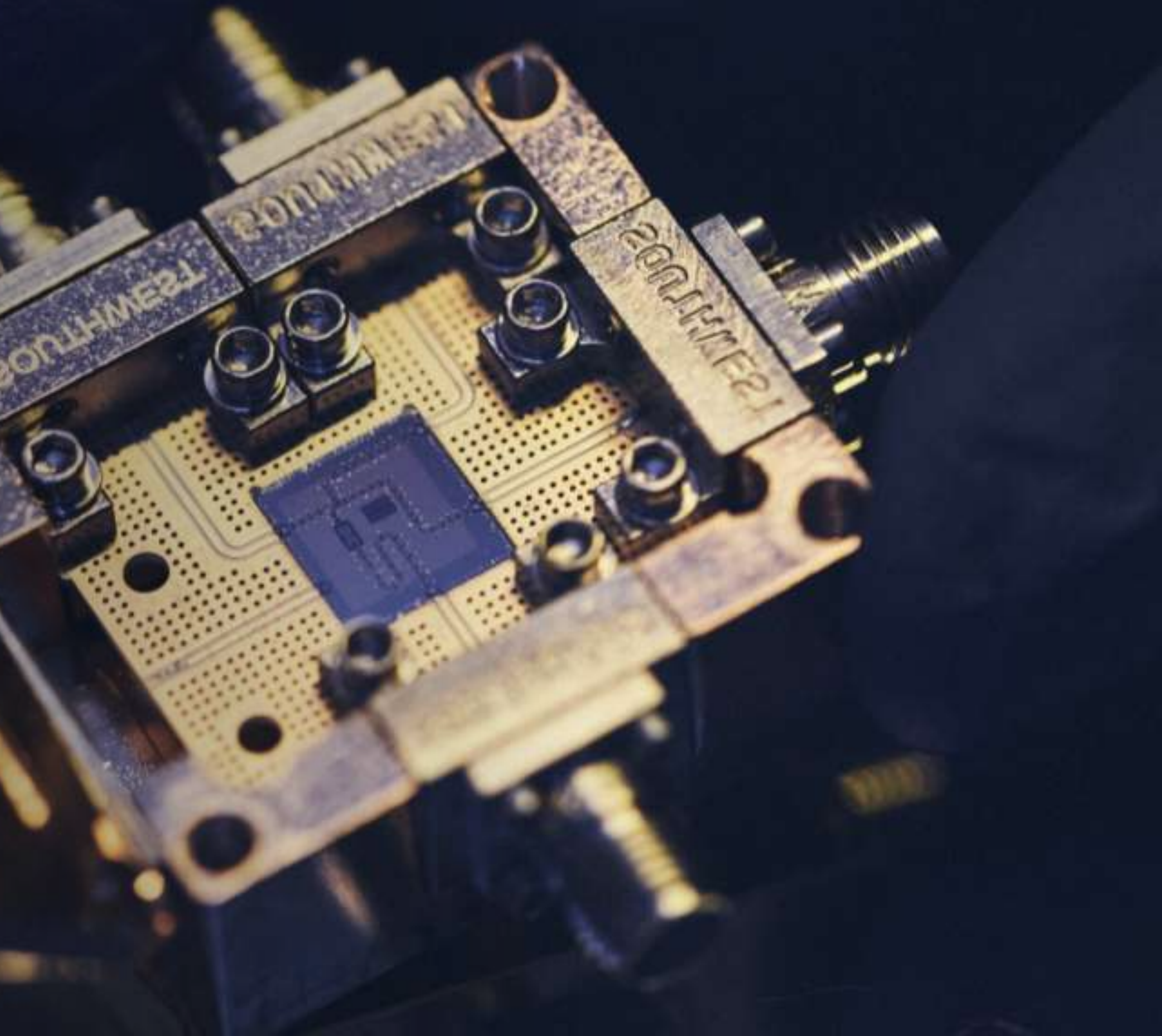
ALICE & BOB

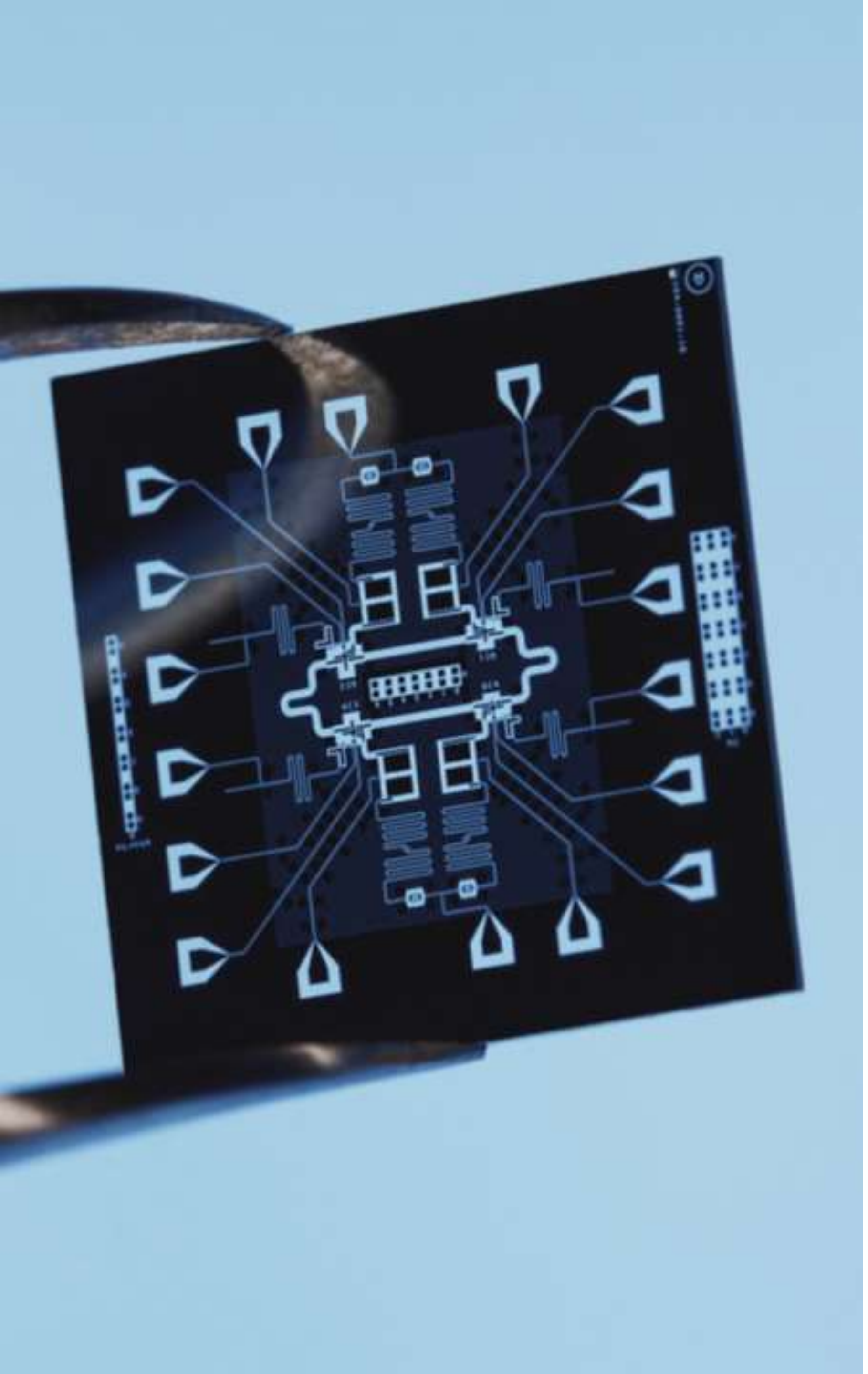
Quantum computing with dissipative cat qubits: a top-to-bottom overview



Ronan Gautier

Center for Quantum Technologies, Singapore

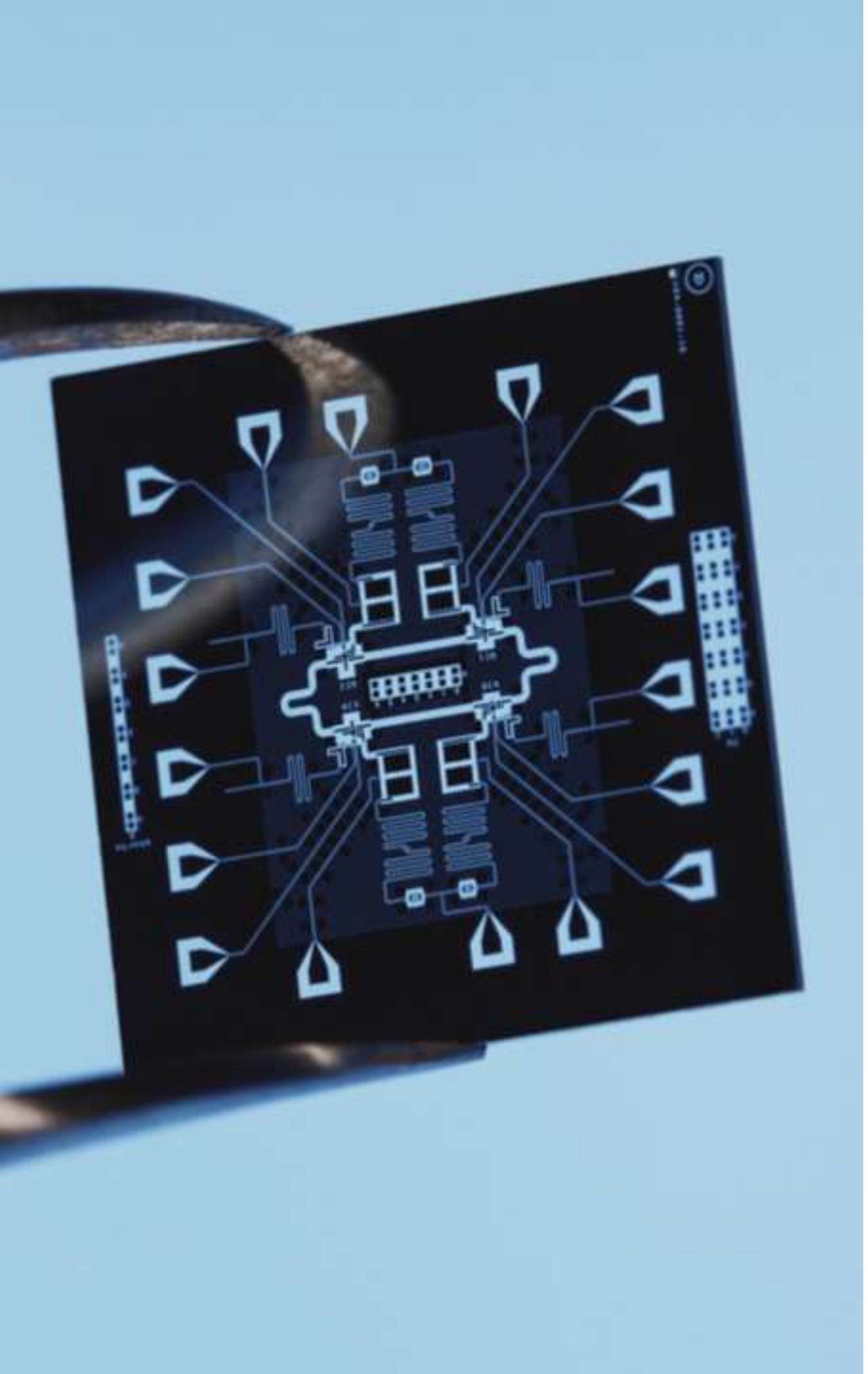
May 29th 2024



01 Quantum error correction with biased noise qubits

02 Macroscopic bit-flip times

03 Experimental progress towards a CNOT



01 Quantum error correction with biased noise qubits

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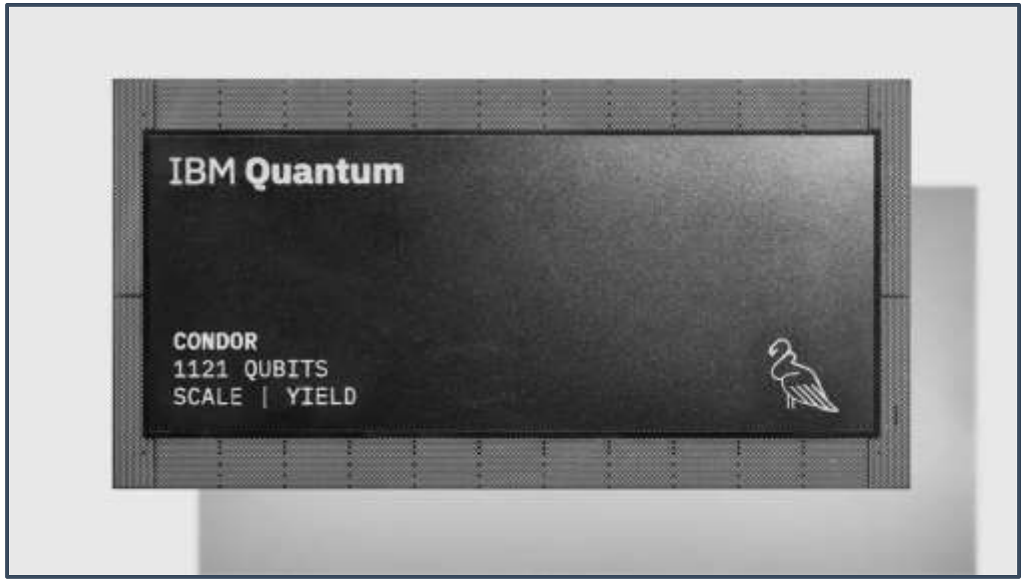
The state of quantum computing



1 Petabyte (10^{15})	**Storage**	1000 qubits
1 ps	**Gate speed**	10 ns
10^{-25}	**Gate errors**	10^{-3}

Focus on problems with exponential speed-up
Still, errors are too frequent → need 10^{-8}

