Towards fault-tolerant quantum computation with superconducting qubits

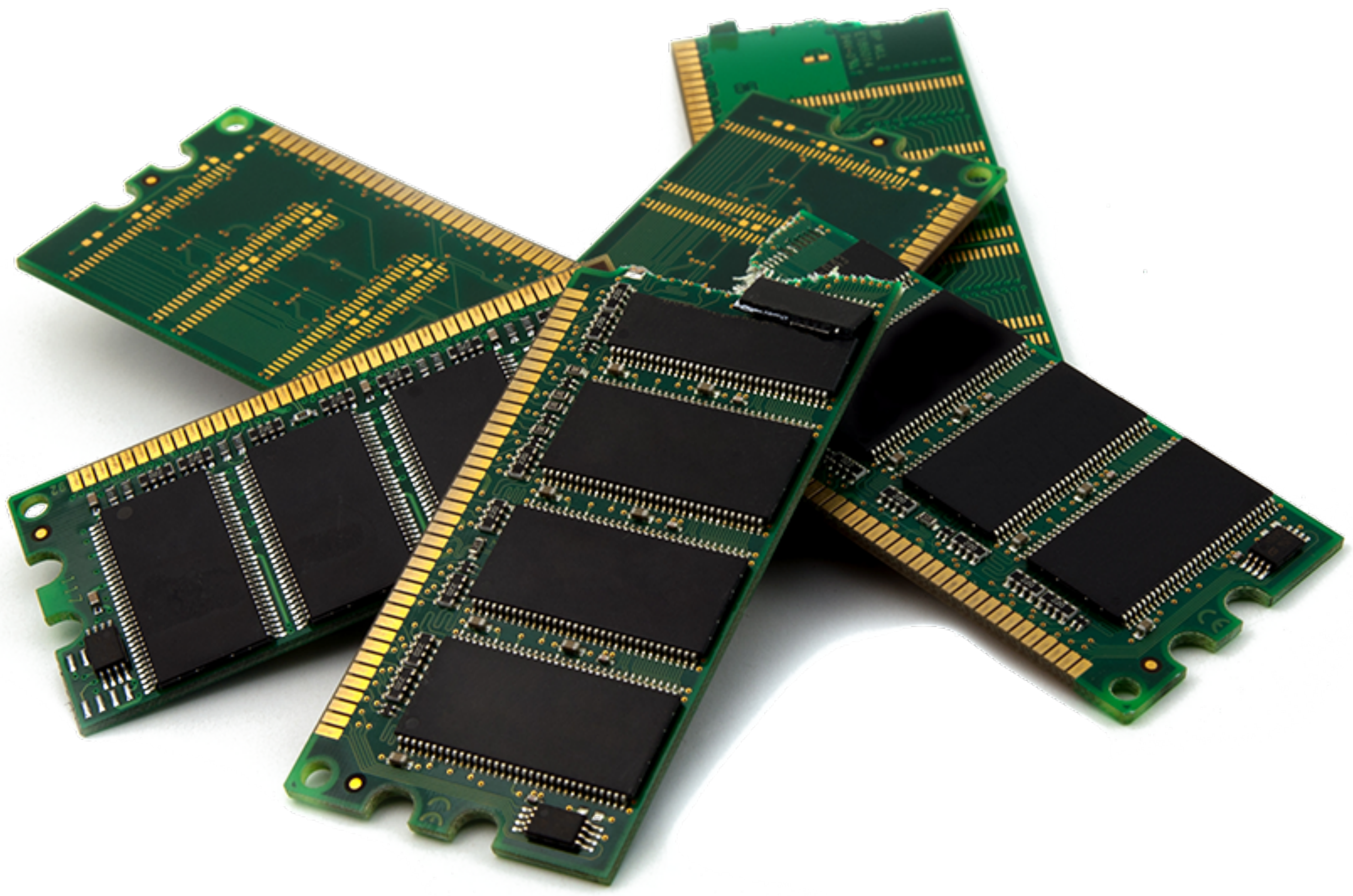
Mazyar Mirrahimi
Quantic team (Inria Paris, ENS Paris, Mines ParisTech, CNRS)

Quantic team
Philippe Campagne-Ibarcq (Exp.)
Zaki Leghtas (Exp.)
Alex Petrescu (Th.)
Pierre Rouchon (Th.)
Alain Sarlette (Th.)
Antoine Tilloy (Th.)

Postdoc/PhD
Thiziri Aissaoui
Adrien Bocquet
Alvise Borgognoni
Leon Carde
Linda Greggio
Pierre Guilmin
Edoardo Lauria
Louis Paletta
F.-M. Le Régent
Vincent Lienhard
Ulysse Réglade
Angela Riva
Rémi Robin
Erwan Roverch
Emilio Rui
Diego Ruiz
Lev-Arcady Sellem
Karanabir Tiwana
Aron Vanselow
Marius Villiers

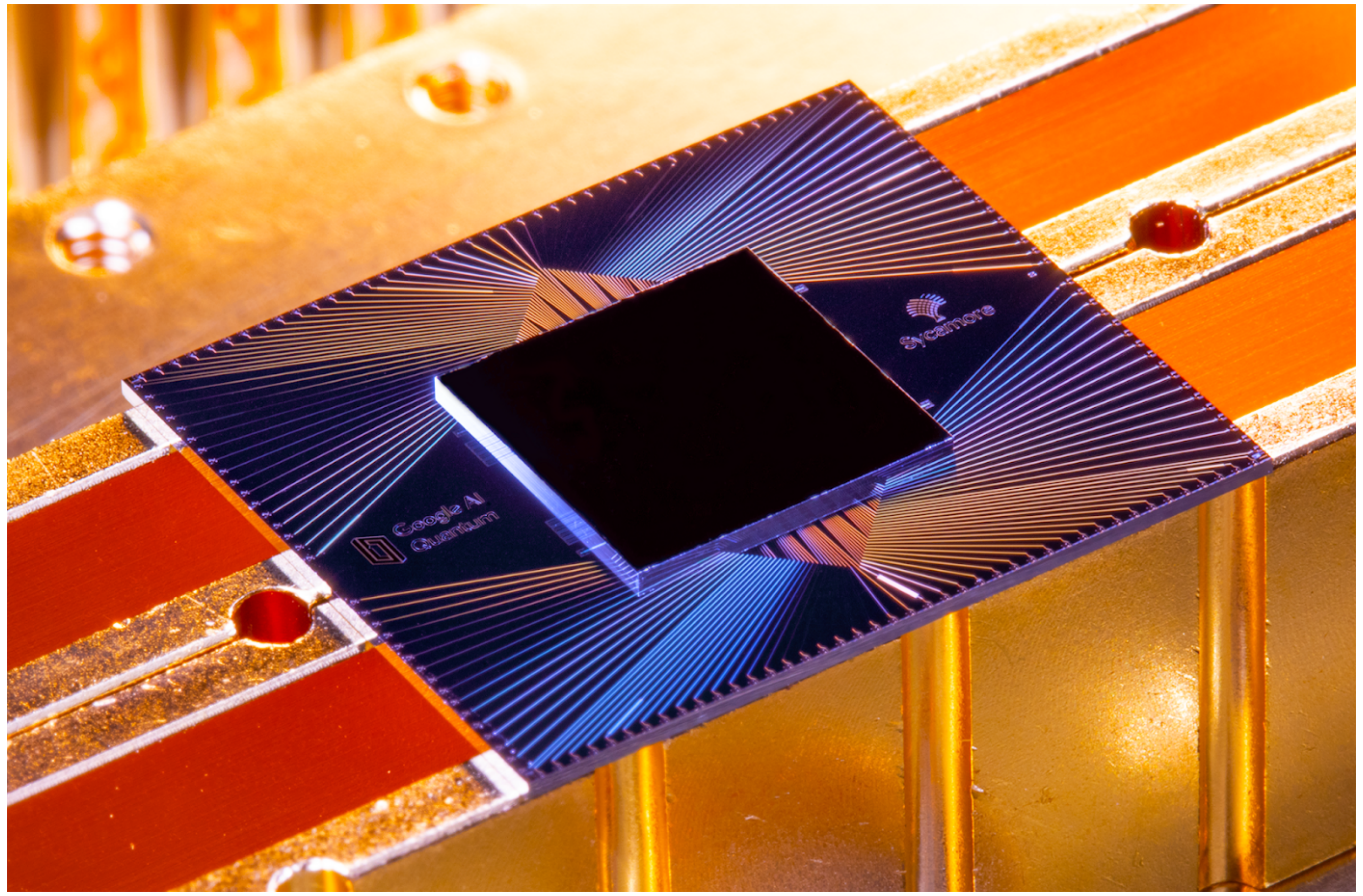
INVENTEURS DU MONDE NUMÉRIQUE

Quantum hardware is (too) noisy



Classical RAM (Random Access Memory)

$\sim 10^{-25}$ errors per bit per operation



Quantum processor

$\sim 10^{-3} - 10^{-4}$ errors per bit per operation

Large scale quantum computation requires $\sim 10^{-10} - 10^{-15}$

Delocalization provides protection

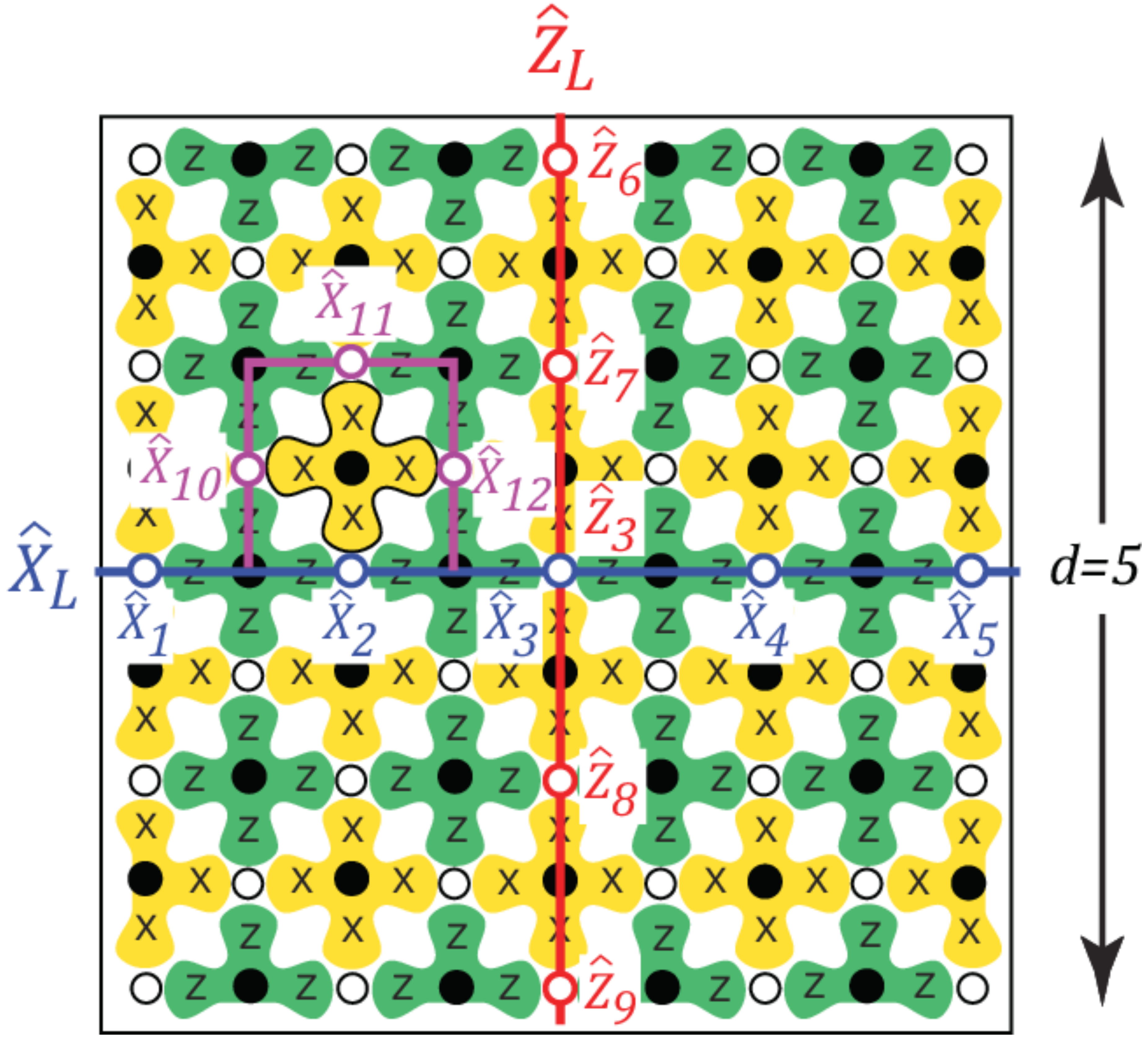
- High rate errors are caused by **local** physical processes

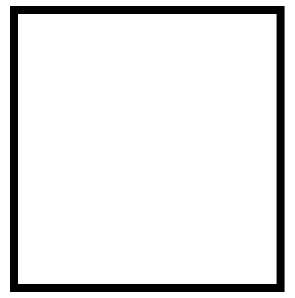
- Encoding the information in **non-local** degrees of freedom protects it

Surface code

$X_L =$ all X along horizontal direction

$Z_L =$ all Z along vertical direction

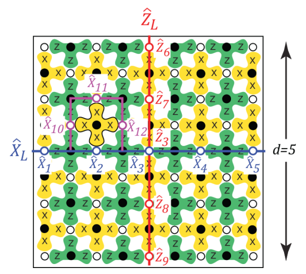


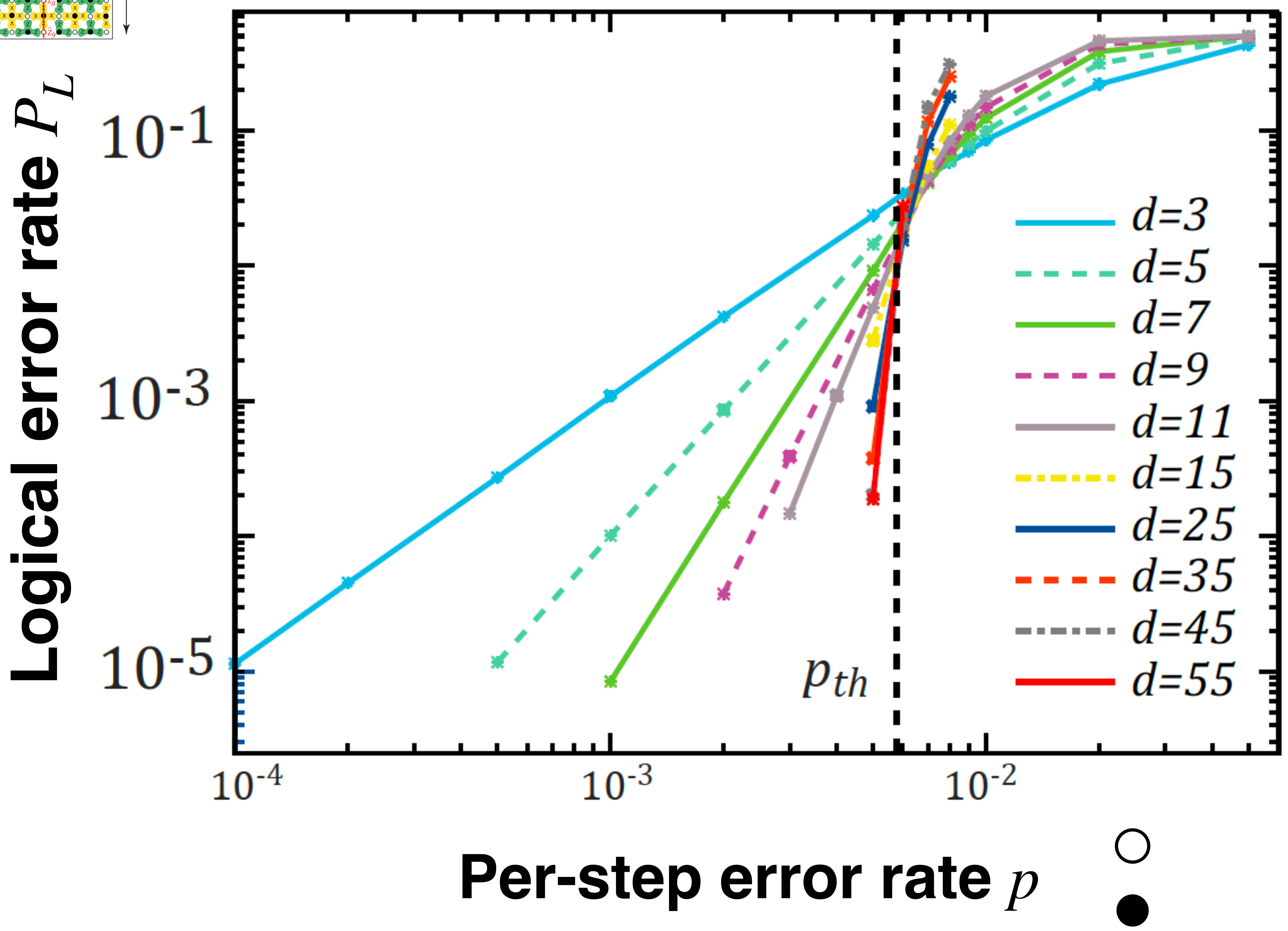
 } « logical » qubit

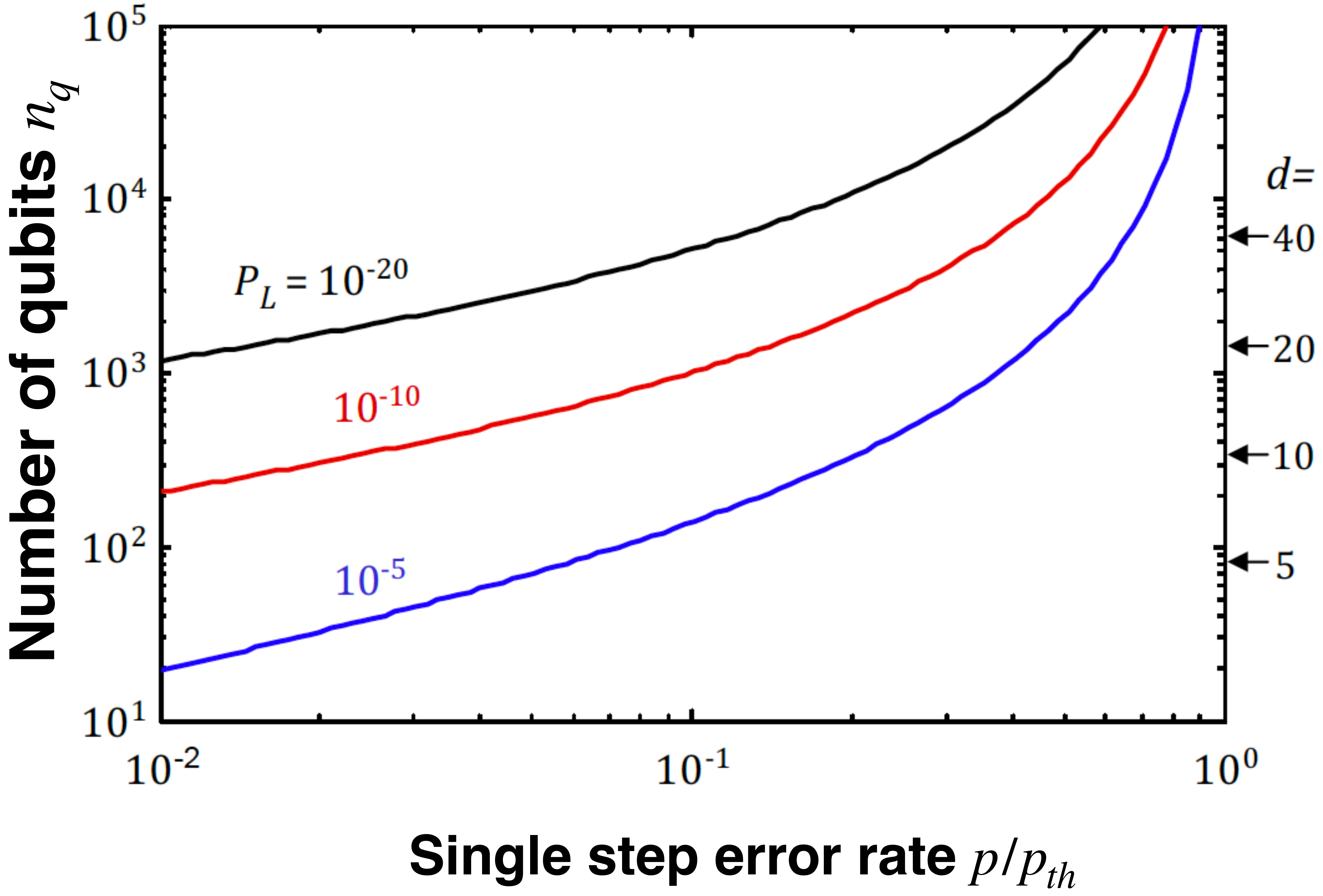
○ data qubit
● syndrome measurement qubit
} « physical » qubits

