Schrödinger Cats, Maxwell's Demon and Quantum Error Correction

Experiment

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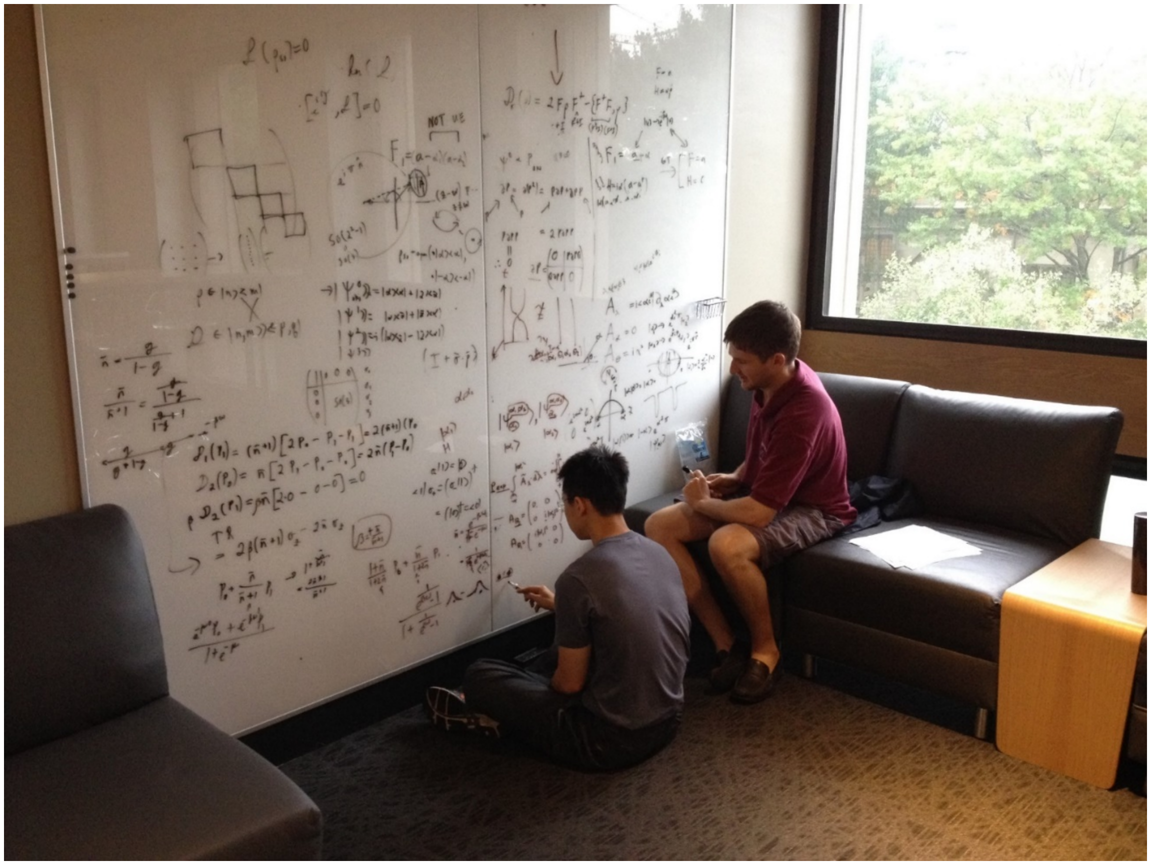

Theory

SMG
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QuantumInstitute.yale.edu

In the first lecture we learned:

An arbitrary quantum channel (CPTP map) is the most general possible operation on a quantum system.

Therefore <u>if quantum error correction is possible</u>, it can be performed via a quantum channel.

$$\rho'_{\mathrm{sys}} = \sum_{k=1}^{d^2} E_k \rho_{\mathrm{sys}} E_k^\dagger$$ 'error map'

$$\rho_{\mathrm{sys}} = \sum_{k=1}^{d^2} R_k \rho'_{\mathrm{sys}} R_k^\dagger$$ 'recovery map'

Under what conditions is recovery possible?

Let the system ('sys') be N physical qubits.
A logical qubit encoded in sys consists of two orthogonal 'words' in the Hilbert of sys

$$\text{code} = \text{span}\left\{ |W_0\rangle, |W_1\rangle \right\}$$

$$P_{\text{code}} = |W_0\rangle\langle W_0| + |W_1\rangle\langle W_1|$$

Knill-Laflamme condition

A recovery map for a set of errors $\left\{ E_1, E_2, \ldots, E_N \right\}$ exists if

$$P_{\text{code}} E_i^\dagger E_j P_{\text{code}} = \alpha_{ij} P_{\text{code}}$$

where α is a Hermitian matrix.

Equivalently $\langle W_\mu | E_i^\dagger E_j | W_\nu \rangle = \alpha_{ij} \delta_{\mu\nu}$
where α_{ij} is state-independent (i.e. independent of μ, ν).

In learning the error, we learn nothing about the stored information.

Knill-Laflamme condition

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where α is a Hermitian matrix.

"Proof:" Let $S \alpha S^\dagger = d$ diagonalize α. Let $K = SE$.

$$P_{\text{code}} K_i^\dagger K_j P_{\text{code}} = d_{ij} P_{\text{code}}$$

Different error states $K_j |W_\mu\rangle$ are orthogonal and hence identifiable by measurement of the projector (which does <u>not</u> tell us about the stored quantum information)

$$\Pi_j = \frac{K_j P_{\text{code}} K_j^\dagger}{d_{jj}}, \quad (\Pi_j)^2 = \Pi_j$$

Given knowledge of which error occurred, there exists a unitary map from the error state back to the original state in the code space.

Errors can be non-unitary (increase entropy) But Knill-Laflamme condition says we can correct them with a unitary, if the choice of unitary is conditioned on measurement result.

$$\Pi_j = \frac{K_j P_{\text{code}} K_j^\dagger}{d_{jj}}, \quad (\Pi_j)^2 = \Pi_j$$

Next up: Quantum Error Correction Codes for Bosonic Modes (microwave photons)

Photons are excitations of harmonic oscillators (e.g. one mode of a microwave resonator)

We will use superpositions of photon Fock states (number states) as quantum code words.

Example: Binomial Code (aka ‘kitten code’)

Code states

$$|W_0\rangle = |2\rangle$$

$$|W_1\rangle = \frac{1}{\sqrt{2}}\left[|0\rangle + |4\rangle\right]$$

Error states

$$a|W_0\rangle = \sqrt{2}|1\rangle$$

$$a|W_1\rangle = \sqrt{2}|3\rangle$$

M. Michael et al., *PRX* **6**, 031006 (2016)

$$H = \omega_0 \hat{n} + H_{\text{damping}}$$

$$\hat{n} = a^\dagger a$$

$$\frac{d}{dt}\langle \hat{n} \rangle = -\kappa \langle \hat{n} \rangle$$

Experimentally realistic error model:

1. Amplitude damping of harmonic oscillator
2. No intrinsic dephasing (frequency noise)

Quantum channel for damped oscillator:

0 photon loss → $E_0\rho(0)E_0^\dagger$

1 photon loss → $E_1\rho(0)E_1^\dagger$

$$\rho(t+\delta t) = E_0\rho(0)E_0^\dagger + E_1\rho(0)E_1^\dagger + \ldots$$

(the "…" is crossed out)

$$E_1 = \sqrt{\kappa\delta t}\; a$$

$$E_1^\dagger E_1 = \kappa\delta t\; \hat{n}$$

Sanity check: probability of 1 photon loss: $p_1 = \mathrm{Tr}\left\{E_1 \rho E_1^\dagger\right\} = \kappa\delta t \langle \hat{n} \rangle$

Quantum channel for damped oscillator:

0 photon loss → E_0; 1 photon loss → E_1

$$\rho(t+\delta t) = E_0\rho(0)E_0^\dagger + E_1\rho(0)E_1^\dagger + \ldots$$

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$$E_1^\dagger E_1 = \kappa\delta t\ \hat{n}$$

Sanity check: probability of 1 photon loss:

$$p_1 = \mathrm{Tr}\left\{E_1\rho E_1^\dagger\right\} = \kappa\delta t\langle\hat{n}\rangle$$

What is E_0 ? Completeness says: $E_0^\dagger E_0 = 1 - E_1^\dagger E_1$

Guess: $E_0 = U\sqrt{1-E_1^\dagger E_1} \approx 1 - \frac{\kappa}{2}\delta t\ a^\dagger a; \quad U = I$

Exact answer:

$$E_0 = \exp\left\{-\frac{\kappa}{2}\delta t\ \hat{n}\right\}$$

$$\rho(t+\delta t) = \rho(t) + \kappa\delta t\left\{a\rho(t)a^\dagger - \frac{1}{2}[a^\dagger a\rho(t) + \rho(t)a^\dagger a]\right\}$$

Lindblad master equation

0 photon loss

1 photon loss

$$\rho(t+\delta t) = E_0\rho(0)E_0^\dagger + E_1\rho(0)E_1^\dagger + \dots$$

[Master Equation]

<u>Quantum trajectory</u> interpretation:

Toss a coin to randomly select

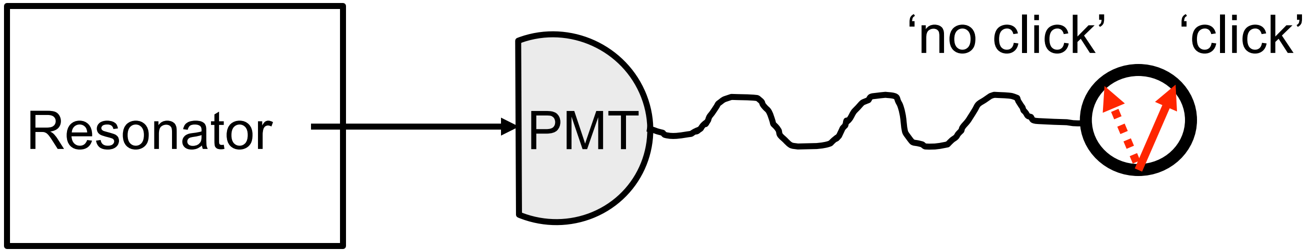
$$\rho(t+\delta t) = \frac{E_0\rho(0)E_0^\dagger}{p_0}$$ with probability $$p_0 = \mathrm{Tr}\left\{E_0\rho(0)E_0^\dagger\right\}$$

or select

$$\rho(t+\delta t) = \frac{E_1\rho(0)E_1^\dagger}{p_1}$$ with probability $$p_1 = \mathrm{Tr}\left\{E_1\rho(0)E_1^\dagger\right\}$$

Each Monte Carlo run simulates an actual experimental history (and gives a pure state). Ensemble averaging gives same result as master equation evolution—density matrix becomes impure.

What if, instead of Monte Carlo data, we had real data?



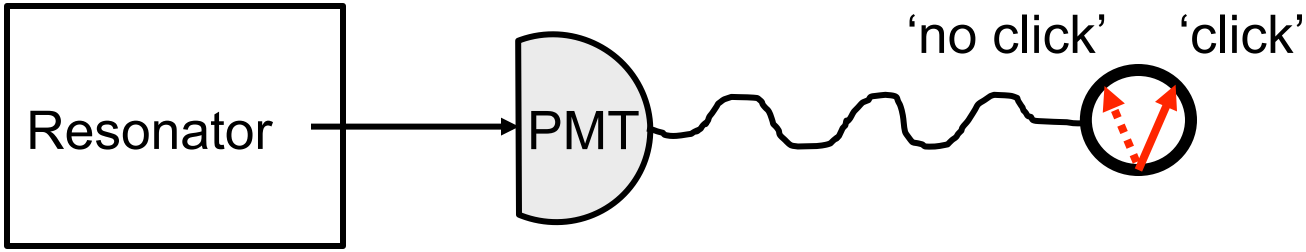
'no click' $\rho_{\mathrm{c}}(t+\delta t) = \dfrac{E_0 \rho(0) E_0^\dagger}{p_0}$ with probability $p_0 = \mathrm{Tr}\left\{E_0 \rho(0) E_0^\dagger\right\}$

'click' $\rho_{\mathrm{c}}(t+\delta t) = \dfrac{E_1 \rho(0) E_1^\dagger}{p_1}$ with probability $p_1 = \mathrm{Tr}\left\{E_1 \rho(0) E_1^\dagger\right\}$

The measurement record tells us exactly the state of the environment. Hence the resonator cannot be entangled with it.

'Conditional density matrix' $\rho_{\mathrm{c}}(t+\delta t)$ must be in a pure state(!)

What if, instead of Monte Carlo data, we had real data?



