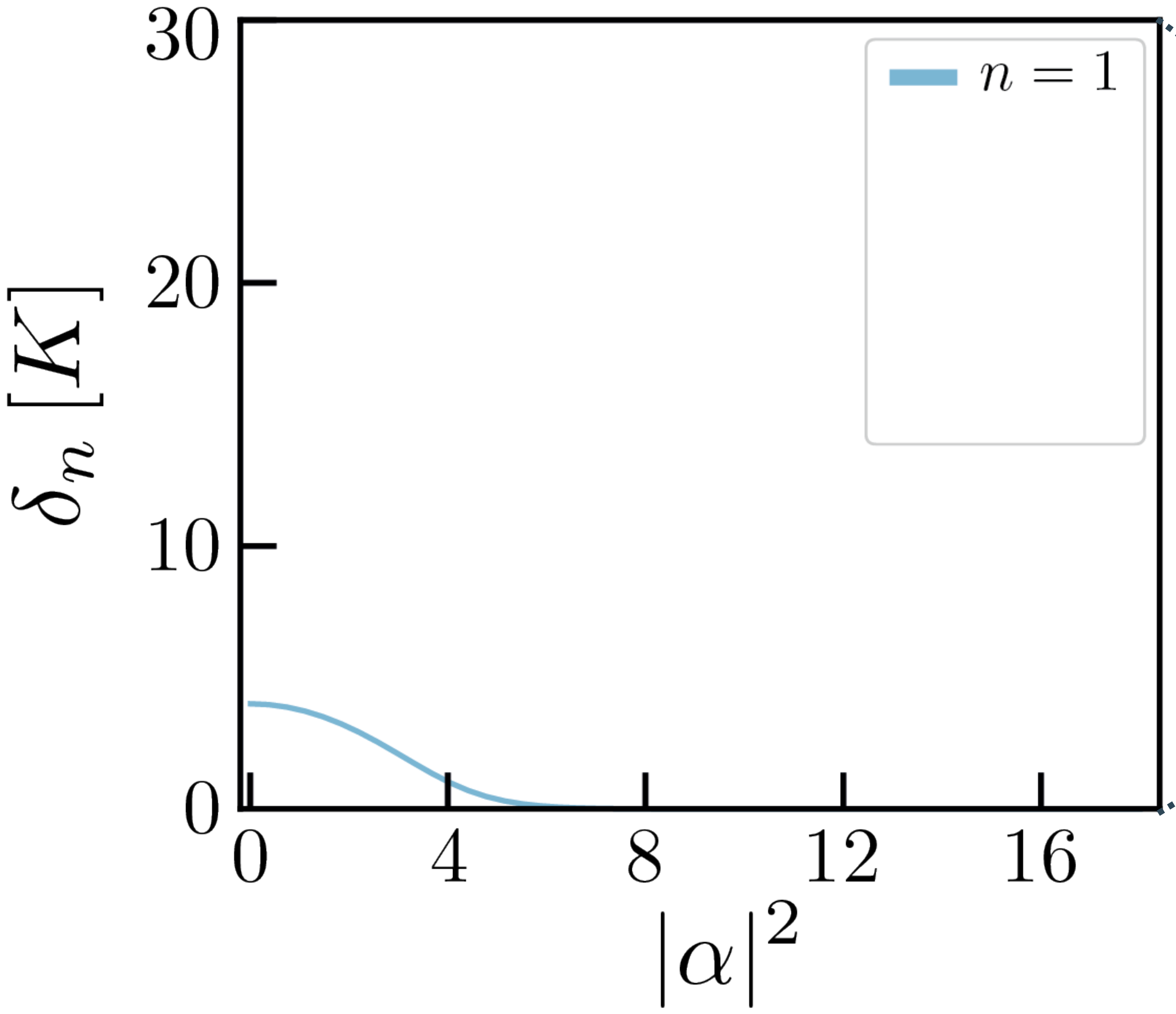

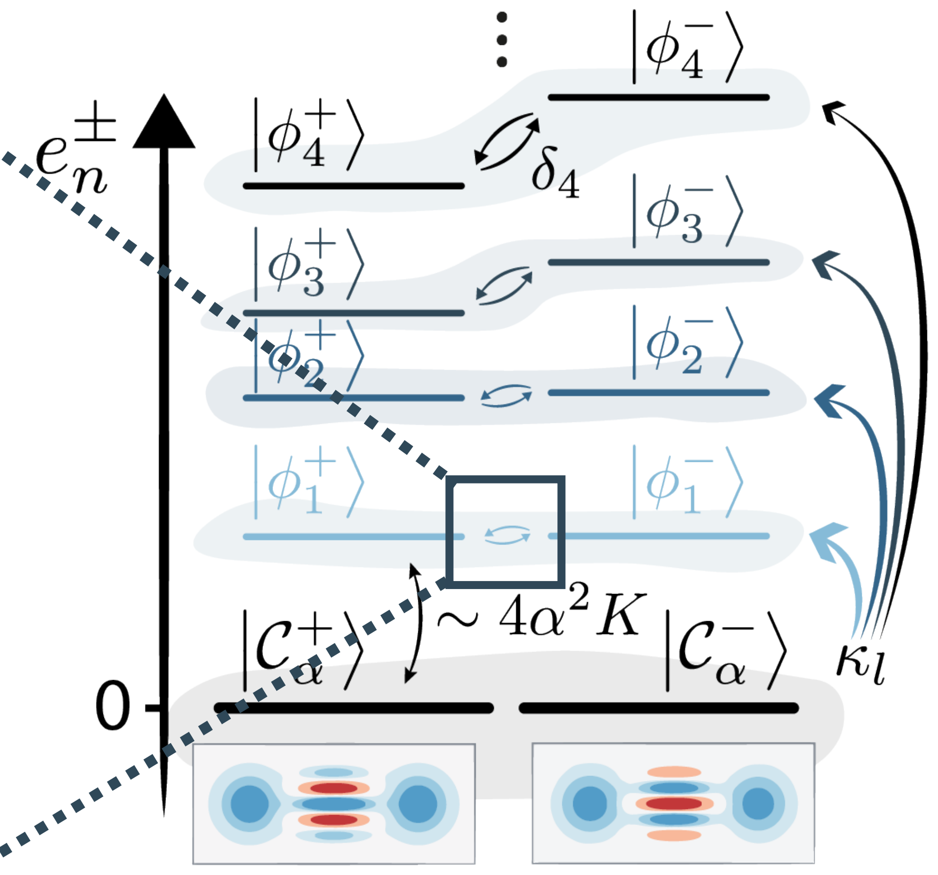

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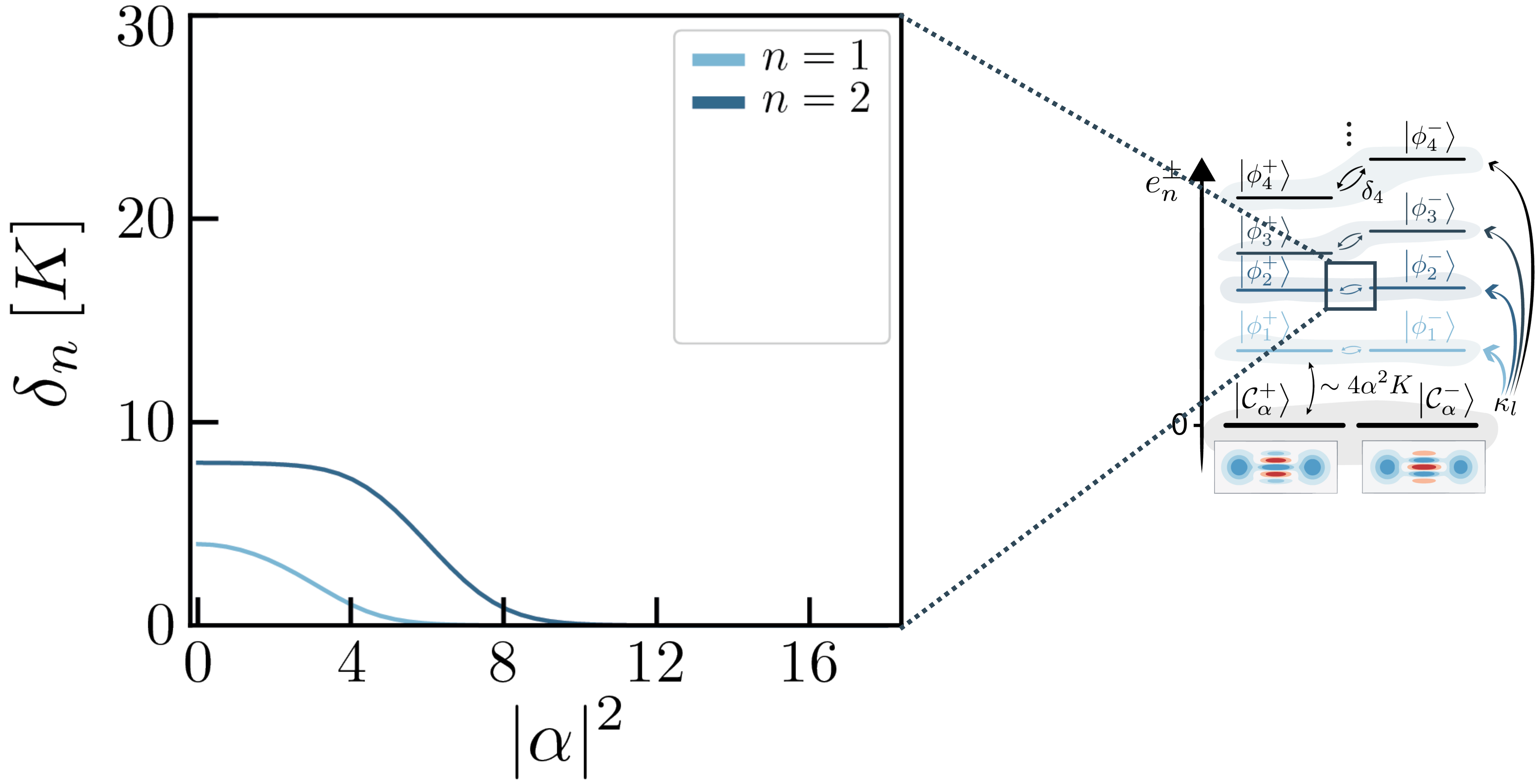

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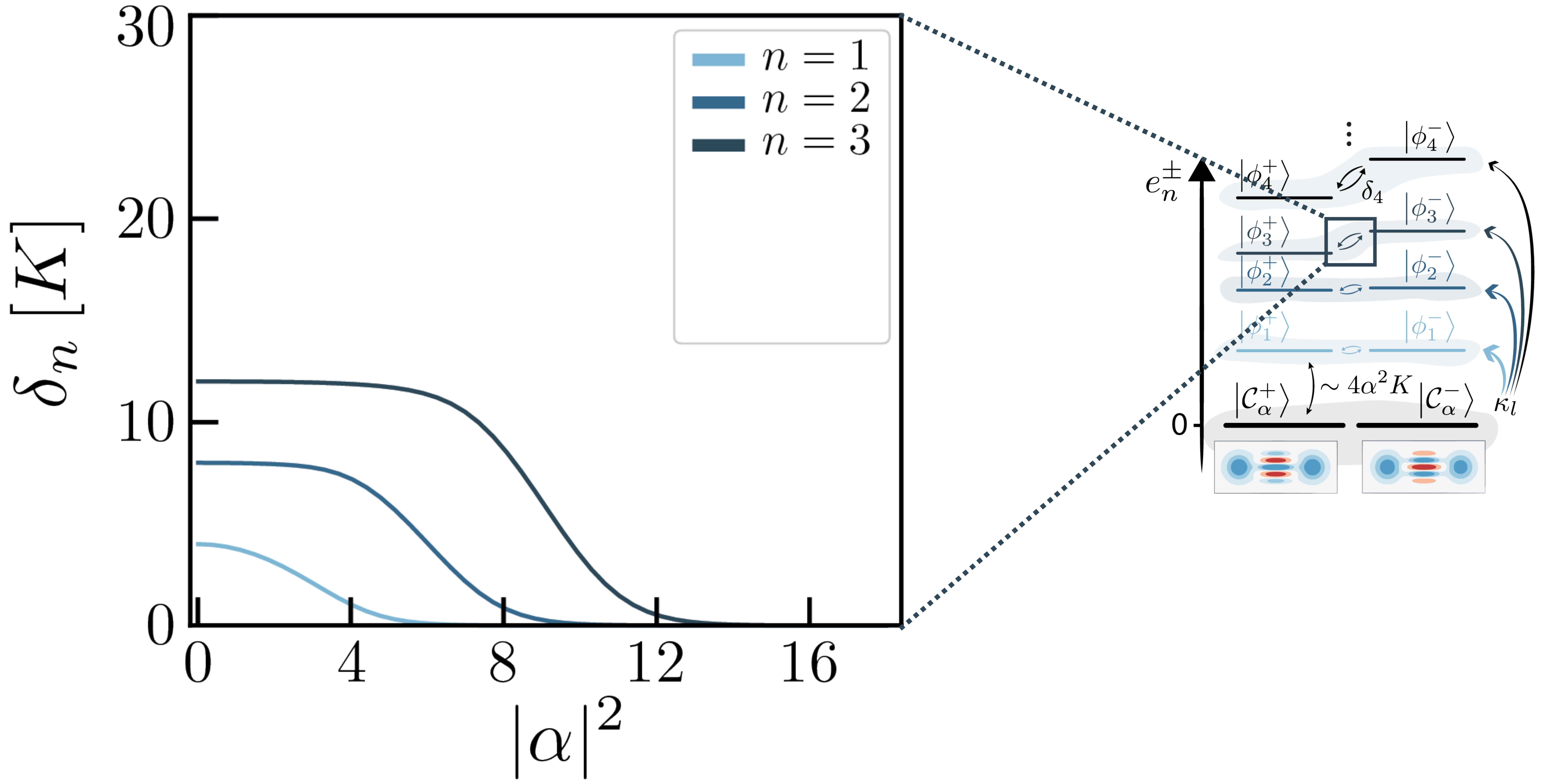

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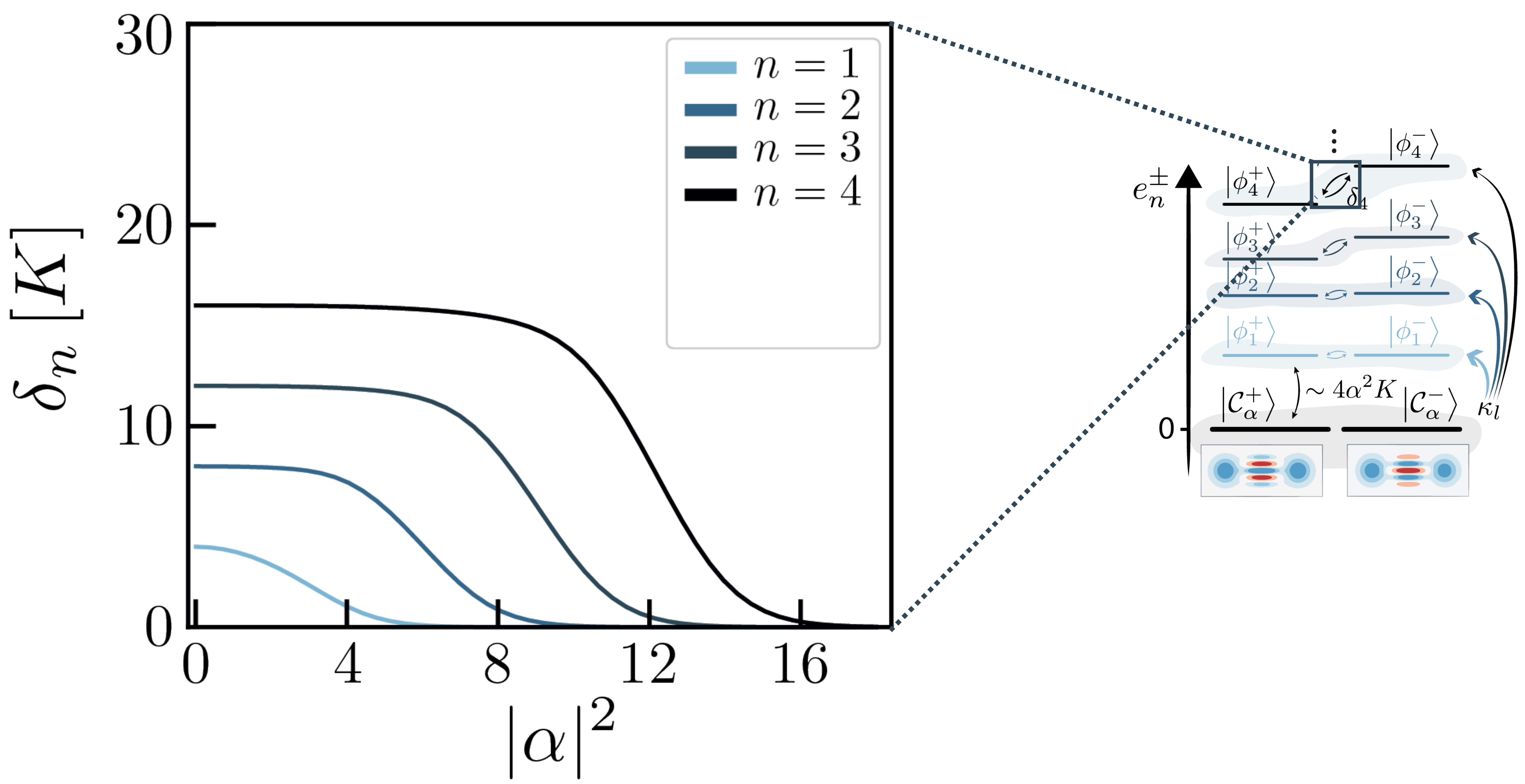

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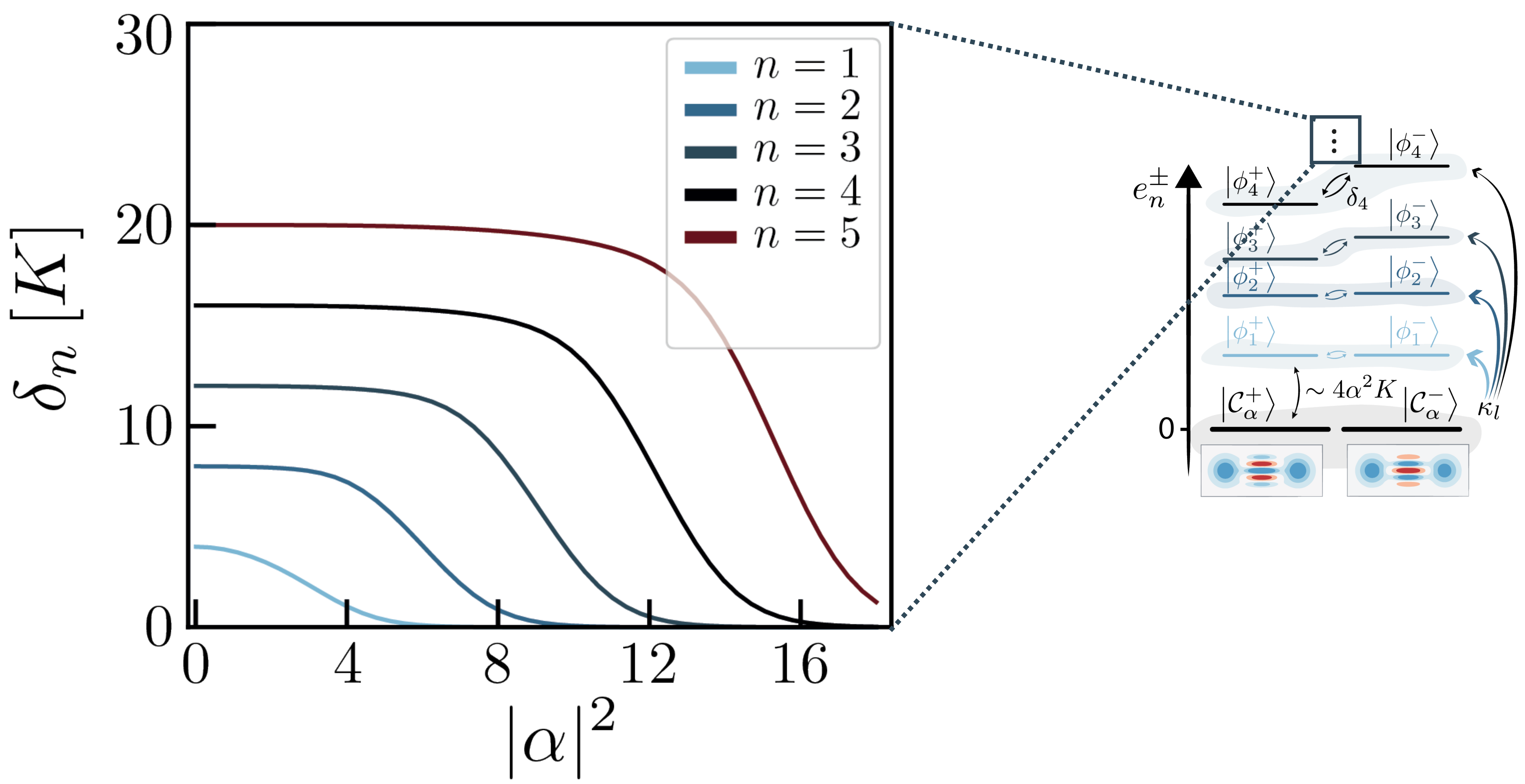

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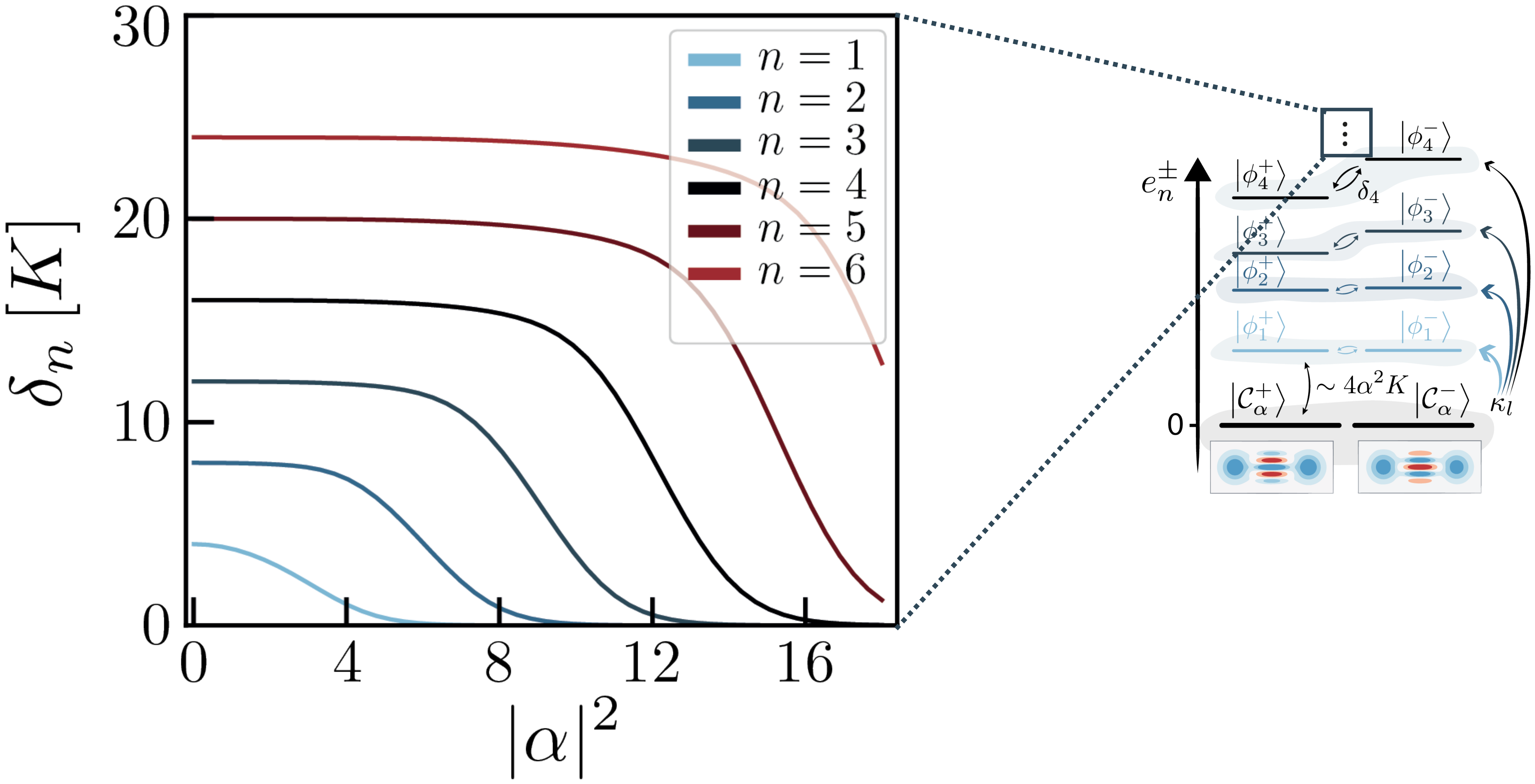

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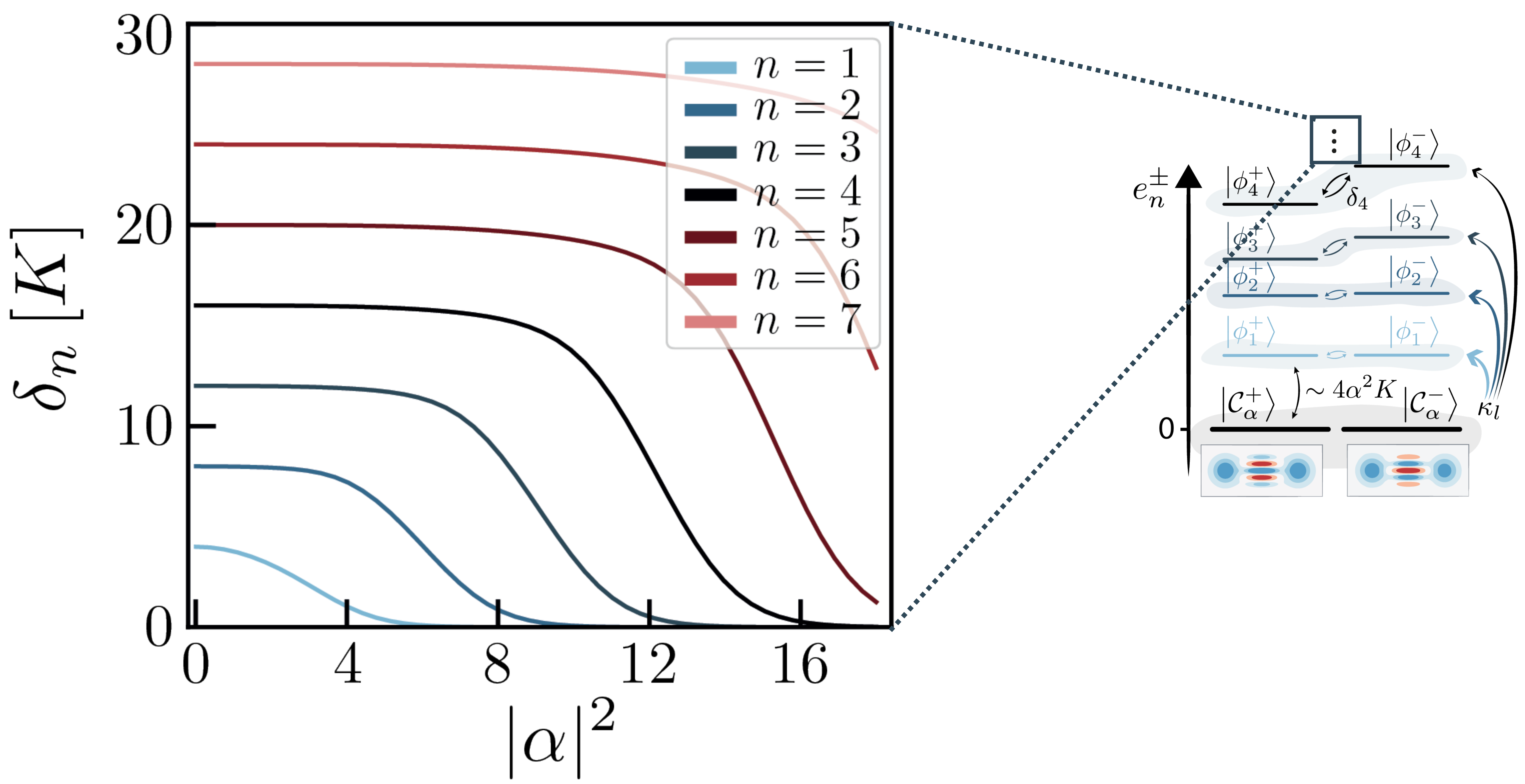
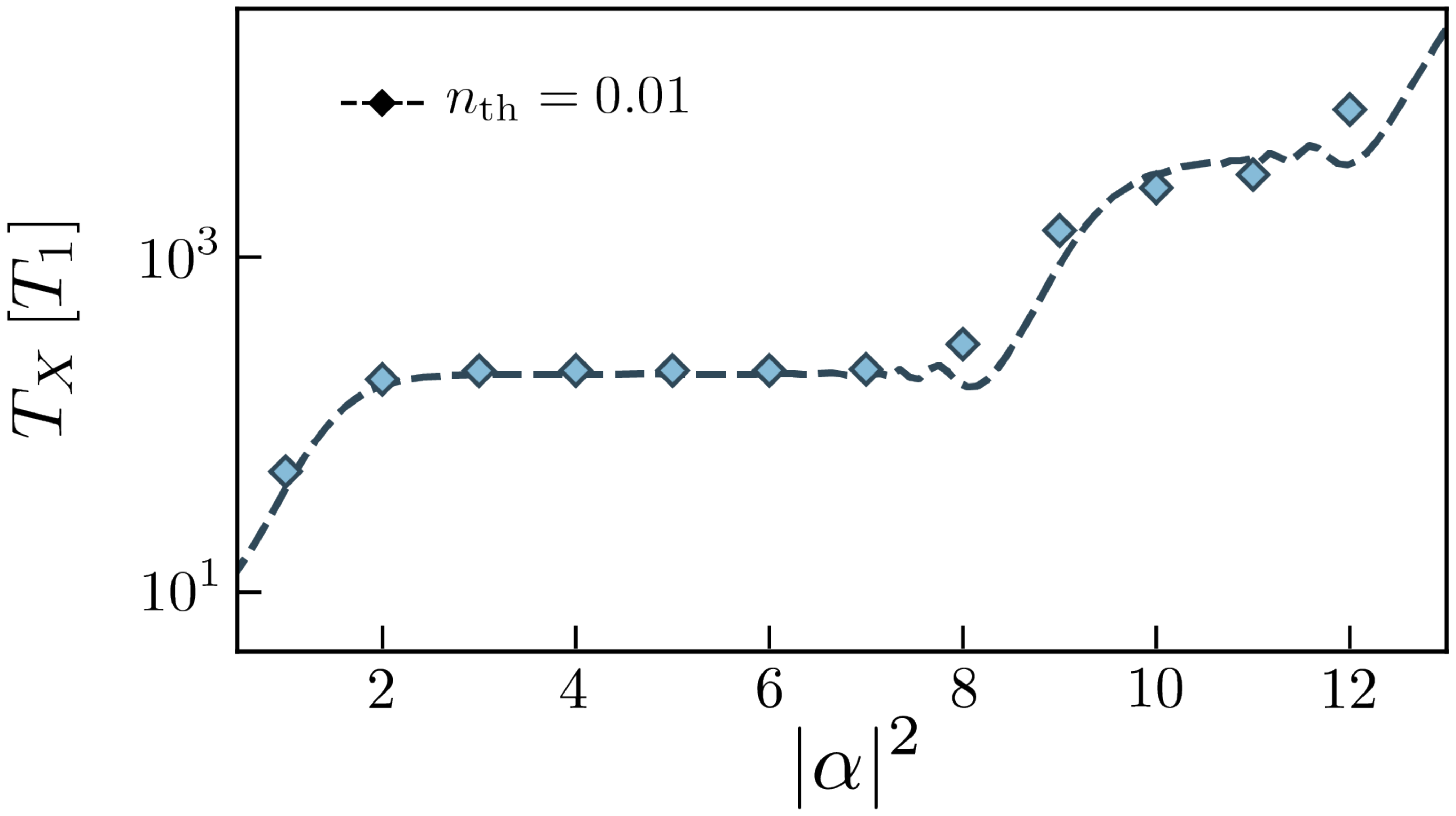


Bit-flip plateaus

Gautier *et al. (2021)*



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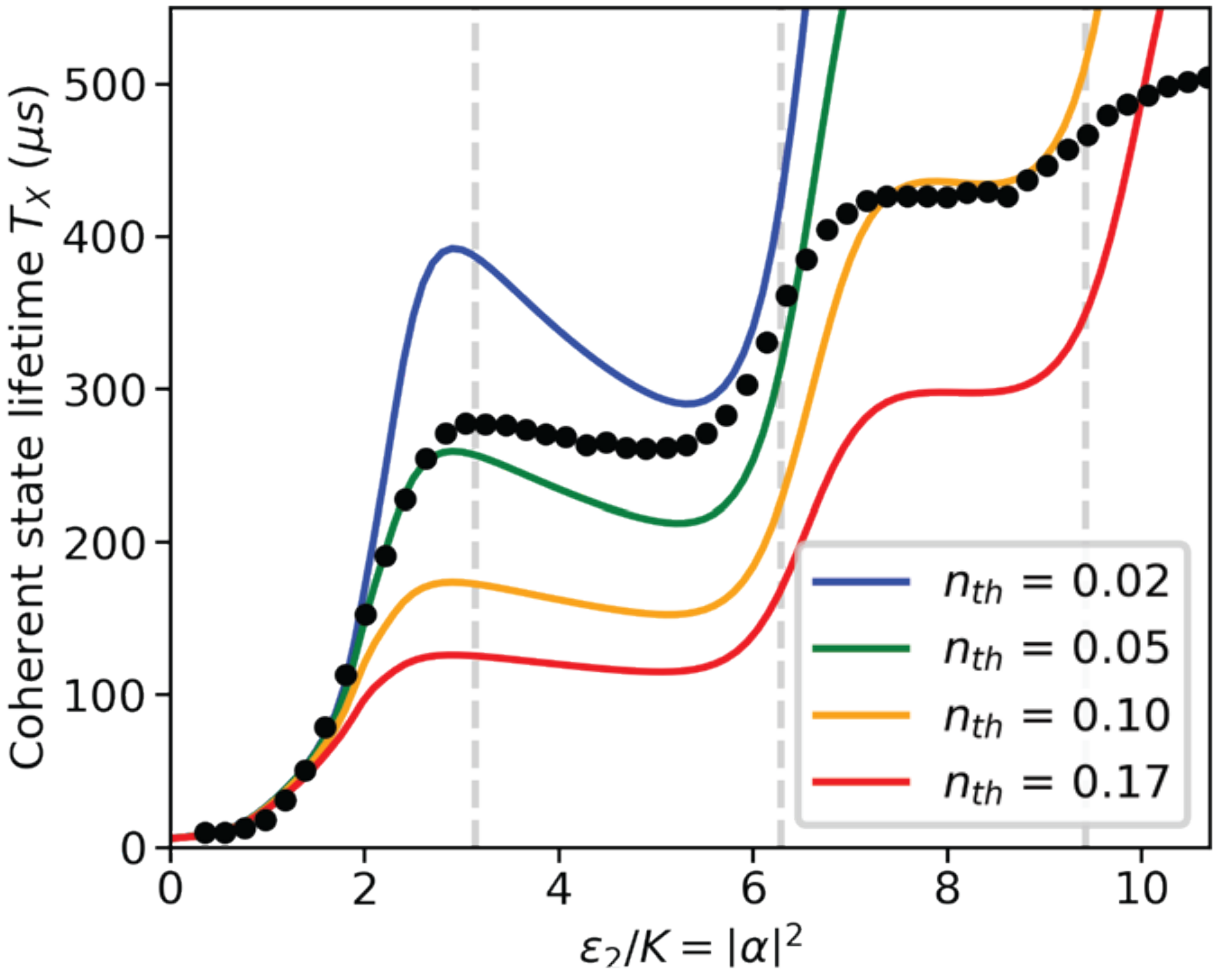

