Inria — INVENTEURS DU MONDE NUMÉRIQUE | LPENS — LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE | MINES ParisTech | PSL

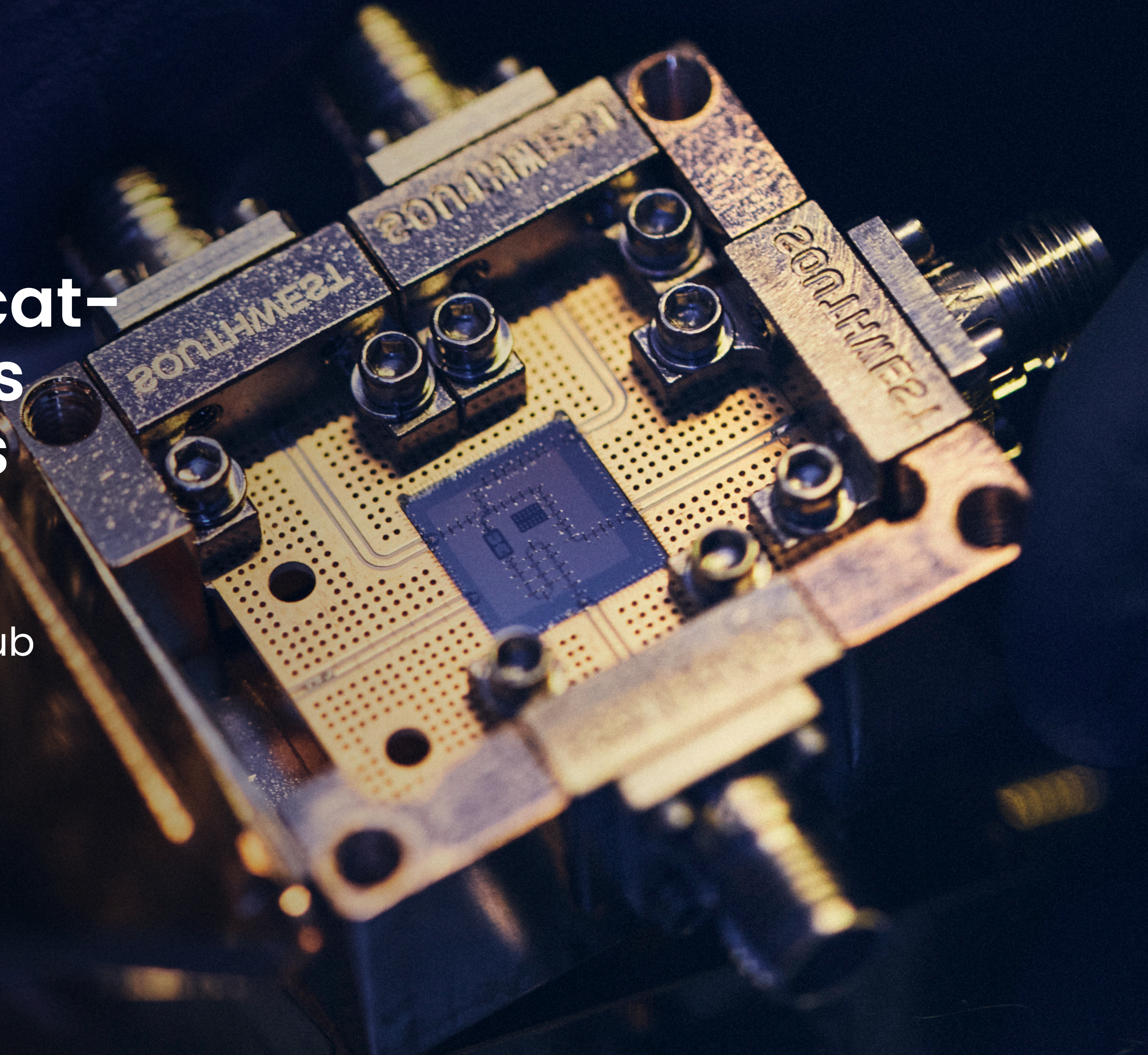
ALICE & BOB

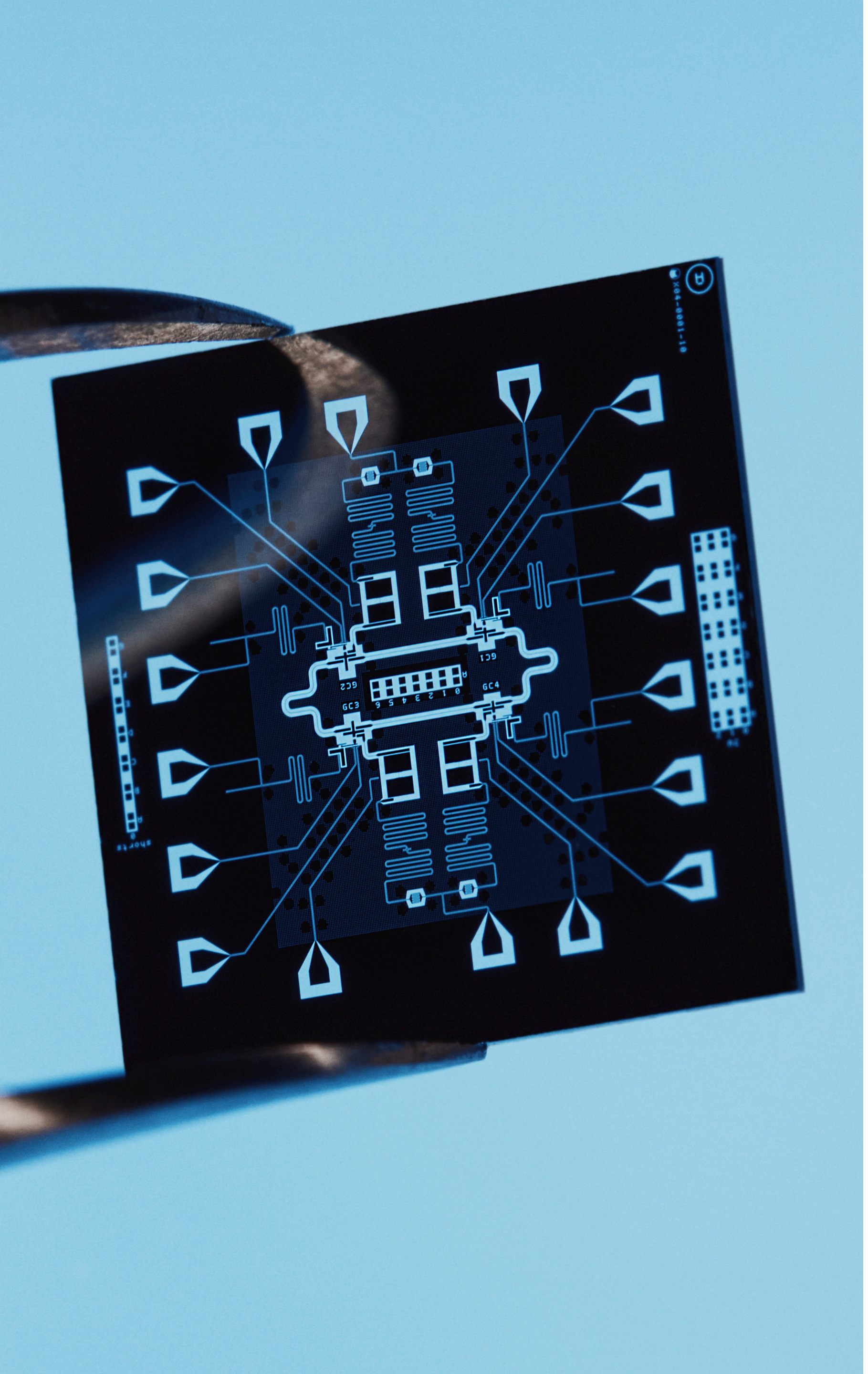
Quantum control of a cat-qubit with bit-flip times exceeding ten seconds

arXiv:2307.06617

Ronan Gautier | ETHZ Quantum Paper Club

December, 14th 2023





01

A primer on cat qubits

A quantum computer for simulating Nature

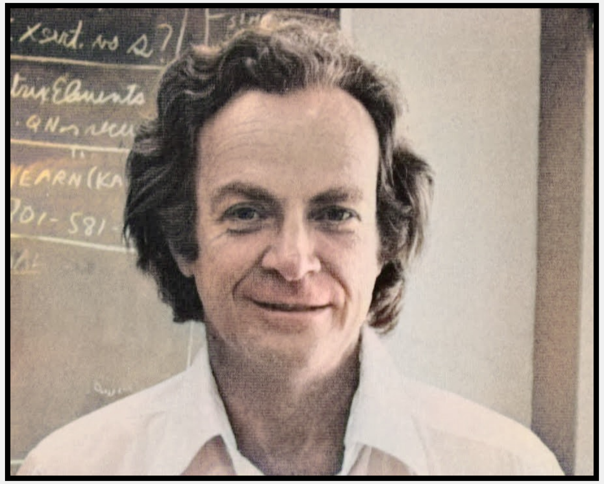
Feynman's 1981 talk

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

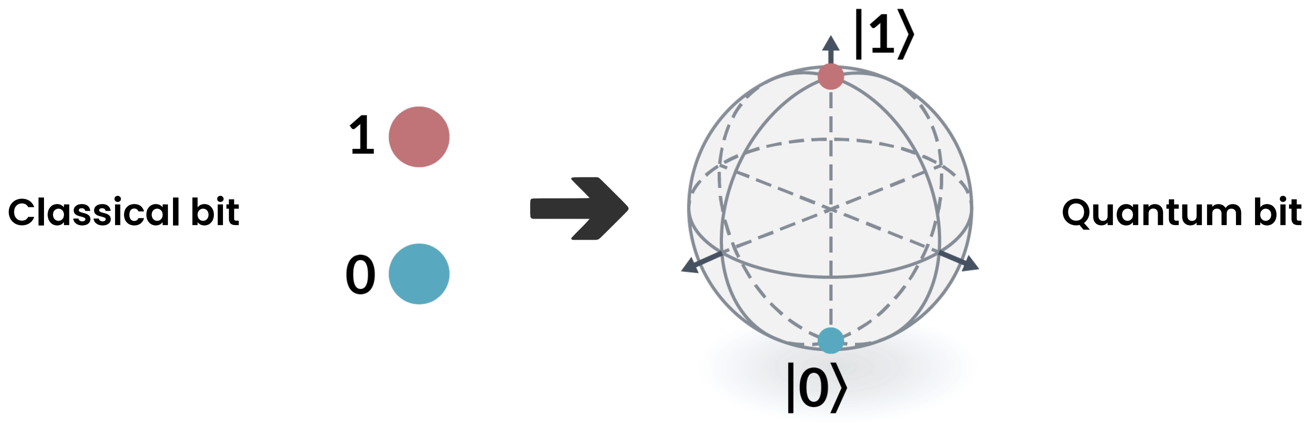
Can you do it with a new kind of computer — a quantum computer? [...] *It's not a Turing machine, but a machine of a different kind.*

Nature isn't classical, dammit, and if you want to make a simulation of Nature, you'd better make it quantum mechanical.

And by golly it's a wonderful problem because *it doesn't look so easy.*"

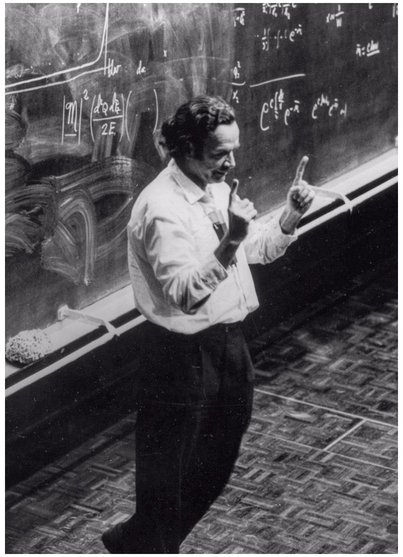


Richard Feynman at Caltech, circa 1980



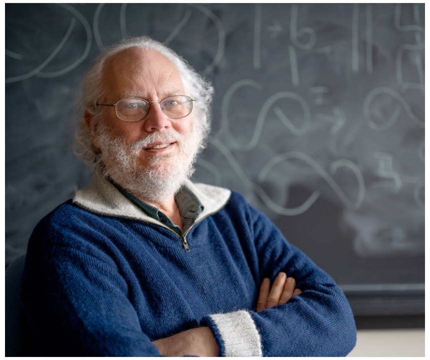
The development of superconducting circuits

