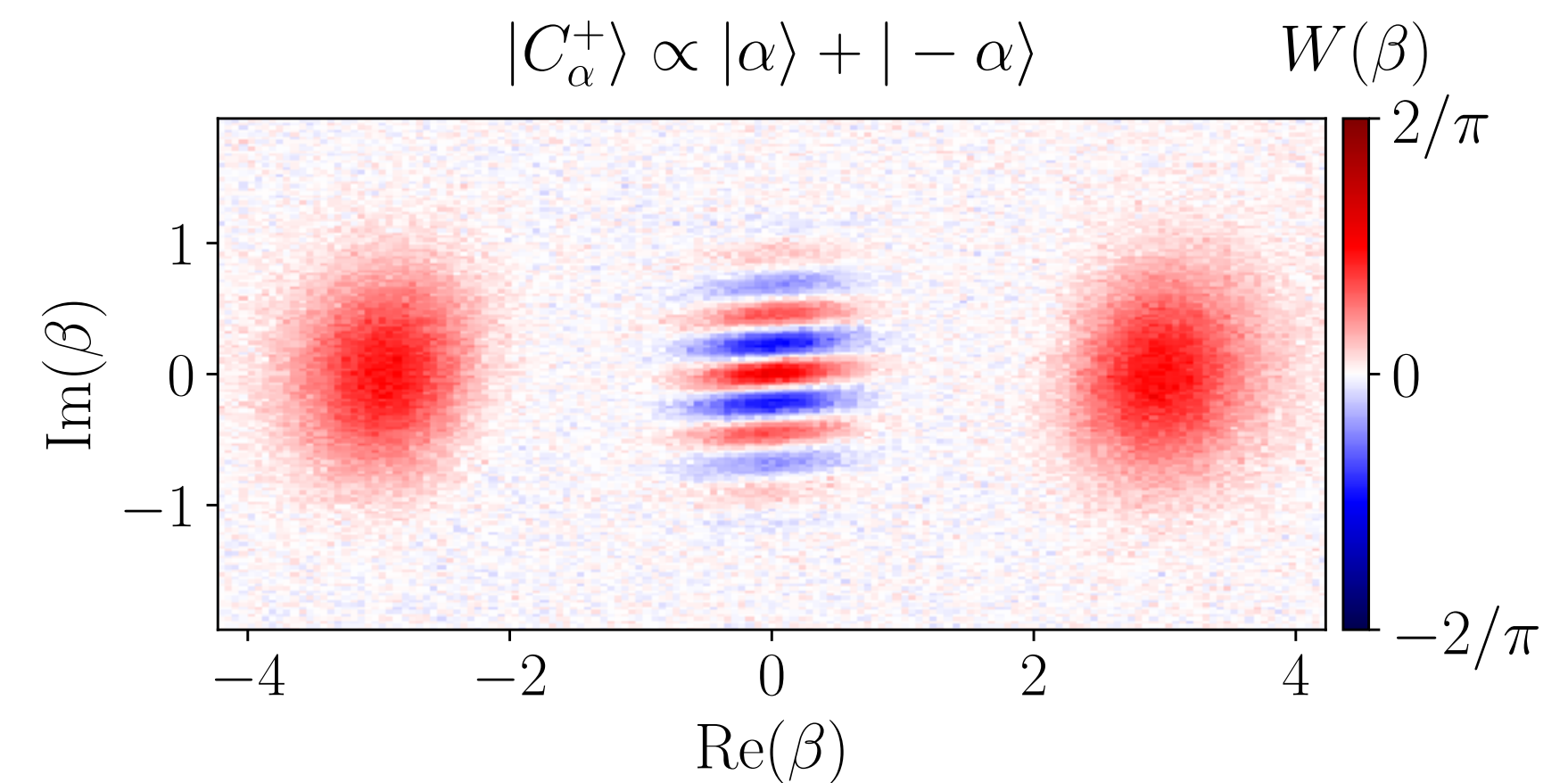
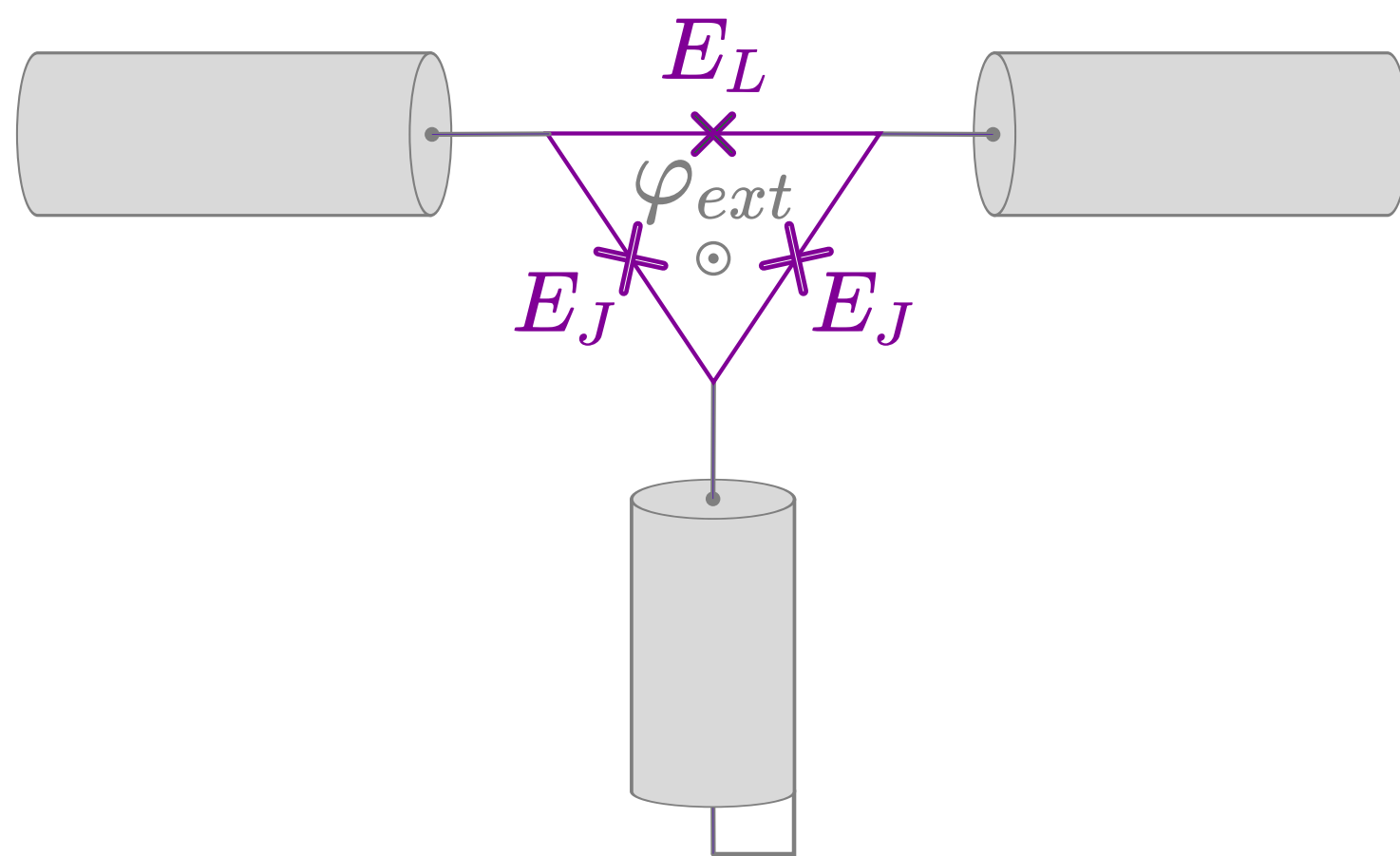


Passive two-photon dissipation for bit-flip error correction of a cat code

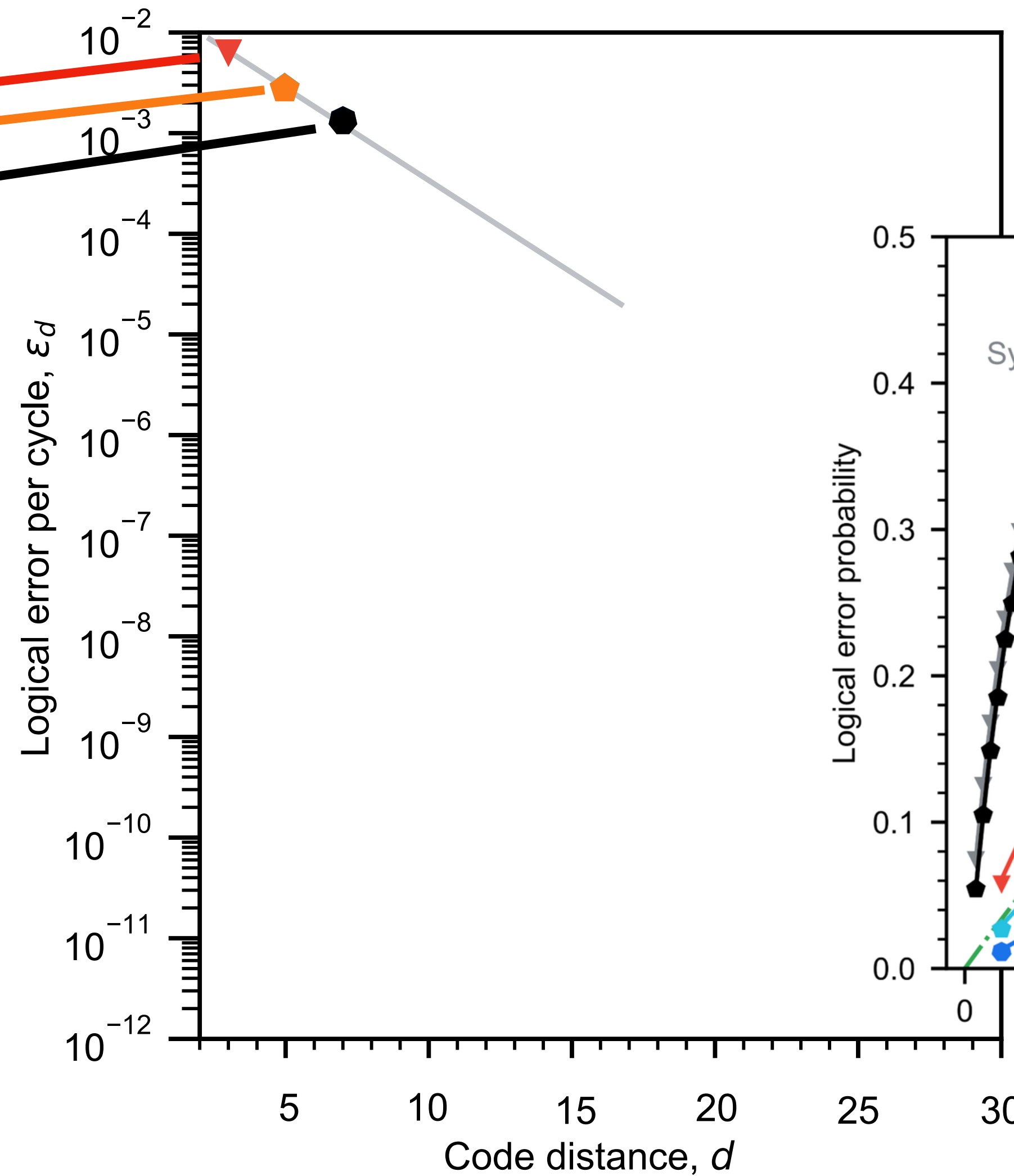
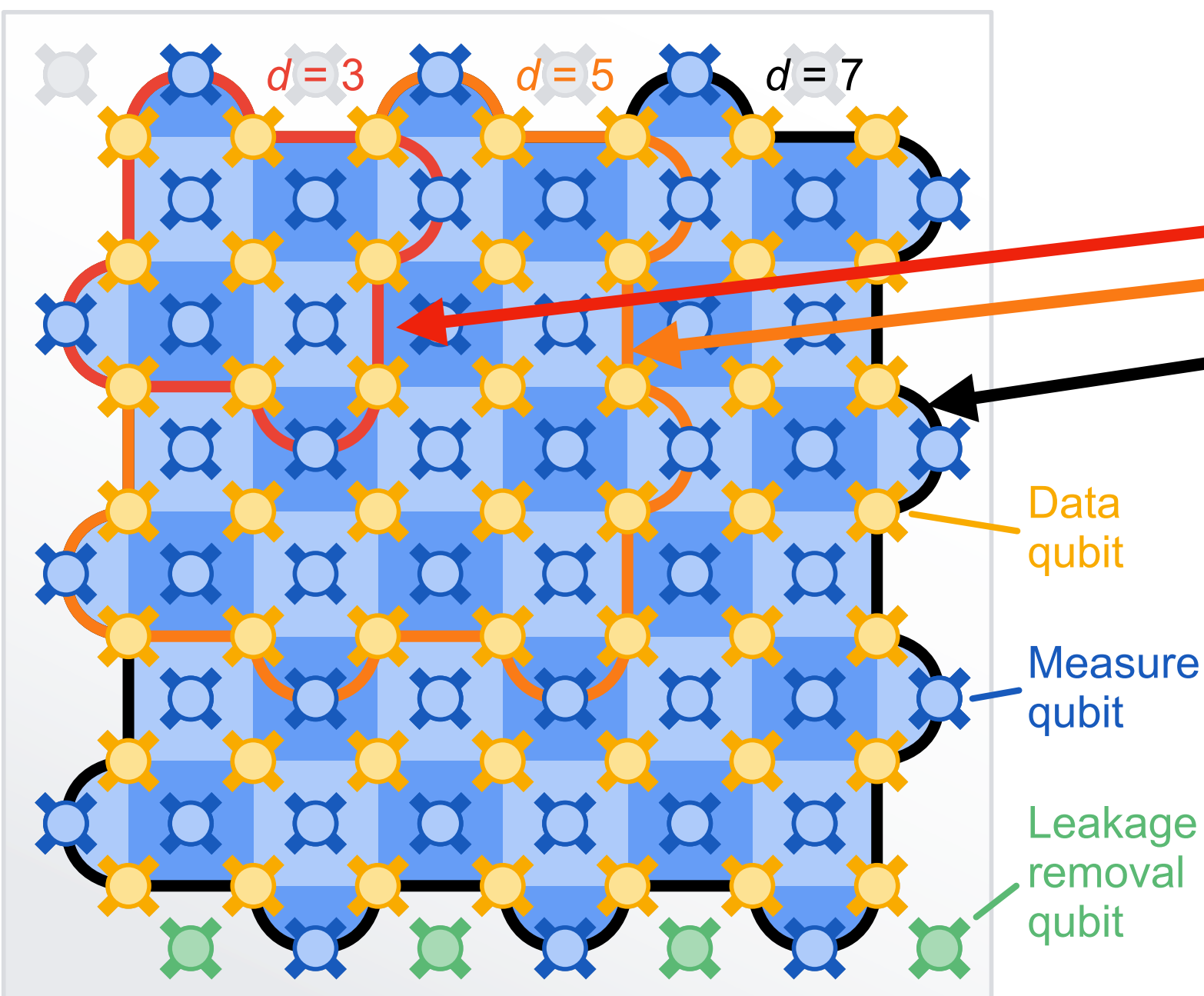
Benjamin Huard

Ecole Normale Supérieure de Lyon, CNRS

Alice and Bob, Paris

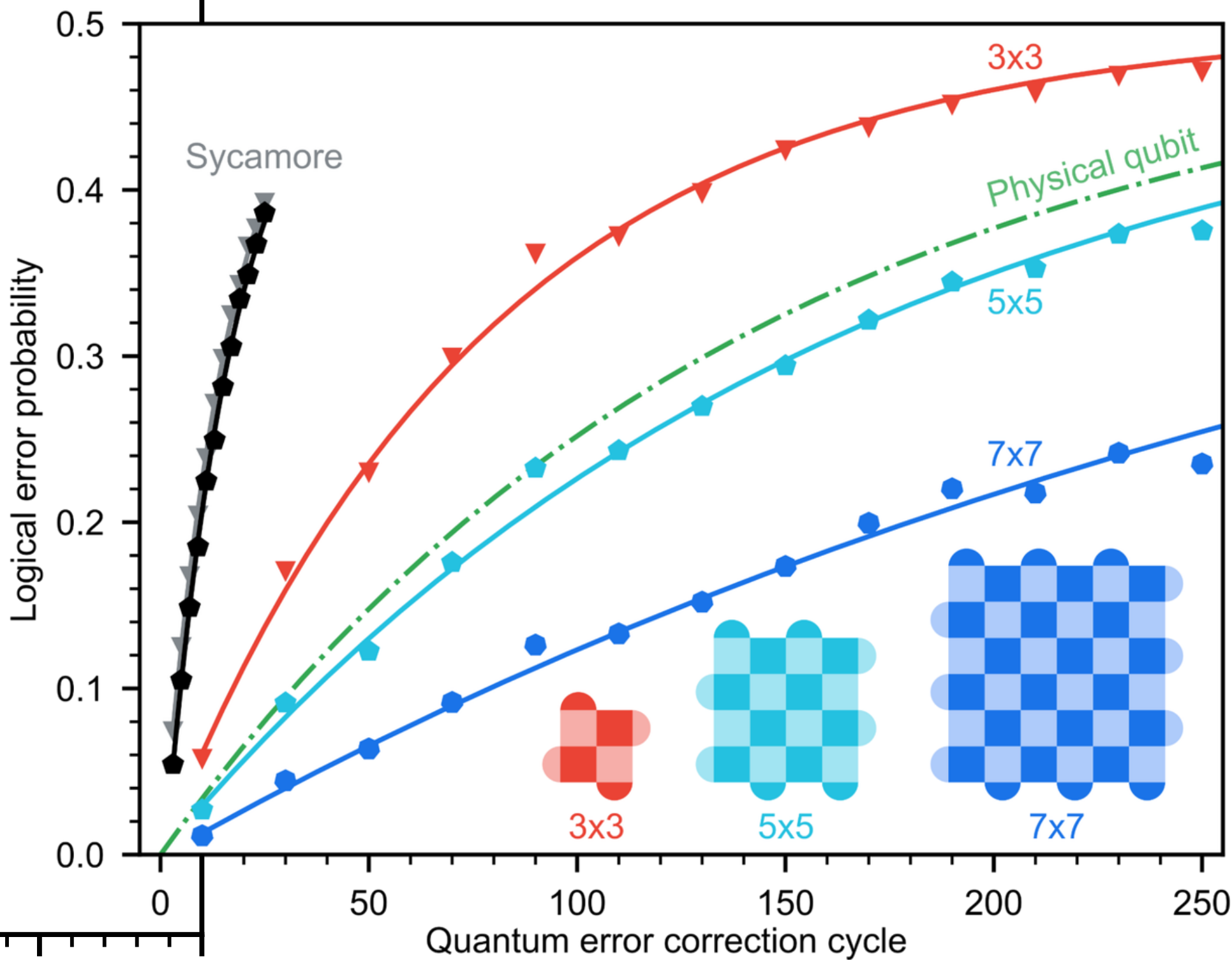


Surface code with transmons

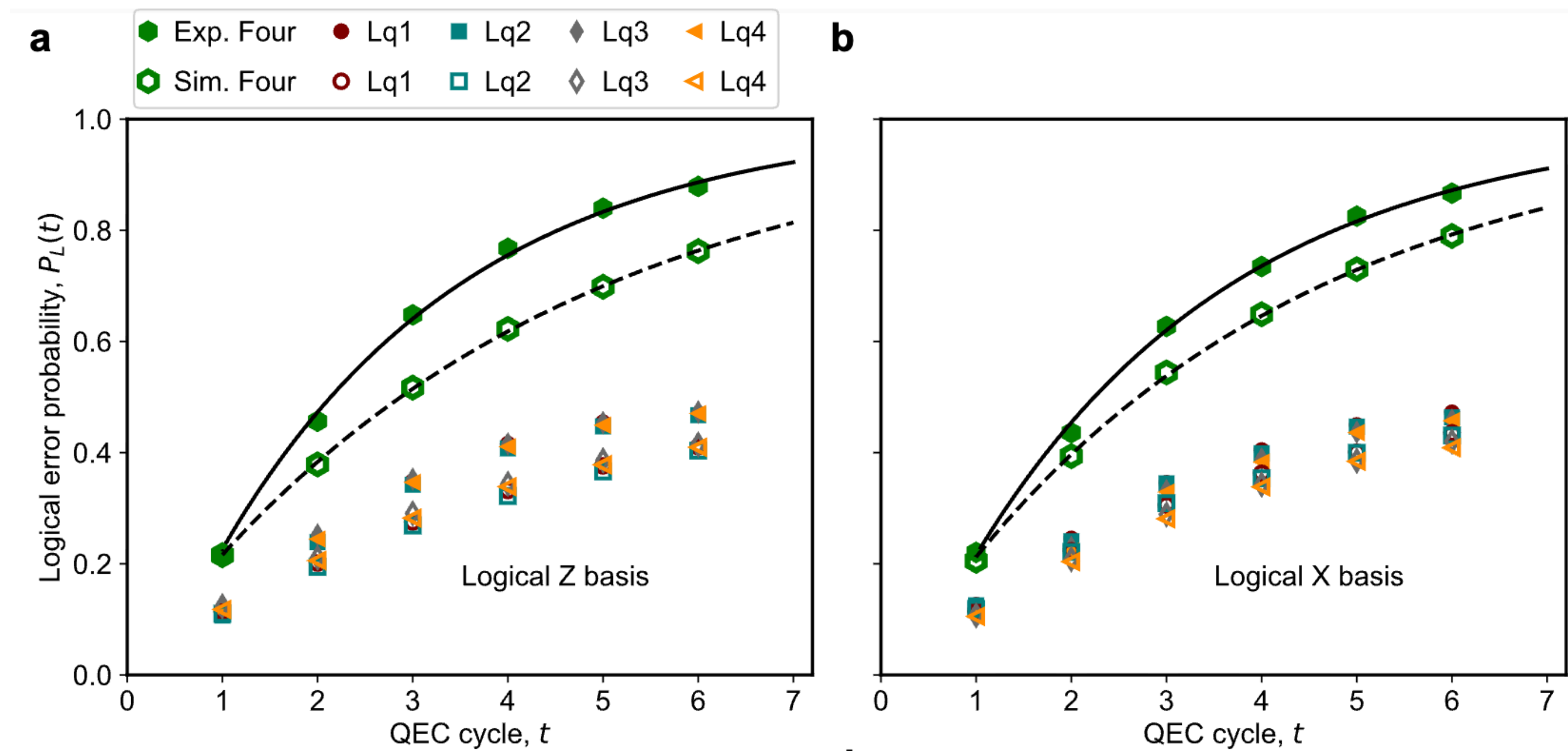
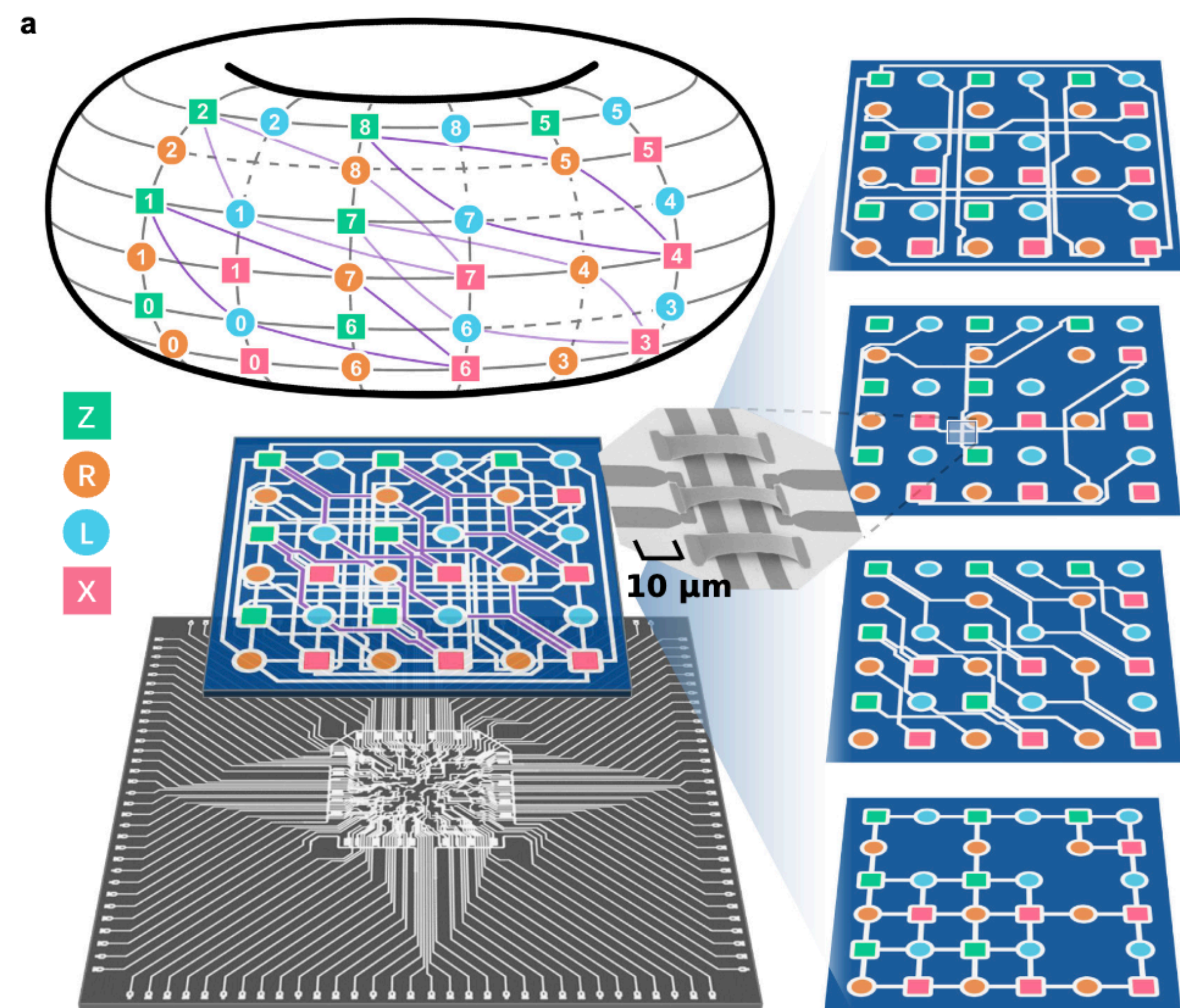


Demonstrated in 2024!

Below threshold and break-even

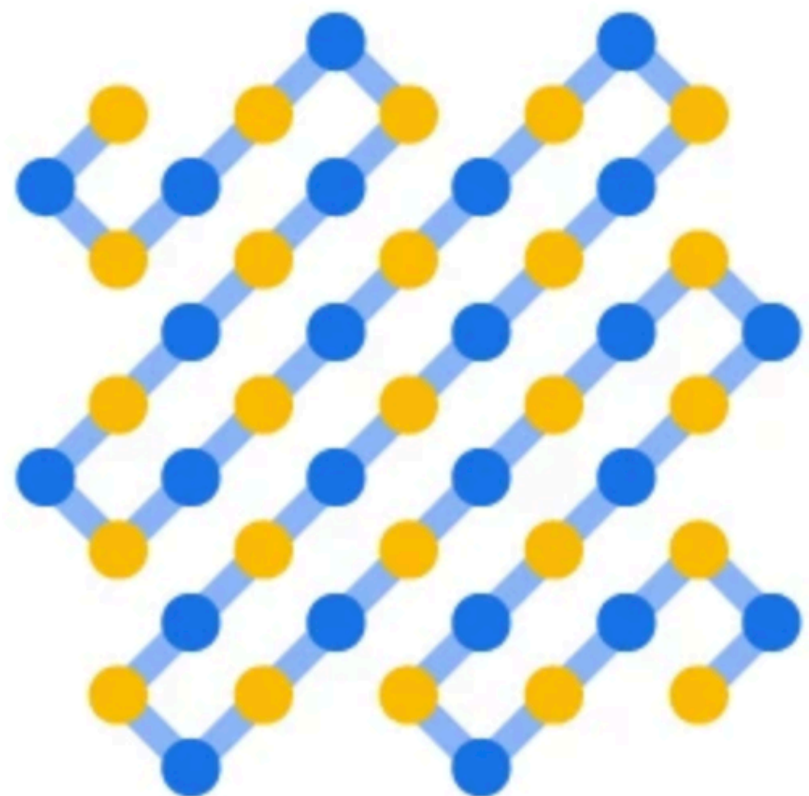
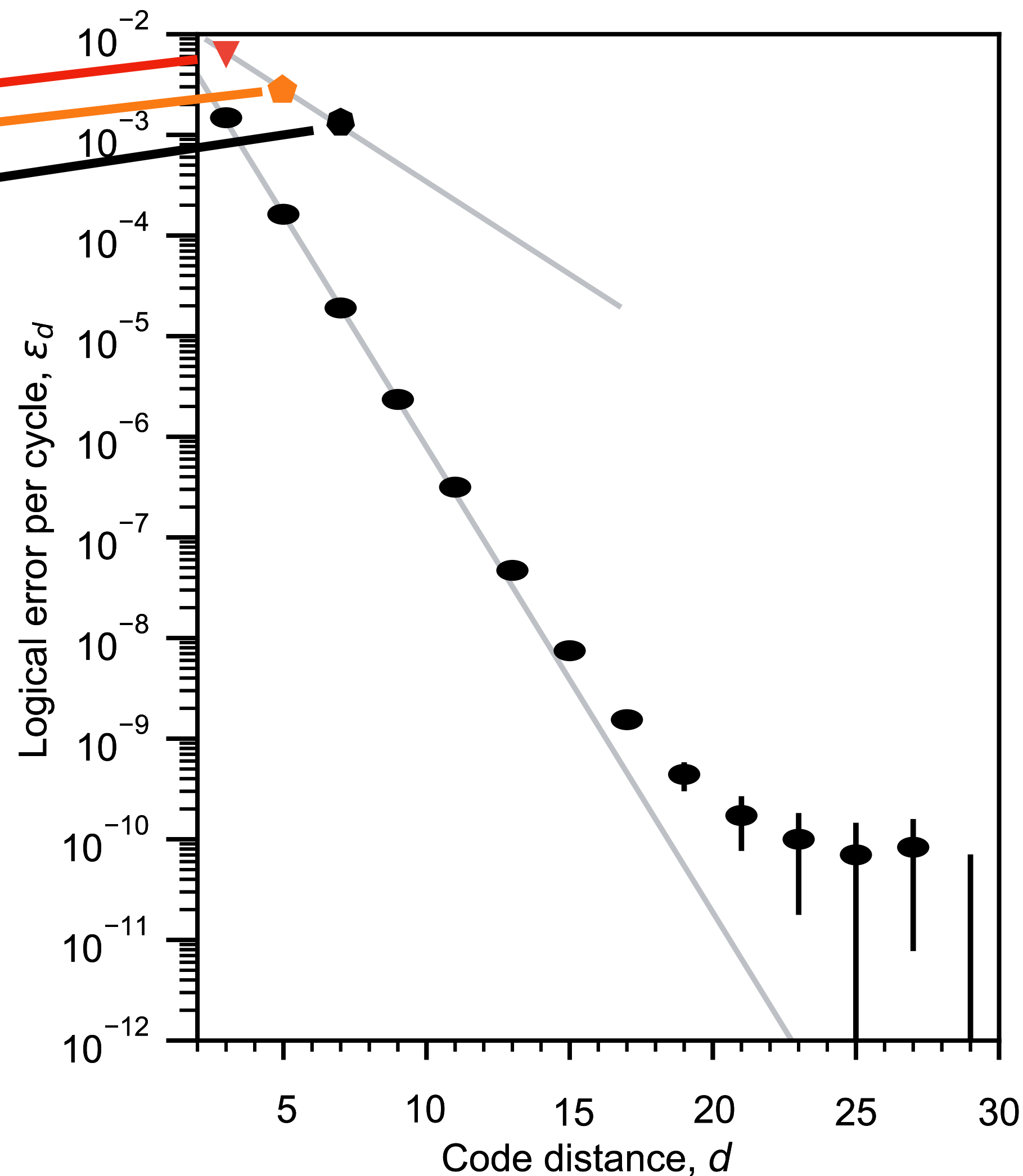
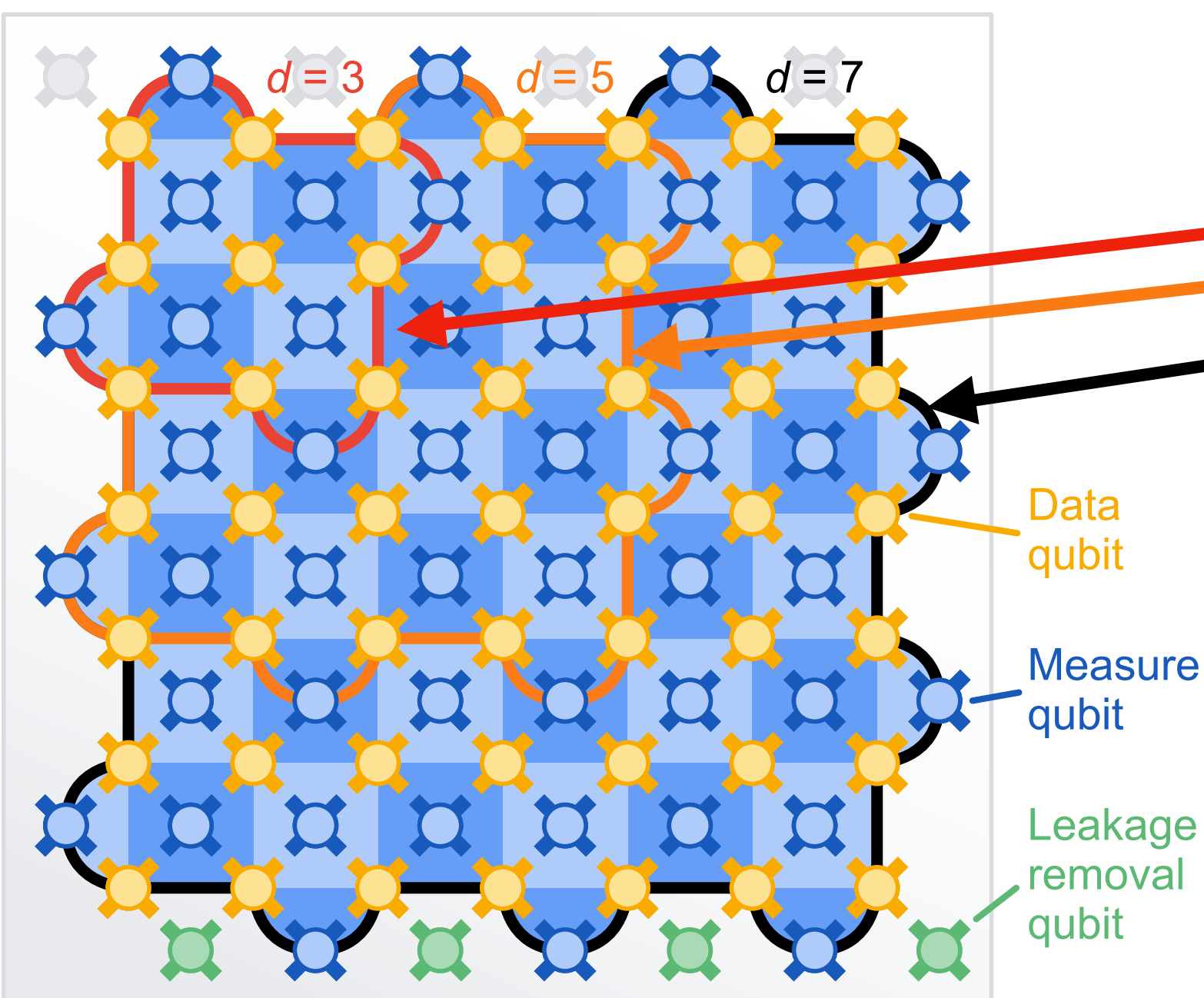