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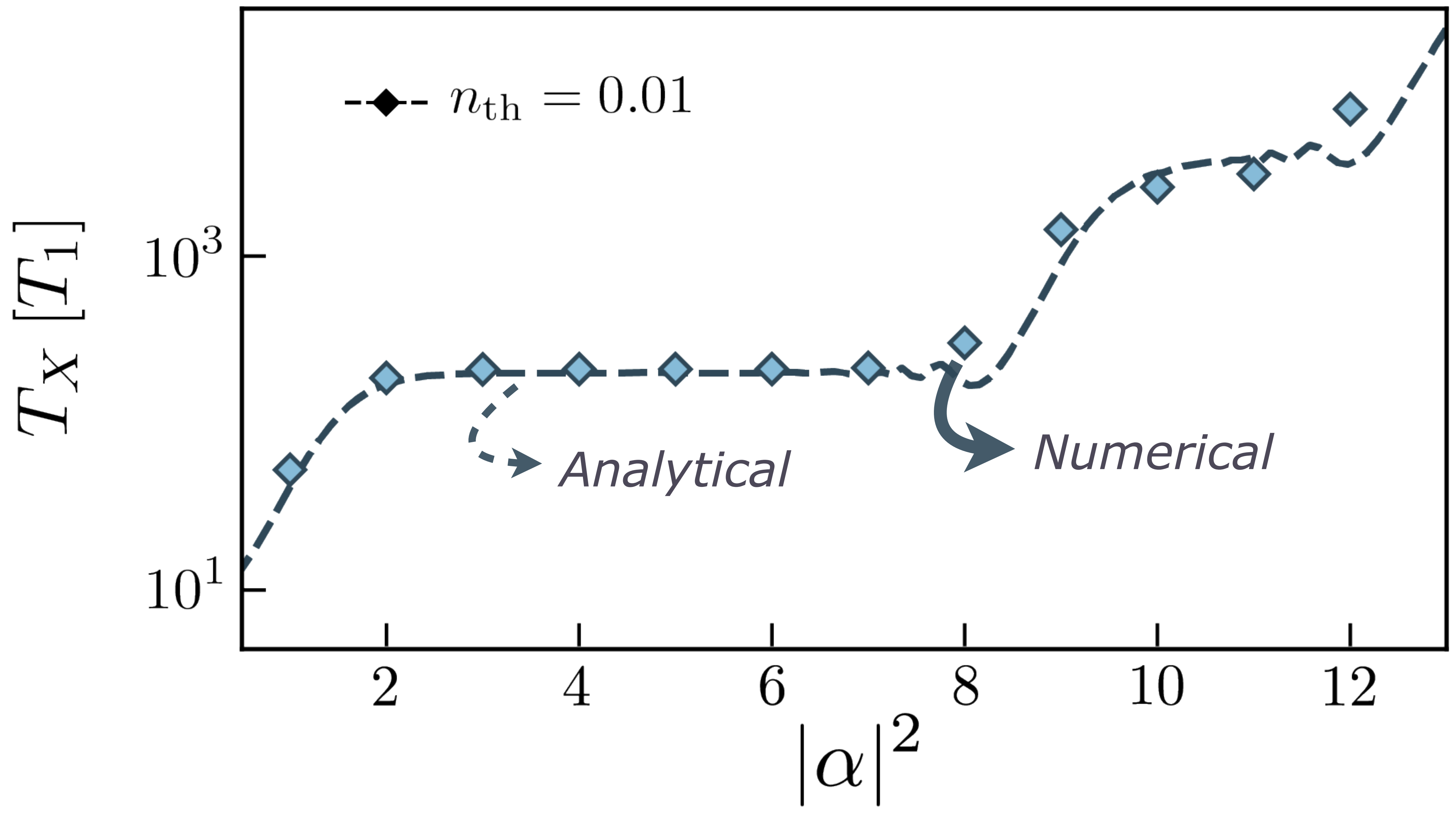

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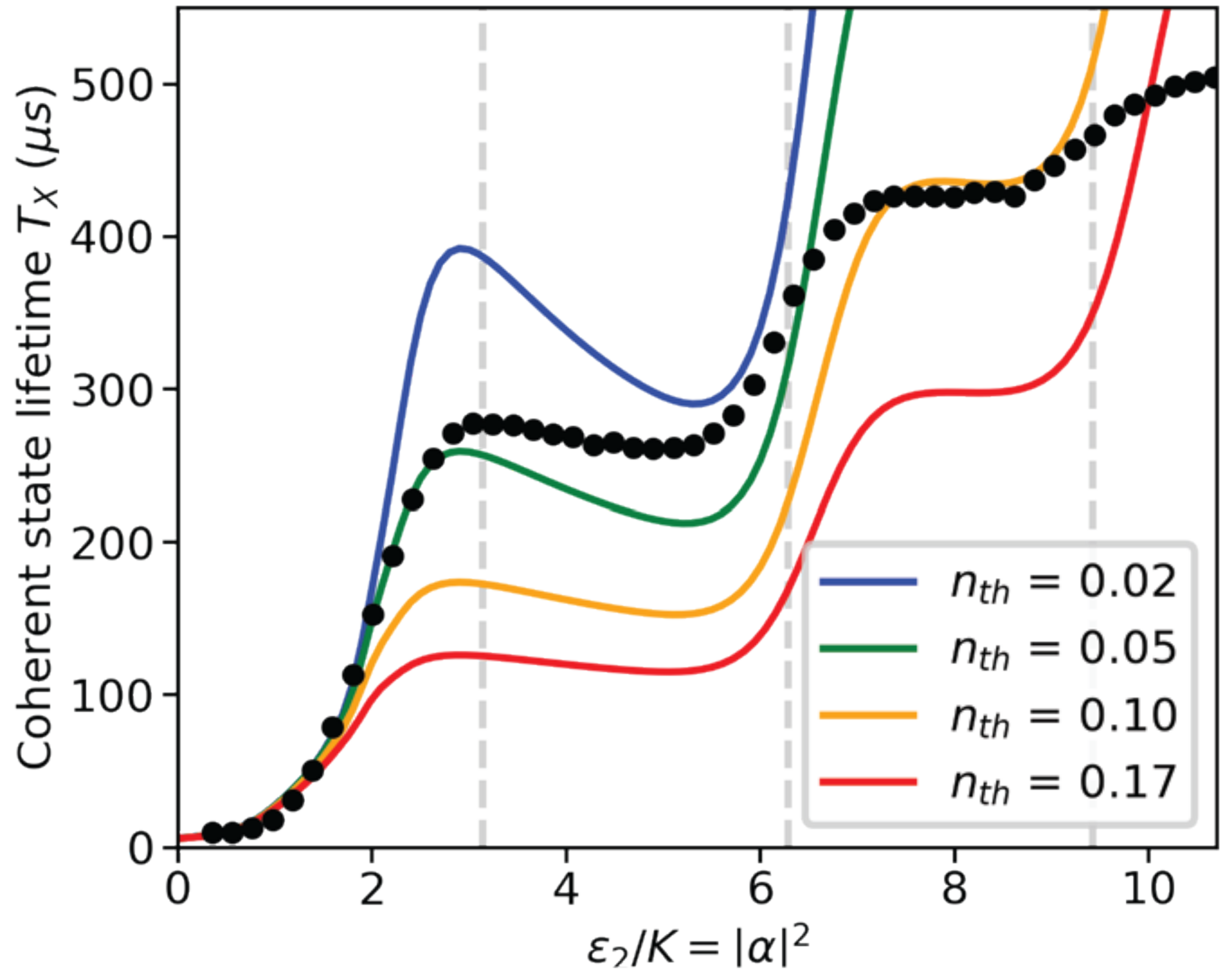

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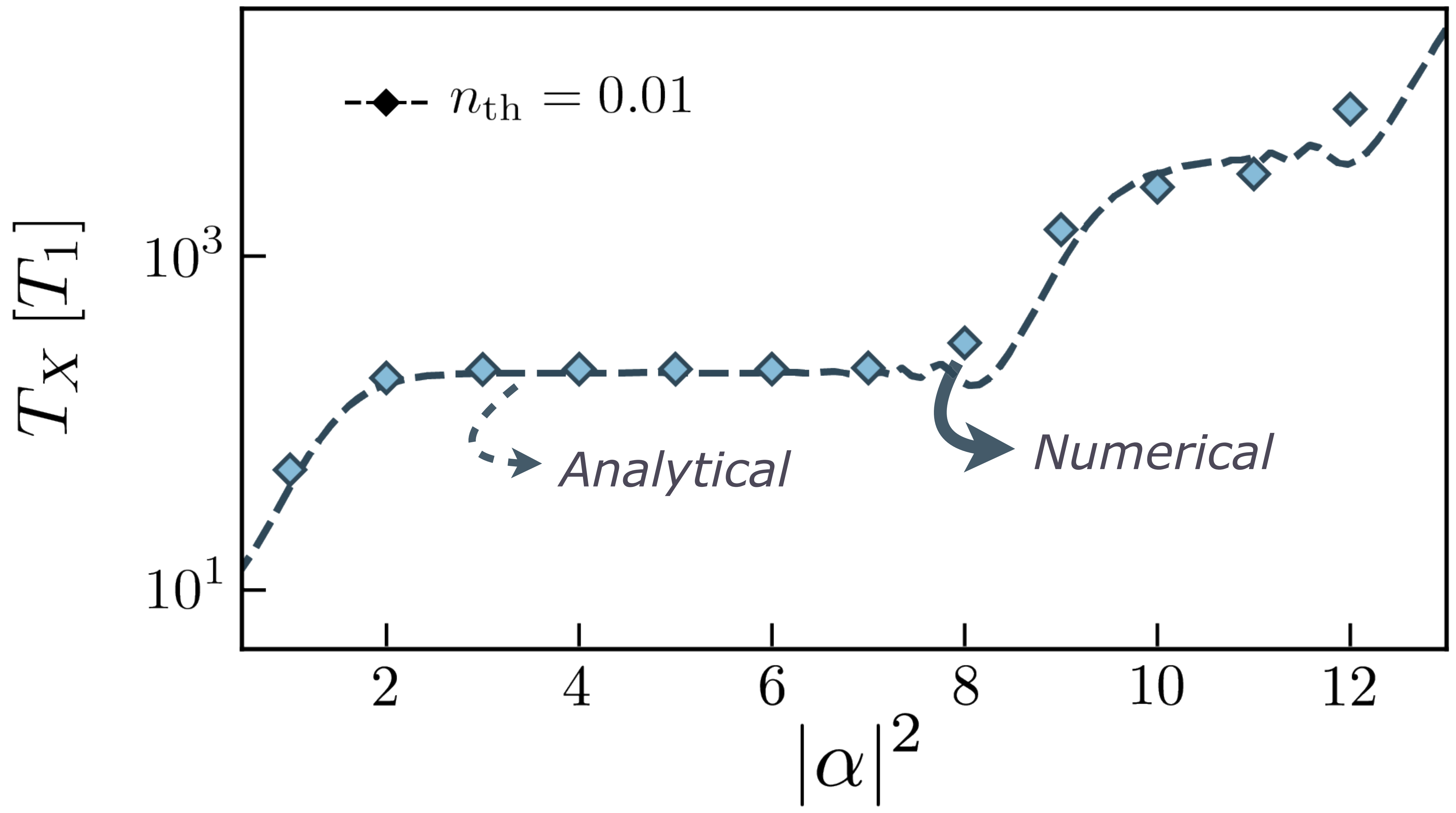

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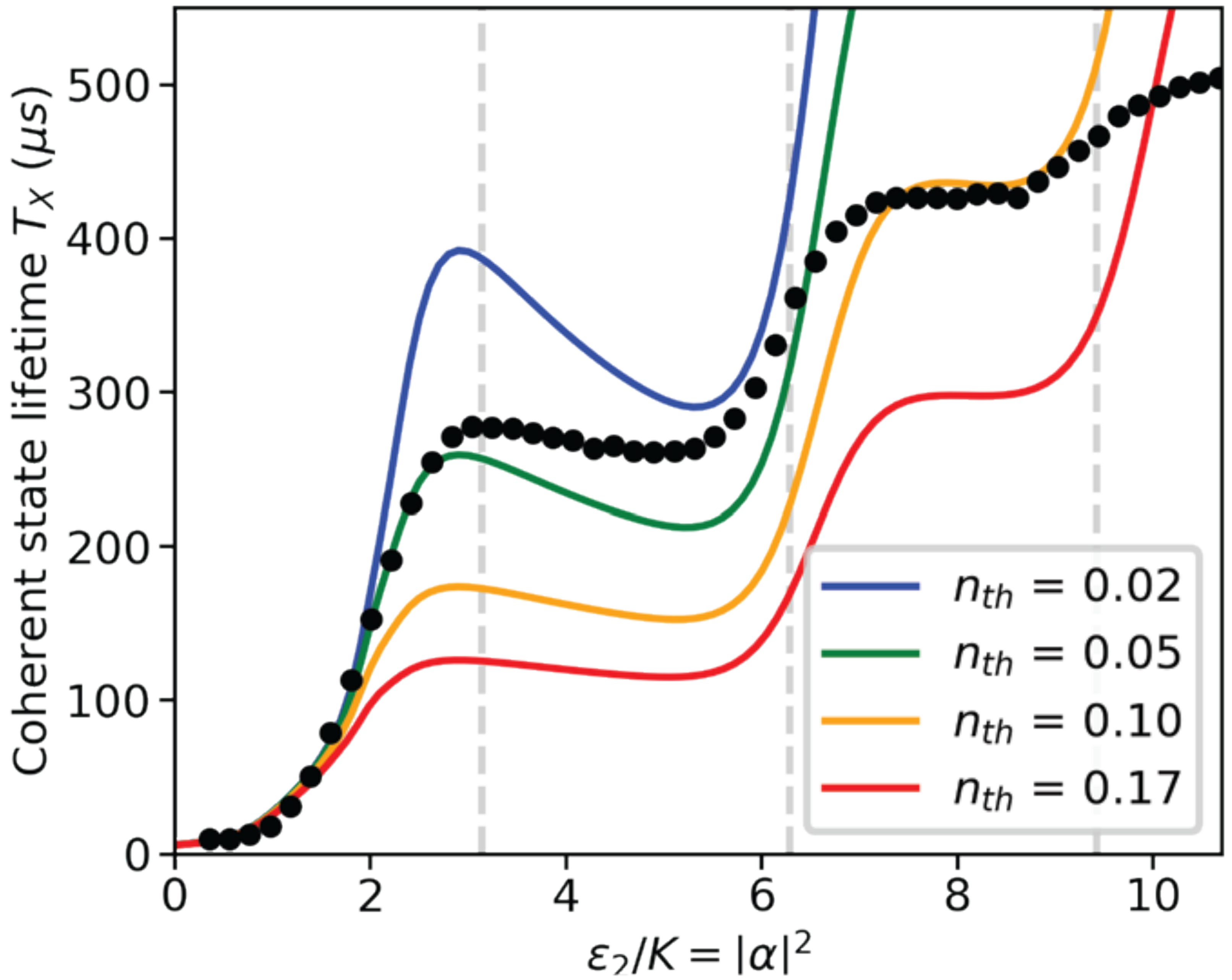

How to retrieve an exponentially biased Kerr cat qubit?

Retrieving the exponential

Combining with two-photon dissipation

$$\frac{d\rho}{dt} = -i[H_{\mathrm{Kerr}}, \rho] + \kappa_2 \mathcal{D}[a^2 - \alpha^2]\rho$$

Retrieving the exponential

Combining with two-photon dissipation

$$\frac{d\rho}{dt} = -i[H_{\text{Kerr}}, \rho] + \kappa_2 \mathcal{D}[a^2 - \alpha^2]\rho$$

- Competition between K and κ_2

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- Fit to $T_X \propto \exp(\gamma|\alpha|^2)$

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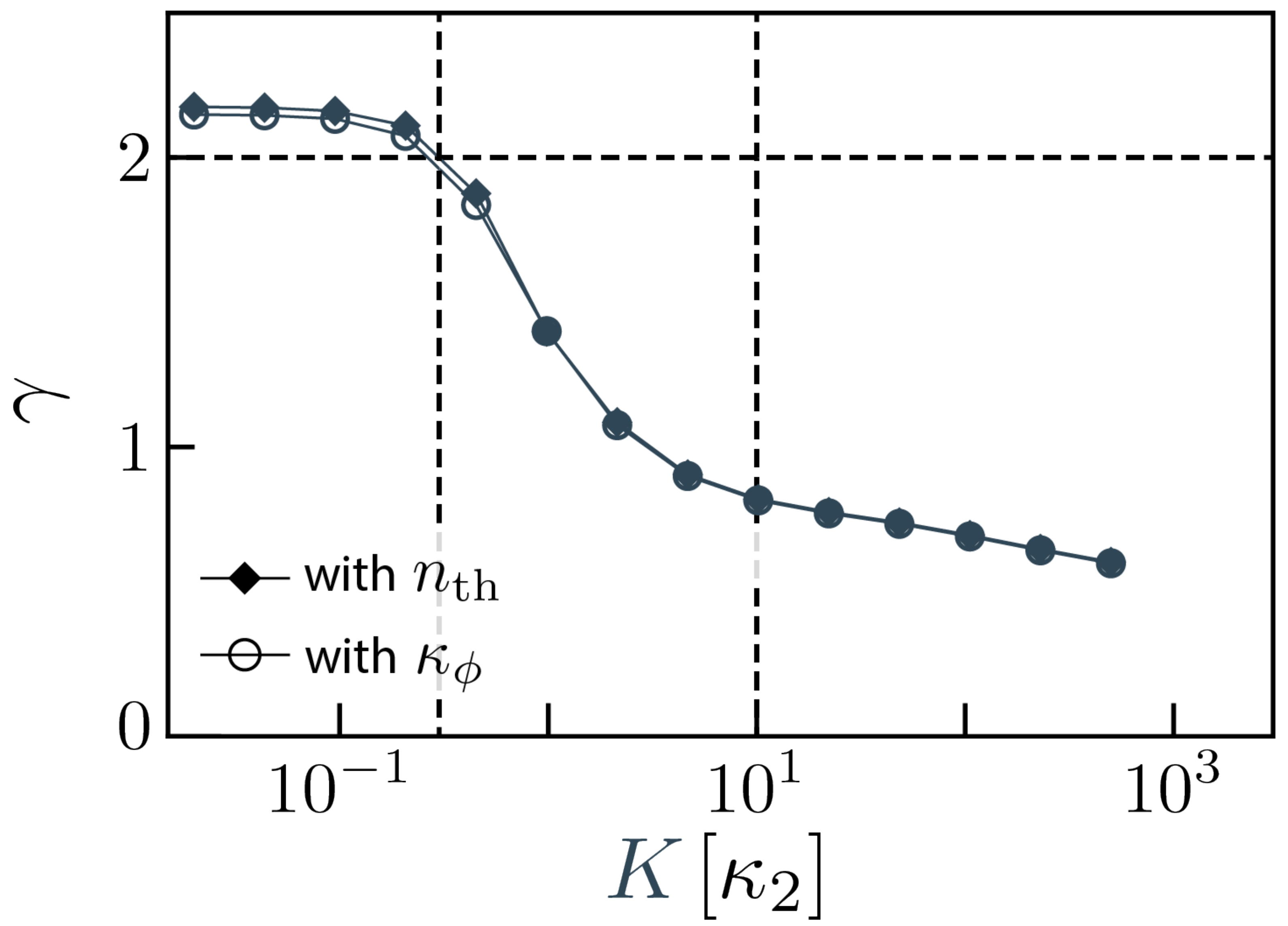

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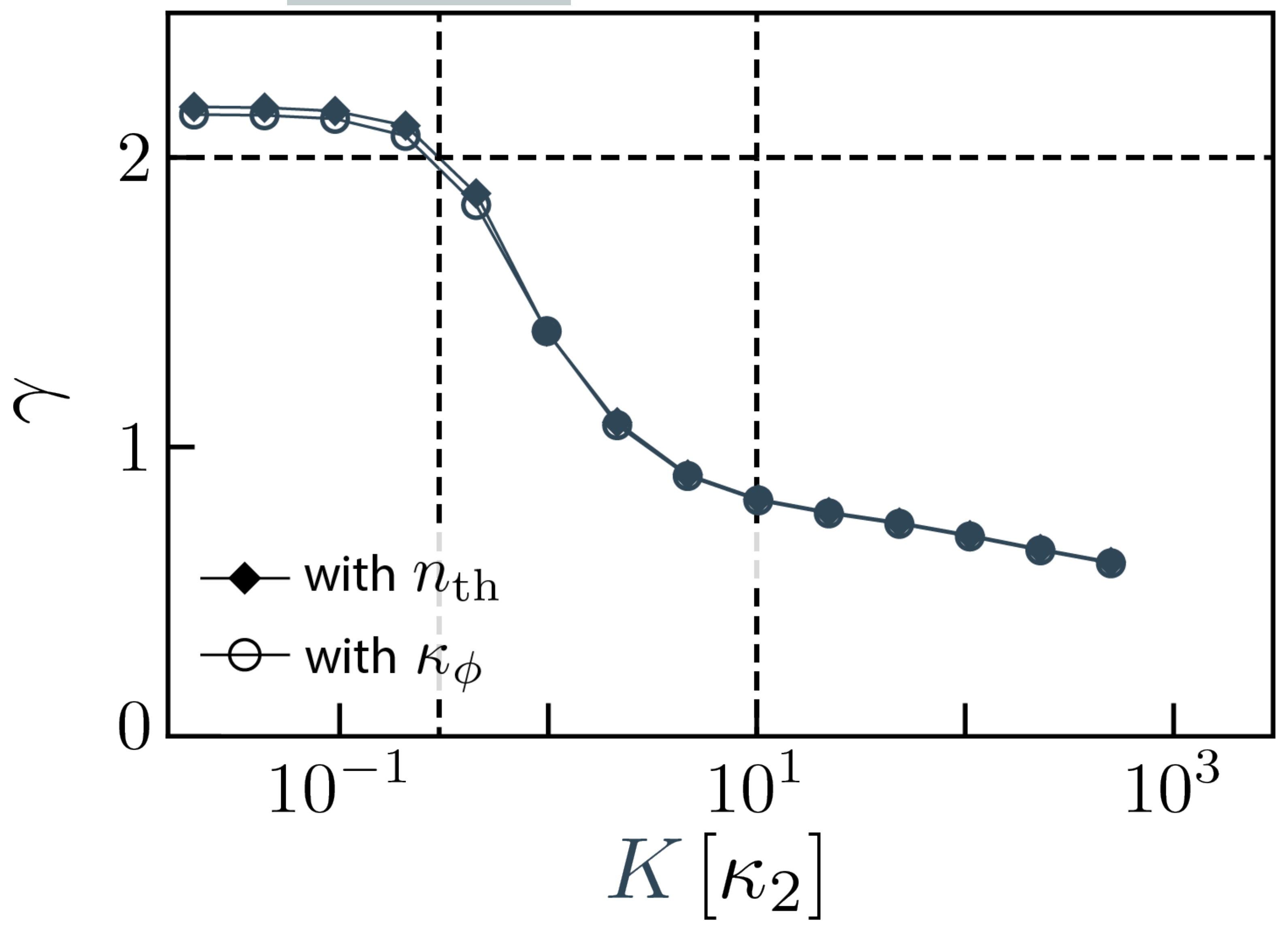
$K \lesssim \kappa_2$



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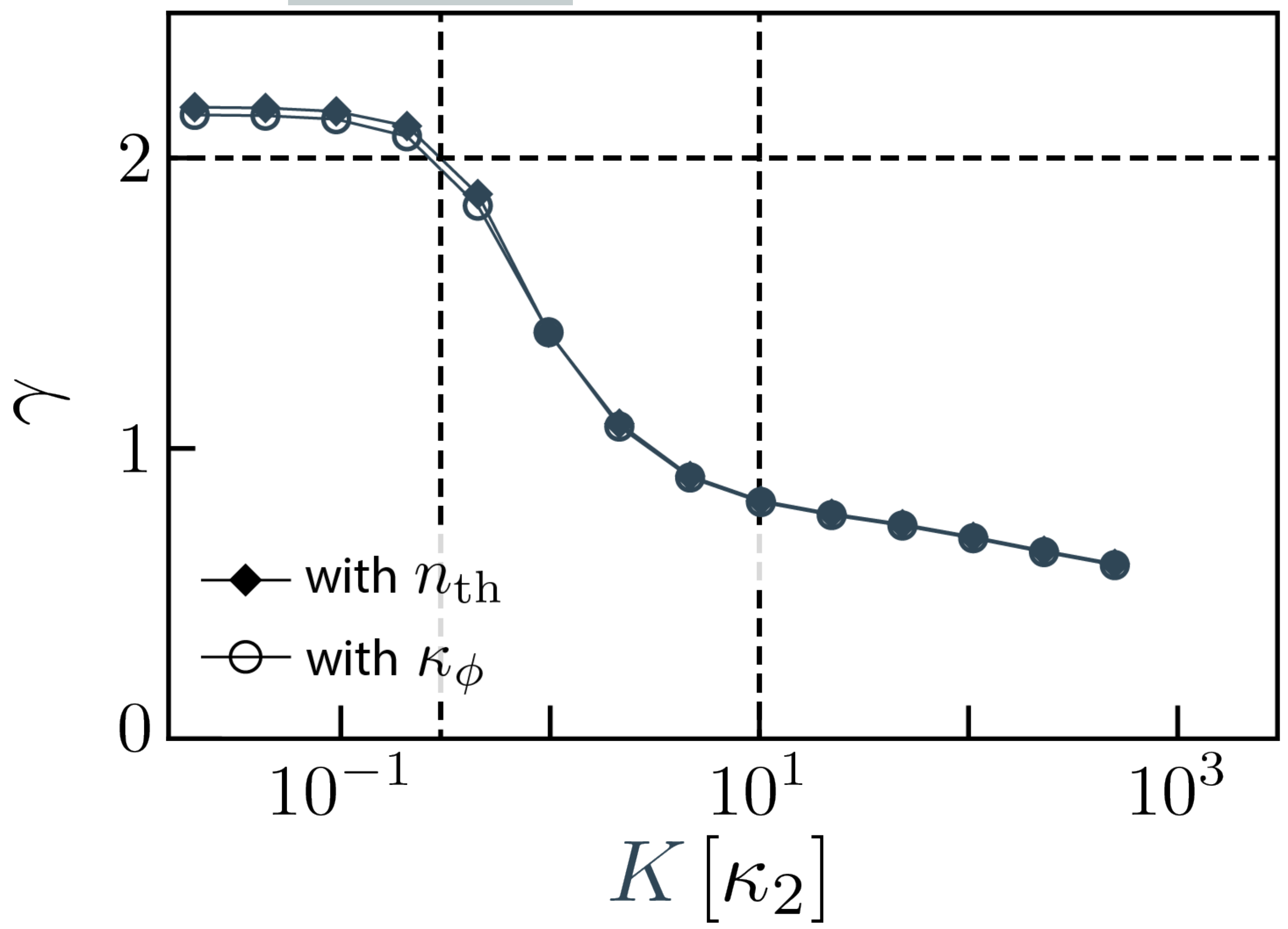
The two-photon exchange Hamiltonian

$$\frac{d\rho}{dt} = -i[H_{\text{TPE}}, \rho] + \kappa_2 \mathcal{D}[a^2 - \alpha^2]\rho$$

with $H_{\text{TPE}} = g_2(a^2 - \alpha^2)\sigma_+ + g_2^*(a^{\dagger 2} - \alpha^{*2})\sigma_-$

- Jaynes-Cummings-like interaction between a two-photon memory and a qubit

$K \lesssim \kappa_2$



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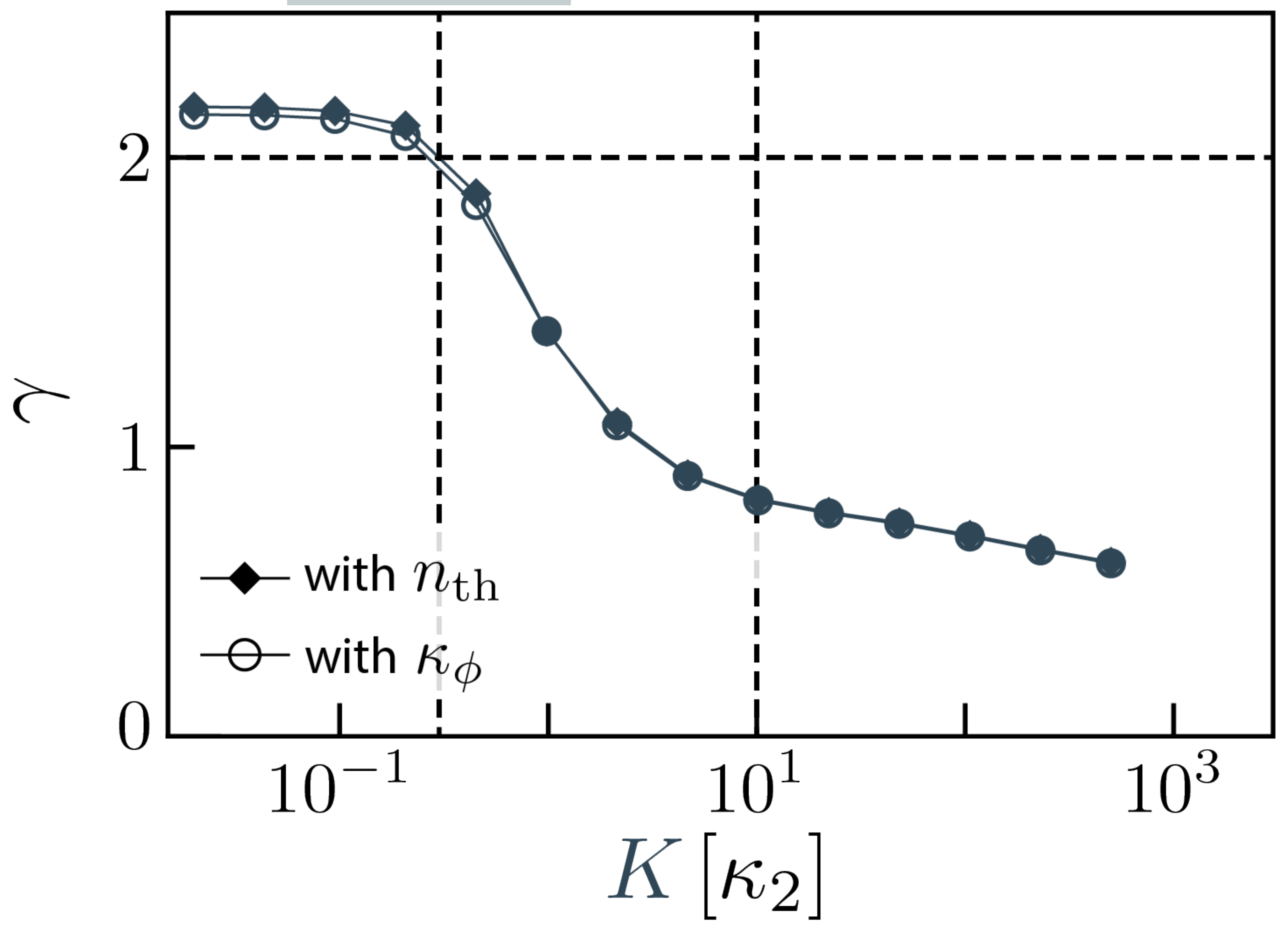
with $H_{\mathrm{TPE}} = g_2(a^2 - \alpha^2)\sigma_+ + g_2^*(a^{\dagger 2} - \alpha^{*2})\sigma_-$

- Jaynes-Cummings-like interaction between a two-photon memory and a qubit
- Eigenenergies $E_n/g_2 = \pm\sqrt{e_n/K}$

$K \lesssim \kappa_2$



Retrieving the exponential

Combining with two-photon dissipation

$$\frac{d\rho}{dt} = -i[H_{\mathrm{Kerr}}, \rho] + \kappa_2 \mathcal{D}[a^2 - \alpha^2]\rho$$

- Competition between K and κ_2
- Fit to $T_X \propto \exp(\gamma|\alpha|^2)$

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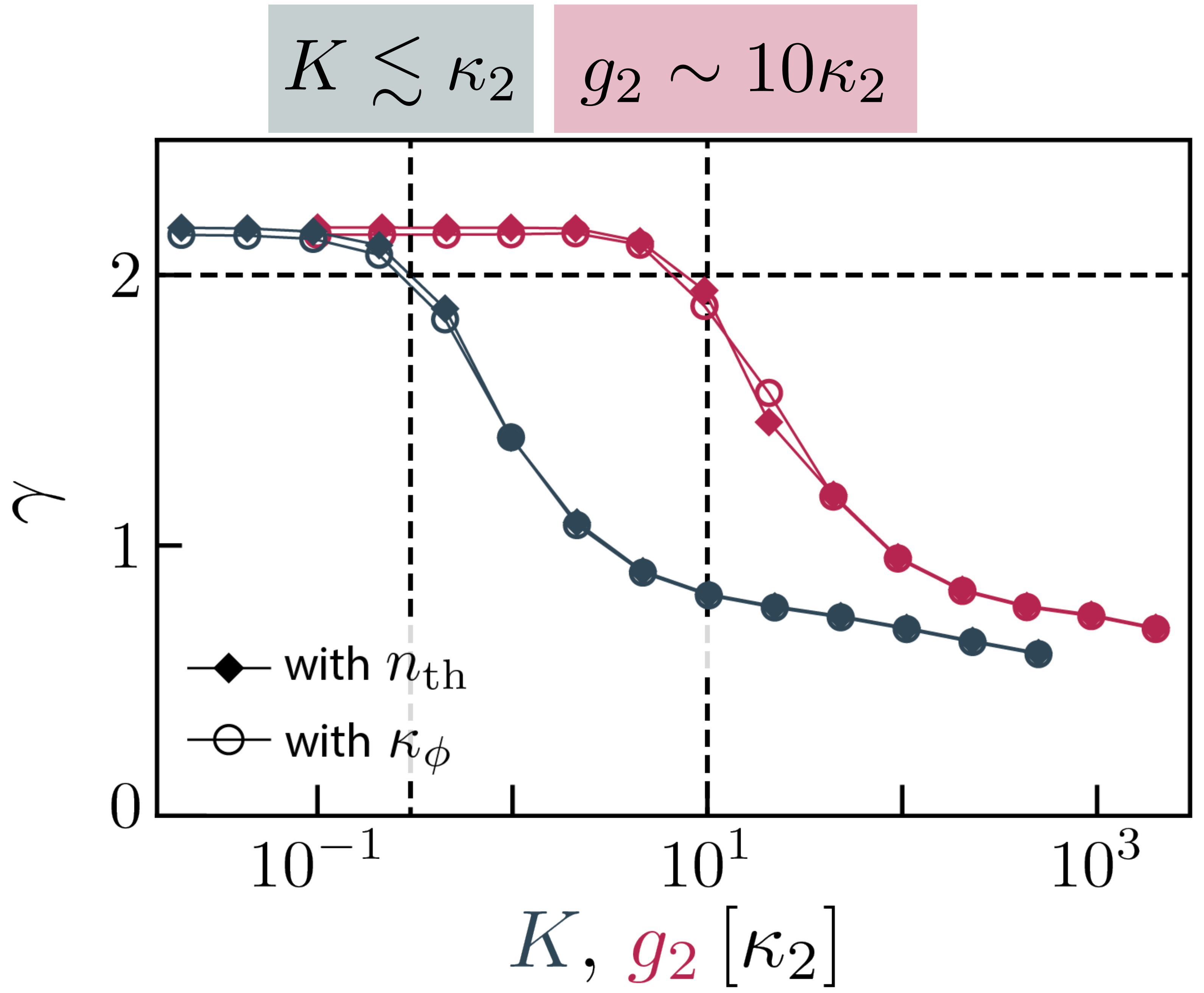

