Challenges and progress toward dynamical stabilization of advanced bosonic qubits

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Alain Sarlette

Back in 2019…

Do you want to participate in Q-feedback ?

Of course, I would love some support on my GKP project !

I'll send you the draft to check the GKP part

The scientific part is great, but why are you requesting 1.9 million euros only ?

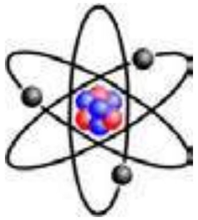
I don't really know how to spend more…

… Have you ever thought about buying a dilution cryostat ?

And in 2021…

“ Pierre, meet your fridge, Boris ! “

Bits and qubits



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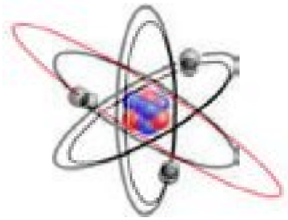
Bits and qubits



1 qubit state = normalized vector in 2D Hilbert space

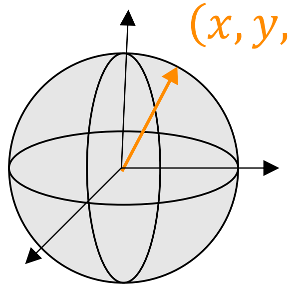
$$|\psi\rangle = \alpha|0\rangle + e^{i\theta}\sqrt{1-\alpha}|1\rangle$$

Pauli matrices:

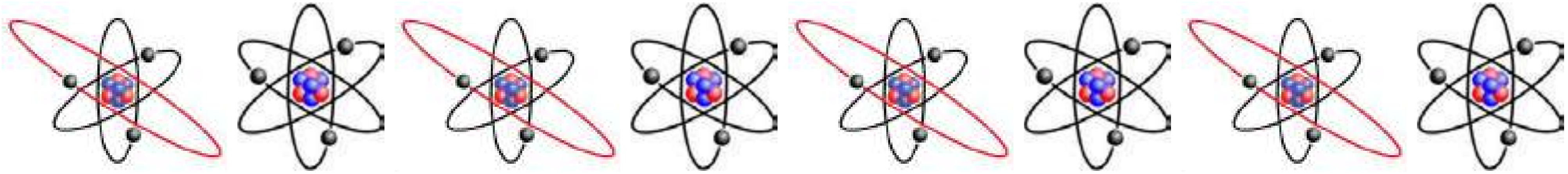
$$X = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \qquad Y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix} \qquad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Bloch sphere representation:

$$(x, y, z) = (\langle\psi|\boldsymbol{X}|\psi\rangle, \langle\psi|\boldsymbol{Y}|\psi\rangle, \langle\psi|\boldsymbol{Z}|\psi\rangle)$$



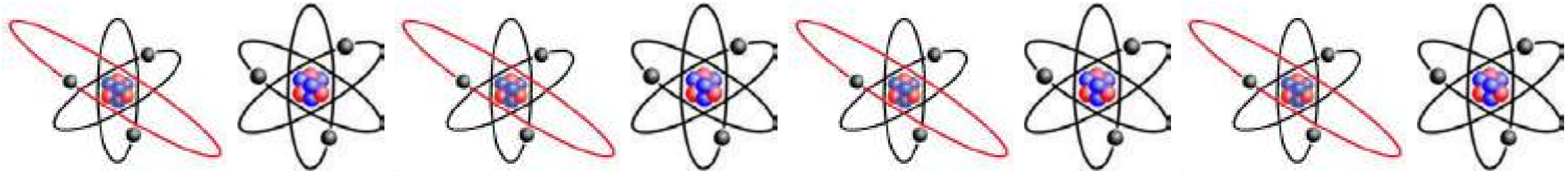
Bits and qubits



$$\alpha_0|000000\rangle + e^{i\theta_1}\alpha_1|000001\rangle + e^{i\theta_2}\alpha_2|000010\rangle + \cdots$$

N qubits state = normalized vector in 2^N- D Hilbert space

Bits and qubits

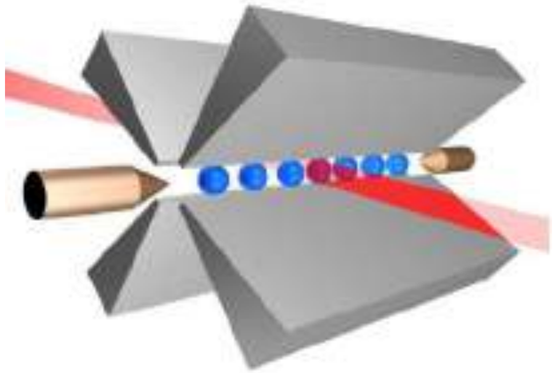


$$\alpha_0|000000\rangle + e^{i\theta_1}\alpha_1|000001\rangle + e^{i\theta_2}\alpha_2|000010\rangle + \cdots$$

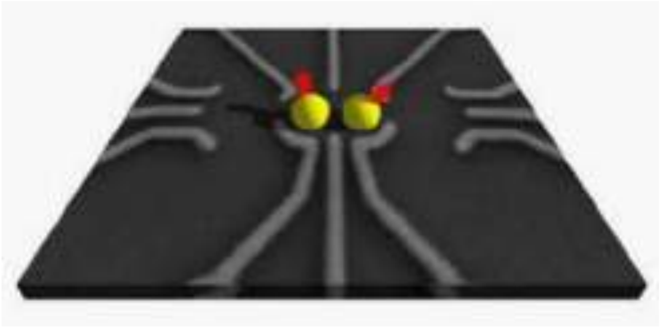
N qubits state = normalized vector in 2^N- D Hilbert space

Quantum computation = unitary transformation = physical evolution

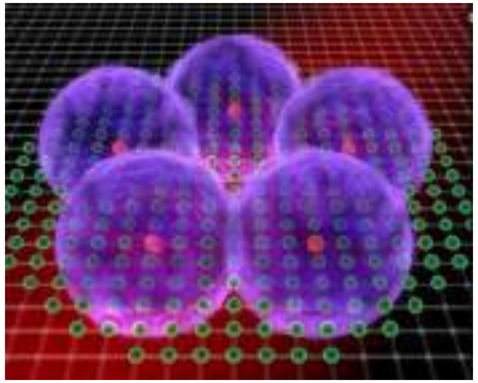
Physical platforms



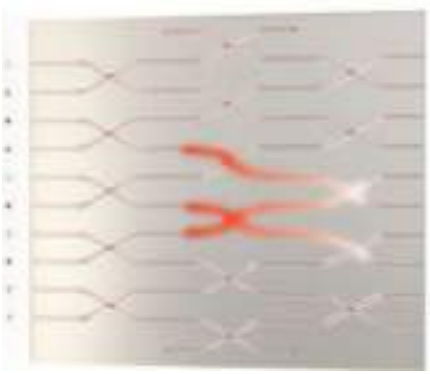
Trapped ions
(picture : Innsbruck university)



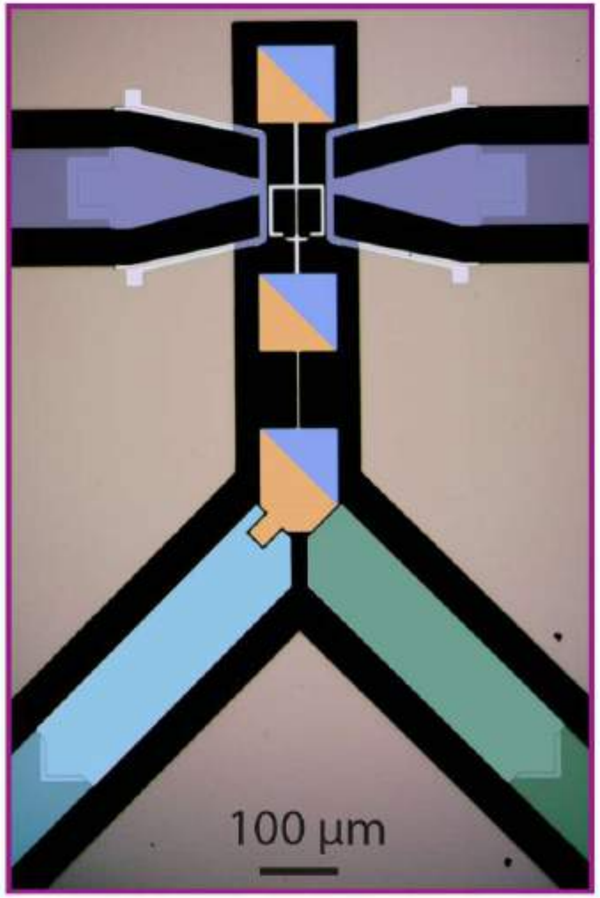
Spins in semiconductor
(picture : Basel university)



Rydberg atoms
(picture : Max Planck institute)

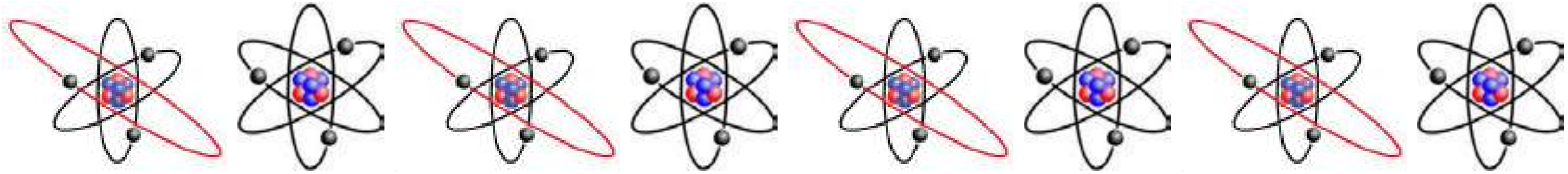


Photonic chips
(picture : Oxford)



Superconducting circuits

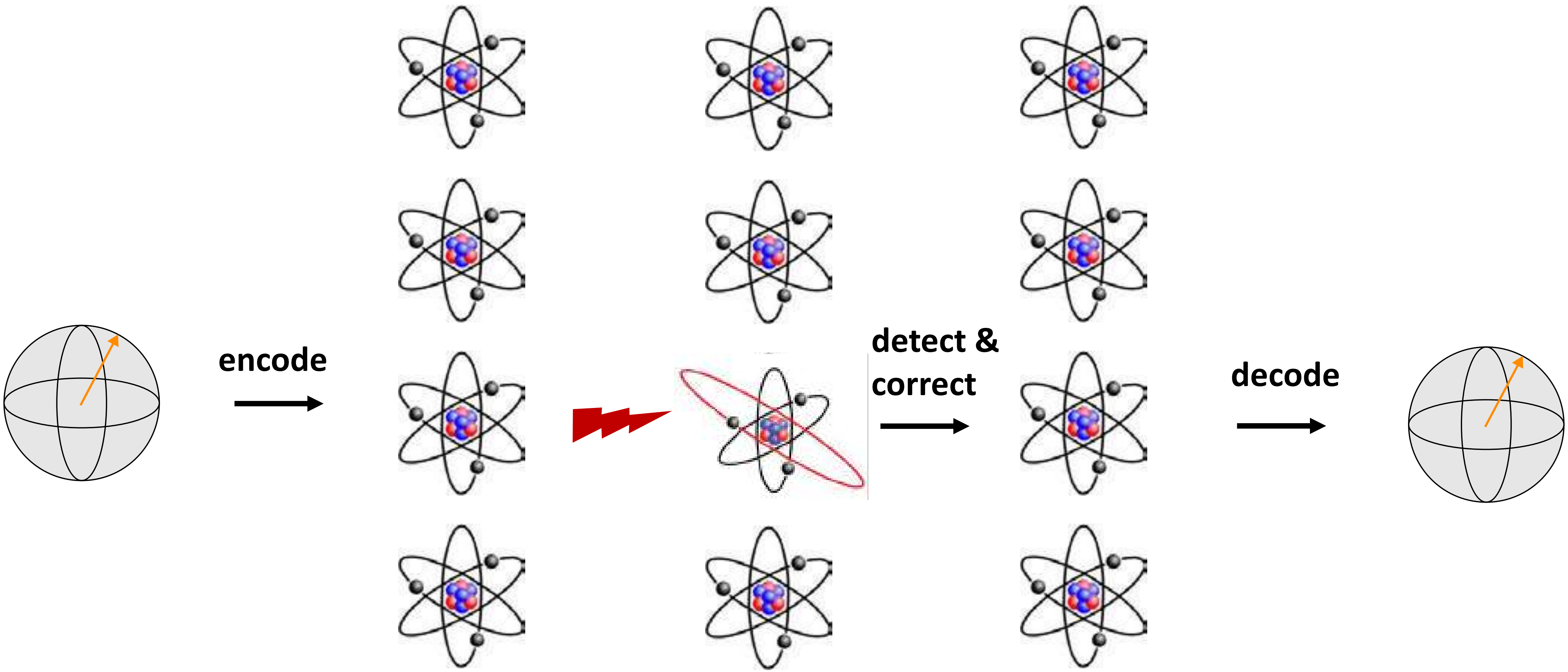
Noise



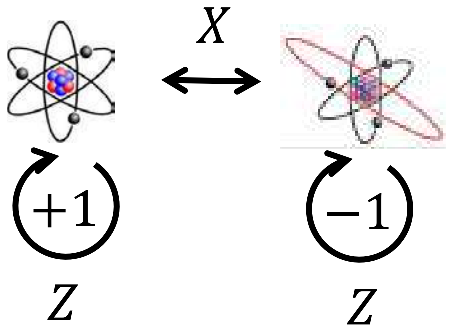
$$\alpha_0|000000\rangle + e^{i\tilde{\theta}_1}\alpha_1|000001\rangle + e^{i\theta_2}\tilde{\alpha}_2|000010\rangle + \cdots$$

Coupling to environment $\longrightarrow$ stochastic evolution

Quantum error-correction



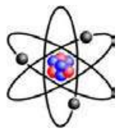
Bit flips and phase flips



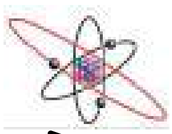
Bit flips

Phase flips

Discrete variable codes: repetition code



X



Bit flips

$+1$ $\quad Z$ $\qquad -1$ $\quad Z$

Phase flips

Noise is local (uncorrelated errors)

X_1, X_2, X_3

$|+Z_L\rangle = |0\rangle|0\rangle|0\rangle$

Z_1, Z_2, Z_3

$|1\rangle|0\rangle|0\rangle$

$|0\rangle|1\rangle|0\rangle$

$|0\rangle|0\rangle|1\rangle$

$|1\rangle|1\rangle|0\rangle$

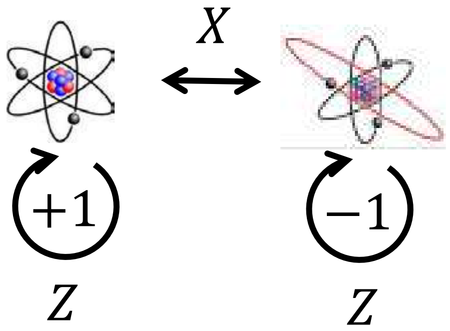
$|1\rangle|0\rangle|1\rangle$

$|0\rangle|1\rangle|1\rangle$

$|-Z_L\rangle = |1\rangle|1\rangle|1\rangle$

Stabilizers: $\{Z_1Z_2, Z_2Z_3, Z_3Z_1\}$

Discrete variable codes: repetition code



Bit flips

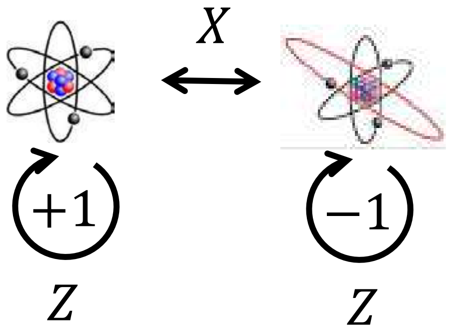
Phase flips

Noise is local (uncorrelated errors)

$$|+X_L\rangle = \frac{|+Z_L\rangle + |-Z_L\rangle}{\sqrt{2}} \xleftrightarrow{Z_1,\, Z_2,\, Z_3} |-X_L\rangle = \frac{|+Z_L\rangle - |-Z_L\rangle}{\sqrt{2}}$$

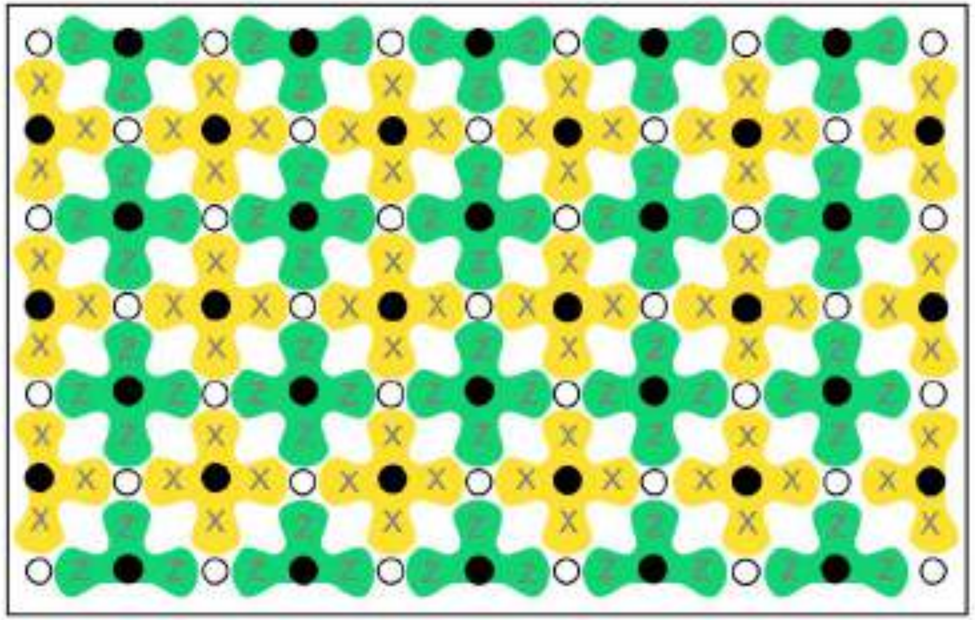
Discrete variable codes: surface code

Local noise:



Bit flips

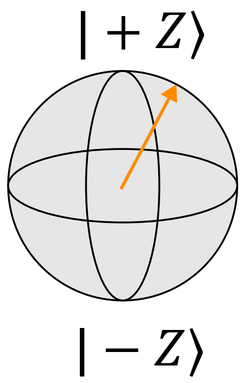
Phase flips

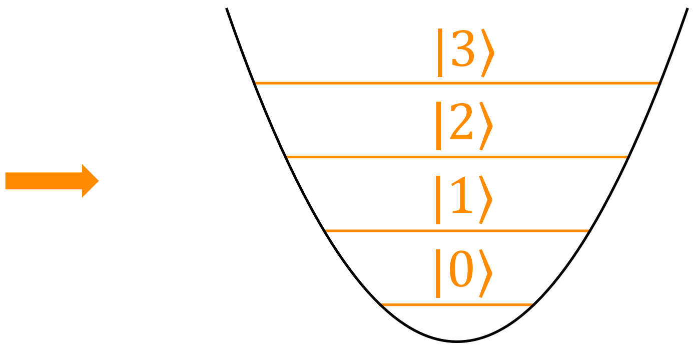


Fowler *et al.*, PRA 2012

Stabilizers: $\{Z_i Z_j Z_k Z_l, X_{i'} X_{j'} X_{k'} X_{l'}\}_{i,j,k,l \text{ and } i',j',k',l' \text{ adjacent}}$

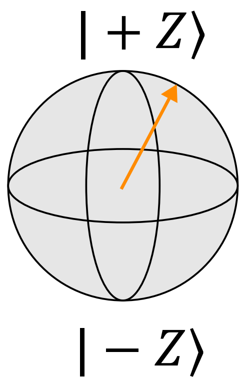
Bosonic qubits

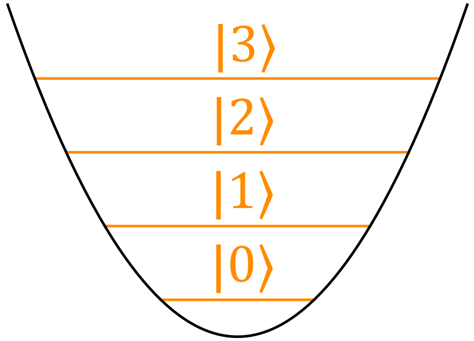




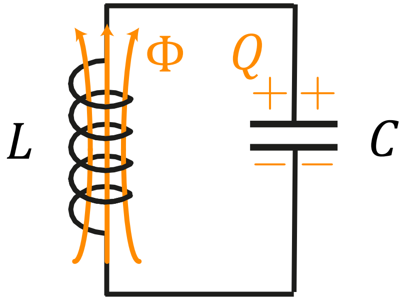
Harmonic oscillator

The harmonic oscillator





Harmonic oscillator



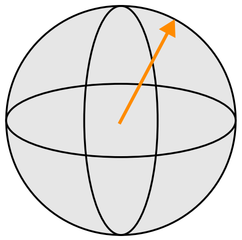
$$[\boldsymbol{\Phi}, \boldsymbol{Q}] = i\hbar$$

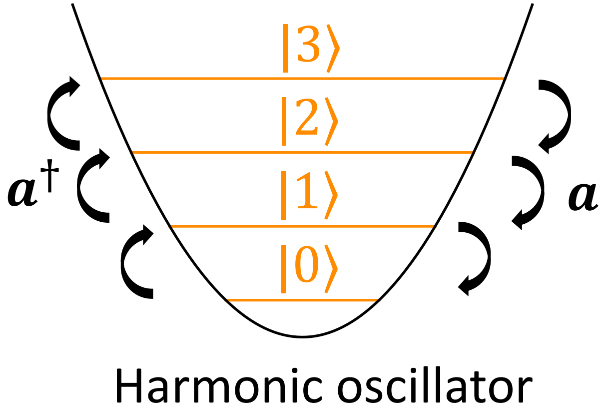
Dynamics (Schrödinger picture):

$$\boldsymbol{H_0} = \frac{1}{2C}\boldsymbol{Q}^2 + \frac{1}{2L}\boldsymbol{\Phi}^2$$

$$|\psi(t)\rangle = e^{-i\boldsymbol{H_0}t/\hbar}|\psi(0)\rangle$$

The harmonic oscillator

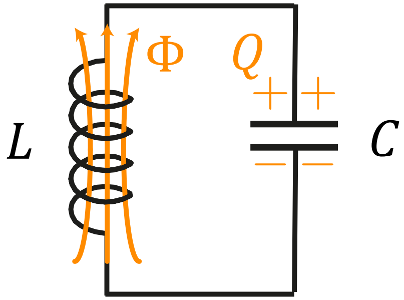




Dynamics (Schrödinger picture):

$$\boldsymbol{H_0} = \frac{1}{2}\omega\left(\boldsymbol{q_0^2} + \boldsymbol{p_0^2}\right)$$

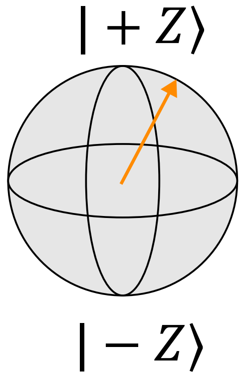
$$|\psi_0(t)\rangle = e^{-i\boldsymbol{H_0}t/\hbar}|\psi_0(t=0)\rangle$$

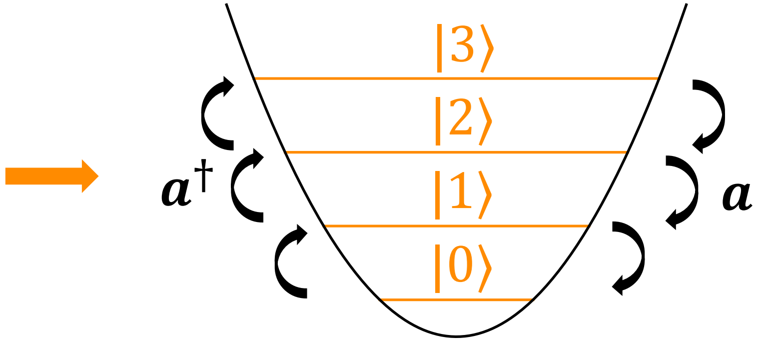


$$\omega = 1/\sqrt{LC} \qquad \boldsymbol{q_0} = (\hbar Z)^{-1/2}\,\boldsymbol{\Phi} \qquad \boldsymbol{a} = (\boldsymbol{q_0} + i\boldsymbol{p_0})/\sqrt{2} \qquad [\boldsymbol{q_0}, \boldsymbol{p_0}] = i$$

$$Z = \sqrt{L/C} \qquad \boldsymbol{p_0} = (Z/\hbar)^{\frac{1}{2}}\,\boldsymbol{Q} \qquad \boldsymbol{a}^\dagger = (\boldsymbol{q_0} - i\boldsymbol{p_0})/\sqrt{2} \qquad [\boldsymbol{a}, \boldsymbol{a}^\dagger] = 1$$

The harmonic oscillator





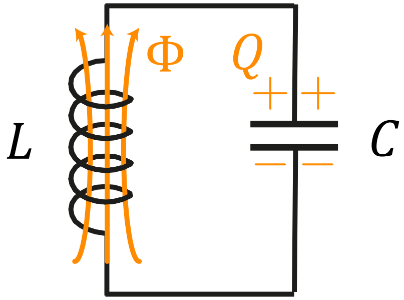
Harmonic oscillator

Dynamics (interaction picture):

$$|\psi(t)\rangle = |\psi(t=0)\rangle \qquad (\boldsymbol{H} = 0)$$

$$\boldsymbol{q} = e^{\frac{i\boldsymbol{H}_0 t}{\hbar}} \boldsymbol{q}_0 e^{-\frac{i\boldsymbol{H}_0 t}{\hbar}}$$

$$\boldsymbol{p} = e^{\frac{i\boldsymbol{H}_0 t}{\hbar}} \boldsymbol{p}_0 e^{-\frac{i\boldsymbol{H}_0 t}{\hbar}}$$



$$\omega = 1/\sqrt{LC} \qquad \boldsymbol{q}_0 = (\hbar Z)^{-1/2}\,\boldsymbol{\Phi} \qquad \boldsymbol{a} = (\boldsymbol{q}_0 + i\boldsymbol{p}_0)/\sqrt{2} \qquad [\boldsymbol{q}_0, \boldsymbol{p}_0] = i$$

$$Z = \sqrt{L/C} \qquad \boldsymbol{p}_0 = (Z/\hbar)^{\frac{1}{2}}\,\boldsymbol{Q} \qquad \boldsymbol{a}^\dagger = (\boldsymbol{q}_0 - i\boldsymbol{p}_0)/\sqrt{2} \qquad [\boldsymbol{a}, \boldsymbol{a}^\dagger] = 1$$

State representation

Wavefunction

$$\forall\, r \in \mathbb{R},\ \ \boldsymbol{q}|r\rangle_q = r|r\rangle_q$$
$$\boldsymbol{p}|r\rangle_p = r|r\rangle_p$$

$$\psi(r) = \ {}_q\langle r|\psi\rangle$$

$$\tilde{\psi}(r) = \ {}_p\langle r|\psi\rangle$$

Density matrix

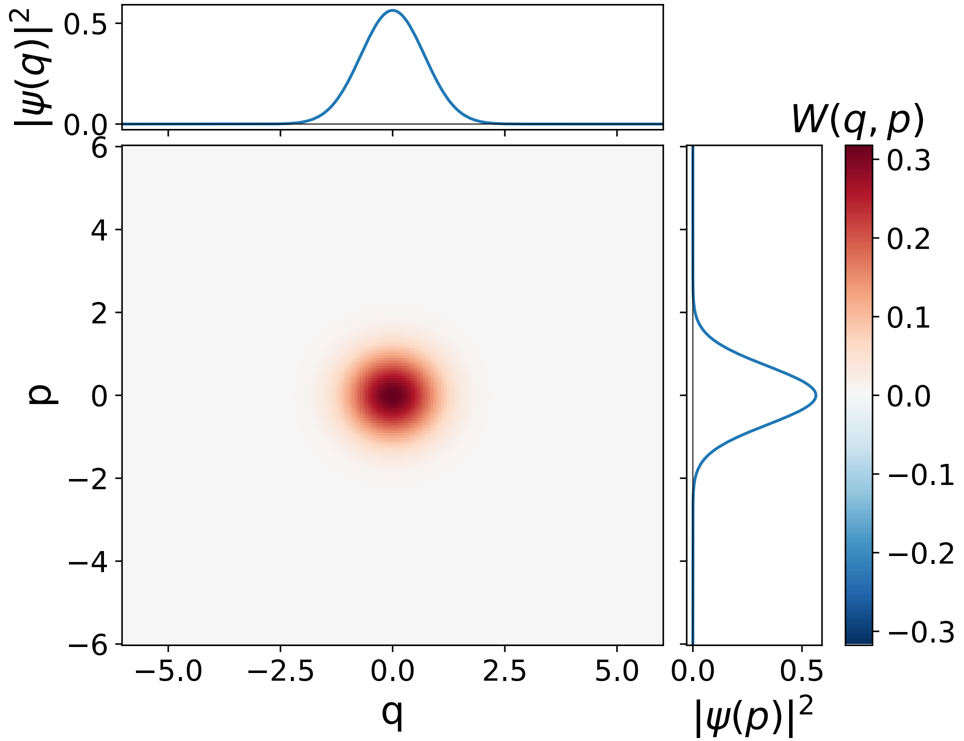
$$\rho = \sum_i p_i\, |\psi_i\rangle\langle\psi_i|$$

$$\sum_i p_i = 1$$

Wigner distribution

$$W(q,p) = \frac{1}{\pi}\int_{-\infty}^{\infty} \psi^*(q+r)\psi(q-r)e^{2ipr}\, dr$$

Vacuum state:



State representation

Wavefunction

$$\forall\, r \in \mathbb{R},\;\; \boldsymbol{q}|r\rangle_q = r|r\rangle_q$$
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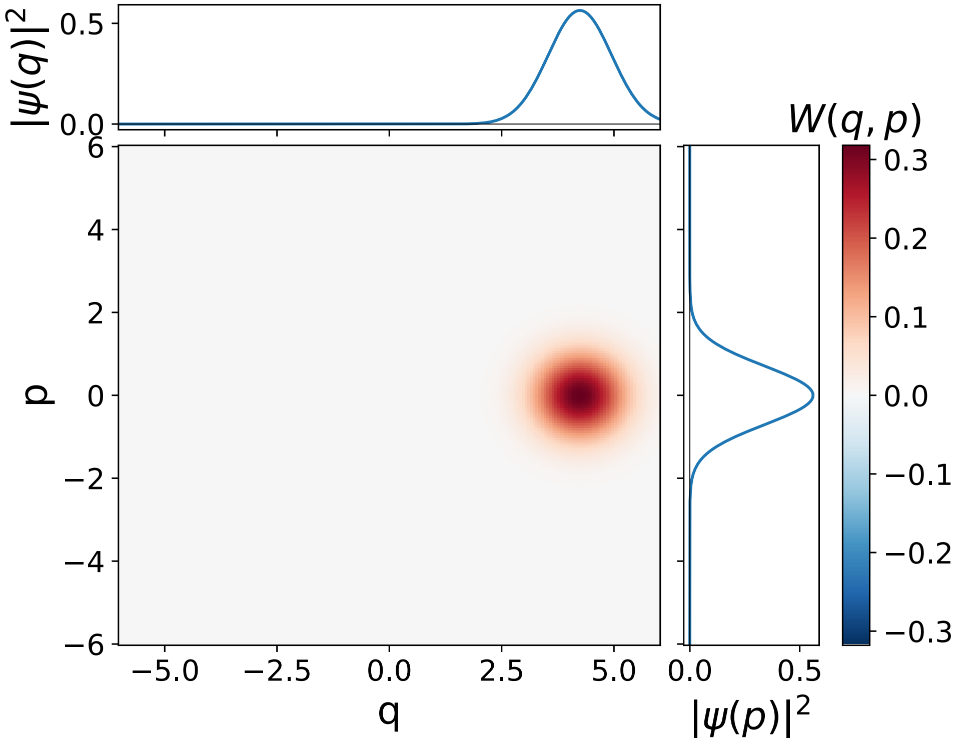
Wigner distribution

$$W(q,p) = \frac{1}{\pi}\int_{-\infty}^{\infty} \psi^*(q+r)\psi(q-r)e^{2ipr}\, dr$$

Coherent state:



State representation

Wavefunction

$$\forall\, r \in \mathbb{R},\ \ \boldsymbol{q}|r\rangle_q = r|r\rangle_q$$
$$\boldsymbol{p}|r\rangle_p = r|r\rangle_p$$

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$$\tilde{\psi}(r) = \ {}_p\langle r|\psi\rangle$$

Density matrix

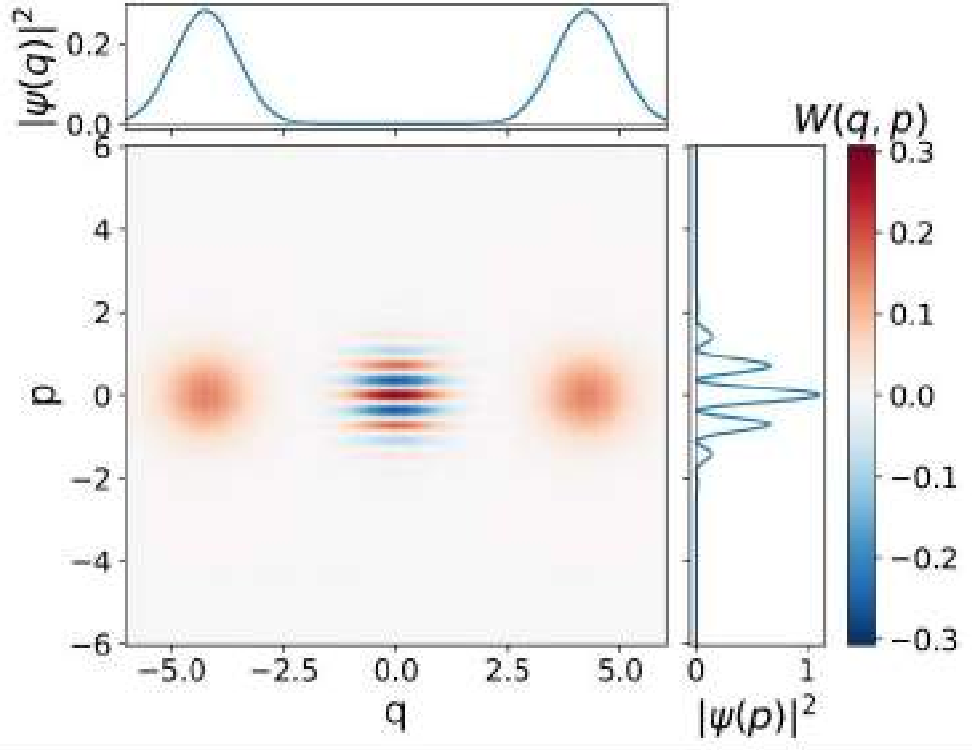
$$\rho = \sum_i p_i\,|\psi_i\rangle\langle\psi_i|$$

$$\sum_i p_i = 1$$

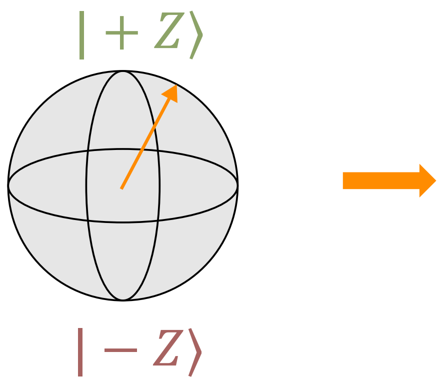
Wigner distribution

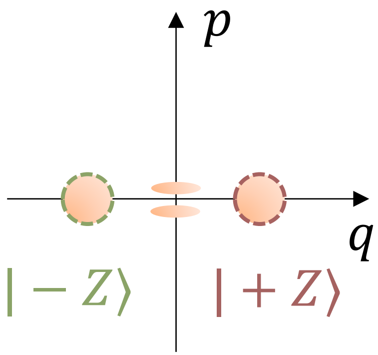
$$W(q,p) = \frac{1}{\pi}\int_{-\infty}^{\infty} \psi^*(q+r)\psi(q-r)e^{2ipr}\,dr$$

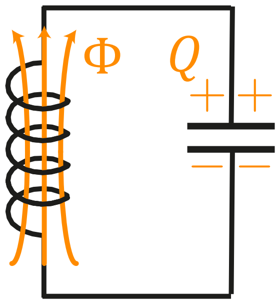
Cat state:



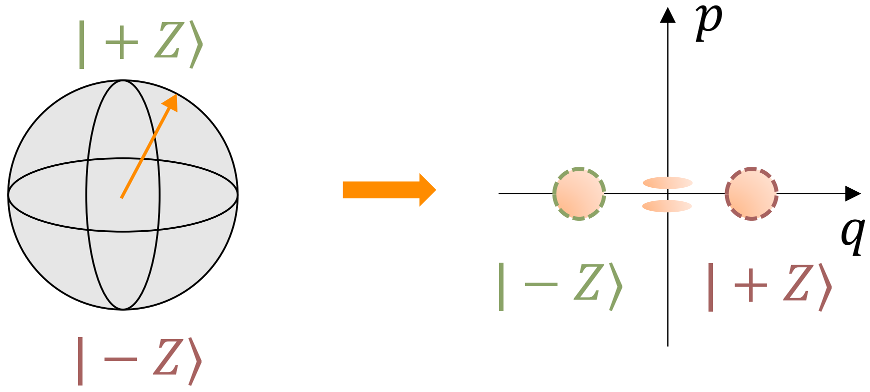
Noise structure

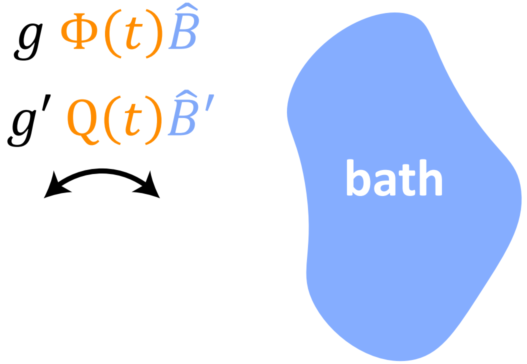


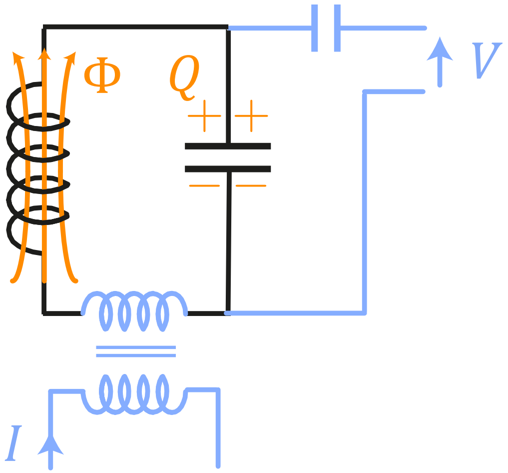




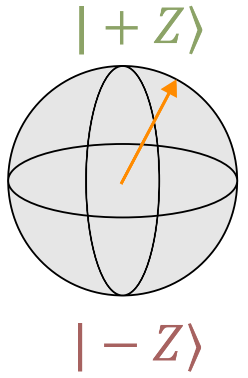
Noise structure

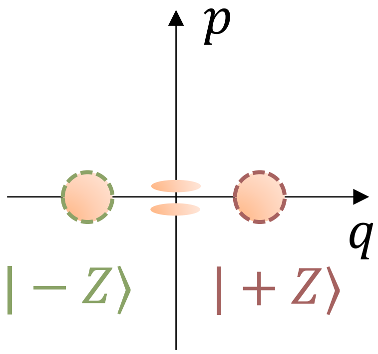






Noise structure





$g\ \Phi(t)\hat{B}$

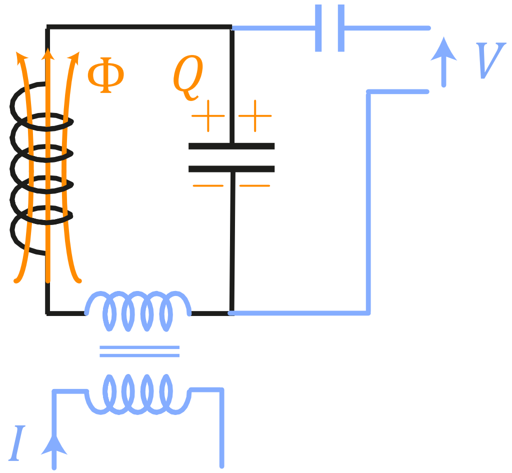
$g'\ \mathrm{Q}(t)\hat{B}'$

$\boldsymbol{S_{BB}(\pm\omega)}$

$\boldsymbol{S_{B'B'}(\pm\omega)}$

$\kappa\,(1+n_{th})\,\mathcal{D}[a]$

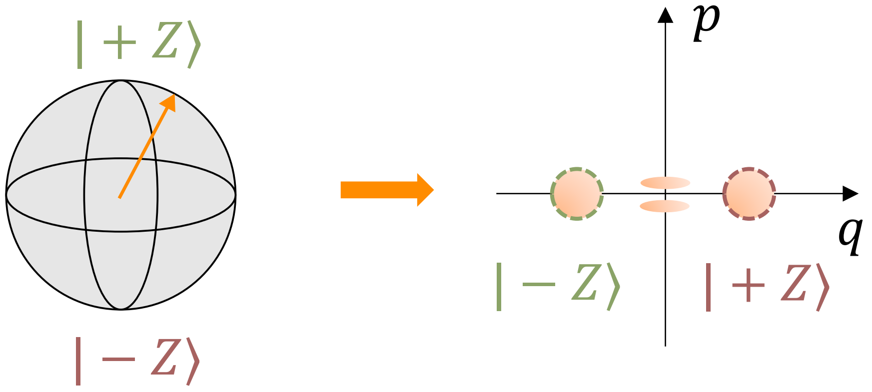
$\kappa\, n_{th}\,\mathcal{D}[a^\dagger]$



$$\dot{\rho} = \sum_i \mathcal{D}[L_i](\rho) = \sum_i L_i \rho L_i^\dagger - \frac{1}{2}(L_i^\dagger L_i \rho + \rho L_i^\dagger L_i)$$

