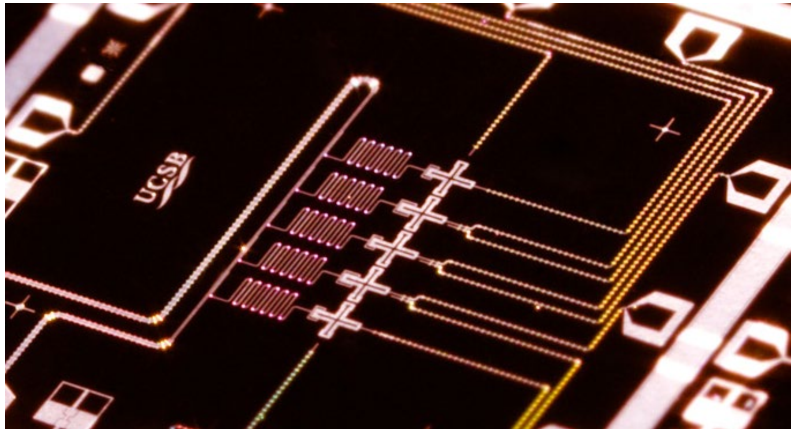
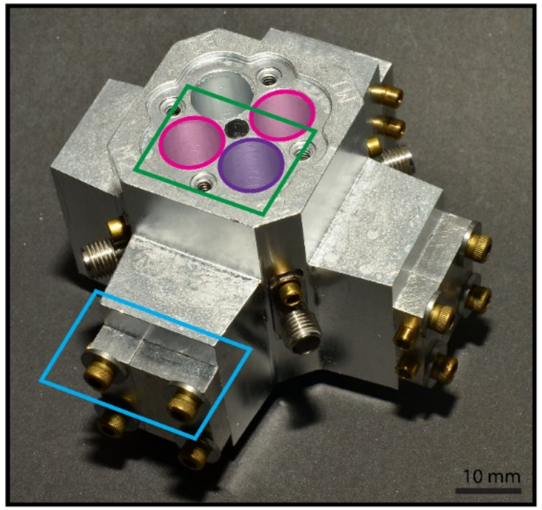
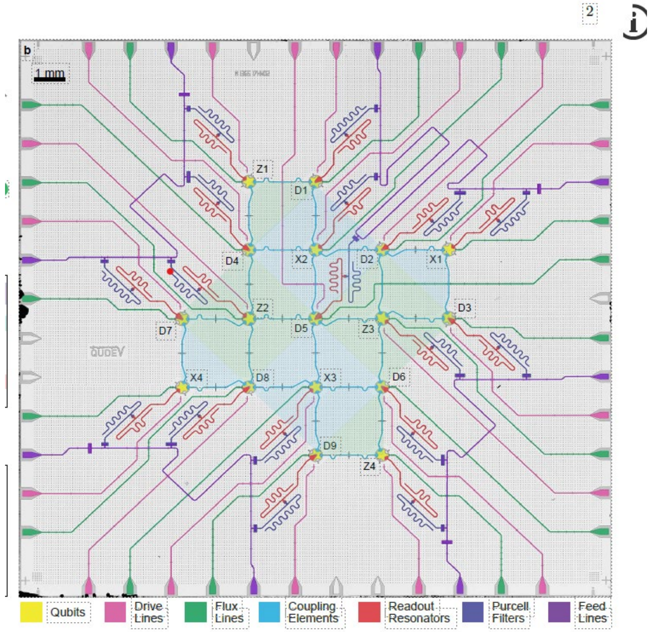
Superconducting Qubits as a Platform for QC







Robert Schoelkopf

Solvay Conference, May 2022

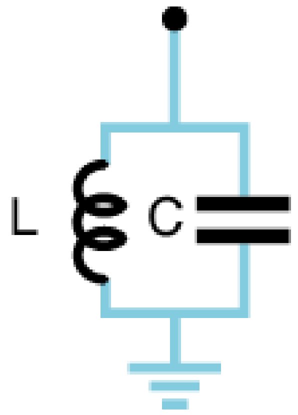
Yale Quantum Institute

http:\quantuminstitute.yale.edu

Disclosure: I am also a co-founder and equity holder at Quantum Circuits, Inc.
www.quantumcircuits.com

Intro to Superconducting Qubits and Circuit QED

Quantizing Circuits



$$H = \frac{Q^2}{2C} + \frac{\varphi^2}{2L}$$
$$= \hbar\omega_0\left(a^\dagger a + \frac{1}{2}\right)$$

"p"

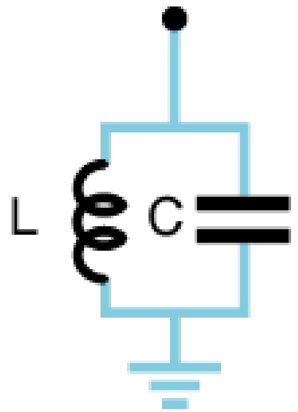
$$\boxed{Q = \frac{1}{i}\sqrt{\frac{\hbar}{2Z_0}}\left(a - a^\dagger\right)}$$

"x"

$$\boxed{\varphi = \sqrt{\frac{\hbar Z_0}{2}}\left(a + a^\dagger\right)}$$

Leggett (1980): are V and I ever quantum?

Quantizing Circuits



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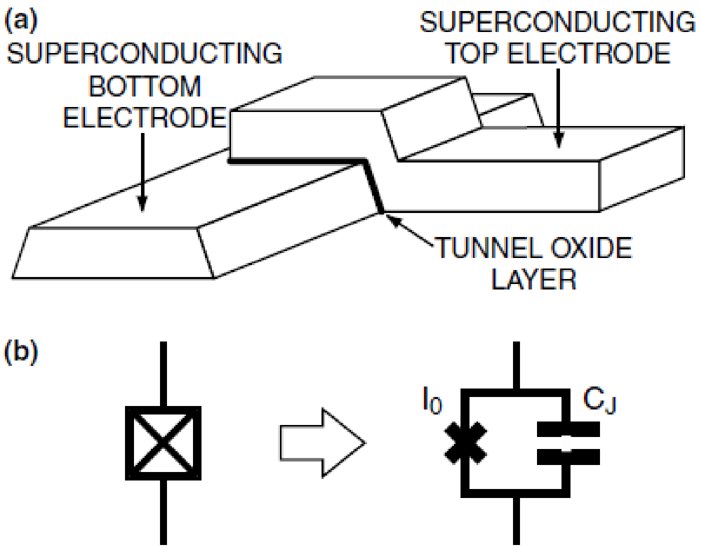


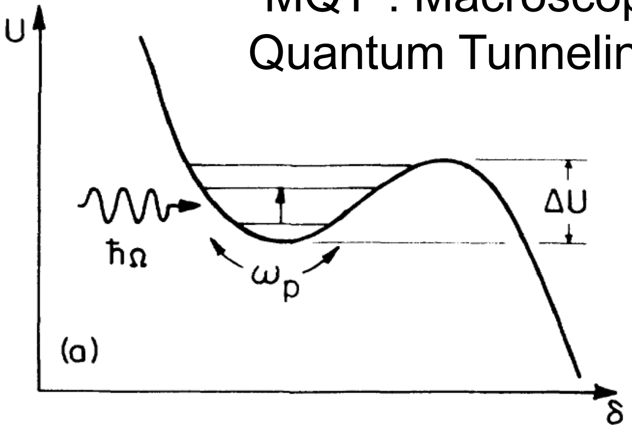
$$H = \frac{Q^2}{2C} + E_J\cos(\phi)$$

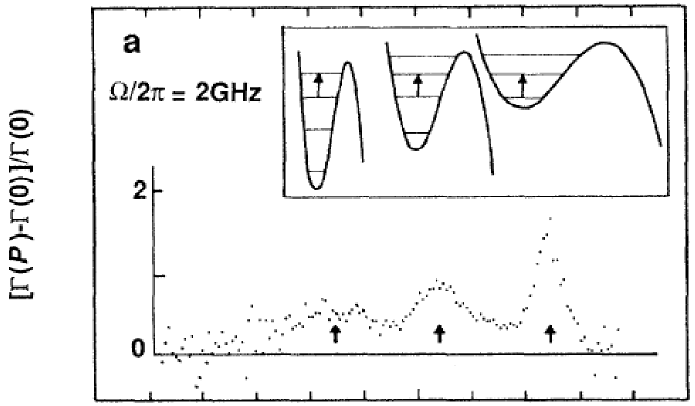
“x”

$$\boxed{\varphi = \sqrt{\frac{\hbar Z_0}{2}}\left(a + a^\dagger\right)}$$

Leggett (1980): are V and I ever quantum?

“MQT”: Macroscopic Quantum Tunneling



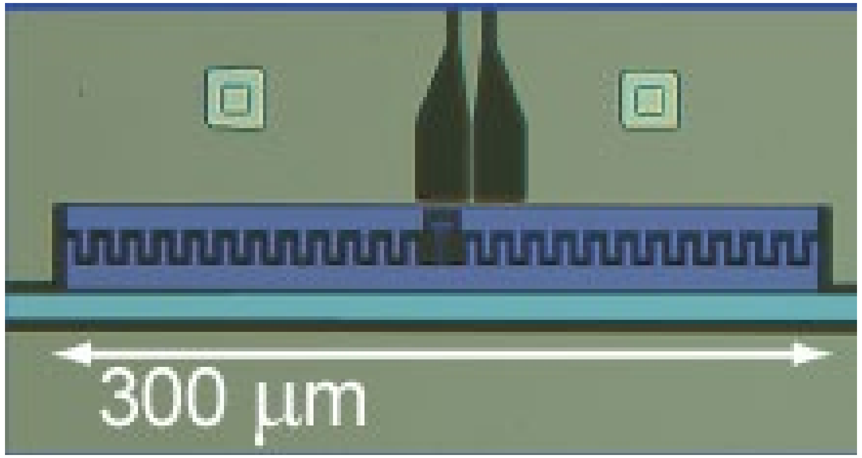


Fore-runner of SC qubits
(pre-Shor!)

