Microwave Photons Wave Mixing for Novel Superconducting qubits

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Outline

- **100 Years of Quantum**
- **Superconducting circuits as a platform for artificial atoms**
- **Encoding schemes with strong light-matter coupling**
  - **Kerr-Cat Qubit**
  - **More wave-mixing with the Transmon qubit**

Quantum Physics

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Control of Large Quantum Systems

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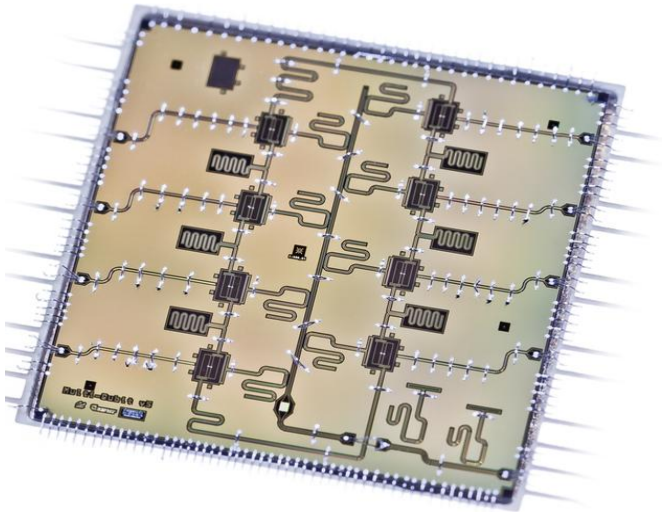
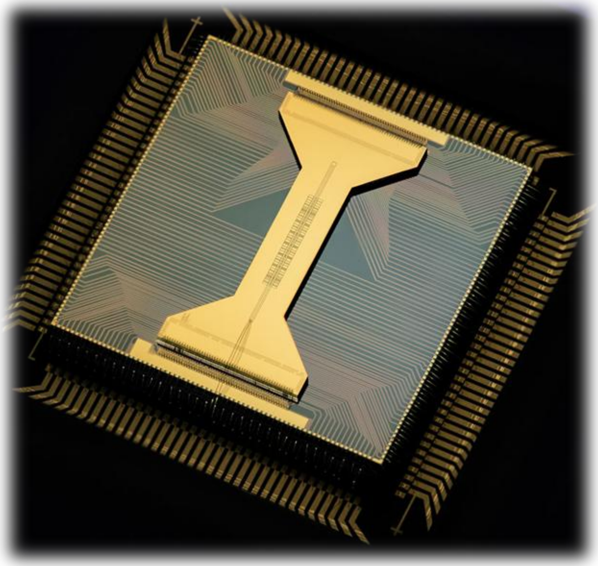
Superconducting circuits



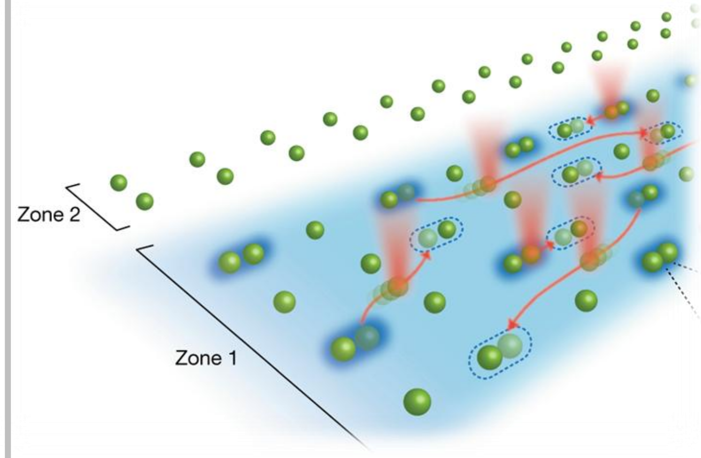
IBM, Google, Amazon
AWS, Alice & Bob…

Trapped Ions



Quantinuum, Ion Q,…

Neutral Atoms

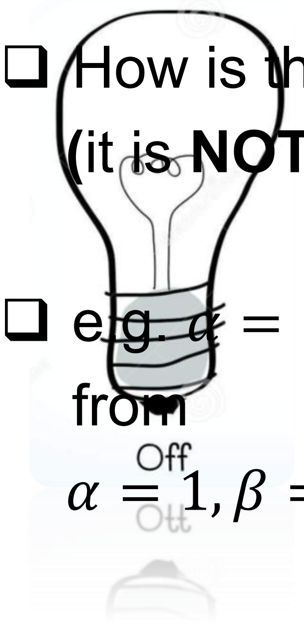


QuEra, PASQAL,…

Classic Vs Quantum lamps

- A classical two-state system is like a lamp which has two, perfectly **distinguishable states**

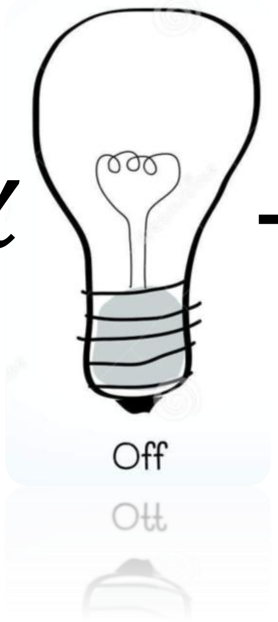
$$1 = |\alpha|^2 + |\beta|^2$$



OR

- ❑ How is this state different? **Spoiler alert:** (it is **NOT Either/Or** it is another state!)
- ❑ e.g. $\alpha = 1, \beta = 1$ can be distinguished from $\alpha = 1, \beta = -1$

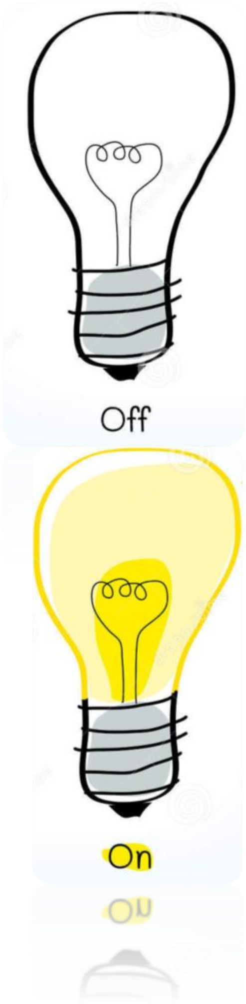
- A quantum system on the other hand can (in principle) exist in a **superposition**!

$\rightarrow \alpha$  $+\beta$ 

Visualization

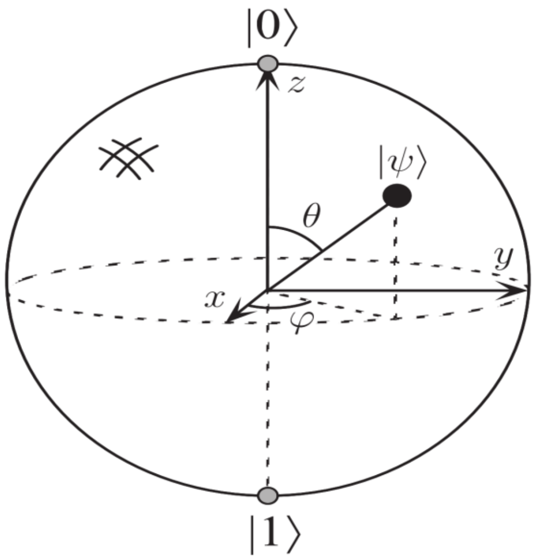
$|0\rangle \rightarrow$

$|1\rangle \rightarrow$



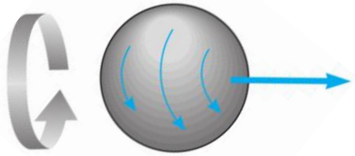
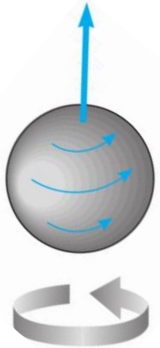
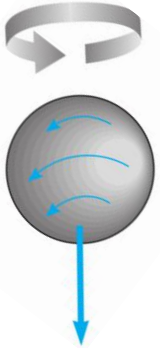
- We can visualize the state as a point on a sphere “Bloch sphere”

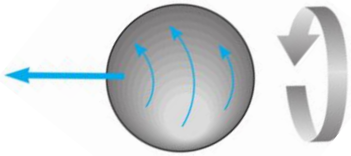
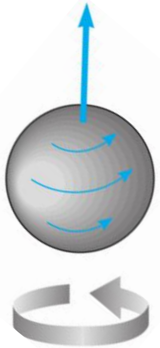
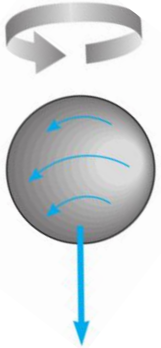
$$|\psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$



Measurement and State Collapse

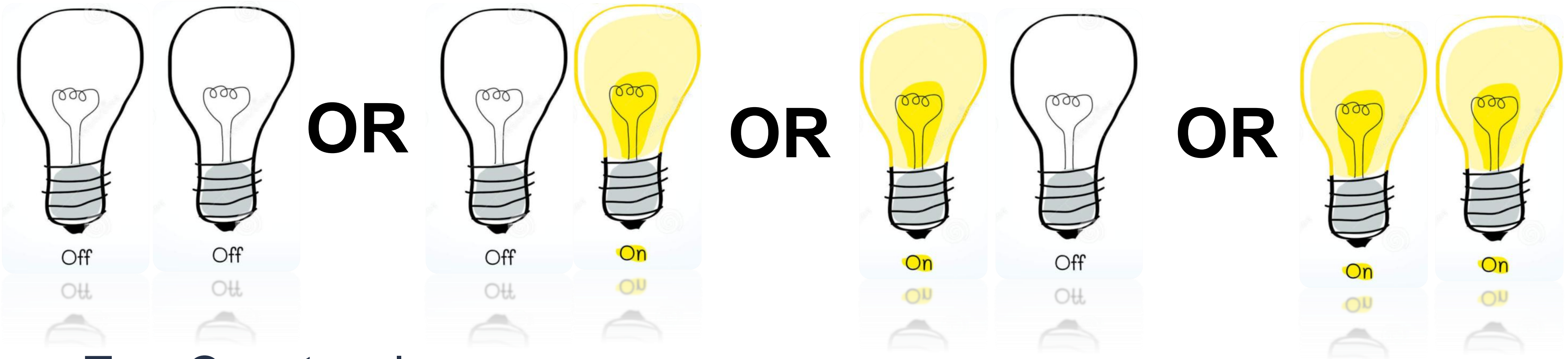
- We say that Z and X are not compatible observables (They don't commute), so measuring one of them **erases** the information related to the other one and **collapses** the system to point in that direction!

 $= \dfrac{1}{\sqrt{2}}$  $+ \dfrac{1}{\sqrt{2}}$ 

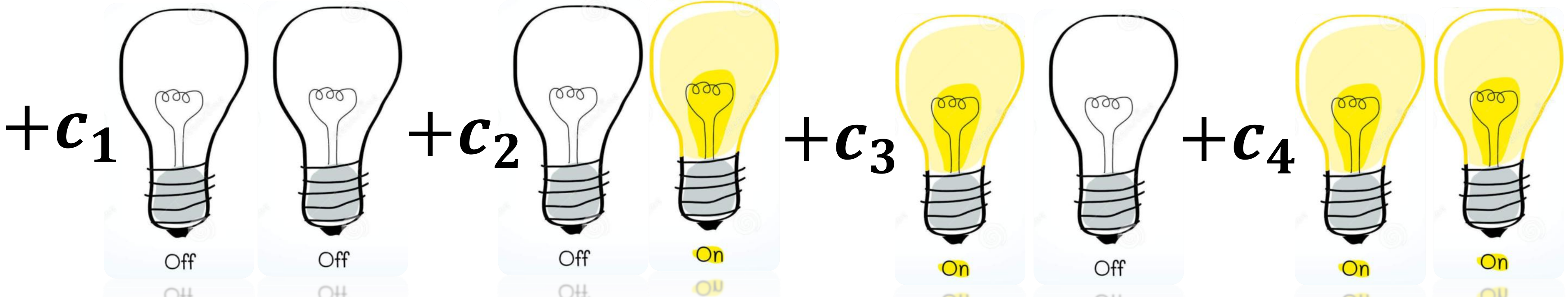
 $= \dfrac{1}{\sqrt{2}}$  $- \dfrac{1}{\sqrt{2}}$ 

Composite Systems

- Two classical lamps



- Two Quantum lamps



$$\sum_i |c_i|^2 = 1$$

Composite systems

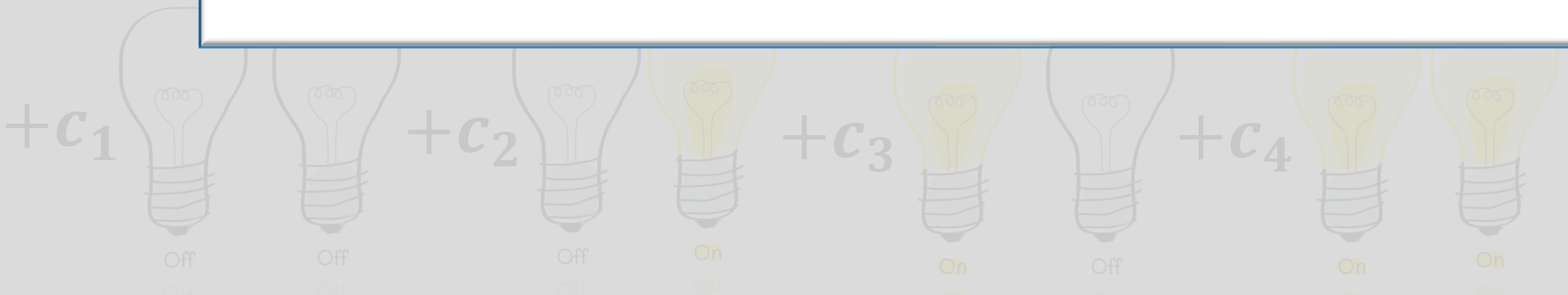
- If you have two lamps

- If I h

Number of coefficients

Classical: $2N$

Quantum: 2^N



Entanglement

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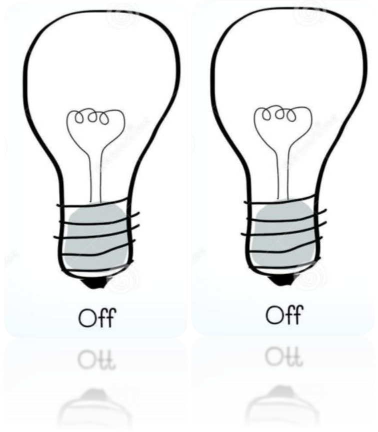
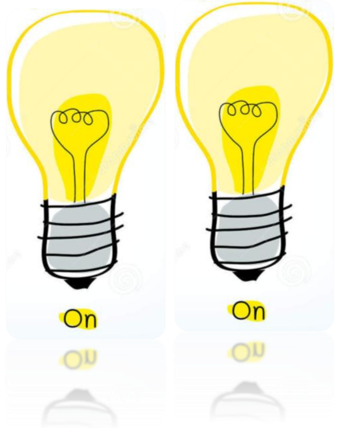
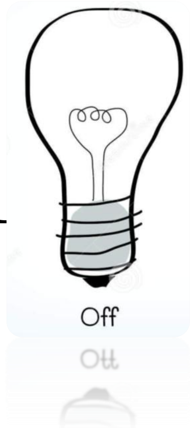
- One day I prepared this state and I gave the second lamp to you

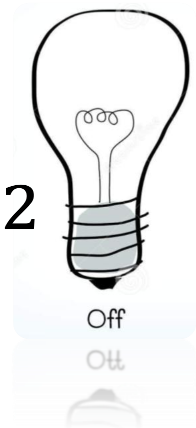
$\frac{1}{\sqrt{2}}$ 

$+\frac{1}{\sqrt{2}}$ 

- This is problematic since the state of each lamp can not be addressed without referring to the other one! This is what we call entanglement

$\big(\alpha_1$ 

$+\beta_1$ 

$\big)\big(\alpha_2$ 

$+\beta_2$ 

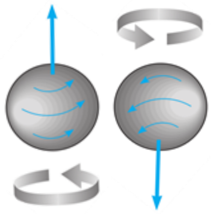
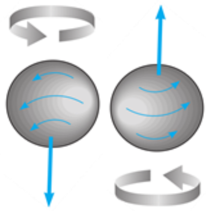
$\big) \rightarrow$

$$\alpha_1\alpha_2 = \beta_1\beta_2 = 1$$
$$\alpha_1\beta_2 = \beta_1\alpha_2 = 0$$

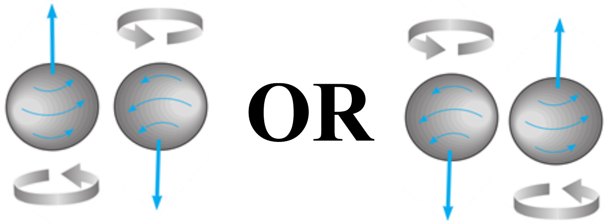
?!!!

Entanglement

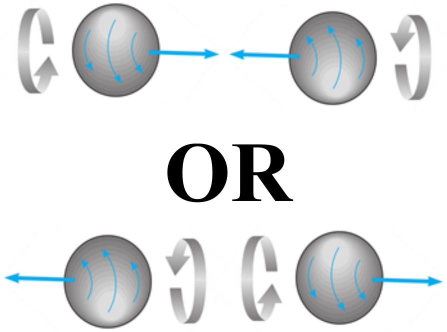
- One day I prepared this state and I gave the second particle to you

$\frac{1}{\sqrt{2}}$  $-\frac{1}{\sqrt{2}}$ 

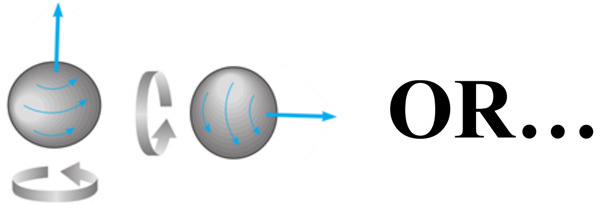
1. If you measure along Z today and I measure Z tomorrow it is guaranteed that we will get opposite values!



2. If you measure along X today and I measure X tomorrow it is guaranteed that we will get opposite values!

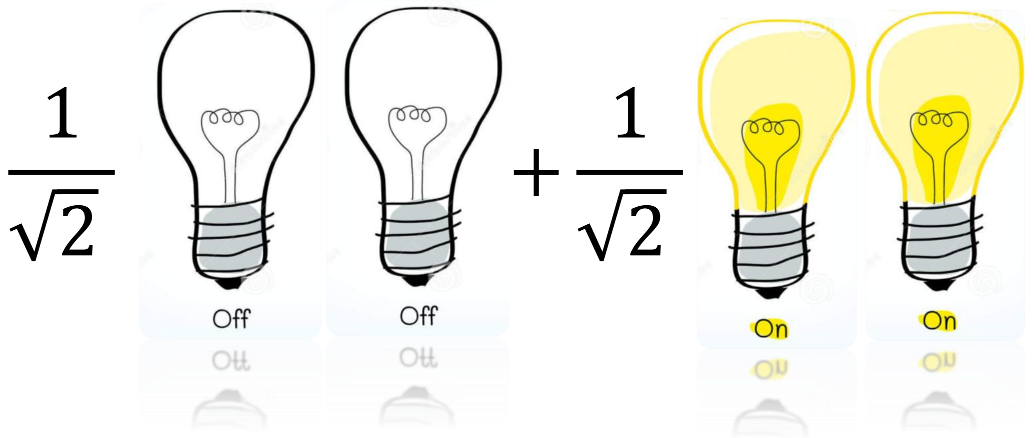


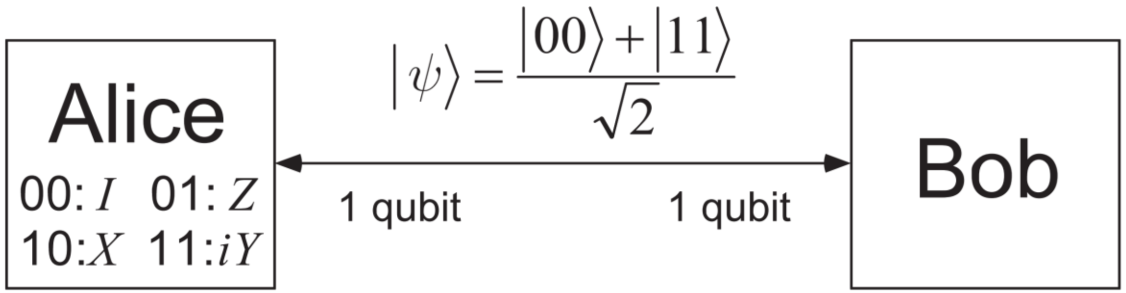
3. If you measure along X and I measure along Z then our results will not be correlated!