qLDPC code with transmons



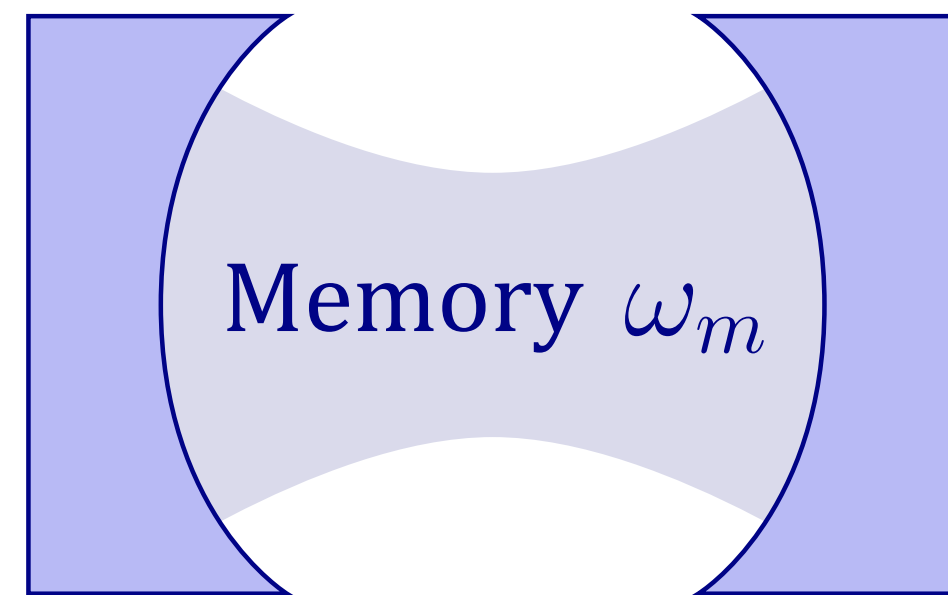
Repetition code with transmons

Easier to correct one type of error only with repetition

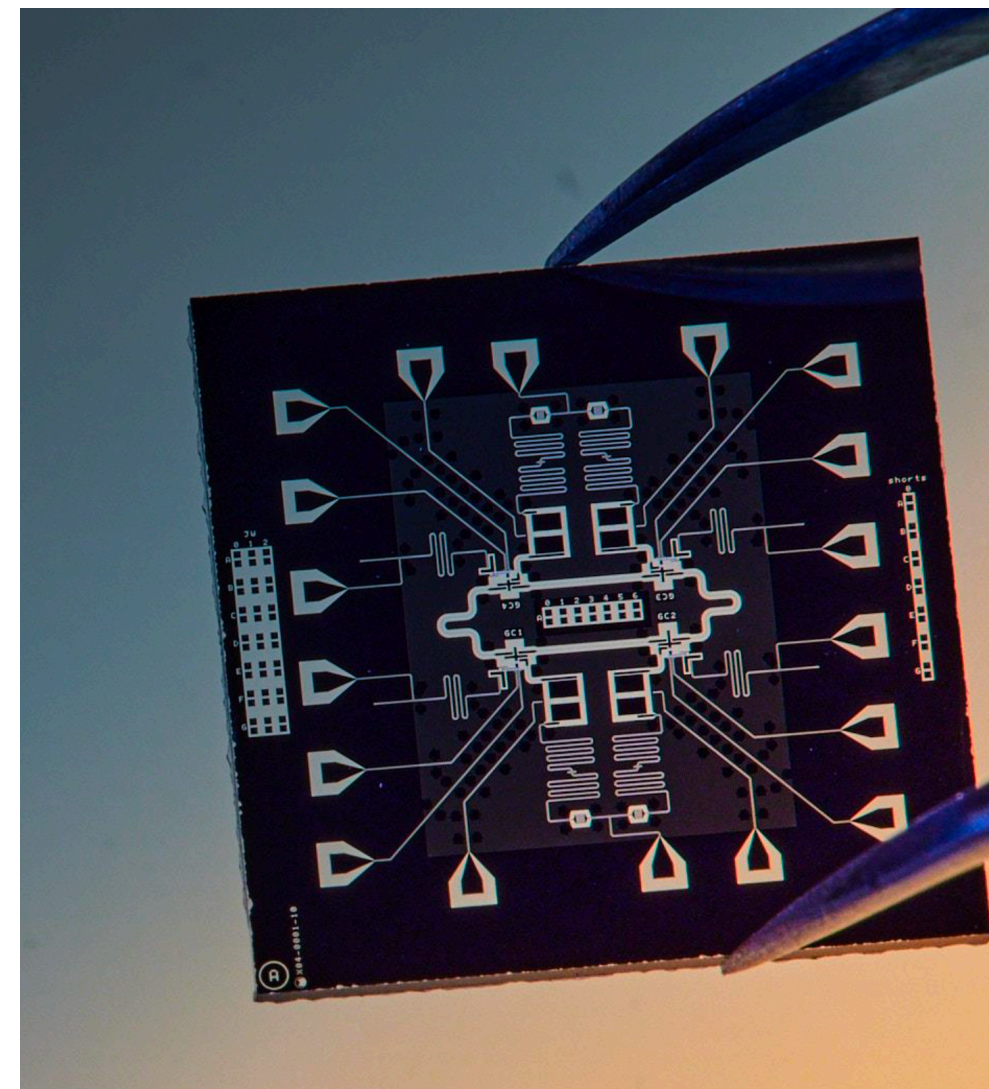


Bosonic codes

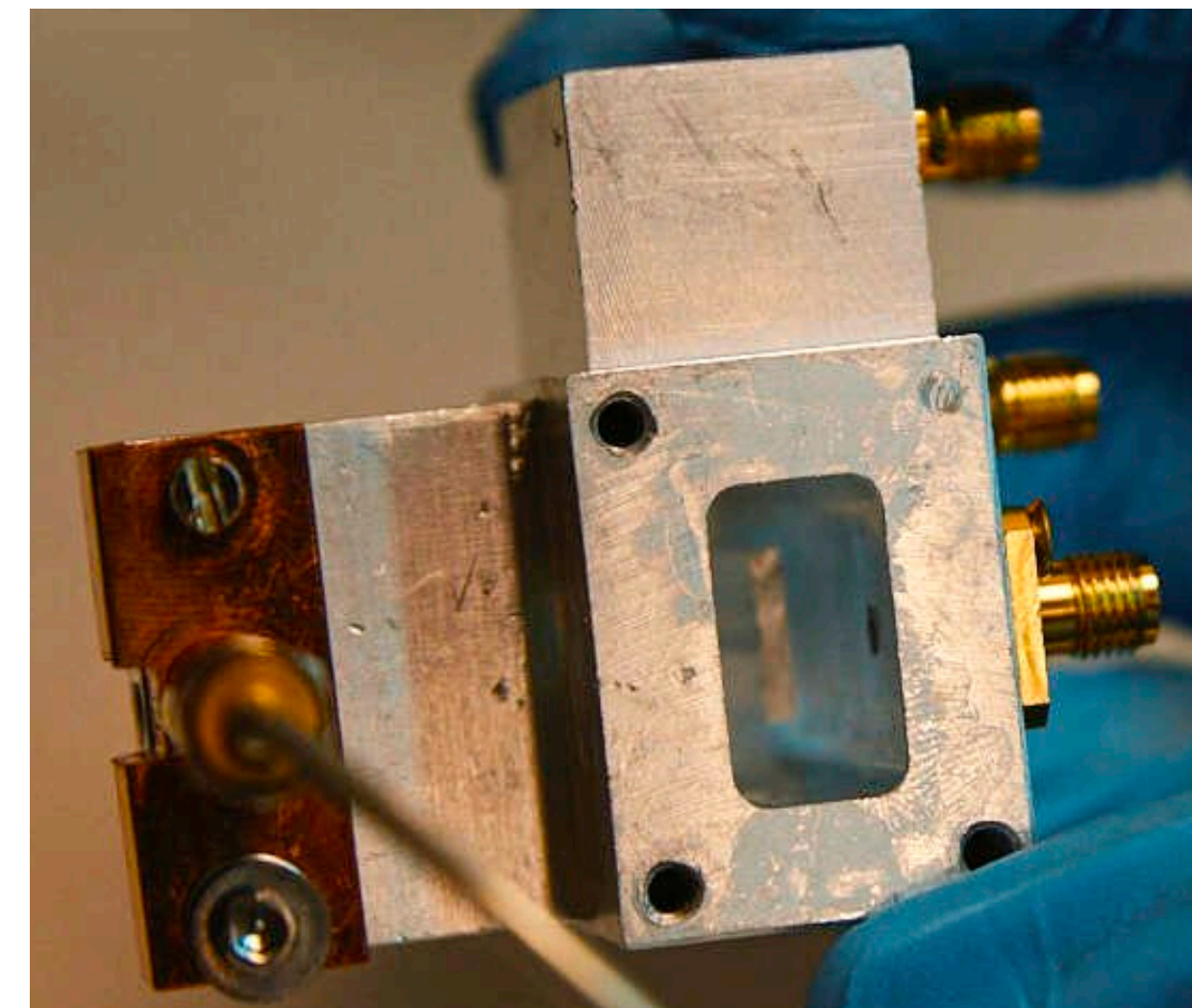
An efficient way of having redundancy



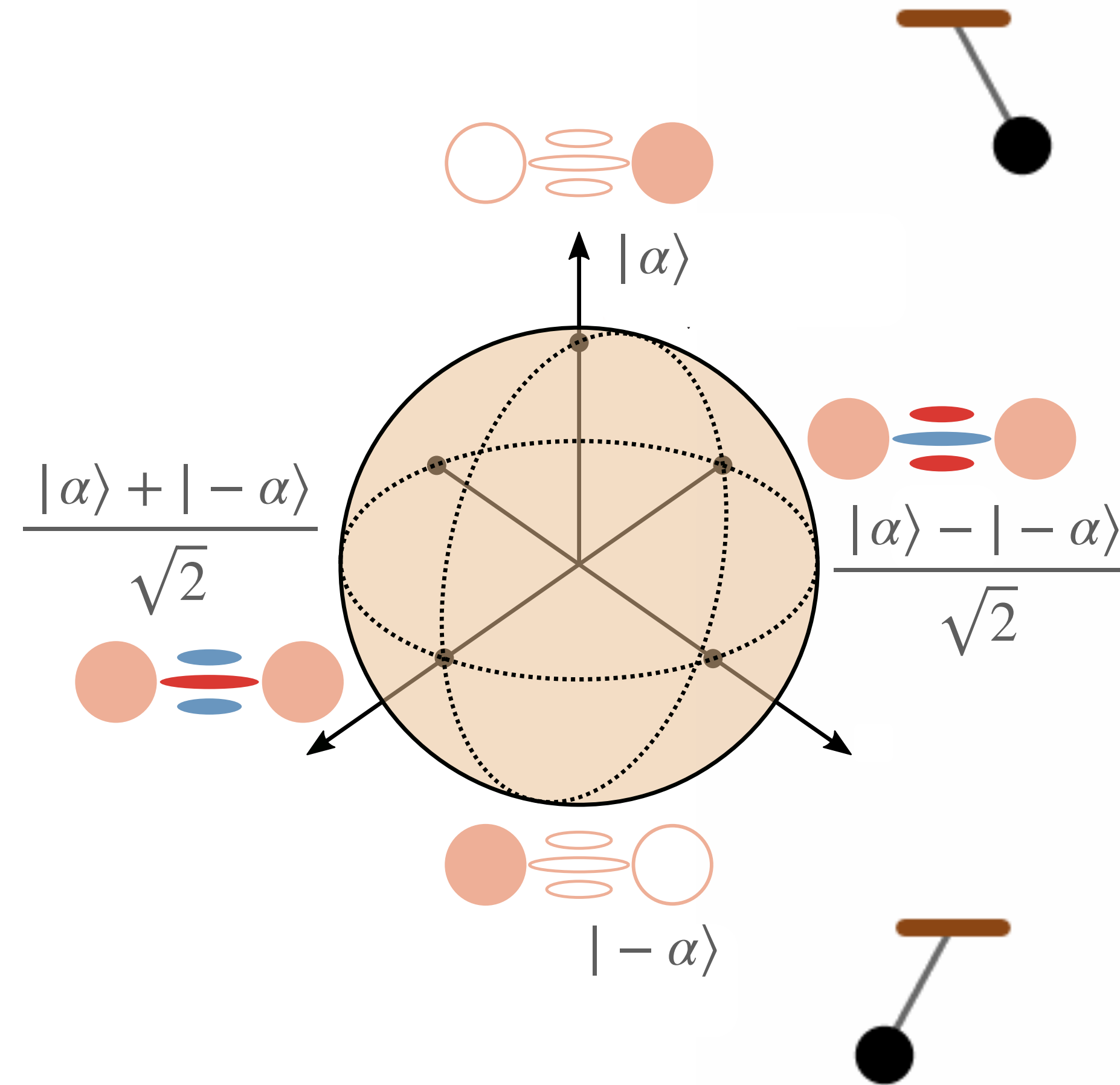
2D structures



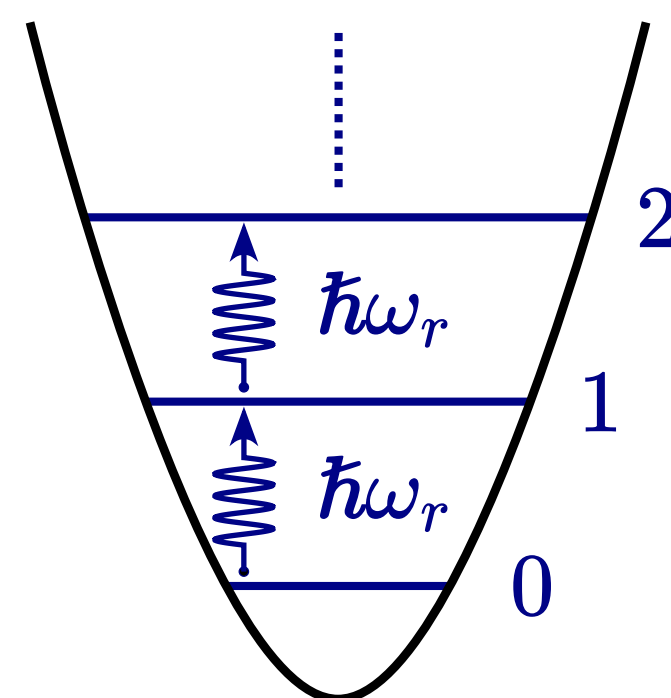
3D cavities



Cat code



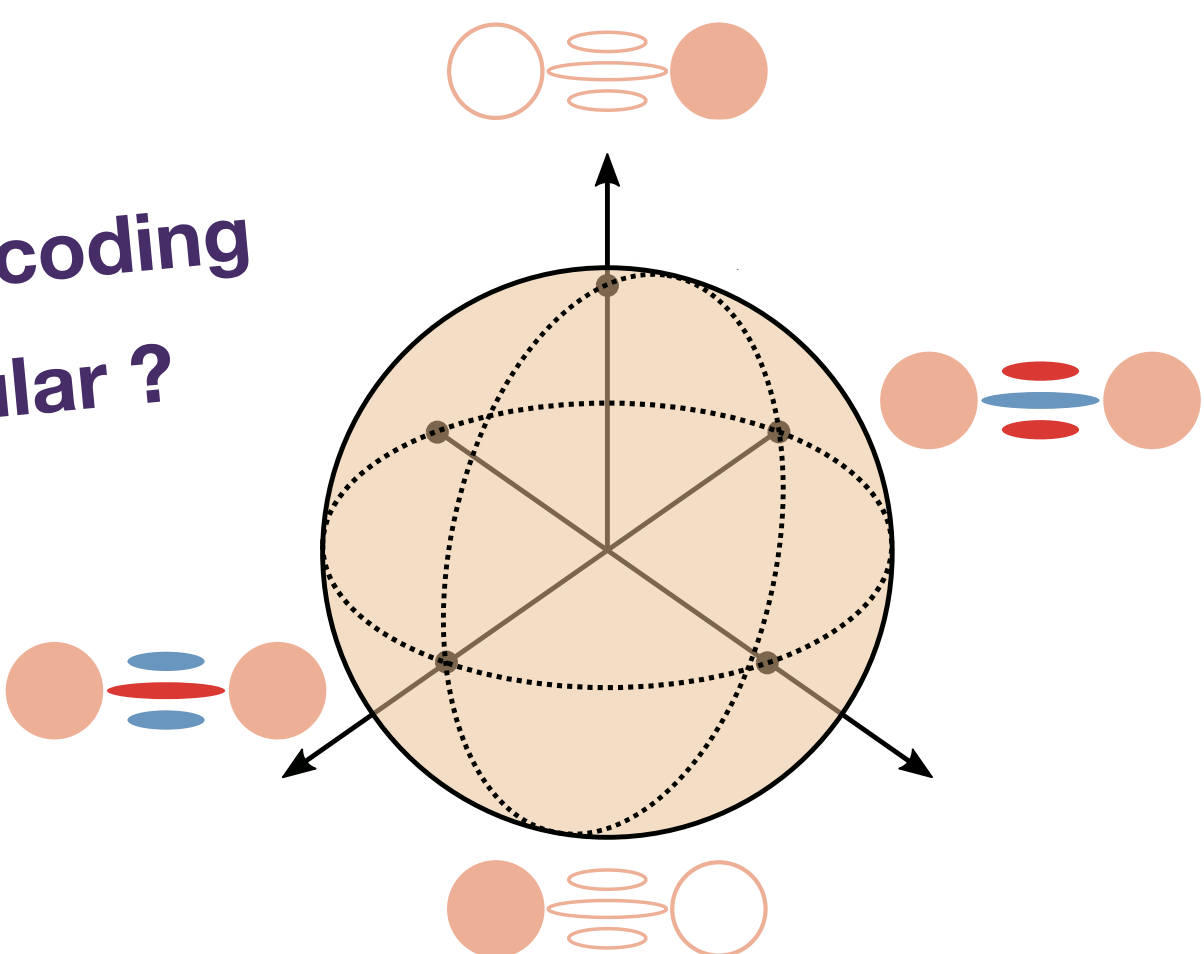
Plenty of potential bosonic qubits



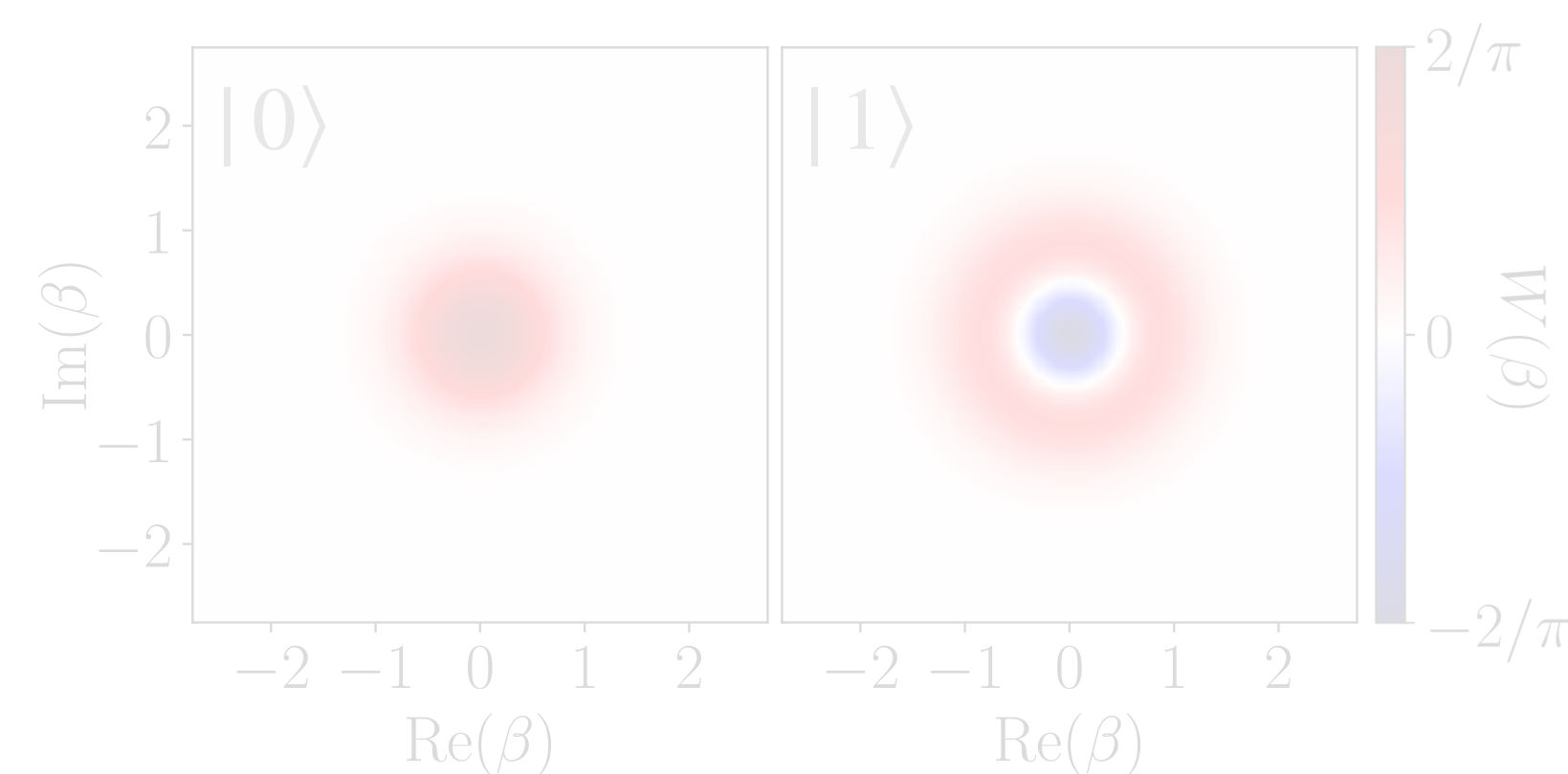
$$H = \hbar\omega_r(a^\dagger a + \frac{1}{2})$$

The cavity is now used to **encode** the information

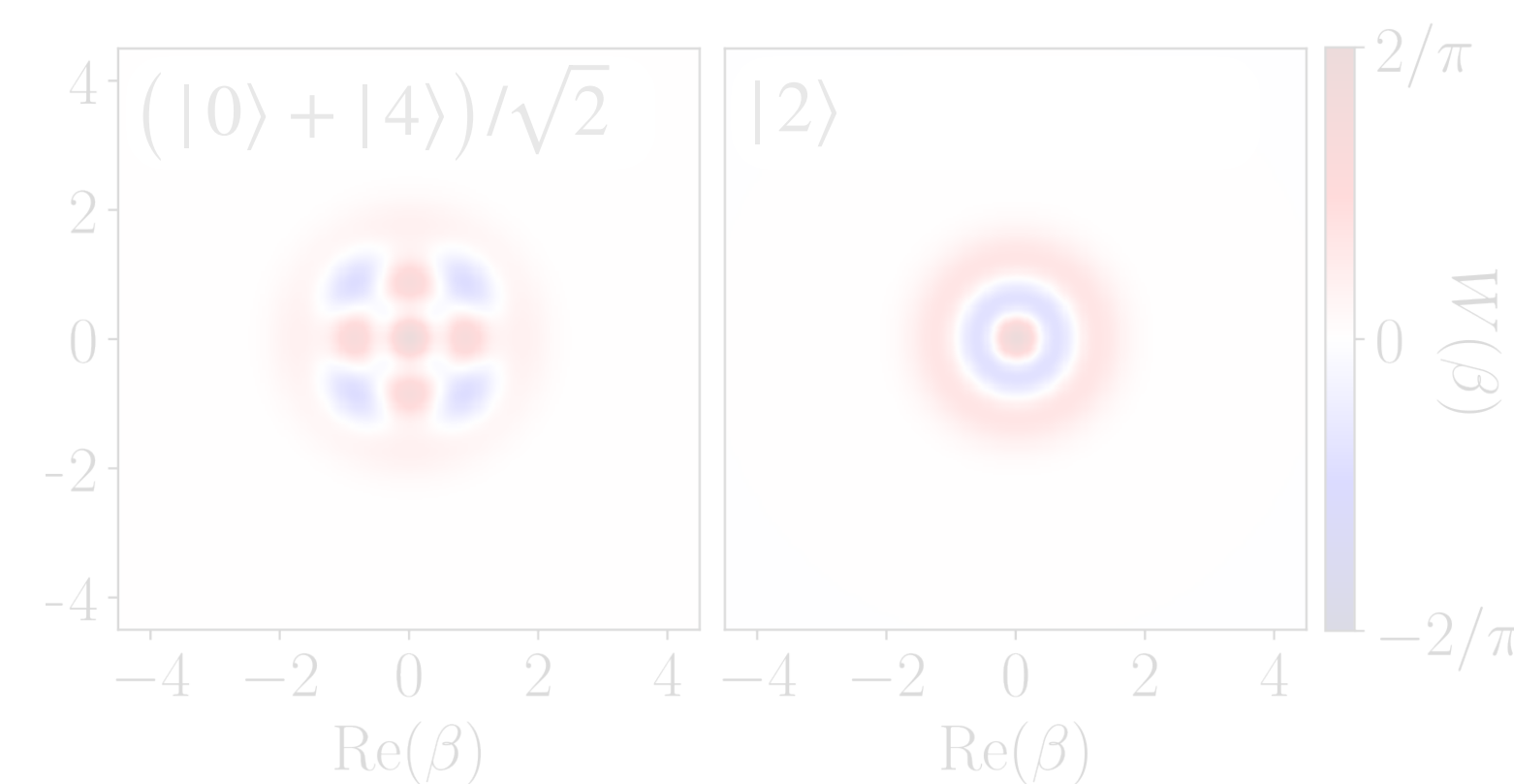
Why this encoding in particular ?



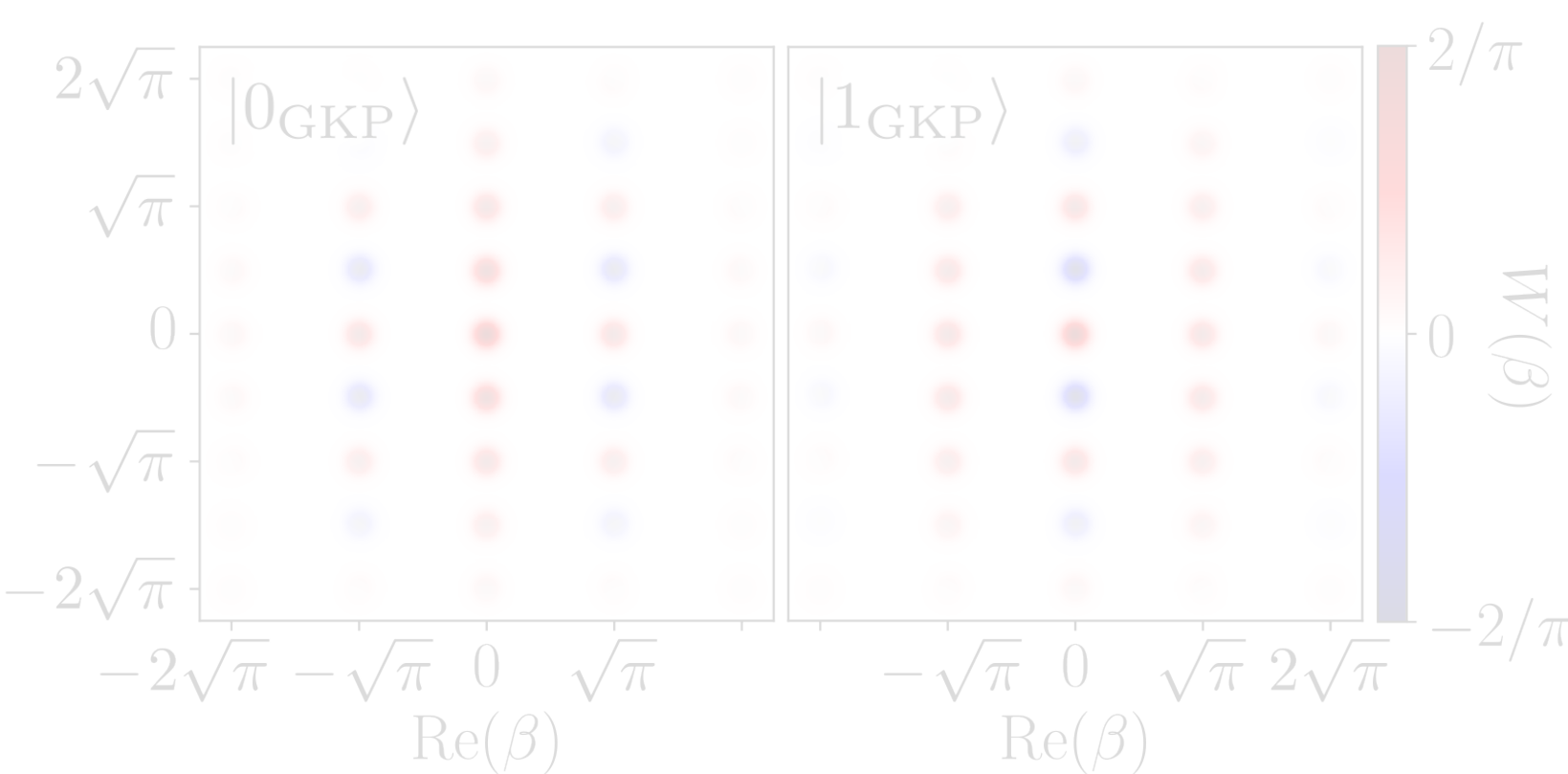
- Fock states



- The Kitten code

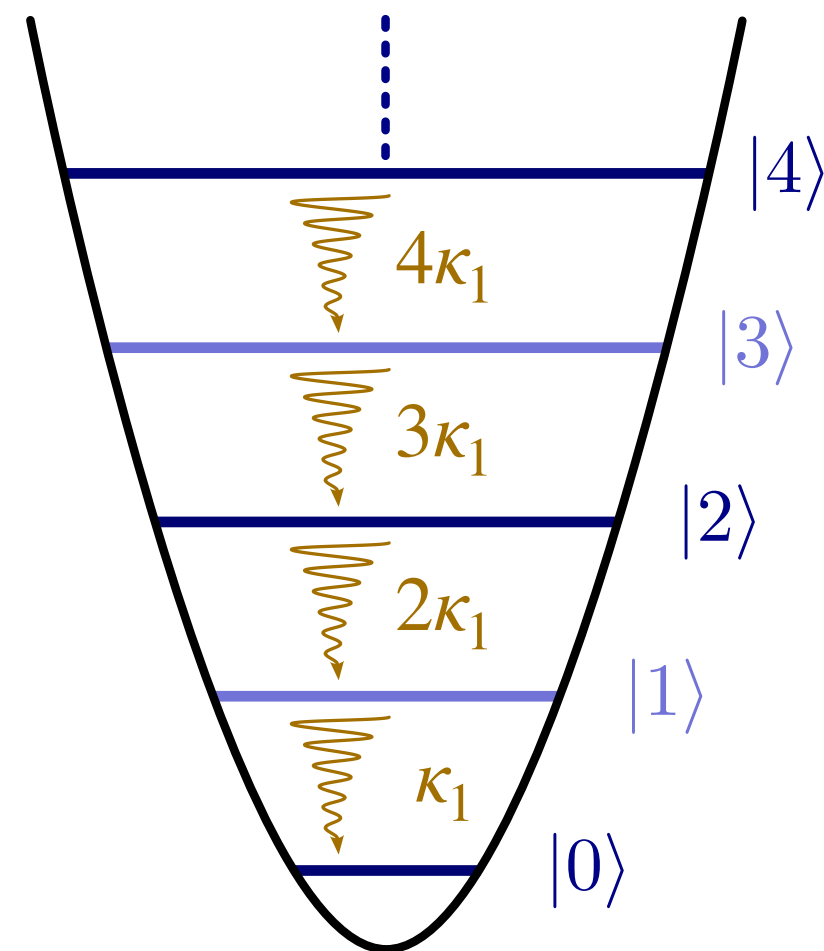
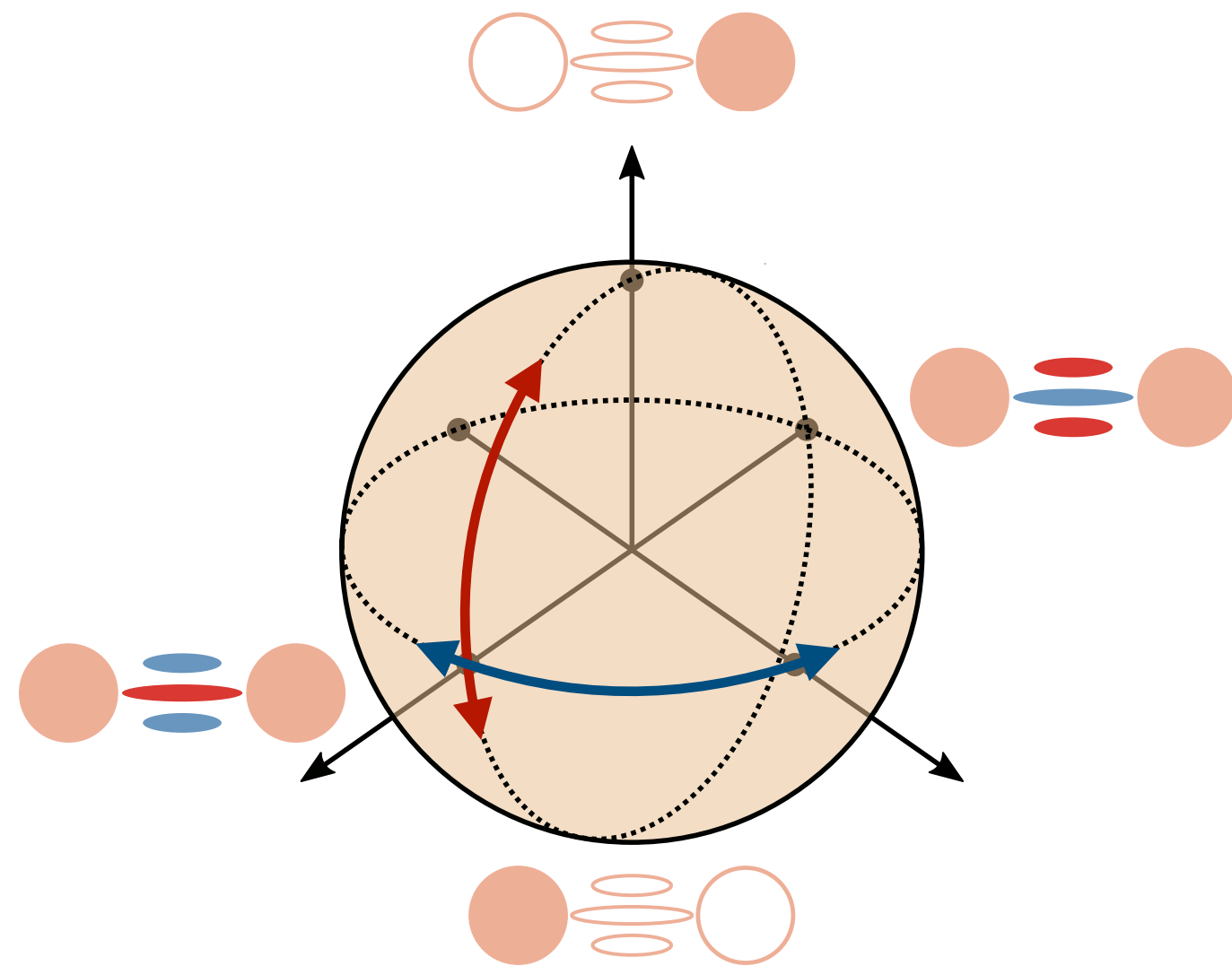


- The GKP code

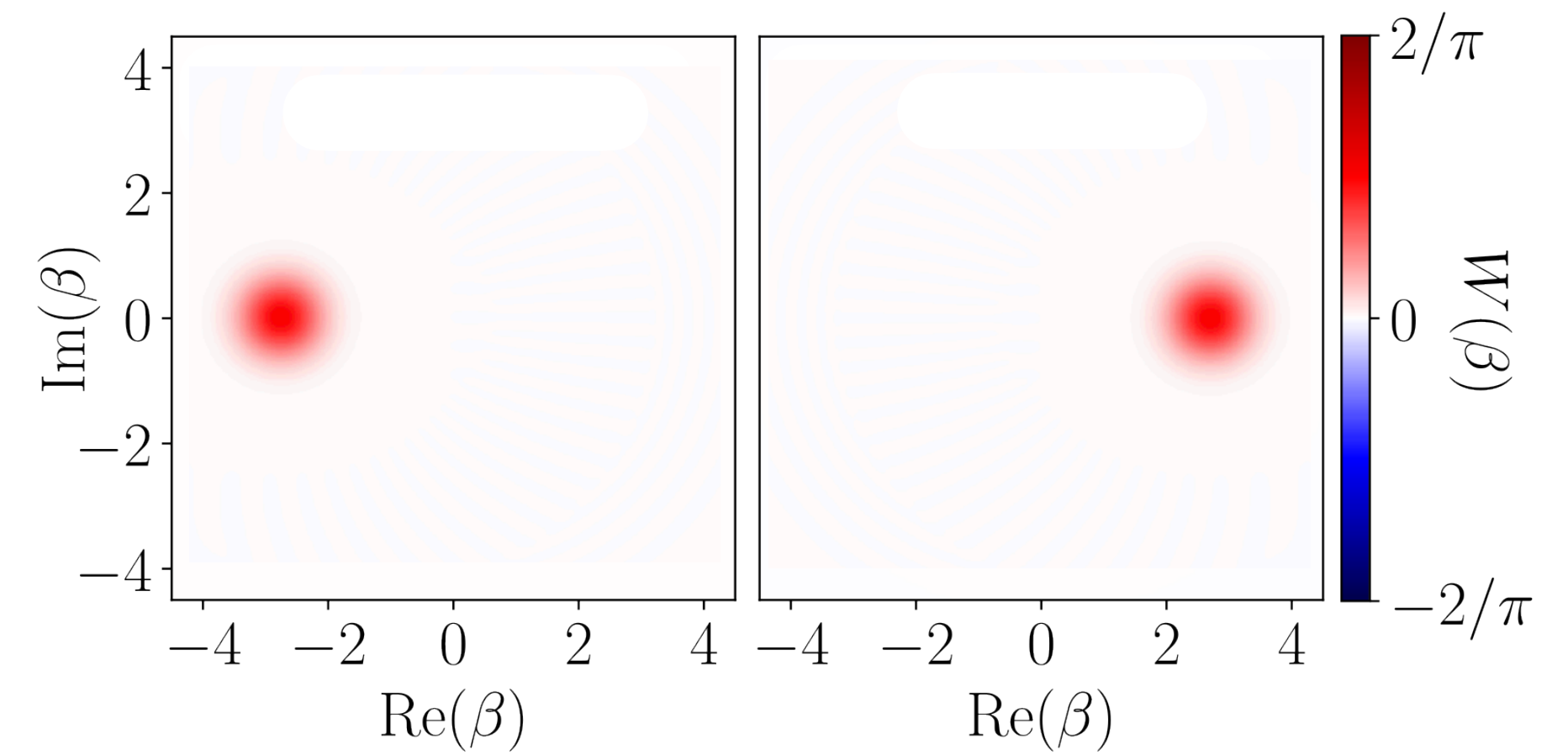


P. Campagne-Ibarcq et al., Quantum error correction of a qubit encoded in grid states of an oscillator, Nature (2020)
 D. Gottesman, A. Kitaev, J. Preskill, Encoding a qubit in an oscillator, PRA (2001)
 J. Guillaud, J. Cohen, M. Mirrahimi, Quantum computing with cat qubits, PRX (2022)
 A. Joshi, K. Not, Y. Gao, Quantum information processing with bosonic qubits in circuit QED, Quantum Sci. Technol (2021)

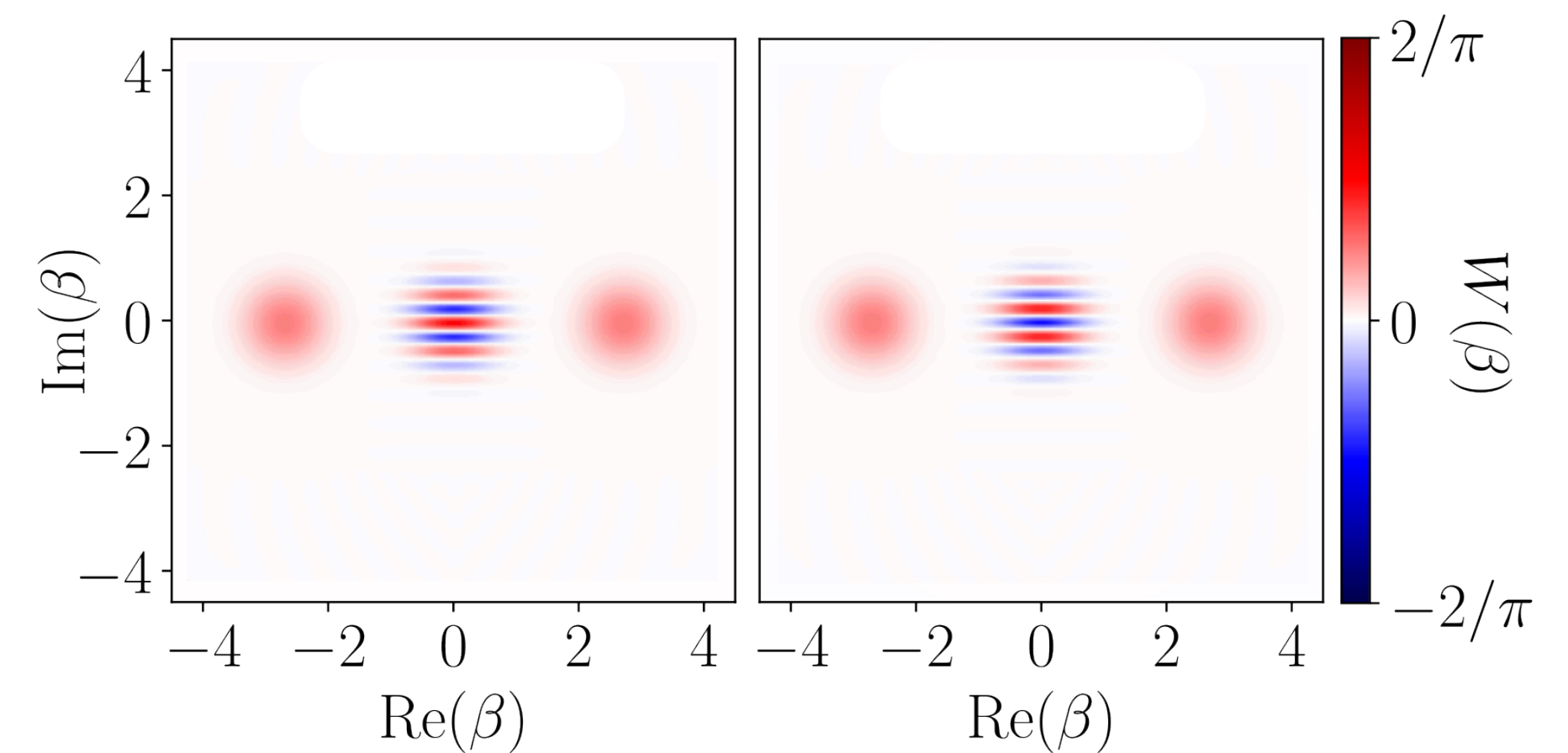
A biased noise qubit



Exponential gain in bit flips $\Gamma_X \propto e^{-\lambda|\alpha|^2}$



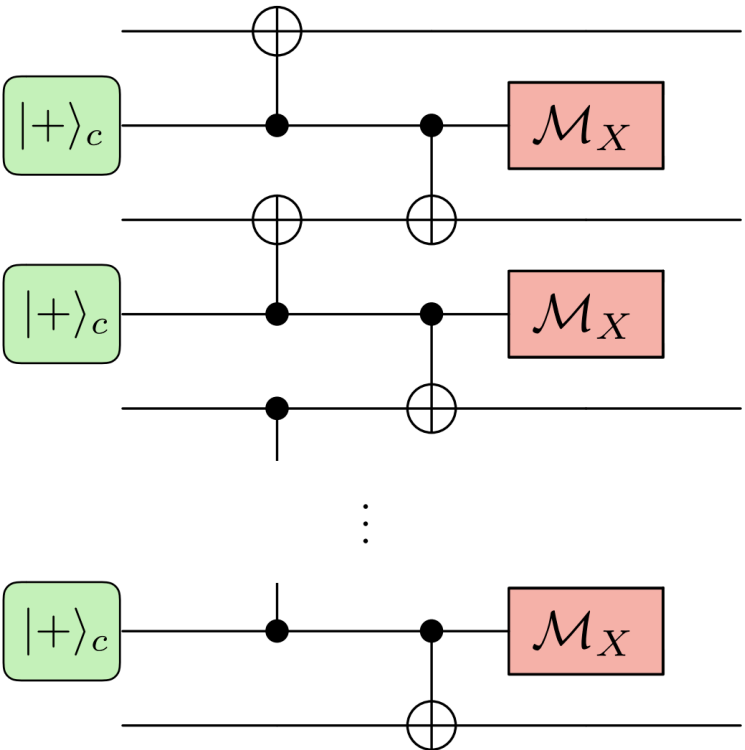
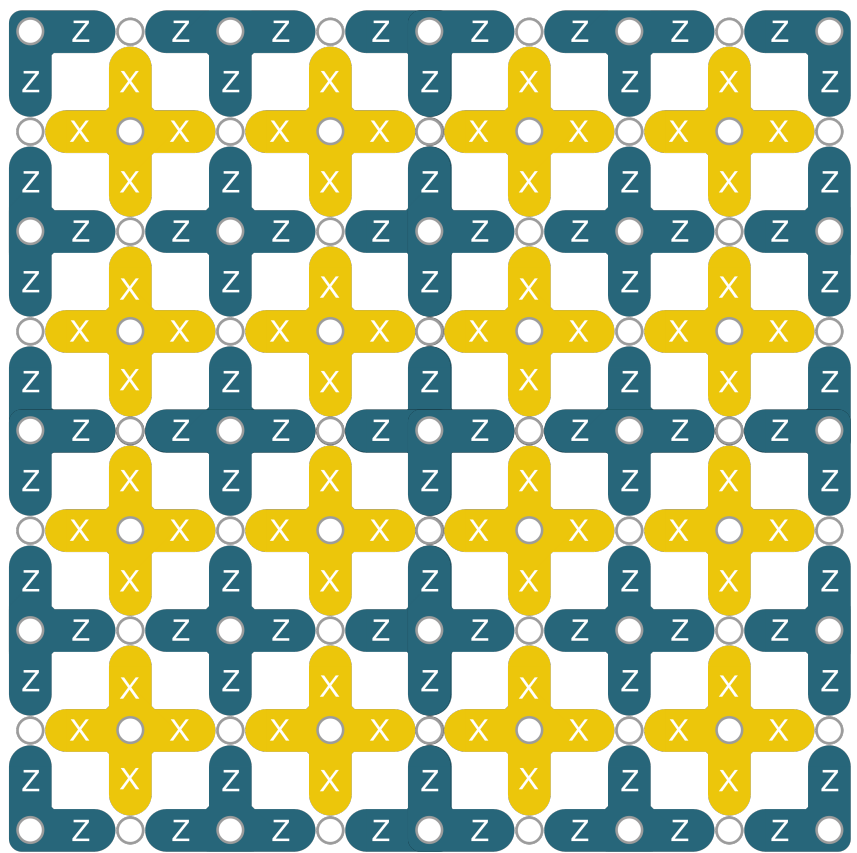
Linear cost in phase flips $\Gamma_Z = 2\kappa_1 |\alpha|^2$



Hardware efficient

Only one type of error

1. Classical codes are sufficient



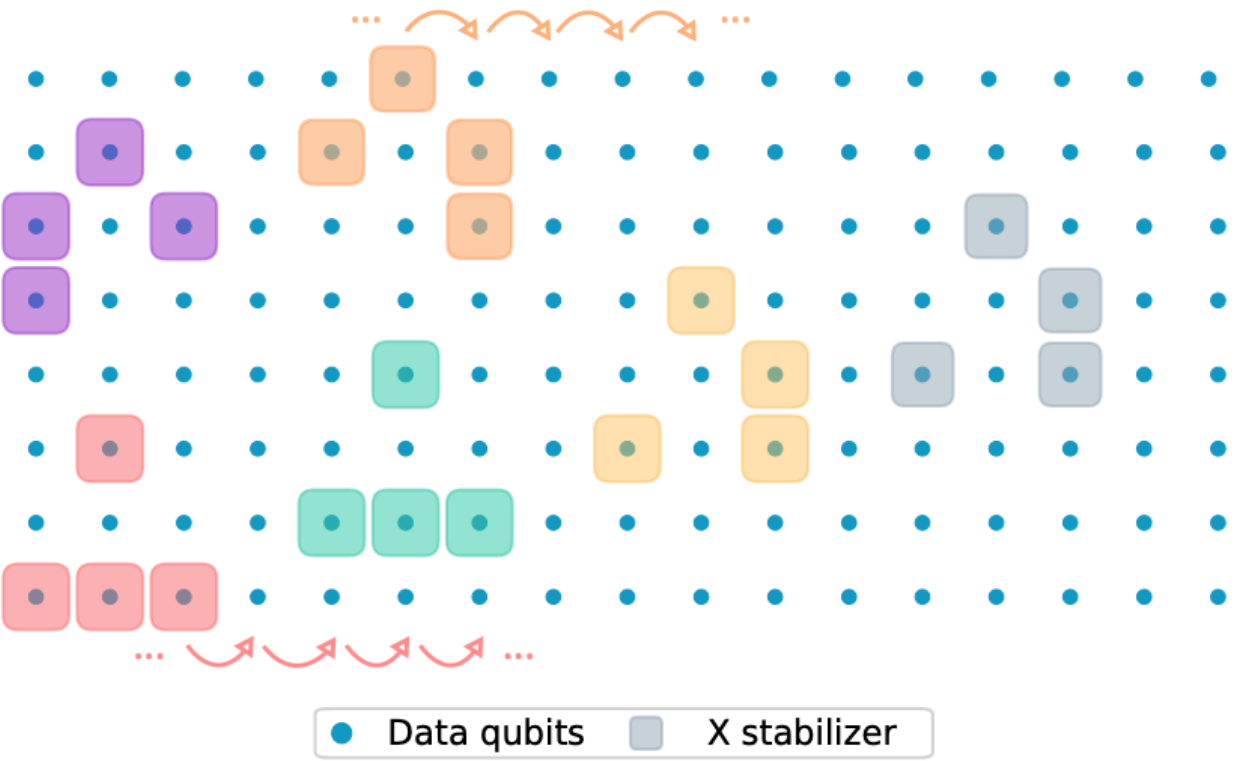
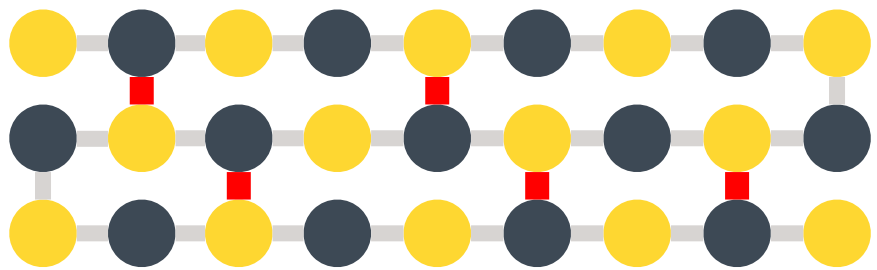
Putterman et al., Nature 2025 (AWS)