Noise in non-linear circuits

Diffusive evolution



$g\ \Phi(t)\hat{B}$

$g'\ Q(t)\hat{B}'$

$S_{BB}(\pm\omega)$

$S_{B'B'}(\pm\omega)$

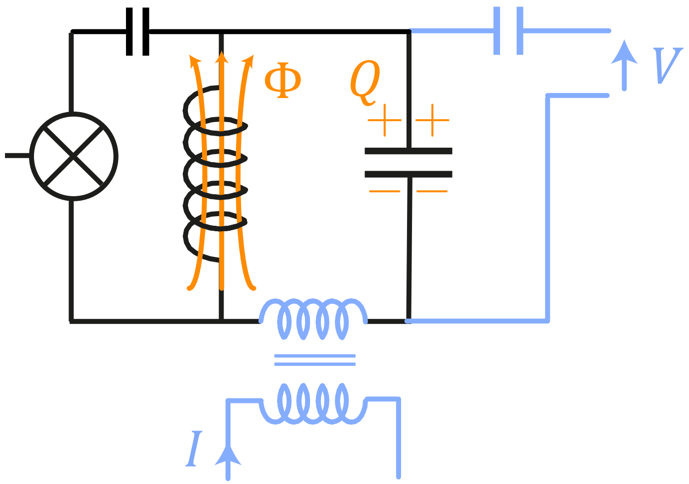
Low-order dissipators :

$\kappa\ (1+n_{th})\ \mathcal{D}[a]$

$\kappa\ n_{th}\ \mathcal{D}[a^\dagger]$

$2\kappa_\phi\ \mathcal{D}[a^\dagger a]$

...



$$H_c(t) = f(\Phi,t) = \sum_{n,k} f_{n,k}(t)\ \ (a^\dagger a)^k a^n + h.c.$$

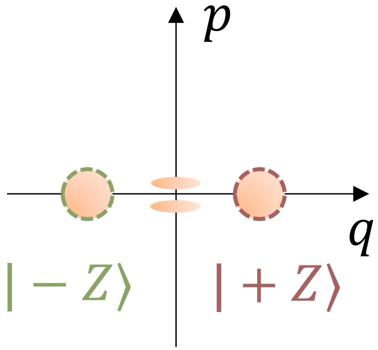
Low-order non-linearity : $f_{n,k} \xrightarrow{n,k\to\infty} 0$

$$\dot{\rho} = \sum_i \mathcal{D}[L_i](\rho) = \sum_i L_i\rho L_i^\dagger - \frac{1}{2}(L_i^\dagger L_i\rho + \rho L_i^\dagger L_i)$$

Noise in non-linear circuits

Diffusive evolution

Distant states → **no flip at short time**



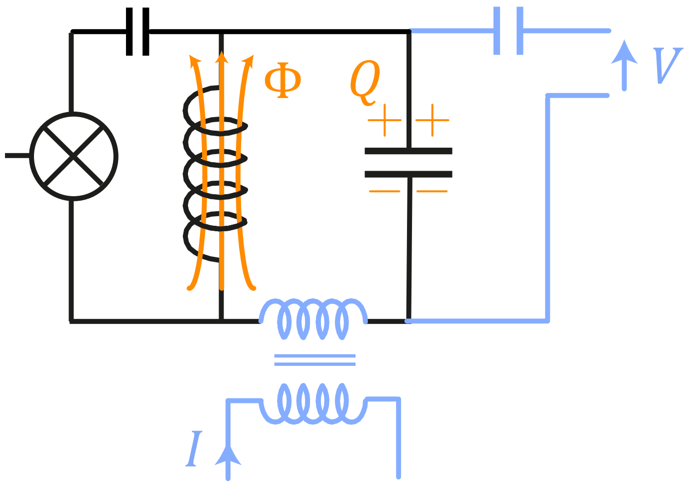
$g\ \Phi(t)\hat{B}$

$g'\ Q(t)\hat{B}'$

$S_{BB}(\pm\omega)$
$S_{B'B'}(\pm\omega)$

Low-order dissipators :

$$\kappa\,(1+n_{th})\,\mathcal{D}[a]$$
$$\kappa\, n_{th}\,\mathcal{D}[a^\dagger]$$
$$2\kappa_\phi\,\mathcal{D}[a^\dagger a]$$
…



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Outline

1. Bosonic codes: structure

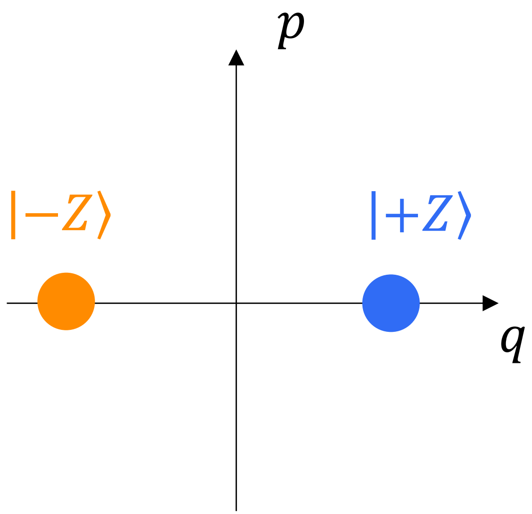
2. Bosonic codes: dissipative stabilization

3. First experimental steps

Schrödinger cat qubits

Code : $\mathrm{Span}\{|+\alpha\rangle, |-\alpha\rangle\}$

Stabilizer: $\boldsymbol{S} = \boldsymbol{a}^2 - \alpha^2 + 1$



$$|+X\rangle = |\mathcal{C}_\alpha^+\rangle \sim |+\alpha\rangle + |-\alpha\rangle \xleftrightarrow{\boldsymbol{a}} |-X\rangle = |\mathcal{C}_\alpha^-\rangle \sim |+\alpha\rangle - |-\alpha\rangle$$

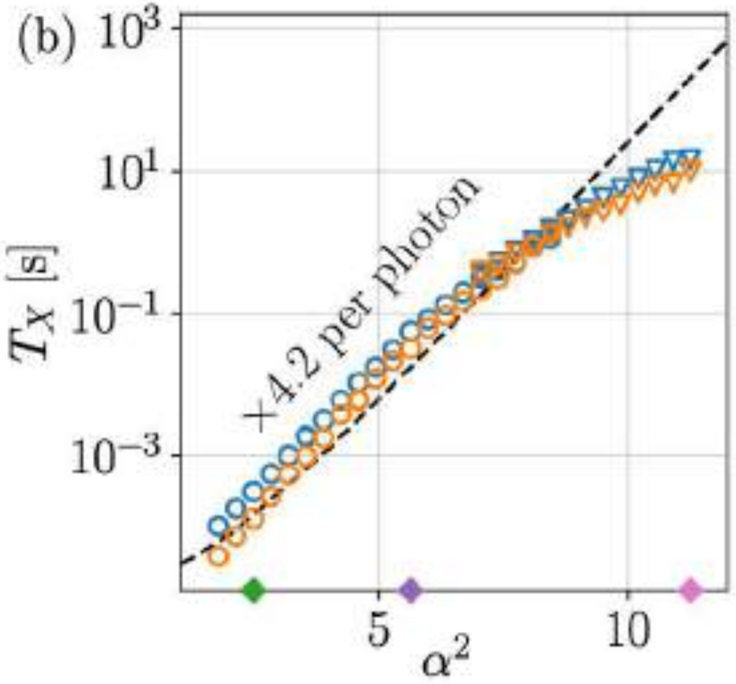
(Even) (Odd)

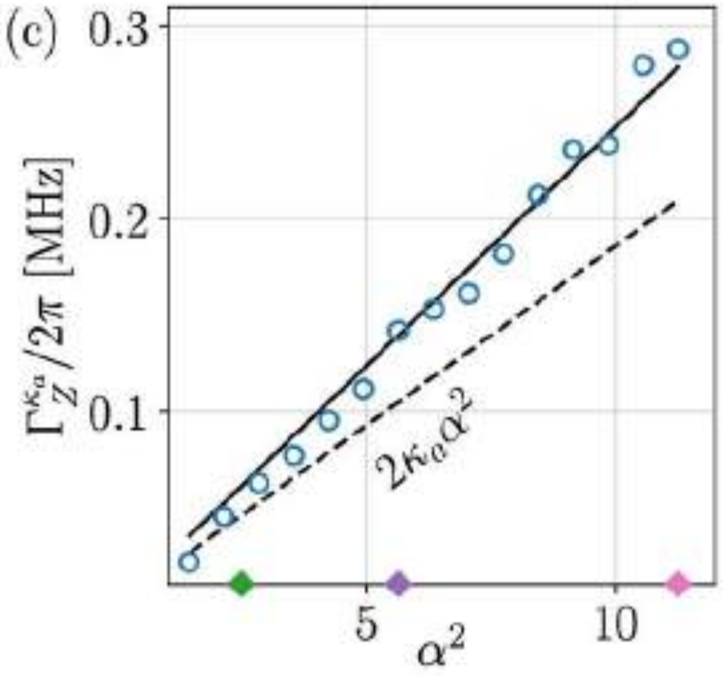
$$|\pm\alpha\rangle \sim \sum_n \frac{(\pm\alpha)^n}{\sqrt{n!}}|n\rangle$$

$$\boldsymbol{a}|\pm\alpha\rangle = \pm\alpha|\pm\alpha\rangle$$

Mirrahimi *et al.* , NJP 2014

A half-protected qubit





protected

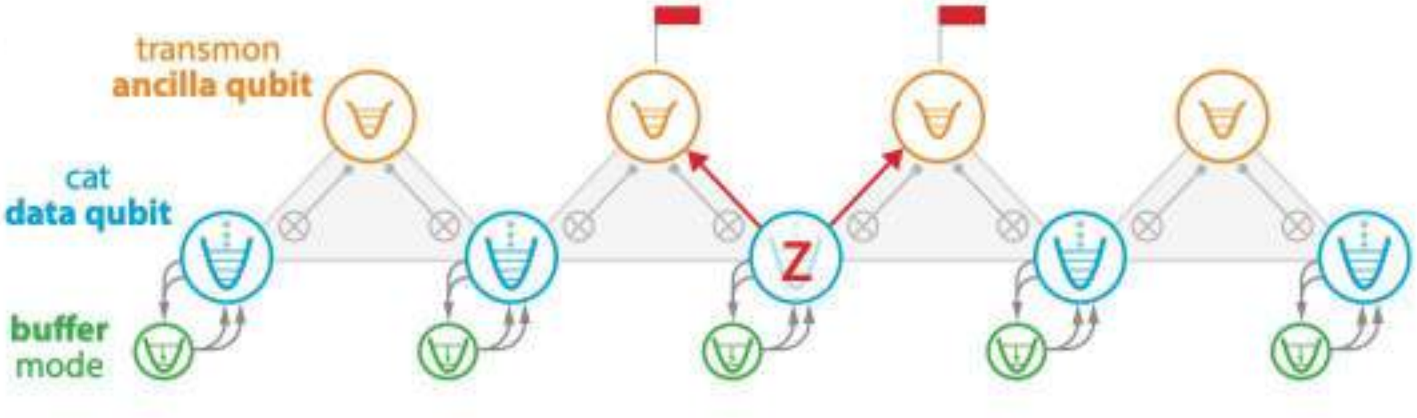
$|+Z\rangle = |\alpha\rangle \longleftrightarrow |-Z\rangle = |-\alpha\rangle$

$|+X\rangle = |\mathcal{C}_\alpha^+\rangle \xleftrightarrow{\boldsymbol{a}} |-X\rangle = |\mathcal{C}_\alpha^-\rangle$

(Even) (Odd)

Réglade *et al.* , Nature 2024

Repetition cat code

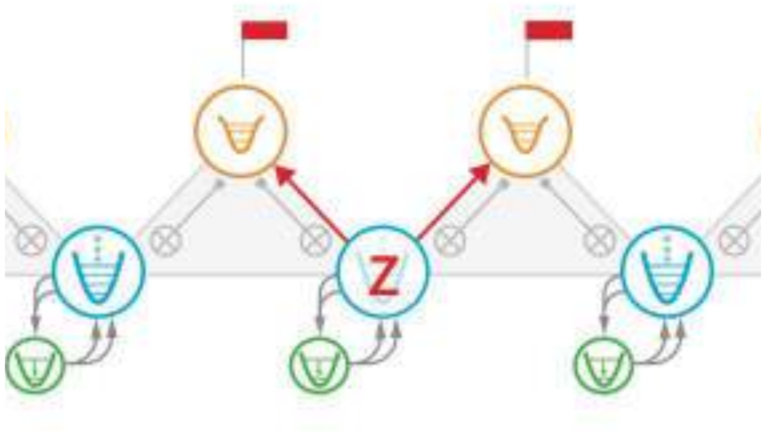


Guillaud & Mirrahimi, PRX, 2019

Putterman *et al.*, Nature, 2025

$X_i X_j$ (joint parity) $\longrightarrow$ photon-loss detection

Repetition cat code



Guillaud, Mirrahimi, PRX, 2019

Putterman *et al.* , Nature, 2025

$$S_i = a_i^2 - \alpha^2 + 1 \; (i = 1,2,3)$$

Distant vs photon loss

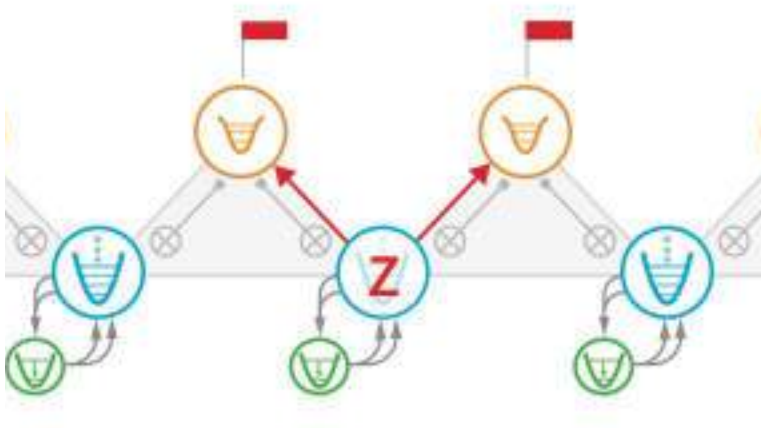
$\boldsymbol{a}$

$$|\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^+\rangle \longleftrightarrow |\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^+\rangle$$

$$|+X\rangle = |\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^+\rangle \longleftrightarrow |\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^+\rangle \qquad |\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^-\rangle \longleftrightarrow |-X\rangle = |\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^-\rangle$$

$$|\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^-\rangle \longleftrightarrow |\mathcal{C}_\alpha^+\rangle|\mathcal{C}_\alpha^-\rangle|\mathcal{C}_\alpha^-\rangle$$

Repetition cat code



Guillaud, Mirrahimi, PRX, 2019

Putterman *et al.*, Nature, 2025

$$S_i = a_i^2 - \alpha^2 + 1 \ (i = 1,2,3)$$

$$|+Z\rangle = |+\alpha\rangle|+\alpha\rangle|+\alpha\rangle + |+\alpha\rangle|-\alpha\rangle|-\alpha\rangle + |-\alpha\rangle|+\alpha\rangle|-\alpha\rangle + |-\alpha\rangle|-\alpha\rangle|+\alpha\rangle$$

Distant supports

$\longleftrightarrow$

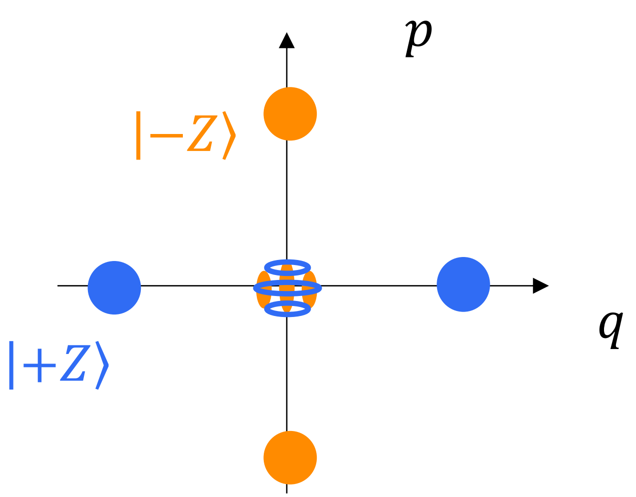
$$|-Z\rangle = |+\alpha\rangle|+\alpha\rangle|-\alpha\rangle + |+\alpha\rangle|-\alpha\rangle|+\alpha\rangle + |-\alpha\rangle|+\alpha\rangle|+\alpha\rangle + |-\alpha\rangle|-\alpha\rangle|-\alpha\rangle$$

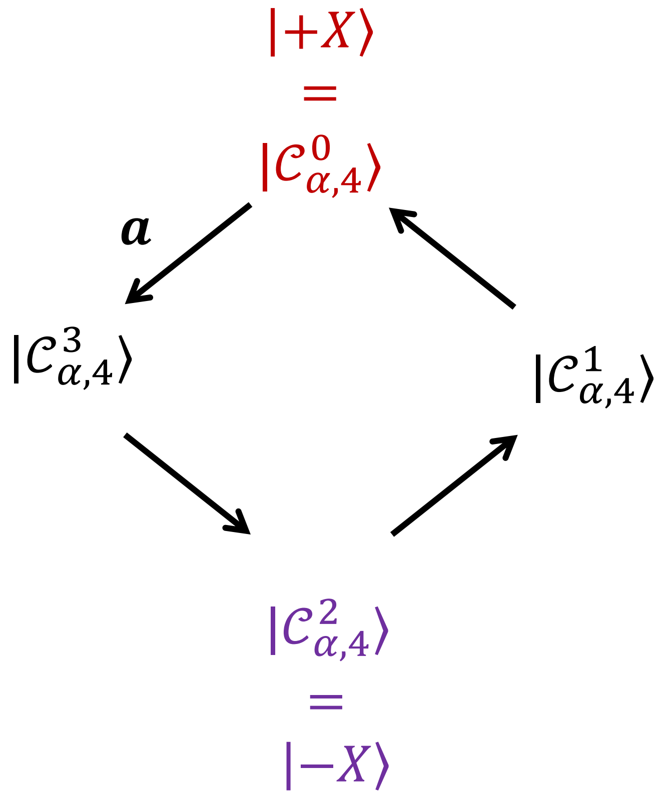
4-legged cat qubits

Code : $\mathrm{Span}\{|\mathcal{C}_\alpha^+\rangle, |\mathcal{C}_{i\alpha}^+\rangle\}$

Stabilizers: $\boldsymbol{S_{\alpha,4} = a^4} - \alpha^4 + 1$

$\boldsymbol{S_{\Pi,4} = e^{i\pi a^\dagger a}}$ ⟶ Photon-loss detection





Mirrahimi *et al.* , NJP 2014

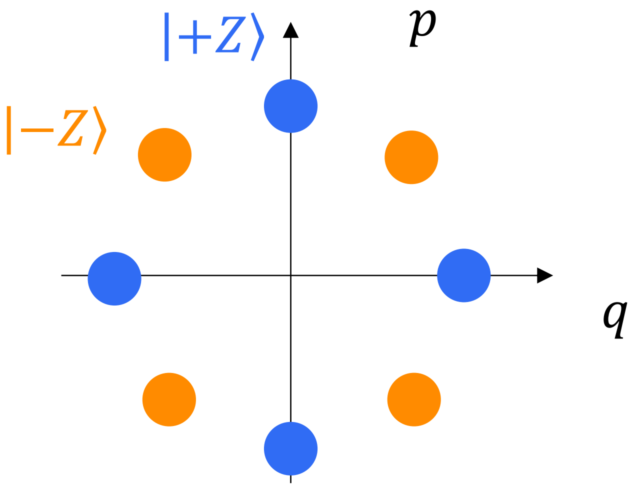
8-legged cat qubits

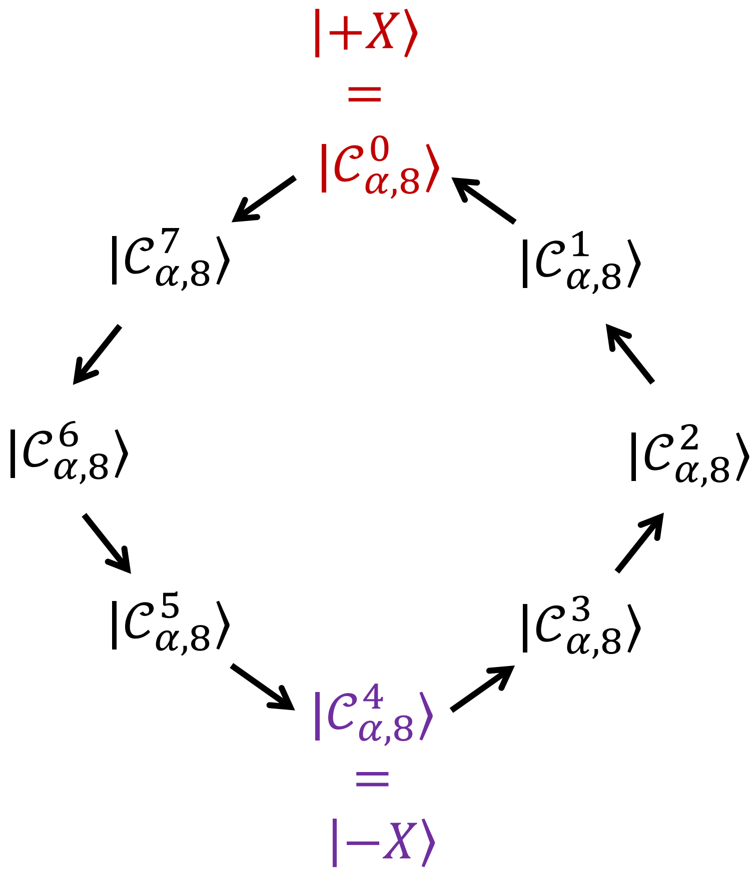
Code : $\mathrm{Span}\{|\mathcal{C}^0_{\alpha,4}\rangle, |\mathcal{C}^0_{e^{i\pi/4}\alpha,4}\rangle\}$

Stabilizers:

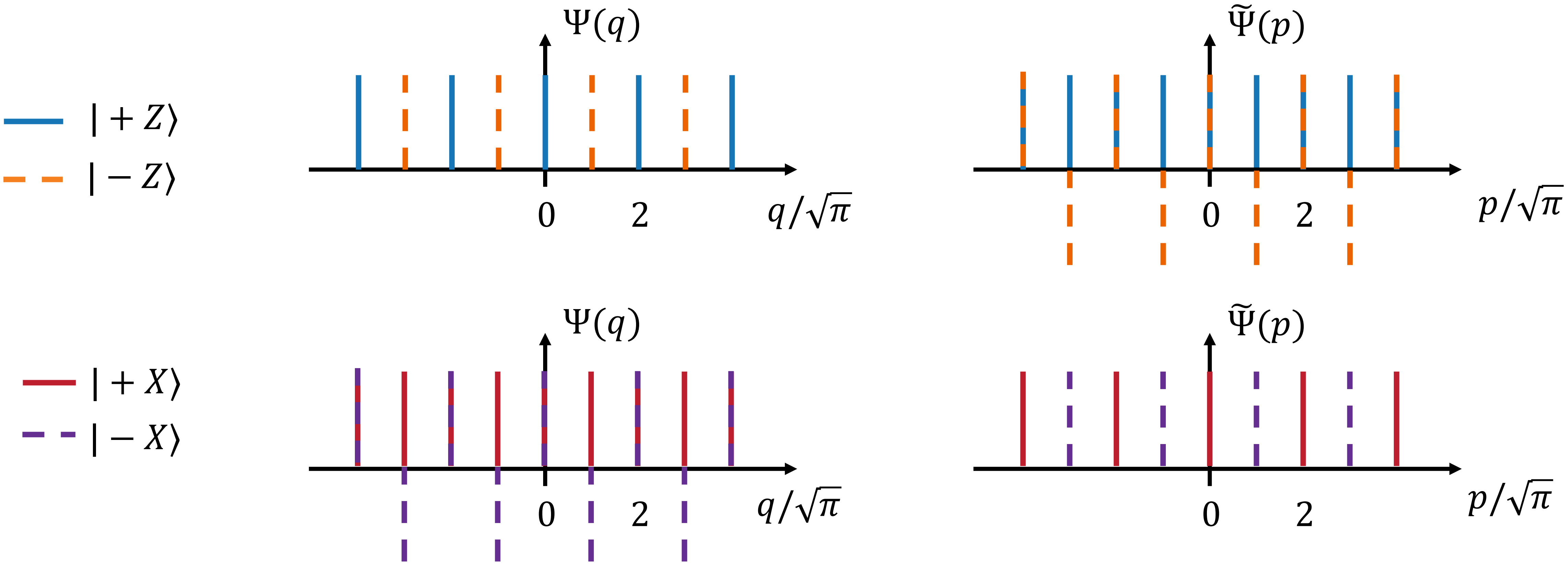
$$\boldsymbol{S_{\alpha,8} = a^8} - \alpha^8 + 1$$

$$\boldsymbol{S_{\Pi,8} = e^{\frac{i\pi}{2}a^\dagger a}} \longrightarrow \text{Photon-loss detection}$$





The GKP code



Stabilizers

$$S_q = e^{i2\sqrt{\pi}q}$$
$$S_p = e^{-i2\sqrt{\pi}p}$$

or

$$\tilde{S}_q = q \bmod \sqrt{\pi}$$
$$\tilde{S}_p = p \bmod \sqrt{\pi}$$

Logical operators

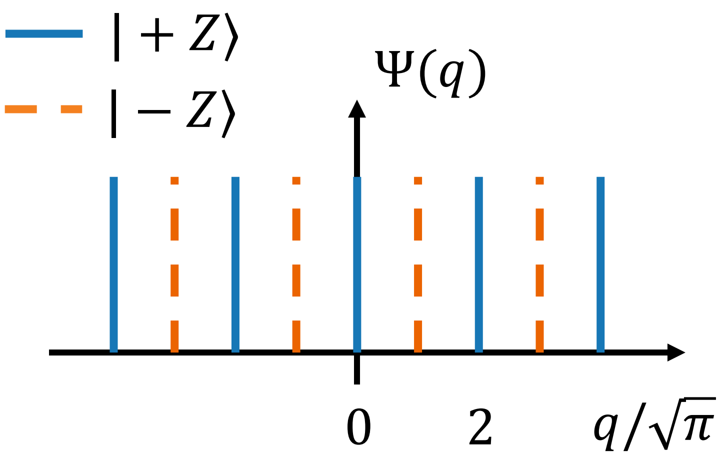
$$Z = e^{i\sqrt{\pi}q}$$
$$X = e^{-i\sqrt{\pi}p}$$
$$Y = e^{i\sqrt{\pi}(q-p)}$$

Gottesman, Kitaev, Preskill, PRA, 2001

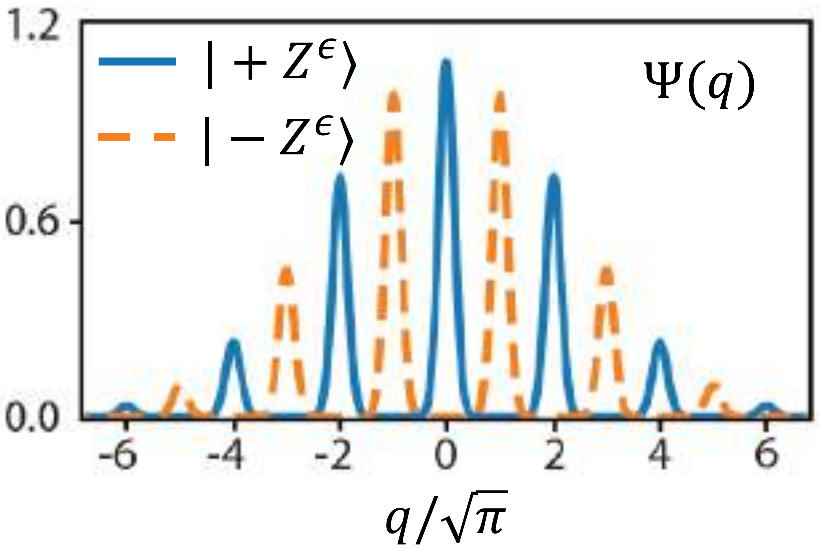
The finite-energy GKP code

$$\boldsymbol{O} = \boldsymbol{e}^{-\frac{\epsilon}{4\sqrt{\pi}}(q^2+p^2)}$$

Infinite-energy code → **Finite-energy code**



$$|\Psi_\epsilon\rangle = \boldsymbol{O}|\Psi\rangle$$



$$\boldsymbol{S_q} = e^{i2\sqrt{\pi}\boldsymbol{q}}$$
$$\boldsymbol{S_p} = e^{-i2\sqrt{\pi}\boldsymbol{p}}$$

$$\boldsymbol{S_\epsilon} = \boldsymbol{OSO^{-1}}$$

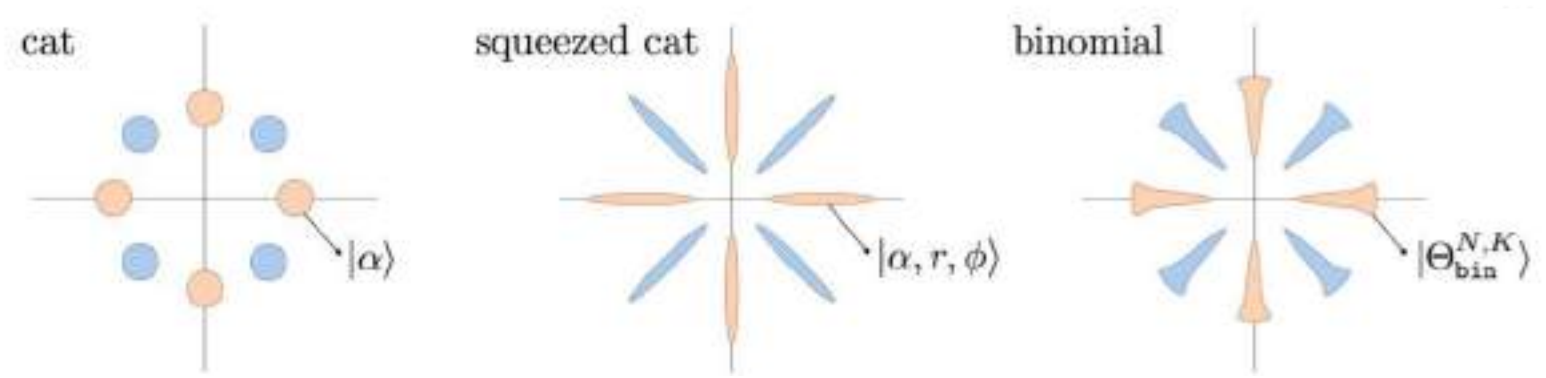
$$\boldsymbol{S_q^\epsilon} = \boldsymbol{e}^{i2\sqrt{\pi}\boldsymbol{q}-\epsilon\boldsymbol{p}}$$
$$\boldsymbol{S_p^\epsilon} = \boldsymbol{e}^{-i2\sqrt{\pi}\boldsymbol{p}-\epsilon\boldsymbol{q}}$$

Royer, *et al.*, PRL, 2020

Gottesman, Kitaev, Preskill, PRA, 2001

Advanced bosonic qubits

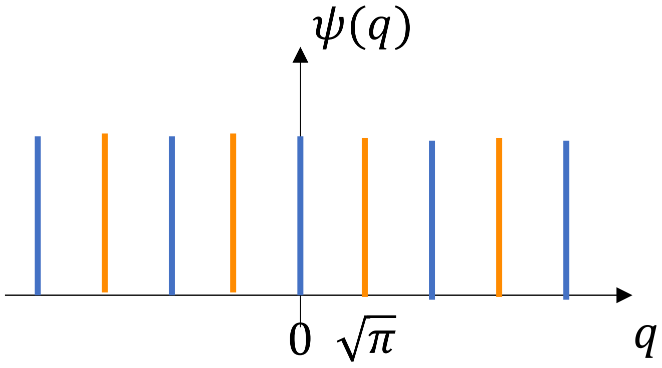
Rotation-symmetric codes Grimsmo, Combes, Baragiola., PRX 2020



$$S_n = U(a^n - \alpha^n + 1)U^\dagger$$

$$S_{\Pi,n} = e^{i\frac{4\pi}{n}a^\dagger a}$$

Translation-symmetric codes Gottesman, Kitaev, Preskill, PRA 2001



$$S_q = e^{i2\sqrt{\pi}q}$$

$$S_p = e^{i2\sqrt{\pi}p}$$

High-order stabilizers

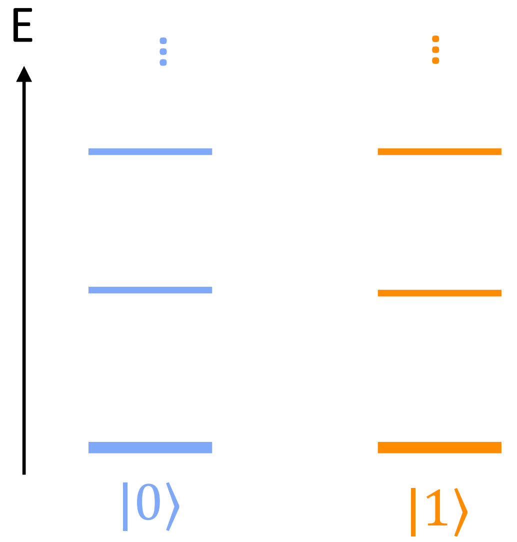
Outline

1. Bosonic codes: structure
2. Bosonic codes: dissipative stabilization
3. First experimental steps

Stabilization flavors

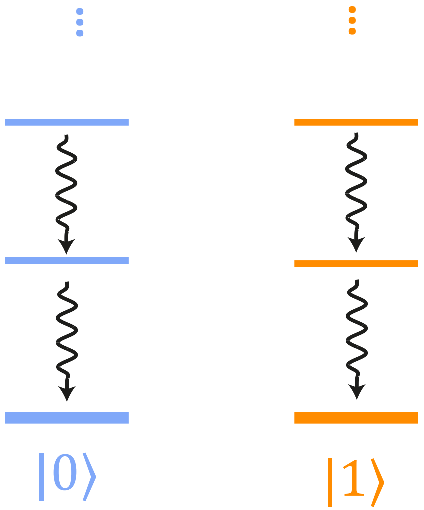
Hamiltonian

$$\boldsymbol{H} = K(\boldsymbol{S}-1)^{\dagger}(\boldsymbol{S}-1)$$



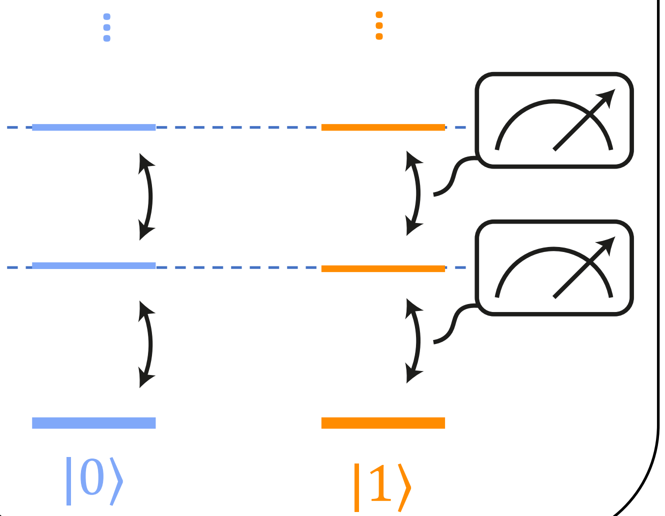
Dissipative

$$\kappa\, \mathcal{D}[\boldsymbol{S}-1]$$



Measurement-based

$$\kappa\, \mathcal{M}[\mathcal{R}(\boldsymbol{S})-1] + \text{feedback}$$



+ colored bath

Putterman, PRL, 2022

If feedback $\propto \Im(\boldsymbol{S})$

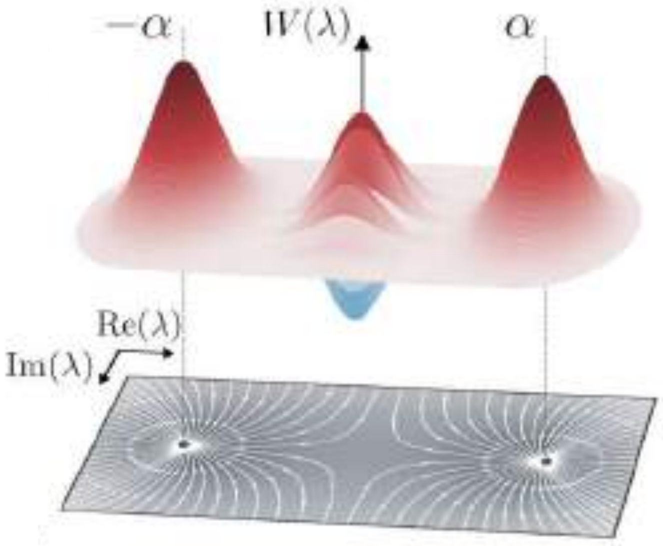
Chia, Wiseman, PRA 2011

Two-legged cat qubits

Code : $\text{Span}\{|+\alpha\rangle, |-\alpha\rangle\}$

Stabilizer: $\boldsymbol{S} = \boldsymbol{a^2} - \alpha^2 + 1$

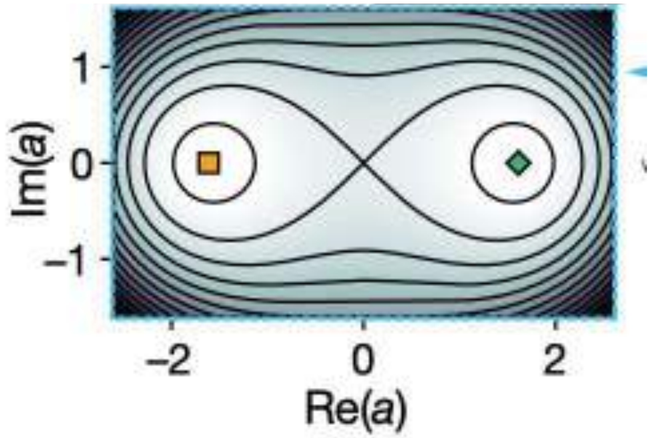
Dissipative



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

Réglade *et al.* , Nature 2024

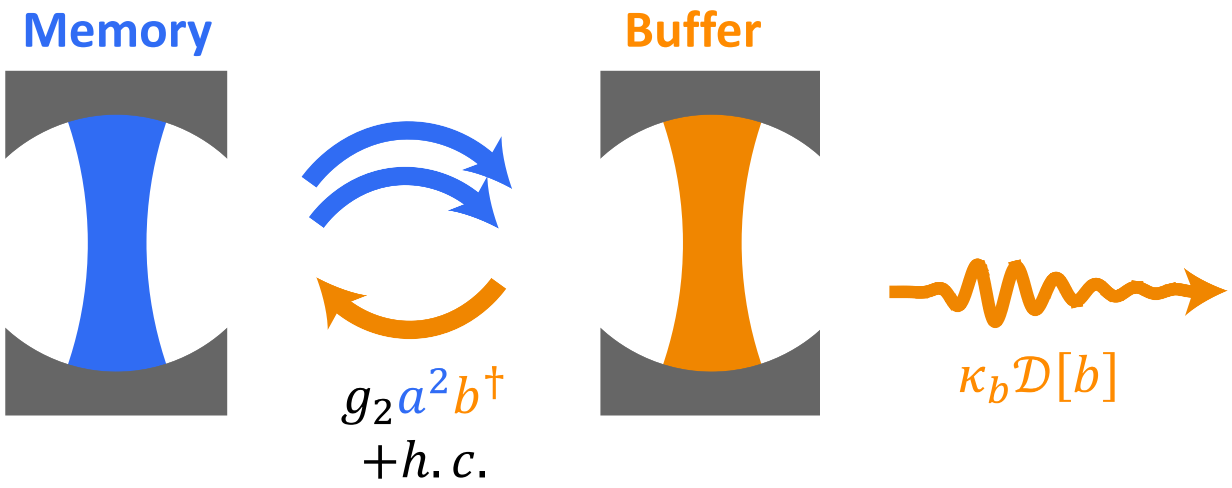
Hamiltonian



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

Grimm *et al.* , Nature 2020

Dissipative stabilization



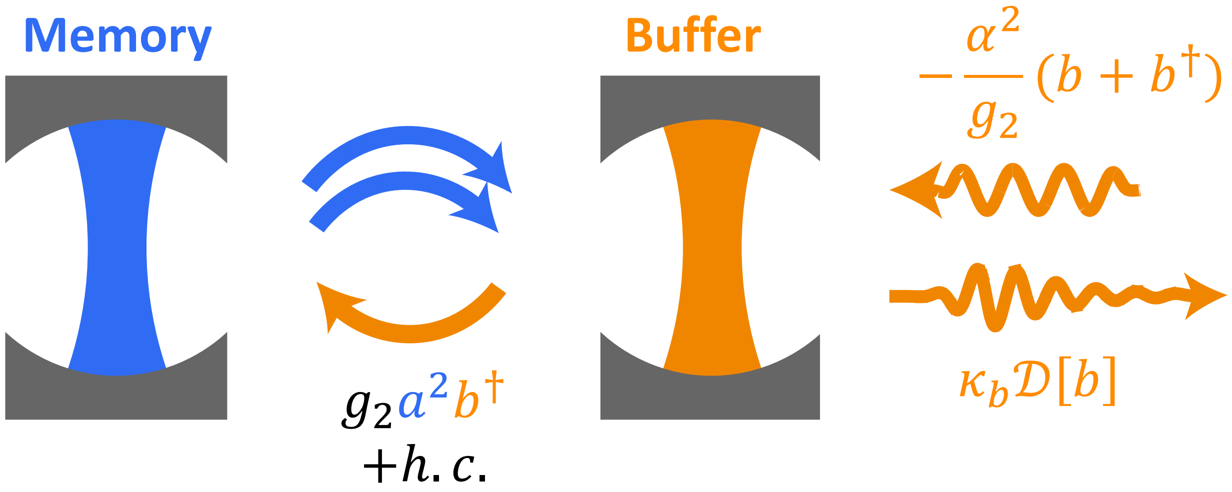
$$H_{int} = g_2\, a^2 b^\dagger + h.c. \xrightarrow{\text{Adiabatic elimination}} \kappa_2\, \mathcal{D}[a^2]$$