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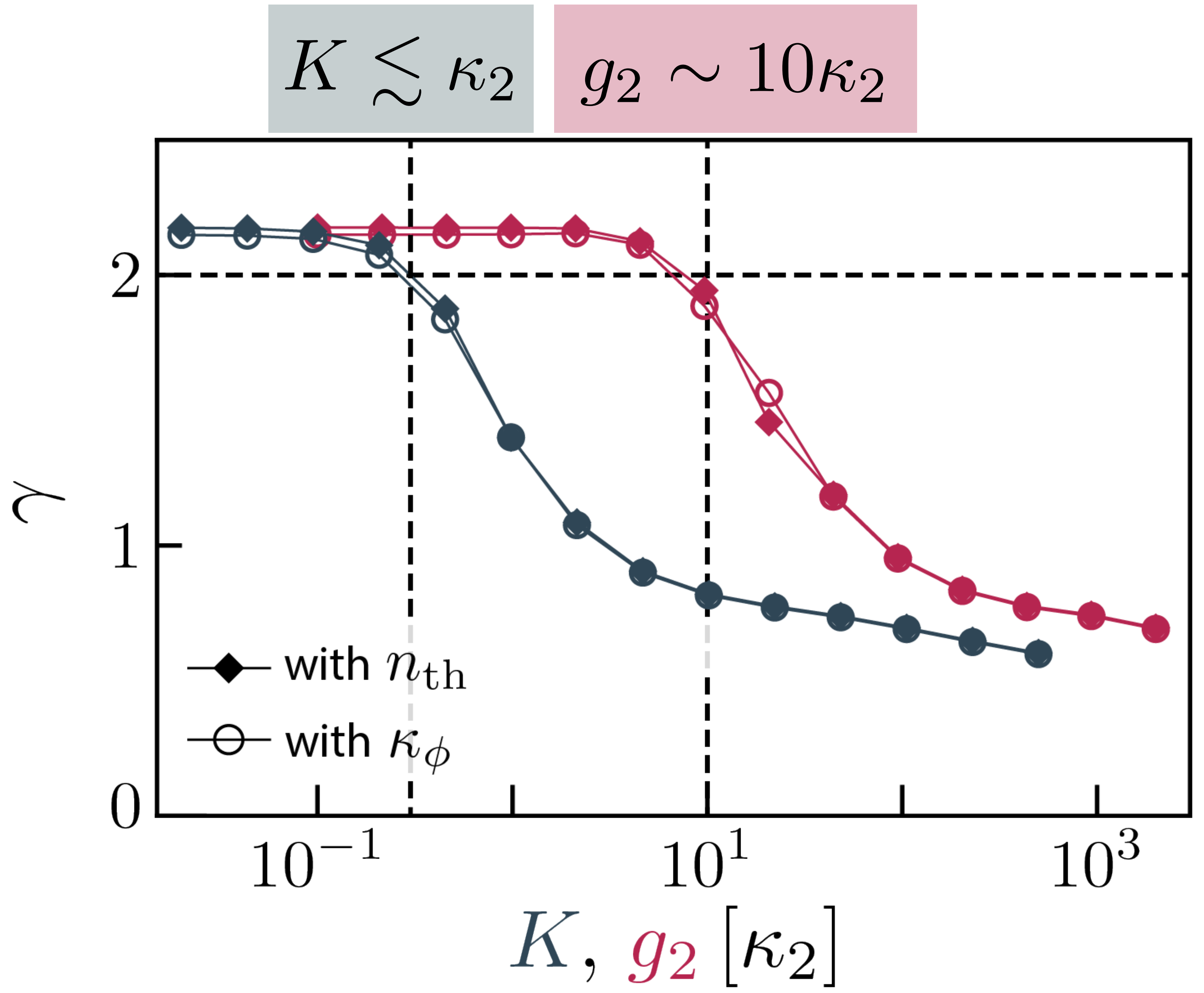
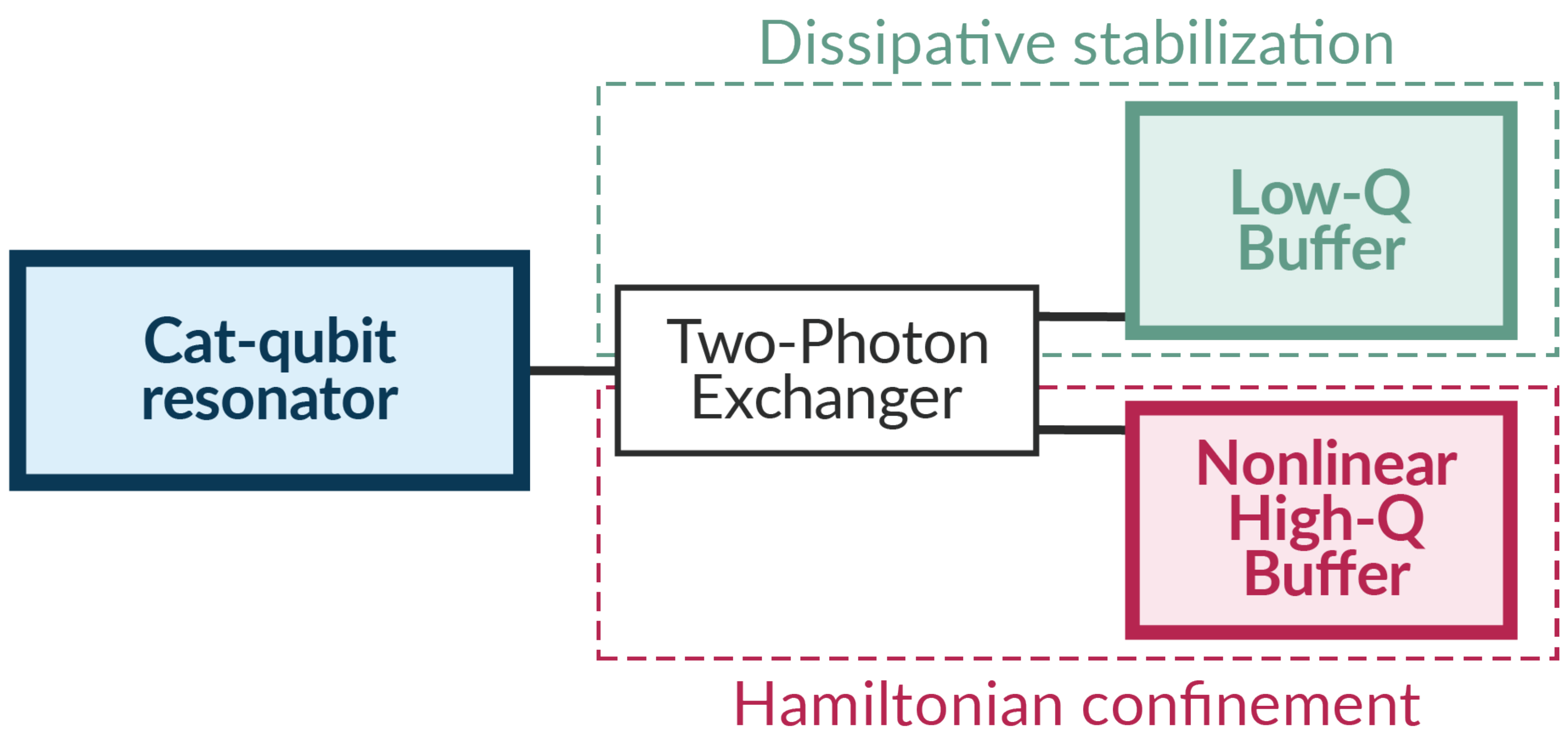
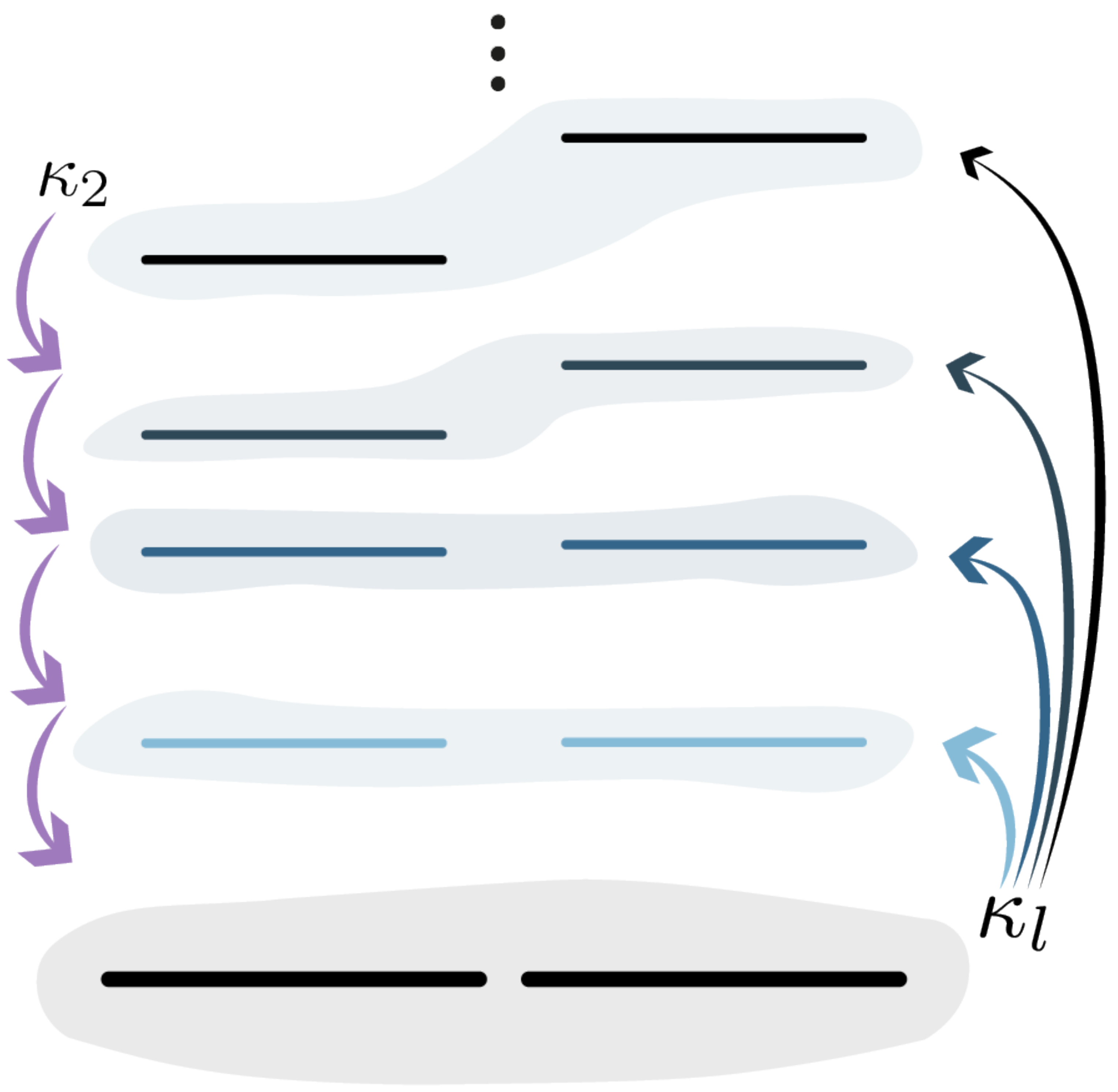
- Jaynes-Cummings-like interaction between a two-photon memory and a qubit
- Eigenenergies $E_n/g_2 = \pm\sqrt{e_n/K}$
- Easier to engineer together with two-photon dissipation





Combined Hamiltonian and dissipative confinement

- Competition between "heating" by leakage, and "cooling" by two-photon dissipation



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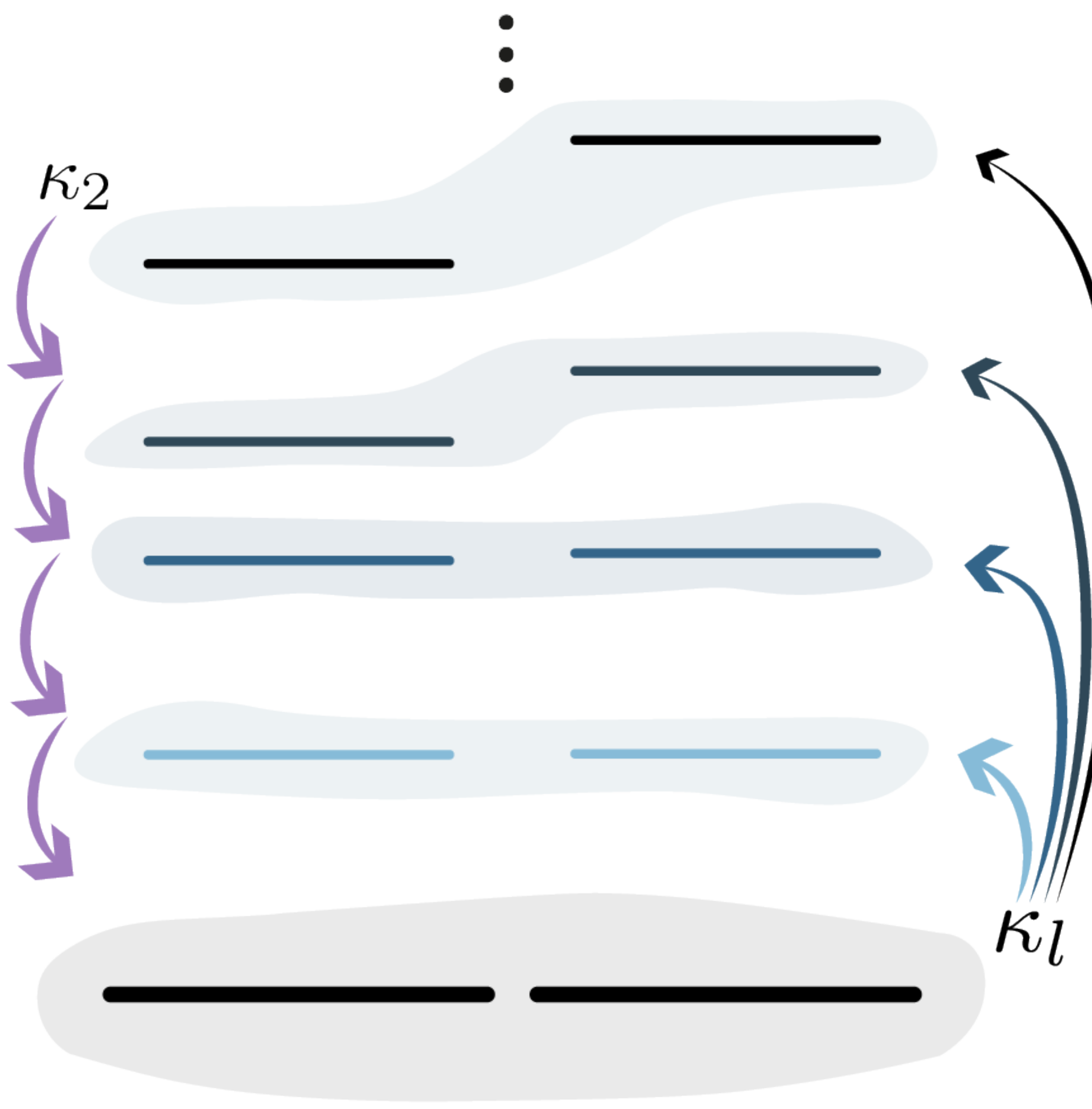

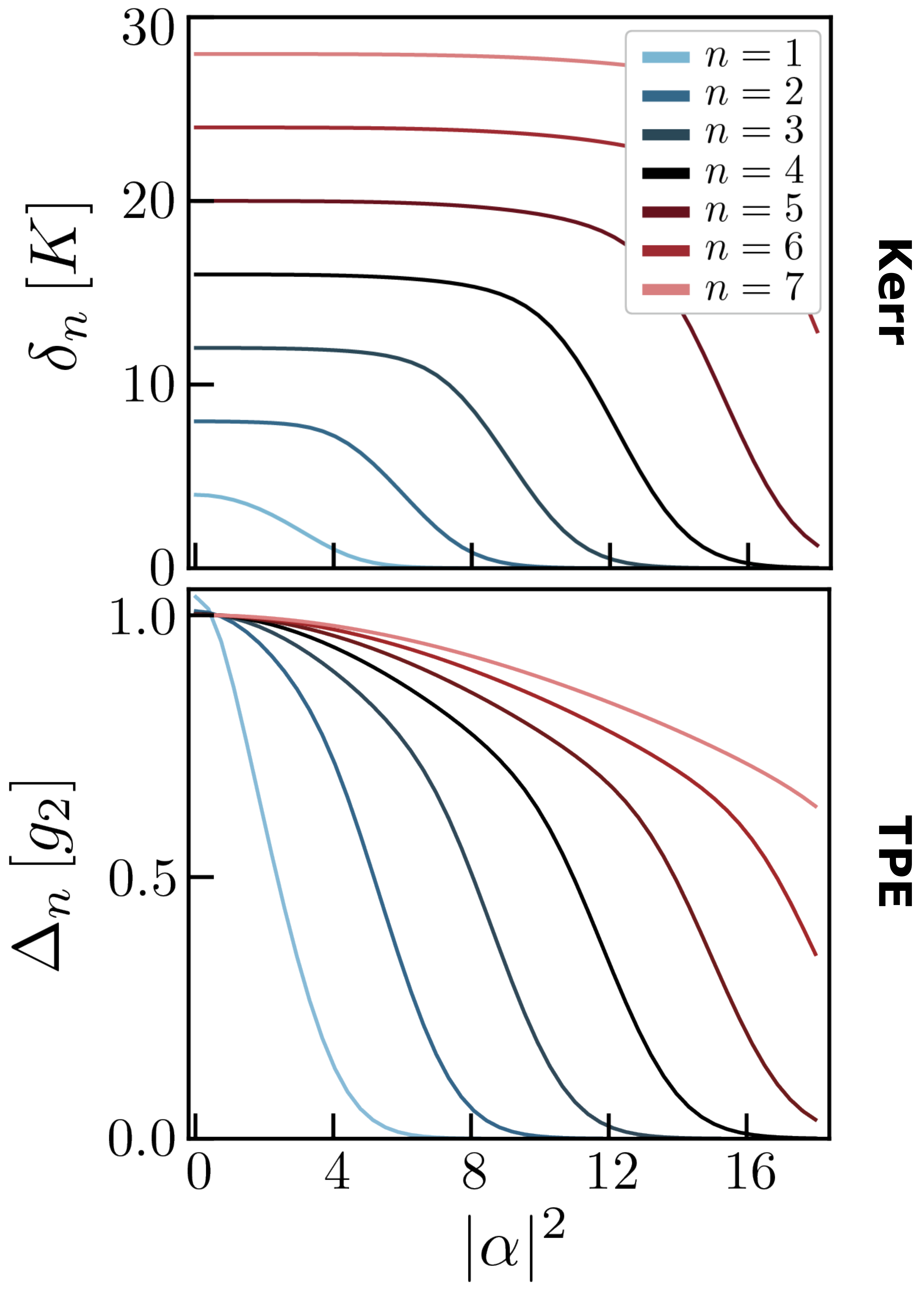

Lifetime and controllability of cat qubits

Kerr cat qubits

Lifetime
➔ $|\alpha|^2$

1. Limited by leakage
2. Weak exponential scaling

[Putterman et al., 2021]
[Gautier et al., 2021]
[Frattini et al., 2022]

Lifetime and controllability of cat qubits

	Kerr cat qubits	**Dissipative cat qubits**
Lifetime ➔ $\|\alpha\|^2$	1. Limited by leakage 2. Weak exponential scaling	Exponential scaling
	[Putterman et al., 2021] *[Gautier et al., 2021]* *[Frattini et al., 2022]*	*[Mirrahimi et al., 2014]* *[Lescanne et al., 2019]*

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Controllability ➔ T_{gate}	Adiabatic theorem ➔ Exponential scaling	
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Lifetime and controllability of cat qubits

	Kerr cat qubits	Dissipative cat qubits
Lifetime ➔ $\lvert\alpha\rvert^2$	1. Limited by leakage 2. Weak exponential scaling	Exponential scaling
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Controllability ➔ T_{gate}	Adiabatic theorem ➔ Exponential scaling	**Linear scaling**
	[Puri et al., 2019] *[Xu et al., 2022]*	*[Mirrahimi et al., 2014]* *[Guillaud et al., 2019]* *[Gautier et al., 2022]*

Summary of PhD contributions

Work on cat qubits

- **RG**, A. Sarlette, M. Mirrahimi, *Combined dissipative and Hamiltonian confinement of cat qubits*, PRX Quantum (2021)
- D. Ruiz, **RG**, J. Guillaud, M. Mirrahimi, *Two-photon driven Kerr quantum oscillator with multiple spectral degeneracies*, Phys. Rev. A (2022)
- **RG**, M. Mirrahimi, A. Sarlette, *Designing high-fidelity Zeno gates for dissipative cat qubits*, PRX Quantum (2022)
- U. Réglade, A. Bocquet, **RG**, *et al.*, *Quantum control of a cat-qubit with bit-flip times exceeding ten seconds*, arXiv (2023)

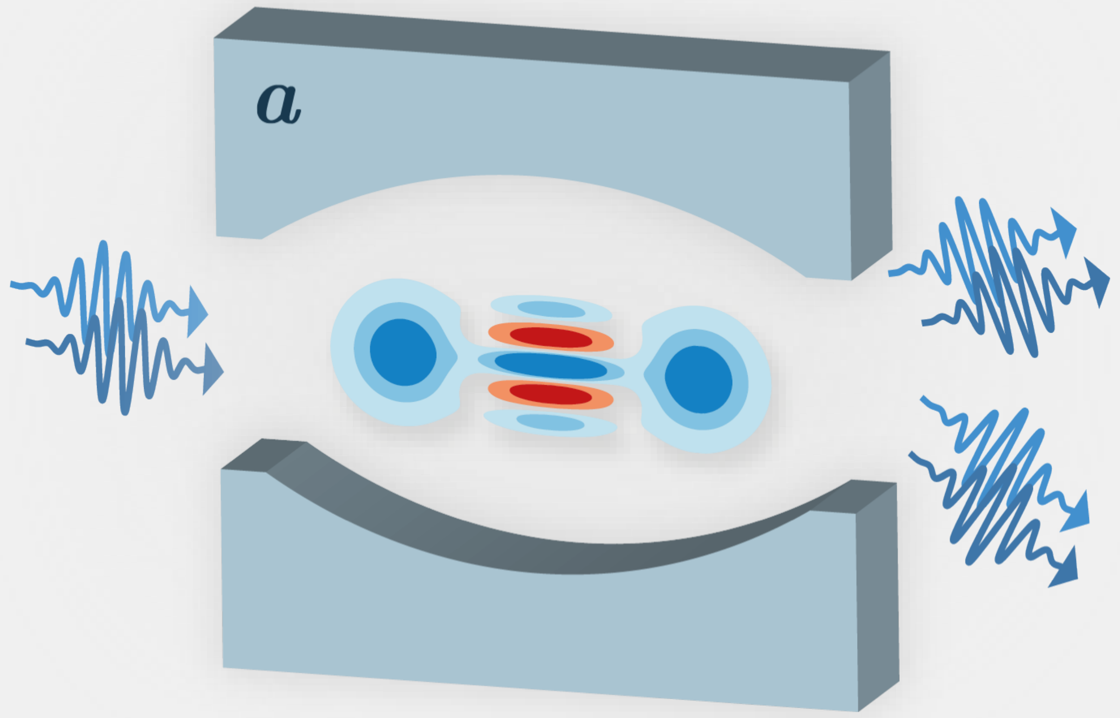
Work on optimal control of open quantum systems

- **RG**, É. Genois, A. Blais, *Optimal readout and reset of a transmon*, in preparation
- P. Guilmin, **RG**, A. Bocquet, É. Genois, *dynamiqs: an open-source library for GPU-accelerated and differentiable quantum simulation*, in preparation

Reservoir engineering of two-photon dissipation

Memory

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



Mirrahimi *et al.* NJP (2014), Lescanne *et al.* Nat. Phy. (2019)

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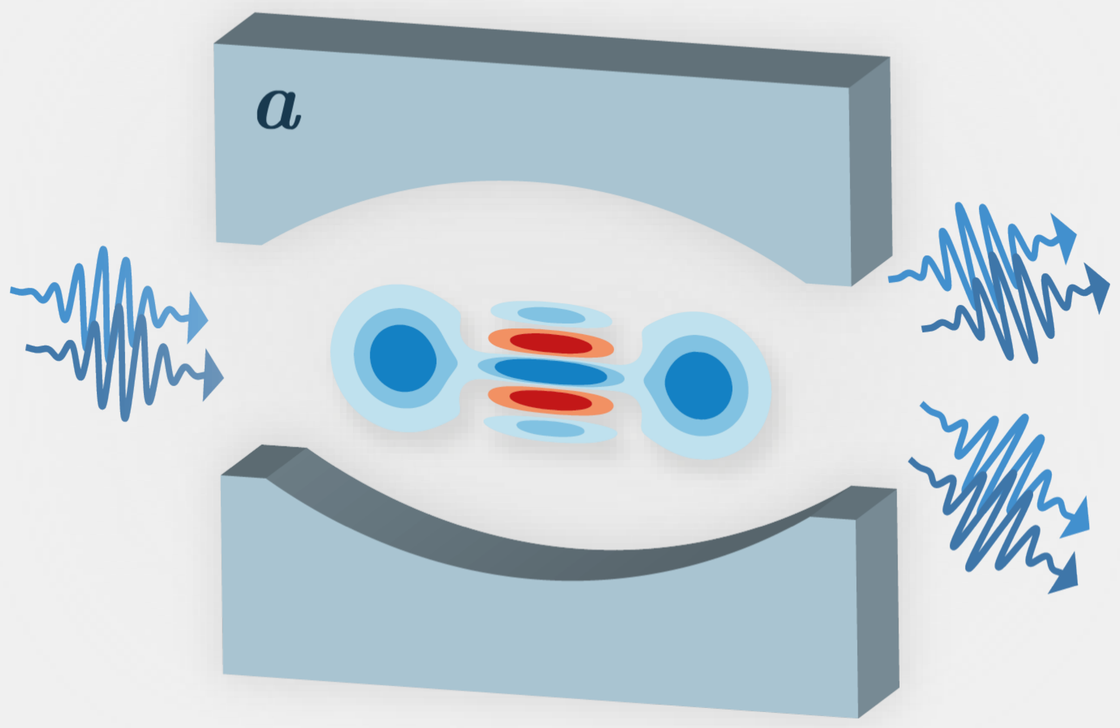
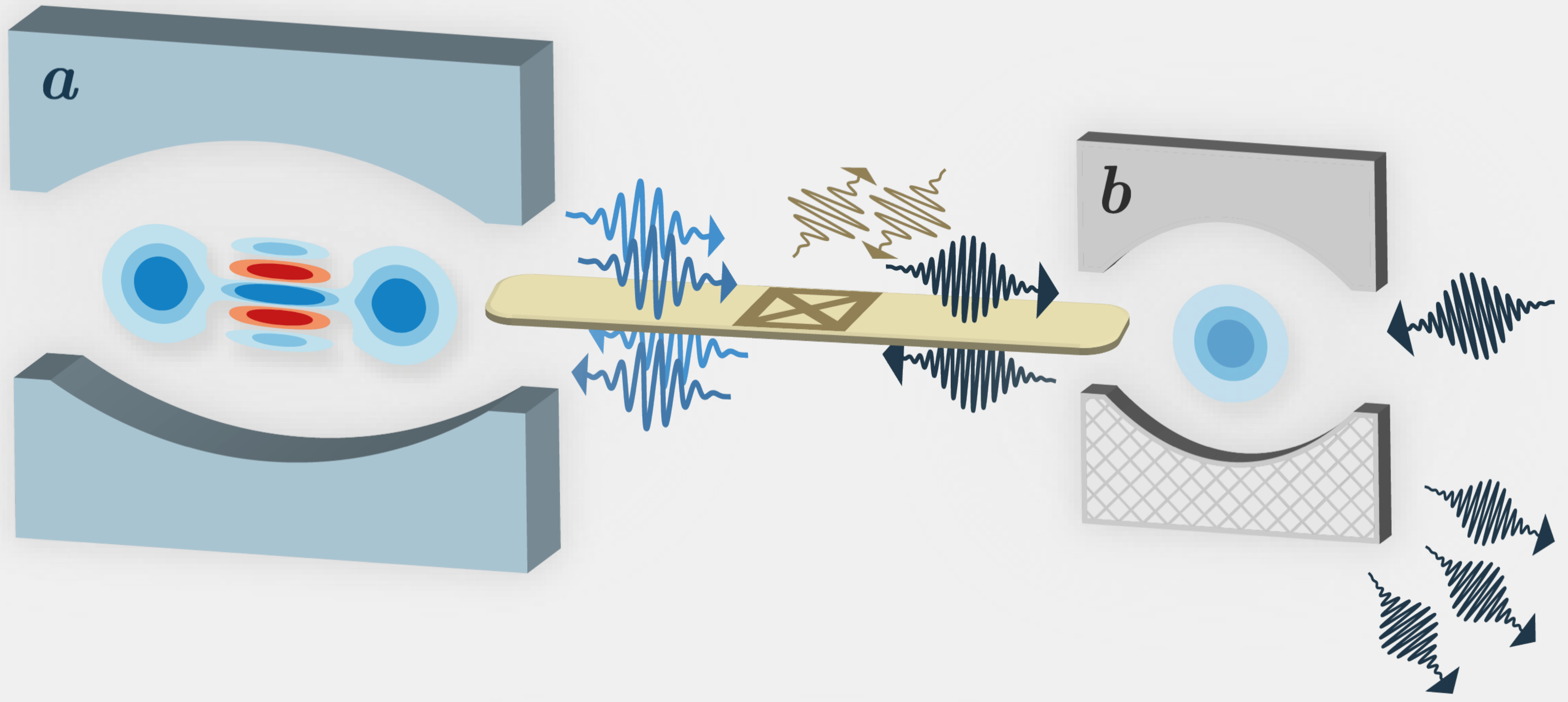


Memory + Buffer

$$\frac{d\rho}{dt} = -i[g_2(a^2 - \alpha^2)b^\dagger + \text{h.c.}, \rho] + \kappa_b \mathcal{D}[b]\rho$$



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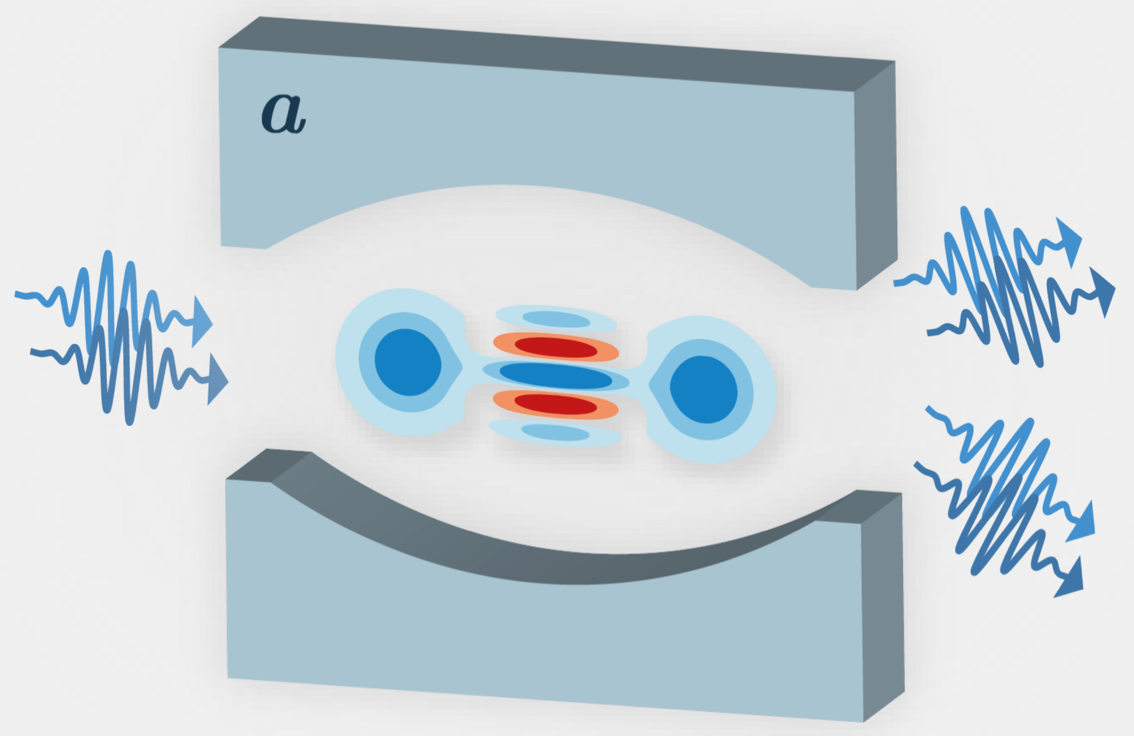

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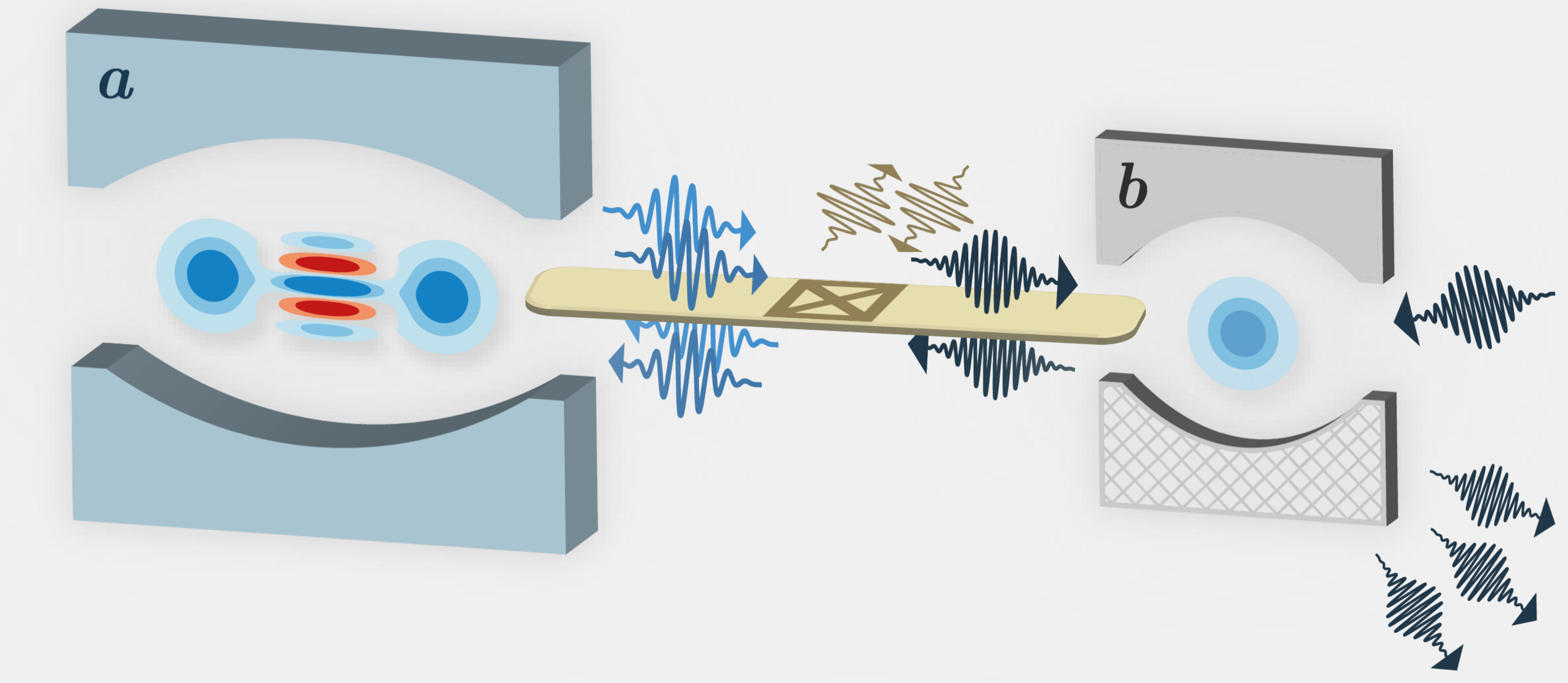


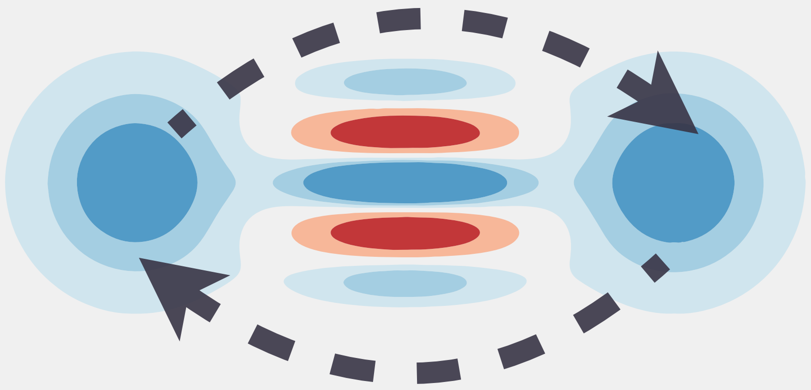
Buffer mode provides inertia ➔ **Gate engineering**

Mirrahimi *et al.* NJP (2014), Lescanne *et al.* Nat. Phy. (2019)

Gates based on the Zeno effect

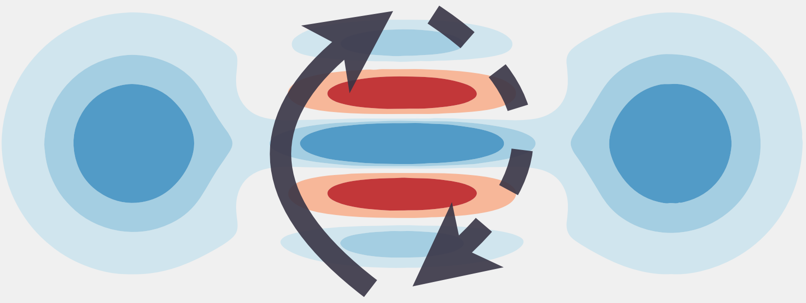
Guillaud *et al.* (2019)

Pauli X



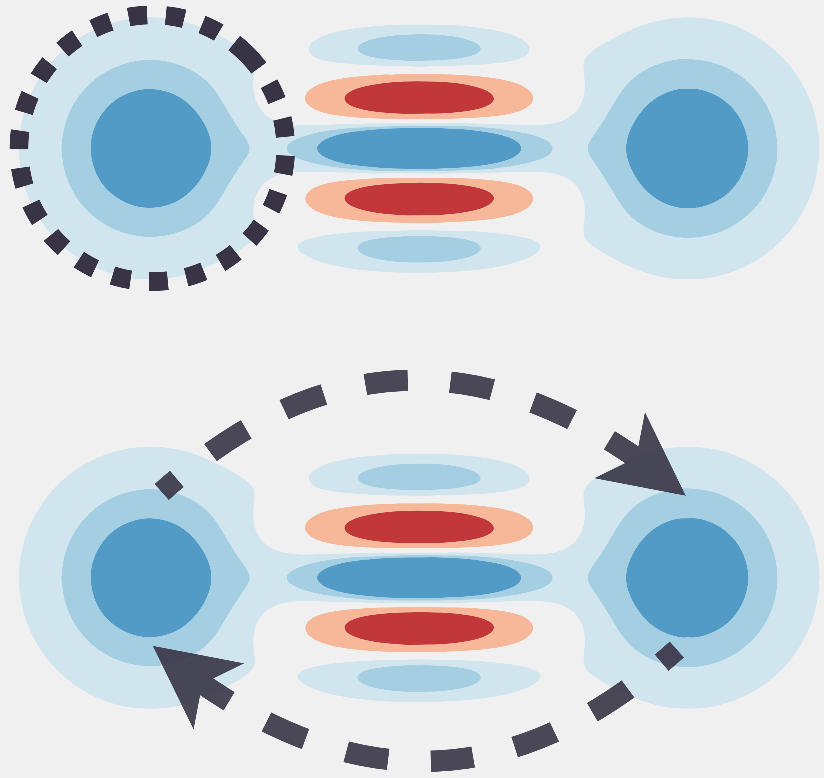
$$H = \Delta_X a^\dagger a$$

Z rotation



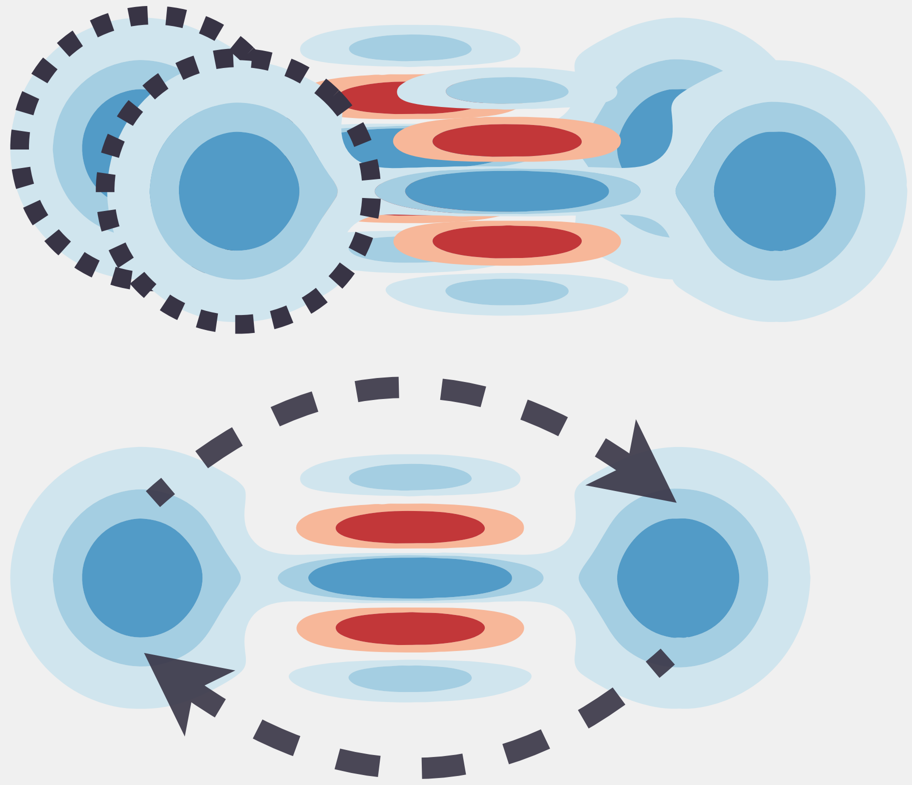
$$H = \varepsilon_Z a^\dagger + \varepsilon_Z a$$