'no click' $$\rho_c(t+\delta t) = \frac{E_0\rho(0)E_0^\dagger}{p_0}$$ with probability $$p_0 = \mathrm{Tr}\left\{E_0\rho(0)E_0^\dagger\right\}$$

'click' $$\rho_c(t+\delta t) = \frac{E_1\rho(0)E_1^\dagger}{p_1}$$ with probability $$p_1 = \mathrm{Tr}\left\{E_1\rho(0)E_1^\dagger\right\}$$

Conditional density matrix is pure: $$\rho_c(t+\delta t) = |\psi_c\rangle\langle\psi_c|$$

If detector clicks: $$|\psi_c\rangle = \frac{E_1|\psi_0\rangle}{\sqrt{\langle\psi_0|E_1^\dagger E_1|\psi_0\rangle}} = \frac{a|\psi_0\rangle}{\sqrt{\langle\psi_0|a^\dagger a|\psi_0\rangle}}$$

But what happens if the detector does <u>not</u> click?

$$|\psi_c\rangle = \frac{E_0|\psi_0\rangle}{\sqrt{\langle\psi_0|E_0^\dagger E_0|\psi_0\rangle}}; \quad E_0 = e^{-\frac{\kappa}{2}\delta t\,\hat{n}}$$

Example 1 (Fock state):

$|\psi_0\rangle = |n\rangle$ (eigenstate of E_0)

$|\psi\rangle = |n\rangle$ (no click)

$|\psi\rangle = |n-1\rangle$ (click)

Example 2: $|\psi_0\rangle = \sqrt{0.99}|0\rangle + \sqrt{0.01}|100\rangle; \quad \langle\psi_0|\hat{n}|\psi_0\rangle = 1$

Click: $|\psi_c\rangle = |99\rangle$ $\langle\psi_c|\hat{n}|\psi_c\rangle = 99$ (!!!)

No click: $|\psi_c\rangle \propto \sqrt{0.99}|0\rangle + \sqrt{0.01}\exp\left(-\frac{\kappa}{2}\delta t\ 100\right)|100\rangle$

State changes even though no click!! $\langle\psi_c|\,n\,|\psi_c\rangle<1.$

But what happens if the detector does <u>not</u> click?

Sir Arthur Conan Doyle: *Silver Blaze*

Scotland Yard Detective: "Is there any other point to which you wish to draw my attention?

Sherlock Holmes: "To the curious incident of the dog during the night."

Detective: "The dog did nothing in the night-time."

Holmes: "That was the curious incident."

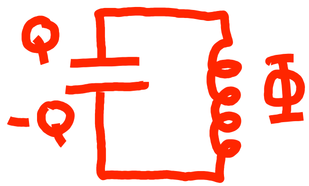
The quantum state changes even if the dog does not bark.

If we keep track of when the dog barks and doesn't bark, the system state remains pure. We will use this for QEC.

One scheme involves some remarkable properties of coherent states and Schrödinger cat states.
(Mazyar Mirrahimi)

Quick review of microwave resonators and photonic states

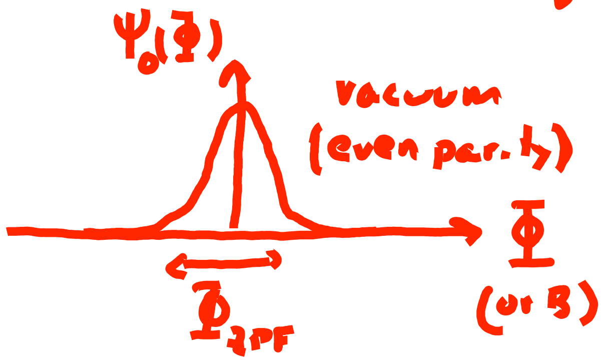
Circuit QED

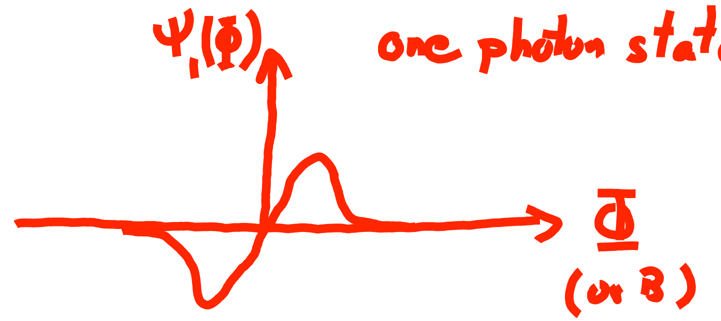


$$H = \frac{Q^2}{2C} + \frac{\Phi^2}{2L}; \quad [\hat{\Phi}, \hat{Q}] = -i\hbar$$

$$\omega_R = \frac{1}{\sqrt{LC}}$$

Photons and <u>first</u> quantization



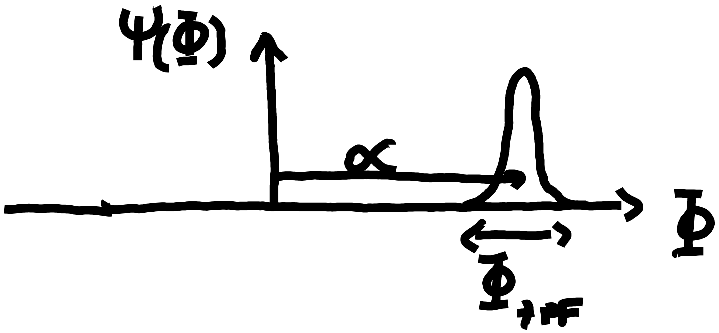


$$P(\Phi) = |\Psi(\Phi)|^2$$

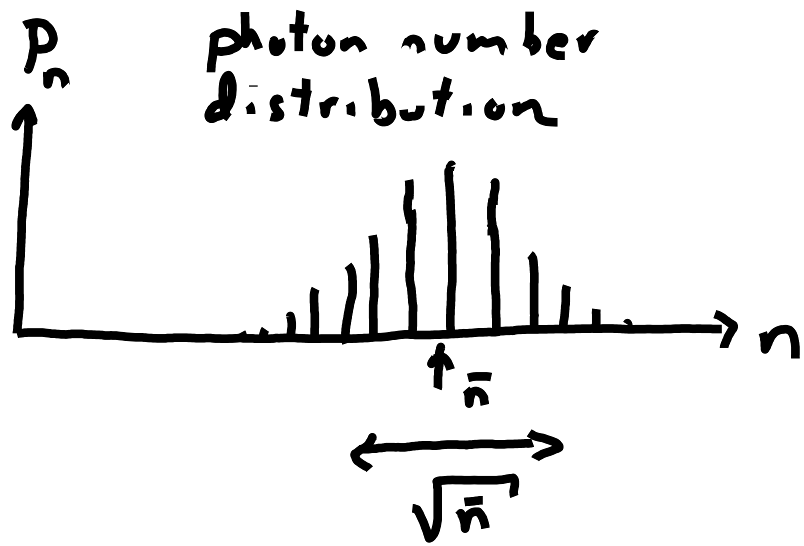
Coherent state is closest thing to a classical sinusoidal RF signal

$$\psi(\Phi) = \psi_0(\Phi - \alpha)$$

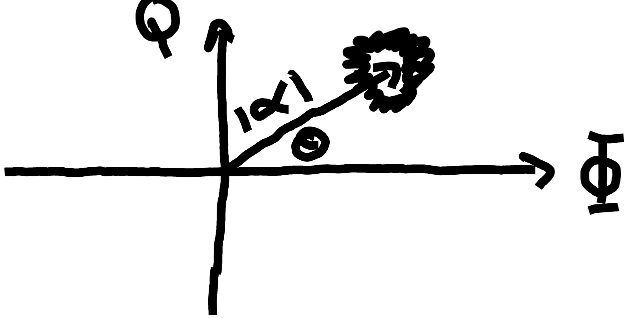
Coherent state = displaced vacuum



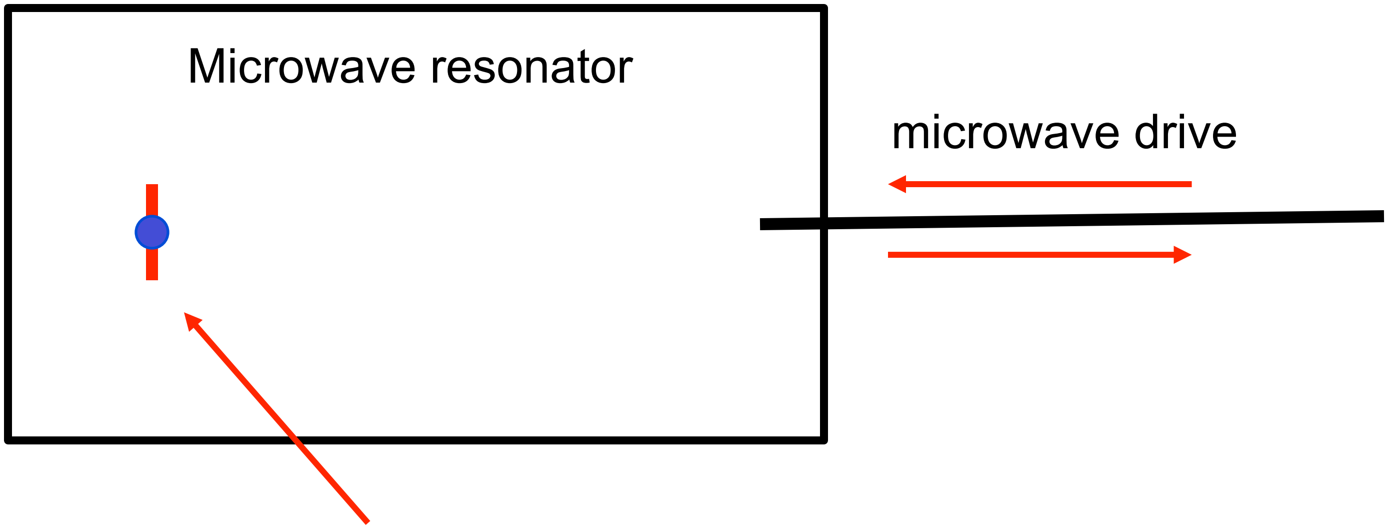
$$\bar{n} = \langle\alpha|a^\dagger a|\alpha\rangle = |\alpha|^2$$



Phase space representation



Experimental setup: superconducting qubit (artificial two-level atom) in a superconducting microwave resonator



artificial atom with states $|g\rangle, |e\rangle$

$$H = \omega_r a^\dagger a + \omega_q |e\rangle\langle e| + 2\chi a^\dagger a |e\rangle\langle e|$$

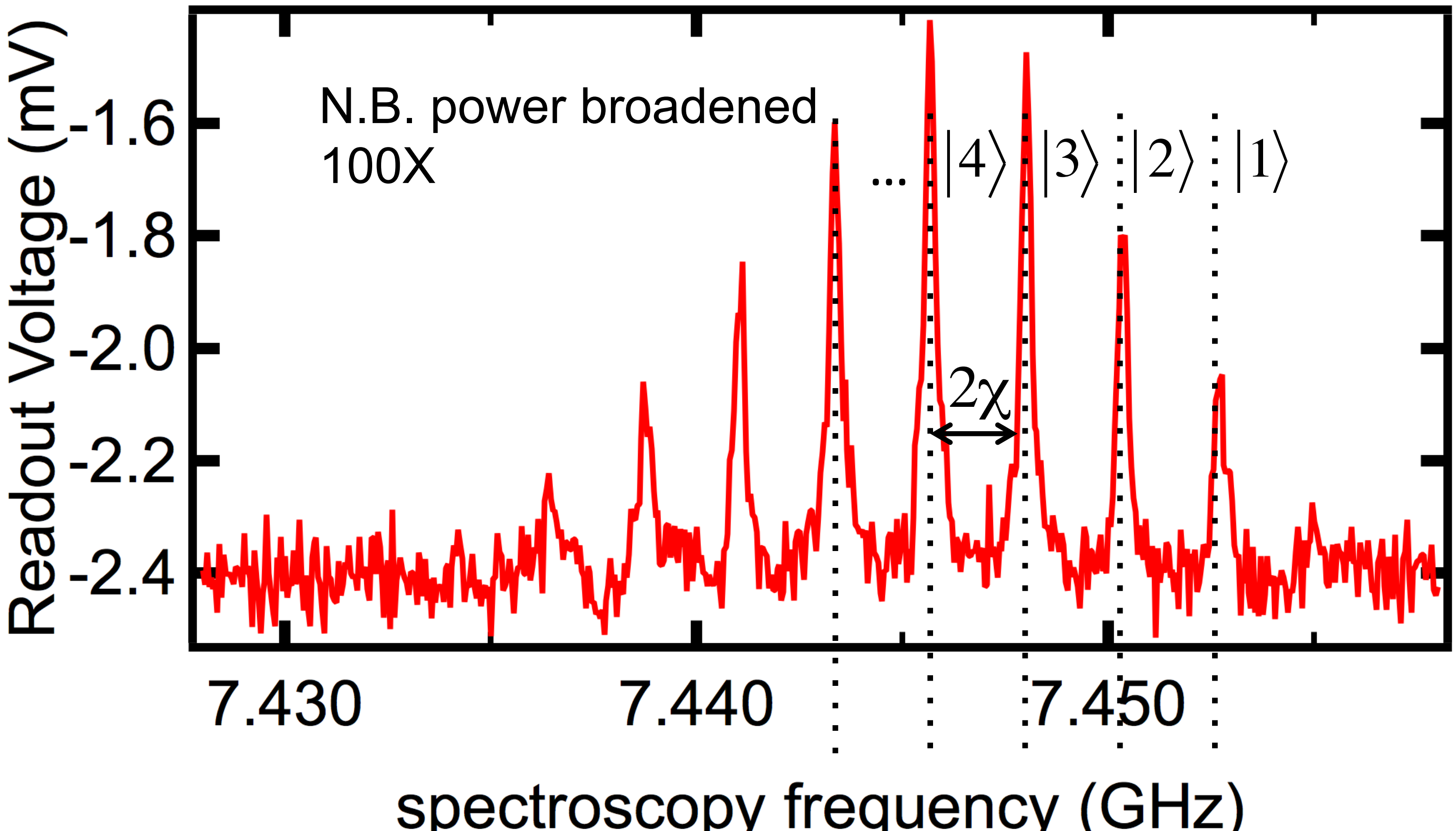
resonator qubit dispersive coupling

Photon number distribution in a coherent state

(measured via quantized light shift of qubit transition frequency)

