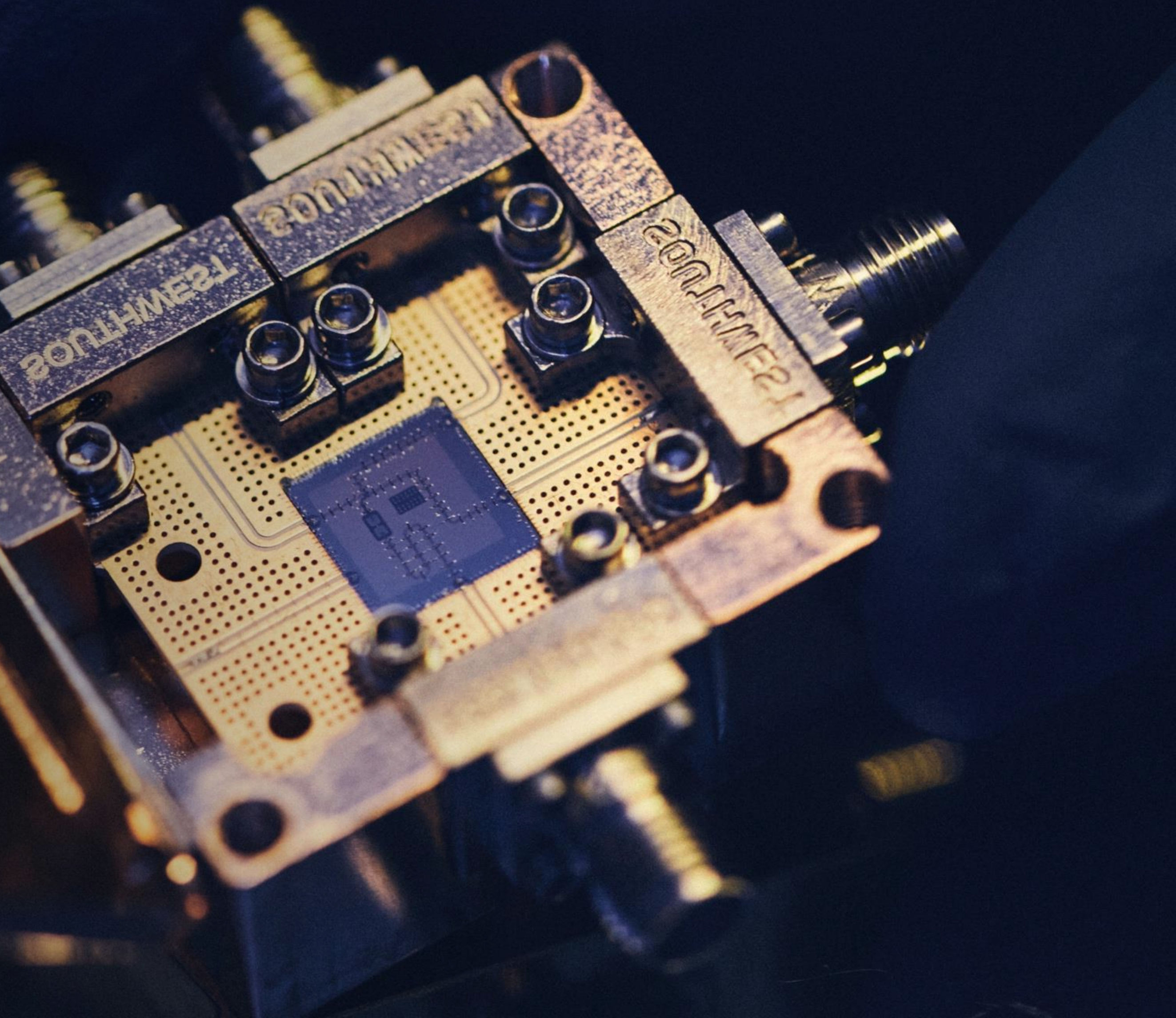
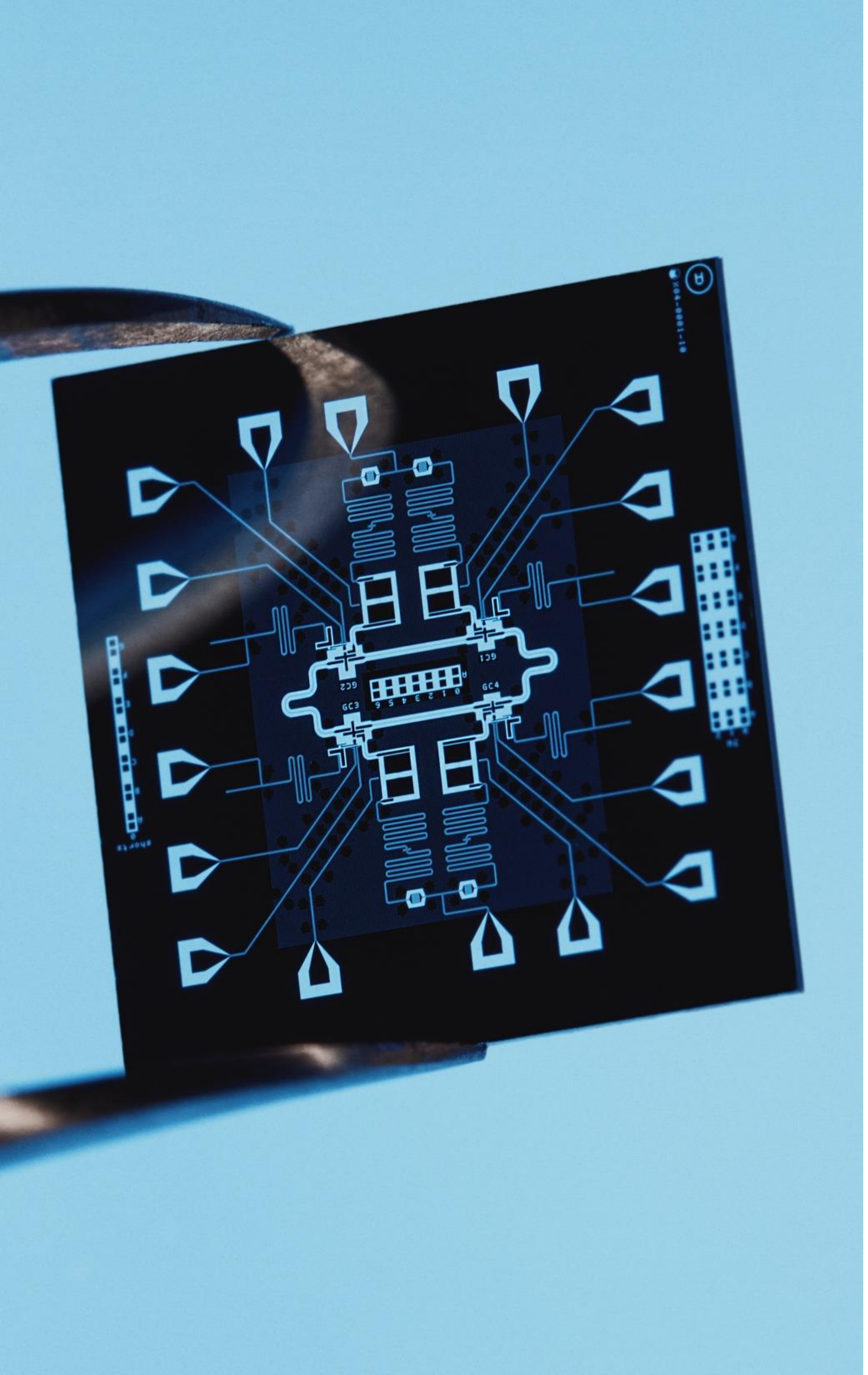


ALICE & BOB

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

Ronan Gautier | Institut Quantique

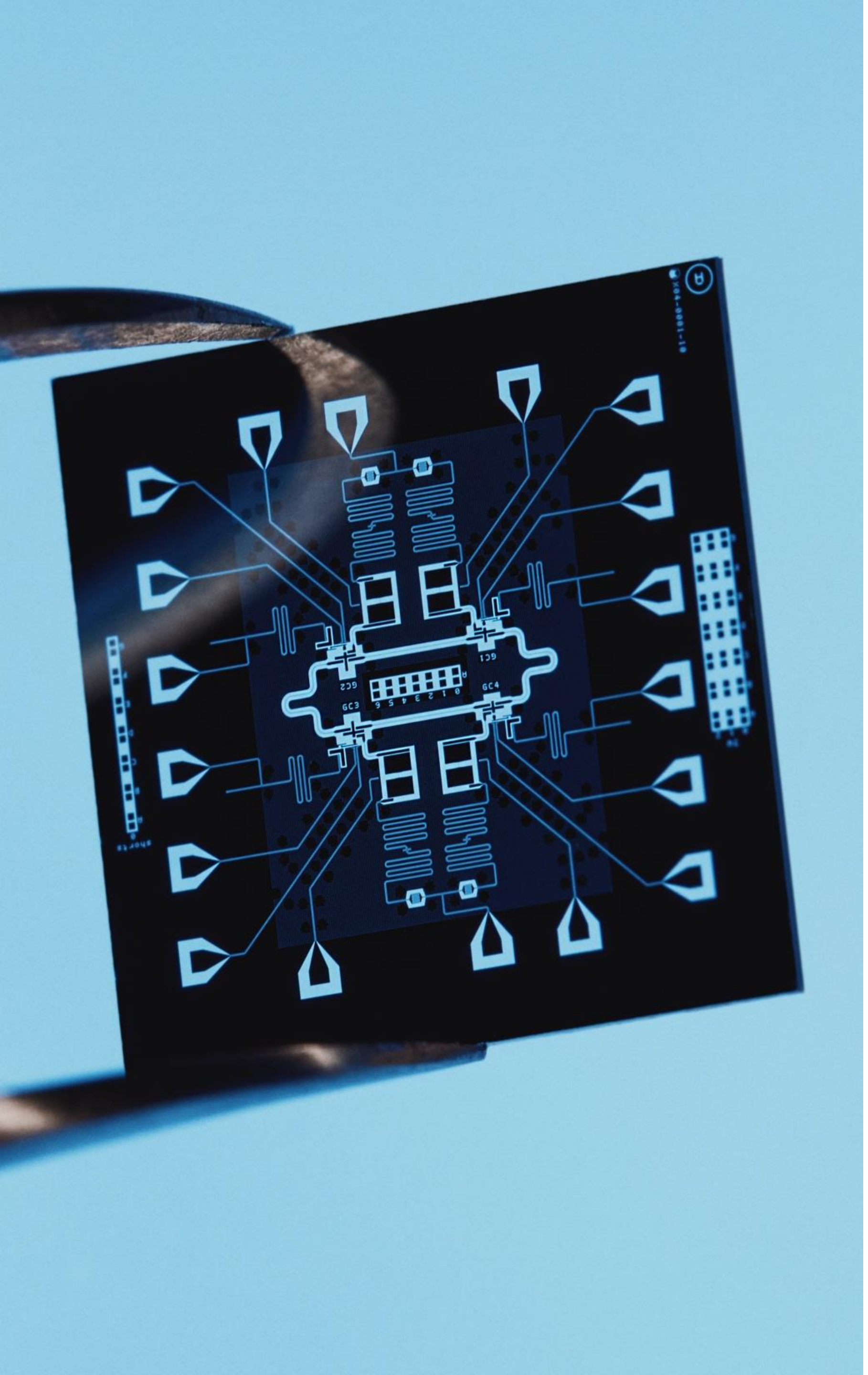
March 13th 2024



01 Quantum error correction with biased noise qubits

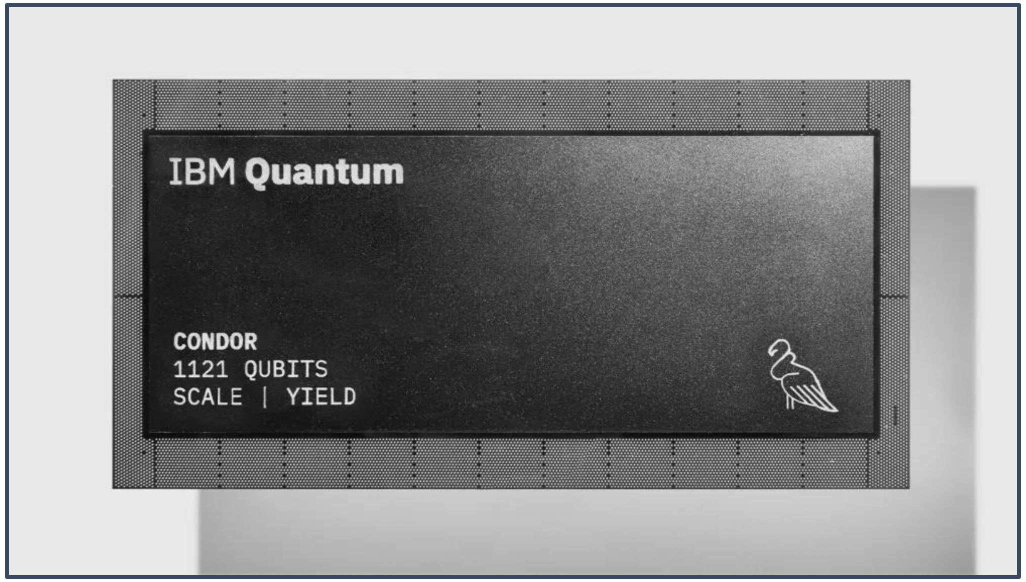
02 Experimental progress towards operating cat qubits

03 Going below threshold



01	Quantum error correction with biased noise qubits
02	Experimental progress towards operating cat qubits
03	Going below threshold