Feynman's talk on QC



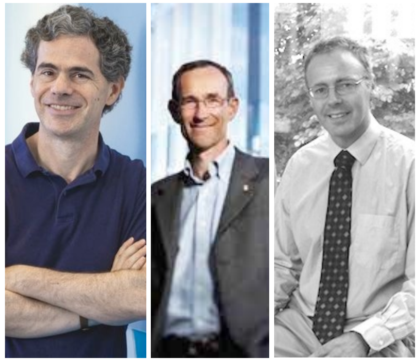
1981

Shor's algorithm



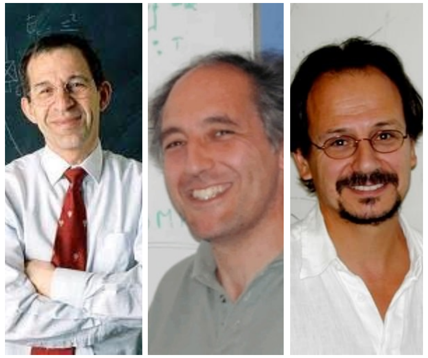
1994

Quantum Error Correction



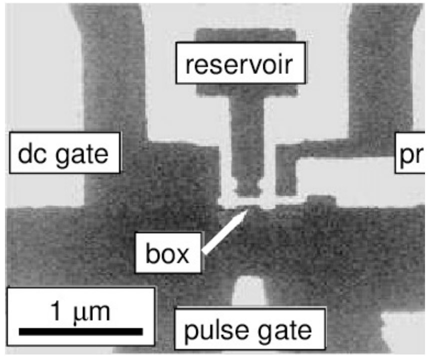
1995-1997

Creation of Quantronics



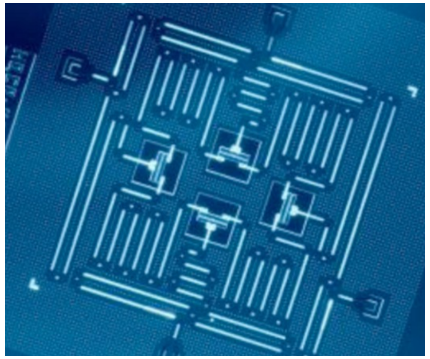
1985

Cooper Pair Box



1999

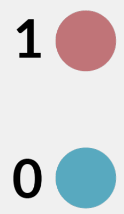
Transmon



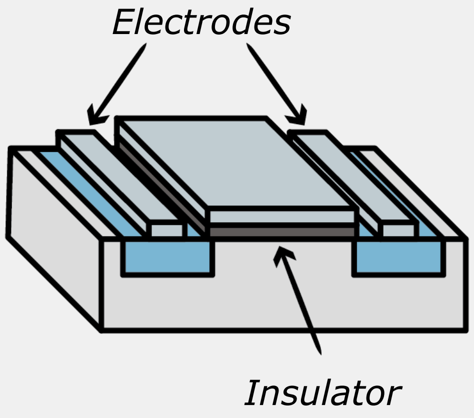
2007

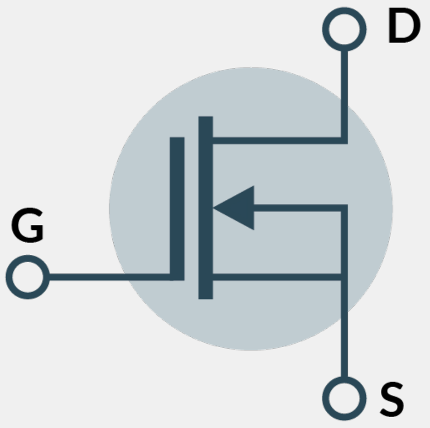
From transistors to transmons

Transistor



Field-Effect Transistor

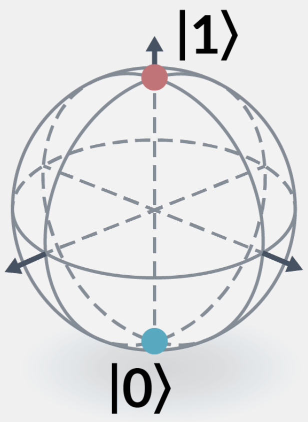




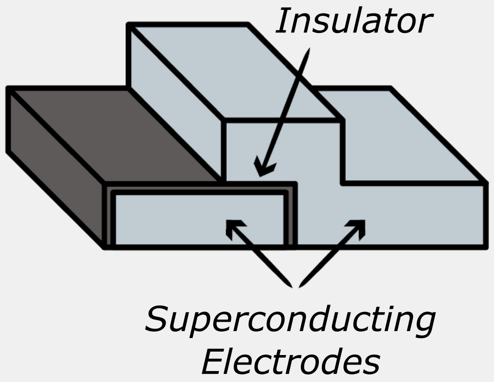
Error per operation

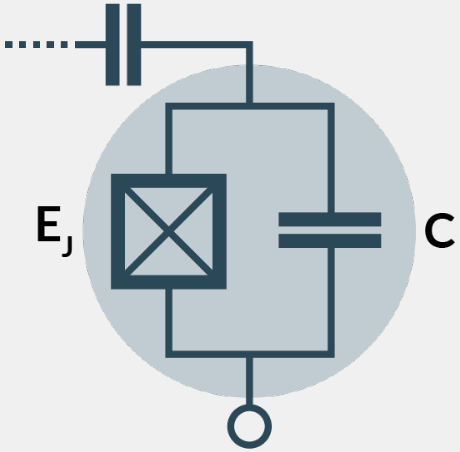
$\sim 10^{-20}$ — 10^{-22}

Transmon



Josephson Junction





Error per operation

$\sim 10^{-2}$ — 10^{-4}

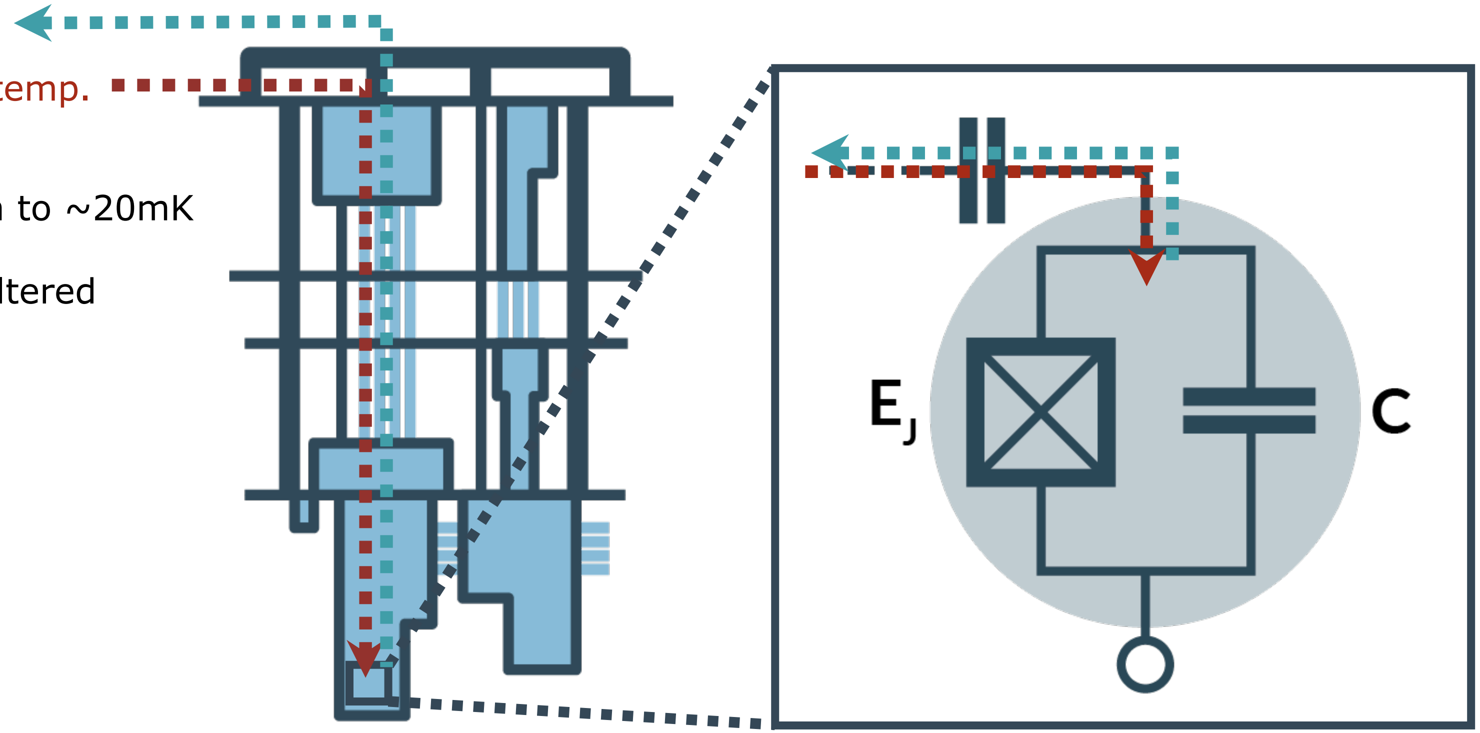
A fundamental predicament

High controllability ⟷ **Long lifetime**

Readout signal

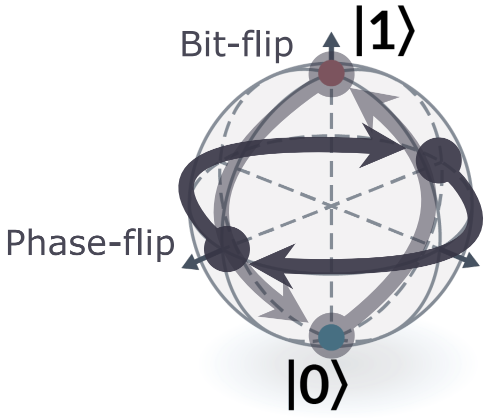
Signal @ room temp.

- Cooled down to ~20mK
- Frequency filtered
- Amplified



Inevitable coupling to bath

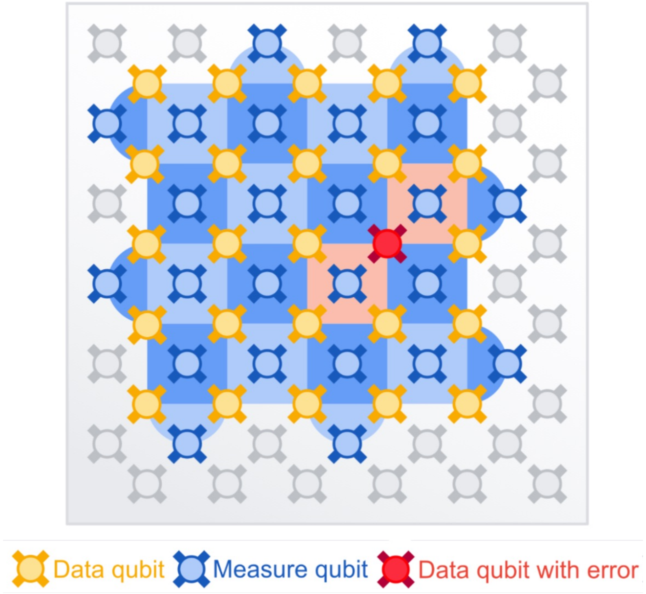
Quantum error correction



Error discretization theorem

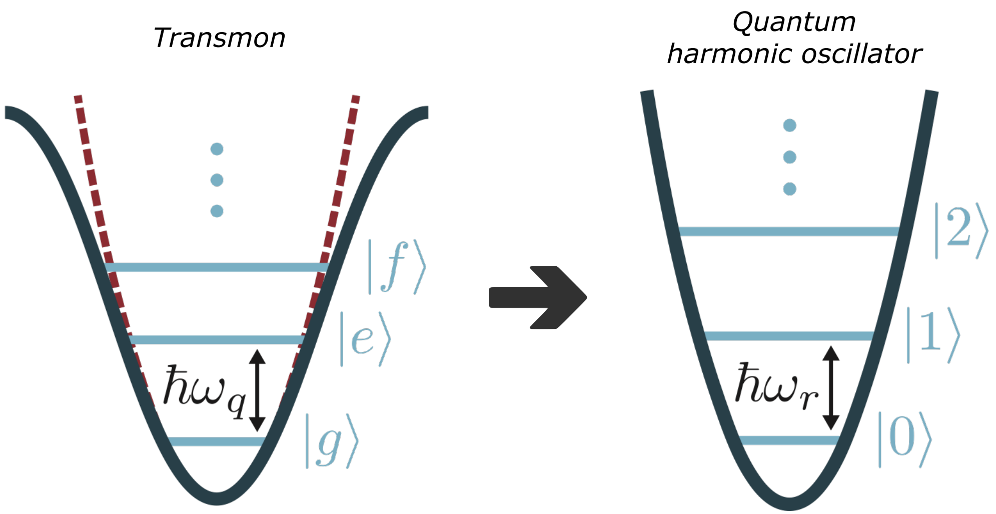
Correcting Pauli errors = correcting arbitrary errors

Discrete qubit codes

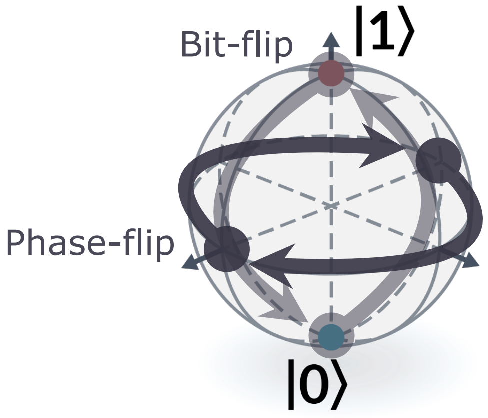


Google Quantum AI, Nature 2022

Bosonic codes



Quantum error correction



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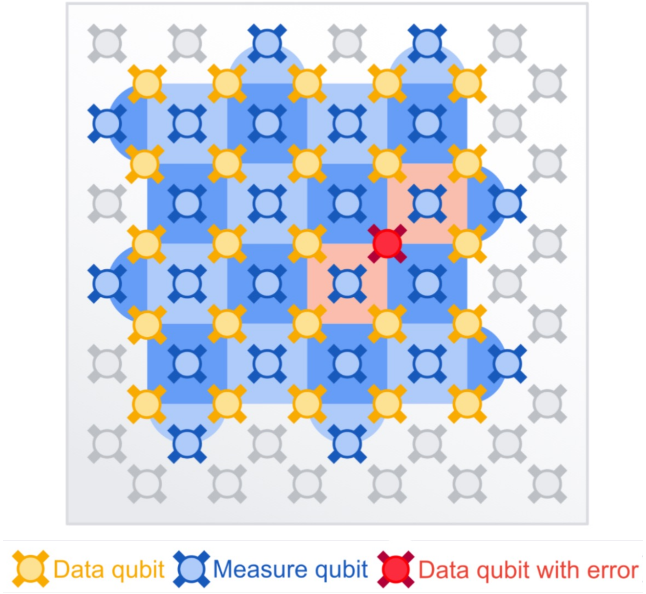

Google Quantum AI, Nature 2022

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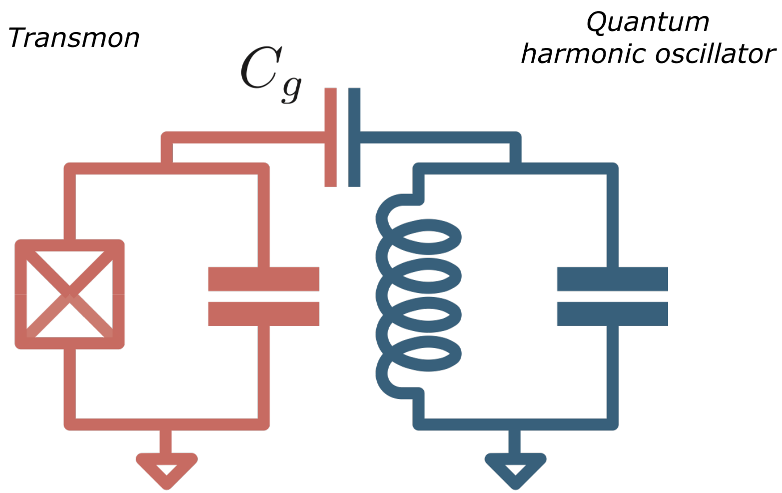
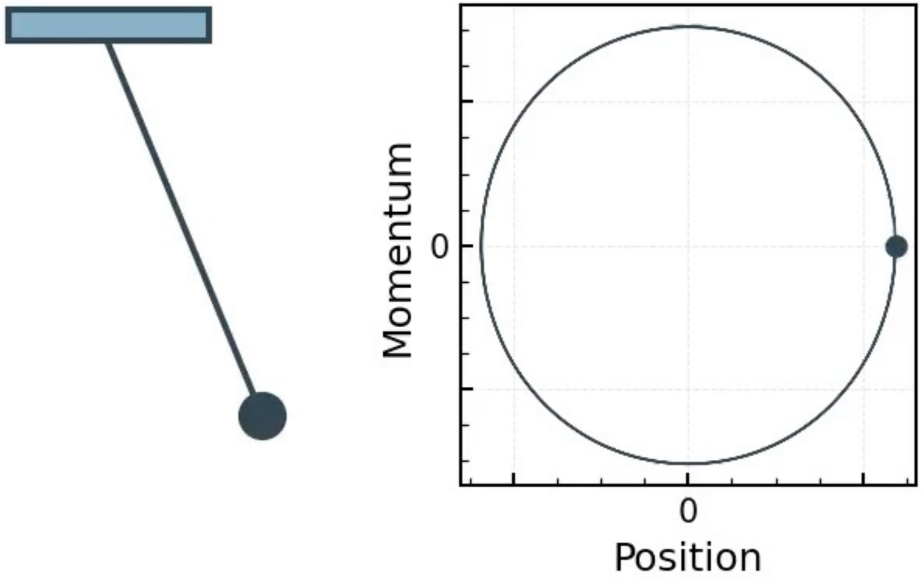


Encoding harmonic oscillators

How can we encode a harmonic oscillator?