A. Fowler et al., Phys. Rev. A 86, 2012.

At the cost of increased physical resource

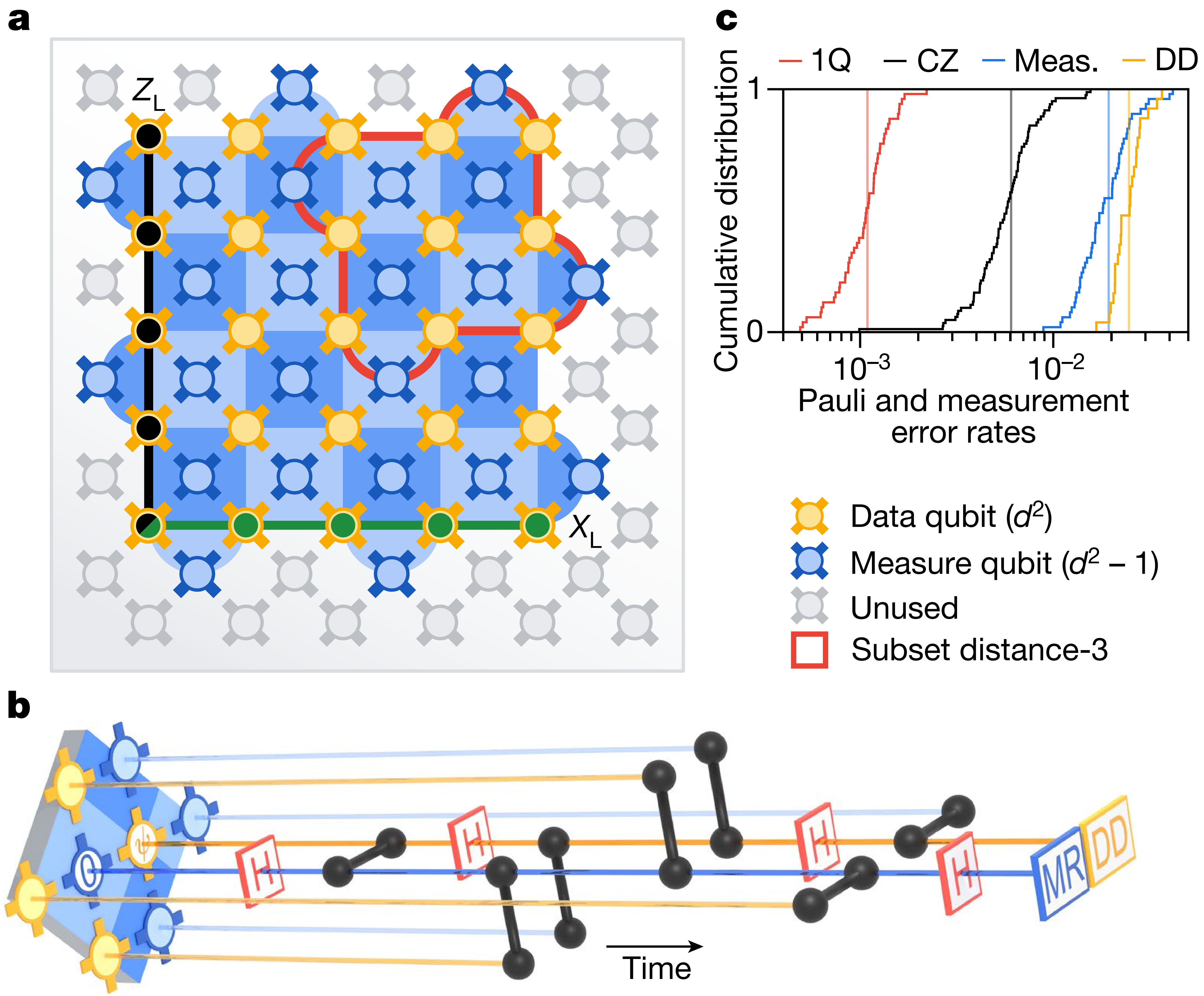




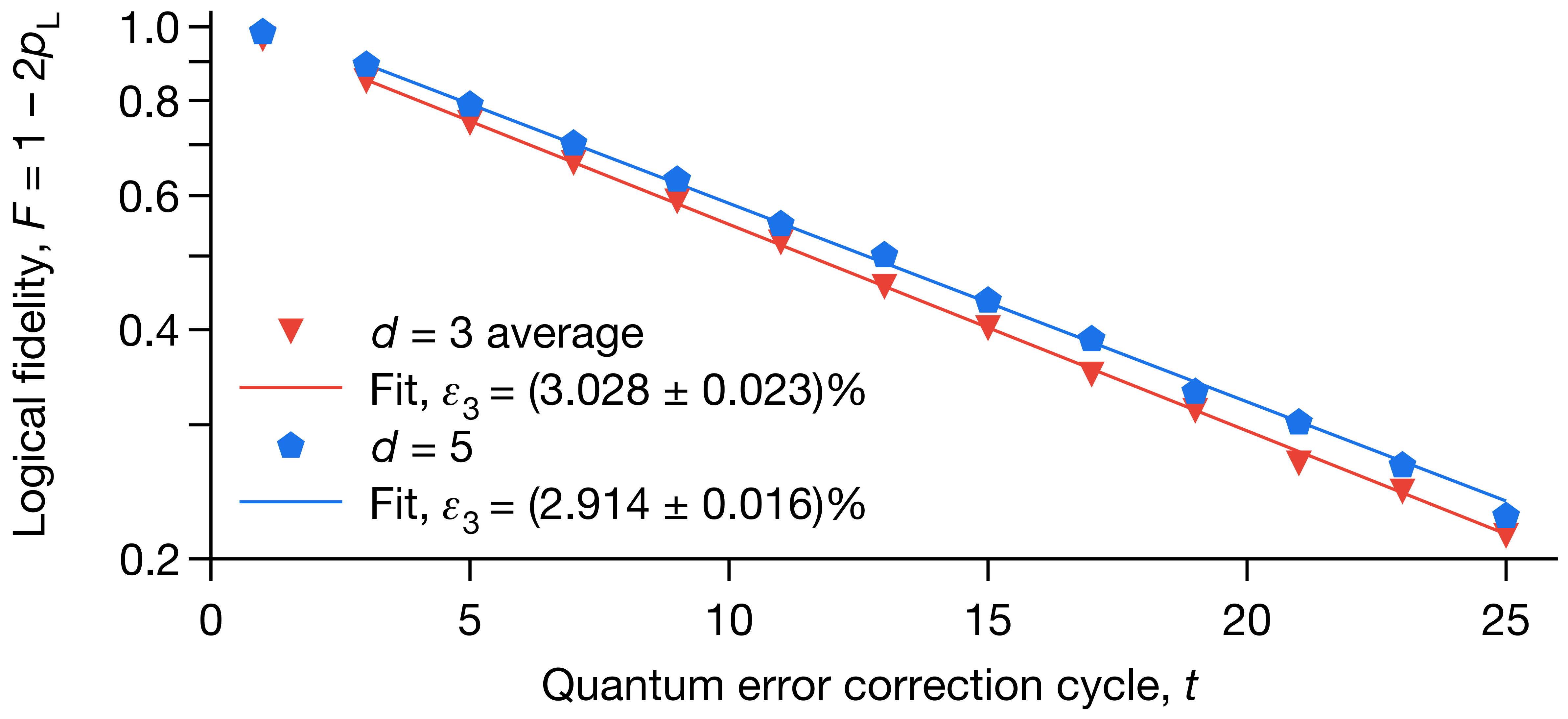


Figures borrowed from A. Fowler et al., Phys. Rev. A 86, 2012.

State of progress



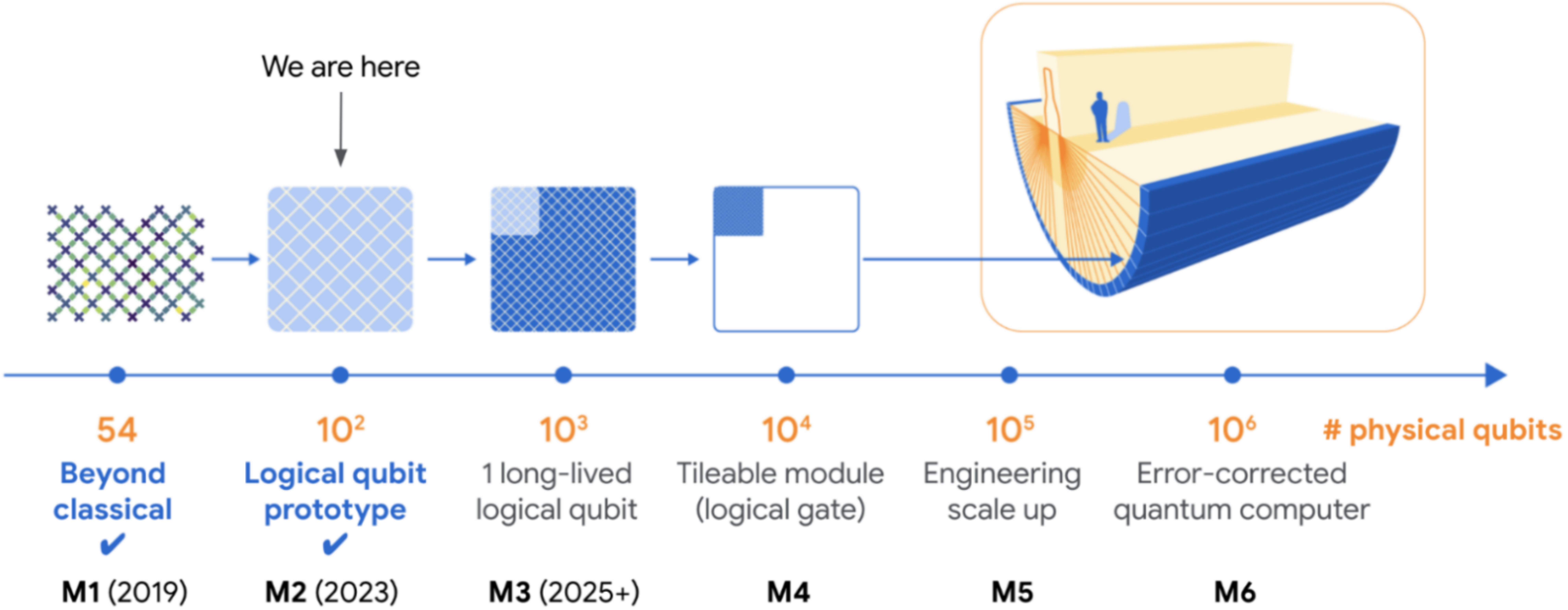
Single-qubit gate time: 25ns
Two-qubit gate time: 34ns
Measurement time: 500ns
Reset time: 100ns



Short term bottleneck: fast high-fidelity measurements

Suppressing quantum errors by scaling a surface logical qubit, Google Quantum AI, Nature, 2023.

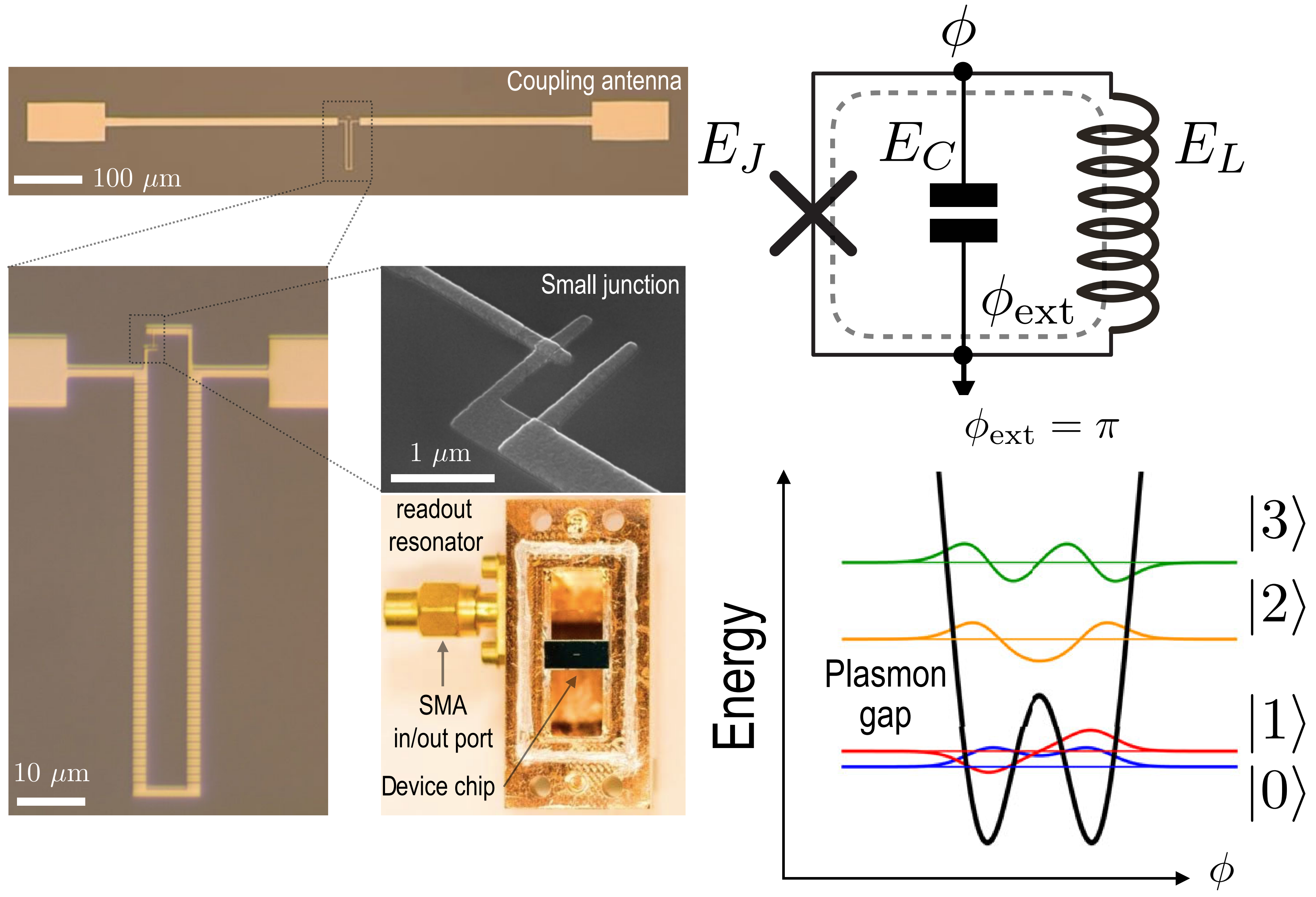
Google roadmap



Possible shortcuts: better building blocks

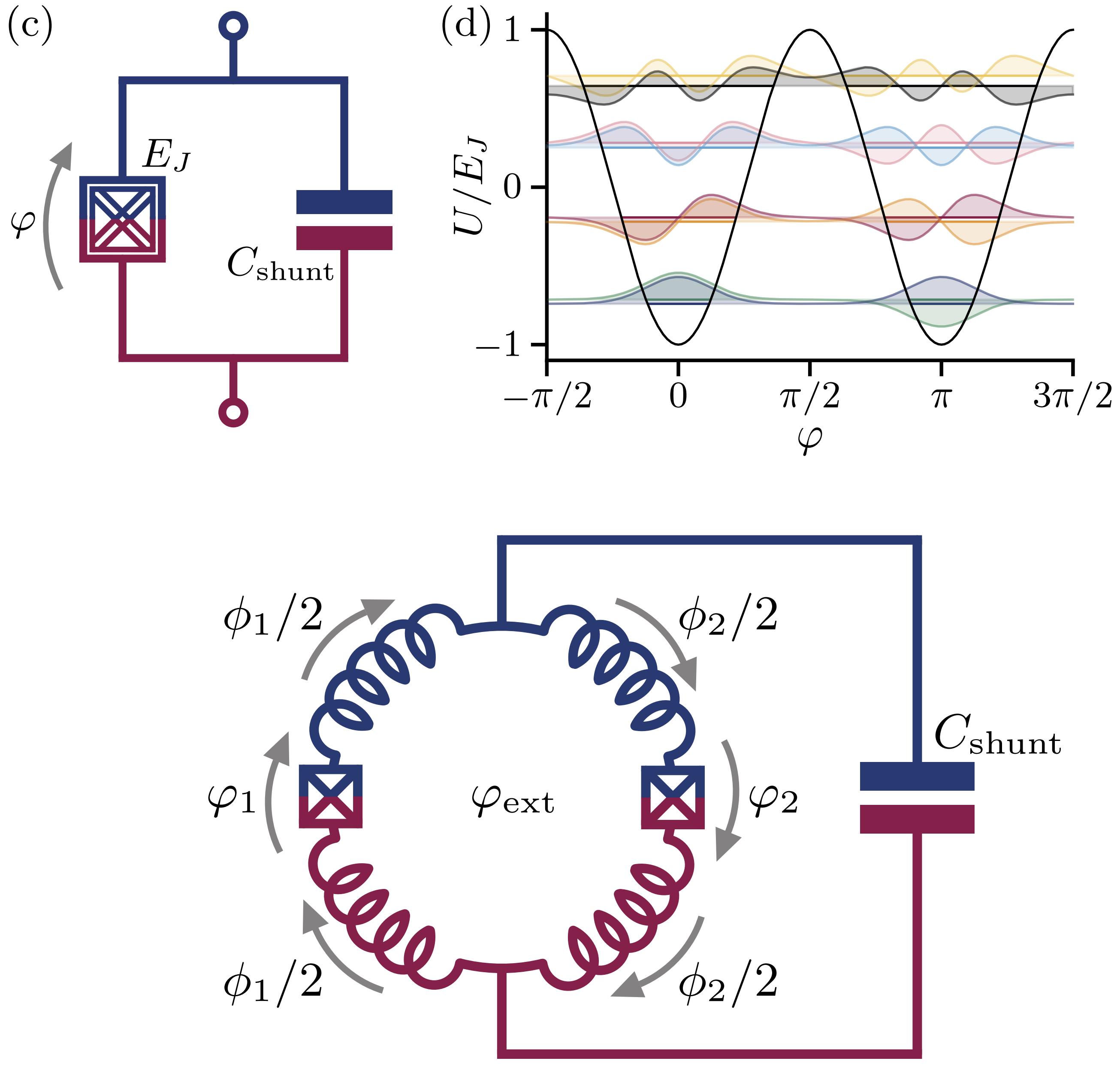
Protected qubits

Fluxonium



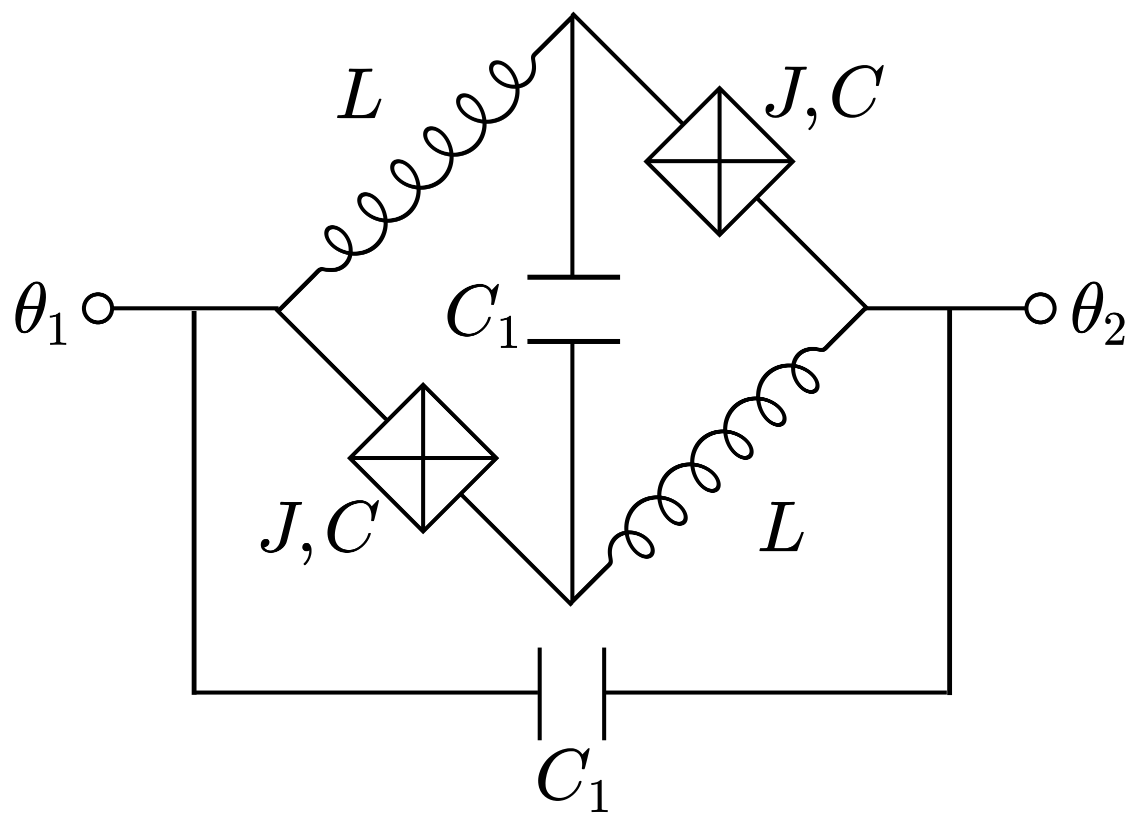
Manucharyan, Devoret et al., Science 2009
Nguyen, Manucharyan et al., PRX 2019

$\cos(2\varphi)$-qubit



Douçot and Vidal, PRL 2002
Smith, Devoret et al., npj Quantum Inf., 2020

$0 - \pi$ qubit

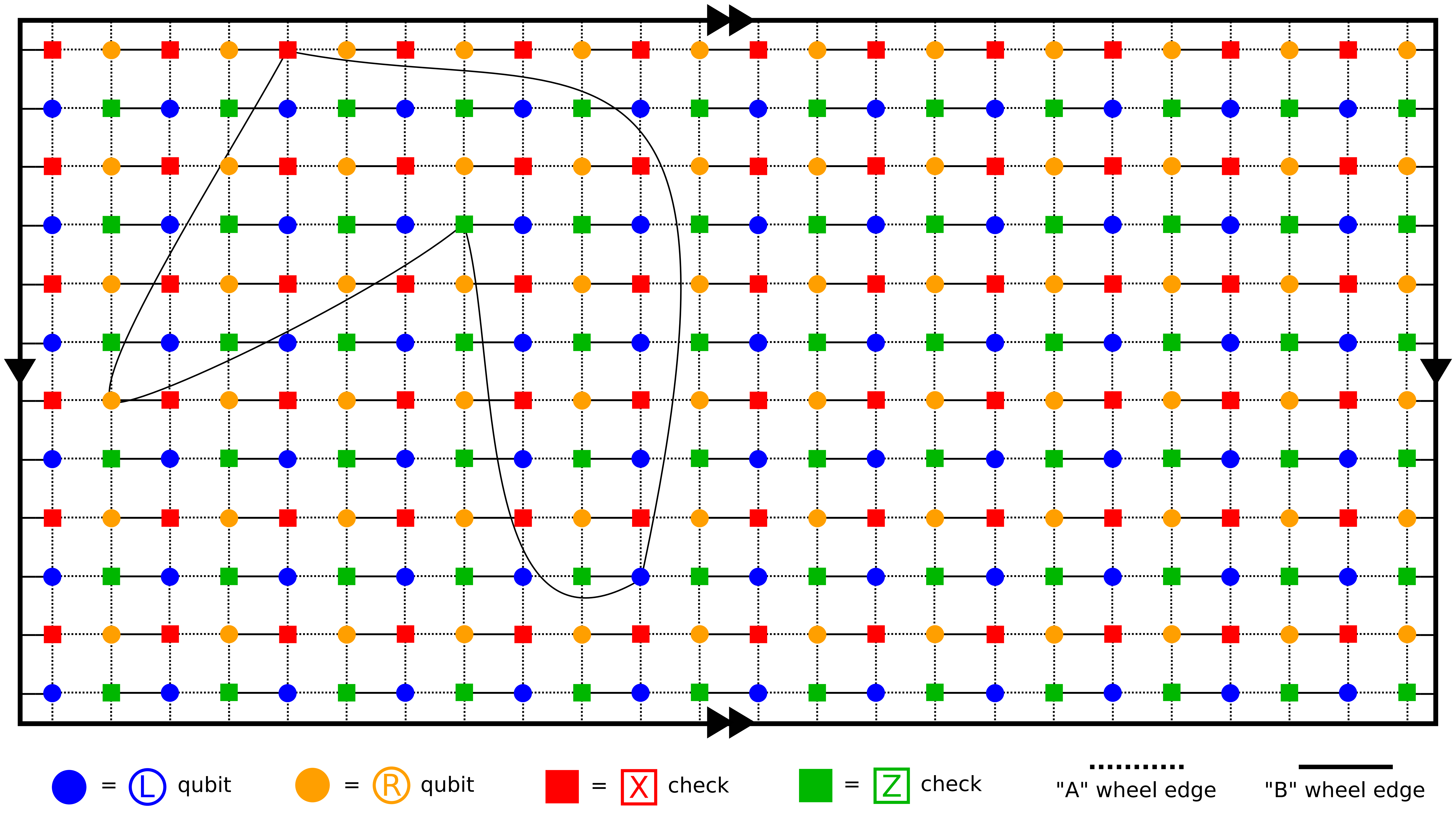


Brooks, Kitaev, Preskill, PRA 2013

Possible shortcuts: better codes

A bi-planar LDPC (Low-Density Parity-Check) code [[n=144,k=12,d=12]]