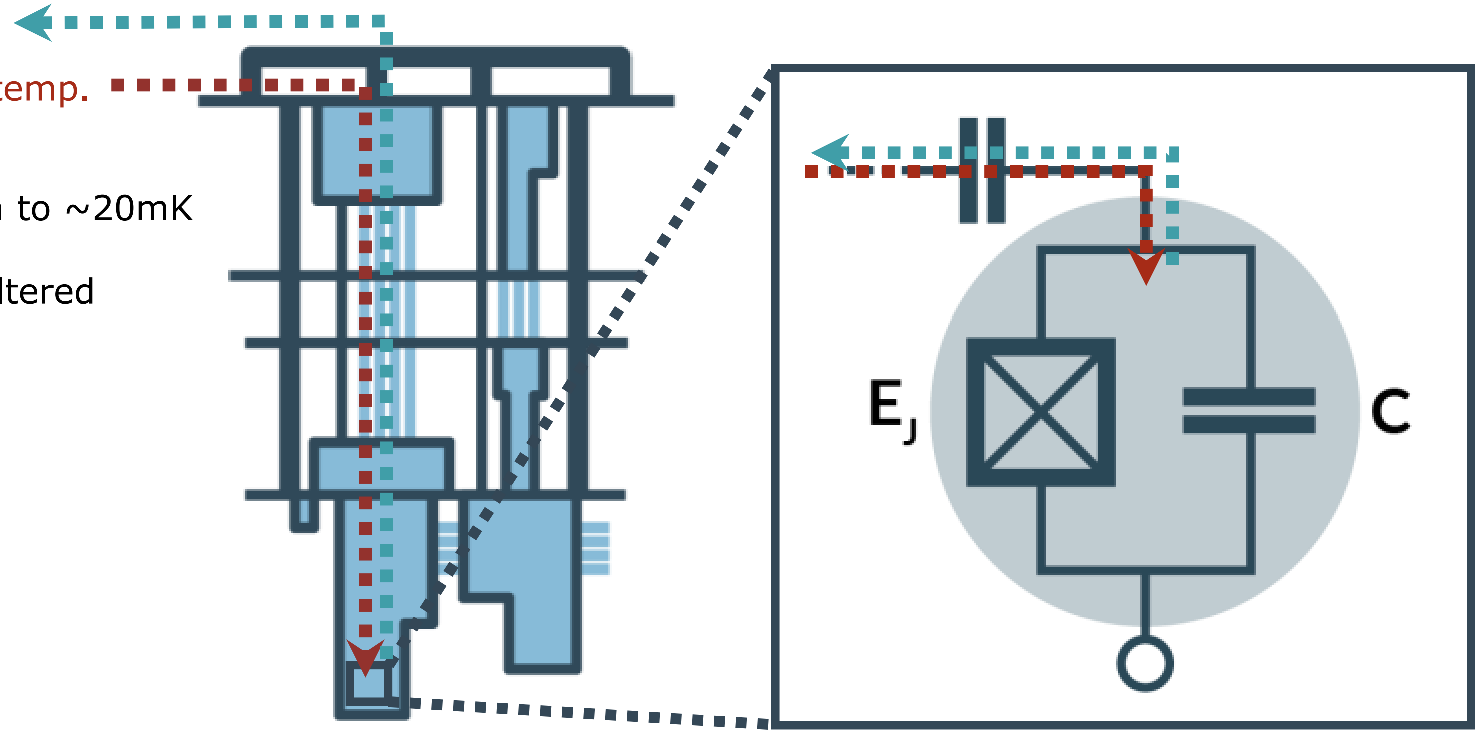
A fundamental predicament

High controllability ⟷ Long lifetime

Readout signal

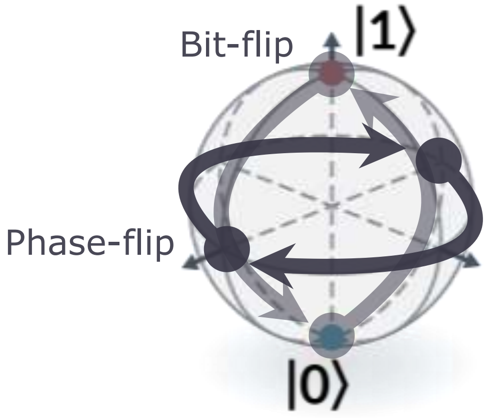
Signal @ room temp.

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



Inevitable coupling to bath

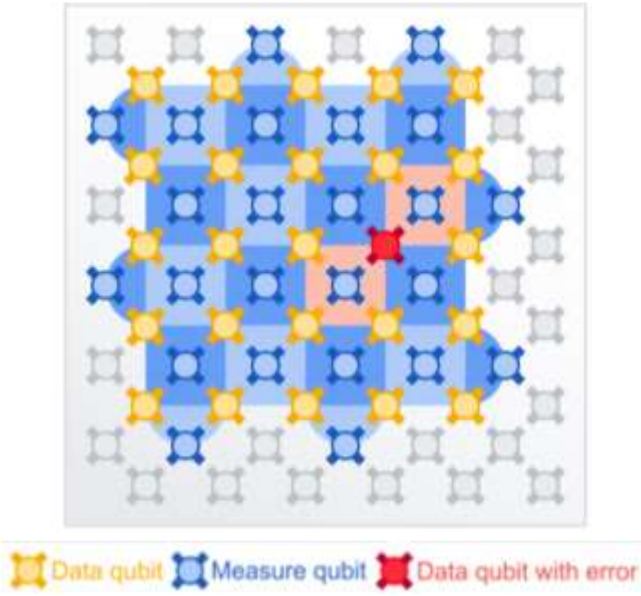
Quantum error correction



Error discretization theorem

Correcting Pauli errors =
Correcting arbitrary errors

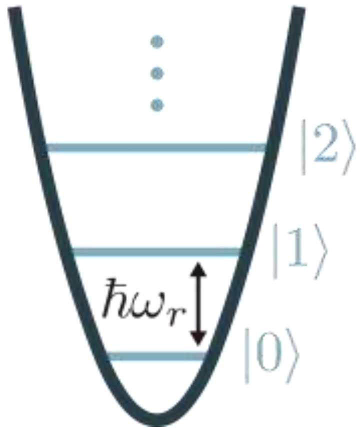
Discrete qubit codes



Google Quantum AI, Nature 2022

Bosonic codes

Quantum harmonic oscillator



P. Shor, PRA (1995); Gottesman, Kitaev, Preskill, PRA (2001)

Practical discrete error correcting codes

$[\![n, k, d]\!]$ with n: number of physical qubits
k: number of logical qubits
d: code distance

Physical constraints: 2D local codes

Bravyi Poulin Theral (BPT) bound: $kd^2 = \mathcal{O}(n)$

→ Surface code saturates the bound

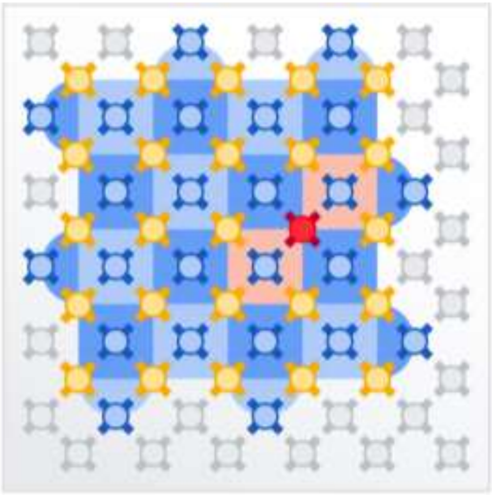
→ Solutions:
- 3D codes
- Long-range connections
- Classical codes

BPT bound for classical codes: $k\sqrt{d} = \mathcal{O}(n)$

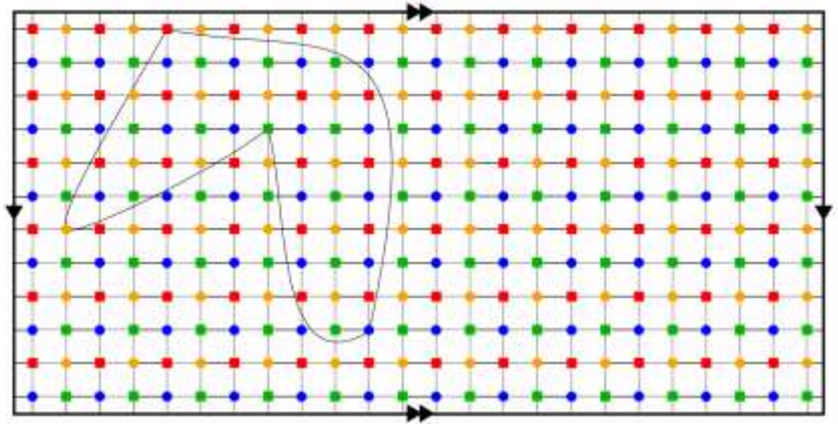
→ In practice, d ~ 10-30

- *Quantum code*: 100-900 physical/logical
- Classical code: **3-6 physical/logical**

$[\![5, 1, 25]\!]$



Google Quantum AI, Nature 2022



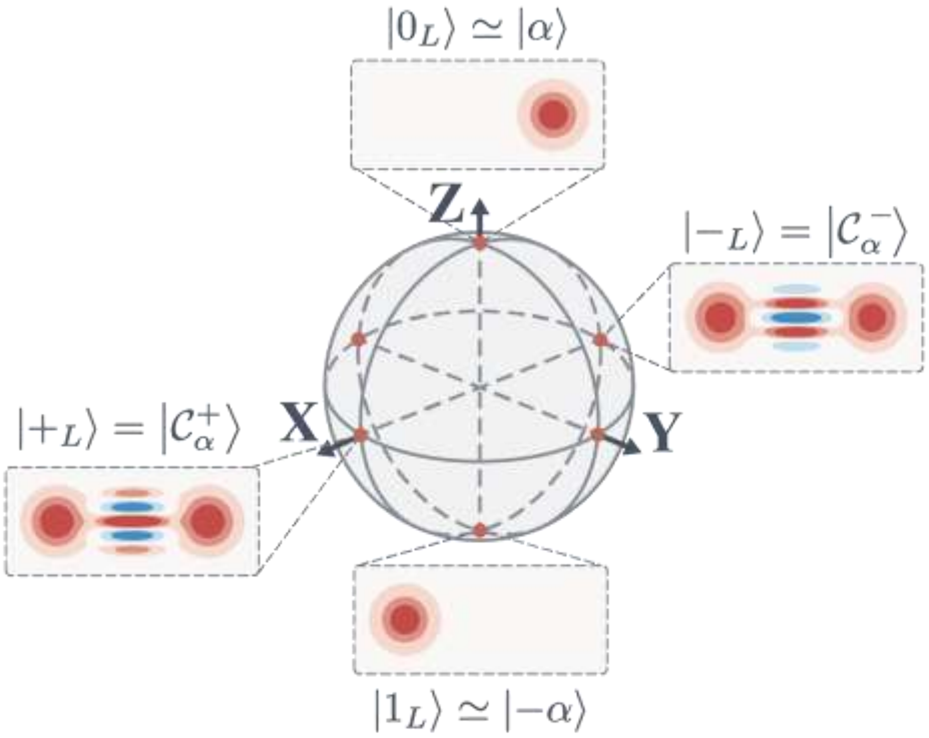
S. Bravyi et al., arXiv 2023

Bravyi, Poulin, Theral, PRL (2009); D. Ruiz et al., arXiv (2024)

Can we afford a classical code?

Need biased-noise qubits: $p_X, p_Y \ll p_Z$

- Small bias → erasure codes (dual-rail), biased quantum codes (XZZX)
- Large bias → classical codes (cat qubits)



Cat qubits: bosonic code with non-local encoding

Fermi's golden rule:

- $\Gamma_Z \propto |\langle -\alpha|H|\alpha\rangle|^2 \propto \exp(-2|\alpha|^2)$
- $\Gamma_X \propto \kappa_1|\alpha|^2$

Two well-known stabilisation schemes:

- Kerr cats → Better gates, limited by thermal noise
- Dissipative cats → More inertia, high bias

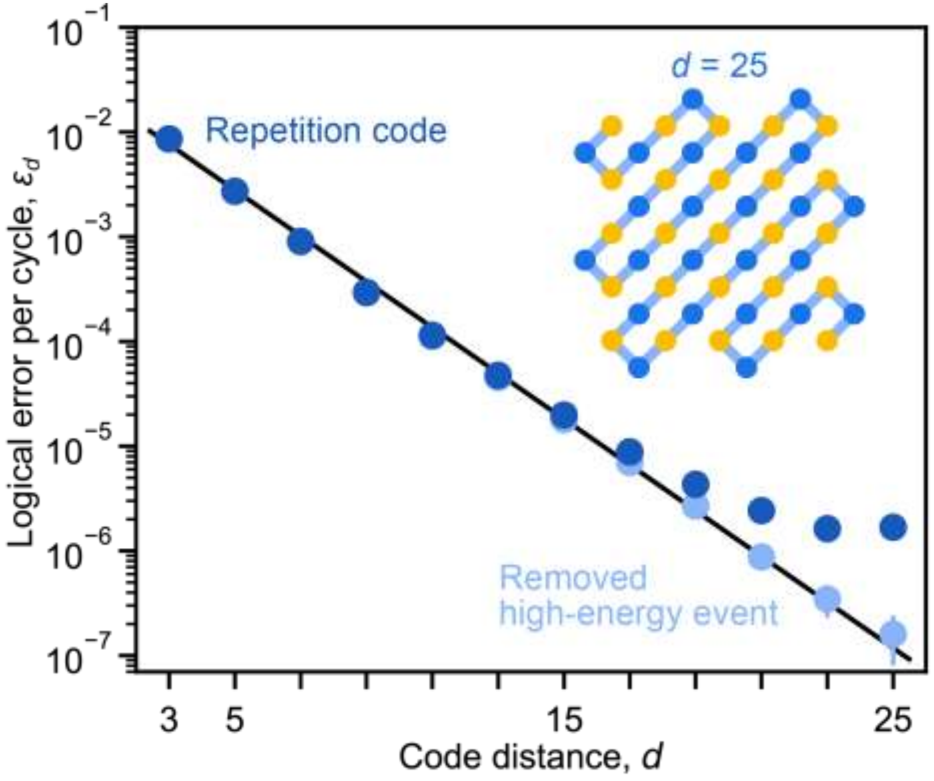
→ Combined cats (**RG** et al., PRXQ 2022)

Is bias enough to afford a classical code?