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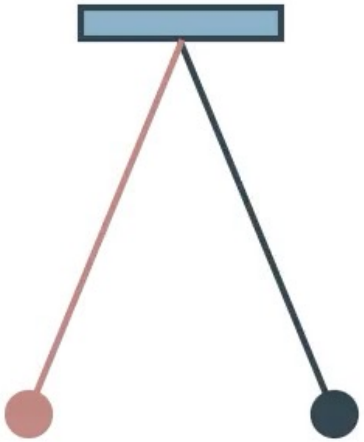

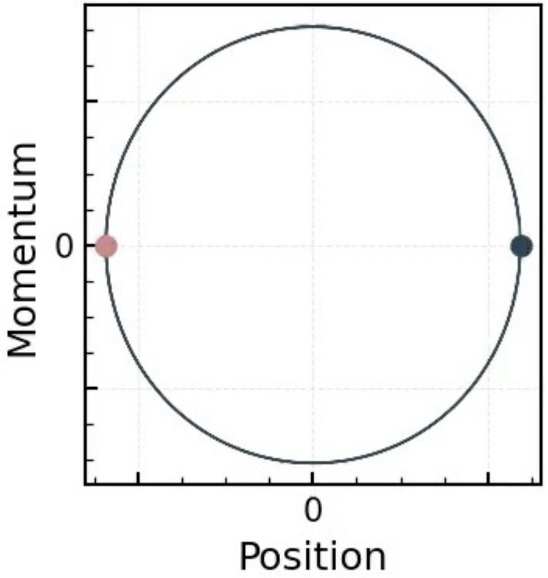

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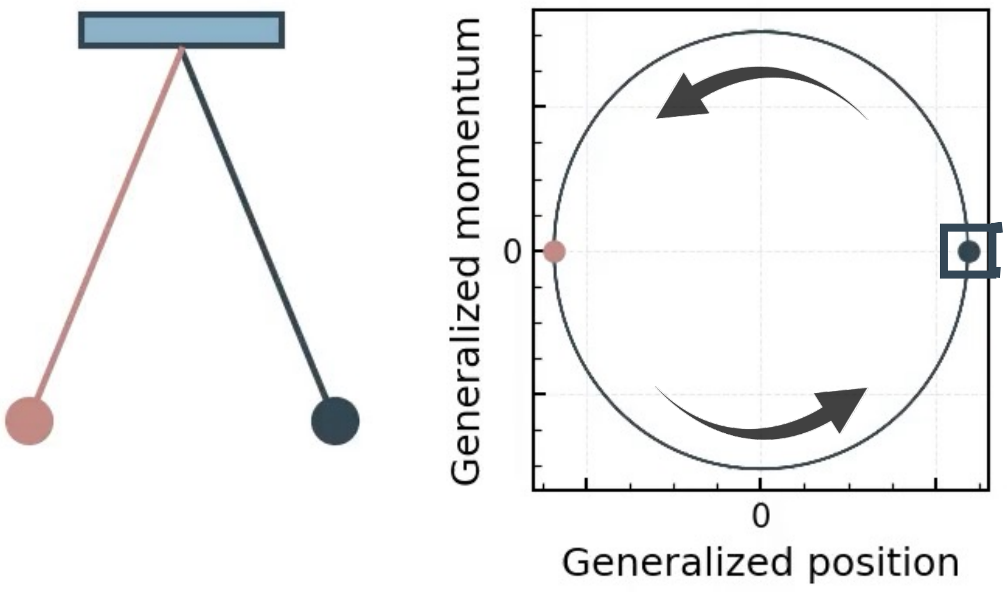
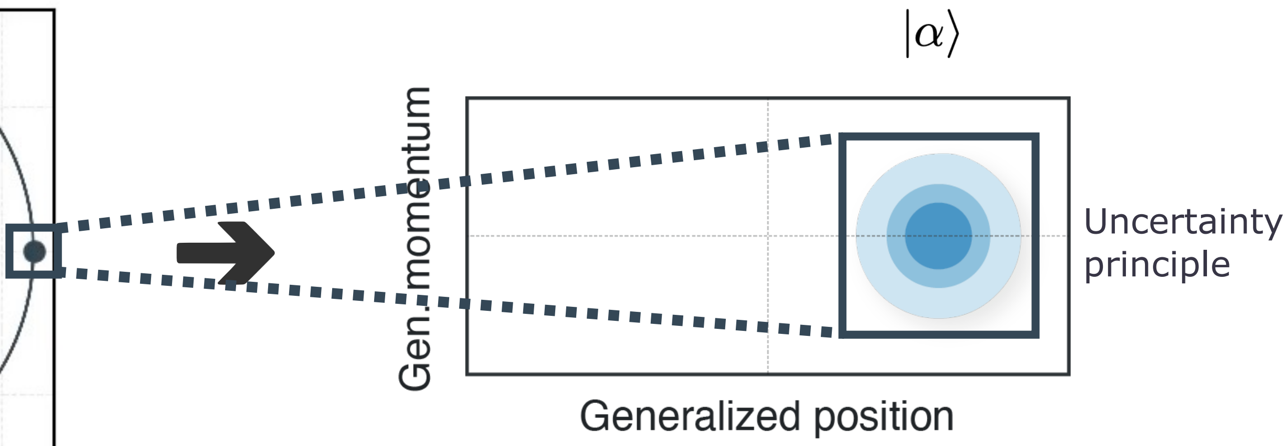


How can we encode a <u>quantum</u> harmonic oscillator?



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

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

Encoding harmonic oscillators

How can we encode a harmonic oscillator?

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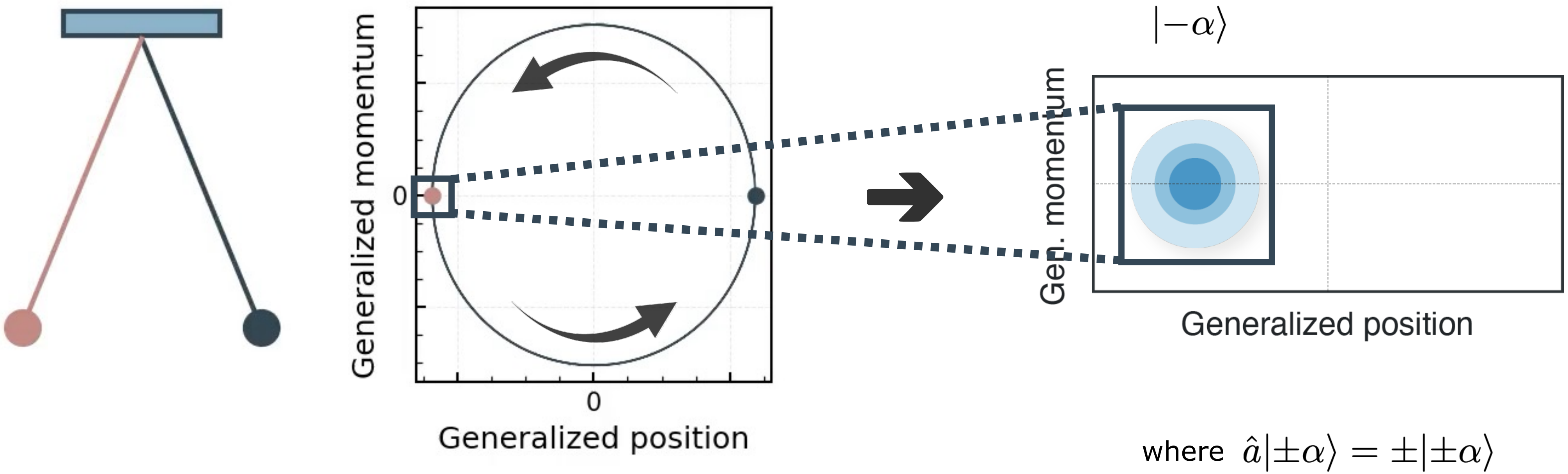

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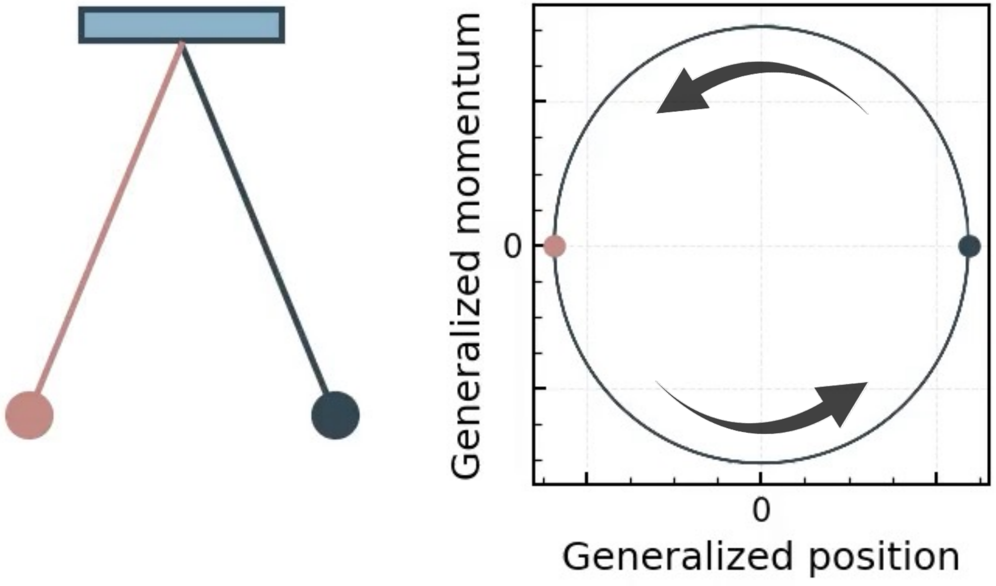

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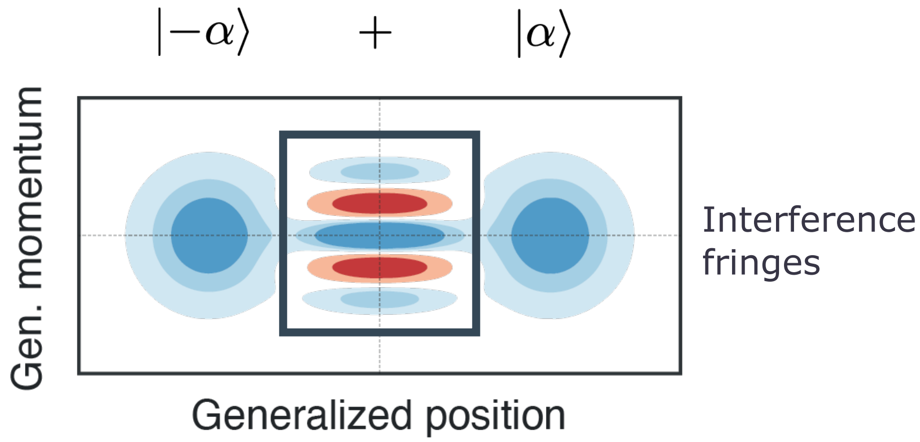

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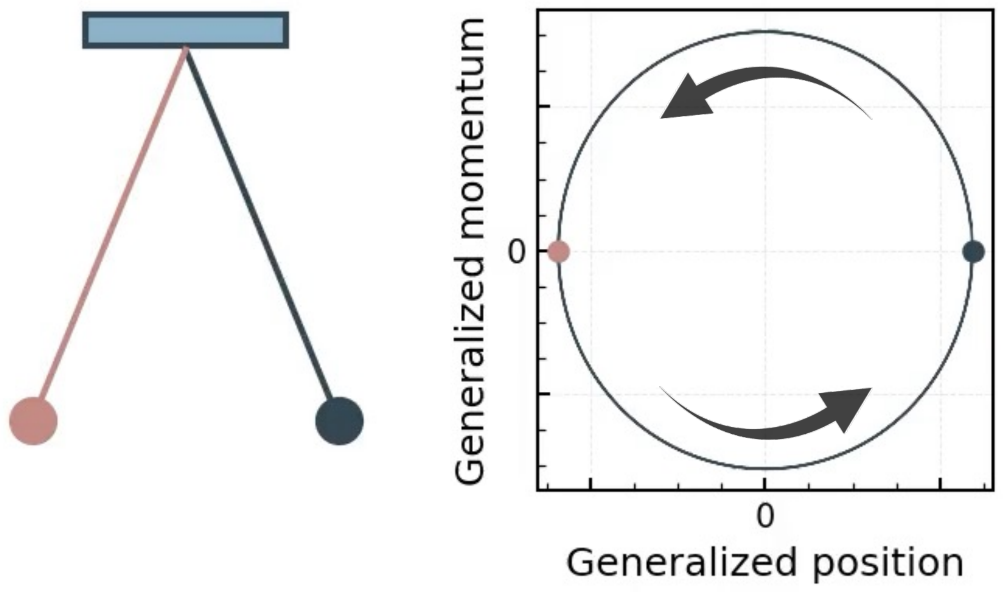

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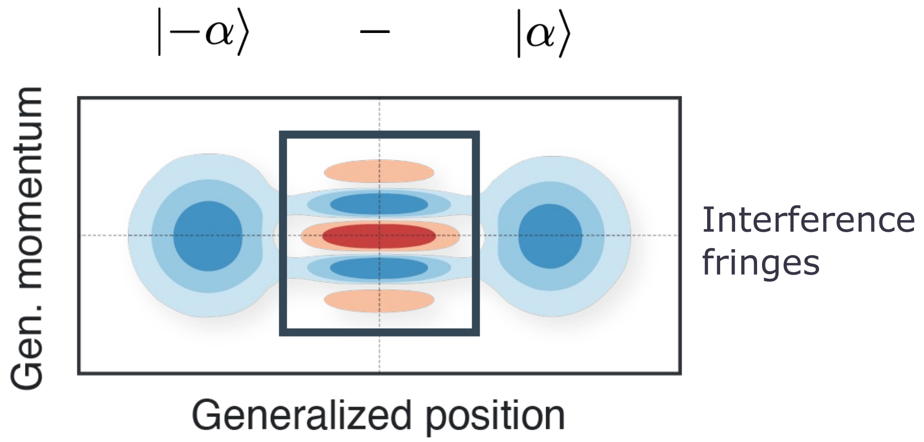