Martinis, Devoret, and Clarke, *PRL* **55**, 1543 (1985).

Devoret, Martinis, and Clarke, *PRL* **55** , 1908 (1985).

Superconducting Qubits

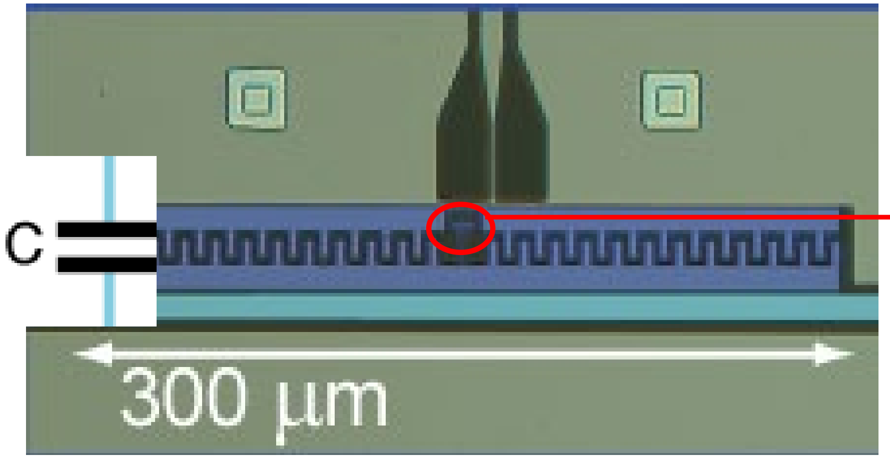


Transmon qubit

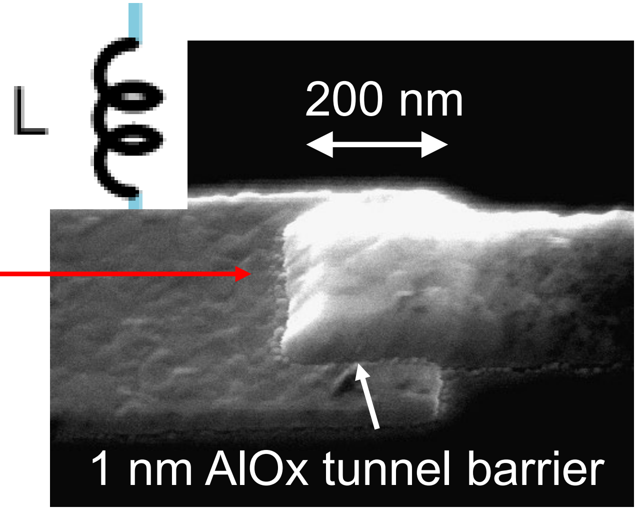
Thy: Koch et al., 2007. Expt: Houck et al., 2008.

Many adopters:
UCSB/Google, IBM, Rigetti, Berkeley, Princeton, Delft, Zurich, Chicago…

Superconducting Qubits



Transmon qubit



Josephson junction

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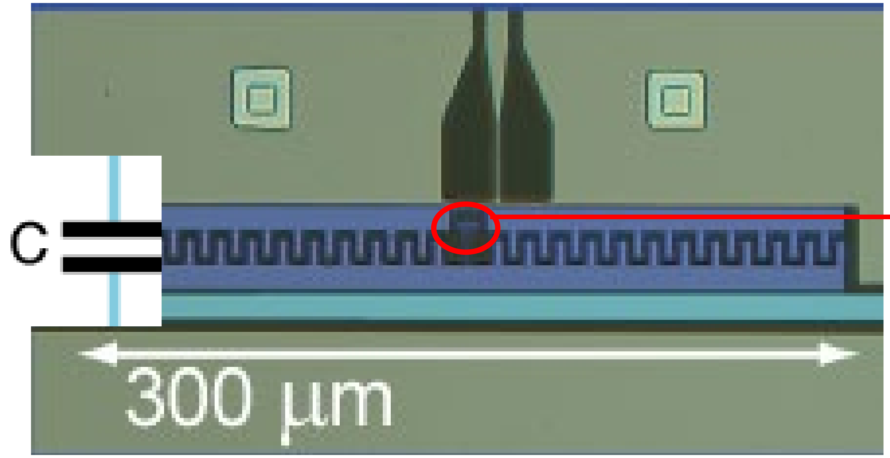
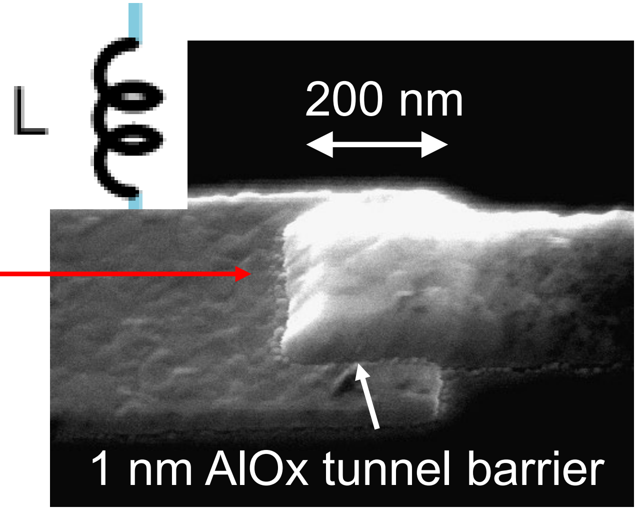
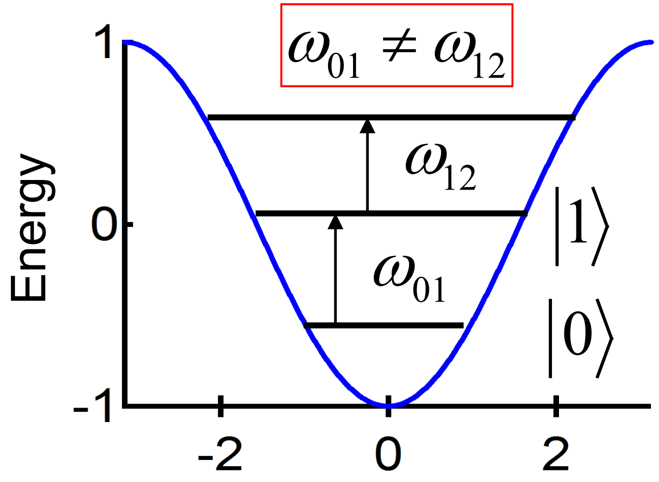
Superconducting Qubits



Transmon qubit



Josephson junction



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

$\hbar\omega/\mathbf{k}_B \sim 0.25\ \mathbf{K}$

Bit energy: ~ 10 μeV or 10^{-24} J
few yocto-Joules!

"Voltage level:" 1 μV (RMS)

Logical "0": ground state

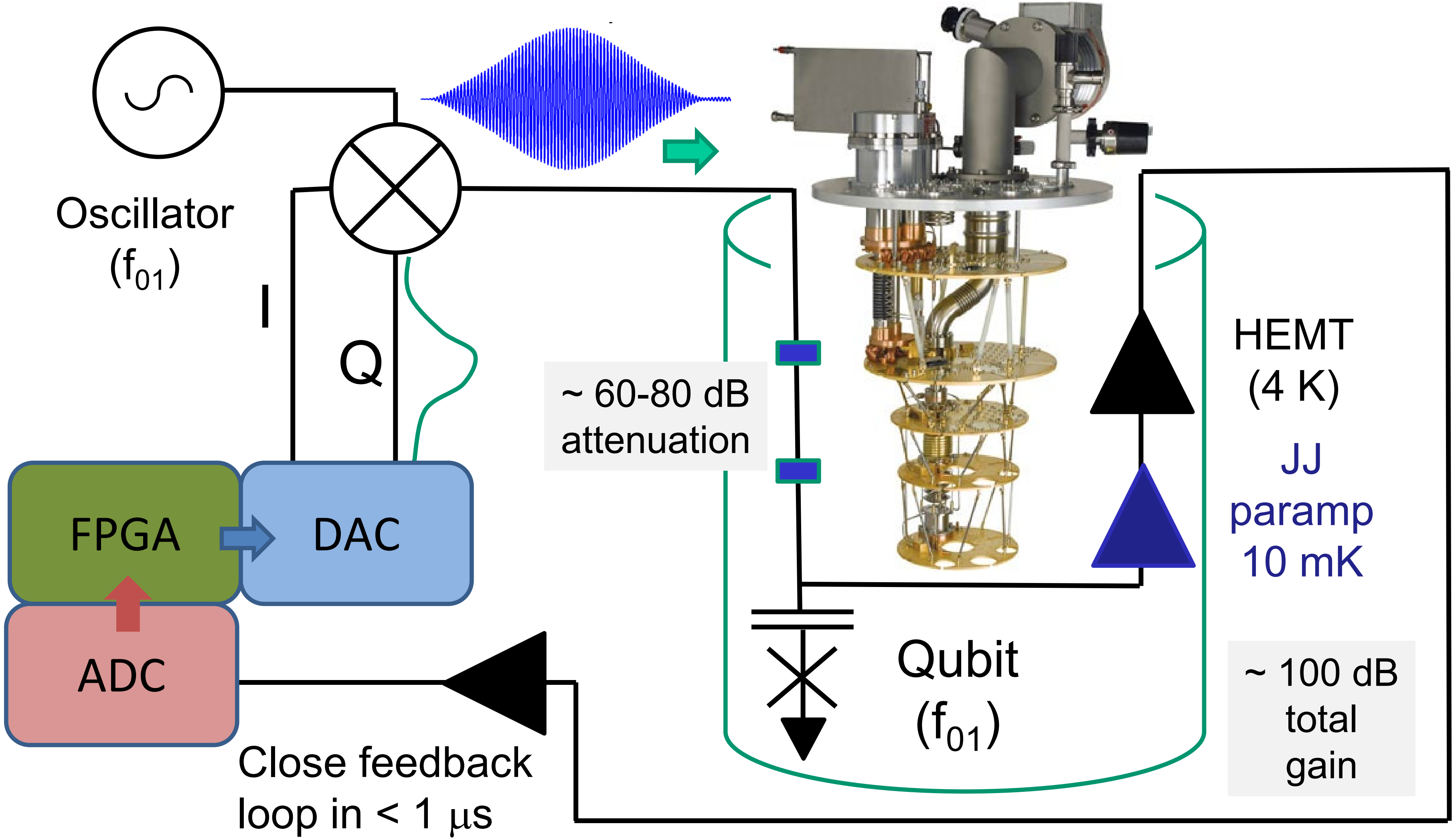
Logical "1": one μ-wave "photon"

Thy: Koch et al., 2007. Expt: Houck et al., 2008.