$$V = 2\chi\,|\mathrm{e}\rangle\langle\mathrm{e}|\;a^\dagger a$$

$[2\chi : \; 3{,}000\,(\kappa, \gamma)]$

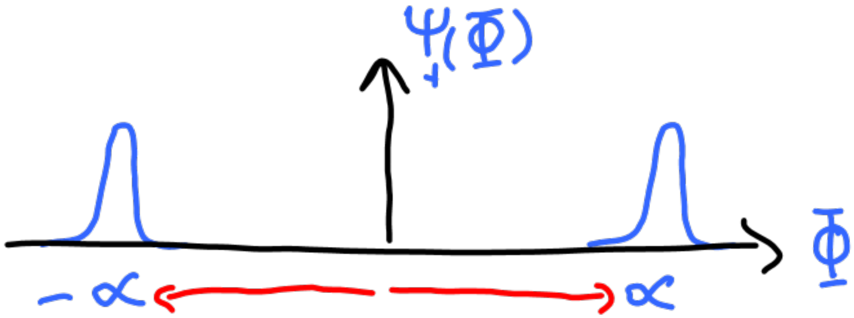


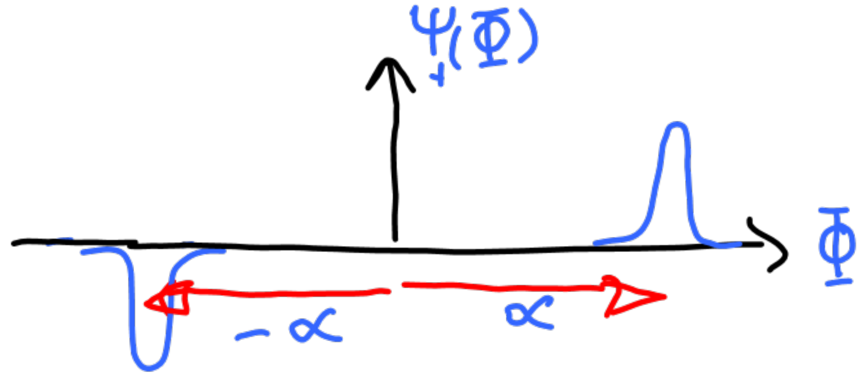
New low-noise way to do axion dark matter detection?

(arXiv:1607.02529)

We will use Schrödinger cat states of cavity photons

'Schrödinger Cat State'





$$|\Psi_+\rangle = \frac{1}{\sqrt{2}}\{|\alpha\rangle + |-\alpha\rangle\}$$

'even cat' only even n's

$$|\Psi_-\rangle = \frac{1}{\sqrt{2}}\{|\alpha\rangle - |-\alpha\rangle\}$$

'odd cat' only odd n's

Superposition of two different 'macroscopic' states

"size" = "distance^2" $= |2\alpha|^2 = 4\bar{n}$

(normalization is only approximate)

Parity of Cat States

$$P = e^{i\pi a^\dagger a} = (-1)^n \rightarrow P = \sum_n p_n (-1)^n$$

Coherent state: $|\psi\rangle = |\alpha = 2\rangle$

Mean photon number: 4

Even parity cat state: $|\psi\rangle = |\alpha\rangle + |-\alpha\rangle$

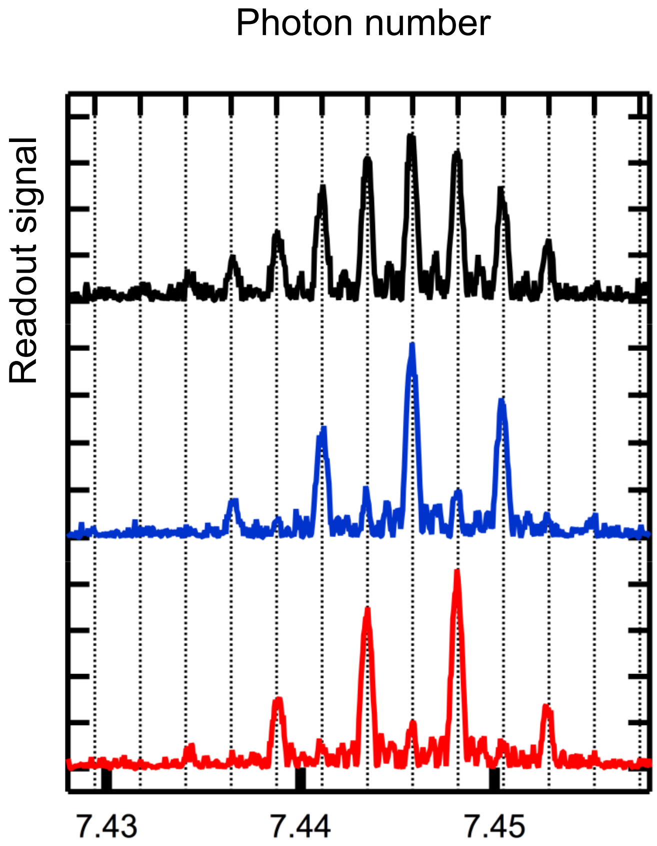
Only photon numbers: 0, 2, 4, …

$$\hat{P}|\psi\rangle = +|\psi\rangle$$

Odd parity cat state: $|\psi\rangle = |\alpha\rangle - |-\alpha\rangle$

Only photon numbers: 1, 3, 5, …

$$\hat{P}|\psi\rangle = -|\psi\rangle$$



Schoelkopf Lab

Key enabling technology: ability to make nearly ideal measurement of photon number parity (<u>without</u> measuring photon number!)

$$\hat{P} = (-1)^{a^\dagger a} = \sum_{n=0}^{\infty} |n\rangle (-1)^n \langle n|$$

We learn whether *n is even or odd without learning the value of n.*

Use dispersive coupling:

$$e^{-iVt} \rightarrow e^{-i\pi|\mathrm{e}\rangle\langle\mathrm{e}|\; a^\dagger a} = |g\rangle\langle g| + |e\rangle\langle e|\hat{P}$$

Measurement is 99.8% QND.
(Can be repeated <u>hundreds</u> of times.)

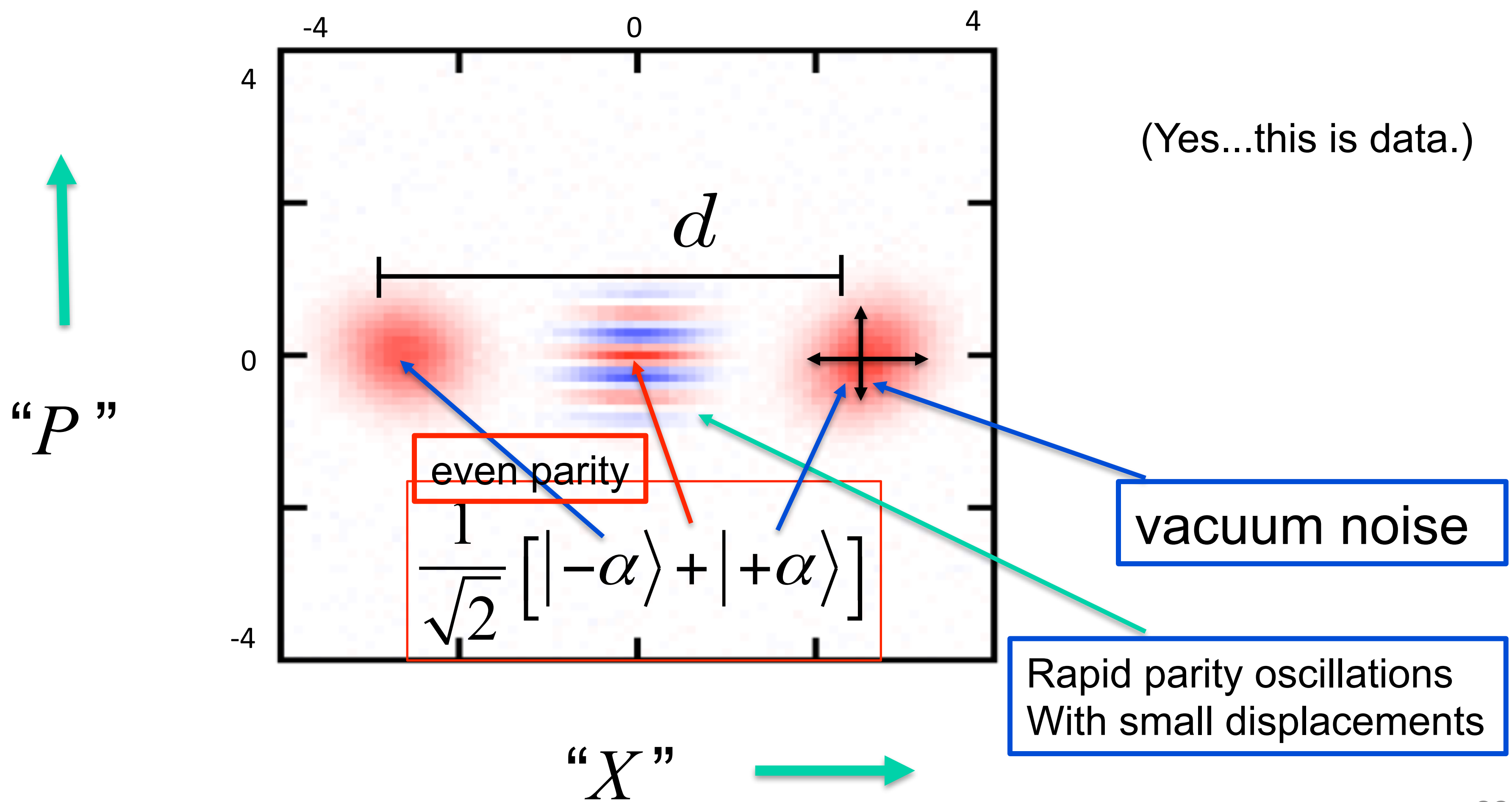
If we can measure parity, we can perform complete state tomography (measure Wigner function)

Wigner Function of a Cat State

Vlastakis, Kirchmair, et al., *Science* (2013)

Interference fringes prove cat is coherent
(even for sizes > 100 photons)

(Yes...this is data.)



Using Schrödinger cat states to store and correct quantum information

The magic of coherent states:

$$|\alpha\rangle = \exp(a^\dagger - a)\,|0\rangle \quad = e^{-\frac{1}{2}|\alpha|^2}\sum_{n=0}^{\infty}\frac{\alpha^n}{\sqrt{n!}}\,|n\rangle$$

Lose a photon and stay in same state!

$$a\,|\alpha\rangle = \alpha\,|\alpha\rangle$$

$$\frac{E_1\,|\alpha\rangle\langle\alpha|\,E_1^\dagger}{p_1} = |\alpha\rangle\langle\alpha|$$

The damped oscillator does NOT entangle with the environment and stays in a pure state!

$$\langle\alpha|\,\hat{n}\,|\alpha\rangle = |\alpha|^2 \quad \text{but} \quad a^\dagger a\,|\alpha\rangle \neq \alpha^*\alpha\,|\alpha\rangle$$

$$\text{Nevertheless} \quad E_0\,|\alpha\rangle = \exp\{-\frac{\kappa\delta t}{2}\hat{n}\}\,|\alpha\rangle = Z(t)\,|e^{-\frac{\kappa}{2}t}\alpha\rangle$$

Hence, damping comes <u>not</u> from loss of photons but from the ‘no click’ events (when the dog does not bark)!