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}

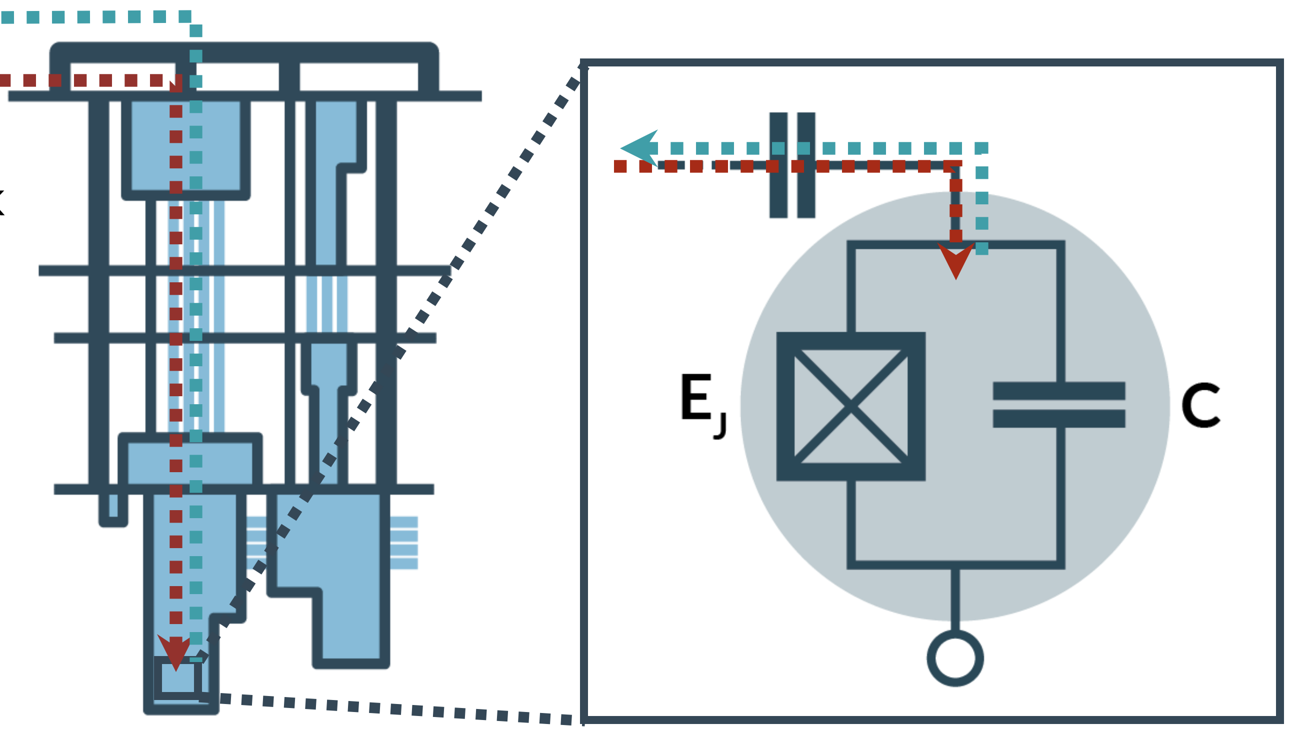
A fundamental predicament

High controllability ⟷ **Long lifetime**

Readout signal

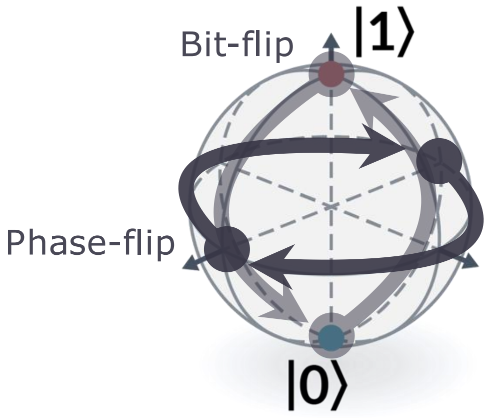
Signal @ room temp.

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



Inevitable coupling to bath

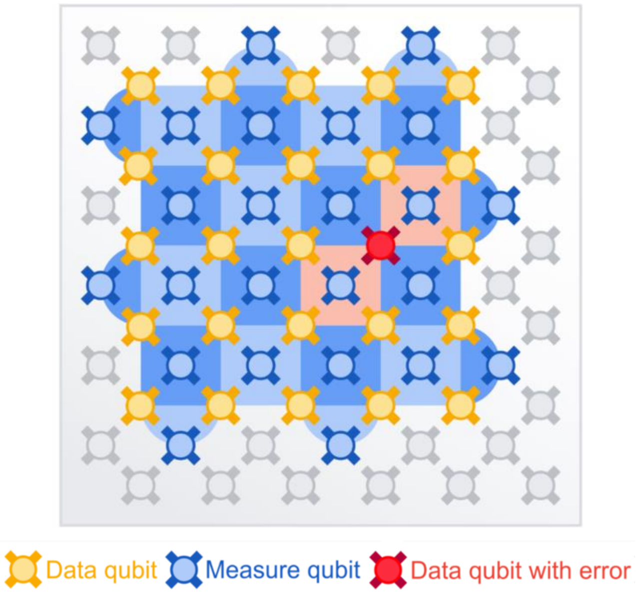
Quantum error correction



Error discretization theorem

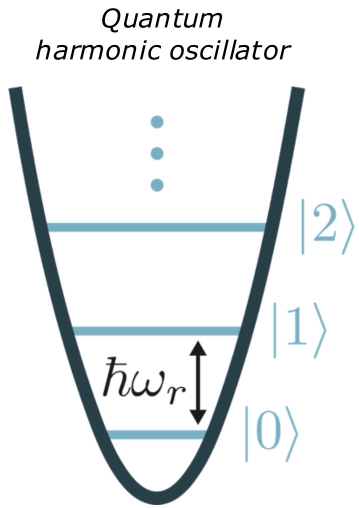
Correcting Pauli errors =
Correcting arbitrary errors

Discrete qubit codes



Google Quantum AI, Nature 2022

Bosonic codes



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

<u>Physical constraints:</u> 2D local codes

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

→ Surface code saturates the bound

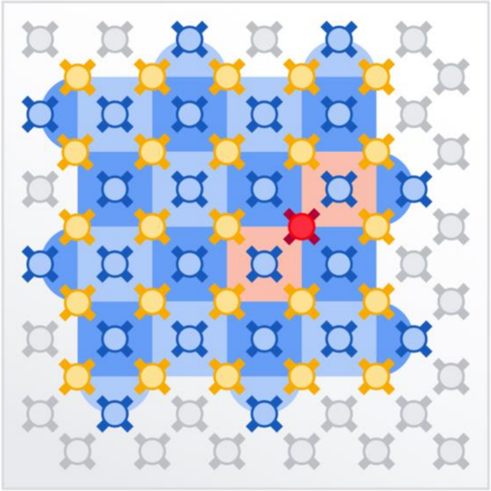
→ Solutions:
- 3D codes
- Long-range connections
- Classical codes

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

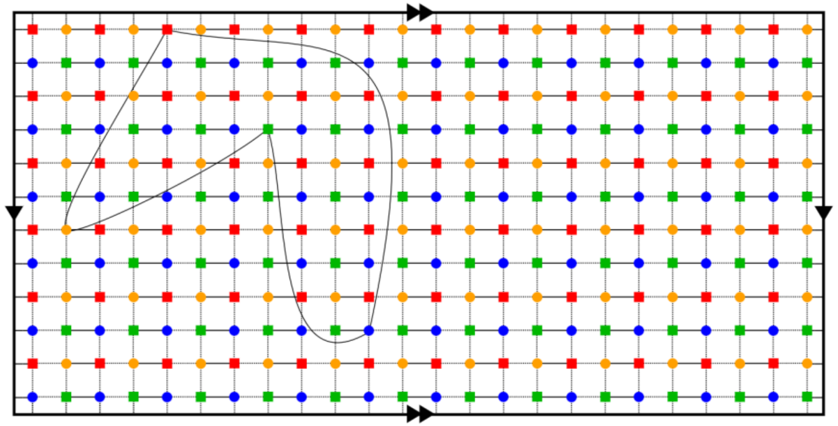
→ In practice, d ~ 10-30

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

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



Google Quantum AI, Nature 2022



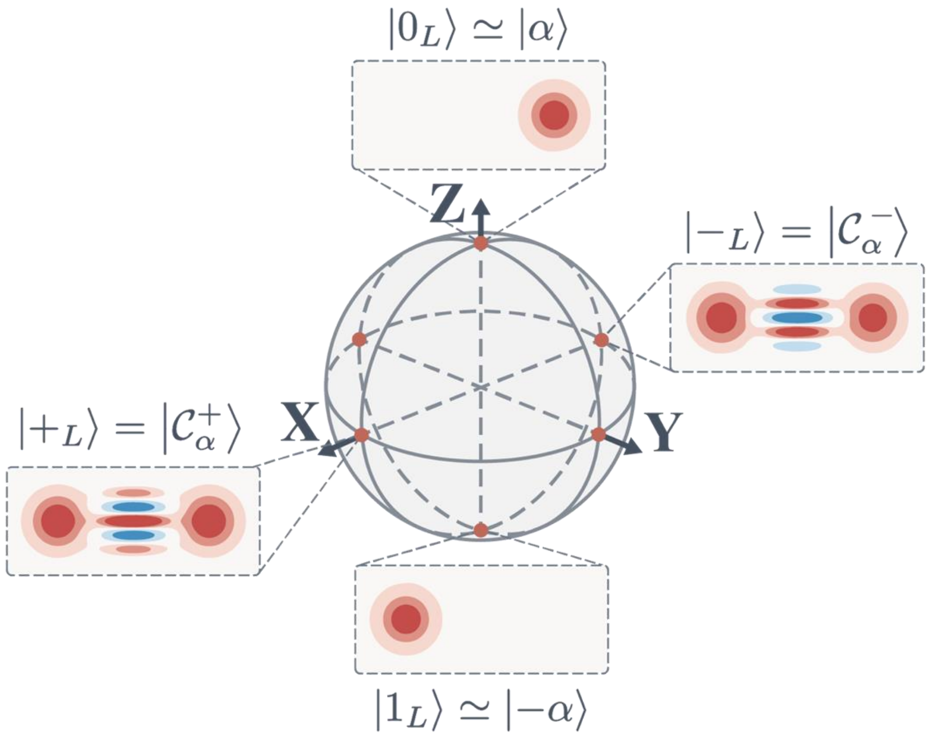
S. Bravyi et al., arXiv 2023

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

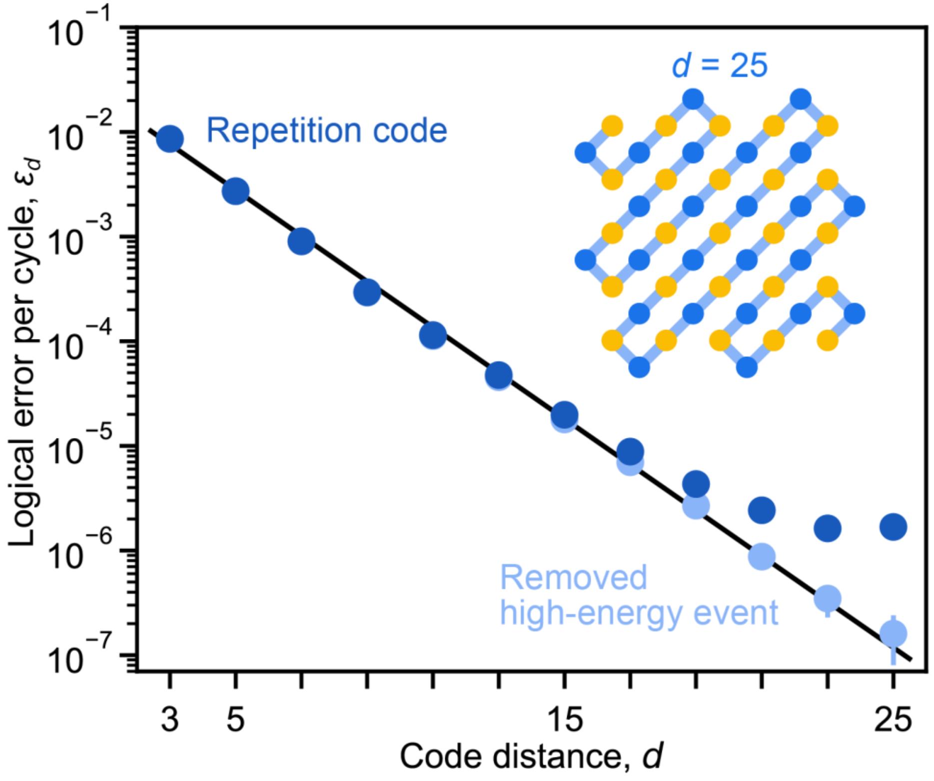
→ Combined cats (**RG** et al., PRXQ 2022)

Is bias enough to afford a classical code?

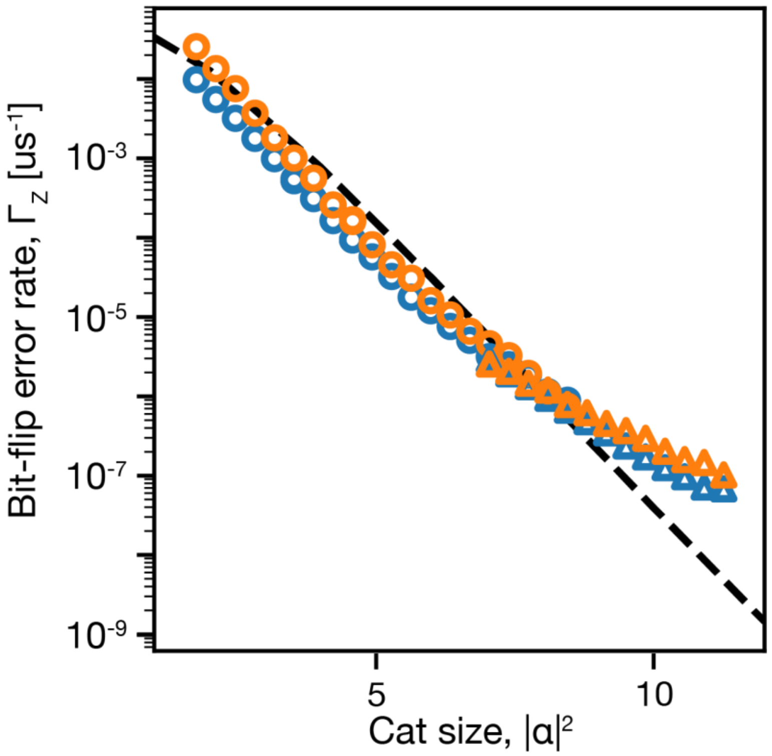
Mirrahimi et al., NJP (2014); Puri et al., npj QI (2017)