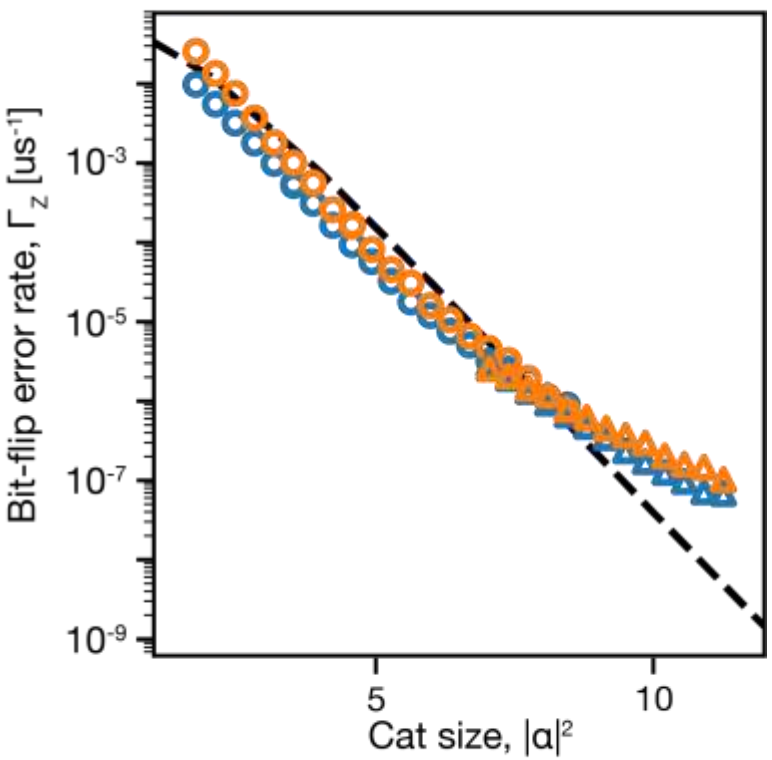
Mirrahimi et al., NJP (2014); Puri et al., npj QI (2017)

A hardware-efficient repetition code

Google Quantum AI, Nature 2022



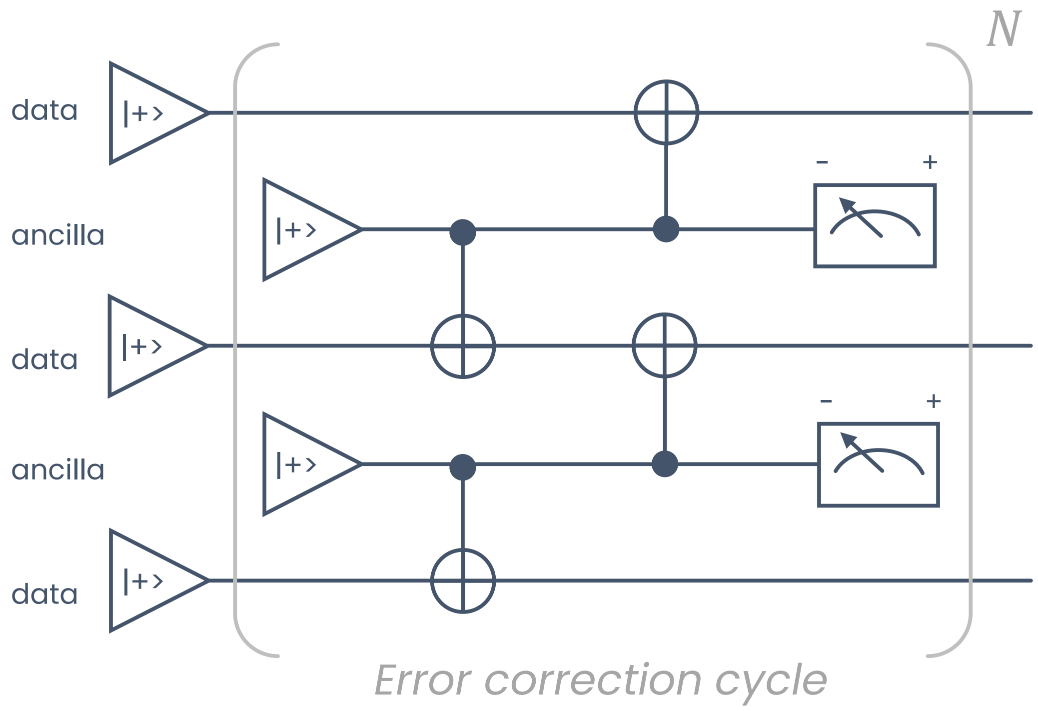
Réglade, Bocquet et al., arXiv 2024



Dissipative cat qubit = bit-flip repetition code

Repetition code error correction cycle

Need to correct phase-flip errors



Logical states: $|+_L\rangle = |+ + \cdots +\rangle, |-_L\rangle = |- - \cdots -\rangle$

Logical operators: $Z_L = \bigotimes_i Z_i$ and $X_L = X_i$

Stabilizer: $S_i = X_i X_{i+1}$

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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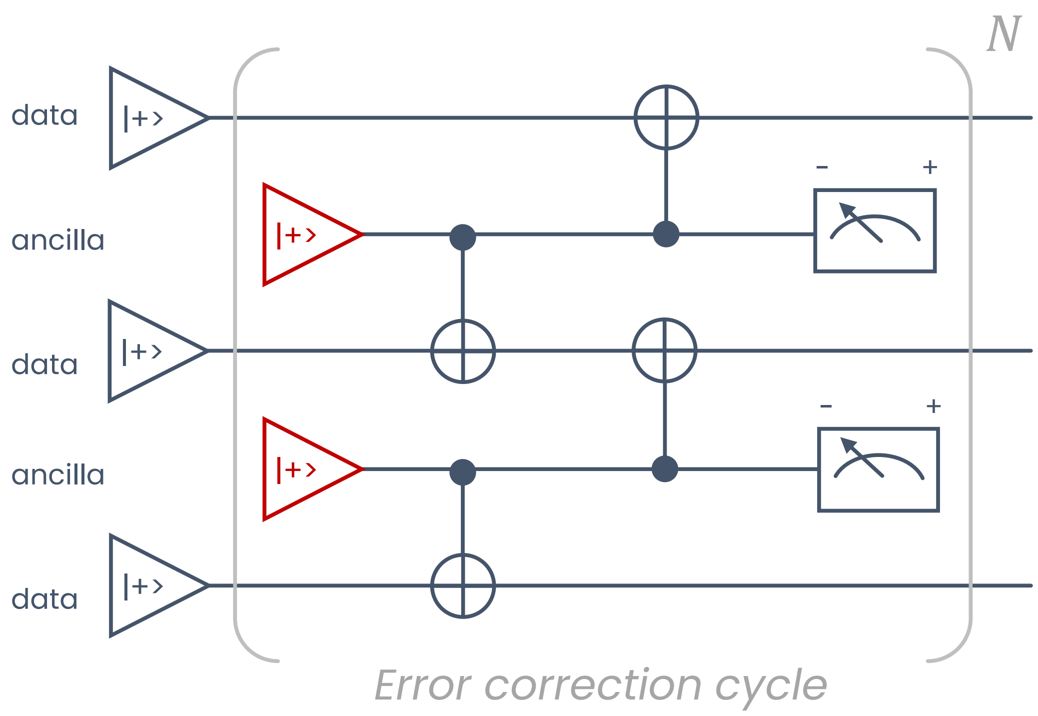

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Repetition code ingredients

- +/- state preparation

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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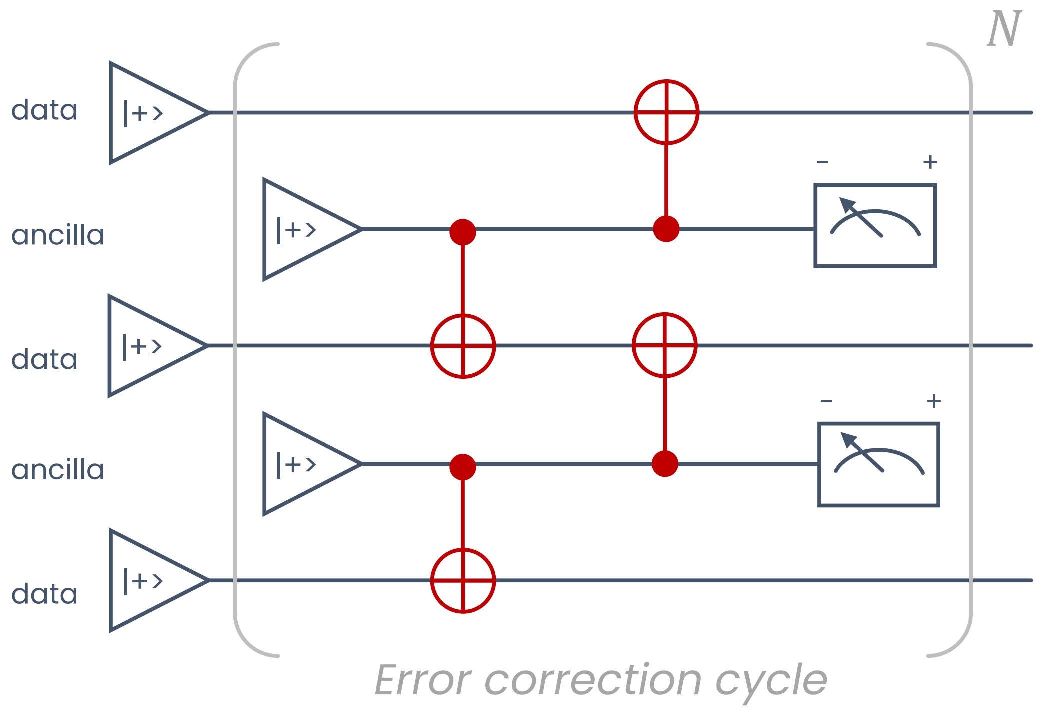

Repetition code ingredients

- +/- state preparation
- CNOT gate

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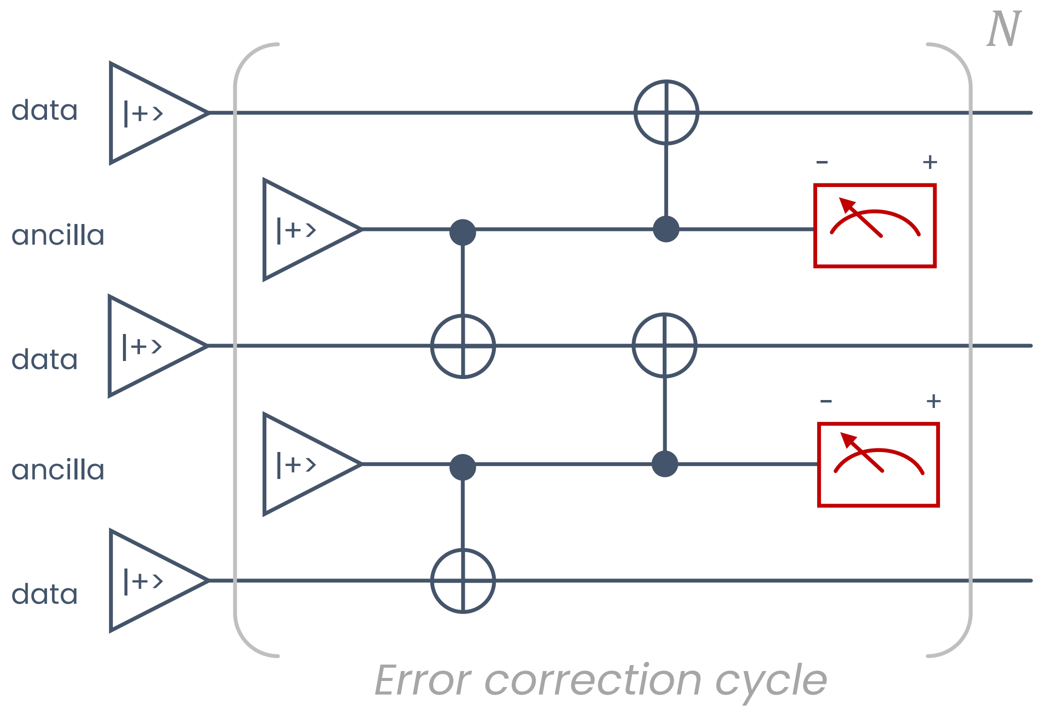

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- +/- state preparation
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Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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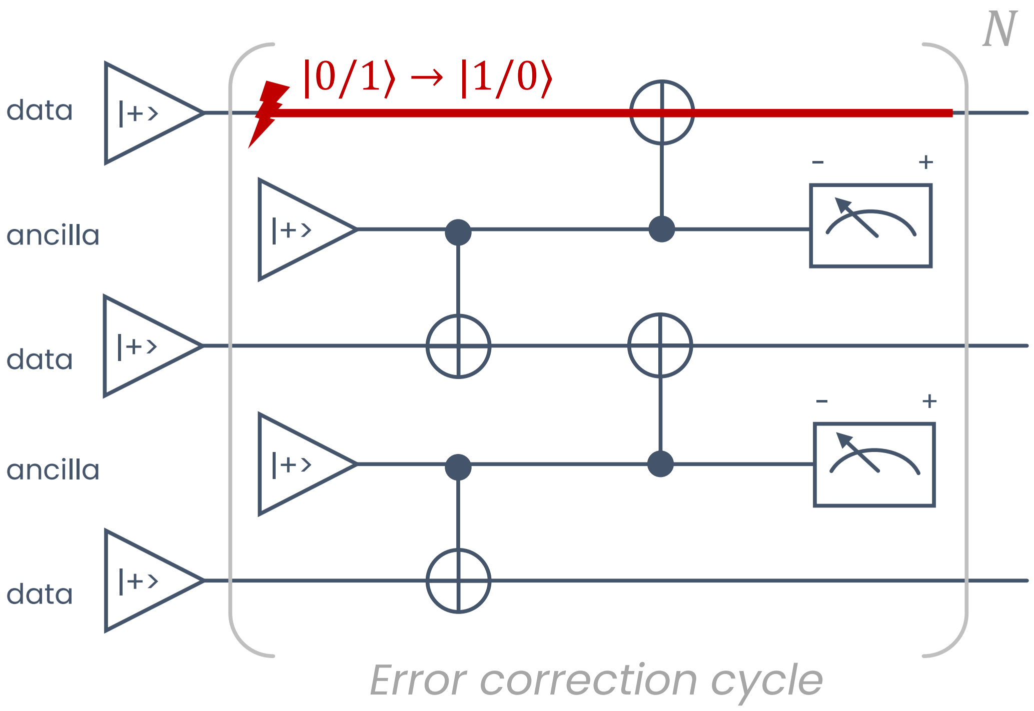