$$g_2 \ll \kappa_b$$

$$\kappa_2 = \frac{4g_2^2}{\kappa_b}$$

Robin, Rouchon, Sellem, Annales Henri Poincarré 2025

Dissipative stabilization



$H_{int} = g_2\,(a^2 - \alpha^2)b^\dagger + h.c.$

$g_2 \ll \kappa_b$

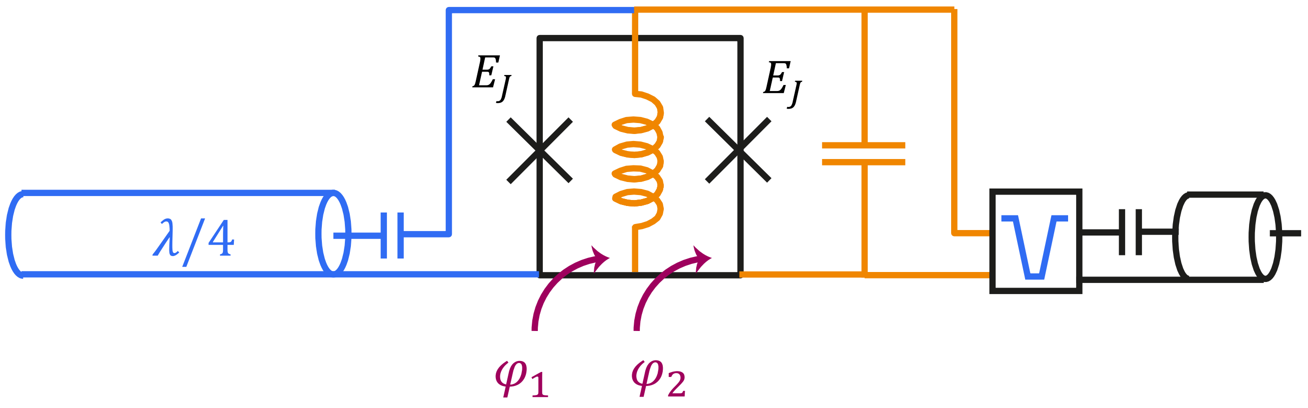
$\xrightarrow{\quad}$ Adiabatic elimination

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

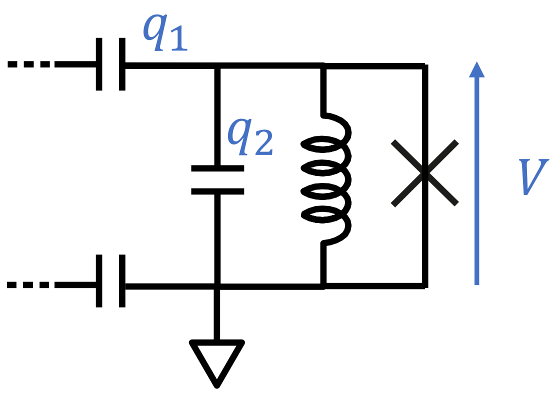
$$\kappa_2 = \frac{4g_2^2}{\kappa_b}$$

Robin, Rouchon, Sellem, Annales Henri Poincarré 2025

2-photon exchange



circuitQED cheat sheet



$$\Phi = \varphi_0 \varphi = \int_{-\infty}^{t} V(t')\, dt'$$

$$Q = q_1 + q_2$$

$$[\Phi, Q] = i\hbar$$

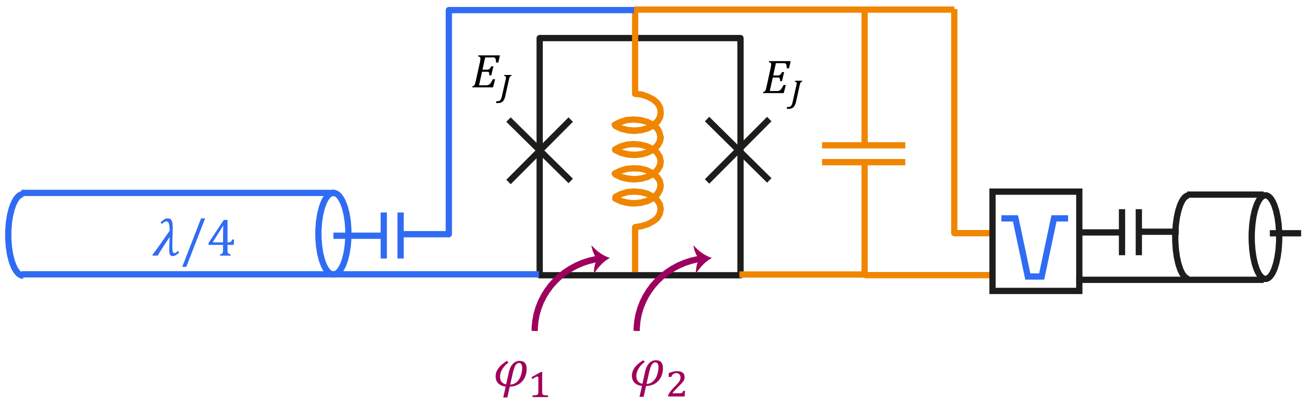
$$U_C = \frac{1}{2C} q^2$$

$$U_L = \frac{1}{2L} \Phi^2$$

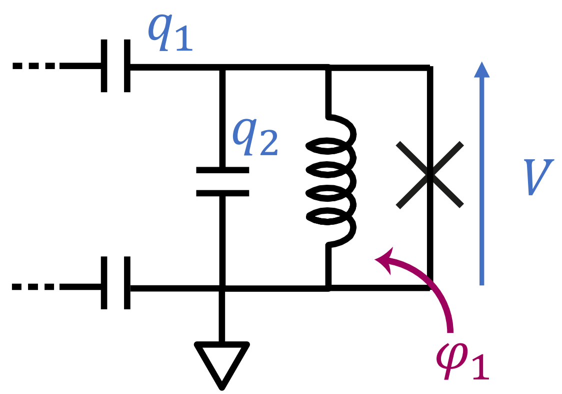
$$U_J = -E_J \cos(\varphi)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

2-photon exchange



circuitQED cheat sheet



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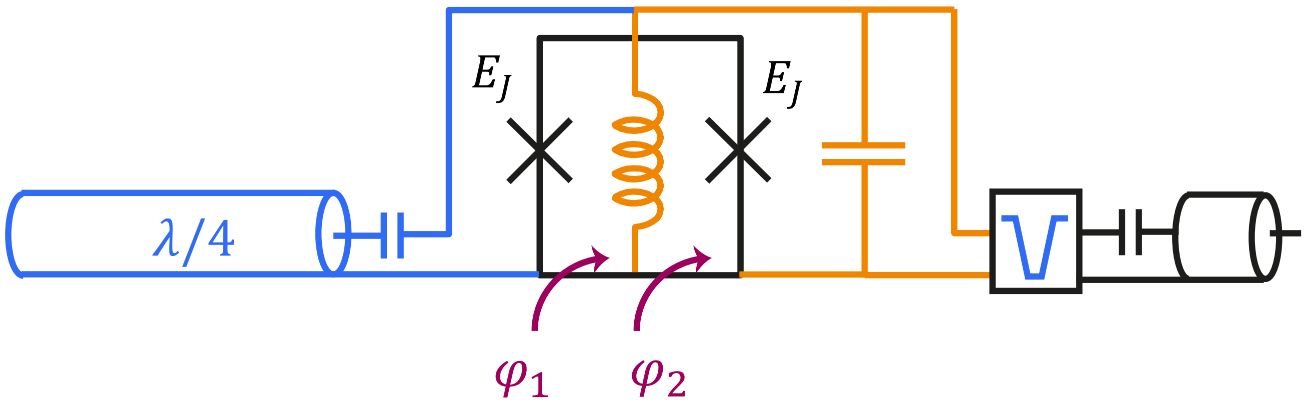
$$U_J = -E_J \cos(\varphi + \varphi_1)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

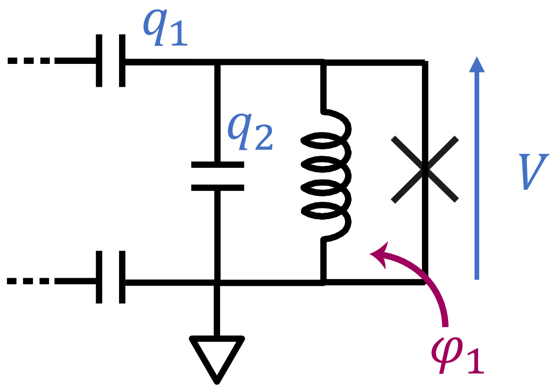
2-photon exchange



$$H = H_{quad} - E_J \cos(\varphi_{J_1} - \varphi_1) - E_J \cos(\varphi_{J_2} + \varphi_2)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

circuitQED cheat sheet



$$\Phi = \varphi_0 \varphi = \int_{-\infty}^{t} V(t')\, dt'$$

$$Q = q_1 + q_2$$

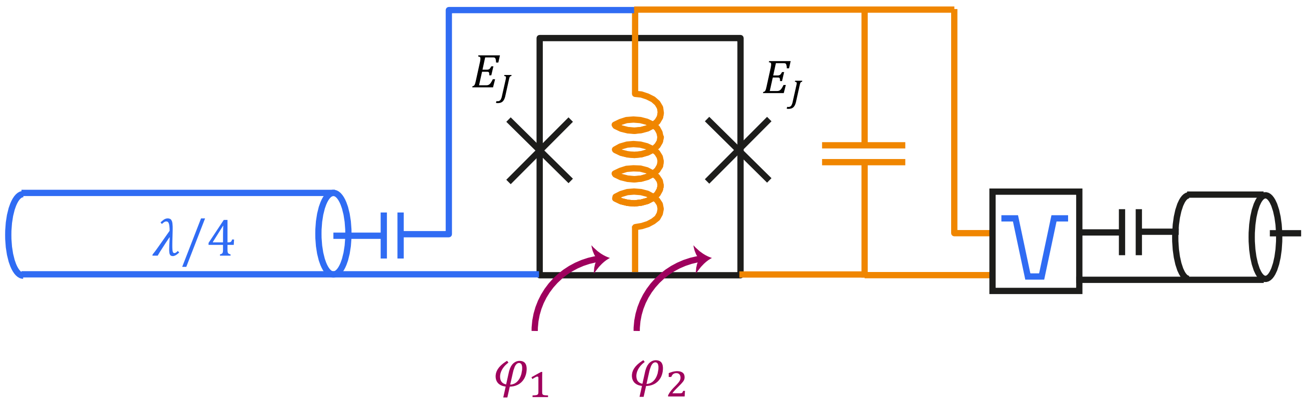
$$[\Phi, Q] = i\hbar$$

$$U_C = \frac{1}{2C} q^2$$

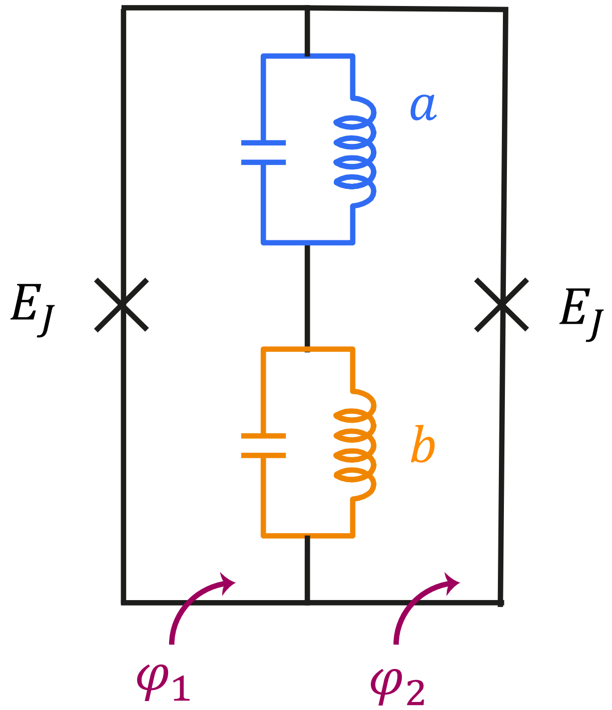
$$U_L = \frac{1}{2L} \Phi^2$$

$$U_J = -E_J \cos(\varphi + \varphi_1)$$

2-photon exchange



Equivalent circuit



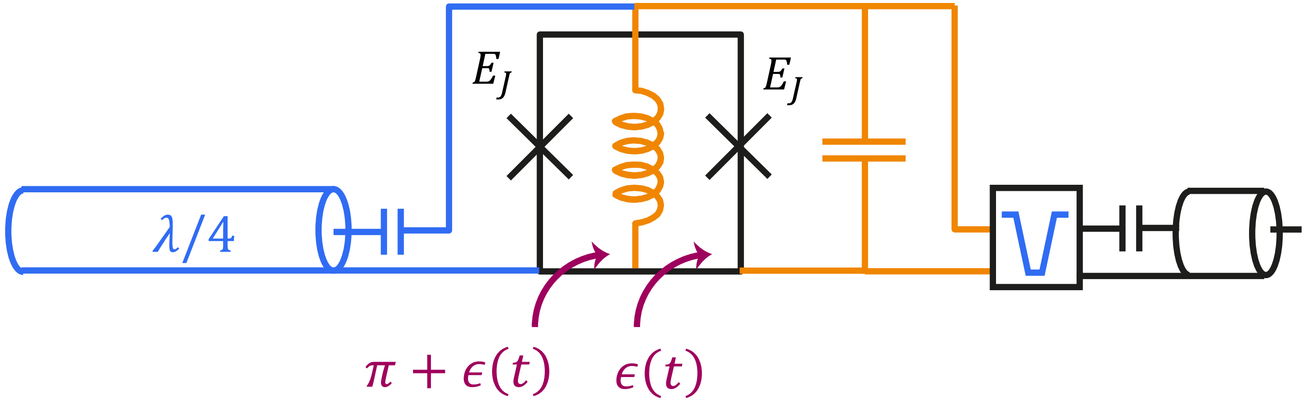
$$H = \omega_a a^\dagger a + \omega_b b^\dagger b - E_J \cos(\varphi_a + \varphi_b - \varphi_1) - E_J \cos(\varphi_a + \varphi_b + \varphi_2)$$

$$\varphi_{ZPF,a} = \sqrt{\pi Z_a / R_q} \qquad \varphi_a = \varphi_{ZPF,a}(a + a^\dagger)$$

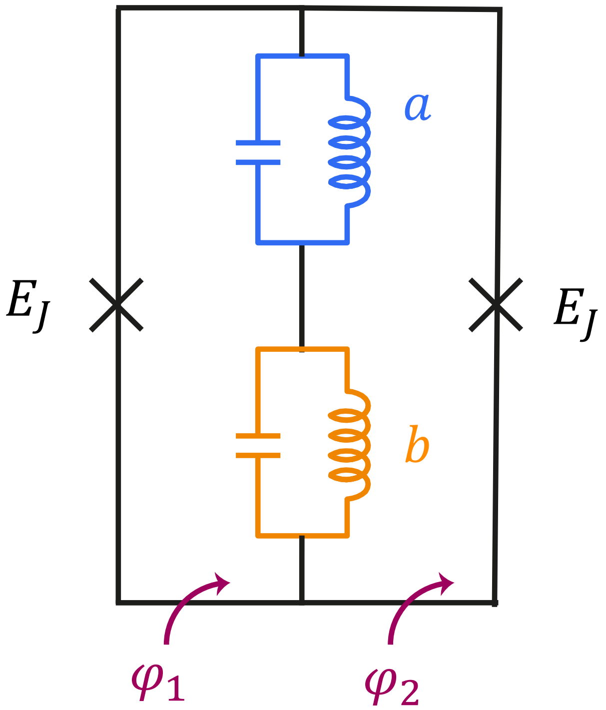
$$\varphi_{ZPF,b} = \sqrt{\pi Z_b / R_q} \qquad \varphi_b = \varphi_{ZPF,b}(b + b^\dagger)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

2-photon exchange



Equivalent circuit



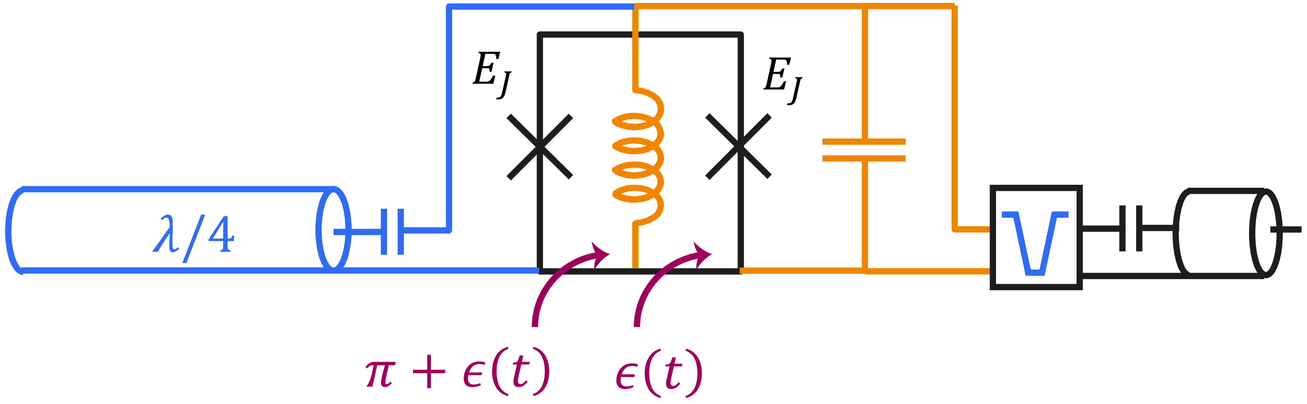
$$H = \omega_a a^\dagger a + \omega_b b^\dagger b - E_J \cos\big(\varphi_a + \varphi_b - \pi - \epsilon(t)\big) - E_J \cos\big(\varphi_a + \varphi_b + \epsilon(t)\big)$$

$$\varphi_{ZPF,a} = \sqrt{\pi Z_a / R_q} \qquad \varphi_a = \varphi_{ZPF,a}(a + a^\dagger)$$

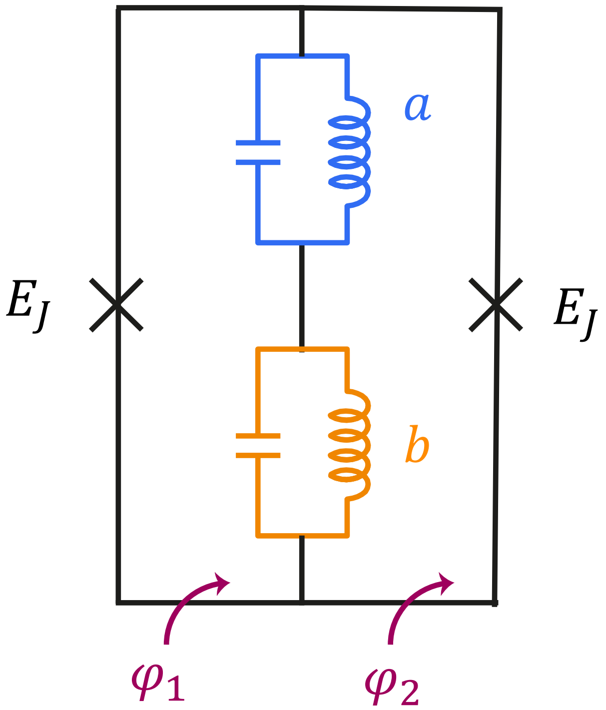
$$\varphi_{ZPF,b} = \sqrt{\pi Z_b / R_q} \qquad \varphi_b = \varphi_{ZPF,b}(b + b^\dagger)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

2-photon exchange



Equivalent circuit



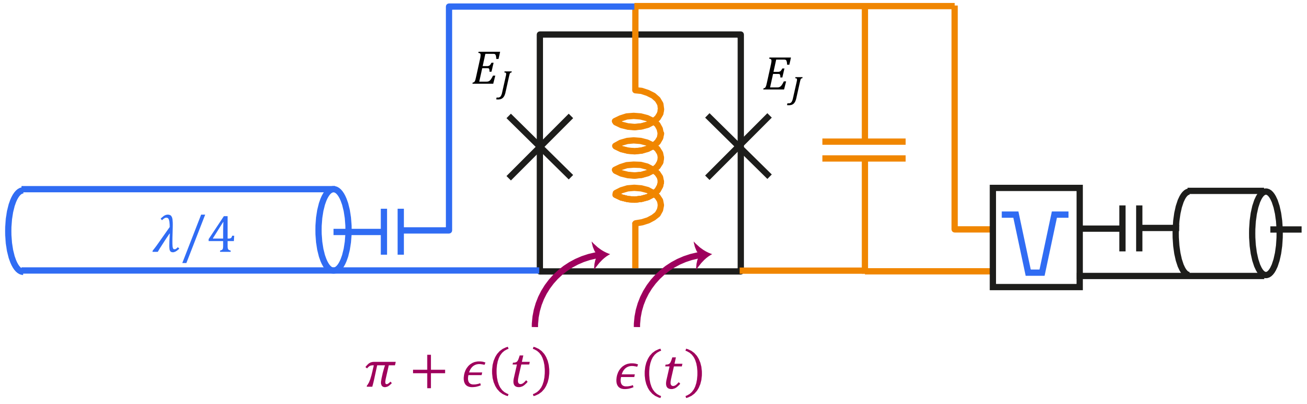
$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + 2E_J \sin(\epsilon(t)) \sin(\varphi_a + \varphi_b)$$

$$\varphi_{ZPF,a} = \sqrt{\pi Z_a / R_q} \qquad \varphi_a = \varphi_{ZPF,a}(a + a^\dagger)$$

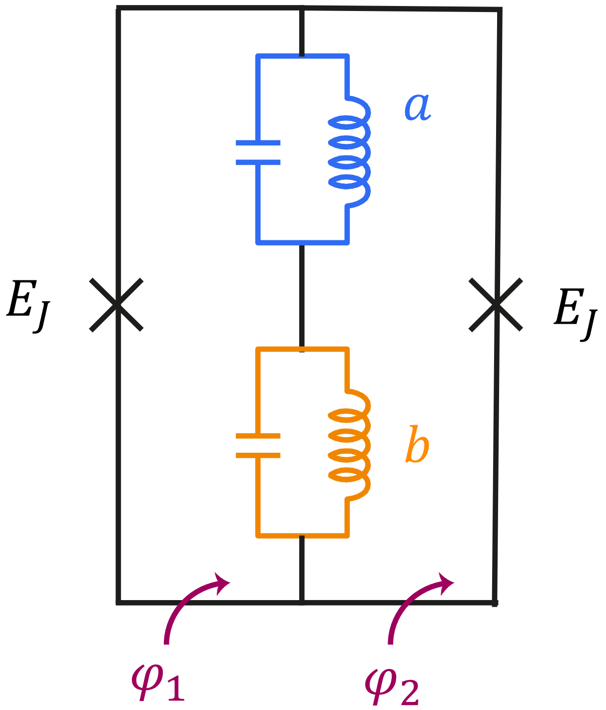
$$\varphi_{ZPF,b} = \sqrt{\pi Z_b / R_q} \qquad \varphi_b = \varphi_{ZPF,b}(b + b^\dagger)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

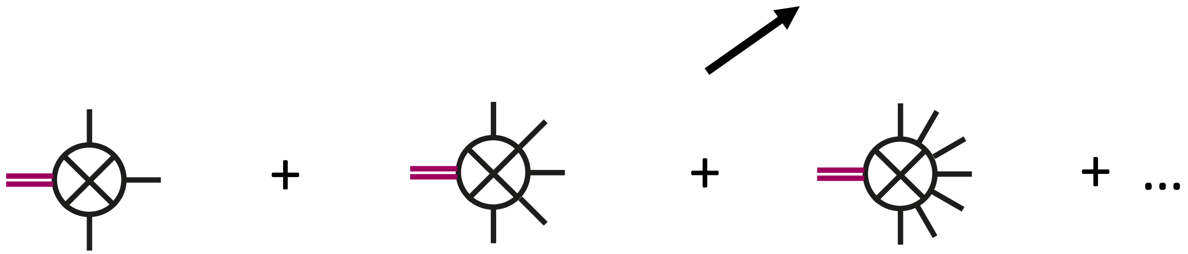
2-photon exchange



Equivalent circuit



$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + 2E_J \sin(\epsilon(t)) \sin(\varphi_a + \varphi_b)$$



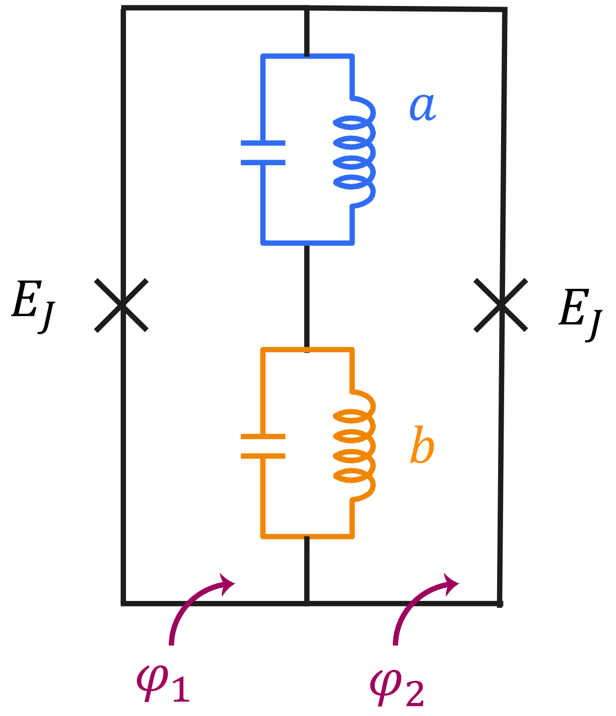
$$\varphi_a = \varphi_{ZPF,a}(a + a^\dagger)$$

$$\varphi_b = \varphi_{ZPF,b}(b + b^\dagger)$$

Asymmetrically Threaded SQUID: Lescanne *et al.* , Nat. Phys. 2020

2-photon exchange

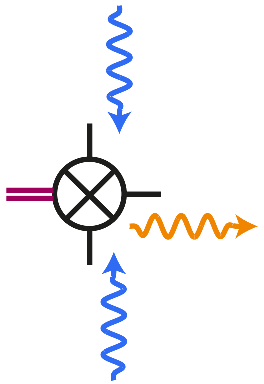
Equivalent circuit



Kerr-free
Operated at sweet-spot

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b + 2E_J \sin(\epsilon(t)) \sin(\varphi_a + \varphi_b)$$

$2\omega_a - \omega_b$



Rotate +
RWA

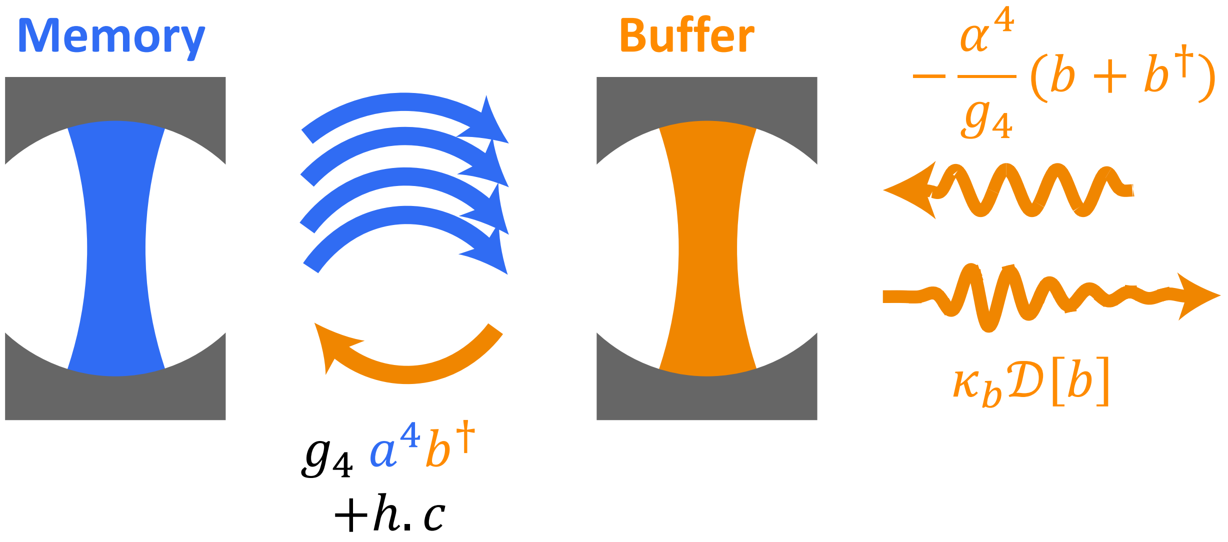
$$\varphi_{ZPF,a}^2 a^2 \varphi_{ZPF,b} b^\dagger + h.c.$$

$$+\mathcal{O}(\varphi_{ZPF}^5)$$

$$\varphi_a = \varphi_{ZPF,a}(a + a^\dagger)$$

$$\varphi_b = \varphi_{ZPF,b}(b + b^\dagger)$$

Dissipative stabilization of 4-legged cats



$H_{int} = g_4\,(a^4 - \alpha^4) b^\dagger + h.c.$ $\longrightarrow$ $\kappa_4\, \mathcal{D}[a^4 - \alpha^4]$

$g_4 \ll \kappa_b$

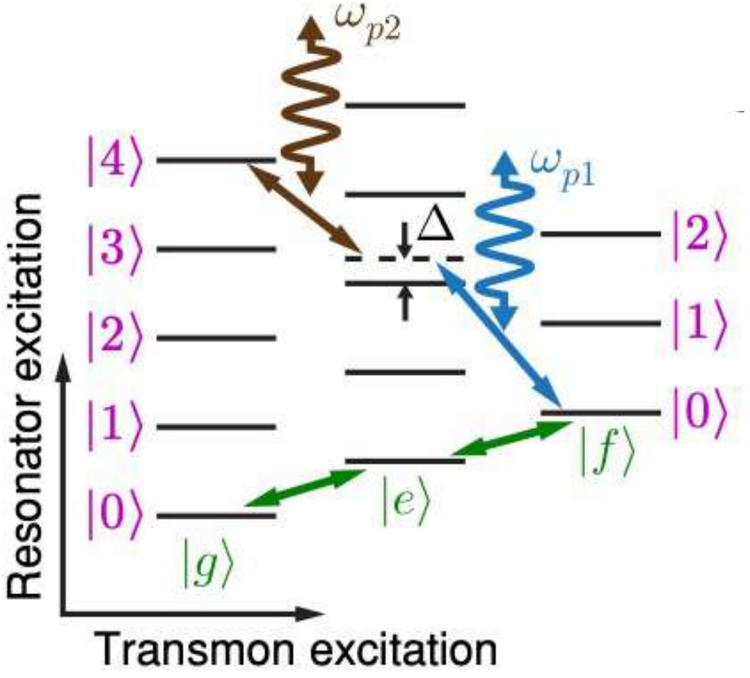
Adiabatic elimination

$\kappa_4 = \frac{4 g_4^2}{\kappa_b}$

Mirrahimi *et al.*, NJP 2014

Simoni *et al.* , arXiv, 2509.05734

From low-order to high-order interaction



Mundhada *et al.*, PRA 2019

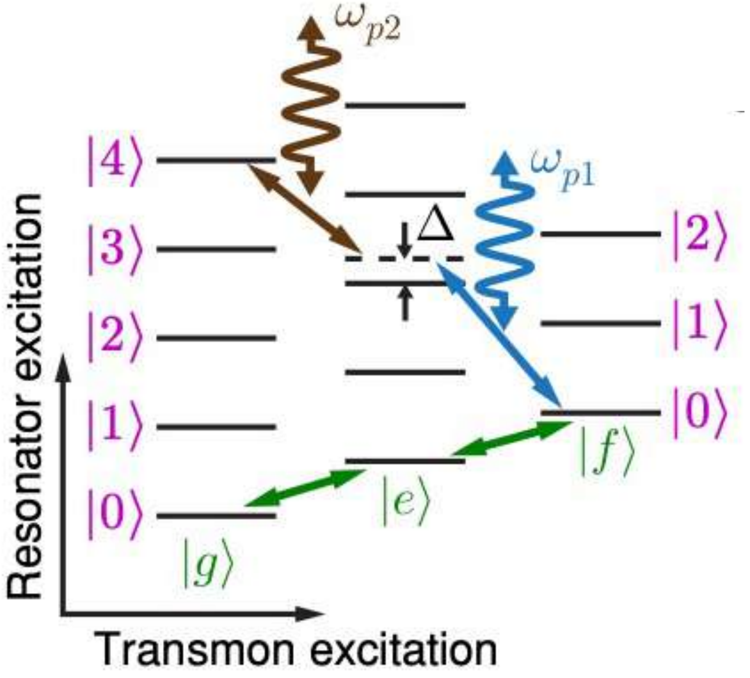
$a^2|e\rangle\langle g|e^{i\Delta t} + h.c.$

$a^2|f\rangle\langle e|e^{-i\Delta t} + h.c.$

$\xrightarrow{\text{Raman cascade}}$ $a^4|f\rangle\langle g| + h.c.$

$\xrightarrow{\text{Adiabatic elimination}}$ $\kappa_4\,\mathcal{D}[a^4]$

From low-order to high-order interaction



Mundhada *et al.*, PRA 2019

$a^2|e\rangle\langle g|e^{i\Delta t} + h.c.$

$a^2|f\rangle\langle e|e^{-i\Delta t} + h.c.$

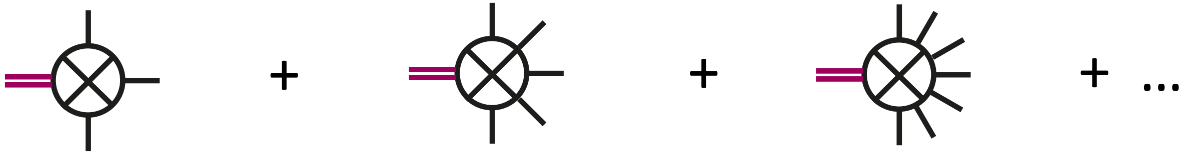
Raman cascade $\longrightarrow$ $a^4|f\rangle\langle g| + h.c.$

Adiabatic elimination $\longrightarrow$ $\kappa_4\,\mathcal{D}[a^4]$

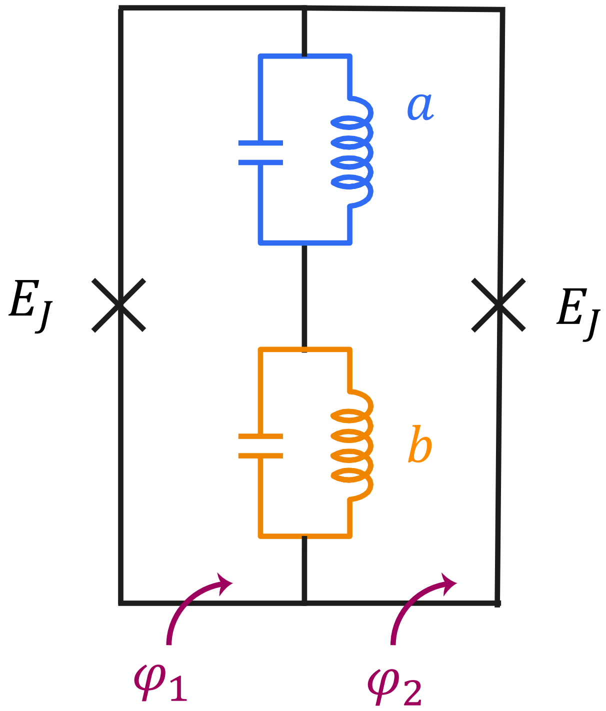
Finite $\boldsymbol{\Delta}$: residual $\boldsymbol{\kappa_2\,\mathcal{D}[a^2]}$