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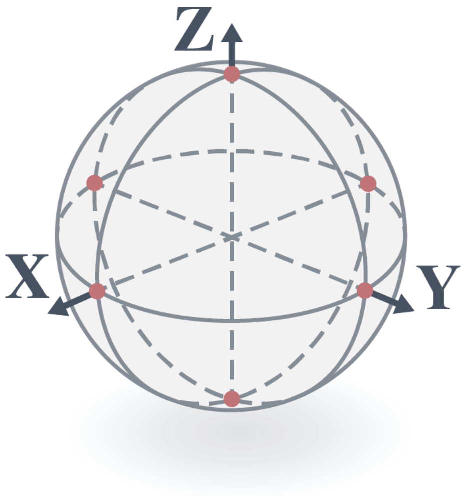
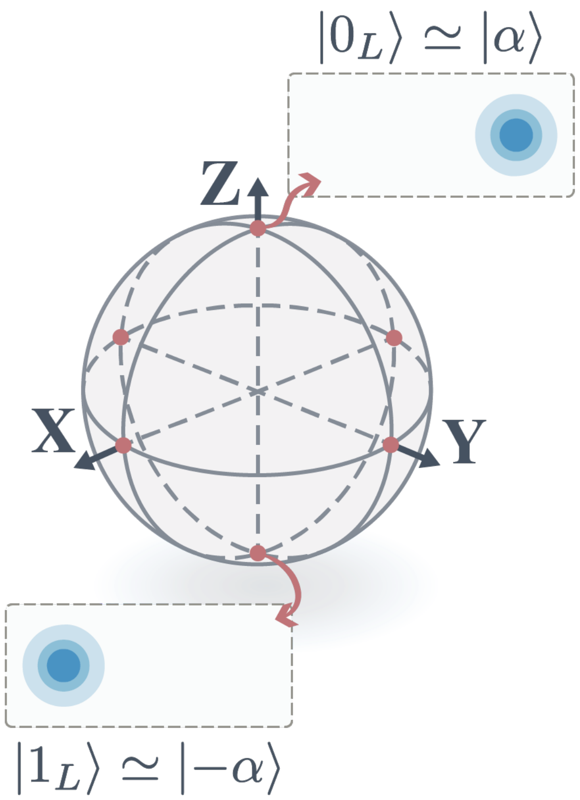
Cat qubits



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

Cat qubits



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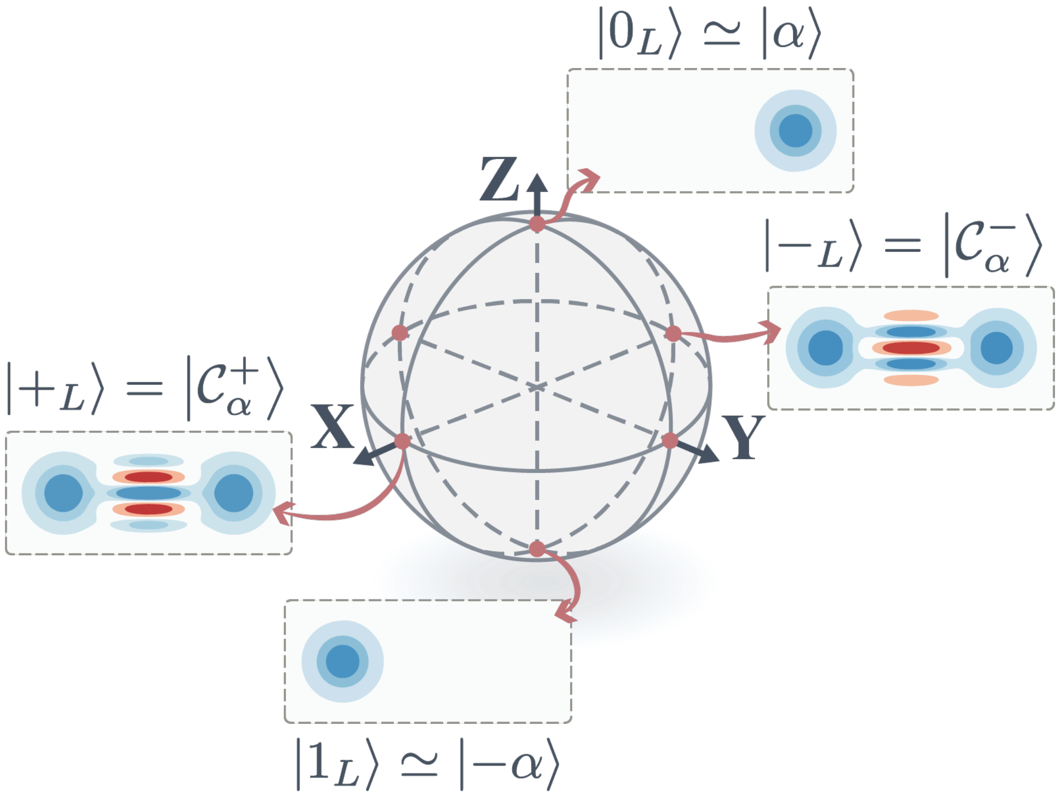

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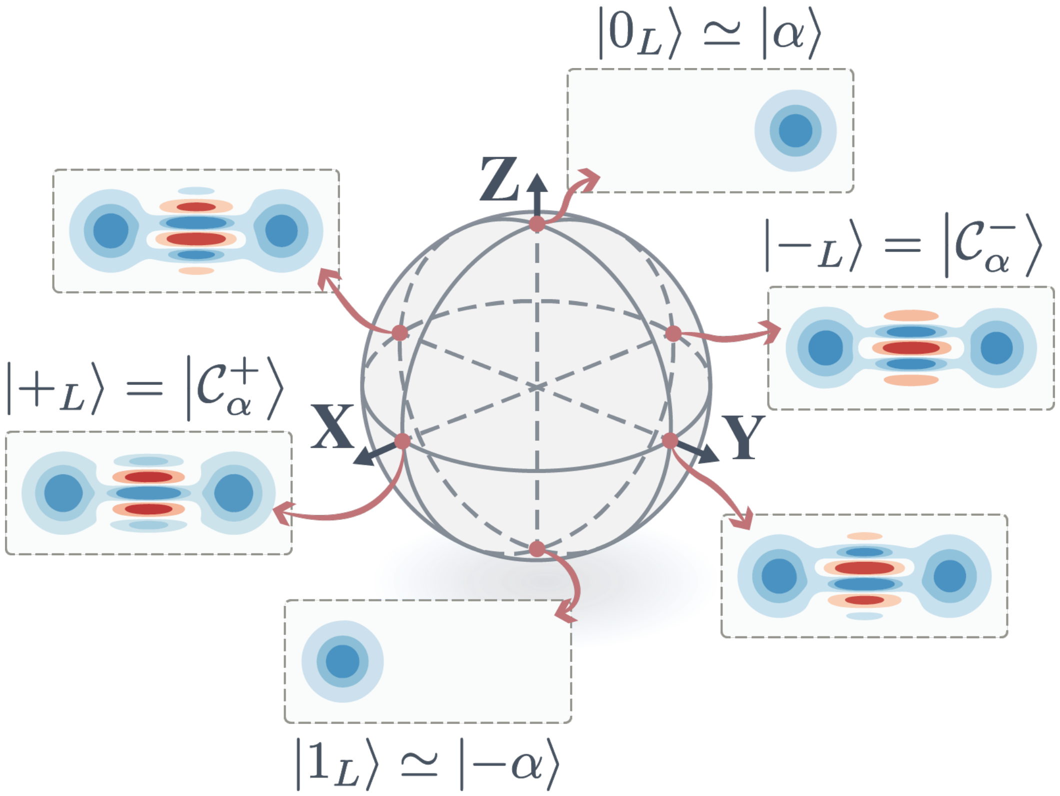

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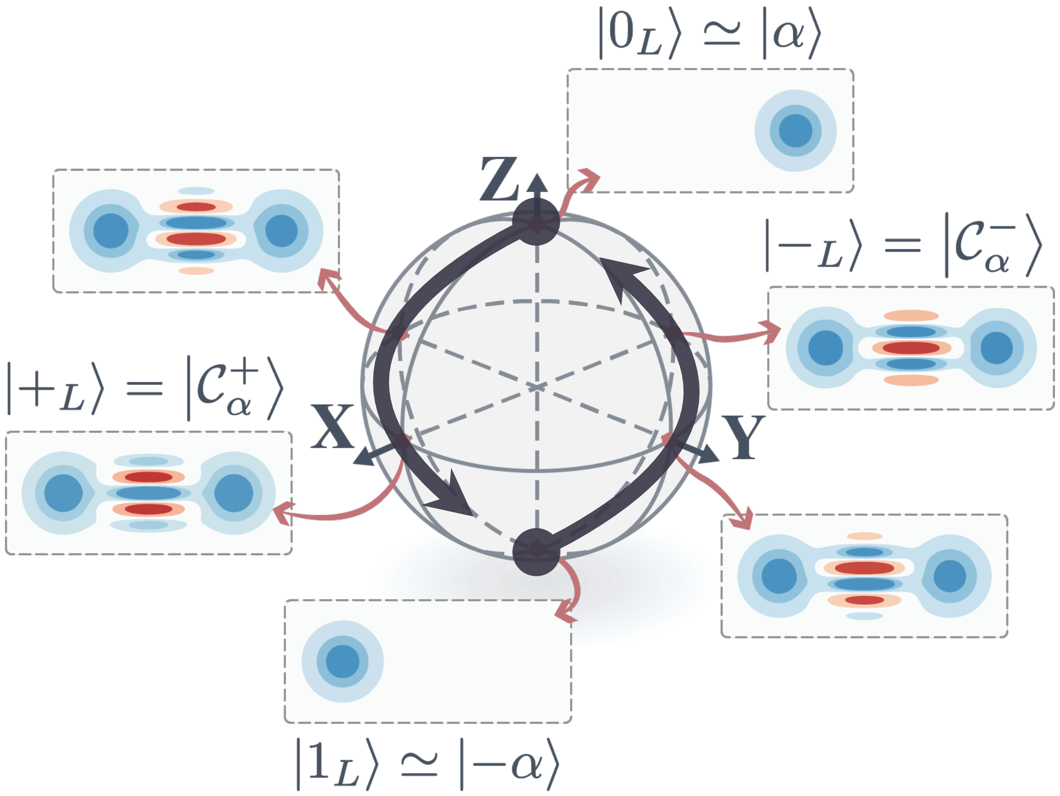
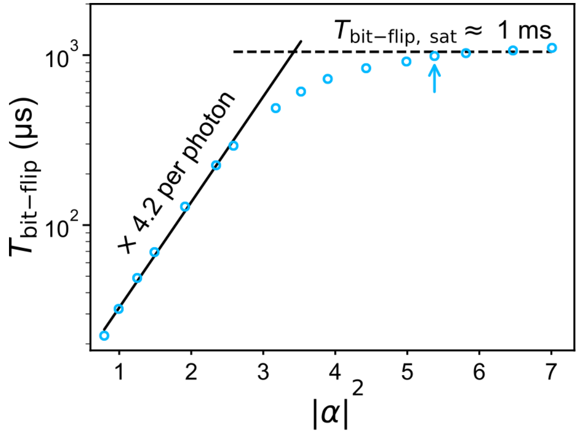


- Cat qubits are **exponentially** biased against <u>bit-flip</u> errors



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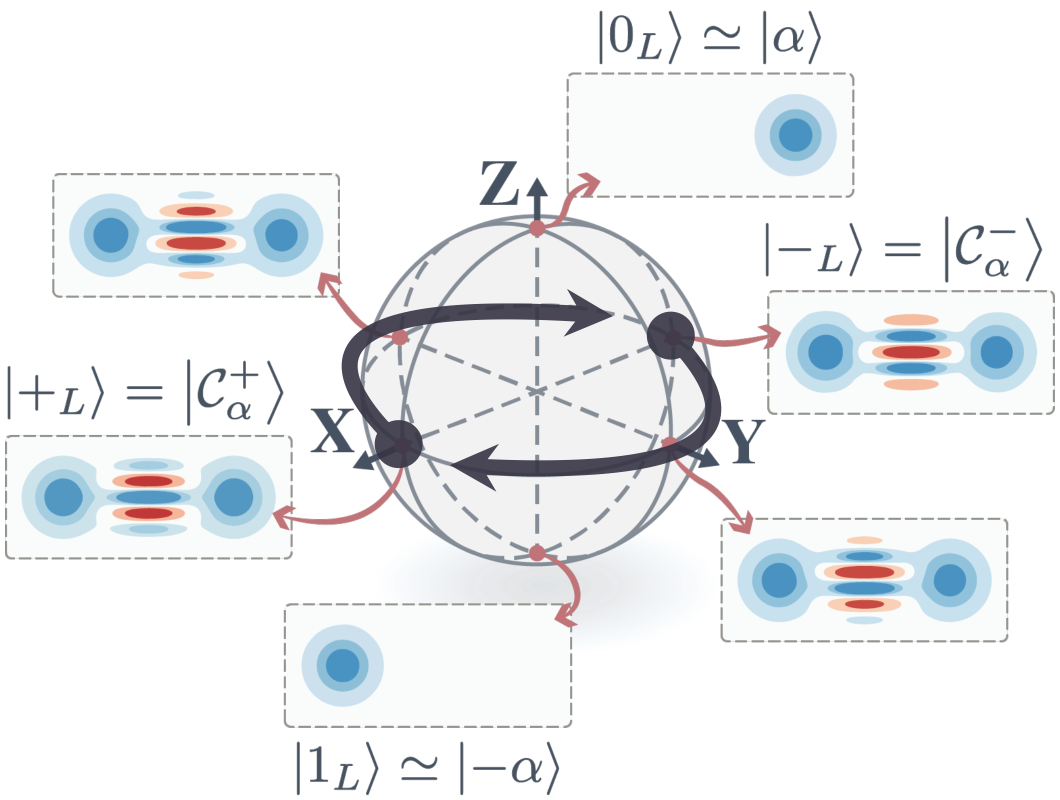

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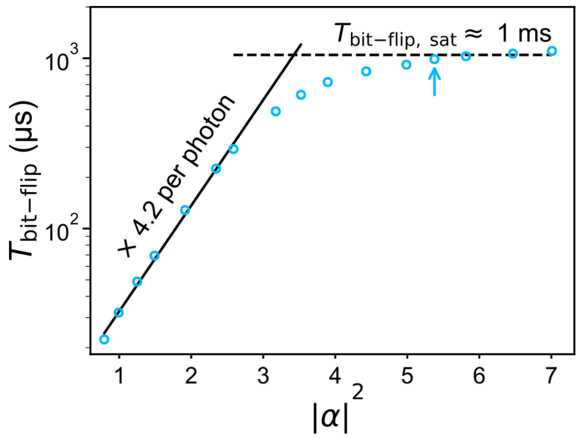
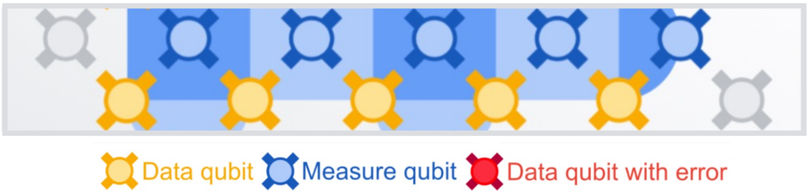