Superdense Coding

- Sharing a Bell pair doubles the information you can share!





$$00 : |\psi\rangle \to \frac{|00\rangle + |11\rangle}{\sqrt{2}}$$

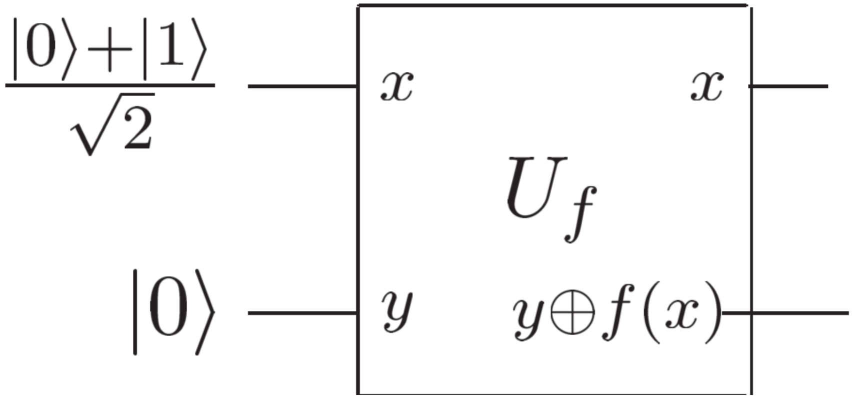
$$01 : |\psi\rangle \to \frac{|00\rangle - |11\rangle}{\sqrt{2}}$$

$$10 : |\psi\rangle \to \frac{|10\rangle + |01\rangle}{\sqrt{2}}$$

$$11 : |\psi\rangle \to \frac{|01\rangle - |10\rangle}{\sqrt{2}}$$

Quantum parallelism

- Quantum parallelism is great but not enough since measurement destroys superposition



$$\frac{|0, f(0)\rangle + |1, f(1)\rangle}{\sqrt{2}}$$

Deutsch's algorithm

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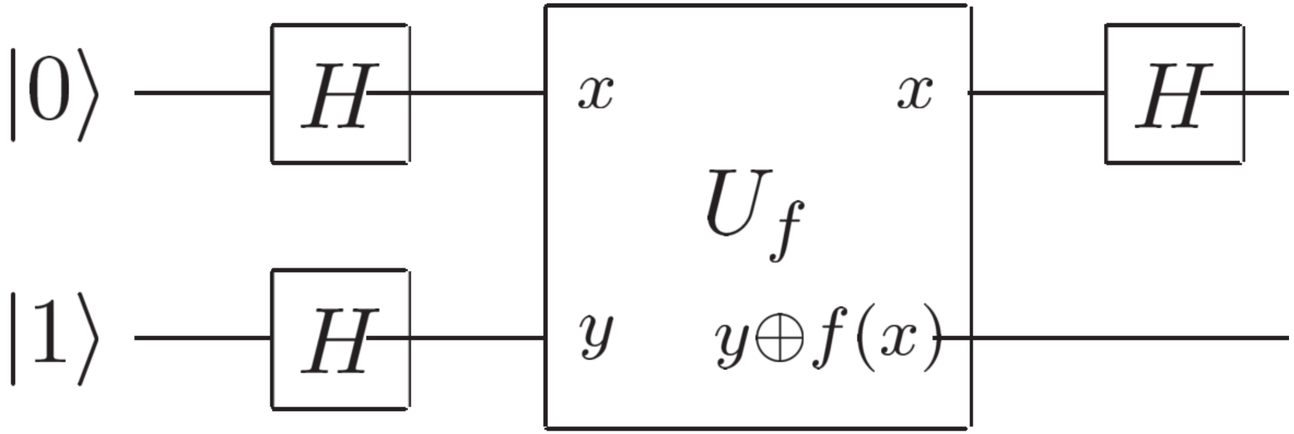
- A simple algorithm to determine if f(x) is constant or balanced (global behaviour) from a single run!

- Can be **scaled** easily to evaluate if the function is constant or balanced beyond the one-bit input



$$\underbrace{\pm|f(0)\oplus f(1)\rangle}\left[\frac{|0\rangle-|1\rangle}{\sqrt{2}}\right]$$

$$\pm|0\rangle \longrightarrow \text{ if } f(0)=f(1)$$

$$\pm|1\rangle \longrightarrow \text{ if } f(0)\neq f(1).$$

How To Quantum?

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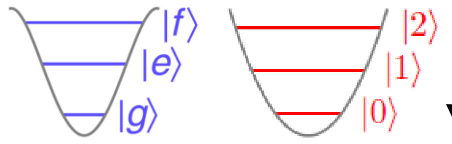
Quantum*

$T \sim 20mK$

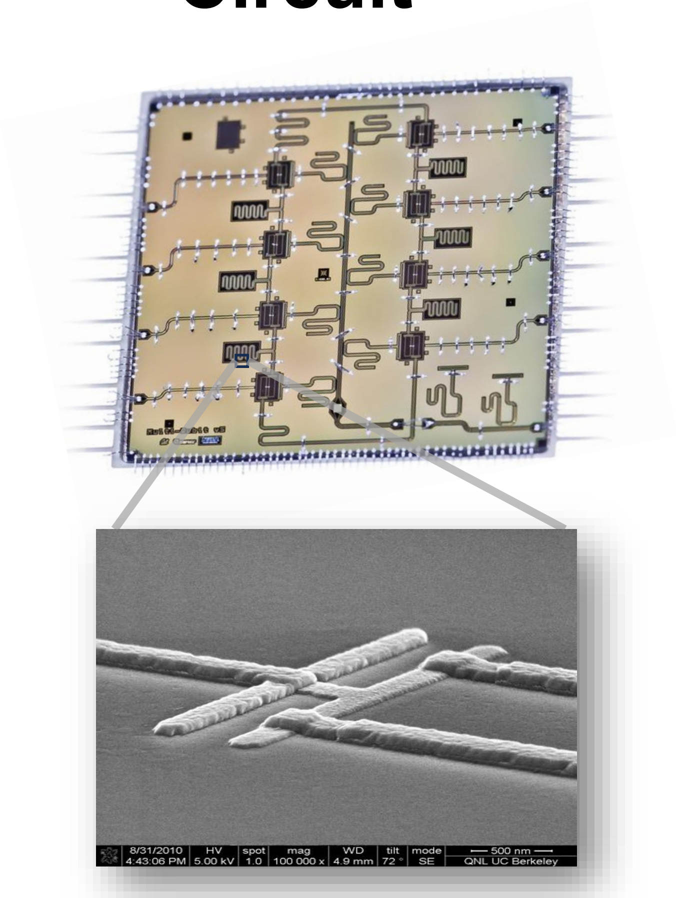
$f \sim 6\ GHz \rightarrow$

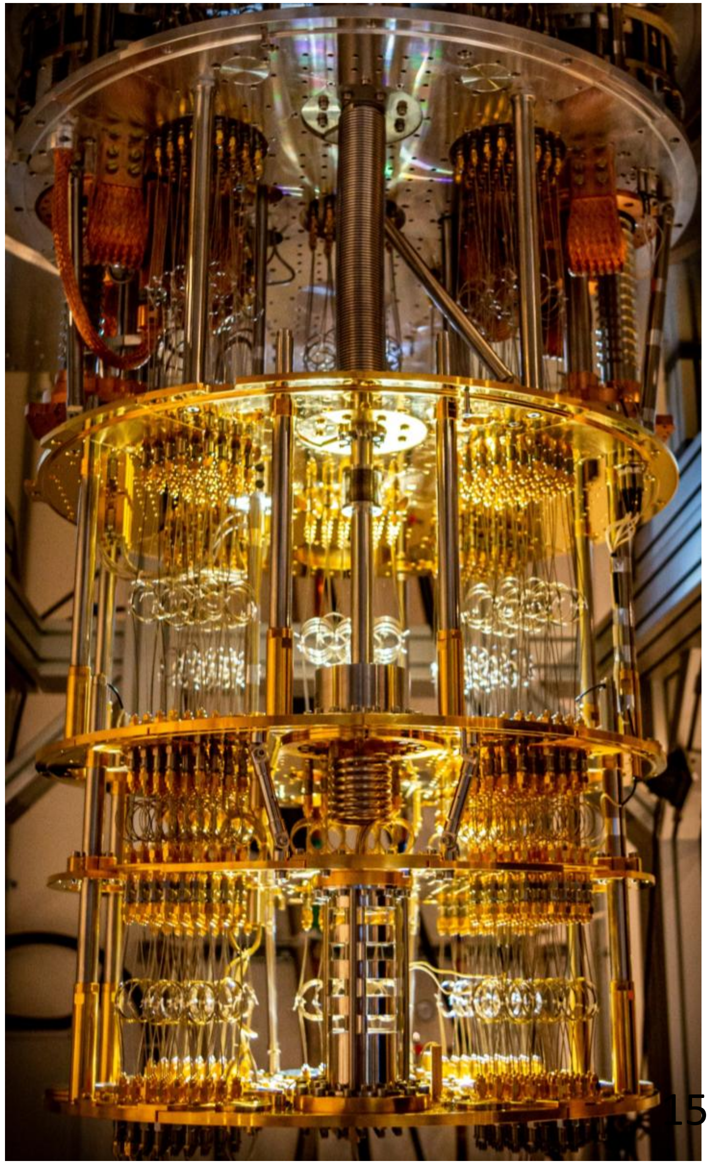
$T \sim 300mK$

$2\Delta \sim 2K$

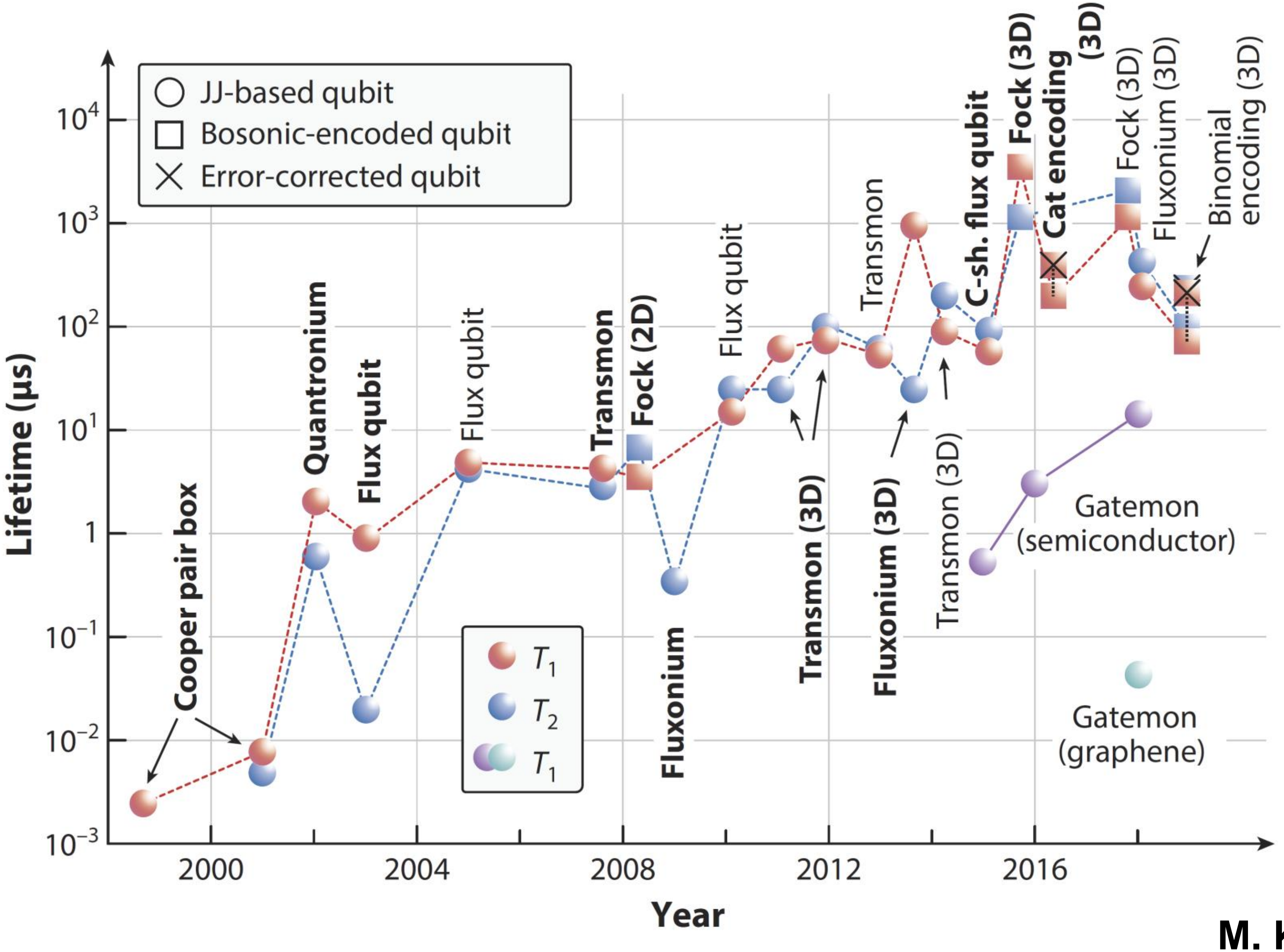


Circuit*





Two Decades of Progress



M. Kjaergaard, et al., Annual Review (2020)

Quantum Coherence

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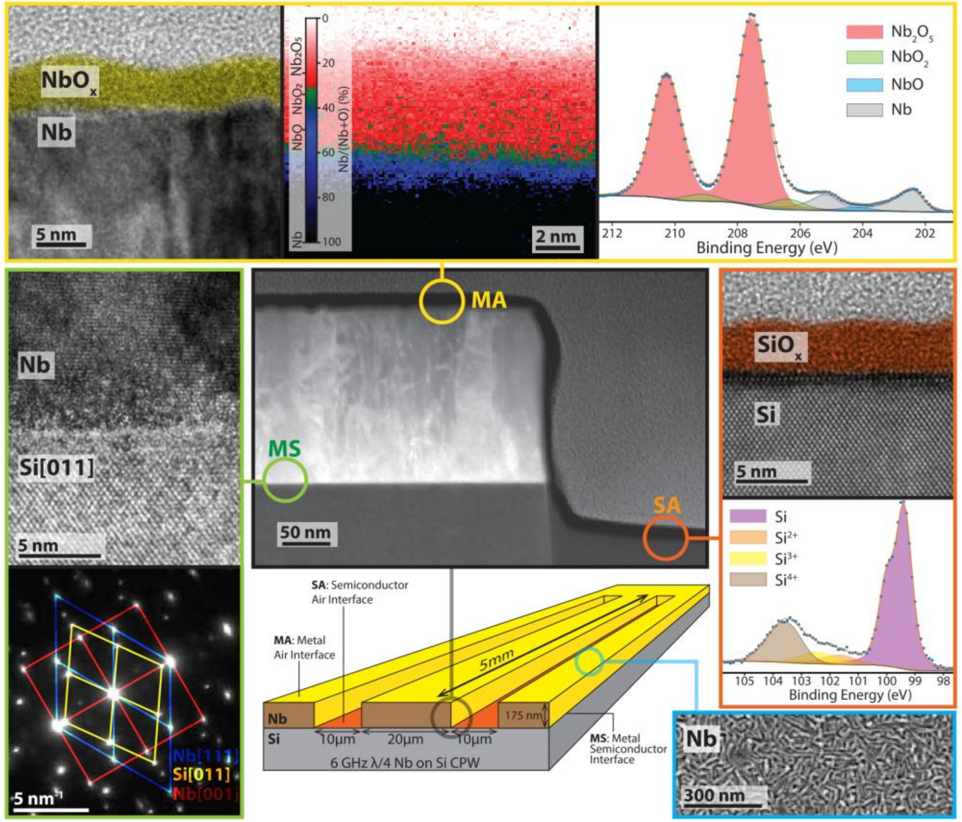
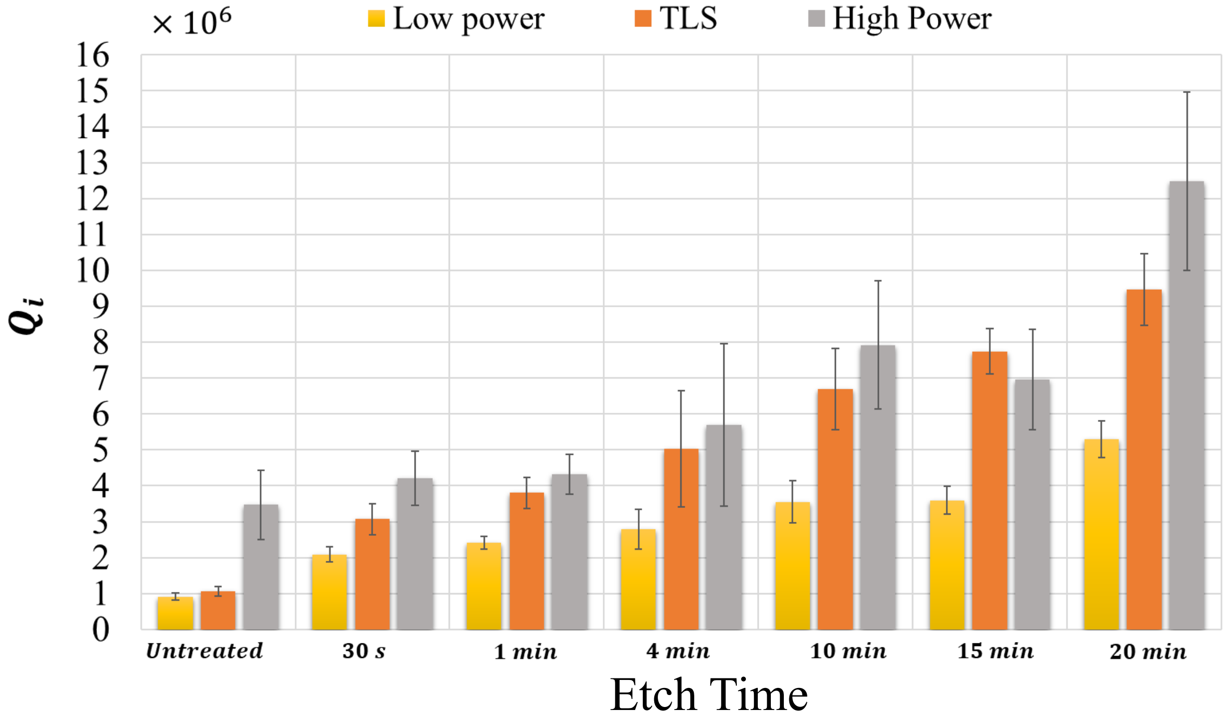
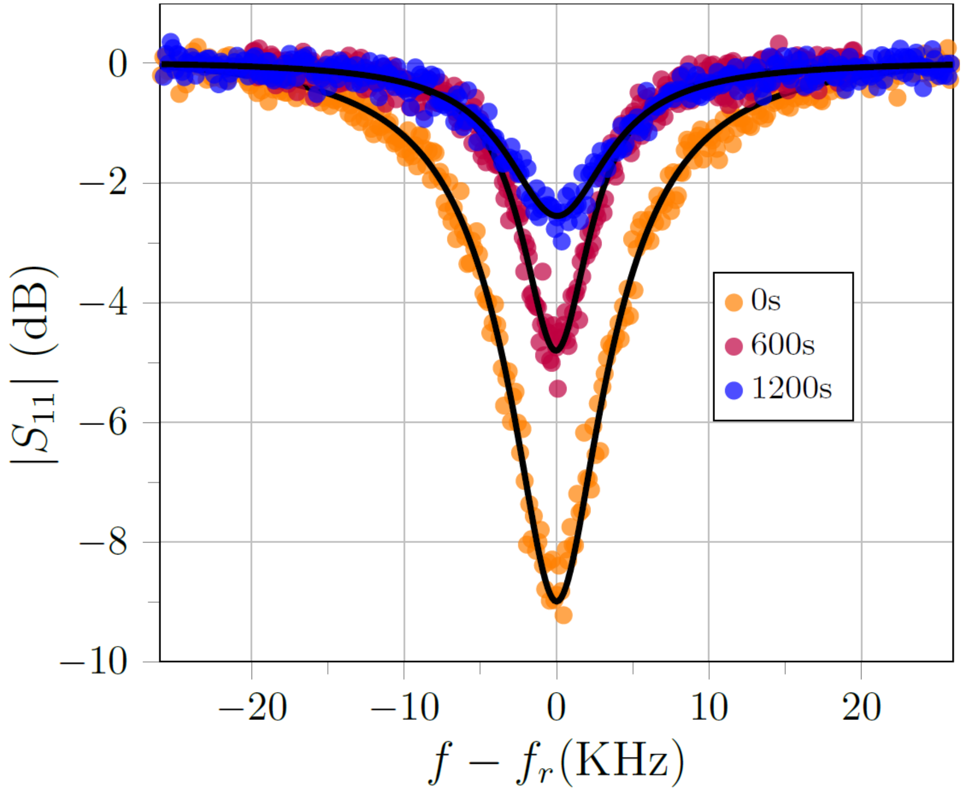


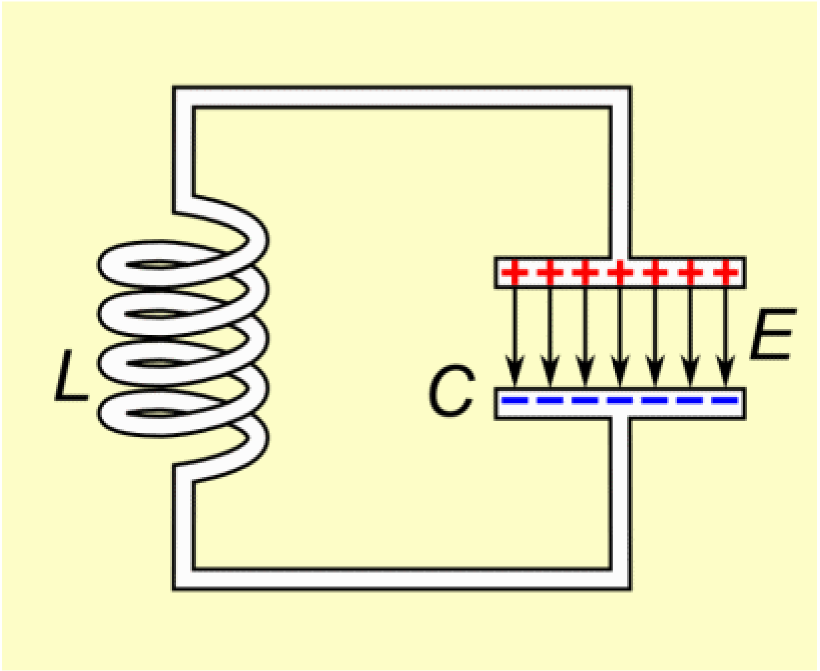


$$\frac{1}{Q_{Low\ Power}} = \frac{1}{Q_{TLS}} + \frac{1}{Q_{High\ Power}}$$

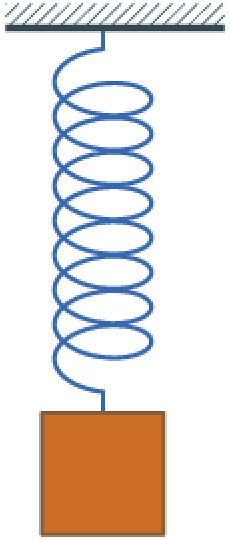
M. Altoé, et al., PRX Quantum (2020)