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Bit-flip requirements

- Data bit-flips must be exponentially suppressed: **data noise bias**

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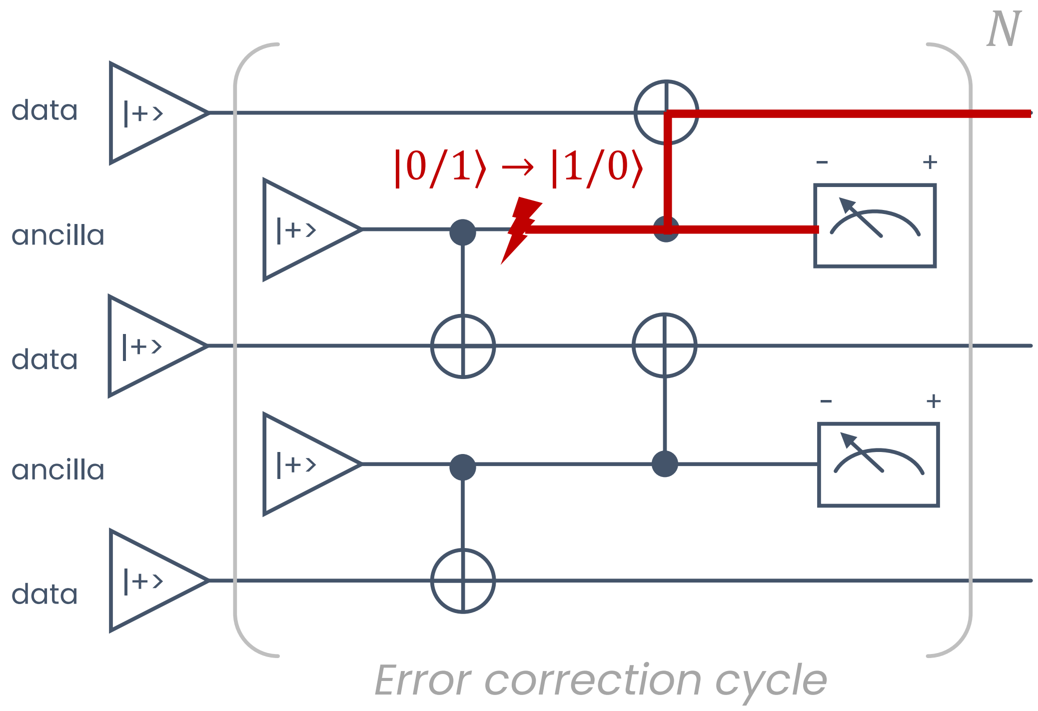

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Repetition code error correction cycle

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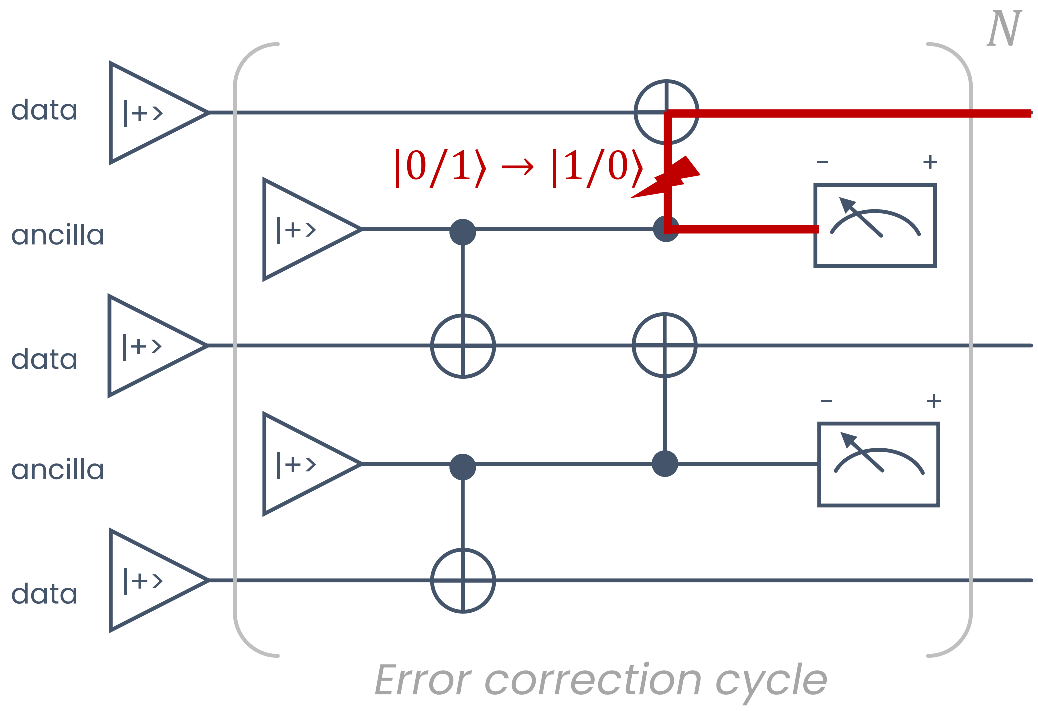

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Guillaud & Mirrahimi, PRX 9, 041053 (2019)

Repetition code error correction cycle

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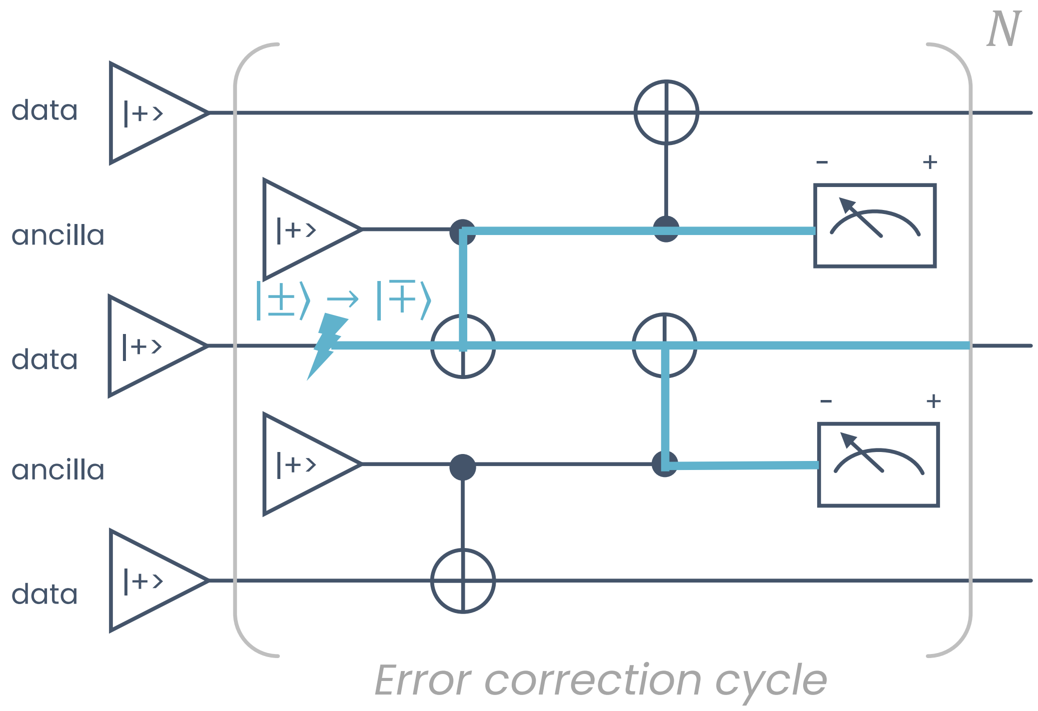

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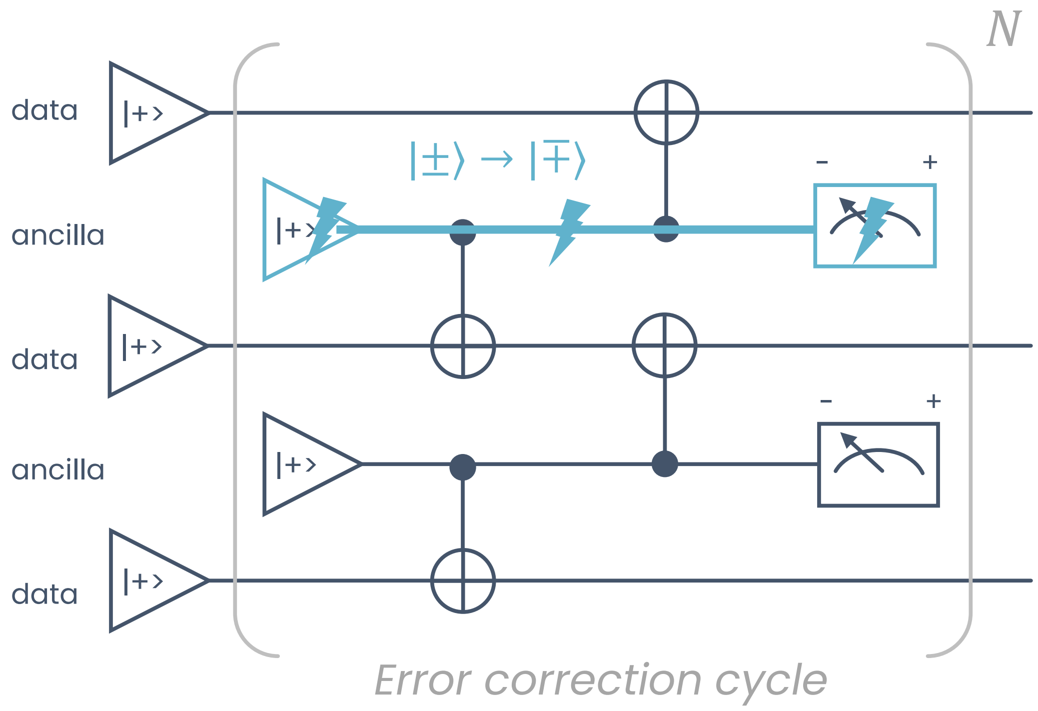
Phase-flip metrics

- Data phase-flip probability: p_{ZD}

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

Repetition code error correction cycle

Need to correct phase-flip errors



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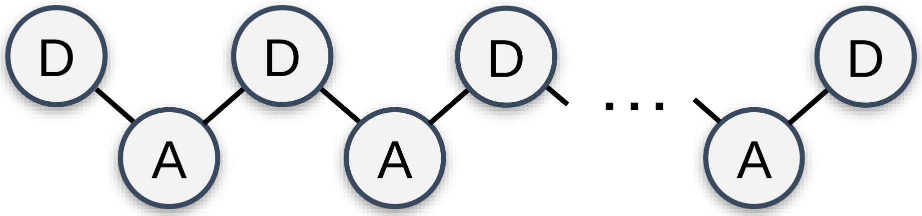
Phase-flip metrics

- Data phase-flip probability: p_{ZD}
- Total error detection failure probability: p_{ZA}

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

Repetition code threshold

d data qubits



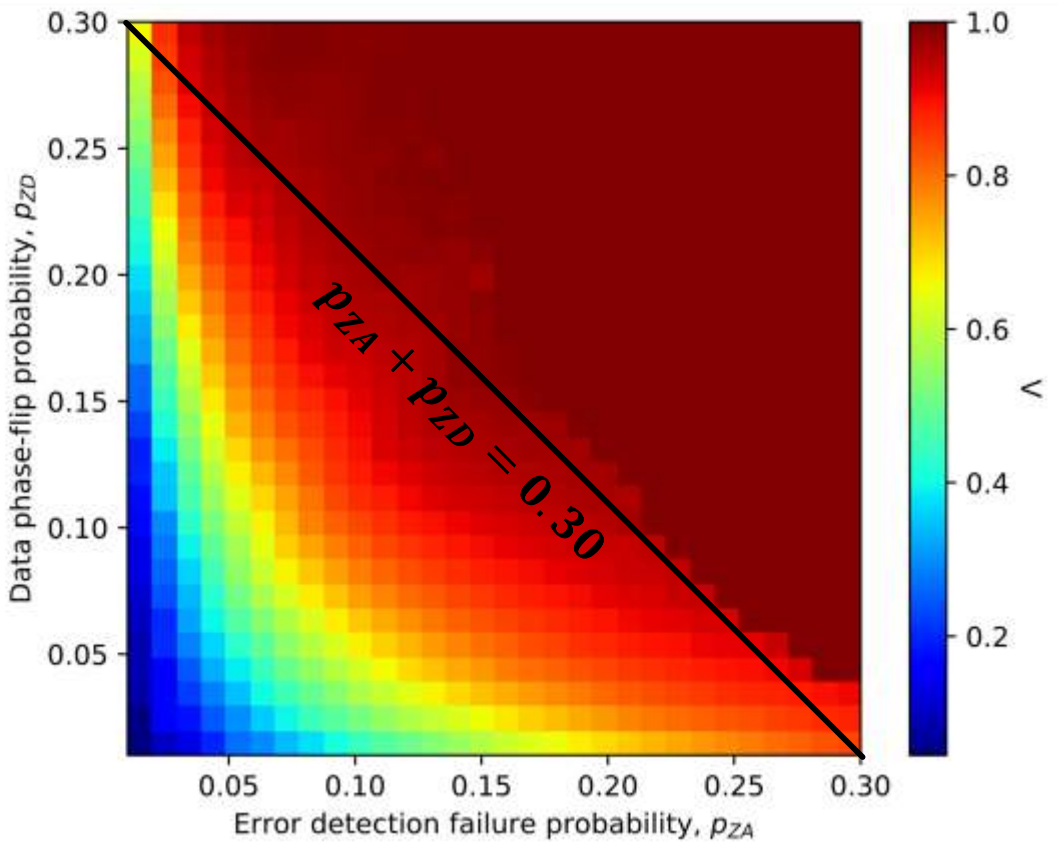
Practical threshold definition:

→ Logical error scales as $p_{ZL} \propto \Lambda^{d/2}$

→ $\Lambda = 1$ when fitted for $d \leq 19$

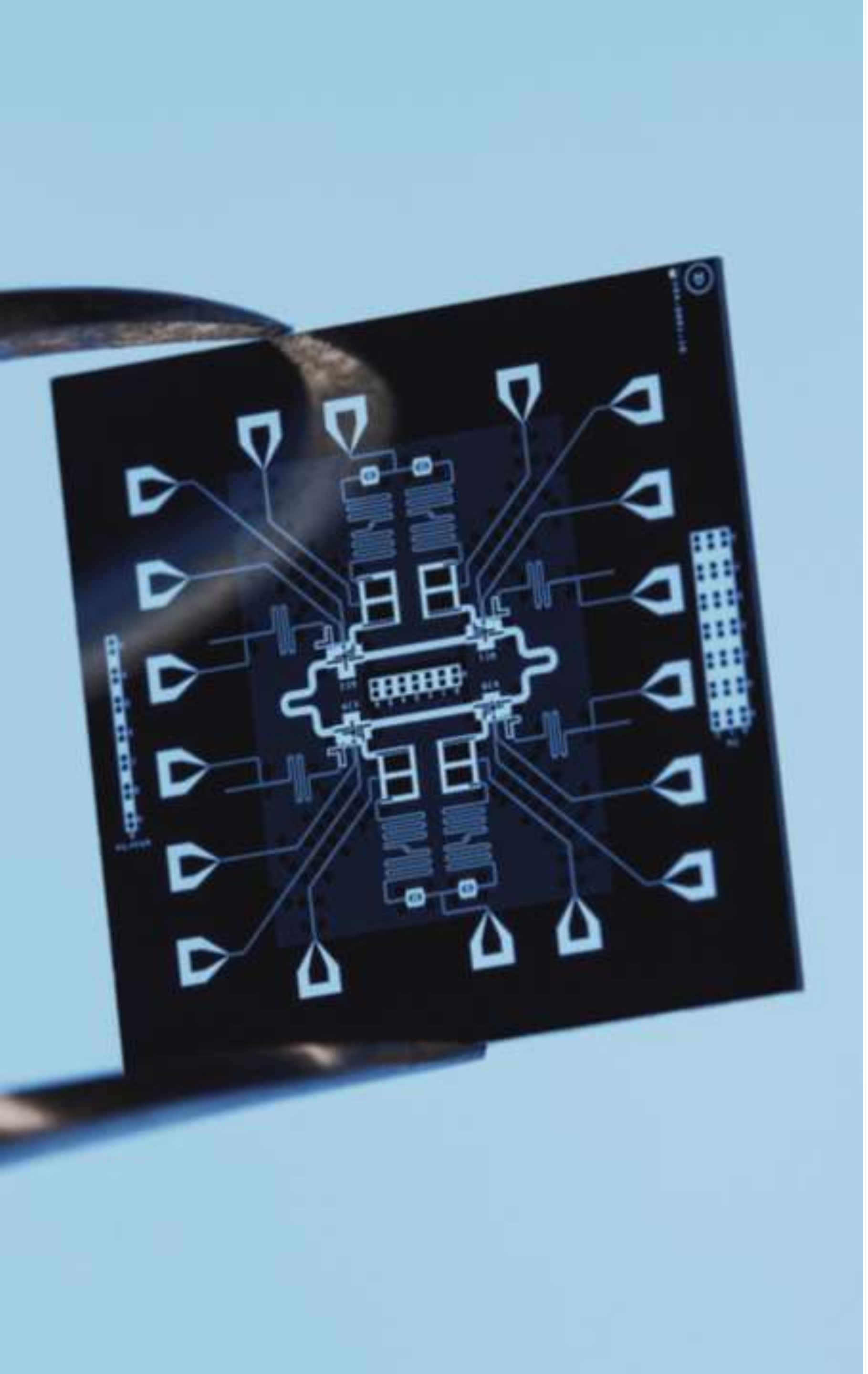
→ Only requires $p_{ZA} + p_{ZD} \leq 0.30$

→ Favours ancilla/data error assymetry



Repetition code is very forgiving

Le Régent et al., Quantum 7, 1198 (2023)



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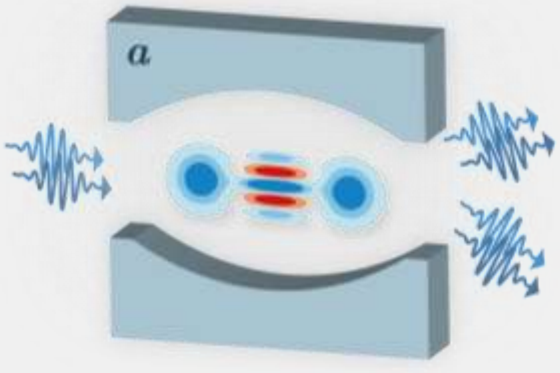
Reservoir engineering of two-photon dissipation

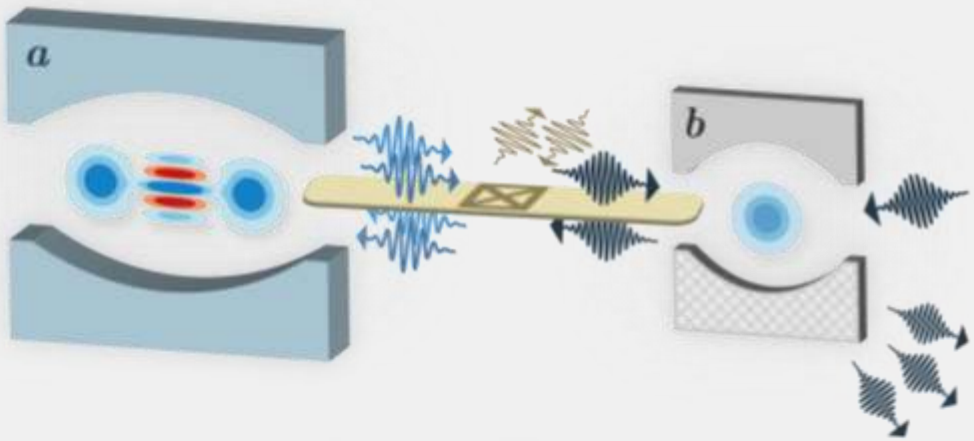
Memory

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



Memory + Buffer

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

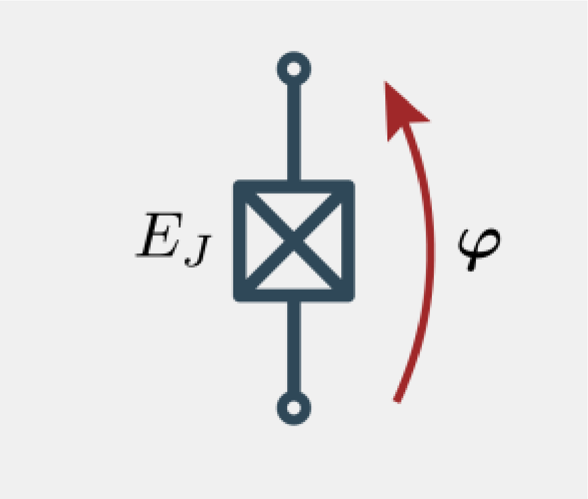


Requires parametric four-wave mixing

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

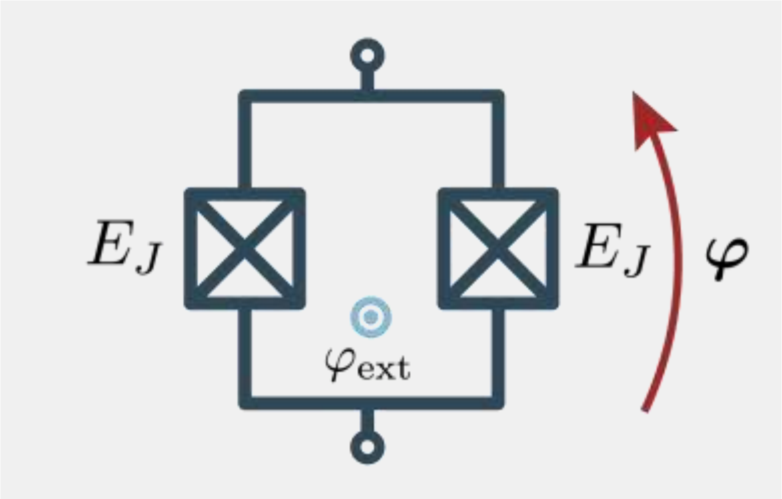
Parametric four-wave mixing

Josephson Junction



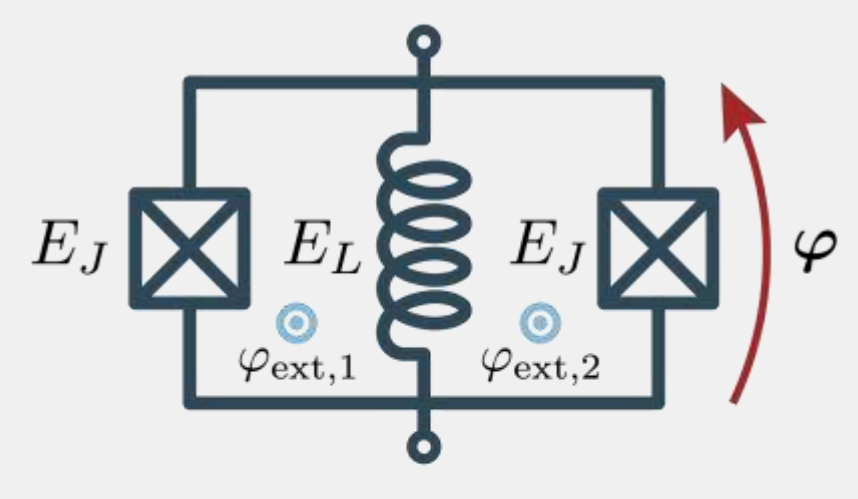
$$\hat{H} = -E_J \cos(\hat{\varphi})$$

SQUID



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

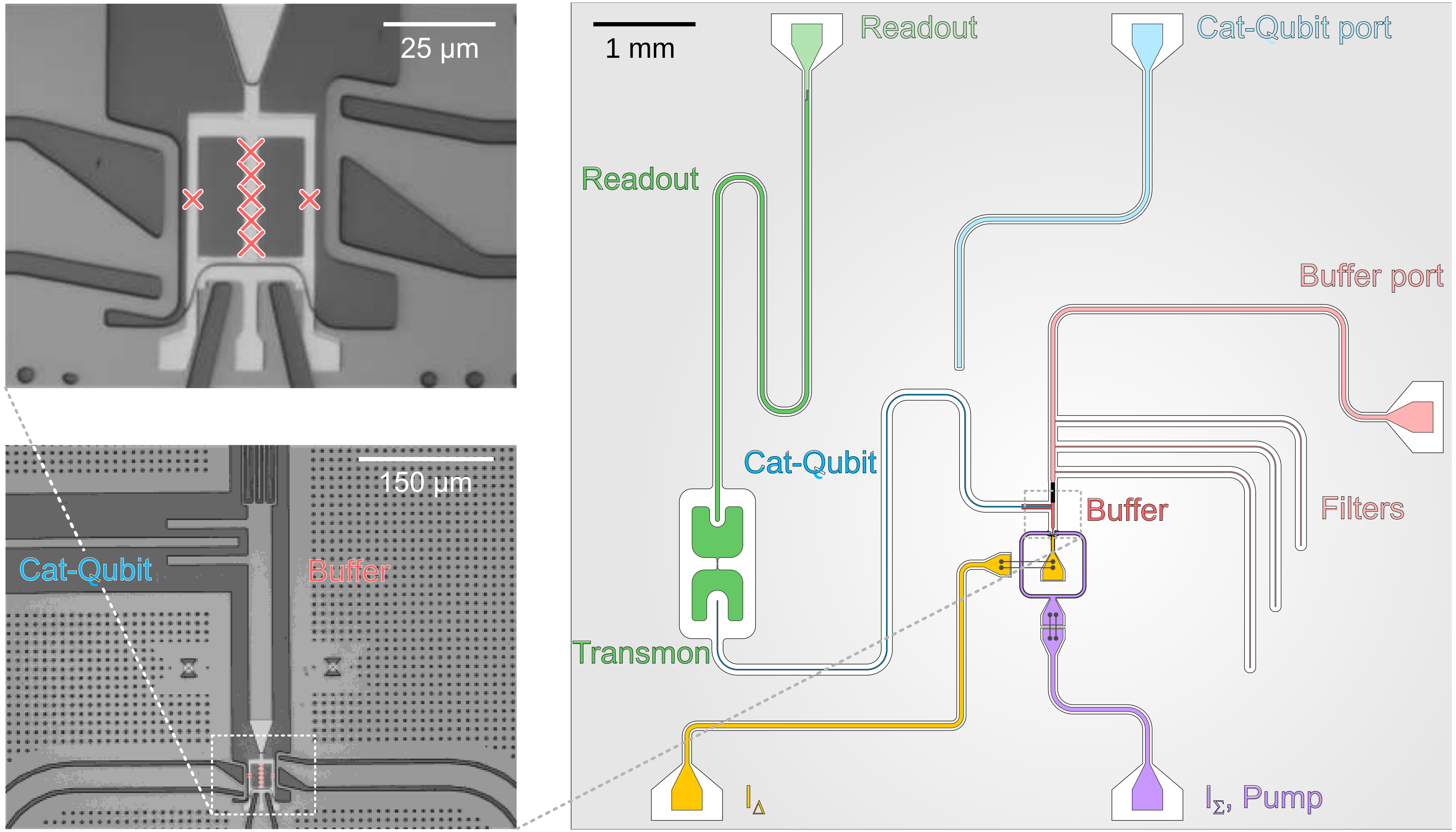
Asymmetrically Threaded SQUID



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

Lescanne et al. Nat. Phy. (2019)