Driven damped oscillator: $V = i\left(\text{Ú}^{*} a - \text{Ú} a^{\dagger}\right)$

$$\frac{d}{dt}\rho(t) = i[V, \rho(t)] + \kappa\left\{a\rho(t)a^{\dagger} - \frac{1}{2}[a^{\dagger}a\rho(t) + \rho(t)a^{\dagger}a]\right\}$$

Lindblad master equation

Define: $b = a - \frac{2\text{Ú}}{\kappa}$

$$\frac{d}{dt}\rho(t) = \kappa\left\{b\rho(t)b^{\dagger} - \frac{1}{2}[b^{\dagger}b\rho(t) + \rho(t)b^{\dagger}b]\right\}$$

$$\rho(\infty) \rightarrow |\,\alpha\rangle\langle\alpha\,|, \qquad \alpha \equiv \frac{2\text{Ú}}{\kappa}$$

Energy is being stochastically dumped into the bath, yet the dissipation stabilizes a pure state (coherent state)!

Can we extend this idea to use dissipation to autonomously stabilize a manifold of 2 states?

Two-photon pumping: $V = i\lambda^2 \left[a^{\dagger 2} - a^2 \right]$

Bath engineering

Two-photon damping: $E_2 = \kappa_2 \delta t \left[a^{\dagger 2} - a^2 \right]$

$$b = (a^2 - \alpha^2)$$

$$\frac{d}{dt}\rho(t) = \kappa \left\{ b\rho(t)b^\dagger - \frac{1}{2}[b^\dagger b\rho(t) + \rho(t)b^\dagger b] \right\}$$

Stable manifold: $\text{span}\left\{ |+\alpha\rangle, |-\alpha\rangle \right\}$
(can be used as a qubit)

Devoret group: arXiv:1705.02401

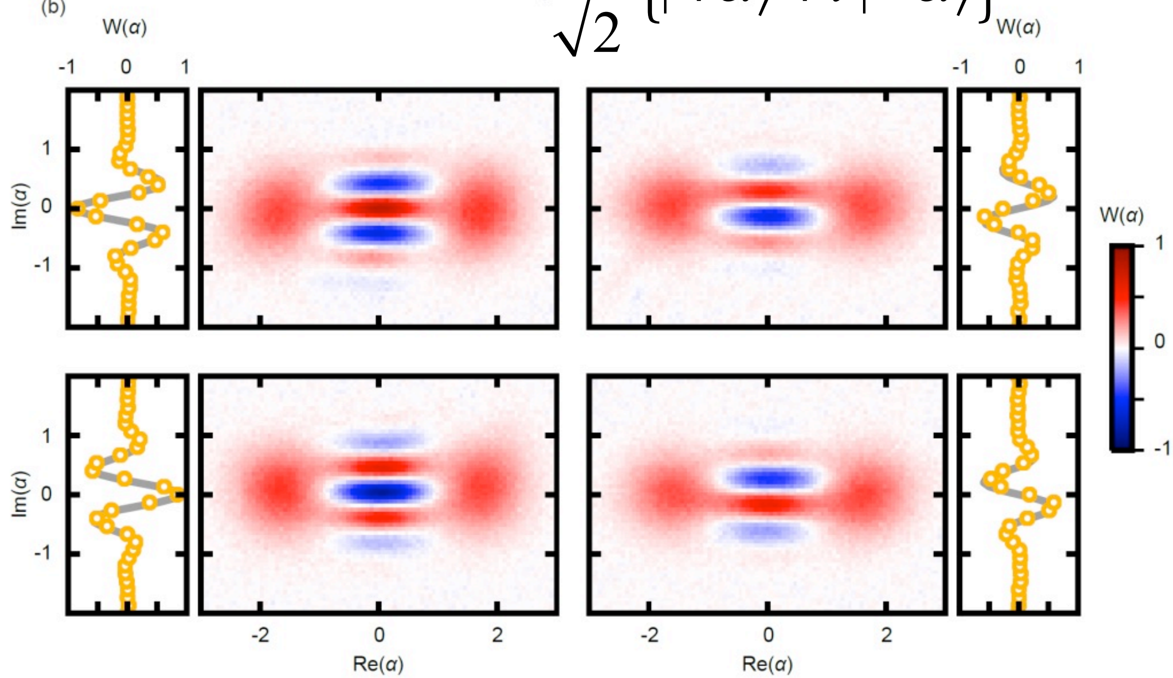
Stable manifold using two-photon pumping and two-photon damping

Expt'l Wigner functions of cat states

$$\frac{1}{\sqrt{2}}\{|+\alpha\rangle + i\,|-\alpha\rangle\}$$

even parity $\frac{1}{\sqrt{2}}\{|+\alpha\rangle + |-\alpha\rangle\}$

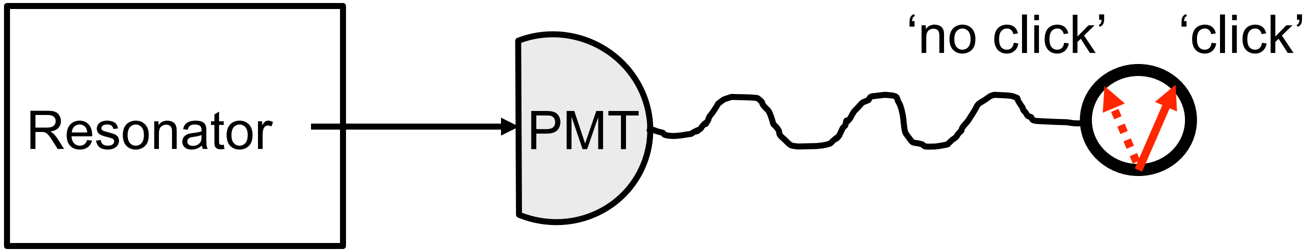
odd parity $\frac{1}{\sqrt{2}}\{|+\alpha\rangle - |-\alpha\rangle\}$



$$\frac{1}{\sqrt{2}}\{|+\alpha\rangle - i\,|-\alpha\rangle\}$$

Problem: still suffers from occasional single-photon loss.

Recall that if we can keep track of the state of the bath the system state remains pure.



'no click' $\rho_c(t+\delta t) = \dfrac{E_0\rho(0)E_0^\dagger}{p_0}$ with probability $p_0 = \mathrm{Tr}\left\{E_0\rho(0)E_0^\dagger\right\}$

'click' $\rho_c(t+\delta t) = \dfrac{E_1\rho(0)E_1^\dagger}{p_1}$ with probability $p_1 = \mathrm{Tr}\left\{E_1\rho(0)E_1^\dagger\right\}$

The measurement record tells us exactly the state of the environment. Hence the resonator cannot be entangled with it.

'Conditional density matrix' $\rho_c(t+\delta t)$ must be in a pure state(!)

Problem: We don't actually have a PMT for microwave photons sitting outside the cavity. (Also some of the photons are lost internally.)

Solution: We are able to measure the photon number parity.

We said before that photon loss leaves coherent state invariant, but actually there is an important phase:

$$a\,|+\alpha\rangle = +\alpha\,|+\alpha\rangle, \qquad a\,|-\alpha\rangle = -\alpha\,|-\alpha\rangle$$

This is necessary to achieve:

even

odd

$$a\left[\frac{1}{\sqrt{2}}\left\{|+\alpha\rangle + |-\alpha\rangle\right\}\right] = \frac{1}{\sqrt{2}}\left\{|+\alpha\rangle - |-\alpha\rangle\right\}$$

code word **error word**

even

odd

$$a\left[\frac{1}{\sqrt{2}}\left\{|+\alpha\rangle + |-\alpha\rangle\right\}\right] = \frac{1}{\sqrt{2}}\left\{|+\alpha\rangle - |-\alpha\rangle\right\}$$

code word **error word**

We therefore need a second code word with even parity.

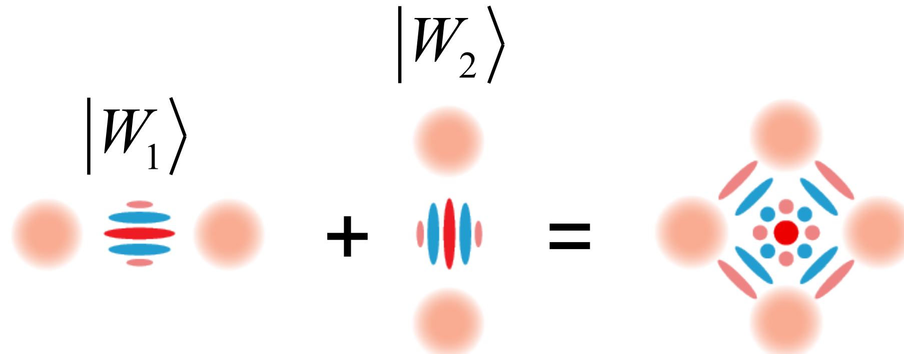
Encode information in two (nearly) orthogonal even-parity code "words"

$$|\psi\rangle = \psi_{\uparrow}|W_1\rangle + \psi_{\downarrow}|W_2\rangle$$

$$|W_1\rangle = |\alpha\rangle + |-\alpha\rangle$$

$$|W_2\rangle = |i\alpha\rangle + |-i\alpha\rangle$$

code word Wigner functions:



Store a ***qubit*** as a ***superposition*** of two cats of same ***parity***

Photon loss flips the parity which is the error syndrome we can measure (and repeat hundreds of times).

Coherent states are eigenstates of photon destruction operator. $a|\alpha\rangle = \alpha|\alpha\rangle$

Effect of photon loss on code words:

$$a|W_1\rangle = a\left(|\alpha\rangle + |-\alpha\rangle\right) \to \left(|\alpha\rangle - |-\alpha\rangle\right) \quad \text{(if } \alpha \text{ real)}$$

$$a^2|W_1\rangle = a^2\left(|\alpha\rangle + |-\alpha\rangle\right) \to \left(|\alpha\rangle + |-\alpha\rangle\right) = |W_1\rangle$$

$$a|W_2\rangle = a\left(|i\alpha\rangle + |-i\alpha\rangle\right) \to i\left(|i\alpha\rangle - |-i\alpha\rangle\right)$$

$$a^2|W_2\rangle = a^2\left(|i\alpha\rangle + |-i\alpha\rangle\right) = (i)^2\left(|i\alpha\rangle + |-i\alpha\rangle\right) = -|W_2\rangle$$

After loss of 4 photons cycle repeats:

$$a^4\left(\xi_1|W_1\rangle + \xi_2|W_2\rangle\right) \to \left(\xi_1|W_1\rangle + \xi_2|W_2\rangle\right)$$

We can recover the state if we know:
(via monitoring parity jumps)

$$N_{\text{Loss}} \mod 4$$

We can recover the state if we know:
(via monitoring parity jumps)