Genuine high-order interactions

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b$$
$$+2E_J \sin(\epsilon(t)) \sin\left(\varphi_{ZPF,a}(a + a^\dagger) + \varphi_{ZPF,b}(b + b^\dagger)\right)$$



Equivalent circuit



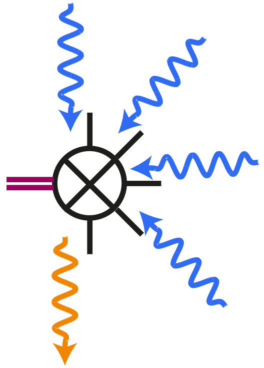
$$\varphi_{ZPF,a} = \sqrt{\pi Z_a / R_q}$$

$$\varphi_{ZPF,b} = \sqrt{\pi Z_b / R_q}$$

Genuine high-order interactions

$$H = \omega_a a^\dagger a + \omega_b b^\dagger b$$
$$+2E_J \sin(\epsilon(t)) \sin\left(\varphi_{ZPF,a}(a + a^\dagger) + \varphi_{ZPF,b}(b + b^\dagger)\right)$$

$4\omega_a - \omega_b$

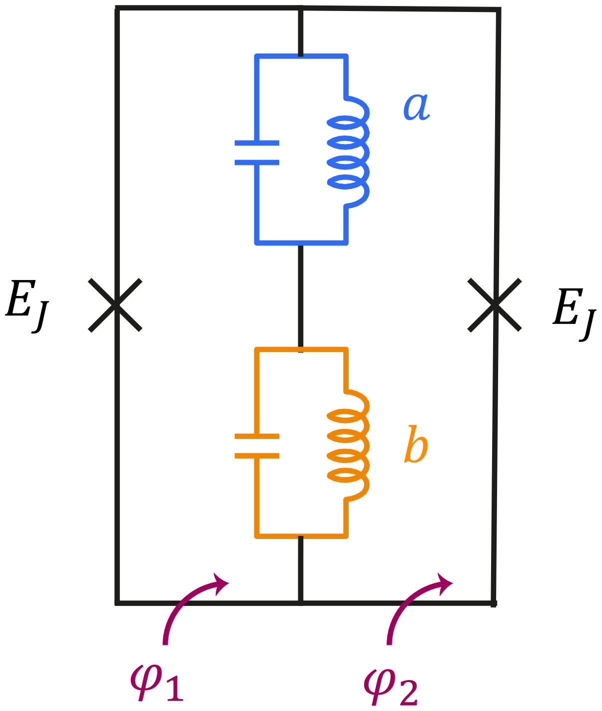


$$\varphi_{ZPF,a}^4\, a^4\, \varphi_{ZPF,b}\, b^\dagger + h.c.$$

$$\downarrow$$

$$\kappa_4\, \mathcal{D}[a^4]$$

Equivalent circuit



$$\left.\begin{matrix}\varphi_{ZPF,a} \\ \varphi_{ZPF,b}\end{matrix}\right\} \sim 1$$

$$\varphi_{ZPF,a} = \sqrt{\pi Z_a / R_q}$$

$$\varphi_{ZPF,b} = \sqrt{\pi Z_b / R_q}$$

Dissipative stabilization of GKP qubits

$$\mathcal{D}\left[\boldsymbol{S}_{\boldsymbol{q}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{i2\sqrt{\pi}\boldsymbol{q}}(\boldsymbol{I} - \epsilon\boldsymbol{p}) - \boldsymbol{I}\right]$$

$$\mathcal{D}\left[\boldsymbol{S}_{\boldsymbol{p}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{-i2\sqrt{\pi}\boldsymbol{p}}(\boldsymbol{I} - \epsilon\boldsymbol{q}) - \boldsymbol{I}\right]$$

Sellem *et al.*, PRX, 2025

Dissipative stabilization of GKP qubits

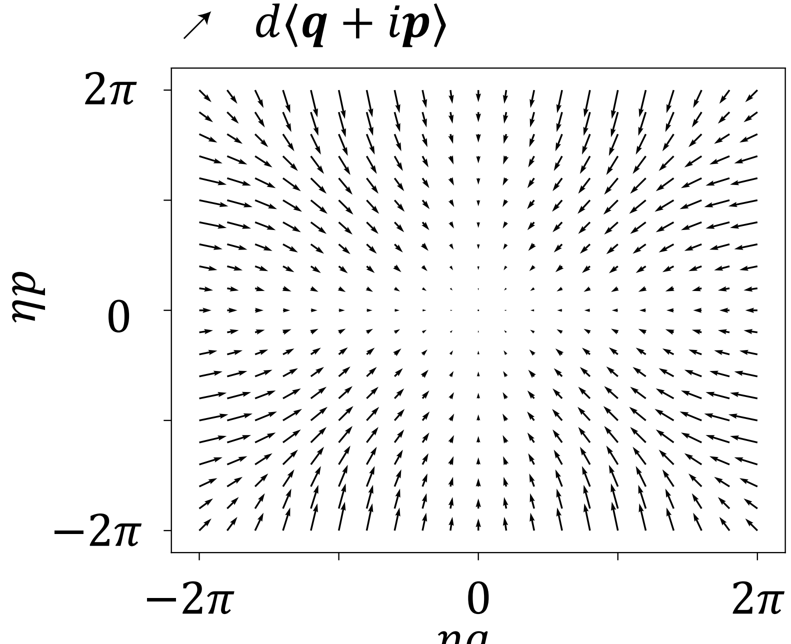
4-dissipator dynamics

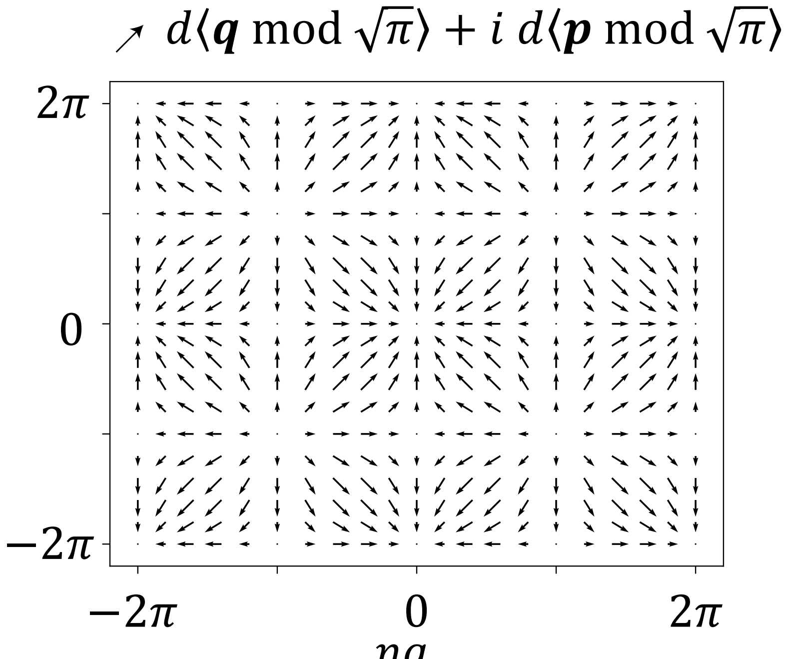
$$\mathcal{D}\left[\boldsymbol{S}_{\boldsymbol{q}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{i2\sqrt{\pi}\boldsymbol{q}}(\boldsymbol{I} - \epsilon\boldsymbol{p}) - \boldsymbol{I}\right]$$

$$\mathcal{D}\left[\boldsymbol{S}_{\boldsymbol{p}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{-i2\sqrt{\pi}\boldsymbol{p}}(\boldsymbol{I} - \epsilon\boldsymbol{q}) - \boldsymbol{I}\right]$$

$$\mathcal{D}\left[\boldsymbol{S}_{-\boldsymbol{q}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{-i2\sqrt{\pi}\boldsymbol{q}}(\boldsymbol{I} + \epsilon\boldsymbol{p}) - \boldsymbol{I}\right]$$

$$\mathcal{D}\left[\boldsymbol{S}_{-\boldsymbol{p}}^{\epsilon} - \boldsymbol{I}\right] \simeq \mathcal{D}\left[e^{i2\sqrt{\pi}\boldsymbol{p}}(\boldsymbol{I} + \epsilon\boldsymbol{q}) - \boldsymbol{I}\right]$$





Sellem *et al.*, PRX, 2025

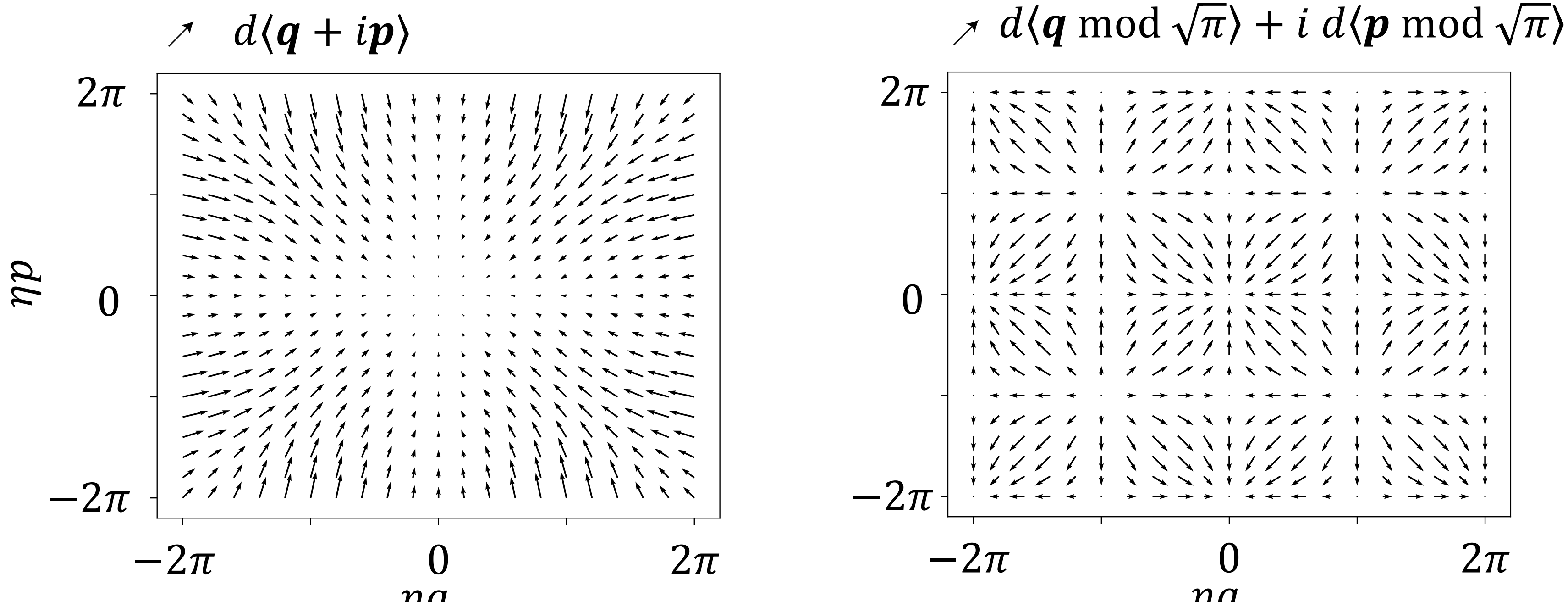
Dissipative stabilization of GKP qubits

4-dissipator dynamics

$$\left.\begin{aligned}
\mathcal{D}[\boldsymbol{S}_{\boldsymbol{q}}^{\epsilon} - \boldsymbol{I}] &\simeq \mathcal{D}[e^{i2\sqrt{\pi}\boldsymbol{q}}(\boldsymbol{I} - \epsilon\boldsymbol{p}) - \boldsymbol{I}] \\
\mathcal{D}[\boldsymbol{S}_{\boldsymbol{p}}^{\epsilon} - \boldsymbol{I}] &\simeq \mathcal{D}[e^{-i2\sqrt{\pi}\boldsymbol{p}}(\boldsymbol{I} - \epsilon\boldsymbol{q}) - \boldsymbol{I}] \\
\mathcal{D}[\boldsymbol{S}_{-\boldsymbol{q}}^{\epsilon} - \boldsymbol{I}] &\simeq \mathcal{D}[e^{-i2\sqrt{\pi}\boldsymbol{q}}(\boldsymbol{I} + \epsilon\boldsymbol{p}) - \boldsymbol{I}] \\
\mathcal{D}[\boldsymbol{S}_{-\boldsymbol{p}}^{\epsilon} - \boldsymbol{I}] &\simeq \mathcal{D}[e^{i2\sqrt{\pi}\boldsymbol{p}}(\boldsymbol{I} + \epsilon\boldsymbol{q}) - \boldsymbol{I}]
\end{aligned}\right\}$$

from modular interactions

$$g\cos(2\sqrt{\pi}\boldsymbol{q}_{\boldsymbol{a}} + \theta)\,\boldsymbol{q}_{\boldsymbol{b}}$$
$$\boldsymbol{p}_{\boldsymbol{b}}$$



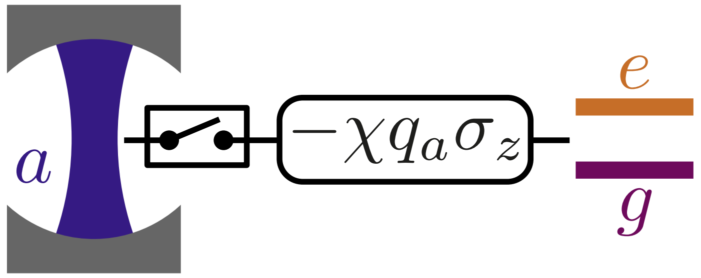
Sellem *et al.*, PRX, 2025

Modular interactions from low-order interactions

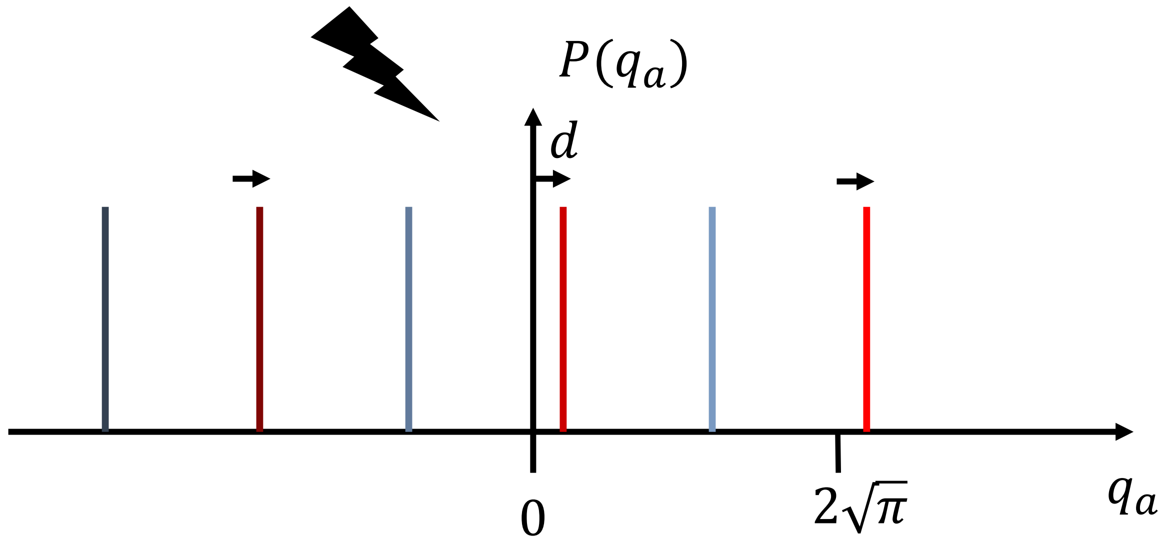
PCI *et al.* , Nature 2020

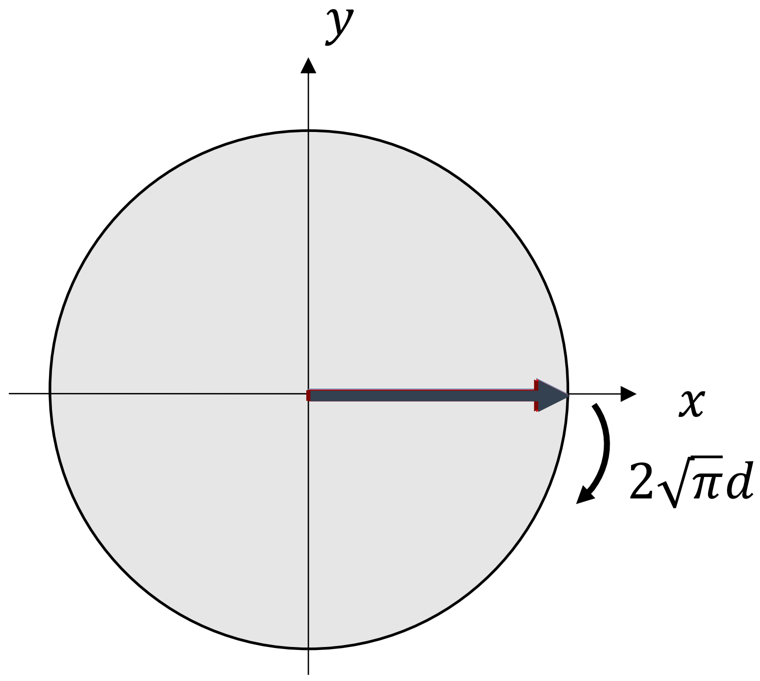
Sivak *et al.* , Nature 2023

Nord Quantique, PRL 2024



$$T_{CD} = \frac{\sqrt{\pi}}{\chi}$$





Modular interactions from low-order interactions

PCI *et al.* , Nature 2020

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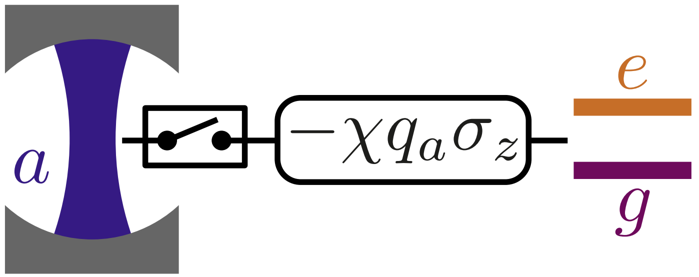
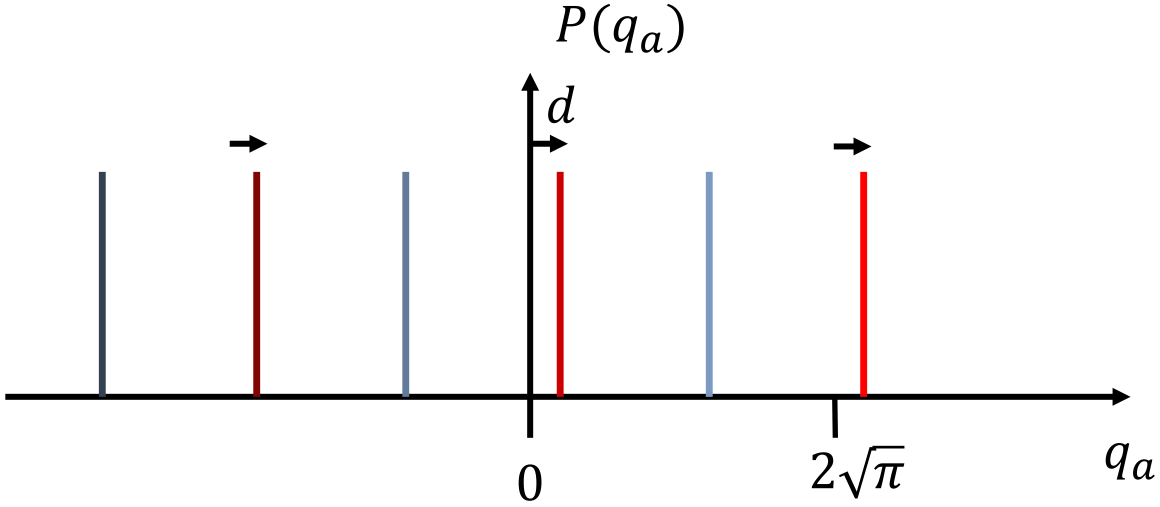
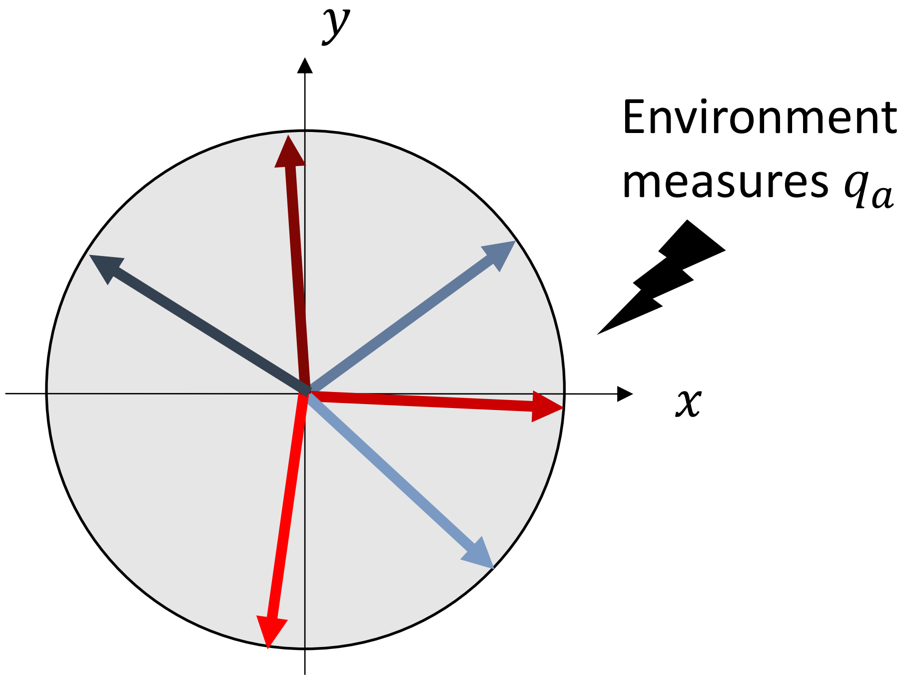
Nord Quantique, PRL 2024



$$T_{CD} = \frac{\sqrt{\pi}}{\chi}$$



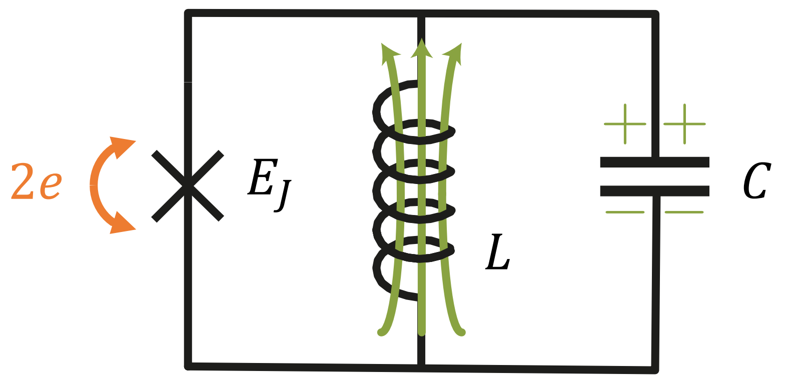


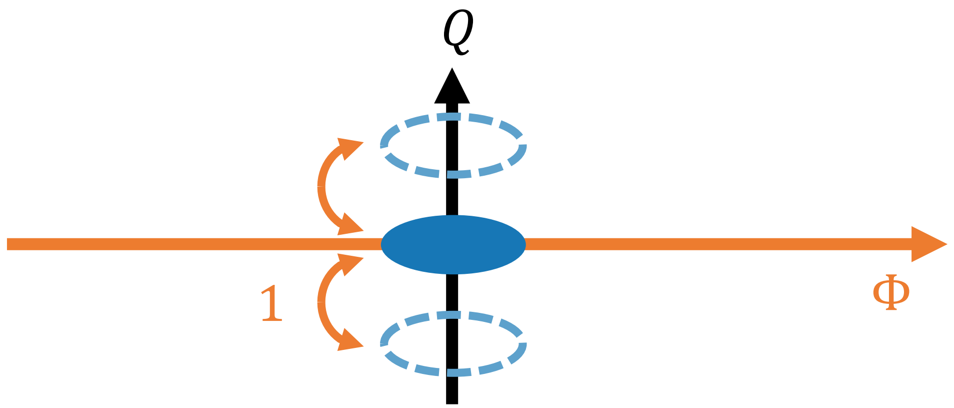
Physical qubit errors ⟶ **GKP qubit errors**

Hamiltonian stabilization of GKP qubits

Goal : $\boldsymbol{H_{GKP}} = -E\cos(2\sqrt{\pi}\boldsymbol{q}) - E\cos(2\sqrt{\pi}\boldsymbol{p})$

$$\boldsymbol{H_0} = \frac{1}{2C}\boldsymbol{Q}^2 + \frac{1}{2L}\boldsymbol{\Phi}^2 - E_J\cos(\boldsymbol{\Phi}/\varphi_0) \qquad [\boldsymbol{\Phi}, \boldsymbol{Q}] = i\hbar$$





Kolesnikow *et al.*, PRL, 2024

Sellem *et al.*, PRX, 2025

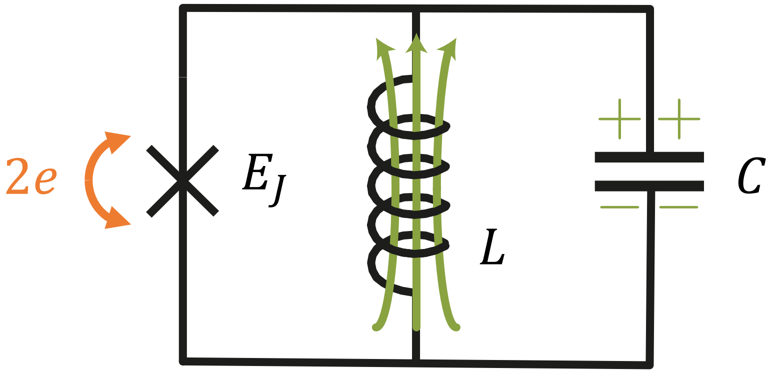
Hamiltonian stabilization of GKP qubits

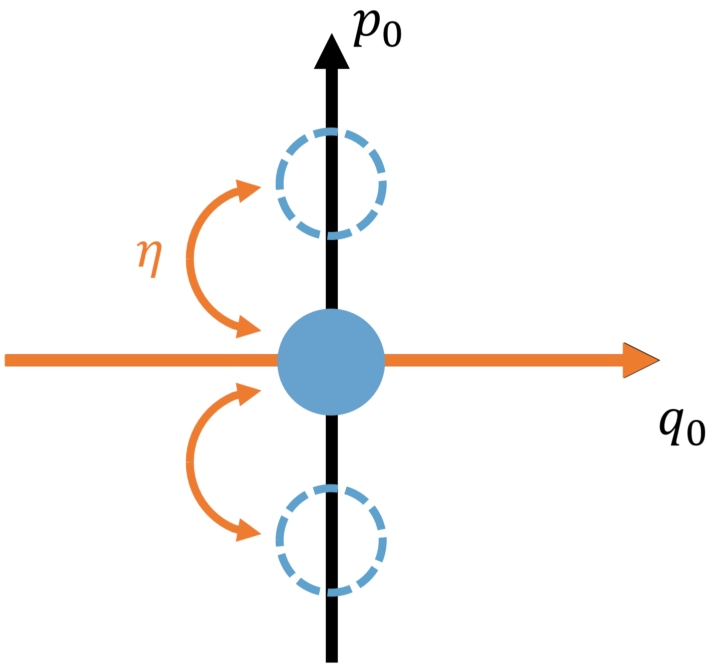
Goal : $\boldsymbol{H_{GKP}} = -E\cos(2\sqrt{\pi}\boldsymbol{q}) - E\cos(2\sqrt{\pi}\boldsymbol{p})$

$$\boldsymbol{H_0} = \frac{1}{2}\omega(\boldsymbol{q_0^2} + \boldsymbol{p_0^2}) - E_J\cos(\eta\boldsymbol{q_0}) \qquad [\boldsymbol{q_0}, \boldsymbol{p_0}] = i$$

$$\omega = \frac{1}{\sqrt{LC}} \qquad \eta = \sqrt{2\pi Z/R_q}$$

$$Z = \sqrt{L/C} \qquad R_q = 6.5\ \mathrm{k}\Omega$$





Kolesnikow *et al.*, PRL, 2024

Sellem *et al.*, PRX, 2025

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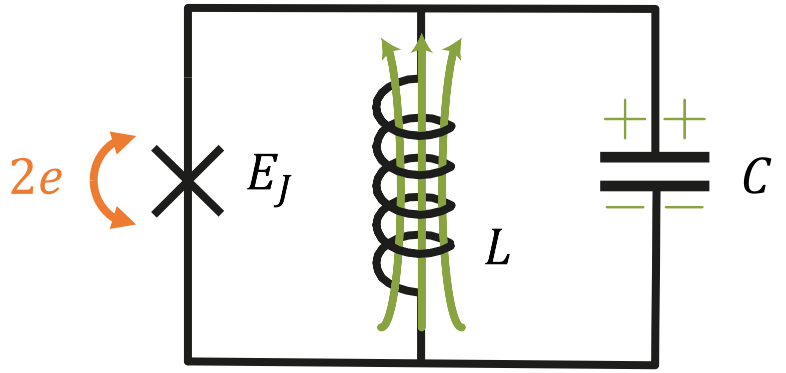
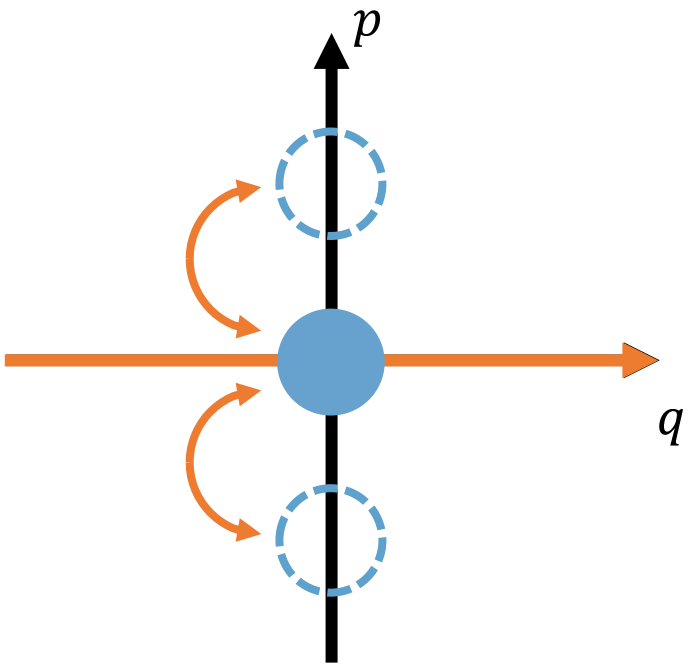
$$\omega = \frac{1}{\sqrt{LC}} \qquad \eta = \sqrt{2\pi Z/R_q}$$

$$\boldsymbol{H}(t) = -E_J\cos(\eta \boldsymbol{q_0}(t)) \qquad [\boldsymbol{q},\boldsymbol{p}] = i$$

$$Z = \sqrt{L/C} \qquad R_q = 6.5\ \mathrm{k}\Omega$$





Rotating frame

Kolesnikow *et al*., PRL, 2024

Sellem *et al*., PRX, 2025

Hamiltonian stabilization of GKP qubits

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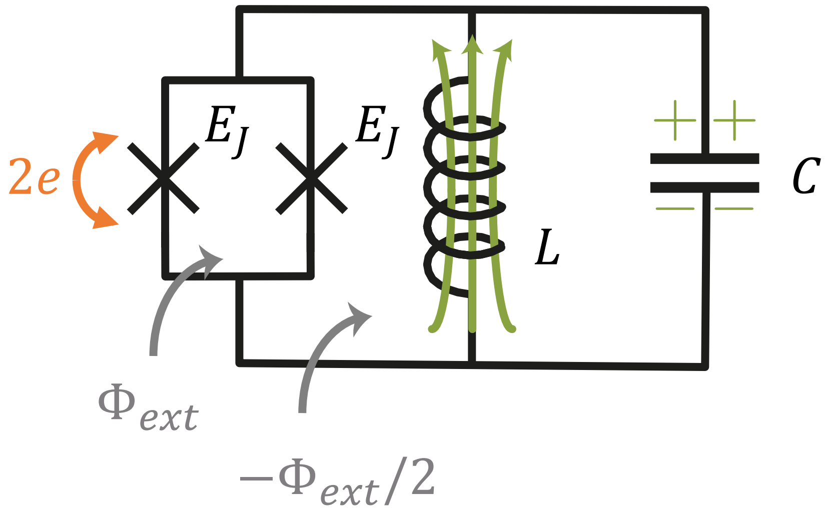
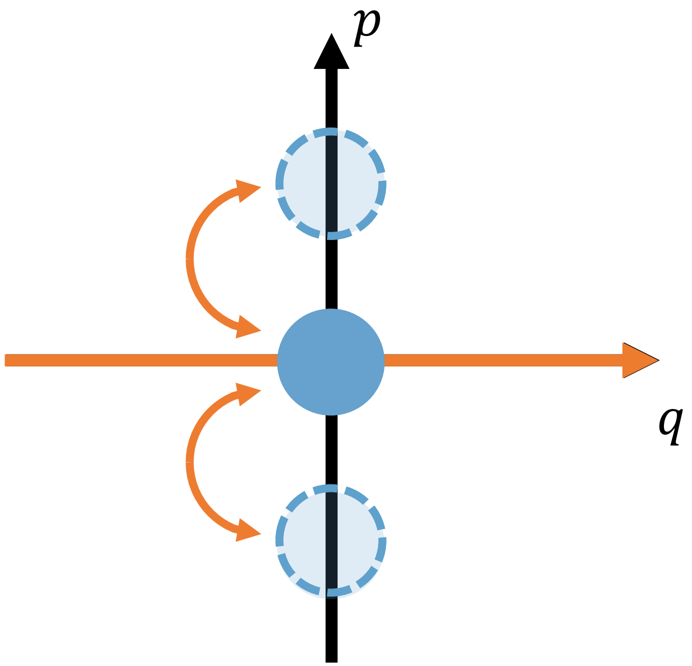
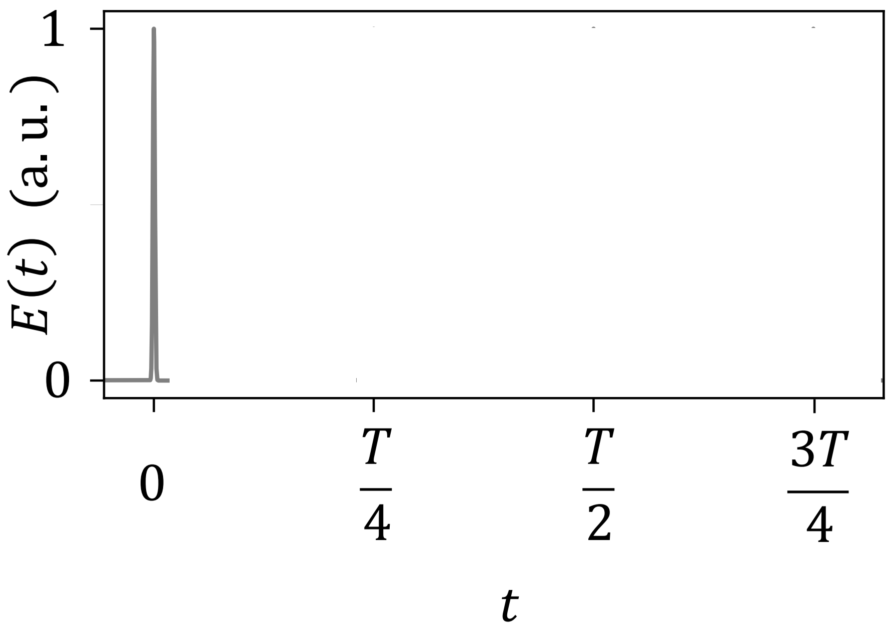




Rotating frame



Hamiltonian stabilization of GKP qubits

Goal : $\boldsymbol{H_{GKP}} = -E\cos(2\sqrt{\pi}\boldsymbol{q}) - E\cos(2\sqrt{\pi}\boldsymbol{p})$

$$\boldsymbol{H}(t) = -E(t)\cos(\eta\, \boldsymbol{q_0}(t)) \qquad [\boldsymbol{q},\boldsymbol{p}] = i$$

$$\omega = \frac{1}{\sqrt{LC}} \qquad \eta = \sqrt{2\pi Z/R_q}$$

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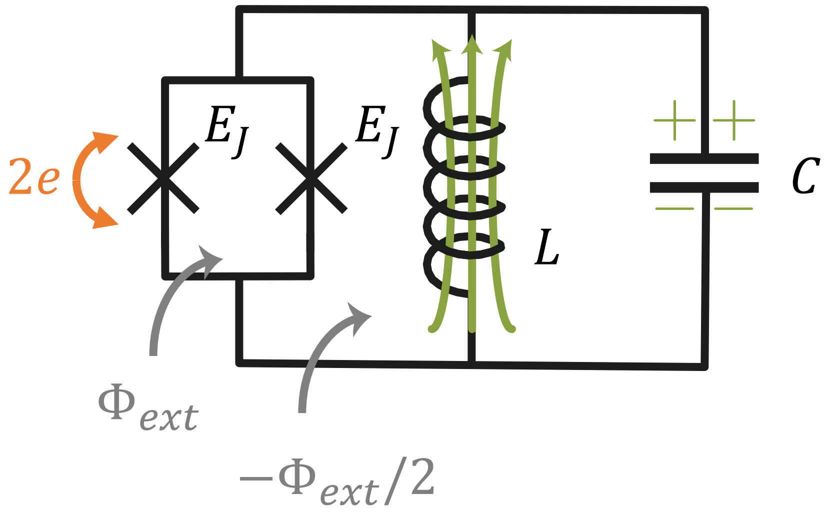
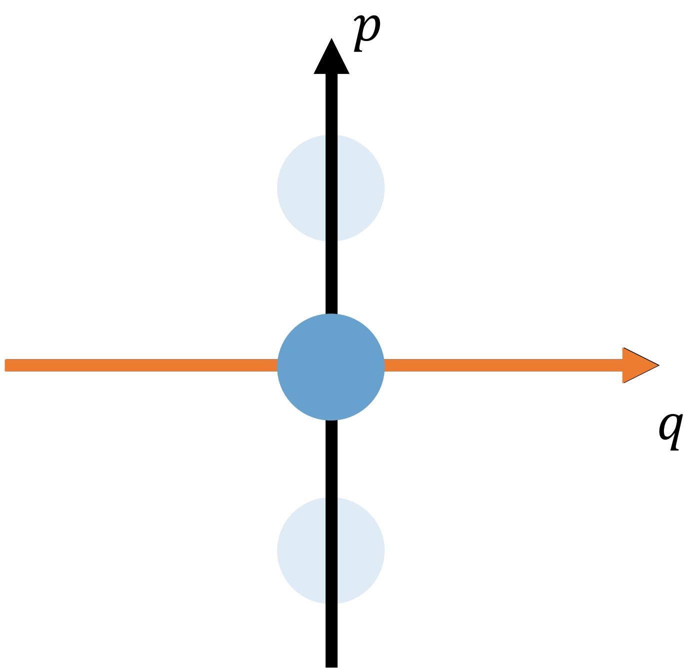
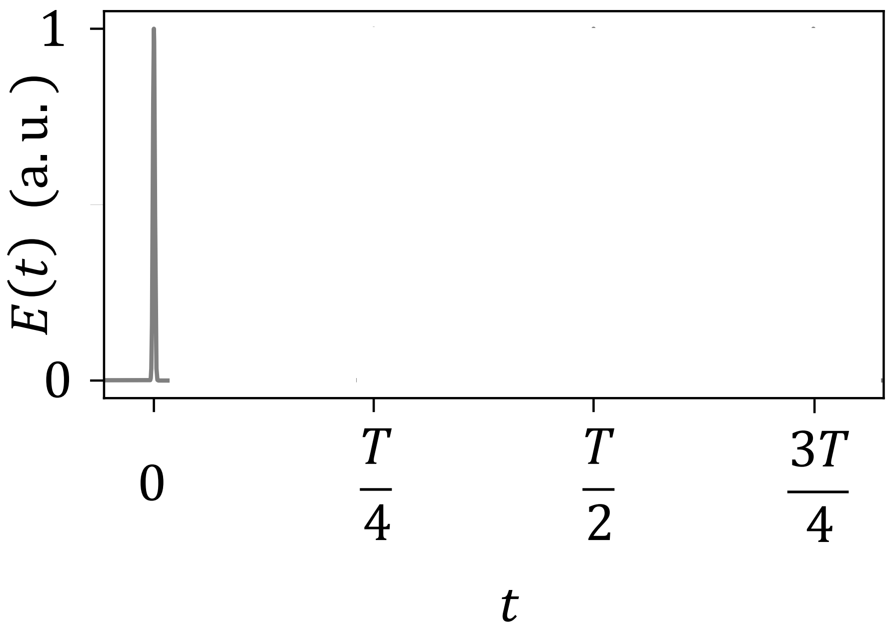