1D repetition code is error resilient

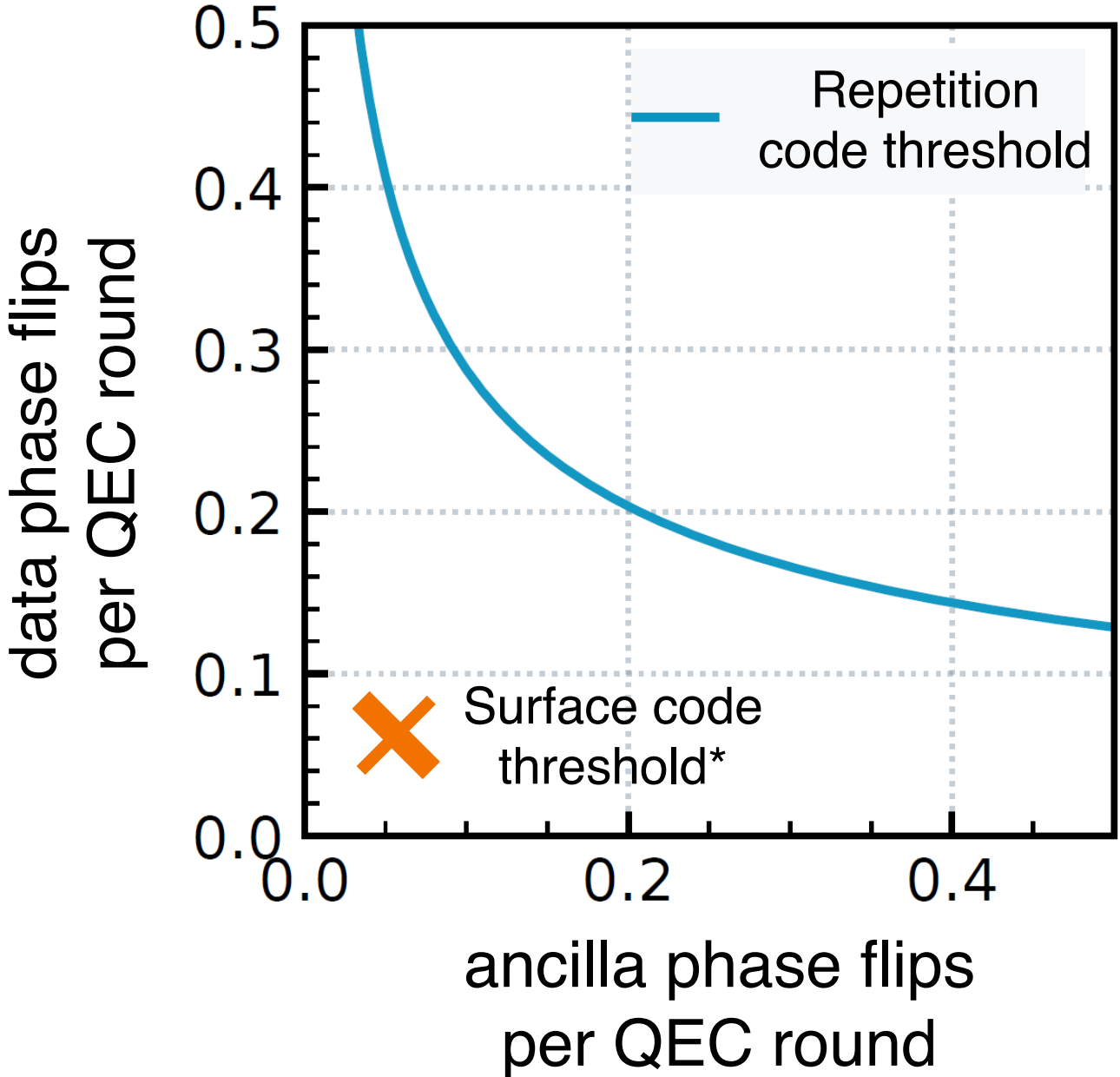
2. High threshold

Distant is local in 1D (zigzag)

3. LDPC codes can be local



Ruiz et al., Nature Comm. (2025)



*assumes equal distribution of errors among qubits & operations

Benchmark: Factoring 2048-bit integers ($\epsilon_L \sim 10^{-15}$)

Surface code + transmons Quantum 5, 433 (2021)

How to factor 2048 bit RSA integers in 8 hours using
20 million noisy qubits

Craig Gidney¹ and Martin Ekerå²

2×10^7 transmons

Repetition code + Cat Qubits PRL 131, 040602 (2023)

**Performance Analysis of a Repetition Cat Code
Architecture: Computing 256-bit Elliptic Curve
Logarithm in 9 Hours with 126 133 Cat Qubits**

[Élie Gouzien](#) ^{1,*}, [Diego Ruiz](#) ^{2,3}, [Francois-Marie Le Régent](#)^{2,3}, [Jéréemie Guillaud](#)², and
[Nicolas Sangouard](#)^{1,†}

3.5×10^5 cat qubits (N/57)

LDPC + Cat Qubits Nature Communications, 16 (2025)

**LDPC-cat codes for low-overhead quantum computing
in 2D**

[Diego Ruiz](#) , [Jéréemie Guillaud](#), [Anthony Leverrier](#), [Mazyar Mirrahimi](#) & [Christophe Vuillot](#)

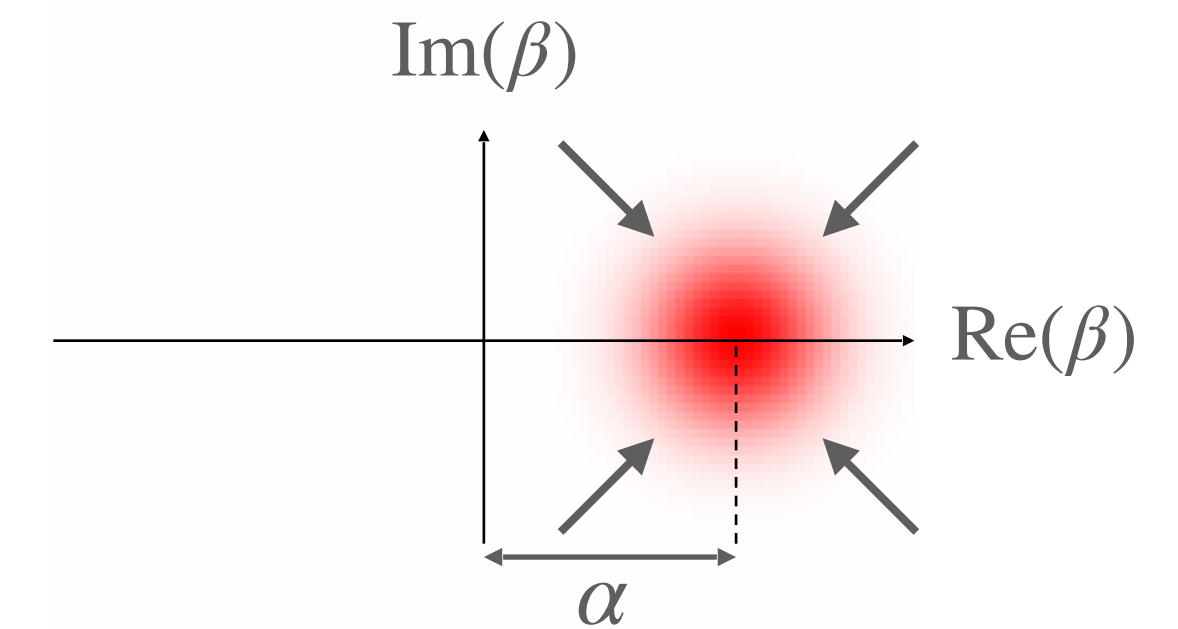
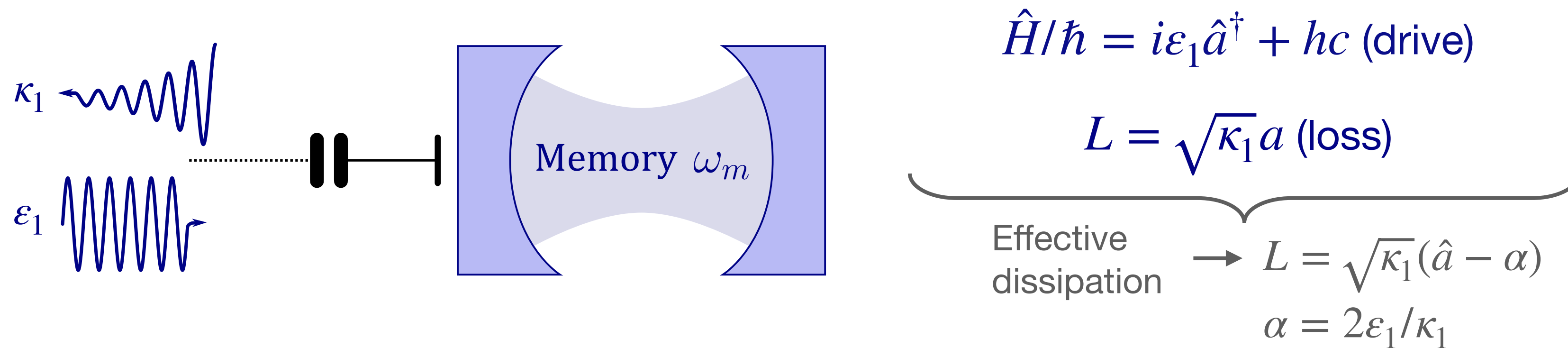
10^5 cat qubits (N/200)

Using dissipation to stabilize cats

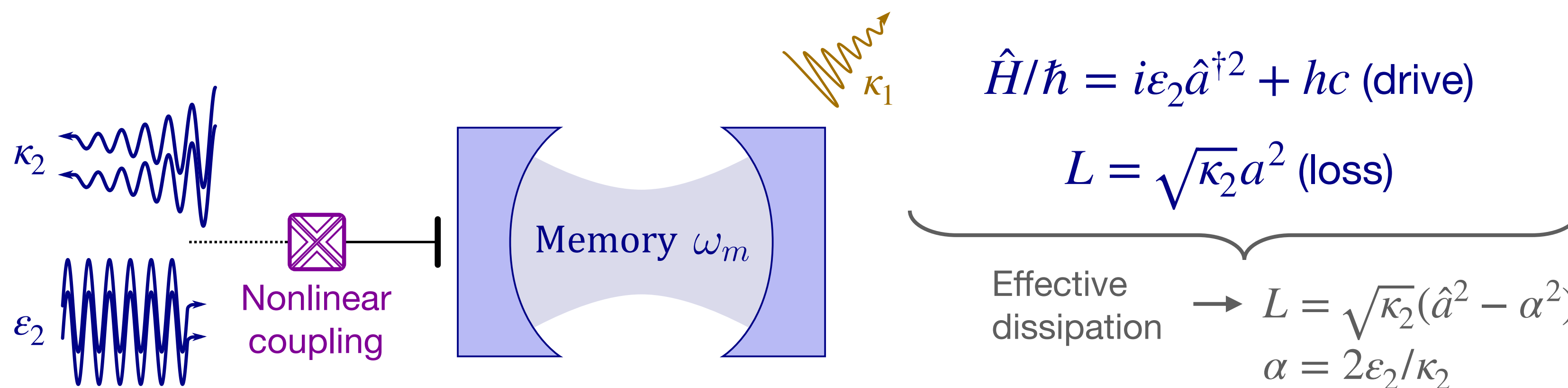
Hamiltonian engineering also possible: « Kerr cats »

And higher order protection also possible

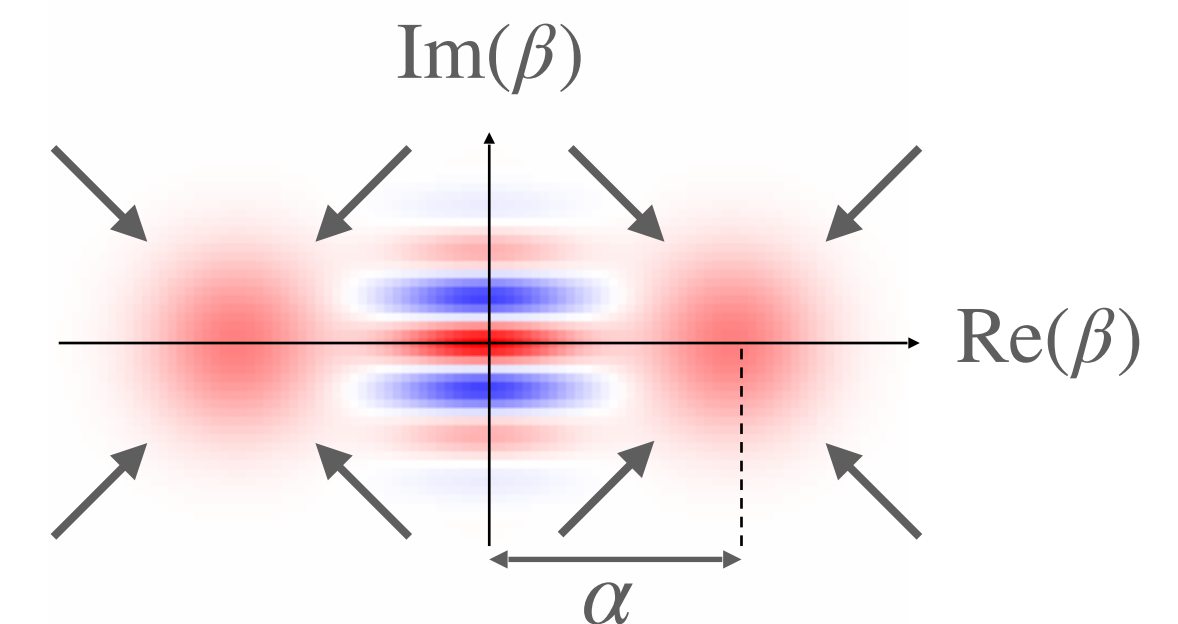
- Single photon coupling



- Two photon coupling



Stabilizes $\mathcal{C} = \text{span} \{ |\alpha\rangle, |-\alpha\rangle \}$



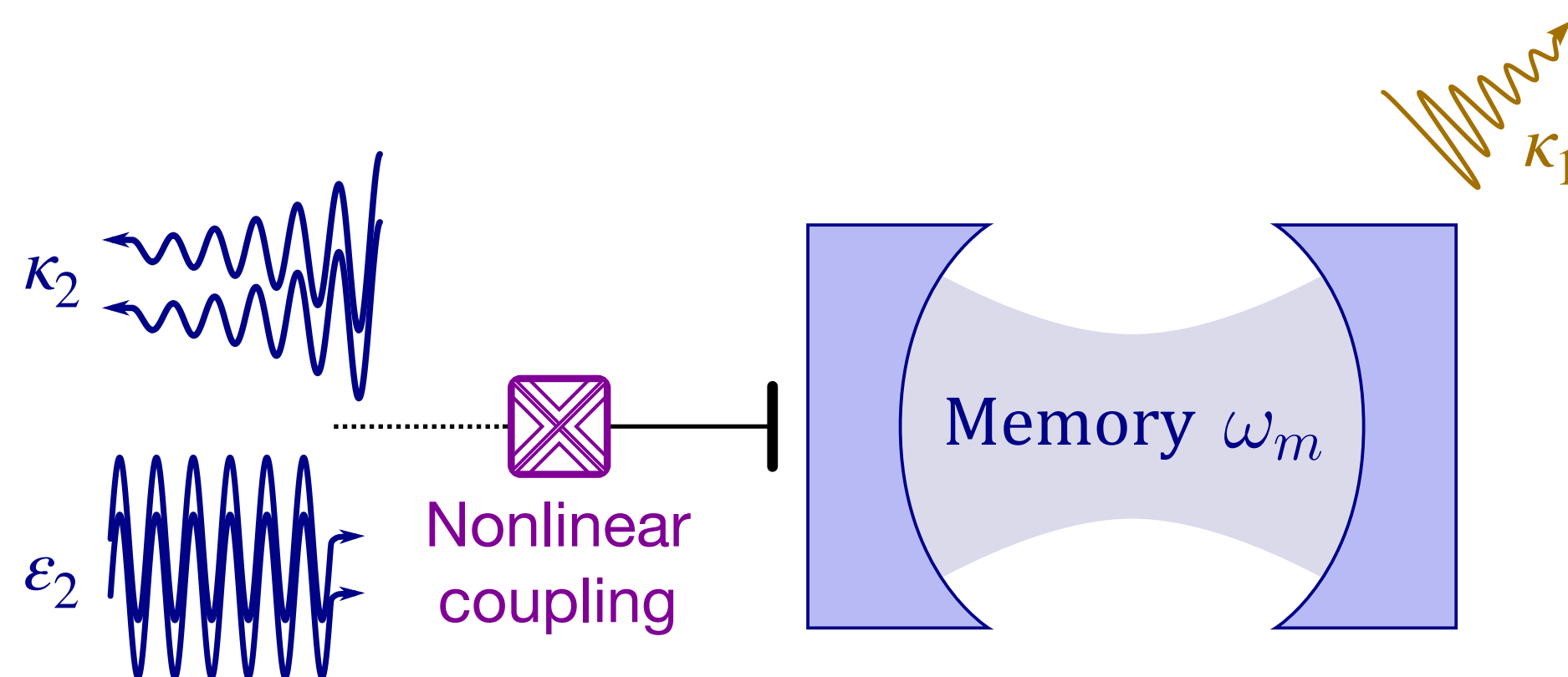
Using dissipation to stabilize cats

« Threshold » for QEC with cat qubits

$$\frac{\kappa_2}{\kappa_1} \gtrsim 100 - 1000$$

Le Régent et al., Quantum 2023 (Inria, A&B)

- Two photon coupling



$$\hat{H}/\hbar = i\varepsilon_2 \hat{a}^{\dagger 2} + hc \text{ (drive)}$$

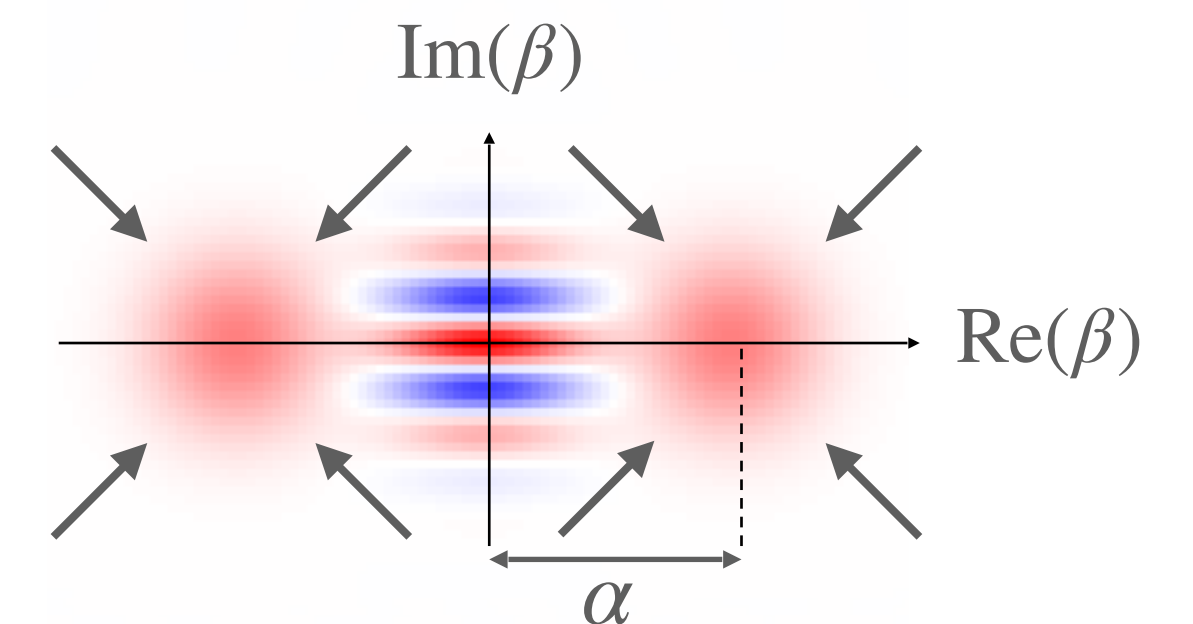
$$L = \sqrt{\kappa_2} a^2 \text{ (loss)}$$

Effective
dissipation

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

$$\alpha = 2\varepsilon_2/\kappa_2$$

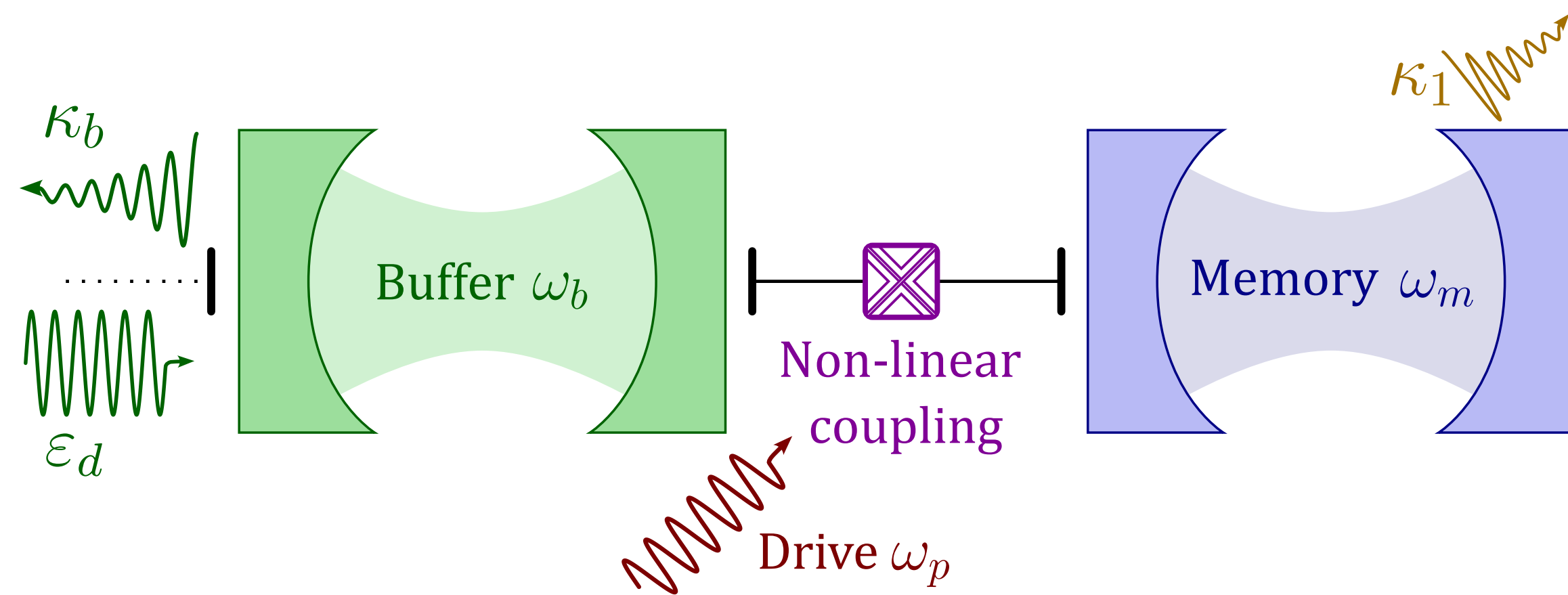
Stabilizes $\mathcal{C} = \text{span} \{ |\alpha\rangle, |-\alpha\rangle \}$



Dissipative cat qubit

First implementation with an active coupling

2 photon dissipation using 4th order non-linearity

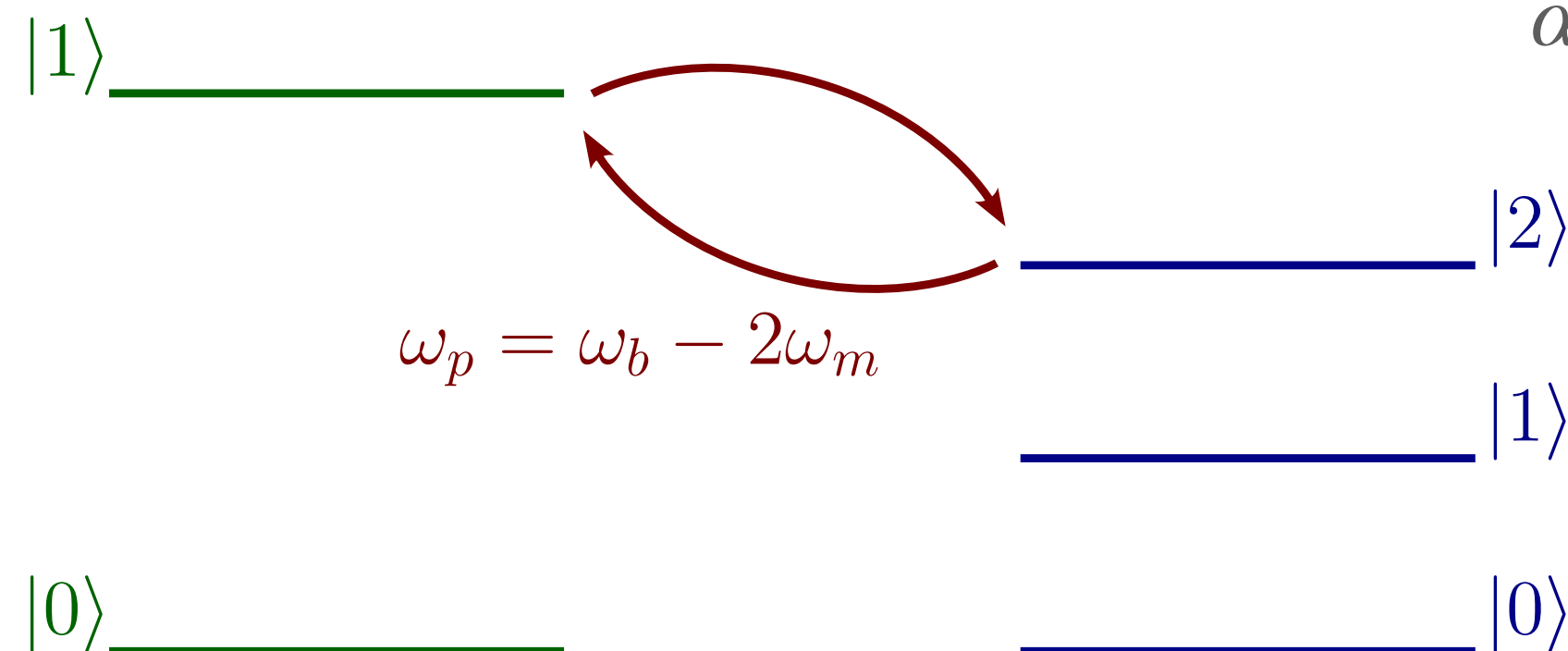


$$\hat{H}_{\text{coupling}}/\hbar = g_2 \hat{a}^{\dagger 2} \hat{b} + g_2^* \hat{a}^2 \hat{b}^{\dagger}$$

Buffer drive ϵ_d & buffer dissipation $\kappa_b \gg g_2$

$$\Rightarrow \hat{L}_2 = \sqrt{\kappa_2} (\hat{a}^2 - \alpha^2),$$

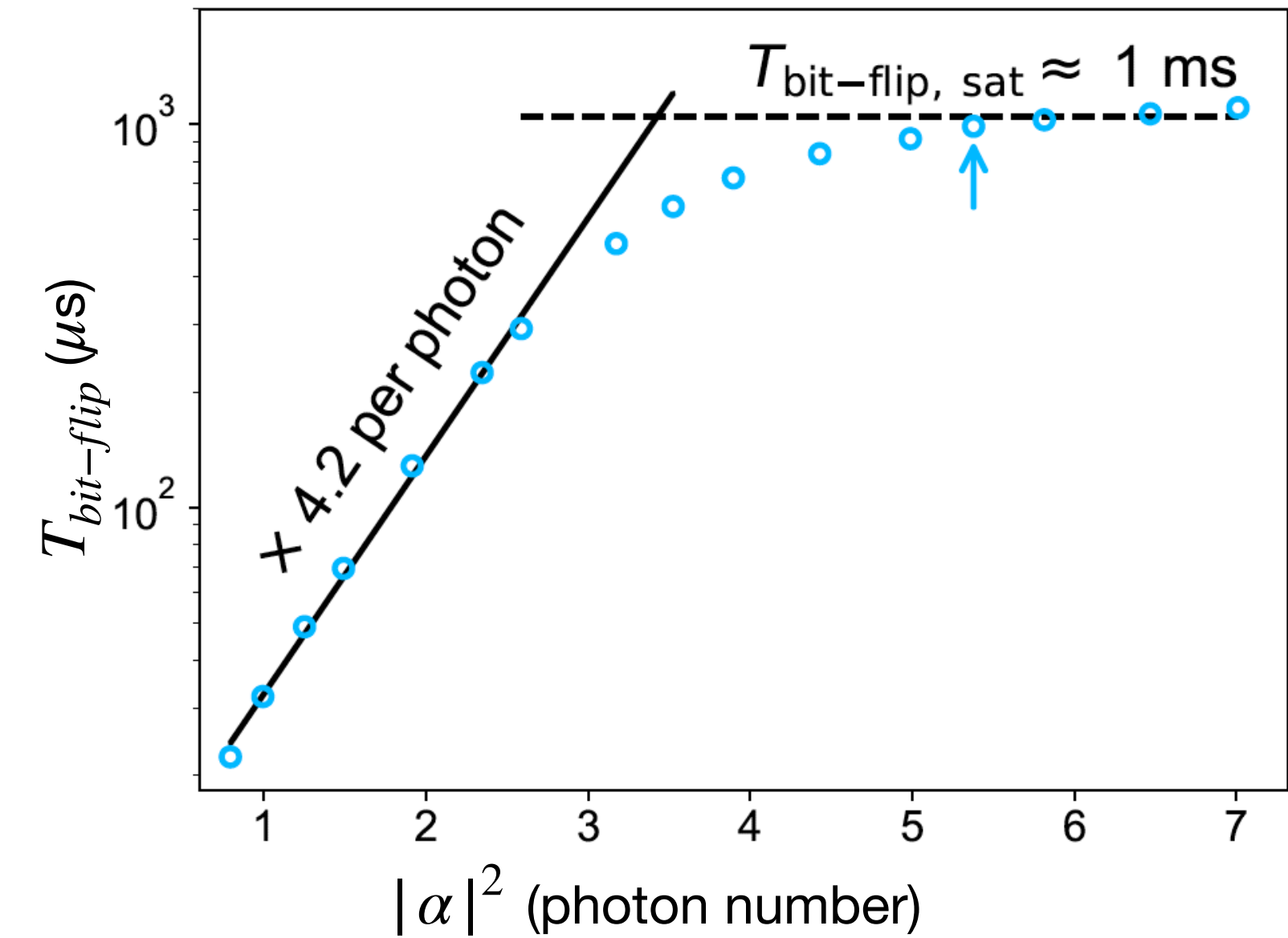
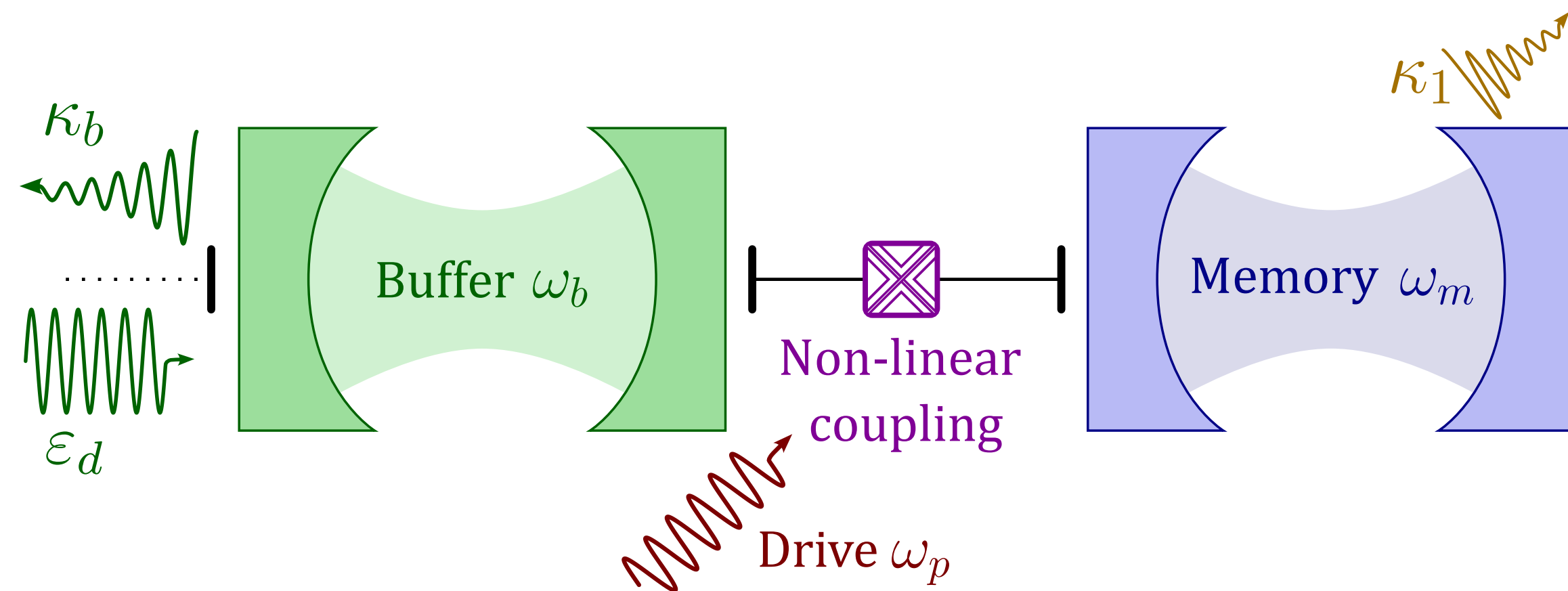
with $\begin{cases} \kappa_2 \sim 4 |g_2|^2 / \kappa_b \\ \alpha^2 \sim -\epsilon_d / g_2^* \end{cases}$



Dissipative cat qubit

First experimental implementation

2 photon dissipation using 4th order non-linearity



- Non-linearity provided by a **transmon**

[S. Touzard et al. PRX 2018 (Yale)]

[Z. Leghtas et al. Science, 2015 (Yale)]

Stabilization, but **no** exponential scaling of $T_{\text{bit-flip}}$

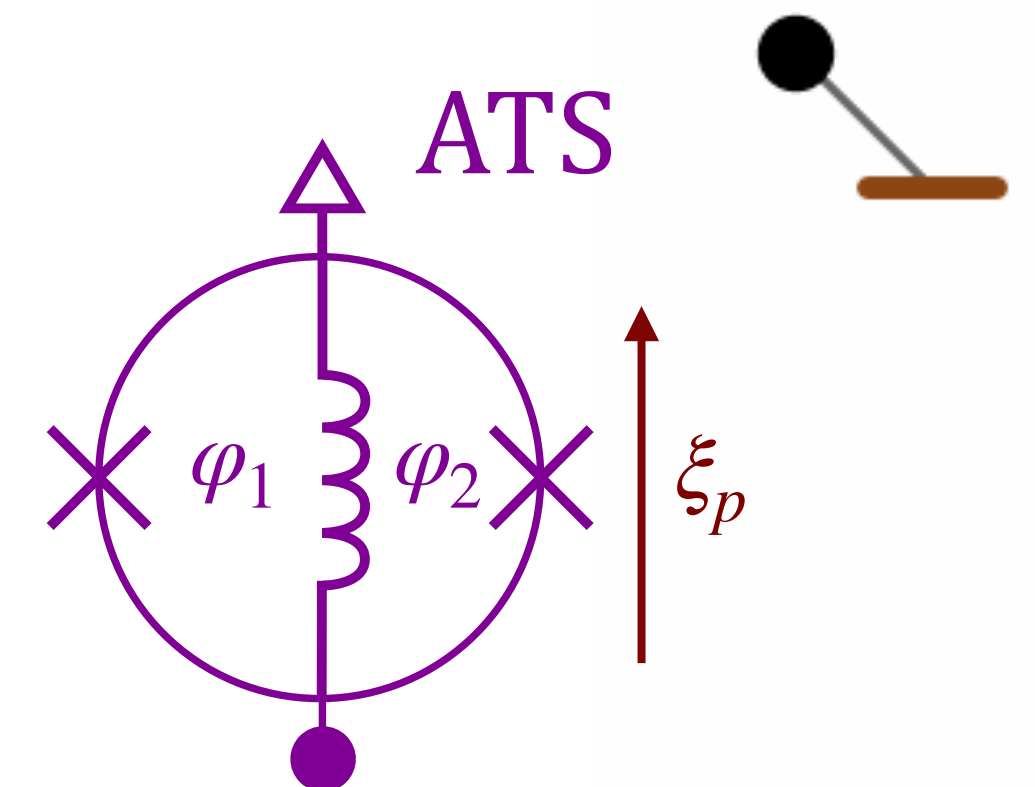
- Non-linearity provided by the **ATS**
(**A**symmetrically **T**hreaded **S**QUID)

[R. Lescanne et al. Nat Phys 2020 (ENS Paris)]

[U. Réglade et al., Nature 2024 (A&B, ENS Paris)]

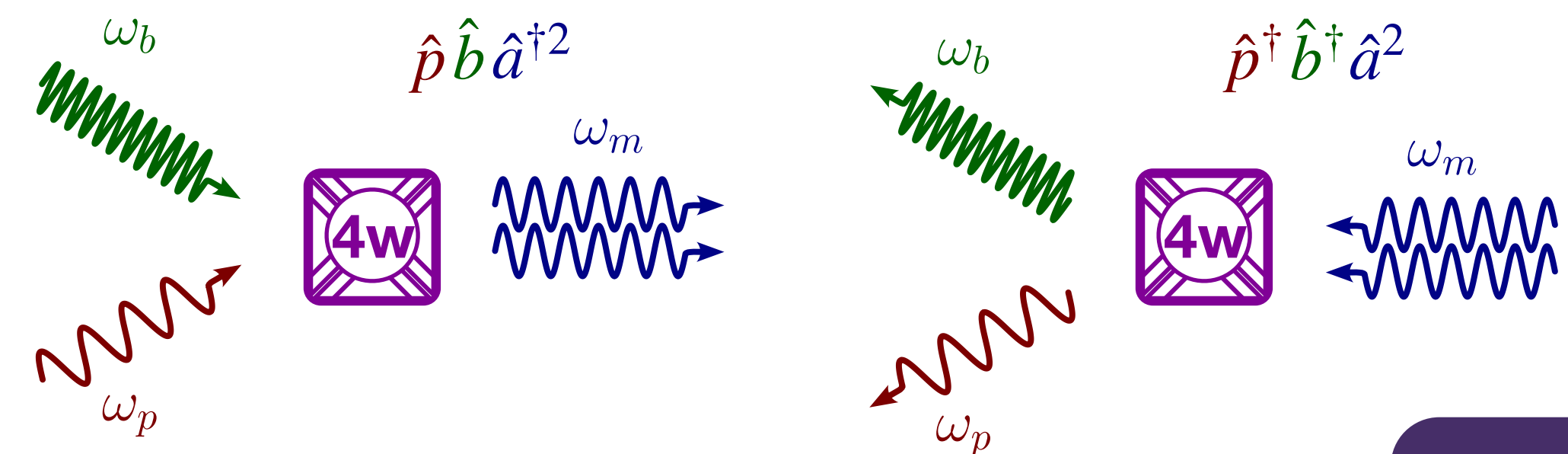
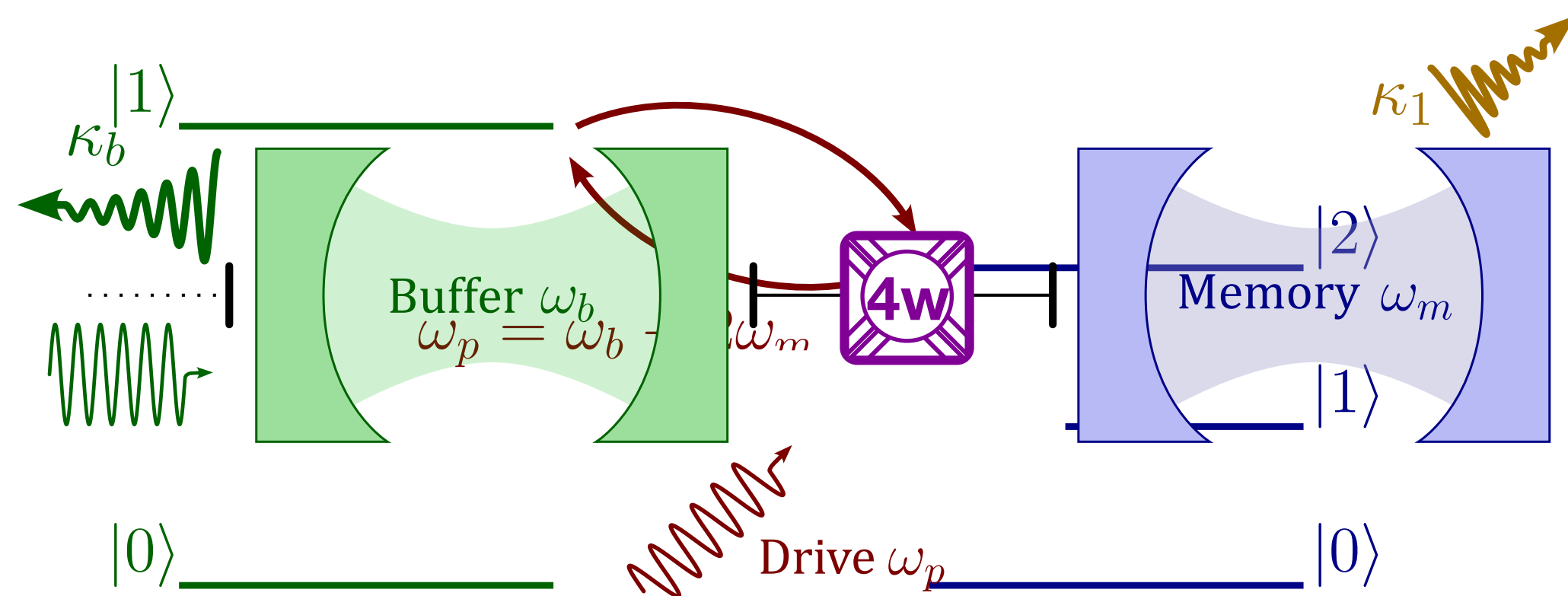
[H. Putterman et al., Nature 2025 (AWS)]