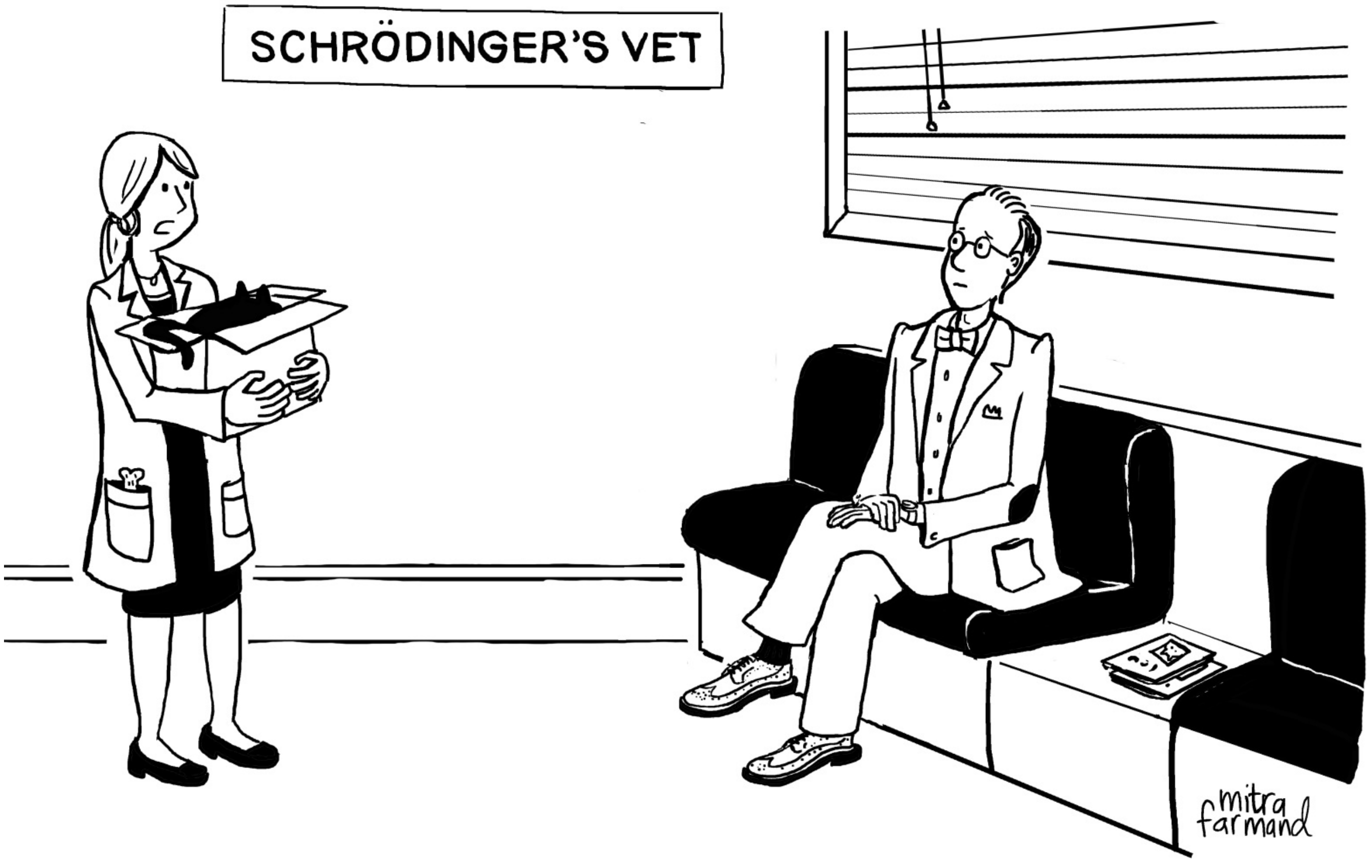
$$N_{\text{Loss}} \mod 4$$

Amplitude damping is deterministic
(independent of the number of parity jumps!)

$$\left|W(t)\right\rangle = \left|e^{-\kappa t/2}\alpha\right\rangle \pm \left|-e^{-\kappa t/2}\alpha\right\rangle$$

Maxwell Demon takes this into account ‘in software.’
(We don’t yet have 4-photon pumping/damping working.)

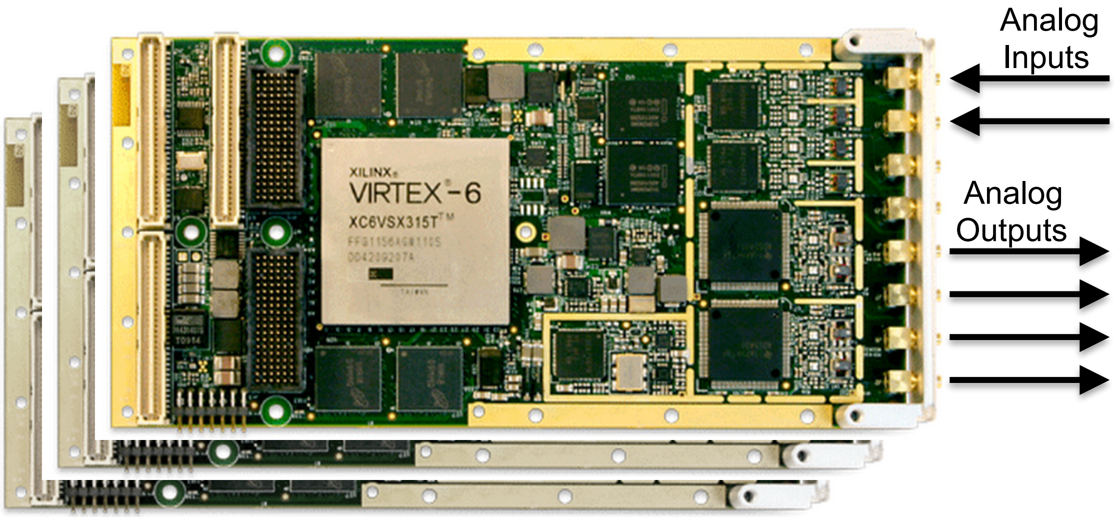
QUANTUM ERROR CORRECTION
Keeping your Cat Alive



"I have good news and bad news"

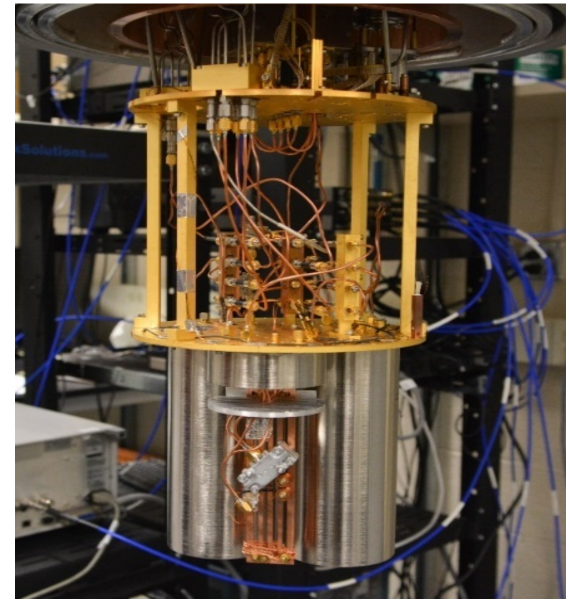
Courtesy of Mitra Farmand

2016: First true Error Correction Engine that works



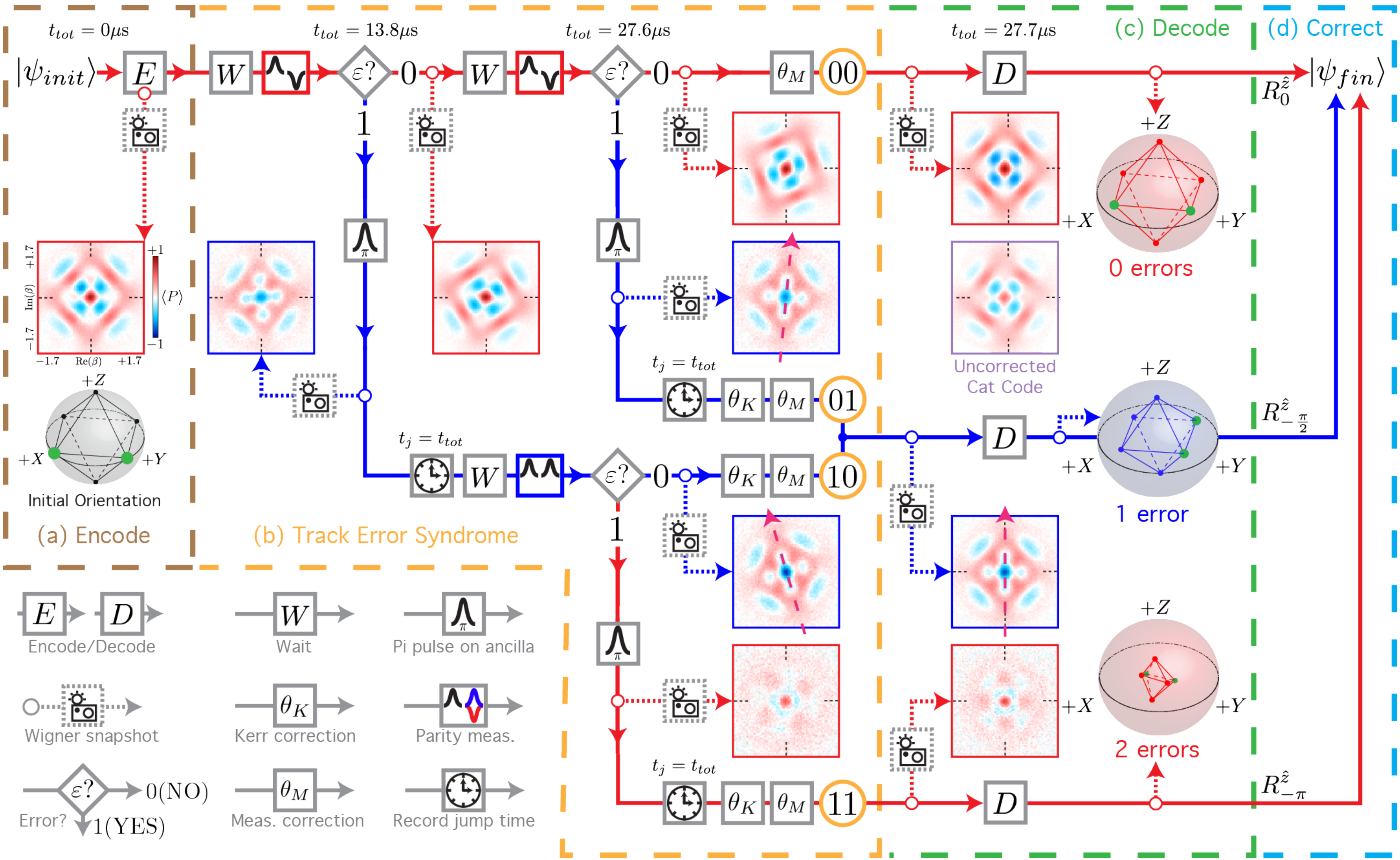
MAXWELL'S DEMON

- Commercial FPGA with custom software developed at Yale
- Single system performs all measurement, control, & feedback (latency ~200 nanoseconds)
- ~15% of the latency is the time it takes signals to move at the speed of light from the quantum computer to the controller and back!



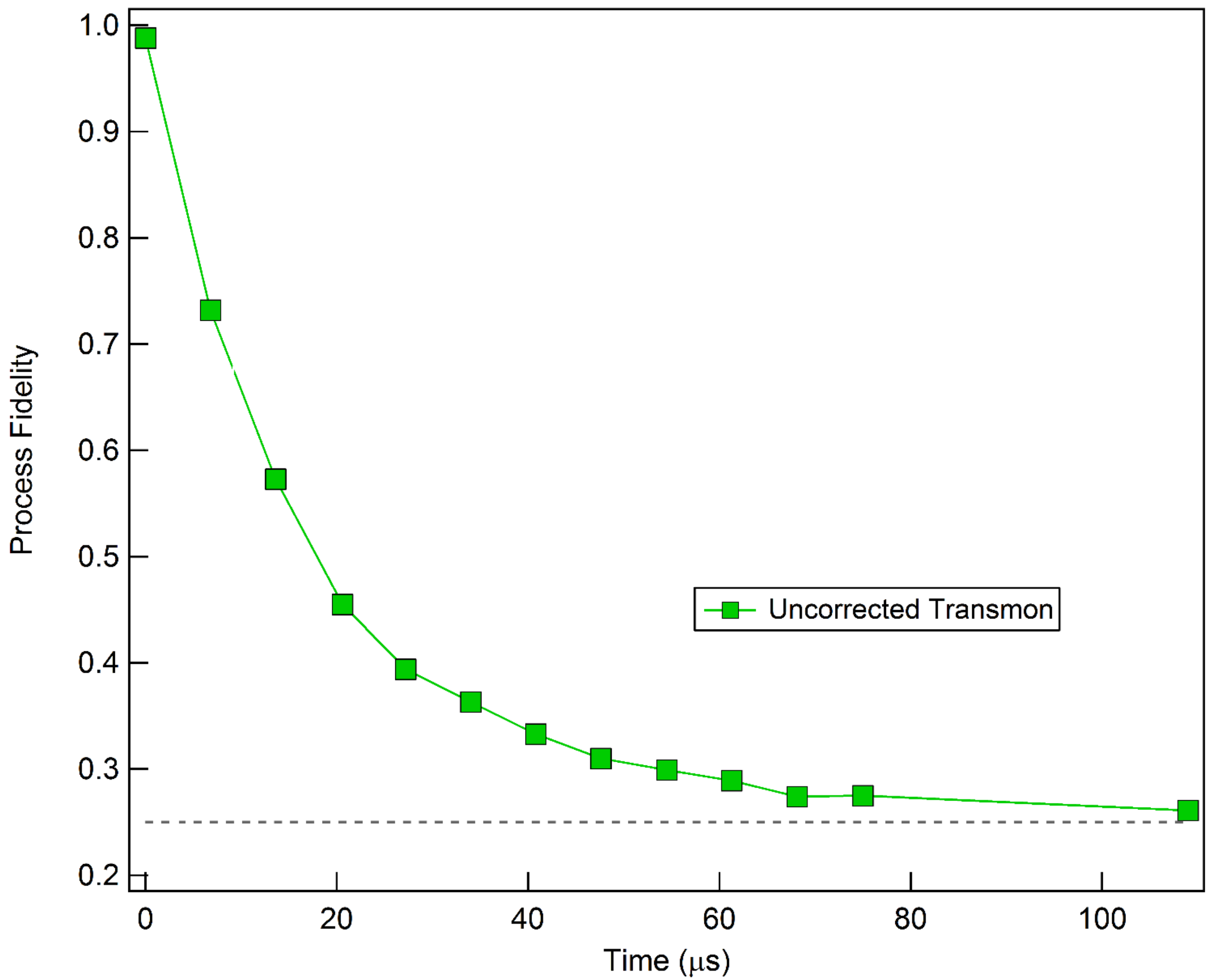
A prototype quantum computer being prepared for cooling close to absolute zero.