A hardware-efficient repetition code

Google Quantum AI, Nature 2022



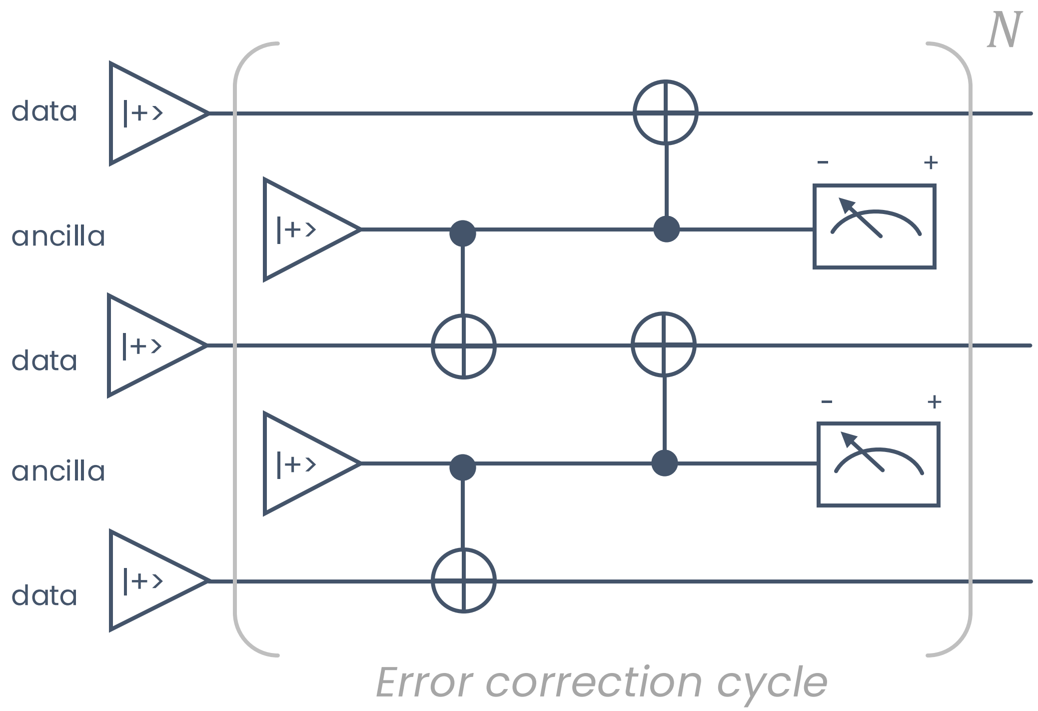
Réglade, Bocquet et al., arXiv 2024



Dissipative cat qubit = bit-flip repetition code

Repetition code error correction cycle

Need to correct phase-flip errors



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

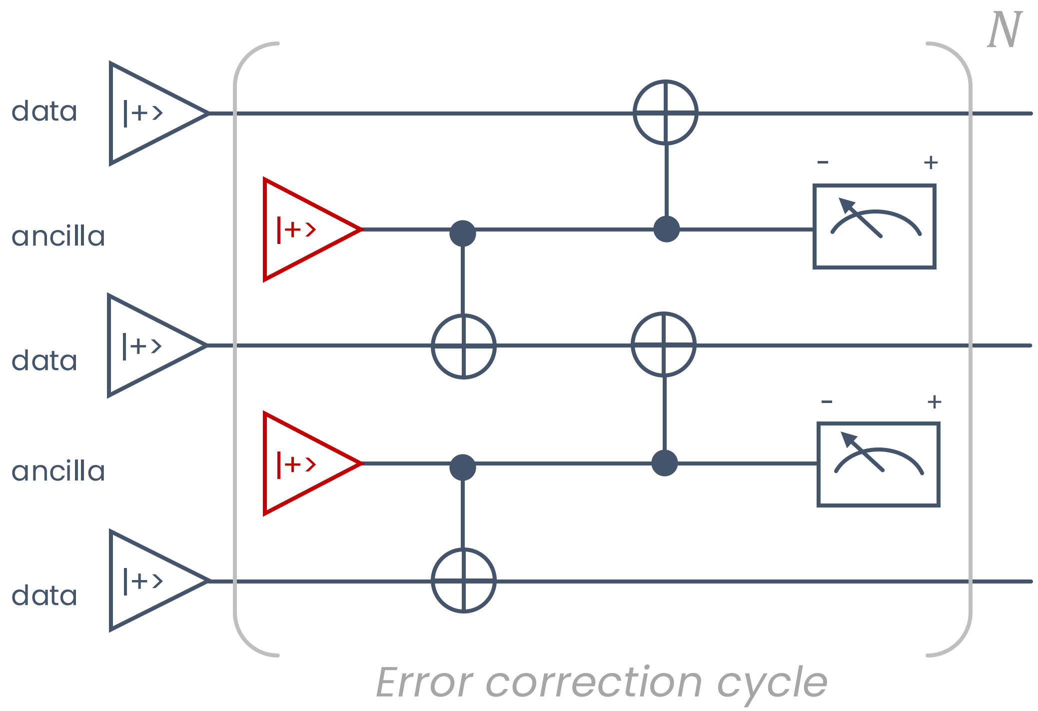
Logical operators: $Z_L = \bigotimes_i Z_i$ and $X_L = X_i$

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

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

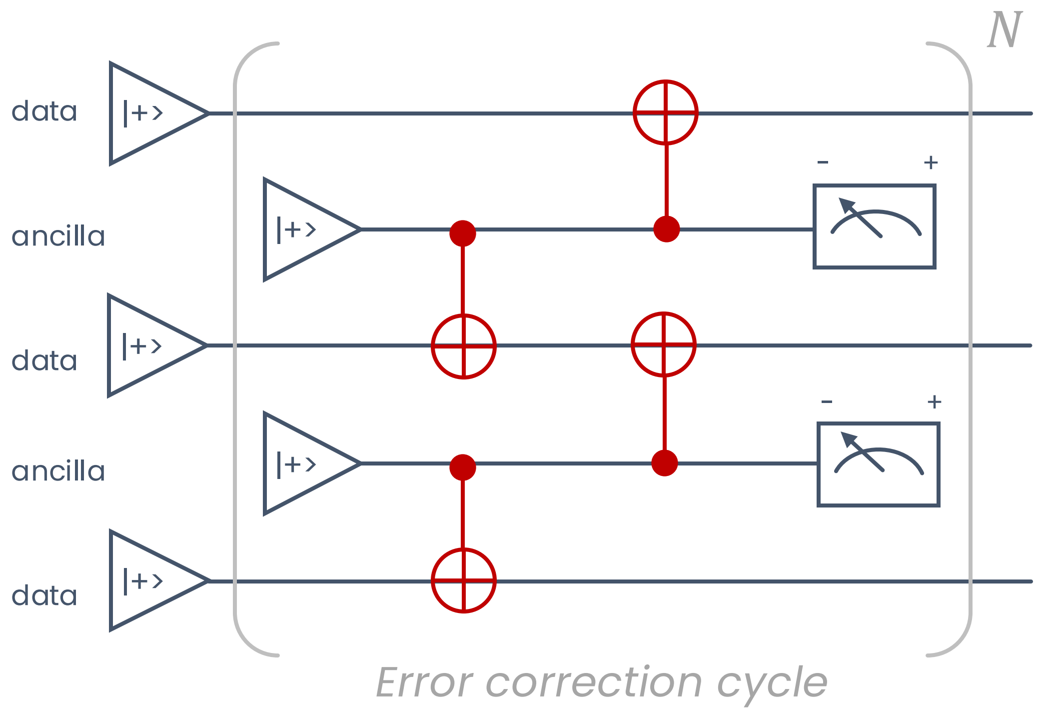
Guillaud & Mirrahimi, PRX 9, 041053 (2019)

Repetition code ingredients

- +/- state preparation

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

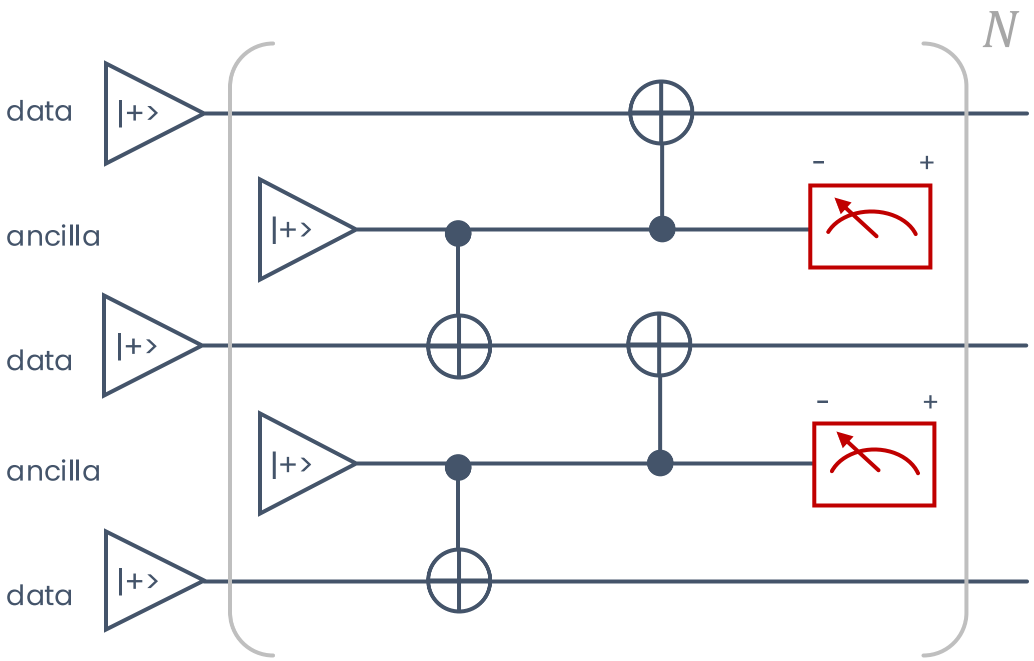
Repetition code ingredients

- +/- state preparation
- CNOT gate

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

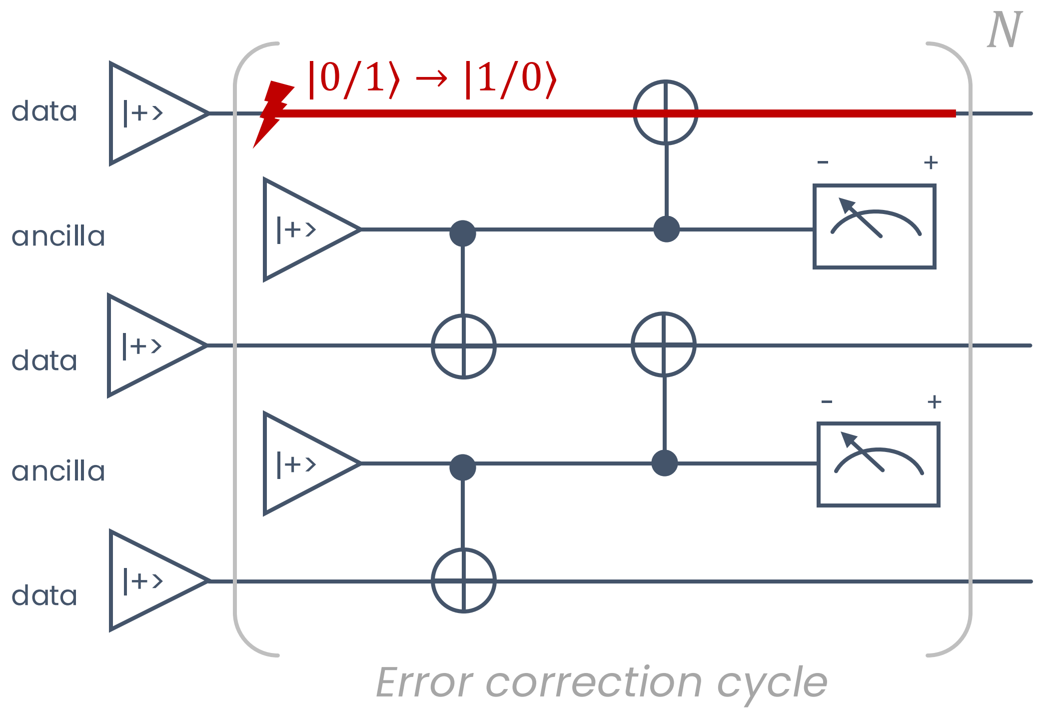
Repetition code ingredients

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

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

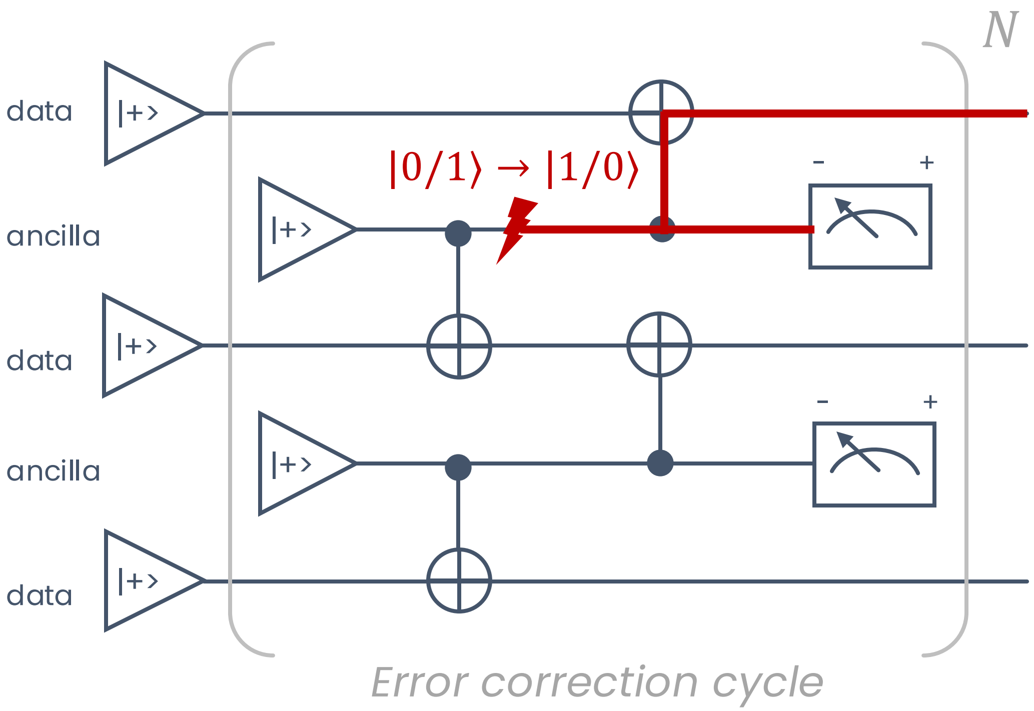
Bit-flip requirements

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

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

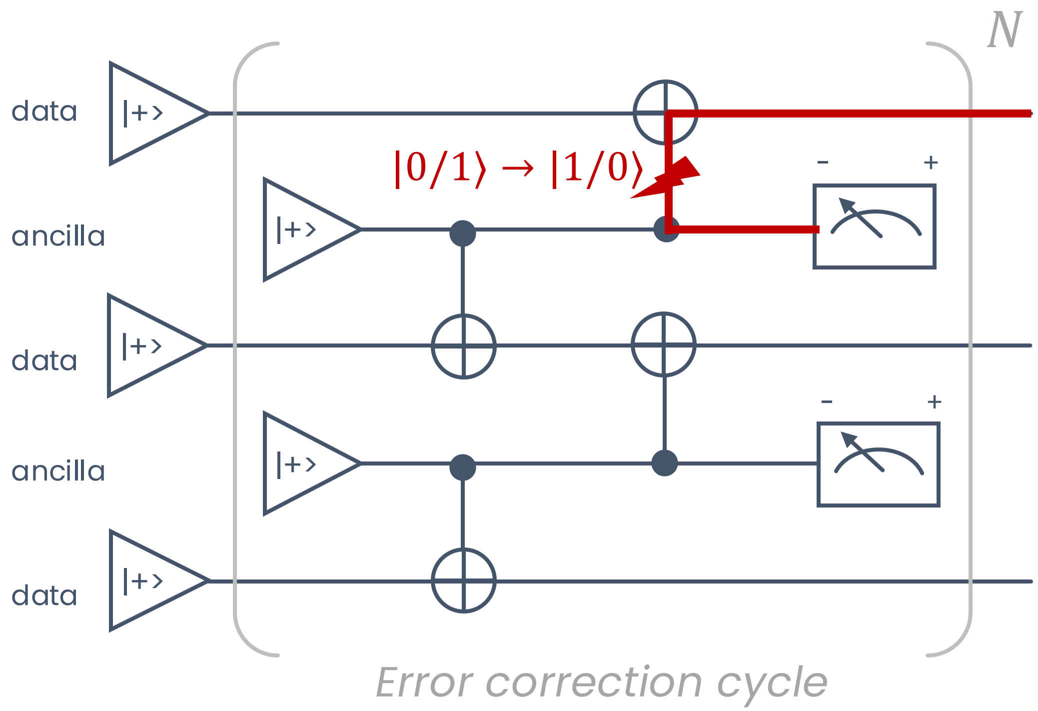
Bit-flip requirements

- Data bit-flips must be exponentially suppressed: **data noise bias**
- Ancilla bit-flips must also be exponentially suppressed: **no error propagation**