Rotating frame



Hamiltonian stabilization of GKP qubits

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$$\boldsymbol{H}(t) = -E(t)\cos(\eta\boldsymbol{q_0}(t)) \qquad [\boldsymbol{q},\boldsymbol{p}] = i$$

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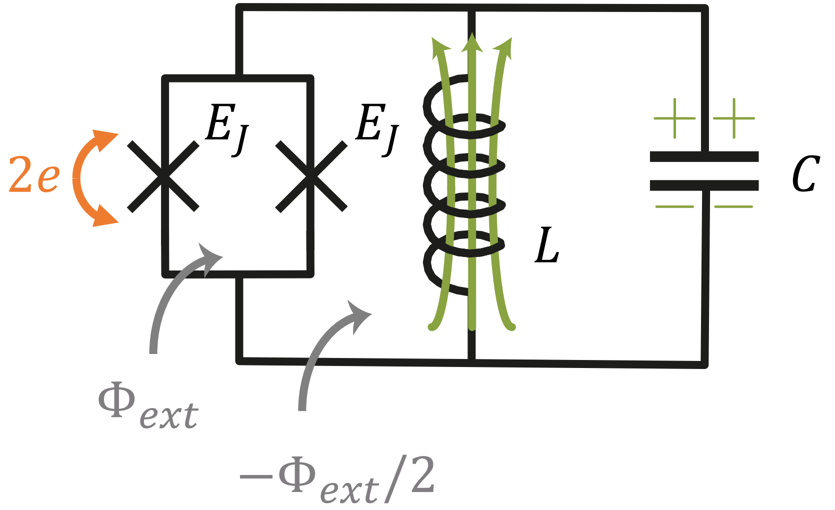
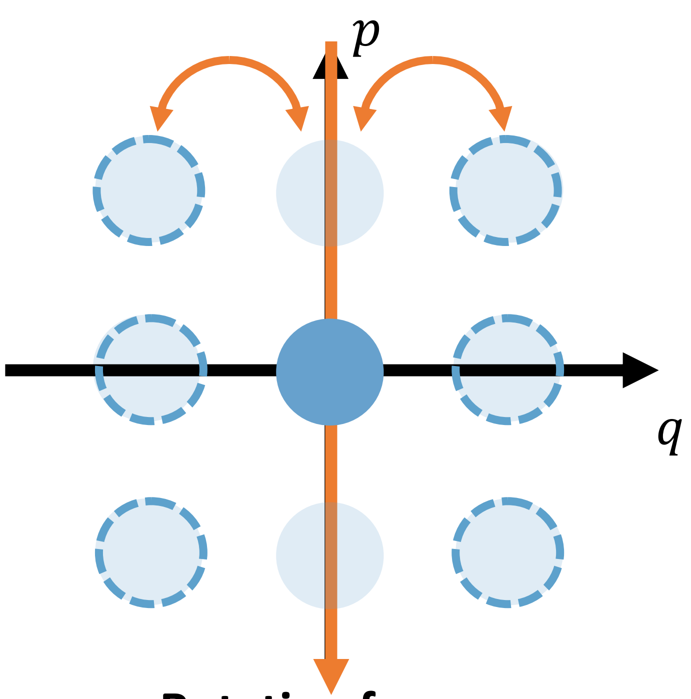
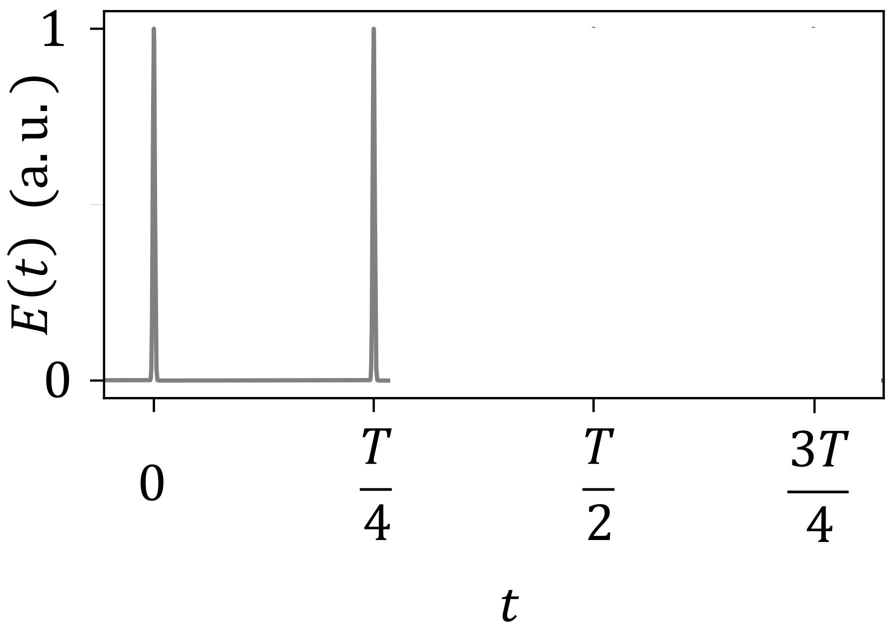
$$Z = \sqrt{L/C} \qquad R_q = 6.5\ \mathrm{k\Omega}$$







Hamiltonian stabilization of GKP qubits

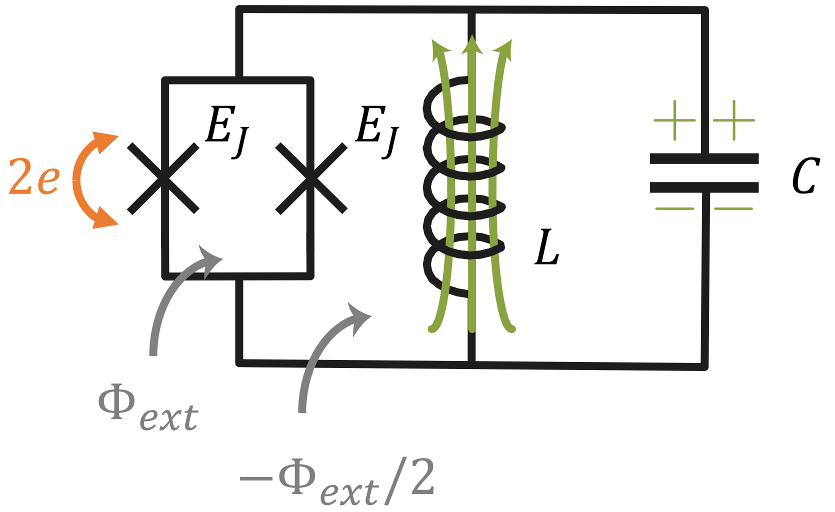
Goal : $\boldsymbol{H_{GKP}} = -E\cos(2\sqrt{\pi}\boldsymbol{q}) - E\cos(2\sqrt{\pi}\boldsymbol{p})$

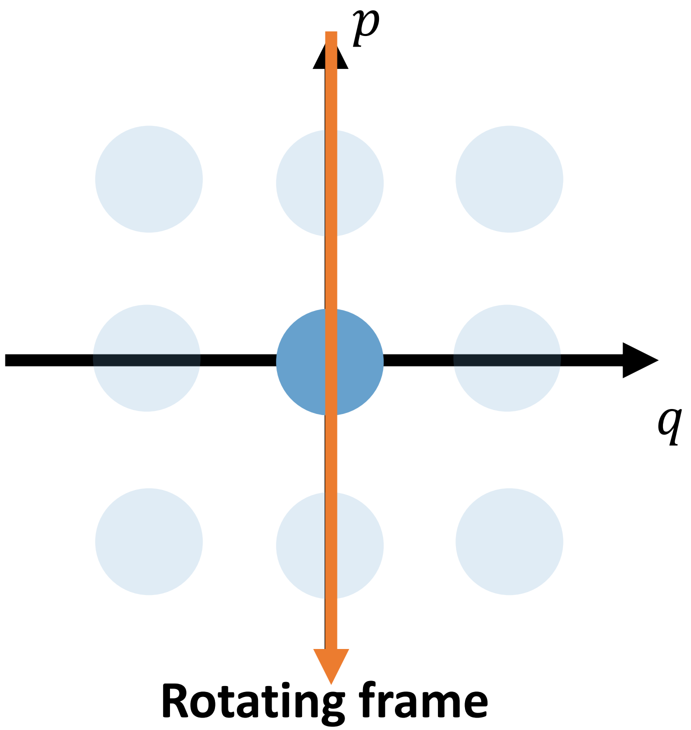
$$\boldsymbol{H}(t) = -E(t)\cos(\eta\boldsymbol{q_0}(t))$$

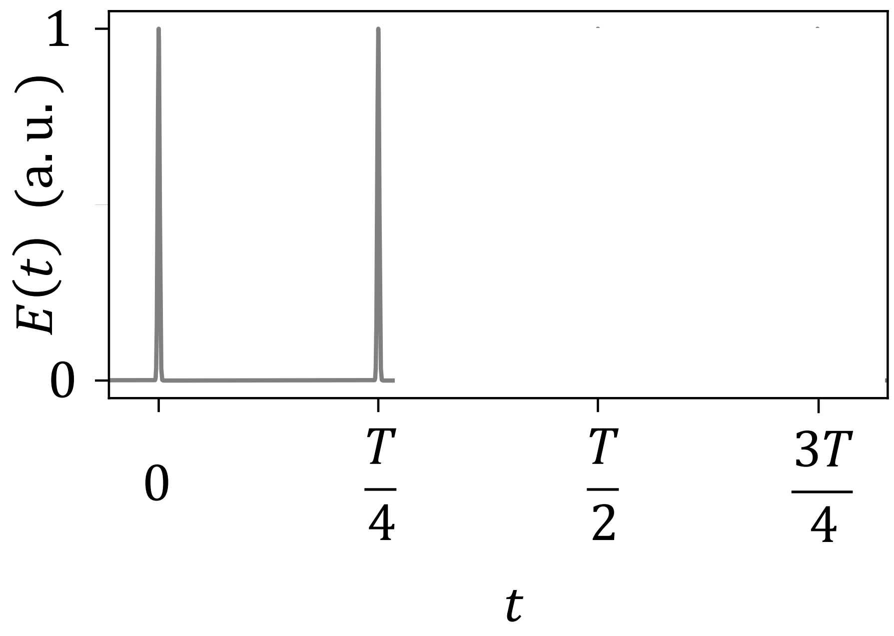
$$[\boldsymbol{q},\boldsymbol{p}] = i$$

$$\omega = \frac{1}{\sqrt{LC}} \qquad \eta = \sqrt{2\pi Z/R_q}$$

$$Z = \sqrt{L/C} \qquad R_q = 6.5\ \mathrm{k}\Omega$$







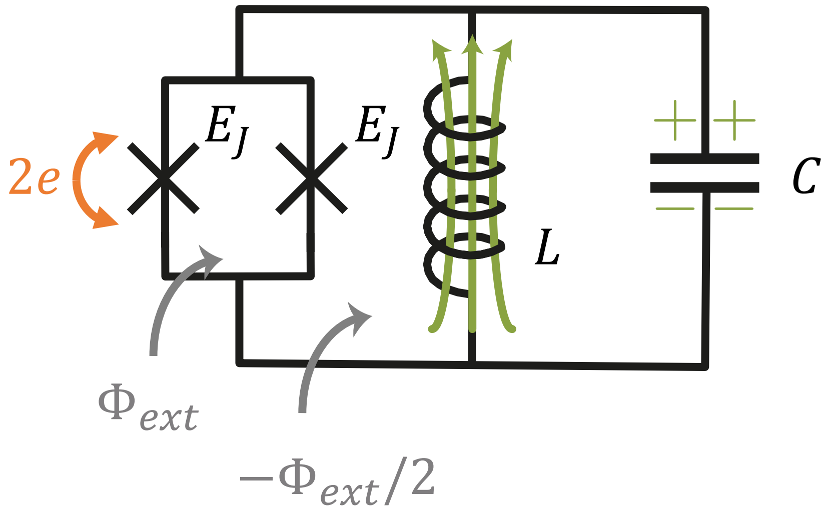
Hamiltonian stabilization of GKP qubits

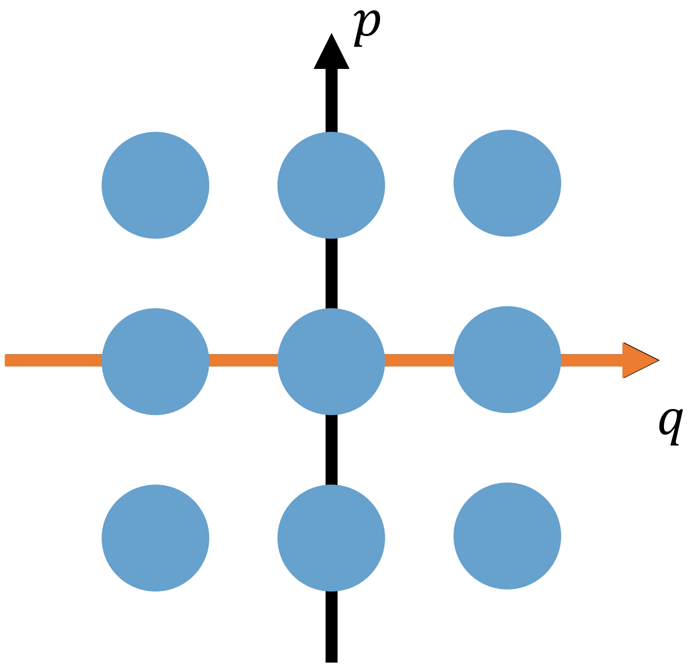
Goal : $\boldsymbol{H_{GKP}} = -E\cos(2\sqrt{\pi}\boldsymbol{q}) - E\cos(2\sqrt{\pi}\boldsymbol{p})$

$$\boldsymbol{H}_{eff} = \overline{\boldsymbol{H}(t)} = -\frac{\overline{E(t)}}{2}\left(\cos(\eta\boldsymbol{q}) + \cos(\eta\boldsymbol{p})\right)$$

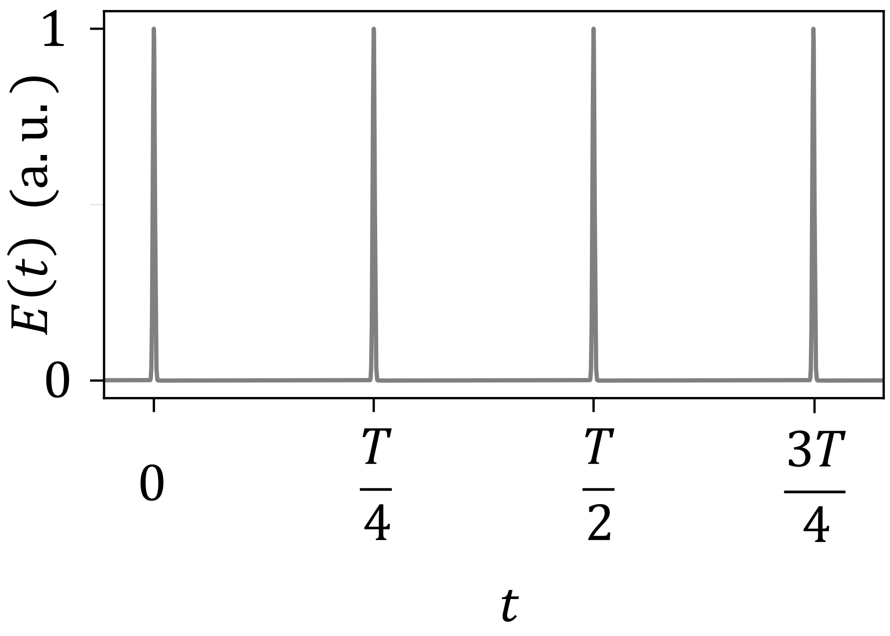
$$\eta = \sqrt{2\pi Z/R_q}$$

$$Z = 2\,R_q$$





Rotating frame

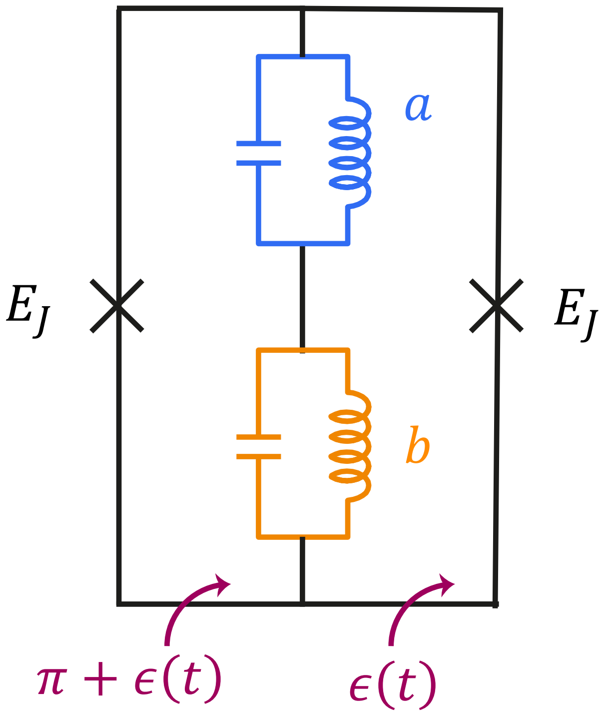


Modular interaction engineering

Goal : $\boldsymbol{H_{mod}} = g\cos(2\sqrt{\pi}\boldsymbol{q_a})\,\boldsymbol{q_b}$

$$H(t) = 2E_J\sin\big(\epsilon(t)\big)\sin\left(\eta_a q_a^0(t) + \eta_b q_b^0(t)\right)$$

Equivalent ATS circuit

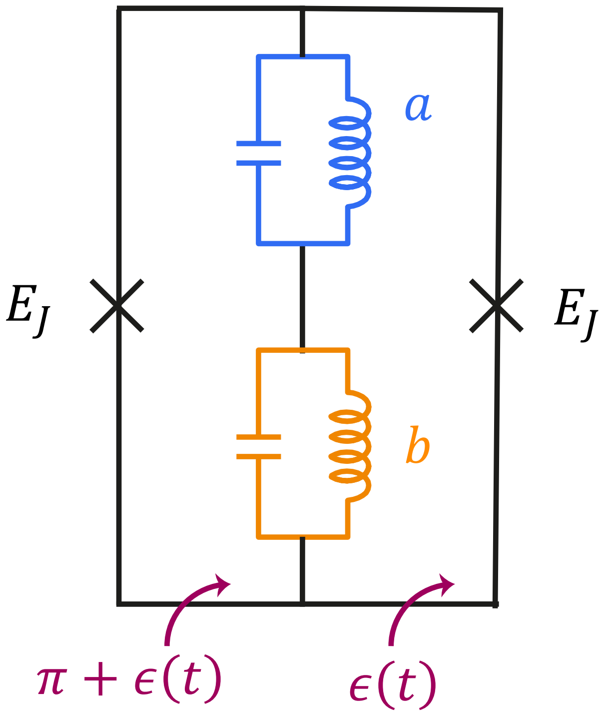


Modular interaction engineering

Goal : $\boldsymbol{H_{mod}} = g\cos(2\sqrt{\pi}\boldsymbol{q_a})\,\boldsymbol{q_b}$

$$H(t) = E(t)\begin{pmatrix} \sin\left(\eta_a q_a^0(t)\right)\cos\left(\eta_b q_b^0(t)\right) + \\ \cos\left(\eta_a q_a^0(t)\right)\sin\left(\eta_b q_b^0(t)\right) \end{pmatrix}$$

Equivalent ATS circuit

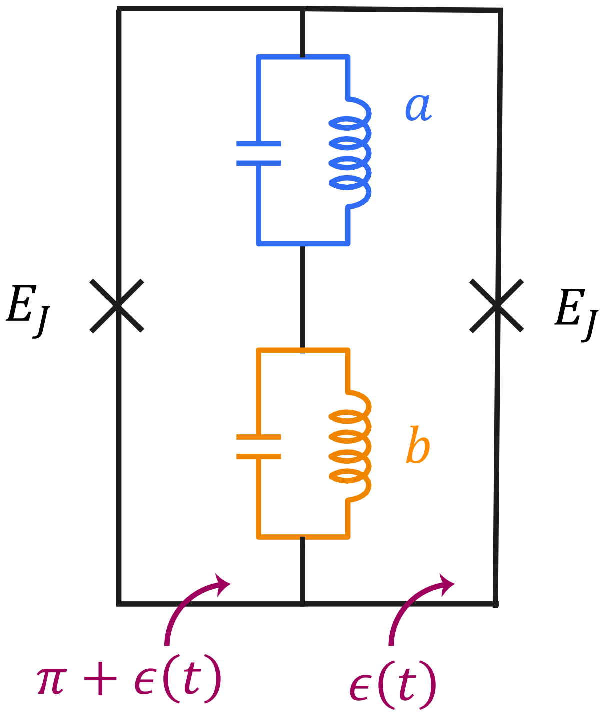


Modular interaction engineering

Goal : $\boldsymbol{H_{mod}} = g\cos(2\sqrt{\pi}\boldsymbol{q_a})\,\boldsymbol{q_b}$

$$H(t) = E(t)\begin{pmatrix}\sin\left(\eta_a q_a^0(t)\right) + \\ \cos\left(\eta_a q_a^0(t)\right)\eta_b q_b^0(t)\end{pmatrix}$$

Equivalent ATS circuit



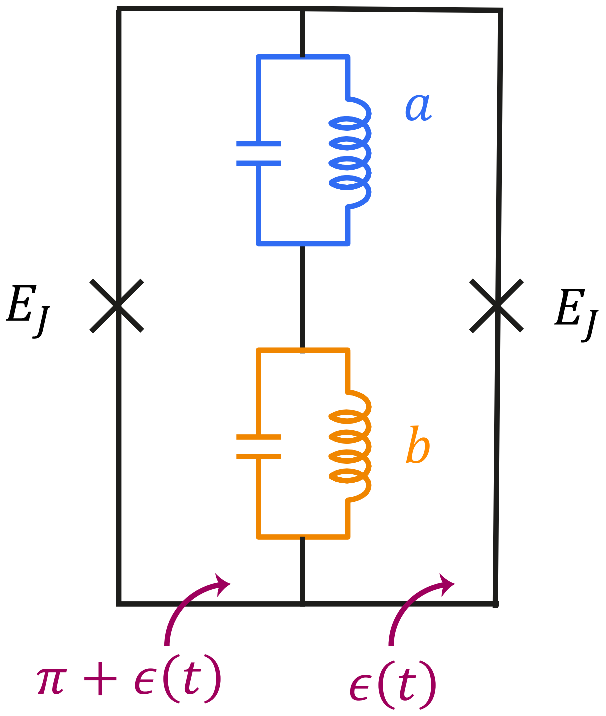
$\boldsymbol{\eta_b \ll 1}$

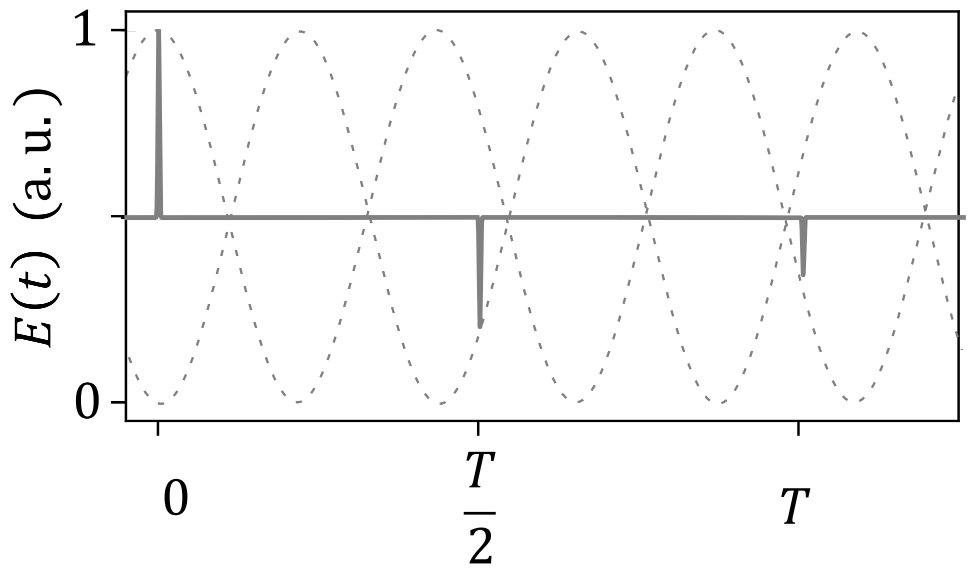
Modular interaction engineering

Goal : $\boldsymbol{H_{mod}} = g\cos(2\sqrt{\pi}\boldsymbol{q_a})\,\boldsymbol{q_b}$

$$H(t) = E(t)\begin{pmatrix} \sin\big(\eta_a q_a^0(t)\big) + \\ \cos\big(\eta_a q_a^0(t)\big)\eta_b q_b^0(t) \end{pmatrix}$$

Equivalent ATS circuit





$\boldsymbol{\eta_b \ll 1} \longrightarrow \overline{\boldsymbol{H(t)}} = \boldsymbol{H_{mod}}$

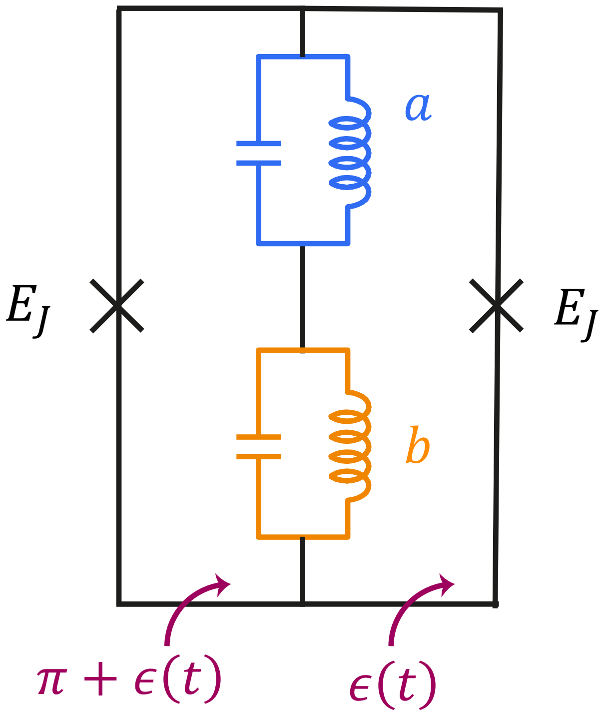
RWA

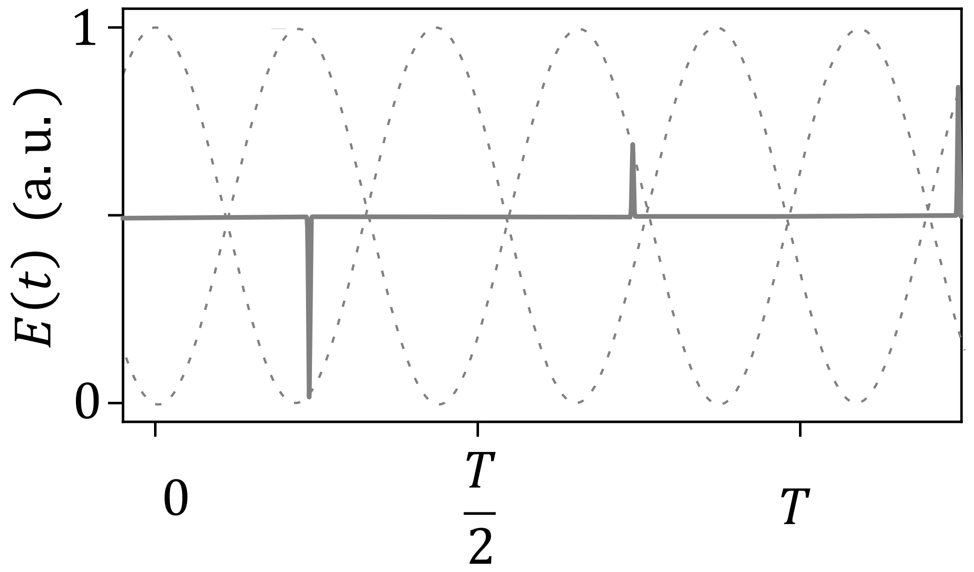
Modular interaction engineering

Goal : $\boldsymbol{H_{mod}} = g\cos(2\sqrt{\pi}\boldsymbol{p_a})\,\boldsymbol{q_b}$

$$H(t) = E(t)\begin{pmatrix} \cos\left(\eta_a q_a^0(t)\right) + \\ \sin\left(\eta_a q_a^0(t)\right)\eta_b q_b^0(t) \end{pmatrix}$$

Equivalent ATS circuit





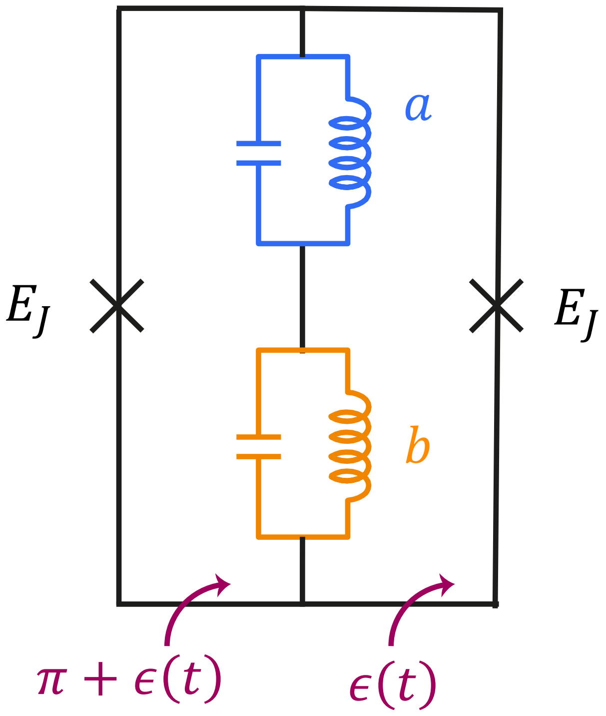
$\boldsymbol{\eta_b \ll 1} \longrightarrow \overline{\boldsymbol{H(t)}} = \boldsymbol{H_{mod}}$

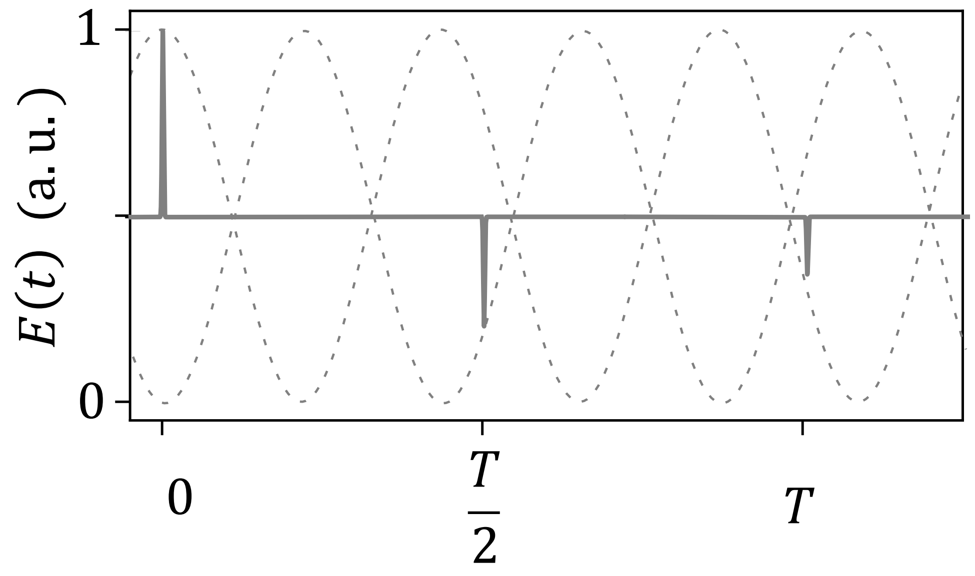
RWA

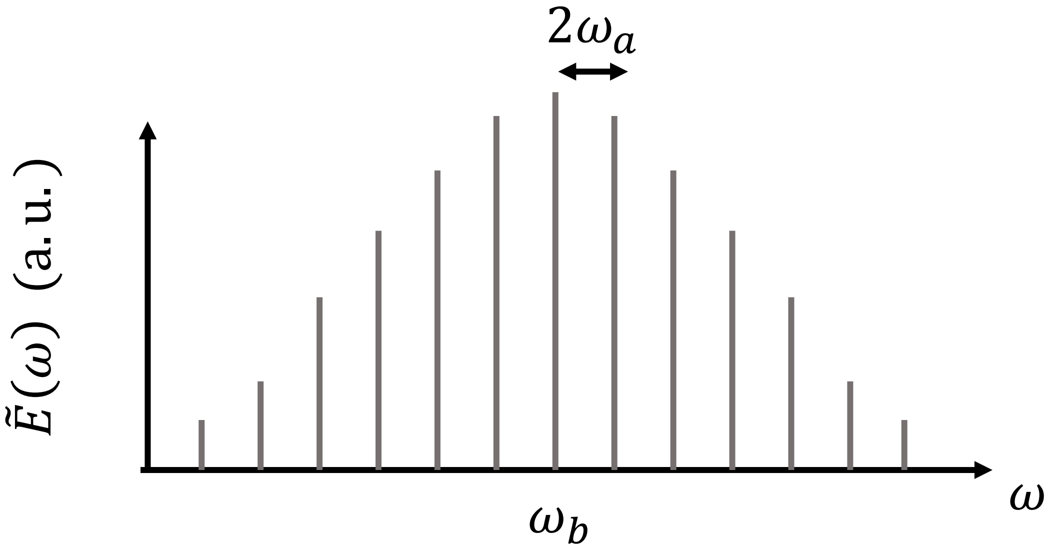
Frequency-comb drive

$\varphi_{ZPF,a} = \sqrt{2\pi}\ \ (Z_a = 13\ \mathrm{k\Omega})$

$\omega_a/2\pi < 1\ \mathrm{GHz}$



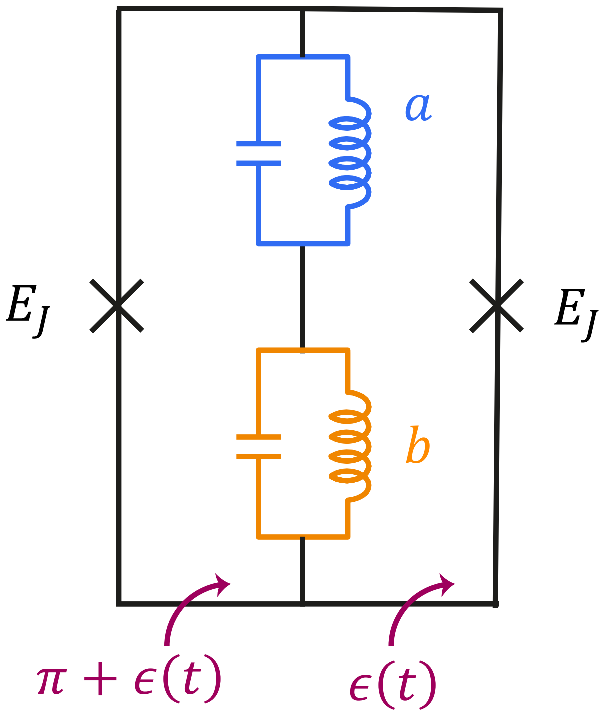


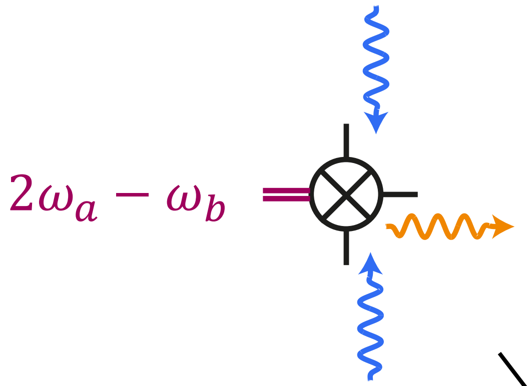


Frequency-comb drive

$\varphi_{ZPF,a} \sim 0.05$

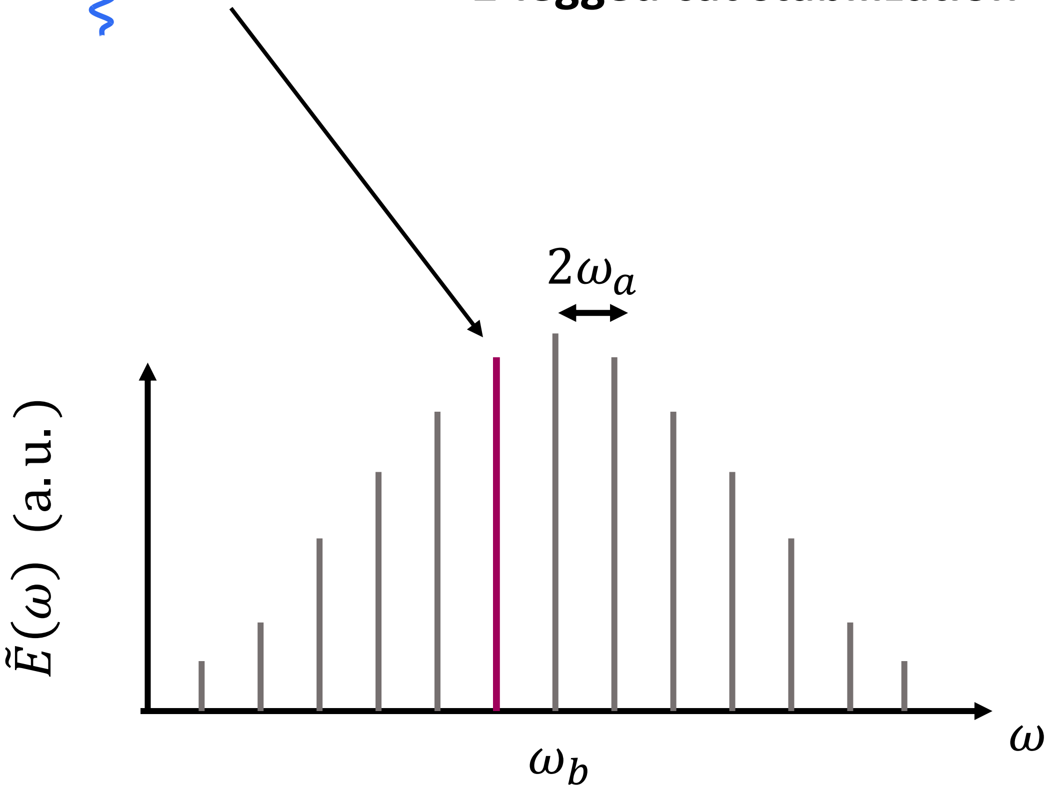
$\frac{\omega_a}{2\pi} \sim 5\ \mathrm{GHz}$





$\varphi_{ZPF,a}^2\, a^2\, \varphi_{ZPF,b}\, b^\dagger + h.c.$

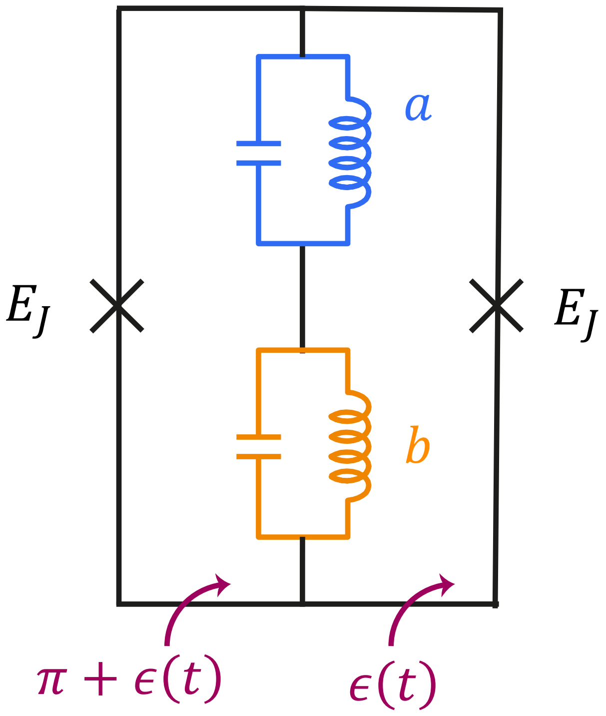
2-legged cat stabilization

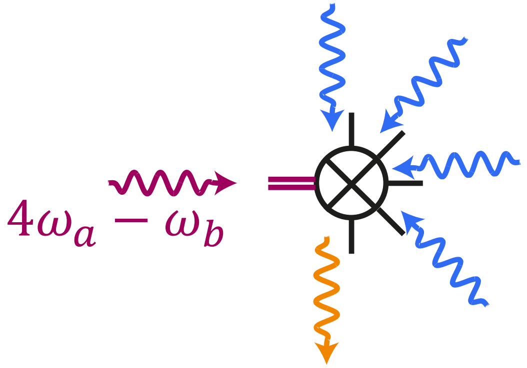


Frequency-comb drive

$\varphi_{ZPF,a} \sim 0.5$

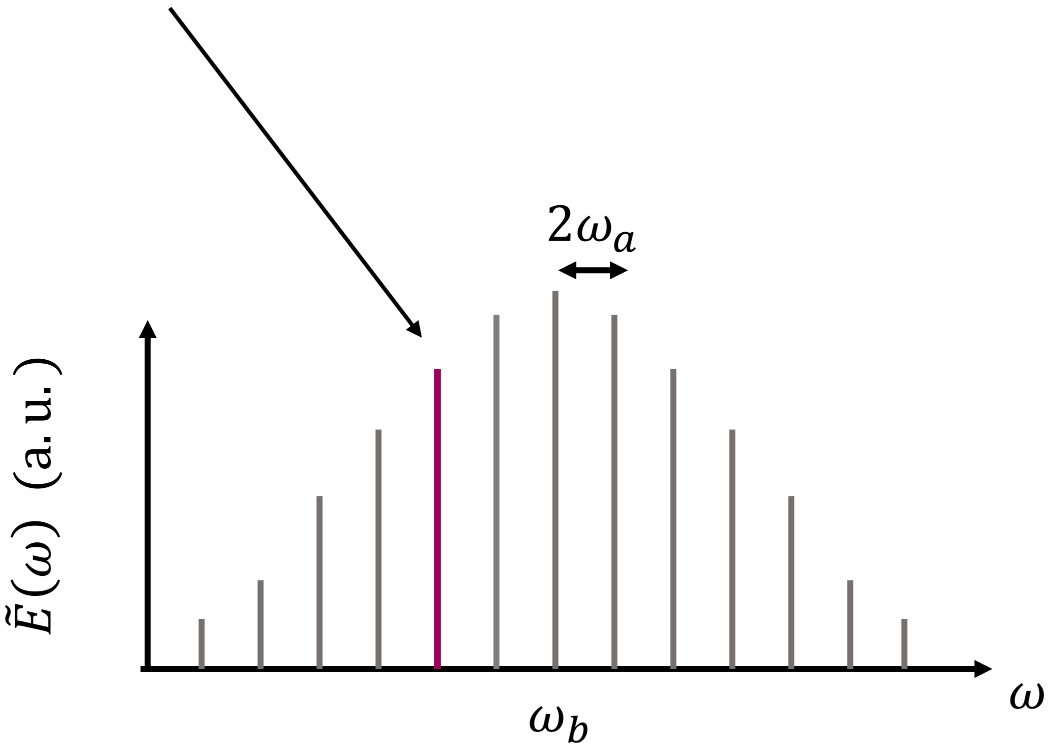
$\frac{\omega_a}{2\pi} \sim 5\ \mathrm{GHz}$





$\varphi_{ZPF,a}^4\, a^4\, \varphi_{ZPF,b}\, b^\dagger + h.c.$

4-legged cat stabilization



5-~~year~~ plan
a.u.