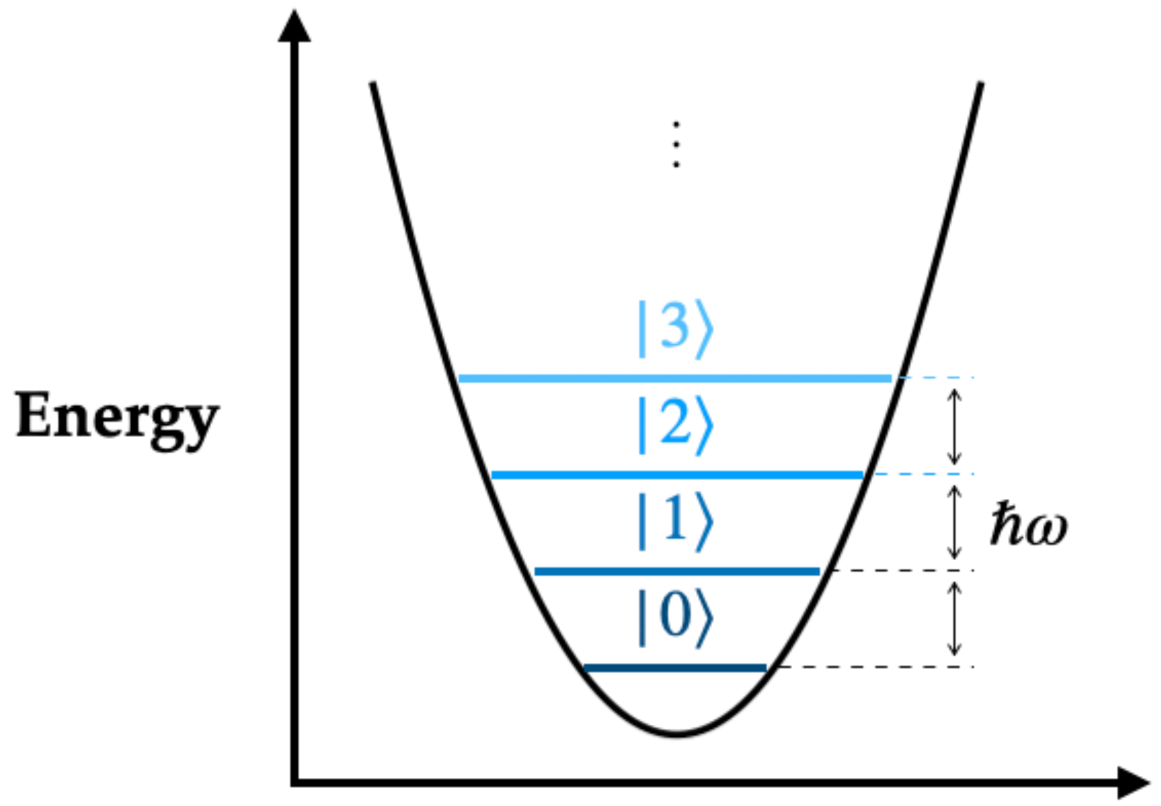
- Perspective of implementation with flip-chip technology
- Challenge of long-range interactions
- Limited capability for fault-tolerant logical gate implementations



High-threshold and low-overhead quantum memory (Theory proposal), IBM, 2023.

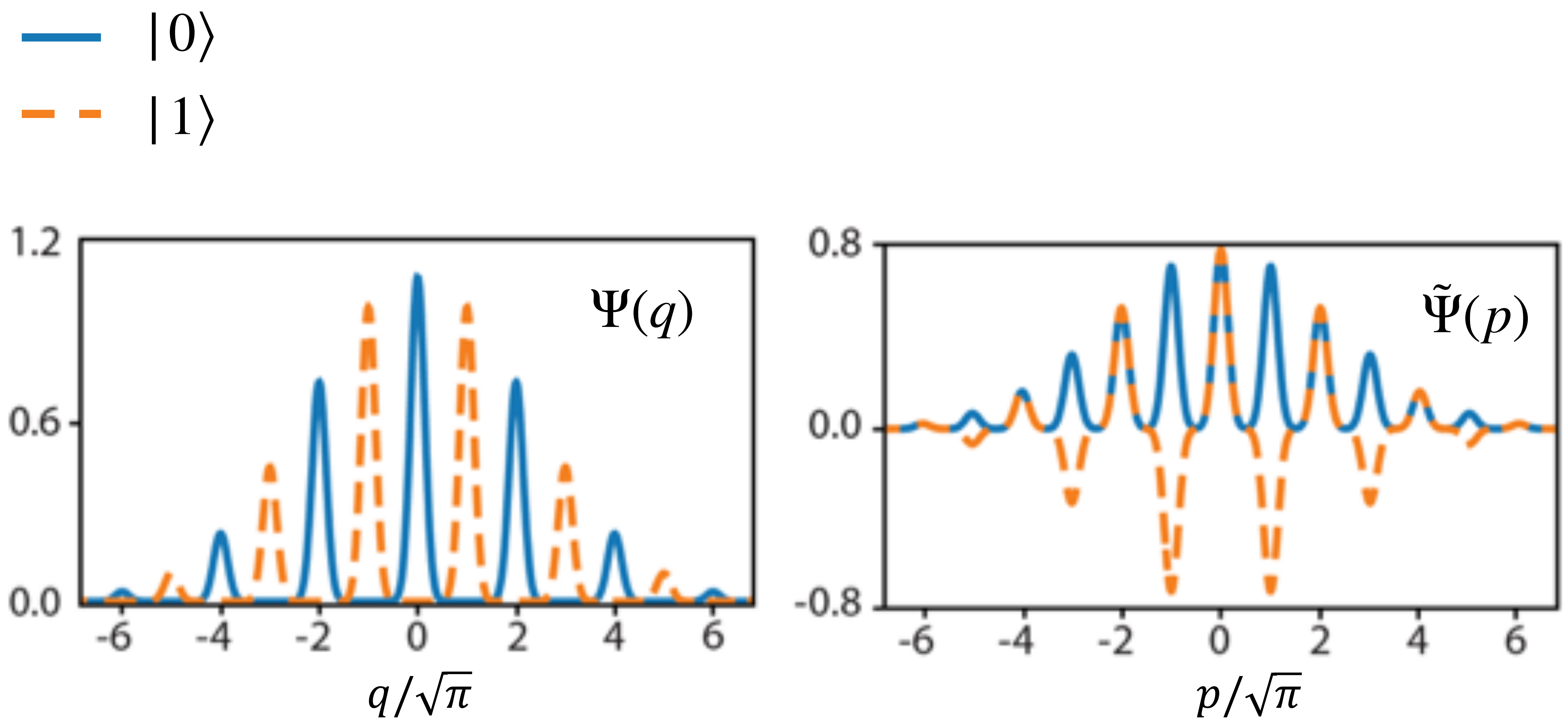
Possible shortcuts: low-level QEC with bosonic codes

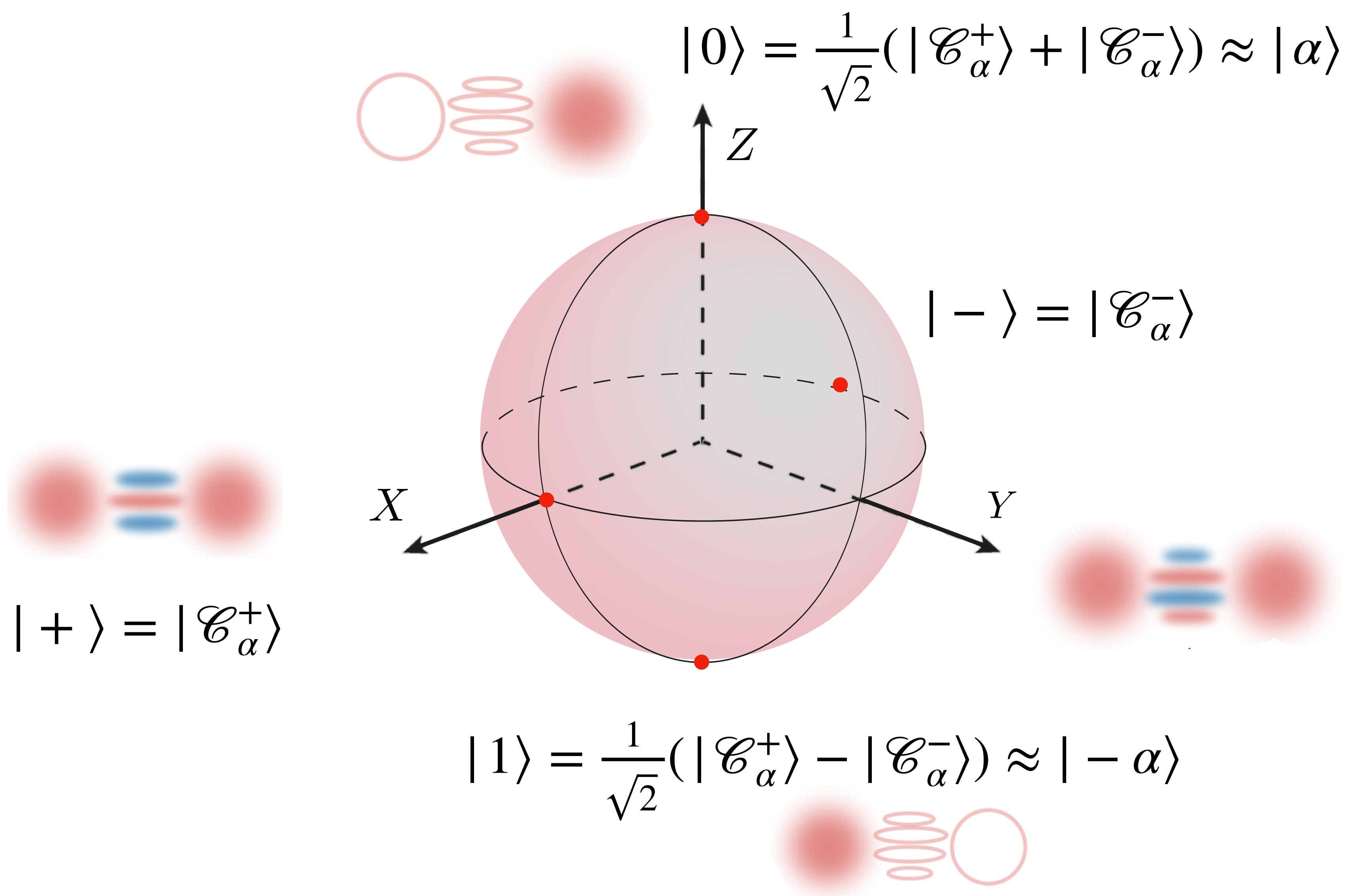
A. Joshi, K. Noh, Y. Gao,
Quantum Sci. Technol. 6 033001 (2021)



$$\hat{H} = \hbar\omega(\hat{a}^\dagger\hat{a} + \frac{1}{2})$$

$$\mathscr{H} = \text{span}\{|n\rangle, n \in \mathbb{N}\}$$

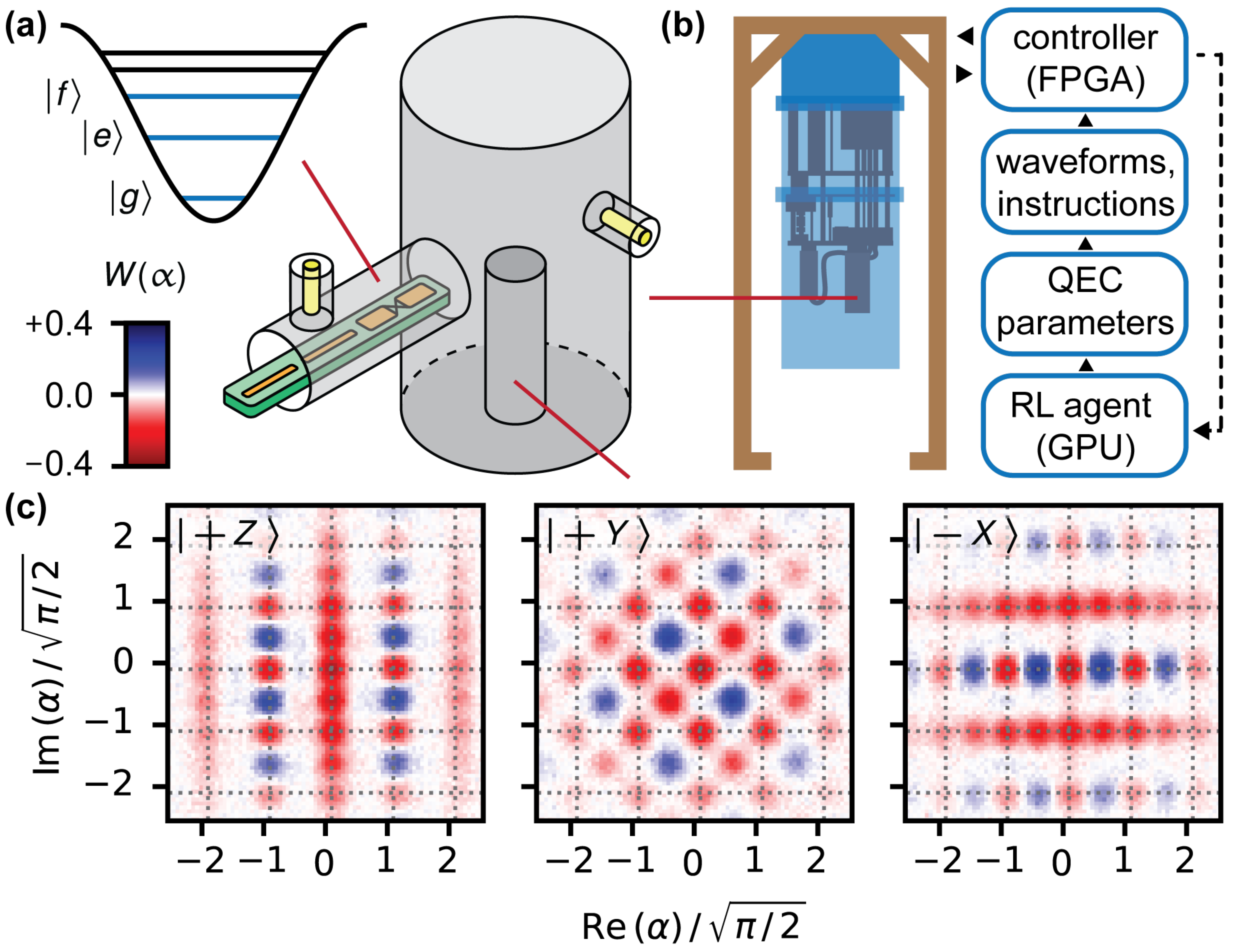


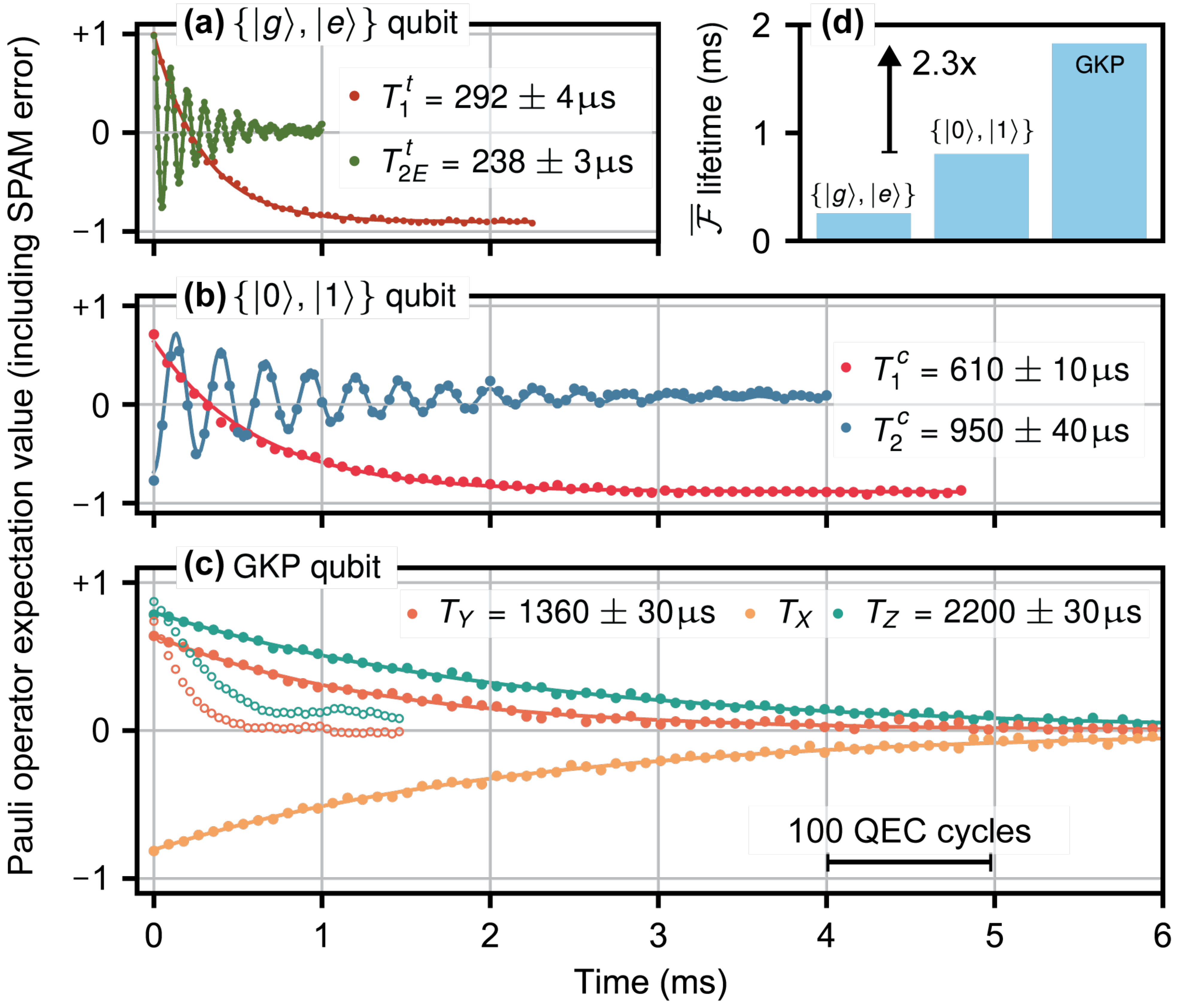


D. Gottesman, A. Kitaev, J. Preskill, Phys. Rev. A 64, 2001.

P.T. Cochrane et al., Phys. Rev. A 59, 1999.
Z. Leghtas et al., Phys. Rev. Lett. 111, 2013.

Low-level QEC with bosonic codes: break-even GKP encoding





Sivak, Devoret et al., Yale Univ., Nature 2022.