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

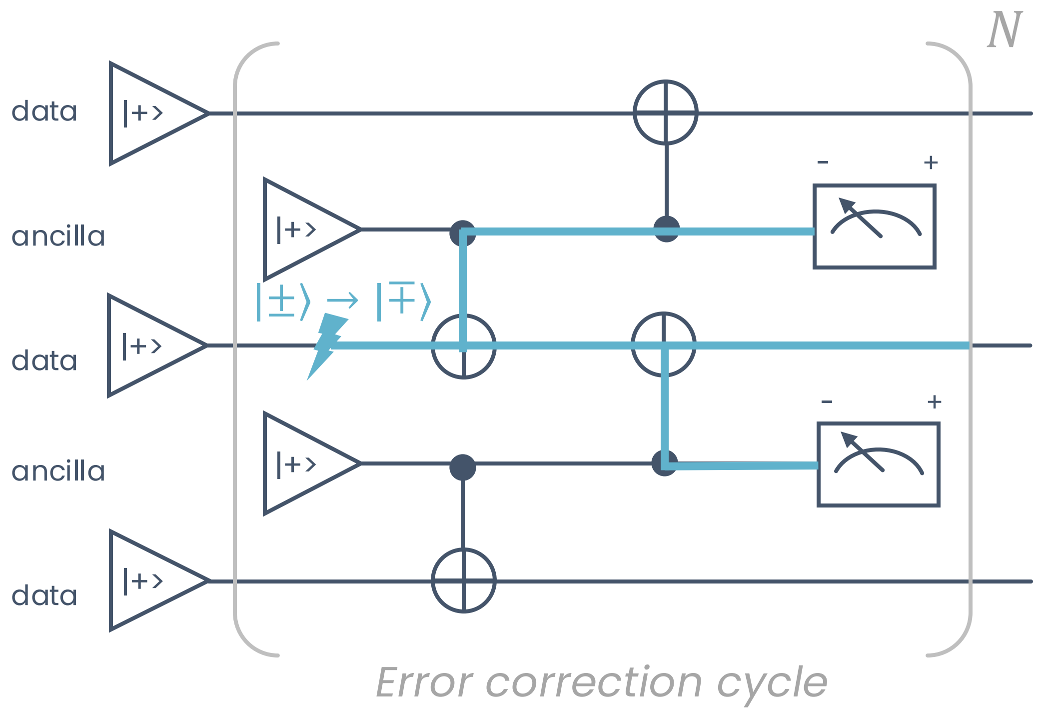
Bit-flip requirements

- 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**

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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**

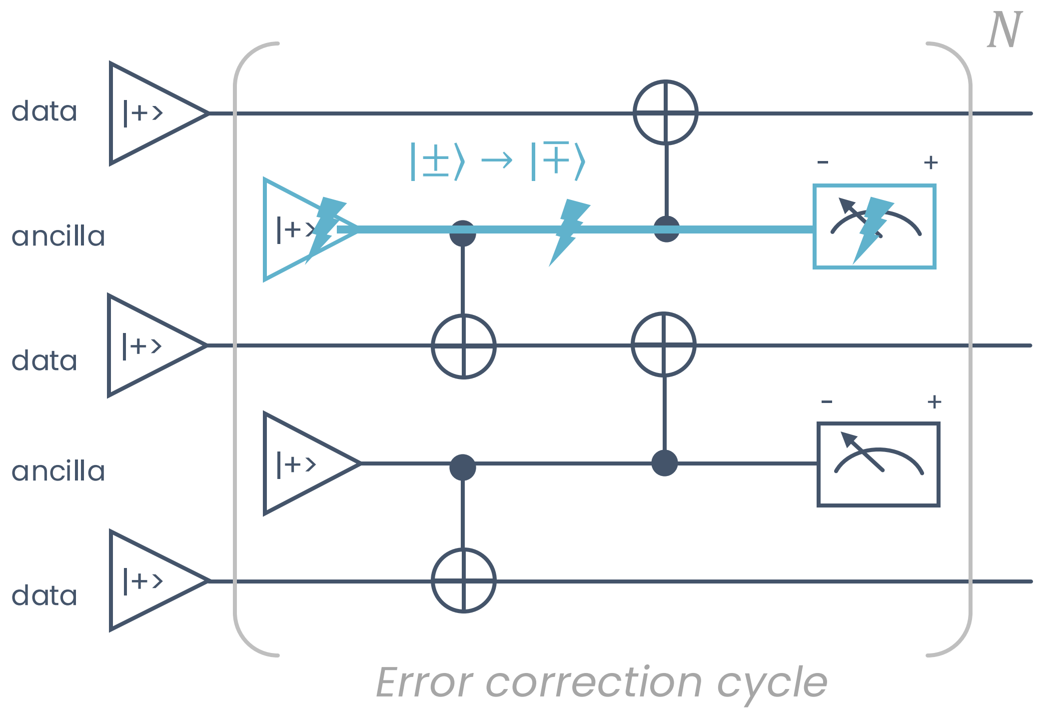
Phase-flip metrics

- Data phase-flip probability: p_{ZD}

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

Repetition code error correction cycle

Need to correct phase-flip errors



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

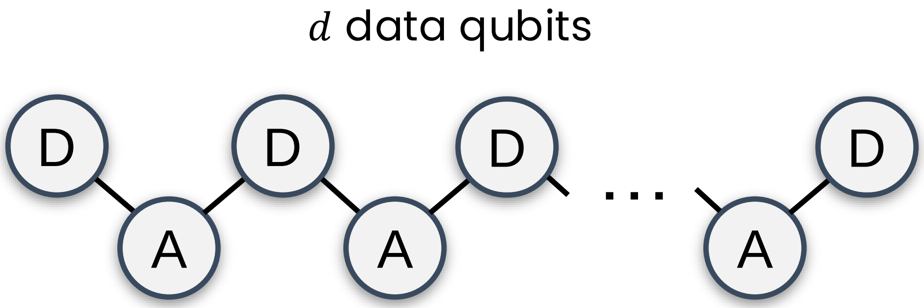
- Data bit-flips must be exponentially suppressed: **data noise bias**
- Ancilla bit-flips must also be exponentially suppressed: **no error propagation**
- Bit-flips must remain exponentially suppressed during CNOT: **bias-preserving gates**

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



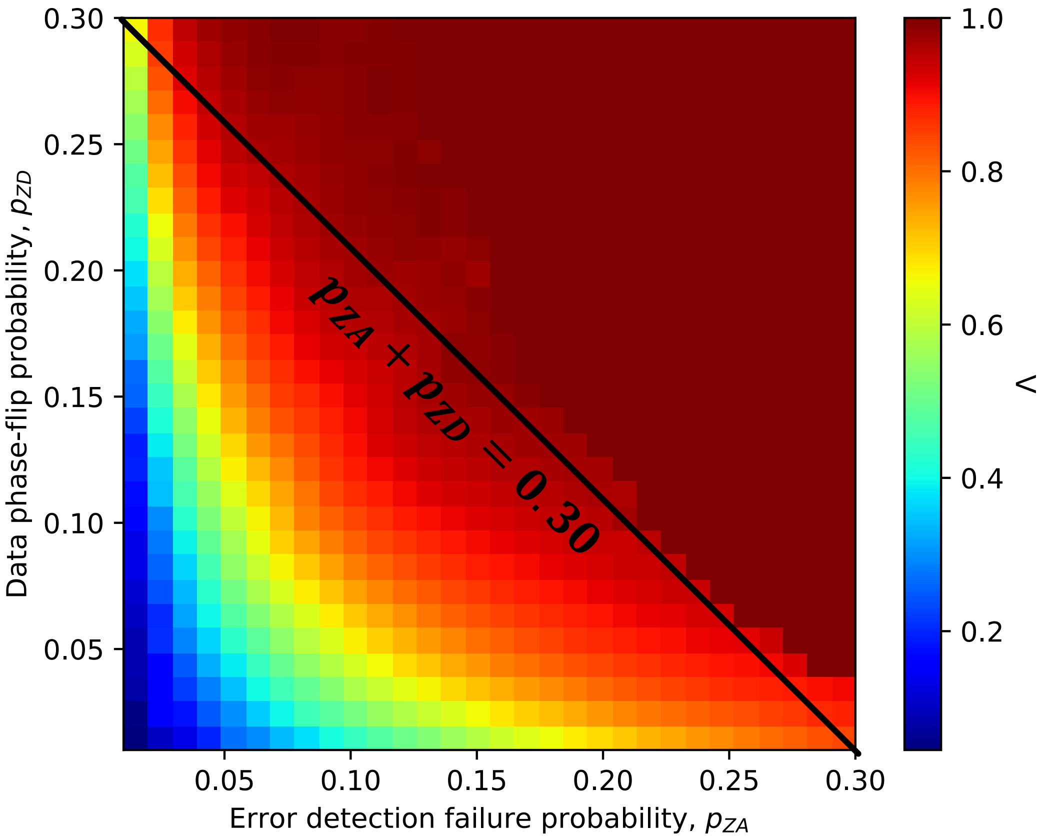
<u>Practical threshold definition:</u>

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

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

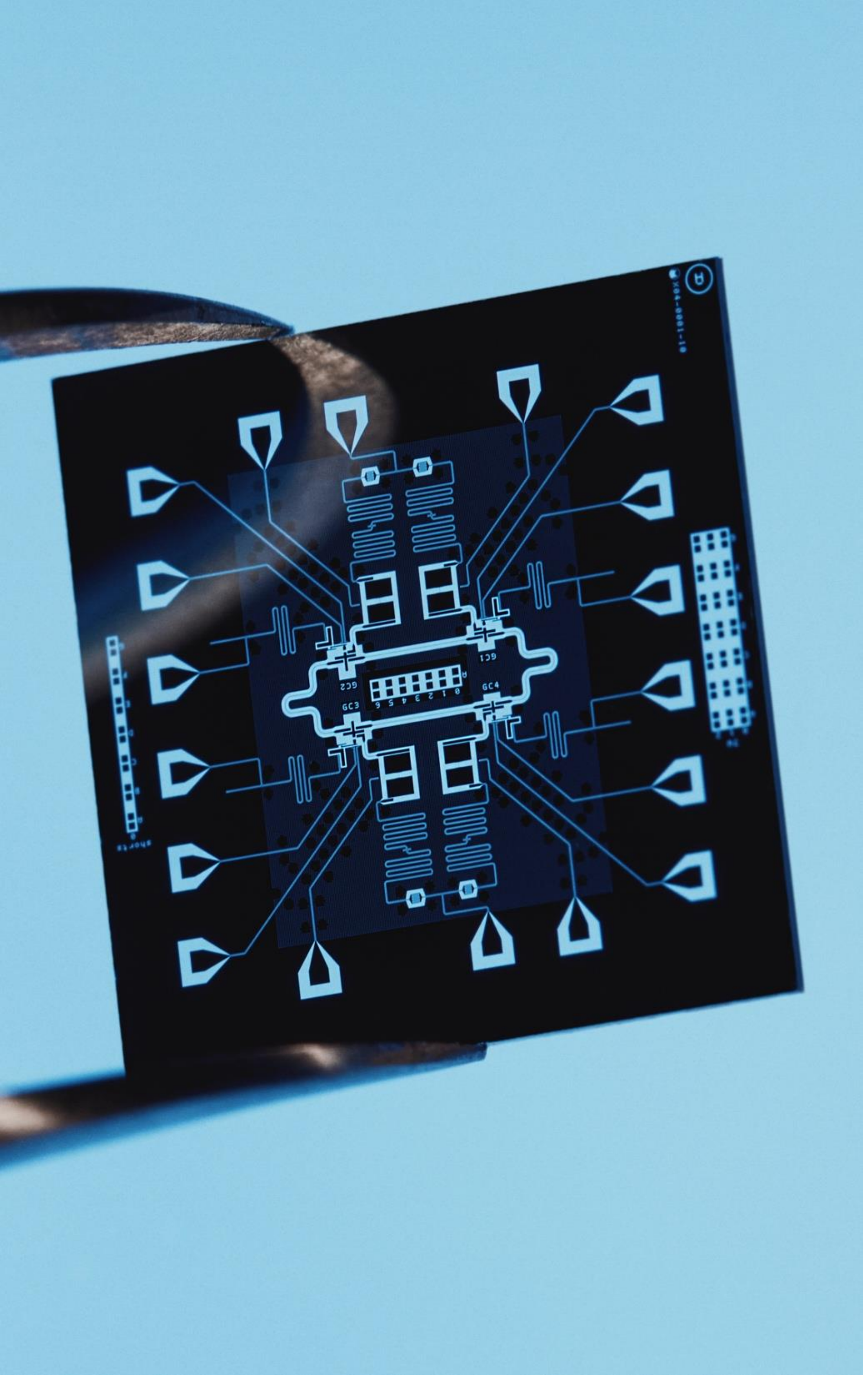
→ Only requires $p_{ZA} + p_{ZD} \leq 0.30$