[R. Rousseau et al., arXiv 2025 (A&B, LKB)]

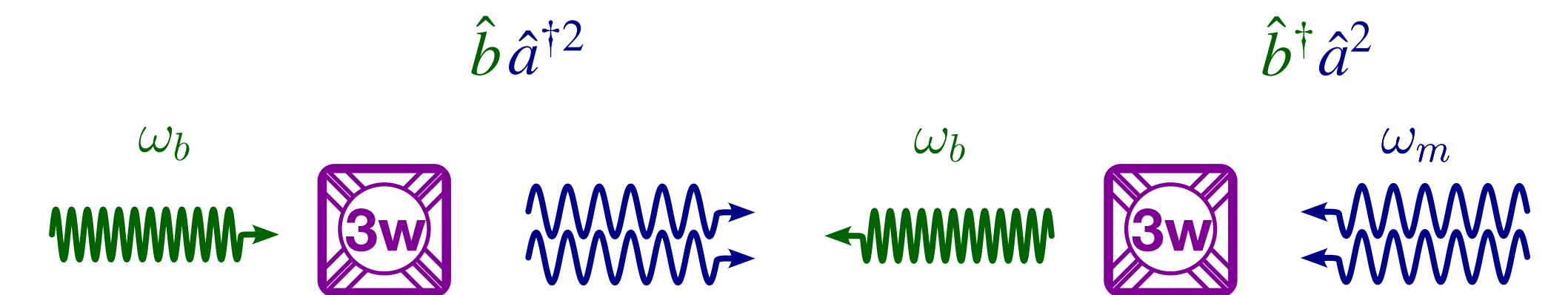
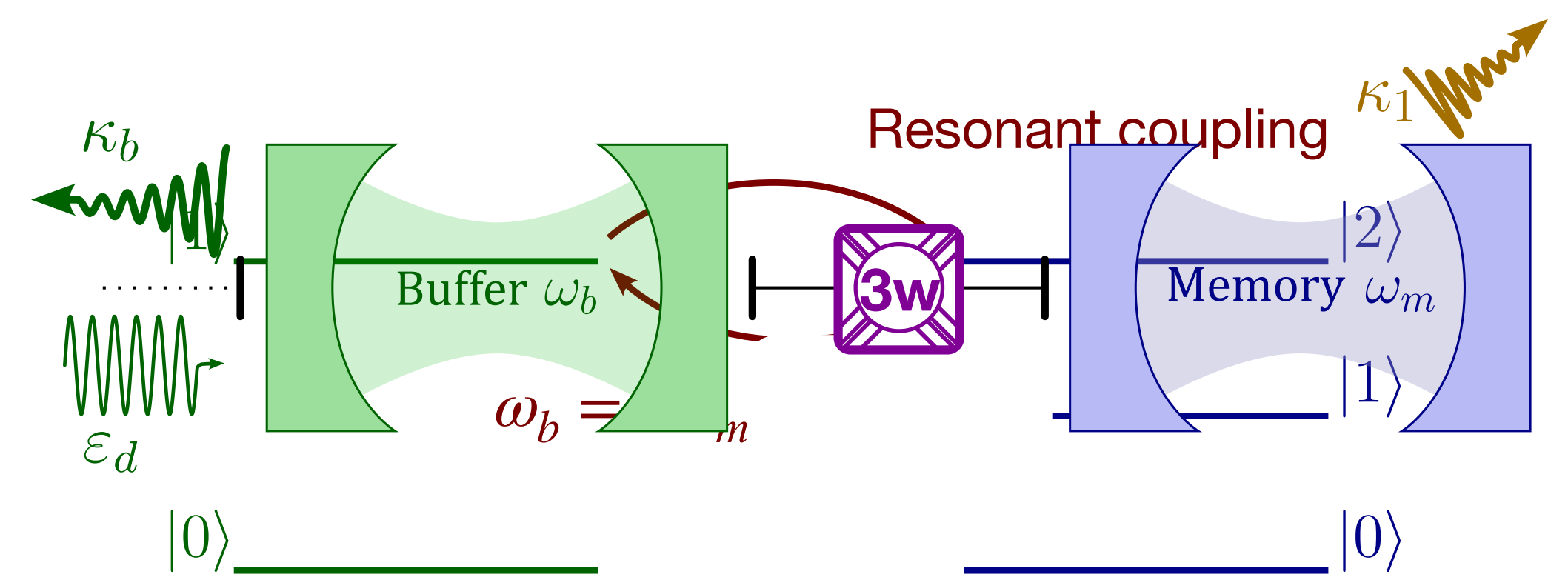


3 wave mixing for stronger coupling

4 wave mixing

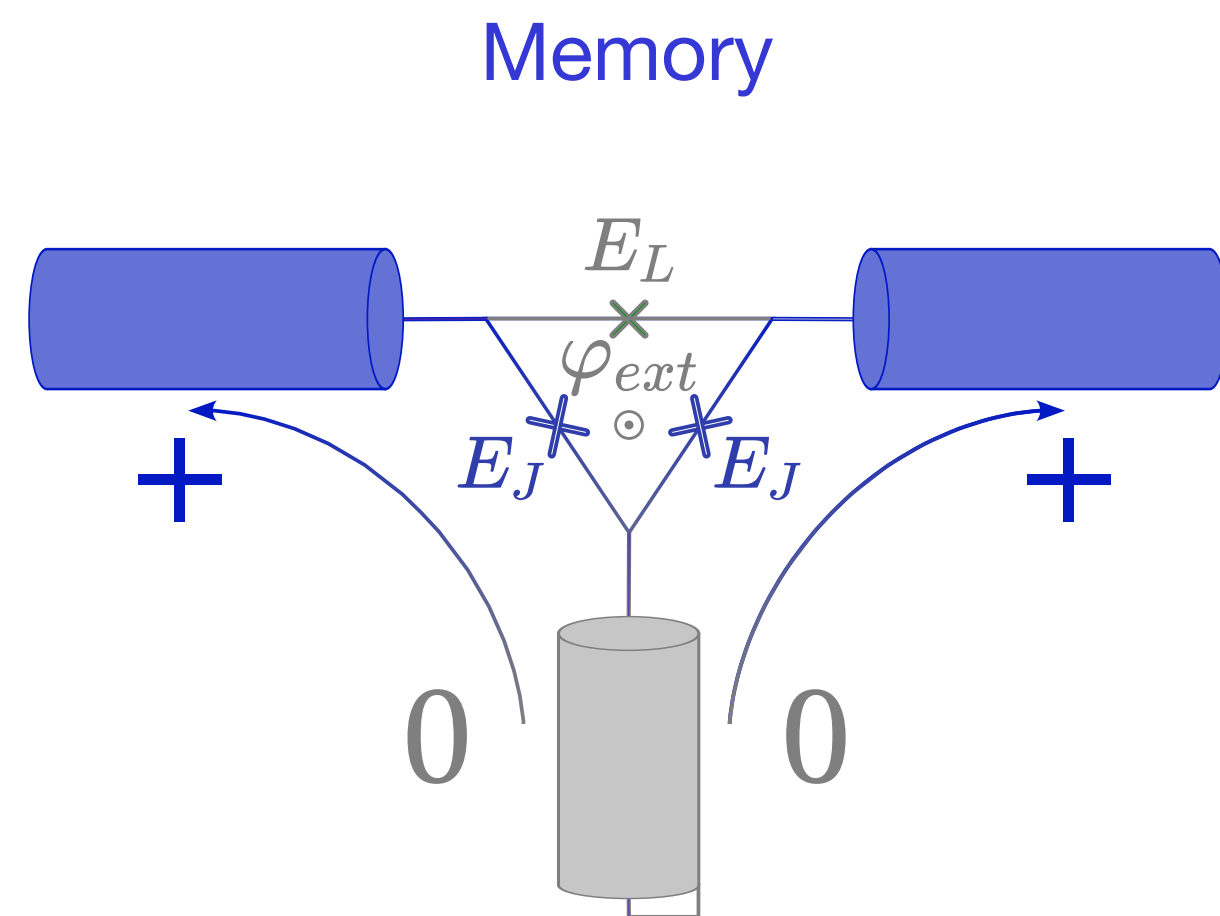
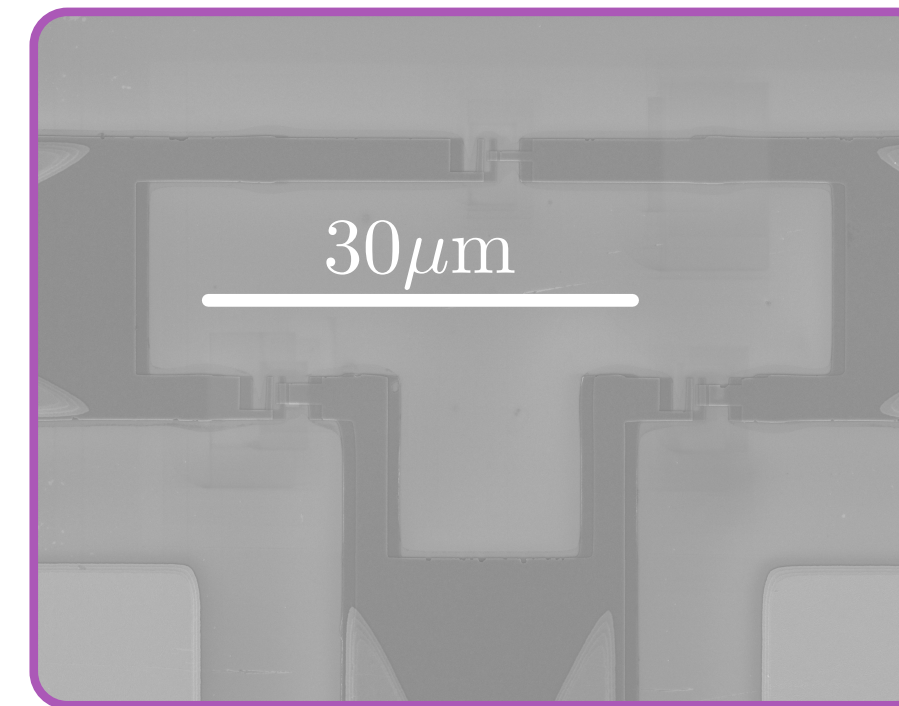
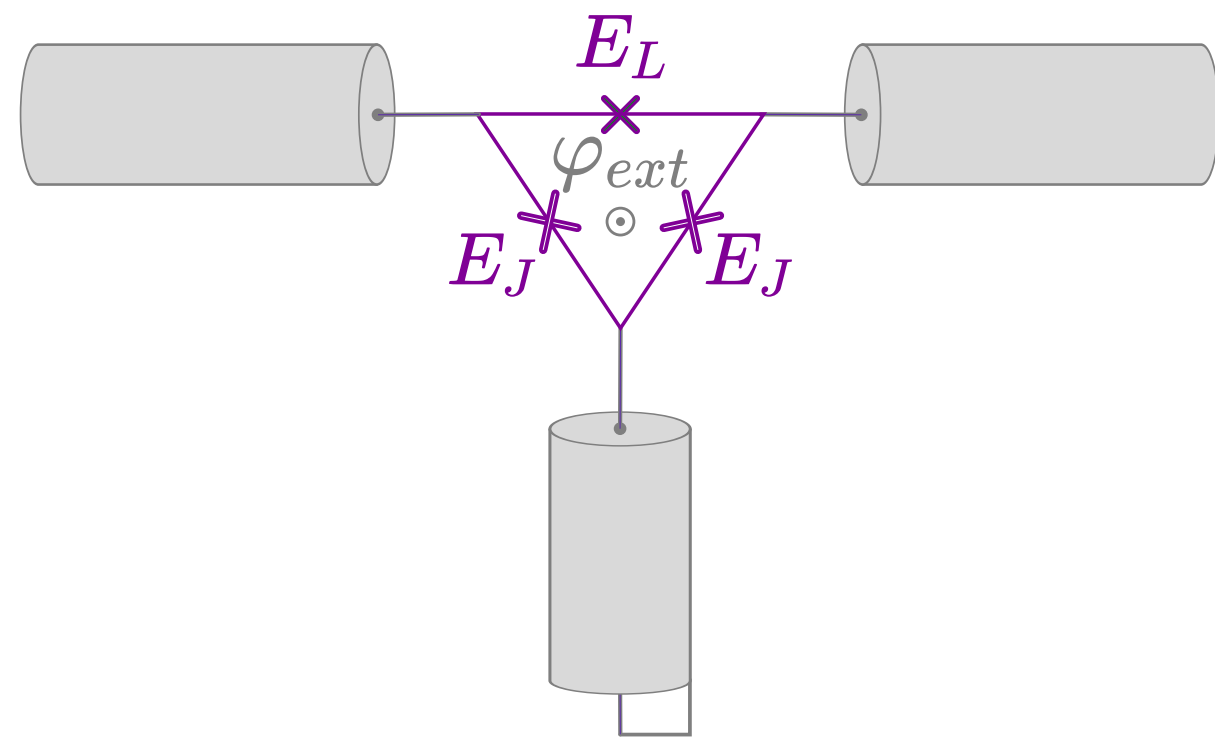


3 wave mixing

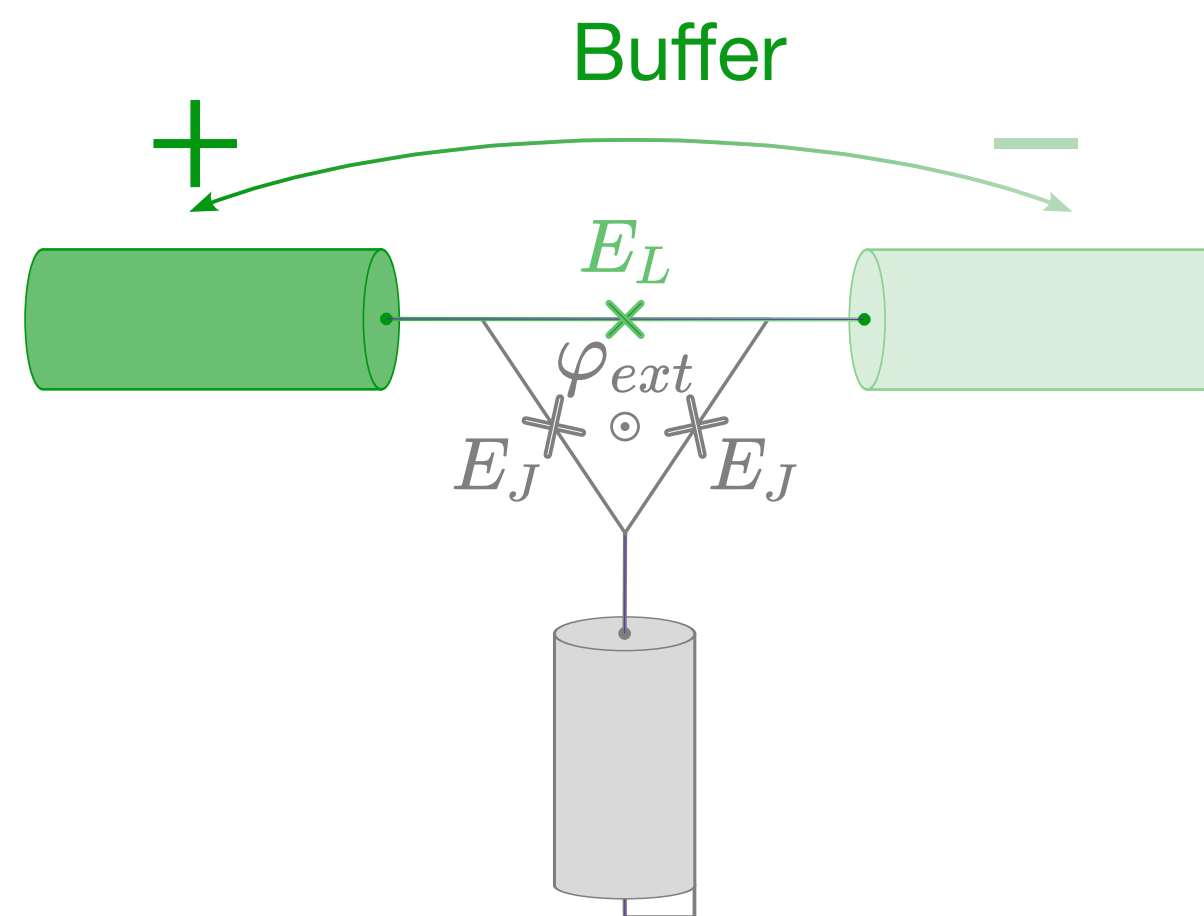


$$\frac{\kappa_2^{3rd}}{\kappa_2^{4th}} \propto \frac{1}{\xi_p^2} \gg 1$$

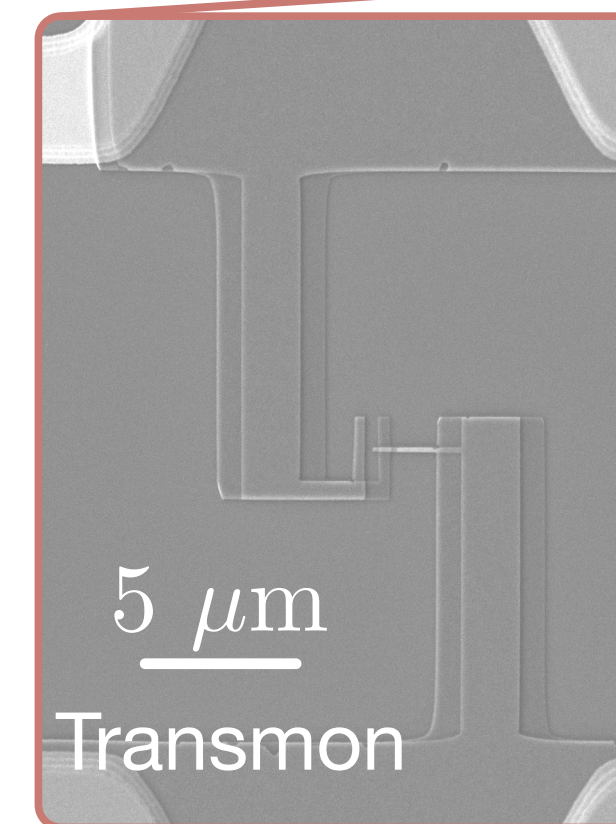
Design of the passive coupler



$$\omega_m = \omega_m(\varphi_{ext})$$



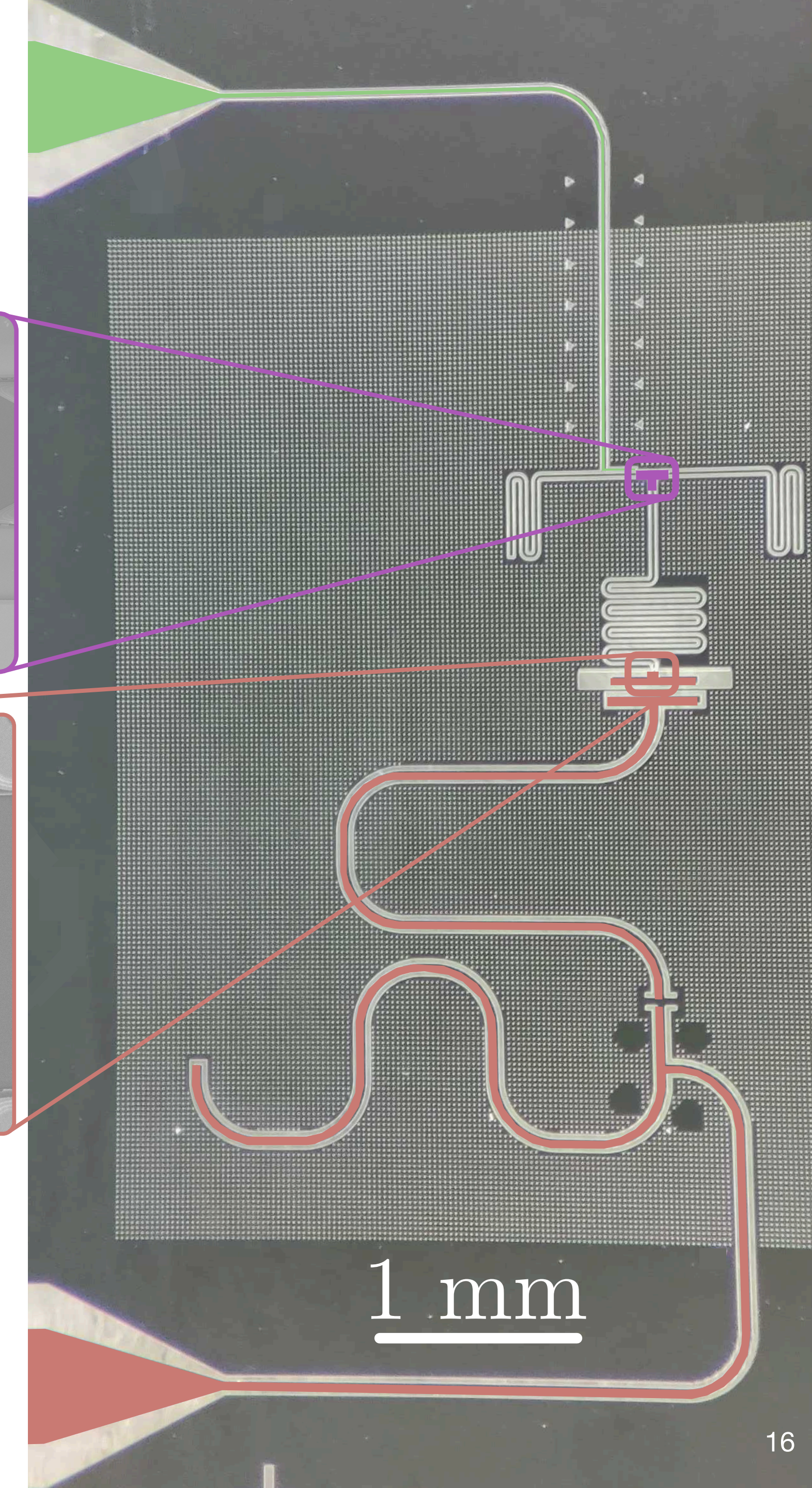
$$\omega_b = \omega_b(\varphi_{ext})$$



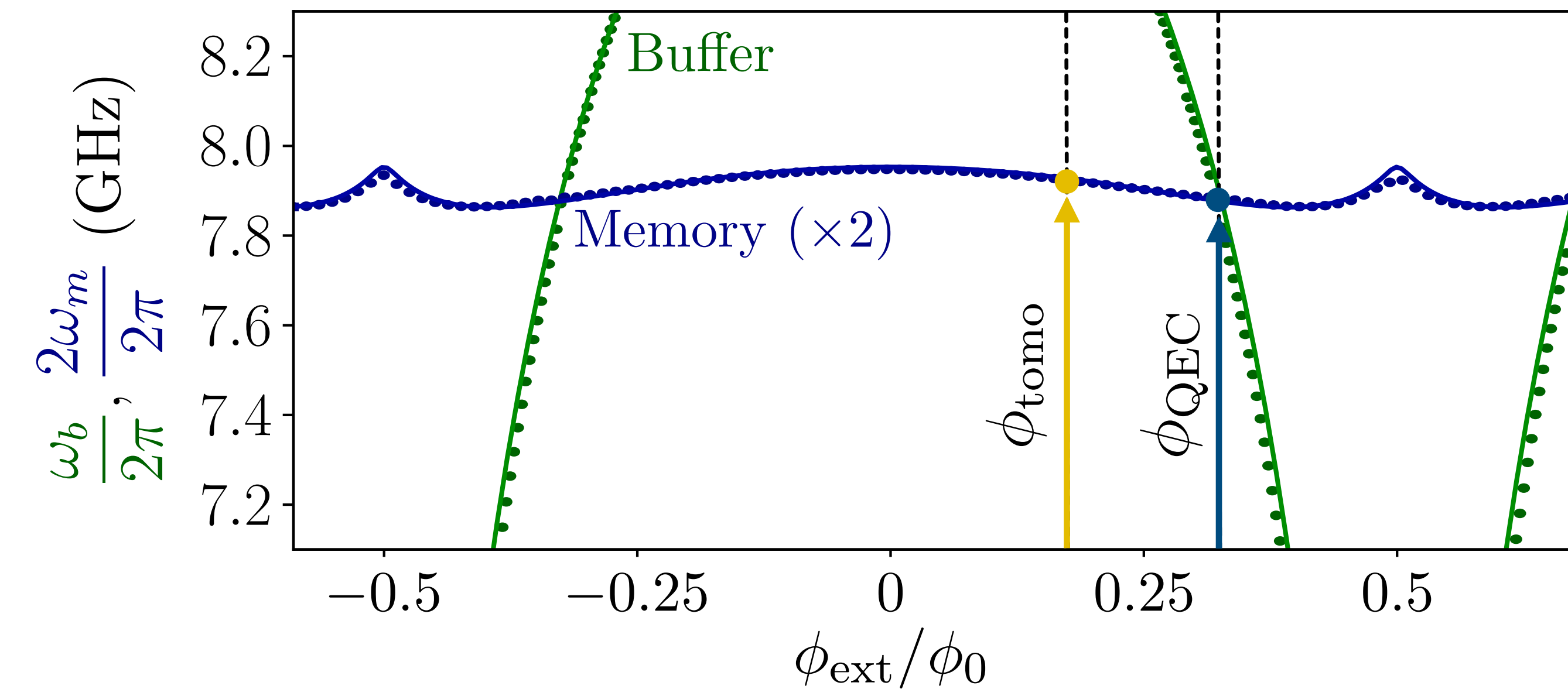
Flux / Buffer drive

Tomography

Coupler



Flux dependence



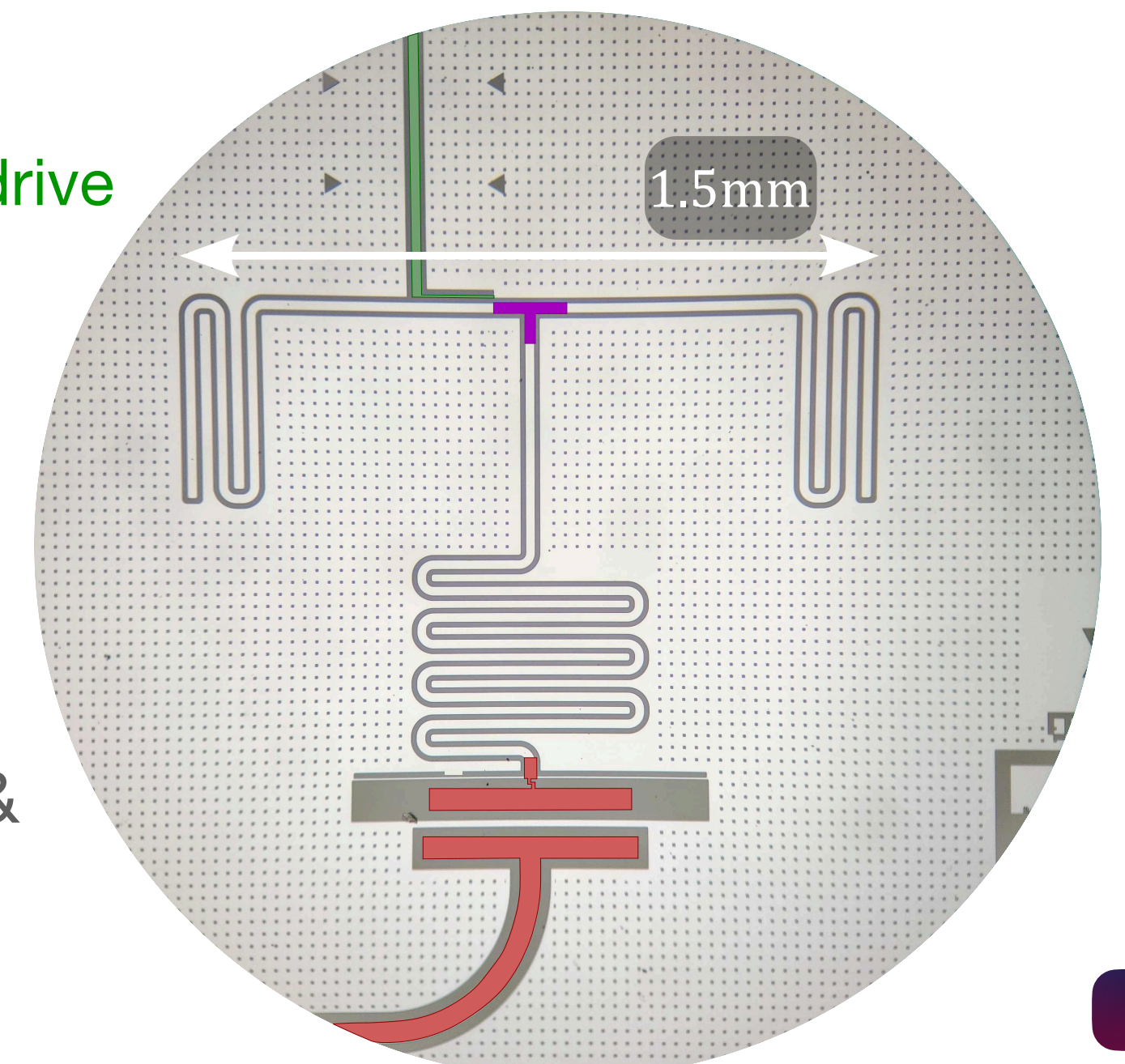
Working flux: $\omega_b = 2\omega_m$, 2 photon dissipation on
Wigner measurement



Tomography flux: $\omega_b \neq 2\omega_m$, 2 photon dissipation off
Wigner measurement

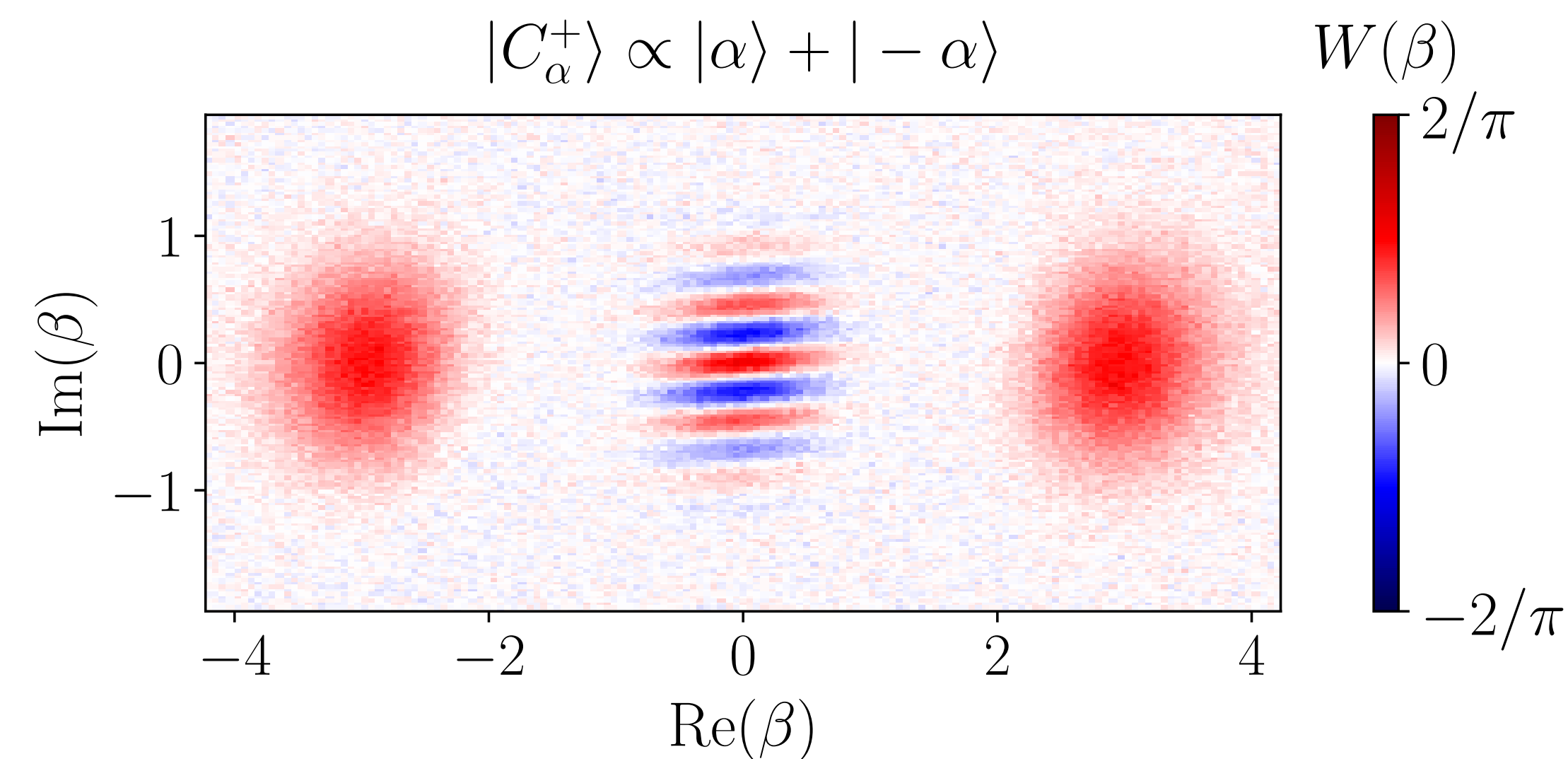
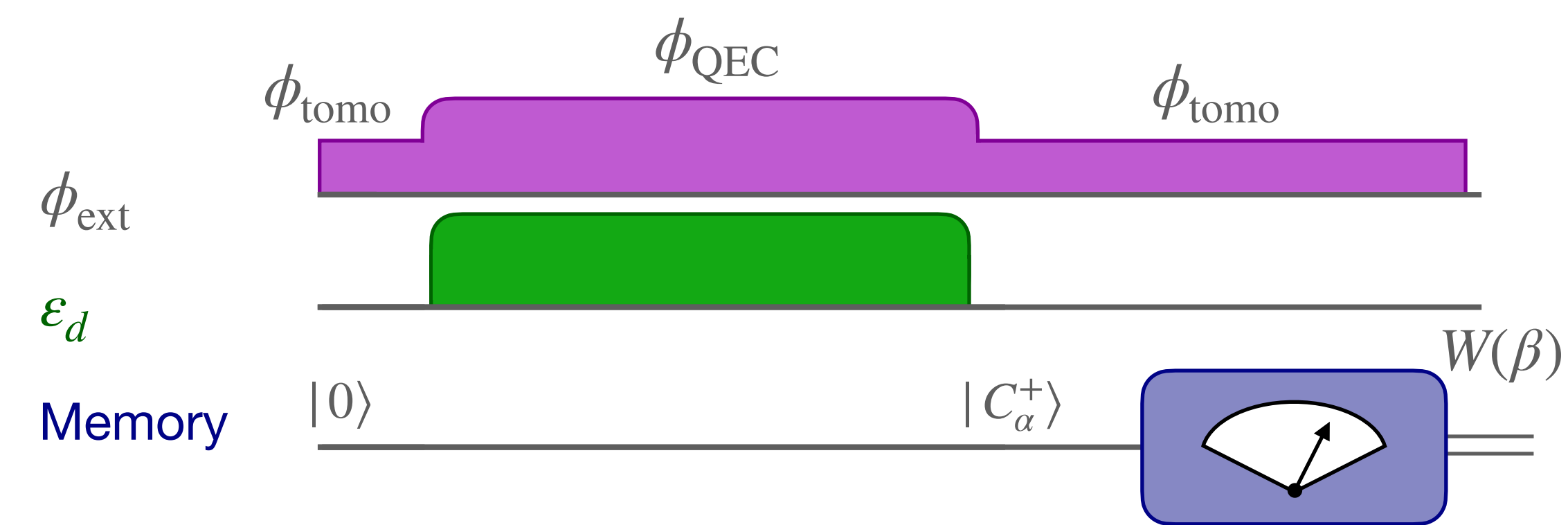
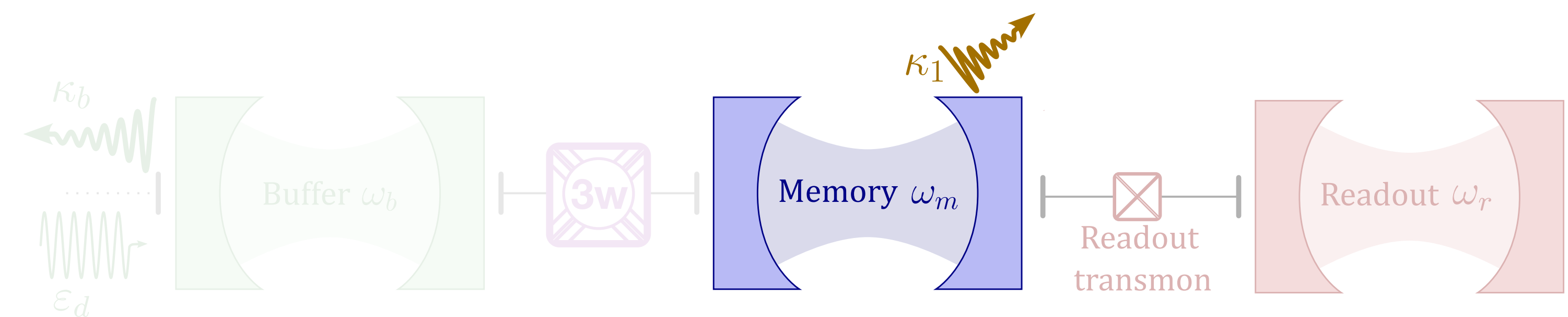


■ Flux / Buffer drive

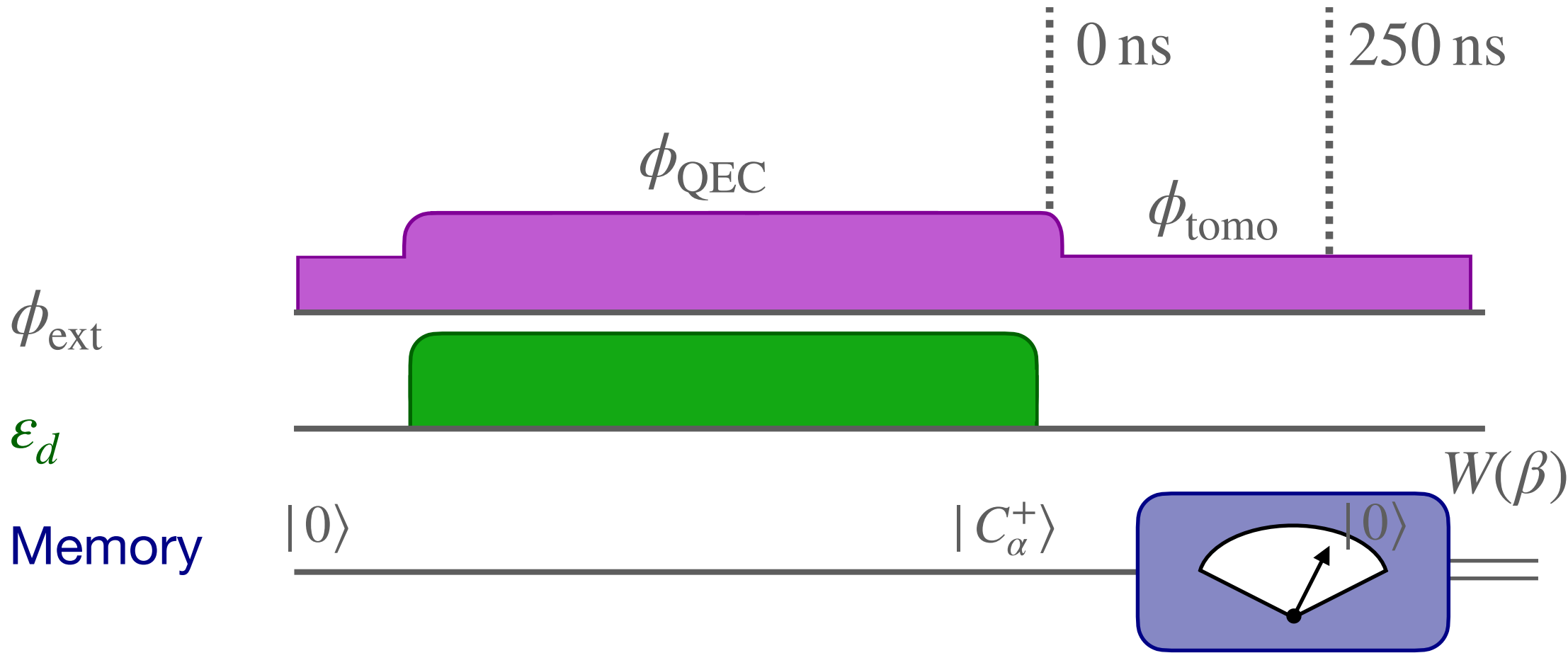


→ Switch the flux to turn on &
off the 2 photon dissipation!