Many adopters:
UCSB/Google, IBM, Rigetti, Berkeley, Princeton, Delft, Zurich, Chicago…

Microwave Control & Measurement

Excite & control with GHz signal on wires:
gate times ~ 10 ns, Fidelities ~ 99.99%



Oscillator
(f_{01})

I

Q

FPGA

DAC

ADC

~ 60-80 dB
attenuation

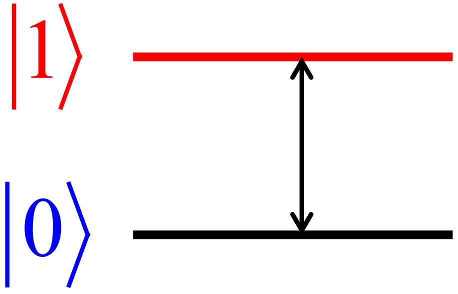
HEMT
(4 K)

JJ
paramp
10 mK

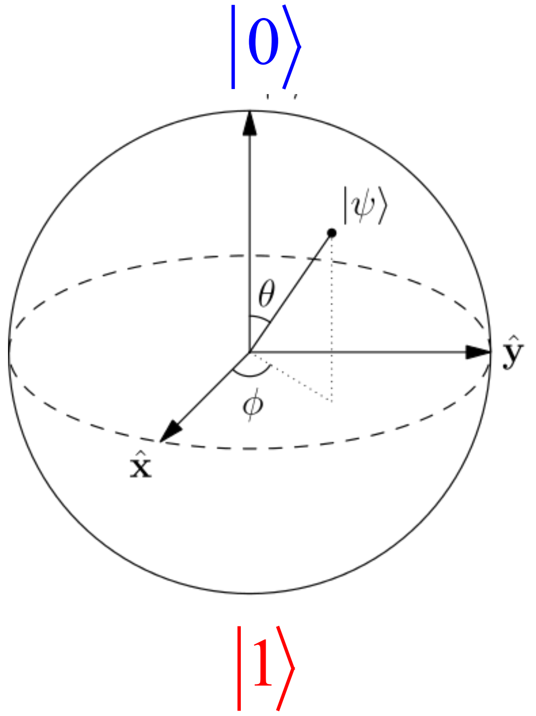
Qubit
(f_{01})

~ 100 dB
total
gain

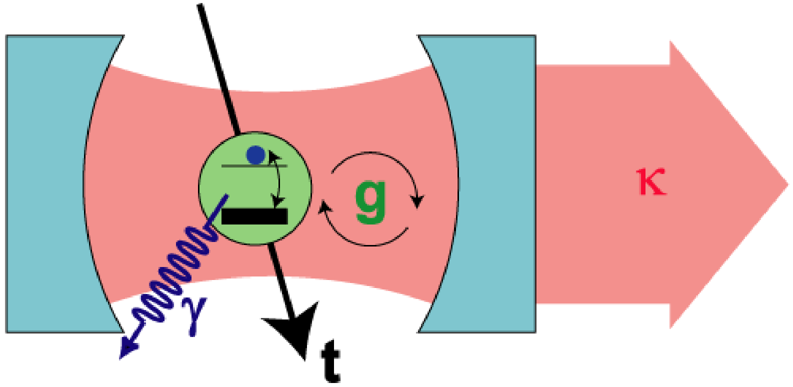
Close feedback
loop in < 1 μs



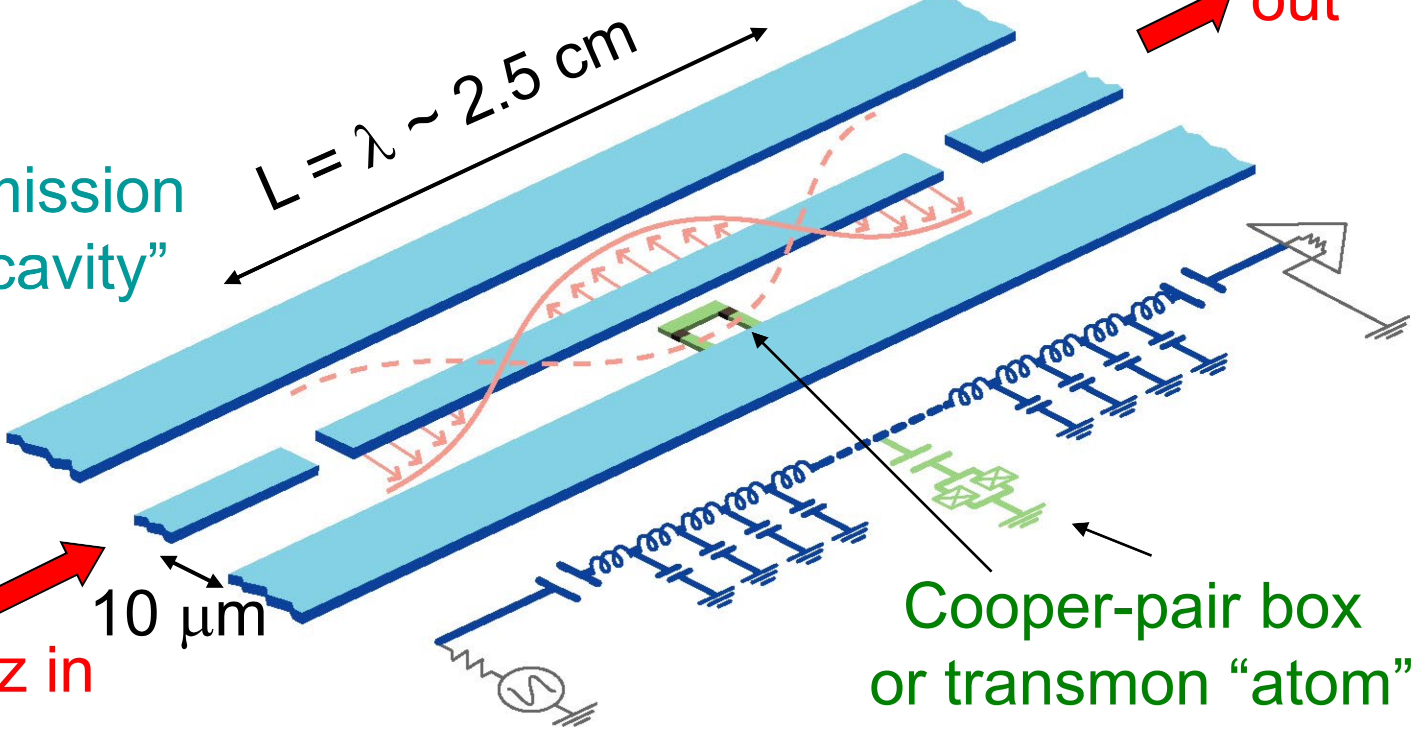
$$f_{01} = \frac{E_1 - E_0}{h} \sim 5-10\,\text{GHz}$$



A Circuit Implementation of Cavity QED



Jaynes-Cummings on a chip



transmission line “cavity”

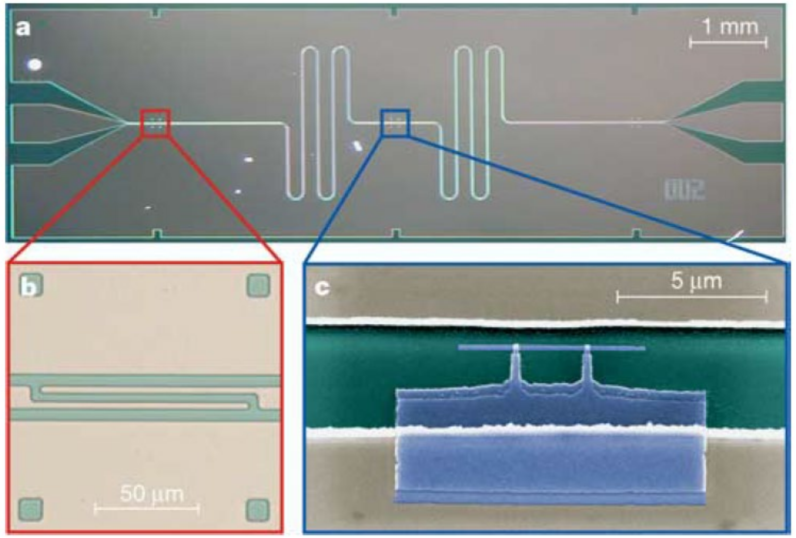
L = λ ~ 2.5 cm

out

10 GHz in

10 µm

Cooper-pair box or transmon “atom”