→ Favours ancilla/data error assymetry



Repetition code is <u>very</u> forgiving

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



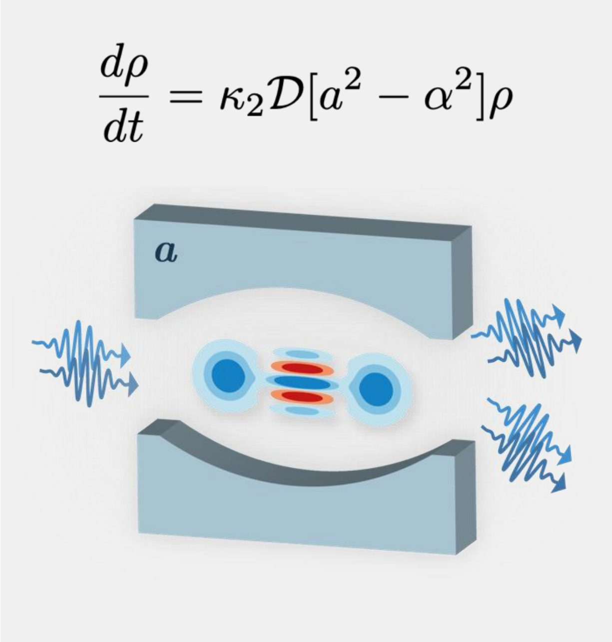
01 Quantum error correction with biased noise qubits

02 Experimental progress towards operating cat qubits

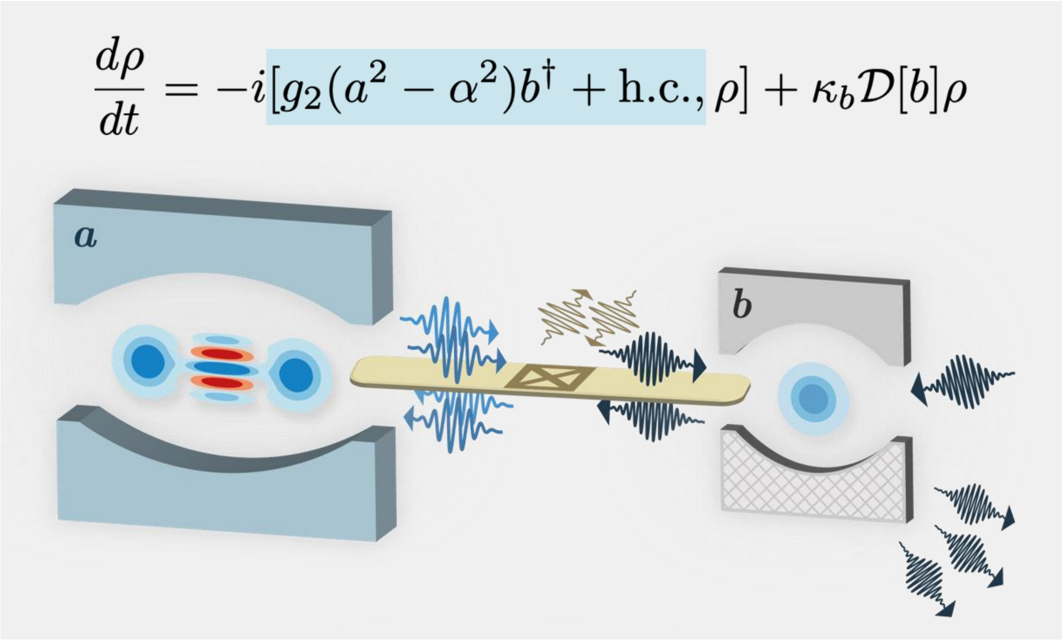
03 Going below threshold

Reservoir engineering of two-photon dissipation

Memory



Memory + Buffer

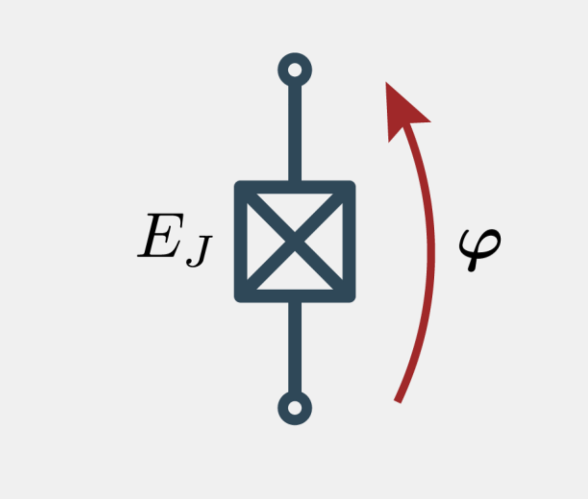


Requires parametric four-wave mixing

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

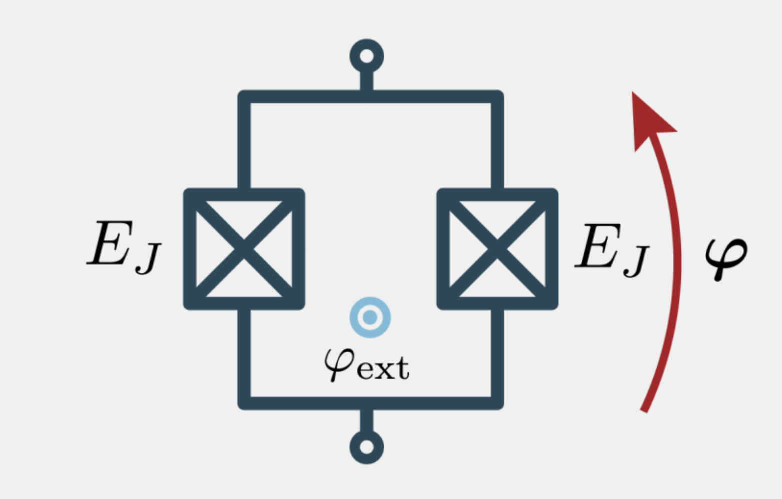
Parametric four-wave mixing

Josephson Junction



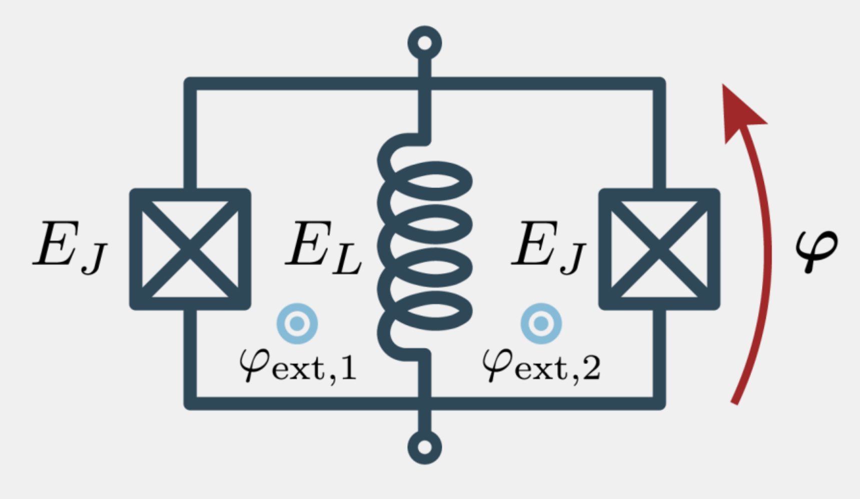
$$\hat{H} = -E_J \cos(\hat{\varphi})$$

SQUID



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

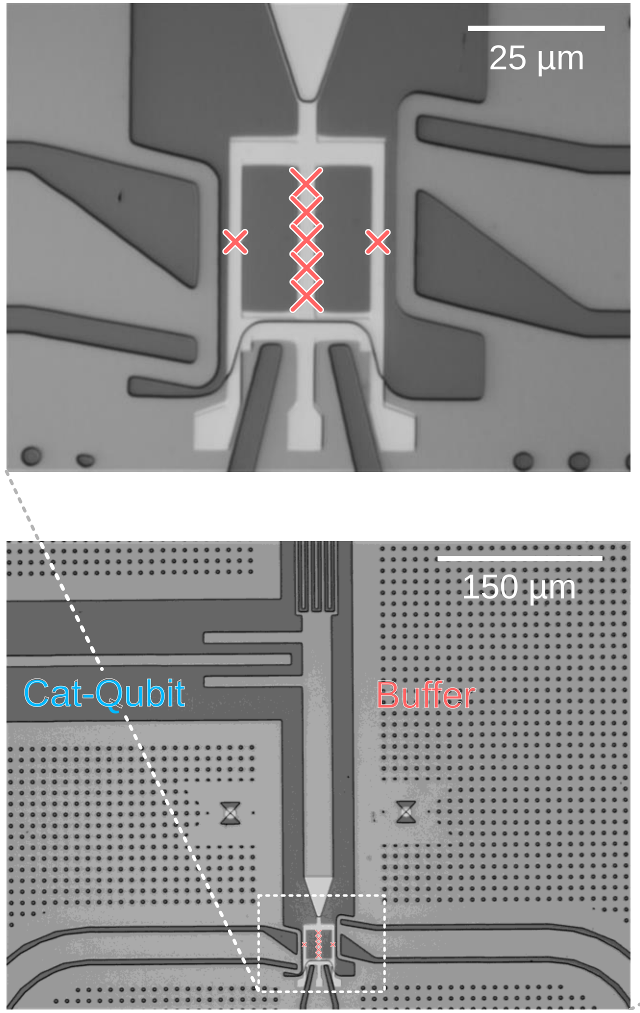
Asymmetrically Threaded SQUID

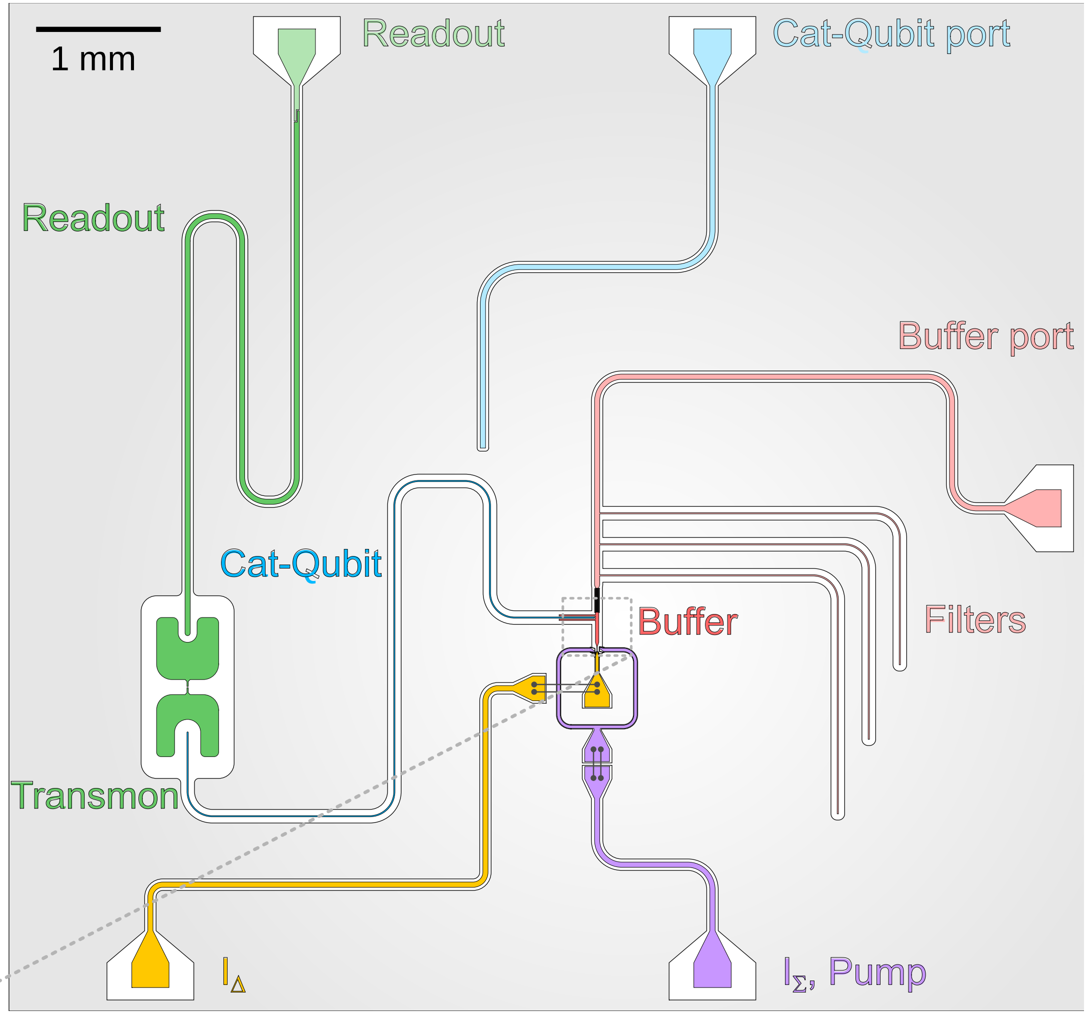


$$\hat{H} = \frac{1}{2} E_L \hat{\varphi}^2 - 2E_J \cos(\varphi_\Sigma) \cos(\hat{\varphi} + \varphi_\Delta)$$
$$\rightarrow \frac{1}{2} E_L \hat{\varphi}^2 - 2E_J \cos(\varphi_\Sigma) \sin(\hat{\varphi})$$

Lescanne et al. Nat. Phy. (2019)