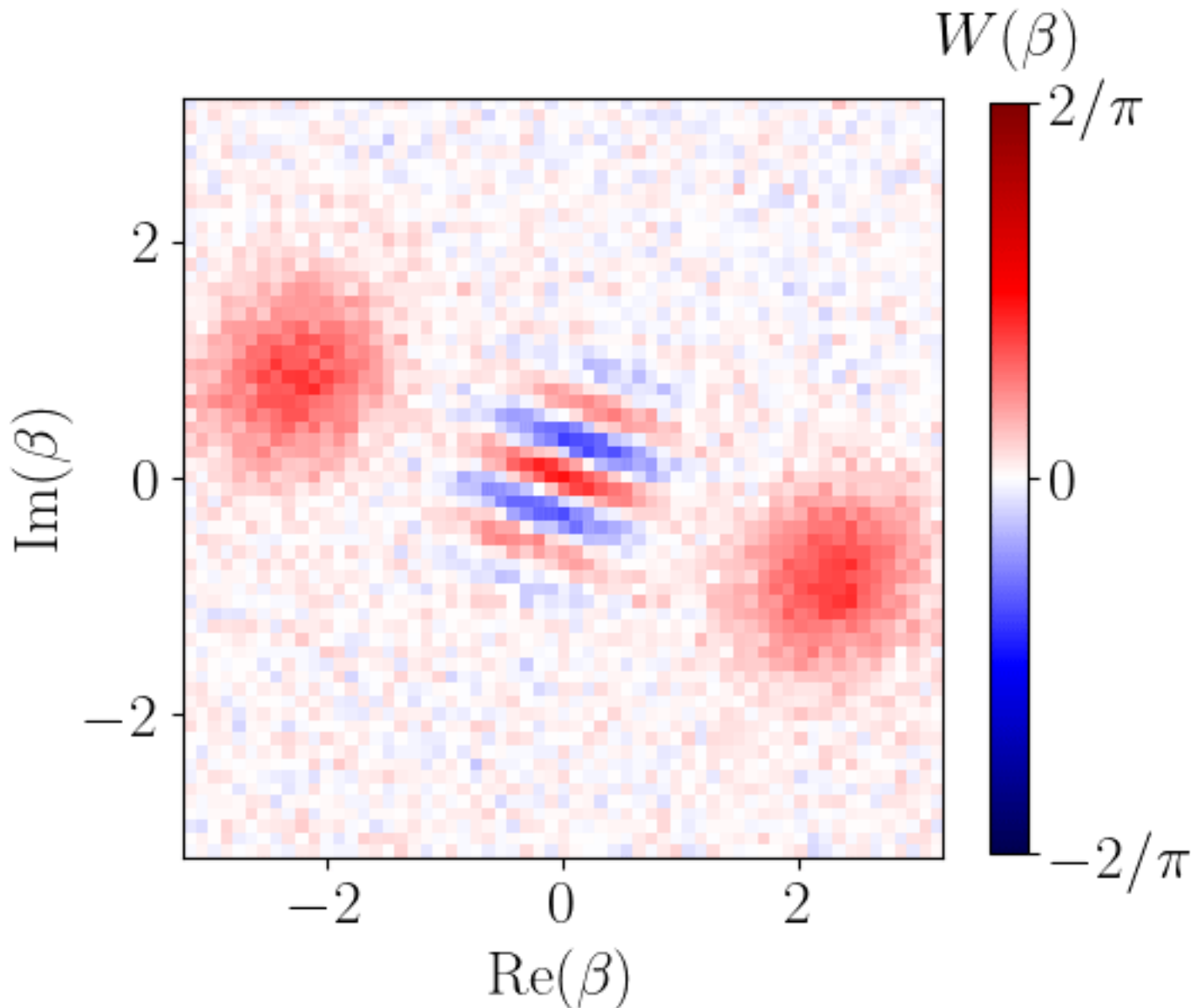
Cat states generation



Estimation of κ_2



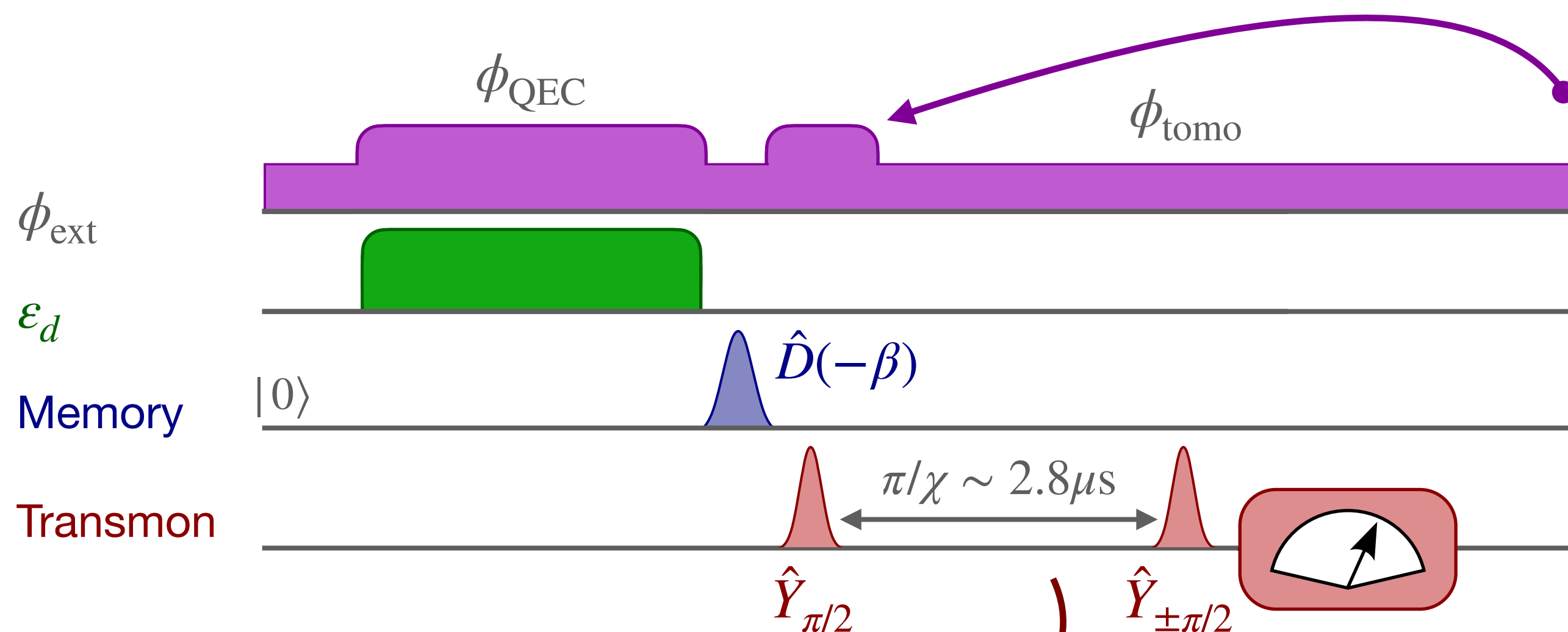
$\kappa_2/\kappa_1 \sim 150$



$\kappa_2/2\pi = 2.16\text{MHz}$

$\kappa_1^{-1} = 11\ \mu\text{s}$

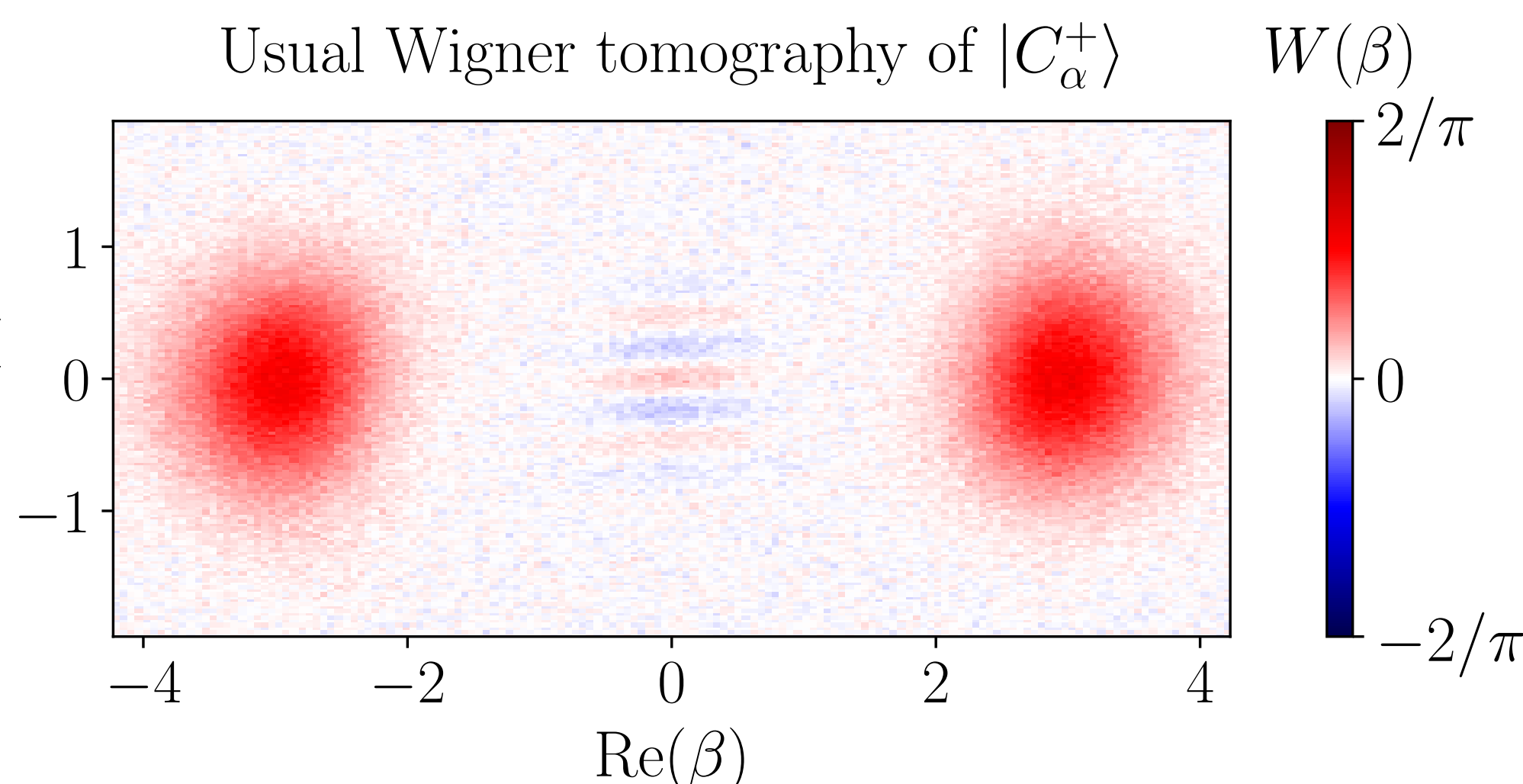
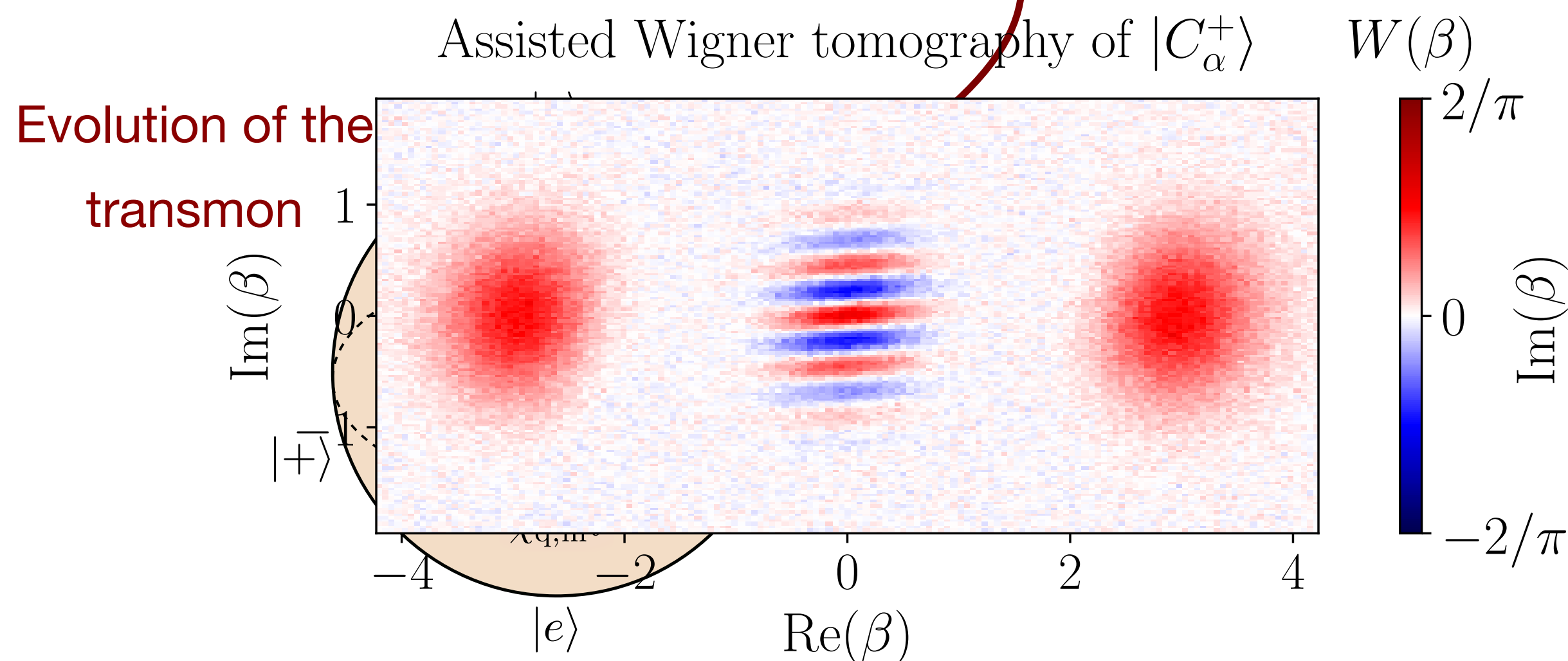
Wigner tomography assisted by 2-photon dissipation



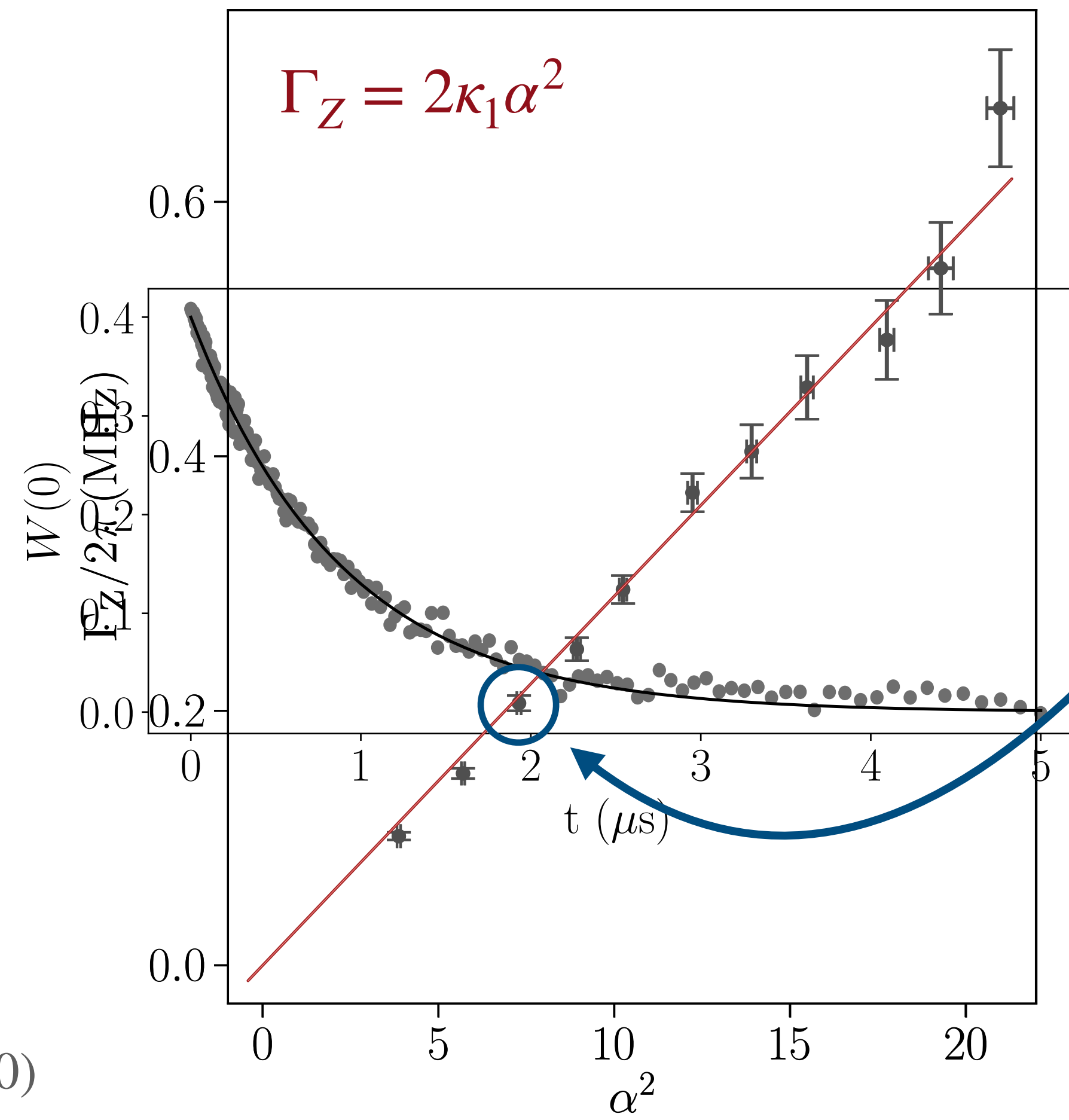
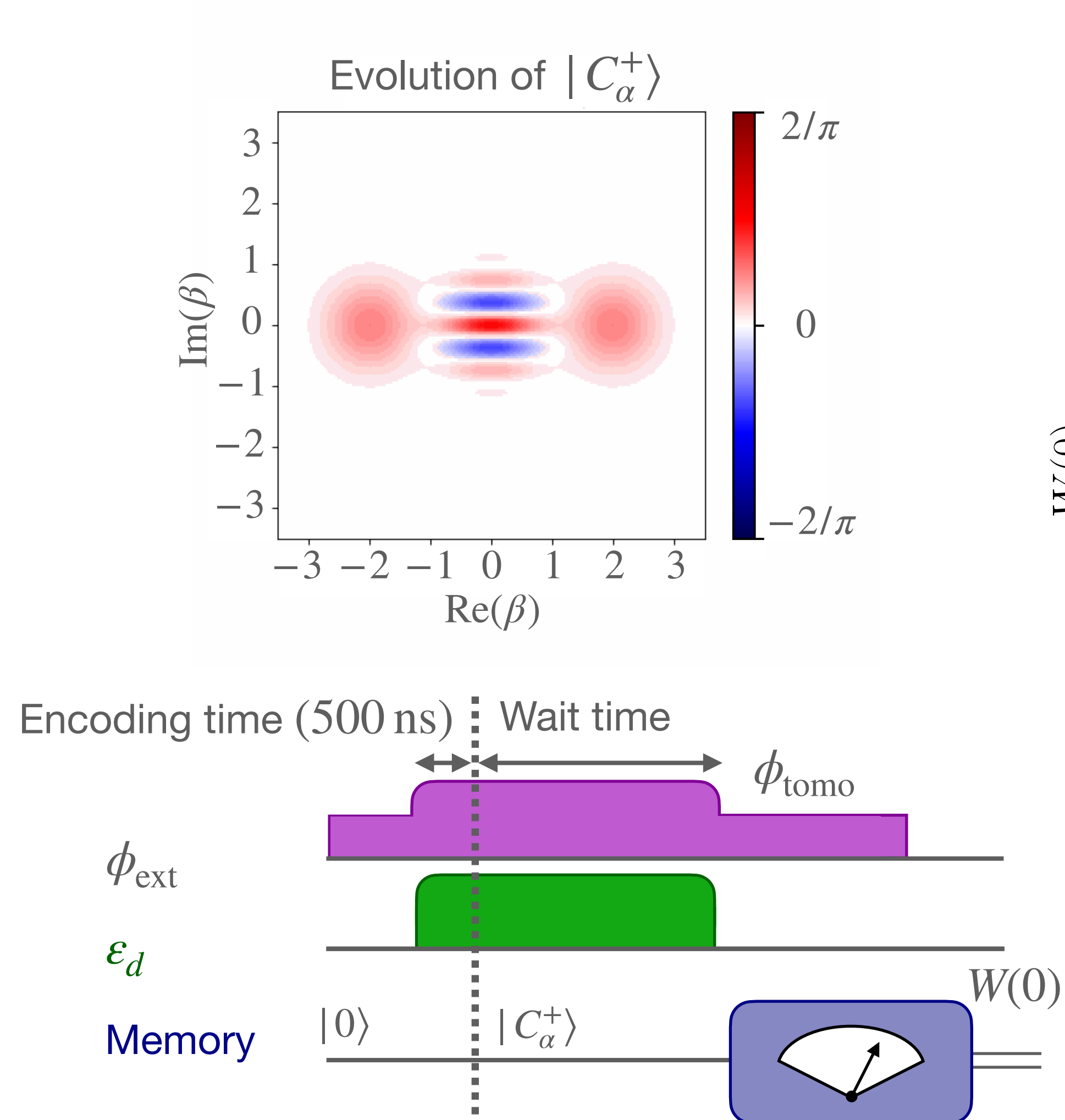
Remove pairs of photons for 300 ns

Errors of standard Wigner tomography

- Loss of photons during waiting time π/χ
- $\hat{Y}_{\pi/2}$ ineffective for $\bar{n} \gg 1$
- For $\bar{n} \gg 1$, $\hat{Y}_{\pi/2}$ may ionize the transmon

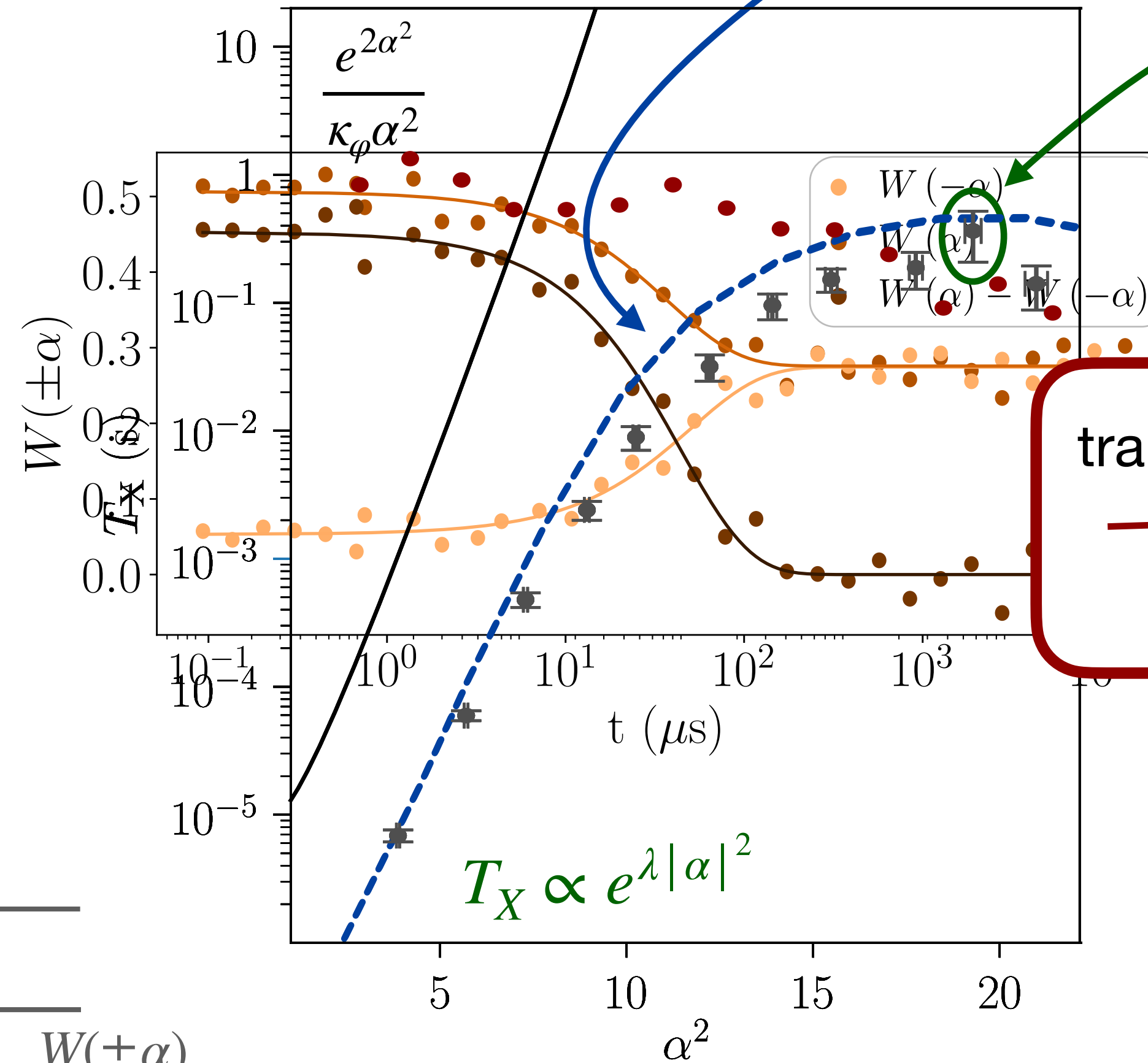
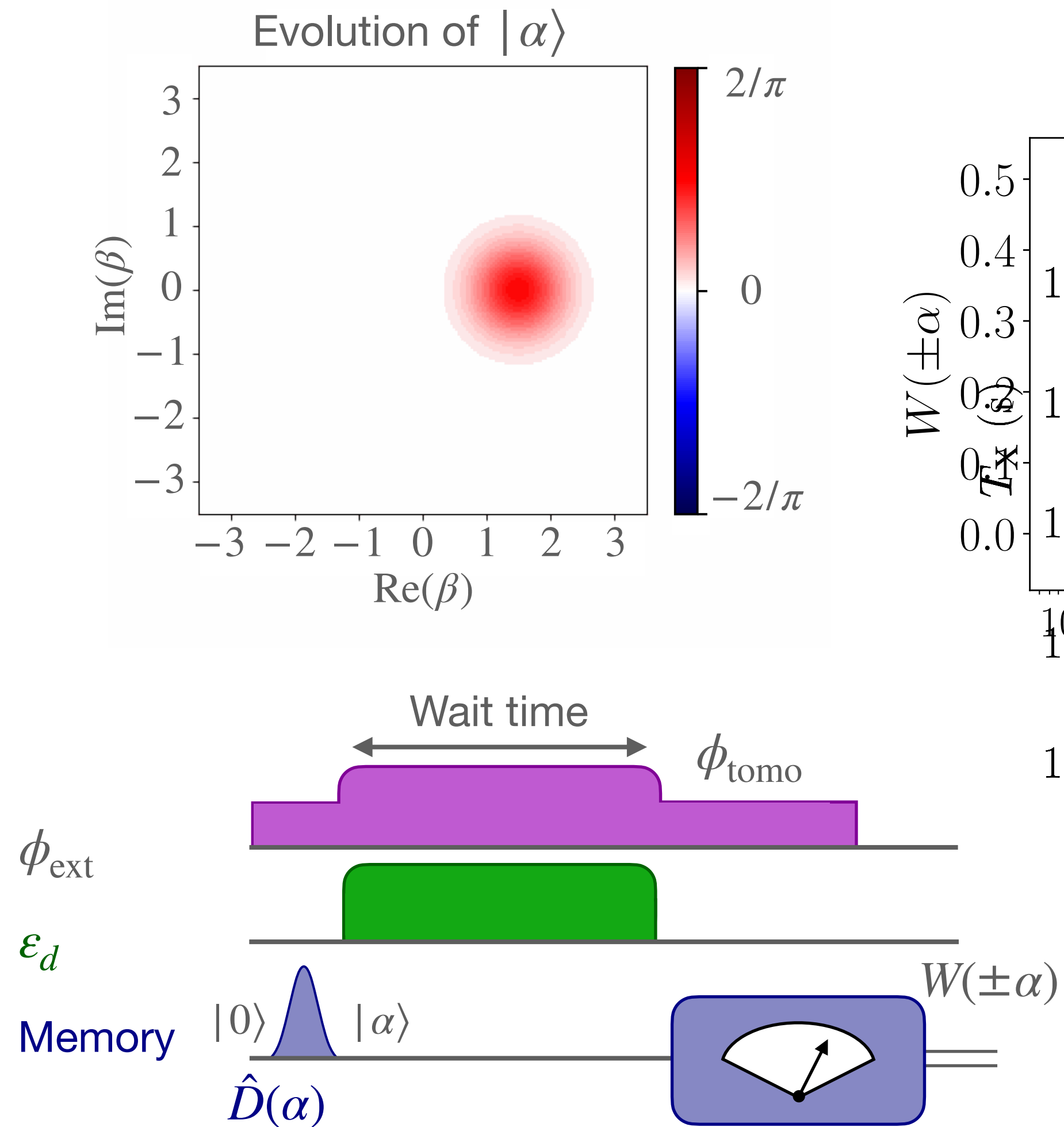


Γ_Z measurement



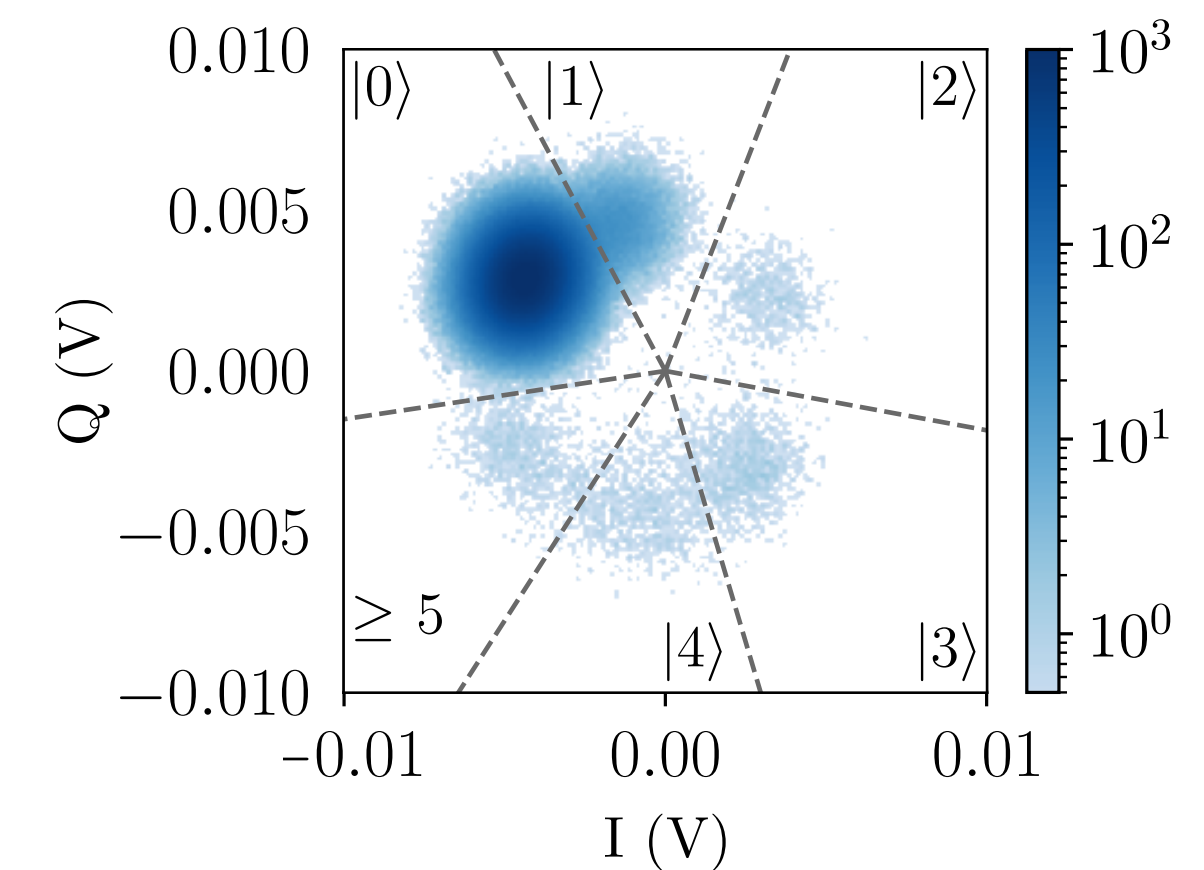
T_X measurement

breakdown of adiabatic
elimination of buffer, $8g_2\alpha > \kappa_b$

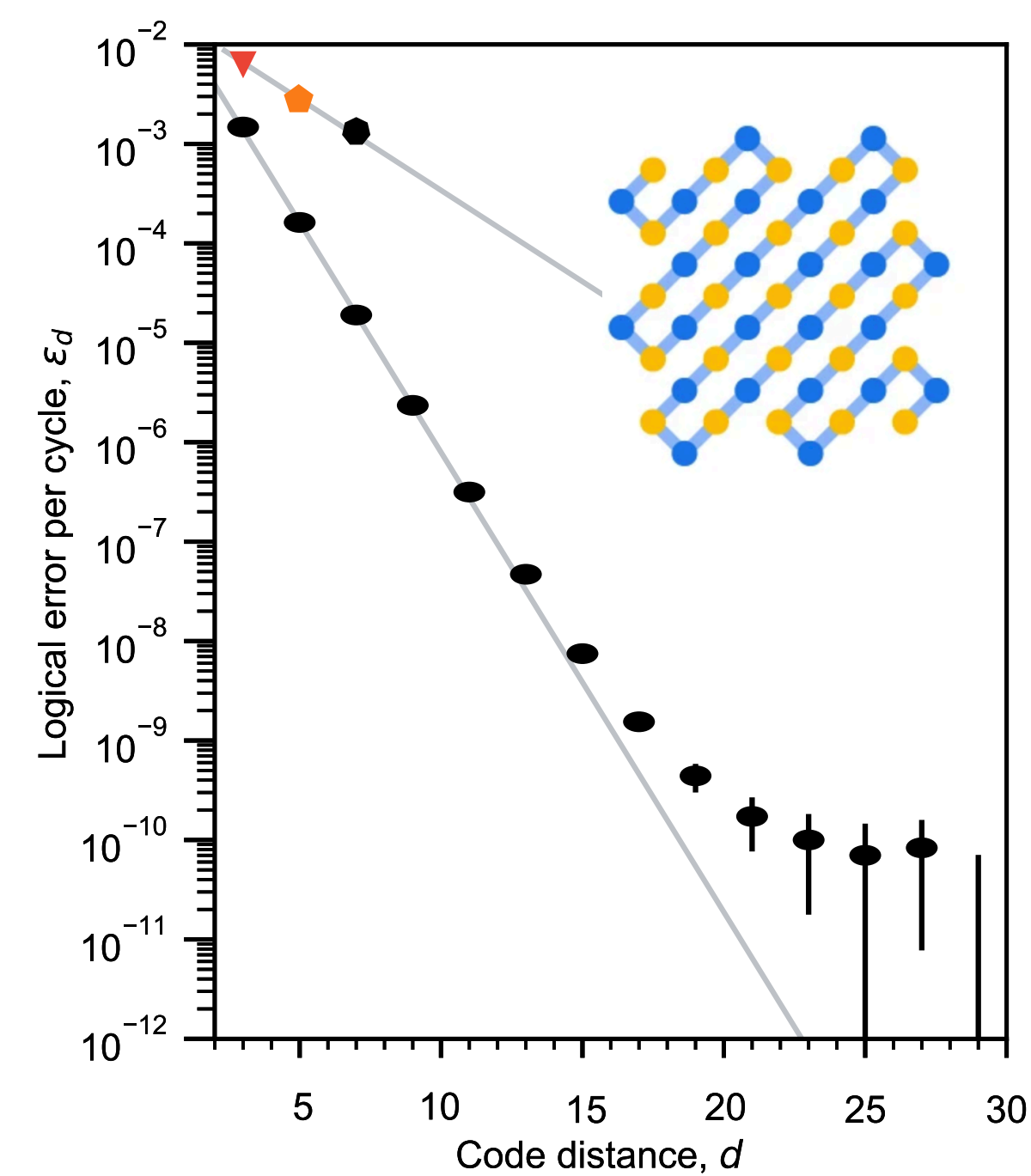


0.3 s

transmon higher states
~~dispersive regime~~
 $\Delta\omega_m \sim \kappa_2\alpha^2$

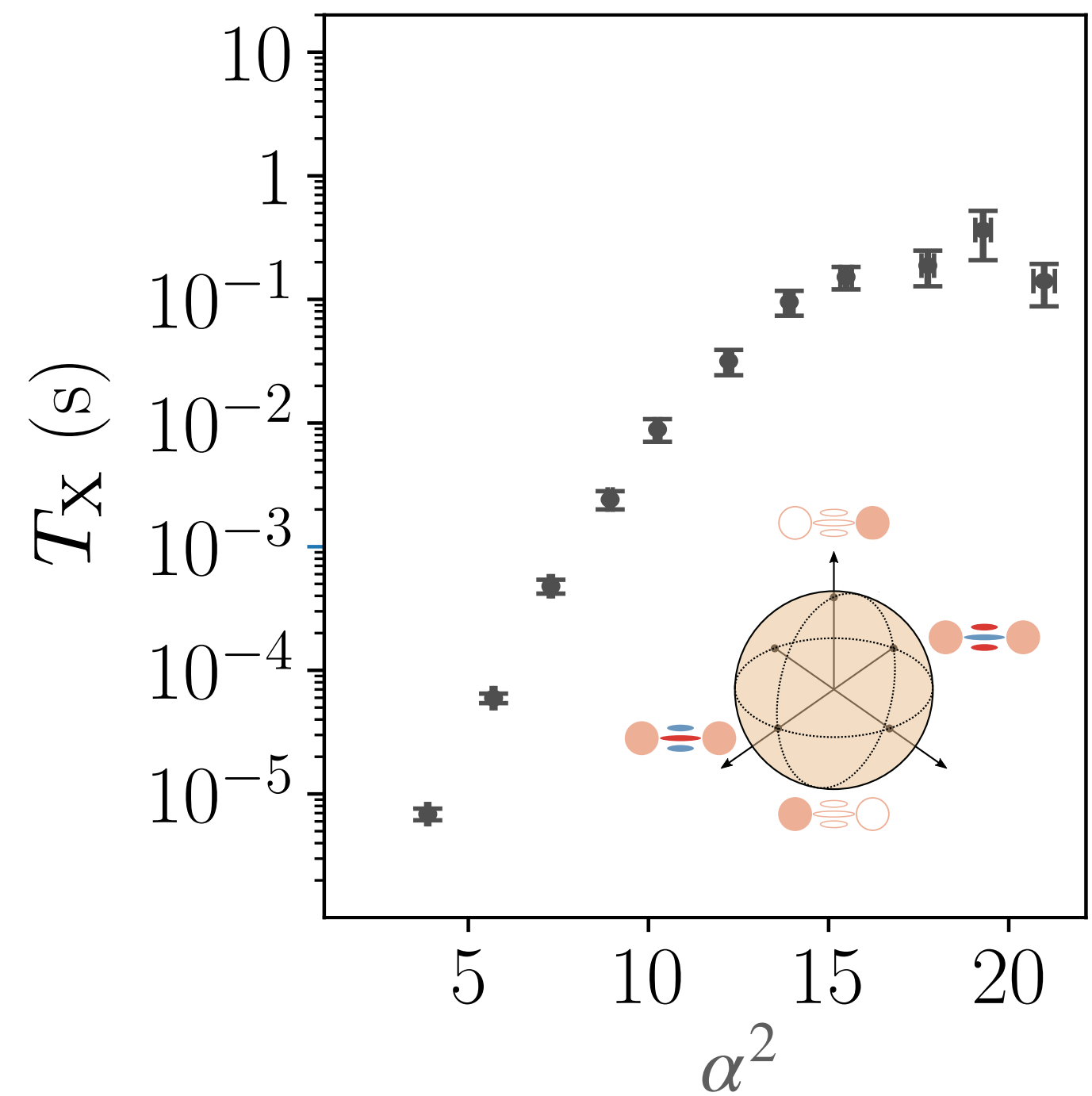


State-of-the-art on bit-flip correction



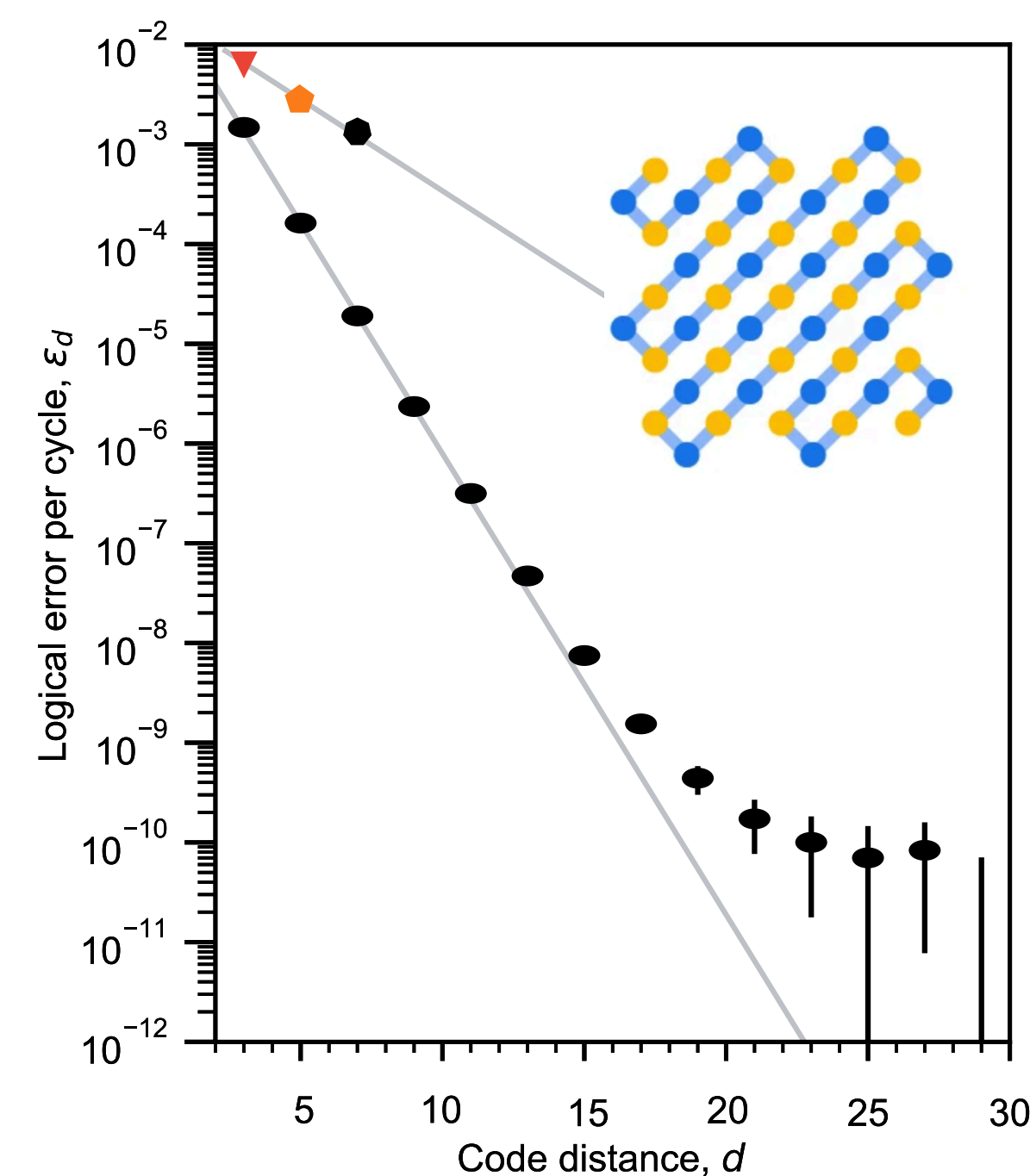
[Google Quantum AI, Nature 2024]