Implementing a Full QEC System: Debugger View



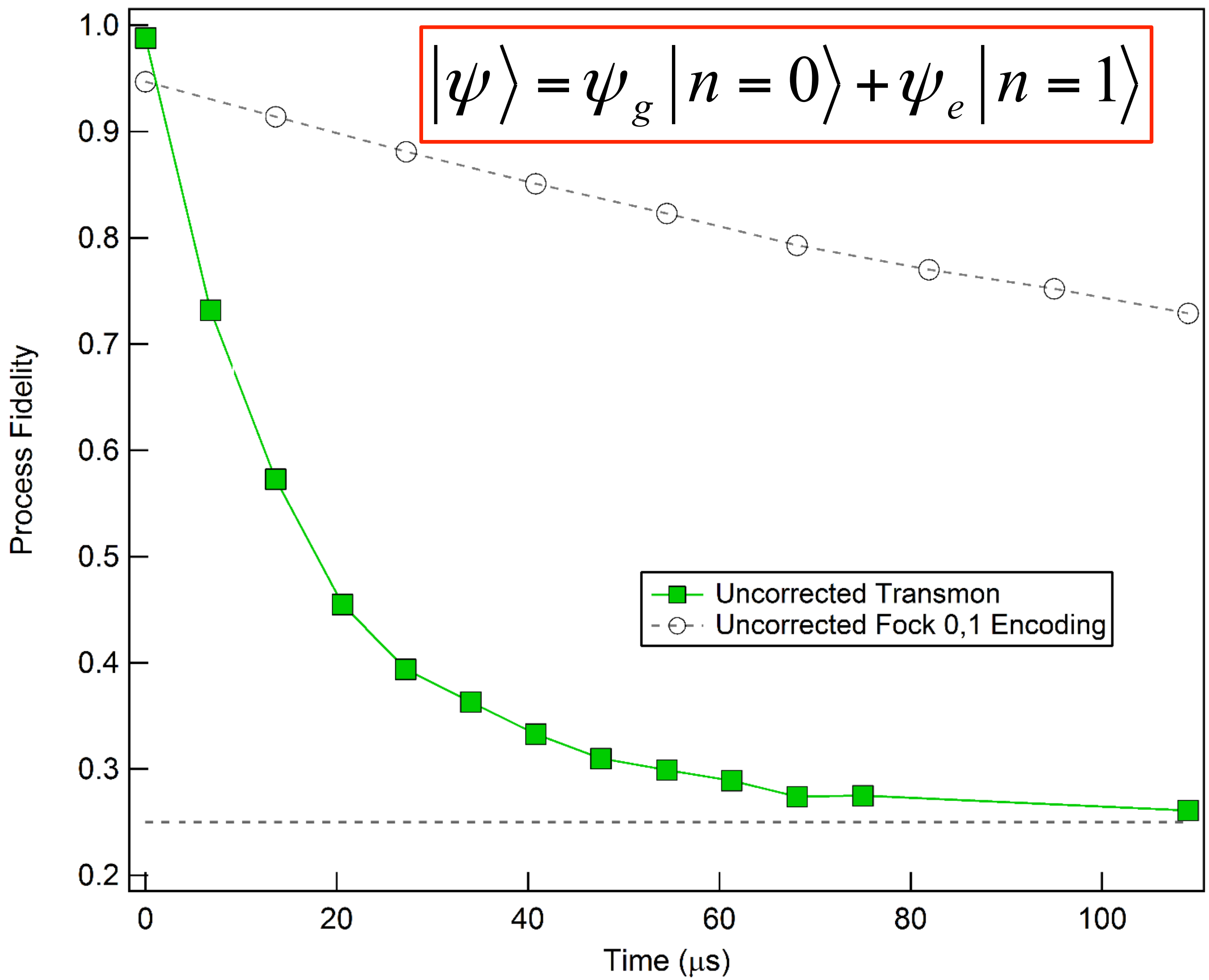
(This is all real, raw data.) Ofek, et al., Nature **536**, 441–445 (2016).