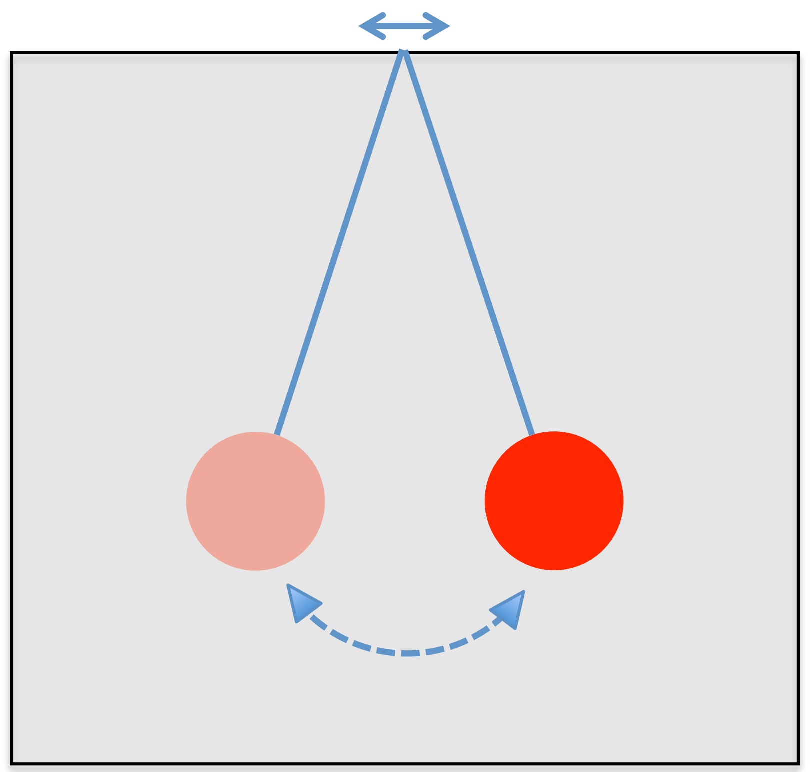
Possible shortcuts: Autonomous QEC by dissipation engineering

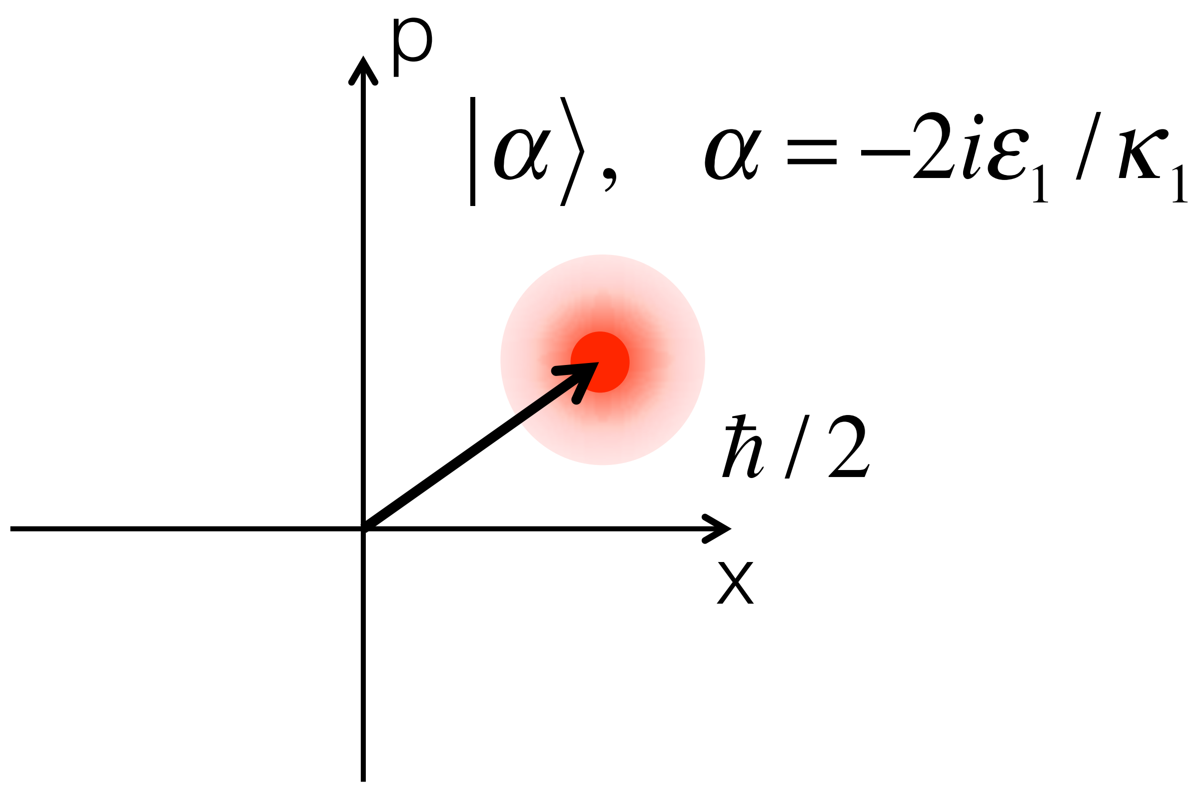
« Single-photon » driven-damped harmonic oscillator

$$H = \epsilon_1^* \hat{a} + \epsilon_1 \hat{a}^\dagger \quad \text{and} \quad L = \sqrt{\kappa_1}\hat{a}$$

$$\frac{d\rho}{dt} = -i[H,\rho] + L\rho L^\dagger - \frac{1}{2}L^\dagger L\rho - \frac{1}{2}\rho L^\dagger L$$

$$\equiv \quad L = \sqrt{\kappa_1}(\hat{a} - \alpha)$$

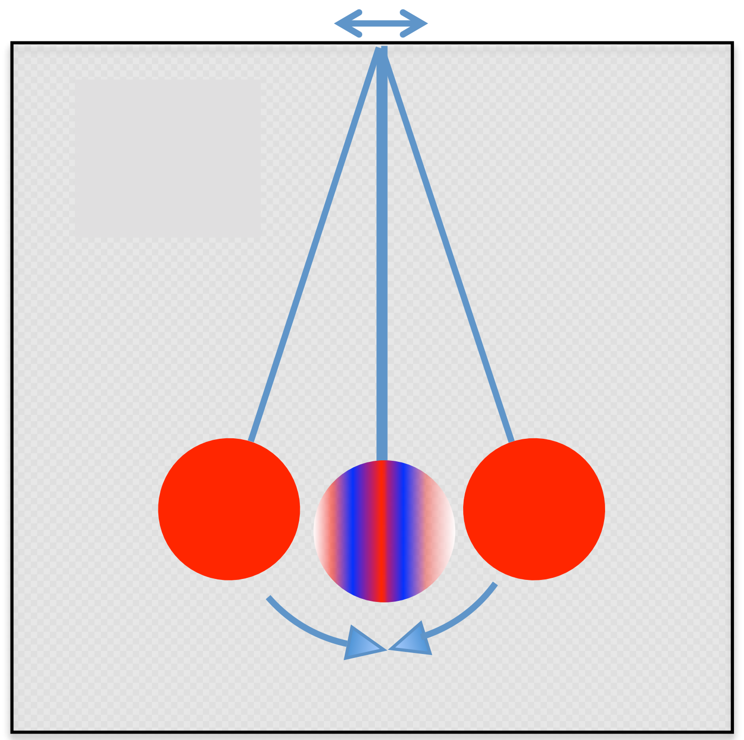


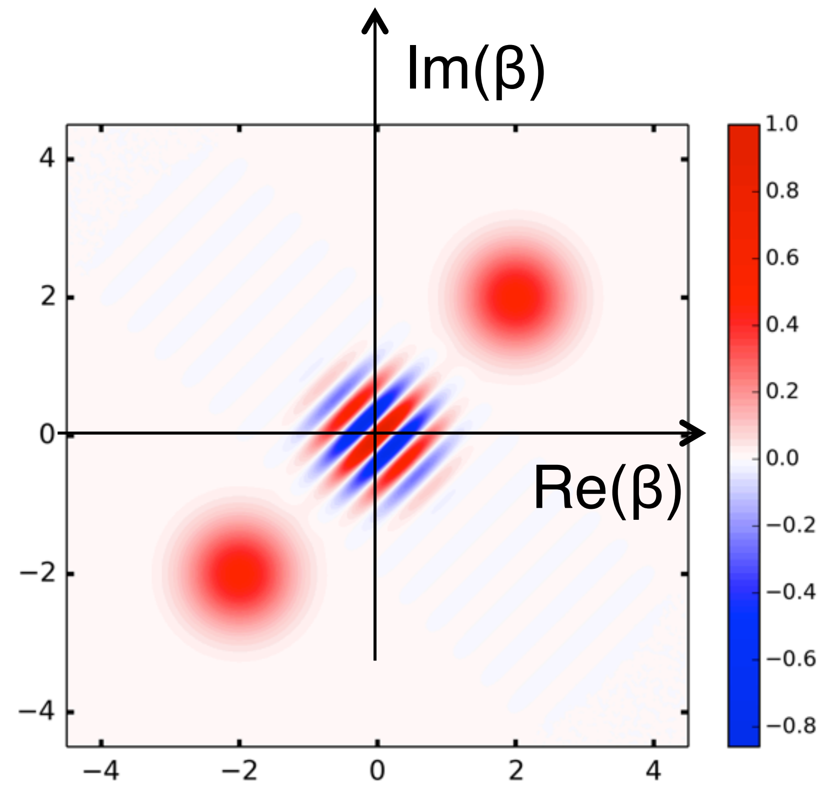


« Two-photon » driven-damped harmonic oscillator

$$H = \epsilon_2^* \hat{a}^2 + \epsilon_2 \hat{a}^{\dagger 2} \quad \text{and} \quad L = \sqrt{\kappa_2}\hat{a}^2$$

$$\equiv \quad L = \sqrt{\kappa_2}(\hat{a}^2 - \alpha^2)$$





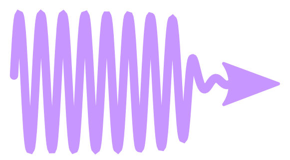
Wigner function W(β)

$$\{|\alpha\rangle, |-\alpha\rangle\} \qquad \alpha = \pm\sqrt{-2i\varepsilon_2/\kappa_2}$$

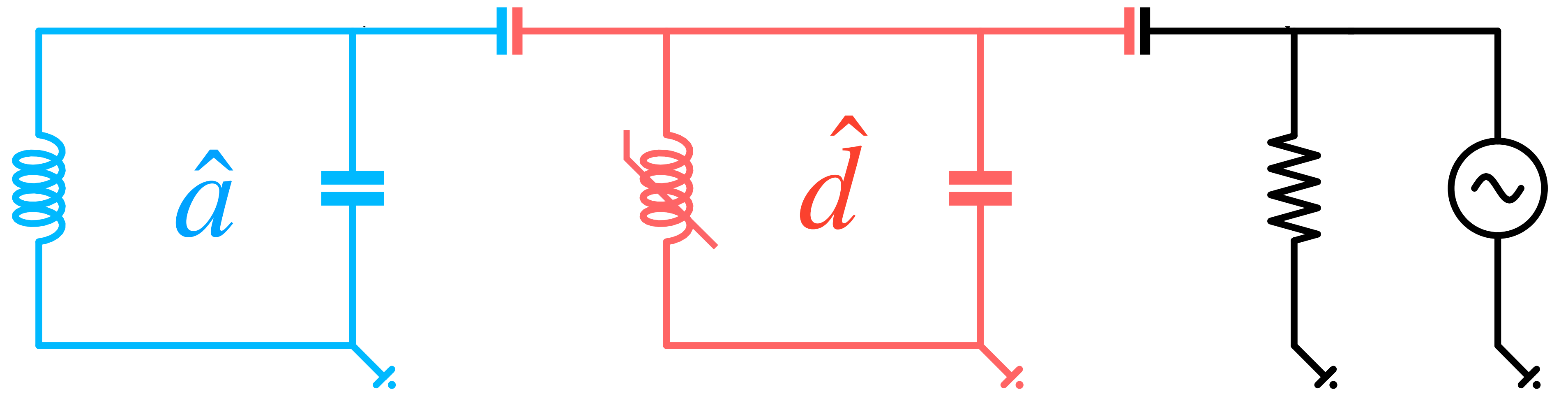
The two-photon exchange

Parametric pumping for 2-photon coupling

$$\hat{H} = g_2 \hat{a}^{\dagger 2} \hat{d} + g_2 \hat{a}^2 \hat{d}^\dagger$$

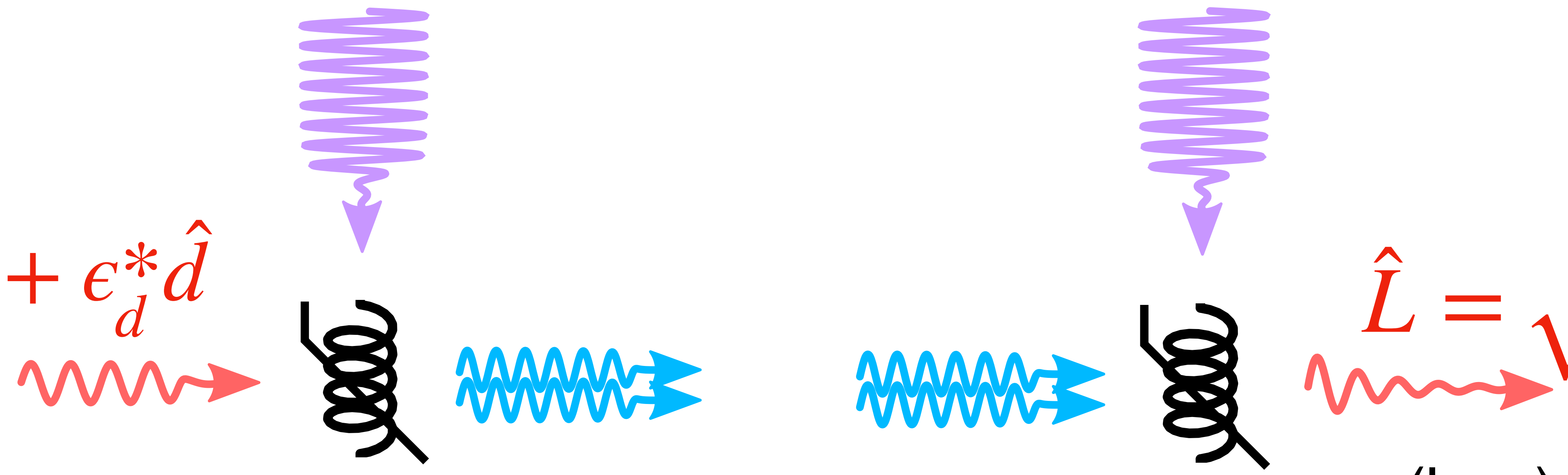


$$\omega_p = 2\omega_a - \omega_d$$



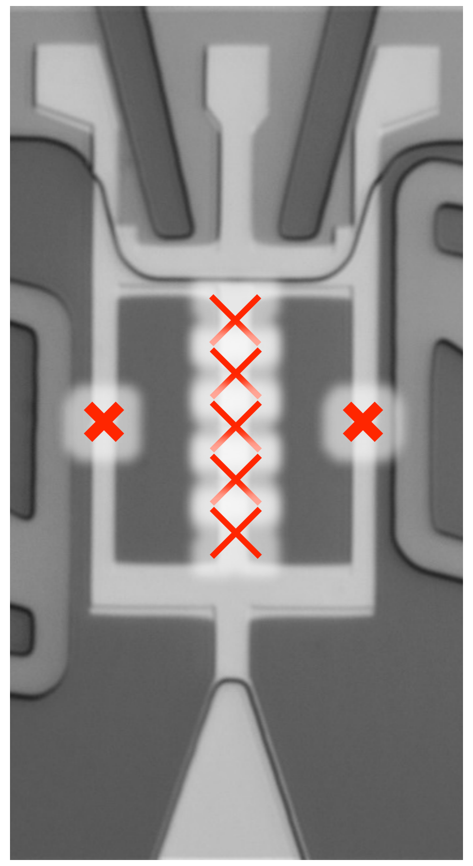
$\hat{H} = \epsilon_d \hat{d}^\dagger + \epsilon_d^* \hat{d}$

(drive)

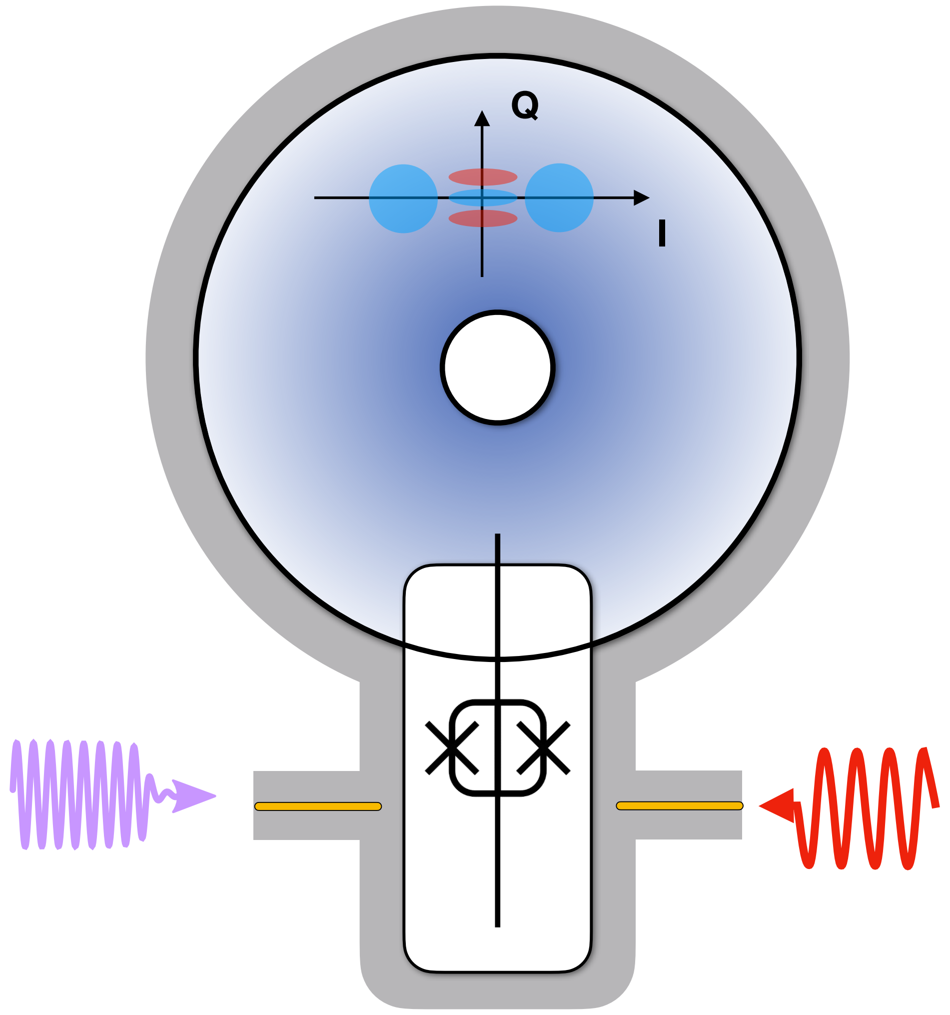


$\hat{L} = \sqrt{\kappa_d}\hat{d}$

(loss)



Parametric mixing device
(4-wave mixing Hamiltonian)



$$\hat{H}_{eff} = \epsilon_2^* \hat{a}^2 + \epsilon_2 \hat{a}^{\dagger 2}$$

(two-photon drive)

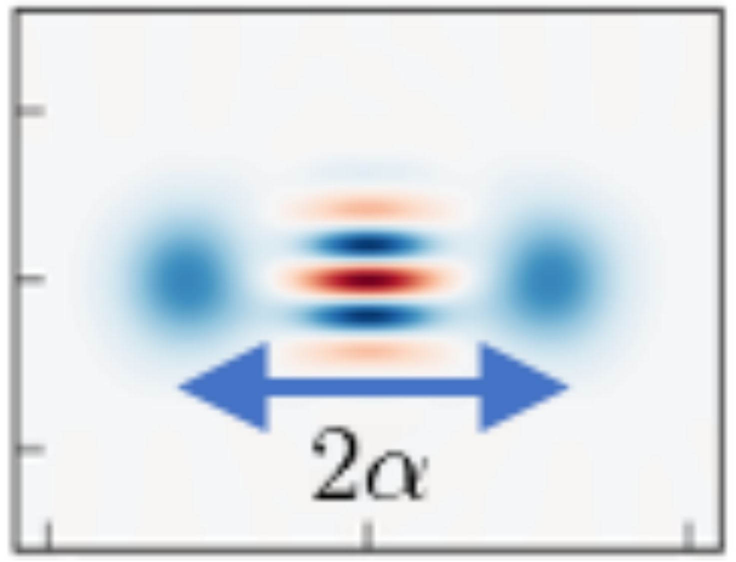
$$\hat{L}_{eff} = \sqrt{\kappa_2}\hat{a}^2$$

(two-photon loss)

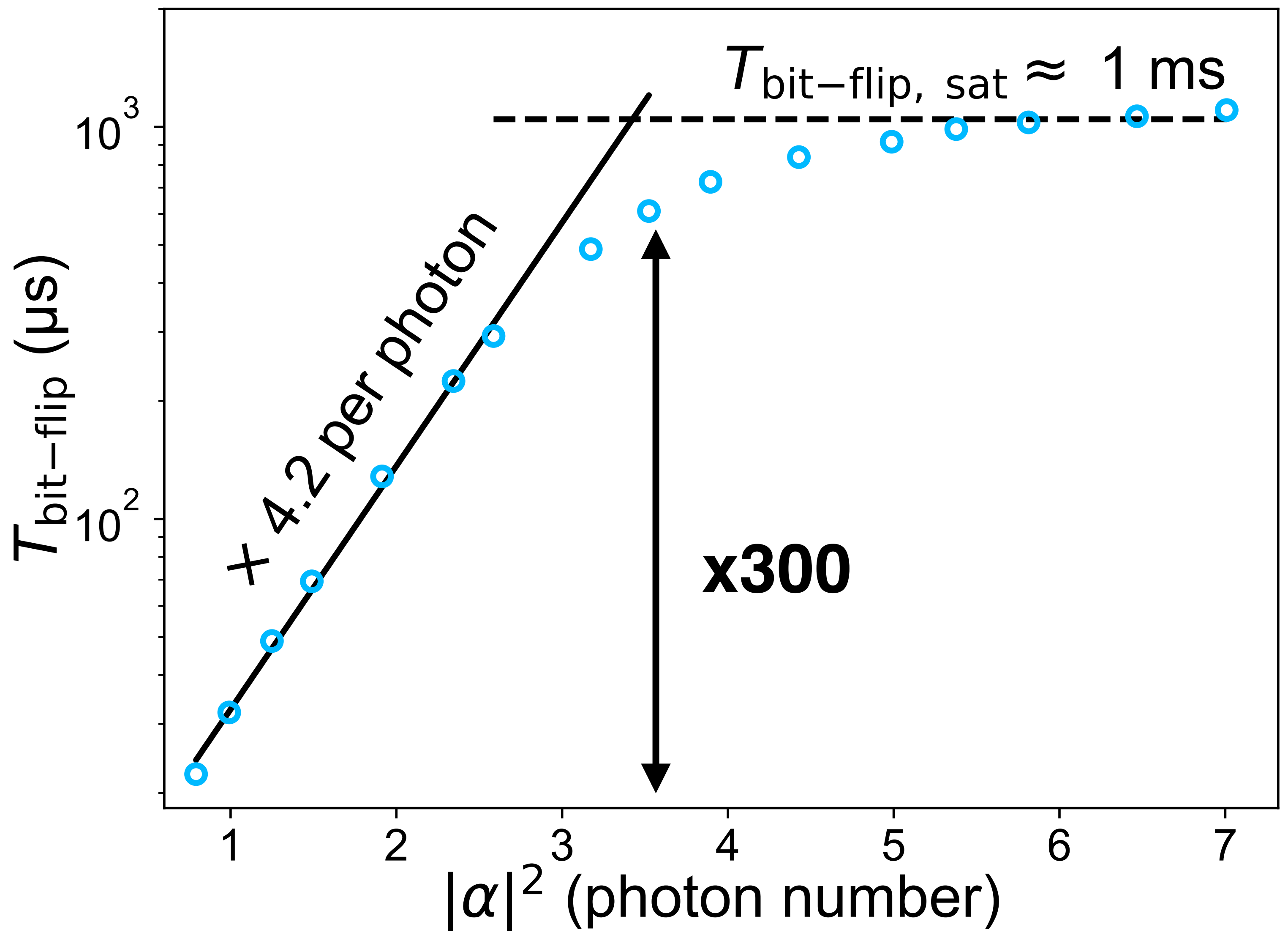
M.M. et al, NJP 2014
Z. Leghtas et al, Science 2015
S. Touzard et al, PRX 2018
R. Lescanne et al., Nature Physics 2020