With the autoparametric cat
and a transmon



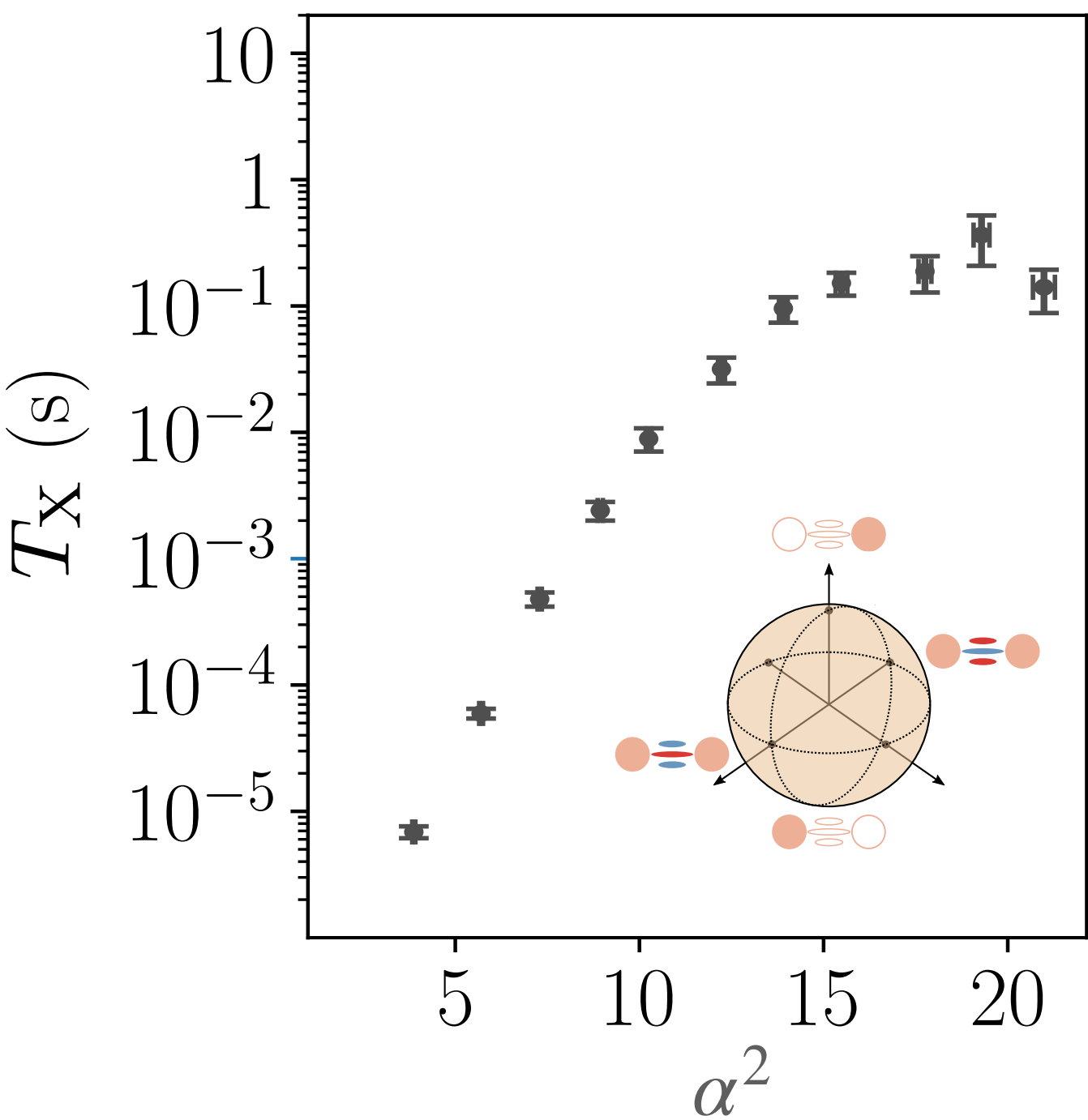
[Marquet et al., PRX (2024)]

State-of-the-art on bit-flip correction



[Google Quantum AI, Nature 2024]

With the autoparametric cat
and a transmon

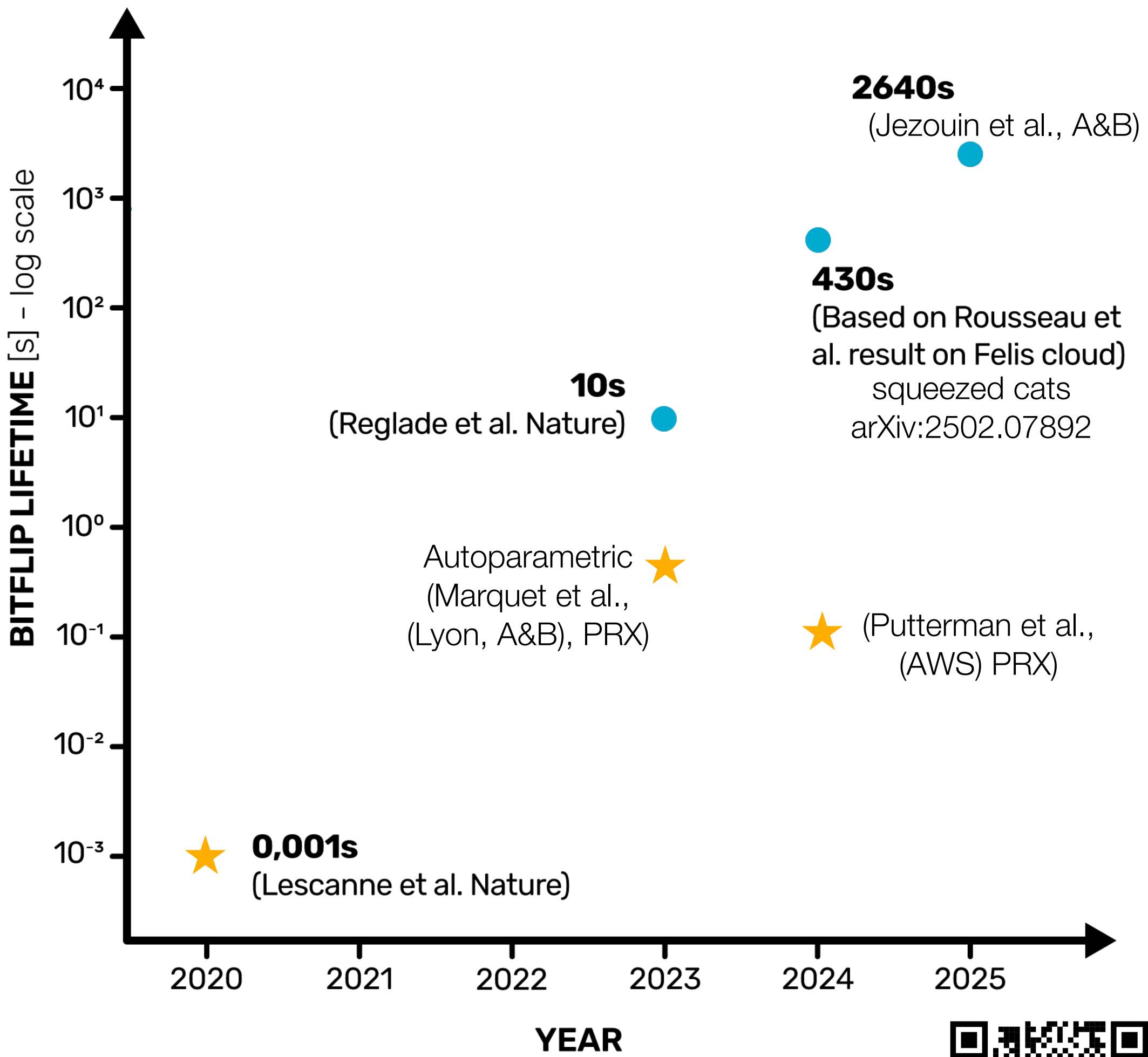


[Marquet et al., PRX (2024)]



★ transmon for readout ● NO transmon

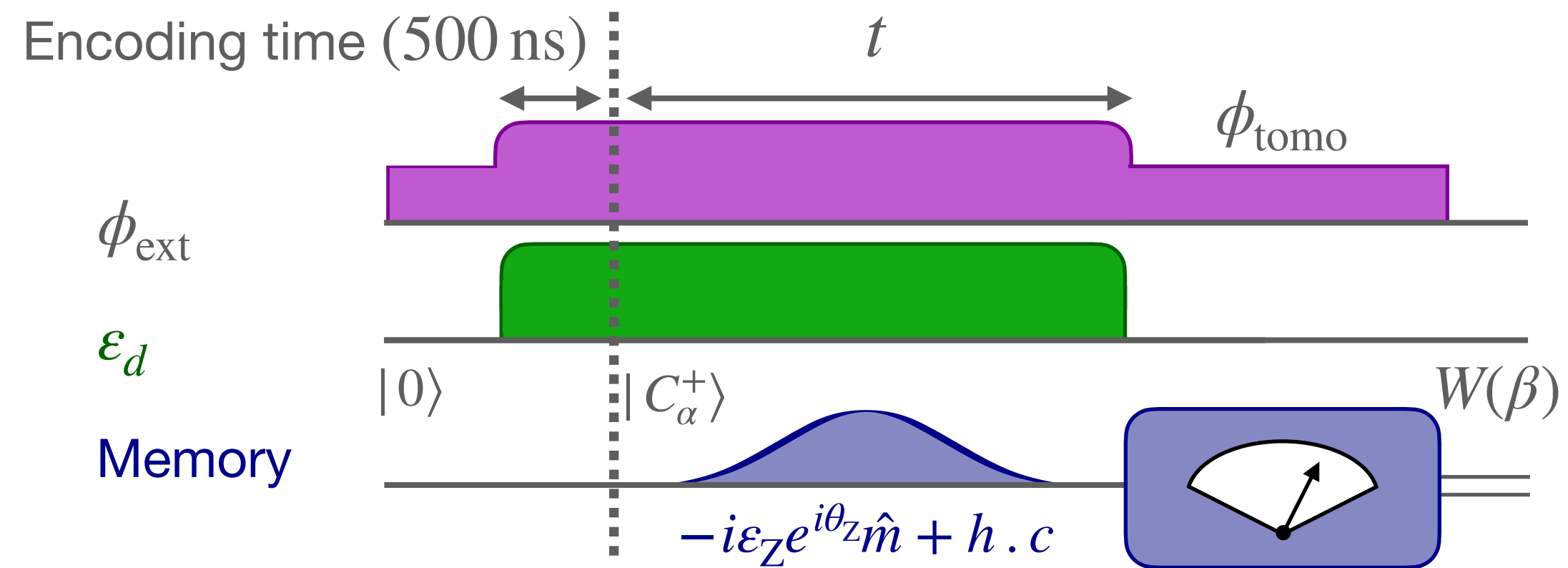
Readout with transmon is a limitation



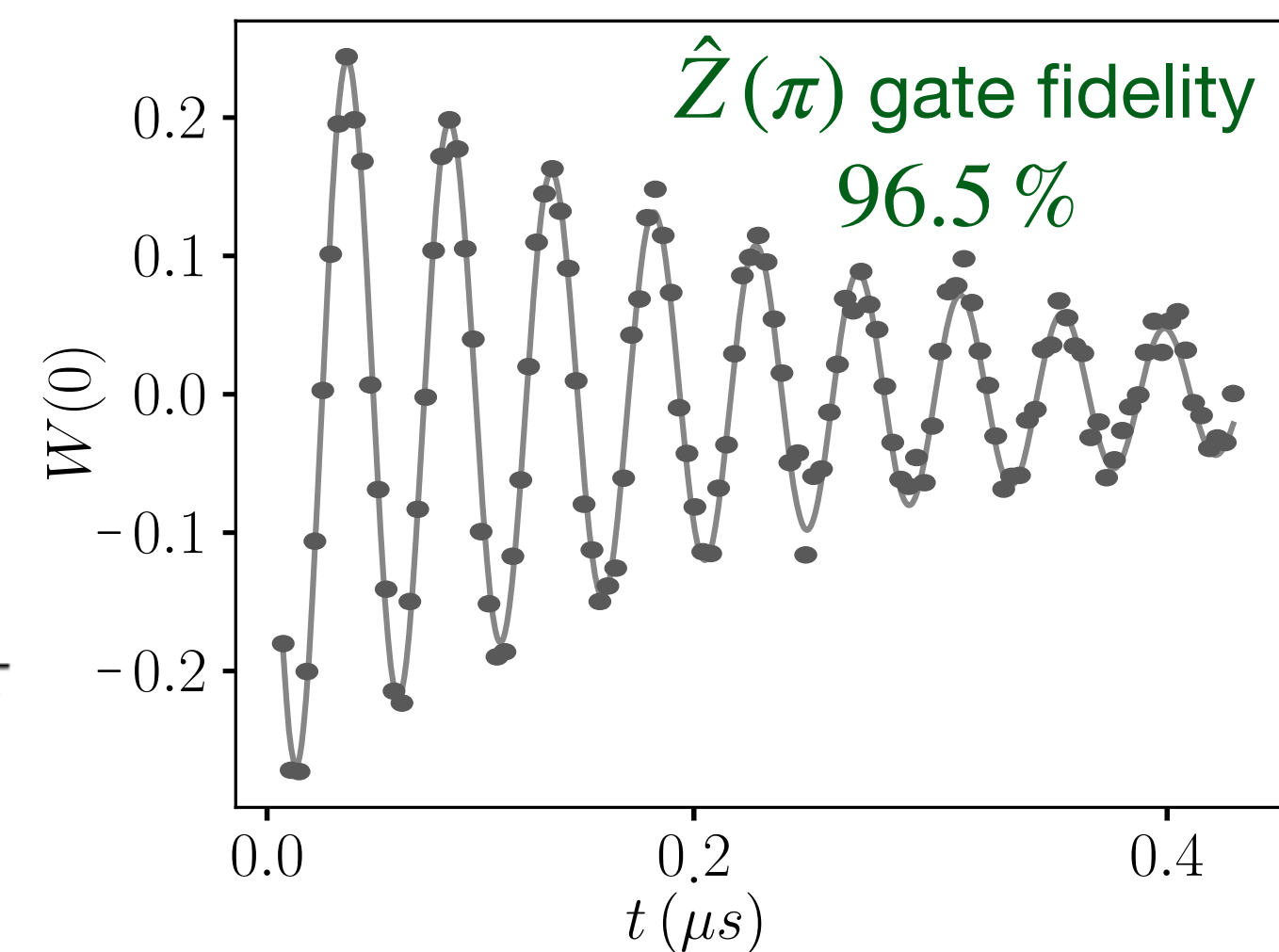
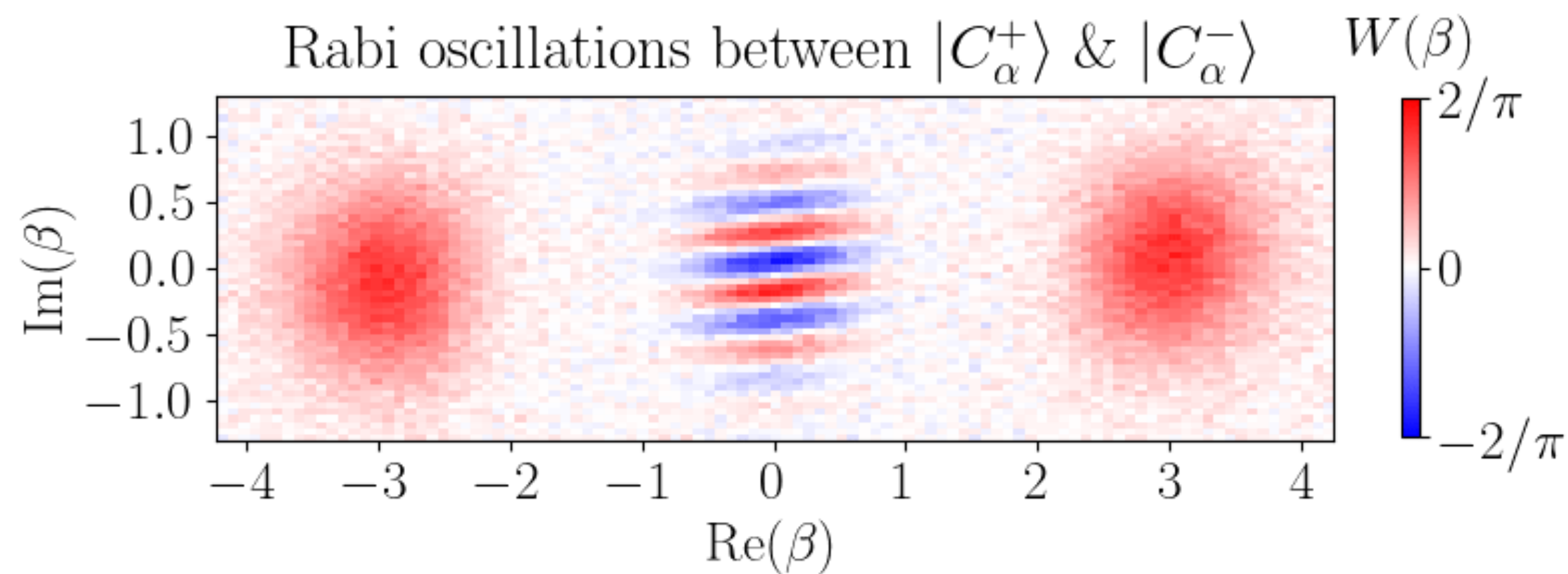
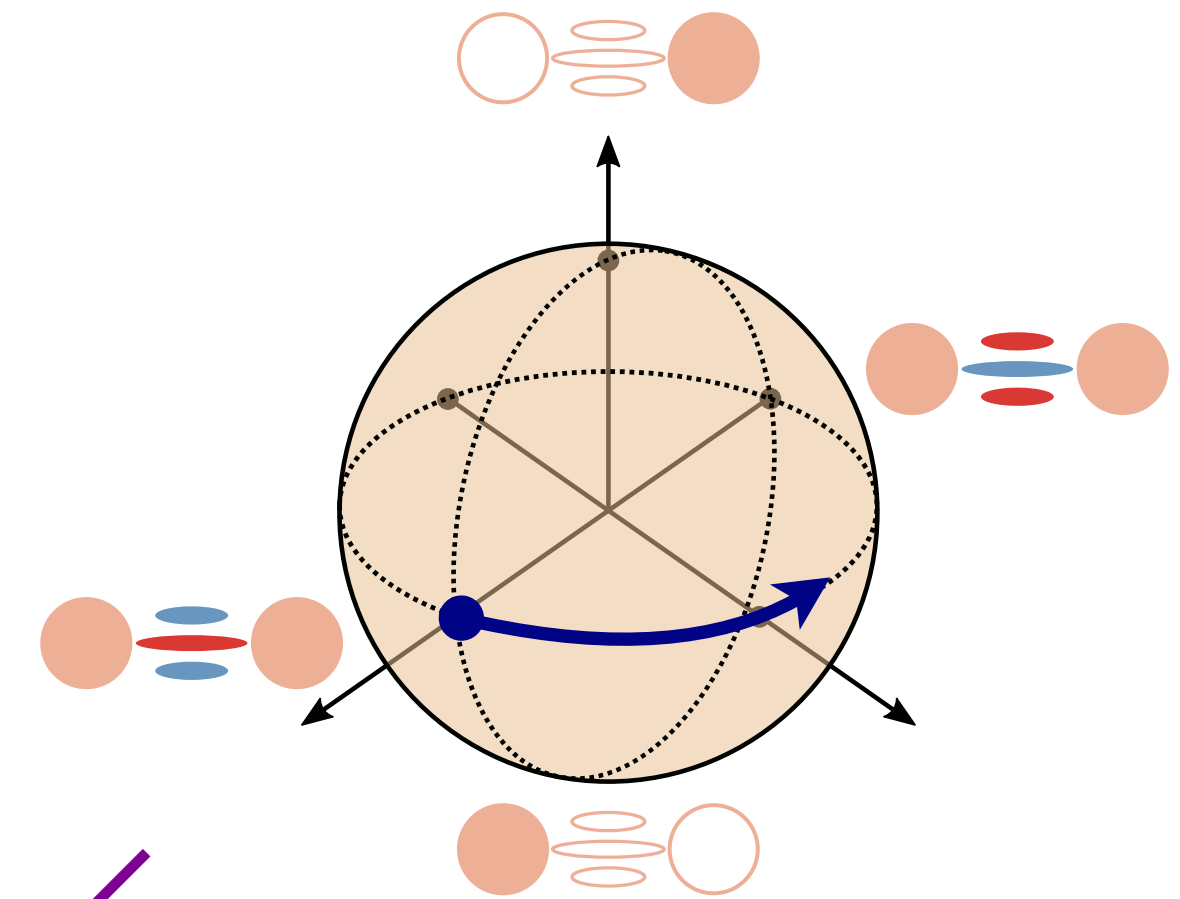
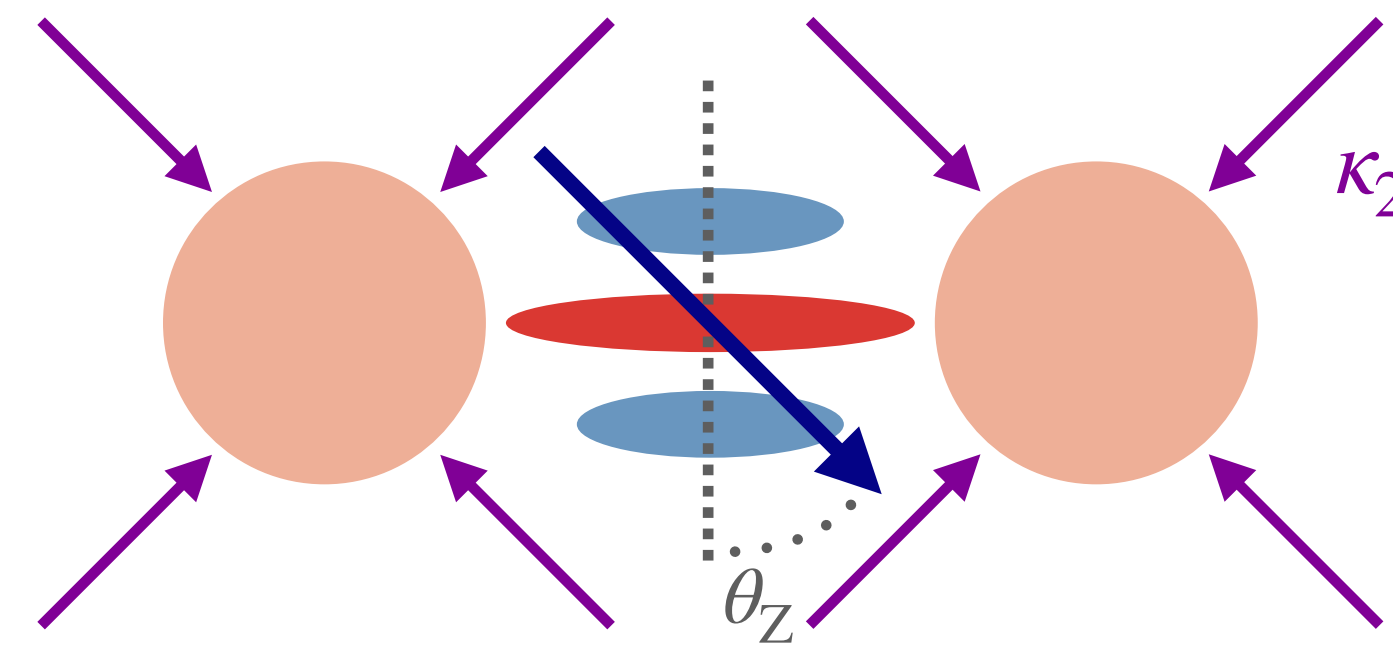
[Jezouin 2025]



Zeno $\hat{Z}(\theta)$ gate



Effect of the memory drive:

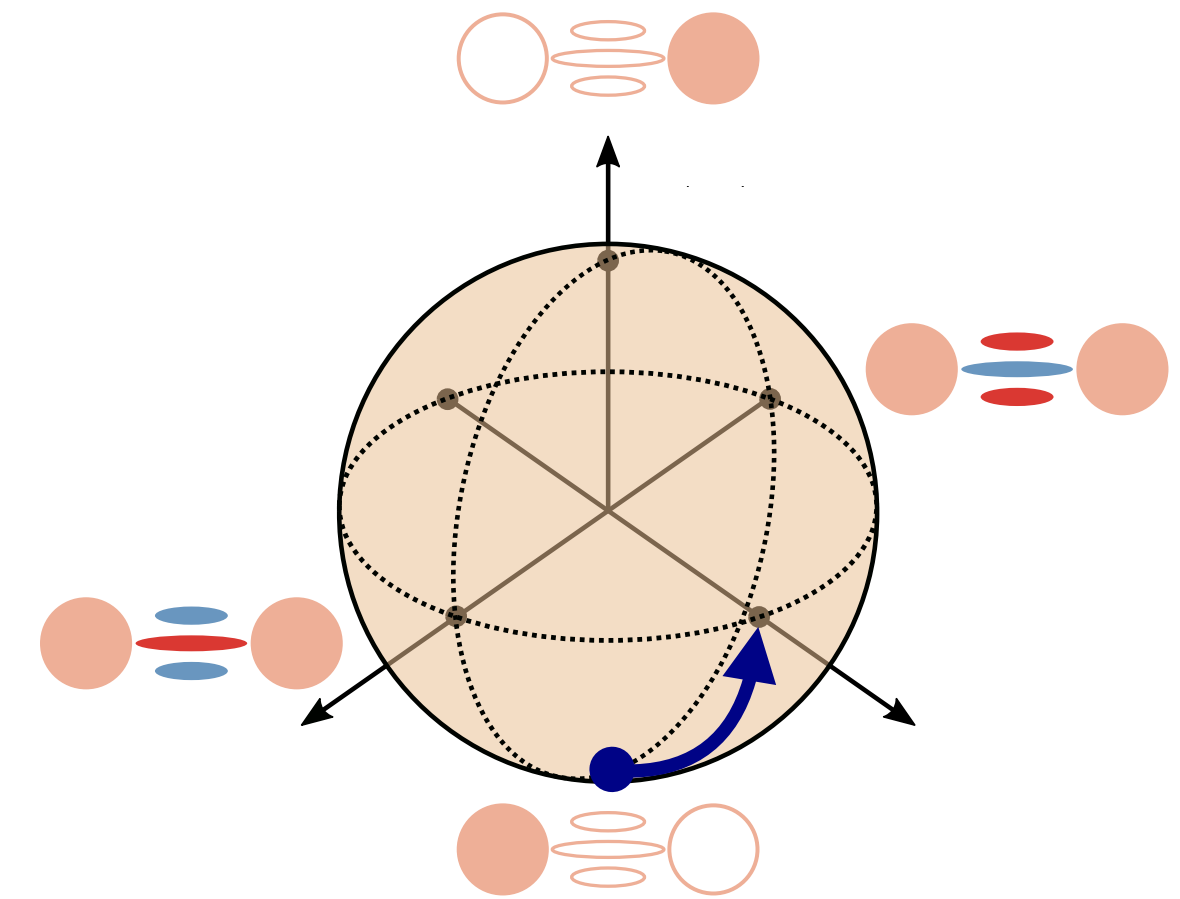
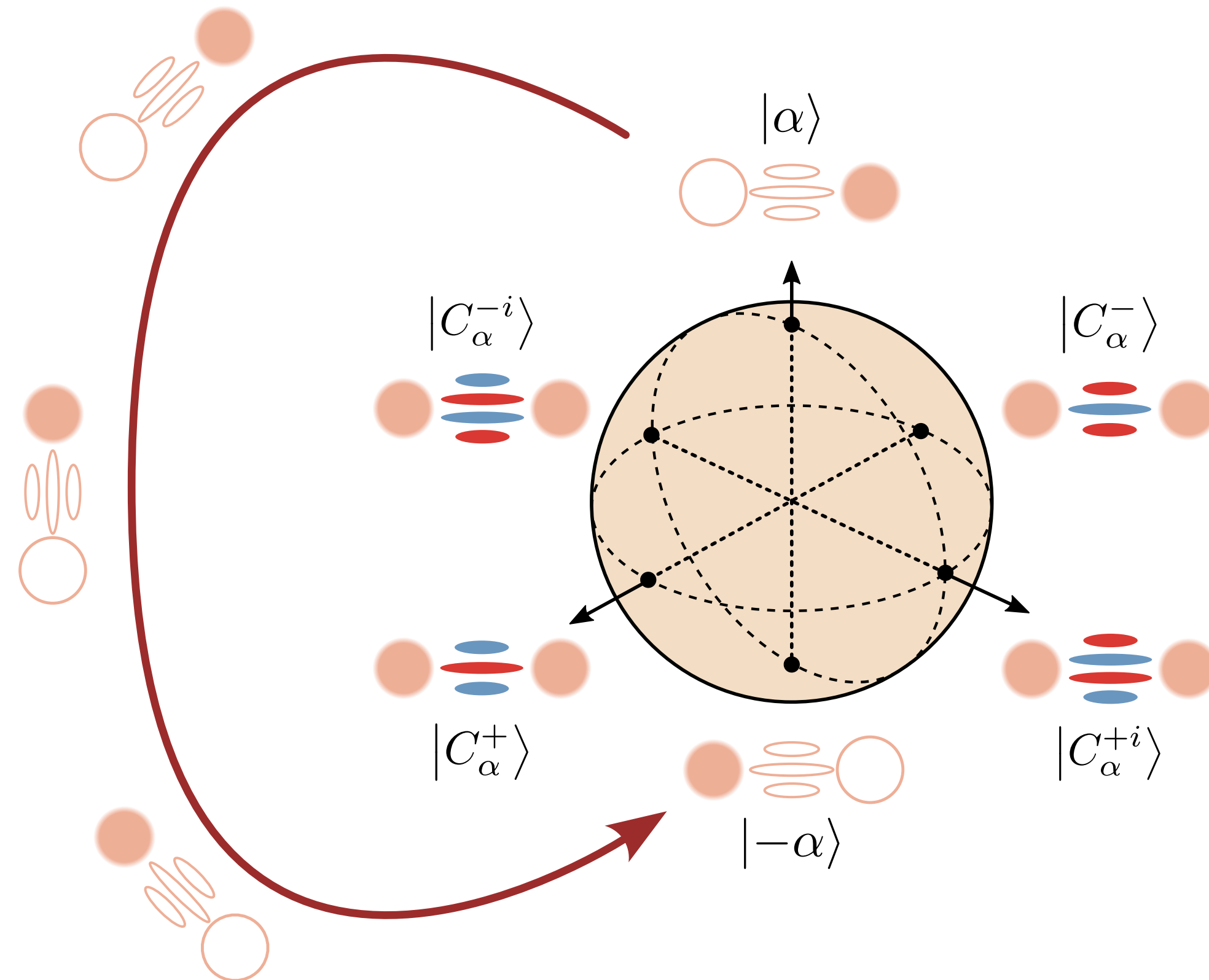


$\hat{X}(\theta)$ gate

2 photon dissipation prevents population transfer between $|\alpha\rangle$ and $|\alpha\rangle$

- Solution 1: continuous deformation of the encoding

Only works for the gate $\hat{X}(\pi)$



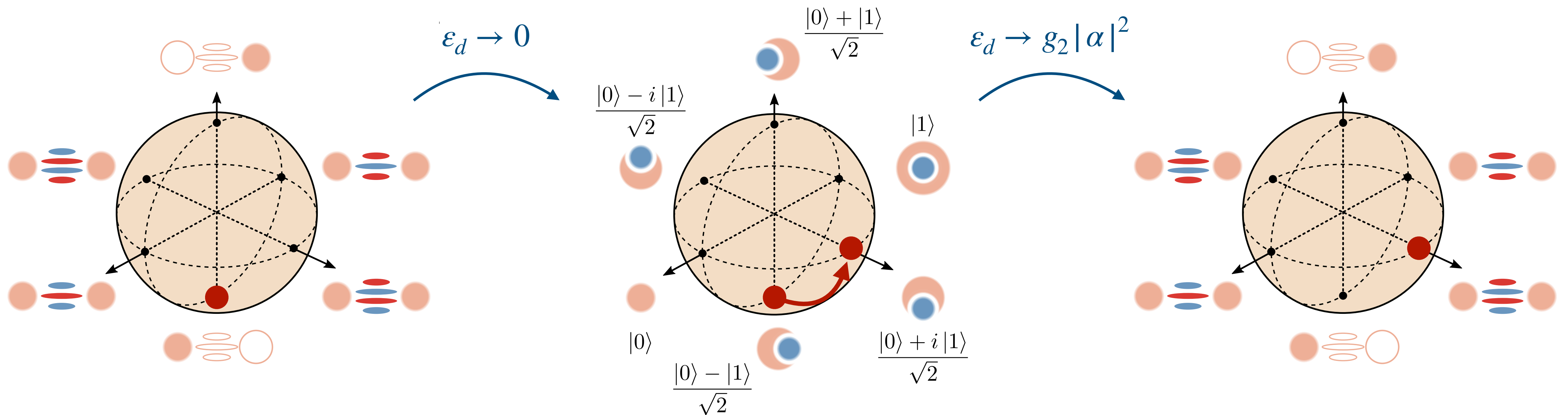
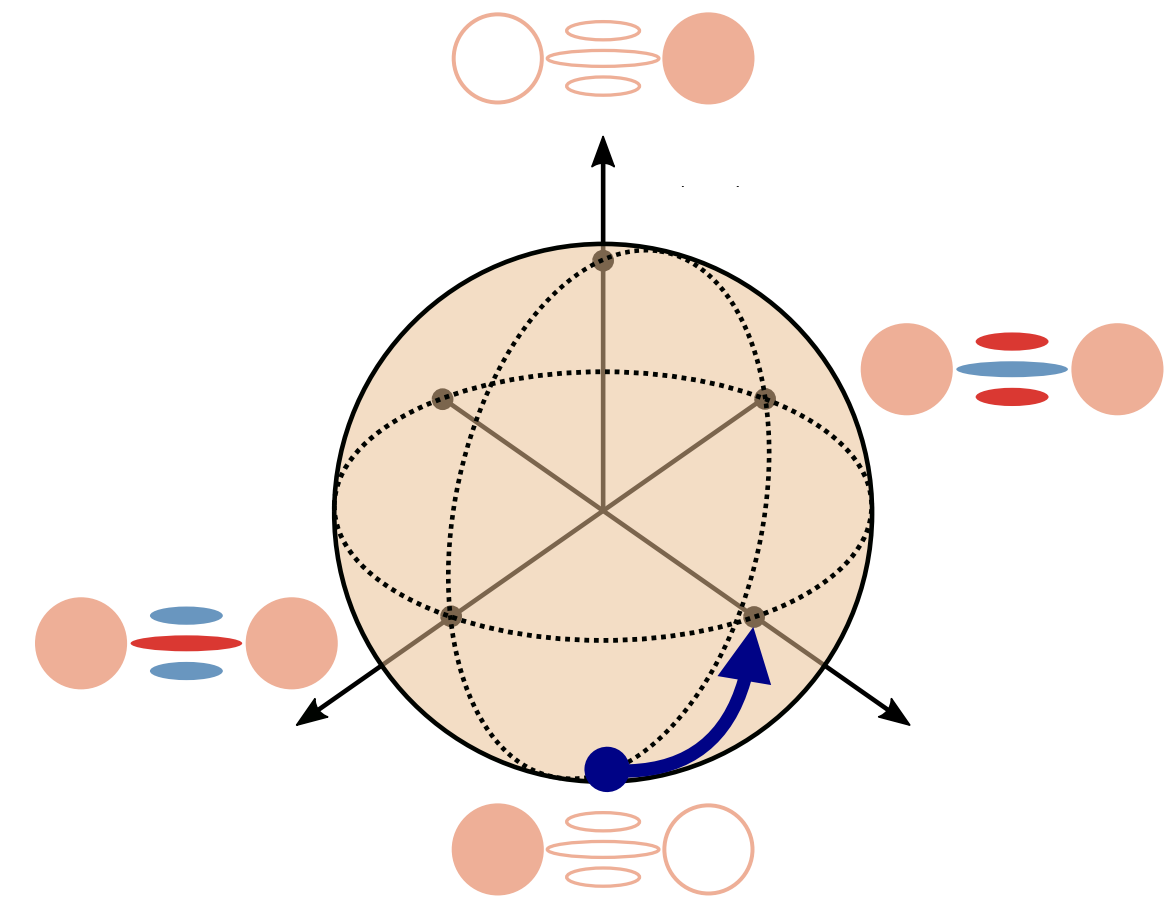
$\hat{X}(\theta)$ gate

2 photon dissipation prevents population transfer between $|\alpha\rangle$ and $|\alpha\rangle$

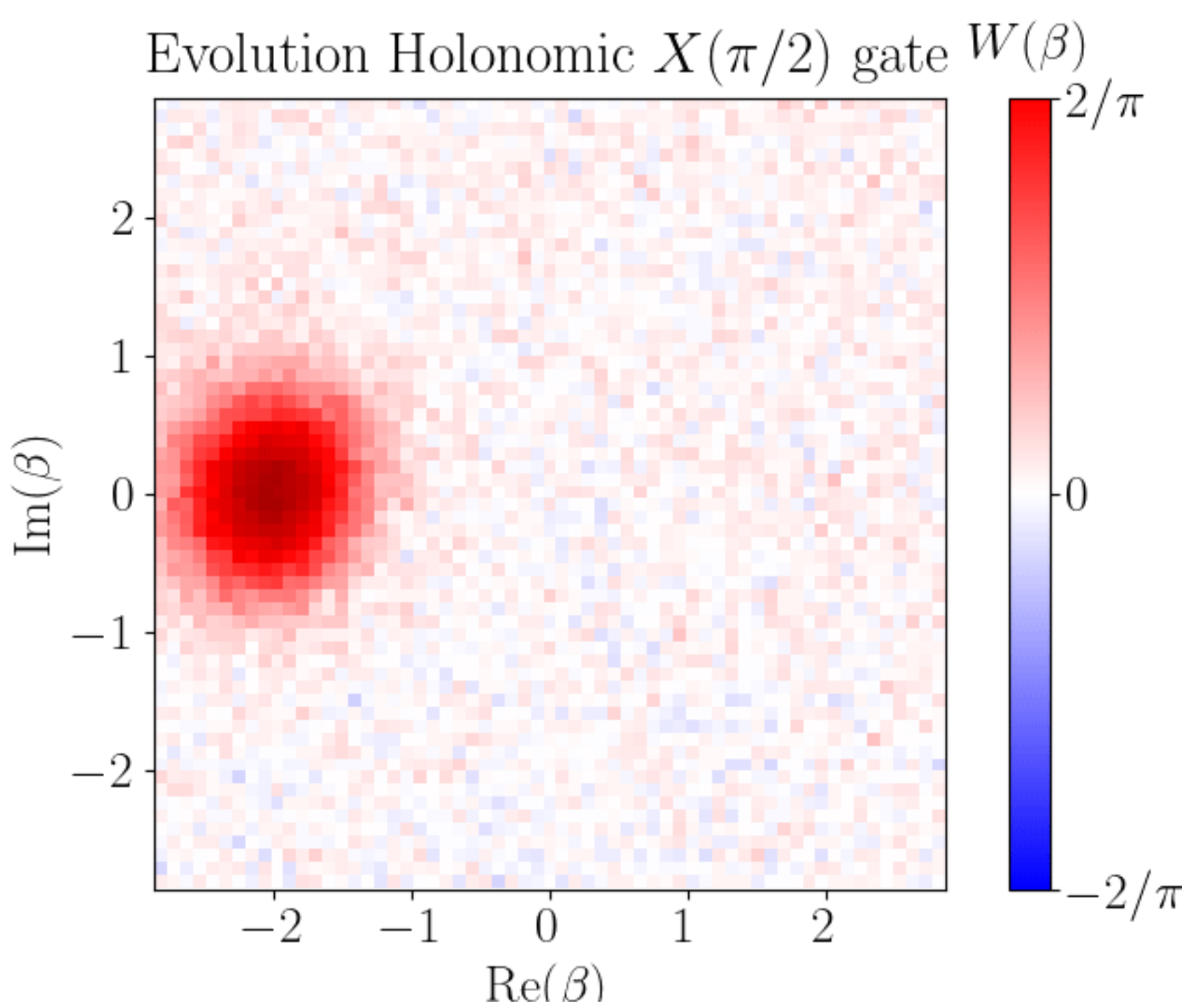
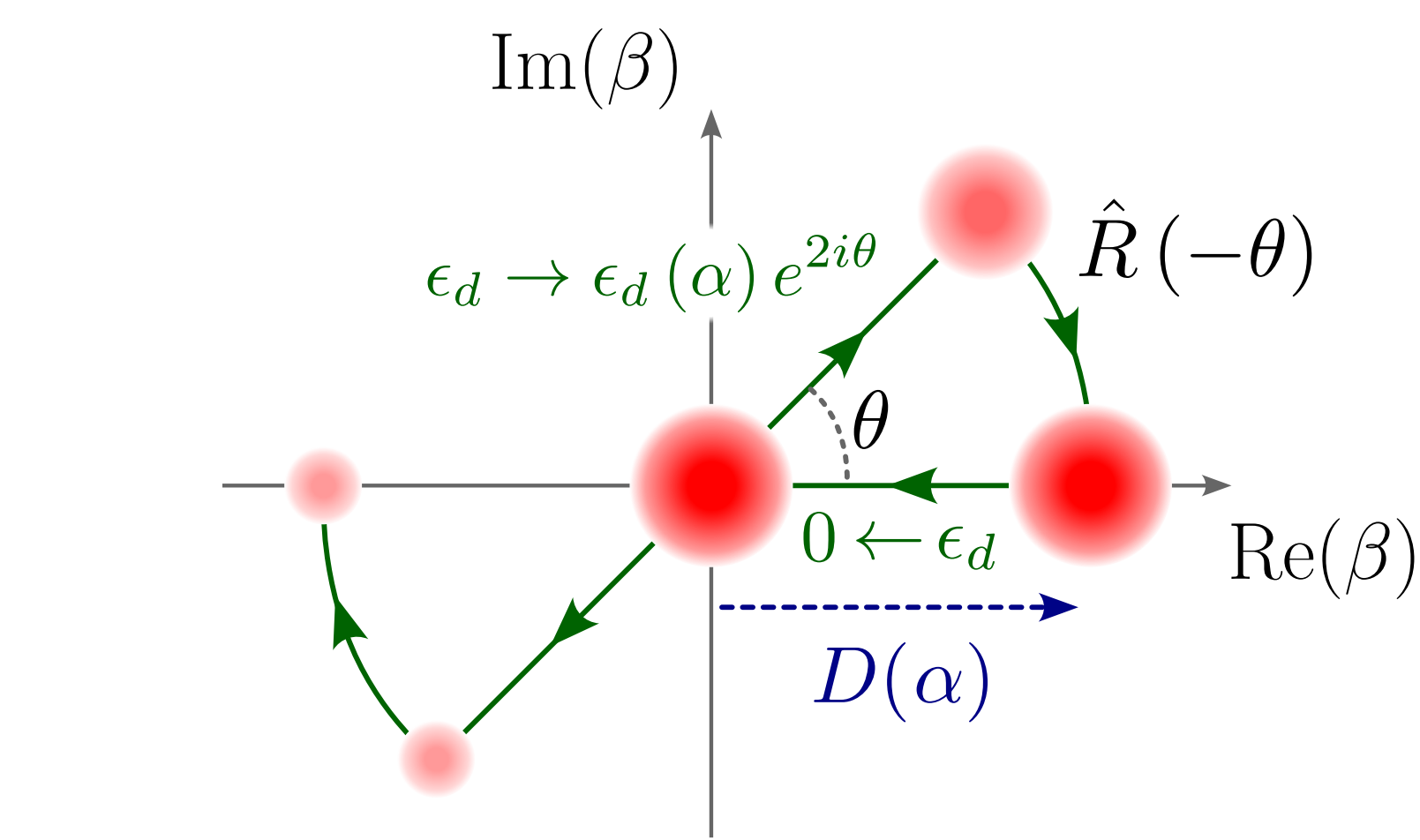
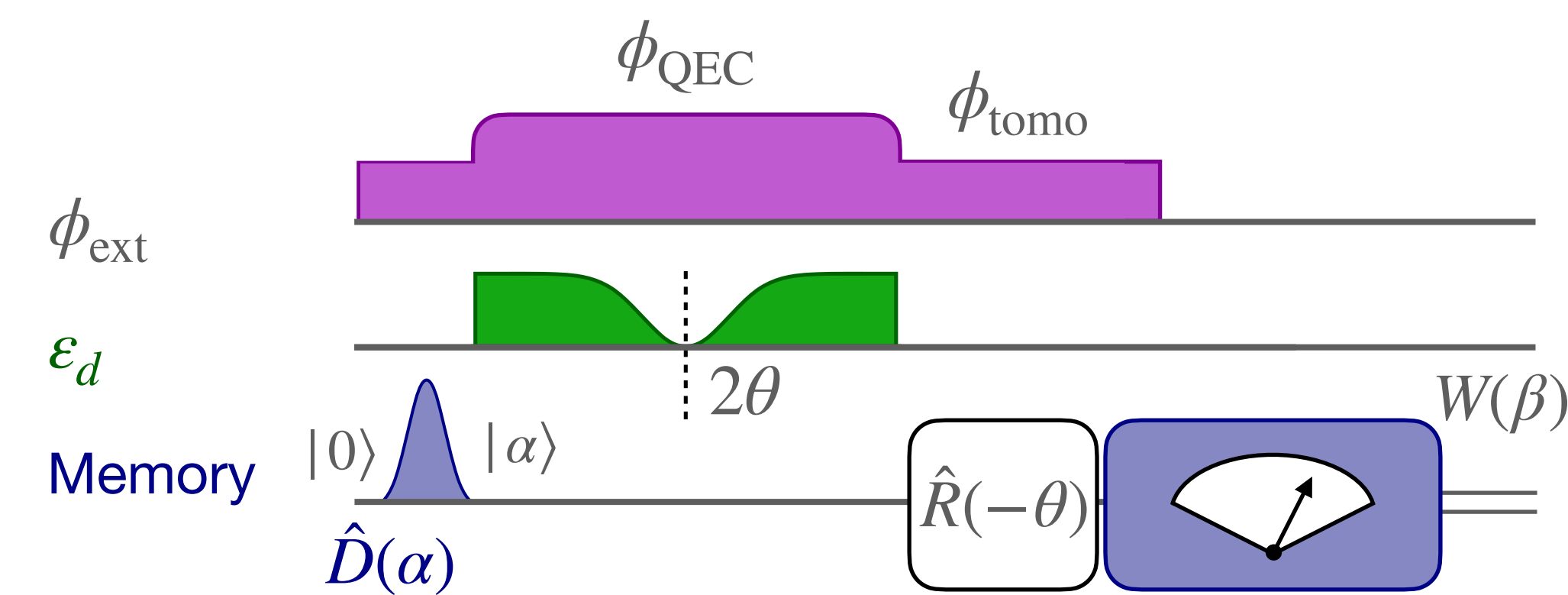
- Solution 1: continuous deformation of the encoding