- A repetition code takes care of phase-flip errors



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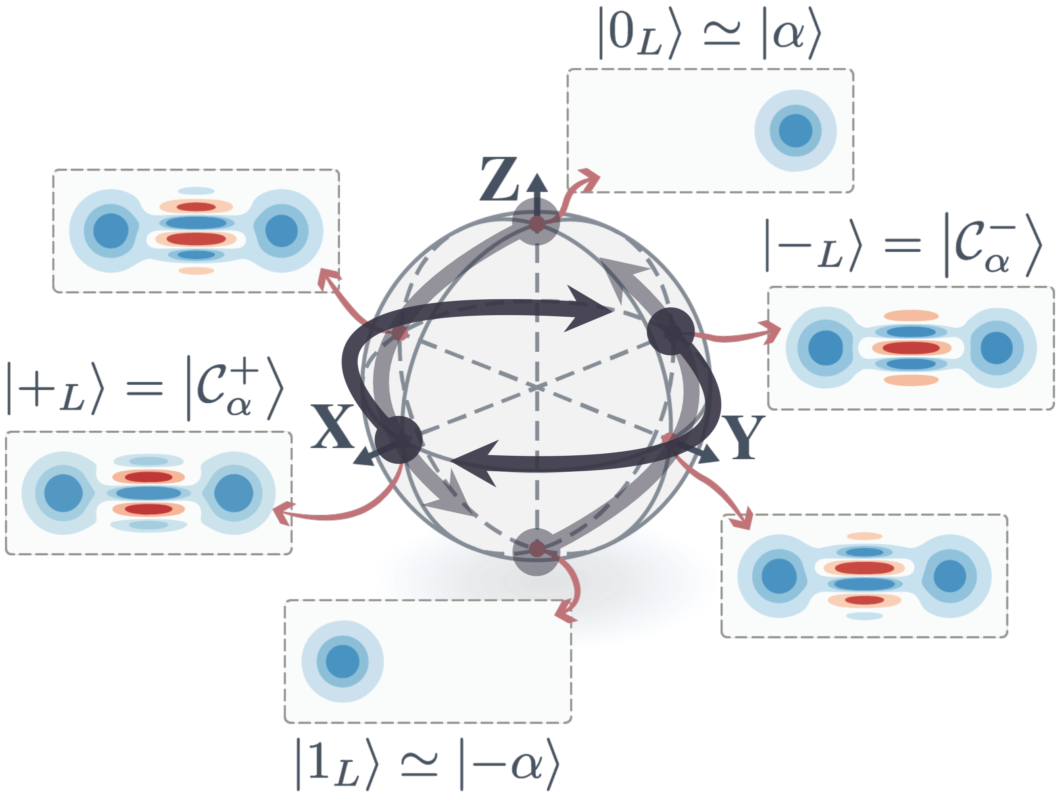

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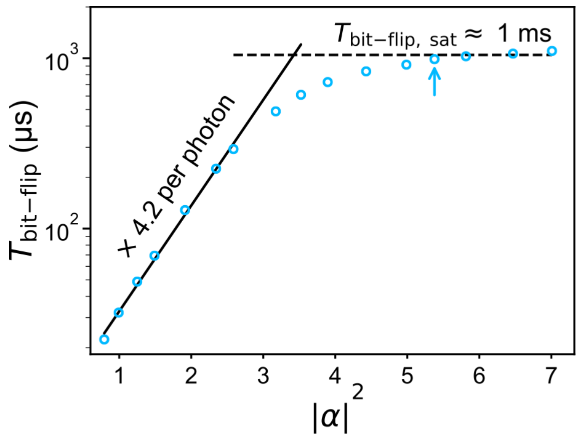

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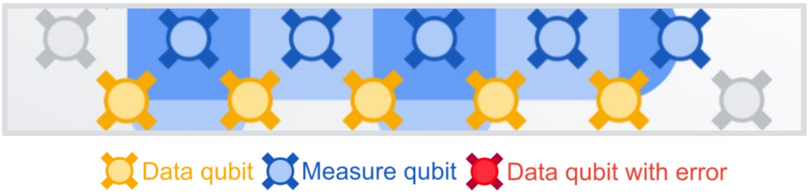


- Inner: cat qubits (bit-flips)
  Outer: repetition code (phase-flips)

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

Protecting cat qubits

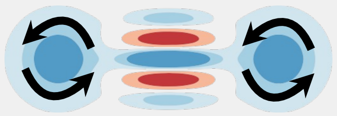
Kerr cat qubits

- Hamiltonian confinement

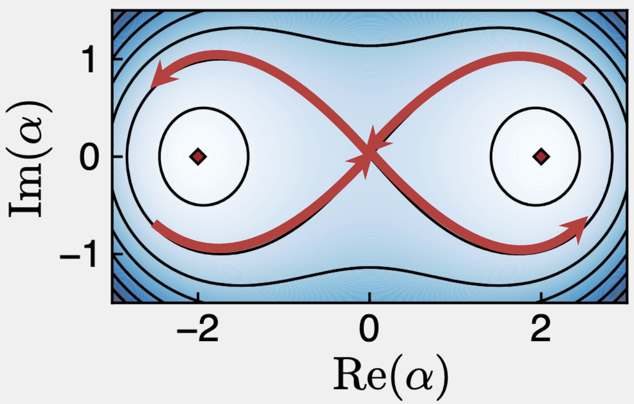
$$H = -K(a^{\dagger 2} - \alpha^{*2})(a^2 - \alpha^2)$$

since $(a^2 - \alpha^2)|\pm\alpha\rangle = 0$

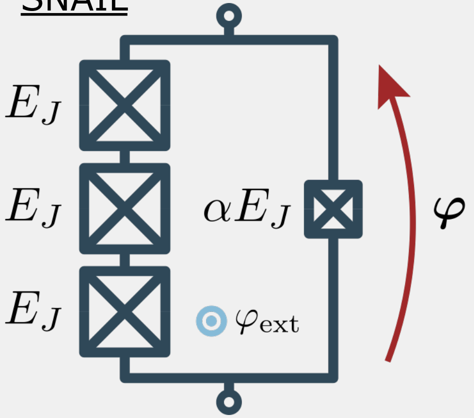
- Kerr non-linearity + two-photon driving



Semiclassical potential



SNAIL

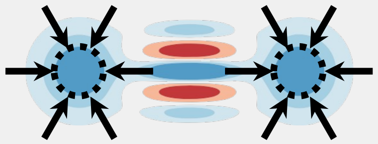


Dissipative cat qubits

- Dissipative stabilization

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

- Two-photon dissipation + two-photon driving



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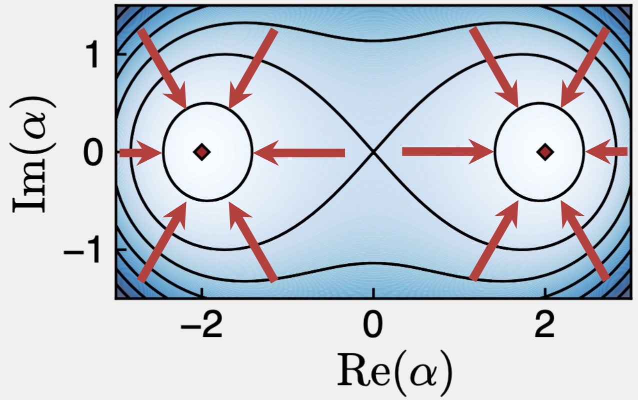
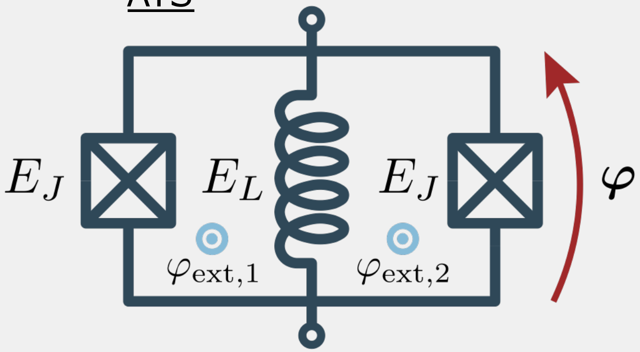
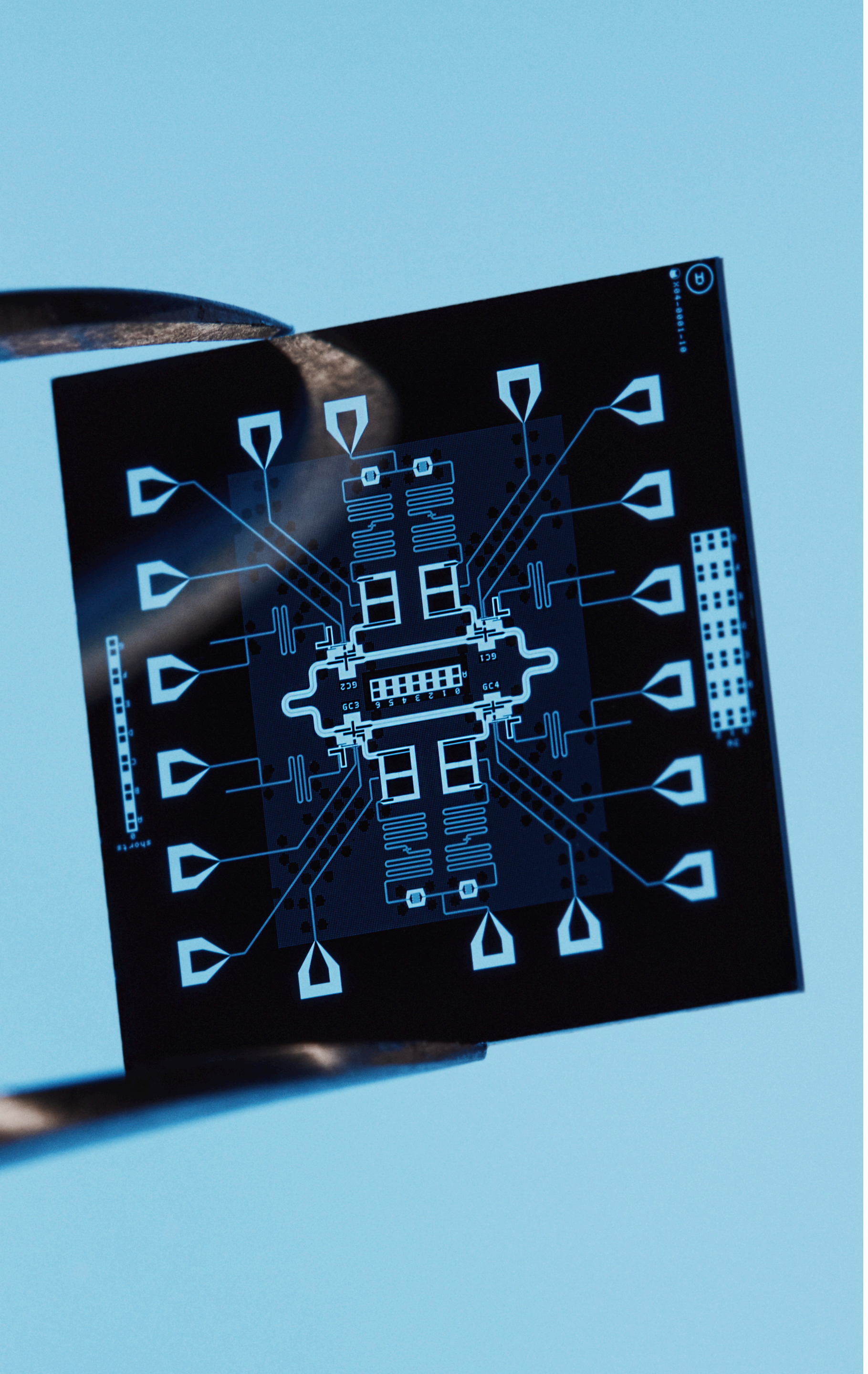


ATS



Puri et al., npj QI (2017); Mirrahimi et al., NJP (2014); Guillaud et al., PRX (2019); Lescanne et al., Nat.Phy (2019)



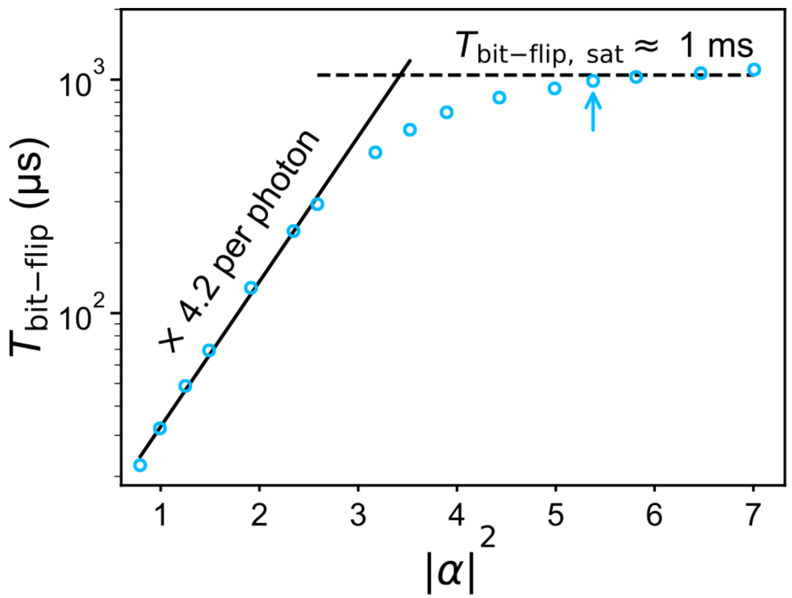
02

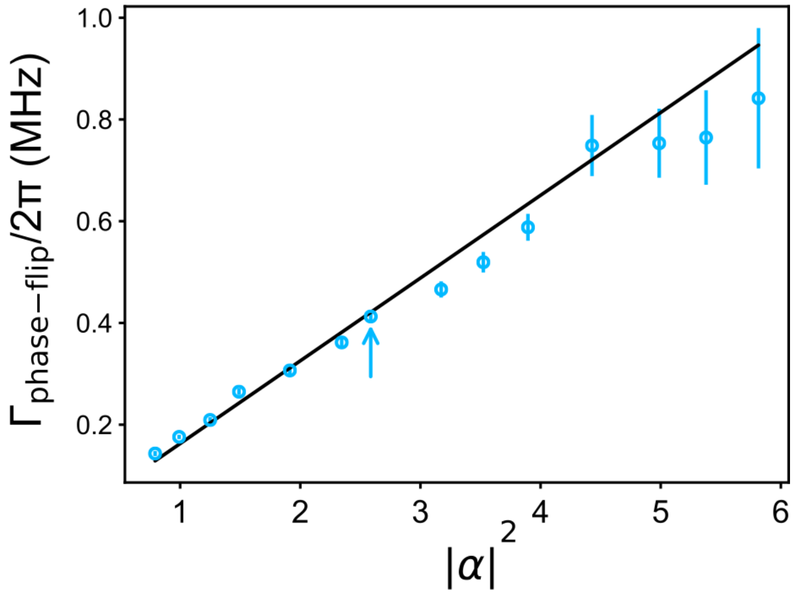
An exponentially biased qubit

Exponential suppression of bit-flips in a qubit encoded in an oscillator

Raphaël Lescanne, Marius Villiers, Théau Peronnin, Alain Sarlette, Matthieu Delbecq, Benjamin Huard, Takis Kontos, Mazyar Mirrahimi & Zaki Leghtas