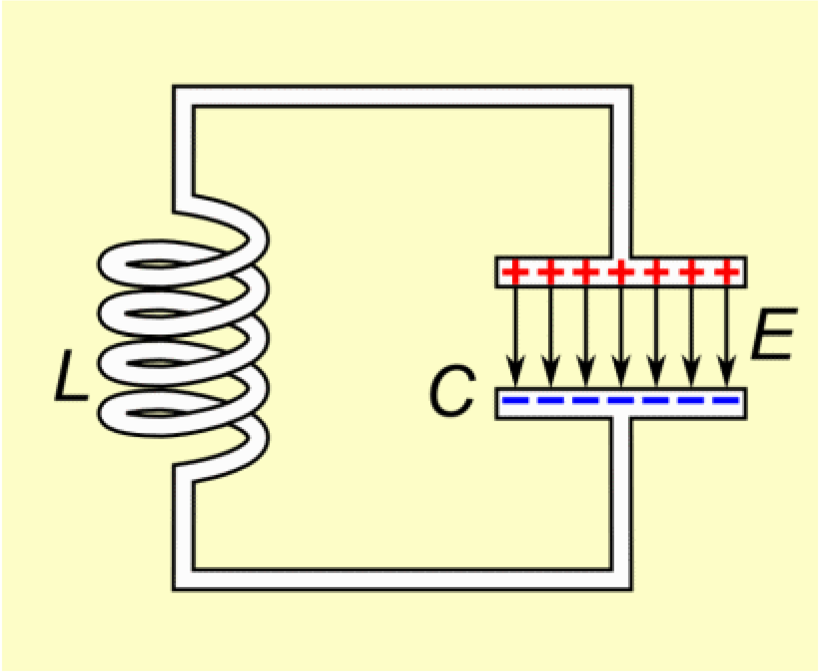
Millions Of Oscillations

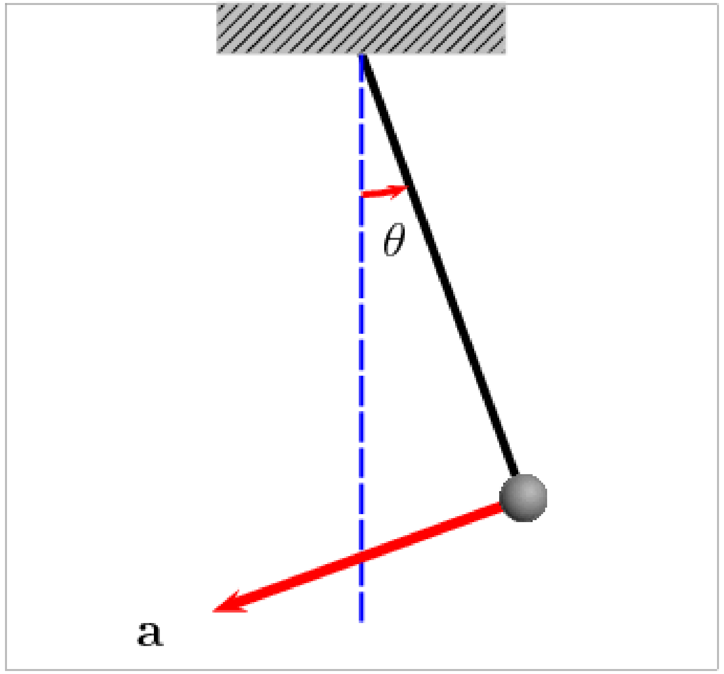




Beyond the Harmonic Oscillators







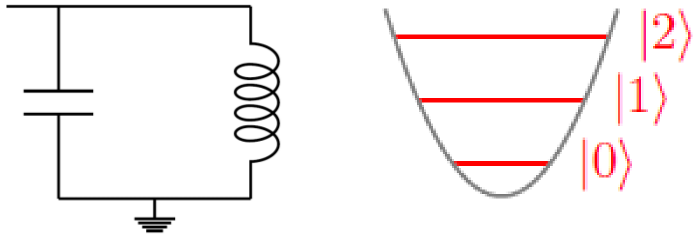
$$U(x) = \frac{1}{2}Kx^2$$

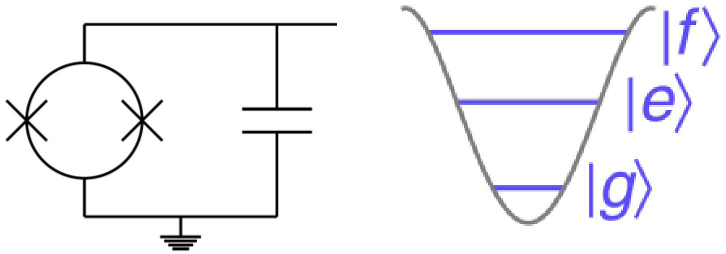
$$U(\Phi) = \frac{\Phi^2}{2L}$$

$$U(\theta) = -cos(\theta)$$

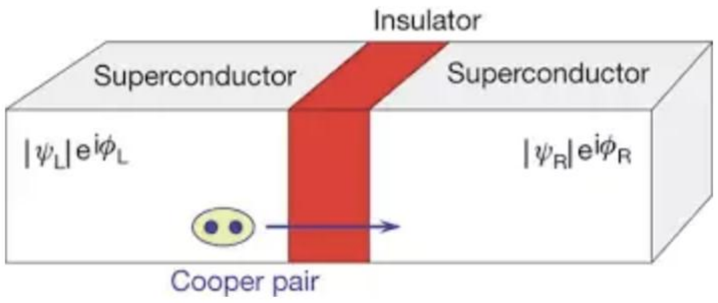
Beyond the Harmonic Oscillators

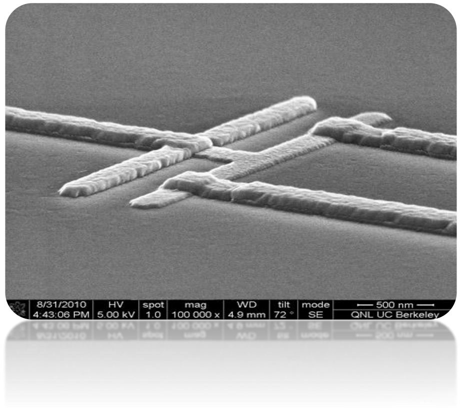
- Josephson junction[1]: S-I-S tunnel barrier
- $I(\delta) = I_0 \sin\phi,\ V(\delta) = \frac{\hbar}{2e}\frac{d\phi}{dt}$
- Non-linear inductor: $V = L_J \frac{dI}{dt}$
- $L_J = \frac{\hbar}{2eI_0 \cos\phi}$
- SQUID loop: tunable energies!





Josephson Junction





[1]Josephson, B. D. *Physics letters* (1962).

Engineering an Artificial Atom

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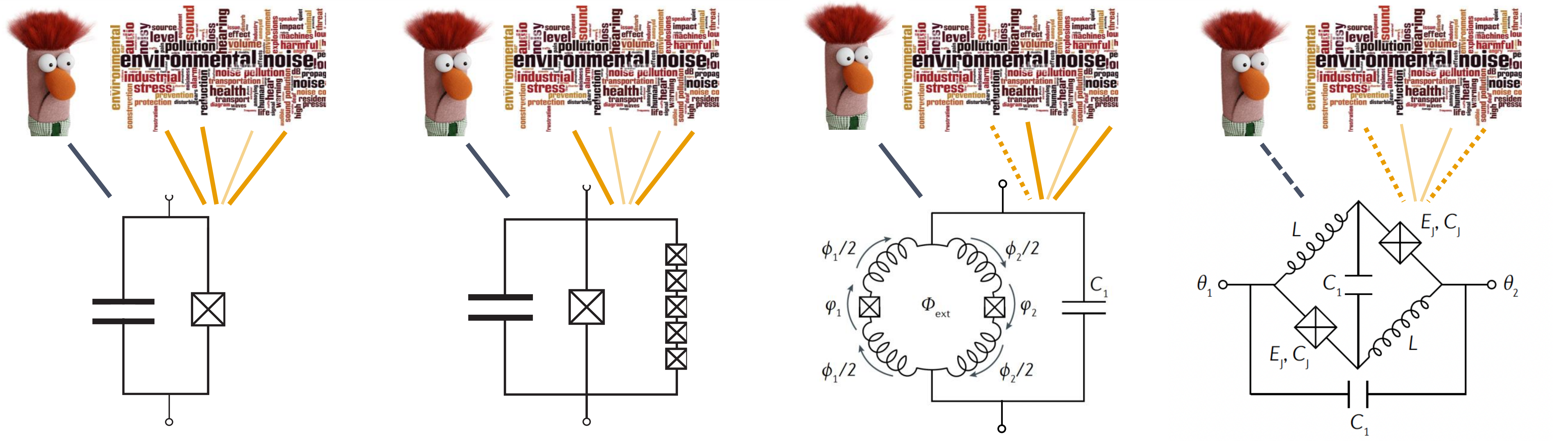


Simple Qubit

Sensitive to Environmental Defects

Complex Qubit

Immune to Environmental Defects

Transmon

- simple fabrication
- easy qubit control
- noise sensitive

Fluxonium

- reasonable fabrication
- flexible qubit control
- noise resilient

Cos 2ϕ

- complex fabrication
- complex qubit control
- partial noise protection

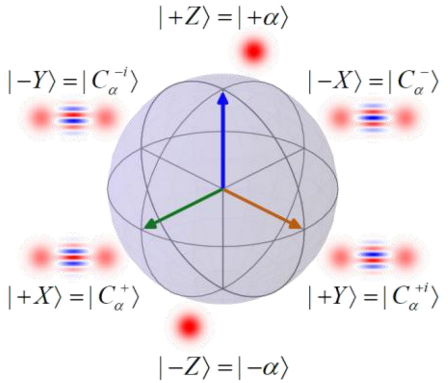
0-π

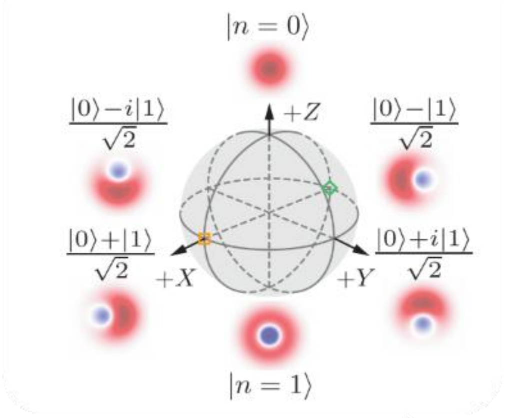
- challenging fabrication
- difficult qubit control
- full noise protection

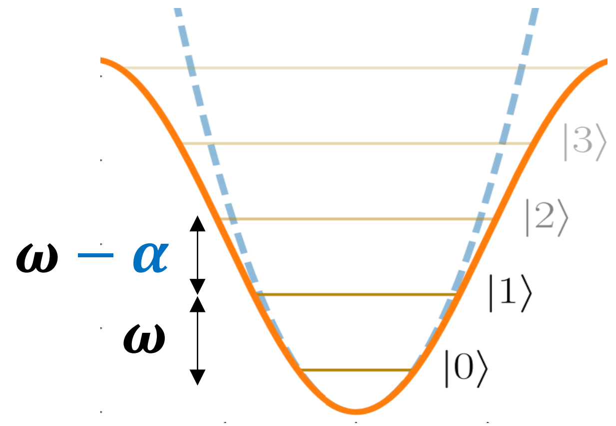
Engineering the Bosonic ladder with JJs

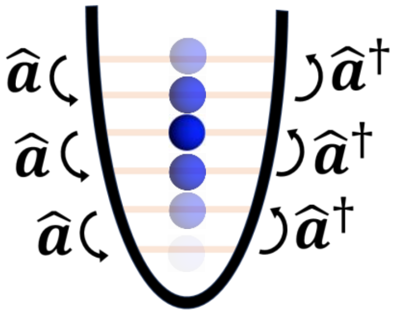
Kerr Cat | Transmon | Anharmonicity

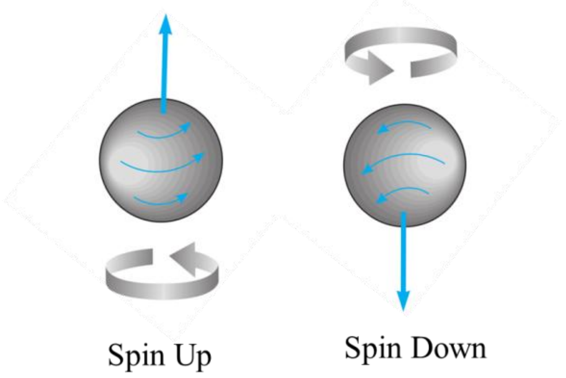
~2 MHz | ~300 MHz



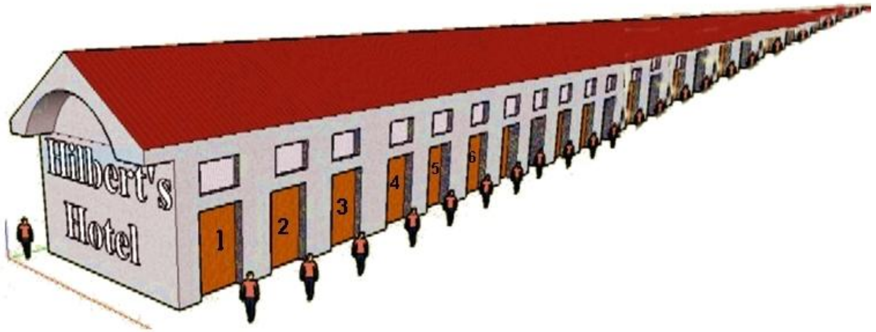








The Hilbert Hotel



Cat States

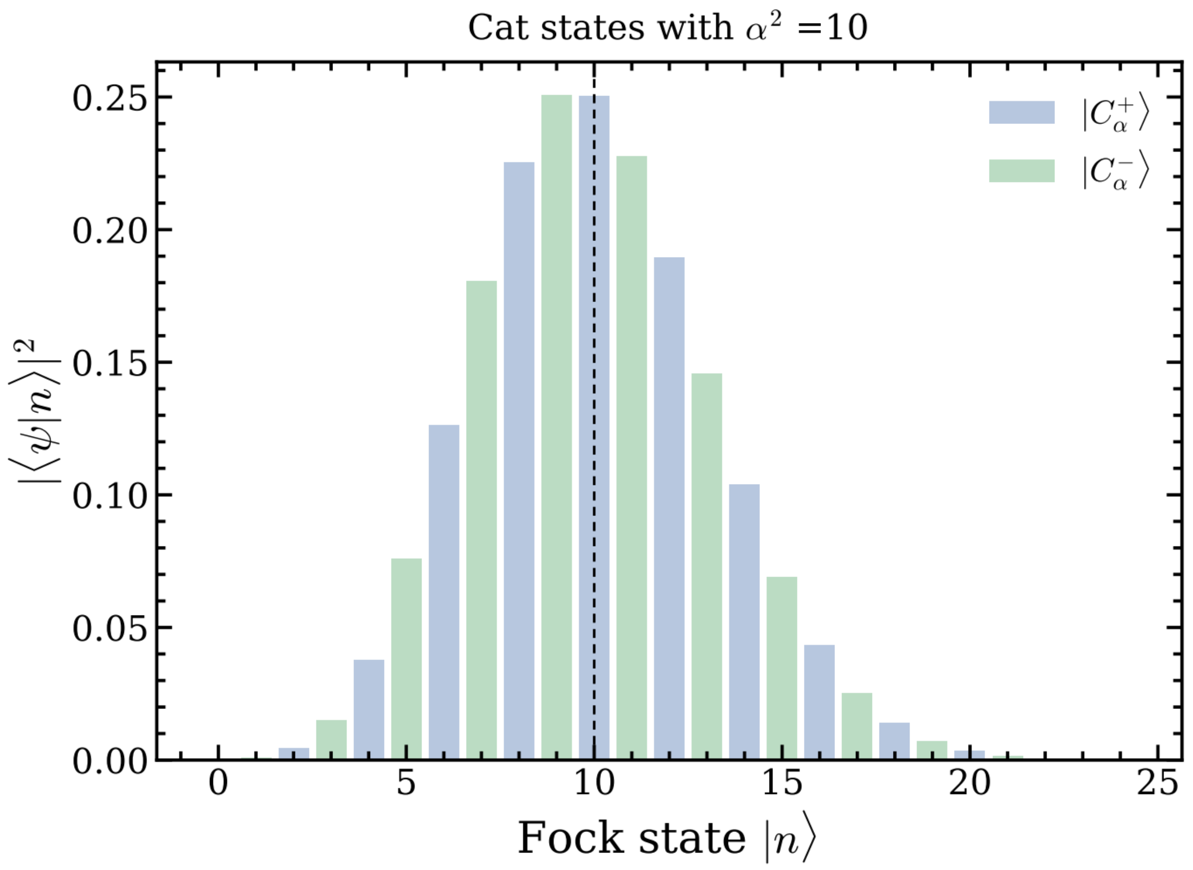
- Cat states are the orthogonal even/odd-parity superposition of the macroscopically distinct coherent states $|\pm\alpha\rangle$

$$\left|C_\alpha^\pm\right\rangle = \frac{1}{\sqrt{1 \pm e^{-2|\alpha|^2}}}\frac{1}{\sqrt{2}}(|\alpha\rangle \pm |-\alpha\rangle)$$

$$|\alpha\rangle = e^{-|\alpha|^2/2}\sum \frac{\alpha^n}{\sqrt{n!}}|n\rangle \longrightarrow \langle\hat{n}\rangle = |\alpha|^2$$

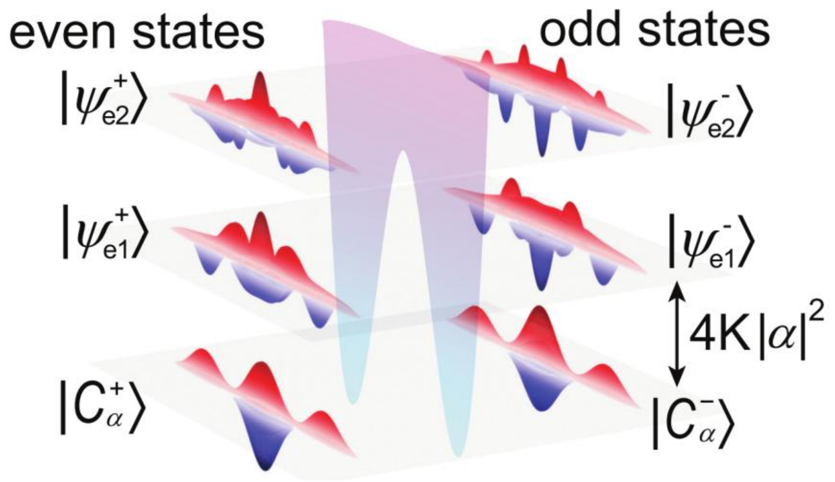
$$\langle -\alpha|\alpha\rangle = e^{-2|\alpha|^2} \xrightarrow{|\alpha|^2 = 3} \sim 0.0025$$

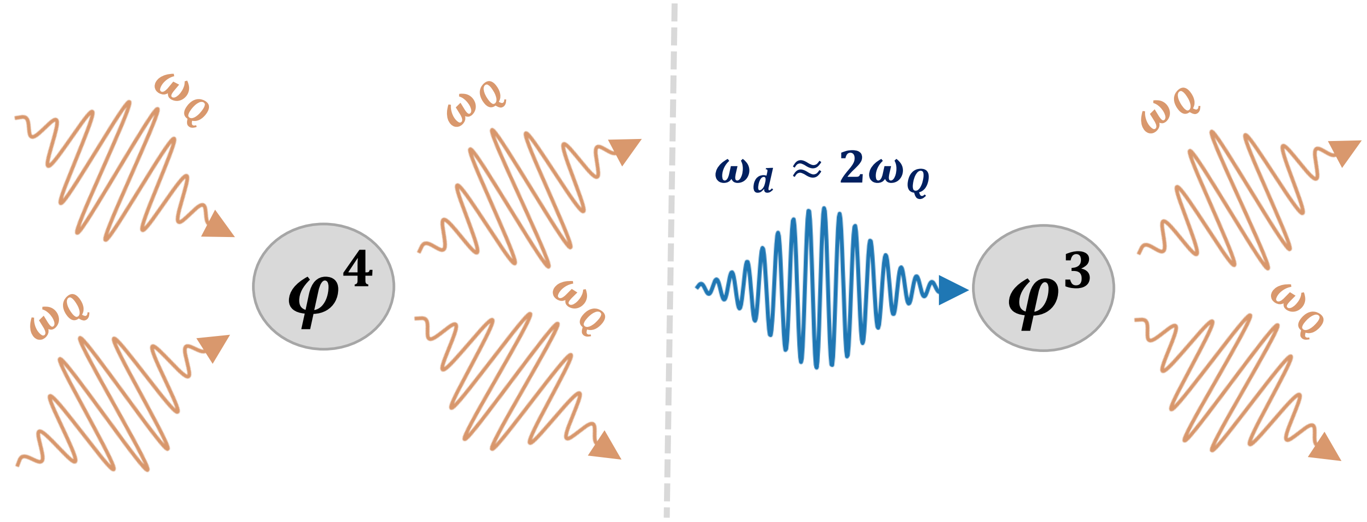
$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle \longrightarrow \hat{a} \simeq \alpha\,\hat{Z}$$



Kerr Cat Qubit Hamiltonian

$$\hat{H}_{KC} = -K\underbrace{\hat{a}^\dagger\hat{a}^\dagger\hat{a}\hat{a}}_{\substack{\text{Kerr non-linearity}\\ \text{4-wave mixing}}} + \epsilon_2\underbrace{(\hat{a}^\dagger\hat{a}^\dagger + \hat{a}\hat{a})}_{\substack{\text{Stabilization drive}\\ \text{3-wave mixing}}}$$





$$\hat{H}_{KC}\,|\alpha\rangle = \epsilon_2\alpha^2|\alpha\rangle \longrightarrow \alpha^2 = \epsilon_2/K$$

$$\hat{P}_c\hat{a}\hat{P}_c = \alpha\hat{Z} - i\alpha e^{-2\alpha^2}\hat{Y} \approx \alpha\hat{Z}$$

$$\hat{P}_c\hat{a}^\dagger\hat{P}_c = \alpha^*\hat{Z} + i\alpha^* e^{-2\alpha^2}\hat{Y} \approx \alpha^*\hat{Z}$$