	4-legged cats	N-legged cats ($5 \leq N \leq 8$)	Generalized cat codes (Rojkov *et al.*, PRX, 2026)	Single GKP state	GKP qubits & gates
Z_a	$500\ \Omega$	$1\ \mathrm{k}\Omega$	$1\ \mathrm{k}\Omega$	$1.6\ \mathrm{k}\Omega$	$13\ \mathrm{k}\Omega$
$\omega_a/2\pi$	5 GHz	2 GHz	2 GHz	1 GHz	0.3 GHz
N_{harm}	1	1	$2-4$	$5-10$	$25-50$

Outline

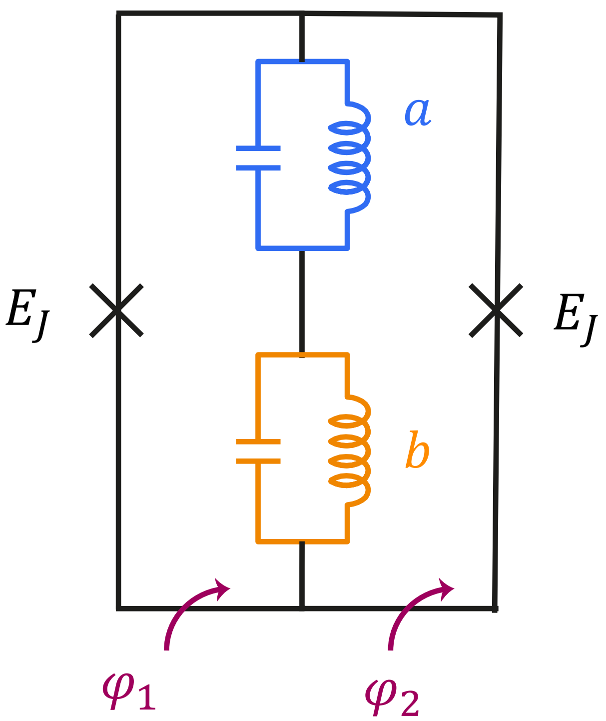
1. Bosonic codes: structure

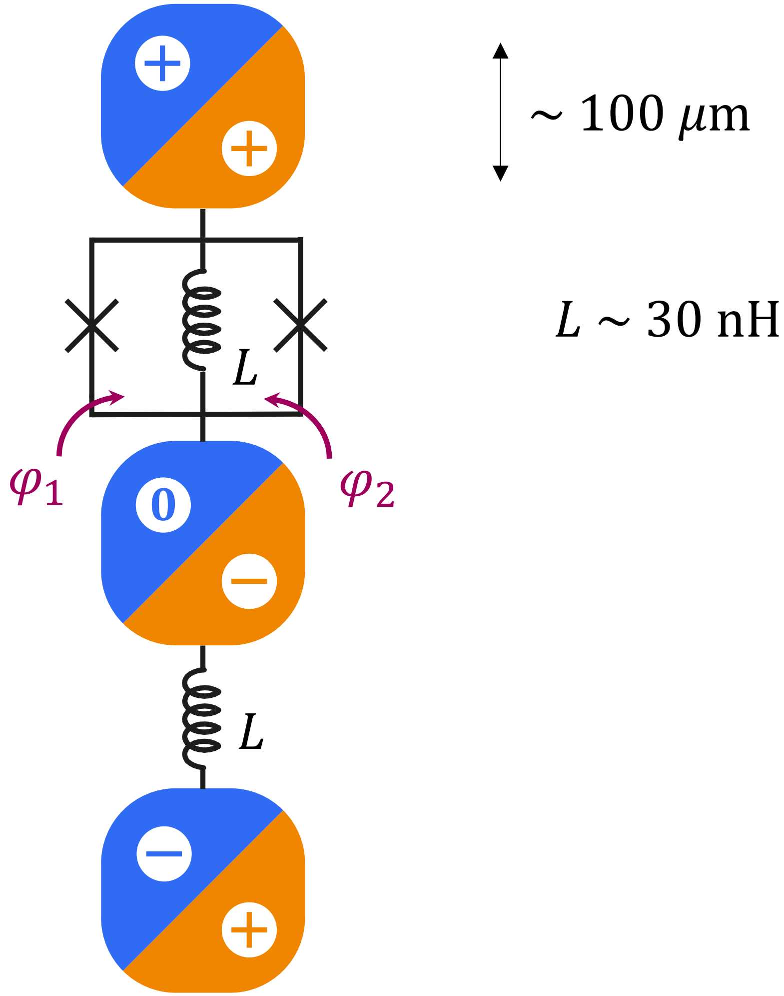
2. Bosonic codes: dissipative stabilization

3. First experimental steps (4-legged cats)

High-impedance circuit

Equivalent circuit





$L \sim 30$ nH

$\left.\begin{matrix}\varphi_{ZPF,a} \\ \varphi_{ZPF,b}\end{matrix}\right\} \sim 0.5$

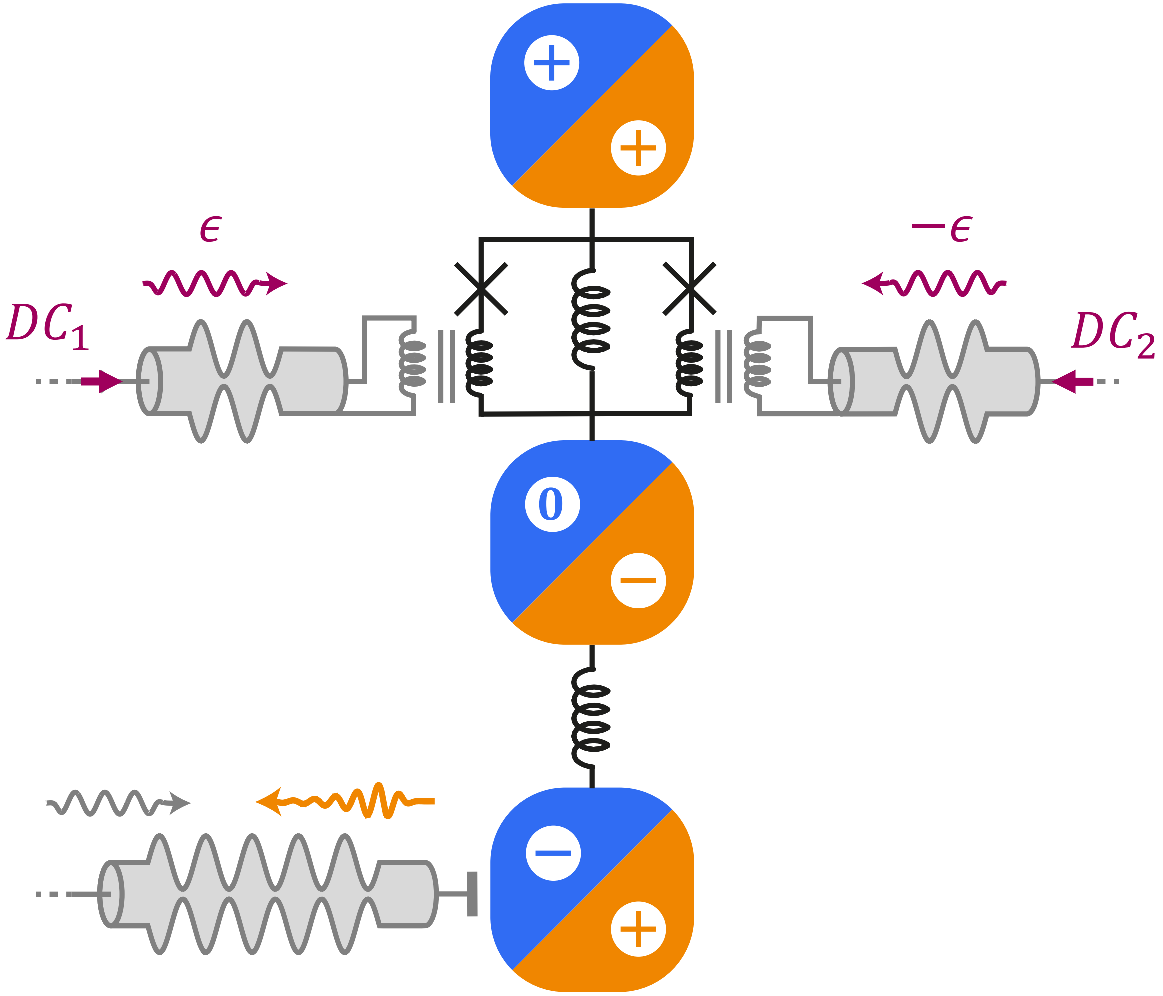
$\omega_a = 2\pi \times 4.5$ GHz

$\omega_b = 2\pi \times 8$ GHz

$E_J = h \times 6$ GHz

Vanselow *et al.* , PRX, 2026

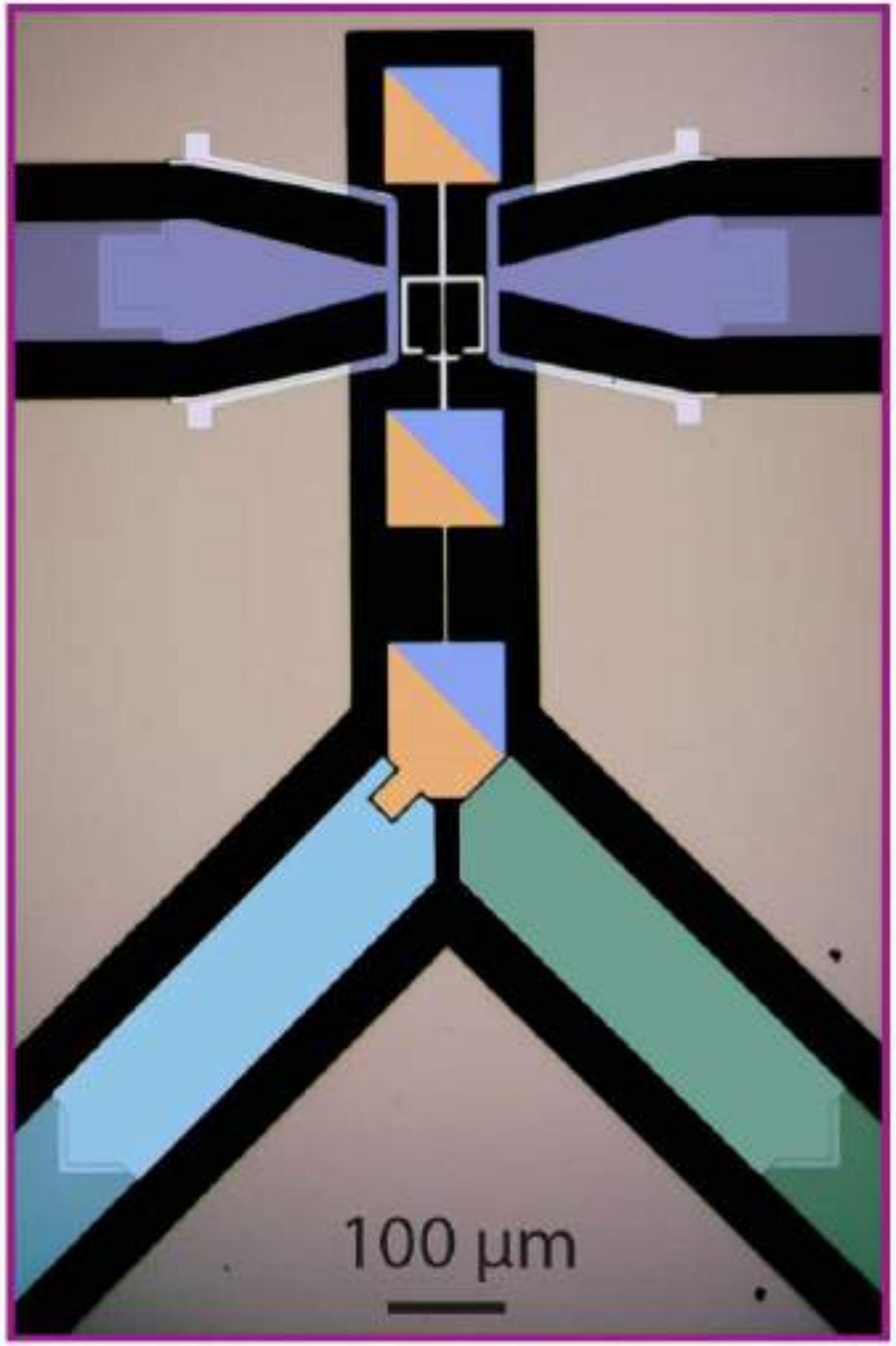
Flux and charge drives

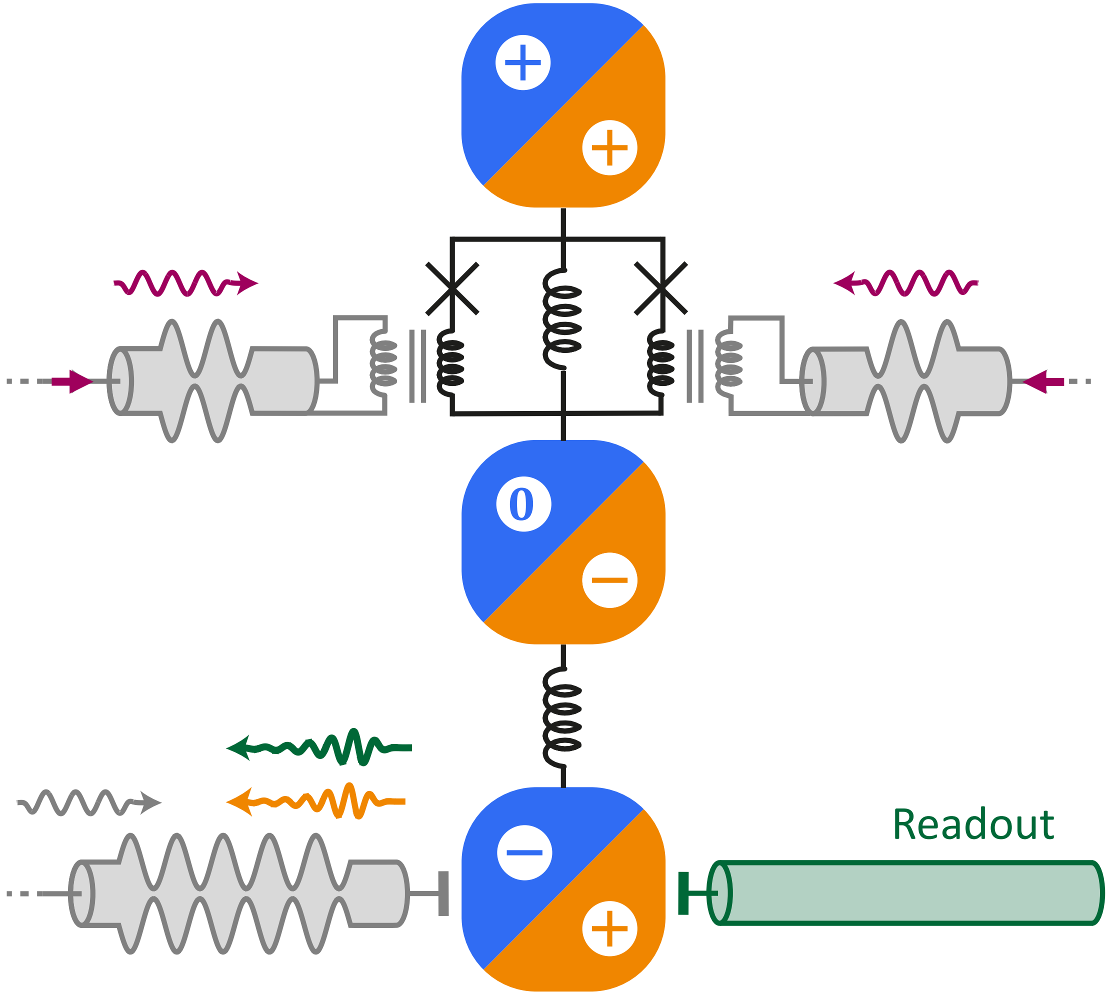


$$\left.\begin{matrix}\varphi_{ZPF,a} \\ \varphi_{ZPF,b}\end{matrix}\right\} \sim 0.5$$

Vanselow *et al.* , PRX, 2026

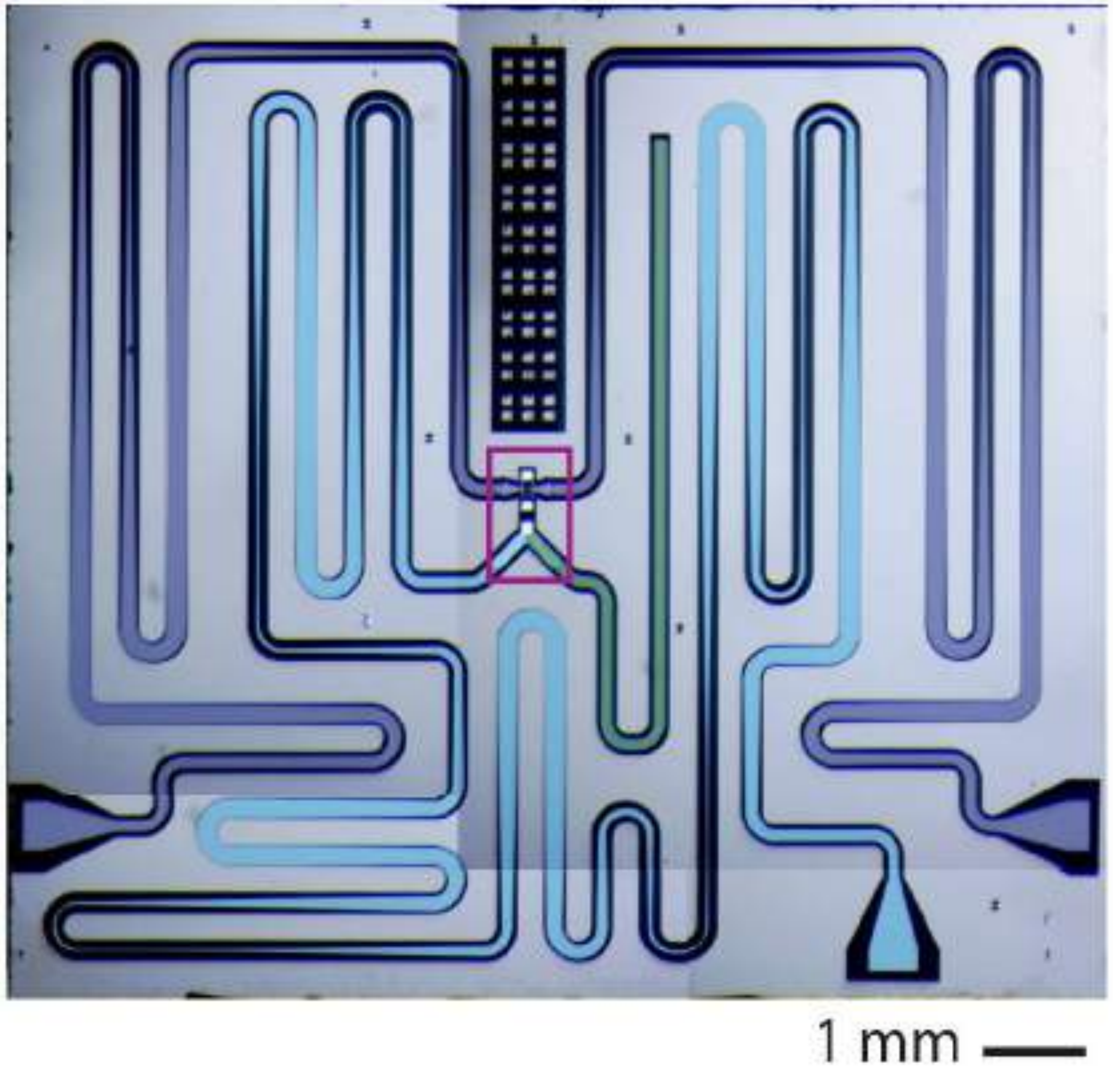
Three-mode circuit

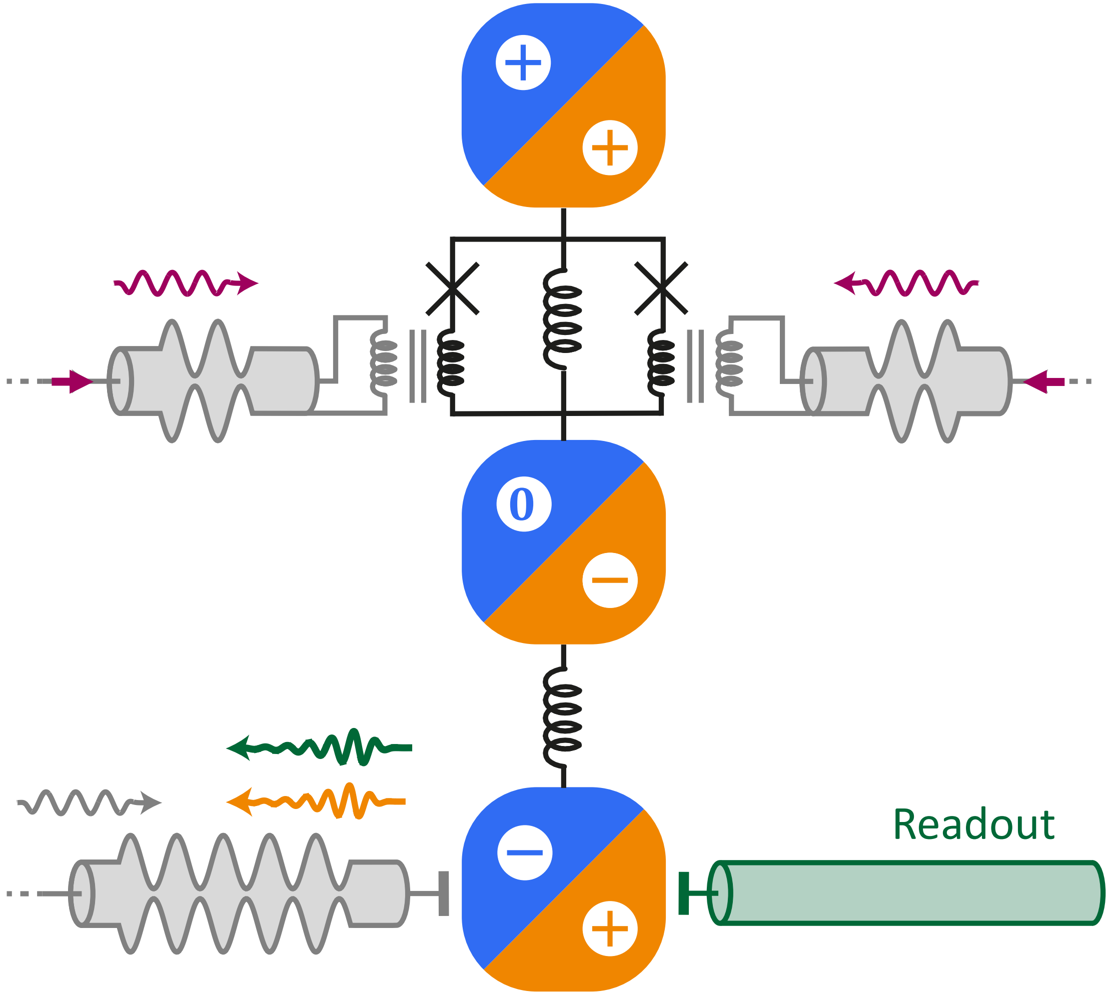




$\varphi_{ZPF,r} \sim 0.05$

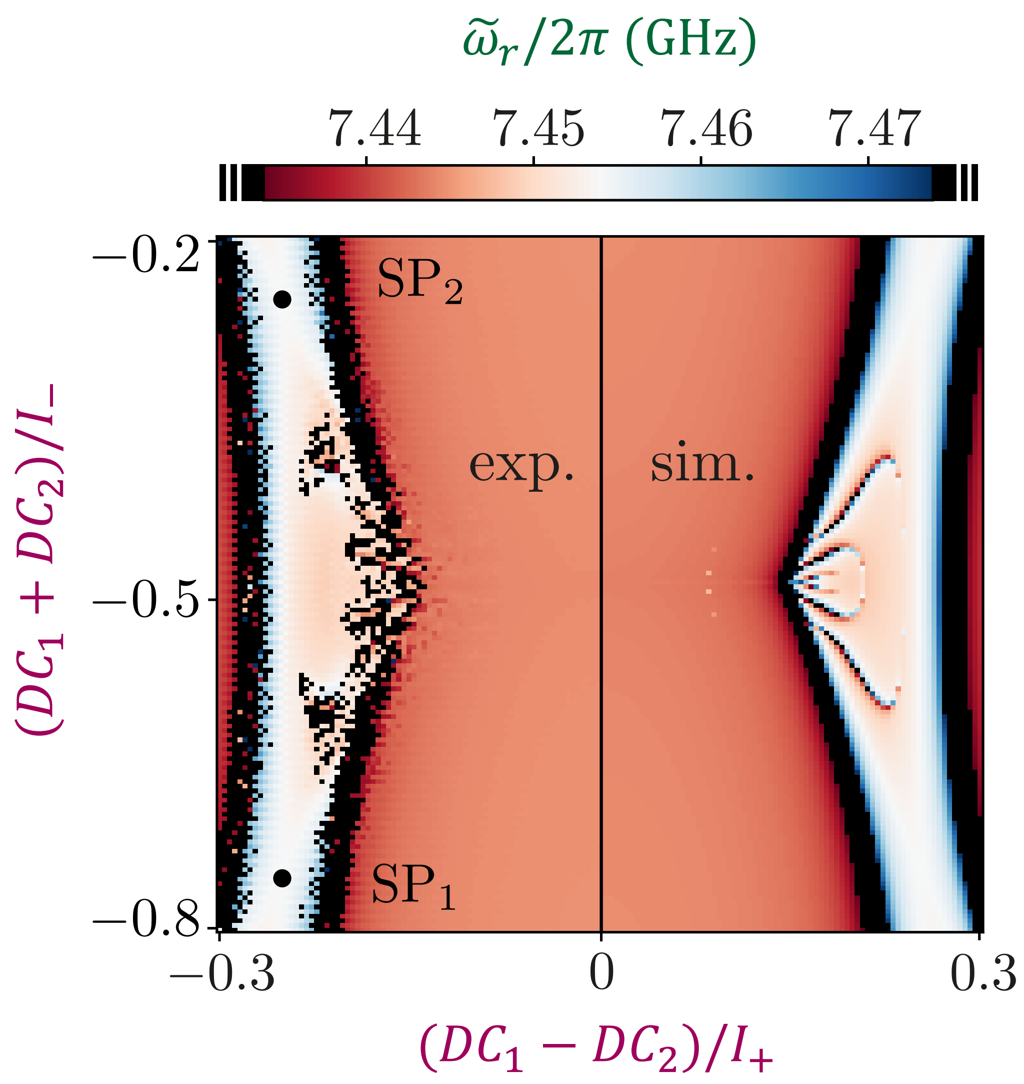
Three-mode circuit

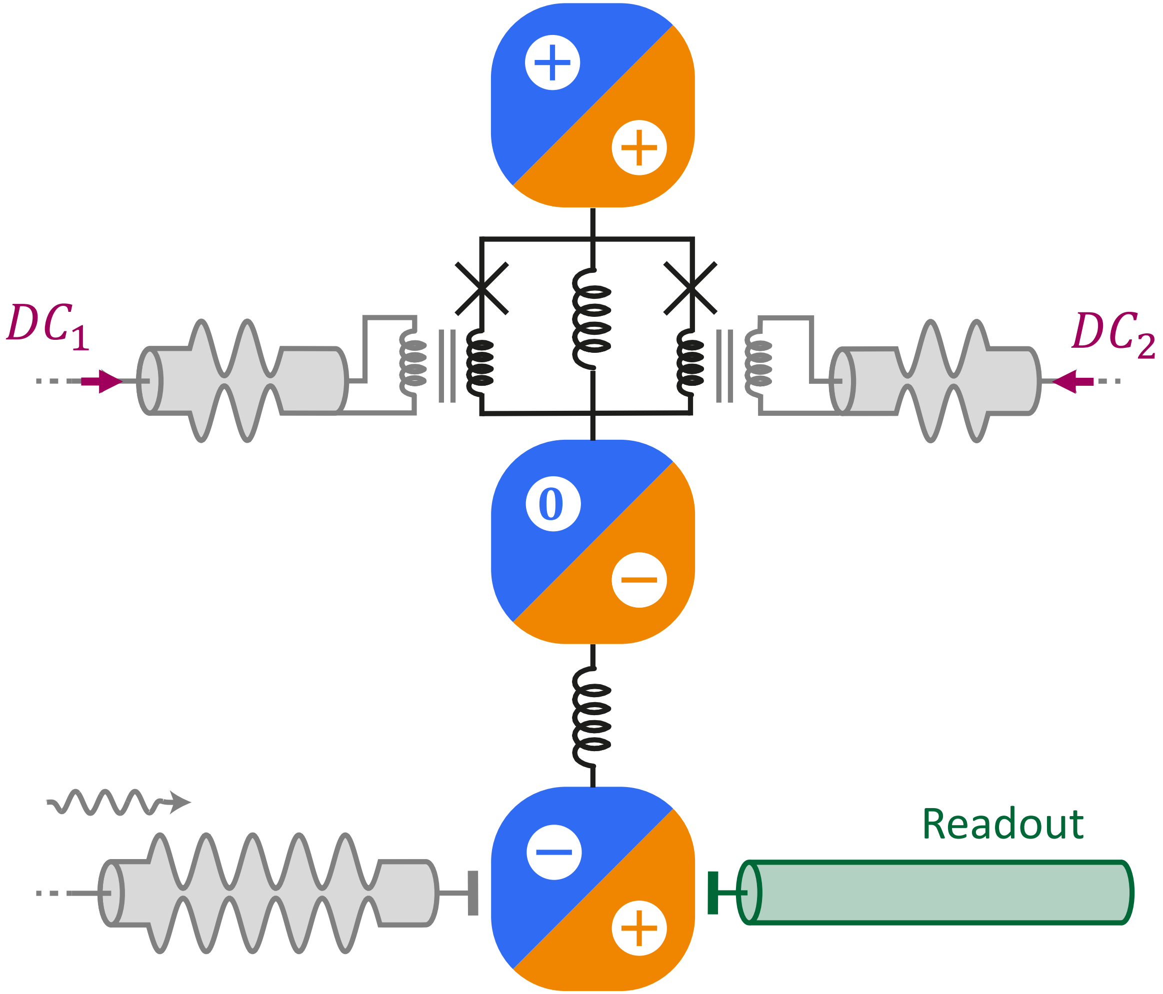




$\varphi_{ZPF,r} \sim 0.05$

Circuit characterization

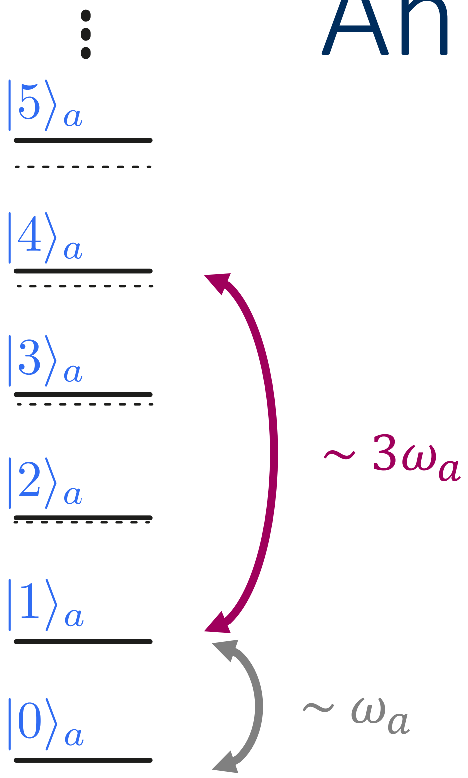


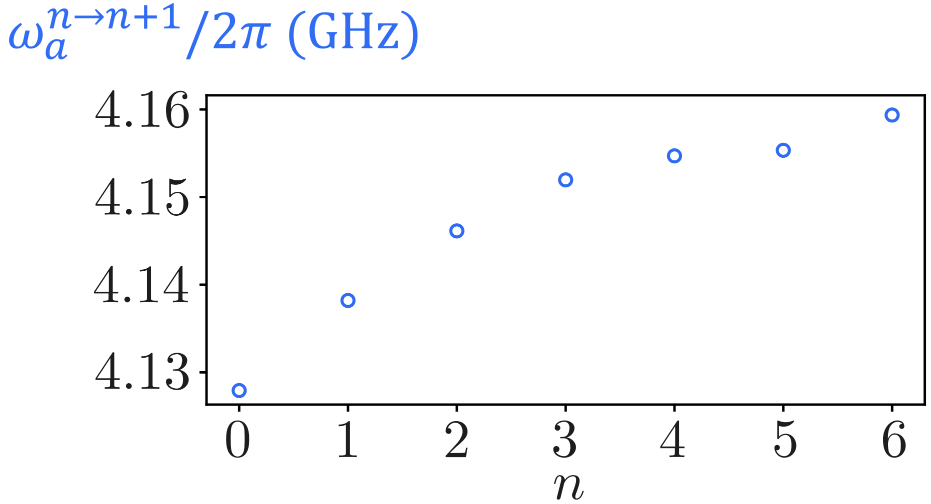


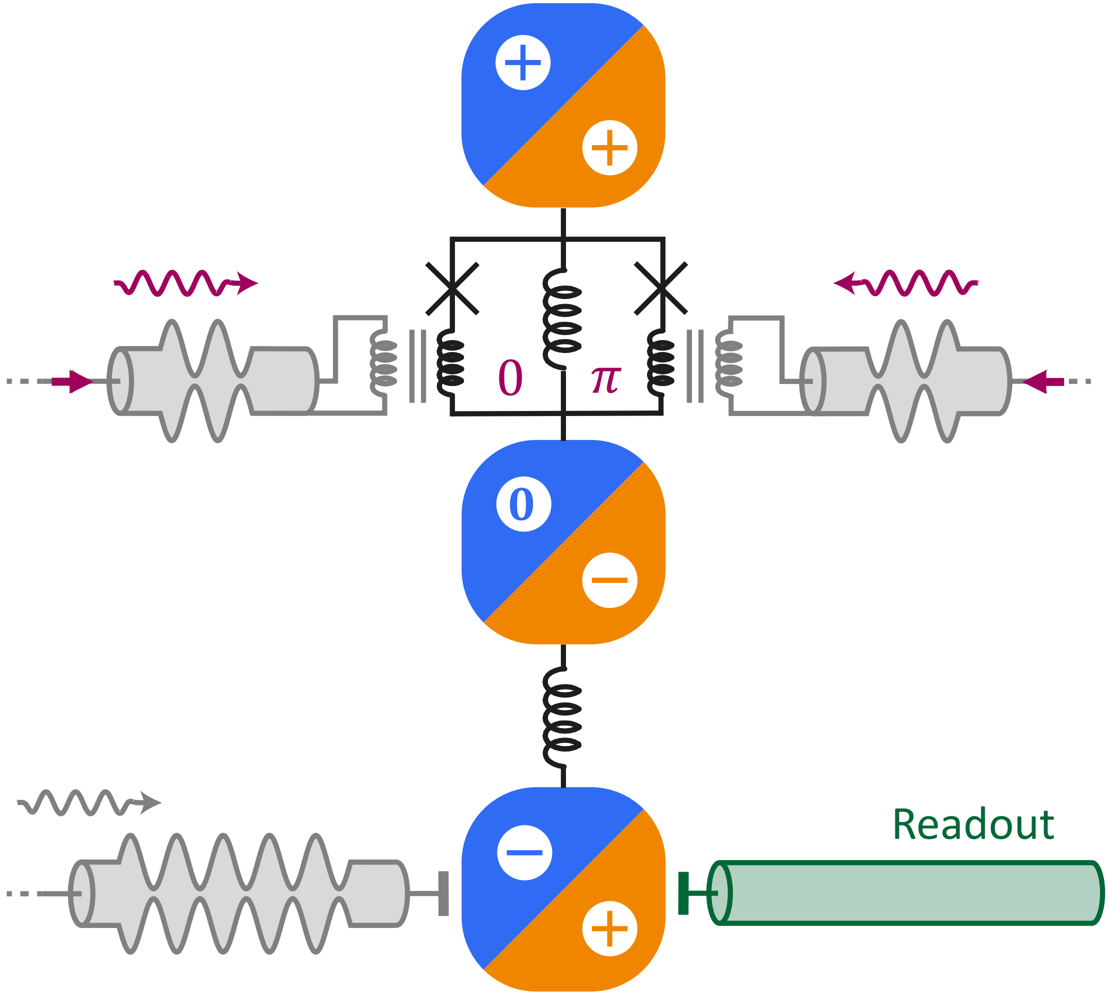
$\varphi_{ZPF,a} = 0.4$ $\varphi_{ZPF,b} = 0.3$