Experimental setup



Lescanne et al. Nat. Phy. (2019)

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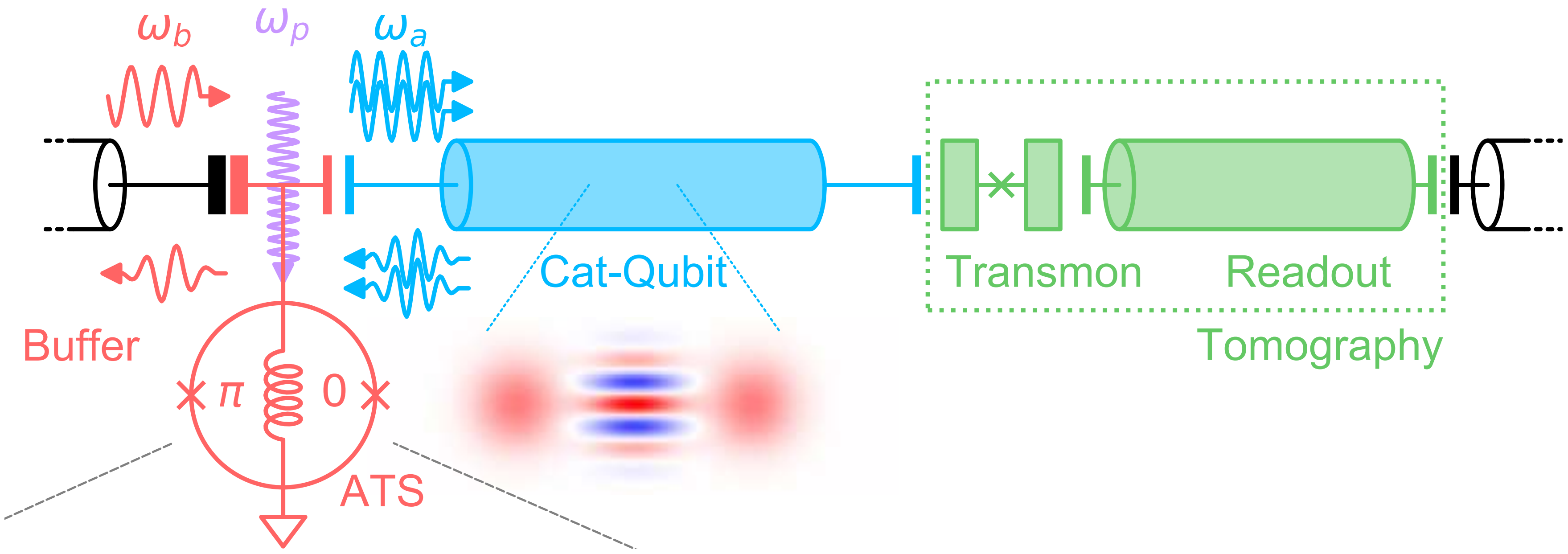
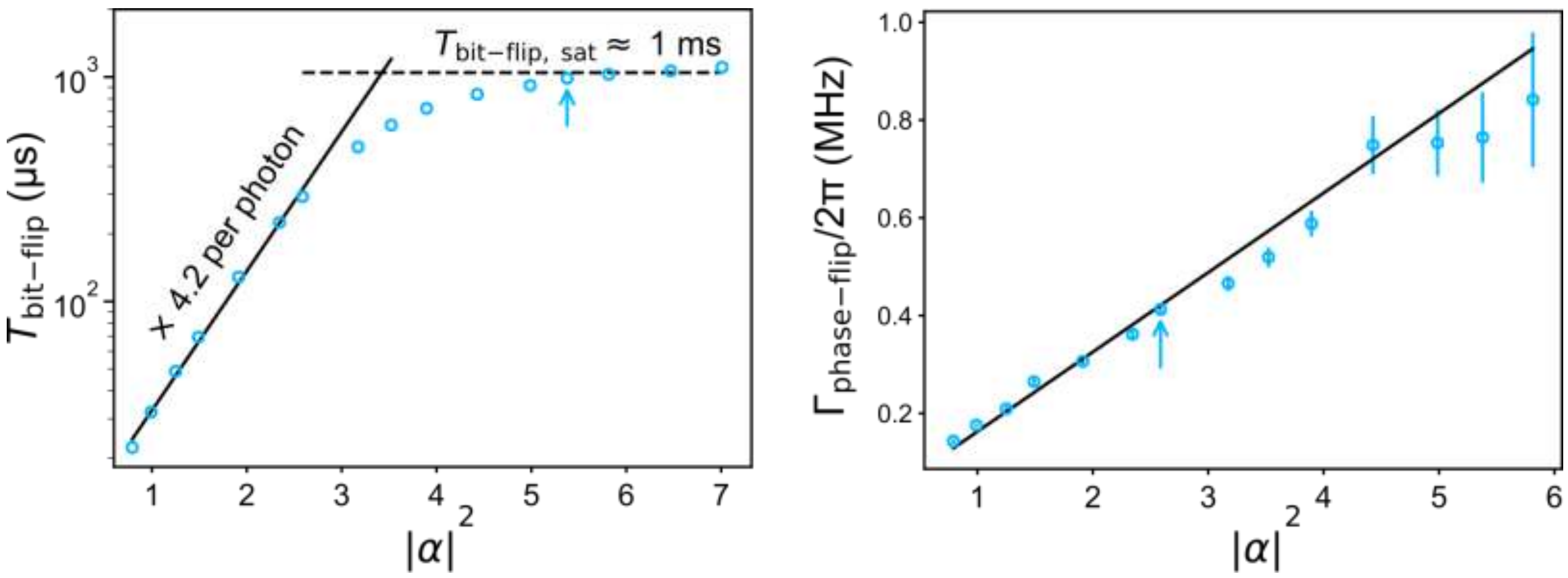


Lescanne et al. Nat. Phy. (2019)

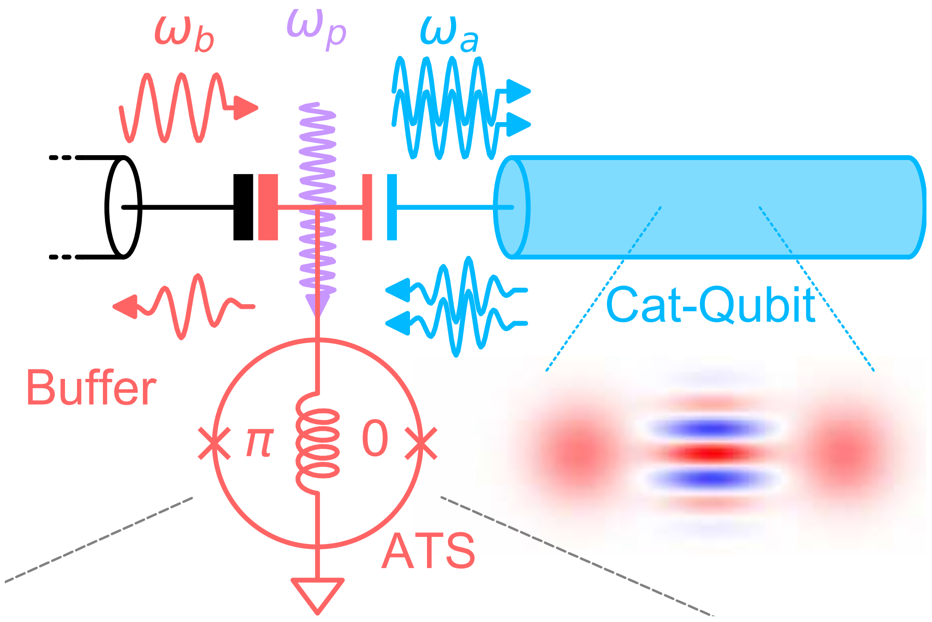
Transmon-induced saturation



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

Lescanne et al. Nat. Phy. (2019)

Transmon-free experimental setup



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 $\hat{P} = e^{i\pi \hat{a}^{\dagger}\hat{a}}$

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

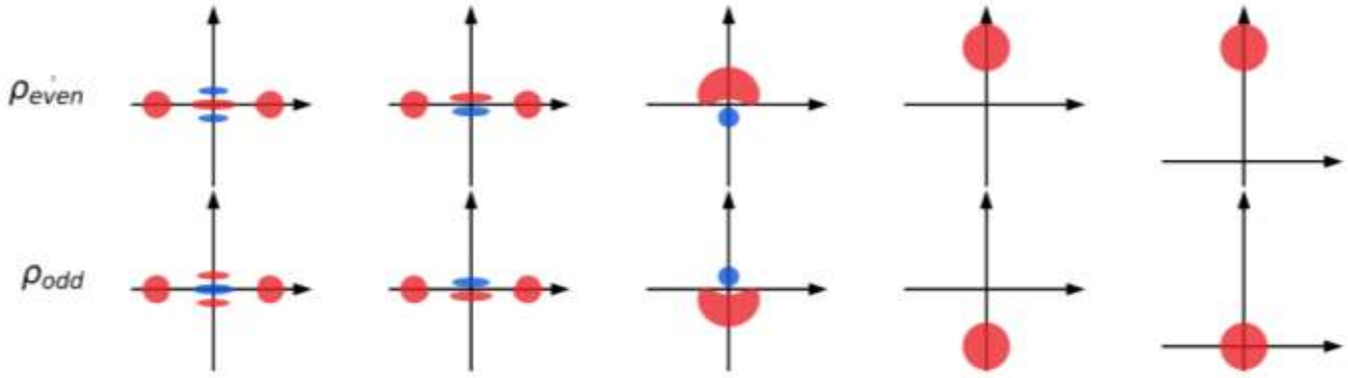
Four-step process:

(1) Displace initial state

(2) Map to cat states while preserving parity (two-ph. diss)

(3) Map parity to coherent states

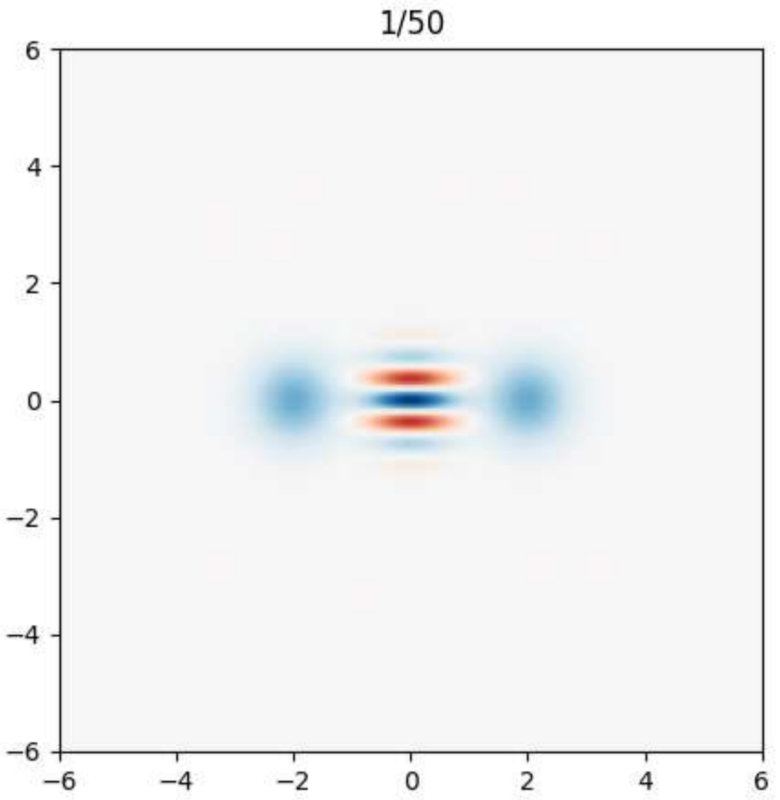
(4) Readout coherent states



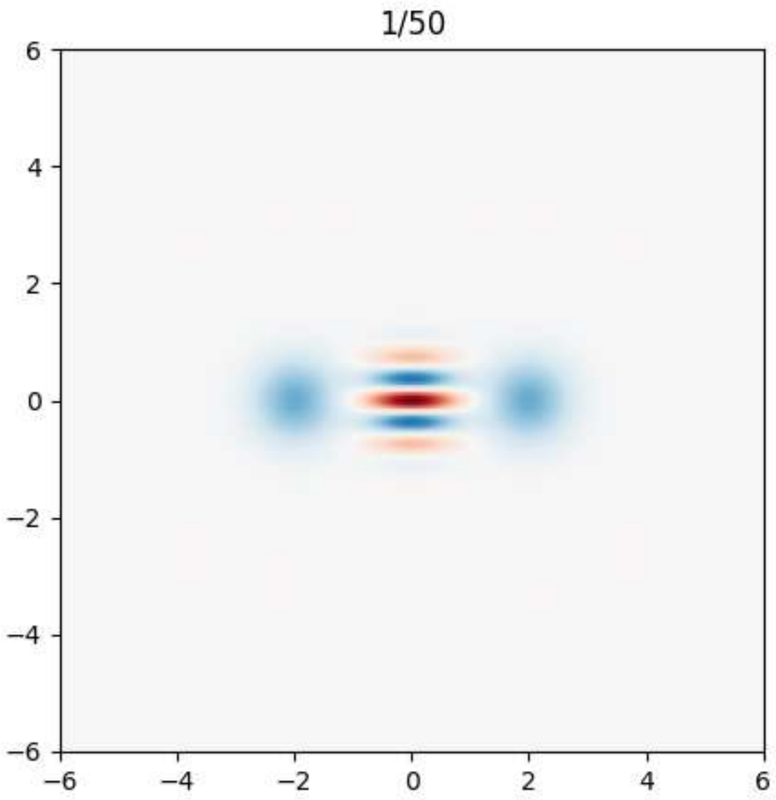
Réglade, Bocquet et al. arXiv (2023); Royer PRA (1977)