S. Puri, et al., SCIENCE ADVANCES. (2020)

A. Grimm, et al., Nature. (2020)

Stabilizing Cats with SNAILs

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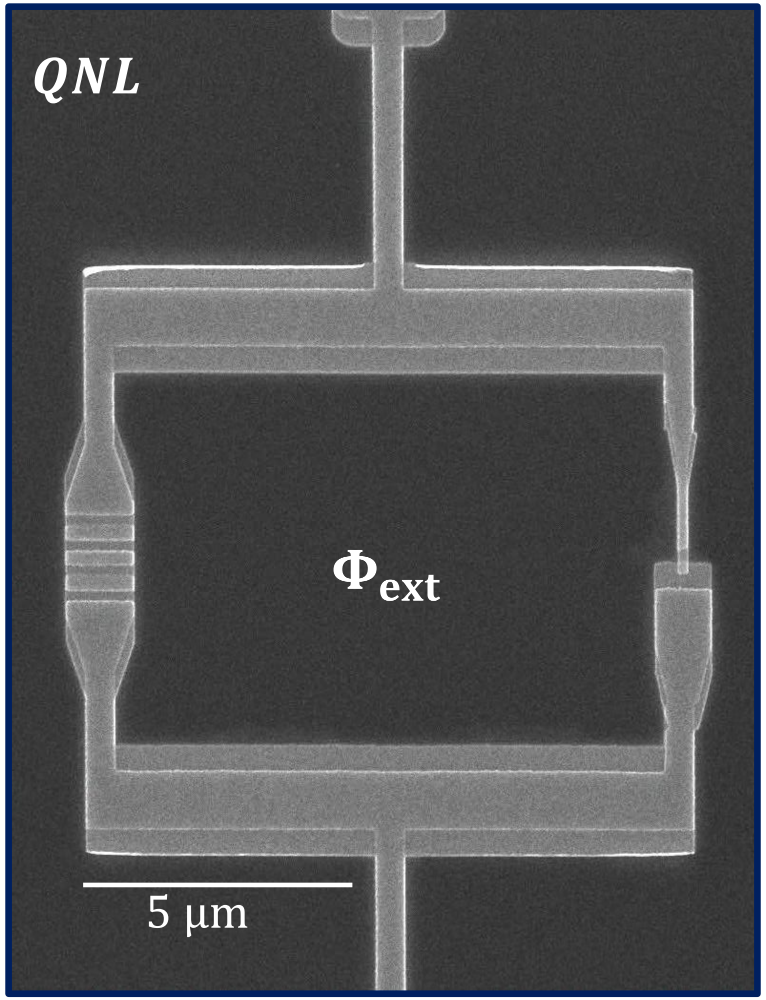


- The SNAIL provides the energy well to host the bound states (φ^2), the third order nonlinearity which generate the squeeze drive (φ^3), and the fourth order nonlinearity which gives the Kerr (φ^4)

$$U_{SNAIL} = -\alpha E_J \cos(\varphi) - 3E_J \cos\left(\frac{\varphi_{ext} - \varphi}{3}\right) = \sum c_i \varphi^i$$

- By expanding U_{SNAIL} in powers of φ we can realize a Hamiltonian of the form:

$$\hat{H}_s = \omega_a \hat{a}^\dagger \hat{a} + g_3\left(\hat{a}^\dagger + \hat{a}\right)^3 + g_4\left(\hat{a}^\dagger + \hat{a}\right)^4 + \cdots$$

$$\hat{H}_{eff} = \Delta_{a,r} \hat{a}^\dagger \hat{a} + g_3\left(\hat{a}e^{-i\omega_r t} - \xi_s e^{i\omega_s t} + H.C.\right)^3 + \cdots$$

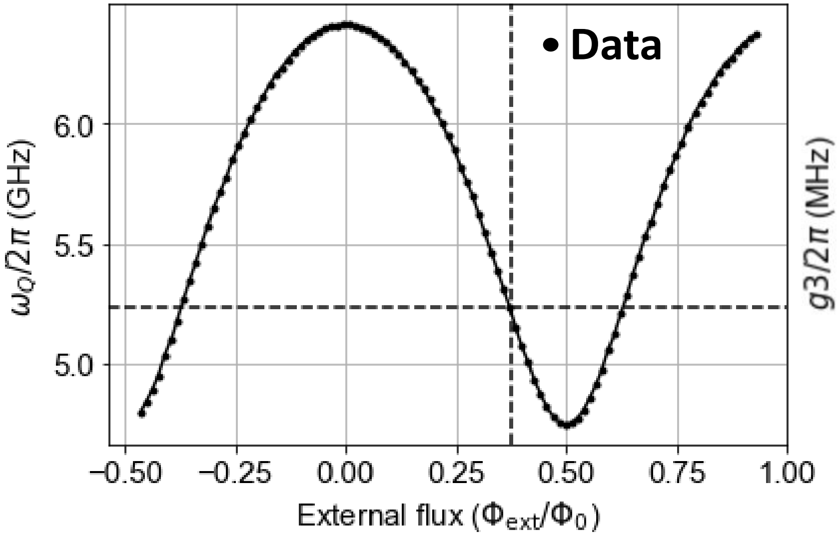
$$\hat{H}_{KC} = \Delta_{a,r} \hat{a}^\dagger \hat{a} - K\hat{a}^\dagger \hat{a}^\dagger \hat{a}\hat{a} + \epsilon_2 \hat{a}^{\dagger 2} + \epsilon_2^* \hat{a}^2 - 4K\hat{a}^\dagger \hat{a}|\xi_s|^2$$

N.E. Frattini, et al., PRA. (2018)

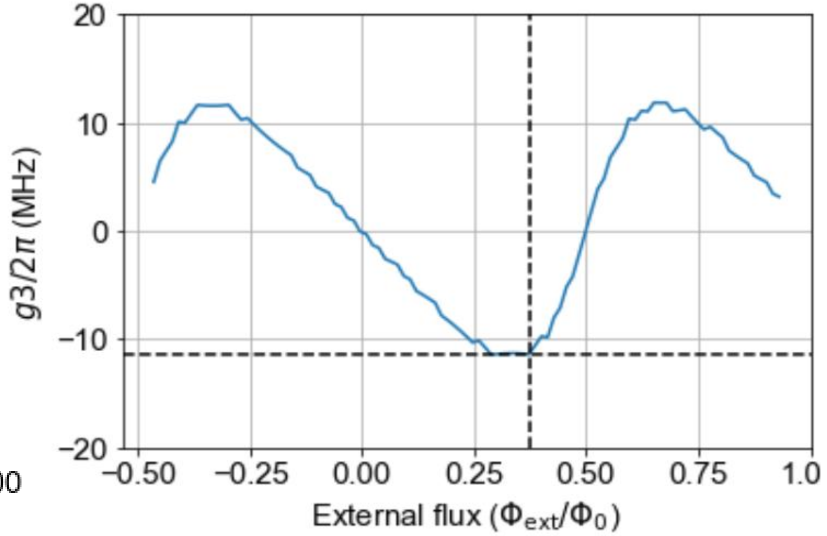
SNAIL Spectrum

- The sample tunes and behaves like what we expect from the analysis of the SNAIL

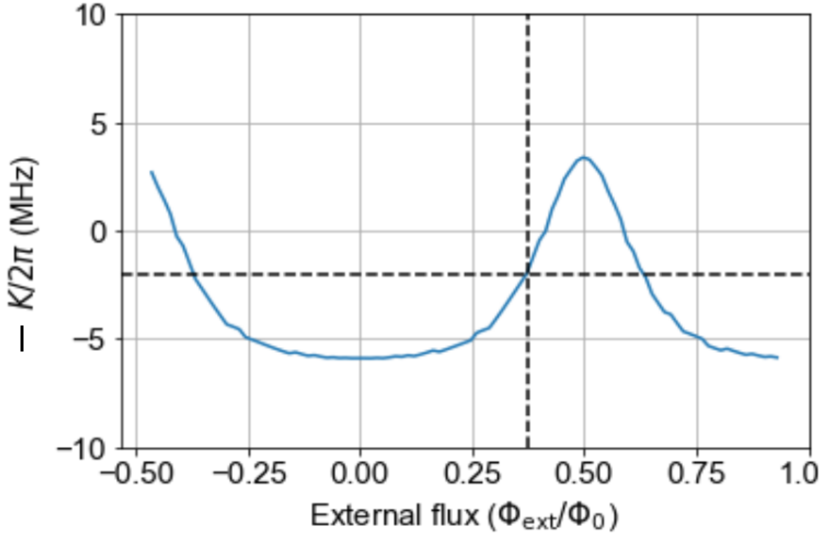
$\omega_F/2\pi \sim 5.32$ GHz



$g_3/2\pi \sim 11.29$ MHz



$K/2\pi \sim 2.84$ MHz



- Measuring the Kerr through $(\omega_{ge} - \omega_{ef})/4\pi = K/2\pi = 2.36\ MHz$

2D Chip Layout

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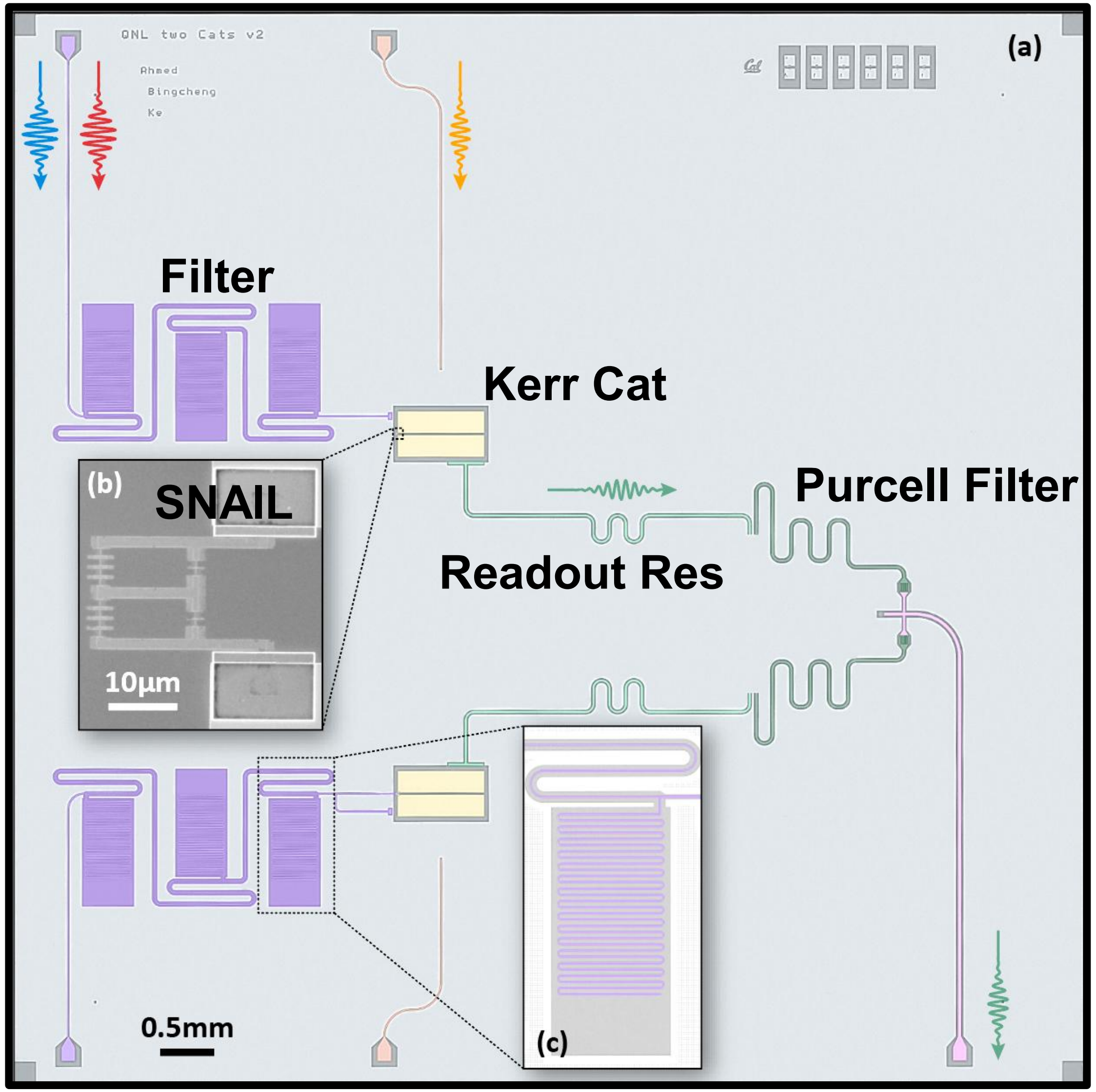
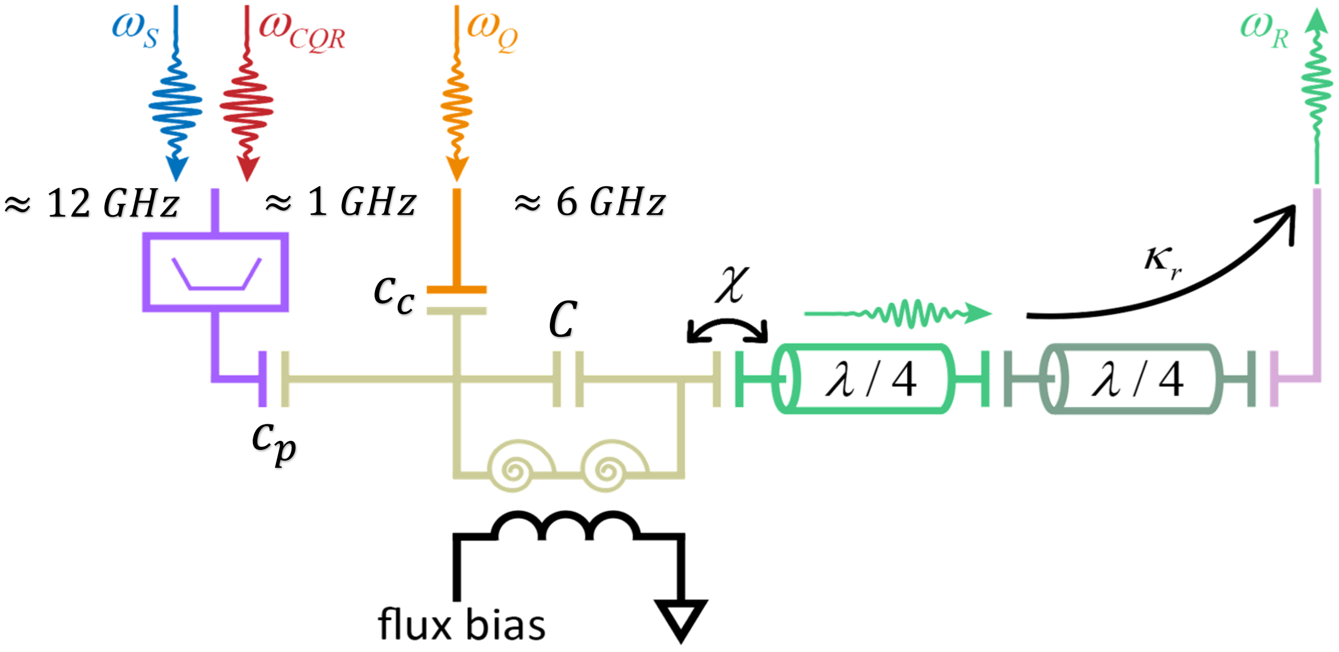
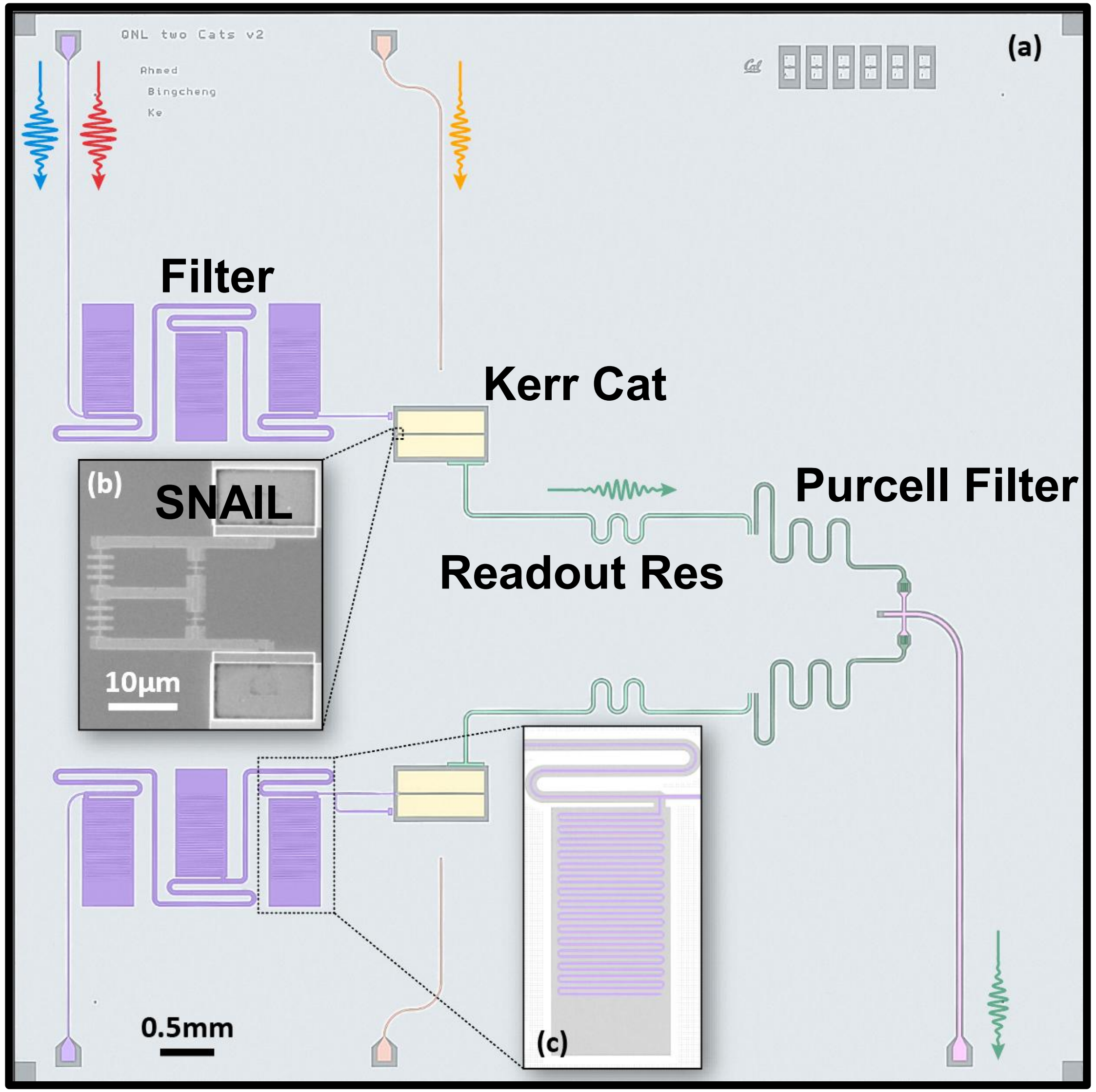


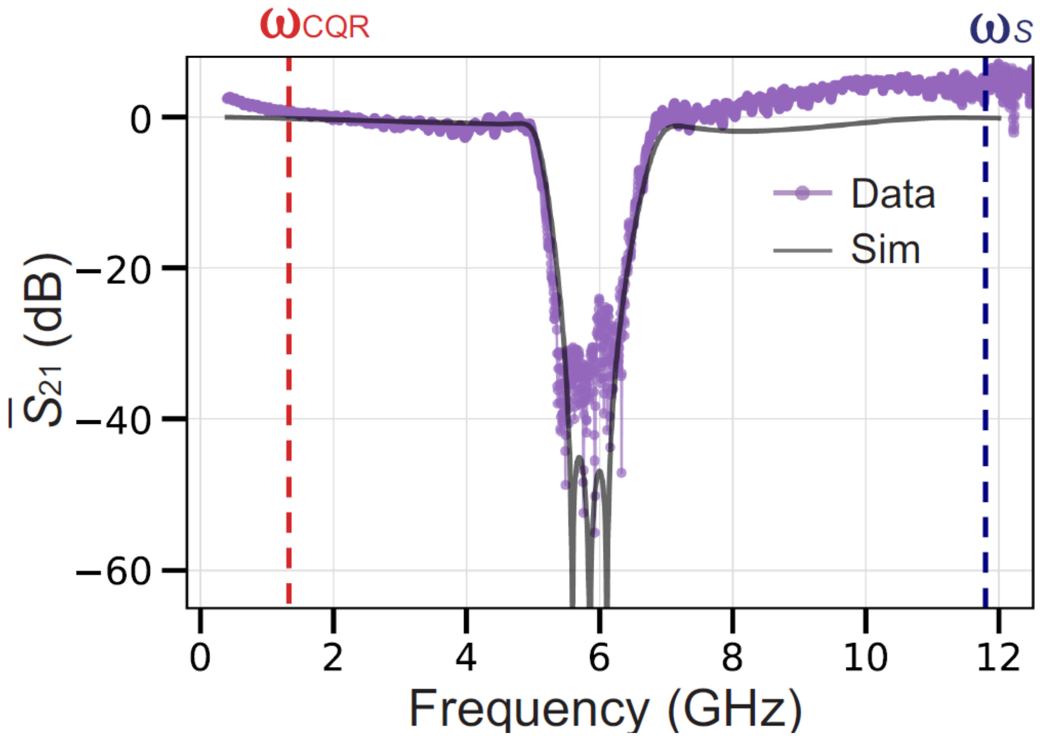


- Charge pumping imposes a **tradeoff** between strong microwave drives or large Purcell decay
- The pump port is **strongly coupled** to the qubit such that the Purcell limit from c_p is ~12us