Cat-qubits: exponential protection against bit-flips

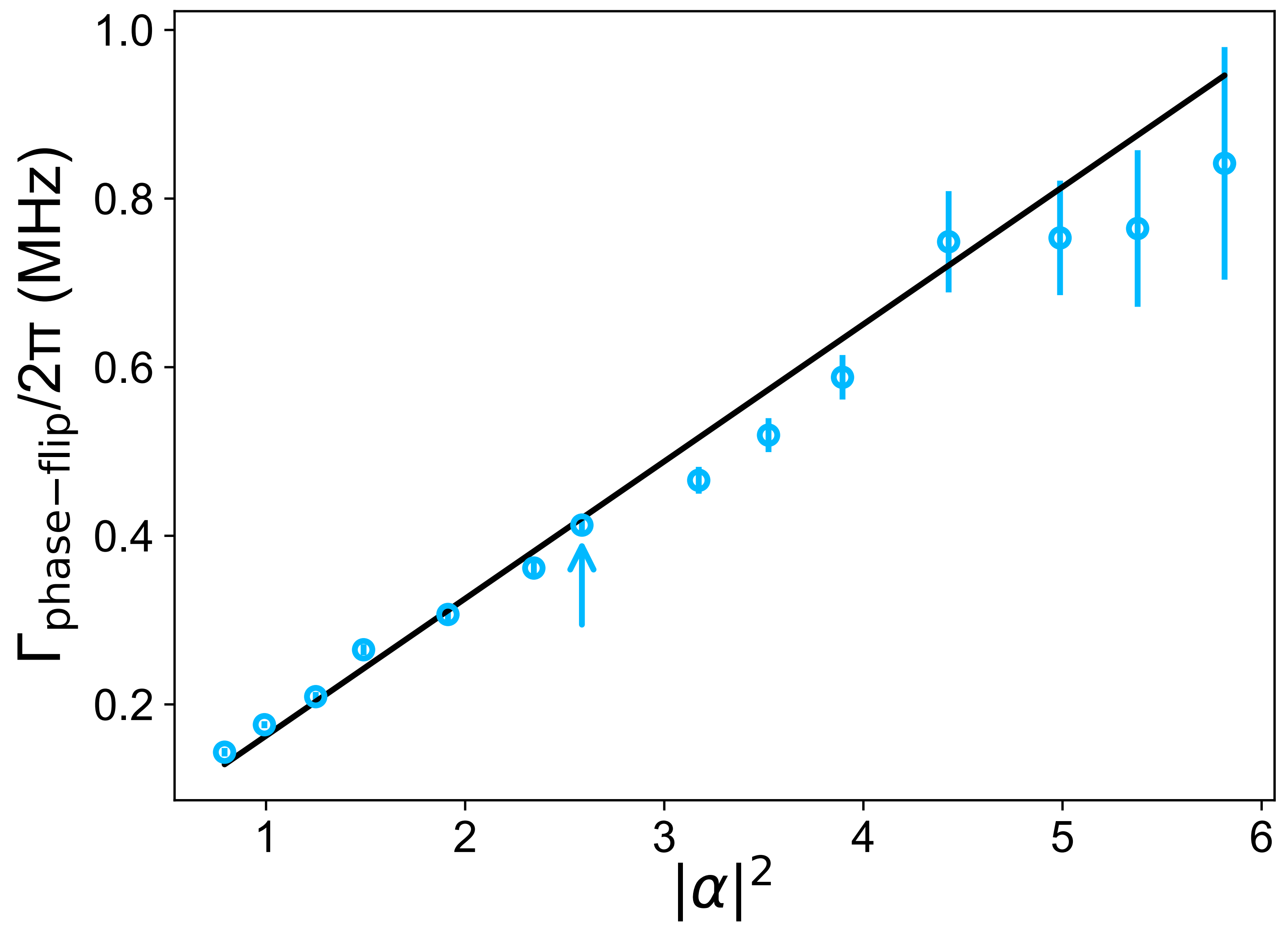
Cat-qubits are exponentially error-biased qubits



$$p_X \propto \exp(-2|\alpha|^2)$$
$$p_Z \propto \kappa_1 |\alpha|^2 t$$



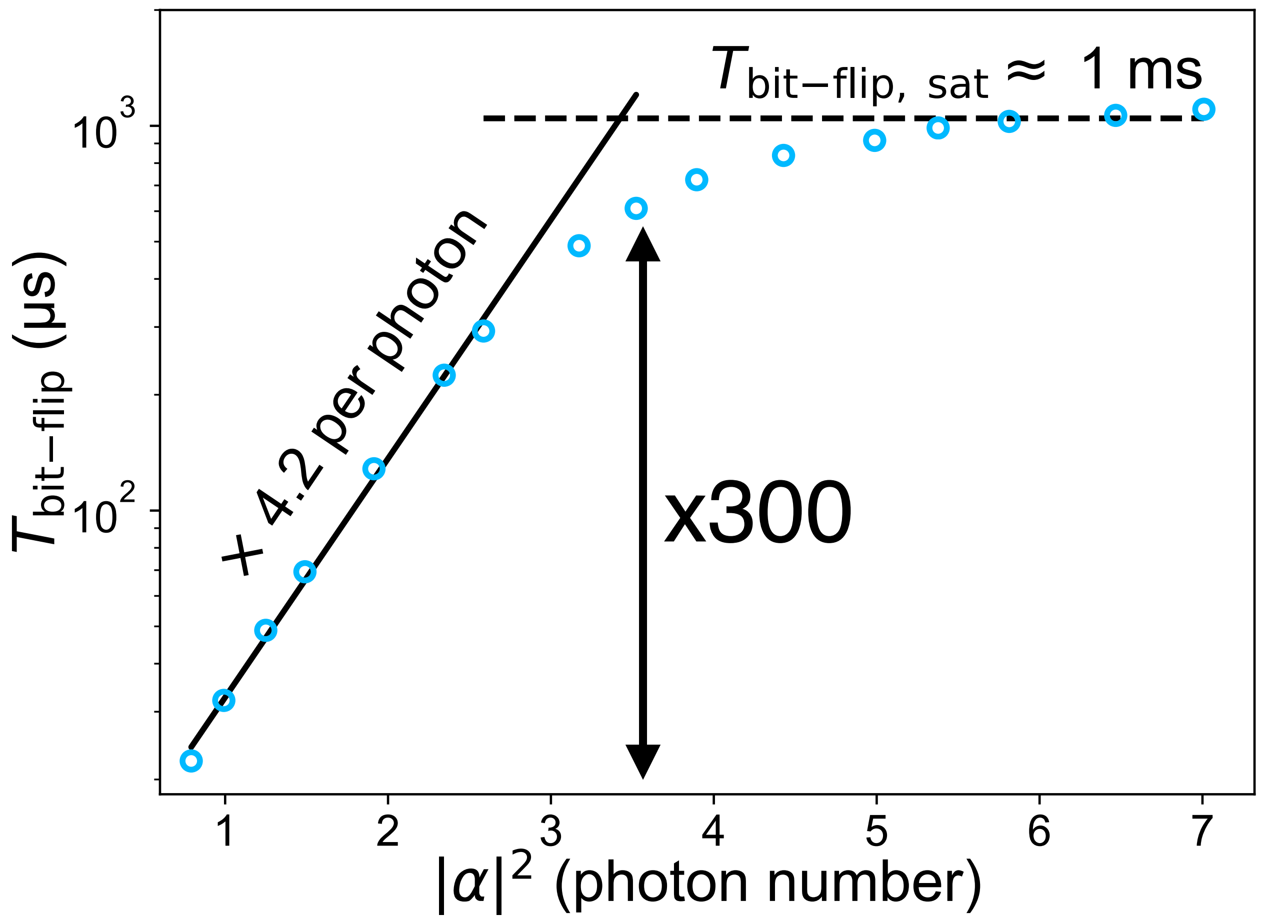
Exponential suppression of bit-flips

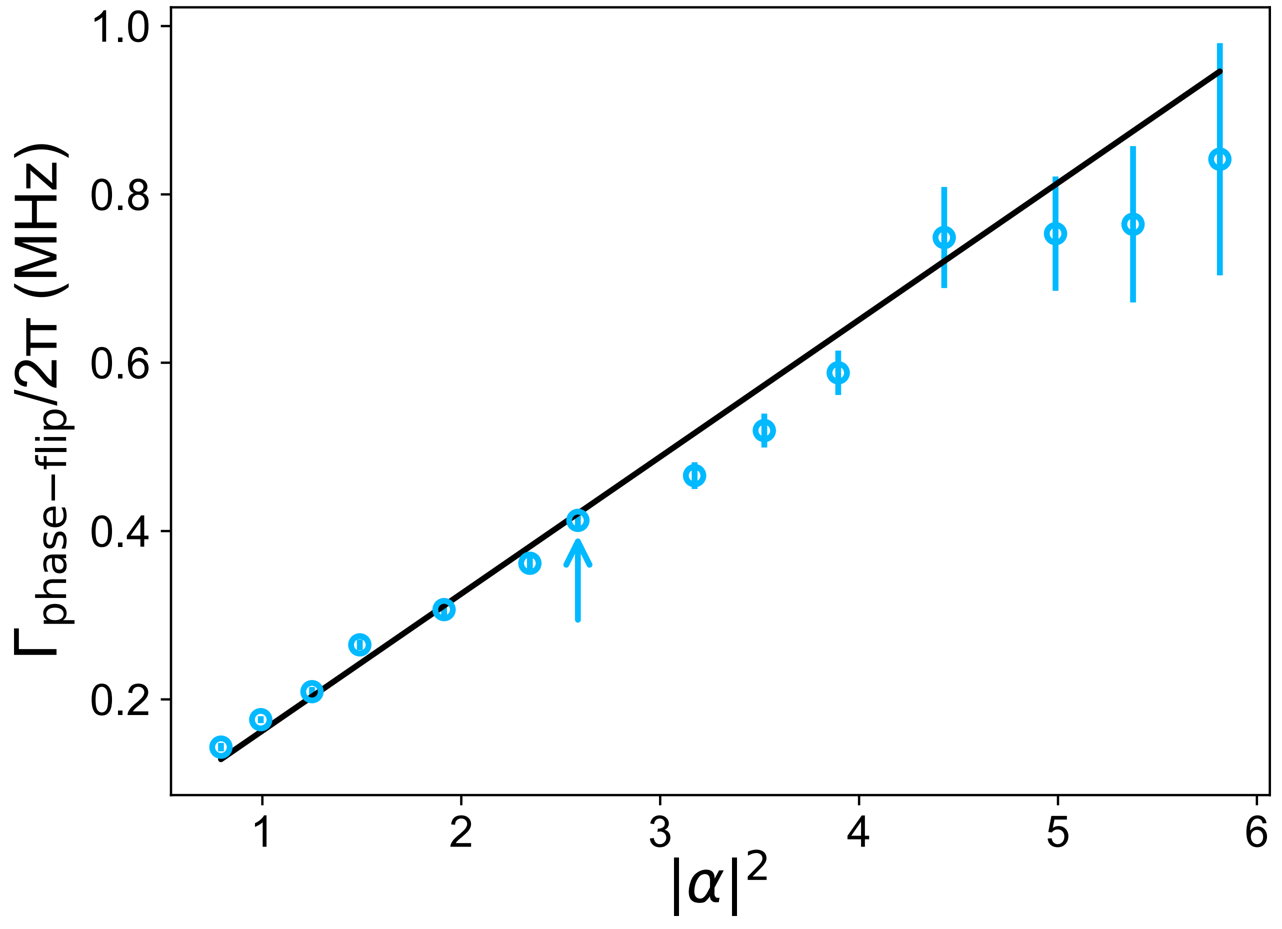


Linear increase of phase-flip rate

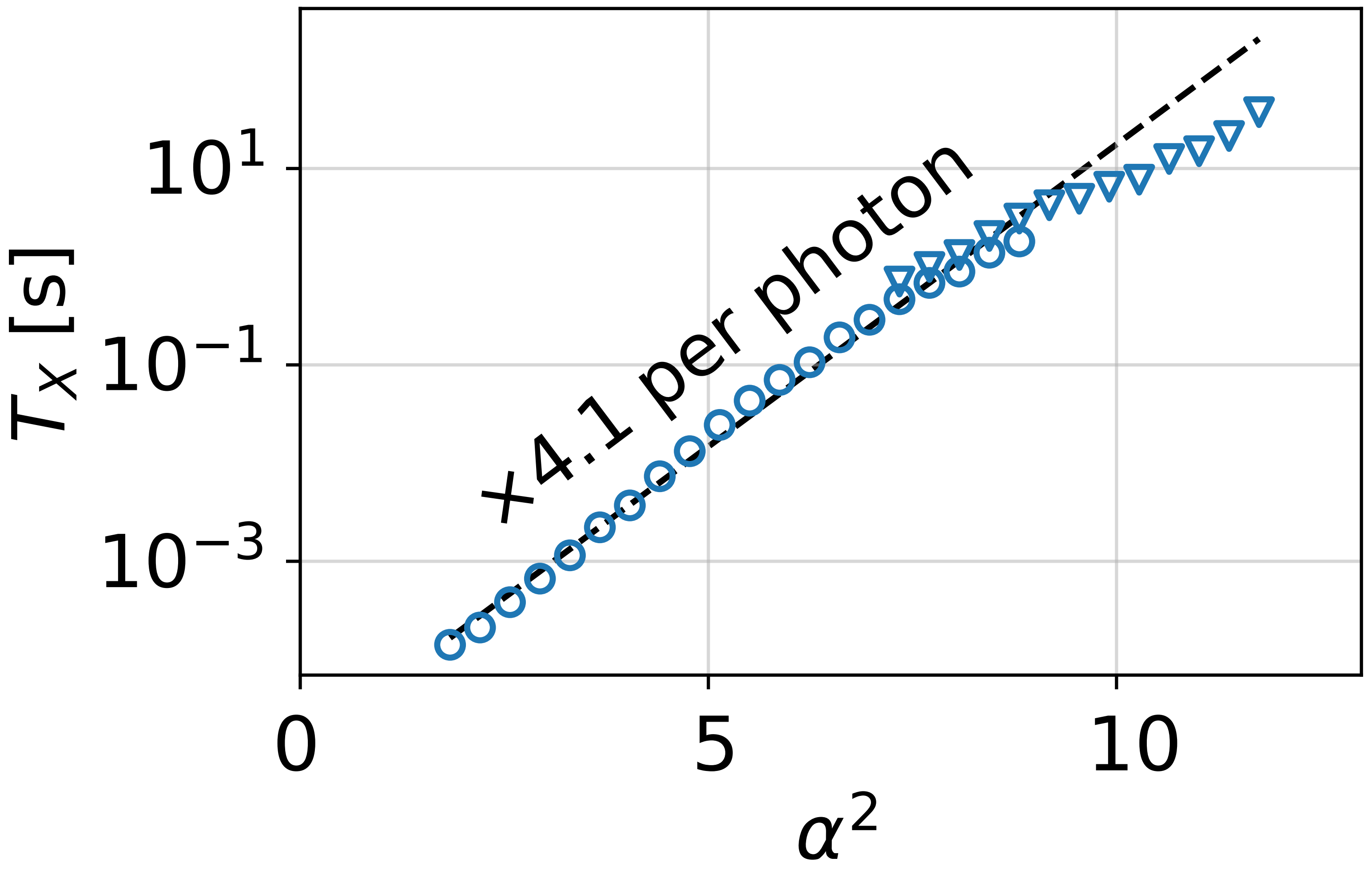
R. Lescanne, Z. Leghtas et al., Nature Physics, 2020

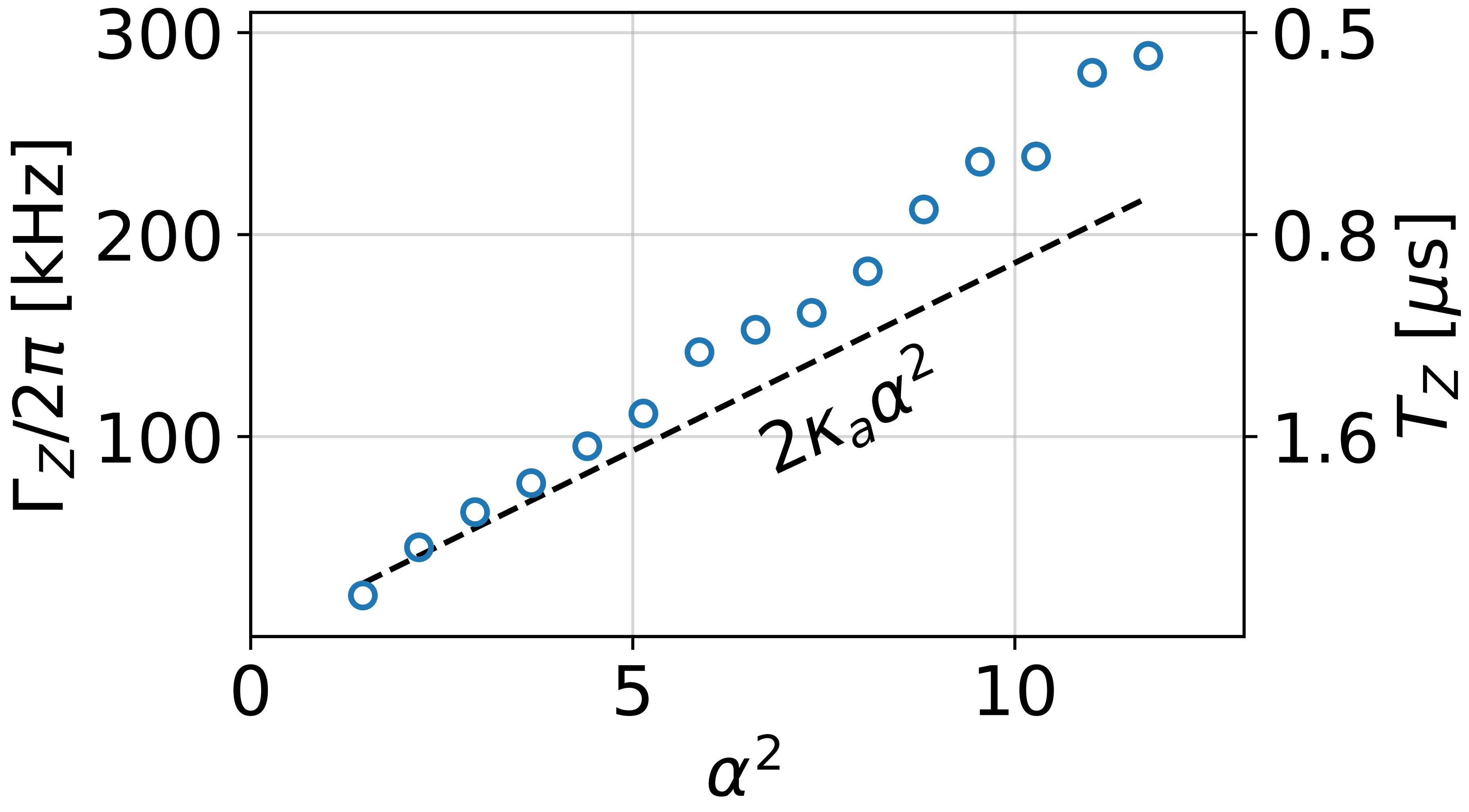
Cat-qubits: exponential protection against bit-flips





R. Lescanne, Z. Leghtas et al., Nature Physics, 2020

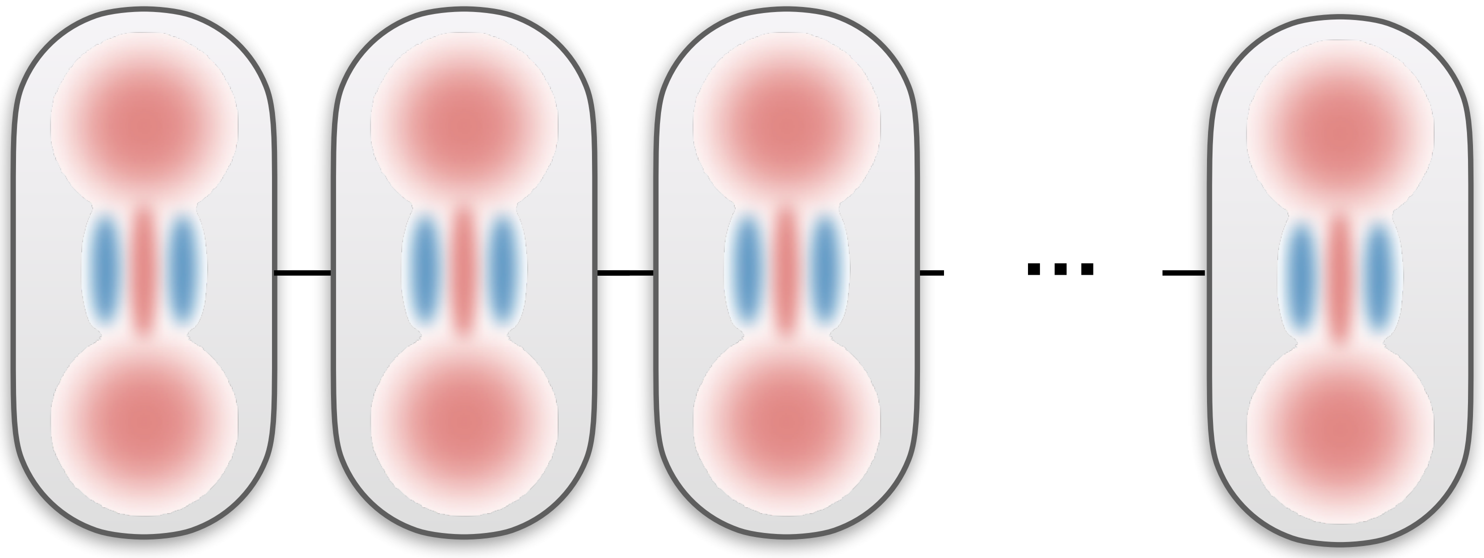




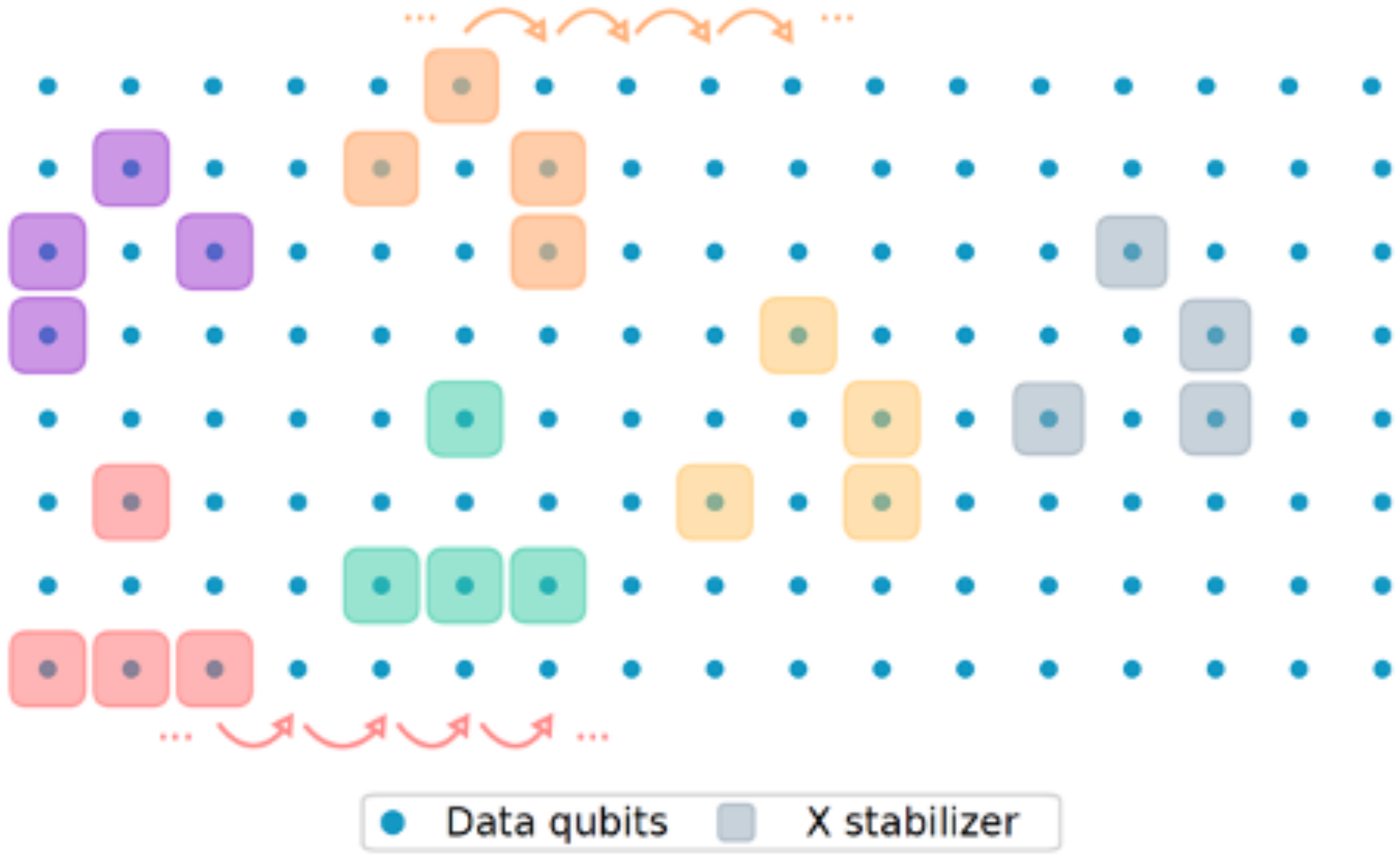
U. Reglade, Z. Leghtas et al., under review, arXiv: 2307.06617 .