CNOT



$$H = \varepsilon_{CX}(a_C^\dagger + a_C - 2\alpha) \otimes (a_T^\dagger a_T - |\alpha|^2)$$

Toffoli



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

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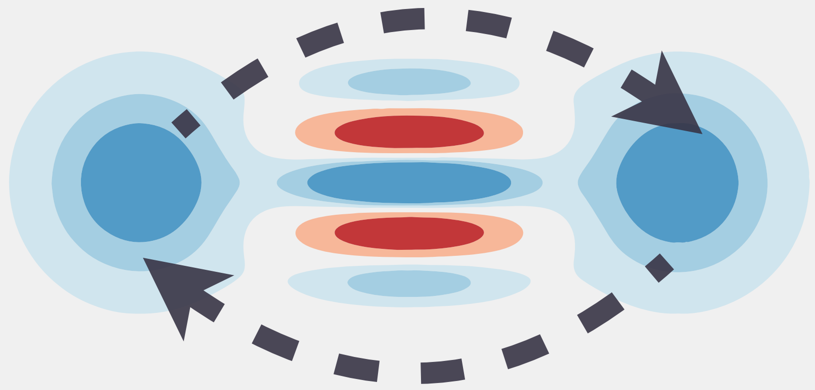

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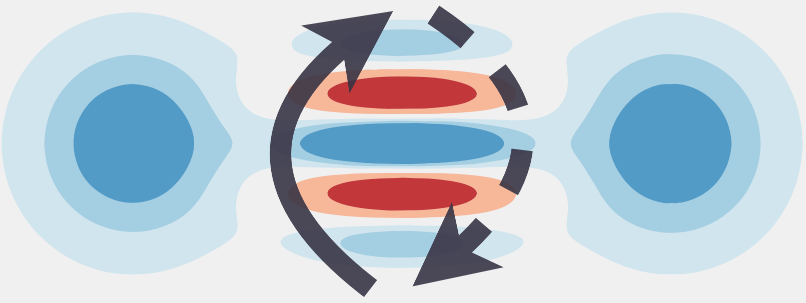

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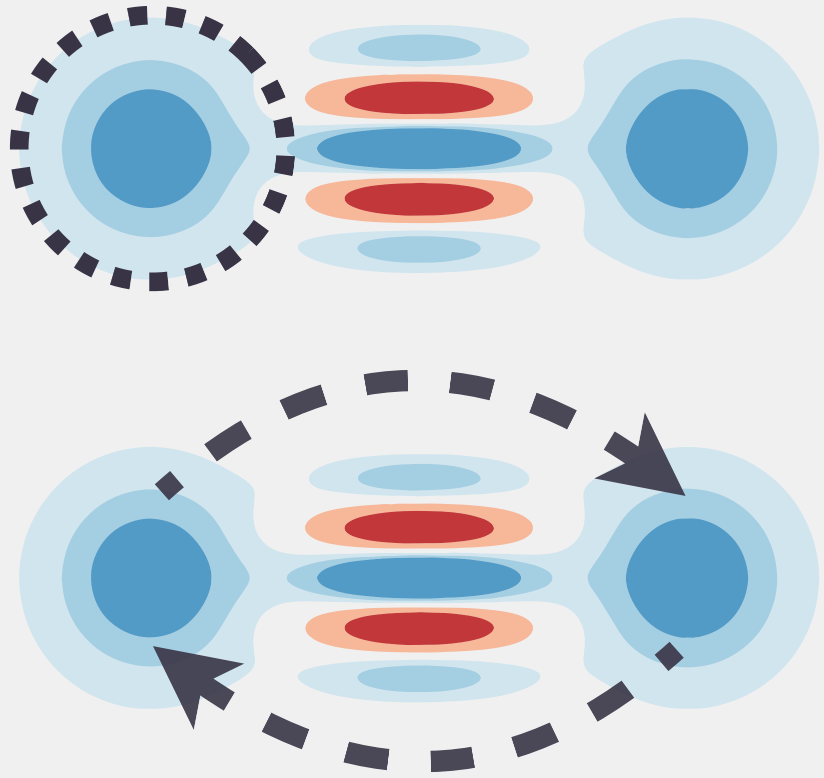

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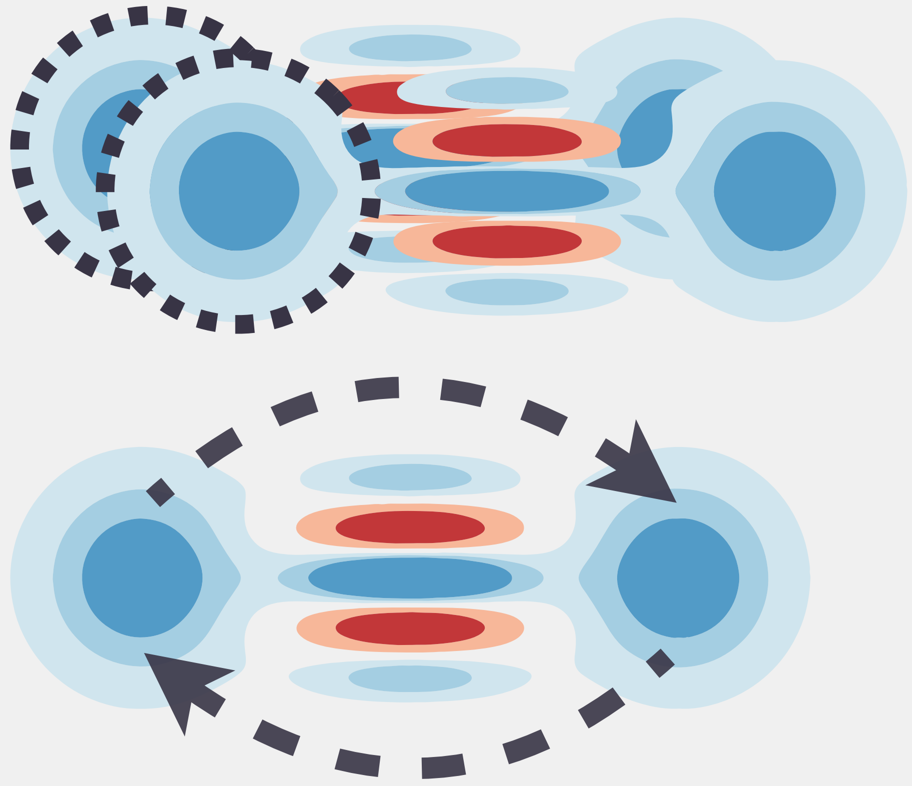

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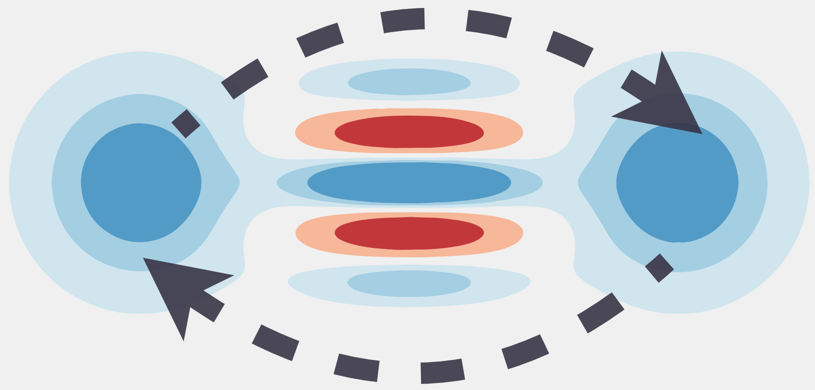

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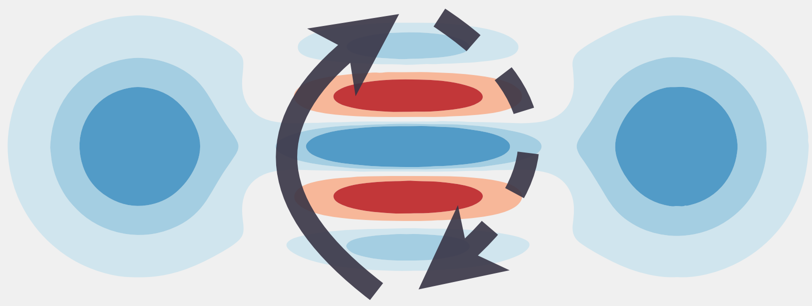

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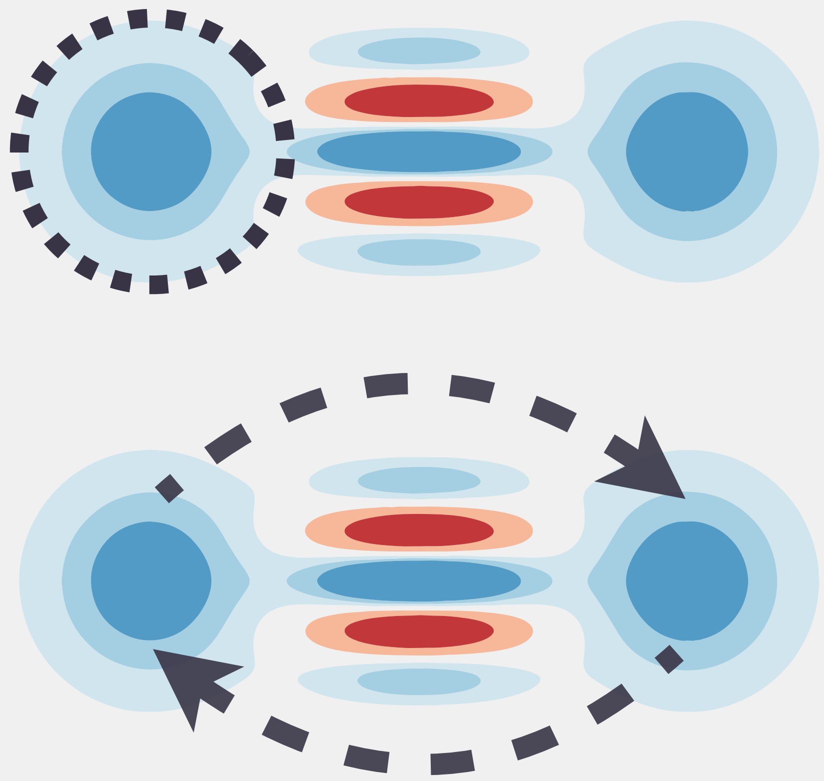

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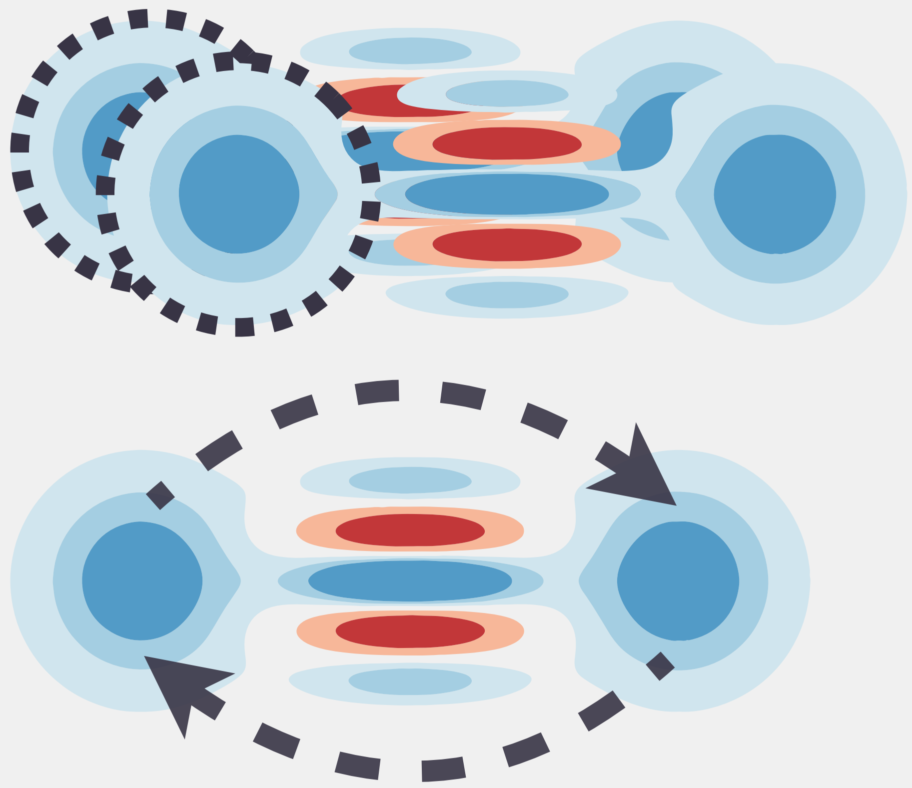

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Gate errors   Cavity lifetime

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

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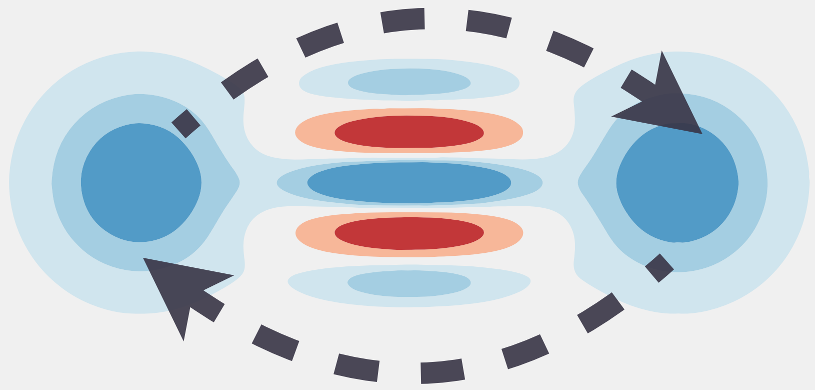

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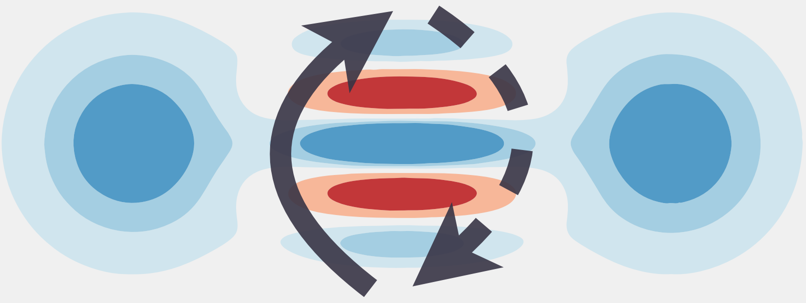

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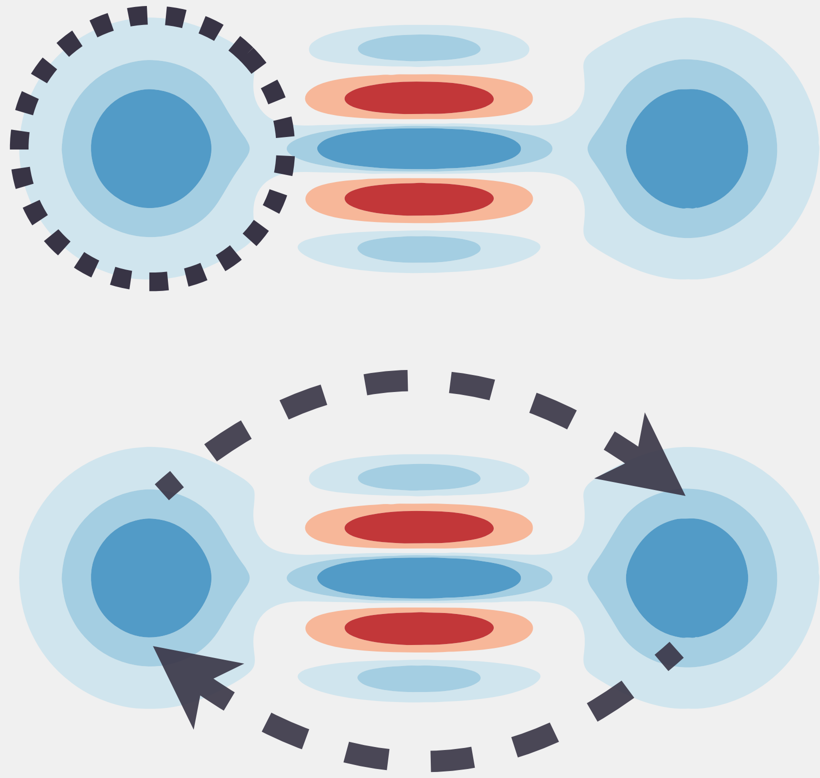

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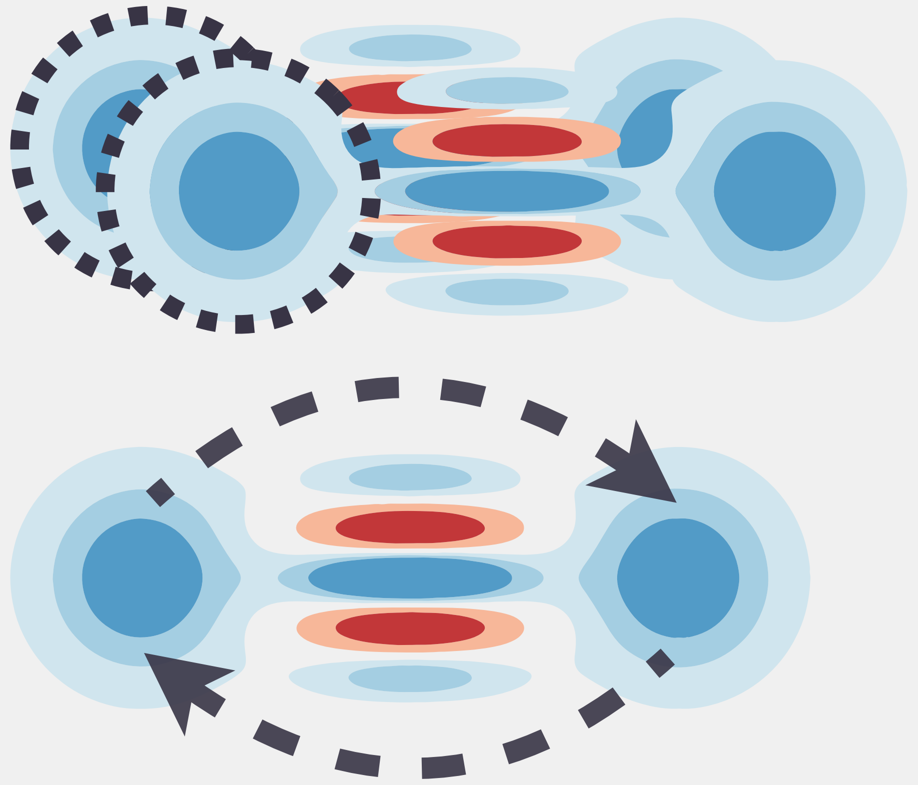

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Gate errors   Cavity lifetime

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

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

Unravelling the origin of gate errors

Hamiltonian of Z rotation gate

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

Gautier *et al.*, PRXQ (2023)

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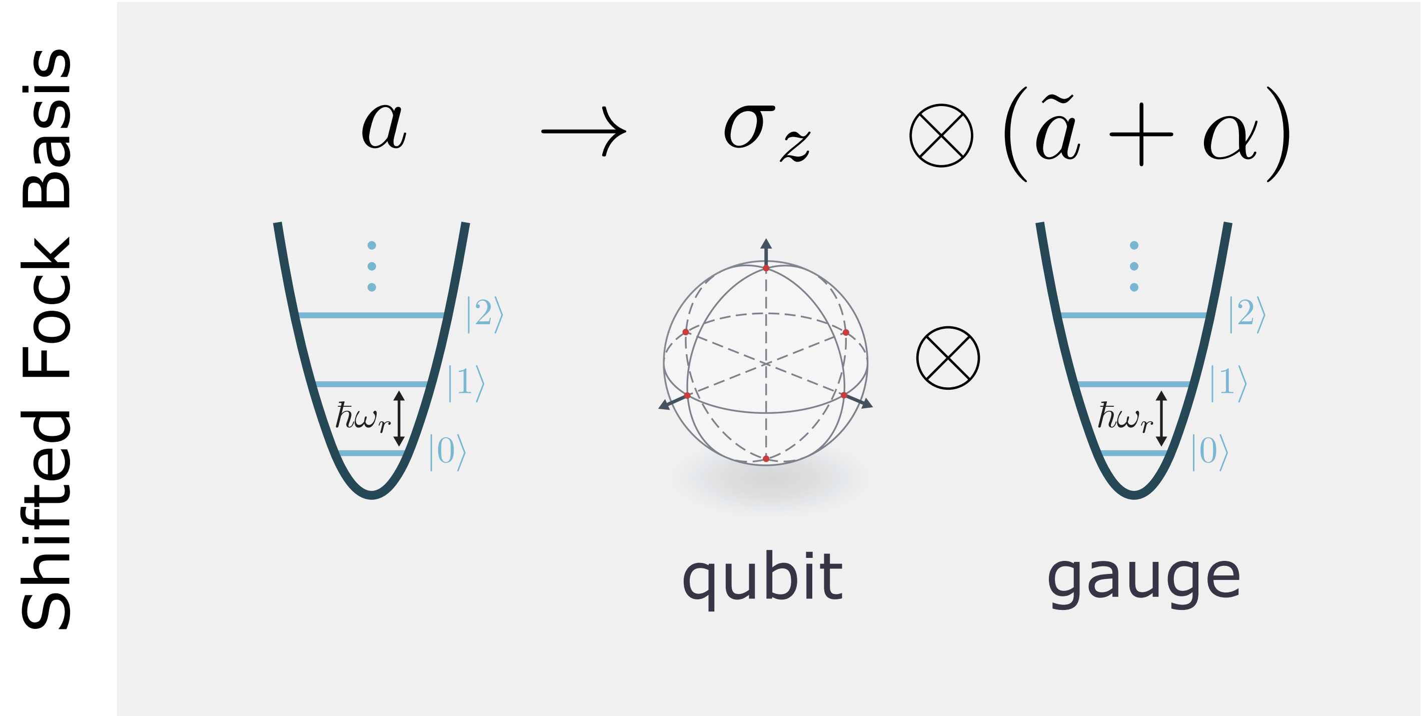
Move in Shifted Fock Basis

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



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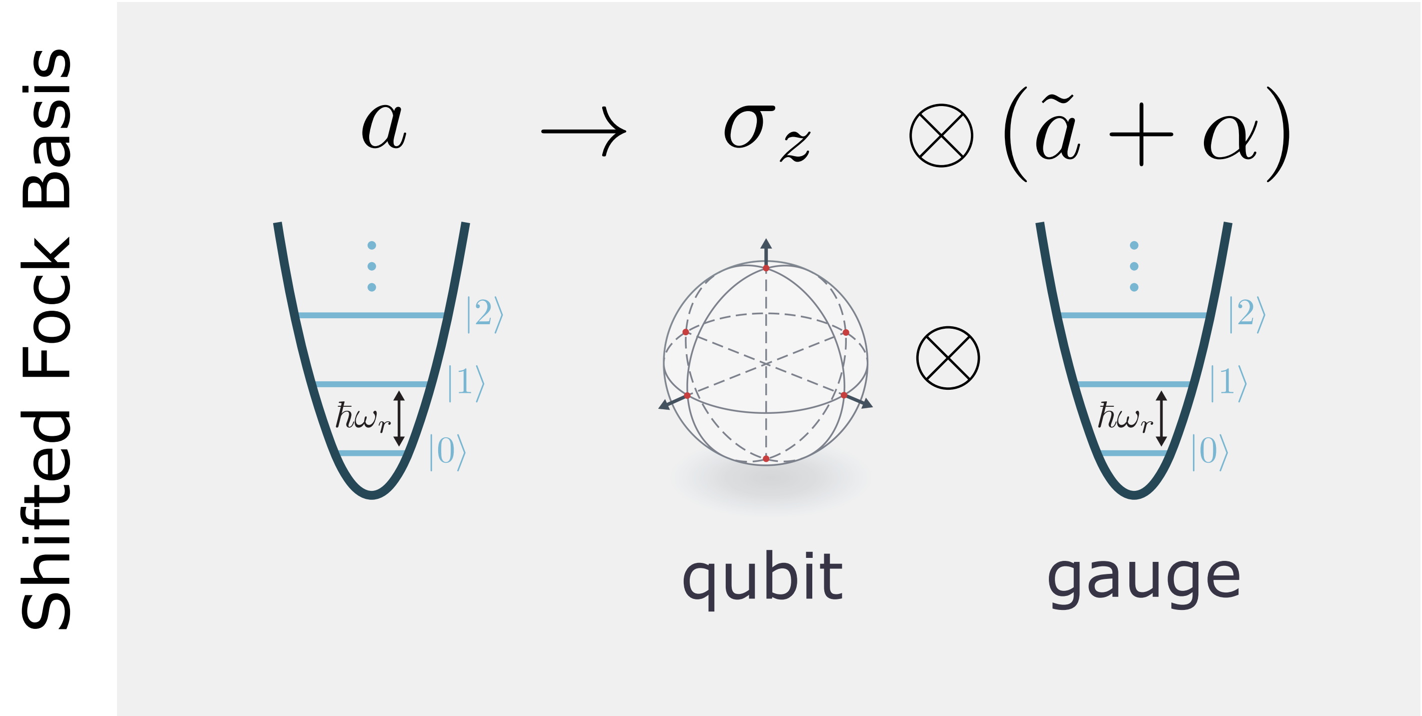

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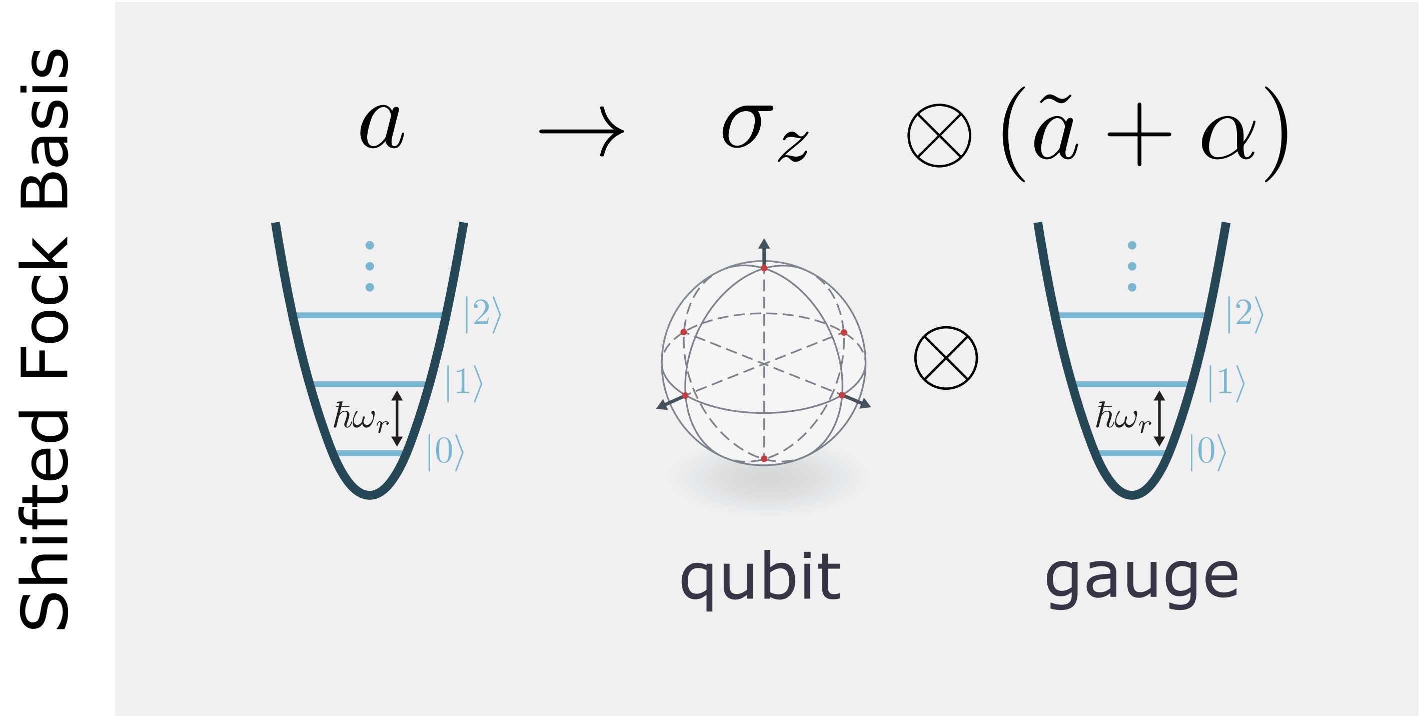
Mean-field description of buffer dynamics

- $\ddot{b} + \frac{1}{2}\kappa_b \dot{b} + \nu^2 b = -\nu\varepsilon_Z\sigma_z$



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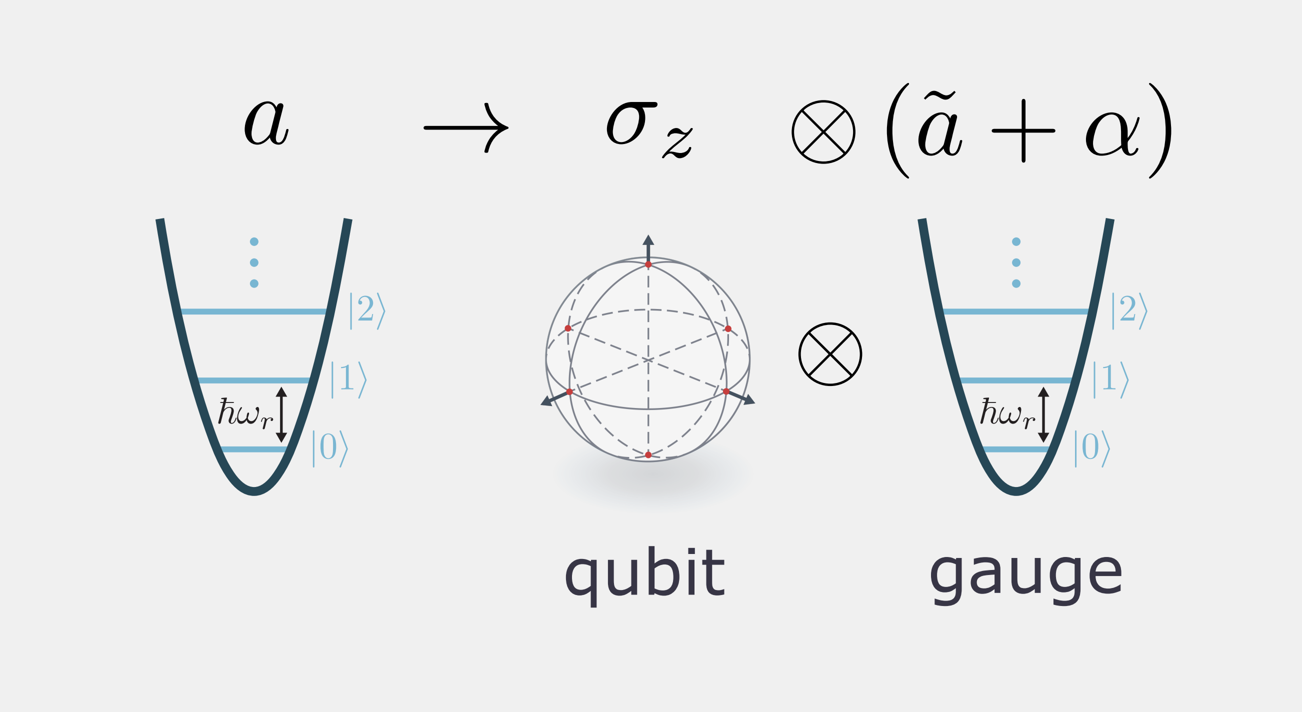
Infinite-time dynamics

- $b \xrightarrow{t\to\infty} -\frac{\varepsilon_Z}{\nu}\sigma_z$

Shifted Fock Basis



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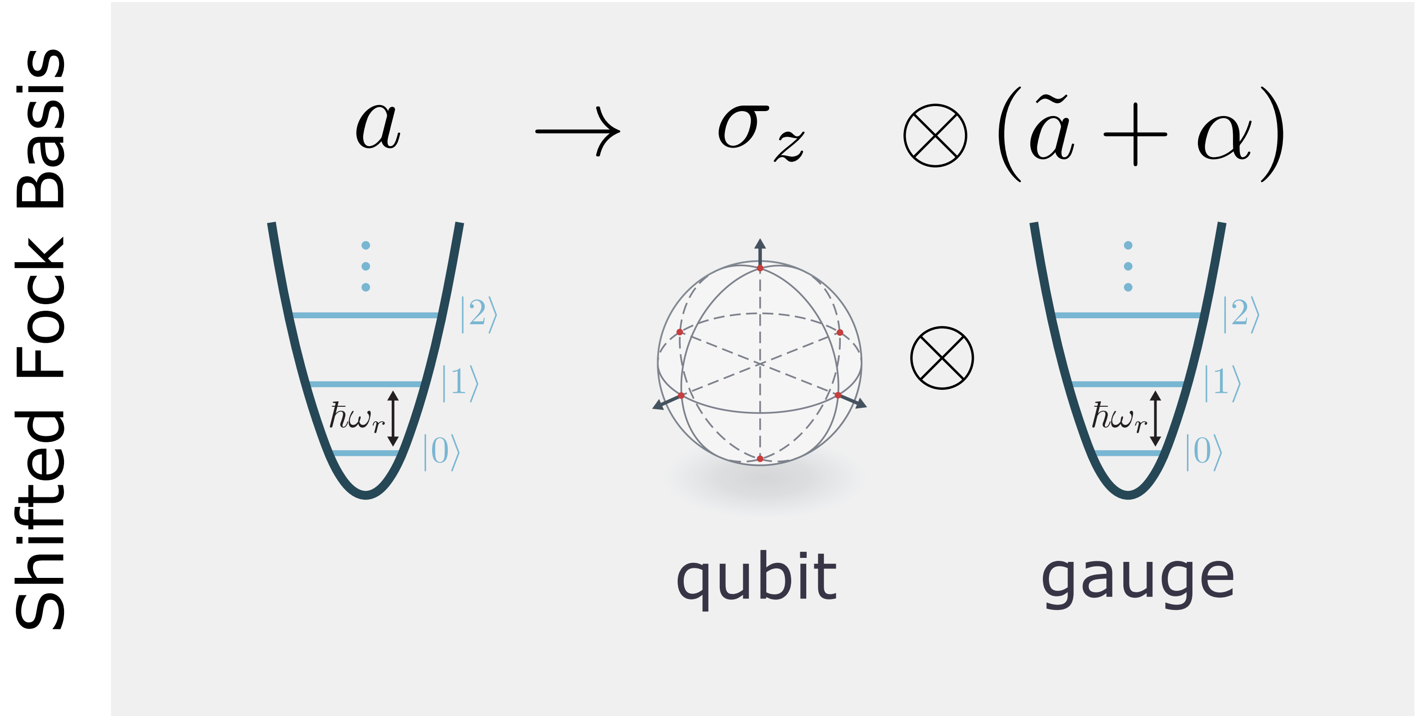