Nature Physics **16**, 509–513 (2020) | Cite this article





$$\Gamma_{\text{bit-flip}} \propto \exp(-\gamma|\alpha|^2)$$

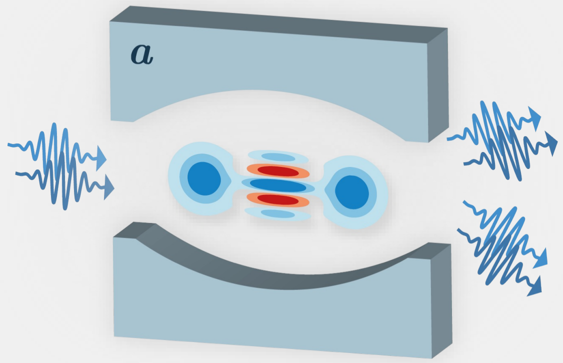
$$\Gamma_{\text{phase-flip}} \propto \kappa_1|\alpha|^2$$

Lescanne *et al.* Nat. Phy. (2019)

Reservoir engineering of two-photon dissipation

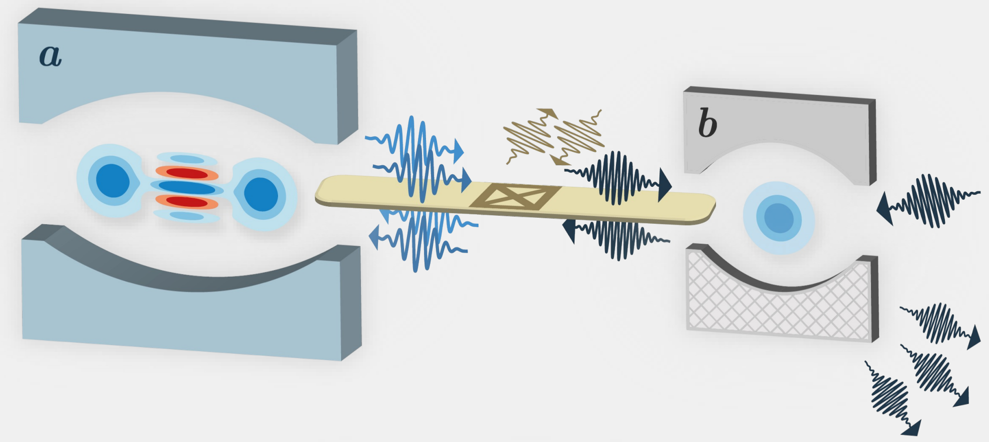
Memory

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



Memory + Buffer

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

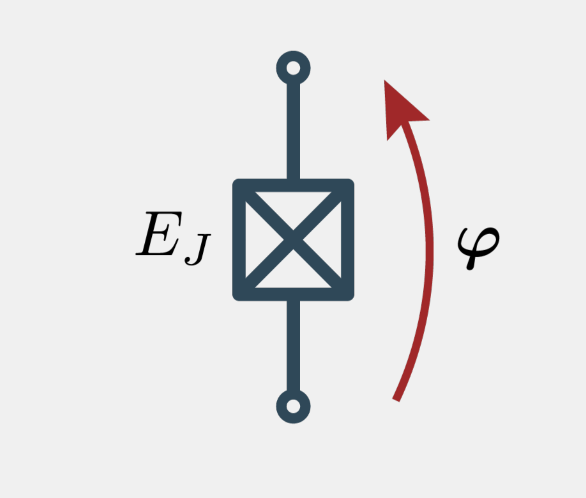


Requires frequency-tunable four-wave mixing

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

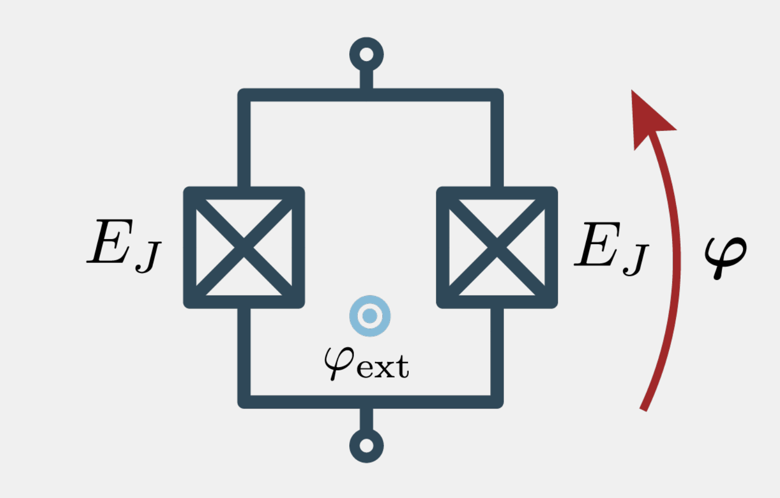
Frequency-tunable four-wave mixing

Josephson Junction



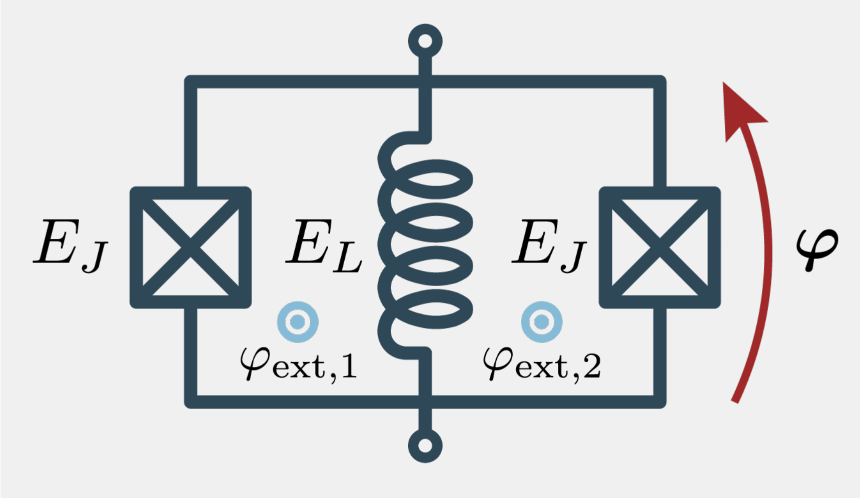
$$\hat{H} = -E_J \cos(\hat{\varphi})$$

SQUID



$$\hat{H} = -E_J \cos(\varphi_{\mathrm{ext}}) \cos(\hat{\varphi})$$

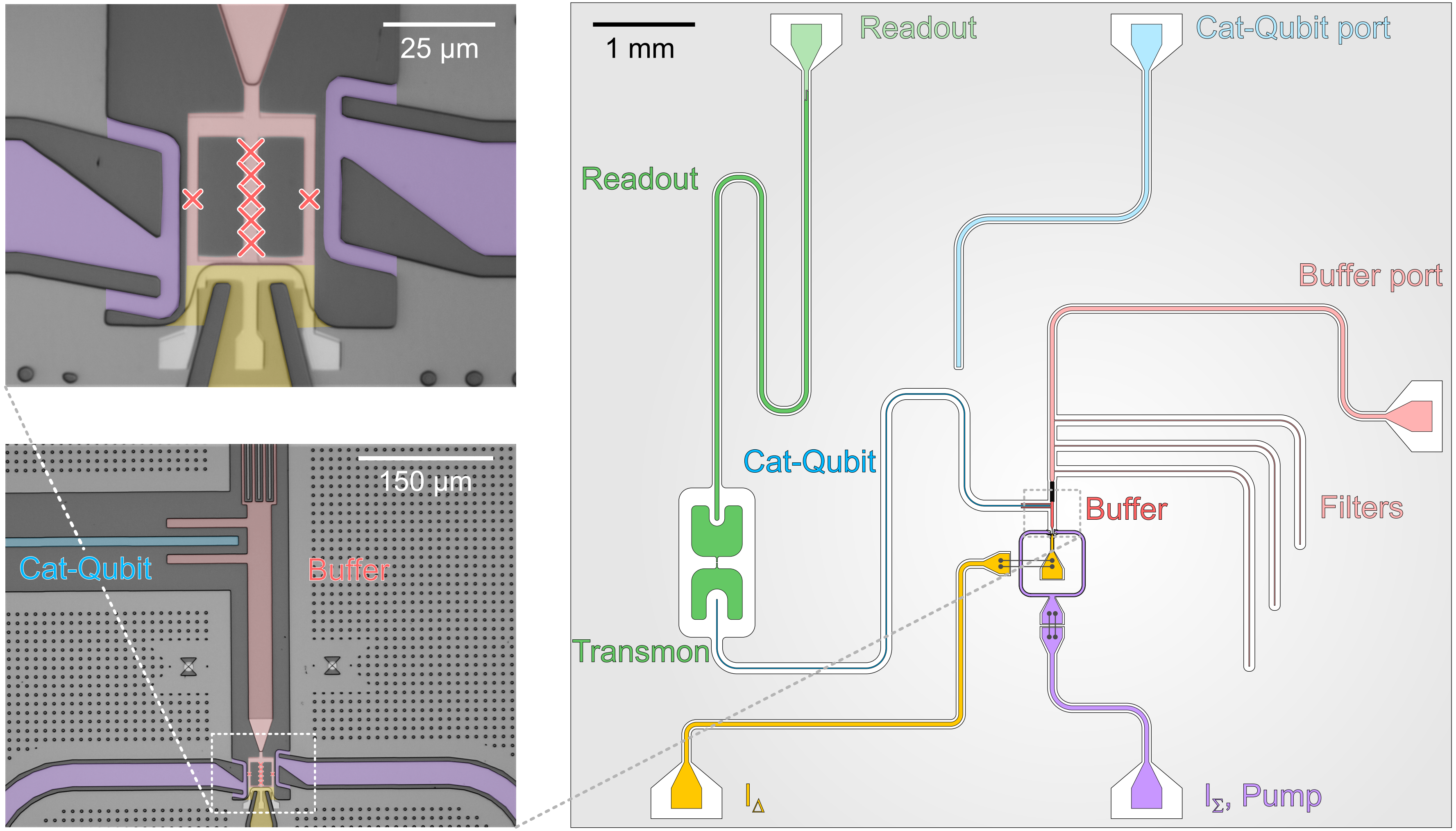
Asymmetrically Threaded SQUID



$$\hat{H} = \tfrac{1}{2} E_L \hat{\varphi}^2 - 2E_J \cos(\varphi_\Sigma) \cos(\hat{\varphi} + \varphi_\Delta)$$
$$\rightarrow \tfrac{1}{2} E_L \hat{\varphi}^2 - 2E_J \cos(\varphi_\Sigma) \sin(\hat{\varphi})$$

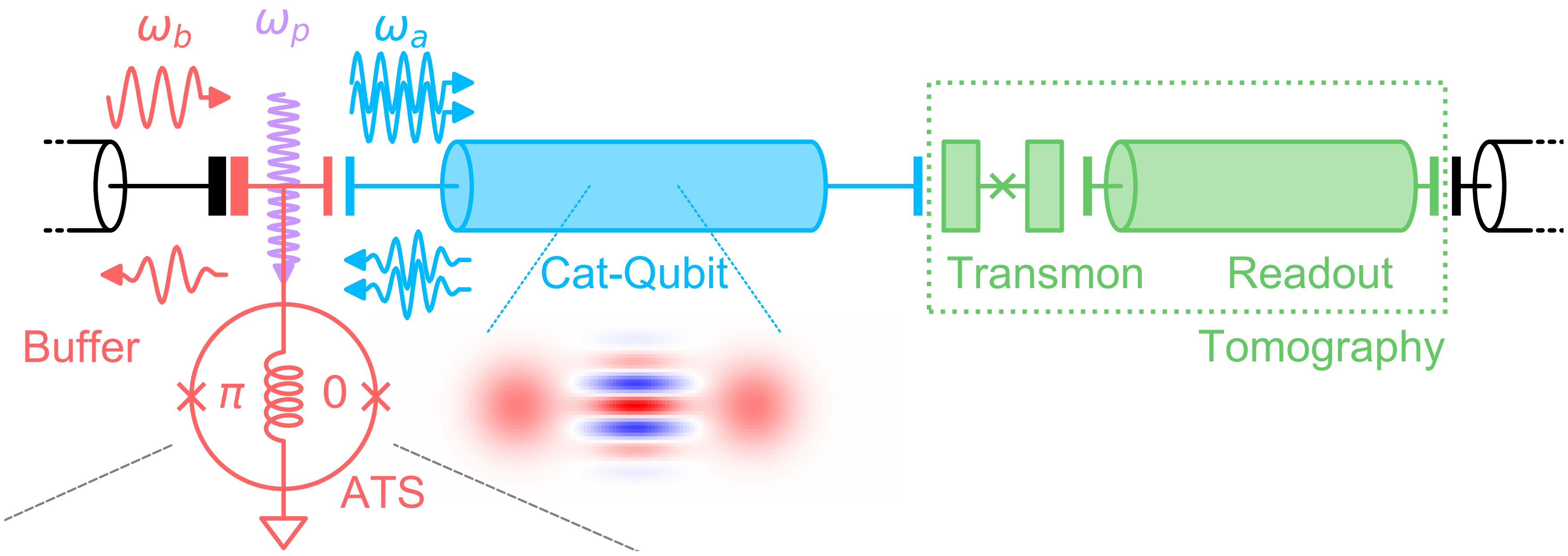
Lescanne *et al.* Nat. Phy. (2019)

Experimental setup



Lescanne *et al.* Nat. Phy. (2019)