A fully protected qubit: strategies

- Large noise bias regime ($\bar{n} > 10 - 15$ photons): repetition code against phase-flips may be sufficient

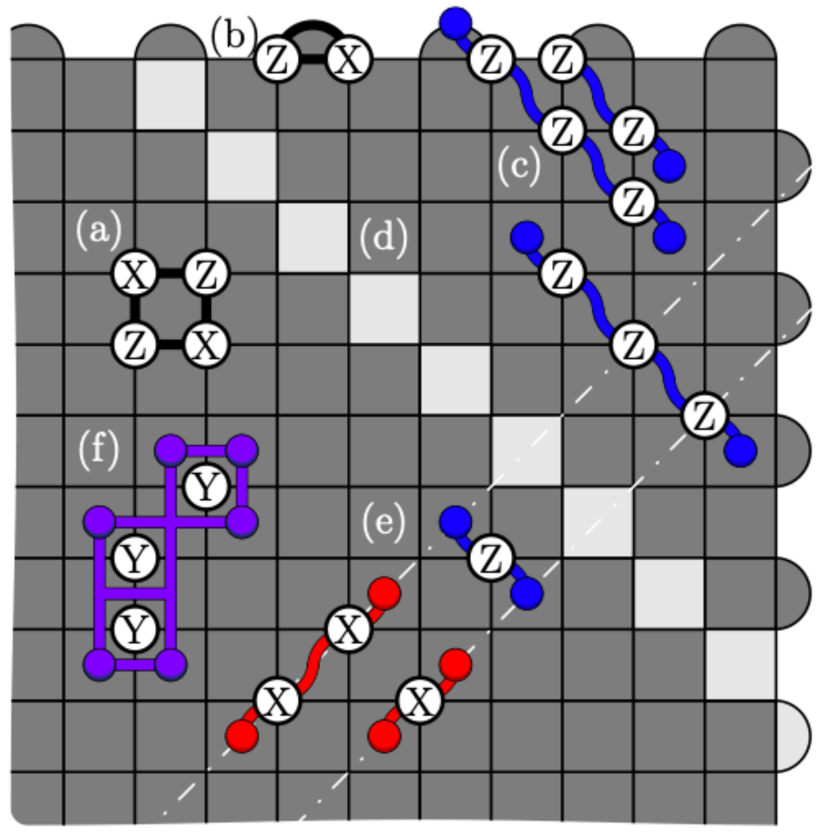


J. Guillaud and MM, PRX 9, 041053, 2019
AWS Blueprint: C. Chamberland et al., PRXQ 3, 010329, 2022

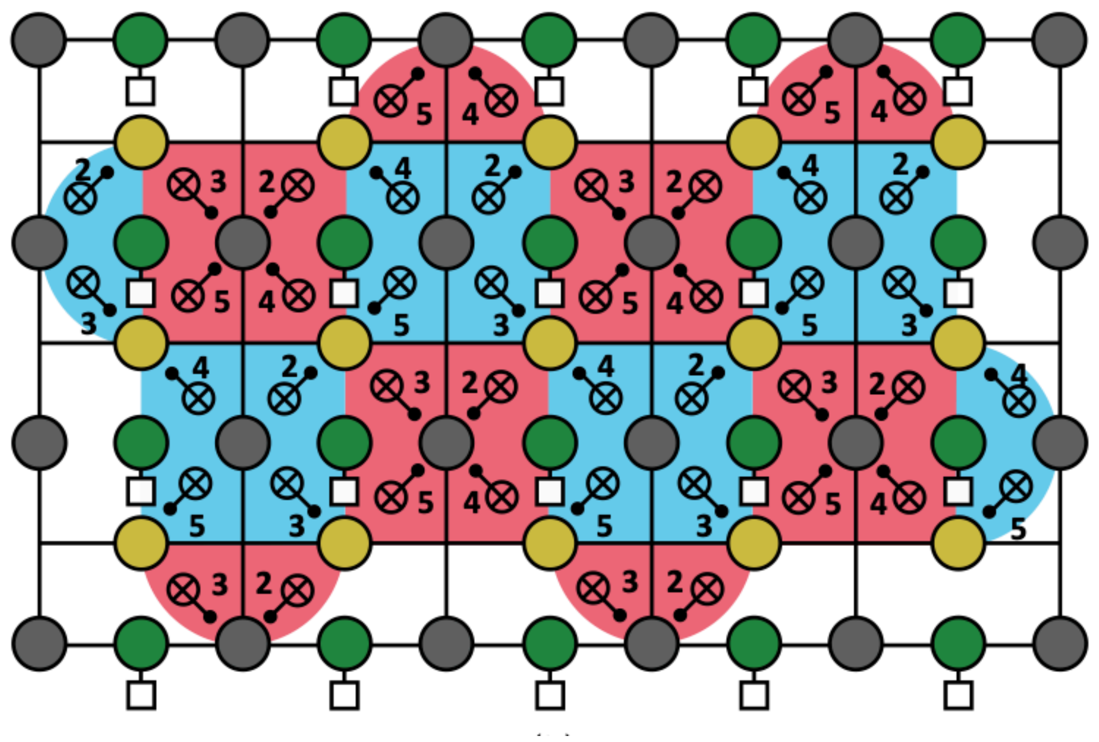


Ruiz et al., arXiv:2401.09541

- Moderate noise bias regime: tailor surface code / use a 1st order correction against bit-flips



J. Pablo Bonilla Ataides *et al,*
Nat. Comm., 2021



C. Chamberland et al,
PRXQ, 2022

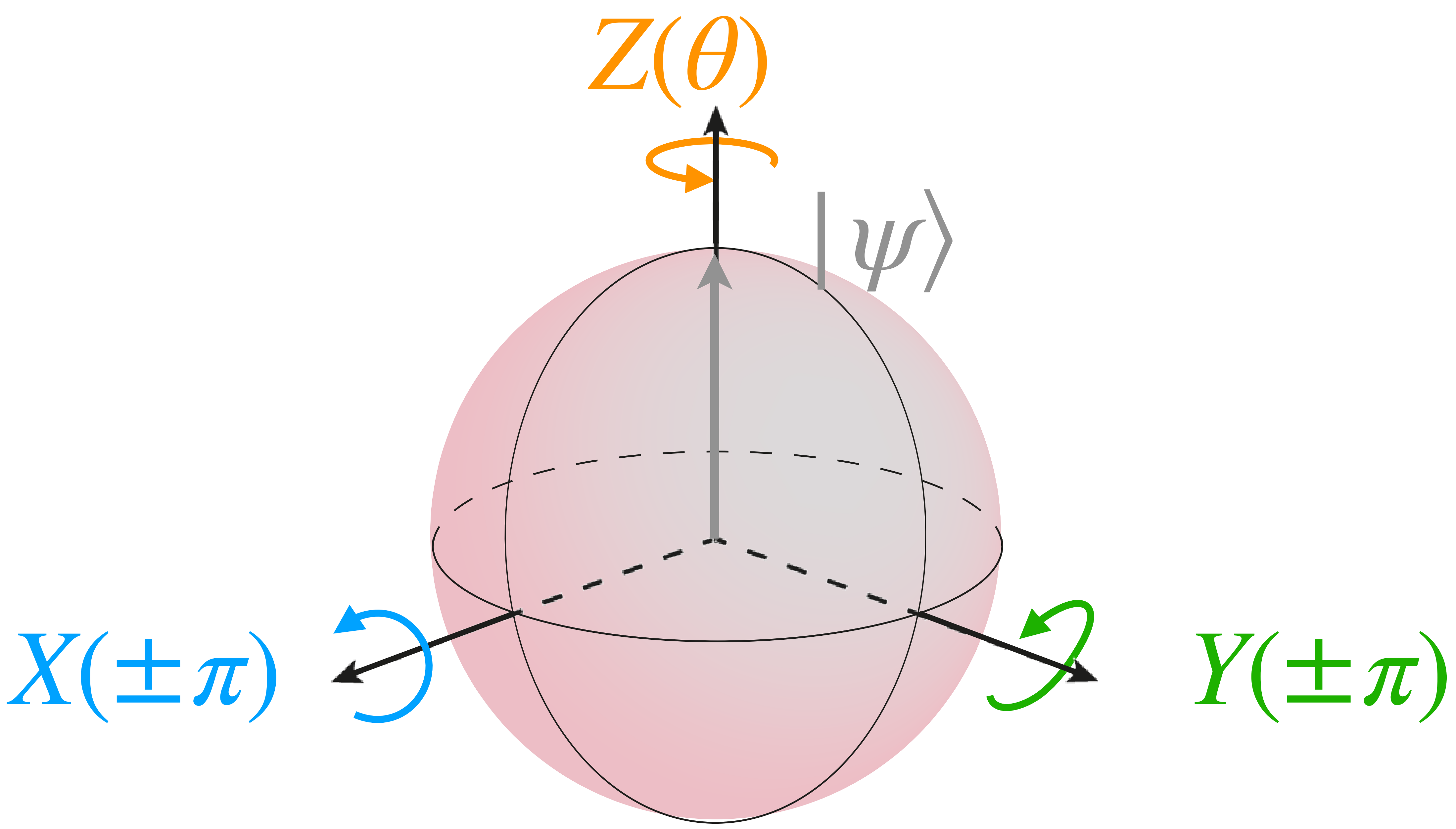
Bias-preserving gates

Definition: A bias-preserving gate preserves the exponential suppression of bit-flips

- A bias-preserving **unitary**

1Q $\begin{cases} UZU^\dagger \propto Z \\ \text{Bias-preserving} : \{\pm X, \ \pm Y, Z(\theta)\} \\ \text{« Depolarizing »} : U(2) \setminus \{\pm X, \ \pm Y, Z(\theta)\} \end{cases}$

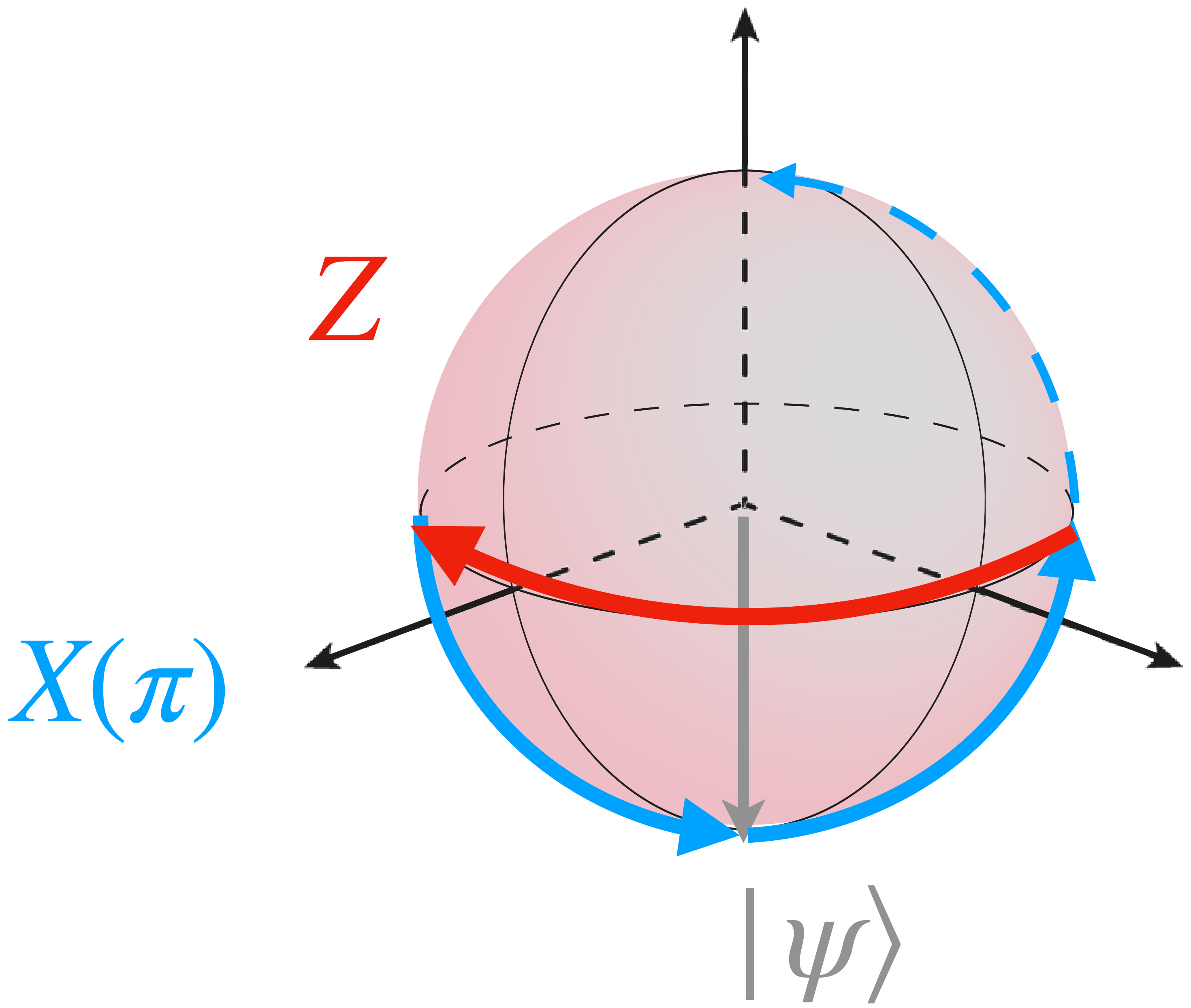
$$HZH^\dagger = X$$



Bias-preserving gates

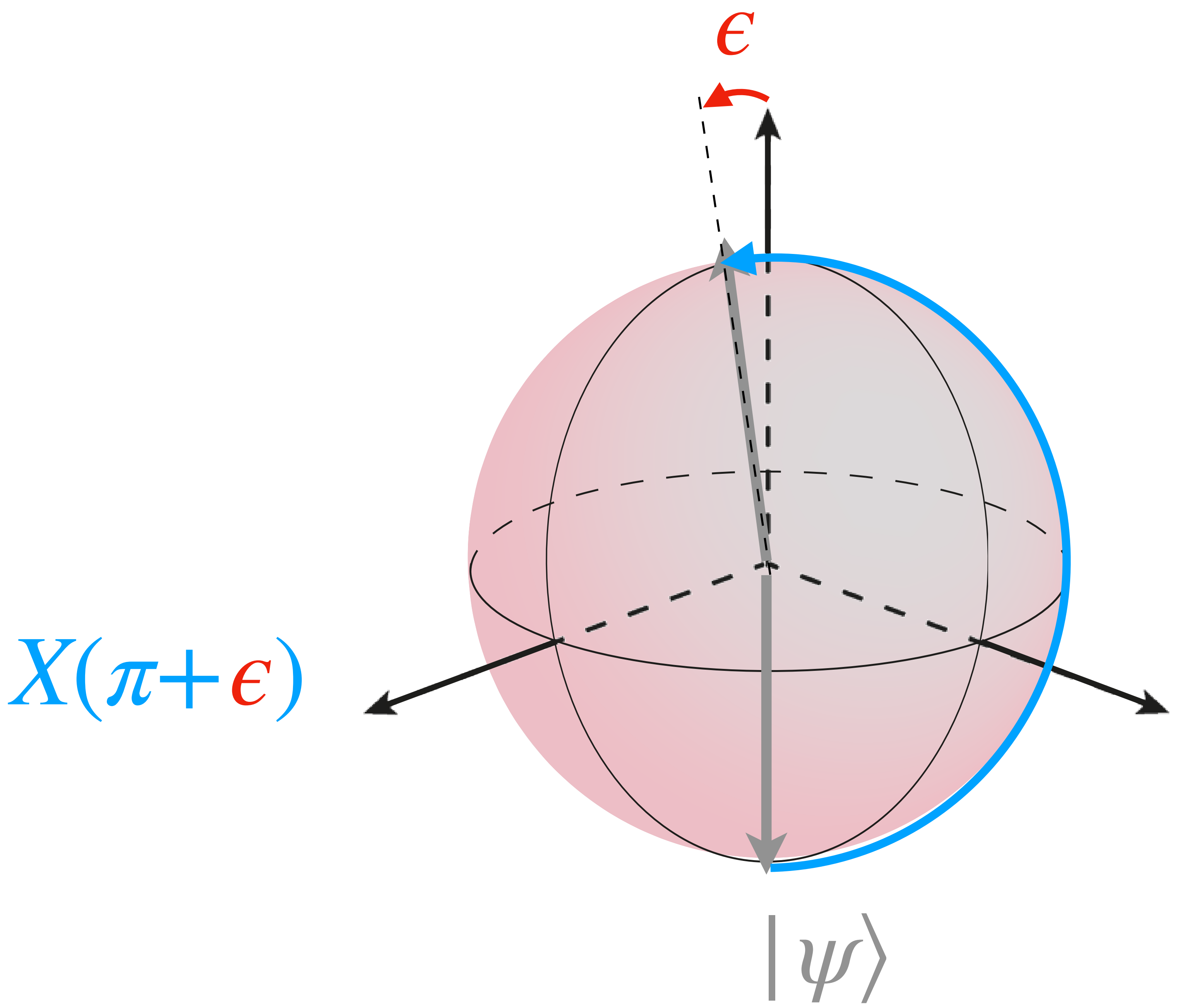
- A bias-preserving **implementation**

$$e^{i\frac{\pi}{2}X}\, Z\, e^{i\frac{\pi}{2}X} = X(XZ)$$



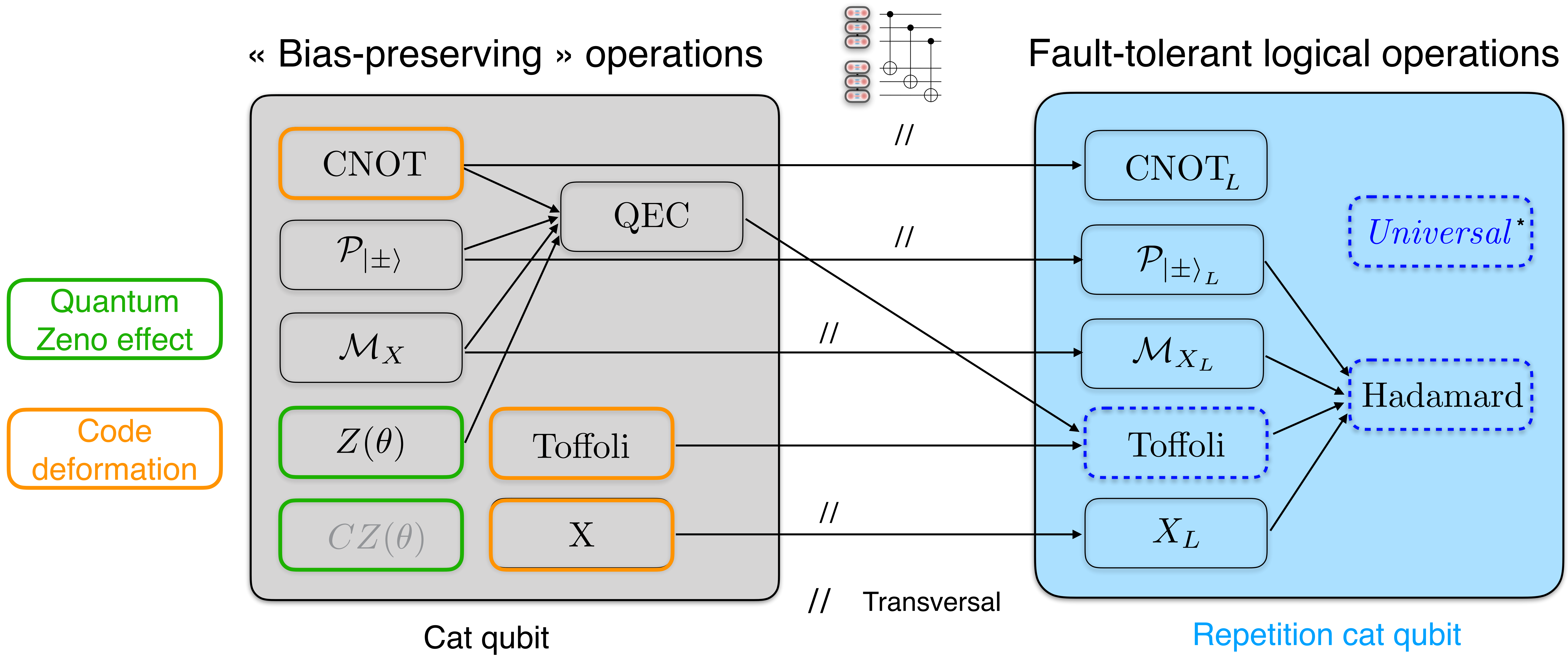
Bias-preserving **continuous process**

$$e^{i(\pi+\epsilon)X} \approx X(I + i\epsilon X)$$



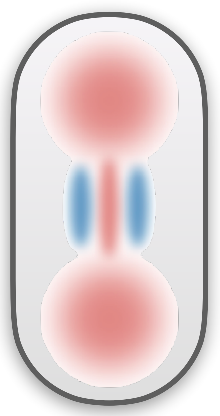
Robustness to systematic errors

Scheme for universal quantum computation



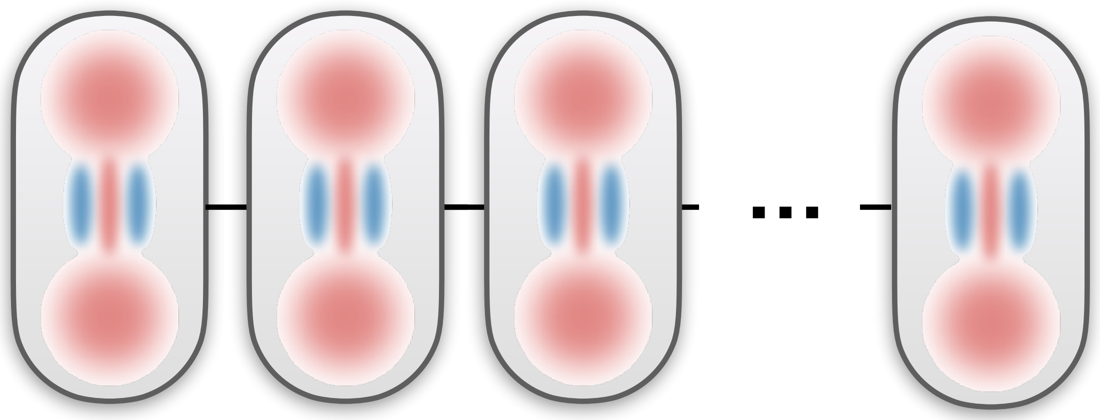
$$|+\rangle = |\mathscr{C}_\alpha^+\rangle$$