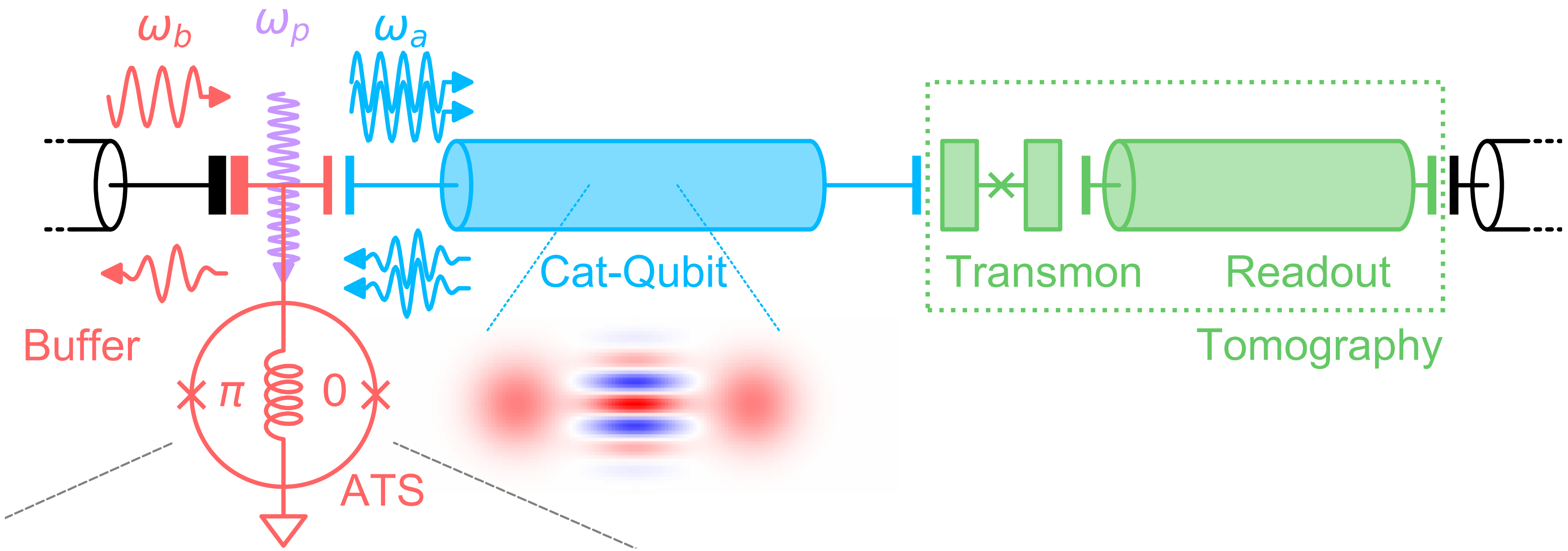
Experimental setup





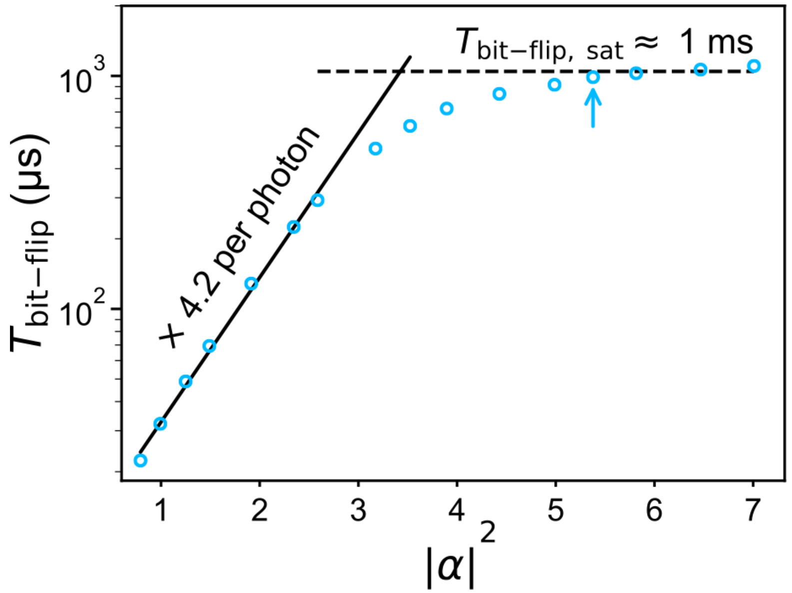
Lescanne et al. Nat. Phy. (2019)

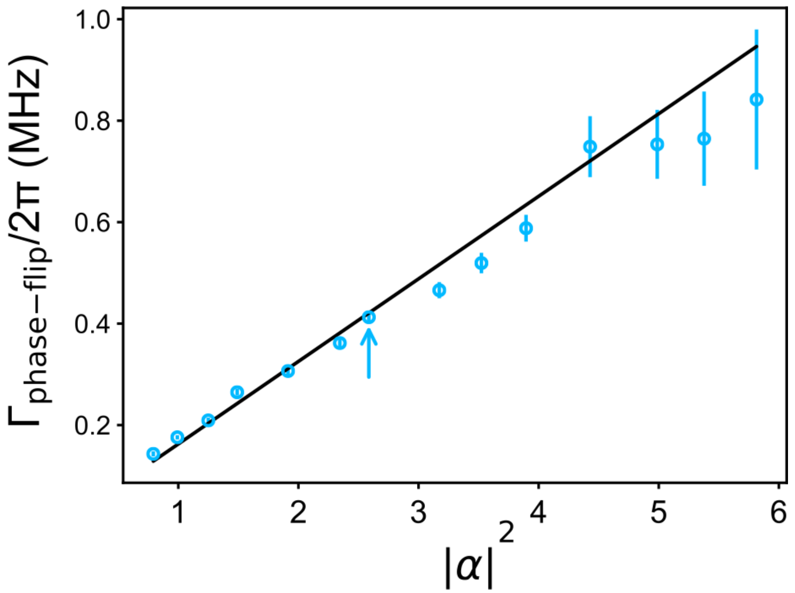
Experimental setup



Lescanne et al. Nat. Phy. (2019)

Transmon-induced saturation



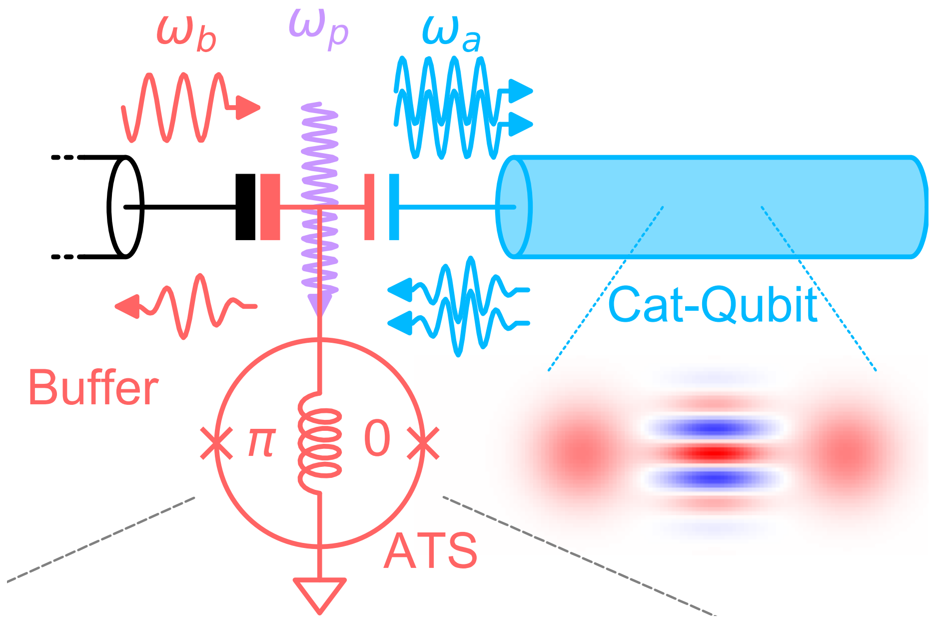


Saturation due to readout transmon

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

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

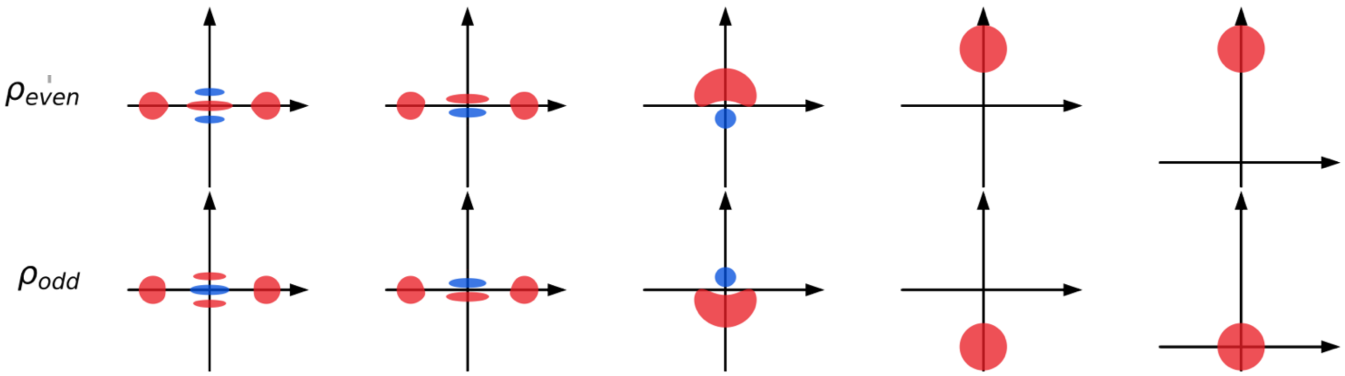
Four-step process:

(1) Displace initial state

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

(3) Map parity to coherent states

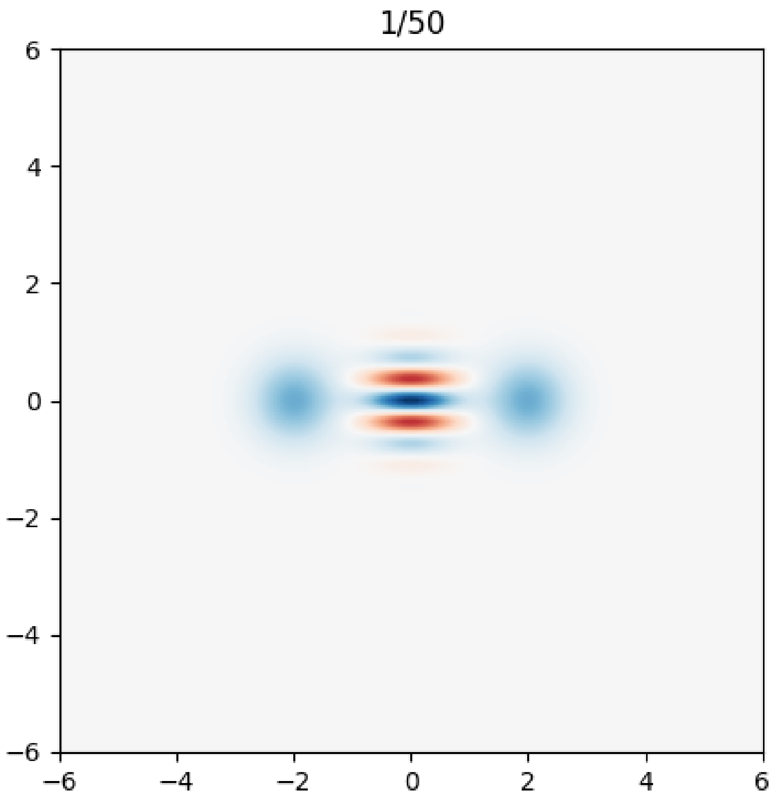
(4) Readout coherent states



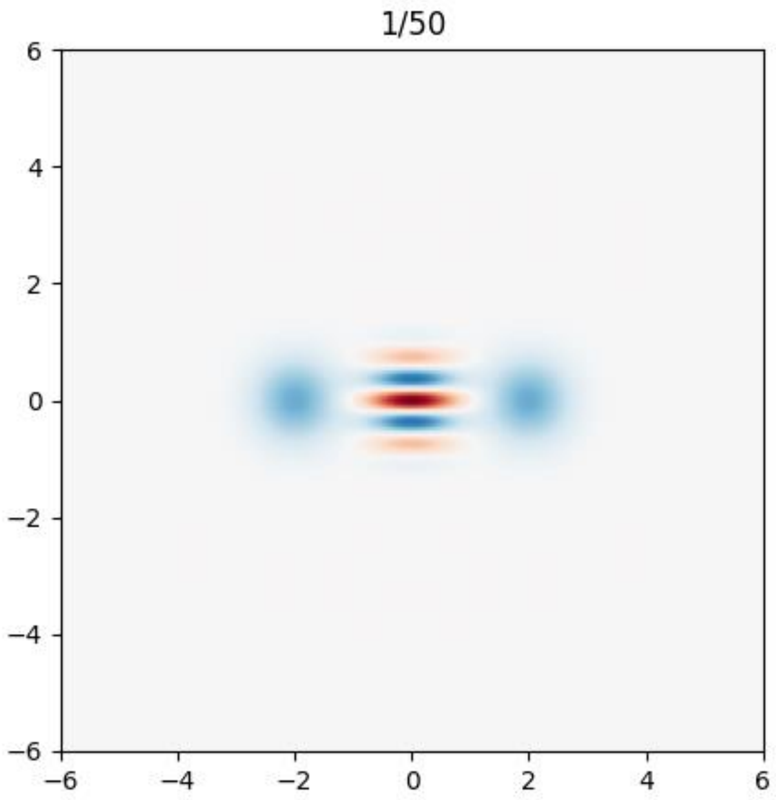
Réglade, Bocquet et al. arXiv (2023); Royer PRA (1977)