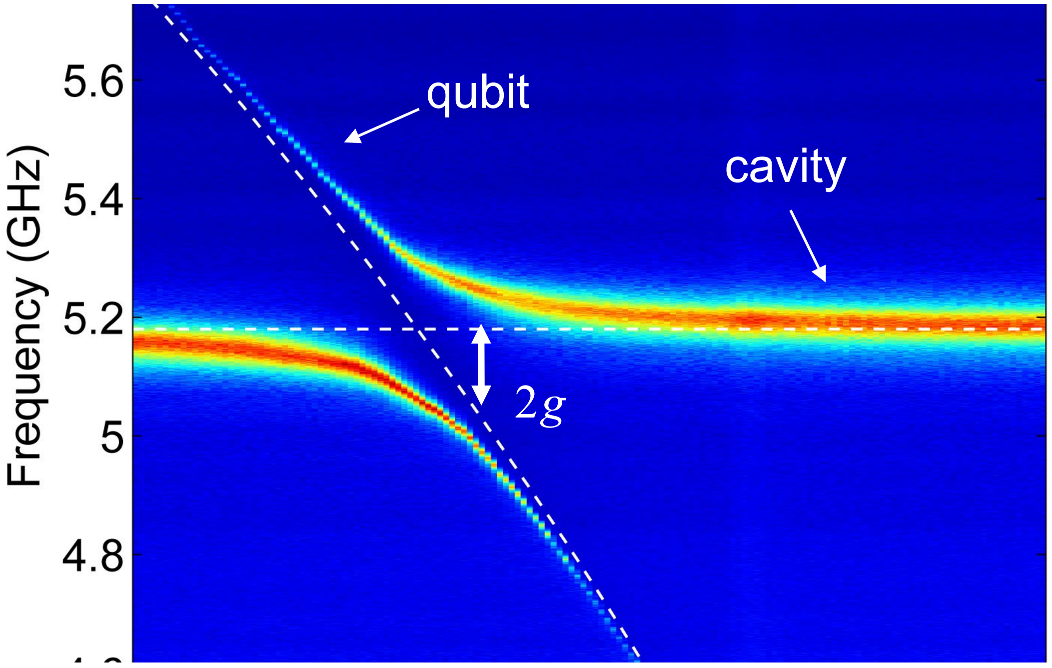
Theory: Blais et al., *Phys. Rev. A* **69**, 062320 (2004)

Expt: Wallraff et al., *Nature* **431**, 132 (2004)

Strong Coupling: Resonant and Dispersive

Resonant

$$\frac{g}{\omega} = \sqrt{\frac{2\alpha}{\varepsilon_r}} \sim 4\%$$



Exchange between qubit and traveling photon
("quantum bus") in ~ 100 ns

Wallraff et al., *Nature* **431**, 132 (2004)

Strong Coupling: Resonant and Dispersive

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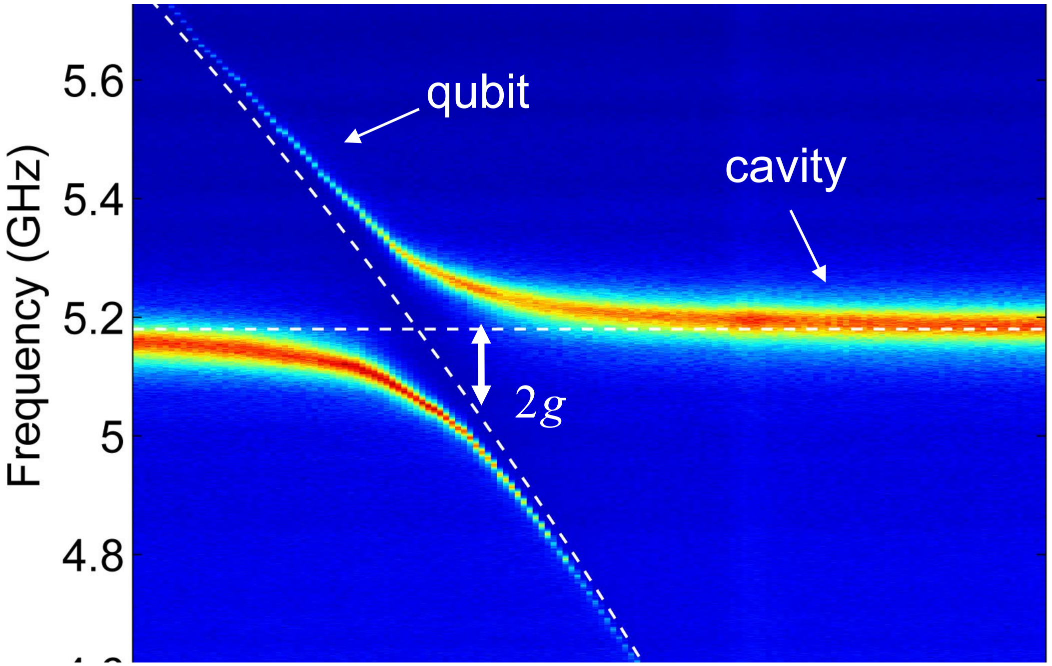
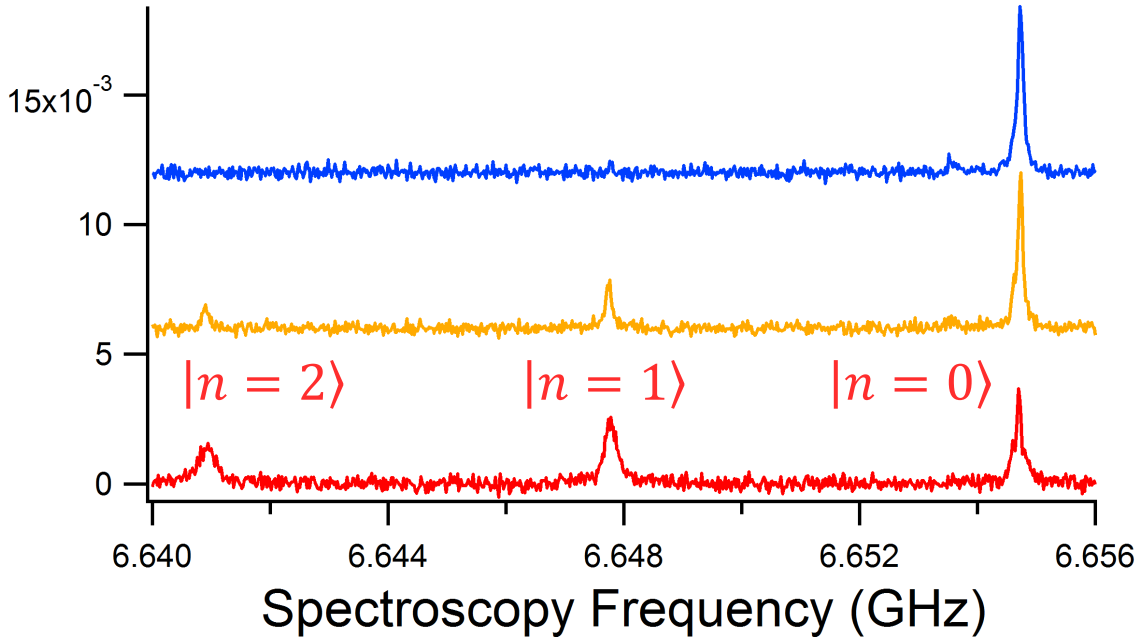
Resonant



Exchange between qubit and traveling photon (“quantum bus”) in ~ 100 ns

Wallraff et al., *Nature* **431**, 132 (2004)