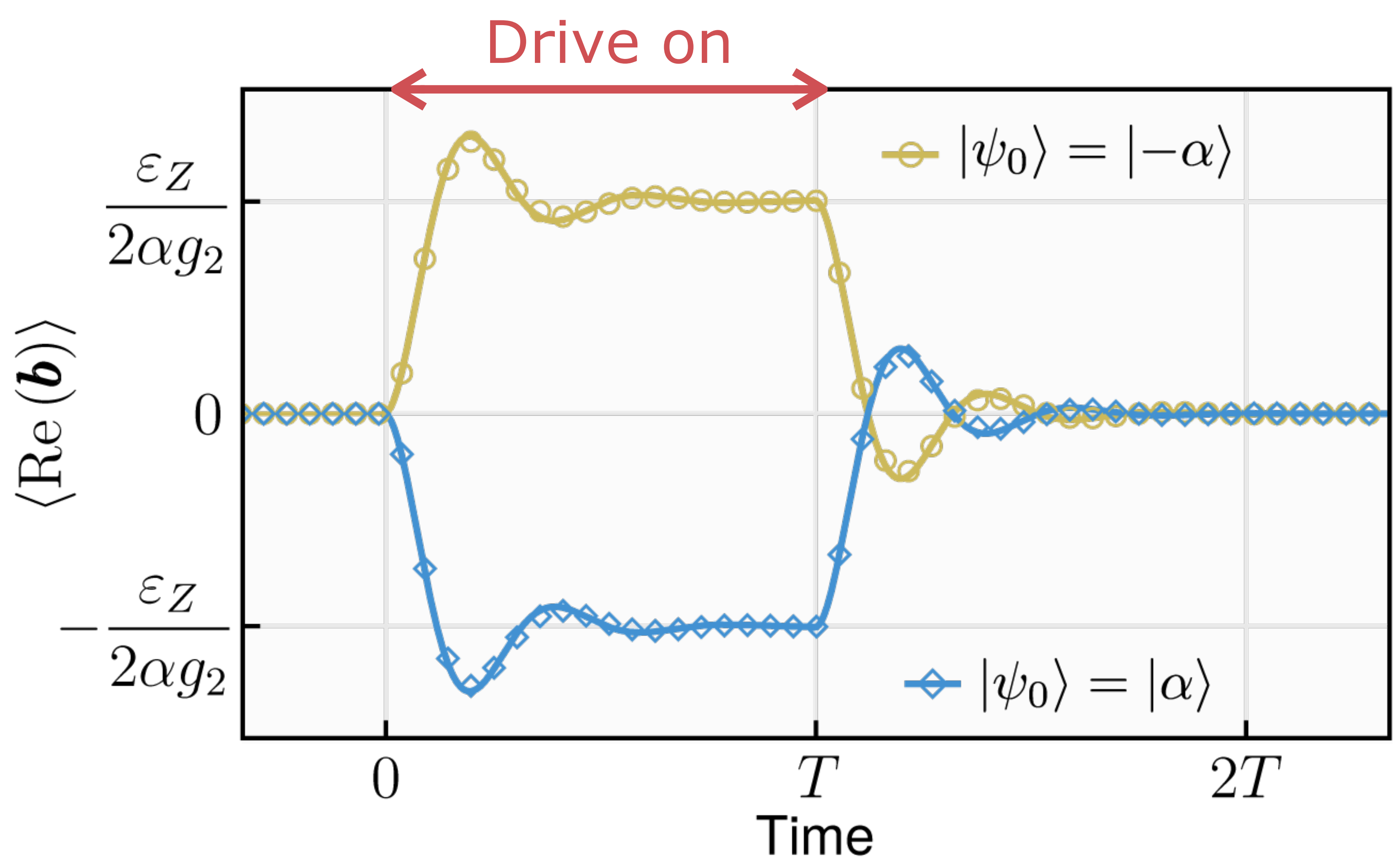

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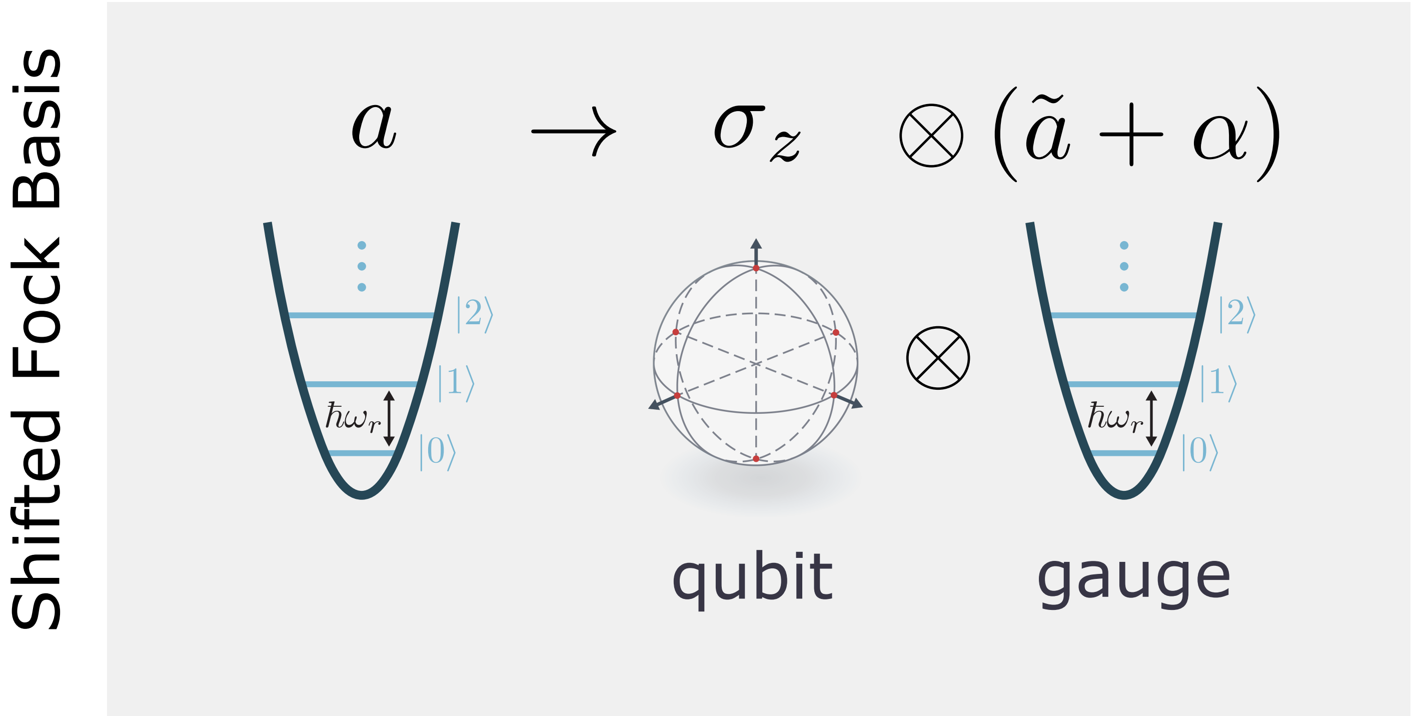
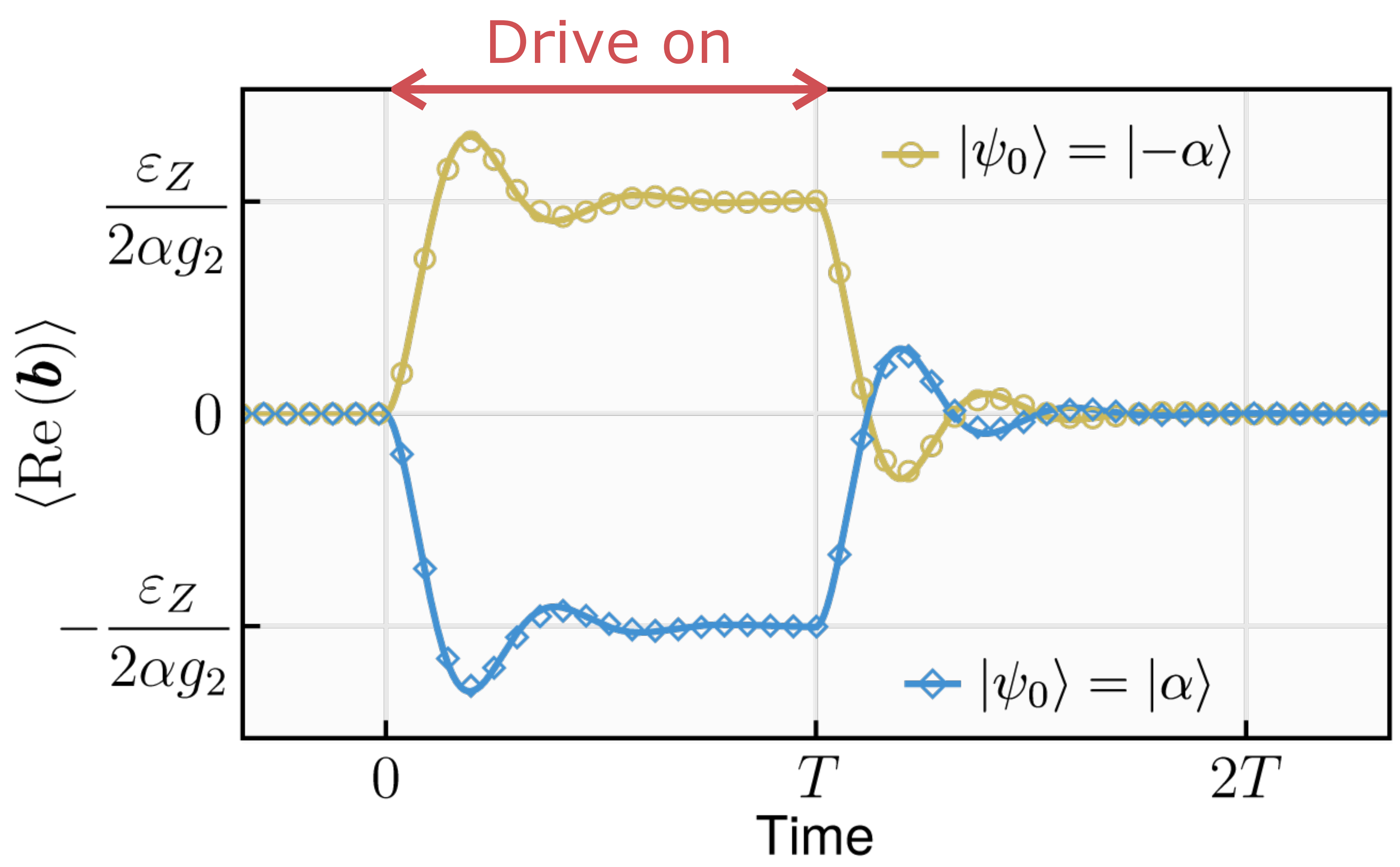
Generalises Zeno gate errors to 2 modes

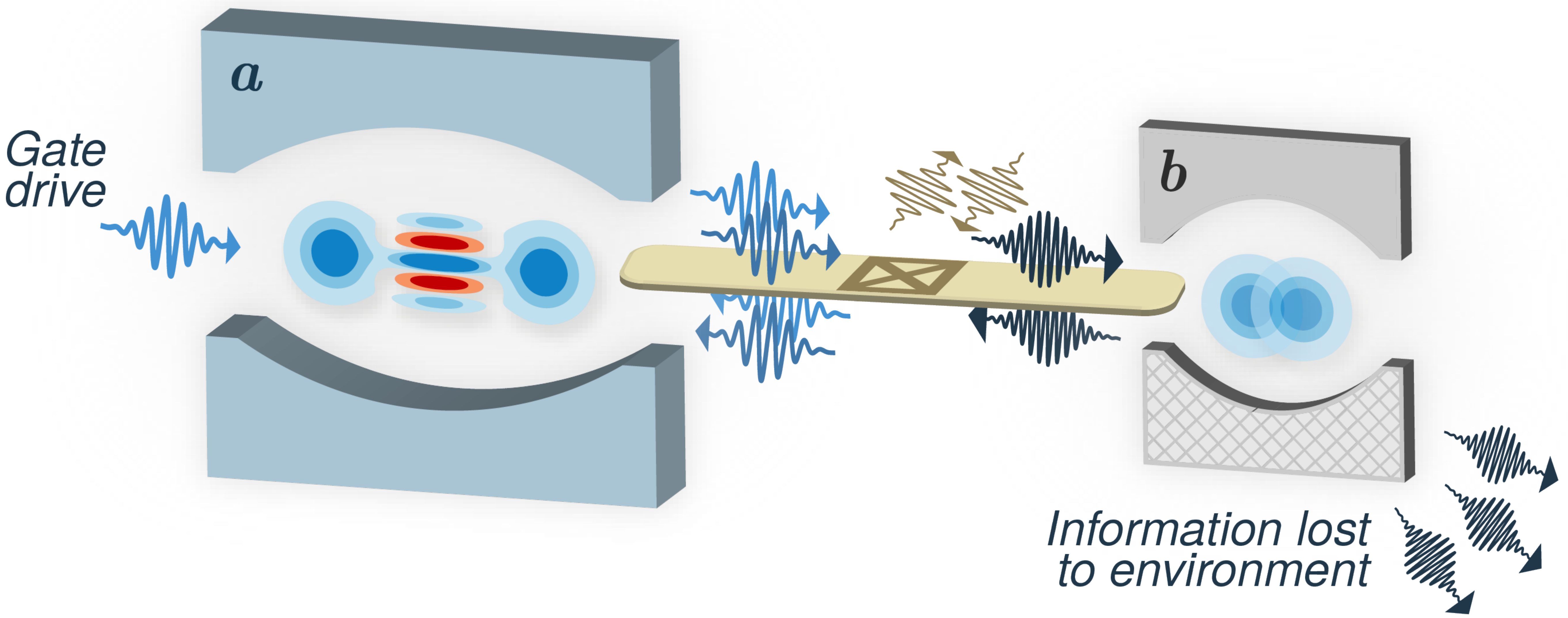
- $p_Z = \frac{\pi^2}{16|\alpha|^4 T}\frac{\kappa_b}{4g_2^2}$





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

From discovery to answers



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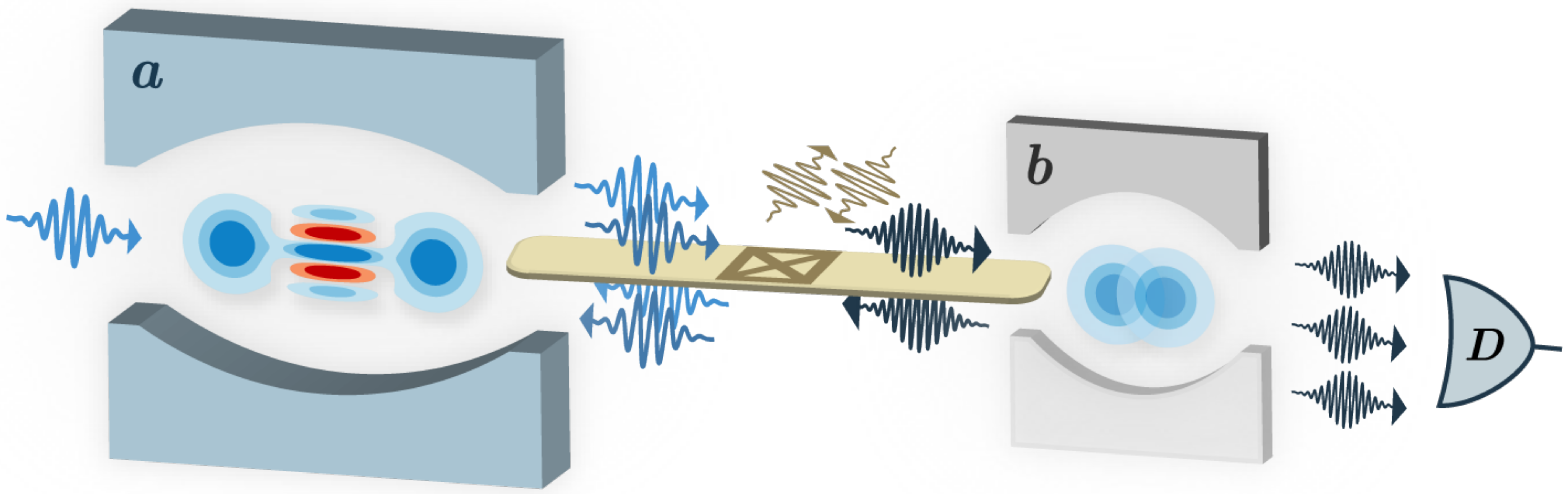

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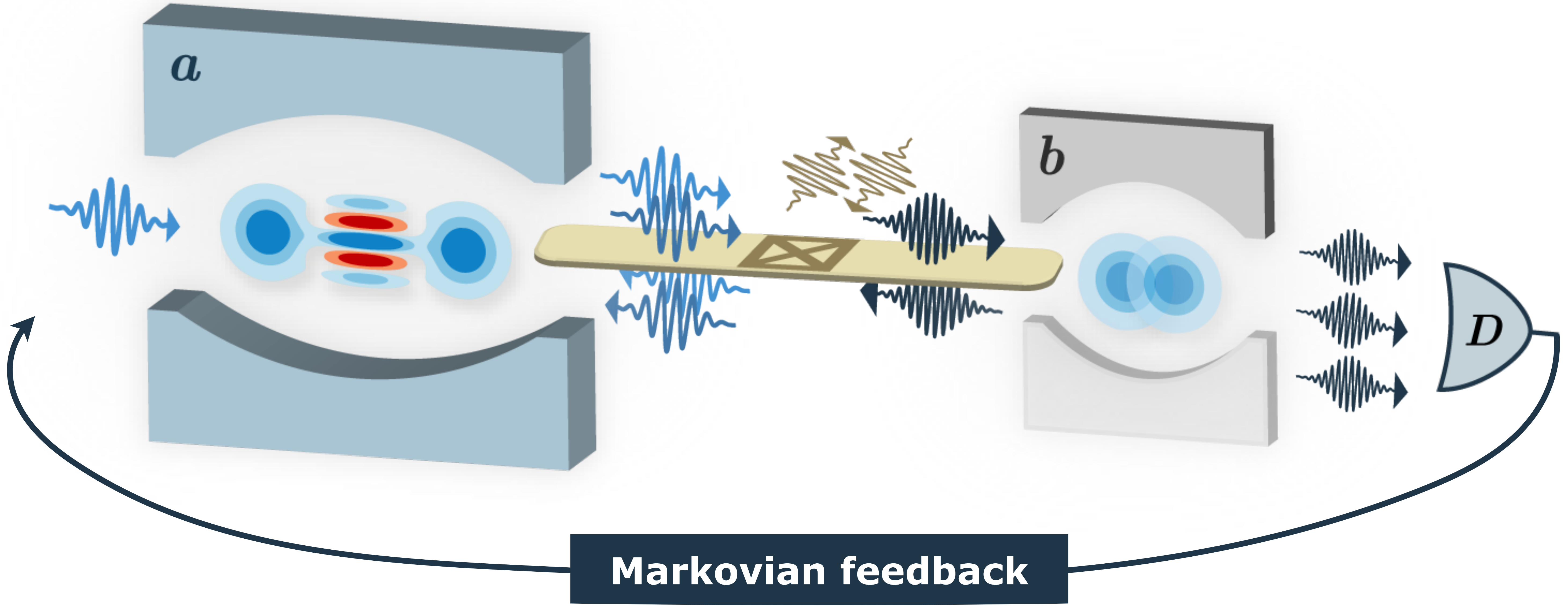

Rabi oscillations with a photodetector

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

$$\frac{d\rho}{dt} = -i[H,\rho]dt + \kappa_b\left(\mathcal{D}_\eta[b]\rho\, dt + \mathcal{J}[\rho]dN_\eta\right)$$

no-jump jump

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

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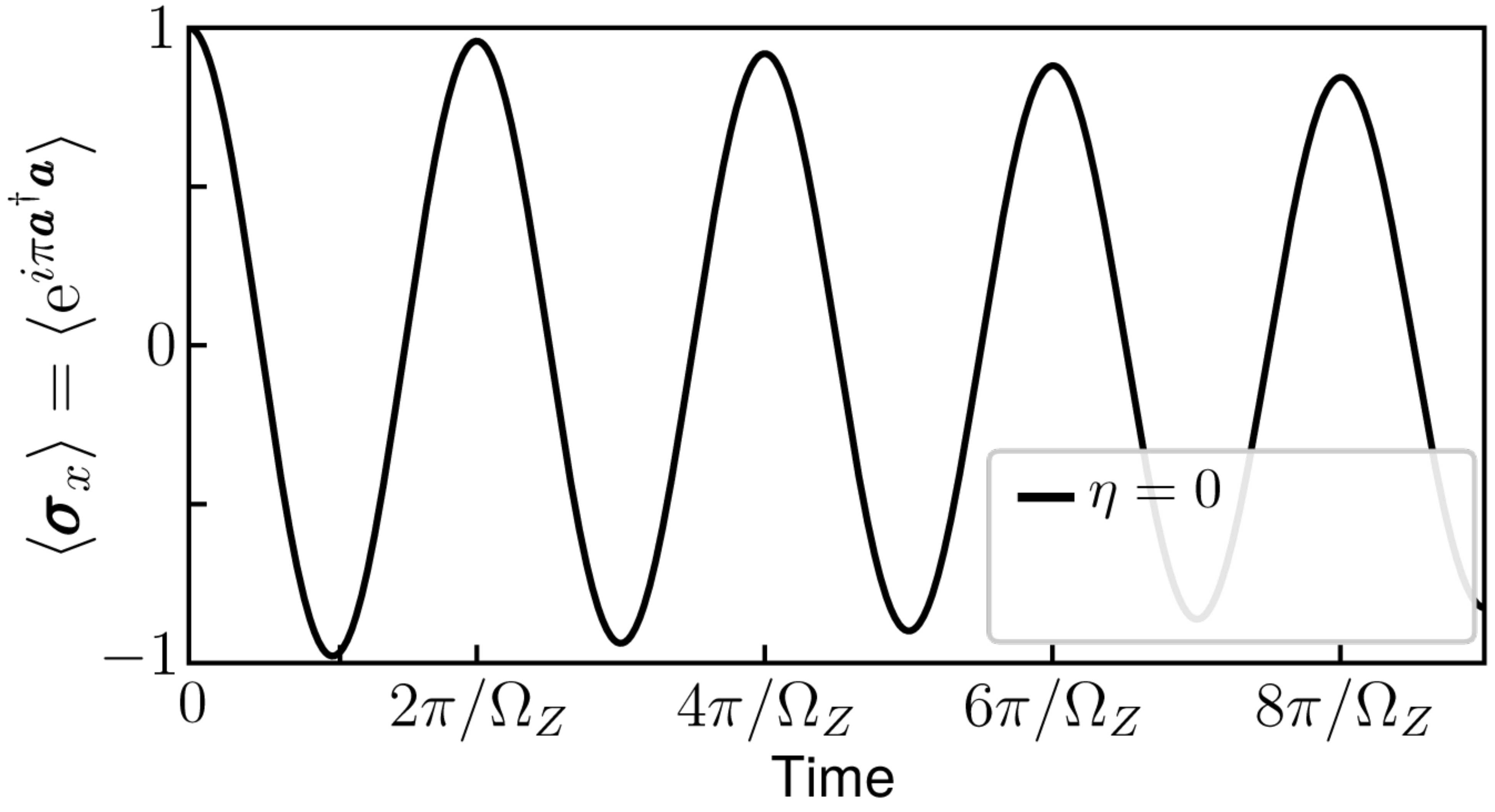

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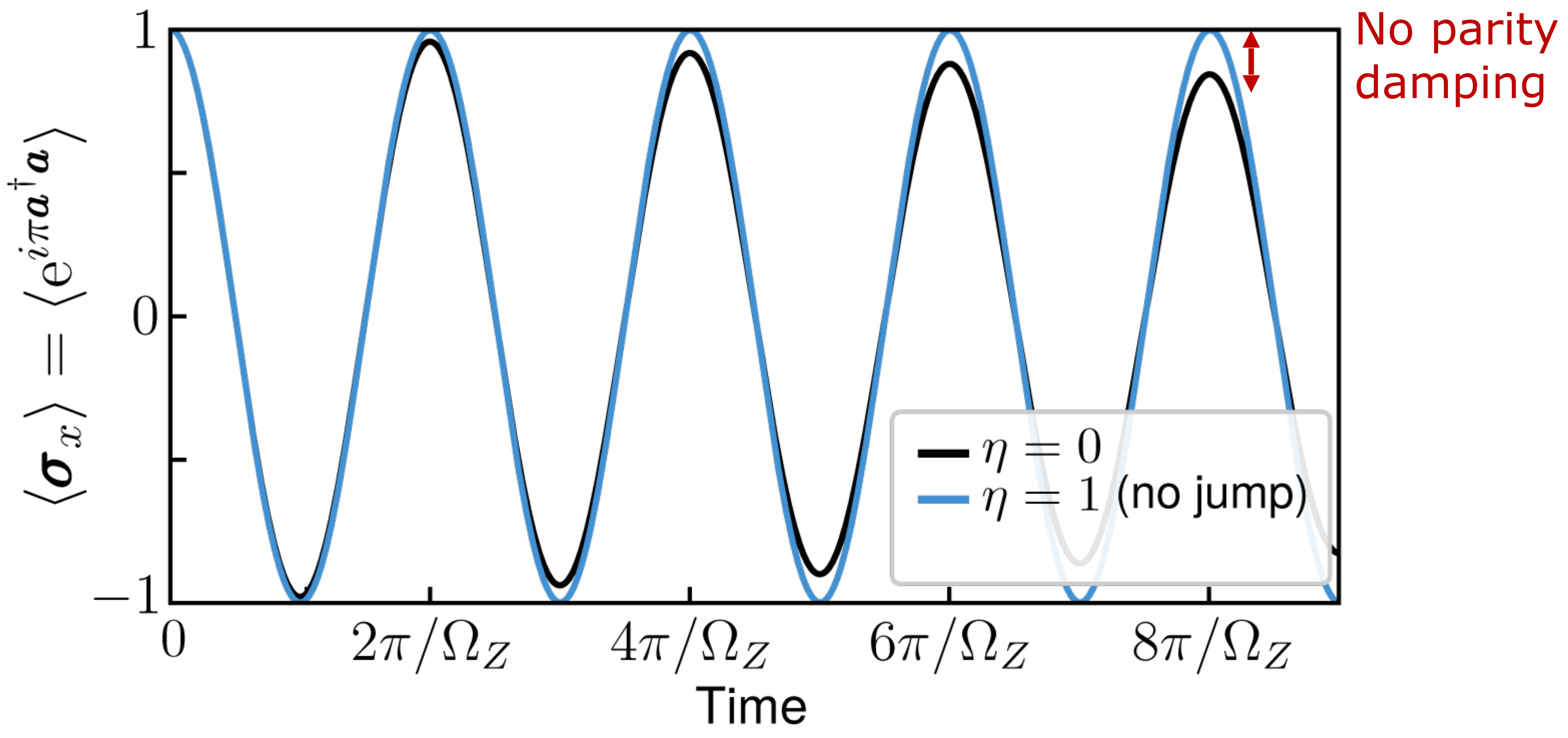
with $0 \leq \eta \leq 1$ (detection efficiency)

Assuming $\eta = 1$

- Preserves purity (no information lost)



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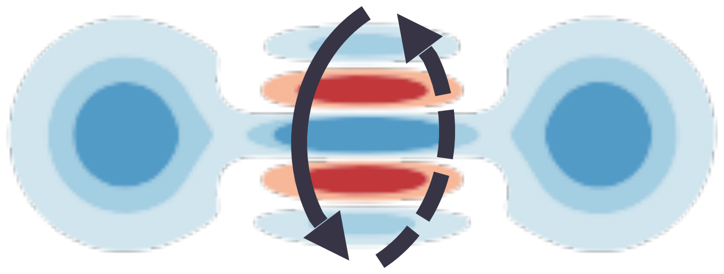
no-jump   jump

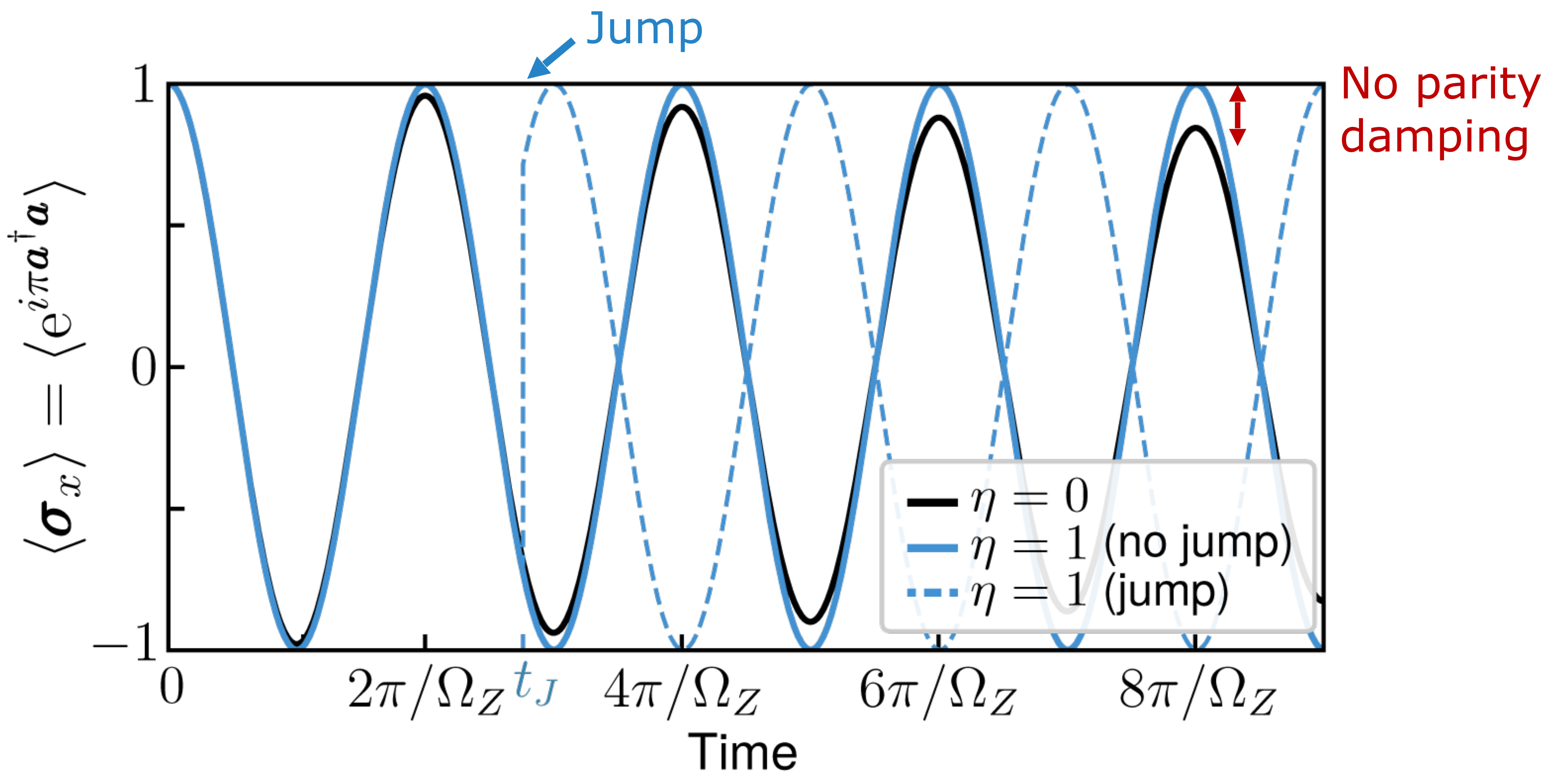
with $0 \leq \eta \leq 1$ (detection efficiency)

Assuming $\eta = 1$

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

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





Gate engineering with a photodetector

Information is lost through the buffer mode
➡ measure the buffer output to retrieve it + **markovian feedback**

$$\frac{d\rho}{dt} = -i[H,\rho]dt + \kappa_b\,(\mathcal{D}_\eta[b]\rho\,dt + \mathcal{J}[\rho]dN_\eta)$$

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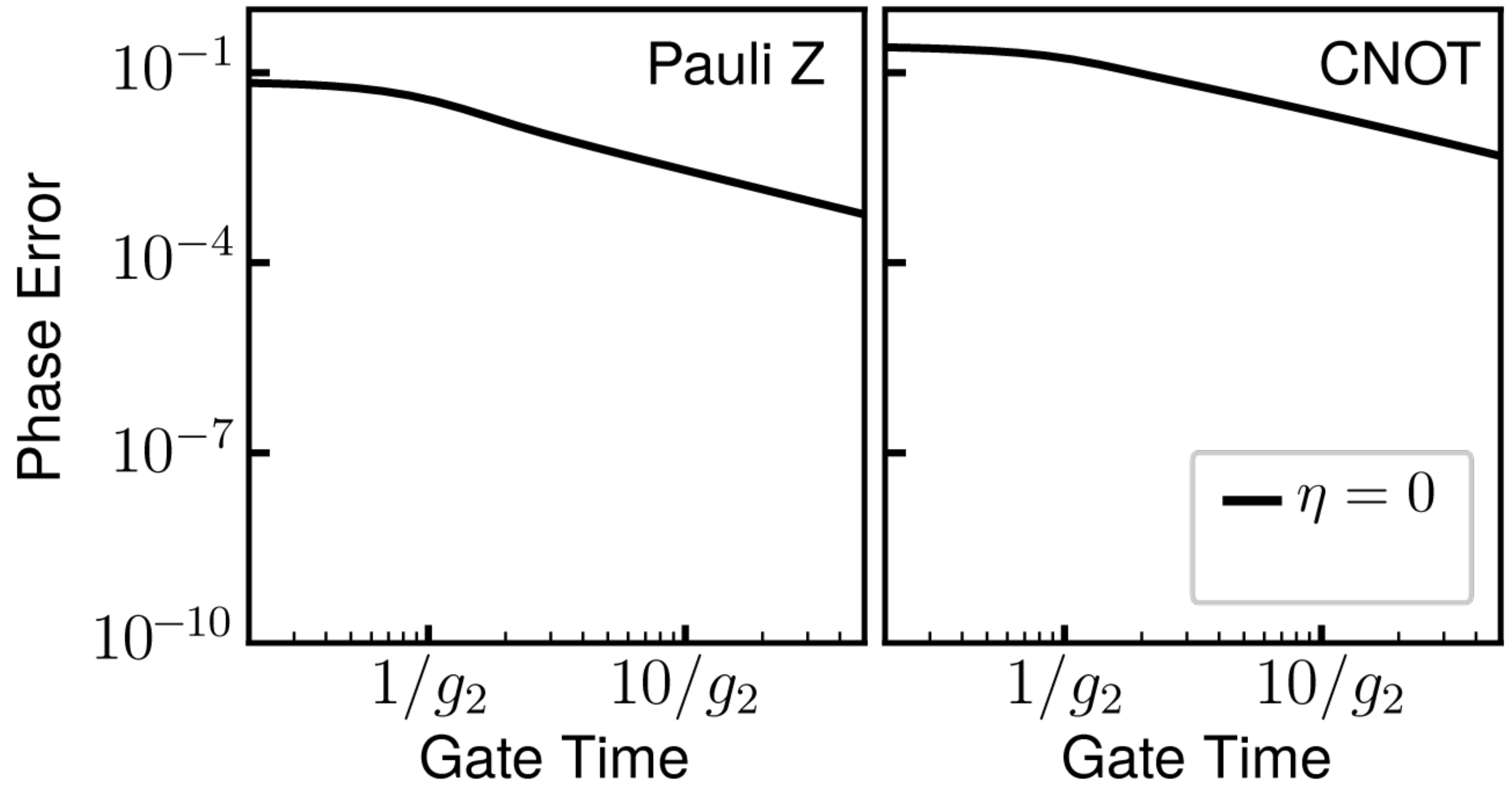

➡ Zeno scaling in 1/T

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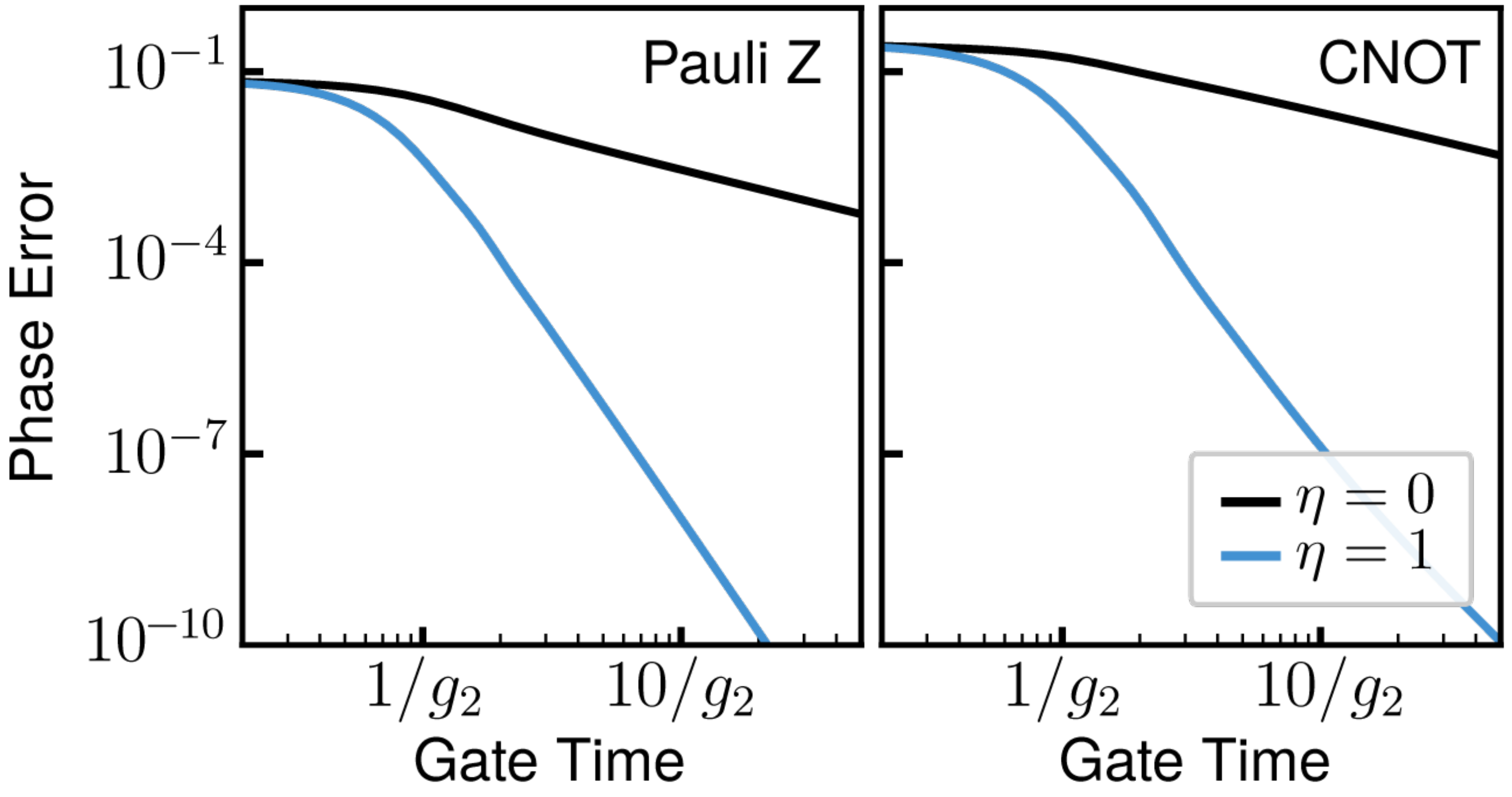