Only works for the gate $\hat{X}(\pi)$

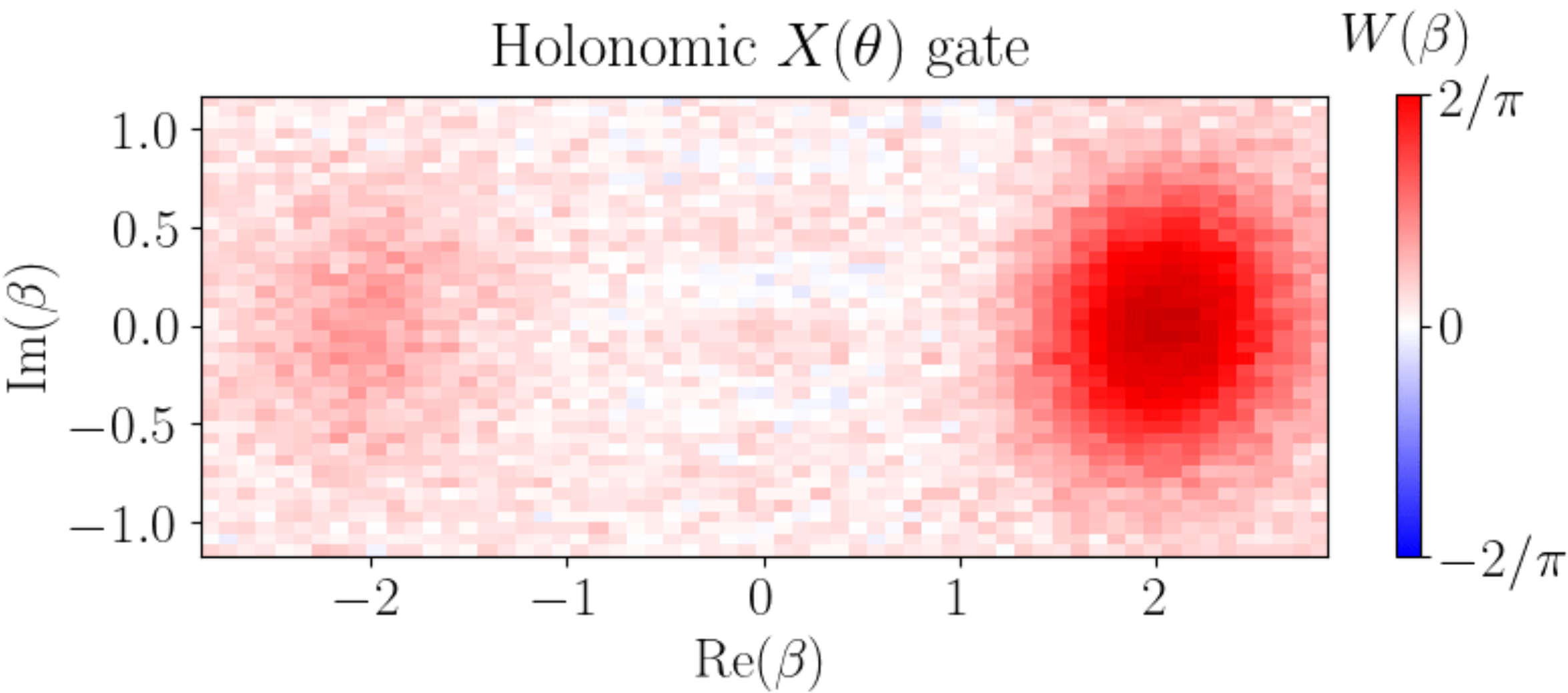
- Solution 2: use the *deflated* manifold $\text{span}(|0\rangle, |1\rangle)$



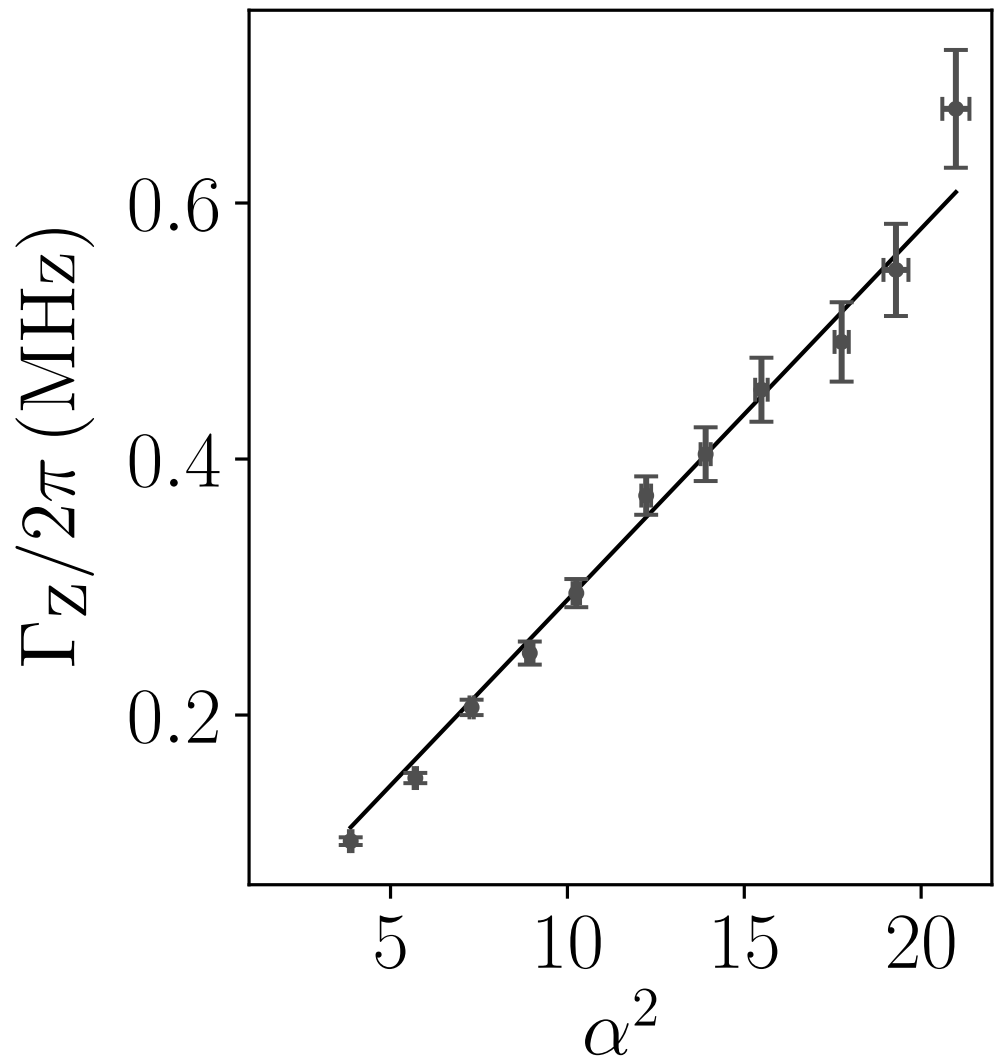
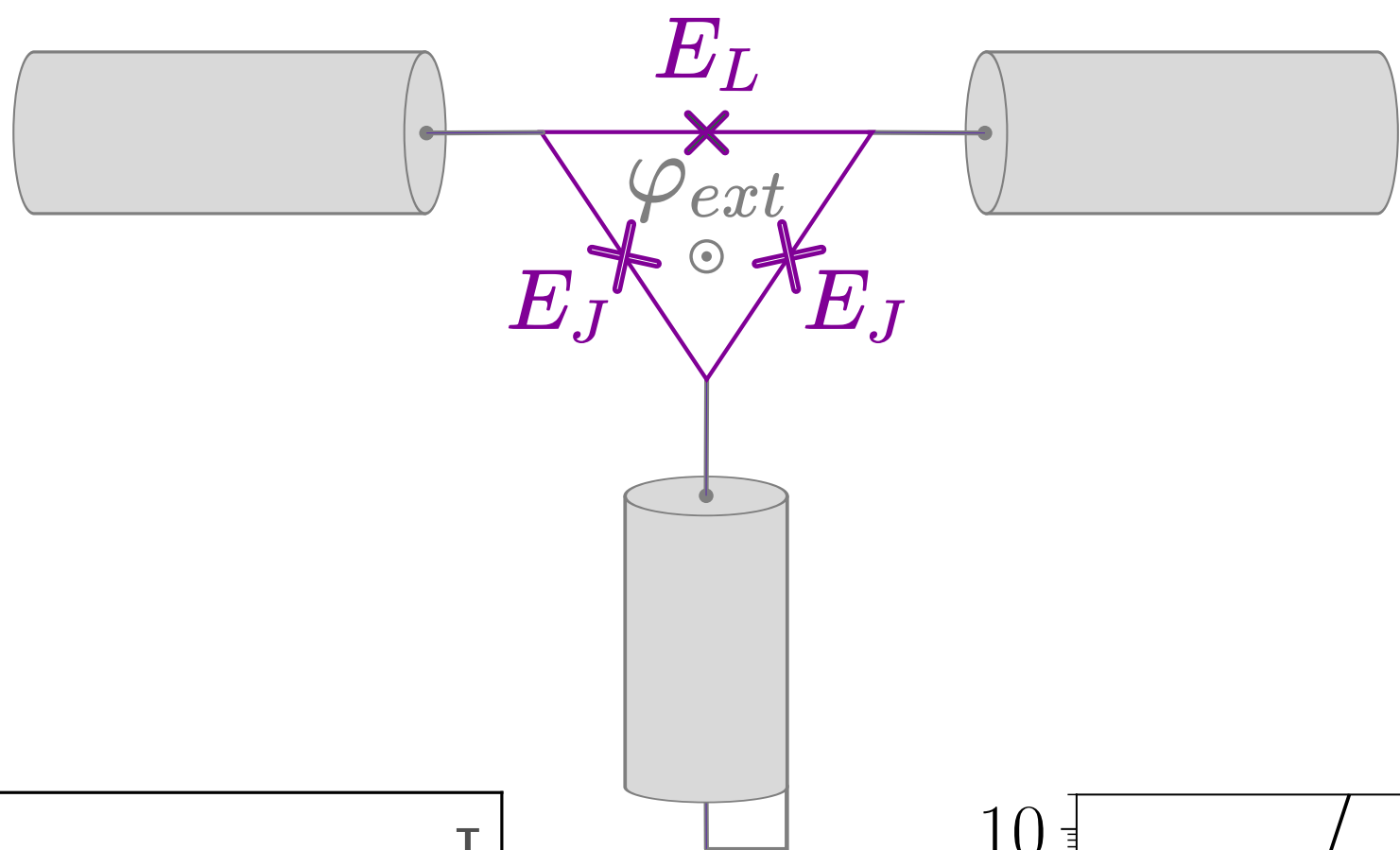
Holonomic $\hat{X}(\theta)$ gate



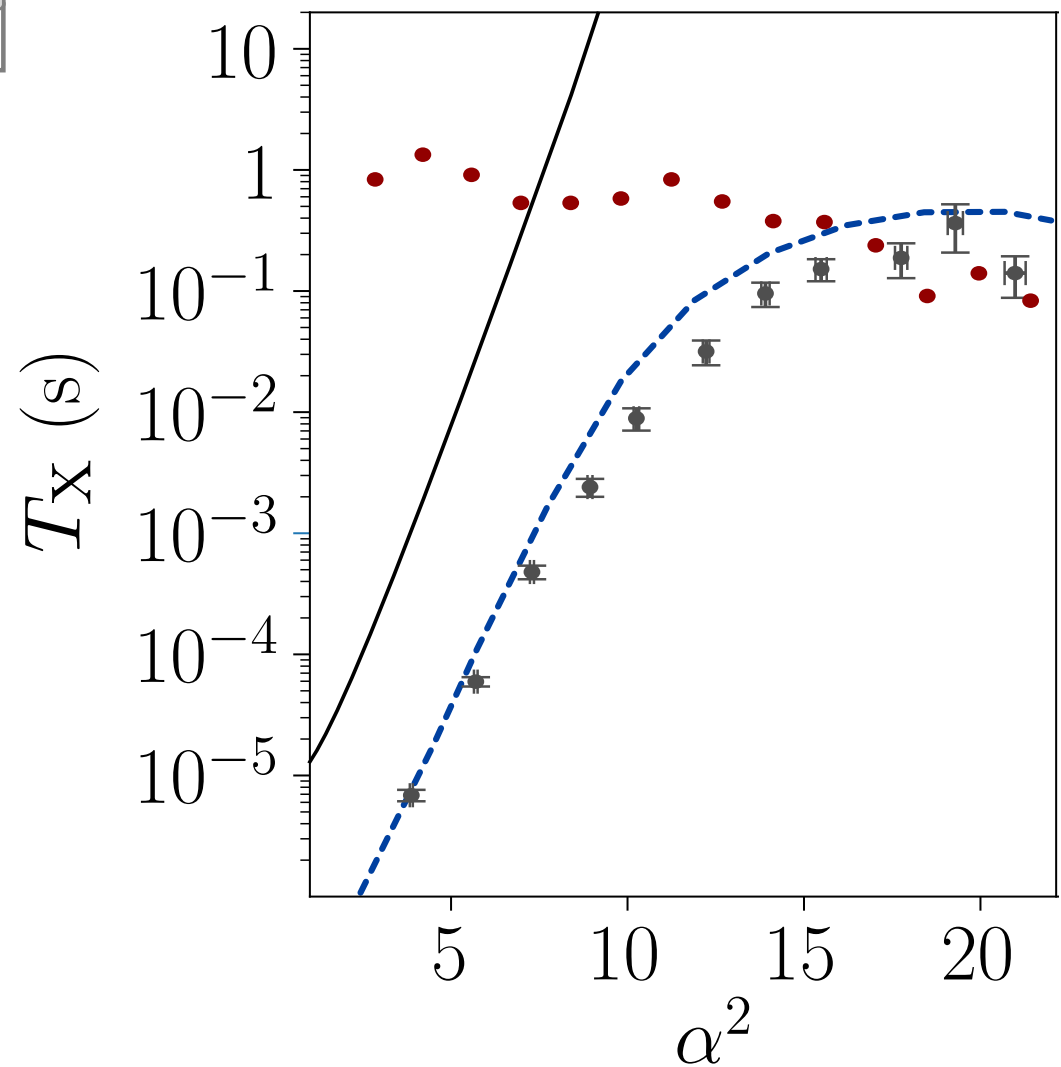
A. Marquet et al., PRApplied 2024 (Lyon, A&B)



Autoparametric cat

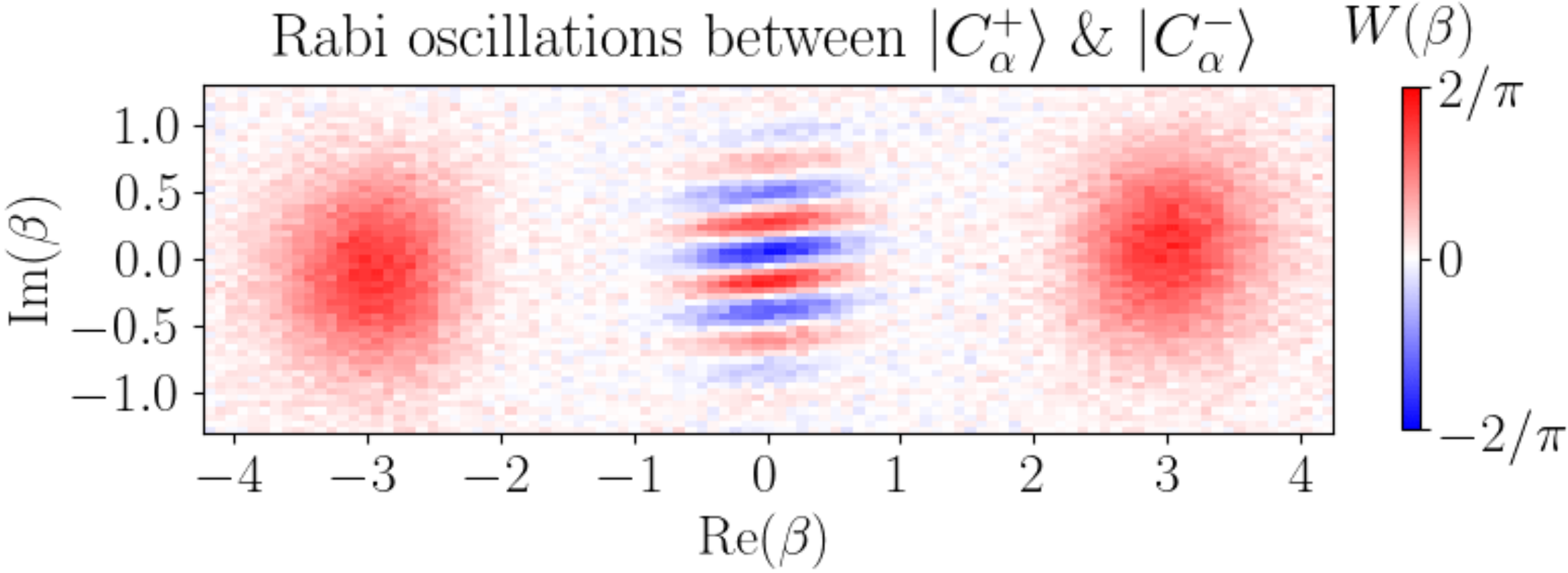


Linear increase
of Γ_Z

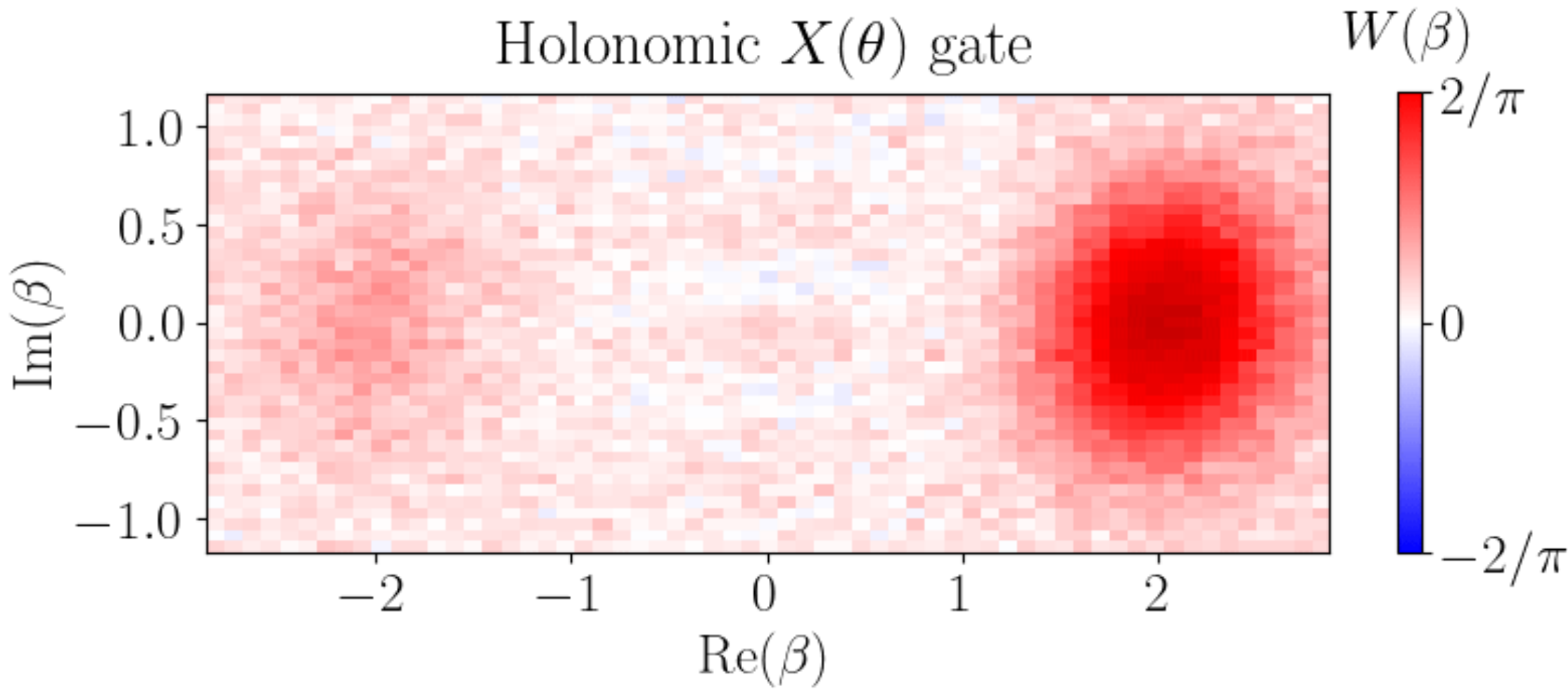


Exponential increase of T_X
up to 0.3 s

A. Marquet et al., PRX 2024 (Lyon, A&B)



A. Marquet et al., PRApplied 2024 (Lyon, A&B)



A. Marquet et al. PR Applied, 2024 (Lyon, A&B)

Perspectives

- Add a flux knob to operate at sweet spot
- Ancilla for repetition codes
- 4-component cat qubits

Thanks!



A. Marquet



A. Essig



J. Cohen



U. Reglade



N. Cottet



A. Murani



E. Albertinale



S. Dupouy



A. Bienfait



T. Peronnin



S. Jezouin



R. Lescanne



B. Huard





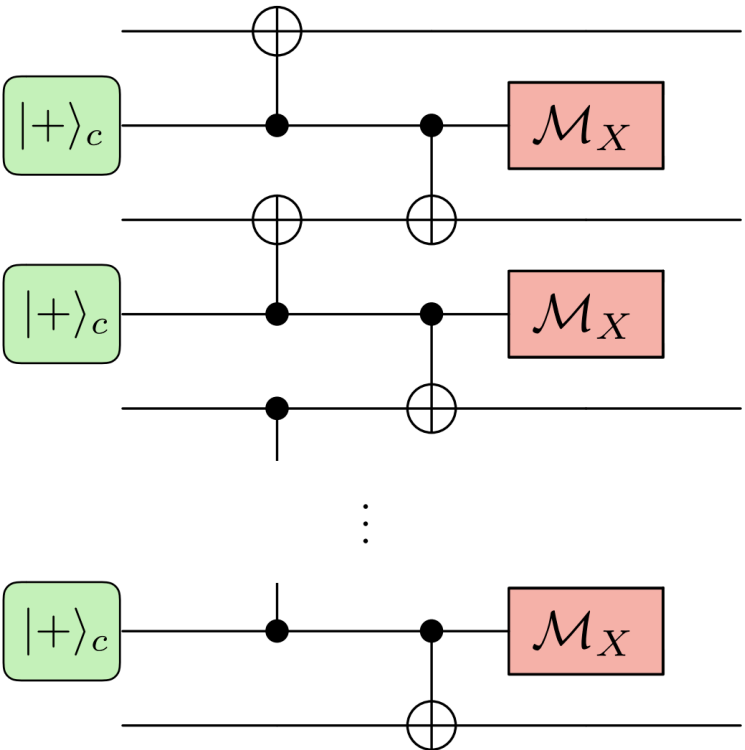
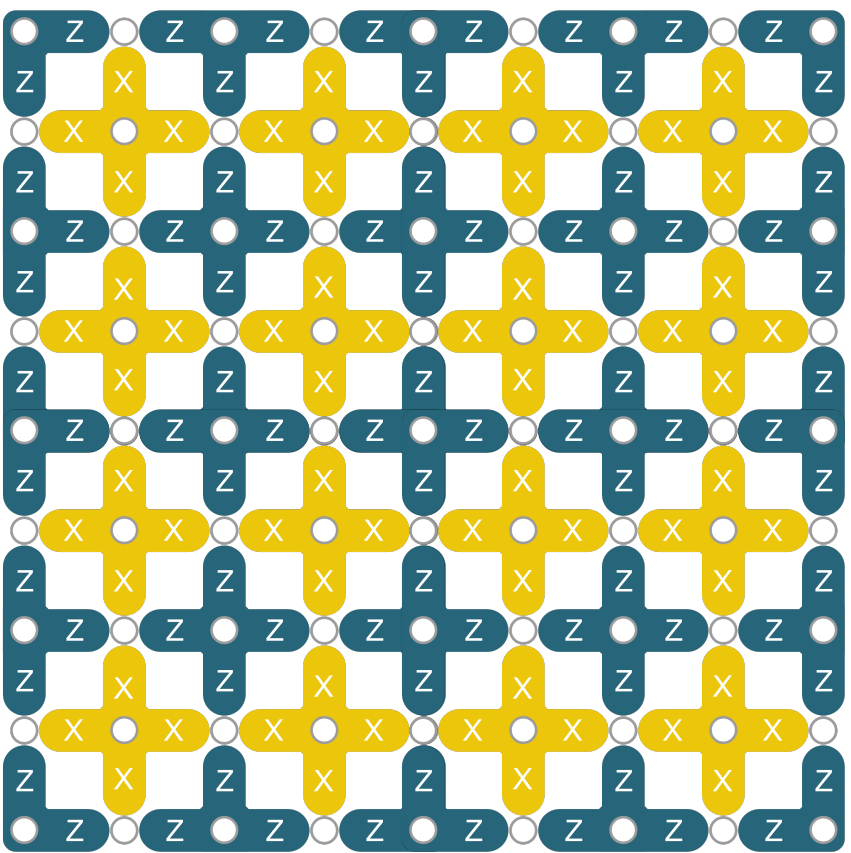
Alice & Bob



Origin of Hardware efficiency

Only one type of error

1. Classical codes are sufficient

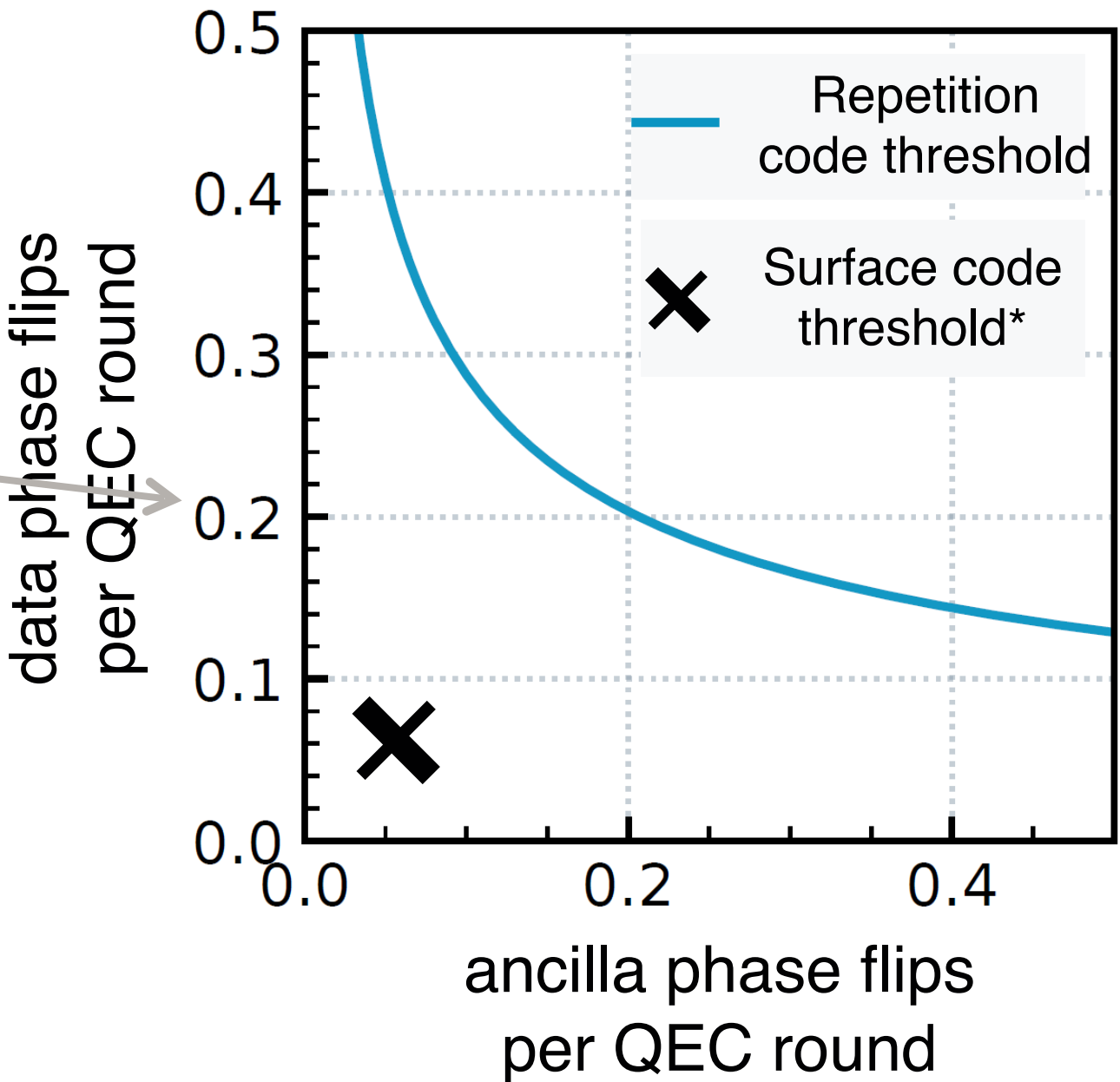
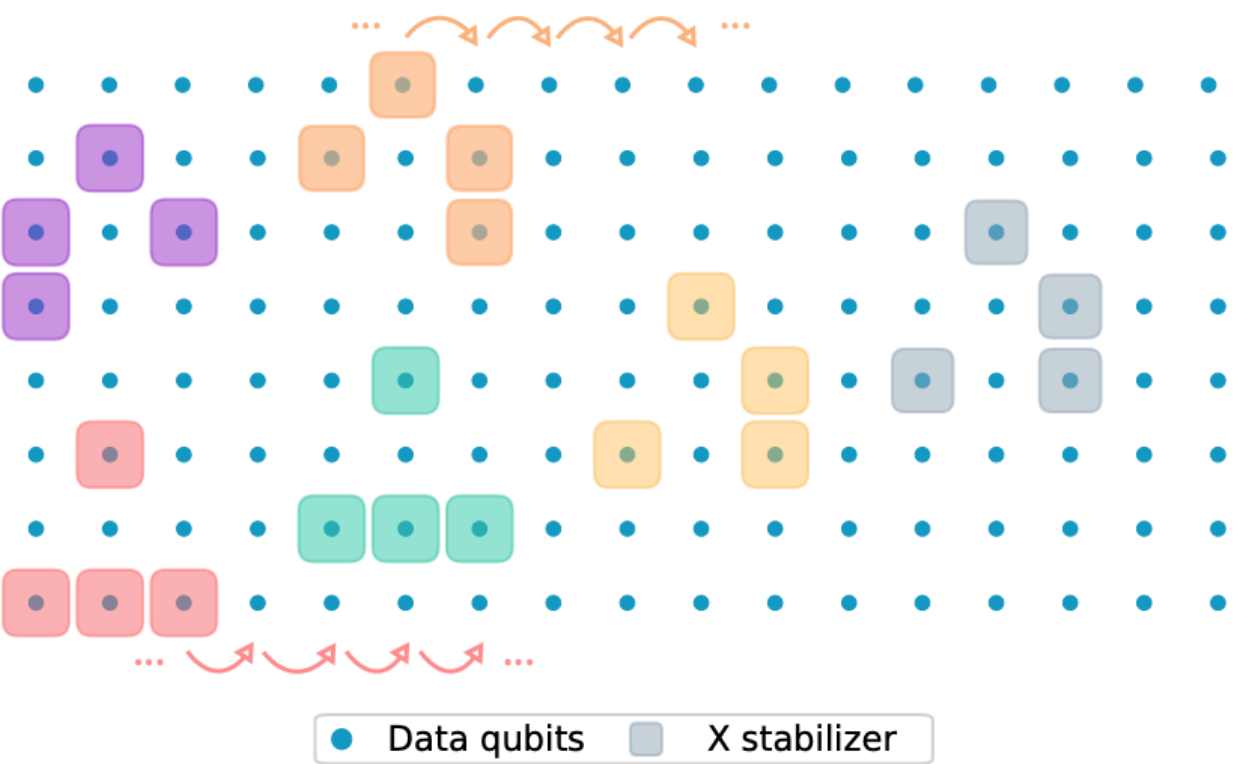
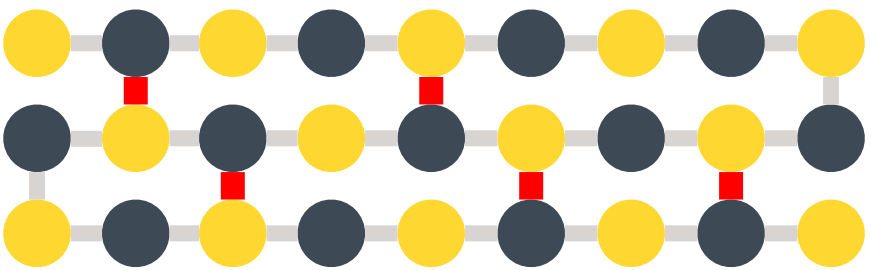


1D repetition code is error resilient

2. High threshold

Distant is local in 1D (zigzag)

3. LDPC codes can be local



*assumes equal distribution of errors among qubits & operations



Concatenating cat qubits in phase-flip LDPC codes

LDPC-cat codes for low-overhead quantum computing in 2D

Diego Ruiz,^{1,2,*} Jérémie Guillaud,¹ Anthony Leverrier,³ Mazyar Mirrahimi,² and Christophe Vuillot⁴

	Surface code + sc qubits [1, 2]	High-rate qLDPC codes + sc qubits [3]	Repetition code + cat qubits [4]	High-rate LDPC code + cat qubits
Short-range interactions	yes (2D)	no (2D)	yes (1D)	yes (2D)
Tanner graph degree	3-4	6	2	4
$N_L = 100$ footprints				
$\epsilon = 10^{-3}$	N = 33,700	2,400 (N/14)	-	-
$\kappa_1/\kappa_2 = 10^{-4}$	-	-	2,100 (N/16)	758 (N/44)



Benchmark: Factoring 2048-bit integers ($\epsilon_L \sim 10^{-15}$)

Surface code + transmons Quantum 5, 433 (2021)

How to factor 2048 bit RSA integers in 8 hours using
20 million noisy qubits

Craig Gidney¹ and Martin Ekerå²

2×10^7 transmons

Repetition code + Cat Qubits PRL 131, 040602 (2023)

Performance Analysis of a Repetition Cat Code
Architecture: Computing 256-bit Elliptic Curve
Logarithm in 9 Hours with 126 133 Cat Qubits

[Élie Gouzien](#) ^{1,*}, [Diego Ruiz](#) ^{2,3}, [Francois-Marie Le Régent](#)^{2,3}, [Jérémy Guillaud](#)², and
[Nicolas Sangouard](#)^{1,†}

3.5×10^5 cat qubits (N/57)

LDPC + Cat Qubits Nature Communications, 16 (2025)

LDPC-cat codes for low-overhead quantum computing
in 2D

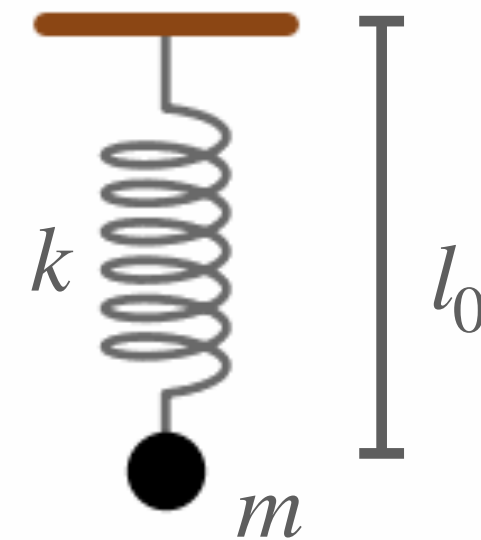
[Diego Ruiz](#) , [Jérémy Guillaud](#), [Anthony Leverrier](#), [Mazyar Mirrahimi](#) & [Christophe Vuillot](#)

10^5 cat qubits (N/200)

3 wave interaction using autoparametric coupling

A classical analogy

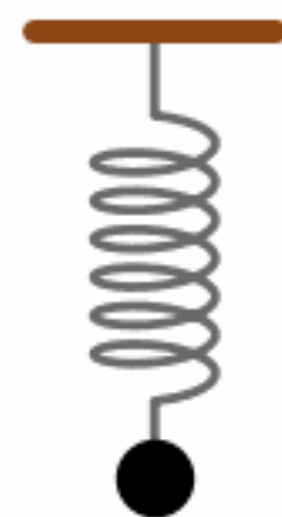
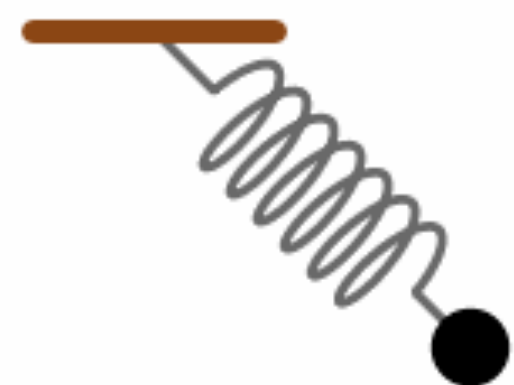
Replace the string in the pendulum by a spring