$\varphi_{ZPF,r} = 0.05$ $E_J = h \times 18$ GHz

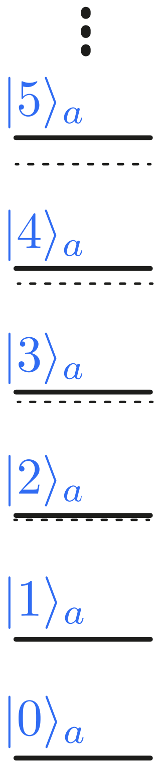
Anharmonicity at the saddle point



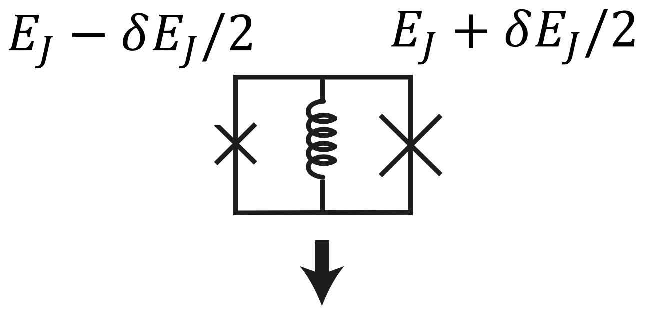




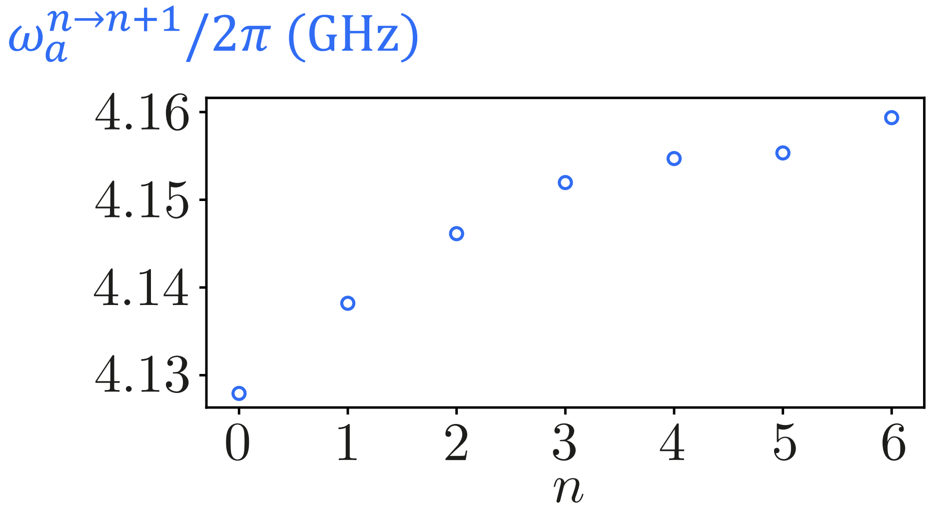
Anharmonicity at the saddle point



$$\varphi = \varphi_{ZPF,a}(a + a^\dagger) + \varphi_{ZPF,b}(b + b^\dagger) + \varphi_{ZPF,r}(r + r^\dagger)$$

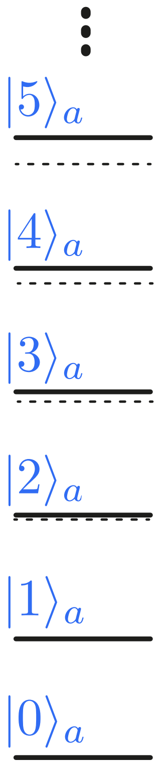


$$\mathrm{H}_{asym} = \delta E_J \cos(\varphi)$$

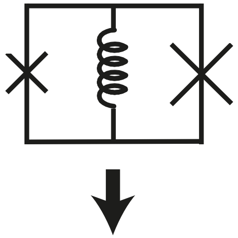


Anharmonicity at the saddle point

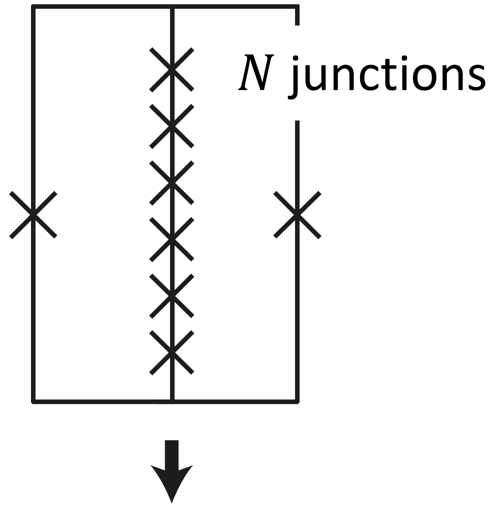
$$\varphi = \varphi_{ZPF,a}(a + a^\dagger) + \varphi_{ZPF,b}(b + b^\dagger) + \varphi_{ZPF,r}(r + r^\dagger)$$



$E_J - \delta E_J/2$ $\qquad$ $E_J + \delta E_J/2$

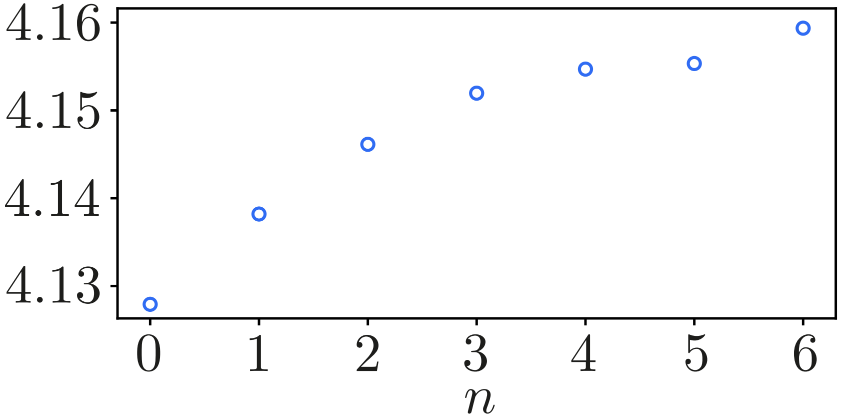


$$\mathrm{H}_{asym} = \delta E_J \cos(\varphi)$$

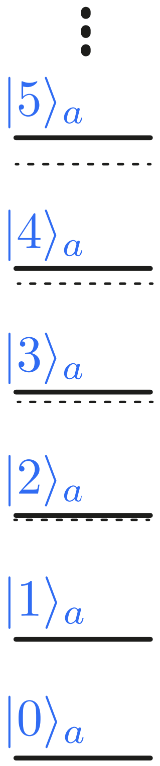


$$\mathrm{H}_{chain} = -\frac{E_L}{24\,N^2}\varphi^4$$

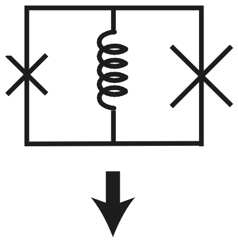
$\omega_a^{n\to n+1}/2\pi$ (GHz)



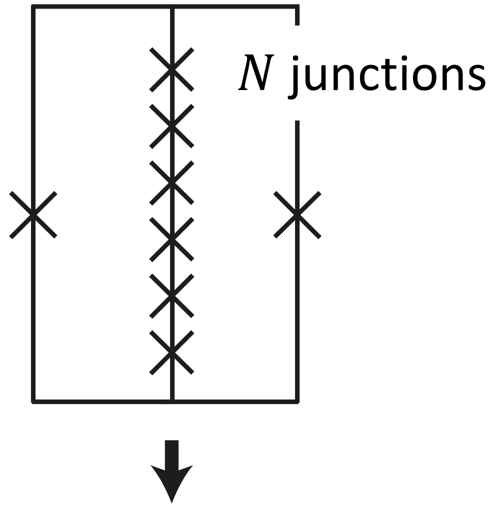
Anharmonicity at the saddle point



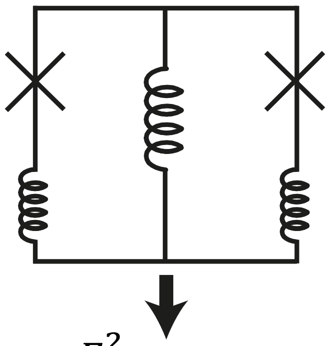
$$\varphi = \varphi_{ZPF,a}(a + a^\dagger) + \varphi_{ZPF,b}(b + b^\dagger) + \varphi_{ZPF,r}(r + r^\dagger)$$



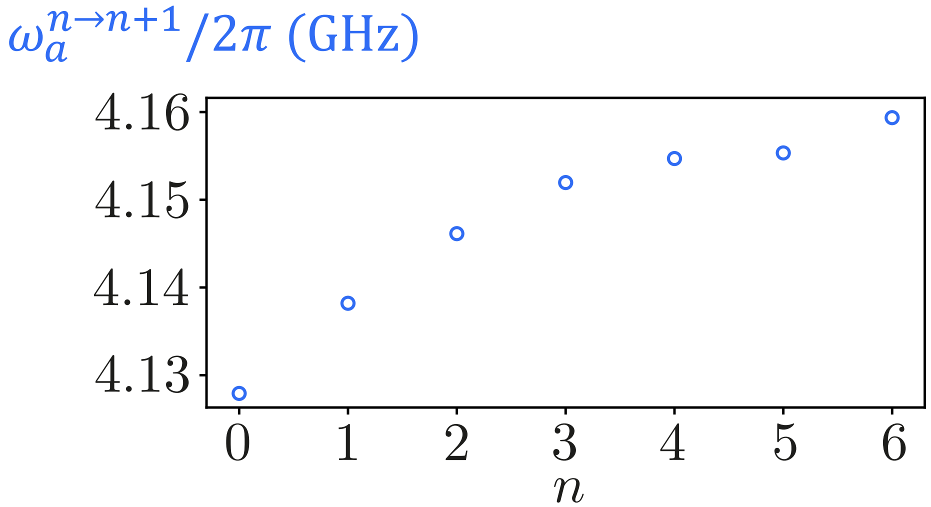
$$\mathrm{H}_{asym} = \delta E_J \cos(\varphi)$$

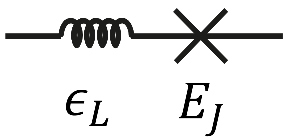


$$\mathrm{H}_{chain} = -\frac{E_L}{24\,N^2}\varphi^4$$



$$\mathrm{H}_{2\varphi} = \frac{E_J^2}{2\epsilon_L}\cos(2\varphi)$$

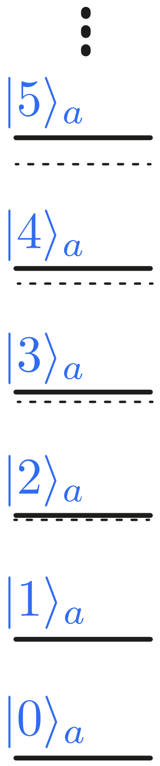




$$V_J(\varphi_i) = -E_J\cos(\varphi_i) + \frac{E_J^2}{4\epsilon_L}\cos(2\varphi_i)$$

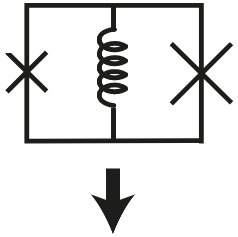
Putterman *et al.* , PRX, 2025
Smith *et al.* , Nat. Comm. , 2025

Anharmonicity at the saddle point

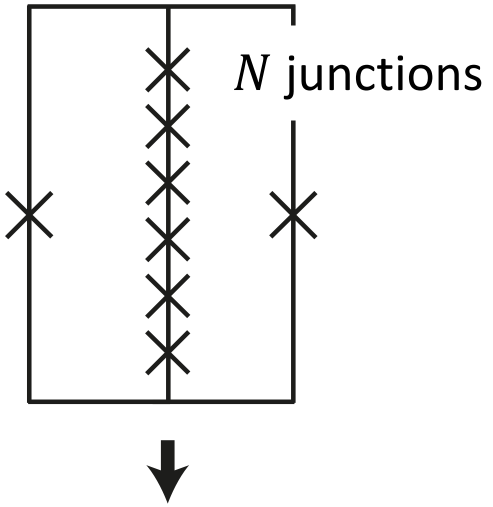


$$\varphi = \varphi_{ZPF,a}\left(a + a^\dagger\right) + \varphi_{ZPF,b}\left(b + b^\dagger\right) + \varphi_{ZPF,r}\left(r + r^\dagger\right)$$

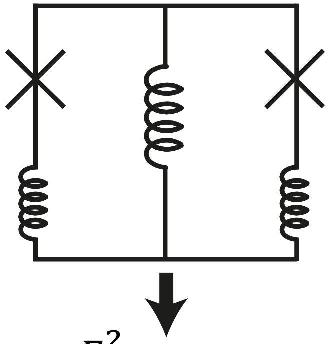
$E_J - \delta E_J/2$ $\quad$ $E_J + \delta E_J/2$



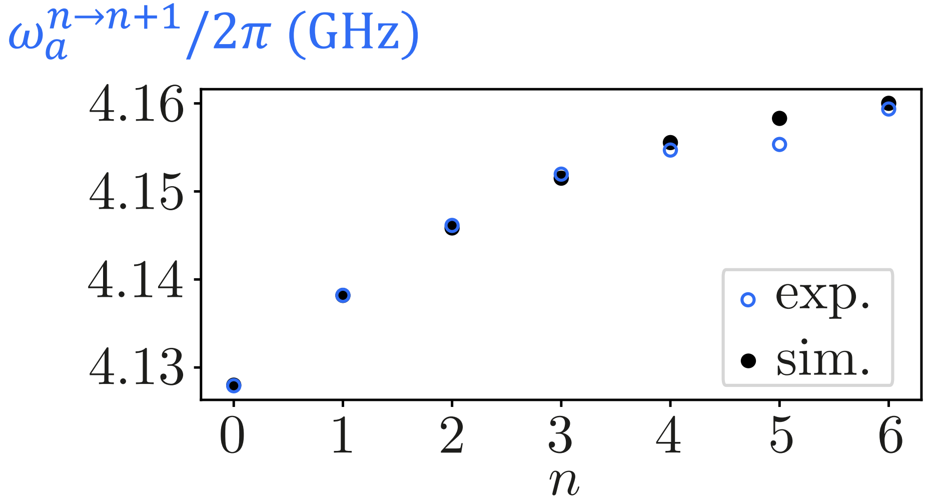
$$\mathrm{H}_{asym} = \delta E_J \cos(\varphi)$$

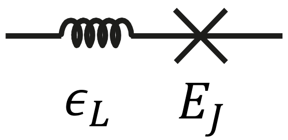


$$\mathrm{H}_{chain} = -\frac{E_L}{24\, N^2}\varphi^4$$



$$\mathrm{H}_{2\varphi} = \frac{E_J^2}{2\epsilon_L}\cos(2\varphi)$$

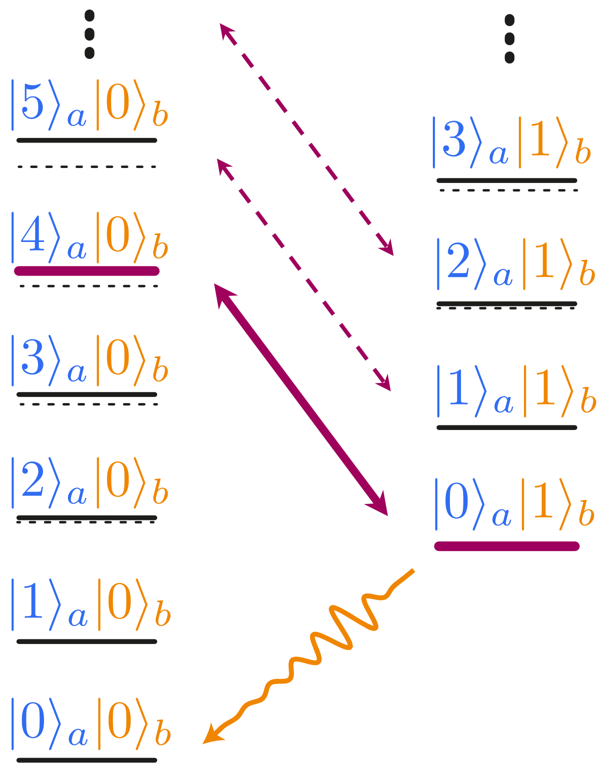




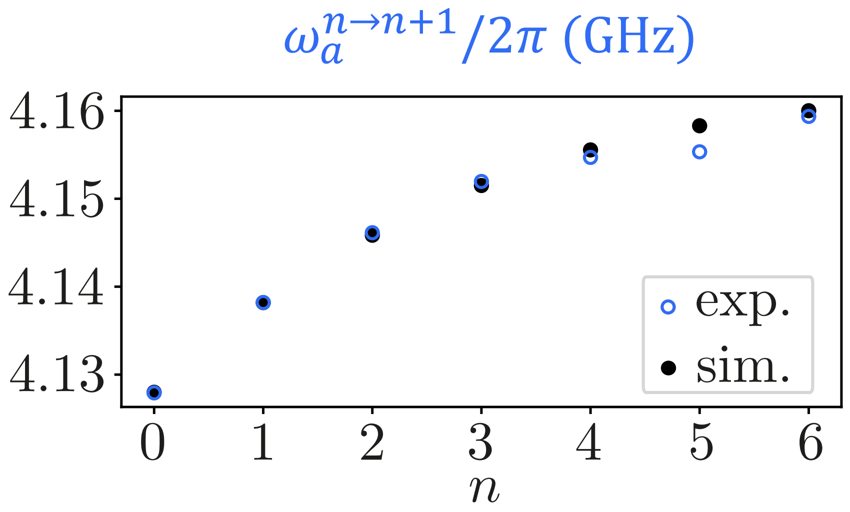
$$V_J(\varphi_i) = -E_J\cos(\varphi_i) + \frac{E_J^2}{4\epsilon_L}\cos(2\varphi_i)$$

$\epsilon_L = h \times 2$ THz $\qquad$ $(E_{2\varphi}/E_\varphi = 0.2\ \%)$

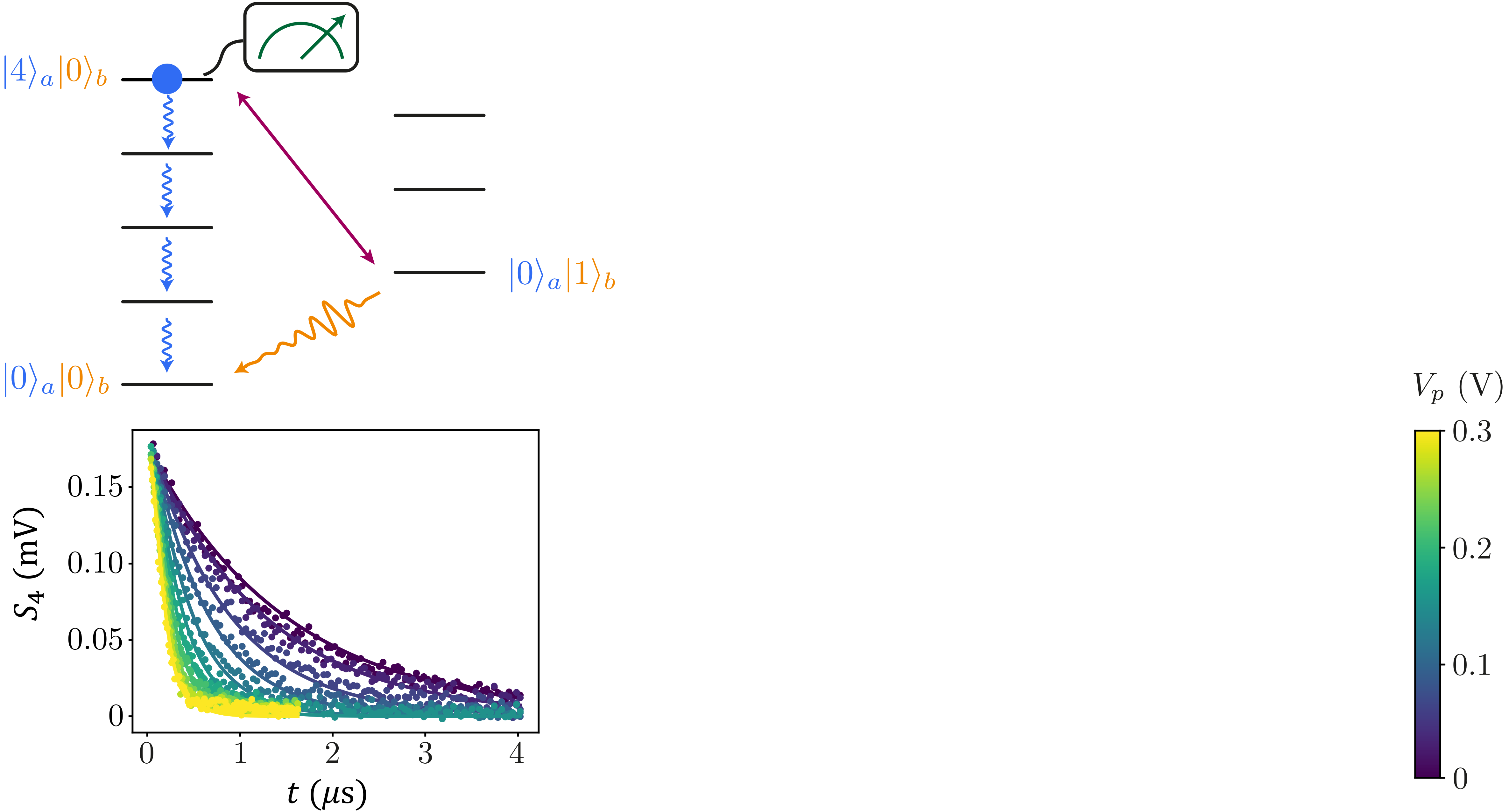
State-dependent dissipation



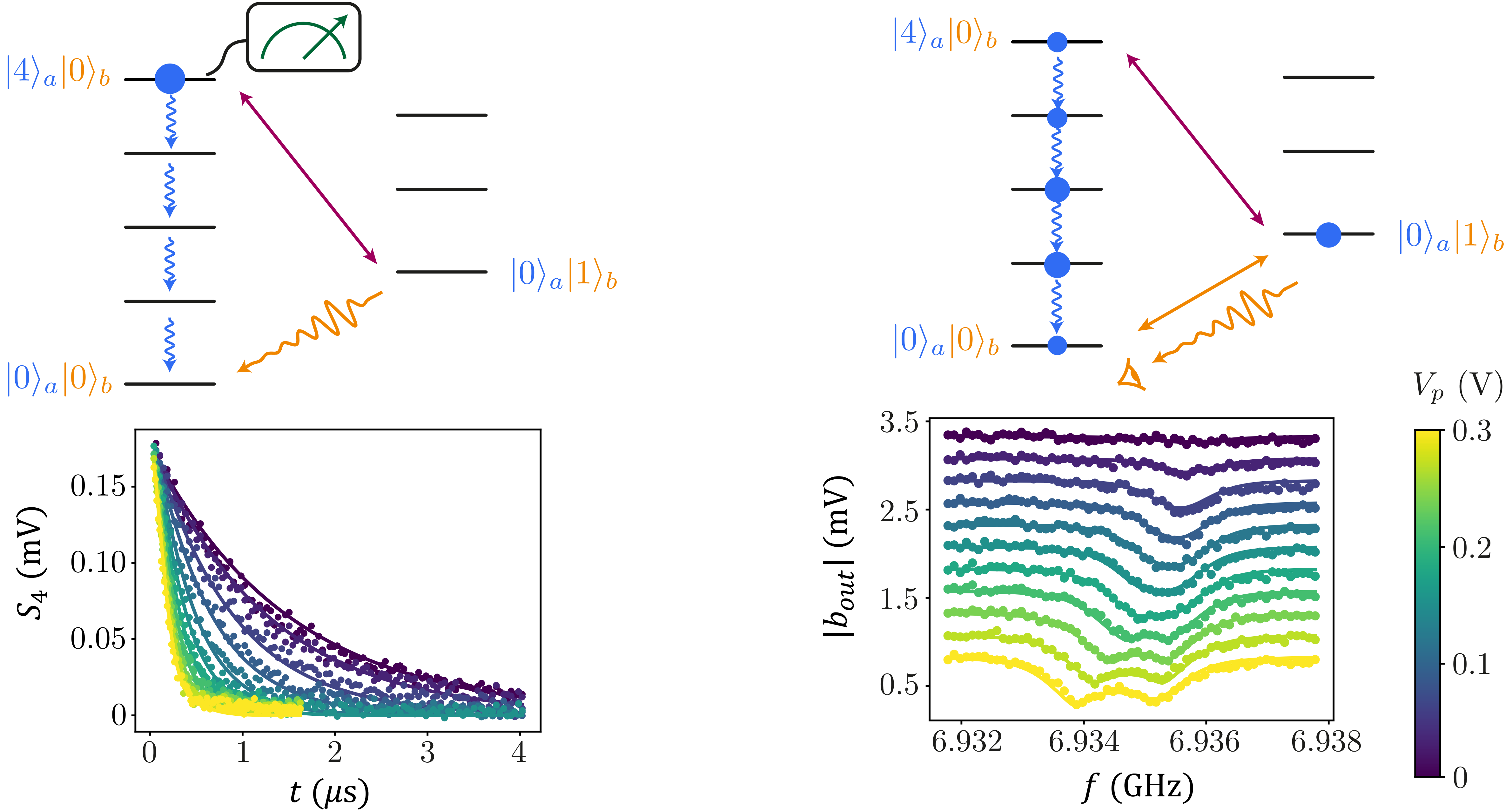
$$\kappa_4\, \mathcal{D}[a^4] \longrightarrow \boldsymbol{\Gamma_4\, \mathcal{D}[|0\rangle\langle 4|]}$$