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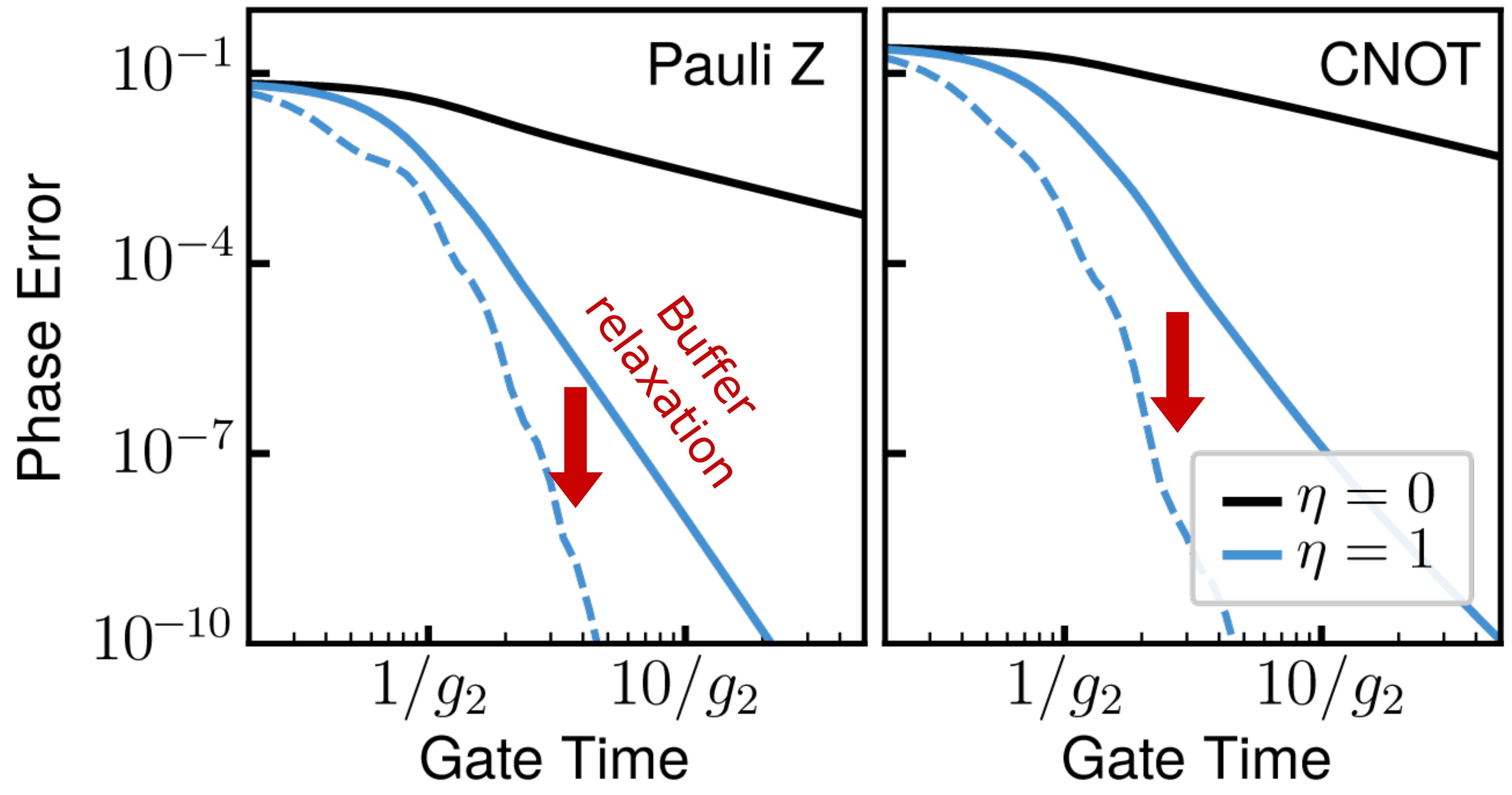

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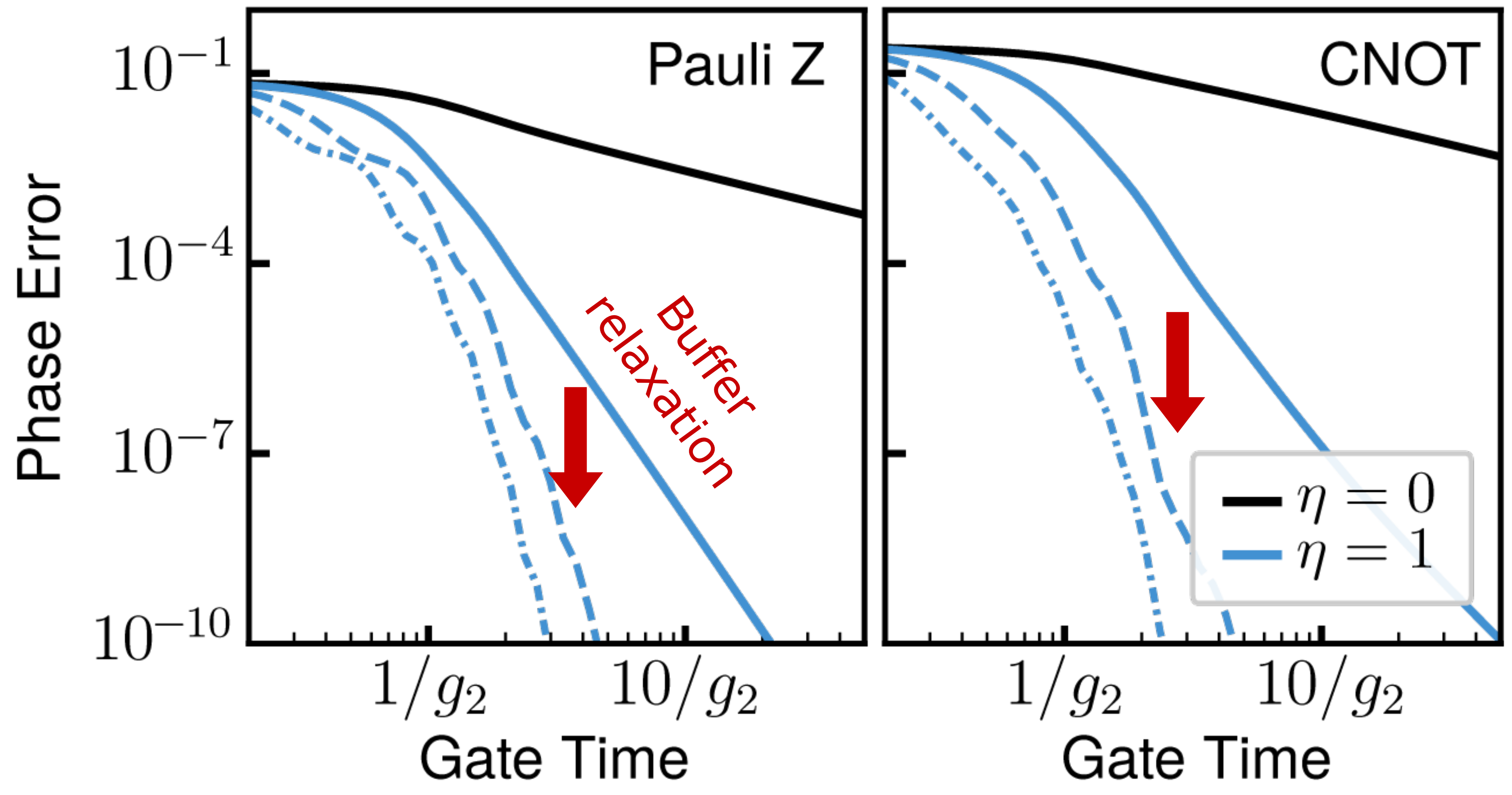

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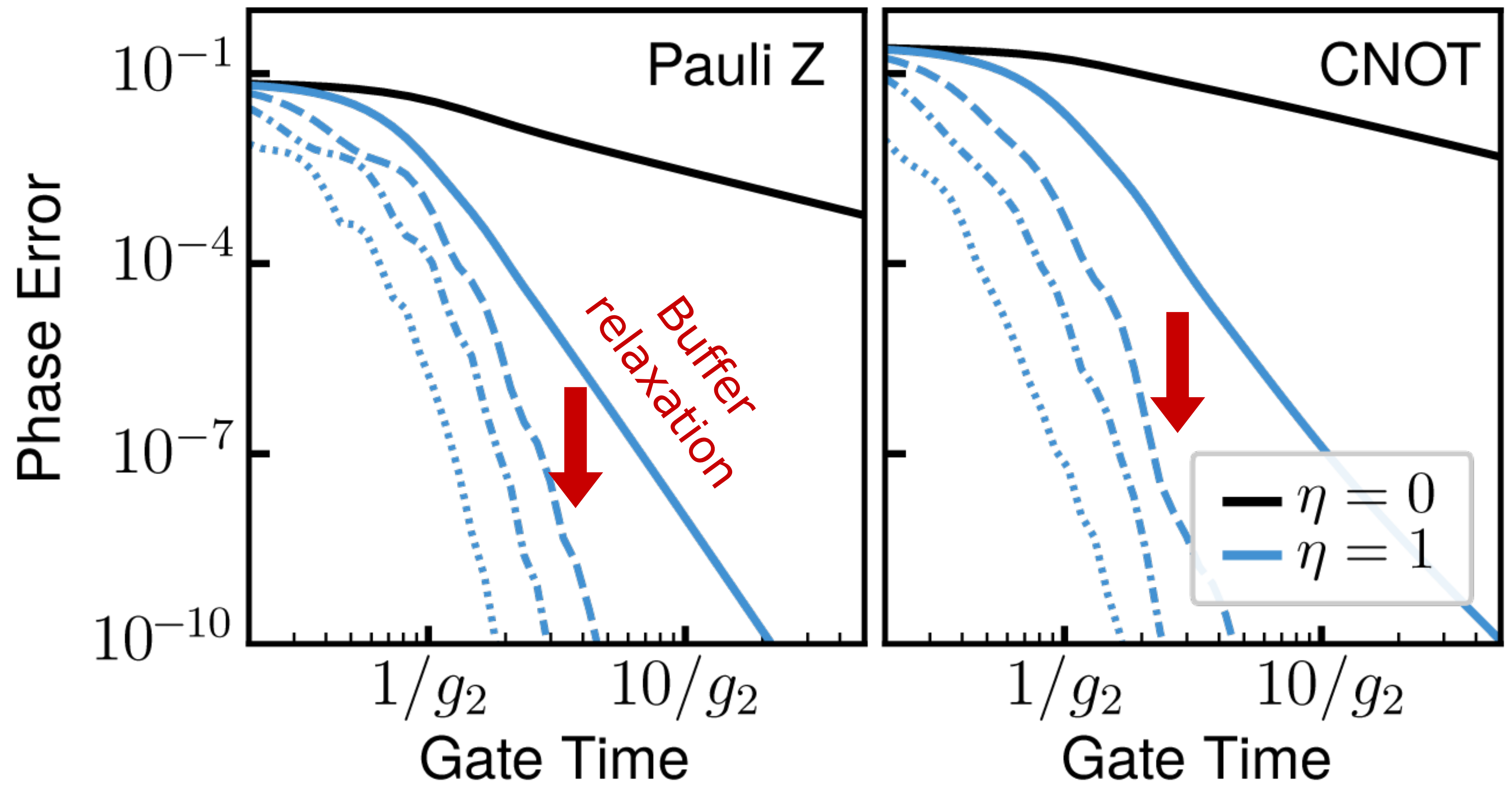

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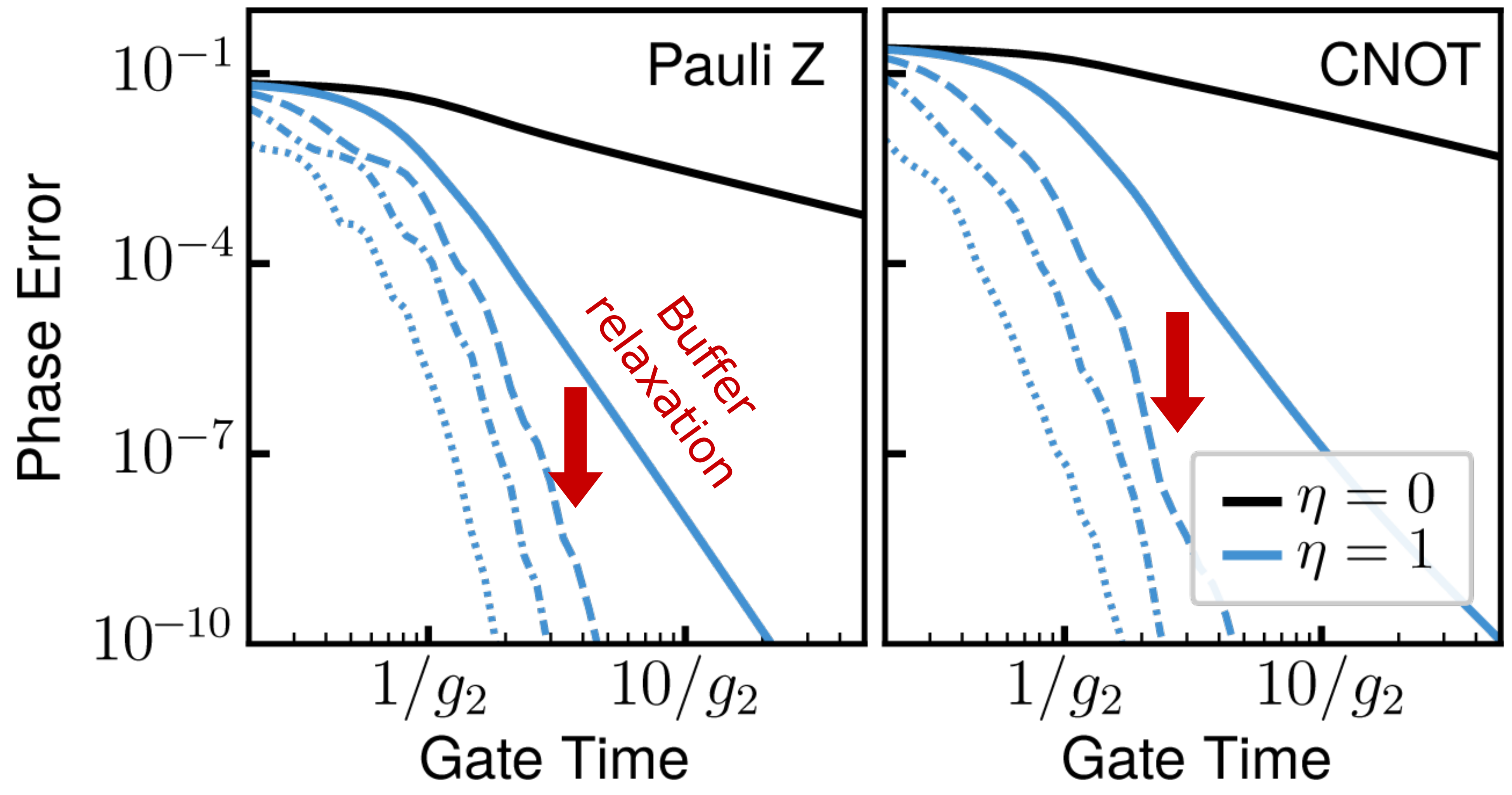

➡ Zeno scaling in 1/T

➡ High-order polynomial scaling

- Can apply feedback once per QEC cycle

Gate engineering with a photodetector

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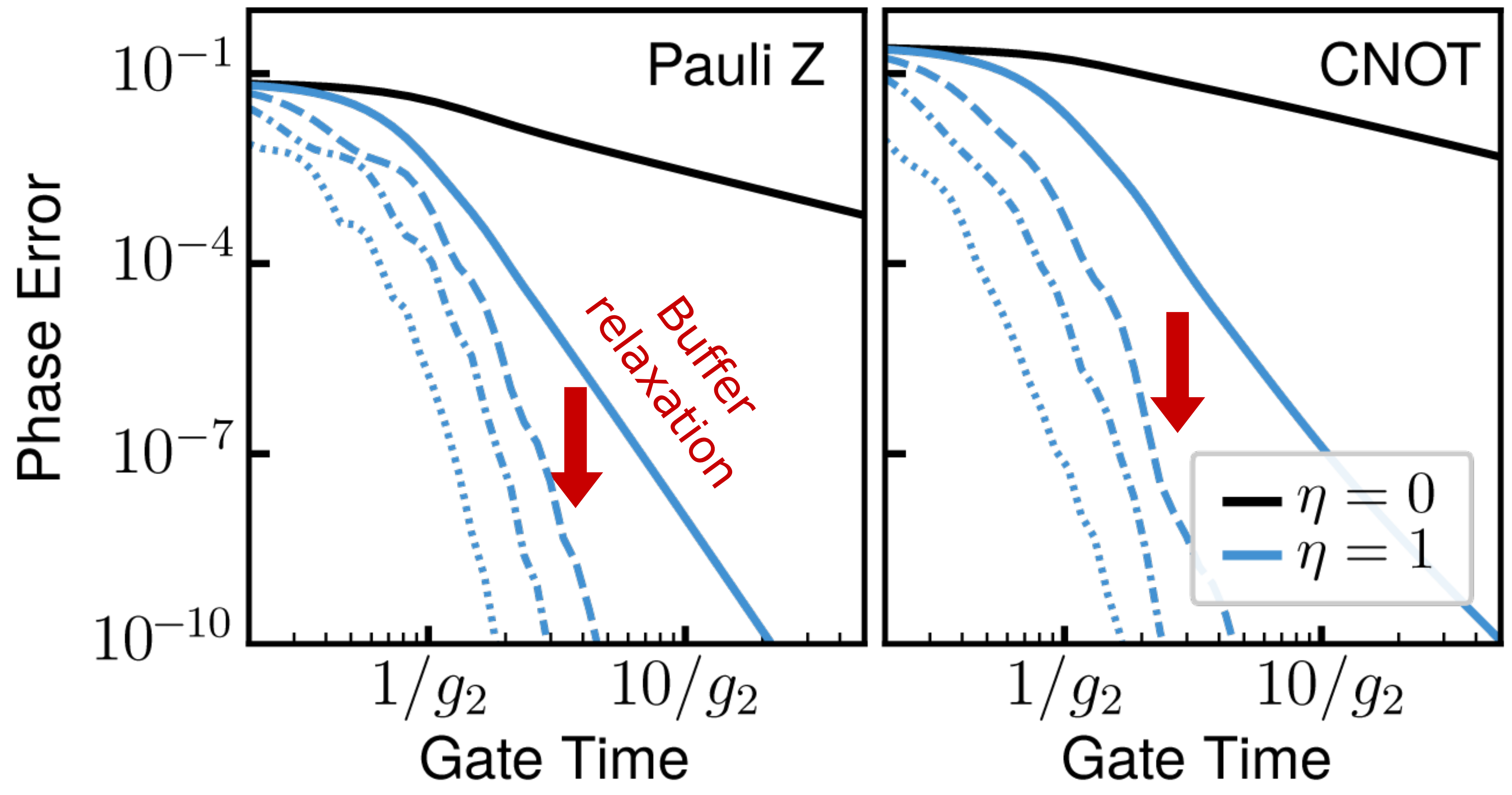

➡ Zeno scaling in 1/T

➡ High-order polynomial scaling

- Can apply feedback once per QEC cycle
- Gate fidelity limited by detection efficiency

Gate engineering with a photodetector

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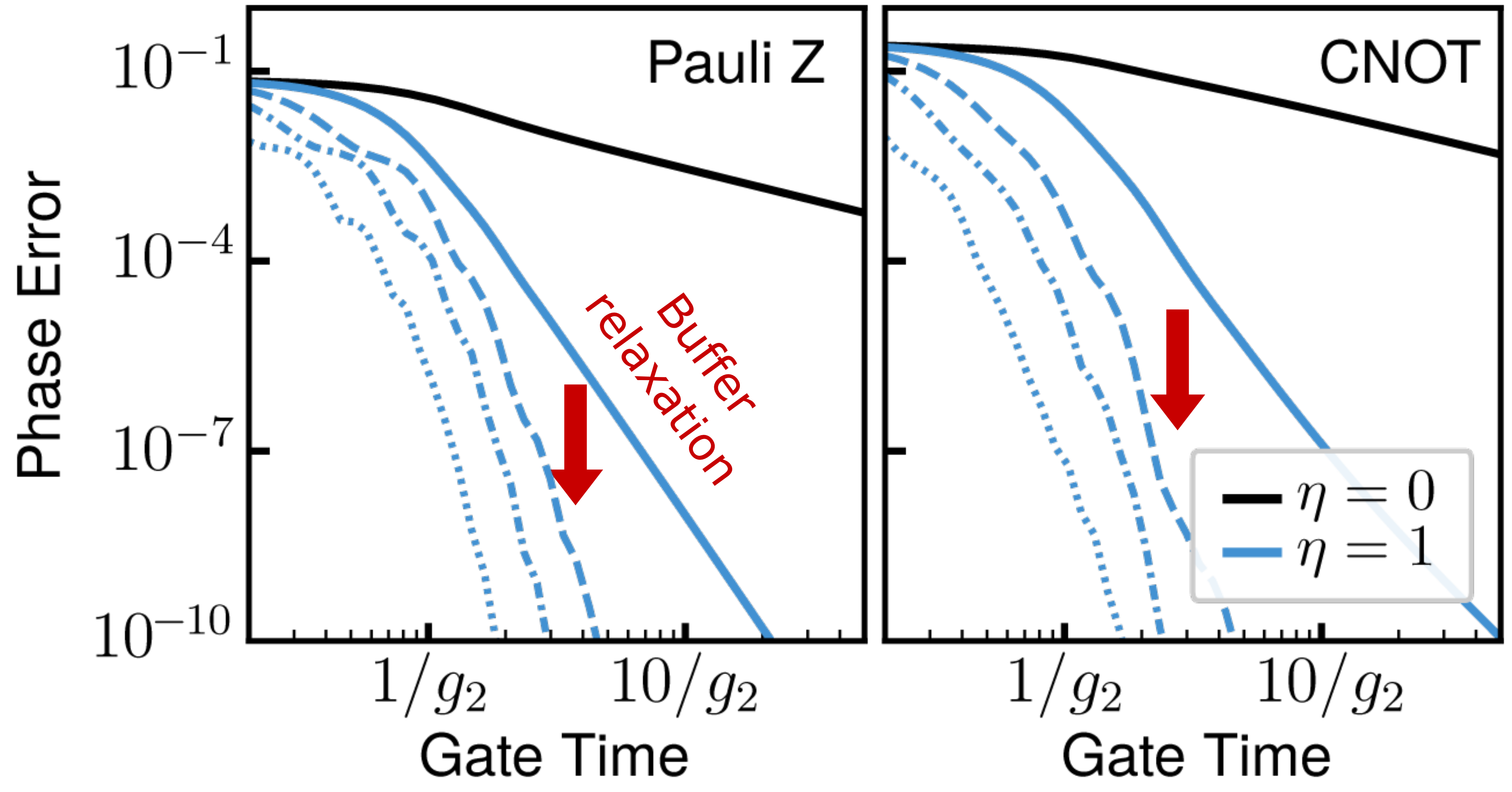
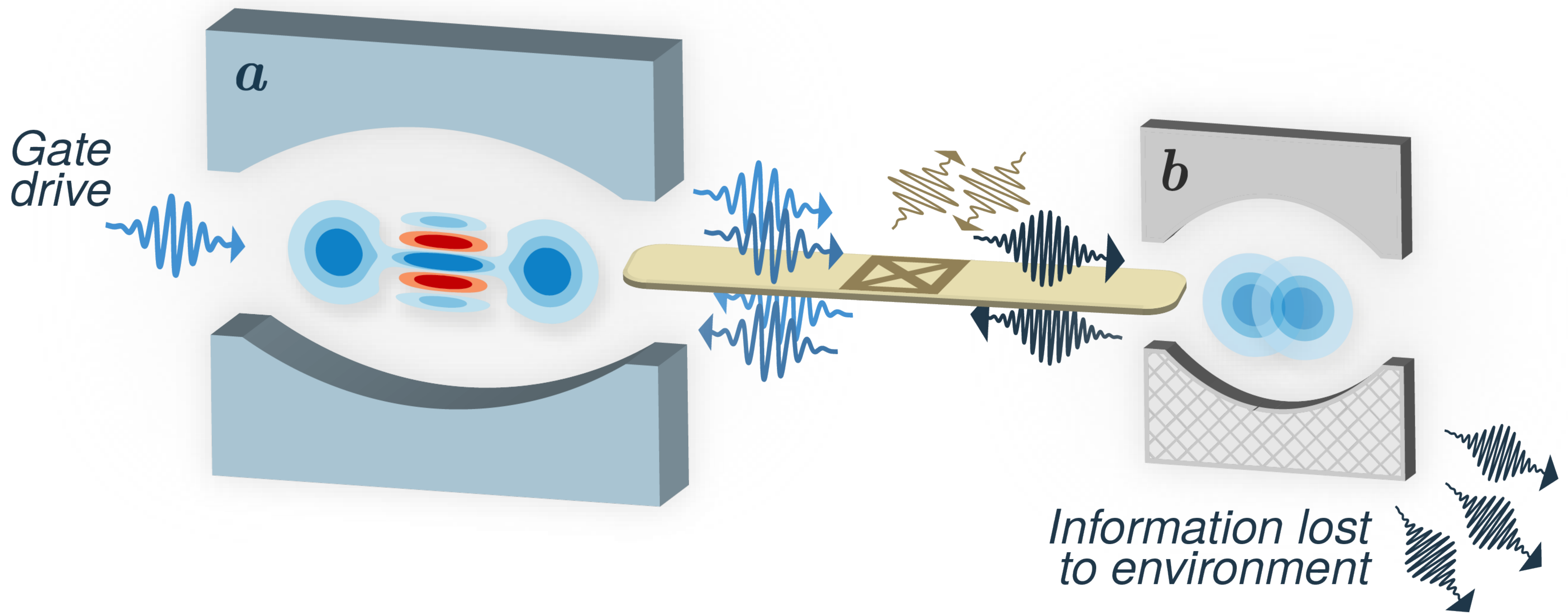


➡ Zeno scaling in 1/T

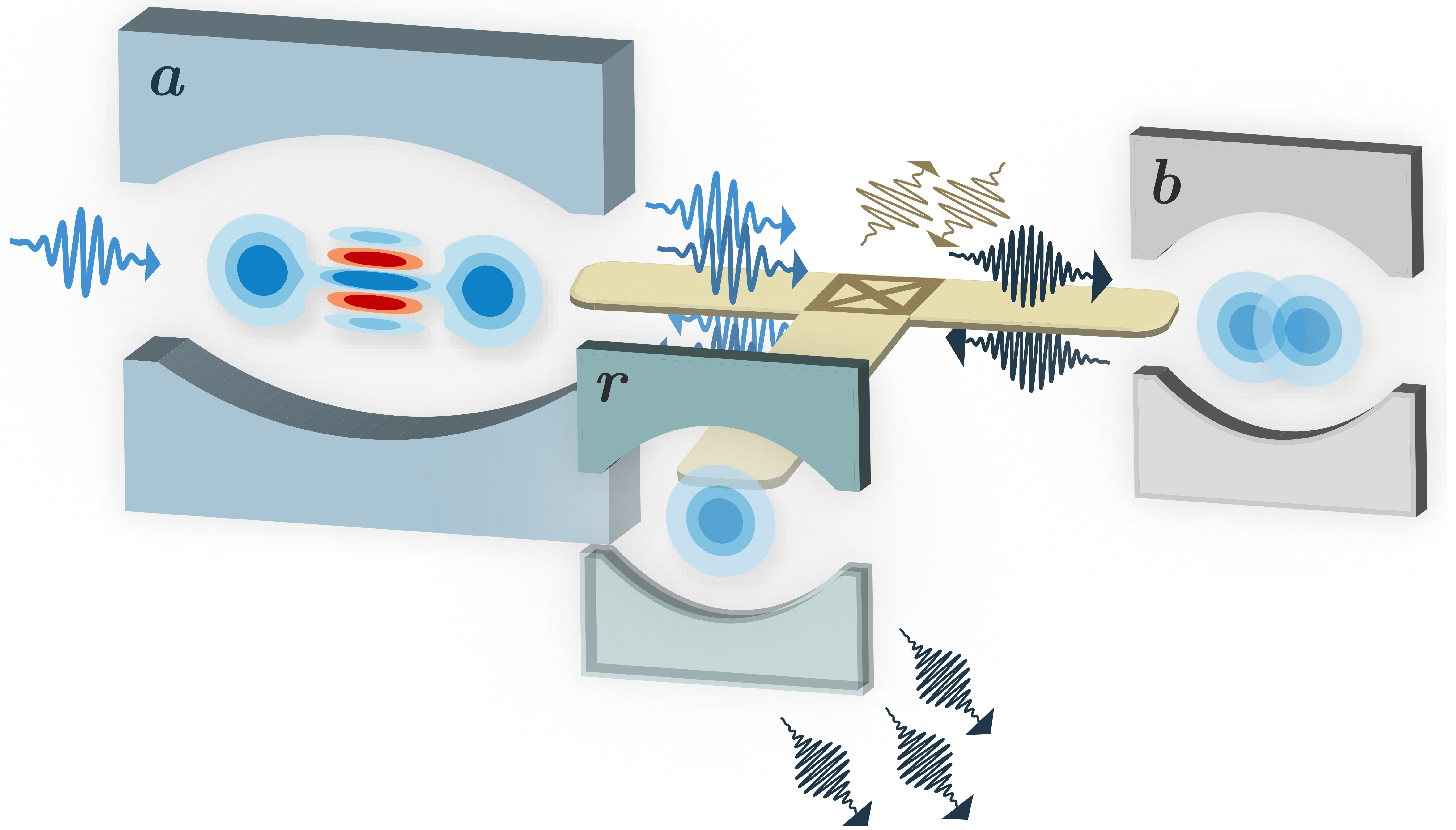
➡ High-order polynomial scaling

- Can apply feedback once per QEC cycle
- Gate fidelity limited by detection efficiency ➡ **Autonomous feedback**

Autonomous feedback



Autonomous feedback



Autonomous feedback

- Correlate buffer photon losses with parity-swaps on memory

$$\frac{d\rho}{dt} = -i[H_{AB} + H_Z, \rho] + \kappa_{ab}\mathcal{D}[ab]\rho$$

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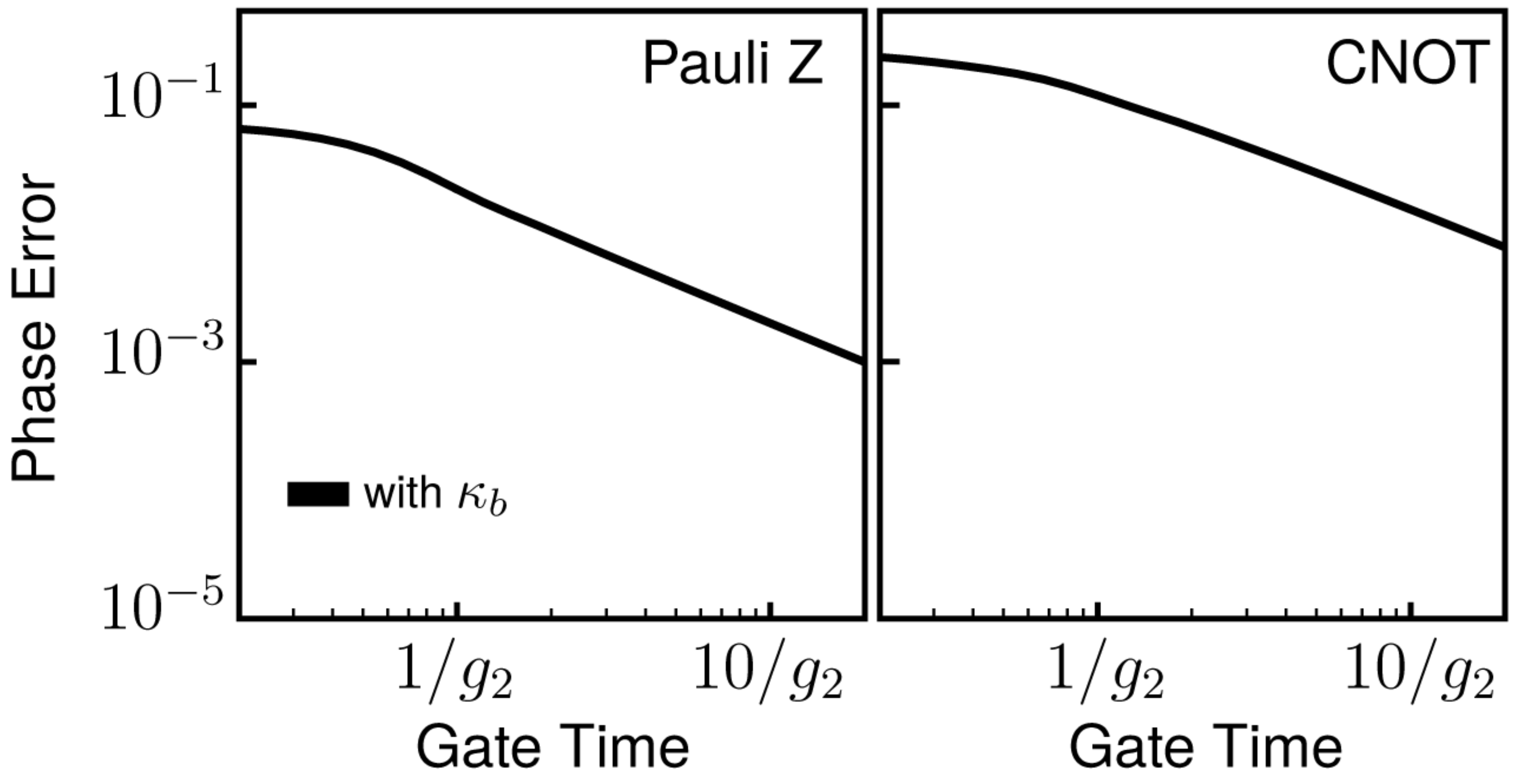

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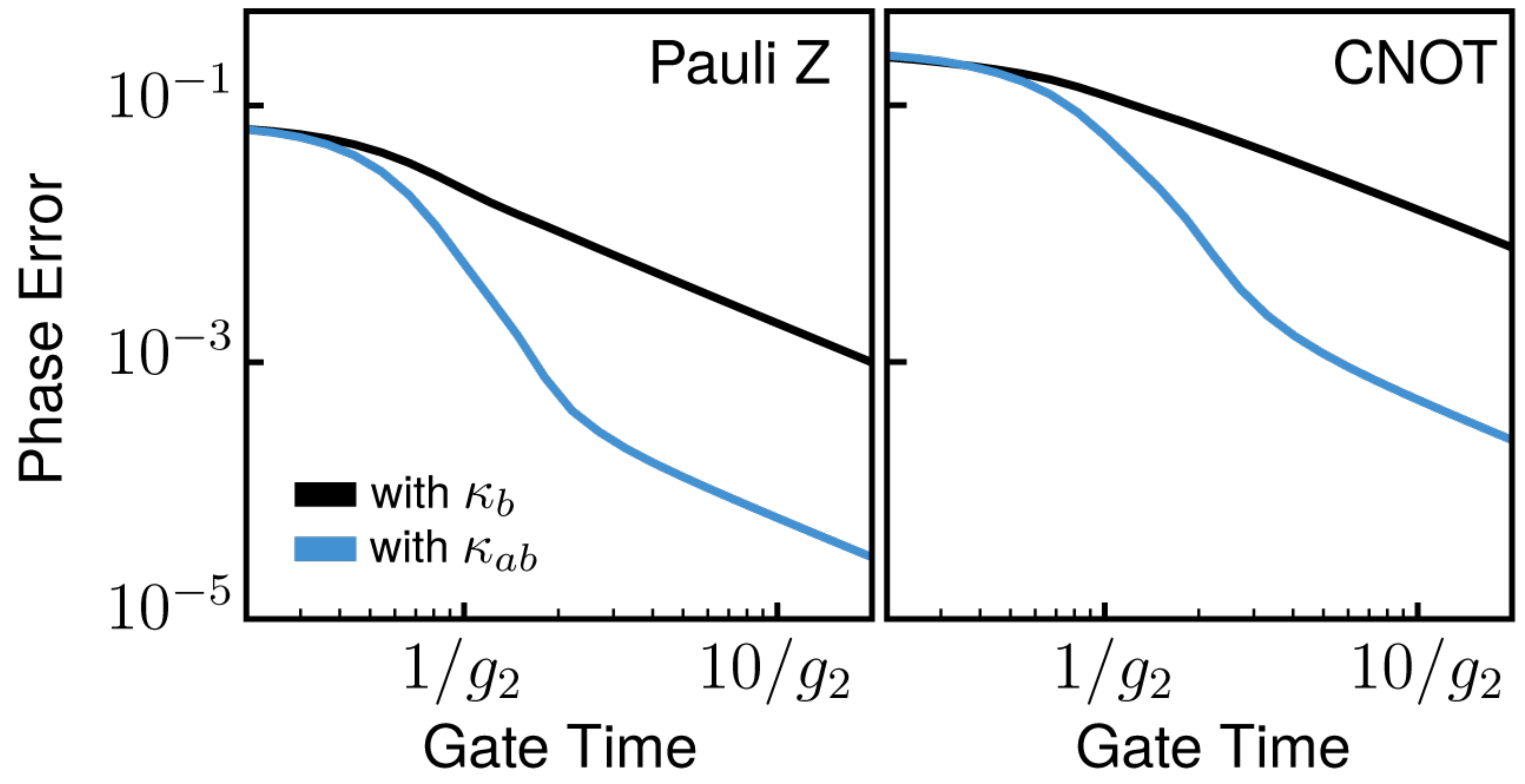