Dispersive

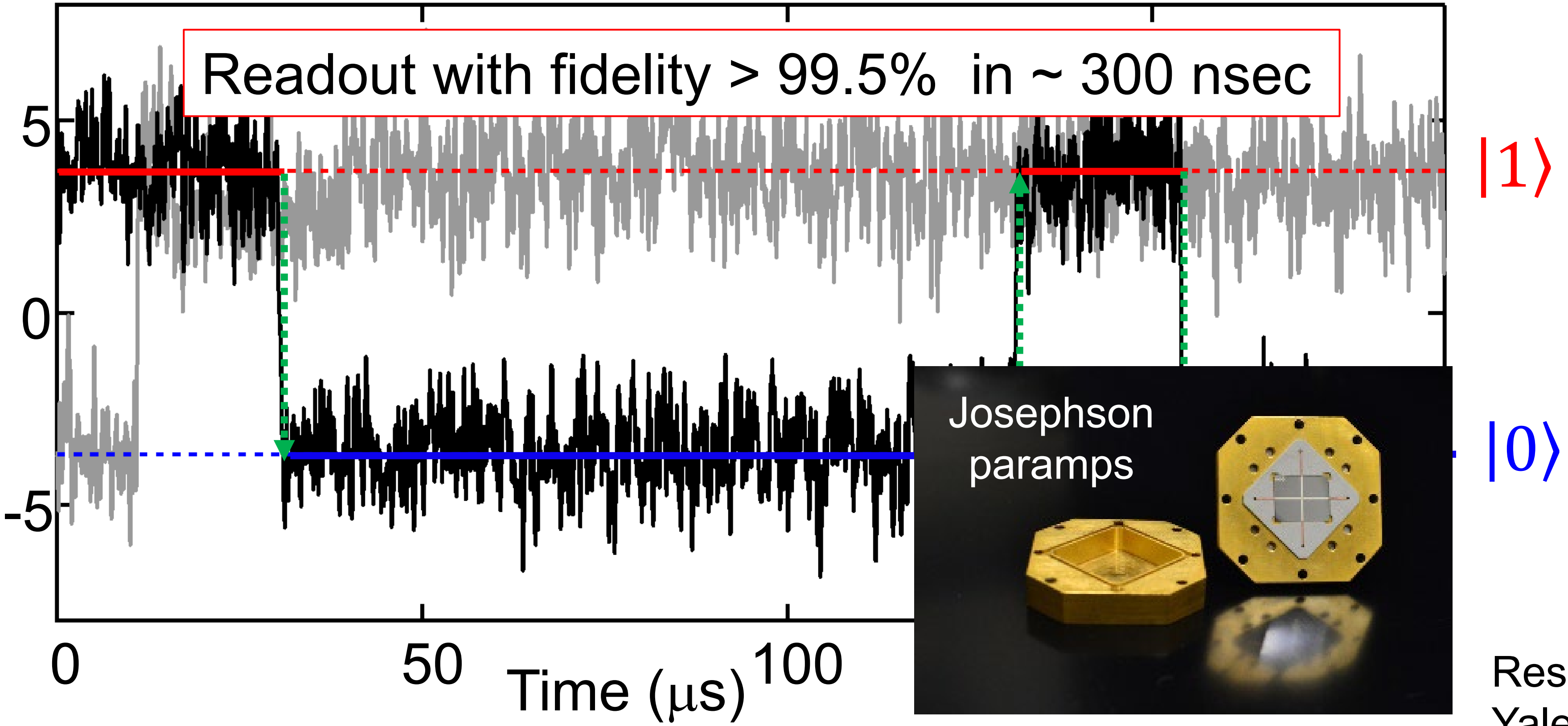


QND measurements of qubits or photons

Schuster et al., *Nature* **445**, 515 (2007)

Dispersive Single Shot QND Measurements

Quantum jumps* of a transmon


Readout with fidelity > 99.5% in ~ 300 nsec

Paramp usage
and multiplexing
now standard practice

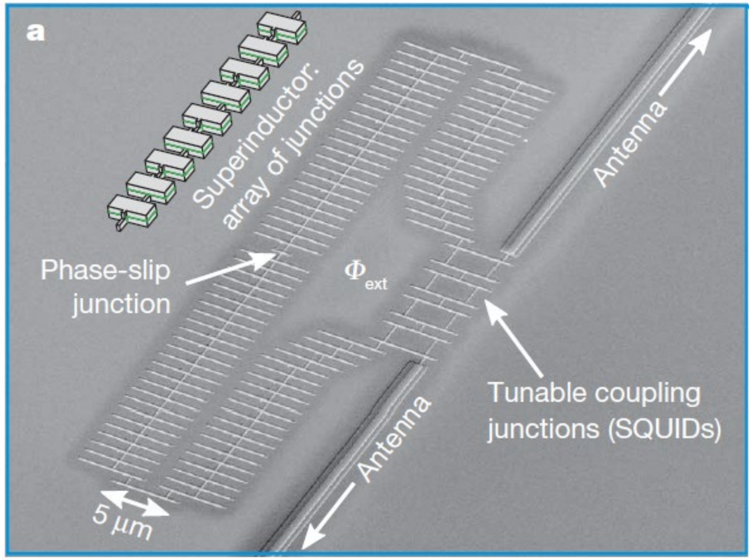
Results from Devoret group,
Yale: Hatridge et al., Science 2013*

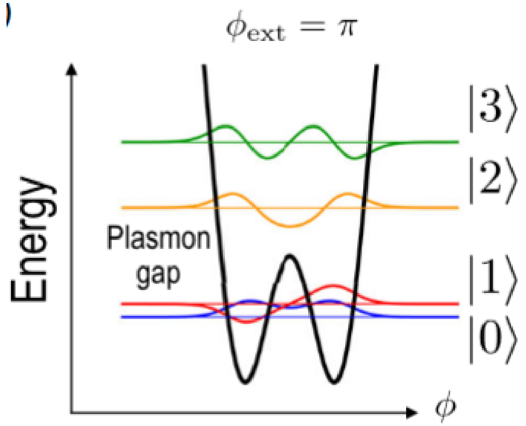
Fast (>1,000 msmts./lifetime) and high-fidelity QND measurements are pre-requisite for QEC

*First jumps: R. Vijay et al., 2011 (Berkeley)

Other Qubits: Hamiltonians by Design

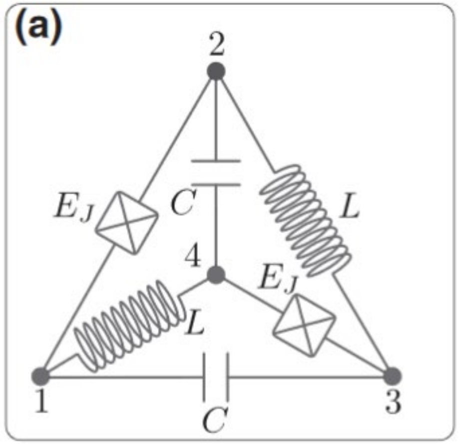
Fluxonium qubit

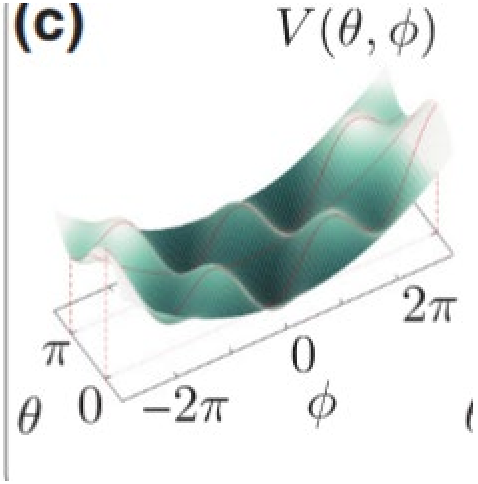


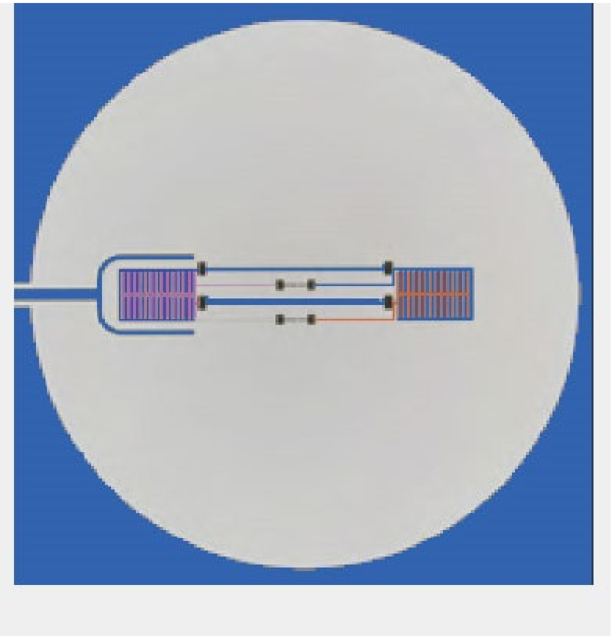


Manucharyan et al., Science 326, 113 (2009)
Nguyen et al., PRX 9, 041041 (2019)

Topologically-protected qubits:
the “Zero-Pi”







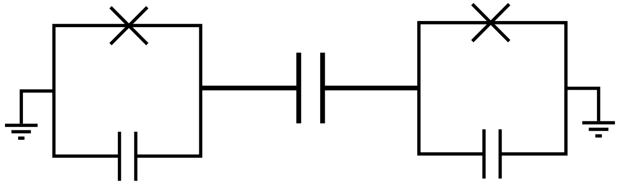
Brooks, Kitaev, and Preskill, PRA 87, 052306 (2013)
Gyenis et al., PRX Quantum 2, 010339 (2021)

Entanglement: Two-qubit Gates

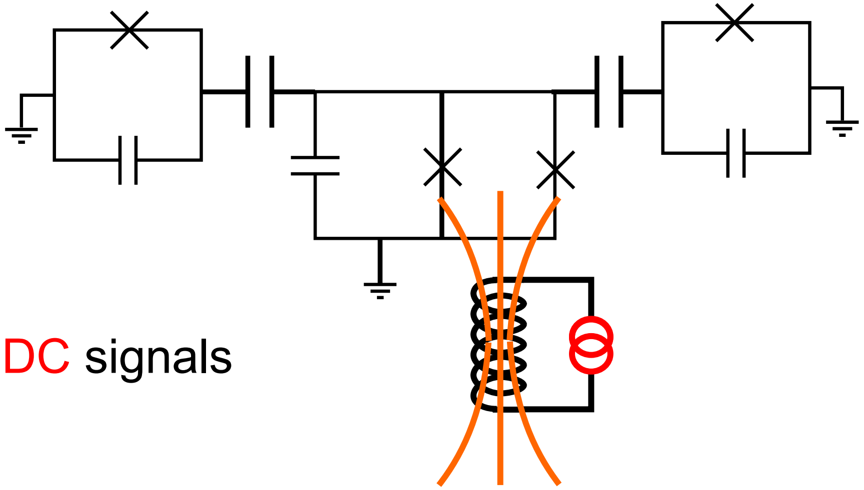
Fast (50-500 ns) entangling interactions through a variety of methods!