$$|-\rangle = |\mathscr{C}_\alpha^-\rangle$$



$$|+\rangle_L = |\mathscr{C}_\alpha^+\rangle^{\otimes n}$$

$$|-\rangle_L = |\mathscr{C}_\alpha^-\rangle^{\otimes n}$$



J. Guillaud and MM, Phys. Rev. X 9, 041053, 2019

« Zeno » gates

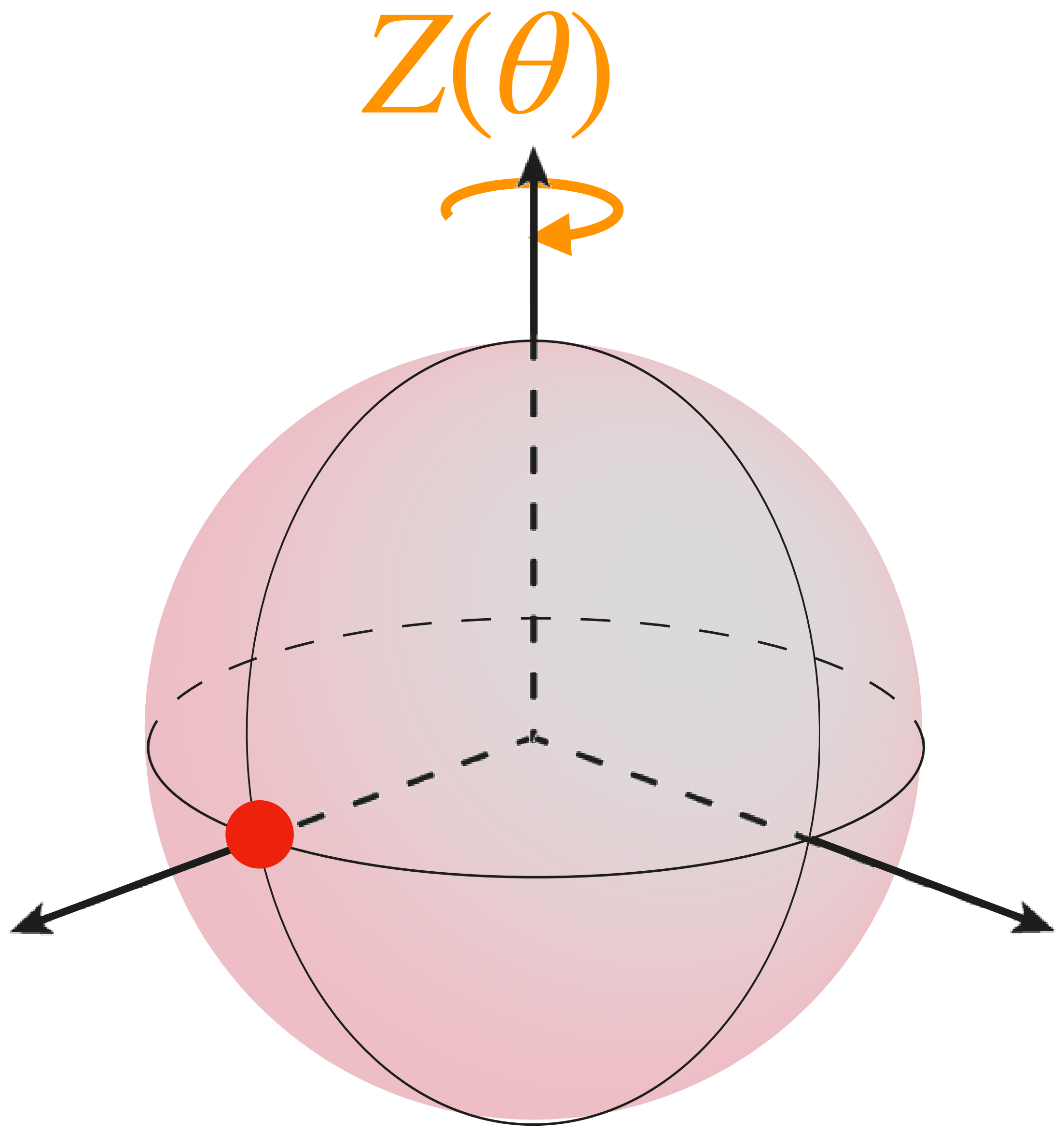
Quantum Zeno recipe *

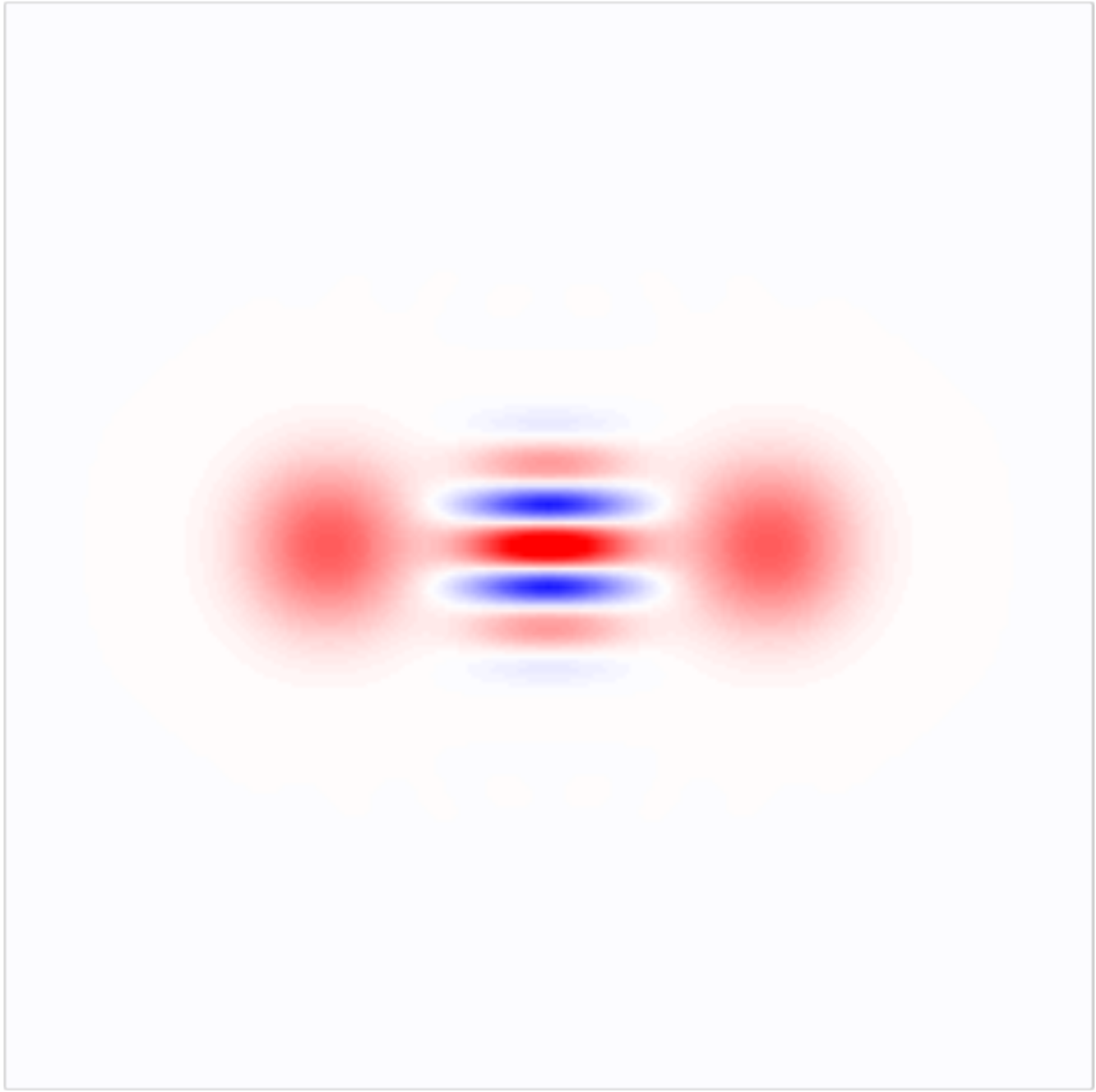
$\sqrt{\kappa_2}(\hat{a}^2 - \alpha^2)$ and $\hat{H}_Z \Rightarrow \epsilon \hat{H}_{eff}$ with $\hat{H}_{eff} = P_\alpha \hat{H} P_\alpha$ $\qquad \epsilon \ll \kappa_2$

$$\hat{H}_Z = \epsilon(\hat{a} + \hat{a}^\dagger) \Rightarrow \hat{H}_{eff} = \epsilon \alpha Z$$

$$P_\alpha = |\mathscr{C}_\alpha^+\rangle\langle\mathscr{C}_\alpha^+| + |\mathscr{C}_\alpha^-\rangle\langle\mathscr{C}_\alpha^-|$$

$$Z = |\mathscr{C}_\alpha^+\rangle\langle\mathscr{C}_\alpha^-| + |\mathscr{C}_\alpha^-\rangle\langle\mathscr{C}_\alpha^+|$$



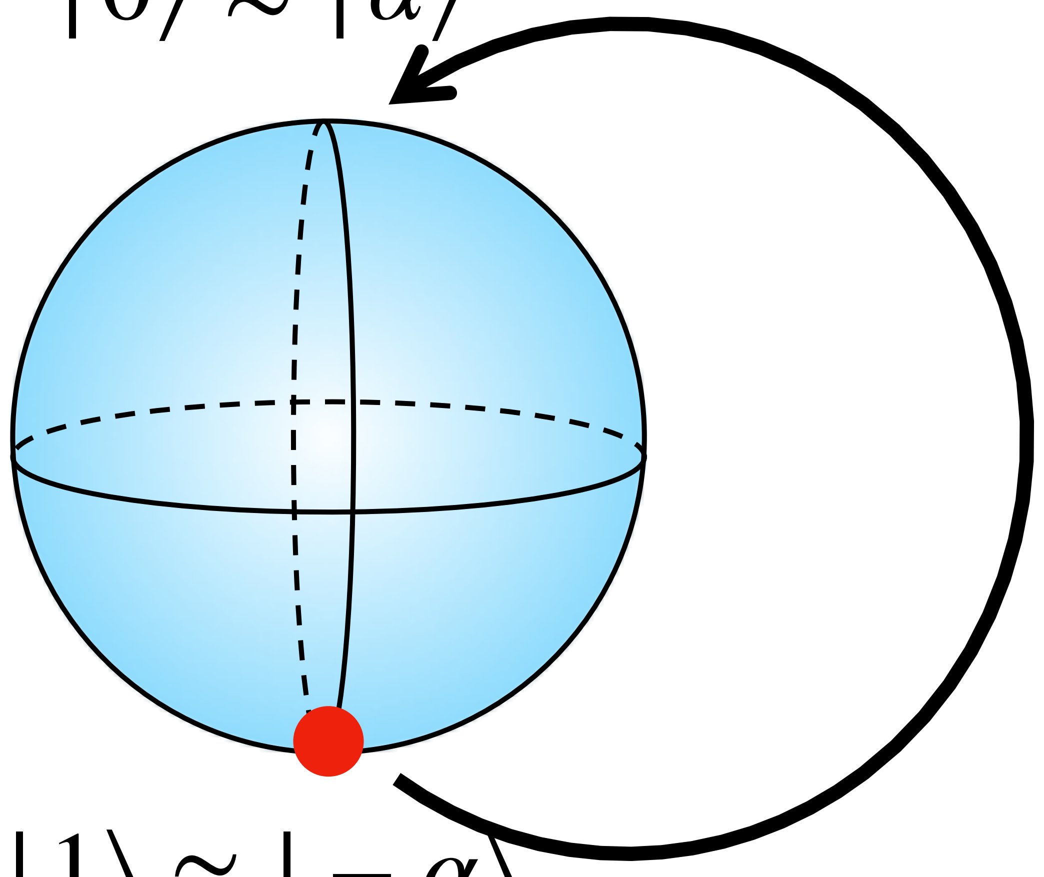


Same recipe for $ZZ(\theta), ZZZ(\theta), \ldots$

M.M. et al, NJP 2014
S. Touzard et al, PRX 2018
Improved designs: R. Gautier et al, PRXQ 2023

Bias-preserving X gate through code deformation

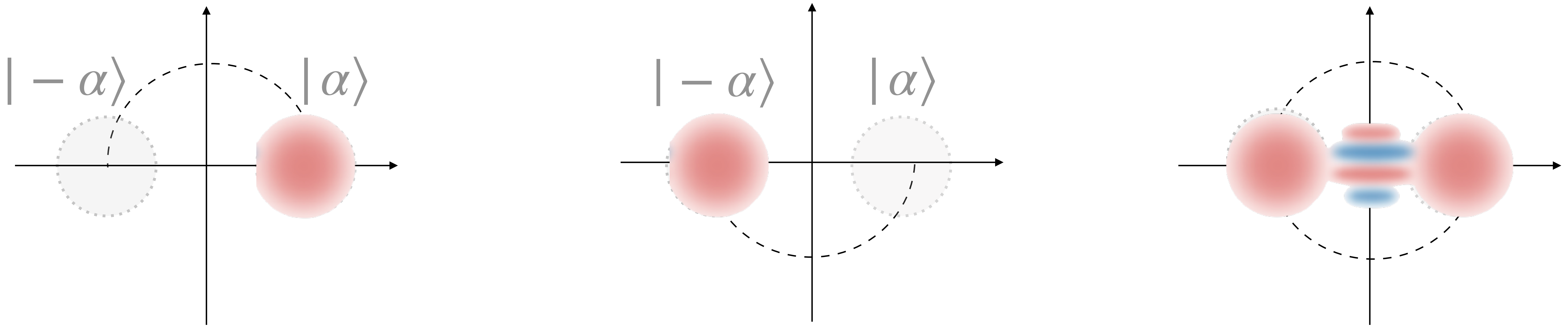
$|0\rangle \approx |\alpha\rangle$



$|1\rangle \approx |-\alpha\rangle$

$X \approx |\alpha\rangle\langle -\alpha| + |-\alpha\rangle\langle\alpha|$

Dissipative realization: $\mathscr{D}[\hat{a}^2 - \alpha^2] \longrightarrow \mathscr{D}[\hat{a}^2 - (\alpha e^{i\pi t/T})^2]$ $\quad |\pm\alpha\rangle \xrightarrow[T]{} |\mp\alpha\rangle$



$|0\rangle \to |1\rangle$ $\quad |1\rangle \to |0\rangle$ $\quad |0\rangle + i|1\rangle \to |0\rangle - i|1\rangle$

J. Guillaud and MM, PRX 9, 041053, 2019

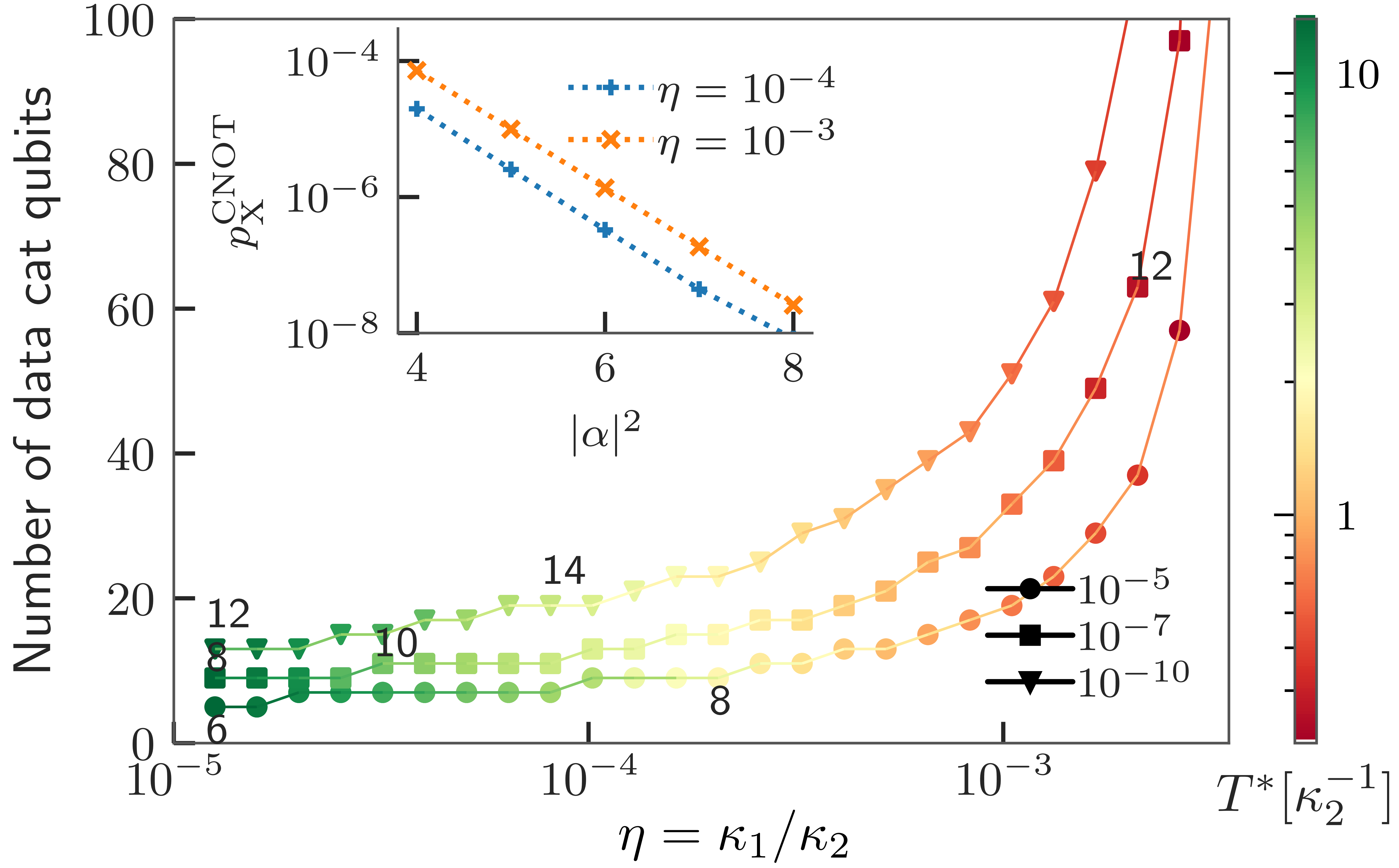
Quantum memory: overhead

Master equation simulation for exponentially suppressed bit-flip errors

$$p_X^{CNOT} = (5.58\sqrt{\frac{\kappa_1}{\kappa_2}} + 1.68\frac{\kappa_1}{\kappa_2})e^{-2\bar{n}} \quad *$$

$$p_L = p_{Z_L} + p_{X_L}$$

$$p_{Z_L} = A(\frac{p}{p_{th}})^{\frac{d+1}{2}} \qquad p_{X_L} \leq 2d(d-1)p_X^{CNOT}$$