Experimental setup

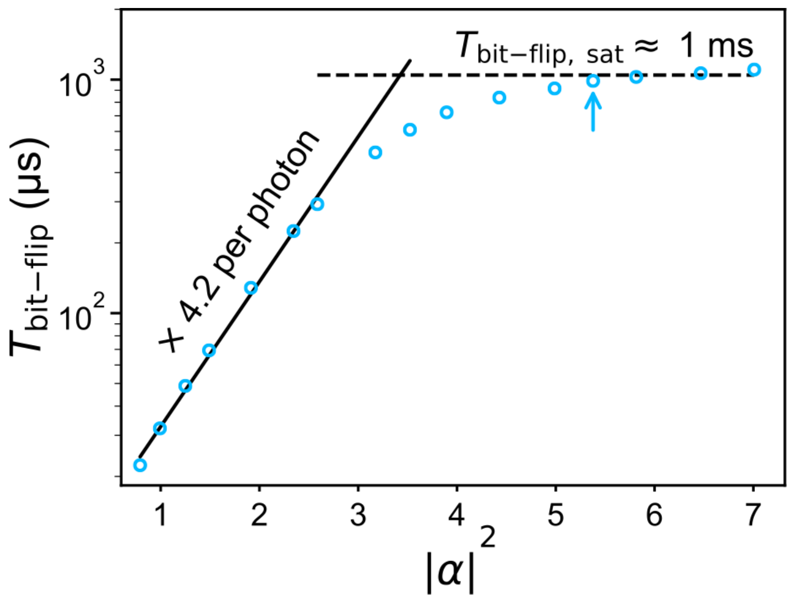


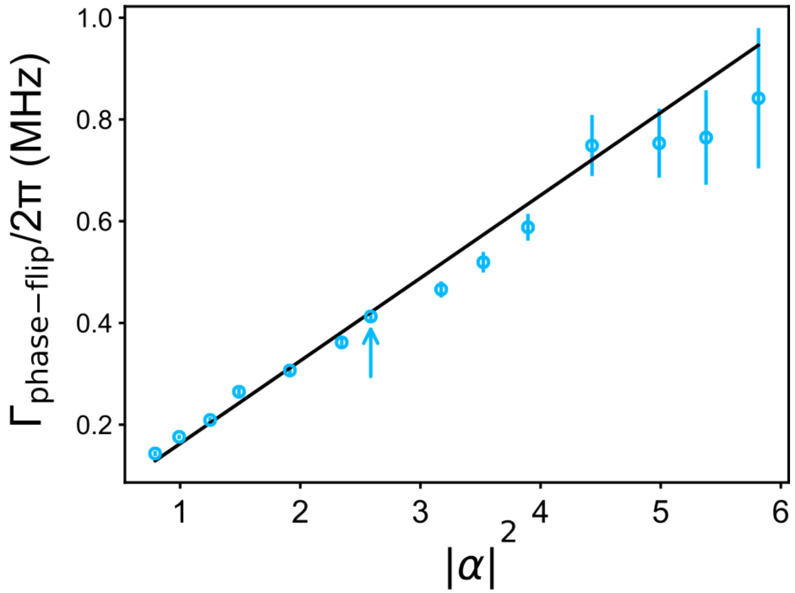
Lescanne *et al.* Nat. Phy. (2019)

Exponential suppression of bit-flips in a qubit encoded in an oscillator

Raphaël Lescanne, Marius Villiers, Théau Peronnin, Alain Sarlette, Matthieu Delbecq, Benjamin Huard, Takis Kontos, Mazyar Mirrahimi & Zaki Leghtas

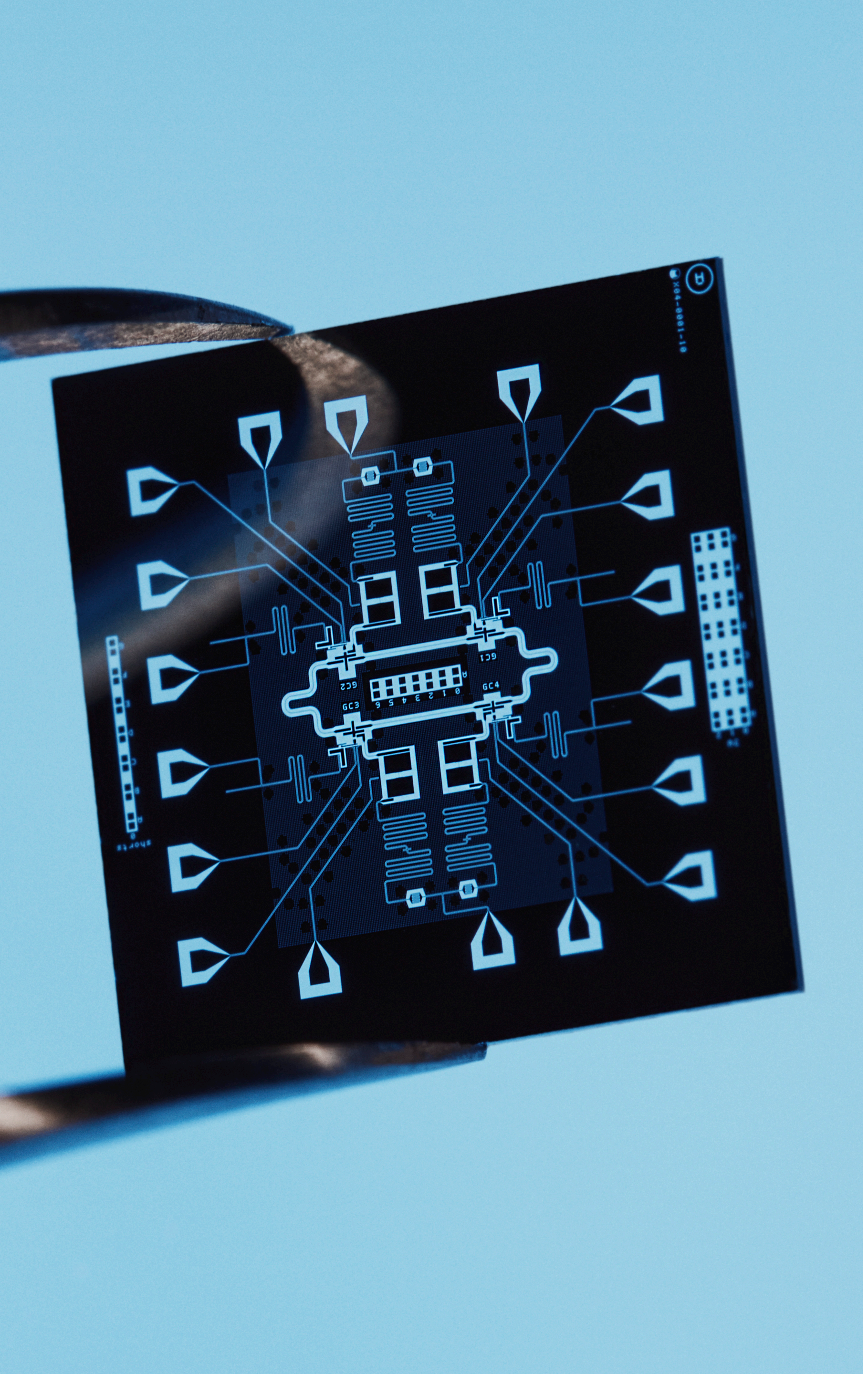
Nature Physics **16**, 509–513 (2020) | Cite this article





Saturation due to readout transmon
Confirmed in Berdou et al. PRX Quantum (2022)

Lescanne *et al.* Nat. Phy. (2019)



03

Macroscopic bit lifetime

Quantum control of a cat-qubit with bit-flip times exceeding ten seconds

U. Réglade,[1,2,†] A. Bocquet,[1,2,†] R. Gautier,[2] A. Marquet,[1,3] E. Albertinale,[1] N. Pankratova,[1] M. Hallén,[1] F. Rautschke,[1] L.-A. Sellem,[2] P. Rouchon,[2] A. Sarlette,[2] M. Mirrahimi,[2] P. Campagne-Ibarcq,[2] R. Lescanne,[1] S. Jezouin,[1,‡] and Z. Leghtas[2,§]

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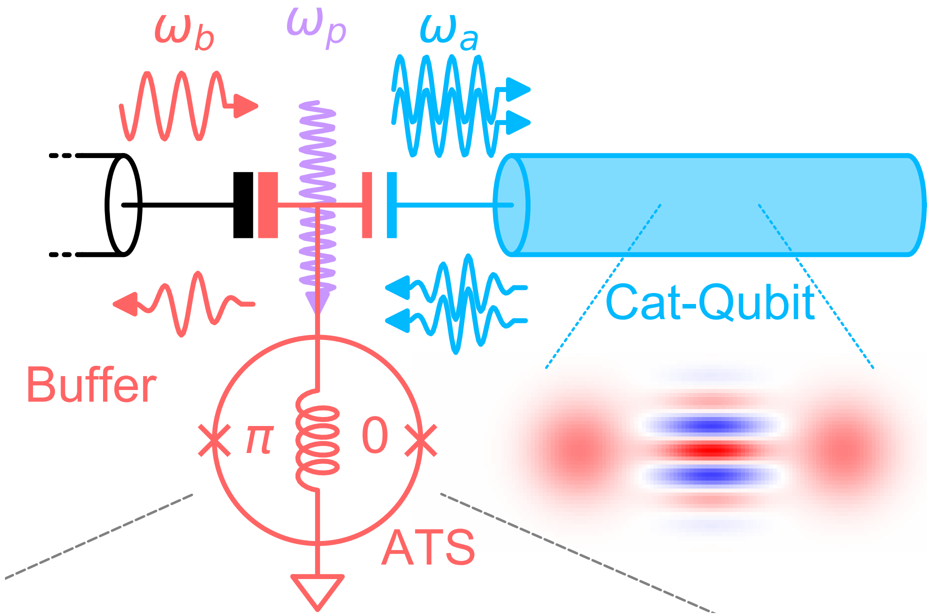
[2] *Laboratoire de Physique de l'Ecole normale supérieure, ENS-PSL, CNRS, Sorbonne Université, Université Paris Cité, Centre Automatique et Systèmes, Mines Paris, Université PSL, Inria, Paris, France*
[3] *Ecole Normale Supérieure de Lyon, CNRS, Laboratoire de Physique, F-69342 Lyon, France*



Problem: how do we readout?

Réglade, Bocquet *et al. arXiv* (2023)

Readout protocol

Wigner distribution

$$W(\lambda) = \langle \hat{D}(\lambda)\hat{P}\hat{D}^\dagger(\lambda)\rangle$$

with parity operator $\hat{P} = \mathrm{e}^{i\pi\hat{a}^\dagger\hat{a}}$

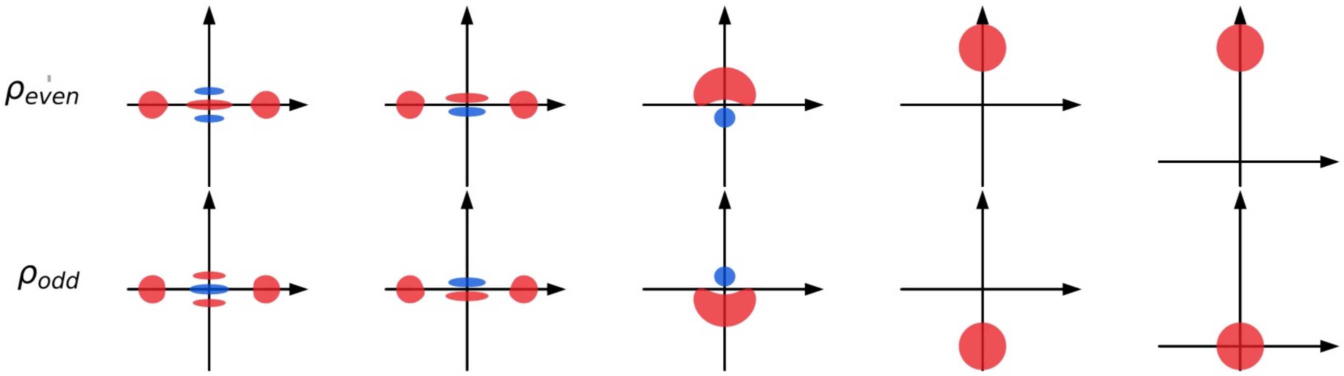
with displacement operator $\hat{D}(\lambda) = \mathrm{e}^{\lambda\hat{a}^\dagger - \lambda^*\hat{a}}$

Three-step process:

(1) Displace state

(2) Map parity to coherent states

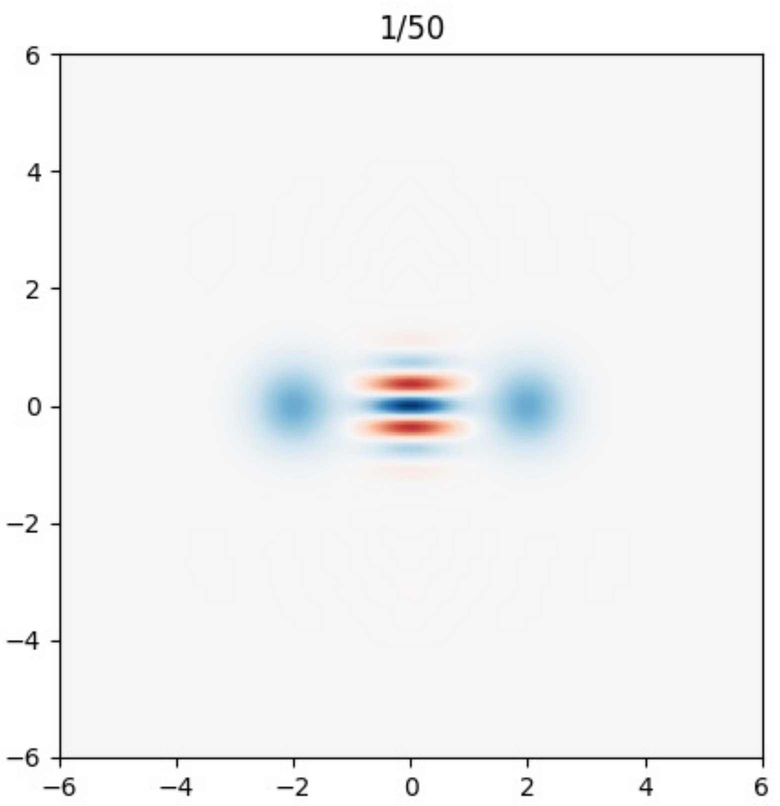
(3) Readout coherent states



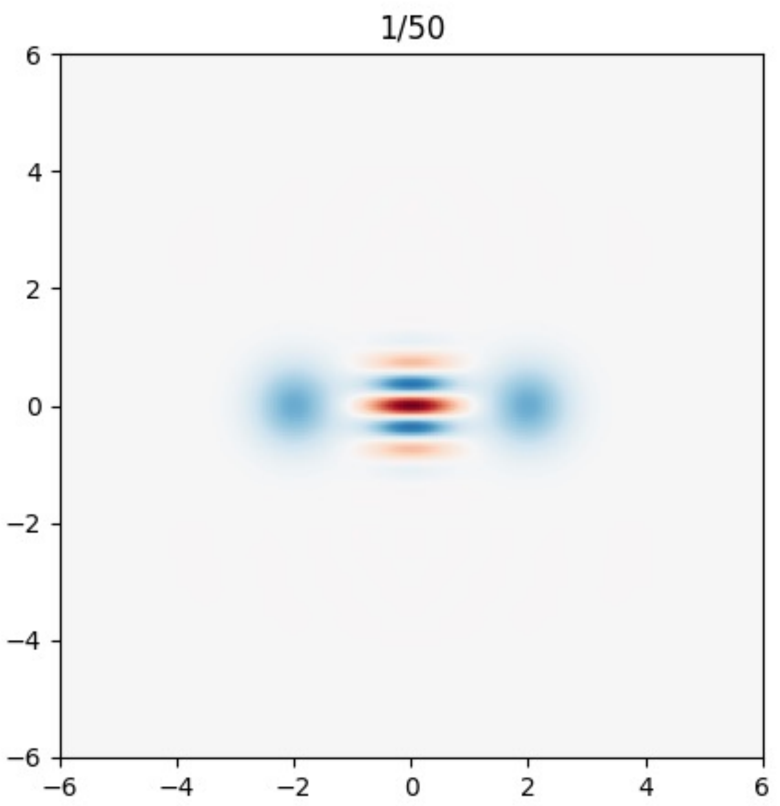
Réglade, Bocquet *et al. arXiv* (2023); Royer PRA (1977)