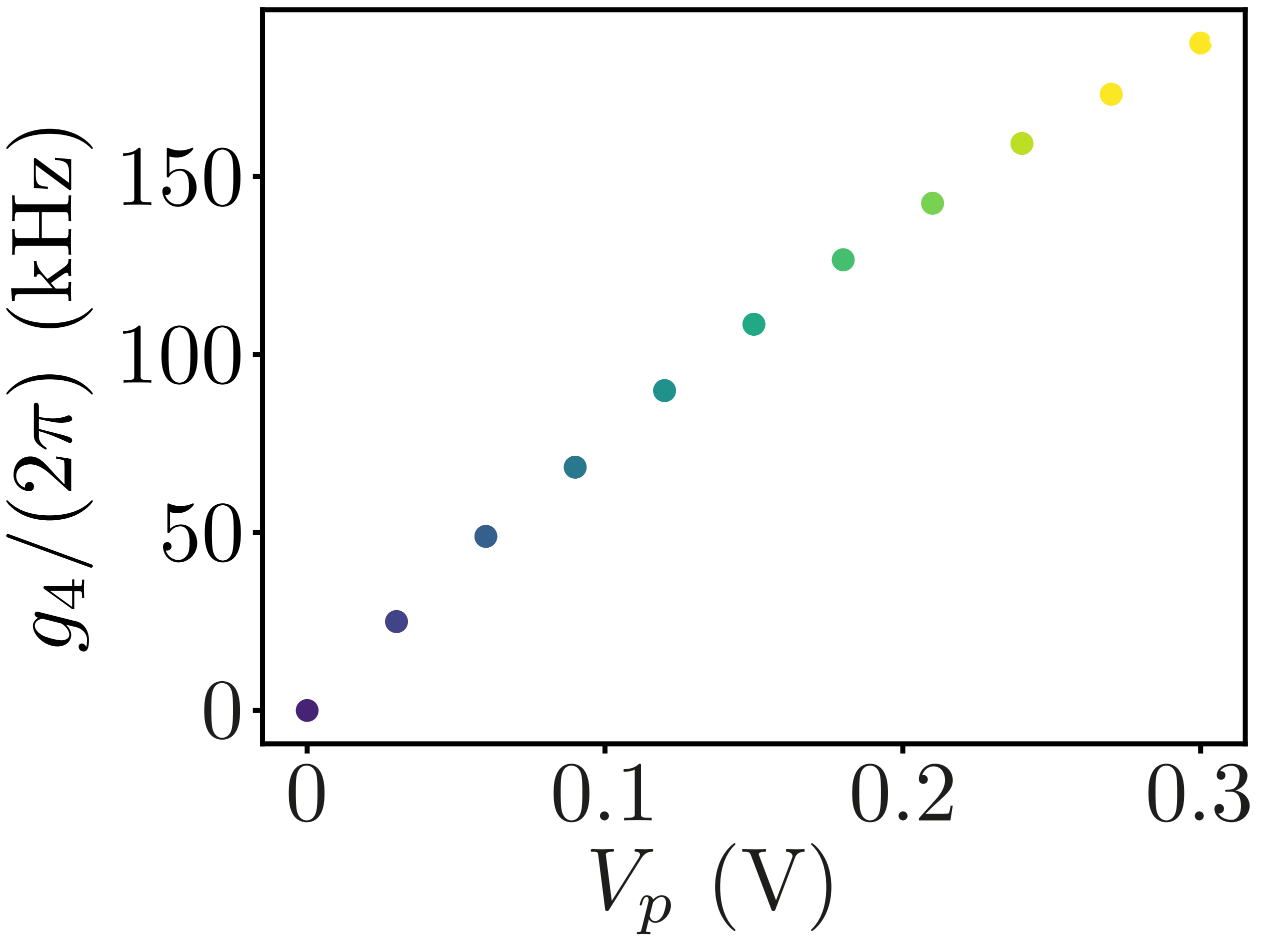
4-to-1 photon exchange



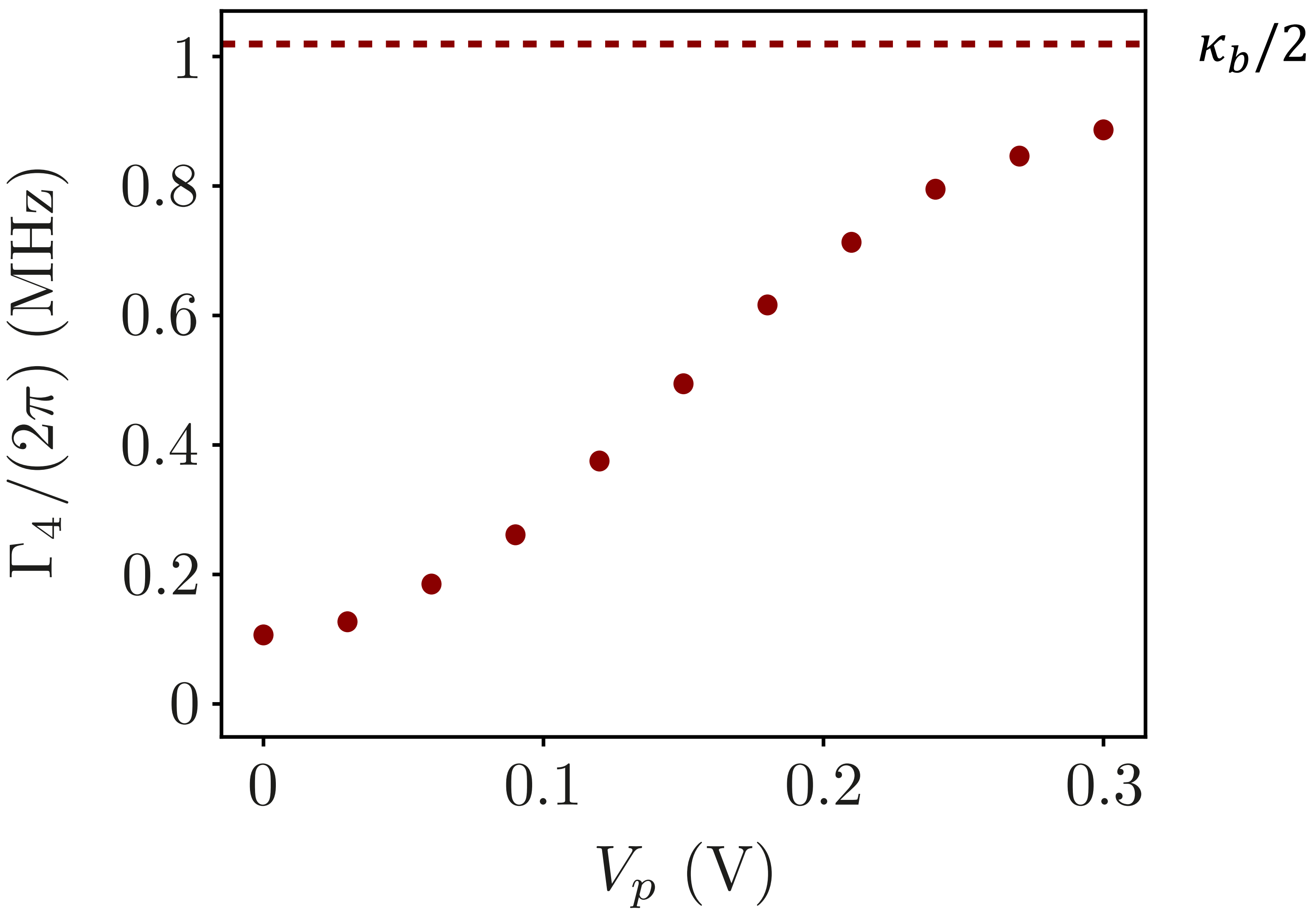
4-to-1 photon exchange



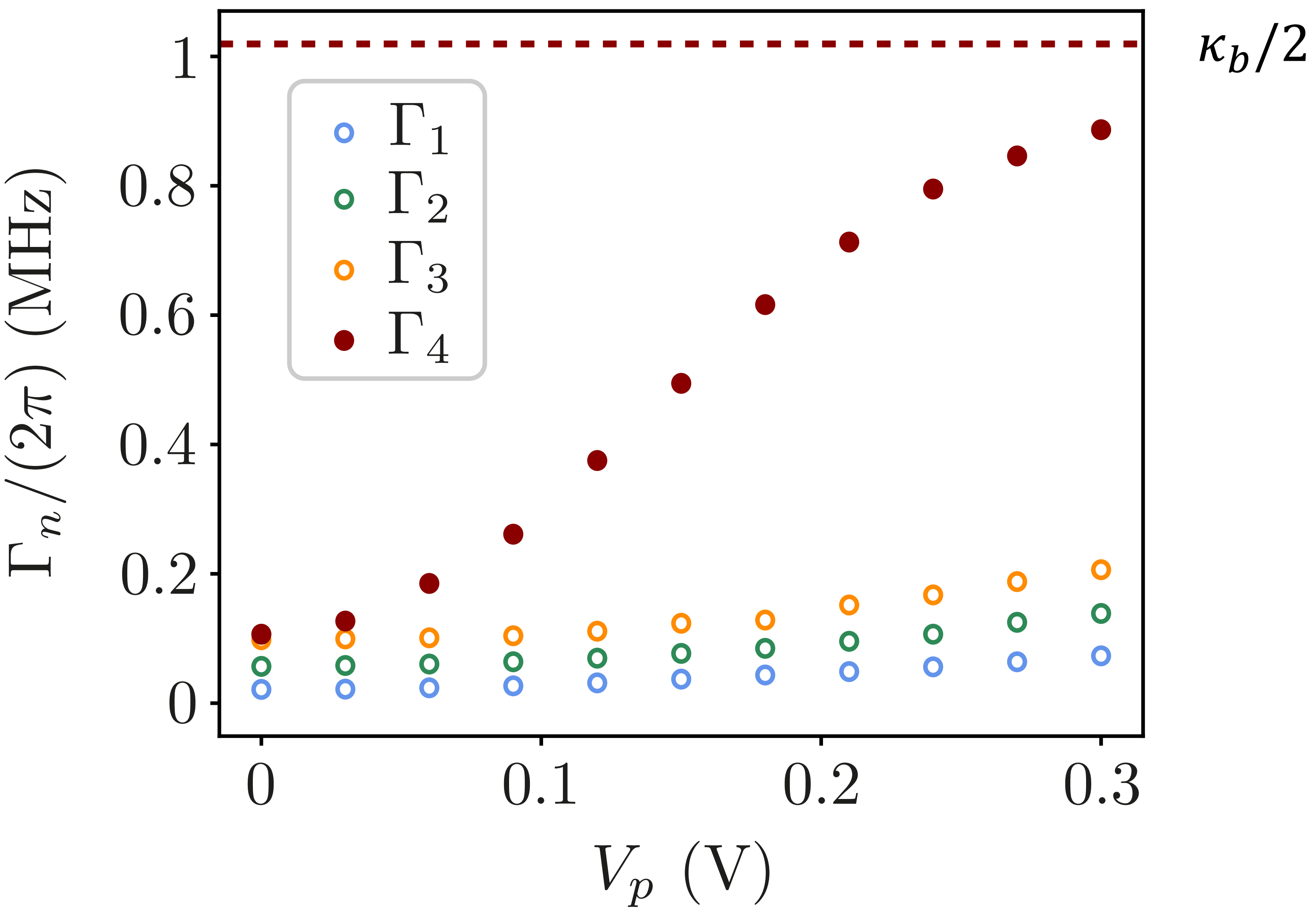
4-to-1 photon exchange



Dissipating quartets of excitations

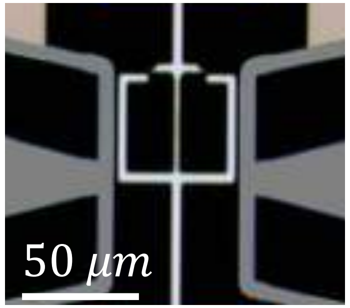


Dissipating quartets of excitations

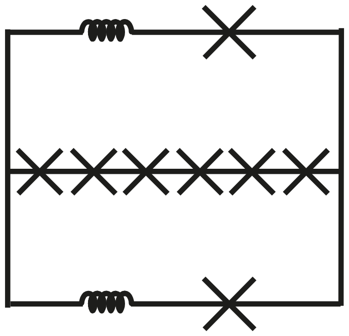


Vanselow *et al.* , PRX, 2026

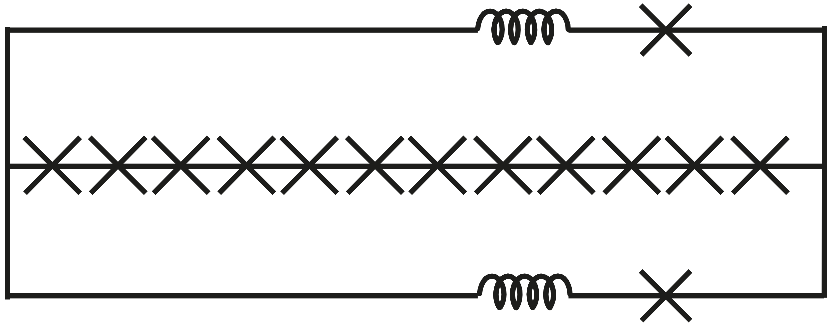
Adapting the ATS's design



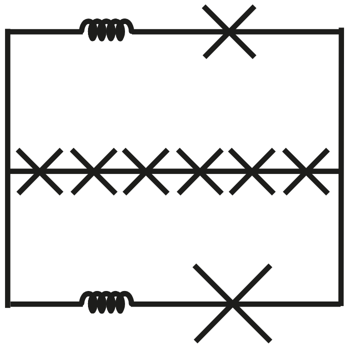
Too few junctions



Too long tracks

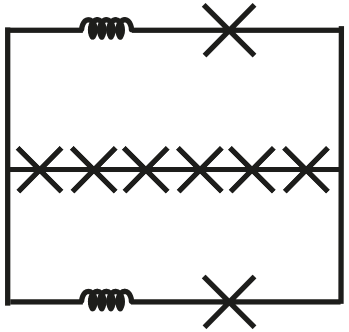


Asymmetry

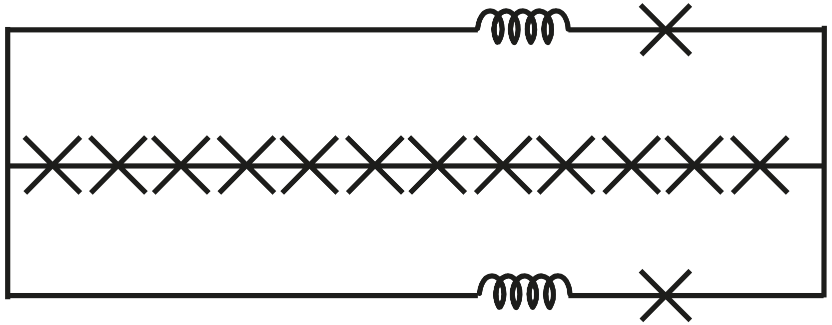


Adapting the ATS's design

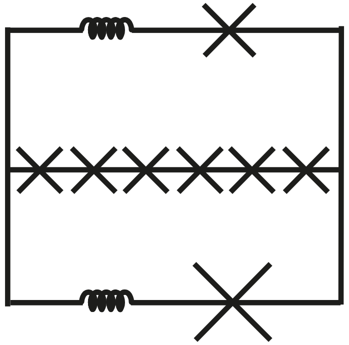
Too few junctions

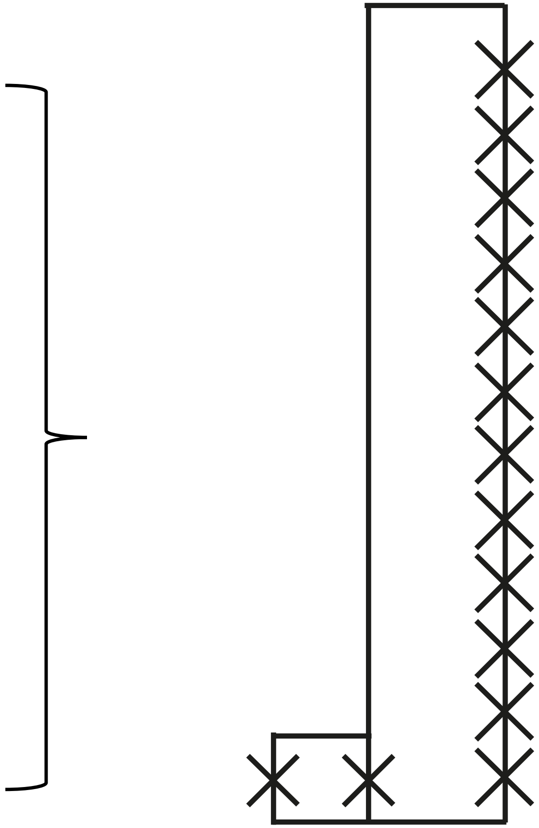


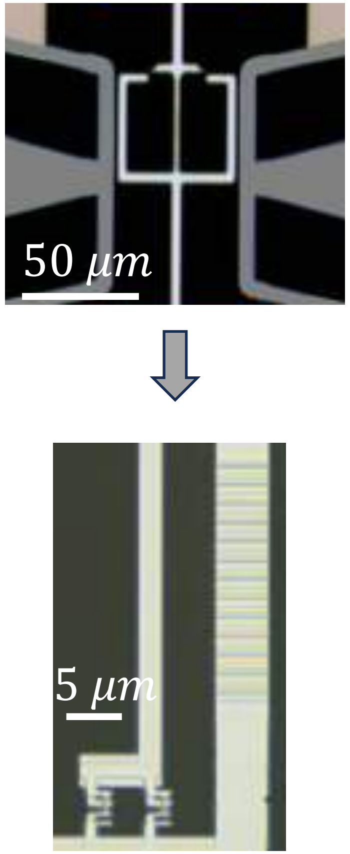
Too long tracks



Asymmetry





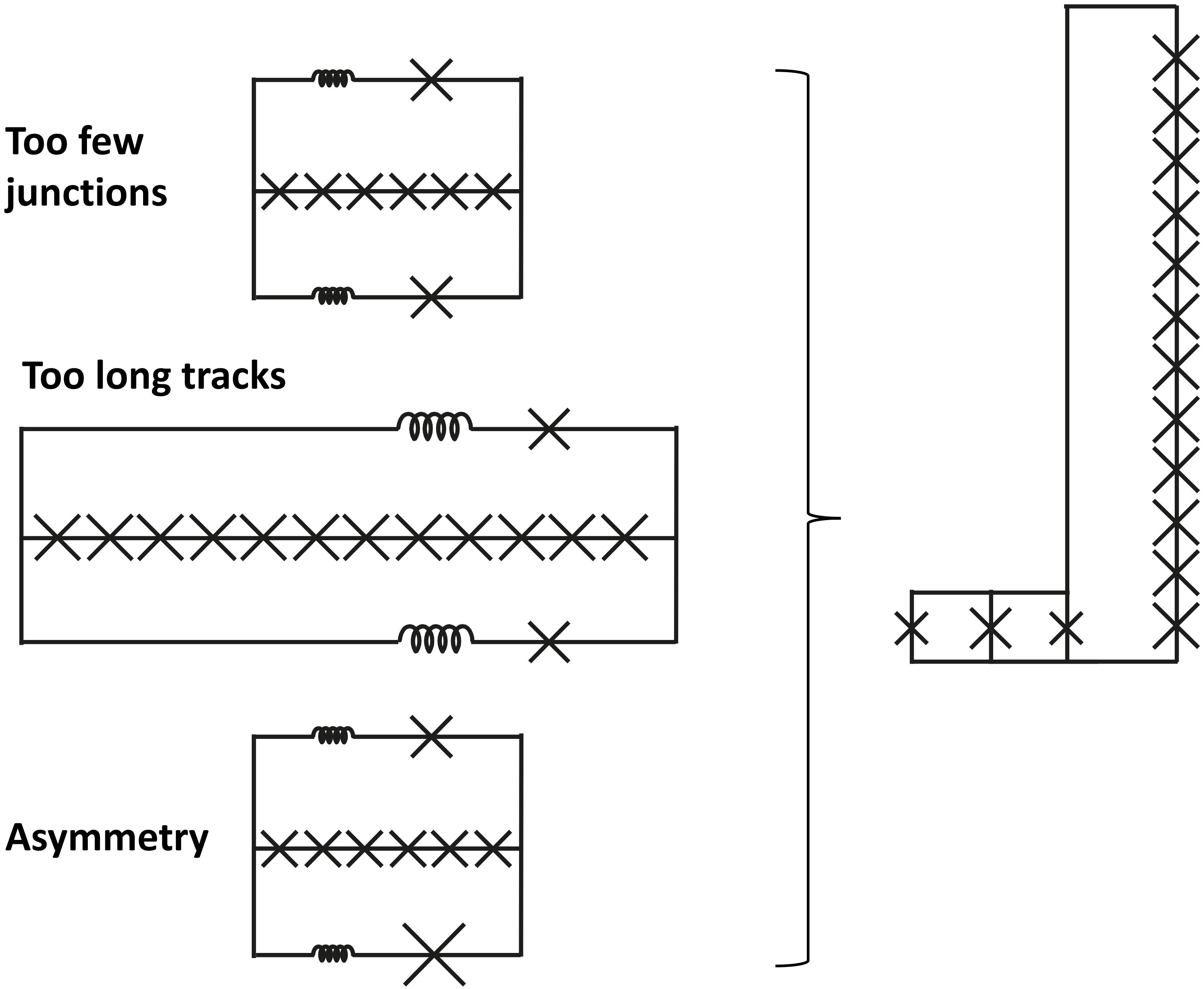


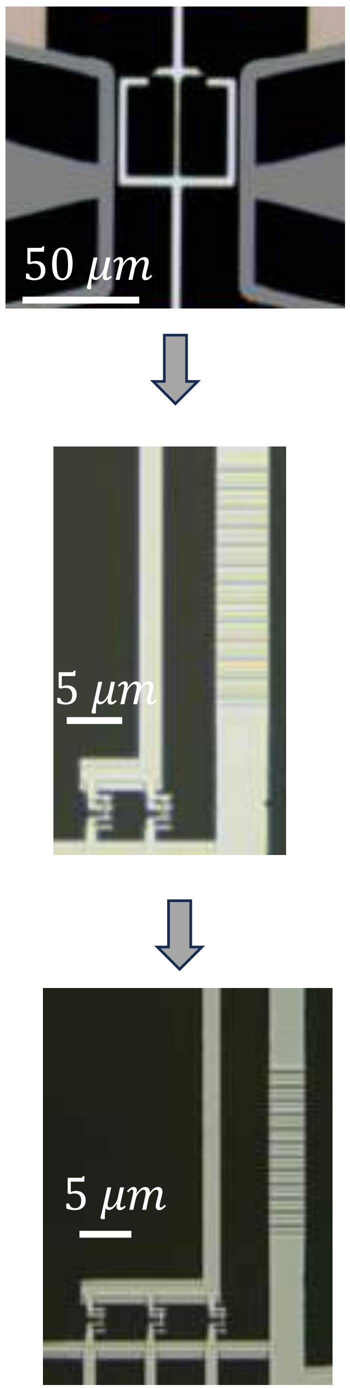
Adapting the ATS's design

Too few junctions

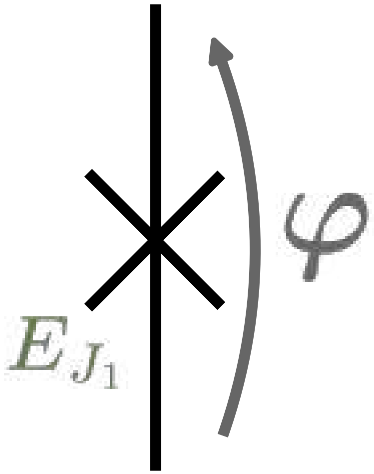
Too long tracks

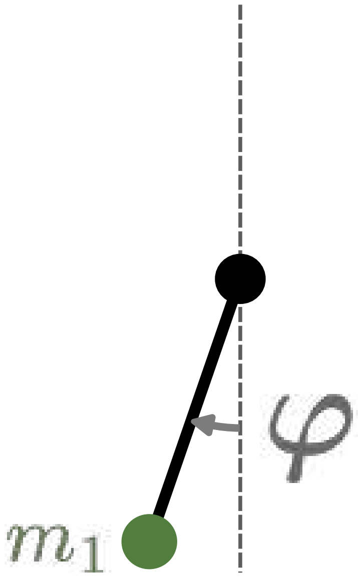
Asymmetry



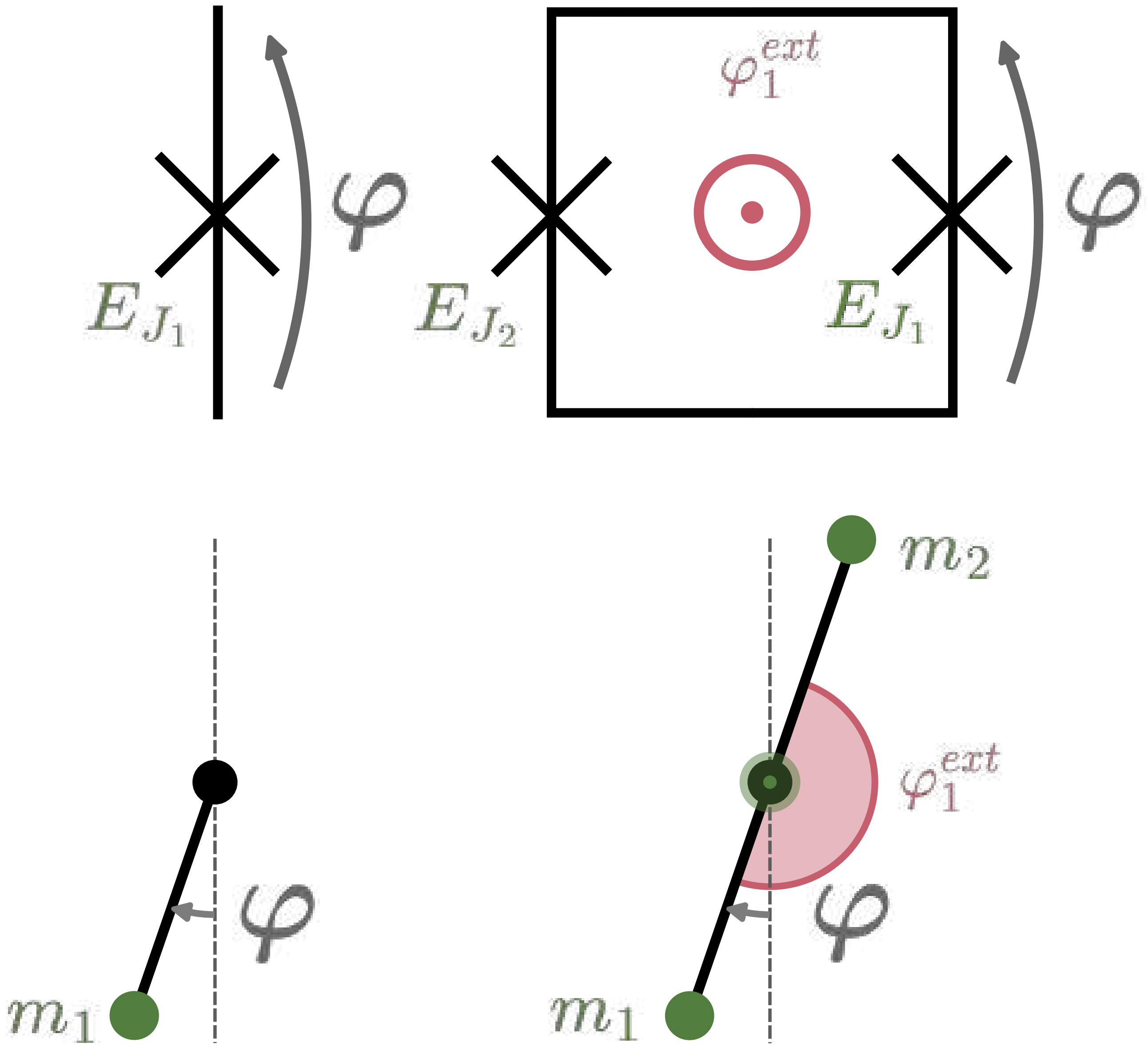


3-SQUID: a mechanical analogy

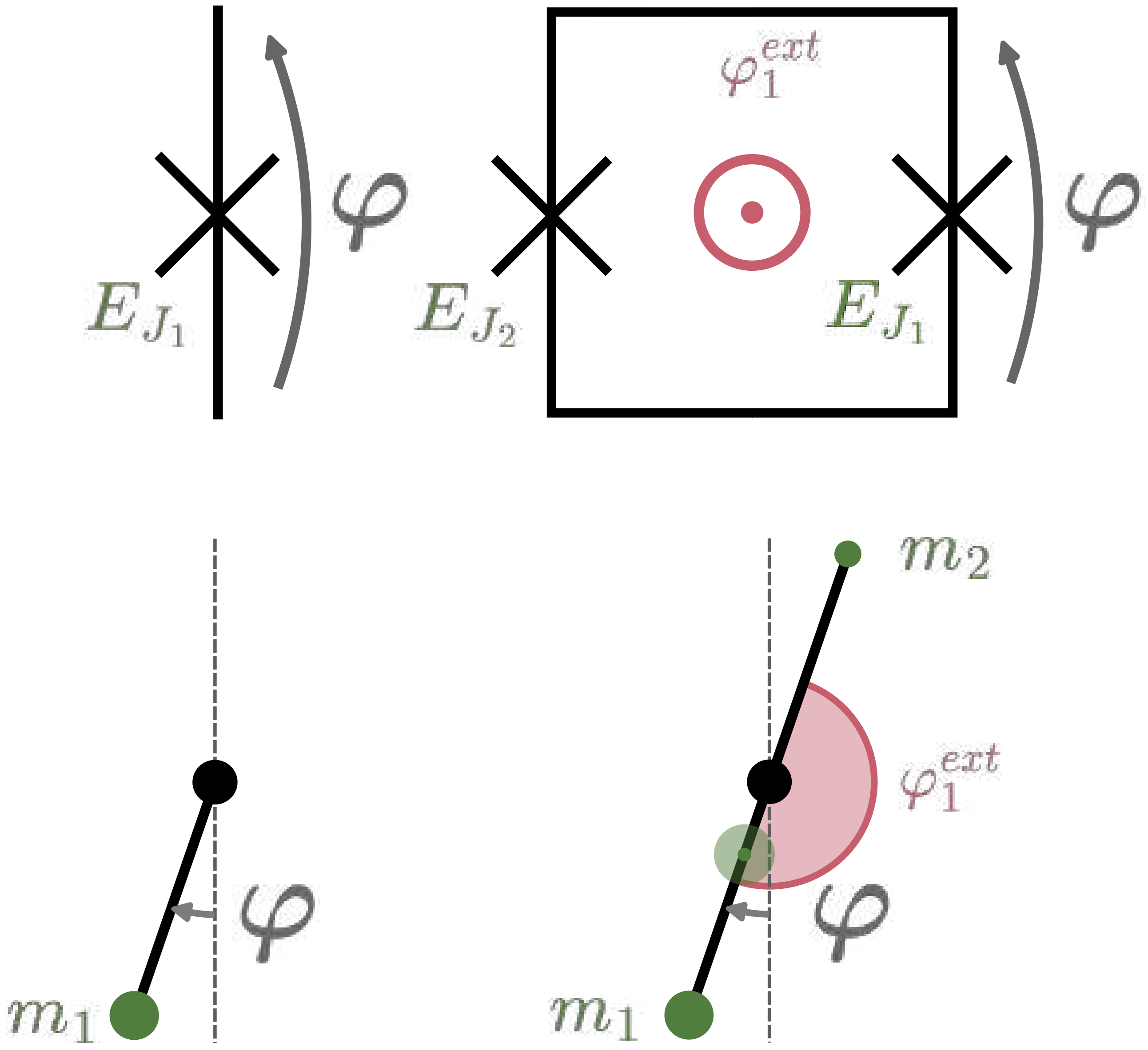




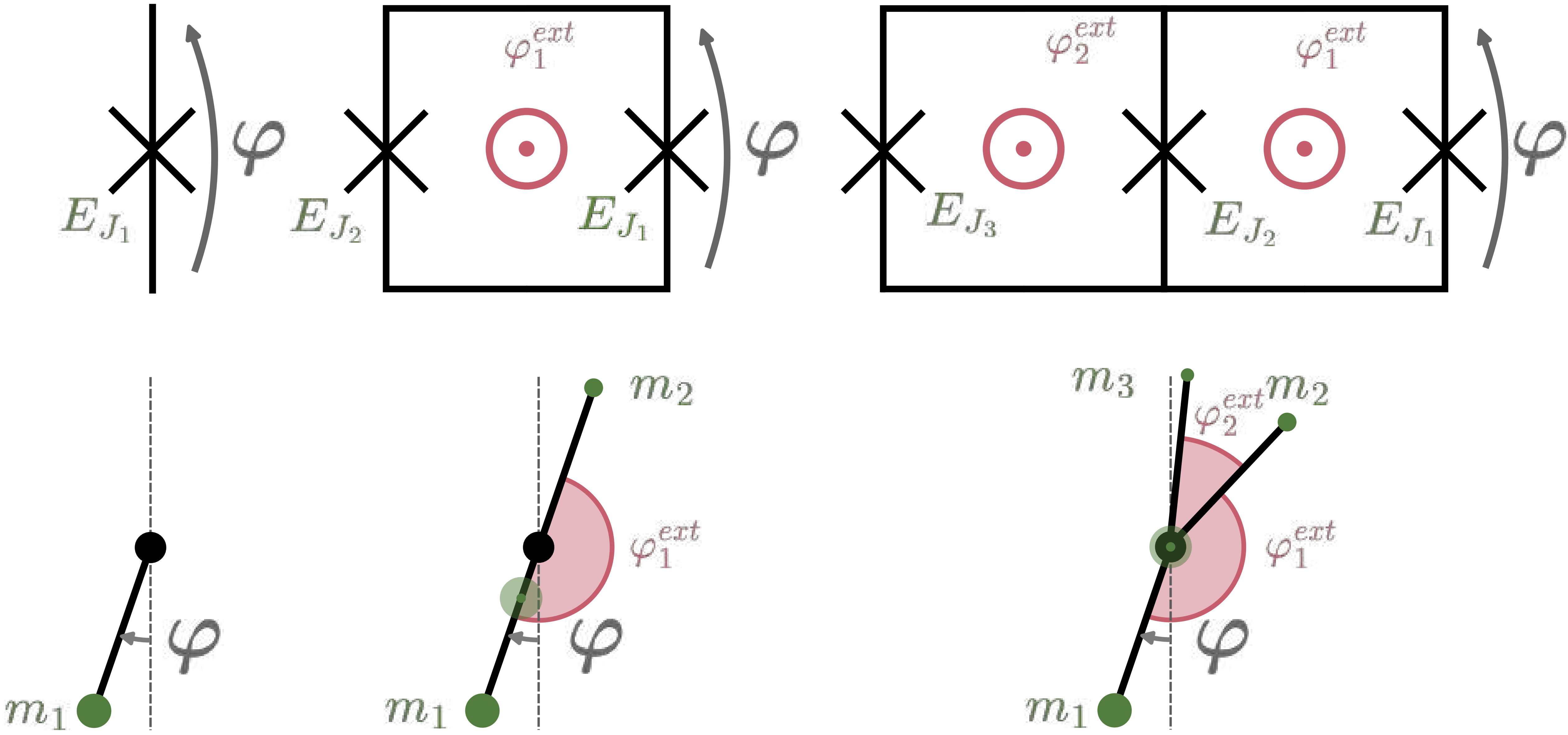
3-SQUID: a mechanical analogy



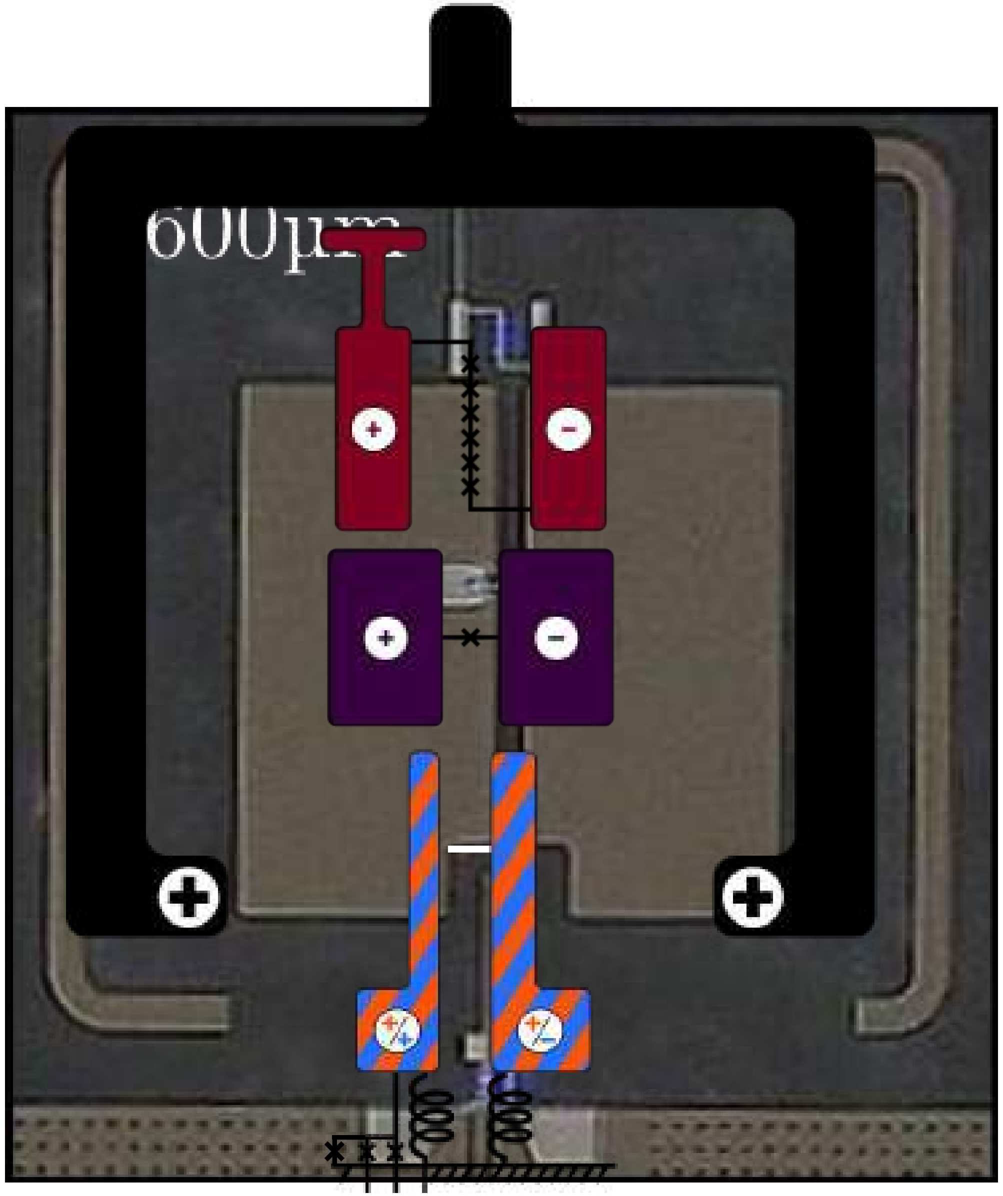
3-SQUID: a mechanical analogy

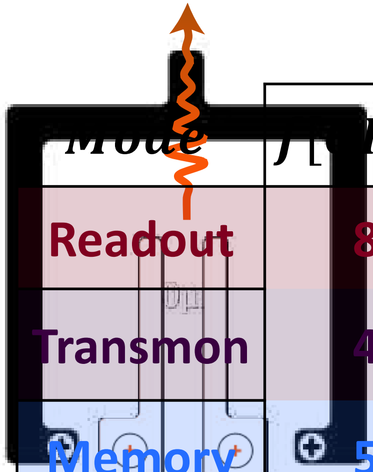


3-SQUID: a mechanical analogy

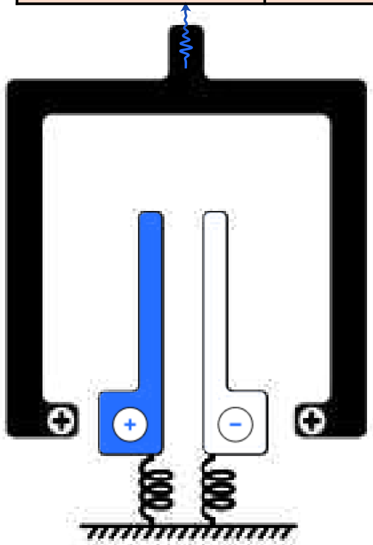


Adapting circuit design : spatial symmetry



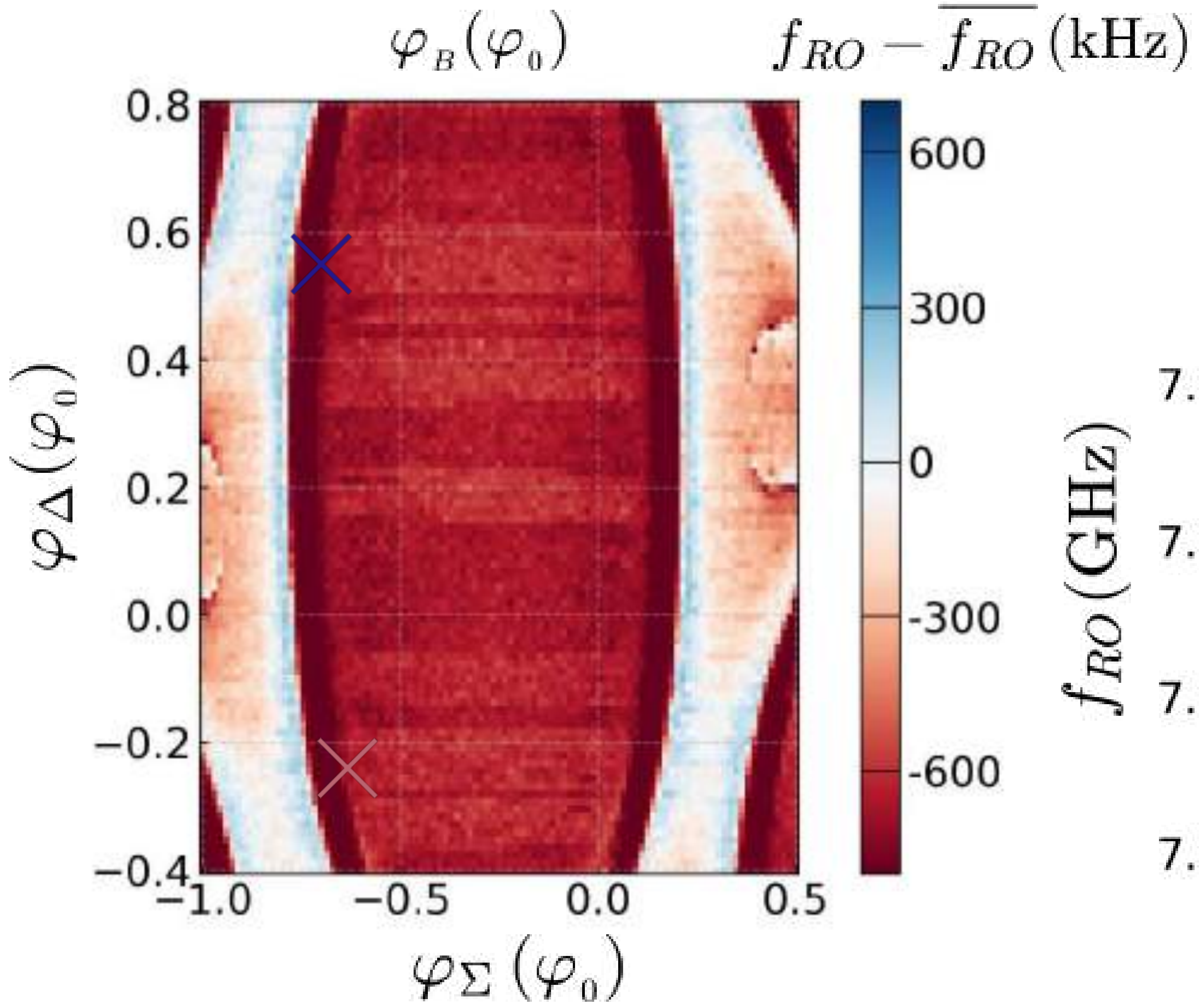


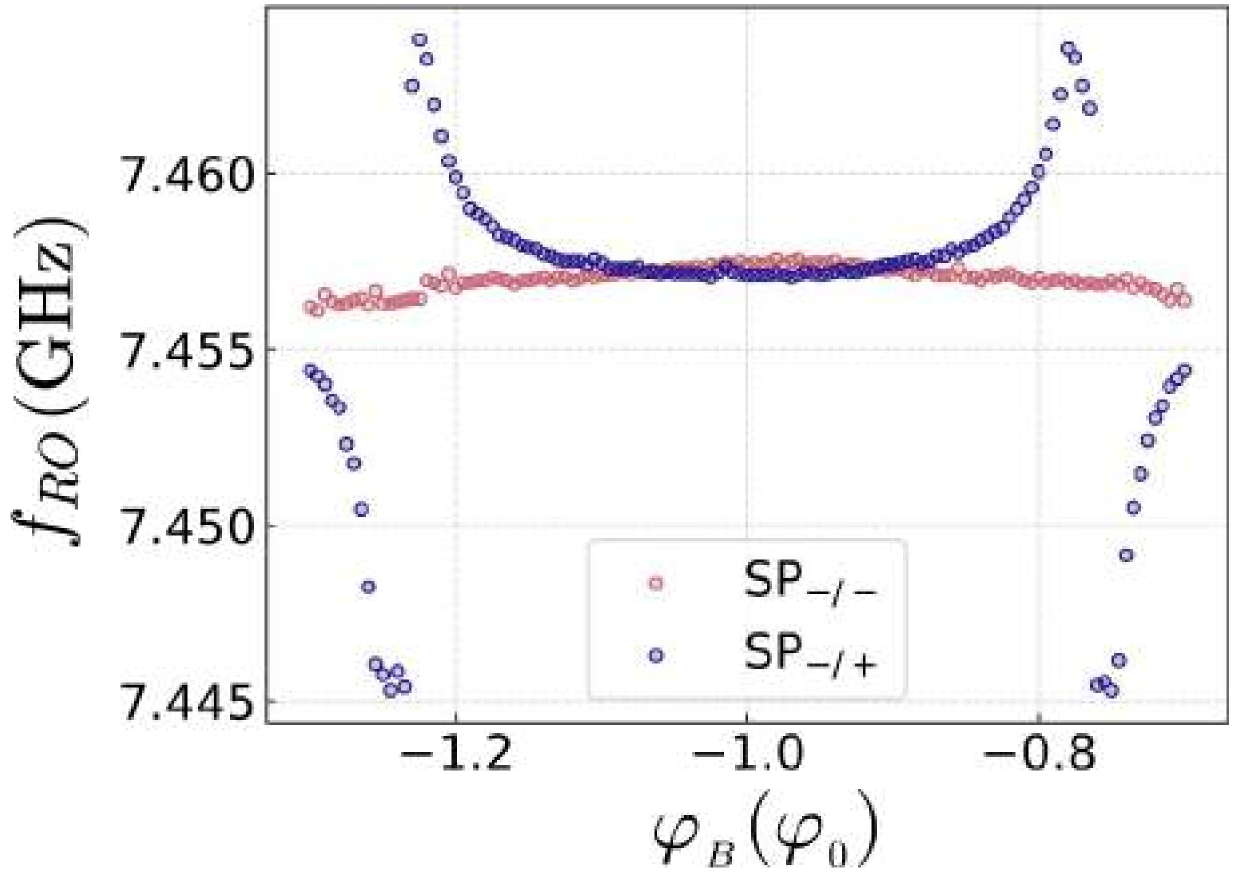
Mode	f [GHz]	$\kappa_{ext}/2\pi(MHz)$	$\varphi_{ATS}^{ZPF}[\varphi_0]$	$\chi_{tX}/2\pi(MHz)$
Readout	8	1	0.02	1
Transmon	4	<1e-3	0.02	200
Memory	5	<1e-3	0.45	1
Buffer	7	40	0.45	~ 0



Preliminary results : 3SQUID

$$\begin{pmatrix} \varphi_\Sigma \\ \varphi_\Delta \\ \varphi_B \end{pmatrix} = \begin{pmatrix} 1/4 & 1/2 & 0 \\ 1/4 & 1/2 & 1 \\ 1 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} \varphi_1^{ext} \\ \varphi_2^{ext} \\ \varphi_3^{ext} \end{pmatrix}$$





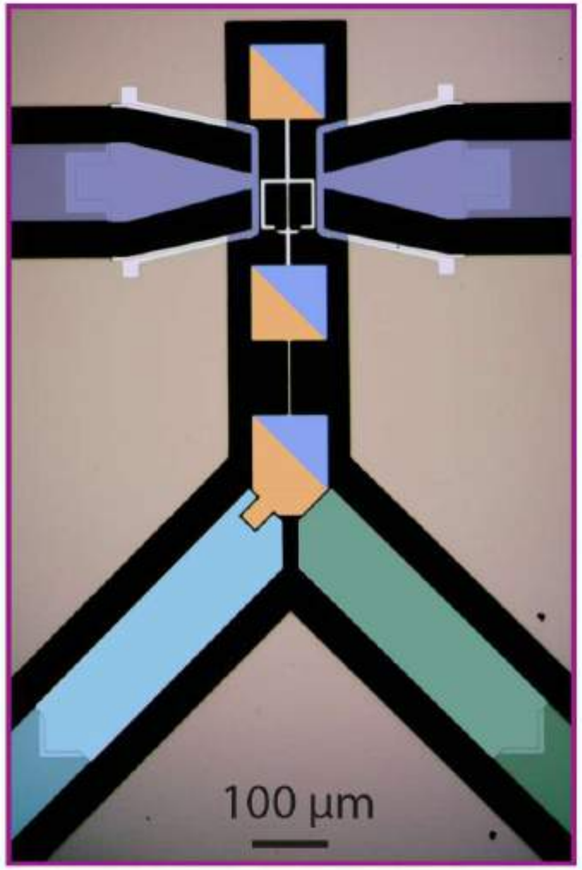
Conclusion

Building a platform for clean
high-order dissipation engineering

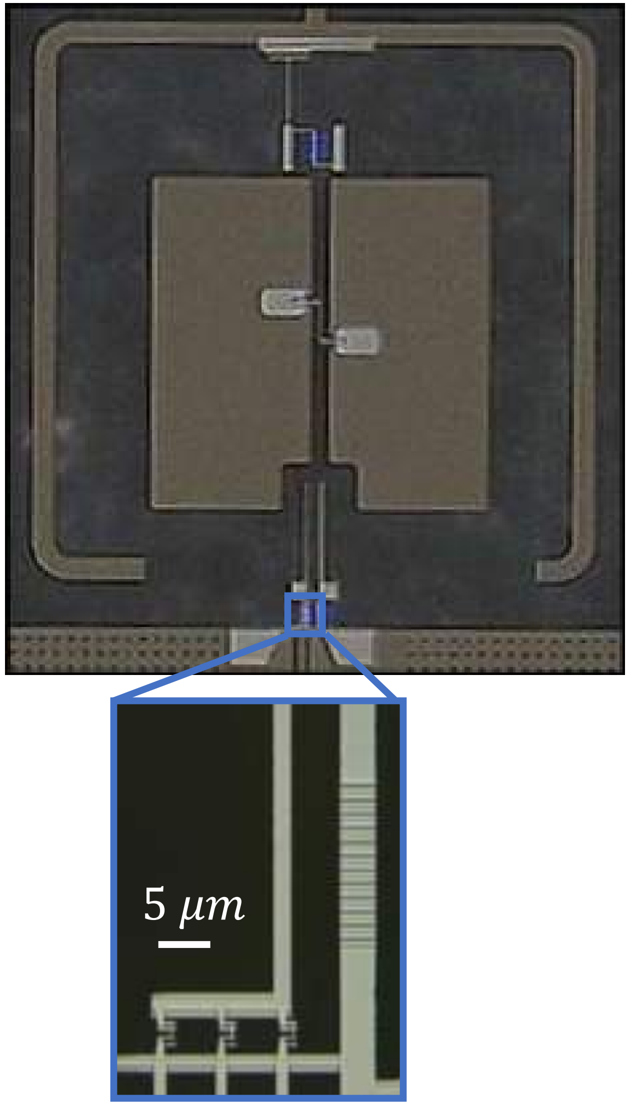
Goal : dissipative stabilization of
advanced bosonic qubits

Challenge : Spurious non-linear processes
(anharmonicity, parametric loss)

Vanselow *et al.* , PRX, 2026 :



Current version:



Thank you !

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