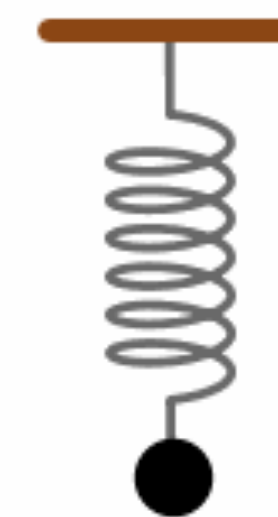
$$\omega_b \neq 2\omega_m$$

Spring mode $\omega_b = \sqrt{\frac{k}{m}}$

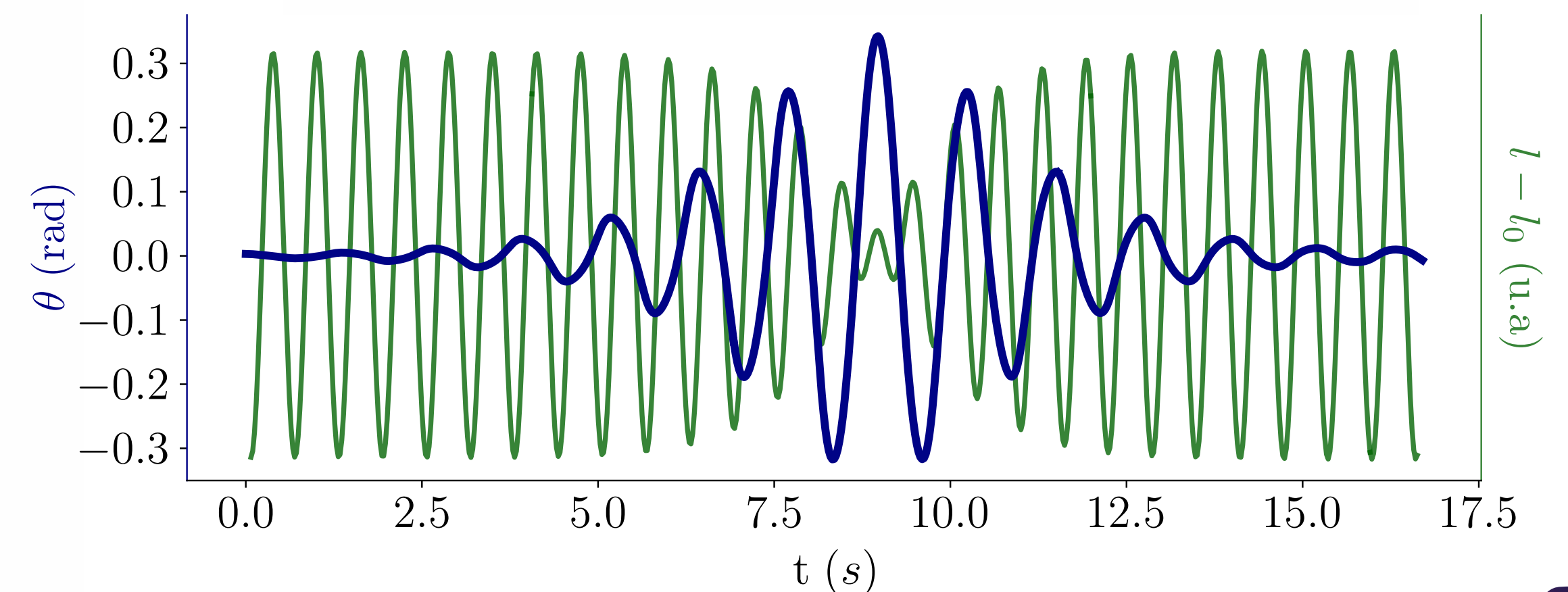
Pendulum mode $\omega_m = \sqrt{\frac{g}{l_0}}$



$$\omega_b = 2\omega_m$$

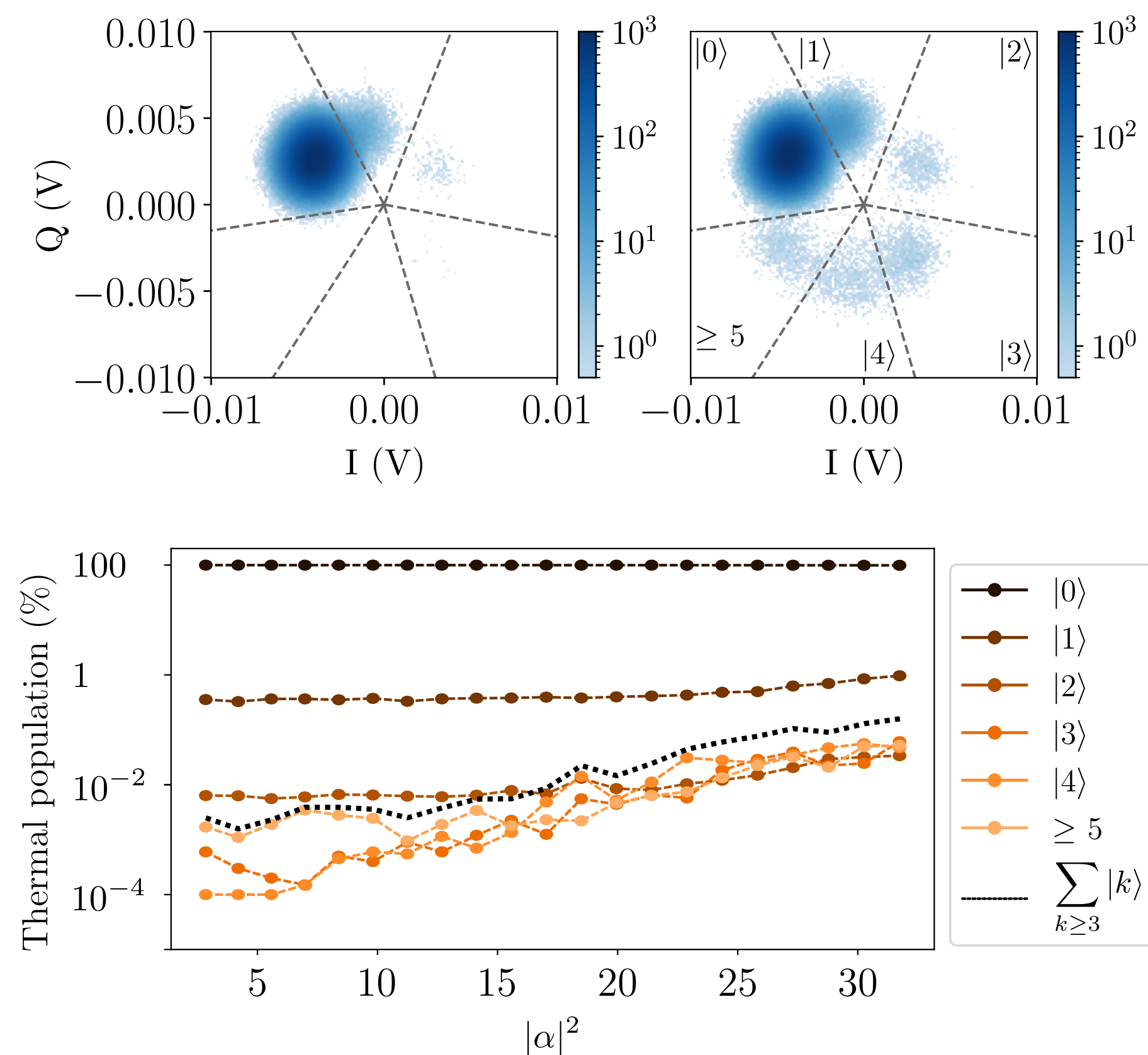


Excitations in the « buffer » mode are converted into pairs of excitations of the « memory » mode

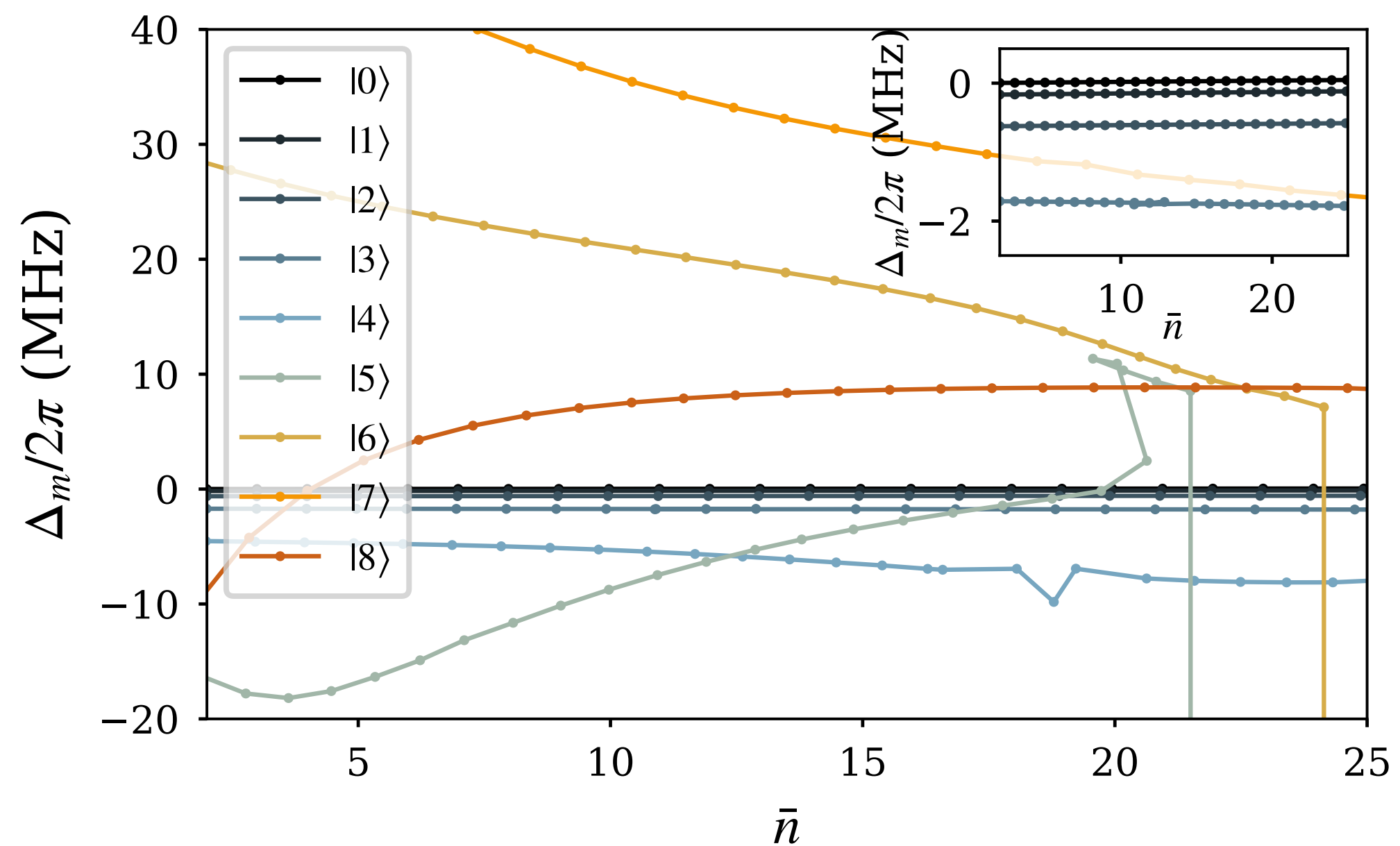


Impact of the transmon's thermal population

Transmon's thermal population

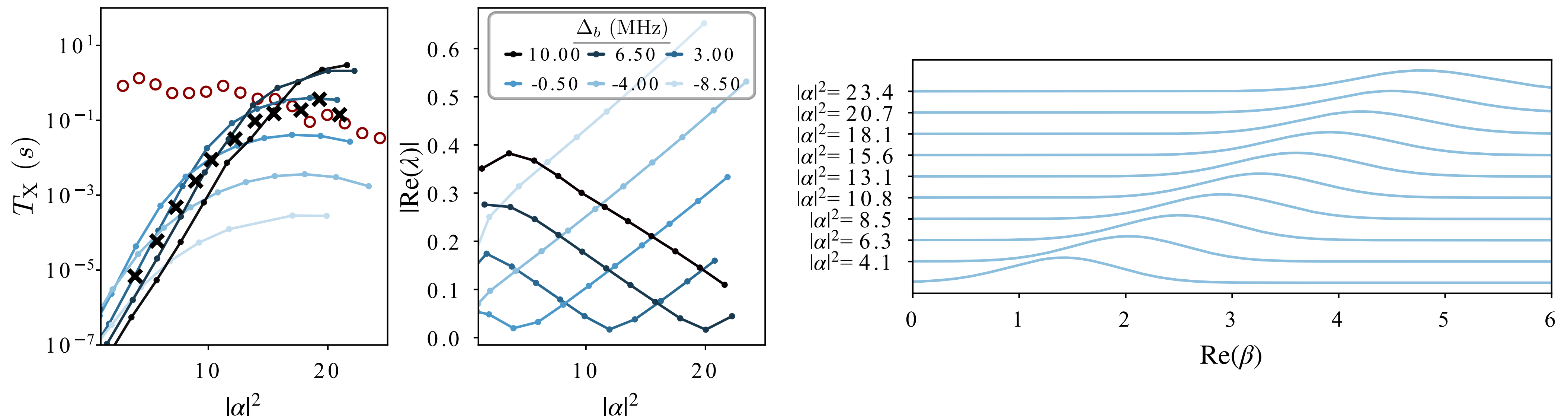


Impact on the memory frequency



Displacement of the buffer mode

- Due to the memory self-Kerr, its frequency shifts when encoding cat states with larger amplitudes
- The drive becomes off detuned, $\Delta_b = \omega_b - \omega_d \neq 0$, leading to a displacement of the buffer
- The buffer then thermalizes, owing either to the buffer dephasing noise $n_{\text{th}}^b = \kappa_\varphi^b |\langle \hat{b} \rangle_{\text{ss}}|^2 / \kappa_b$, or large self-Kerr $\chi_{bb}/2\pi \approx 10$ MHz which leads to a small squeezing, converted into an effective thermal population $n_{\text{th}}^b = \sinh^2(r)$ by single photon loss.
- Buffer photons are converted to memory photons, creating a heating term of the form $\hat{m}^{\dagger 2}$. Alternatively, the cross-Kerr effect χ_{mb} can lead to an increased memory dephasing rate.



Comparison between the different stabilization methods

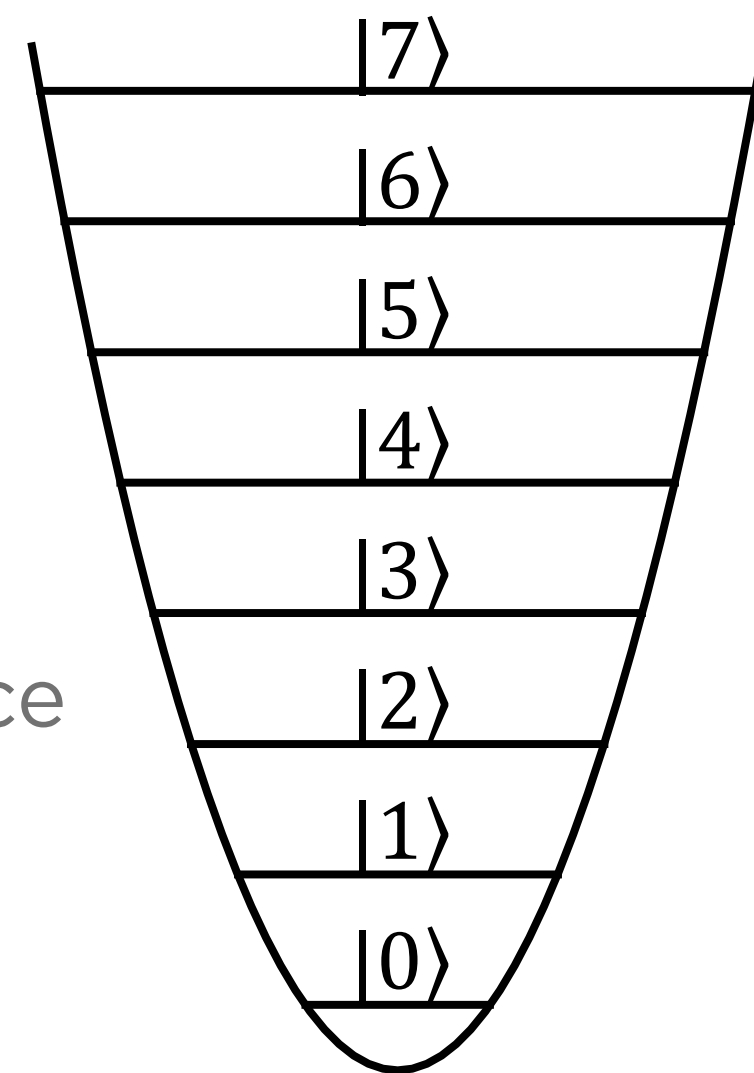
Metric	Kerr cats [14, 15]	ATS stabilized cat [19, 39]	Autoparametric cat
g_2	Irrelevant	$g_2 = E_J \epsilon_0 \varphi_{\text{ZPF},b} (\varphi_{\text{ZPF},m})^2$ $= 2\pi \times 0.76 \text{ MHz}$	$g_2 = E_J \overbrace{\sin(\bar{\varphi}_J)}^{\gg \epsilon_0} \varphi_{\text{ZPF},b} (\varphi_{\text{ZPF},m})^2$ $= 2\pi \times 6 \text{ MHz}$
Number of RF/DC/both lines	2/1/0	3/0/2	1/0/1
$\hat{Z}(\pi/2)$ gate time (ns) $\frac{\pi}{2\text{Re}(4\alpha\epsilon_Z)}$	24 ns	118 ns	14 ns
$\hat{Z}(\pi/2)$ gate fidelity $F = 1/2 + e^{-\pi\kappa_z/2\Omega_z}/2$	85.7%	85.3%	98%*
CNOT gate	Theoretical proposal [69]	Theoretical proposal [26] & experimental implementation on coherent states [70]	See sec. K
κ_2/κ_1	Irrelevant	0.9×10^2	Adiabatic elimination limits it to 1.5×10^2
Maximal T_X	Up to about a ms then observed decrease for larger $ \alpha ^2$ likely due to non-RWA terms	Unknown up to 10 s demonstrated	Up to 0.3 s limited by excitation of transmon higher states or buffer thermalization
Geometrical constraint	Translation symmetry [15]	Junction symmetry	Junction symmetry
Memory protection	Bandpass filter	Notch filter	In situ protection by symmetry, notch filter is optional
T_X scaling in photon number	Increase by successive steps No clear observation of exponential scaling yet	Exponential scaling Limited by breakdown of the adiabatic elimination	Exponential scaling Limited by breakdown of the adiabatic elimination & buffer thermalization



WHY DOES IT WORK ?

Redundancy

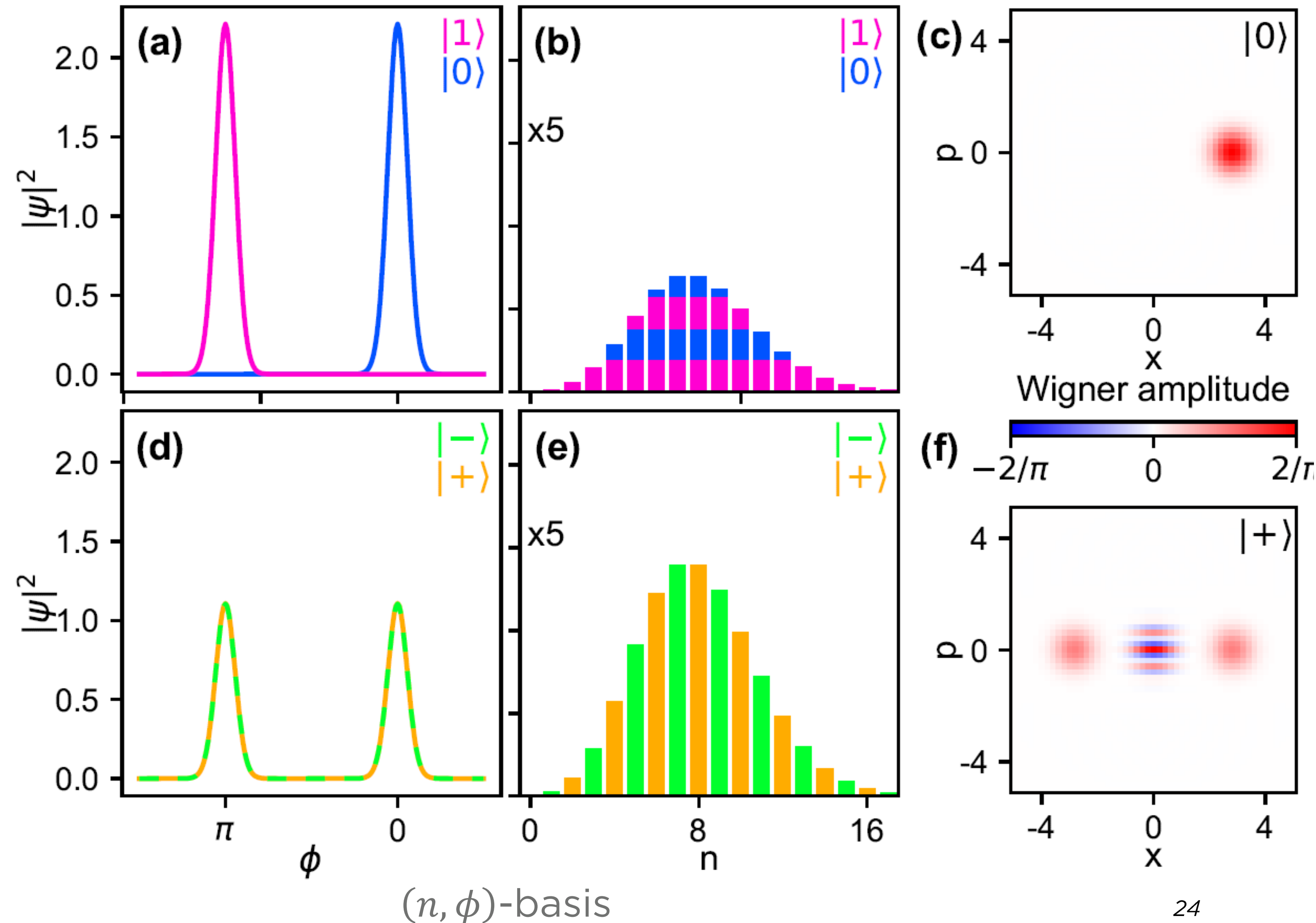
We need a big Hilbert space to protect against (local) errors



Harmonic oscillator
“infinite” Hilbert space

Distance

We encode information in
distant location in this space

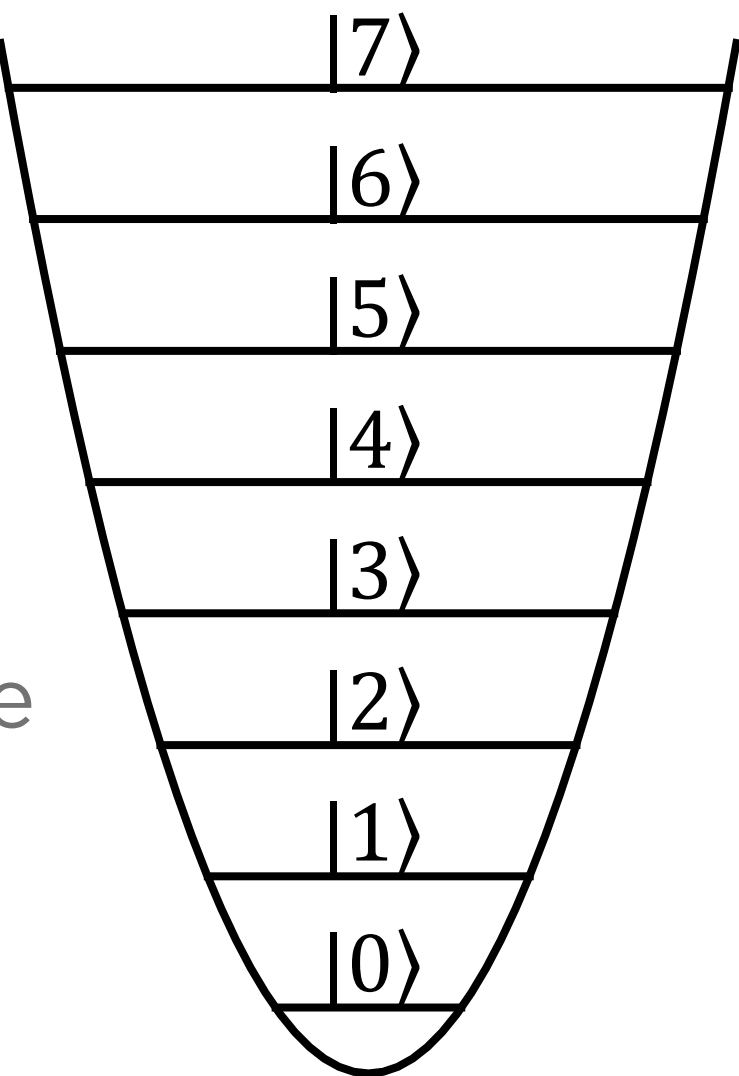




WHY DOES IT WORK ?

Redundancy

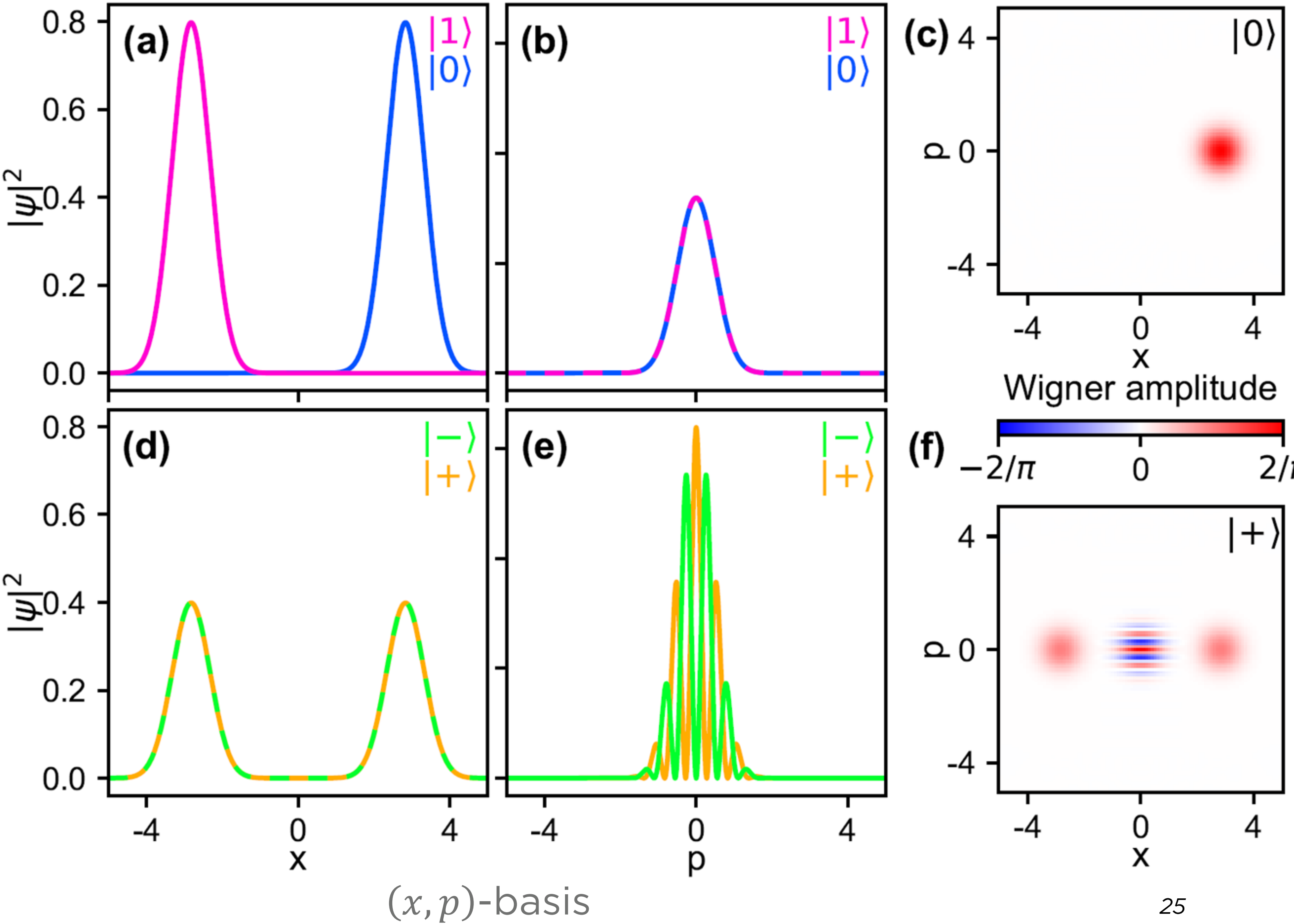
We need a big Hilbert space to protect against (local) errors



Harmonic oscillator
“infinite” Hilbert space

Distance

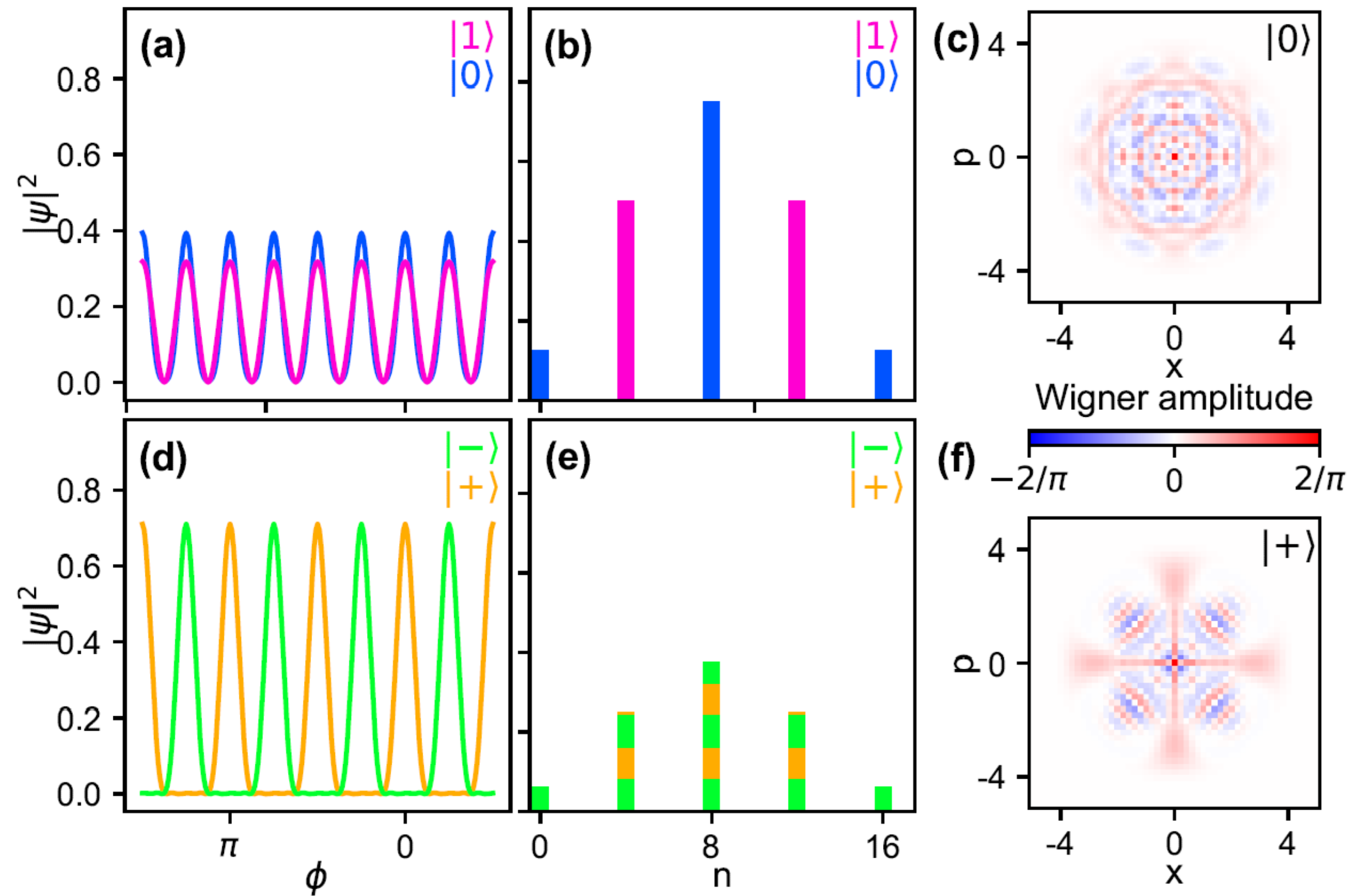
We encode information in distant location in this space





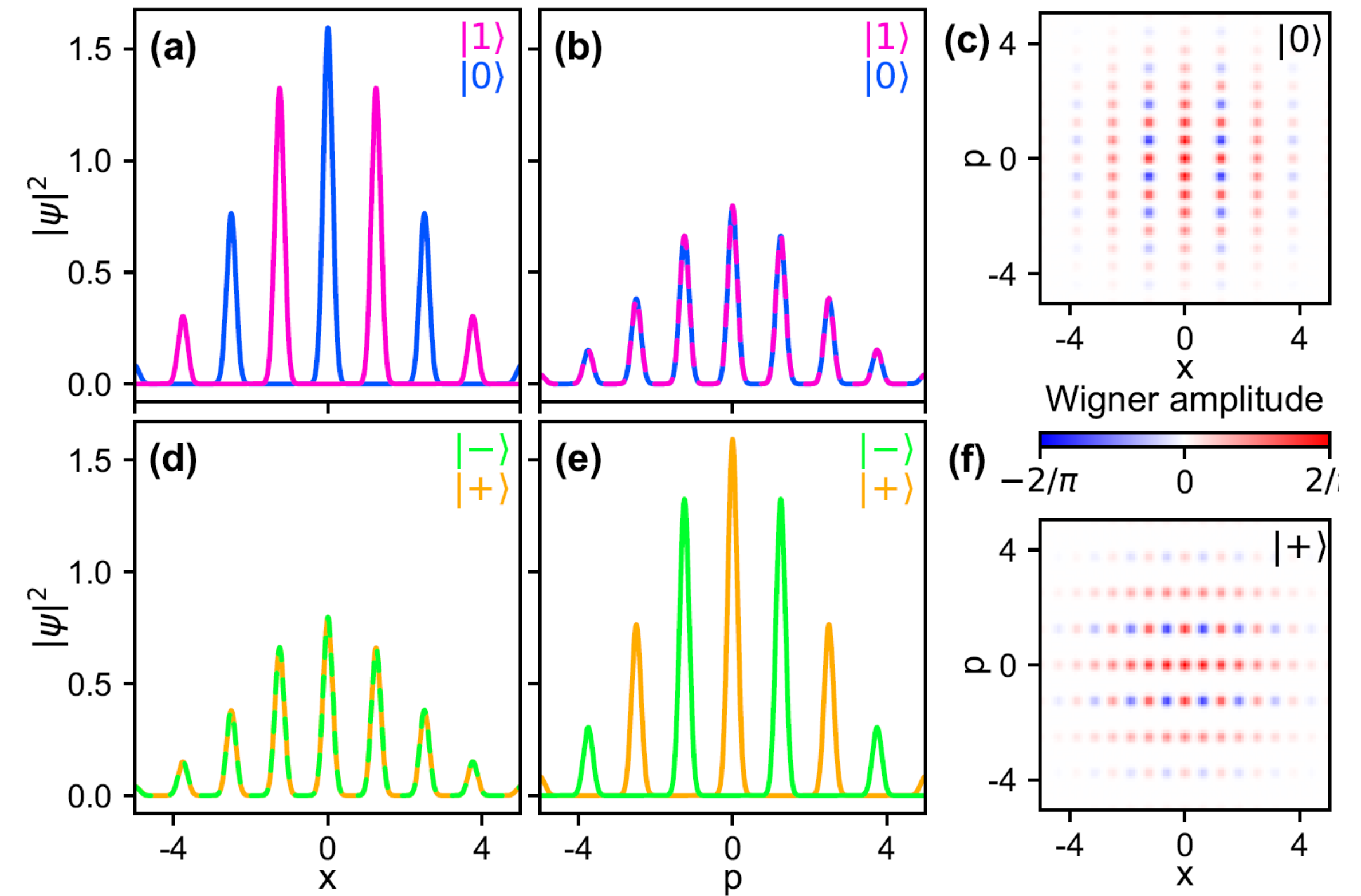
OTHER POSSIBLE BOSONIC ENCODINGS

Binomial codes



M. H. Michael et al. PRX, 6, 031006 (2016)
Z. Ni et al. Nature, 616, 56-60 (2023)

GKP code

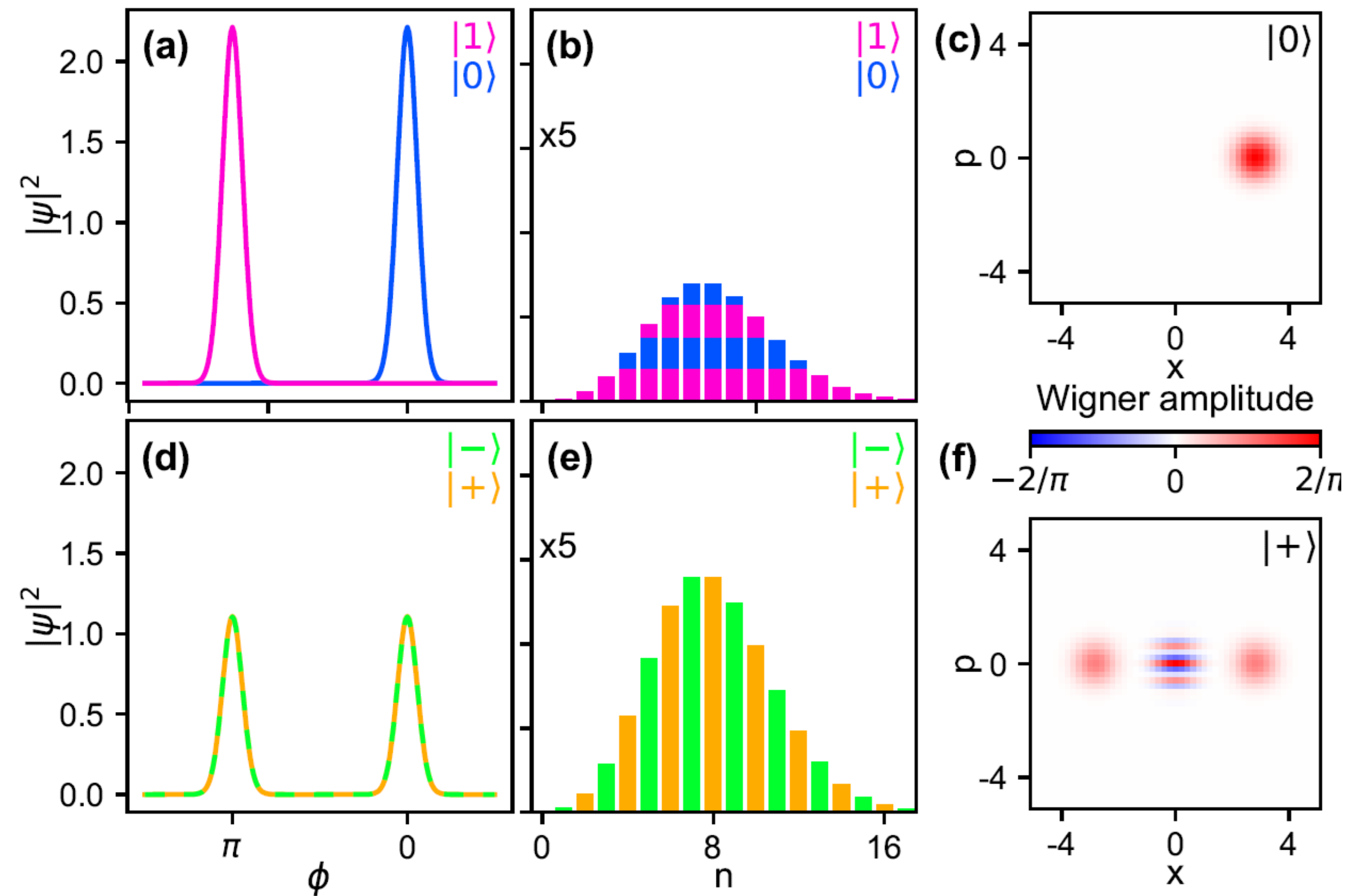


Gottesman et al. Phys. Rev. A 64, 012310 (2001)
V. V. Sivak et al. Nature volume 616, pages 50–55 (2023)

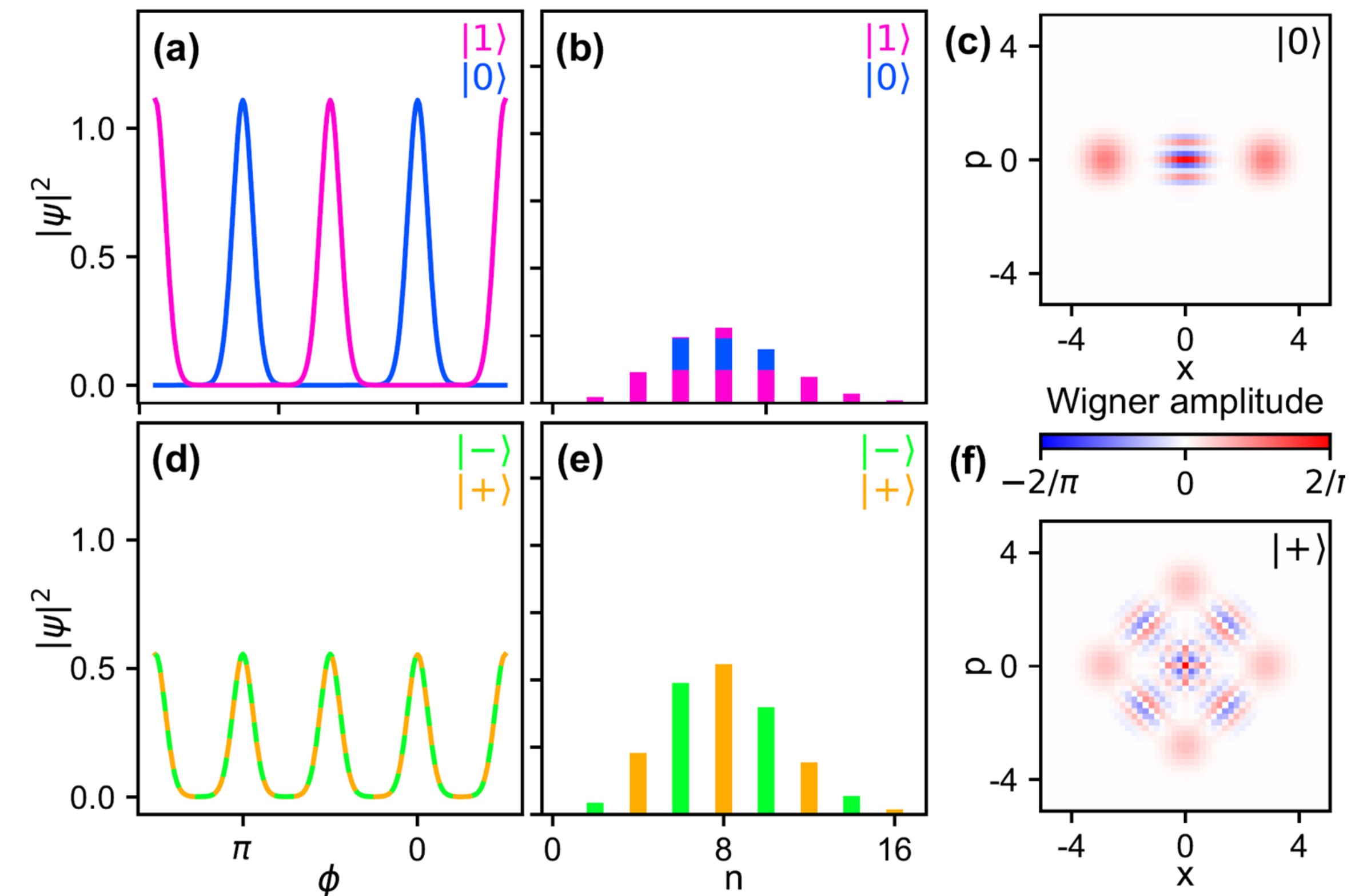


ANOTHER THE CAT QUBIT

2 component (legged) cat



4 component (legged) cat



M. Mirrahimi et al. New J. Phys. 16 045014 (2014)

N. Ofek et al. Nature 536, 441–445 (2016)