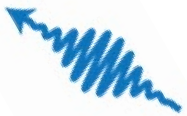
“Local” interactions:

Fixed (linear) coupler



Tunable (non-linear) coupler





Actuate either with RF or DC signals

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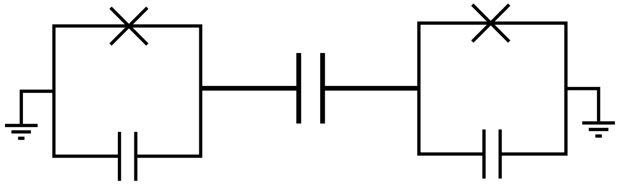

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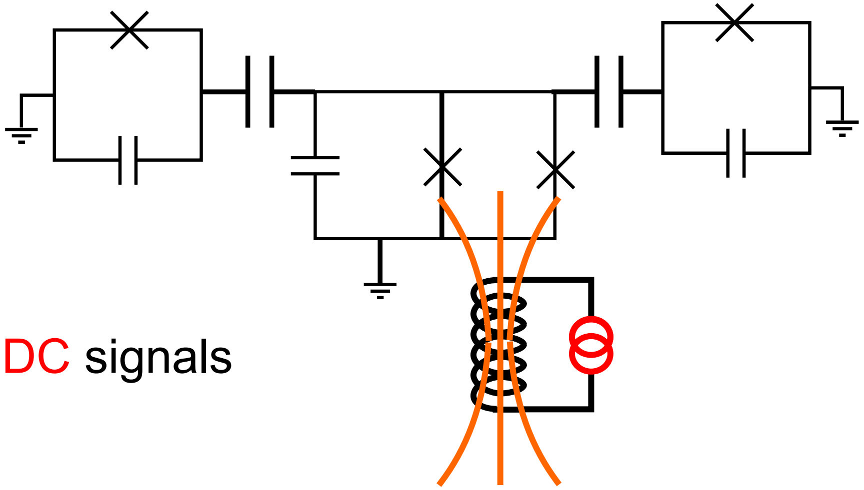
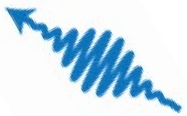
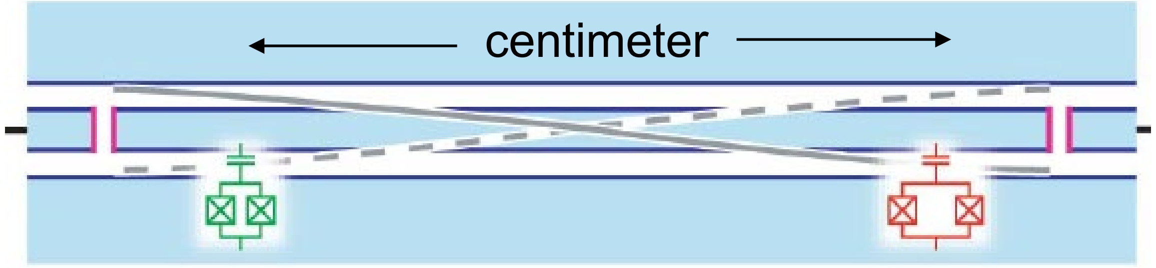




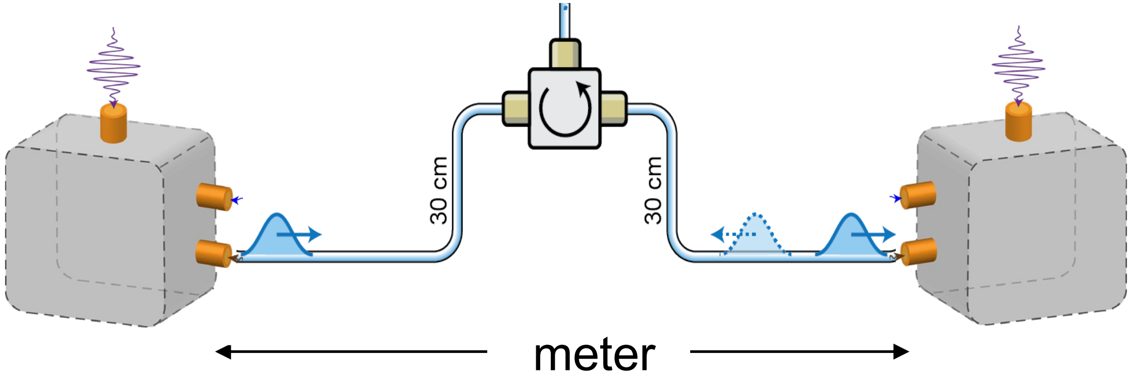
Actuate either with RF or DC signals

“Non-local” or longer range interactions:

Transmission line as bosonic quantum bus



Remote entanglement over a coax



Considerations: gates

- Is fidelity just about coherence? – $1 - F \sim t_{gate}/T_{coh}$
  - Cross talk and systematic errors - the "law of geometric averages"

- What's the best gate/instruction set?
  - "Discrete" (CNOT) vs. continuous - e.g. $fsim(\theta, \phi)$, $eSWAP(\theta)$

- Calibration – every qubit is unique!
  - But hardware is remarkably stable, controls should not limit

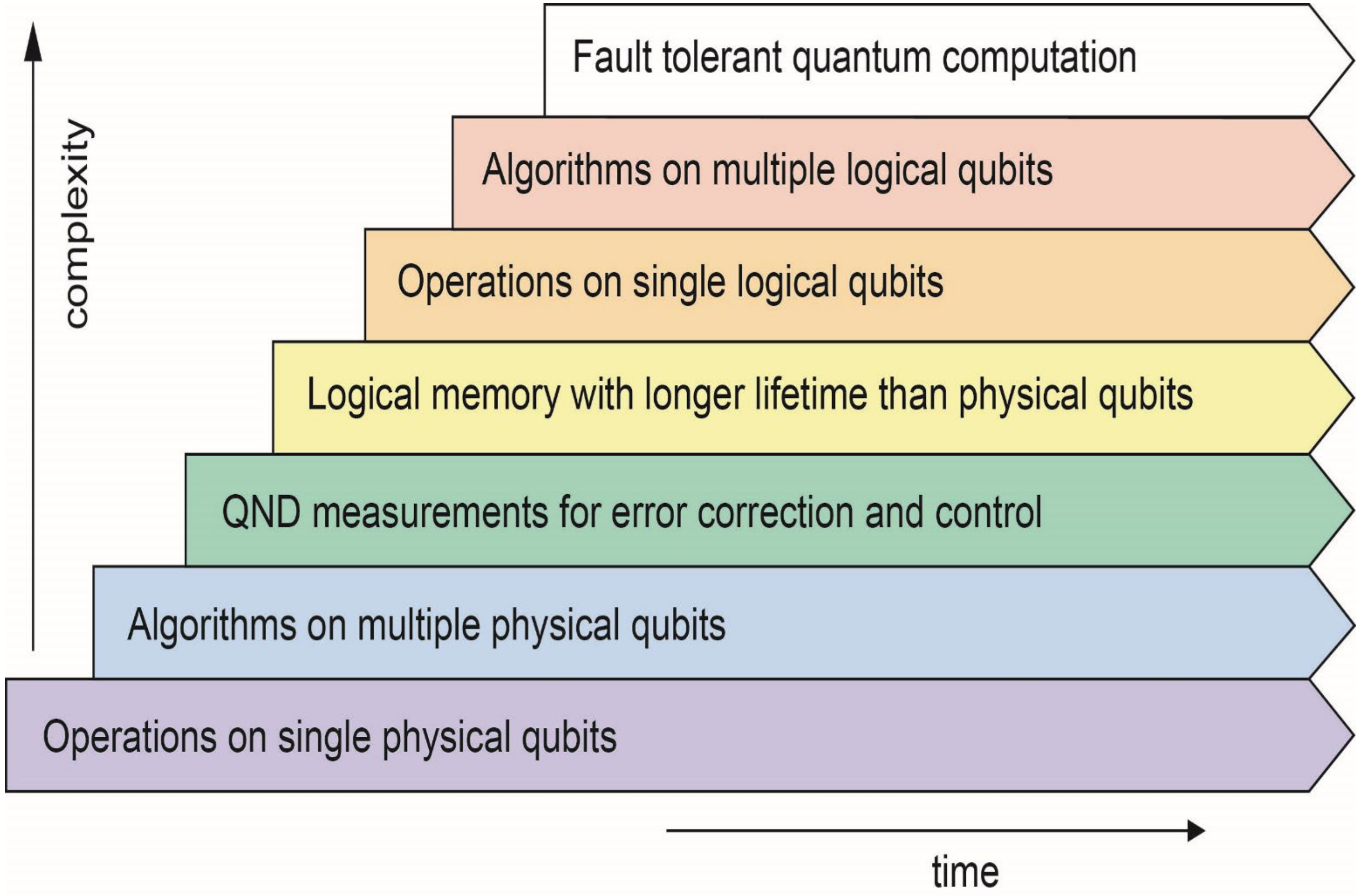
- Benchmarking and characterization
  - Not just rates, but types of errors, even rare ones, matter

- Fixed vs. tunable qubits?
  - Tunability brings flexibility, but also 1/f noise

- RF vs. DC (baseband) actuation?

Challenges and Future Prospects

Where are Superconducting Qubits Today?



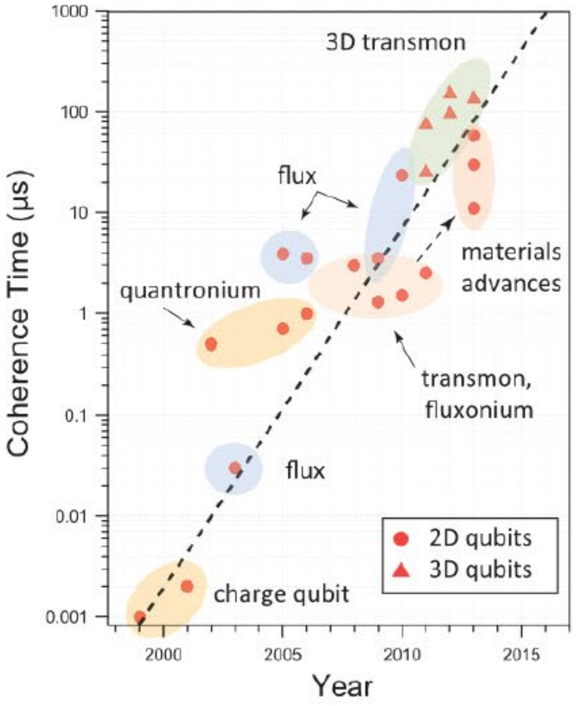
Theory and practice
of error-correction
and fault tolerance
testable in lab today

- Noisy intermediate scale computing (NISQ) machines are here!
- Next goal is to make QC robust and scalable via error-correction.