A. Hajr, et al., Physical Review X(2024)

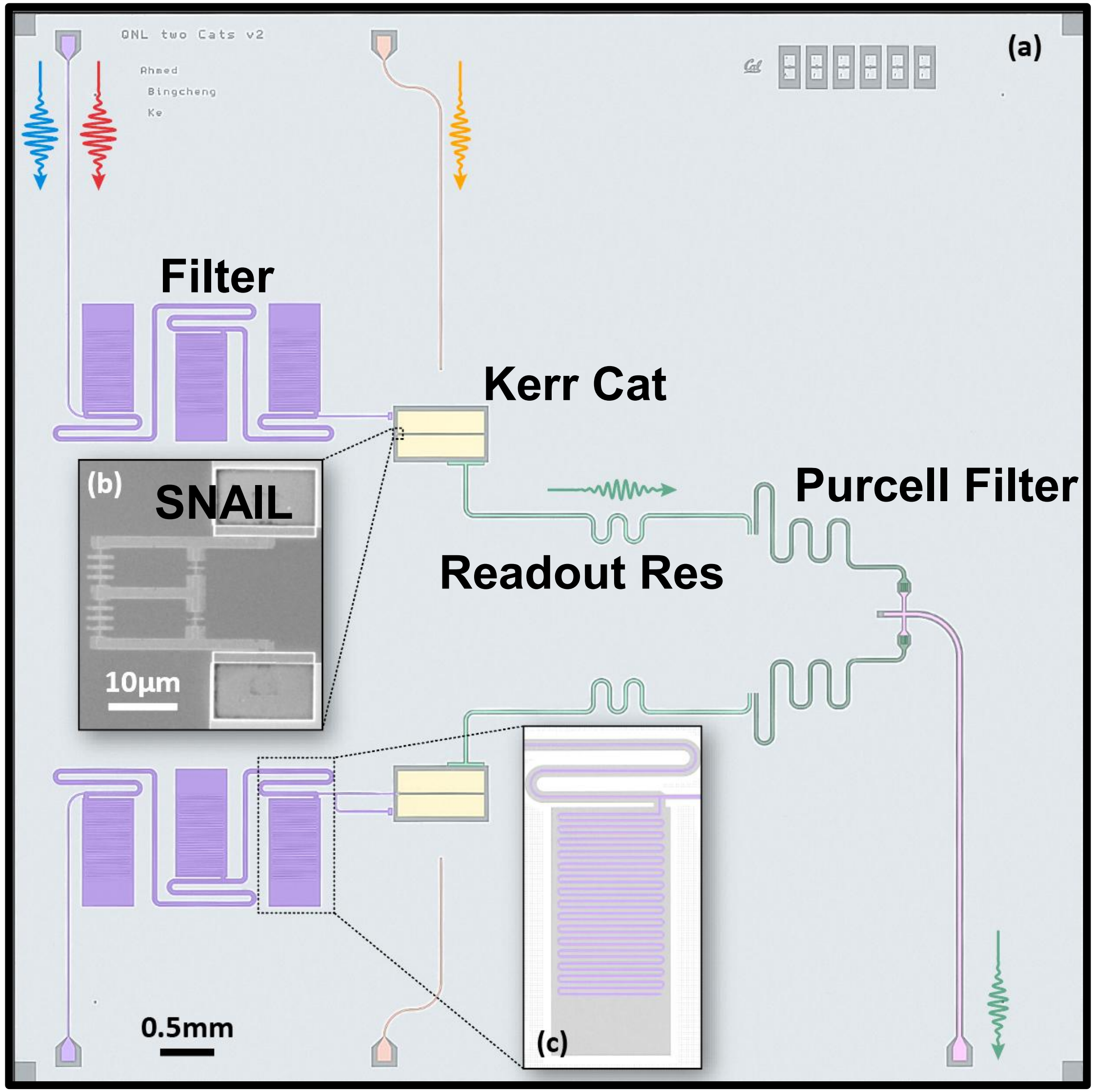
Band Block Filter

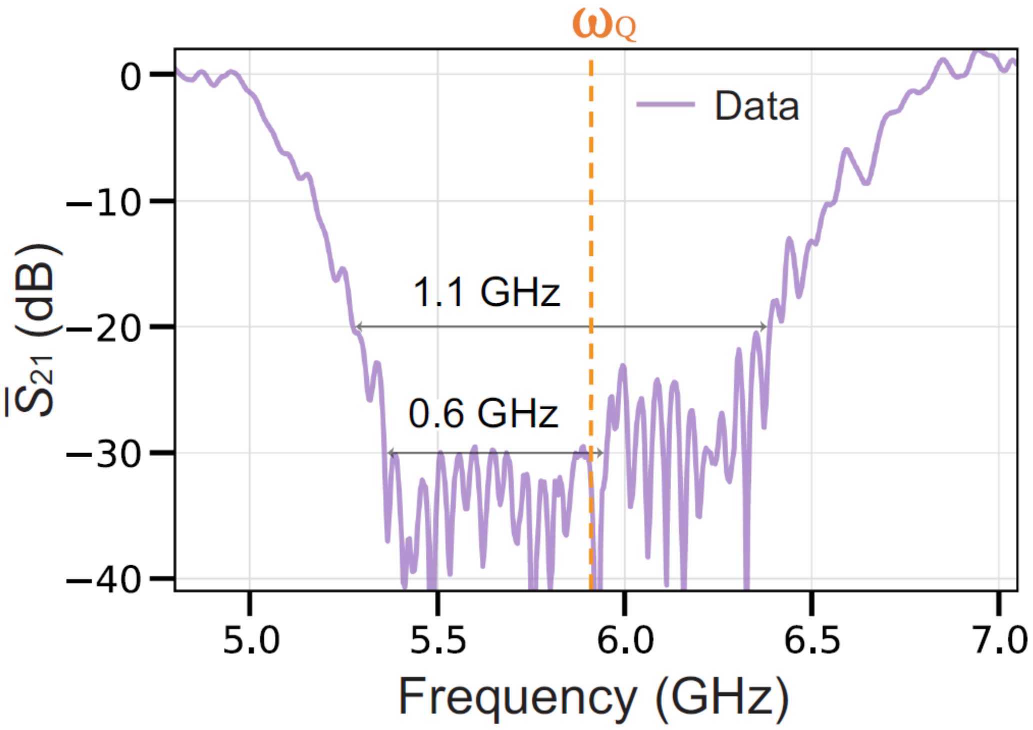




- A band stop filter suppresses the Purcel decay while enabling high and low frequency processes

Band Block Filter





- With **30dB** of isolation at the qubit frequency the Purcell limit increase to **~12ms**
- The large bandwidth enables strong qubit-qubit coupling with mitigated Purcell

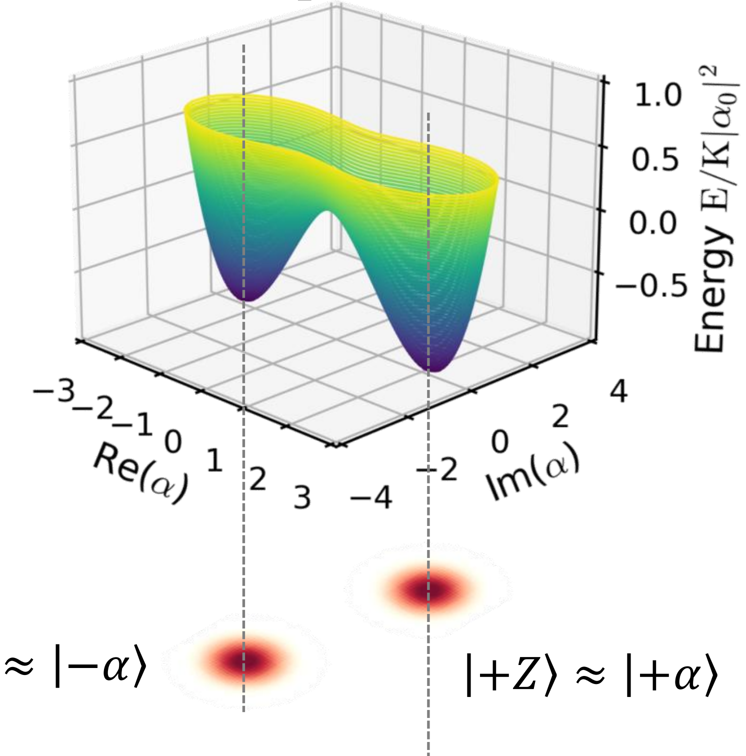
Universal Control: Z Rotation

On-resonance drive shifts energy of coherent states→ Z gate

- Single qubit Z rotation: $\mathrm{H_Z} = \epsilon_z^* \hat{a}^\dagger + \epsilon_z \hat{a}, \rightarrow 2\alpha \mathrm{Re}[\epsilon_z]\sigma_z$
- Shift the energy of the coherent states $|\pm Z\rangle$

$\epsilon_z = 2K$

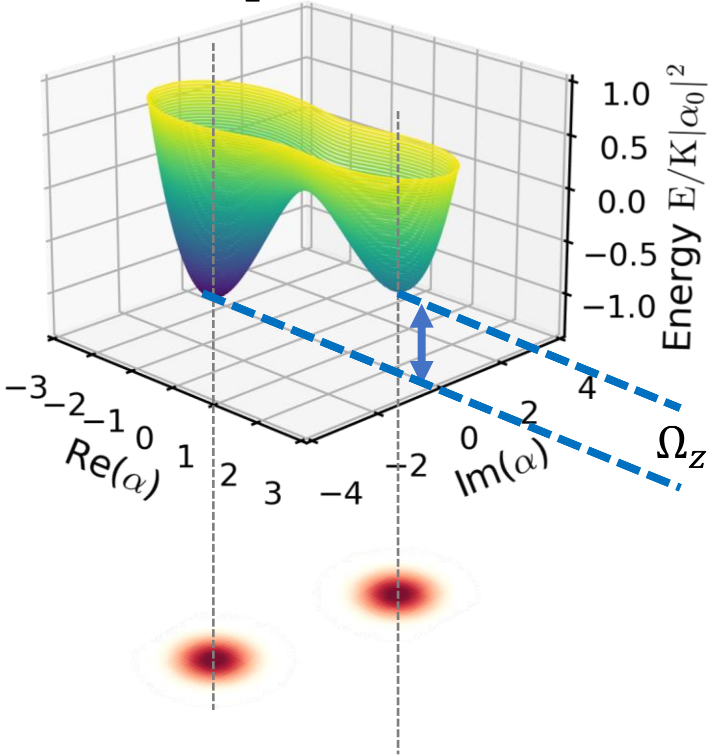
$\boldsymbol{\epsilon_z = 0}$



$|-Z\rangle \approx |-\alpha\rangle$

$|+Z\rangle \approx |+\alpha\rangle$

$\boldsymbol{\epsilon_z = 2K}$



$\Omega_z = 4\alpha \mathrm{Re}[\epsilon_z]$

Universal Control: X Rotation

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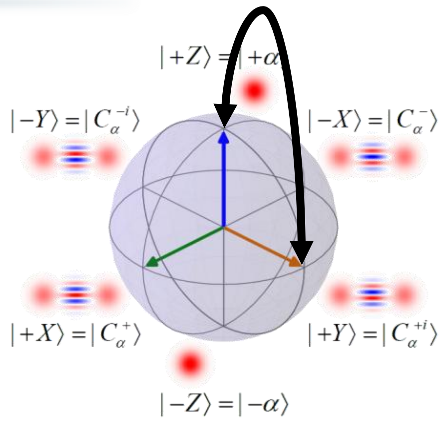
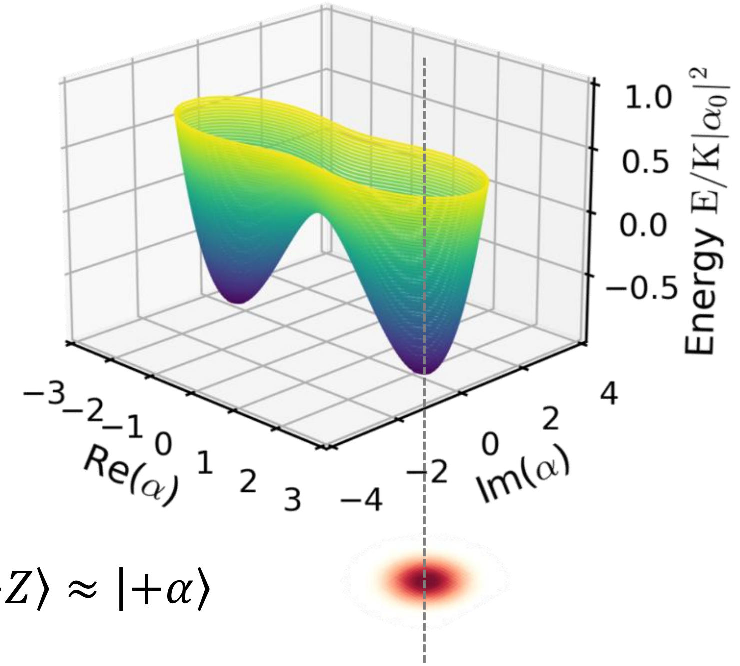
Negative Detuning Δ leads to coherent states tunneling → $\boldsymbol{X(\pi/2)}$



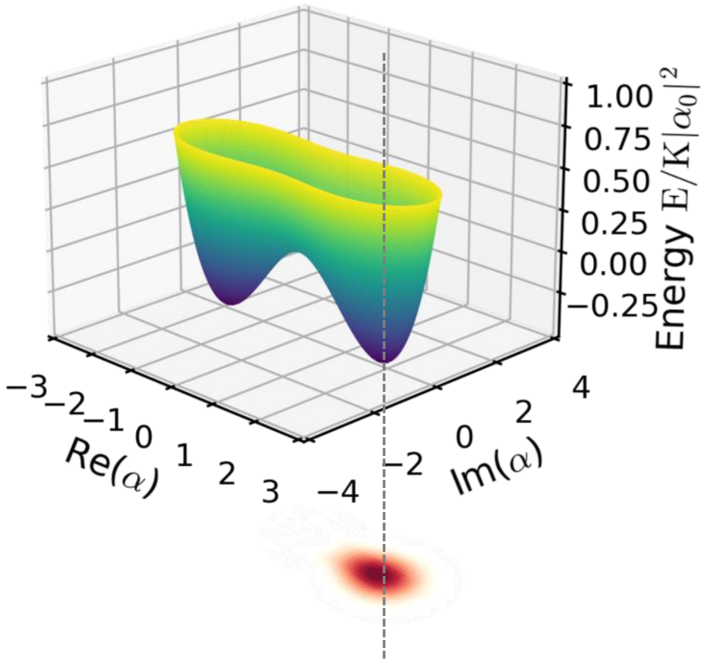
- Single qubit $X(\pi/2) \ \rightarrow \Delta(t)\hat{a}^\dagger\hat{a} + H_{KC}$
  - ➢ Adiabatically tune the drive, to reduce the well
  - ➢ Two coherent state $|\pm Z\rangle$ will tunnel across two wells

$\boldsymbol{\Delta = 0}$

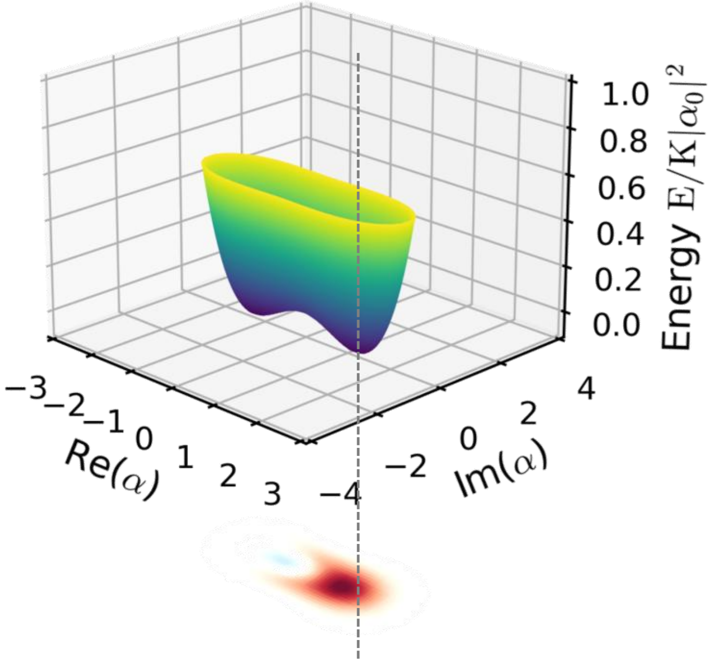


$|+Z\rangle \approx |+\alpha\rangle$

$\boldsymbol{\Delta = -3K}$



$\boldsymbol{\Delta = -7K}$

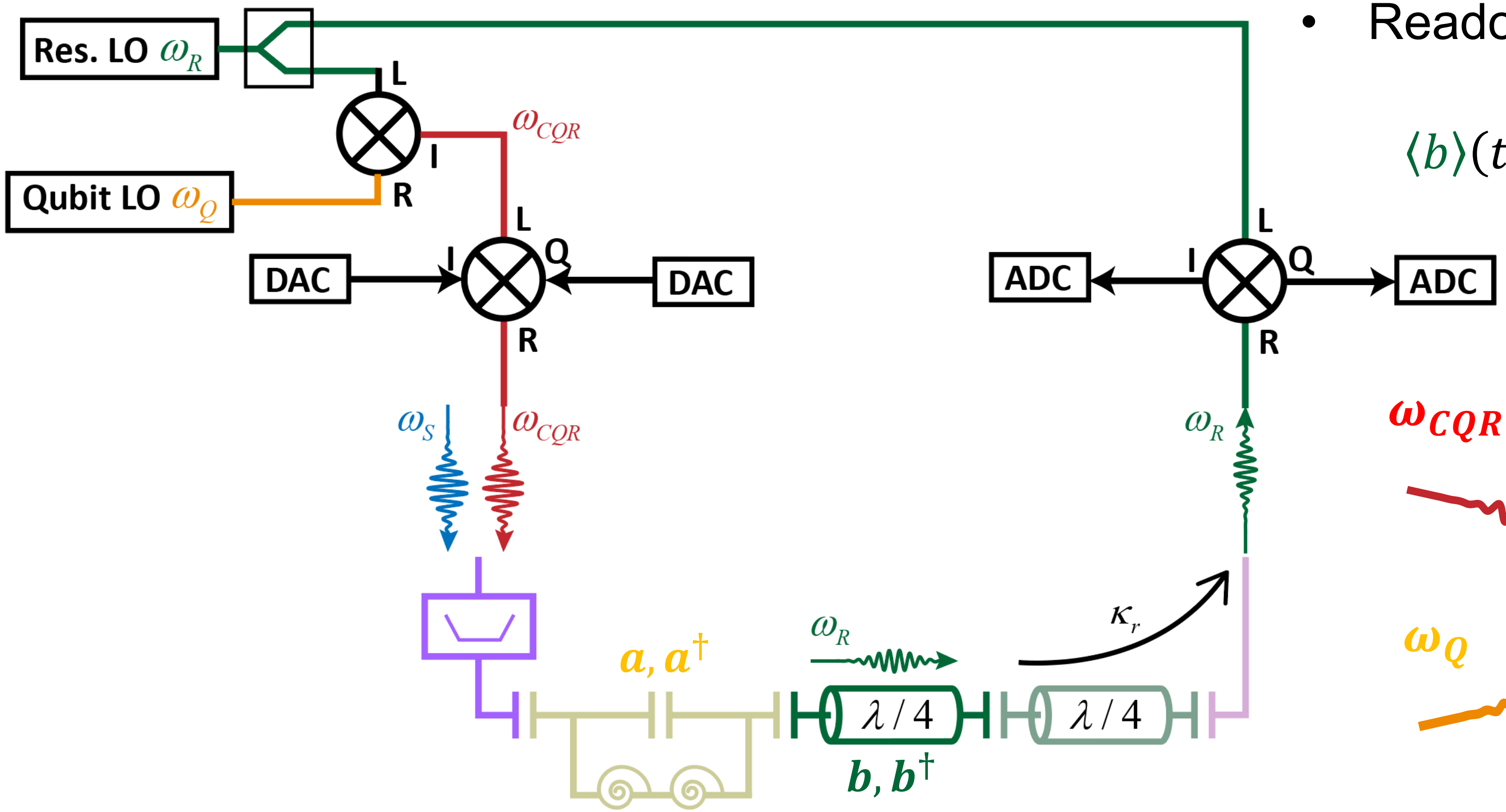


Cat Readout

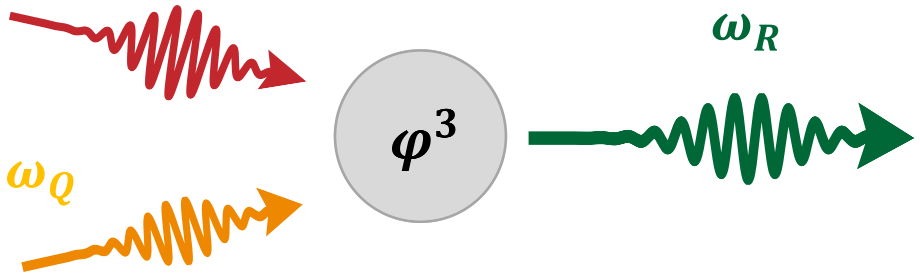
- Three wave mixing → longitudinal readout
  - $\epsilon_{CQR} a^{\dagger} b + \mathrm{h.c.} \rightarrow 2\alpha\epsilon_{CQR}(b + b^{\dagger})\sigma_z$

- Readout resonator state

$$\langle b\rangle(t, \sigma_z) \propto \frac{\epsilon_{CQR}\alpha}{\kappa_r}\left(1 - e^{-\kappa_r t/2}\right)\sigma_z$$