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$

Autonomous feedback

- Correlate buffer photon losses with parity-swaps on memory

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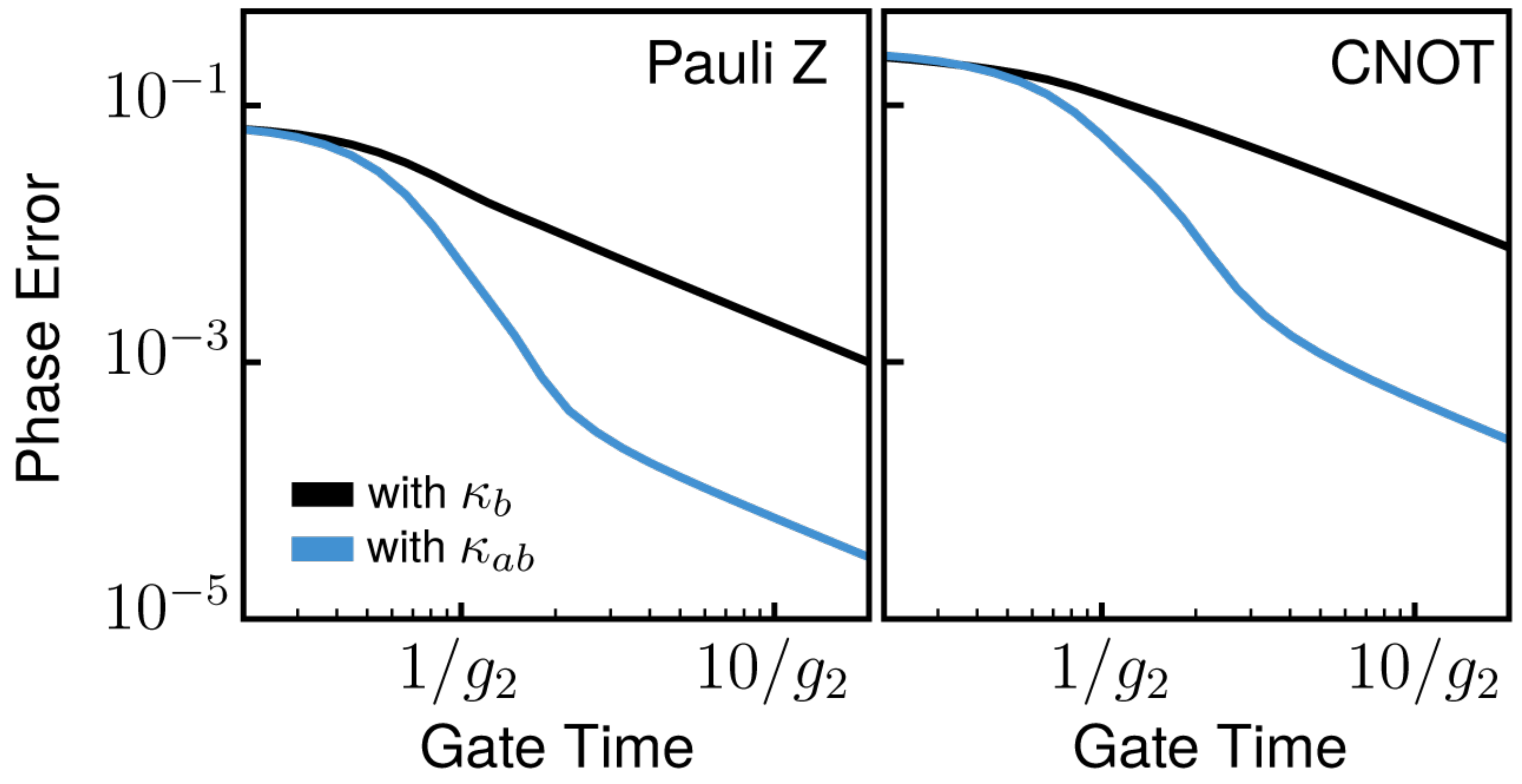

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^nX gate with no additional experimental overhead

Autonomous feedback

- Correlate buffer photon losses with parity-swaps on memory

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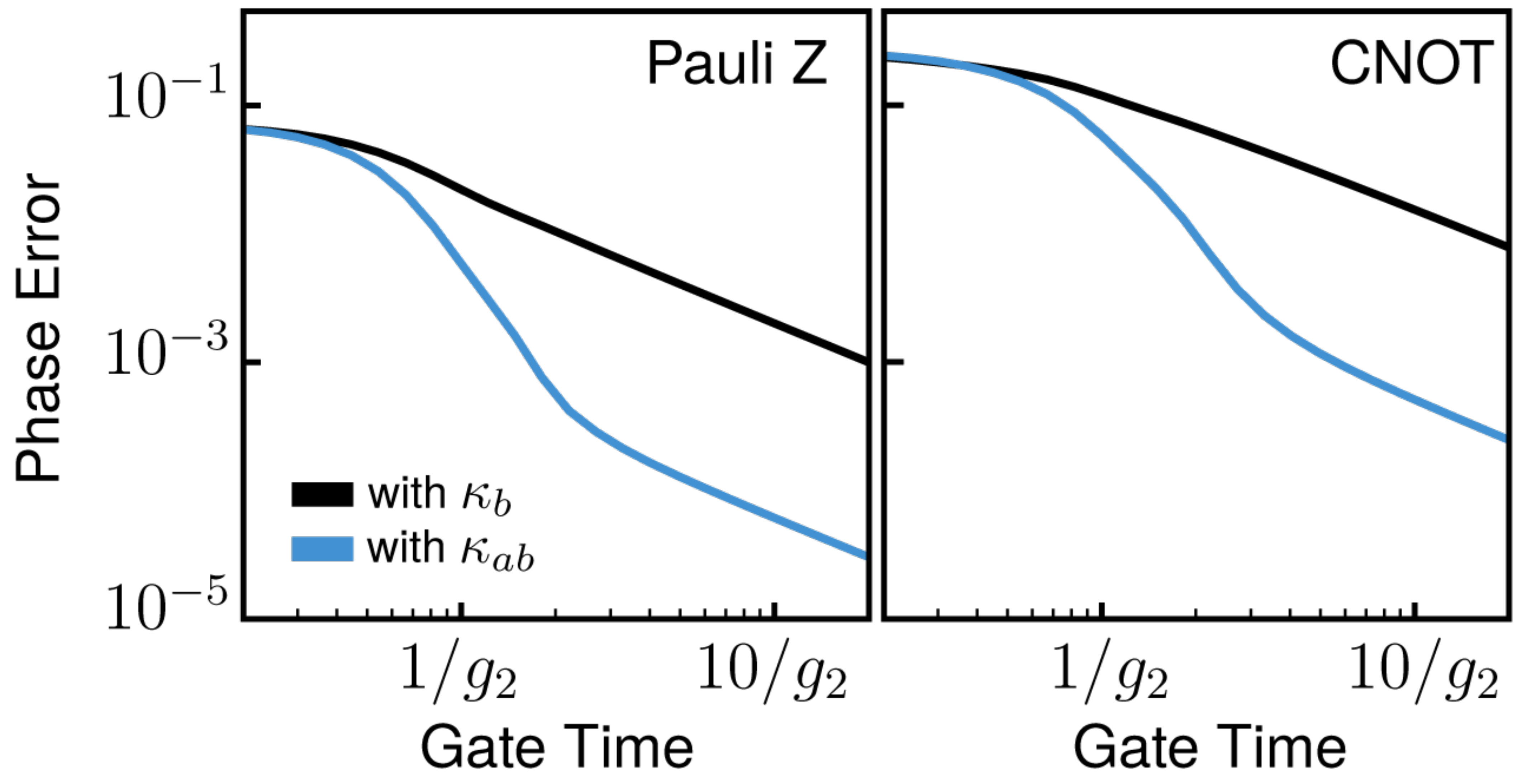

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^nX gate with no additional experimental overhead
- Autonomous correction of **cavity losses** with squeezed cats

Autonomous feedback

- Correlate buffer photon losses with parity-swaps on memory

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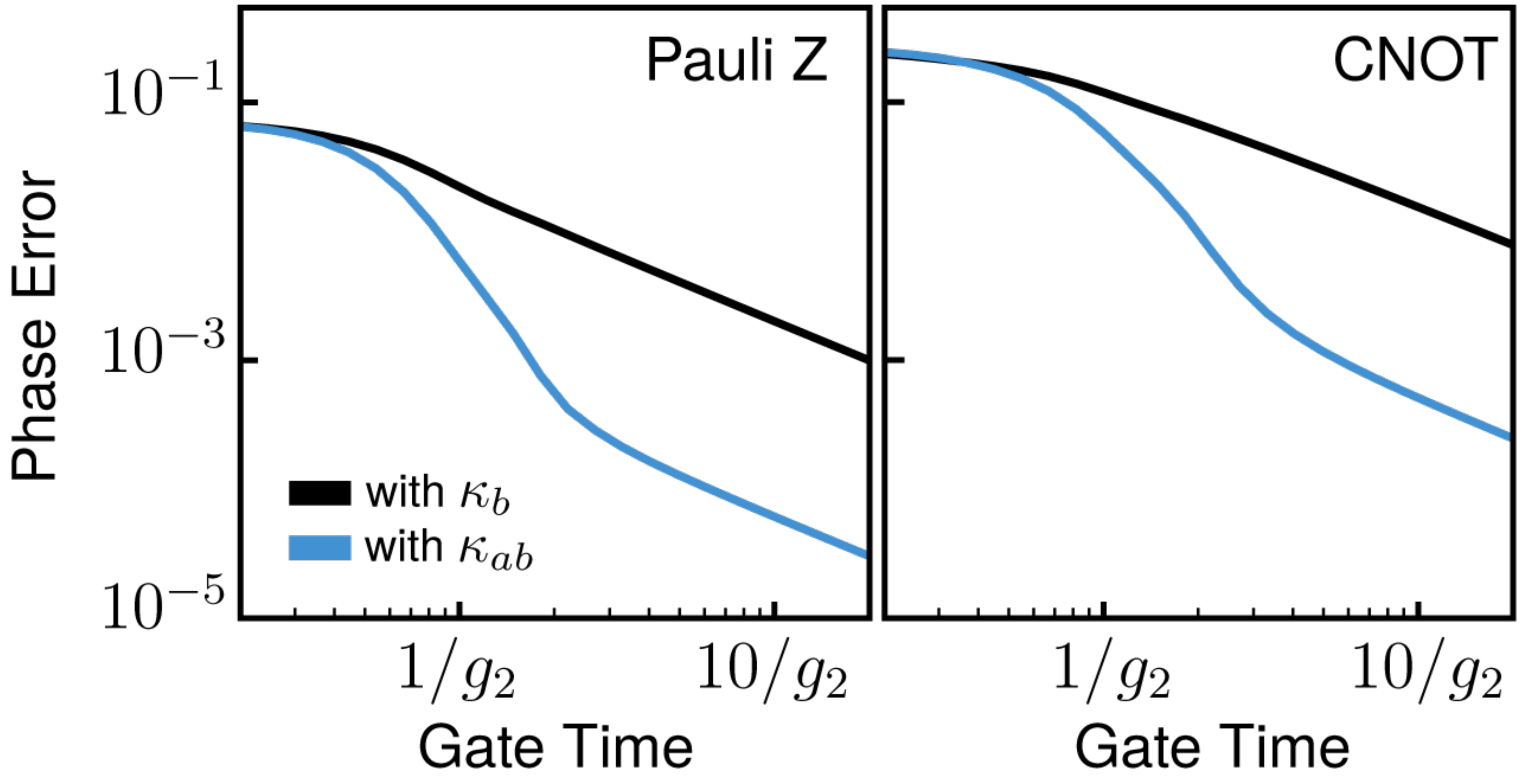

- **x50** gate fidelity improvement (limited by second-order effects), independent of $|\alpha|^2$
- Generalizable to any C^nX gate with no additional experimental overhead
- Autonomous correction of **cavity losses** with squeezed cats
- Can tune dissipation in situ

Summary of gate designs

Gautier et al. (2022)

		Hamiltonian $\boldsymbol{H}$	Dissipator $\mathcal{D}$	Gate Errors
Ref. [30, 37]	Standard Zeno	$\boldsymbol{H}_{AB} + \boldsymbol{H}_Z$	$\kappa_b \mathcal{D}[\boldsymbol{b}]$	$p_Z^{(0)} \equiv \frac{\pi^2}{16\lvert\alpha\rvert^4 T} \frac{\kappa_b}{4g_2^2}$
Ref. [50]	Combined dissipation and TPE Hamiltonian	$\boldsymbol{H}_{AB} + \boldsymbol{H}_Z + \boldsymbol{H}_{TPE}$ with $\boldsymbol{H}_{TPE} \equiv g_2'(\boldsymbol{a}^2 - \alpha^2)\boldsymbol{\sigma}_+ + \text{h.c.}$	$\kappa_b \mathcal{D}[\boldsymbol{b}]$	$p_Z = \frac{1}{1 + (2g_2'/\kappa_2)^2} p_Z^{(0)}$
Sec. V	Buffer photodetection with classical feedback	$\boldsymbol{H}_{AB} + \boldsymbol{H}_Z$	$\kappa_b \mathcal{D}[\boldsymbol{b}]$ (photodetected)	$p_Z \gtrsim (1-\eta) p_Z^{(0)}$ (detection efficiency η)
Sec. VI	Cat-buffer autonomous feedback	$\boldsymbol{H}_{AB} + \boldsymbol{H}_Z$	$\kappa_{ab} \mathcal{D}[\boldsymbol{ab}]$	$p_Z = \mu\, p_Z^{(0)}$ with $\mu \gtrsim 0.02$
Sec. VII	Locally flat Hamiltonian	$\boldsymbol{H}_{AB} + \boldsymbol{H}_{Z,N}$ with $\boldsymbol{H}_{Z,N} = \varepsilon_Z \sum_{n=0}^{N} c_n (\boldsymbol{a} + \boldsymbol{a}^\dagger)^{2n+1}$	$\kappa_b \mathcal{D}[\boldsymbol{b}]$	$p_Z = \nu \lvert\alpha\rvert^{-2N} p_Z^{(0)}$ with $\nu \sim 1$
Sec. VIII	Discrete jump	$\boldsymbol{H}_{AB}$	$\kappa_b \mathcal{D}[\boldsymbol{b}] + \kappa_Z \mathcal{D}[\boldsymbol{a}_\theta \boldsymbol{\sigma}_+]$	$p_Z = \exp\big(-\kappa_Z \lvert\alpha\rvert^2 T\big)$

High-Fidelity Control and stabilization of Cat Qubits

Work on cat qubits

- **RG**, A. Sarlette, M. Mirrahimi, *Combined dissipative and Hamiltonian confinement of cat qubits*, PRX Quantum (2021)
- D. Ruiz, **RG**, J. Guillaud, M. Mirrahimi, *Two-photon driven Kerr quantum oscillator with multiple spectral degeneracies*, Phys. Rev. A (2022)
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Work on optimal control of open quantum systems

- **RG**, É. Genois, A. Blais, *Optimal readout and reset of a transmon*, in preparation
- P. Guilmin, **RG**, A. Bocquet, É. Genois, *dynamiqs: an open-source library for GPU-accelerated and differentiable quantum simulation*, in preparation

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Thank you to all colleagues @ Inria, ENS, Alice & Bob, and Institut Quantique

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Université de Sherbrooke · ENS · MINES ParisTech · cnrs · Inria

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Supplementary slides

Quantum Optimal Control

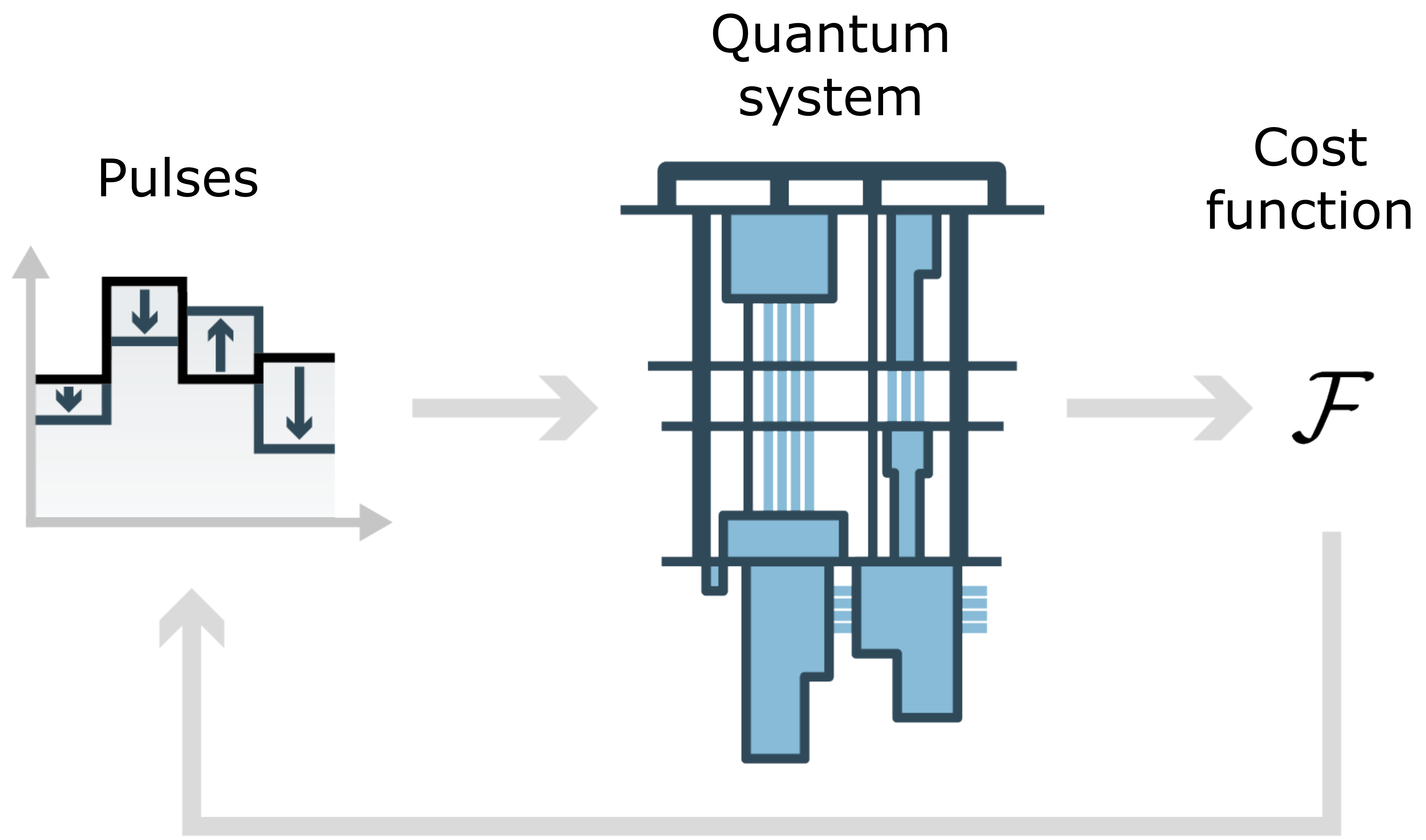
QOC Finding an optimal set of parameters for a given operation

Gradient-free

- DRAG
- Chopped Random Basis (CRAB)
- Nelder-Mead
- STIRAP
- Reinforcement Learning

Gradient-based

- Krotov
- GRAPE
- Automatic Differentiation
- Adjoint state



✓ Any closed or open system, any cost function, low memory overhead, fast

Optimal Control with Automatic Differentiation

Objective Minimize a cost function

$$C = C(\theta, \hat{\rho}(t_0), \ldots, \hat{\rho}(t_n))$$

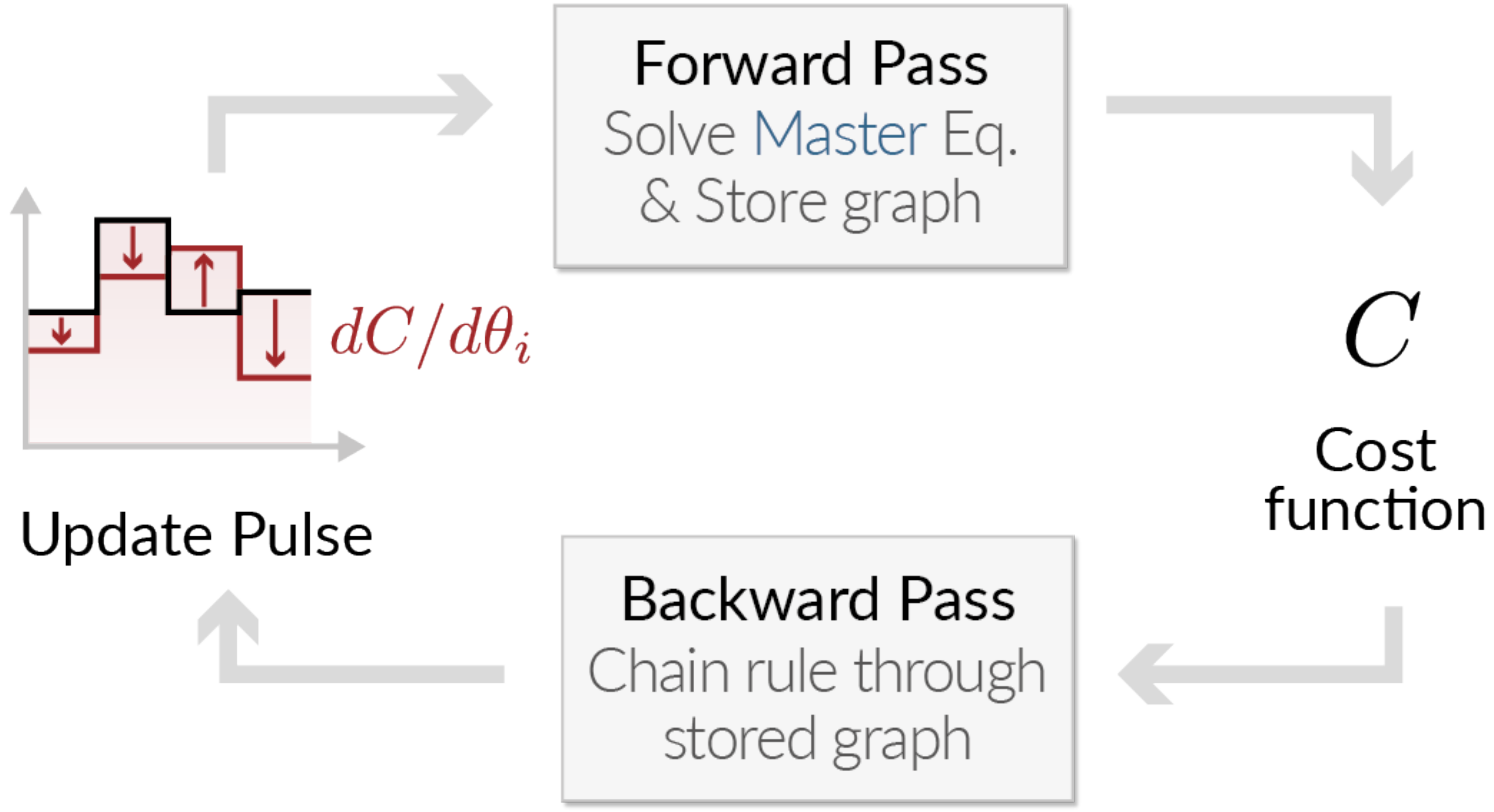
Master Equation

$$\frac{d\hat{\rho}}{dt} = \mathcal{L}\hat{\rho} \equiv -i[\hat{H}, \hat{\rho}] + \sum_k \mathcal{D}[\hat{L}_k]\hat{\rho}$$

Gradients

$$\frac{dC}{d\theta_i} = \frac{\partial C}{\partial \theta_i} + \sum_k \frac{\partial C}{\partial \hat{\rho}(t_k)} \frac{d\hat{\rho}(t_k)}{d\theta_i}$$

- Store graph of operations
- Backward through graph using chain rule



Memory overhead in $\mathcal{O}(N_t \times N^2)$

Transmon readout → $N_t \sim 10^4$, $N \sim 1000$ → $\sim 1,16\,\mathrm{TB}$

Adjoint State Quantum Optimal Control

Objective Minimize a cost function

$$C = C(\theta, \hat{\rho}(t_0), ..., \hat{\rho}(t_n))$$

Master Equation

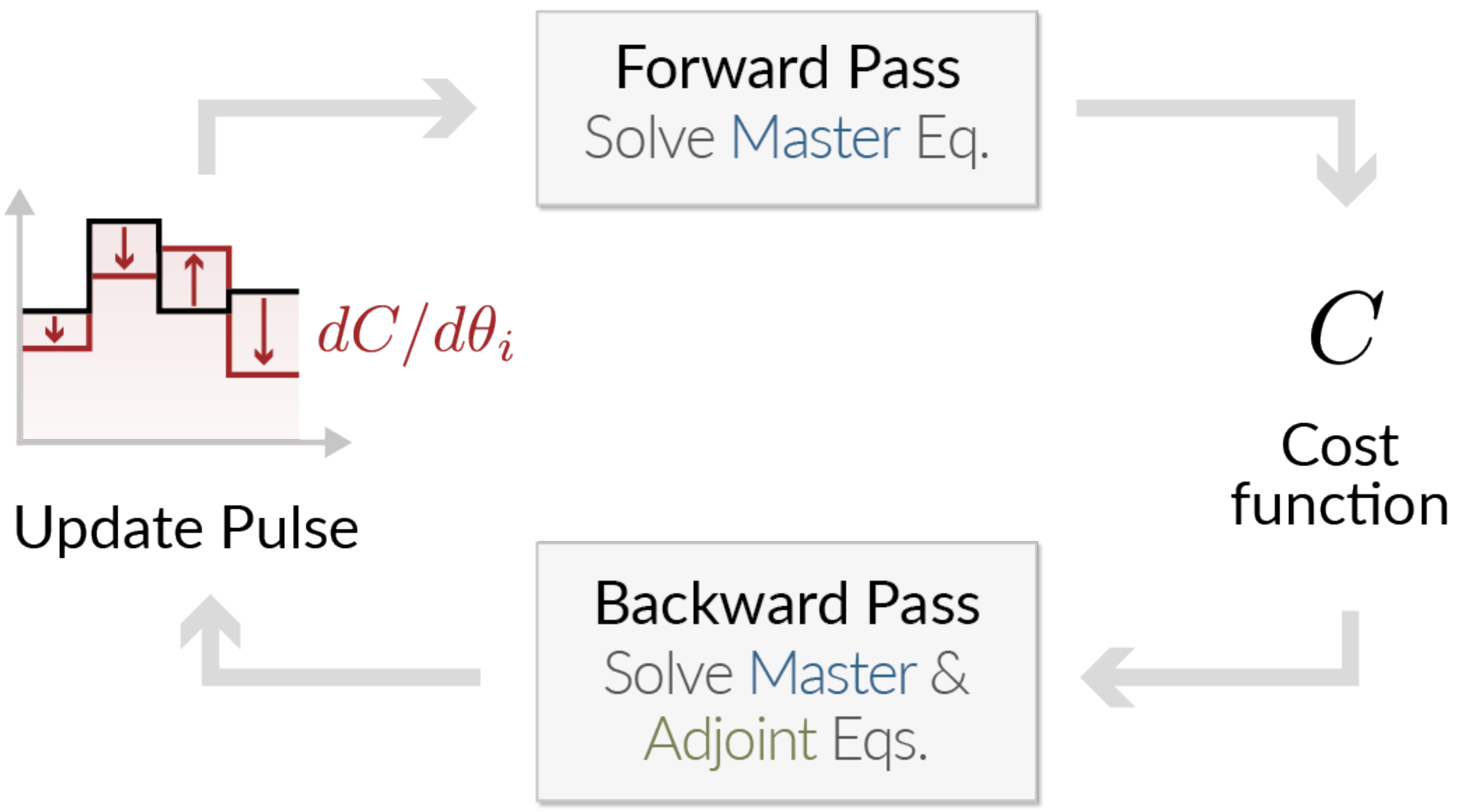
$$\frac{d\hat{\rho}}{dt} = \mathcal{L}\hat{\rho} \equiv -i[\hat{H}, \hat{\rho}] + \sum_k \mathcal{D}[\hat{L}_k]\hat{\rho}$$

Adjoint state $\hat{\phi}(t) = dC/d\hat{\rho}(t)$

$$\frac{d\hat{\phi}}{dt} = -\mathcal{L}^\dagger\hat{\phi} \equiv -i[\hat{H}, \hat{\phi}] - \sum_k \mathcal{D}^\dagger[\hat{L}_k]\hat{\phi}$$

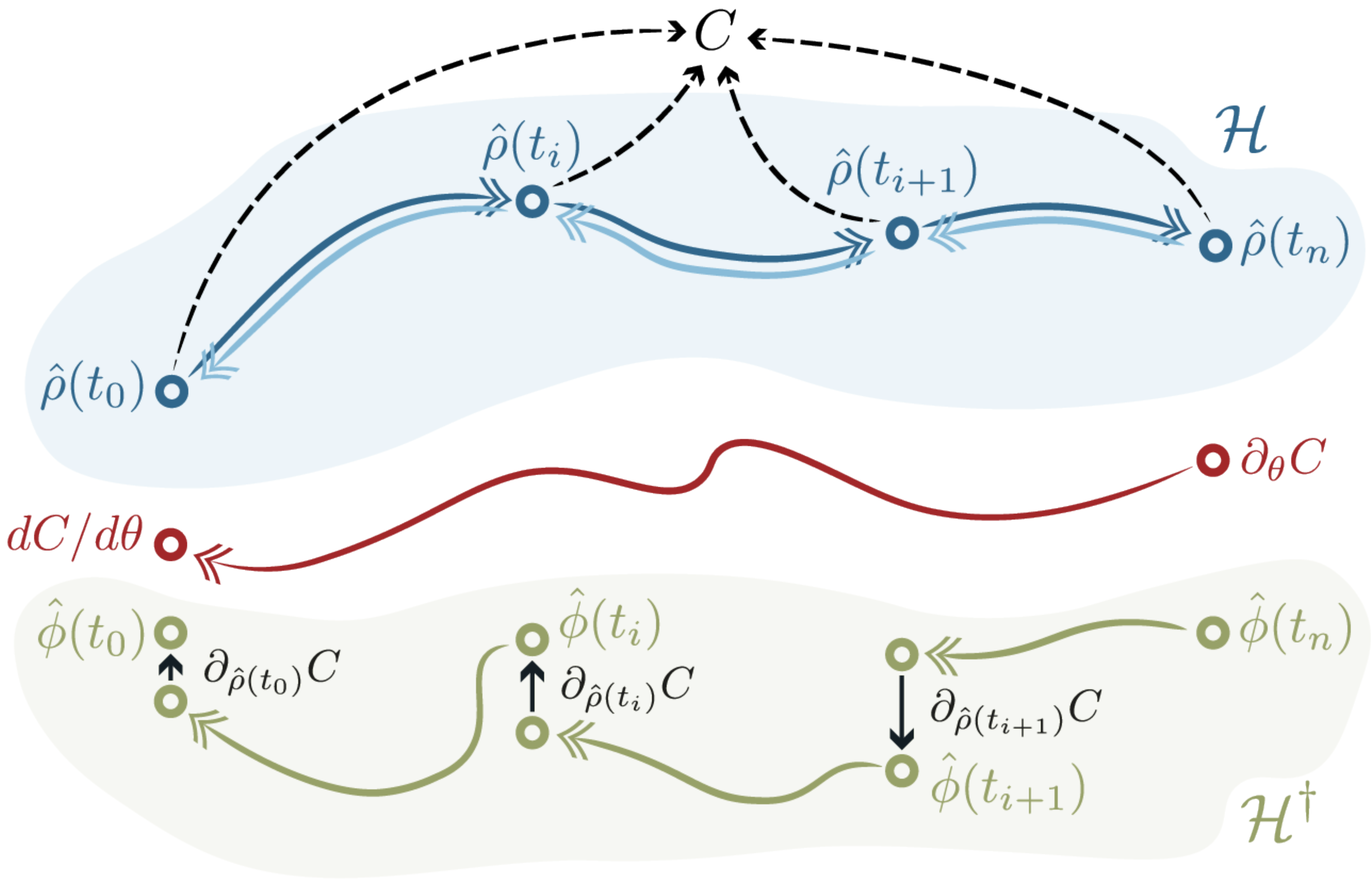
Gradients

$$\frac{dC}{d\theta} = \frac{\partial C}{\partial \theta} - \int_{t_n}^{t_0} \partial_\theta \,\mathrm{Tr}\left[\hat{\phi}^\dagger(t)\mathcal{L}(t,\theta)\hat{\rho}(t)\right] dt$$



Pontryagin (1961), Chen et al., NeurIPS (2018)

Adjoint State Quantum Optimal Control



Adjoint State Quantum Optimal Control

Objective Minimize a cost function

$$C = C(\theta, \hat{\rho}(t_0), ..., \hat{\rho}(t_n))$$

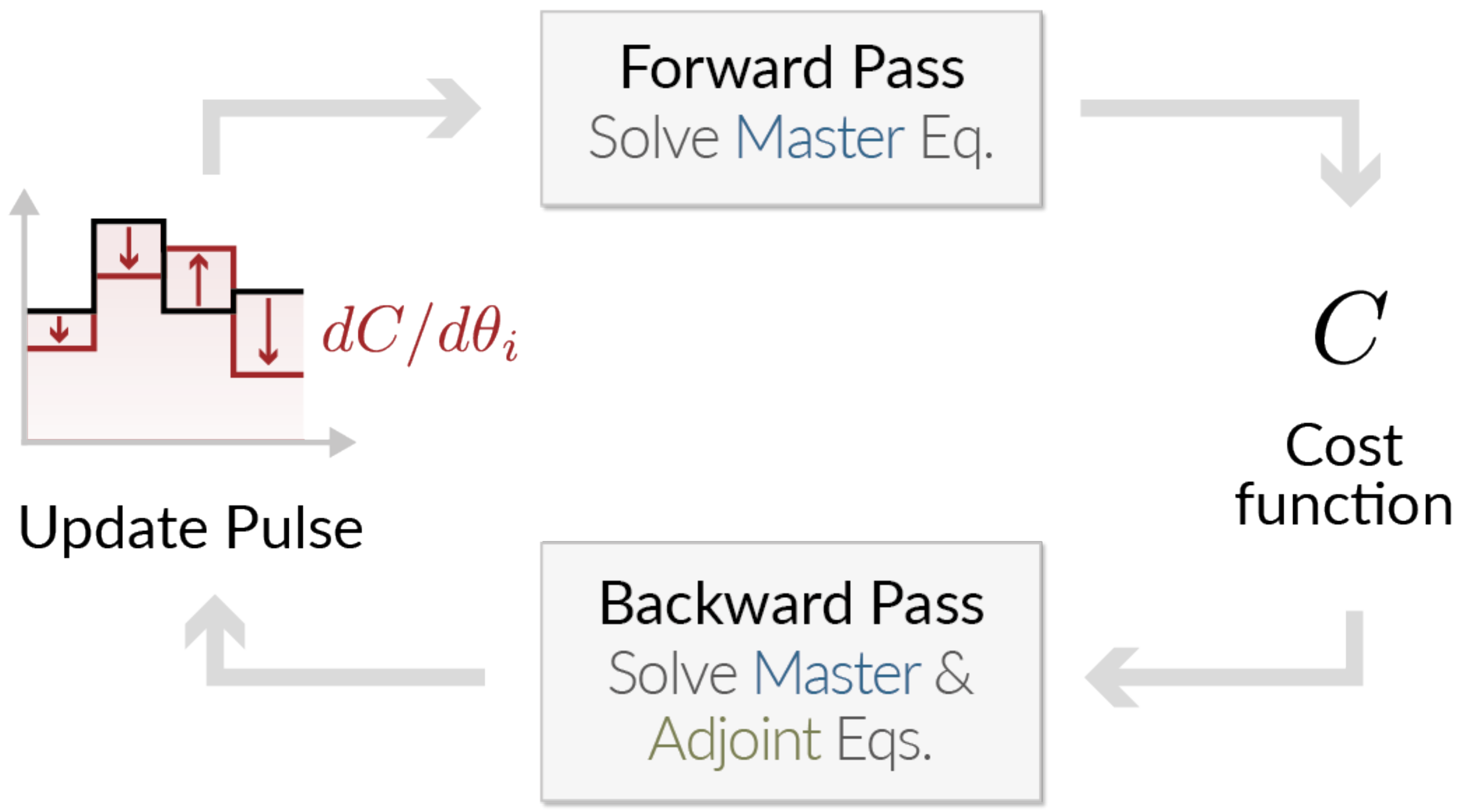
Gradient descent

- Adam
- Stochastic Gradient Descent
- L-FBGS

Space-time costs

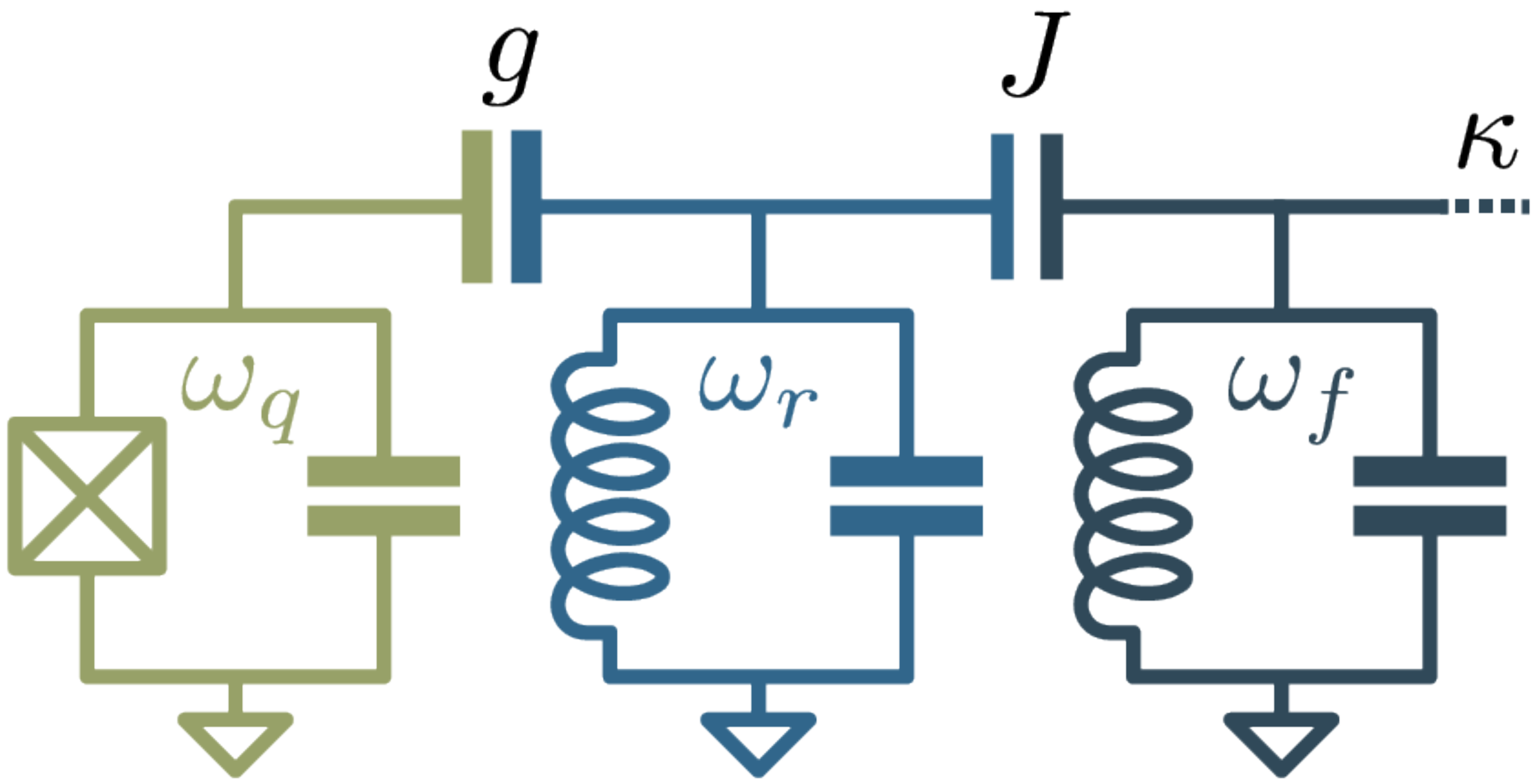
- Memory cost $\mathcal{O}(N_{cp} \times N^2)$
- Time cost $\mathcal{O}(4T_{\mathrm{ME}})$
- Can trade memory for numerical stability