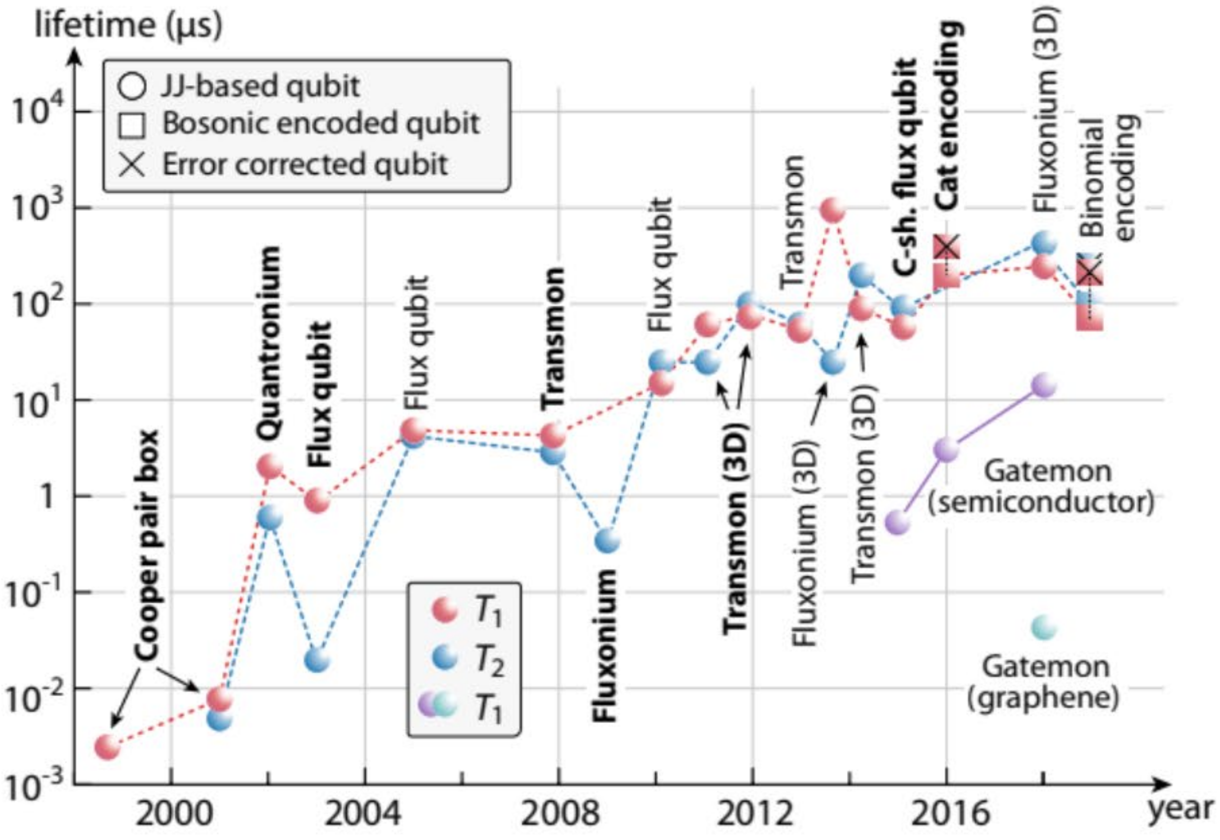
from M. Devoret and RS, Science (2013)

Improving Device Performance

20 years of progress in coherence



Oliver and Welander, MRS 2013



Kjaergaard et al, arXiv:1905.13641v1 (Oliver)

Qubit lifetimes have improved by ~ six orders of magnitude, from ns to ms
but still FAR from fundamental limits

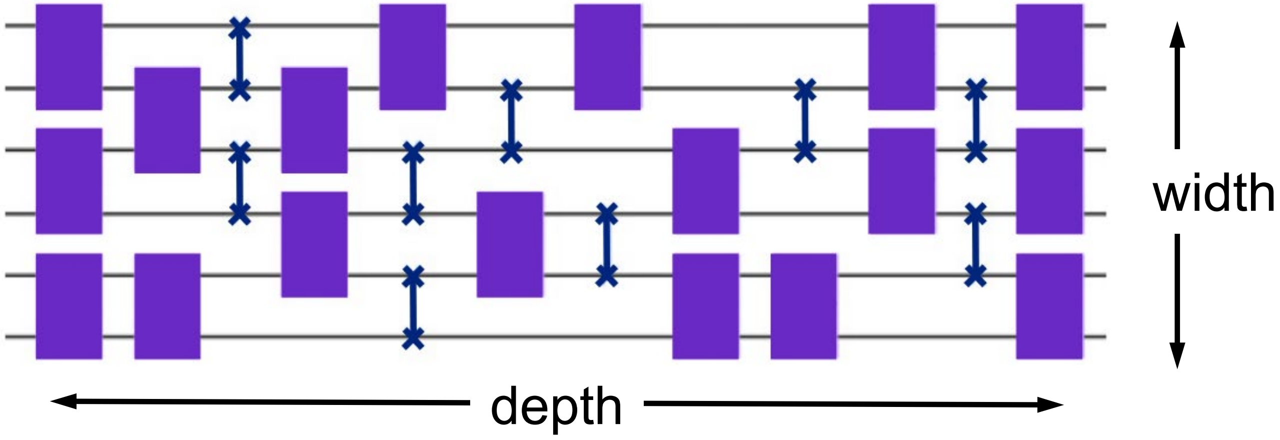
State of Play in Computing Today

- Machines with 10 to 100 qubits online today
  IBM, Google, Rigetti, Oxford Quantum, QCI (coming soon), …

- Gate fidelities
  - Single qubit: > 99.9%
  - Two-qubit: 99% -> 99.9%

- Development of benchmarks and performance metrics

e.g. quantum volume



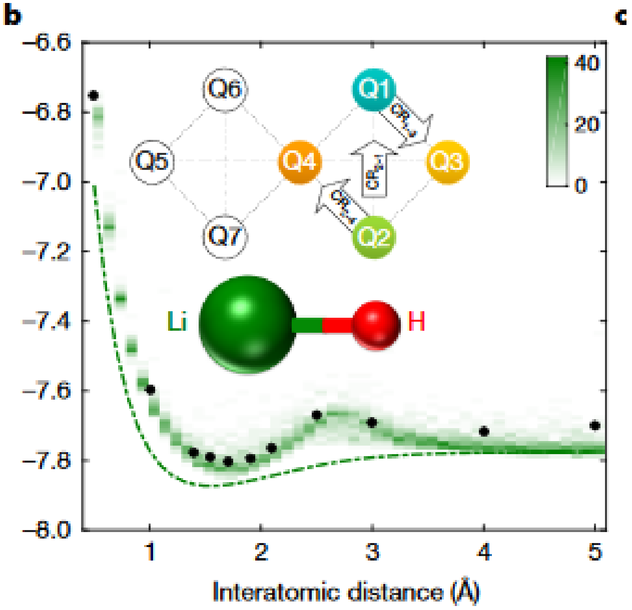
$$QV \sim 2^{(\#\ of\ entangled\ qubits)}$$

Cross et al.,
PRA **100**, 032328 (2019)

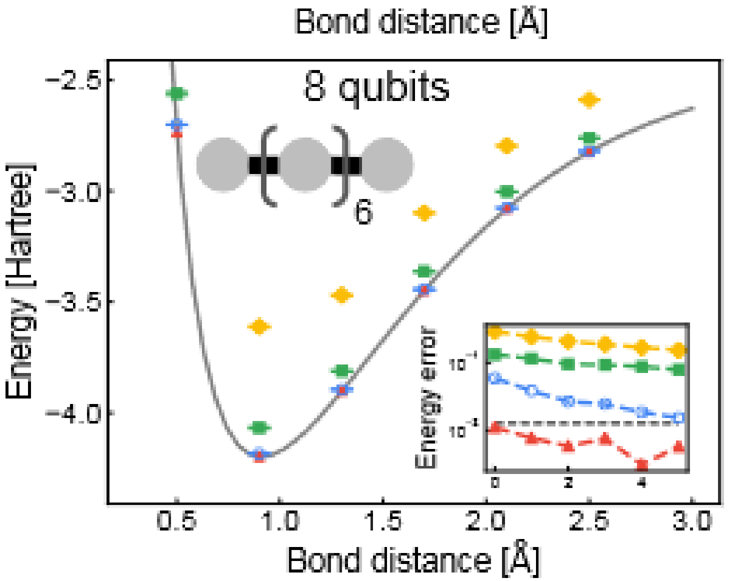
Quantum Simulation with Programmable Machines