Process Fidelity: Uncorrected Transmon



$\tau \approx 15 \mu s$

System's Best Component

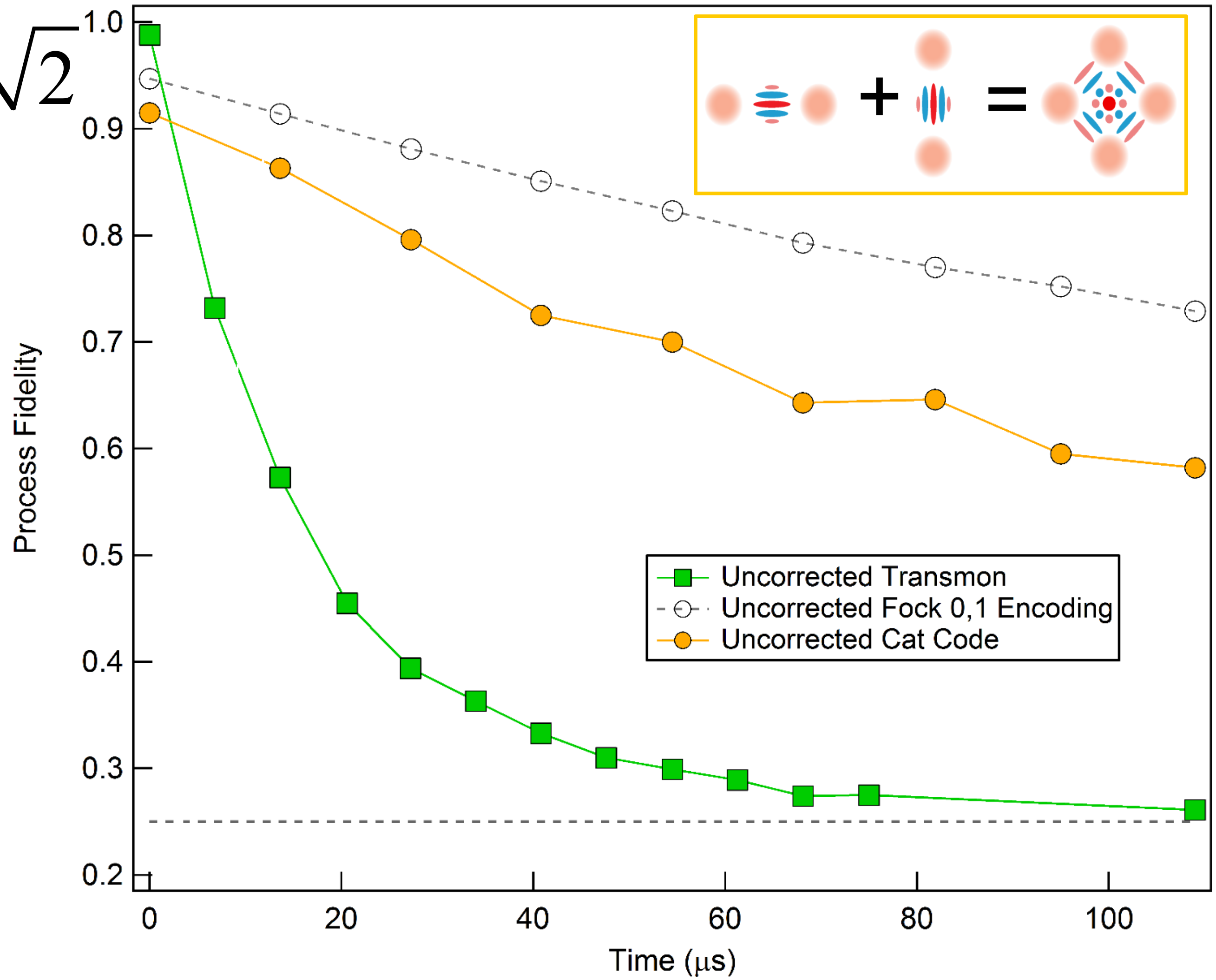


$\tau \approx 290\mu s$

$\tau \approx 15\mu s$

Process Fidelity: Cats *without* QEC

$\alpha = \sqrt{2}$



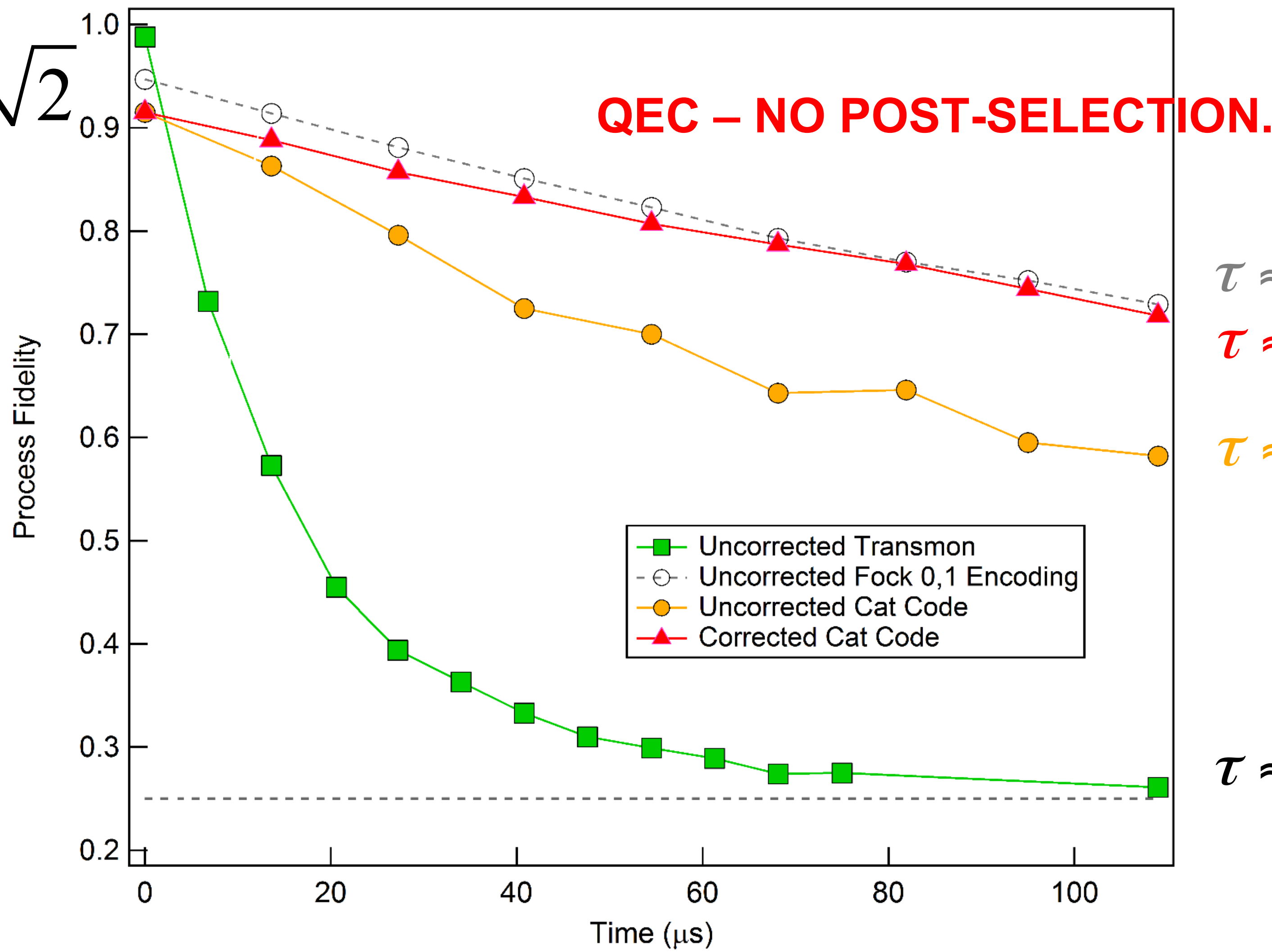
$\tau \approx 290\mu s$

$\tau \approx 130\mu s$

$\tau \approx 15\mu s$

Process Fidelity: Cats *with* QEC

$\alpha = \sqrt{2}$



$\tau \approx 290\mu s$

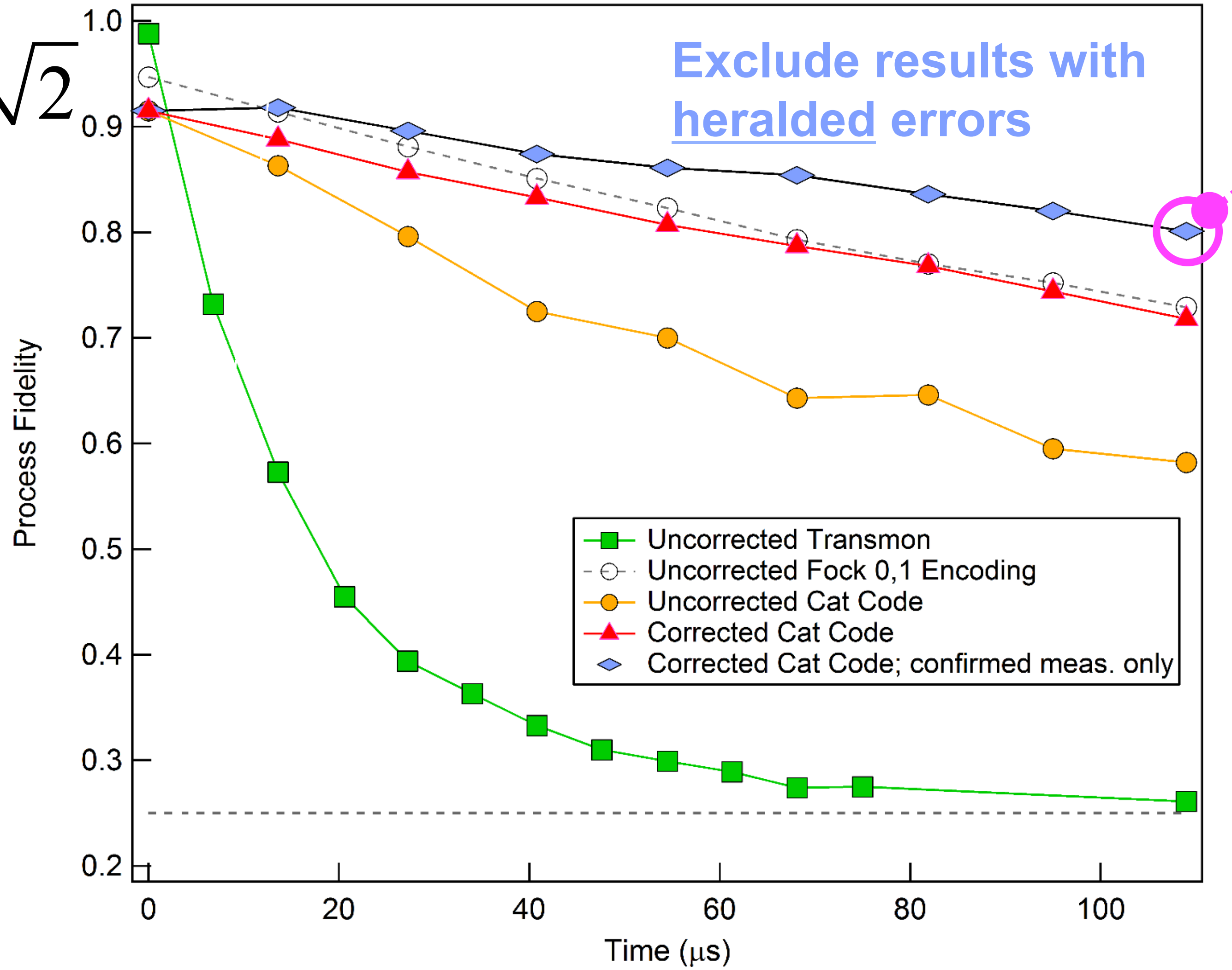
$\tau \approx 320\mu s$

$\tau \approx 130\mu s$

$\tau \approx 15\mu s$

Only High-Confidence Trajectories

$$\alpha = \sqrt{2}$$



Still keep ~80% of data

$\tau \approx 560\mu s$

$\tau \approx 290\mu s$

$\tau \approx 320\mu s$

$\tau \approx 130\mu s$

$\tau \approx 15\mu s$

We are on the way!

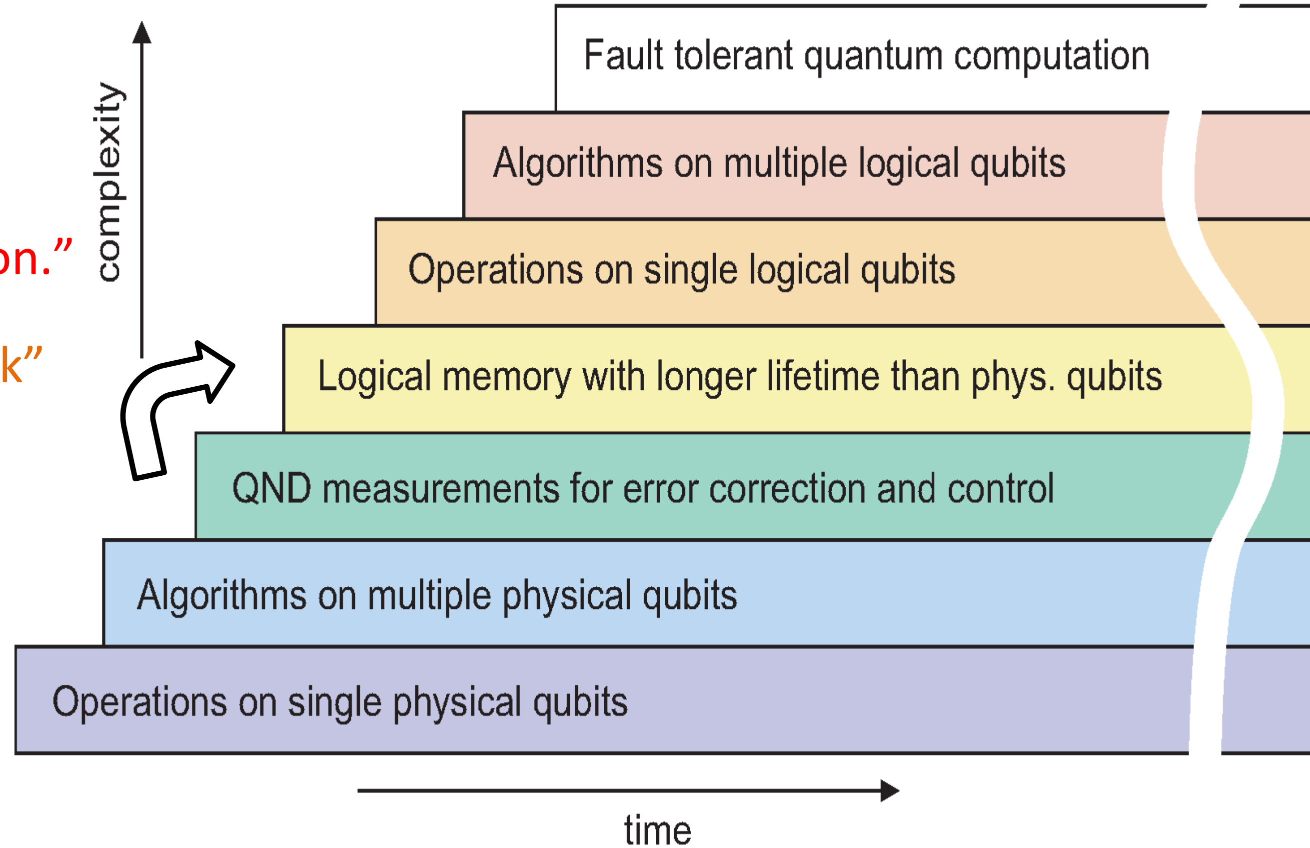
“Age of Qu. Error Correction.”

“Age of Quantum Feedback”

“Age of Measurement”

“Age of Entanglement”

“Age of Coherence”



Achieved goal of reaching “break-even” point for error correction.
Now need to surpass by 10x or more.

M. Devoret and RS, Science (2013)

Experiment:

‘Extending the lifetime of a quantum bit with error correction in superconducting circuits,’

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

Theory:

‘cat codes’
Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).

‘kitten codes’
M. Michael et al., Phys. Rev. X **6**, 031006 (2016).
‘New class of error correction codes for a bosonic mode’

Thanks for listening!

QuantumInstitute.yale.edu

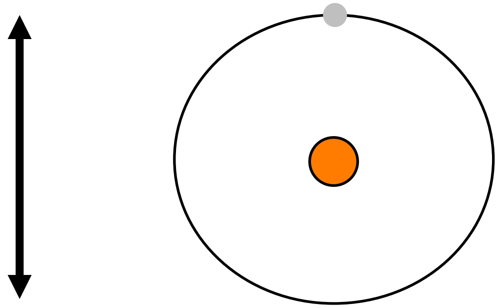
Extra slides

Storing information in quantum states sounds great…,

but how on earth do you build a quantum computer?

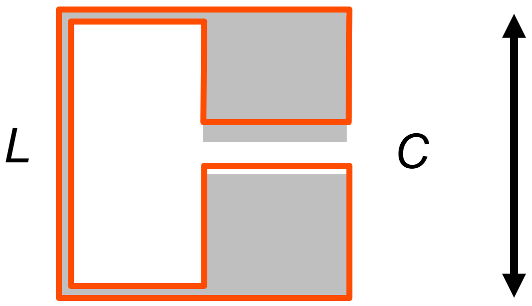
ATOM vs CIRCUIT

Hydrogen atom



10^{-7} mm

Superconducting circuit oscillator



0.1 - 1 mm

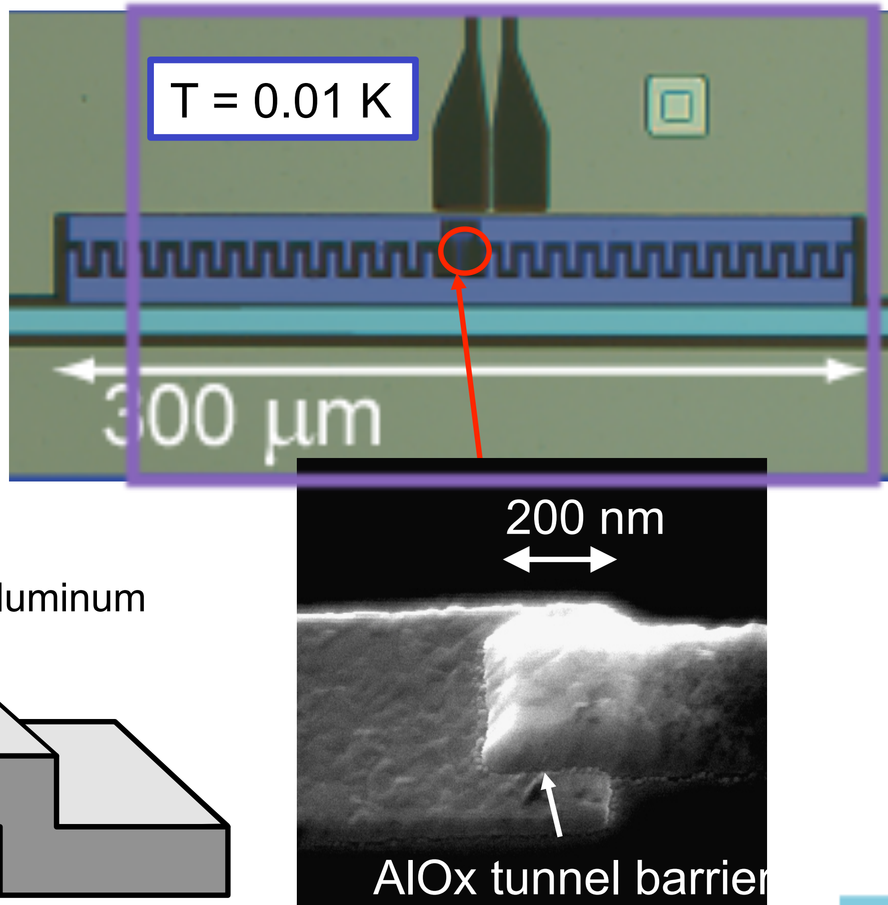
(Not to scale!)