Mapping parity to coherent states

Even parity

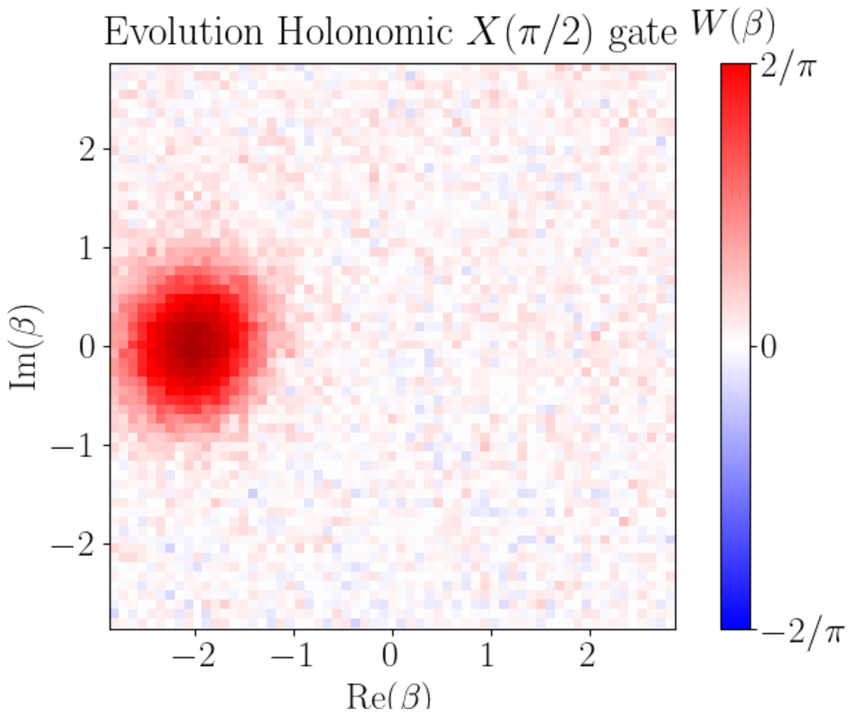


Odd parity



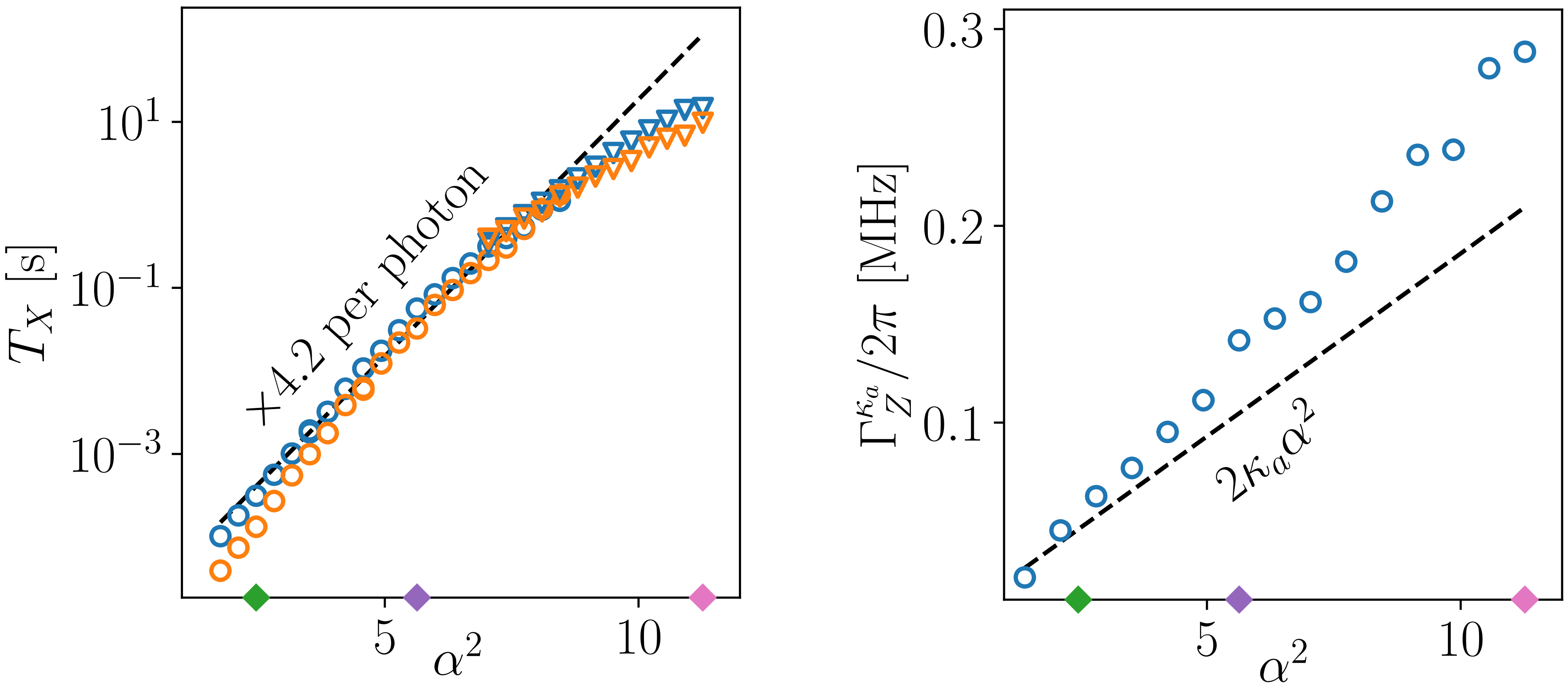
Réglade, Bocquet et al. arXiv (2023); V. Albert et al. PRL (2016)

Readout protocol



Réglade, Bocquet et al. arXiv (2023); V. Albert et al. PRL (2016)

Exponentially biased qubits

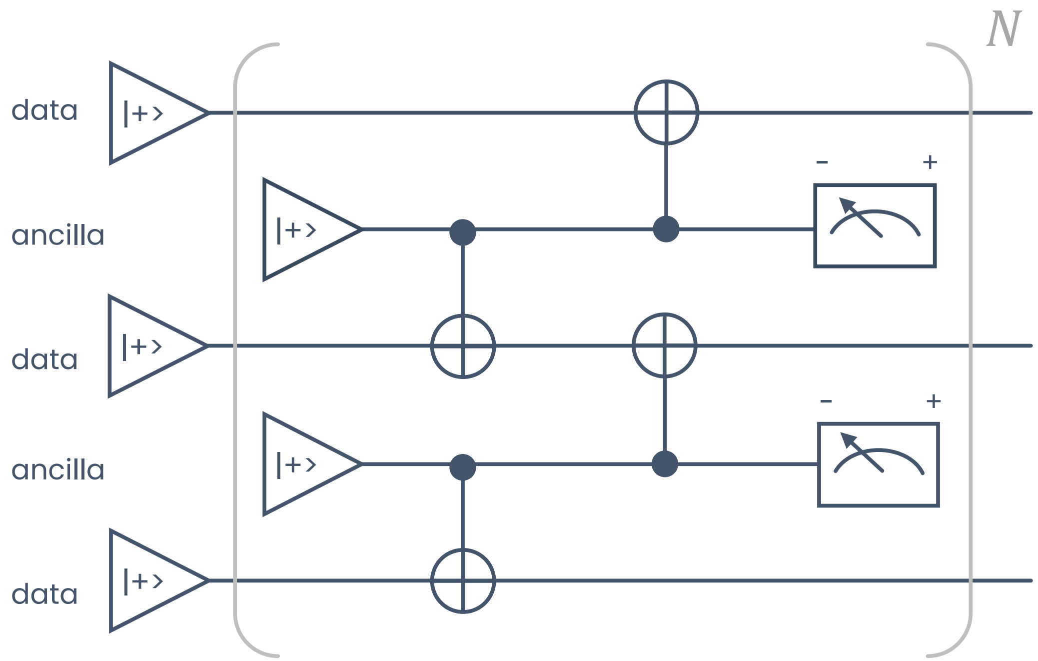


Bit lifetime at > 10 seconds !

Réglade, Bocquet et al. arXiv (2023)

Repetition code error correction cycle

Need to correct phase-flip errors



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Repetition code ingredients

- ✓ +/- state preparation
- CNOT gate
- ✓ Parity measurement

Bit-flip requirements

- ✓ Data bit-flips must be exponentially suppressed: **data noise bias**
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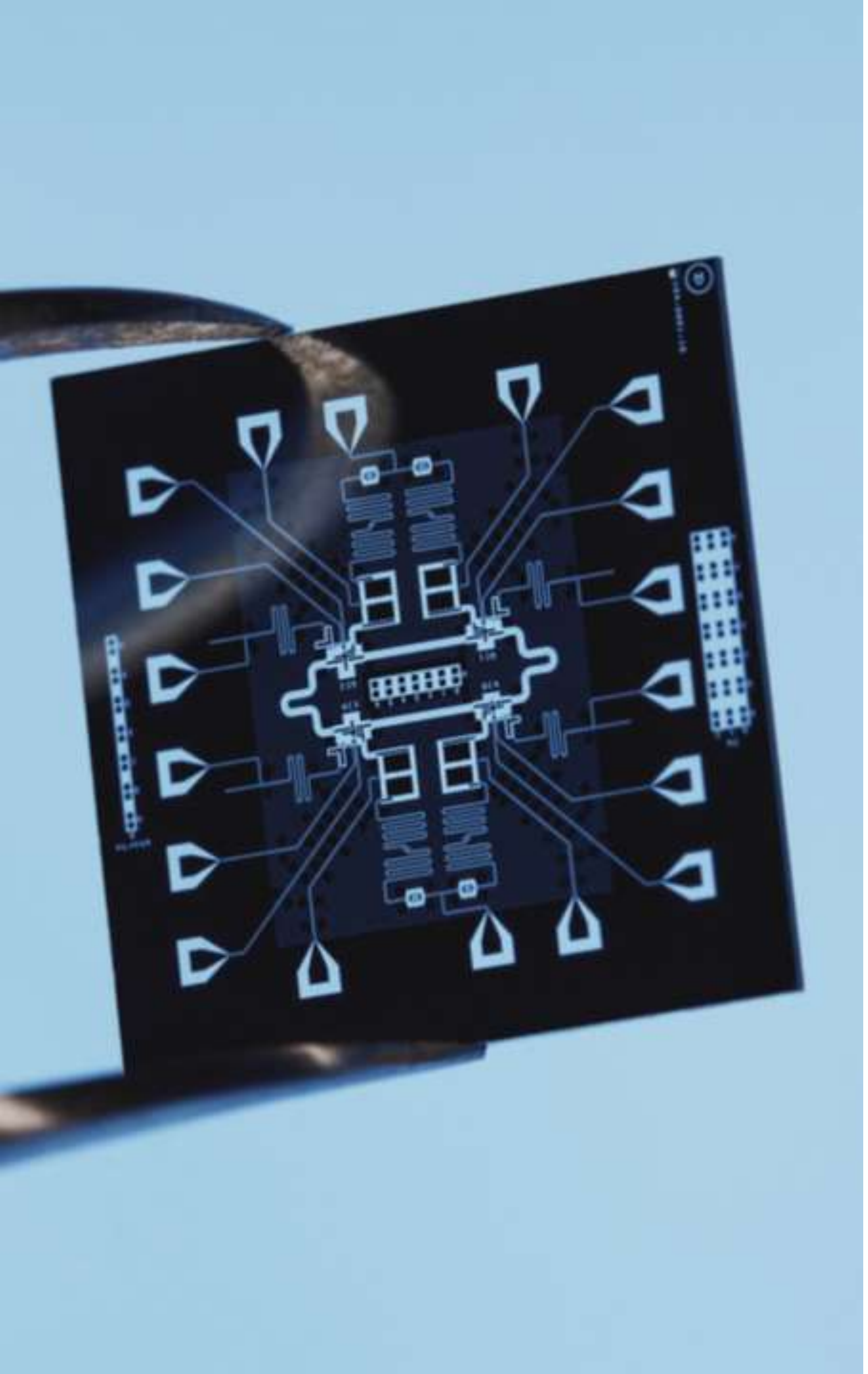
Guillaud & Mirrahimi, PRX 9, 041053 (2019)