Mapping parity to coherent states

Even parity

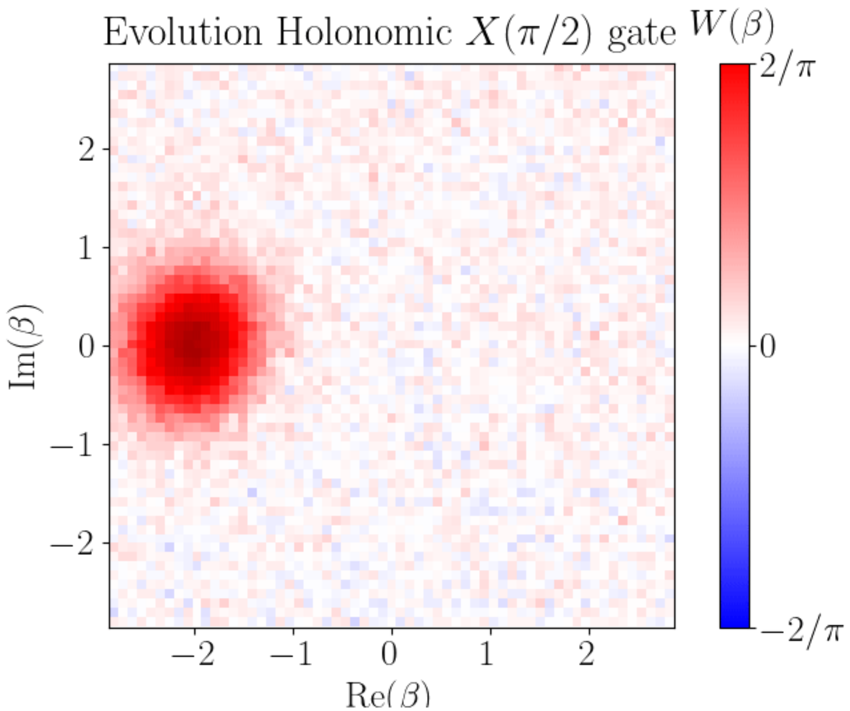


Odd parity



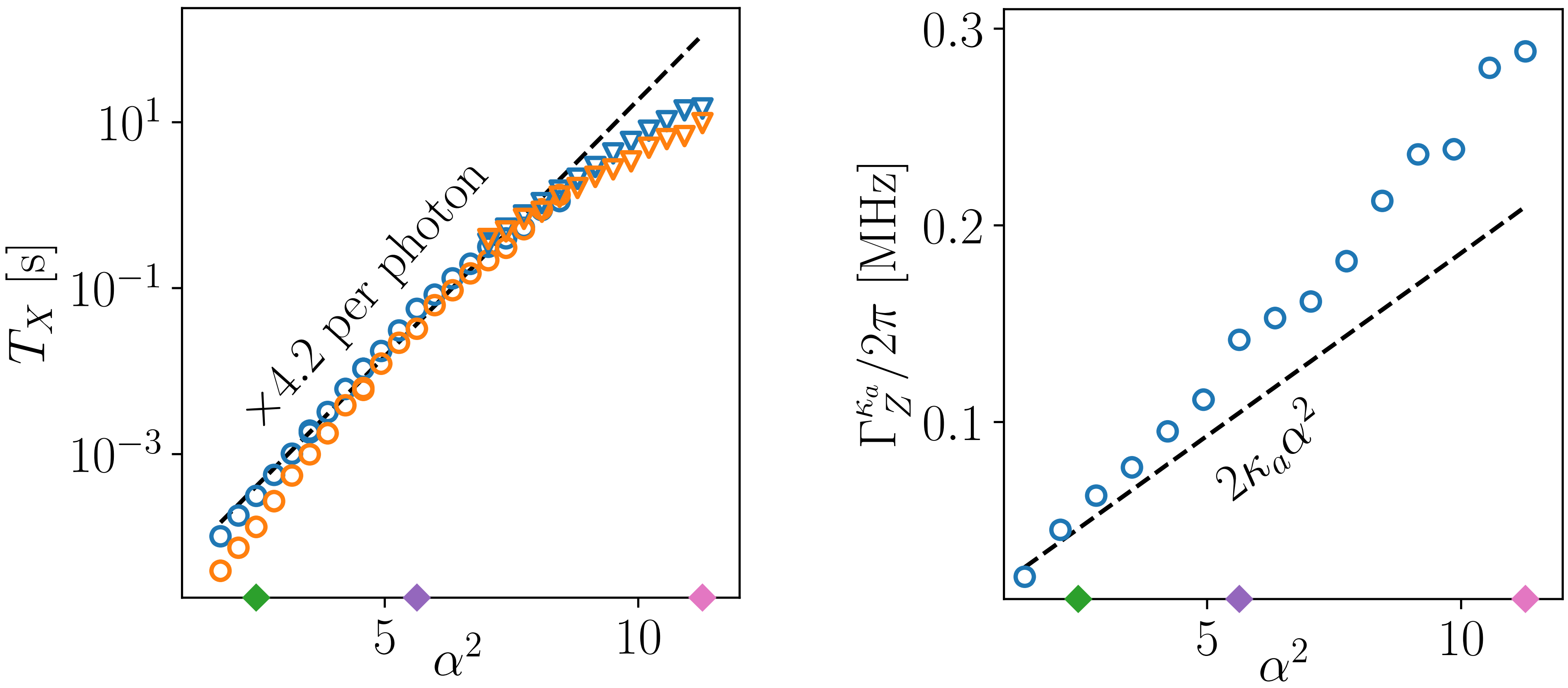
Réglade, Bocquet et al. arXiv (2023); V. Albert et al. PRL (2016)

Readout protocol



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

Exponentially biased qubits

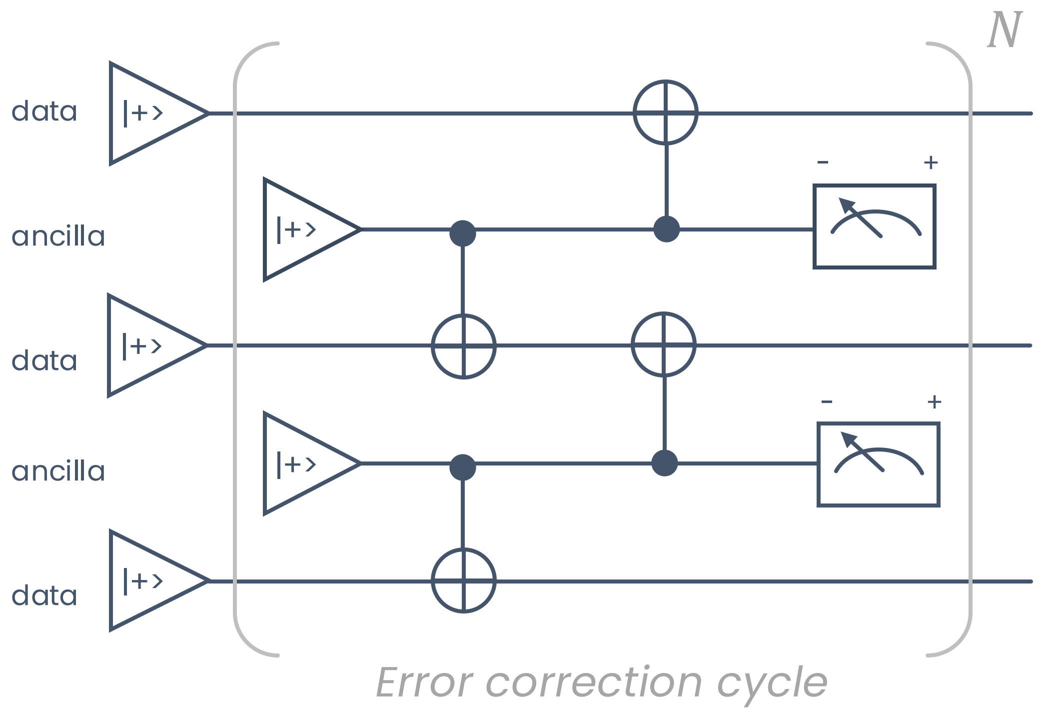


Bit lifetime at > 10 seconds !

Réglade, Bocquet et al. arXiv (2023)

Repetition code error correction cycle

Need to correct phase-flip errors



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

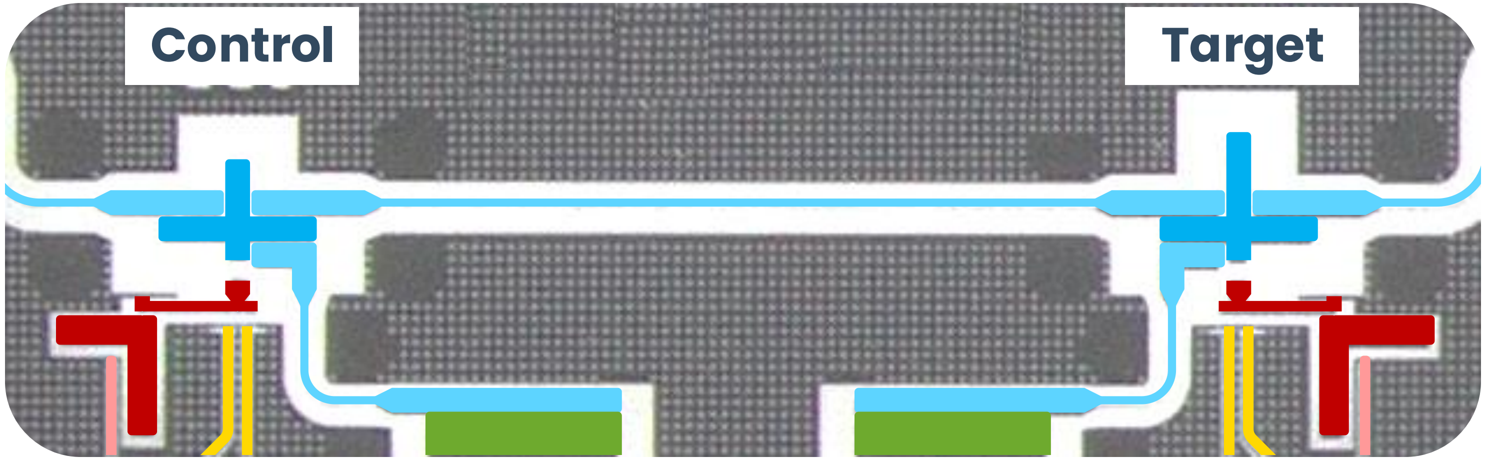
- ✓ +/- state preparation
- CNOT gate
- ✓ Parity measurement

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**

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

CNOT scheme



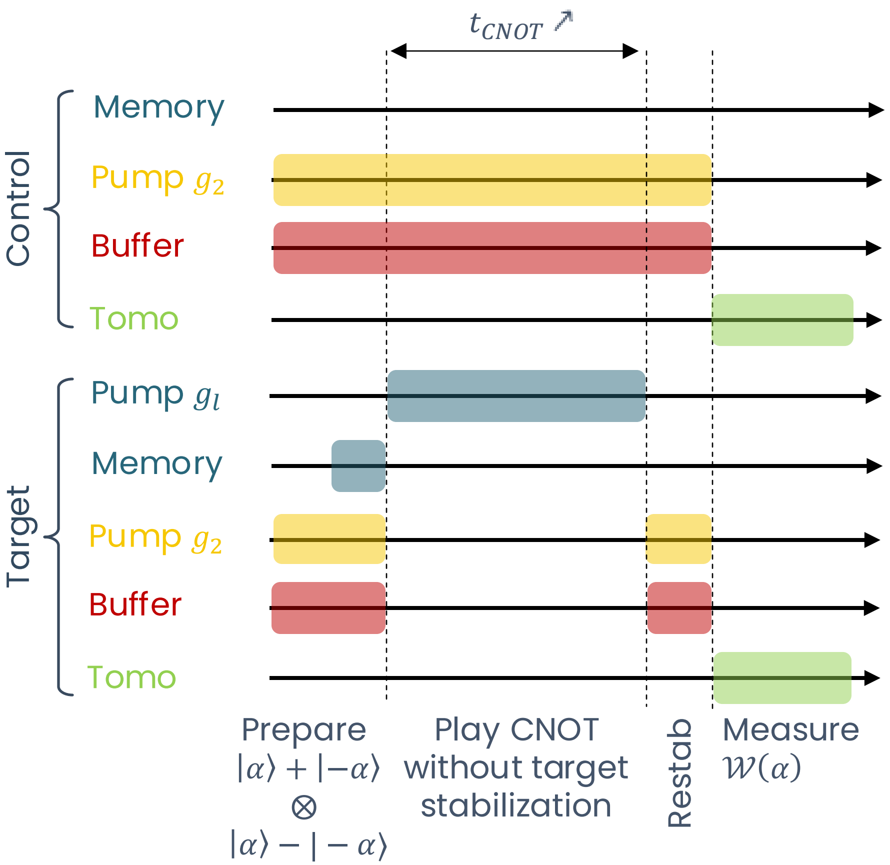
Two-photon pump at $\omega_p = 2\omega_a^{ctrl} - \omega_b^{ctrl}$

Longitudinal pump at $\omega_p = \omega_a^{ctrl}$

Selects longitudinal coupling

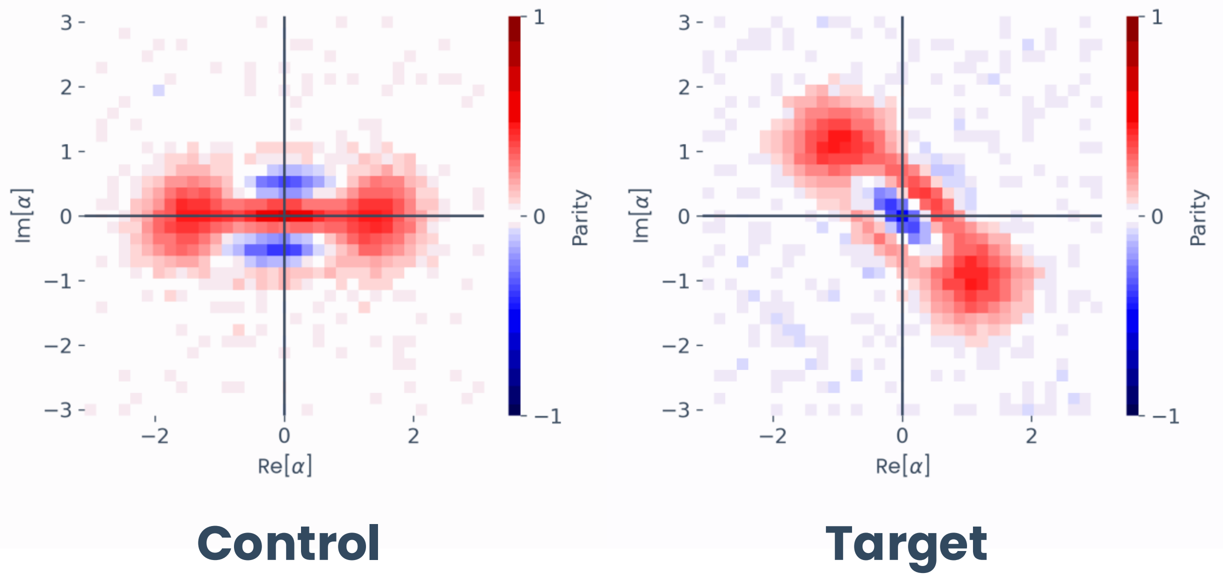
$H_l = g_l\,(a_c + a_c^+ + 2\alpha) \otimes a_t^+ a_t$