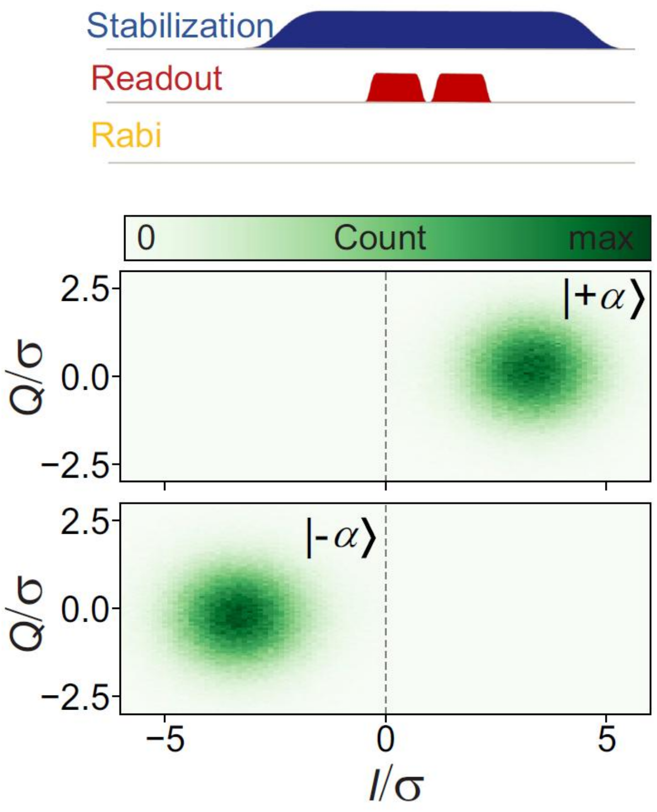


$\omega_{CQR} \approx \omega_R - \omega_Q$



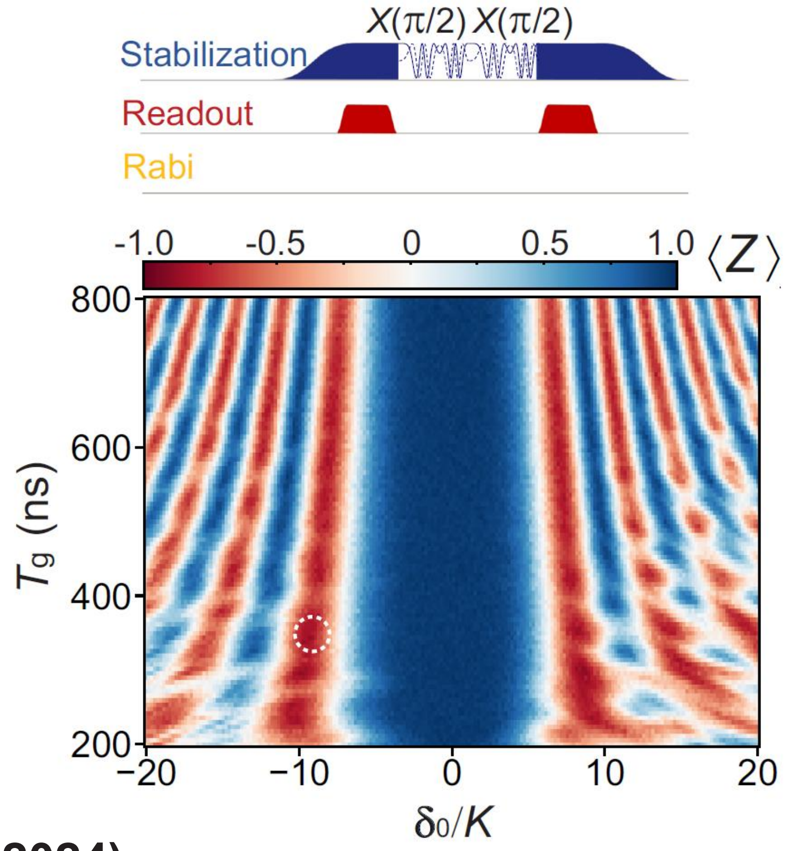
Readout and Universal Control

Cat Quadrature Readout with QNDness of up to 99.6%

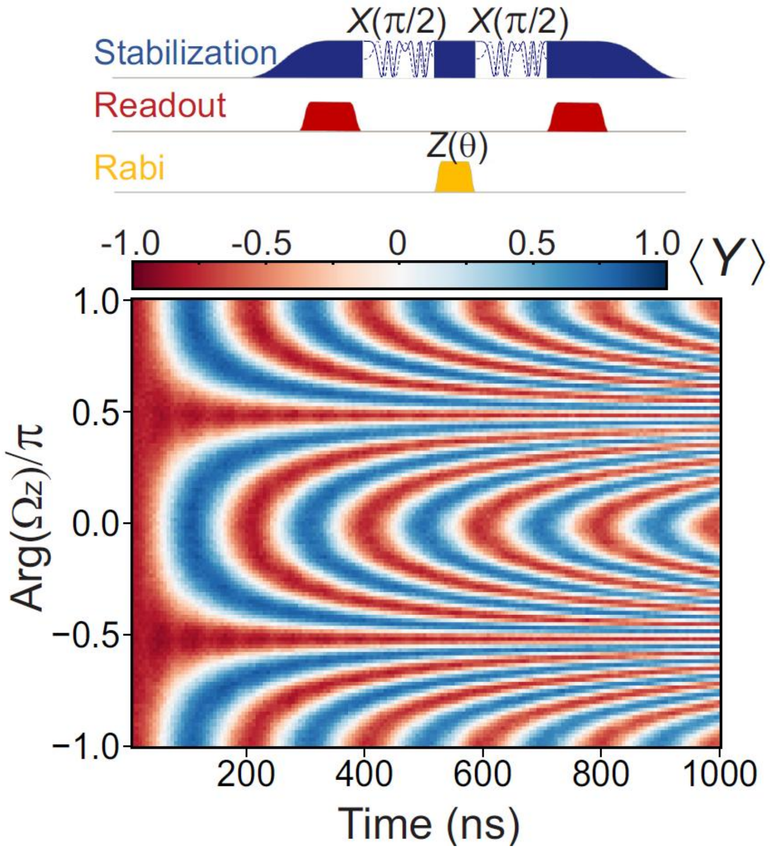


New implementation of the $X(\pi/2)$ gate: $\epsilon_2 \rightarrow \epsilon_2 e^{i\delta(t)t}$

$\Delta(t) = \left(\delta(t) + t\dot{\delta}(t)\right)/2$



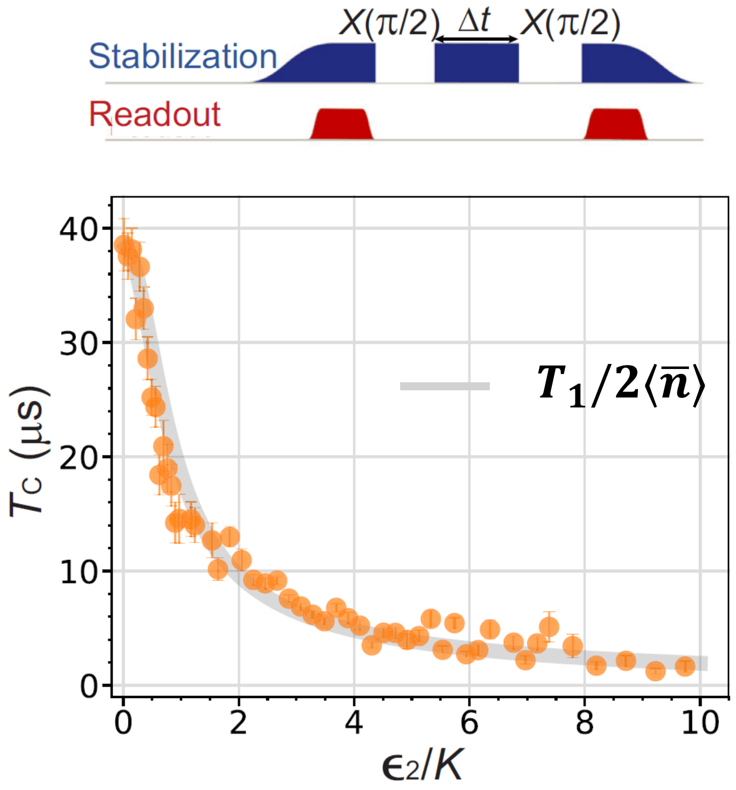
Fast cat Rabi oscillations in timescales of ~100ns for continuous $Z(\theta)$ rotations



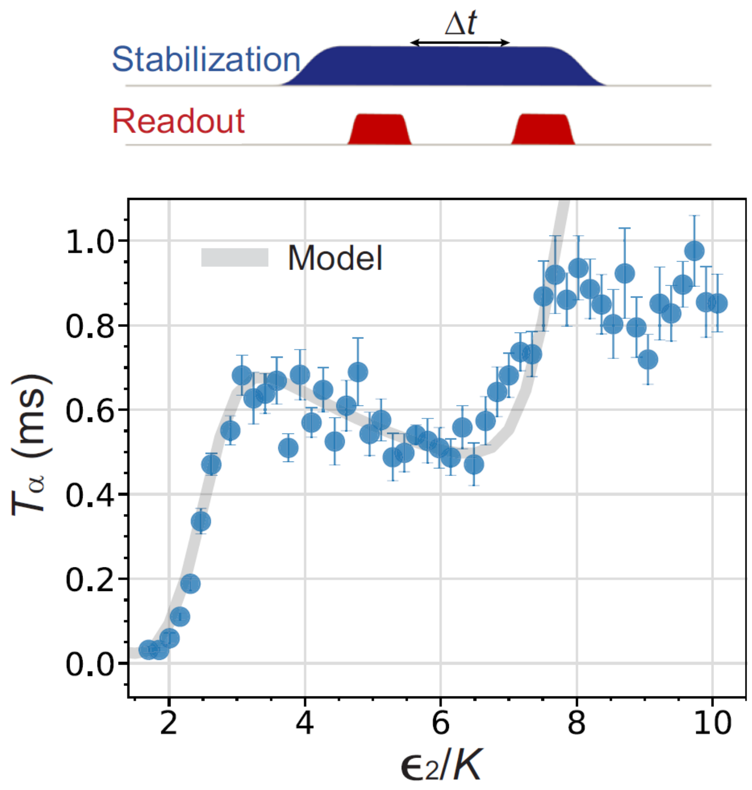
A. Hajr, et al., Physical Review X(2024)

Lifetime

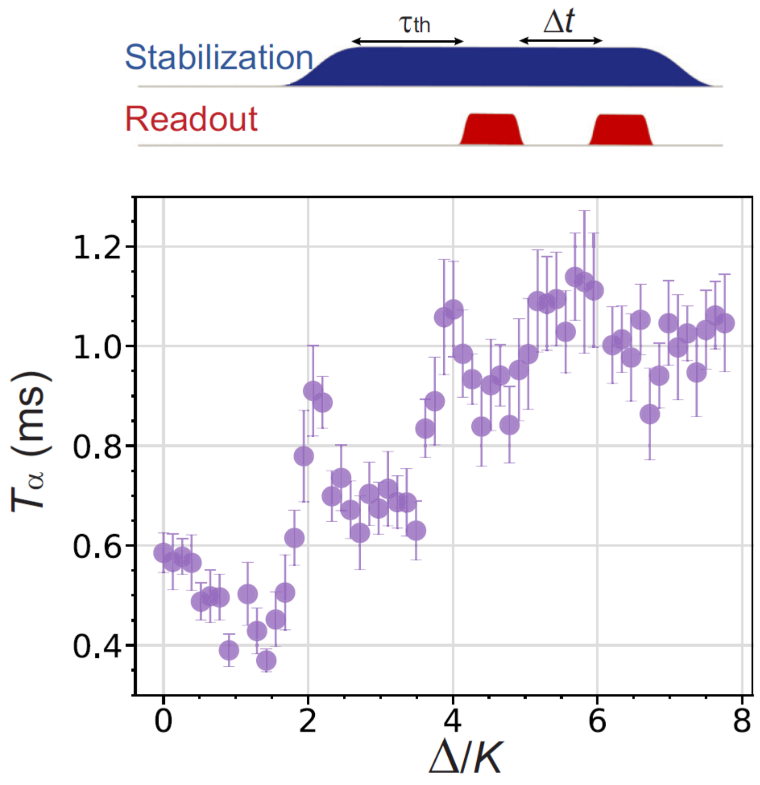
Cat States lifetime limited by the single photon lifetime of 38.5 μs



Coherent States lifetime approaching 1ms limited by heating form the SNAIL



Coherent States lifetime exceeding 1ms with controlled red detuning



Benchmarking

$X(\pi/2), \Delta = 2K$

	I	X	Y	Z
I	1.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000
X	-0.002 ±0.0015	0.893 ±0.0080	-0.010 ±0.0077	0.005 ±0.0078
Y	0.000 ±0.0016	-0.011 ±0.0093	0.034 ±0.0085	-0.854 ±0.0051
Z	0.003 ±0.0014	-0.002 ±0.0079	0.953 ±0.0042	0.034 ±0.0061

$\mathcal{F} = 92.(4)\%$

$Z(\pi/2), \Delta = 2K$

	I	X	Y	Z
I	1.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000
X	0.000 ±0.0019	0.001 ±0.0051	-0.984 ±0.0035	-0.002 ±0.0067
Y	0.001 ±0.0018	0.984 ±0.0035	0.000 ±0.0050	-0.004 ±0.0073
Z	0.000 ±0.0001	-0.000 ±0.0091	0.001 ±0.0089	1.000 ±0.0002

$\mathcal{F} = 99.1(8)\%$

-1 0 1

$X(\pi/2), \Delta = 0$

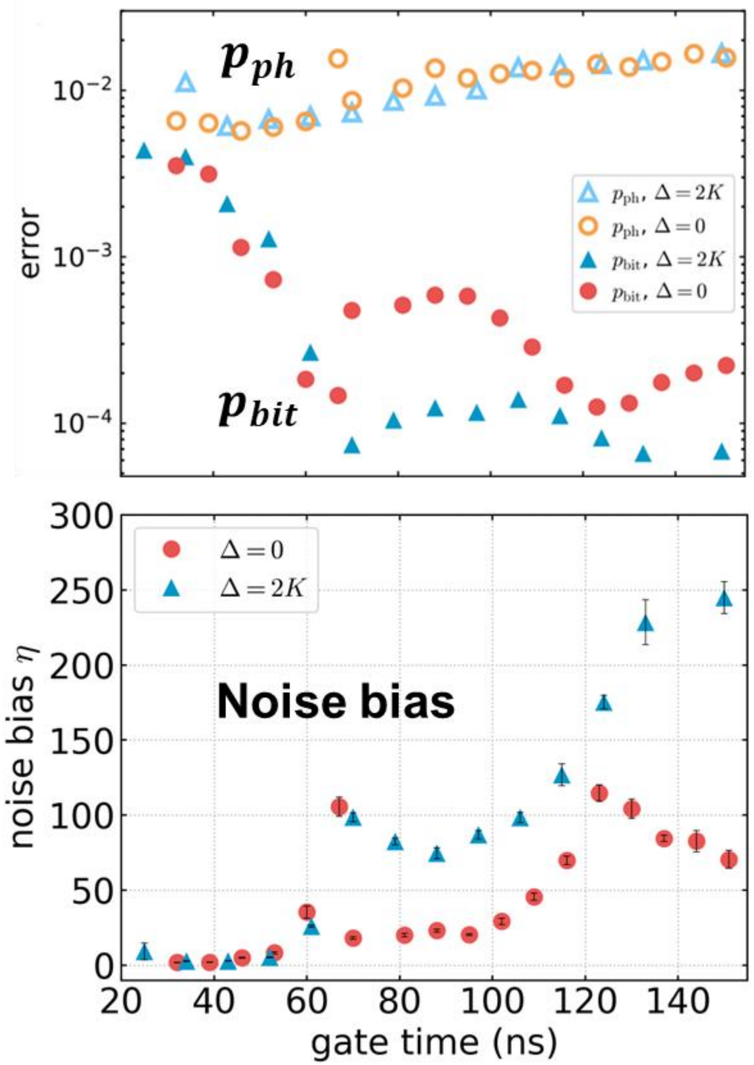
	I	X	Y	Z
I	1.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000
X	0.002 ±0.0016	0.900 ±0.0071	0.004 ±0.0063	0.020 ±0.0069
Y	0.001 ±0.0015	-0.019 ±0.0078	0.067 ±0.0062	-0.986 ±0.0045
Z	-0.004 ±0.0013	-0.005 ±0.0064	0.899 ±0.0031	0.076 ±0.0050

$\mathcal{F} = 94.(7)\%$

$Z(\pi/2), \Delta = 0$

	I	X	Y	Z
I	1.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000	0.000 ±0.0000
X	0.000 ±0.0018	-0.007 ±0.0042	-0.985 ±0.0031	0.004 ±0.0059
Y	-0.001 ±0.0017	0.985 ±0.0029	-0.006 ±0.0041	0.008 ±0.0063
Z	0.000 ±0.0001	-0.007 ±0.0070	0.004 ±0.0070	1.000 ±0.0002

$\mathcal{F} = 99.2(5)\%$



Limitations

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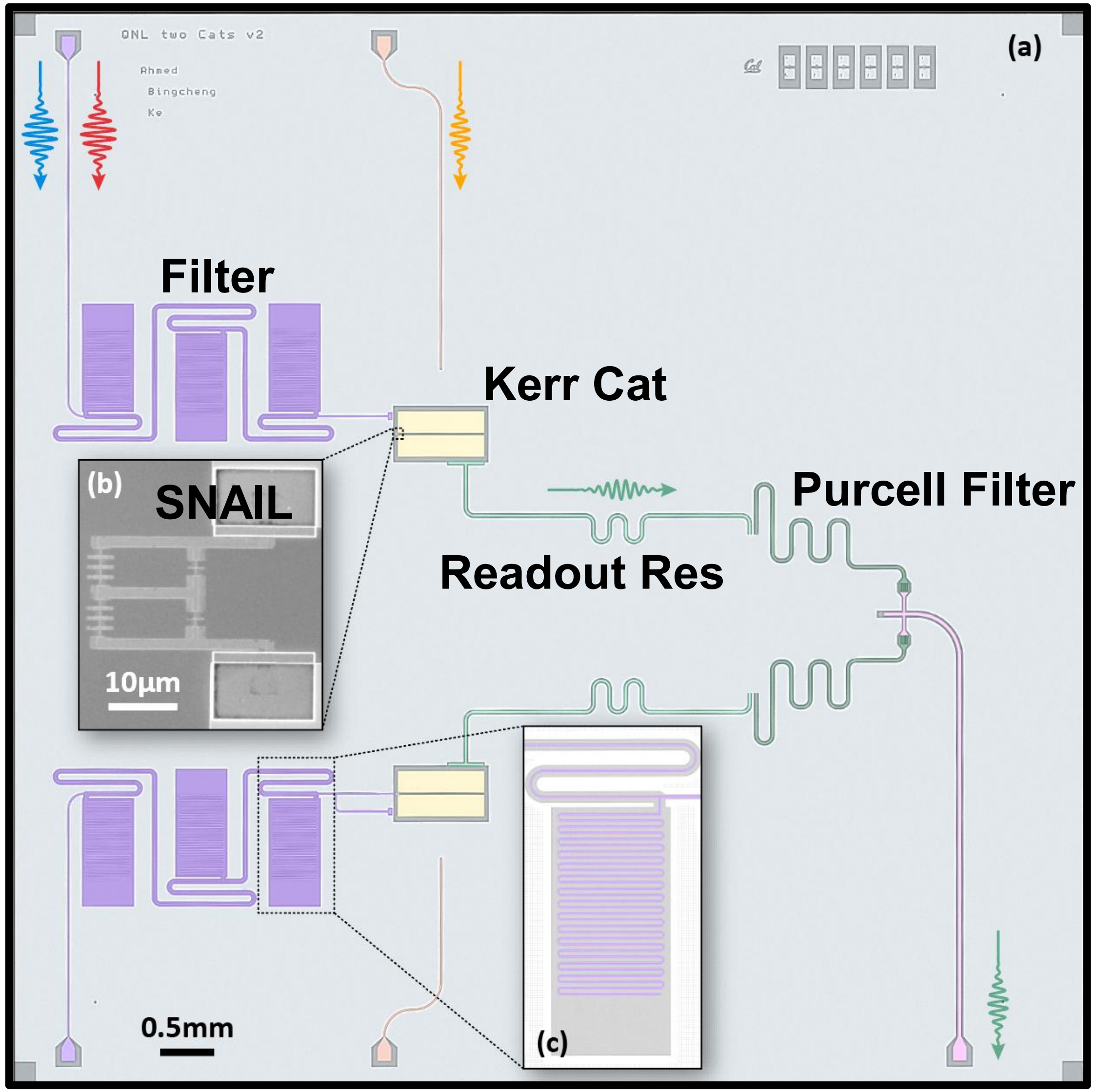
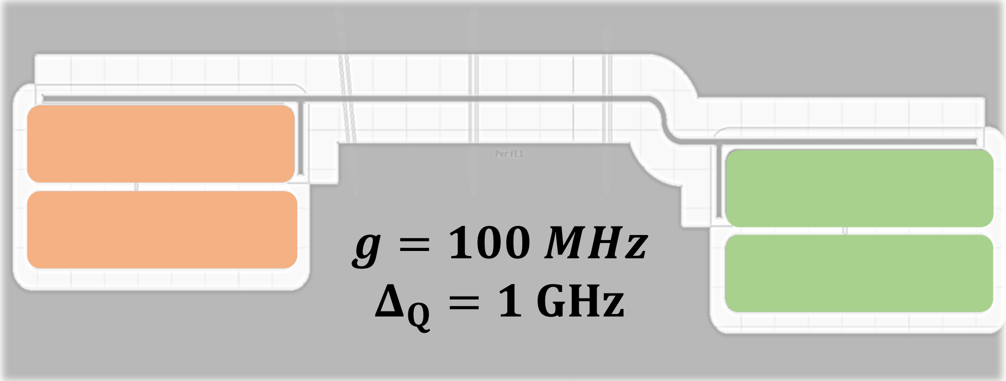


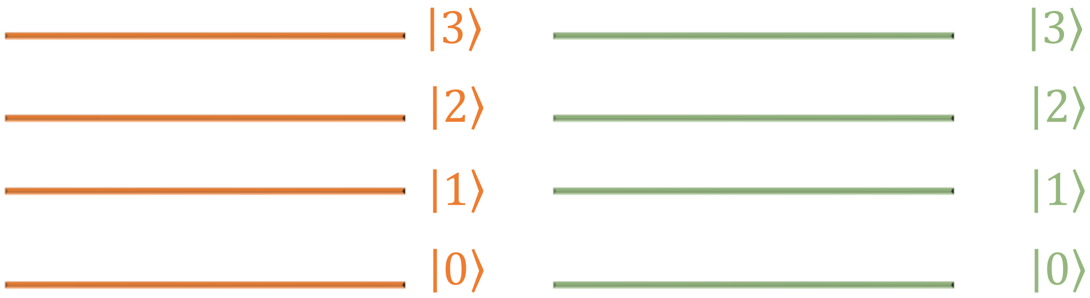
Parameter	Value
SNAILmon Qubit frequency $\omega_Q/2\pi$	5.9 GHz
SNAILmon capacitive shunt energy E_c/h	118 MHz
Number of SNAILs	2
SNAILmon junctions asymmetry α	0.1
SNAILmon Kerr nonlinearity $K/2\pi$	1.2 MHz
Fock qubit single-photon decay time T_1	38.5 μs
Fock qubit Ramsey decay time T_2^*	3μs
Readout resonator frequency $\omega_R/2\pi$	7.1 GHz
Readout resonator linewidth $\kappa_R/2\pi$	0.4 MHz
Readout to oscillator cross-Kerr $\chi/2\pi$	40 KHz
Readout resonator internal quality factor $Q_{R,i}$	3×10^5
Purcell filter frequency $\omega_P/2\pi$	7.2 GHz
Purcell filter linewidth $\kappa_P/2\pi$	60 MHz

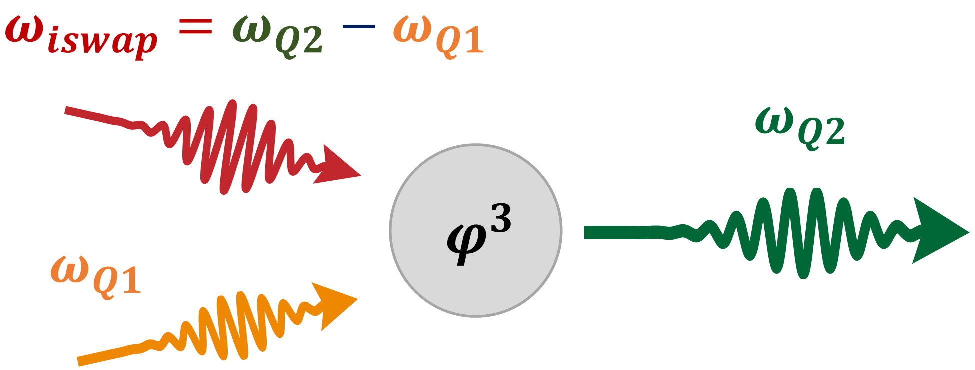
Next Generation of Cats

- Driving both SNAILs at the difference frequency activates a beam splitter interaction which can be used to implement a CZ gate:

$$\hat{H}_{BS} = J\left(\hat{a}_1^{\dagger}\hat{a}_2 + \hat{a}_1\hat{a}_2^{\dagger}\right) \rightarrow 2J\alpha^2 Z_1 Z_2$$