Mapping parity to coherent states

Even parity

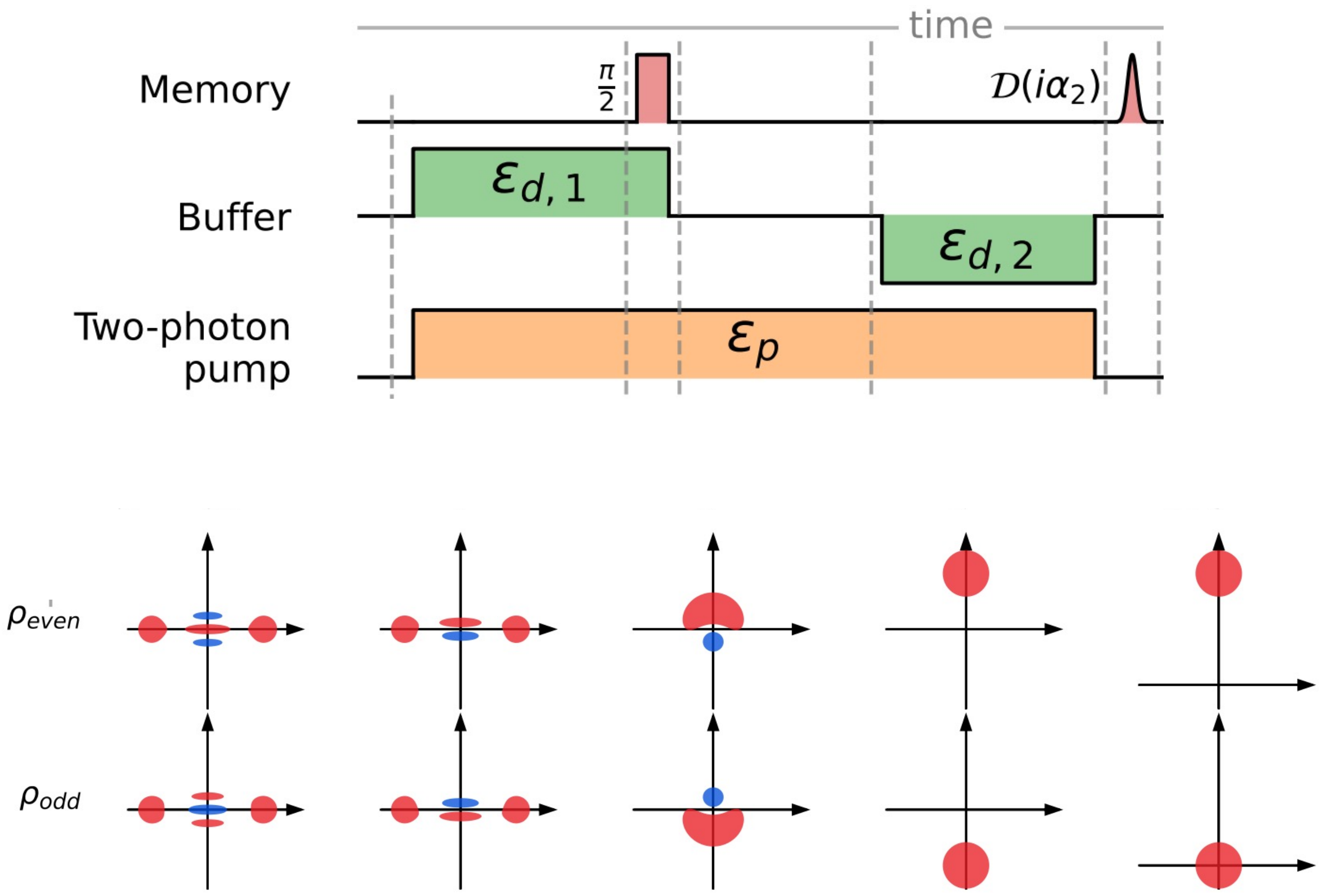


Odd parity



Réglade, Bocquet *et al.* *arXiv* (2023)

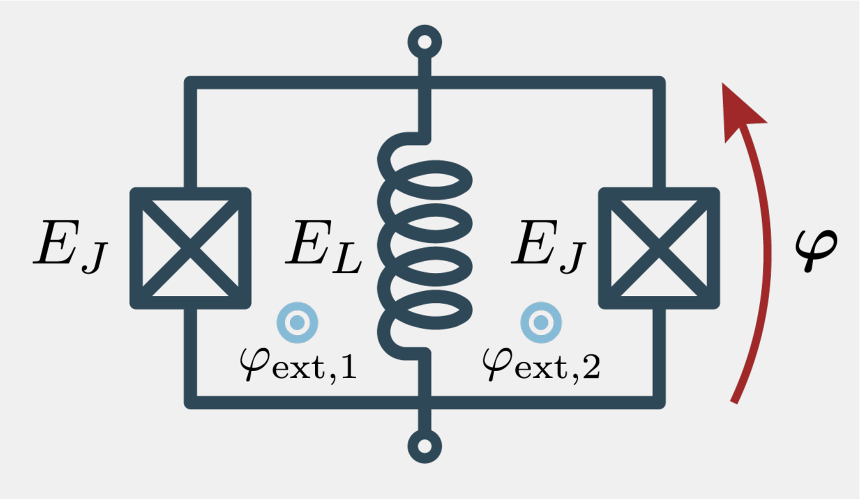
Pulse sequence



Réglade, Bocquet *et al.* *arXiv* (2023)

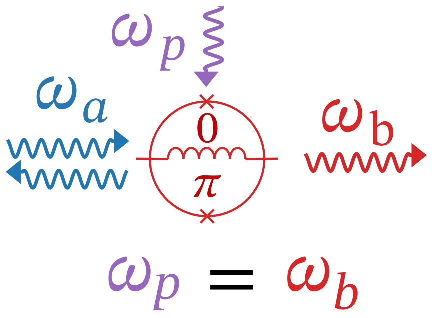
Readout of coherent states

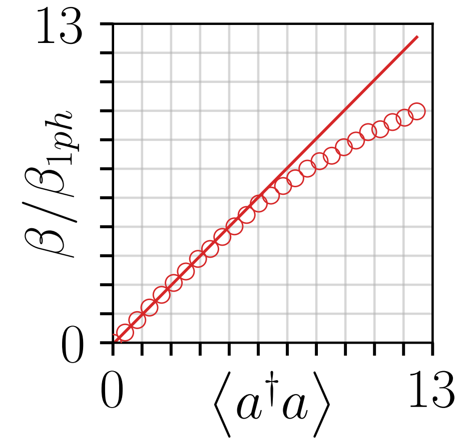
Asymmetrically Threaded SQUID



$$\omega_{\mathrm{pump}} = \omega_b \quad \Rightarrow \quad \hat{H} = g_l \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger)$$

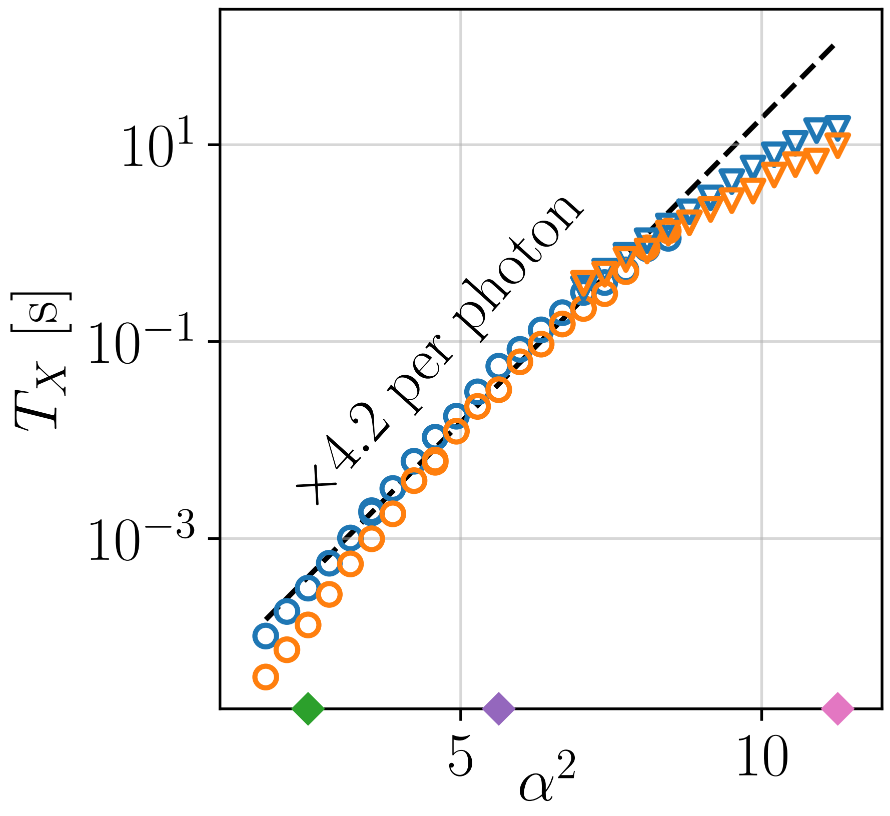
$$\begin{cases} \hat{a}^\dagger \hat{a} = 0 : \text{Buffer stays in vacuum} \\ \hat{a}^\dagger \hat{a} > 0 : \text{Buffer is displaced} \end{cases}$$

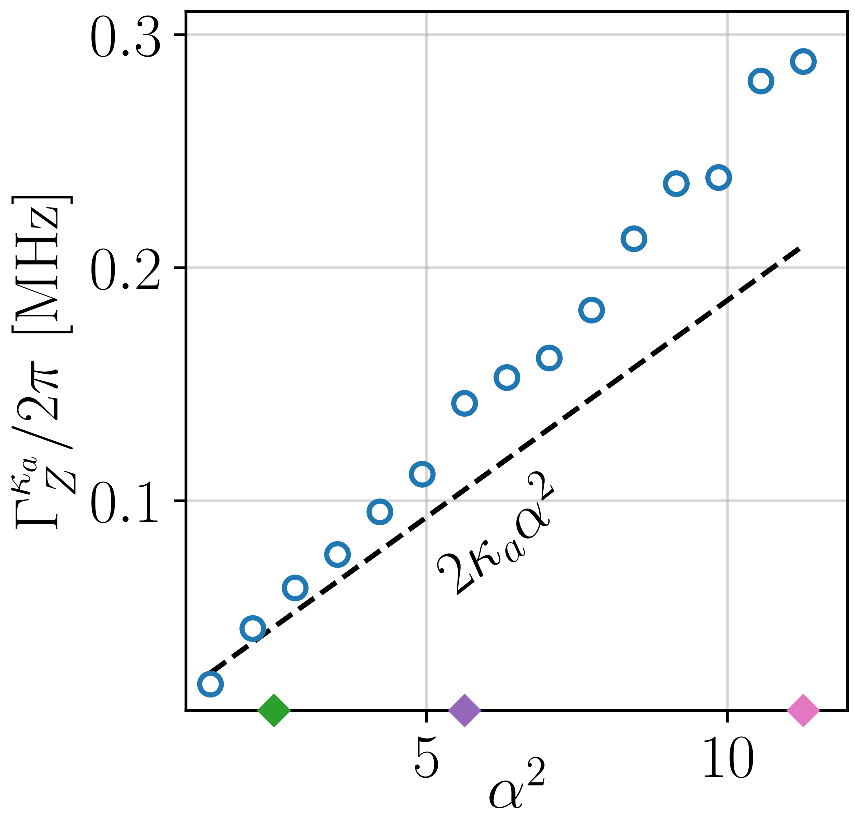




Réglade, Bocquet *et al.* *arXiv* (2023)

Exponentially biased qubits

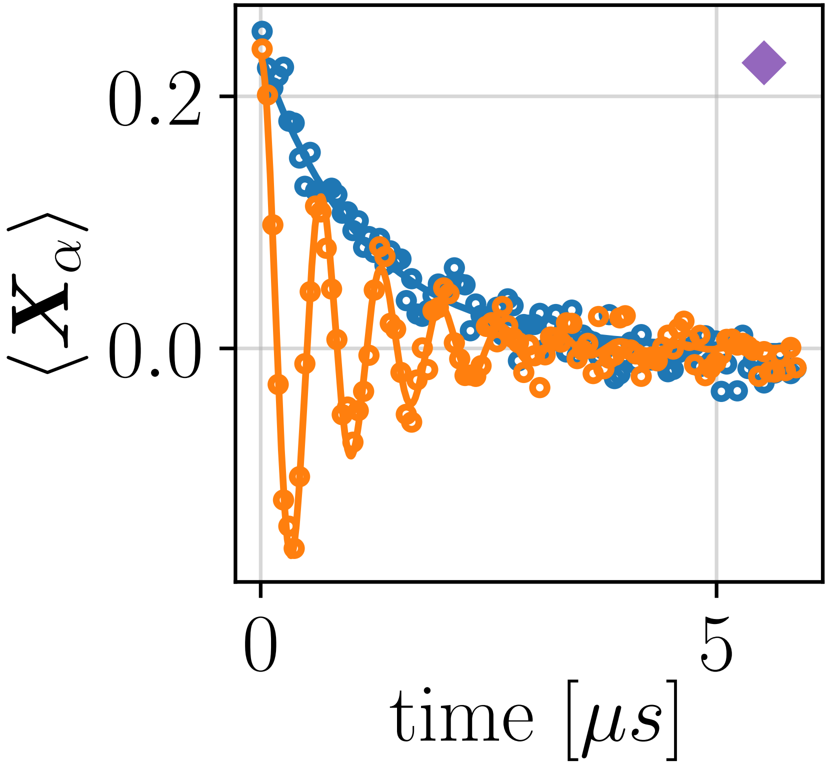




Bit lifetime at > 10 seconds !

Réglade, Bocquet *et al. arXiv* (2023)

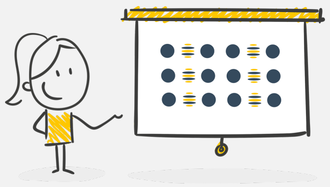
Rabi oscillations



Coherent control of interference fringes up to ~1us

Réglade, Bocquet *et al. arXiv* (2023)

Thank you for your attention!



Cat qubits are exponentially biased qubits
→ outer quantum error-correcting code with small footprint

In 2019, saturation at 1ms (transmon)
→ In 2023, lifetime at >10s

Coherent control of fringes in a bias-preserving way