CNOT at play



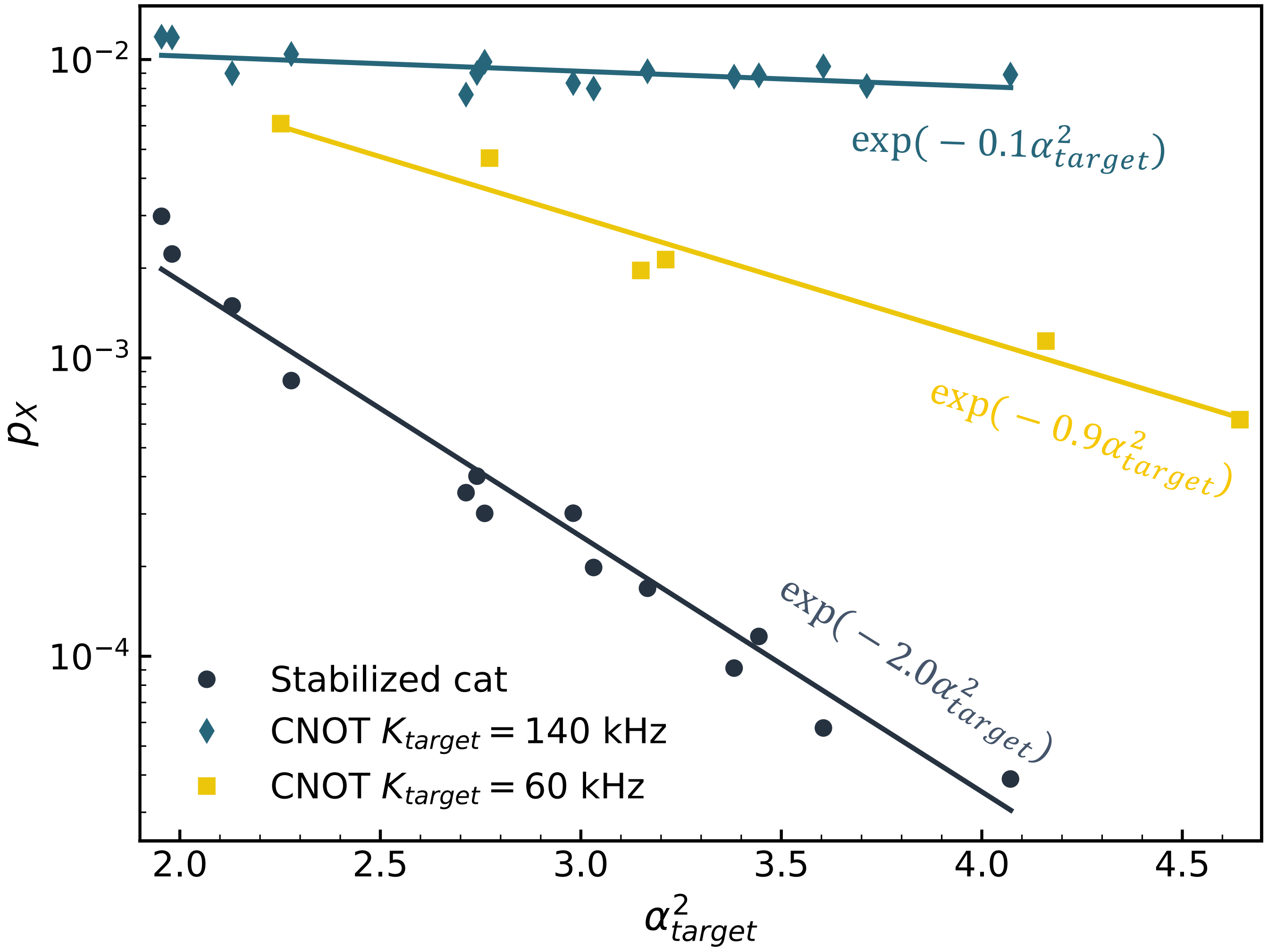
$g_l/2\pi = 220$ kHz

$T_{CNOT} = 400$ 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.

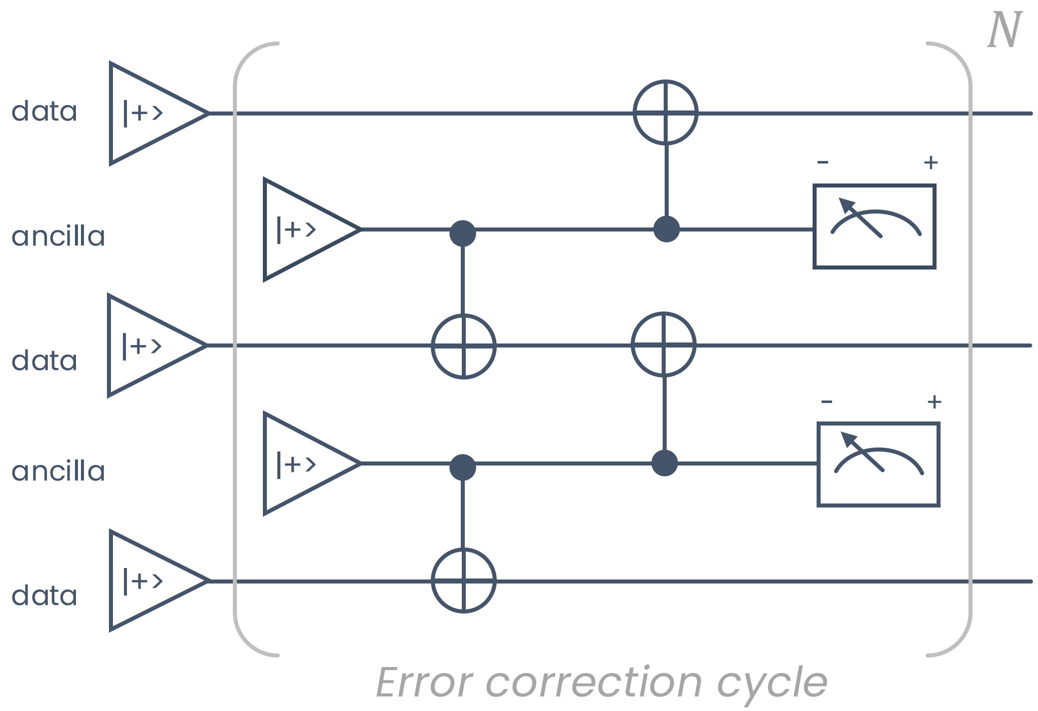
Solutions

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

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

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

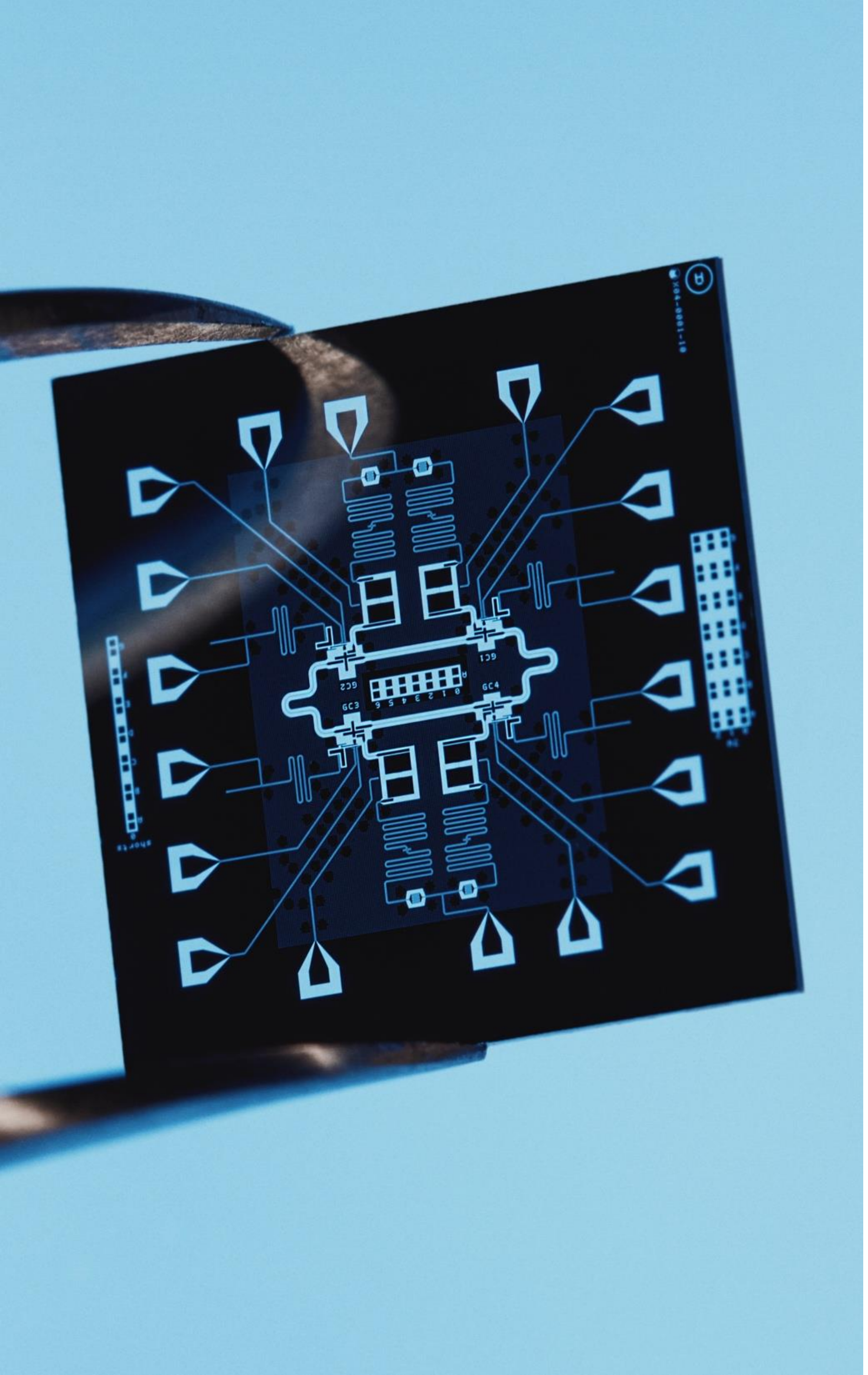
Repetition code ingredients

- ✓ +/- 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**

Guillaud & Mirrahimi, PRX 9, 041053 (2019)



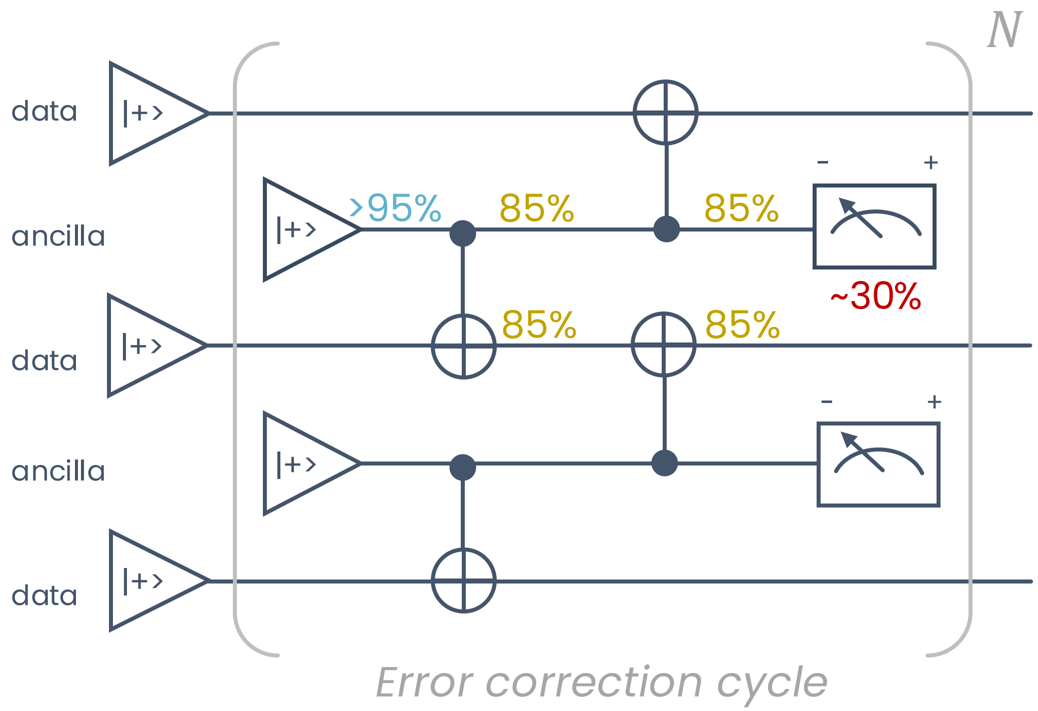
01 Quantum error correction with biased noise qubits

02 Experimental progress towards operating cat qubits

03 **Going below threshold**

Going below threshold

How far are we from the threshold?



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

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

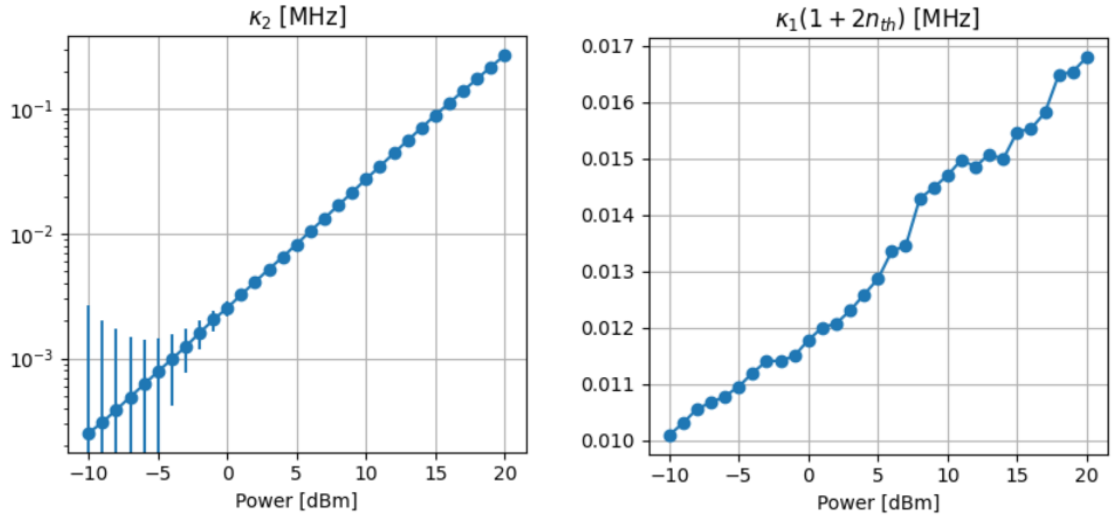
Stabilizer: $S_i = X_i X_{i+1}$

Guillaud & Mirrahimi, PRX 9, 041053 (2019)

To go below threshold:

- Better readout scheme → WIP
- Improve bare cavity T_1
- Improve k_2

T_1 degradation under pump:



Parametric effect? Junction modes? Thermalization?...

→ WIP