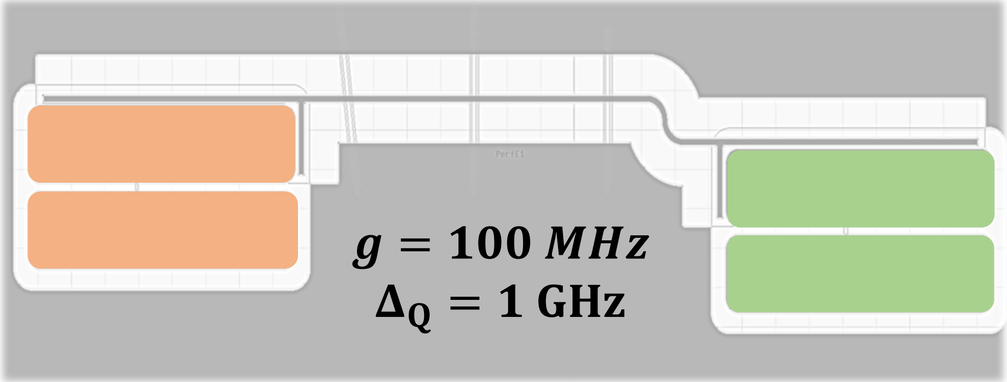


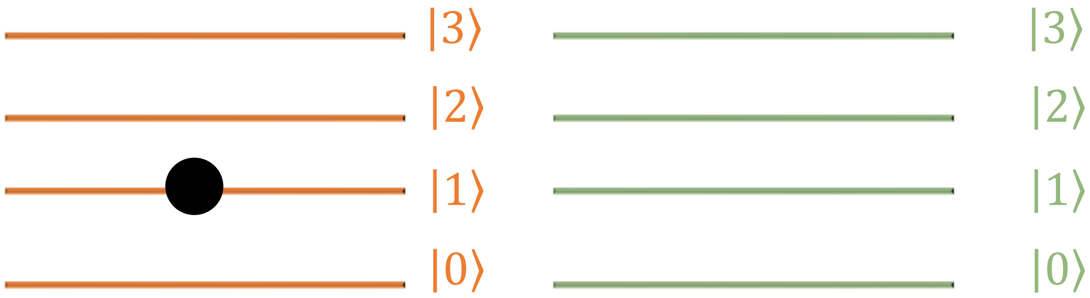


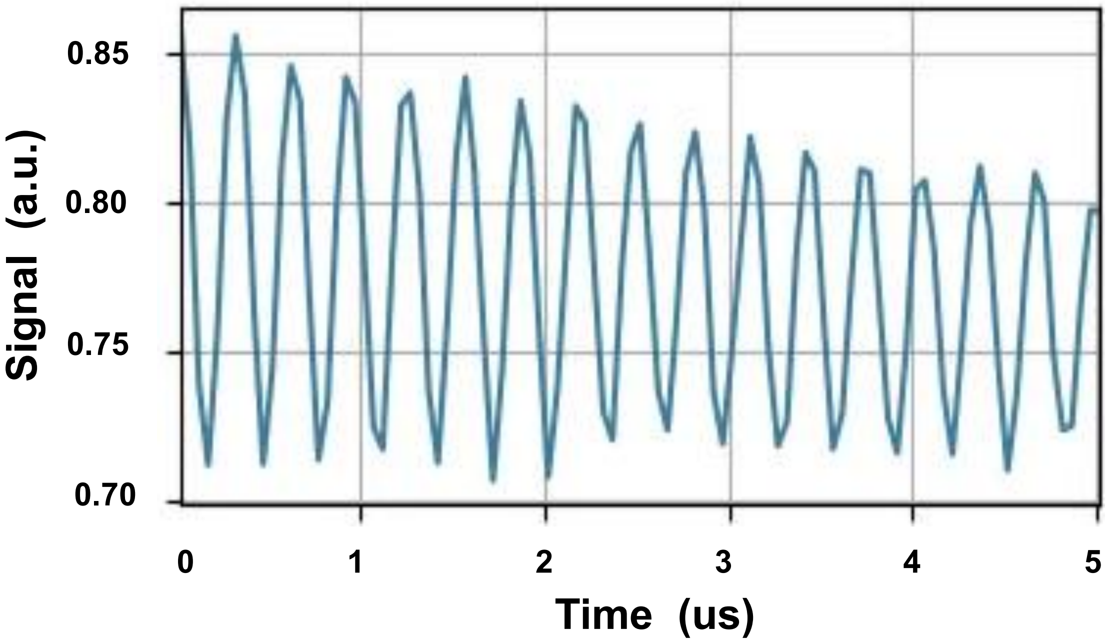
Next Generation of Cats

- Driving both SNAILs at the difference frequency activates a beam splitter interaction which can be used to implement a CZ gate:

$$\hat{H}_{BS} = J(\hat{a}_1^\dagger \hat{a}_2 + \hat{a}_1 \hat{a}_2^\dagger) \to 2J\alpha^2 Z_1 Z_2$$







Double SQUID for efficient wave-mixing

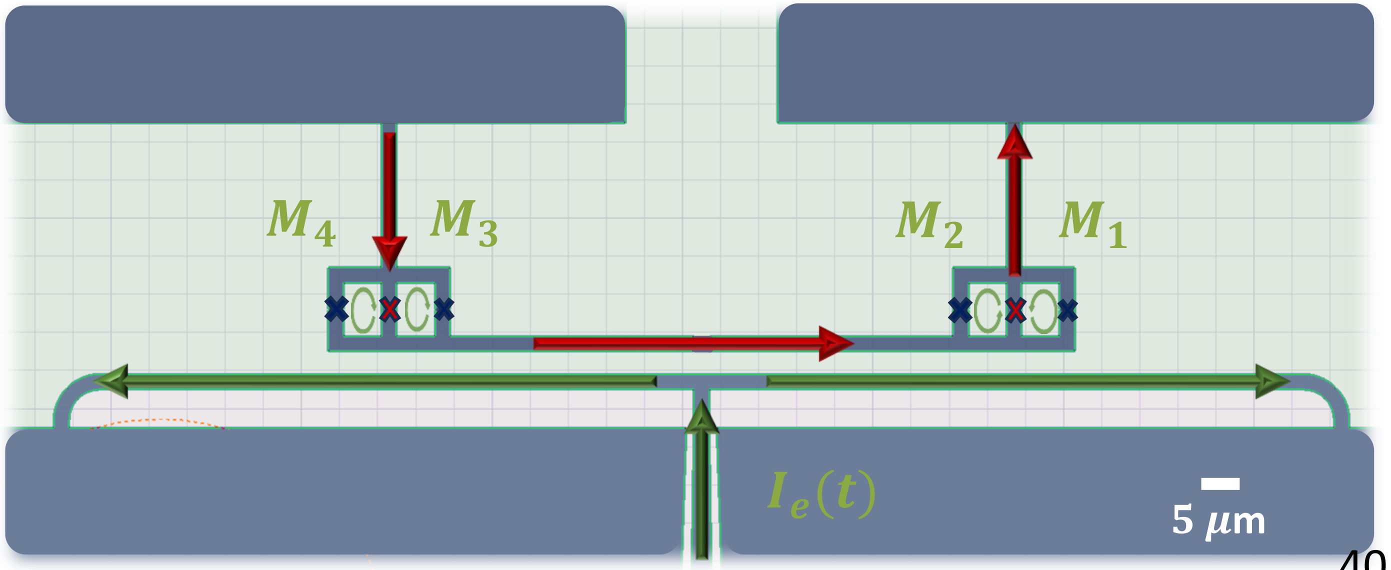
- The Double-SQUID designs show theoretical promise to realize higher nonlinearities
- The SQUID implements squeezing and ideally does not store any energy
- A large well with small anharmonicity provides the Kerr and stores the energy

$$\hat{H}_{SQUID} = -4E_J^S \cos\left(\phi_\Sigma\right) \cos\left(\frac{\hat{\phi}}{2}\right) = 4E_J^S \sin\left(\delta\phi_\Sigma \cos(\omega_p t)\right)\cos\left(\frac{\hat{\phi}}{2}\right) \approx \frac{1}{2} E_J^S\, \delta\phi_\Sigma \cos(\omega_p t)\, \phi_{ZPF}^2 \left(\hat{\boldsymbol{a}} + \hat{\boldsymbol{a}}^\dagger\right)^2$$

$$\hat{H}_T = 4E_c\, \hat{n}^2 - 2E_j \cos\left(\hat{\phi}/2\right)$$

$$\epsilon_2 = \frac{E_J^S}{2E_J} \delta\phi_\Sigma \omega_Q$$

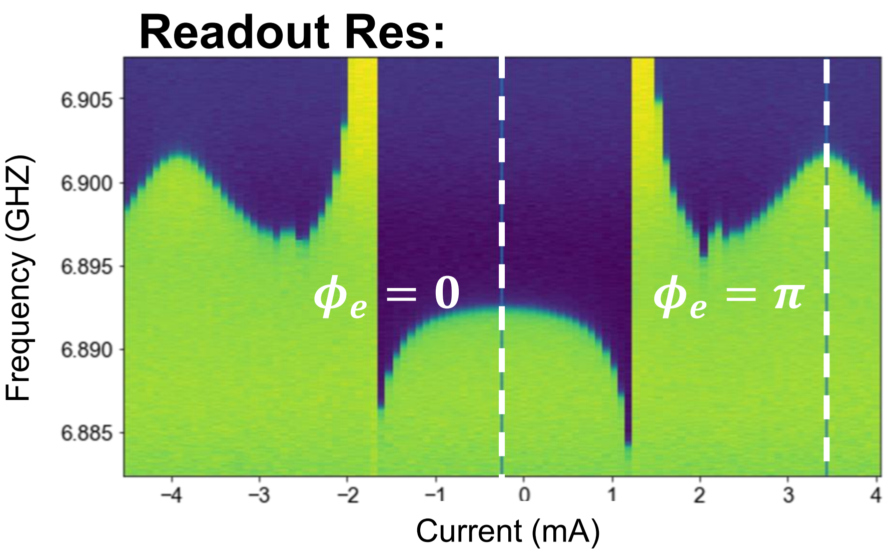
$$K = \frac{1}{4}(E_C/2)$$

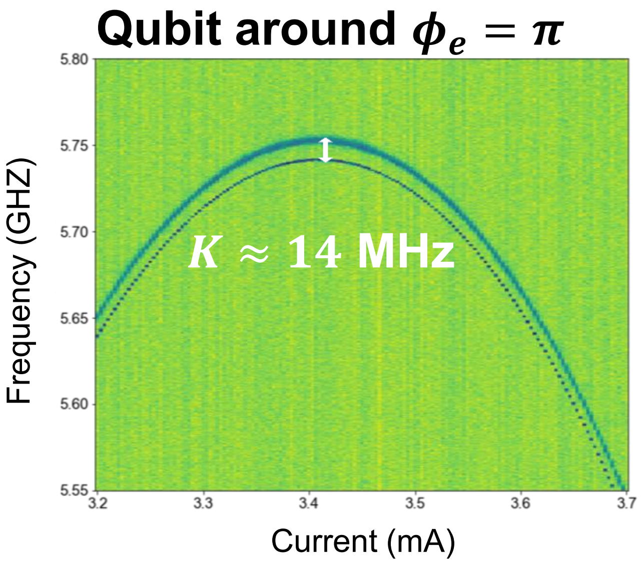


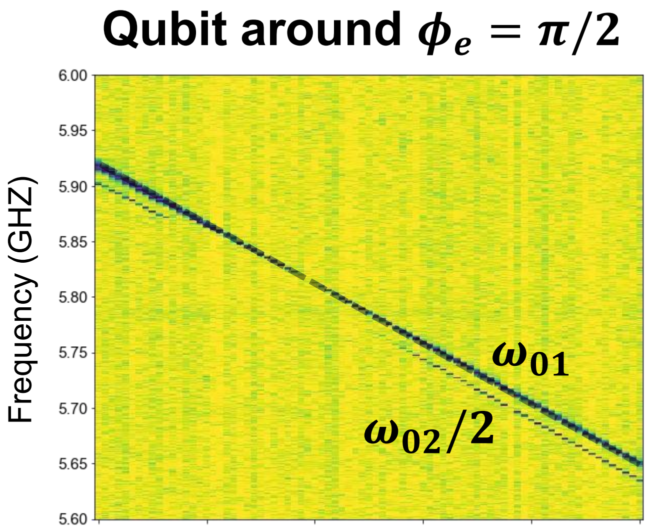
R. Lescanne, et al., Nature Physics (2024)

B. Bhandari, et al., arXiv(2024)

Biasing the Double SQUID

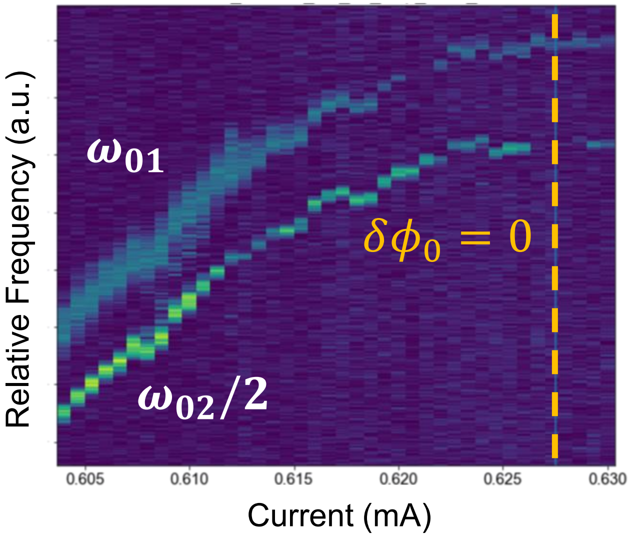






The desired operation point $\phi_e = \pi/2$ corresponds to first order sensitivity and second order insensitivity to the flux

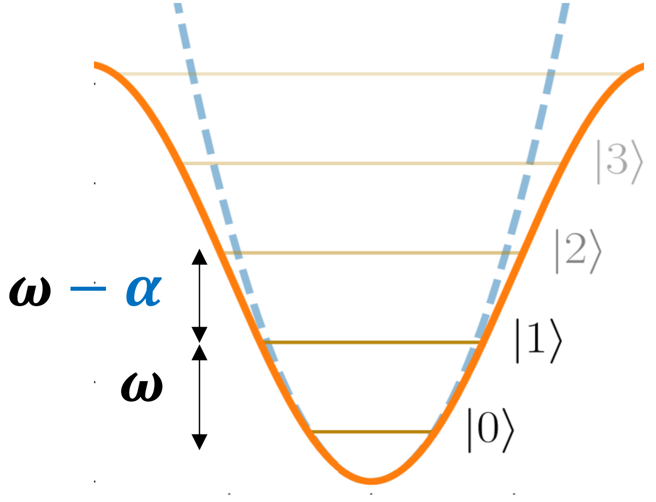
$$\hat{H}_S = -4E_j^S \sin(\delta\phi_e(t)) \cos\left(\frac{\hat{\phi}}{2}\right) + 4E_j^S \delta\phi_0 \cos(\delta\phi_e(t)) \cos\left(\frac{\hat{\phi}}{2}\right)$$

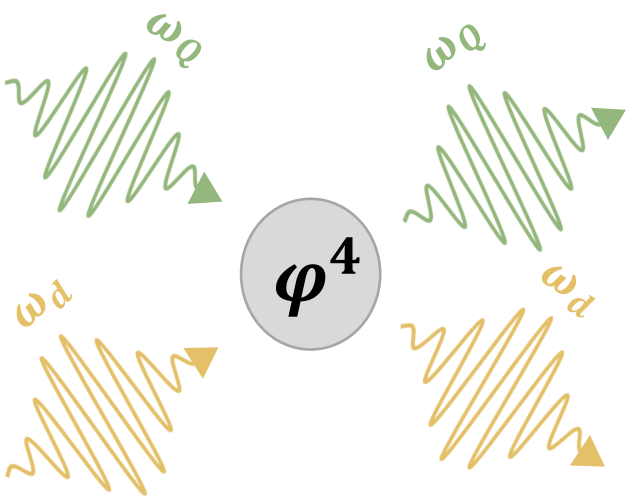


Nonlinear light-matter coupling

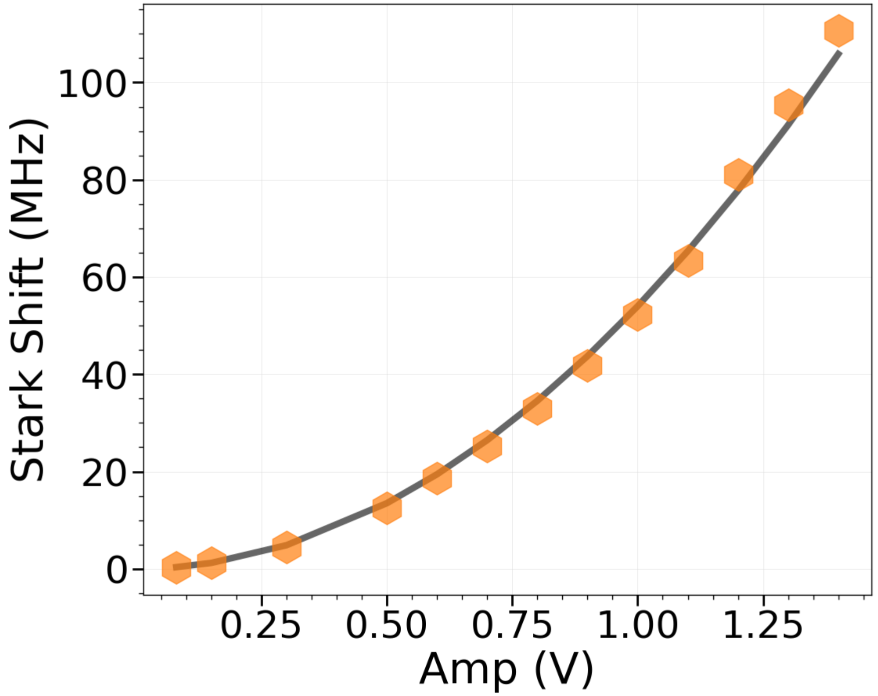
- With 4-wave mixing we can perform AC Stark shifts

$$\hat{H}_T = 4E_c\,\hat{n}^2 - E_j\cos(\hat{\phi}) = 4E_c\,\hat{n}^2 - E_j\left(-\frac{1}{2!}\hat{\phi}^2 + \frac{1}{4!}\hat{\phi}^4\right)$$





Stark Shift: $\omega_d/2\pi = 350\ MHz$



Nonlinear light-matter coupling

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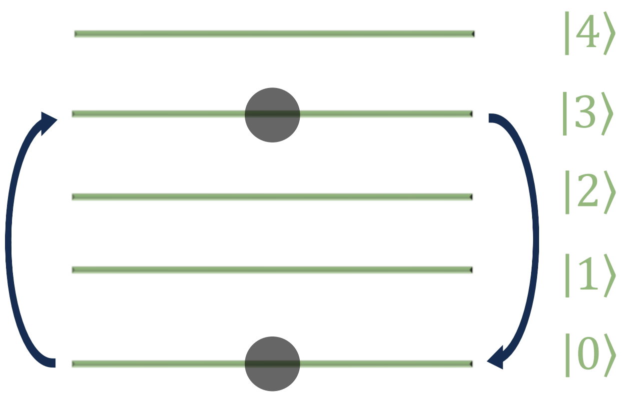
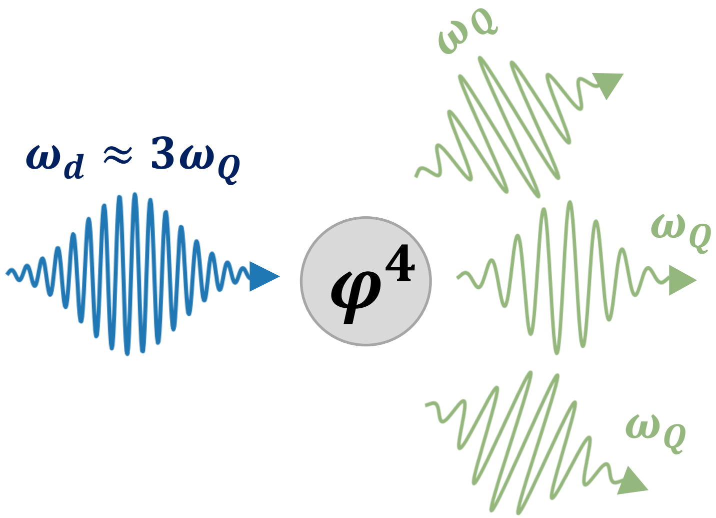
- The atom decay is a linear process which can be combated with nonlinear driving

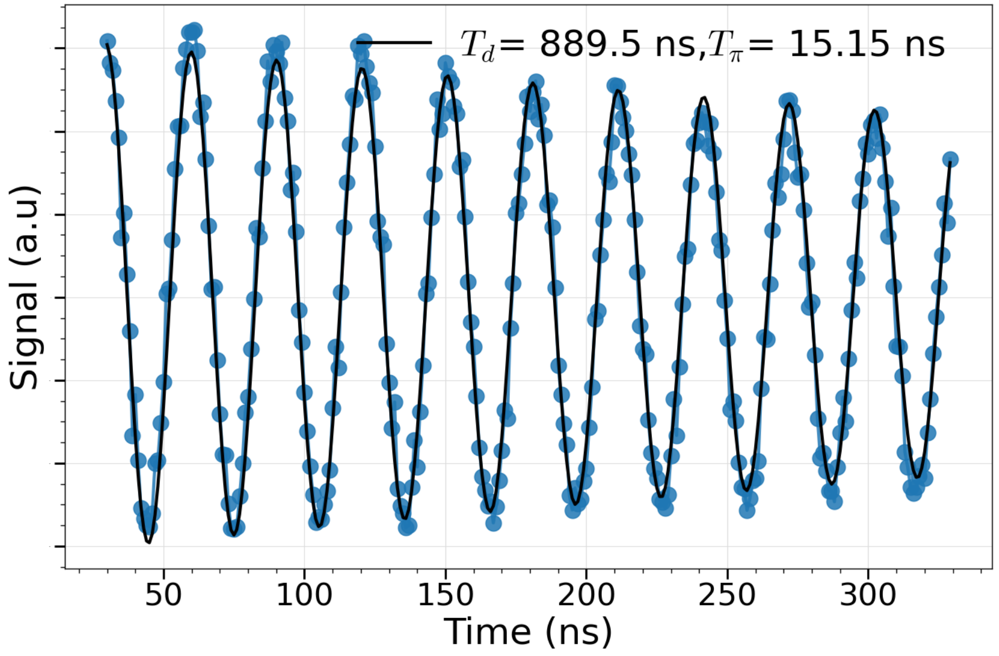
$$\hat{H}_T = 4E_c\,\hat{n}^2 - E_j \cos(\hat{\phi}) \approx 4E_c\,\hat{n}^2 - E_j\left(-\frac{1}{2!}\hat{\phi}^2 + \frac{1}{4!}\hat{\phi}^4\right)$$



$$\boldsymbol{\epsilon_3(t)(\hat{a}^\dagger\hat{a}^\dagger\hat{a}^\dagger + \hat{a}\hat{a}\hat{a})}$$



0-3 Rabi: $\omega_d/2\pi \approx 15.5\ GHz$



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Dr. Kan-Heng Lee

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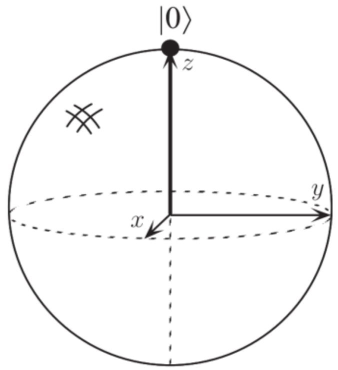
Dr. Nicholas E Frattini

Prof. Andrew N Jordan
Prof. Justin G Dressel
Irwin Huang
Bibek Bhandari

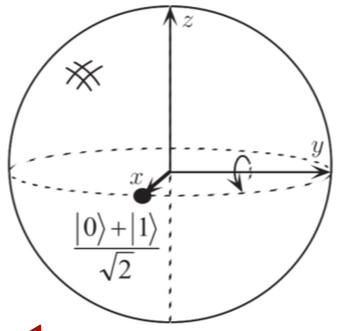
Quantum measurement

- Imagine that I decided to give one of two states $|\psi_0\rangle$ or $|\psi_1\rangle$ Which are not orthogonal



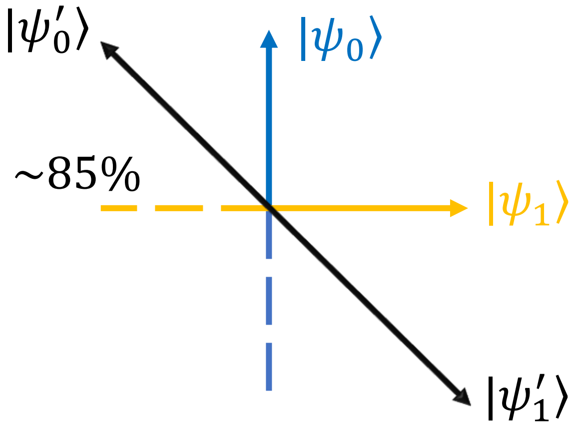
$|0\rangle$

OR



$\frac{1}{\sqrt{2}}(|0\rangle + |1\rangle)$

- You can not orient your detector to distinguish the two perfectly!