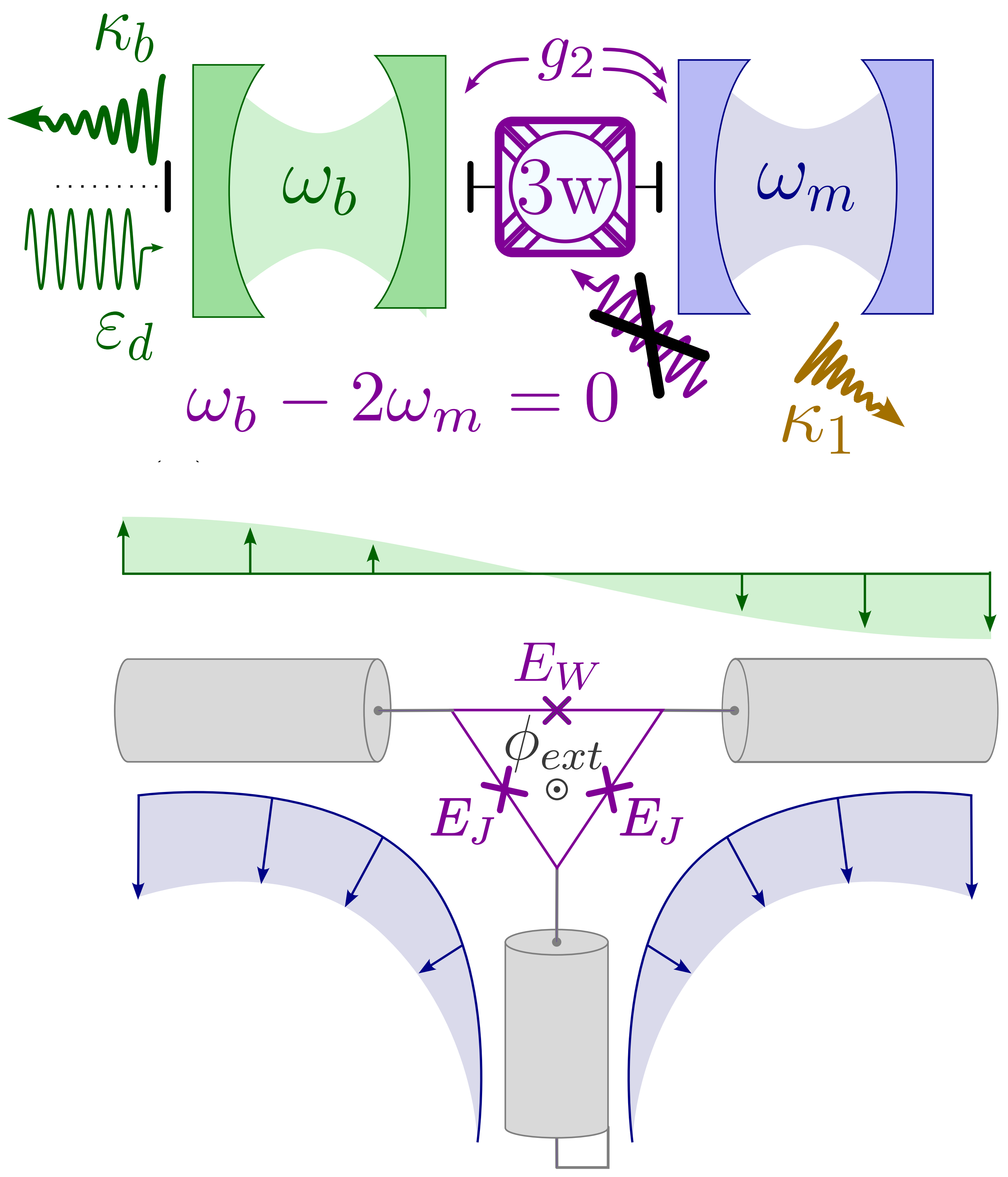


Simulations neglecting leakage**

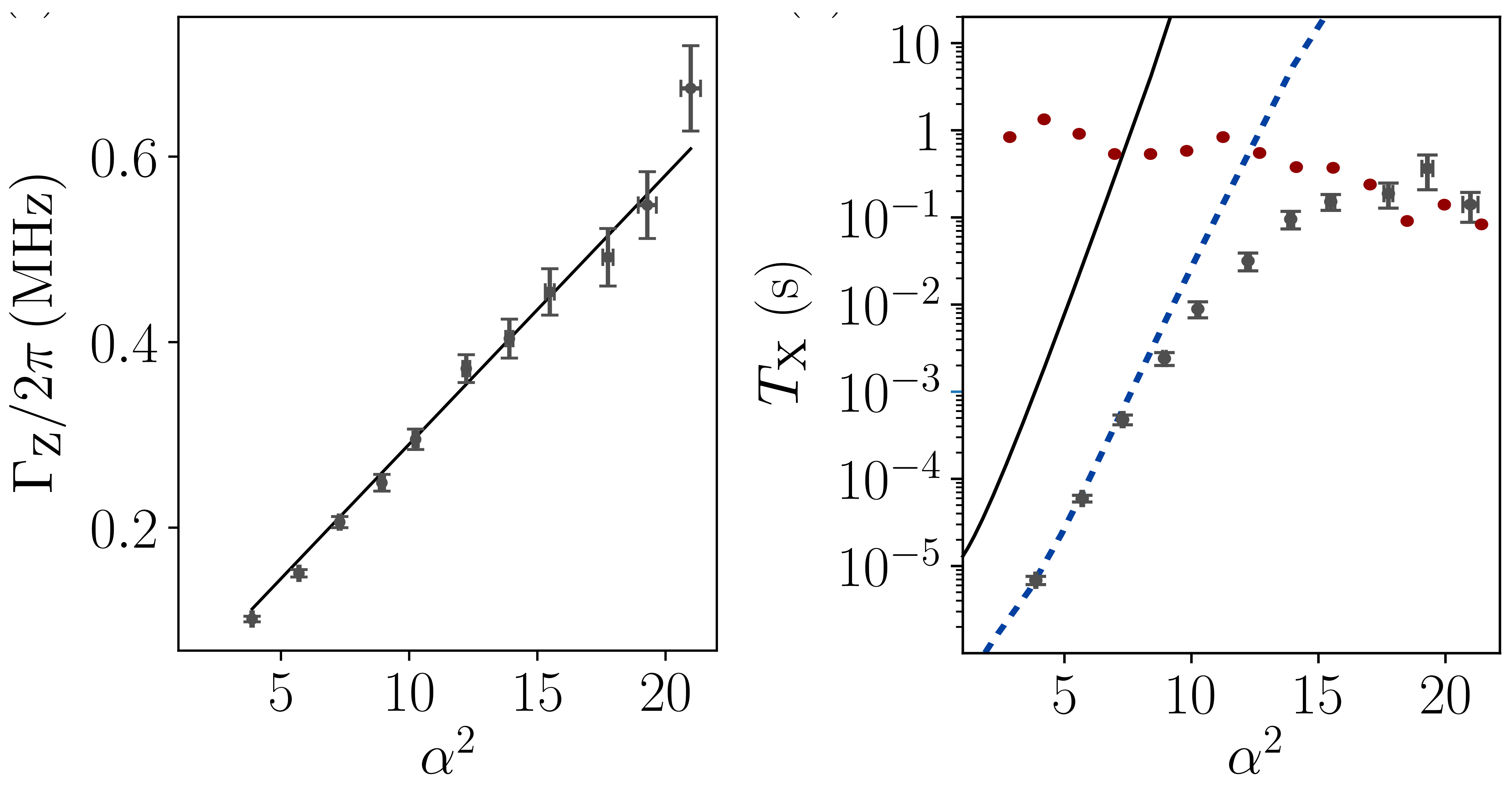
* C. Chamberland et al, PRXQ, 2022

** See F.M. Le Regent et al., Quantum, 2023 for leakage considerations.

Where are the experiments?



New circuit design for non-parametric 3-wave mixing *



Similar bit-flip and phase-flip scaling

$$\eta = \frac{\kappa_1}{\kappa_2} = \frac{1}{150}$$

* A. Marquet, B. Huard et al., arXiv:2307.06761

Summary & outlook

- **Quantum error correction and fault-tolerance**: holy grail of quantum information processing

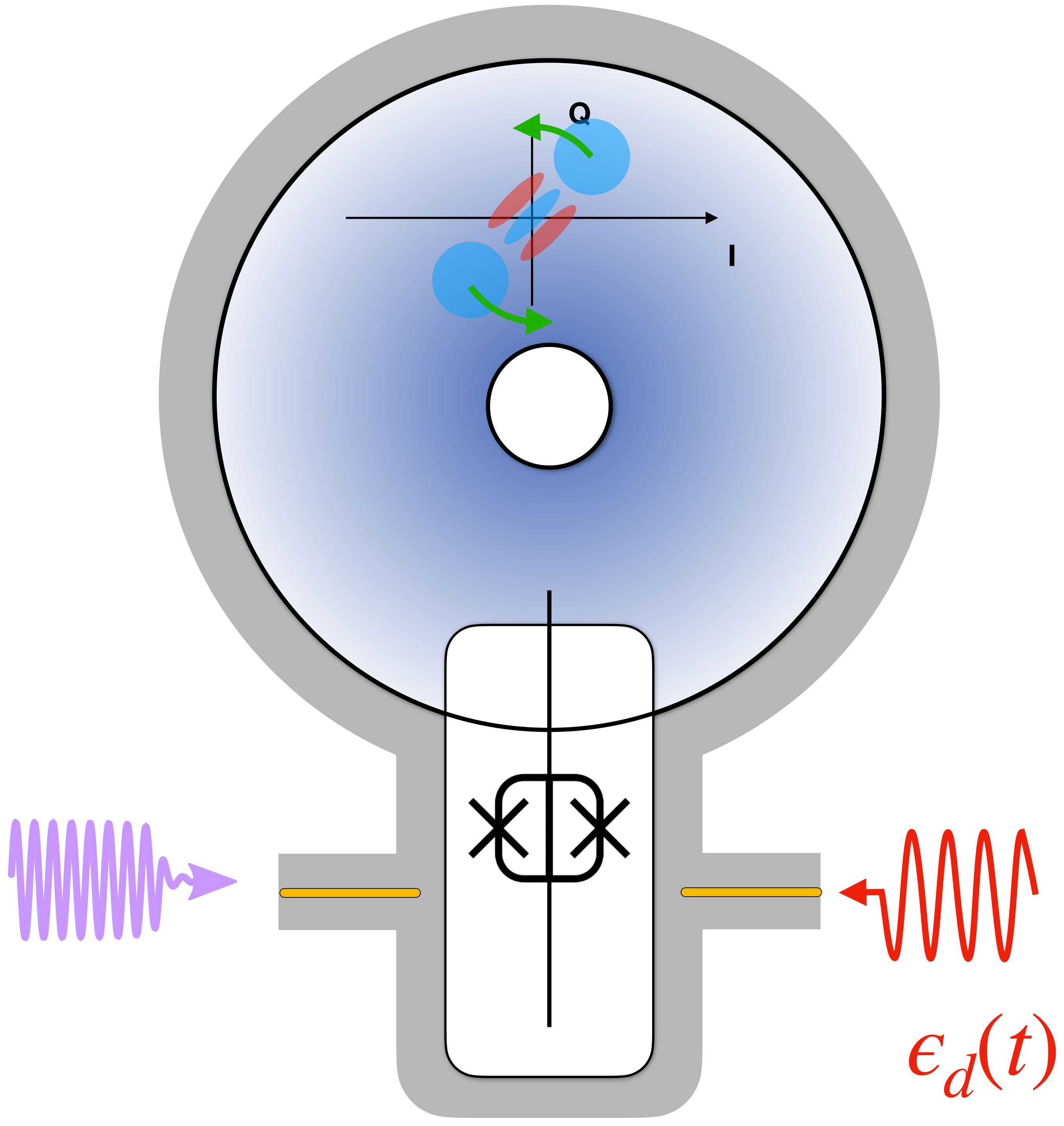
- Initial successful experiments of quantum error correction for a quantum memory but a tough path forward: larger chips by a factor 10 with better gate/measurement performances (a factor of 10).

- Many possible shortcuts: protected qubits, better codes, low-level error correction, autonomous stabilization.

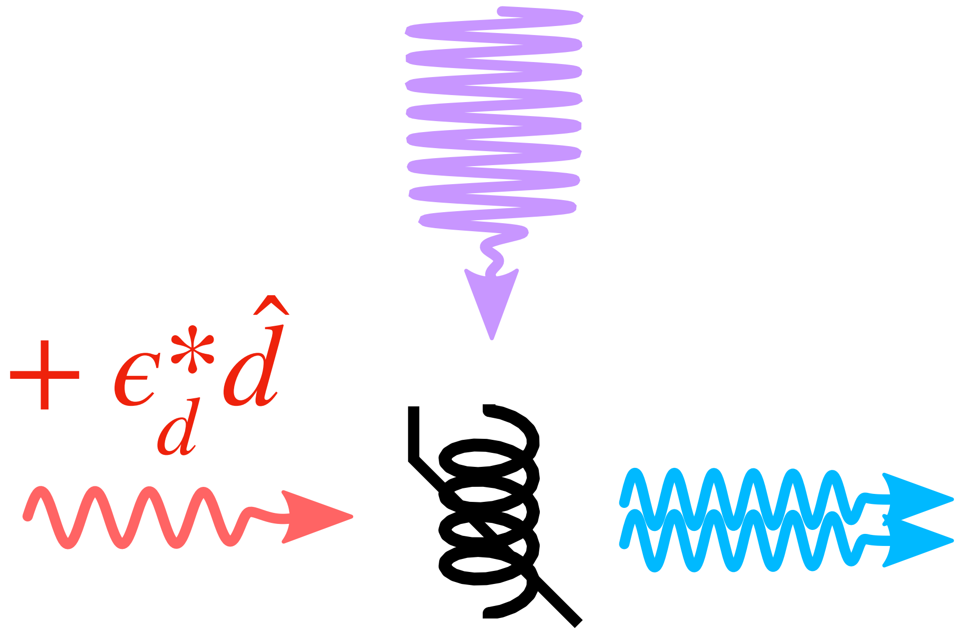
Physical implementation

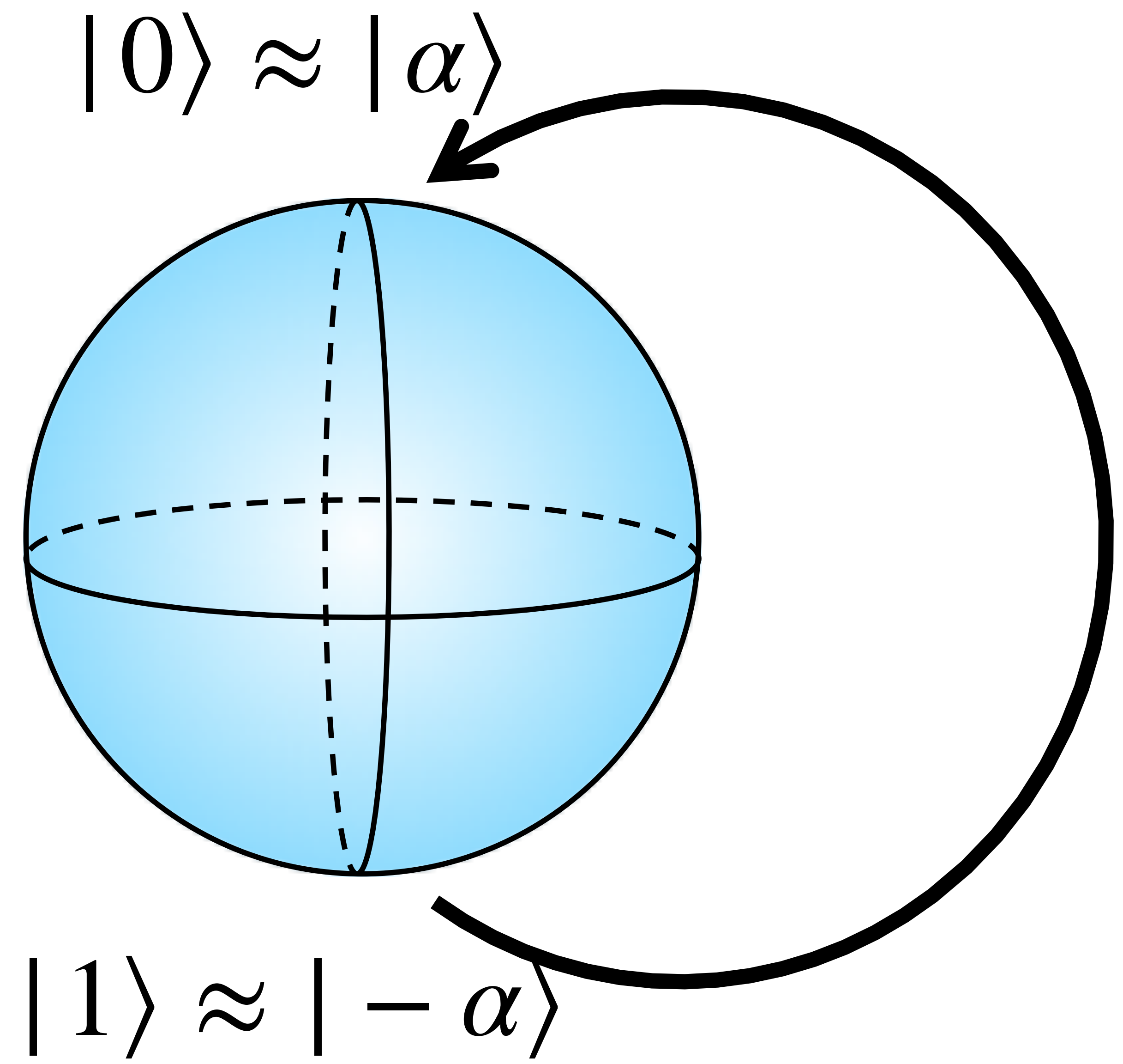
Dissipative realization:

$$\sqrt{\kappa_2}(\hat{a}^2 - \alpha^2) \to \sqrt{\kappa_2}(\hat{a}^2 - (\alpha e^{i\pi t/T})^2)$$



$$\hat{H} = \epsilon_d \hat{d}^\dagger + \epsilon_d^* \hat{d}$$





Realization: 4-wave mixing + 2 pumps

$$\hat{H}_1 = g_2(\hat{d}^\dagger \hat{a}^2 + \textbf{h.c.}) \qquad \hat{H}_2 = \epsilon_d(t) d^\dagger + \textbf{h.c.}$$

Bias-preserving CNOT gate (& Toffoli gate)

$$L_a = \sqrt{\kappa_2}(\hat{a}^2 - \alpha^2)$$ Control = $\hat{a}$, Target = $\hat{b}$

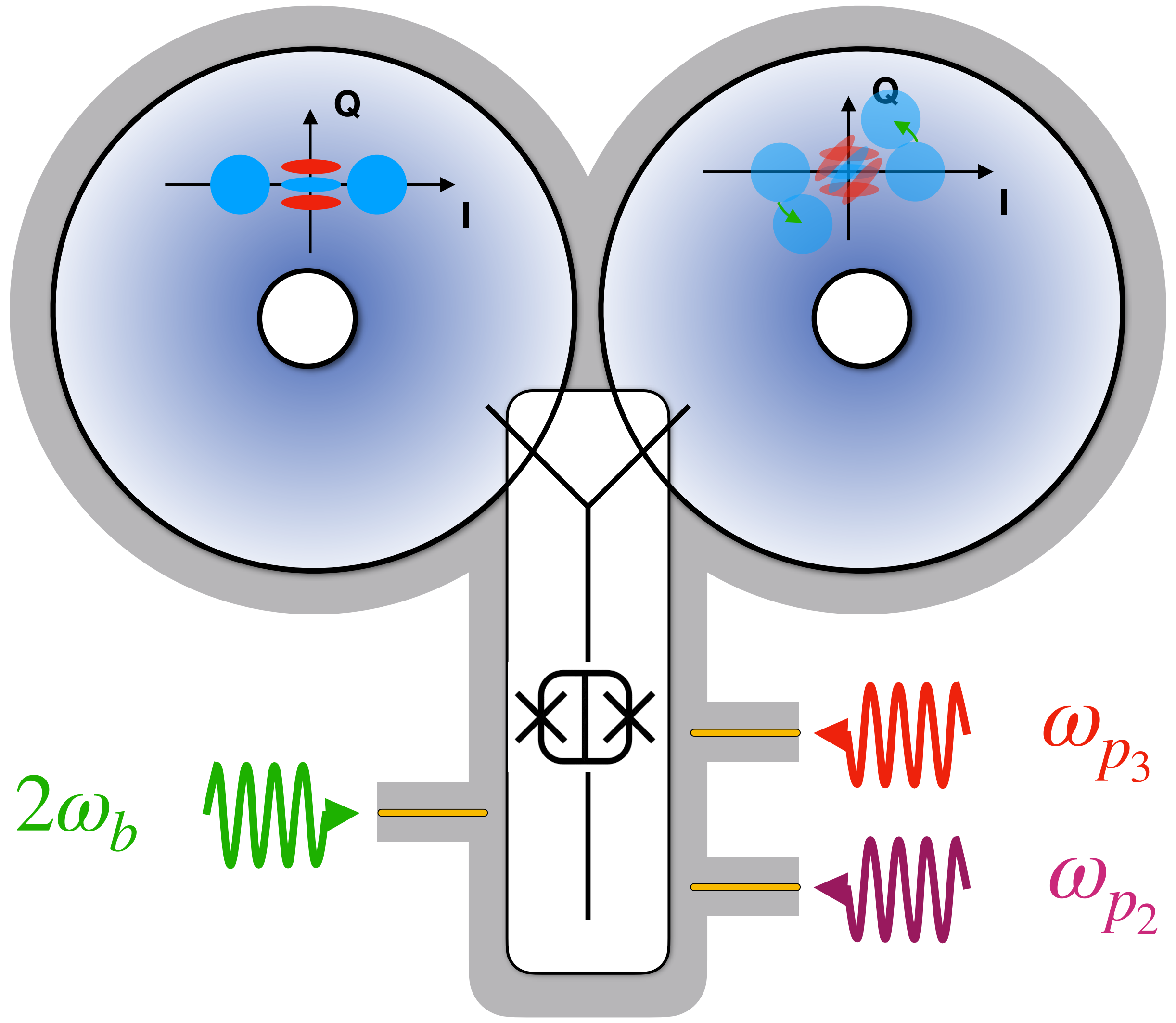
$$L_b = \sqrt{\kappa_2}[\hat{b}^2 - \frac{\alpha}{2}((\hat{a}+\alpha) - e^{2i\pi t}(\hat{a}-\alpha))]$$

CNOT $\approx |\alpha\rangle\langle\alpha| \otimes I + |-\alpha\rangle\langle-\alpha| \otimes (|\alpha\rangle\langle-\alpha| + |-\alpha\rangle\langle\alpha|)$

Control (Qubit a) **Target (Qubit b)**

Qubit a in $|0\rangle \approx |\alpha\rangle \rightarrow \mathcal{D}[\hat{b}^2 - \alpha^2]$

Qubit a in $|1\rangle \approx |-\alpha\rangle \rightarrow \mathcal{D}[\hat{b}^2 - (\alpha e^{i\pi t})^2]$



$\omega_{p_1} = \omega_d - 2\omega_b$

$\omega_{p_3} = \omega_d$

$\omega_{p_2} = \frac{1}{2}(\omega_d - \omega_a)$

<u>Experimental realization:</u> TWM + Phase and amplitude modulation

$\hat{H}_1 = g_2(\hat{d}^\dagger \hat{b}^2 + \textbf{h.c.})$ $\hat{H}_2 = g_1(t)\hat{d}^\dagger \hat{a} + \textbf{h.c.}$ $\hat{H}_3 = \epsilon_2(t) d^\dagger + \textbf{h.c.}$

J. Guillaud and MM, PRX 9, 041053, 2019