Demonstration on transmon readout & reset



Transmon-resonator-filter model

$$\hat{H} = 4E_C\hat{n}_t^2 - E_J\cos(\hat{\varphi}_t) + \omega_r\hat{a}^\dagger\hat{a} + \omega_f\hat{f}^\dagger\hat{f} + ig\hat{n}_t(\hat{a}^\dagger - \hat{a}) + J(\hat{f}^\dagger\hat{a} + \hat{a}^\dagger\hat{f})$$



$E_J/2\pi = 16\,\text{GHz}$

$E_c/2\pi = 315\,\text{MHz}$

$E_J/E_c \approx 51$

$\omega_t/2\pi = 6\,\text{GHz}$

$\omega_r/2\pi = 7.2\,\text{GHz}$

$\omega_p/2\pi = 7.21\,\text{GHz}$

$g/2\pi = 150\,\text{MHz}$

$J/2\pi = 30\,\text{MHz}$

$\kappa_p/2\pi = 30\,\text{MHz}$

$\kappa_q/2\pi = 8\,\text{KHz}$

$\bar{n}_{\text{crit}} = 16$

Readout Drive Purcell filter $\Omega_f(t)\hat{f}^\dagger + \Omega_f(t)^*\hat{f}$

f0g1 reset Drive transmon f0-g1 and e-f transitions $\Omega_{f0g1}(t)\hat{n}_t + \Omega_{ef}(t)\hat{n}_t$

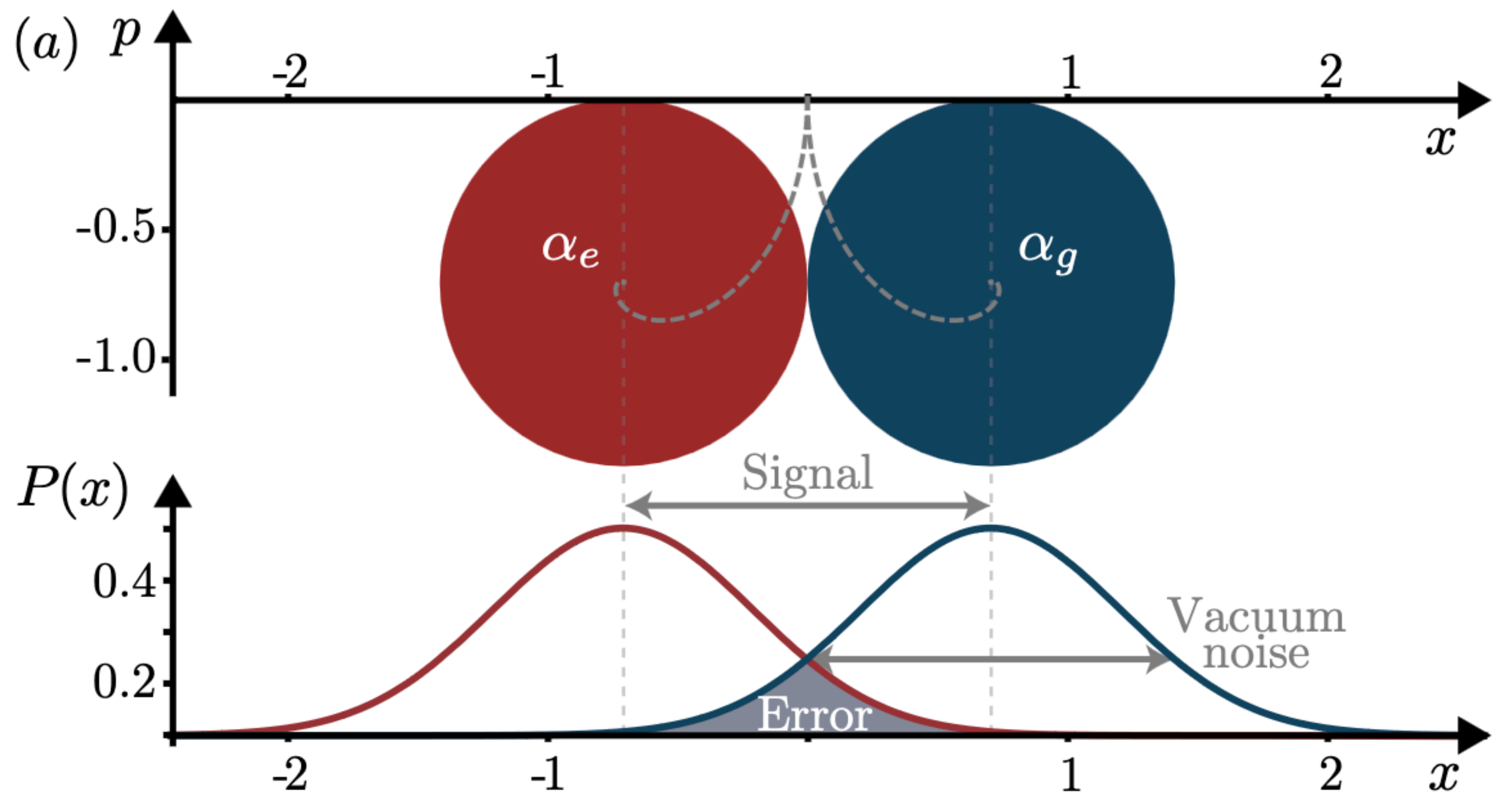
Optimizing readout

Objective Maximize SNR in shortest time

Cost function

$$\mathrm{SNR} = \sqrt{2\kappa\eta \int_0^T |\beta_e - \beta_g|^2 dt}$$

(from Bultink et al., APL 2018)



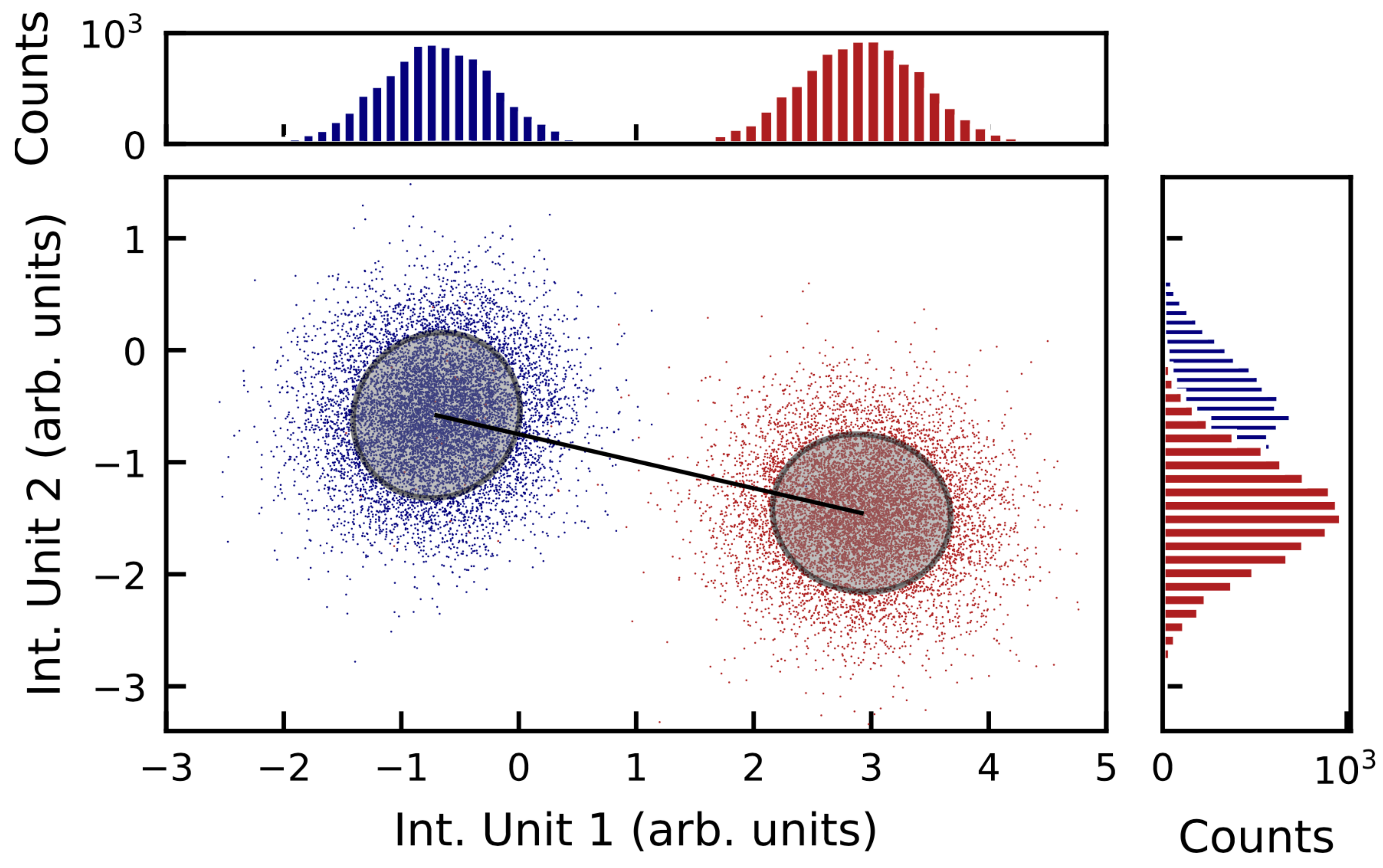
(from Blais et al., RMP 2020)

Parameters

- Pulses (1ns bins, continuous filter)
- Drive frequencies

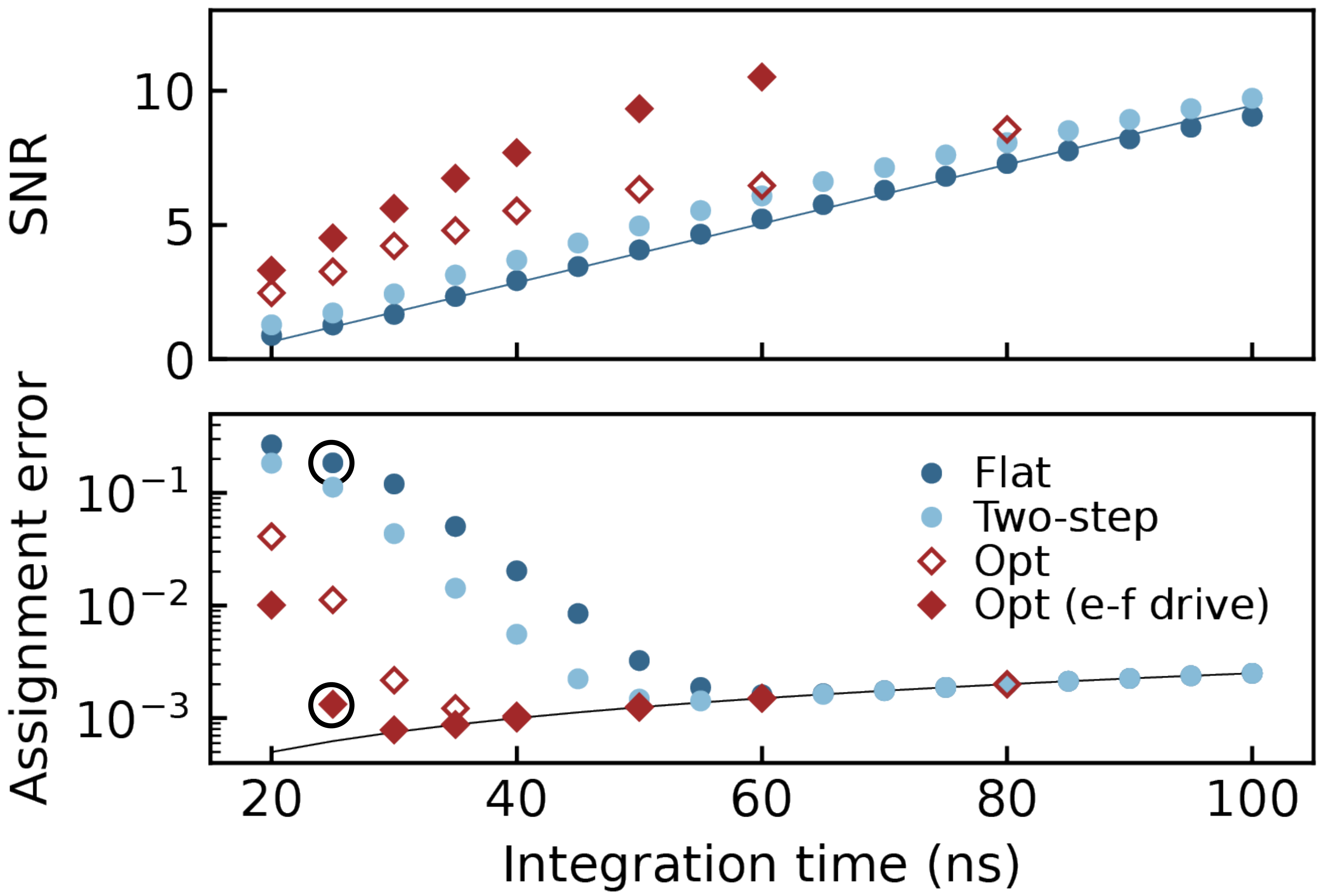
Other costs

- Resonator population < $\bar{n}_{\mathrm{crit}}$
- Forbidden resonator states
- Maximum pulse amplitudes



(from Swiadek et al., in prep.)

Optimizing readout - Preliminary results



Signal-to-Noise Ratio

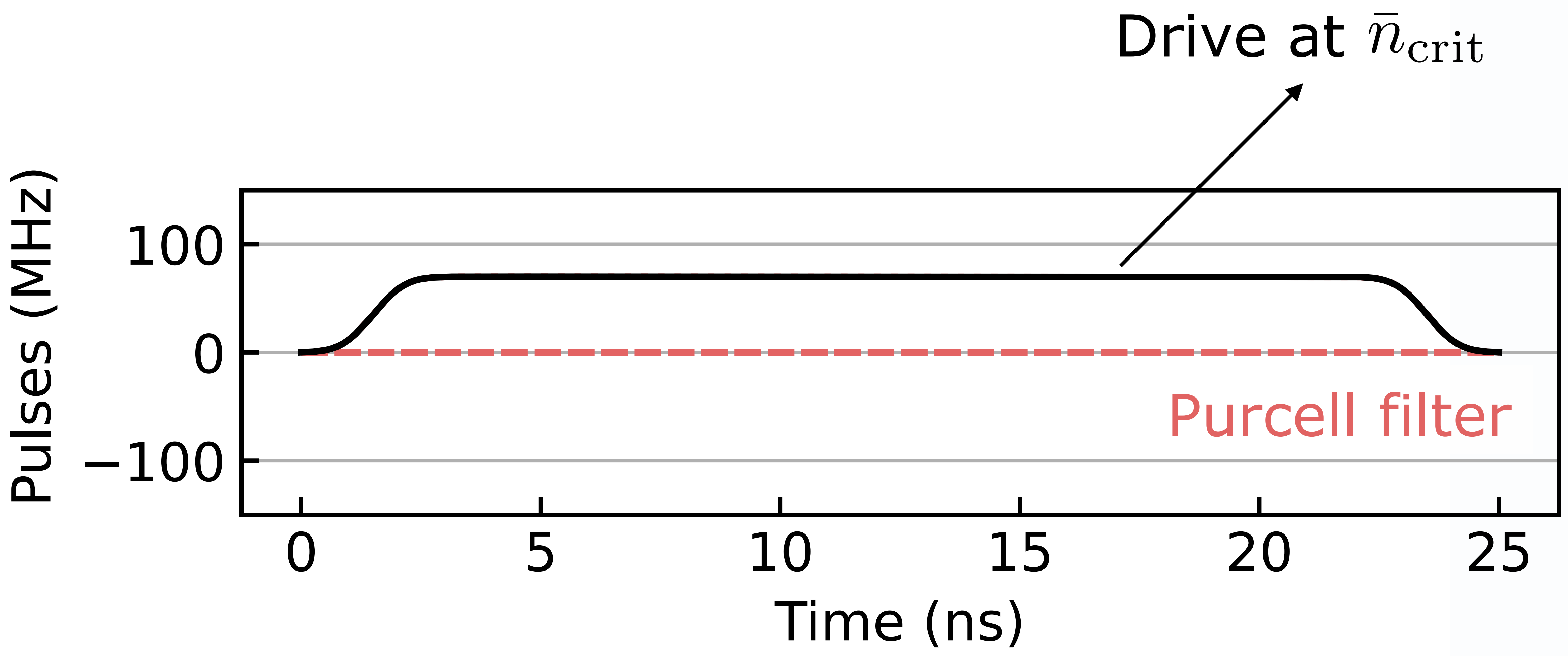
$$\mathrm{SNR} = \sqrt{2\kappa\eta \int_0^T |\beta_e - \beta_g|^2 dt}$$

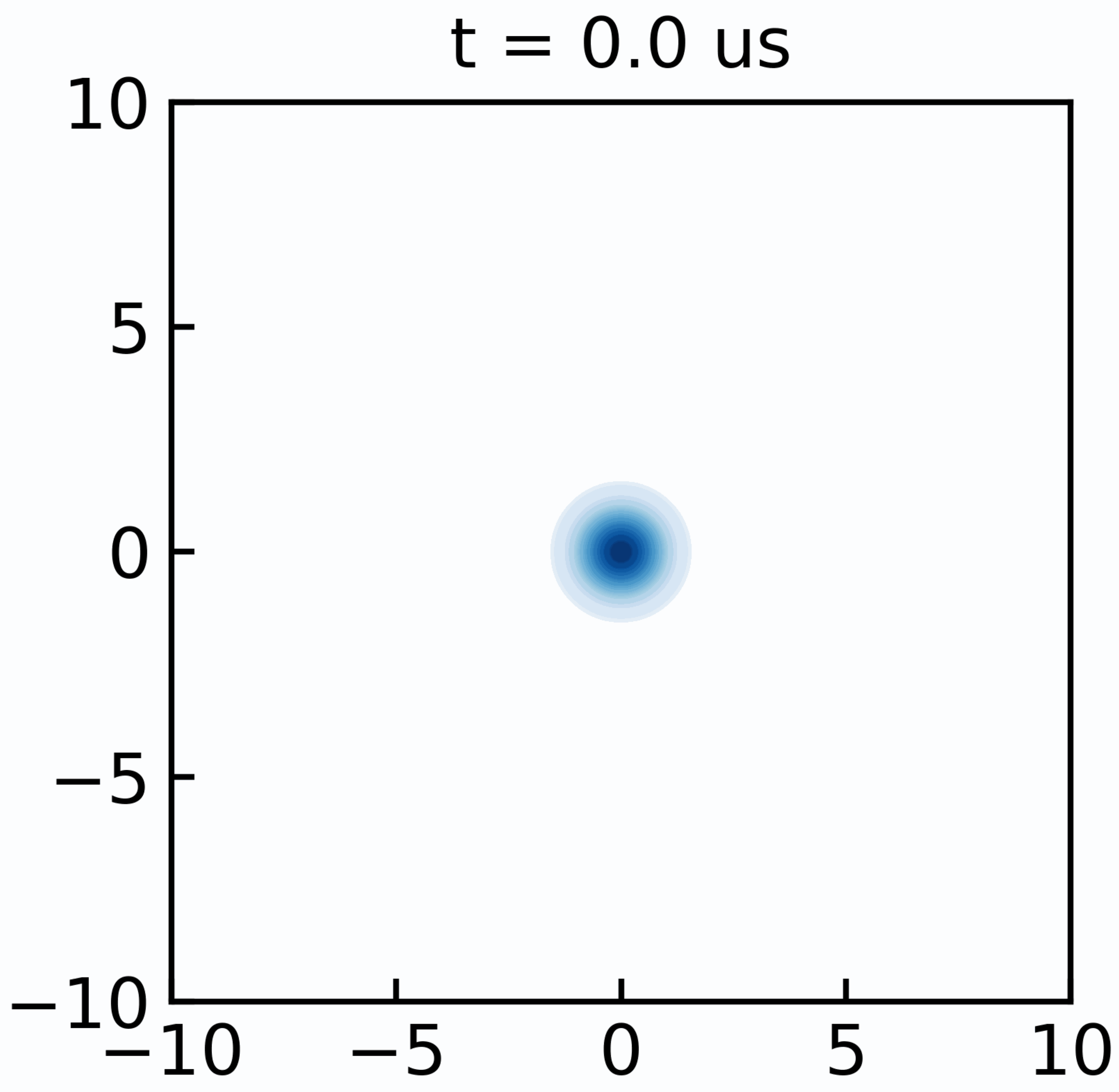
Assignment error

$$\varepsilon_a = \frac{1}{2}\left(P(e|g) + P(g|e)\right]$$
$$\sim \frac{1}{2}\left(1 - \mathrm{erf}(\mathrm{SNR}/2) + \tau/T_1\right)$$

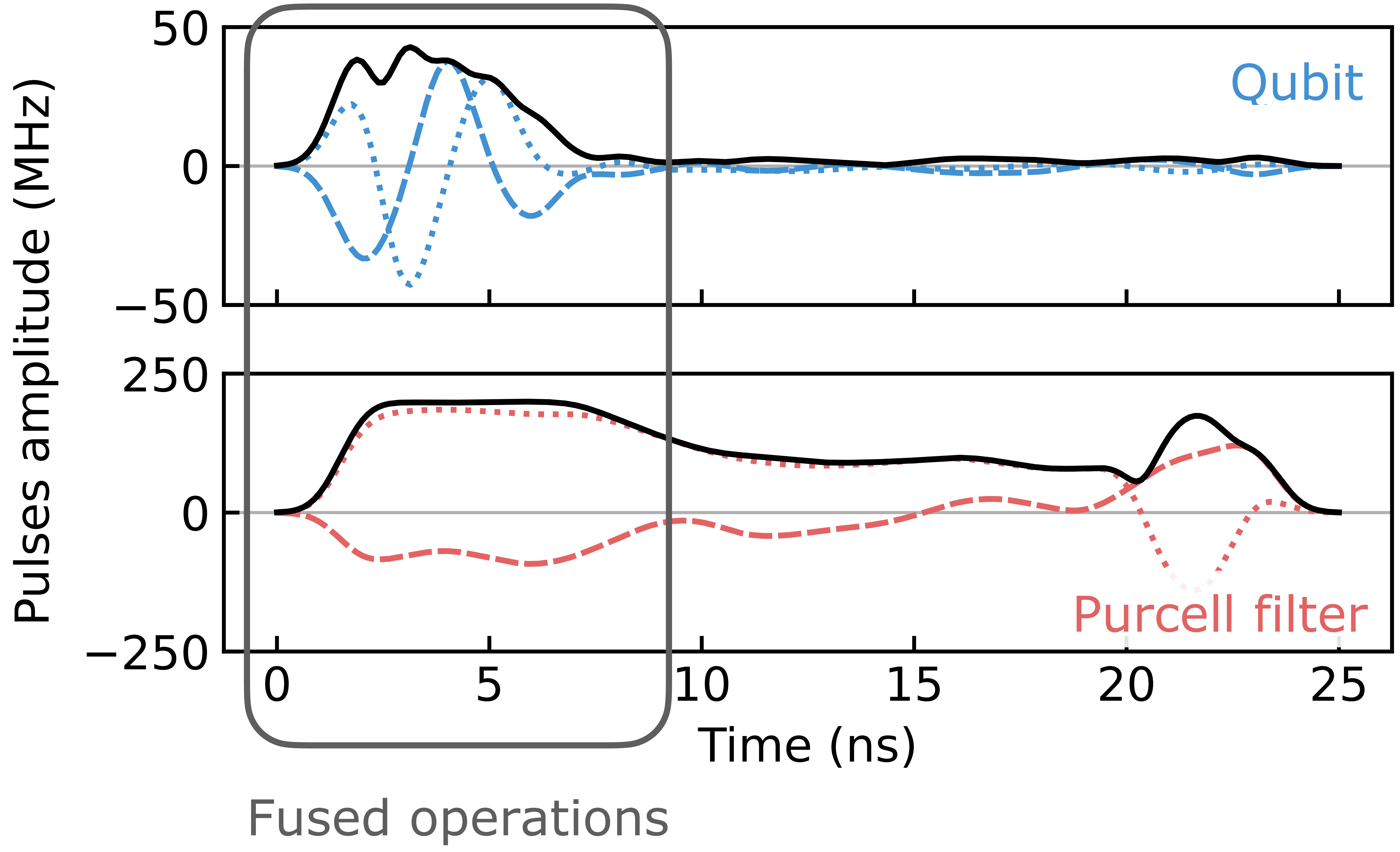
~55ns to ~30ns !

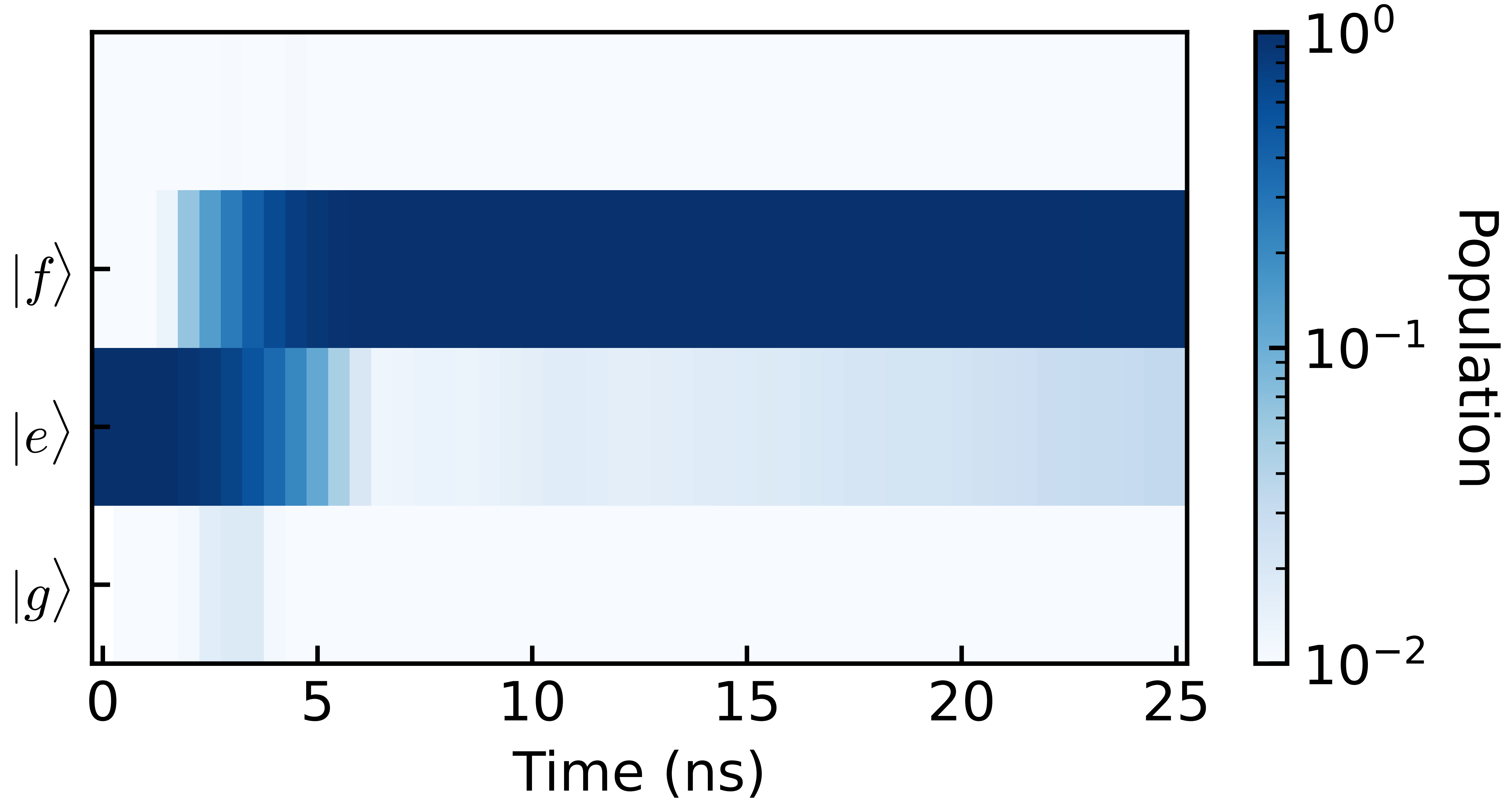
Optimizing readout - Flat readout



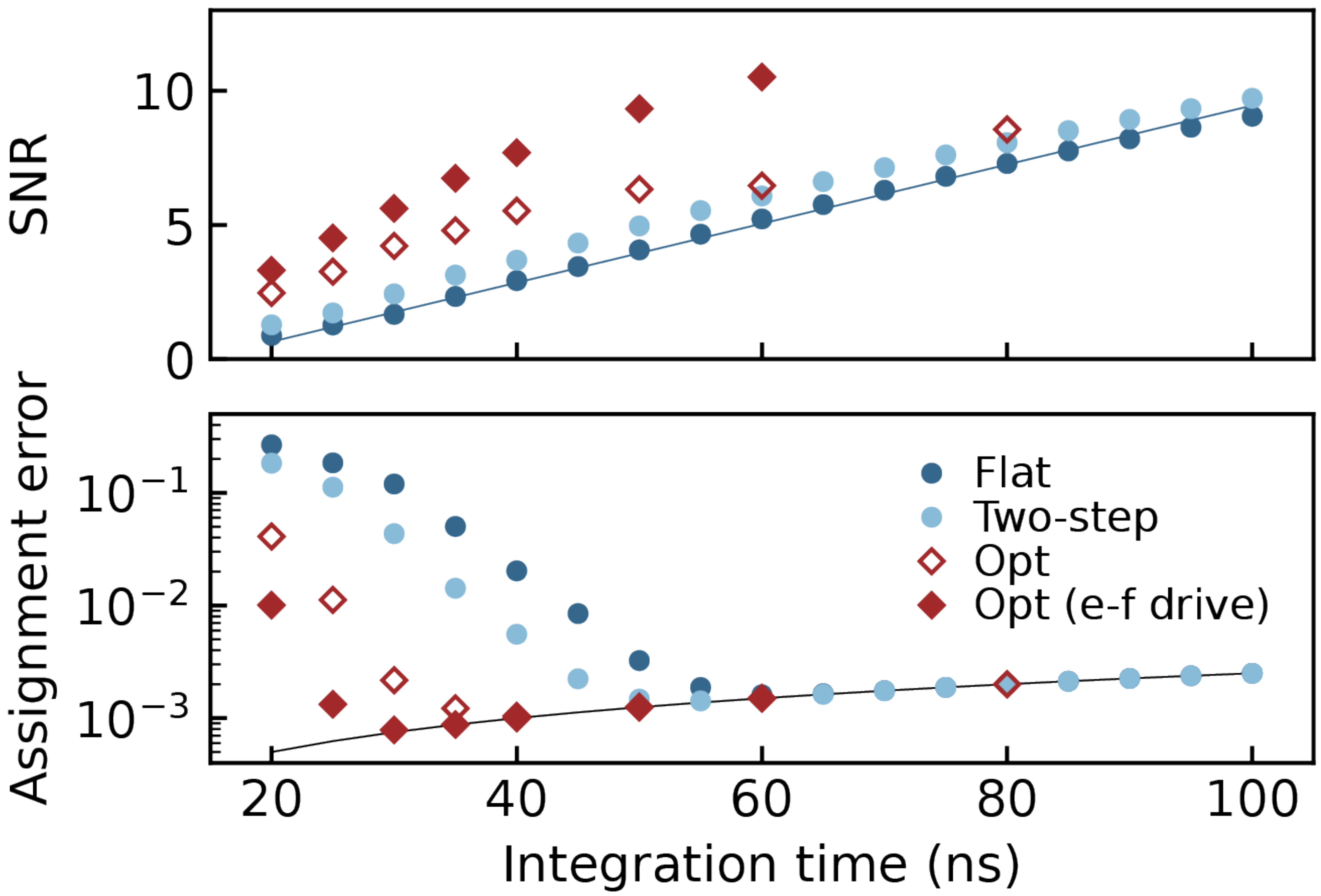


Optimizing readout - Preliminary results





Optimizing readout - Preliminary results



Signal-to-Noise Ratio

$$\mathrm{SNR} = \sqrt{2\kappa\eta \int_0^T |\beta_e - \beta_g|^2 dt}$$

Assignment error

$$\varepsilon_a = \frac{1}{2}\left(P(e|g) + P(g|e)\right] \\ \sim \frac{1}{2}\left(1 - \mathrm{erf}(\mathrm{SNR}/2) + \tau/T_1\right)$$

~55ns to ~30ns !

A library for efficient differentiable solvers

Differentiable solvers with PyTorch

- Solve SE, ME and SME
- Gradients with automatic or adjoint differentiation

Features

- GPU & CPU support
- Supports batching for density matrices & Hamiltonians
- Useful for optimal control, parameter estimation, state tomography…
- Many solvers (Dormand-Prince 5, Rouchon 1&2, Explicit exponentiation,…)

Open-source @ *github.com/dynamiqs/dynamiqs*

Co-developed with Pierre Guilmin, Adrien Bocquet & Élie Genois

dynamiqs

The dynamiqs library

(1) Works as a drop-in replacement to QuTiP

```python
import qutip as qt
import dynamiqs as dq

# parameters
N = 32
delta = 4.0
kappa = 0.1
alpha = 2.0j

# operators
a = qt.destroy(N)
H = delta * a.dag() * a
L = sqrt(kappa) * a

# mesolve arguments
rho0 = qt.coherent_dm(N, alpha)
tsave = np.linspace(0.0, 1.0, 11)

# solve ME
rhos, _ = dq.mesolve(H, L, rho0, tsave)
```

(2) Compute gradients in a few lines

```python
import torch
import dynamiqs as dq

# parameters
N = 32
delta = torch.tensor(4.0, requires_grad=True)
kappa = torch.tensor(0.1)
alpha = torch.tensor(2.0j, requires_grad=True)

# operators
a, adag = dq.destroy(N), dq.create(N)
H = delta * adag @ a
L = sqrt(kappa) * a

# mesolve arguments
rho0 = dq.coherent_dm(N, alpha)
tsave = torch.linspace(0.0, 1.0, 11)

# solve ME
rhos, _ = dq.mesolve(H, L, rho0, tsave)

# compute gradient of some loss
loss = dq.expect(adag @ a, rhos[-1])
loss.backward()
```