1 electron

$\sim 10^{12}$ electrons

'Artificial atom'

How to Build a Qubit with an Artificial Atom…



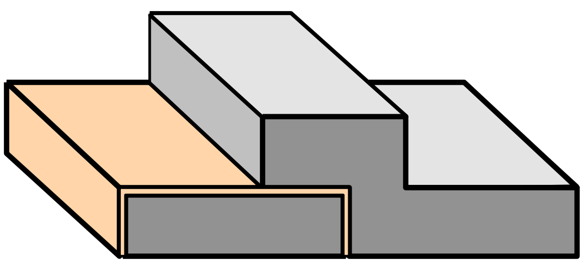
Superconducting integrated circuits are a promising technology for <u>scalable</u> quantum computing

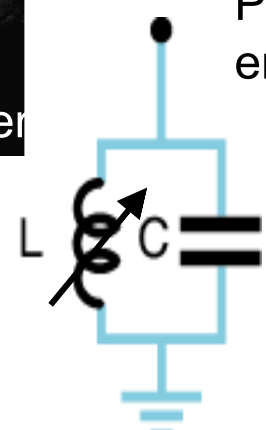
<u>Josephson junction:</u>

The "transistor of quantum computing"

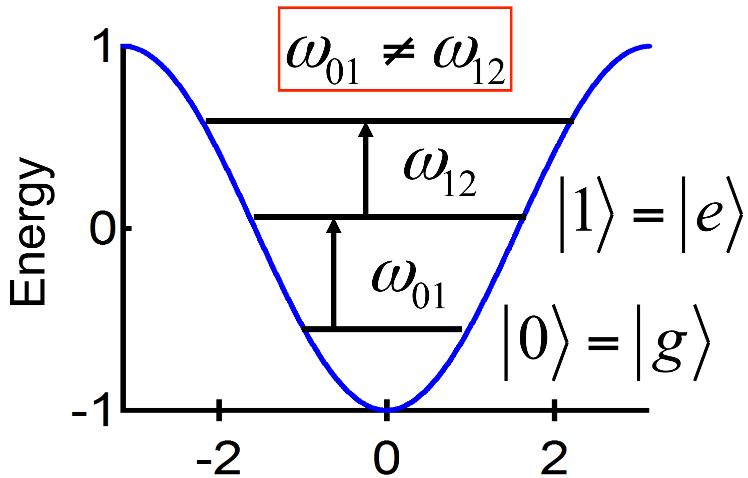
Provides <u>anharmonic</u> energy level structure

Aluminum/AlOx/Aluminum

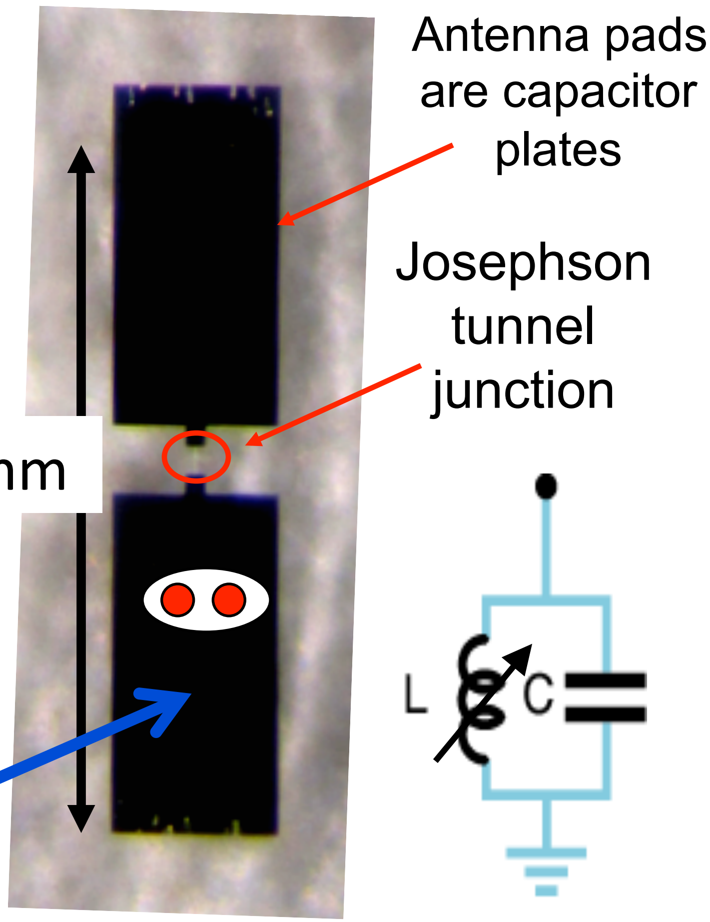




Transmon Qubit



$\omega_{01} \sim 5 - 10$ **GHz**



10^{12} mobile electrons

Superconductivity gaps out single-particle excitations

Quantized energy level spectrum is <u>*simpler*</u> than hydrogen

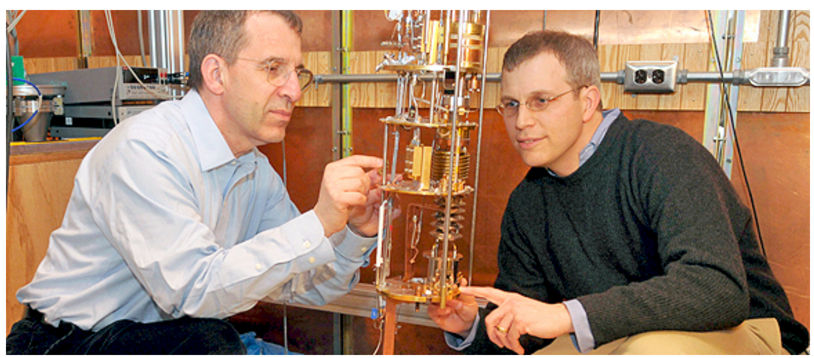
Quality factor $Q = \omega T_1$ <u>*comparable*</u> *to* that of hydrogen 1s-2p

<u>Enormous</u> transition dipole moment

The first electronic quantum processor (2009)

Executed Deutsch-Josza and Grover search algorithms

Lithographically produced integrated circuit with semiconductors replaced by superconductors.

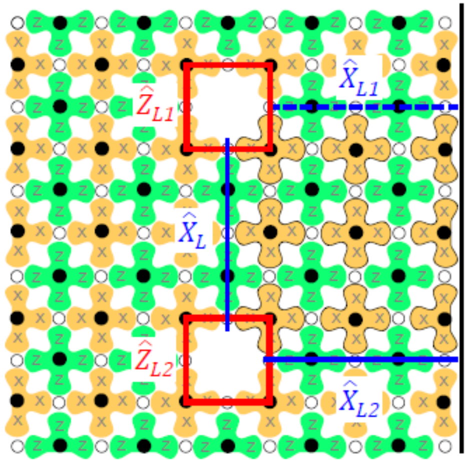


Michel Devoret

Rob Schoelkopf

DiCarlo et al., Nature **460**, 240 (2009)

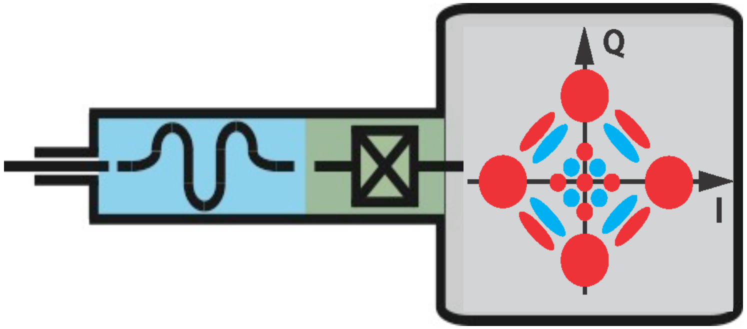
Scale then correct



Surface/Toric Code
(readout wires <u>not</u> shown)

- Large, complex:
  - <u>Non-universal</u> (Clifford gates only)
  - Measurement via many wires
  - Difficult process tomography
- Large part count
- Fixed encoding

Correct then scale



Cat Code Photonic Qubit
hardware shortcut
(readout wire shown)

- Precision:
  - <u>Universal</u> control (all possible gates)
  - Measurement via single wire
  - Easy process tomography
  - Long-lived cavities
  - Fault-tolerant QEC
- Reduced part count
- Flexible encoding

All previous attempts to overcome the factor of *N* *and reach the 'break even' point of QEC have failed.*

With major technological advances a 49-transmon 'surface code' might conceivably break even at $T_2 = 40\mu s$.
[O'Brien et al. arXiv:1703.04136]

However to date, good repeatable (QND) (weight 4) error syndrome measurements have not been demonstrated
[Takita et al., *Phys. Rev. Lett.* **117**, 210505 (2016)]

'Scale up and then error correct' seems almost hopeless.

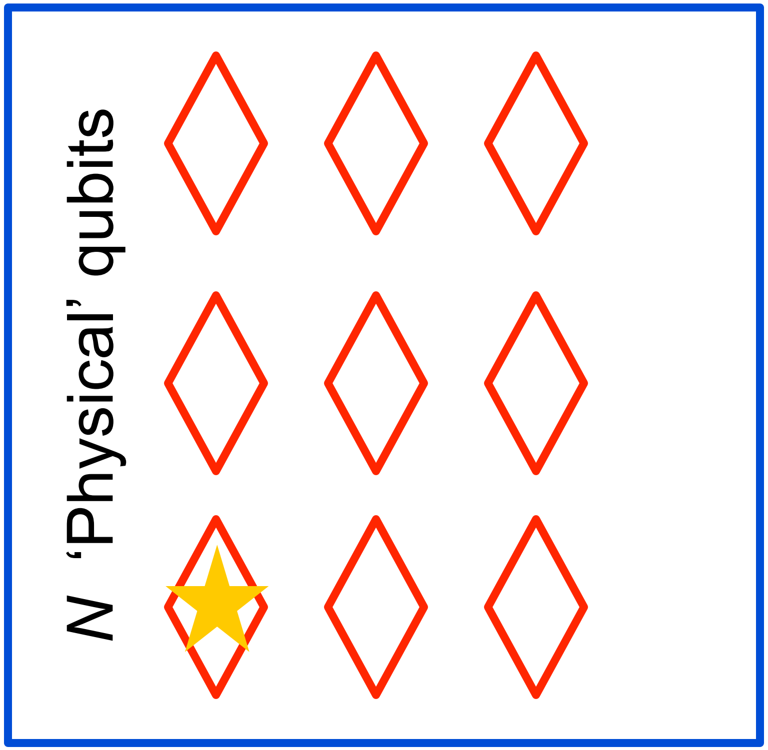
We need a simpler and better idea...

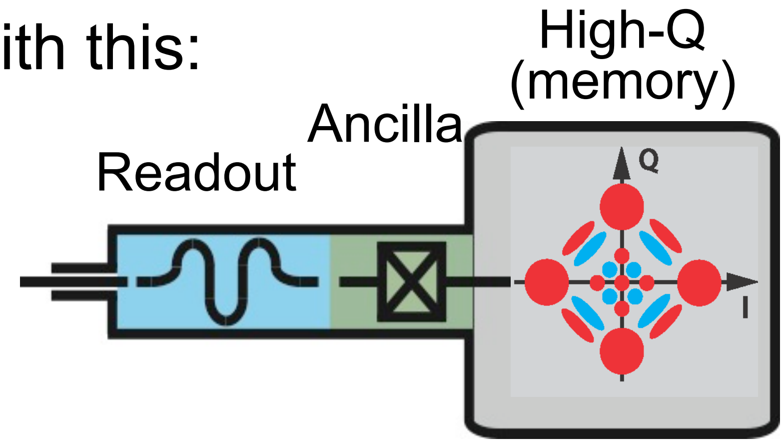
'Error correct and then scale up!'

“Hardware-Efficienct Bosonic Encoding”

Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).

Replace ‘Logical’ qubit with this:





- Cavity has longer lifetime (~ms)
- Large Hilbert space
- Single dominant error channel
  photon loss: $\Gamma = \kappa \langle \hat{n} \rangle$
- Single readout channel

earlier ideas: Gottesman, Kitaev & Preskill, PRA 64, 012310 (2001)
Chuang, Leung, Yamamoto, PRA 56, 1114 (1997)

Photonic Code States

Can we find novel (multi-photon) code words that can store quantum information even if some photons are lost?

Ancilla transmon coupled to resonator gives us universal control to make 'any' code word states we want.