- Unfortunately, you can not use a probe p without affecting the state!

$$|\psi_0\rangle|p_0\rangle \to |\psi_0\rangle|p_1\rangle$$

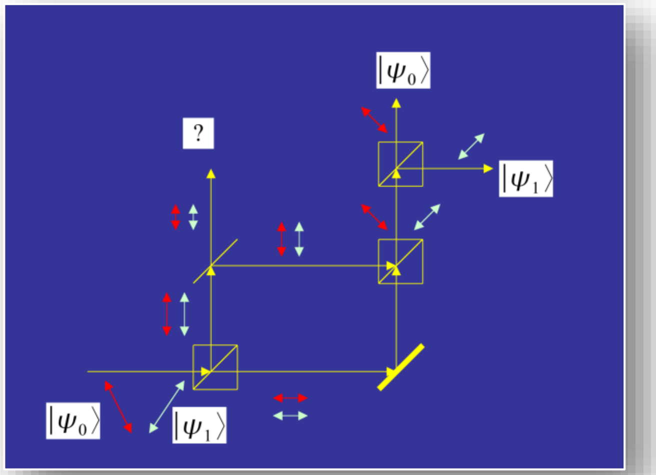
$$|\psi_1\rangle|p_0\rangle \to |\psi_1\rangle|p_2\rangle$$

U_a can not change inner product

$$\langle\psi_1|\psi_0\rangle = \langle\psi_1|\psi_0\rangle\langle p_2|p_1\rangle$$

$$1 = \langle p_2|p_1\rangle$$

- Unambiguous measurement for a price? (POVM)

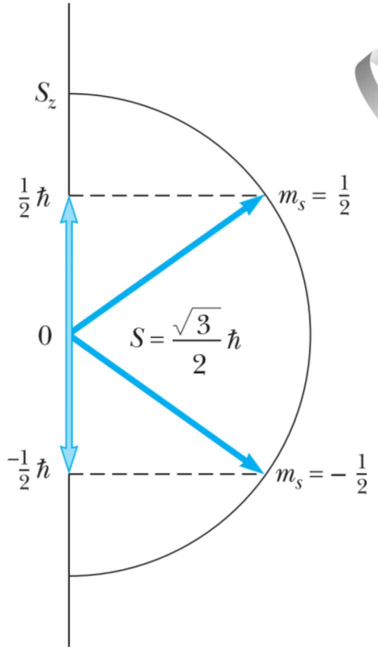


Not All Operators Commute

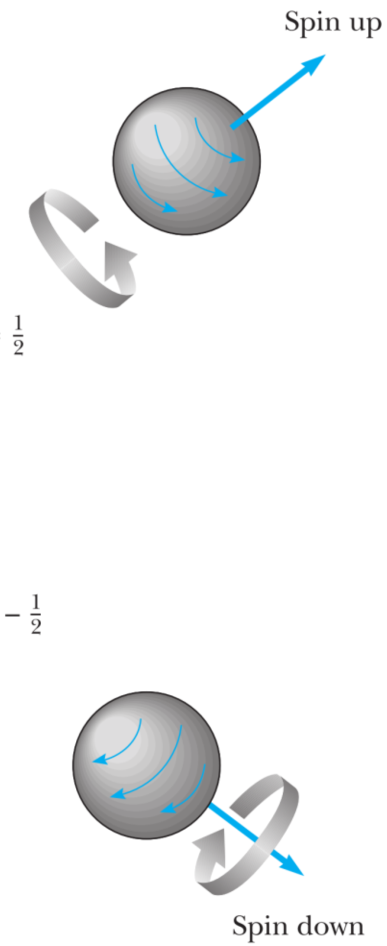
$$\hat{p}_x|\psi\rangle = c_1|\psi\rangle$$
$$\hat{x}|\psi\rangle = c_2|\psi\rangle$$

No psi such that c1, c2 are numbers

- If two operators do not commute (e.g. spin components, position and momentum) then they do not have common eigenbasis
- You can not prepare a state so that you have **sharp** values for each operator
- As a result you can not define a direction for the z-axis so that $S_z = |\vec{S}|$ nor the position and the momentum can be described by a single values simultaneously



?!!!



Benchmarking the noise-bias

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n gates sampled from single qubit CX dihedral group: $\mathcal{D}_1 = \langle X, T = Z(\pi/4)\rangle / U(1)$

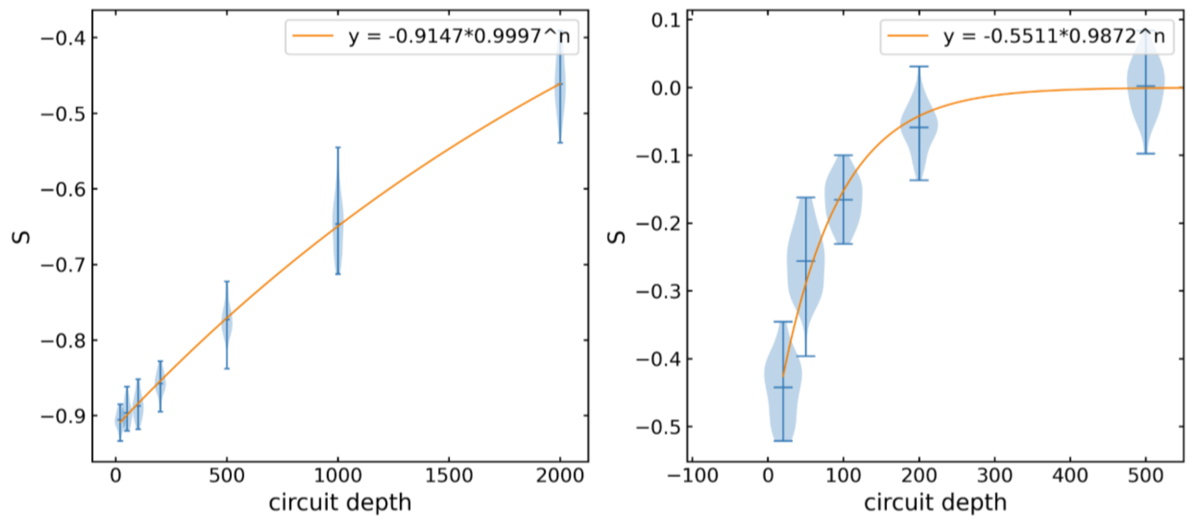
$\rho = |0\rangle\langle 0|$ — H — P — D_1 — ……… — D_n — D_{n+1} — H — $M \rightarrow |0\rangle$ or $|1\rangle$

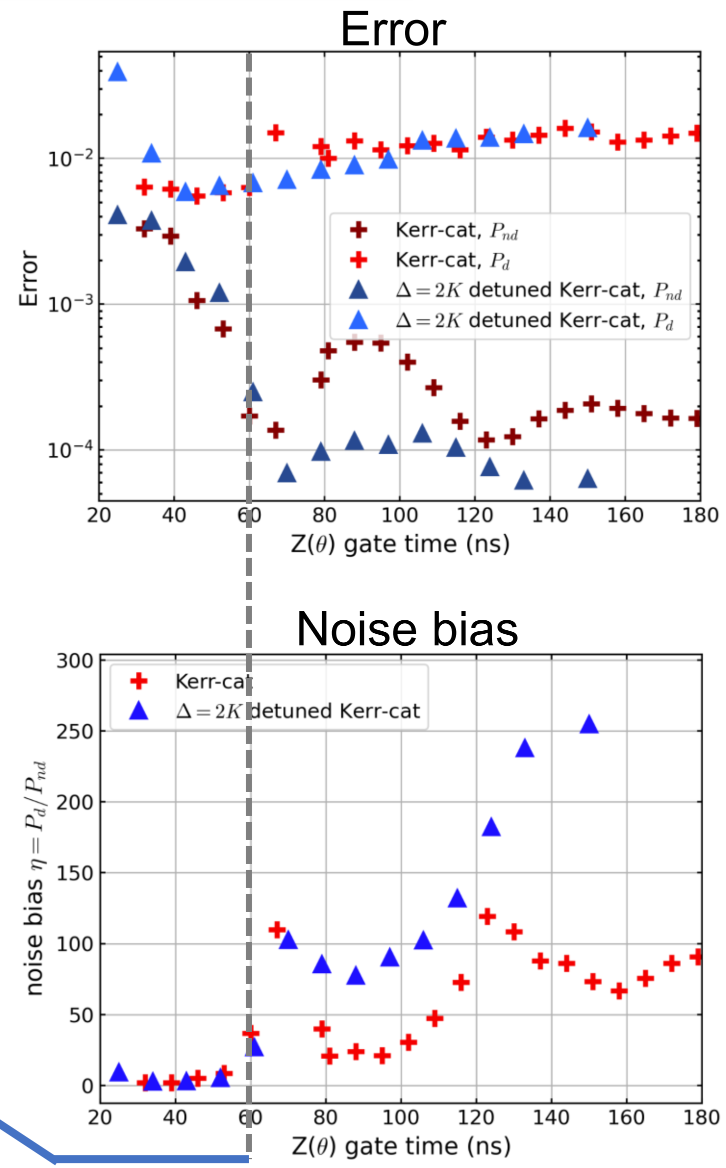
$\rho = |0\rangle\langle 0|$ — P — D_1 — ……… — D_n — D_{n+1} — $M \rightarrow |0\rangle$ or $|1\rangle$

1 gate sampled from single qubit Pauli group: $\mathcal{P}_1 = \langle X, Z\rangle / U(1)$

$D_{n+1} = (D_n D_{n-1} \dots D_1 P)^{-1} \in \mathcal{D}_1$

- Prepare and measure in X axis and Z axis
- fit the result with circuit depth n into exponential
- Extract bit-flip error P_{nd} and phase-flip error P_d from fitting





Nonlinear light-matter coupling

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- The wave mixing processes are proportional to the displacement of the drive

$$\hat{H}_T = 4E_c\,\hat{n}^2 - NE_j\cos(\hat{\phi}) = 4E_c\,\hat{n}^2 - NE_j\sum_n(-1)^n\frac{(\hat{\phi})^{2n}}{(2n)!}$$

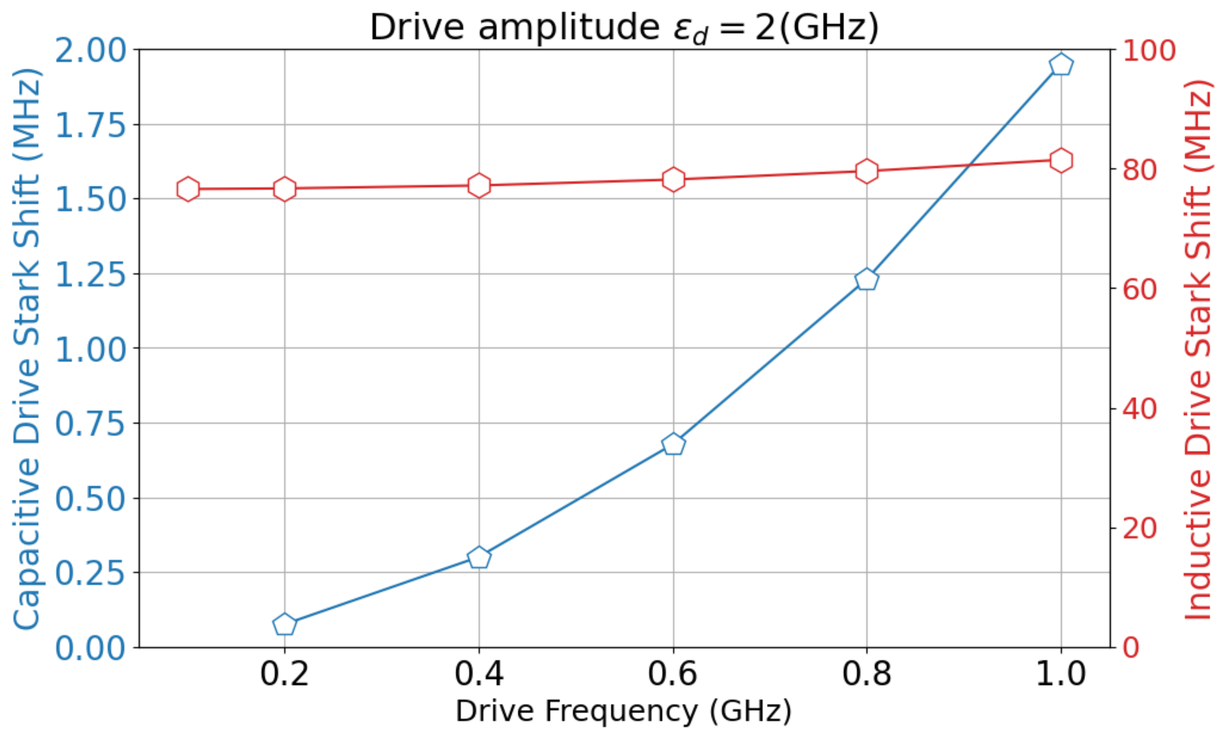
- This displacement depends on the **frequency of the drive** and whether it is **capacitive** or **inductive (which is not the case for on-resonance drives)**

$$\hat{H}_c = i\epsilon_d\cos(\omega_d t)\,(\hat{a}-\hat{a}^\dagger)$$

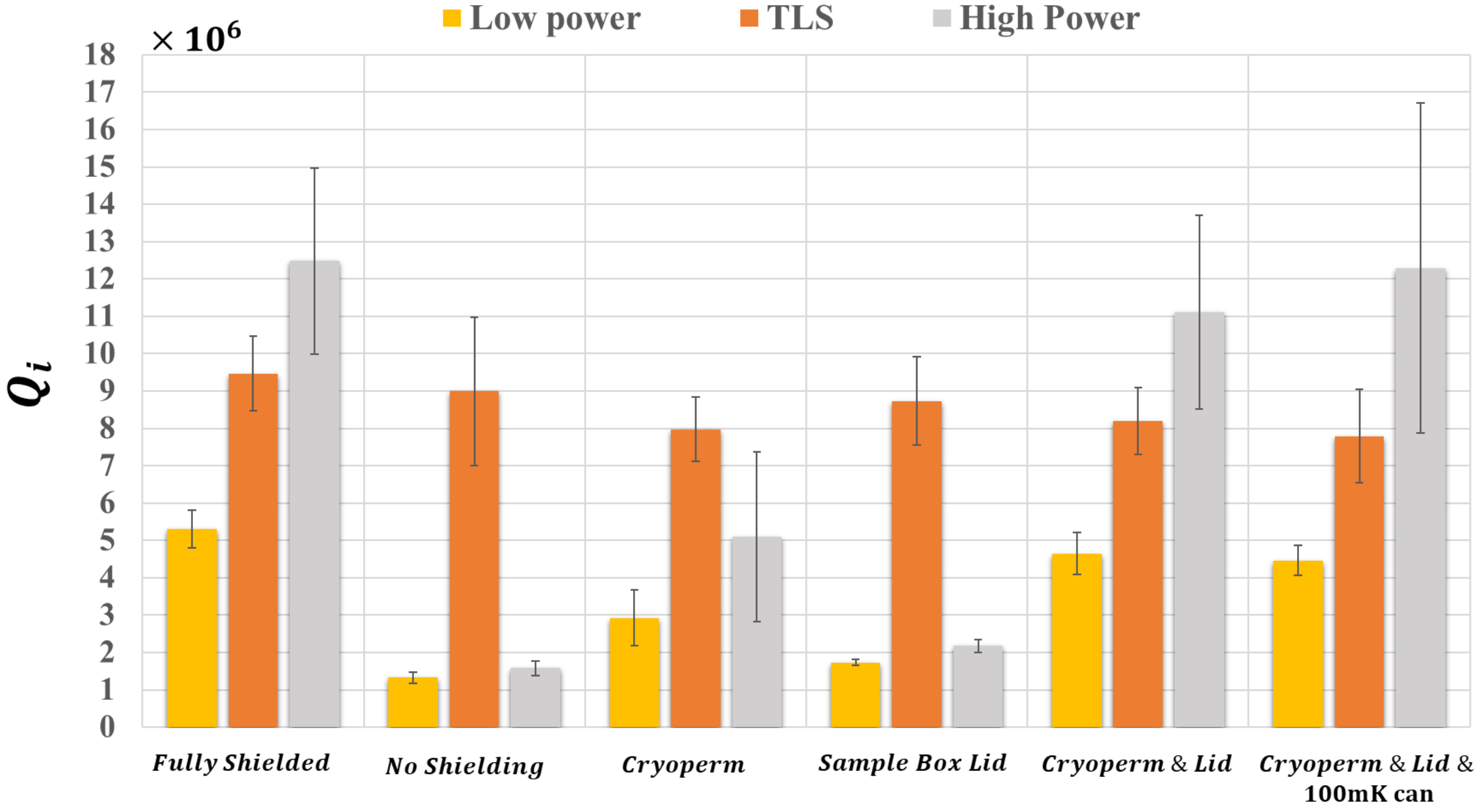
$$\xi_c = \frac{\epsilon_d}{\omega_Q-\omega_d} - \frac{\epsilon_d}{\omega_Q+\omega_d}$$

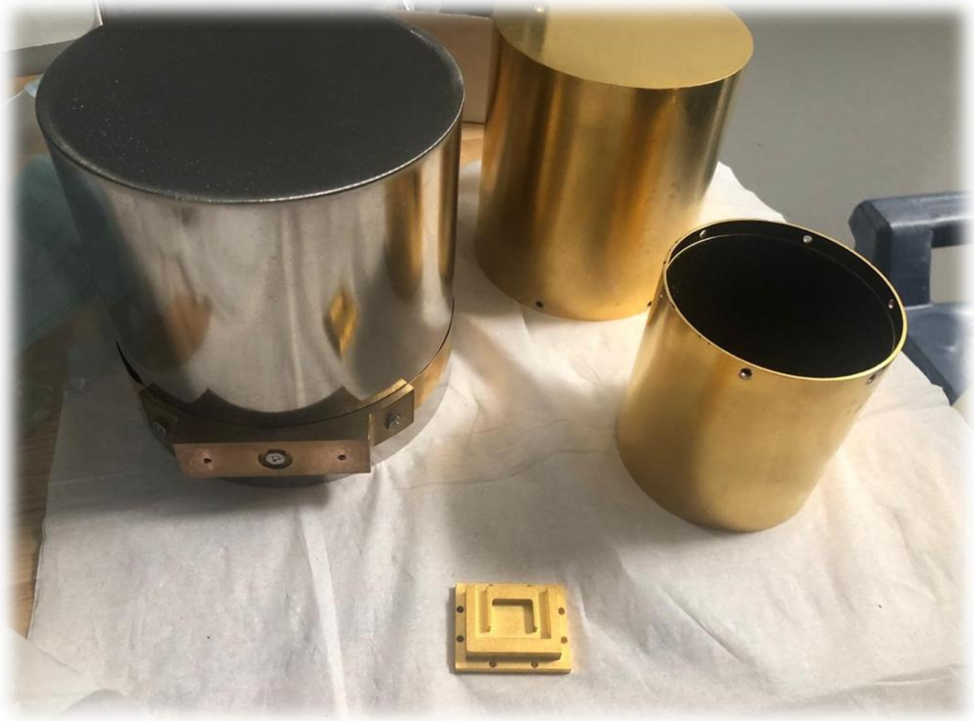
$$\hat{H}_I = \epsilon_d\cos(\omega_d t)\,(\hat{a}+\hat{a}^\dagger)$$

$$\xi_I = \frac{\epsilon_d}{\omega_Q-\omega_d} + \frac{\epsilon_d}{\omega_Q+\omega_d}$$



Shielding the system from radiation





- The impact of the shielding will not visible if the sample is the sample is not good enough
- IR shielding is crucial, but we have enough
- Magnetic shielding is crucial, but do we have enough?