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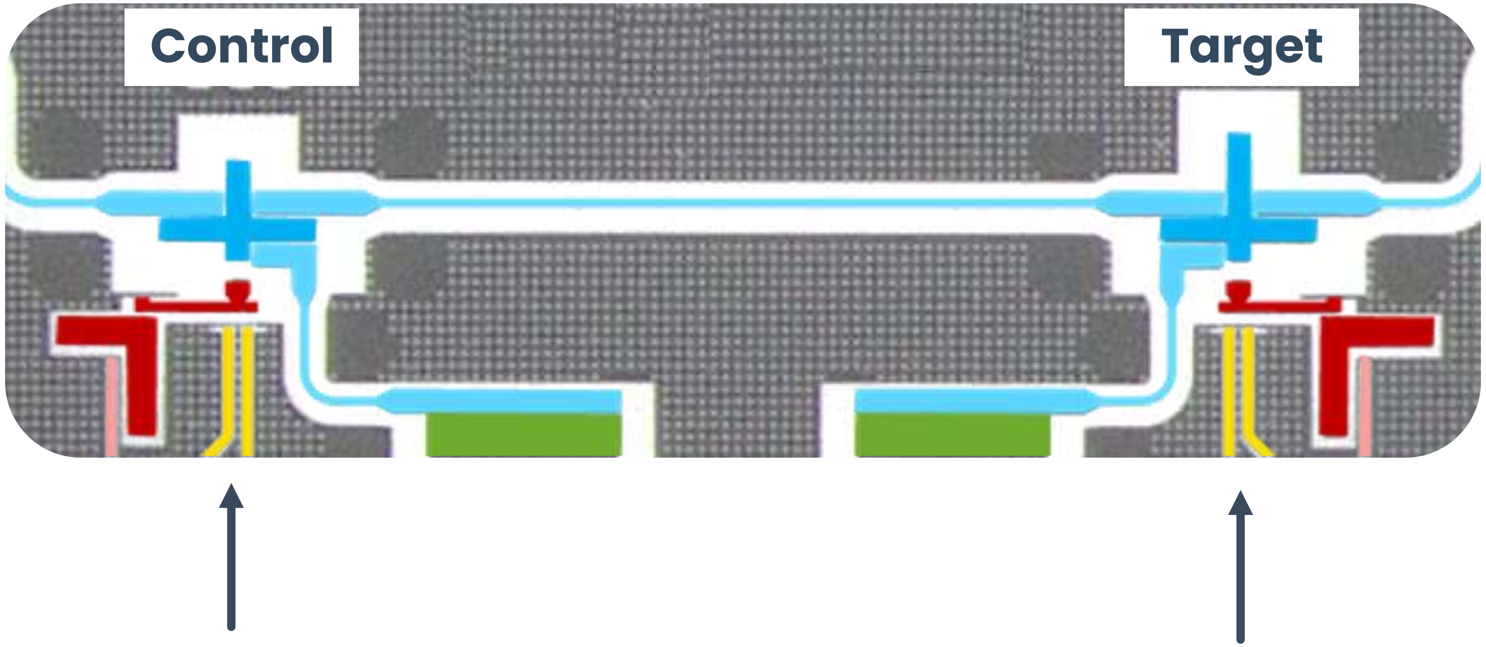
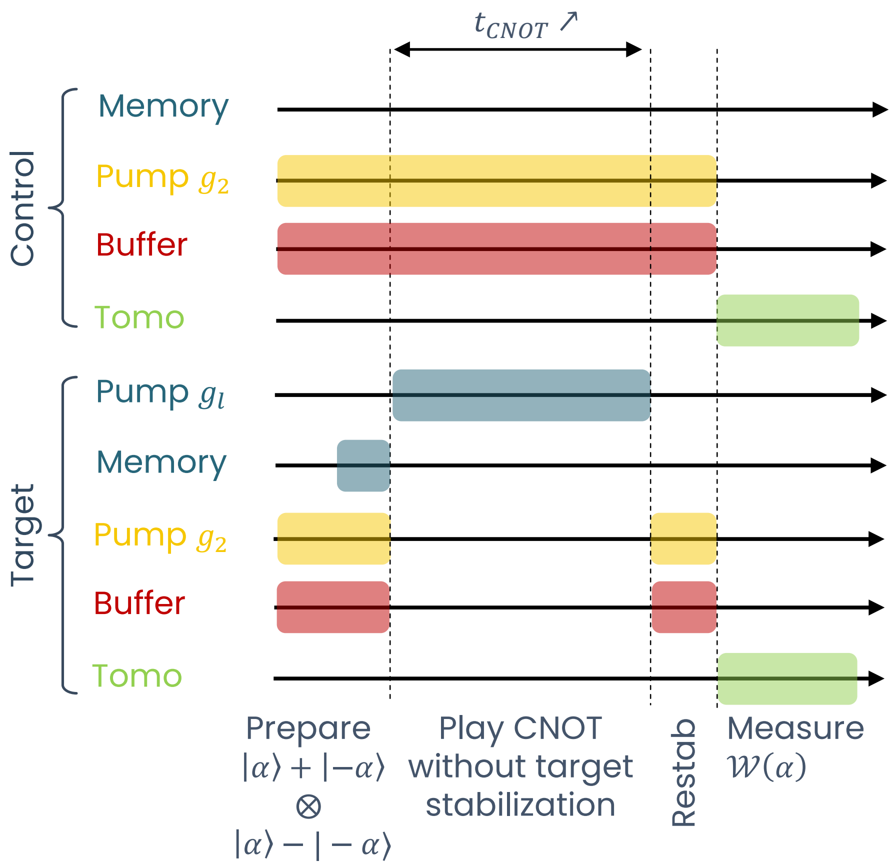
CNOT scheme



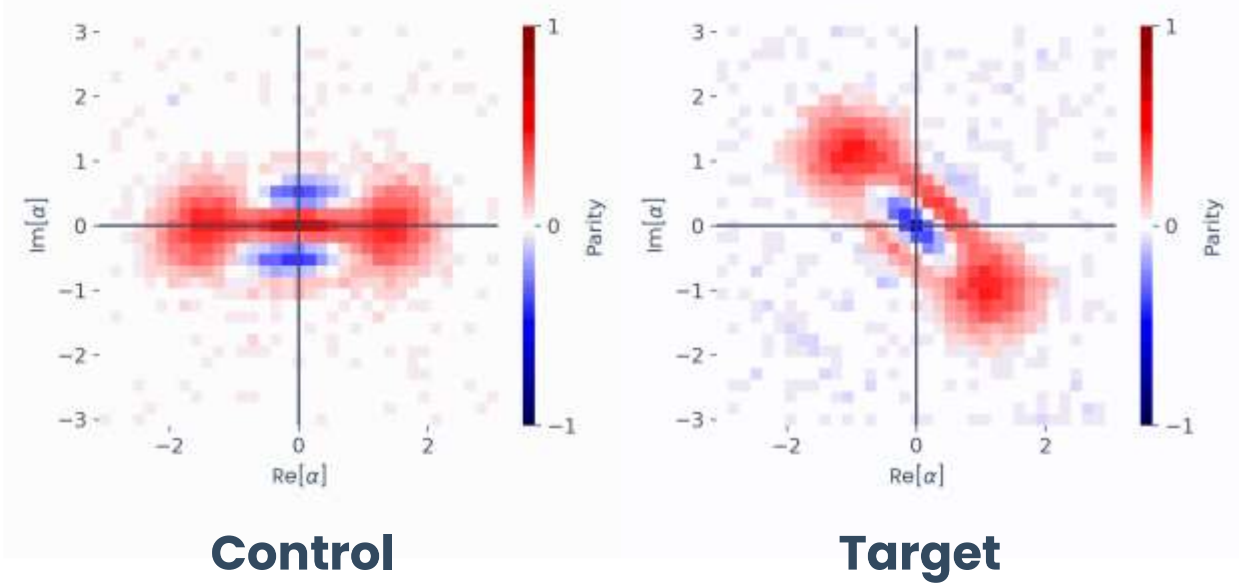
Two-photon pump
at $\omega_p = 2\omega_a^{ctrl} - \omega_b^{ctrl}$

Longitudinal pump at $\omega_p = \omega_a^{ctrl}$
Selects longitudinal coupling
$H_l = g_l\,(a_c + a_c^{+} + 2\alpha) \otimes a_t^{+} a_t$

CNOT at play

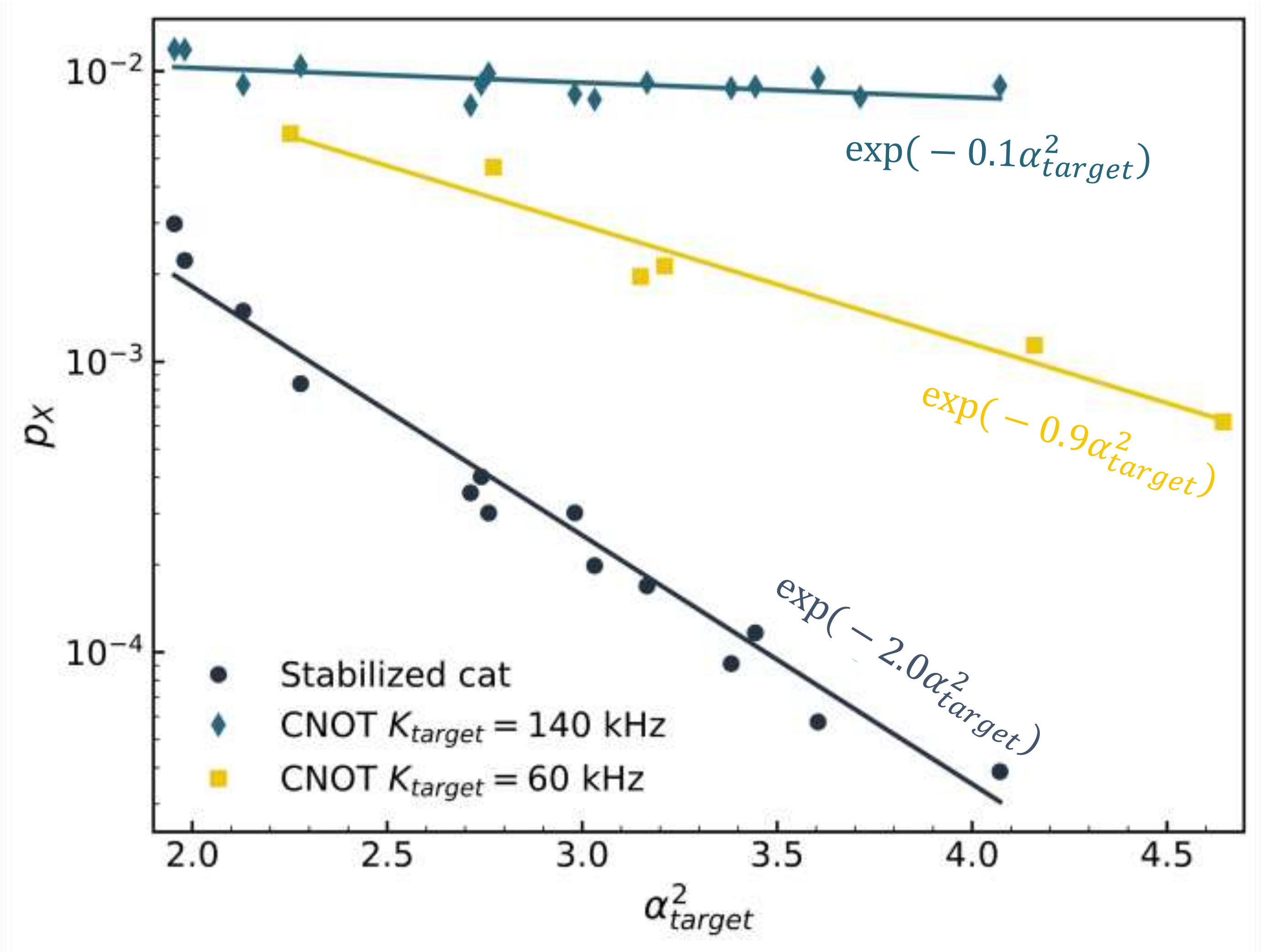


$g_l/2\pi = 220$ kHz
$T_{CNOT} = 400$ ns



$$p_{ZA}^{CNOT} \approx 0.15 \quad p_{ZD}^{CNOT} \approx 0.15$$

Characterizing bit-flips



Bit-flip scaling is limited by leakage while stabilization is turned off.

Solutions

- Further reduce Kerr and dephasing
- Engineer **conditional** rotation of the two-photon dissipation on the target

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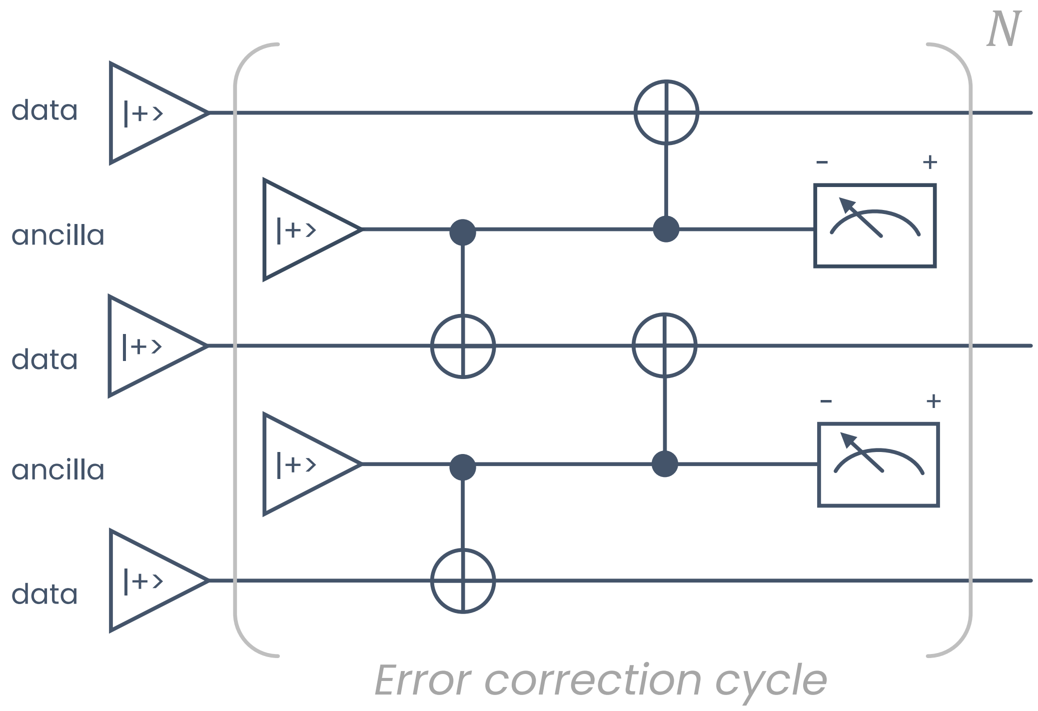
Repetition code error correction cycle

Need to correct phase-flip errors



Logical states: $|+_L\rangle = |+ + \cdots +\rangle, |-_L\rangle = |- - \cdots -\rangle$

Logical operators: $Z_L = \otimes_i Z_i$ and $X_L = X_i$

Stabilizer: $S_i = X_i X_{i+1}$

Repetition code ingredients

- ✓ +/- state preparation
- ✓ CNOT gate
- ✓ Parity measurement

Bit-flip requirements

- ✓ Data bit-flips must be exponentially suppressed: **data noise bias**
- ✓ Ancilla bit-flips must also be exponentially suppressed: **no error propagation**
- ✓ Bit-flips must remain exponentially suppressed during CNOT: **bias-preserving gates**

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