Variational quantum chemistry algorithms

Boson sampling for Franck-Condon

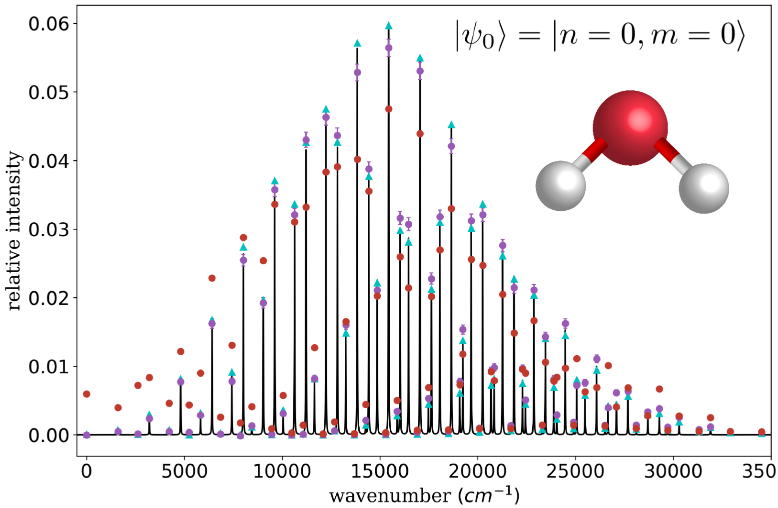


Kandela et al.,
Nature **549**, 242 (2017)



Rubin et al.,
Science **369**, 1084 (2020)

$$H_2O \xrightarrow{h\nu} H_2O^+ \left(\tilde{B}\,{}^2B_2\right) + e^-$$



Wang et al.,
PRX **10**, 021060 (2020)

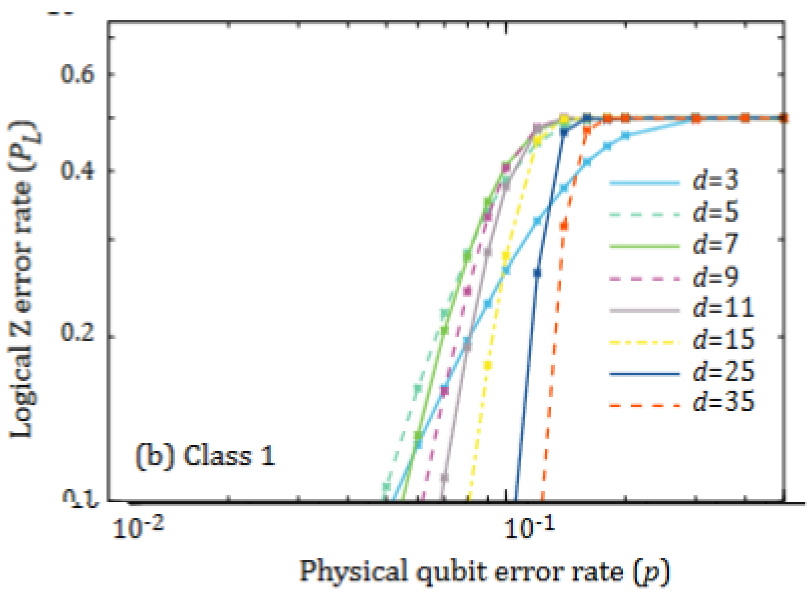
Still not clear if/how/when NISQ calculations can reach quantum advantage…

Requirements and Challenges for QEC

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \rightarrow \alpha|000\rangle + \beta|111\rangle$$

1. **complexity:** “send more qubits please!”
2. **overhead:** errors get worse before they get better
3. **performance:** keep errors low while scaling
4. **ancilla measurement:** fast, without disturbing the rest of system
5. **fault-tolerance**: keep errors correctable and make things better
   first step is reaching “breakeven” to keep up with the overhead

QEC threshold for surface code

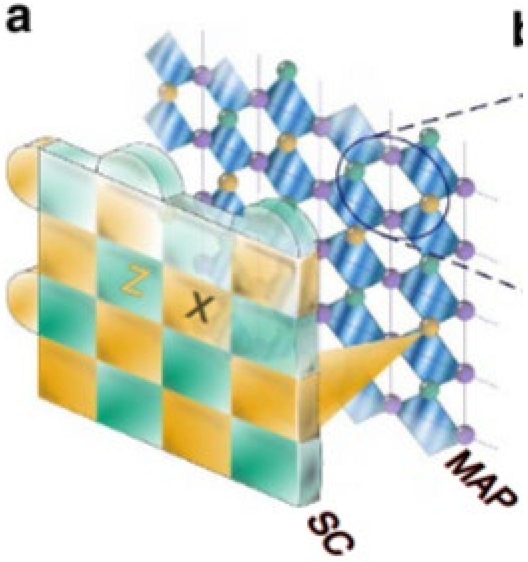


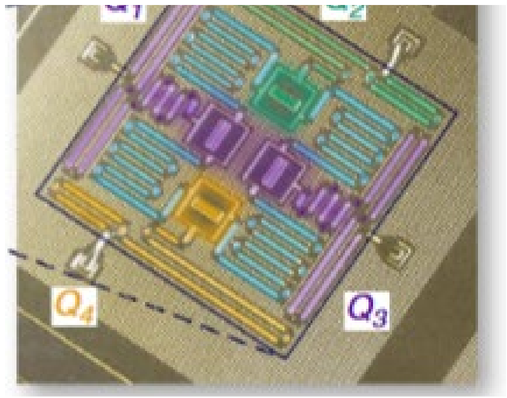
e.g. Fowler et al.,
PRA **86**, 032324 (2012)

Next goal: error correction that improves computer operation by > 10x

Experimental Progress on QEC with Transmons

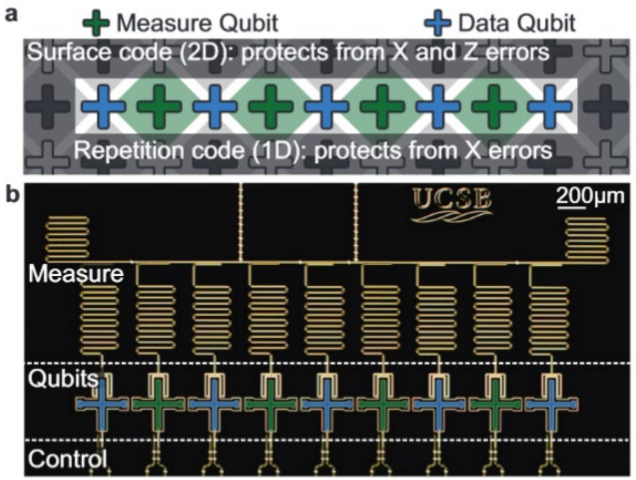
4 bit error detection

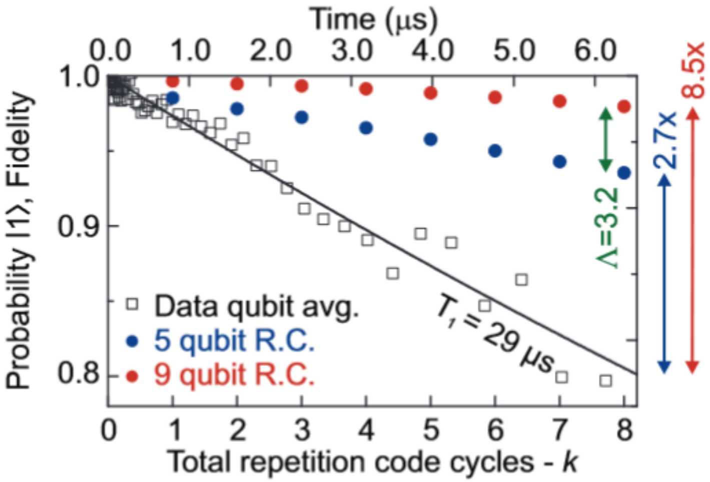




Corcoles et al., Nature Comms **6**, 6979 (2015)

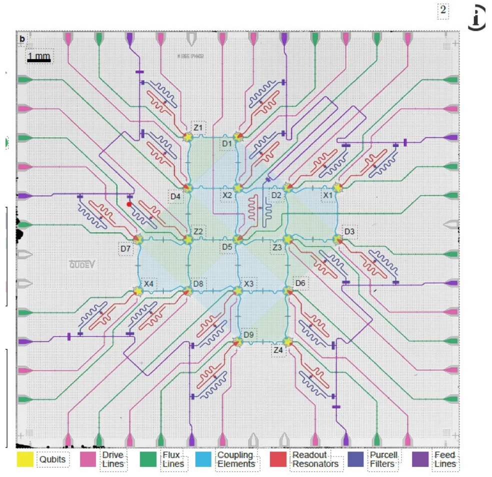
Bit-flip correction

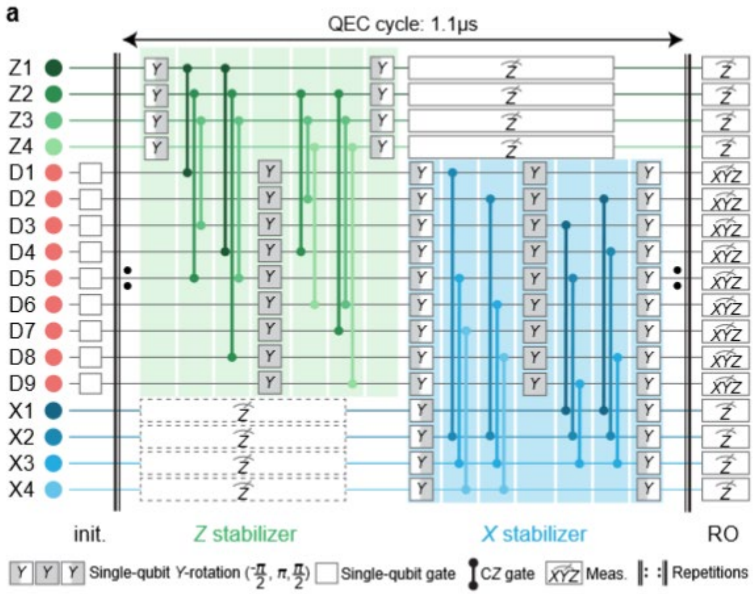




Kelly et al., Nature **519**, 66 (2015)

Surface-17

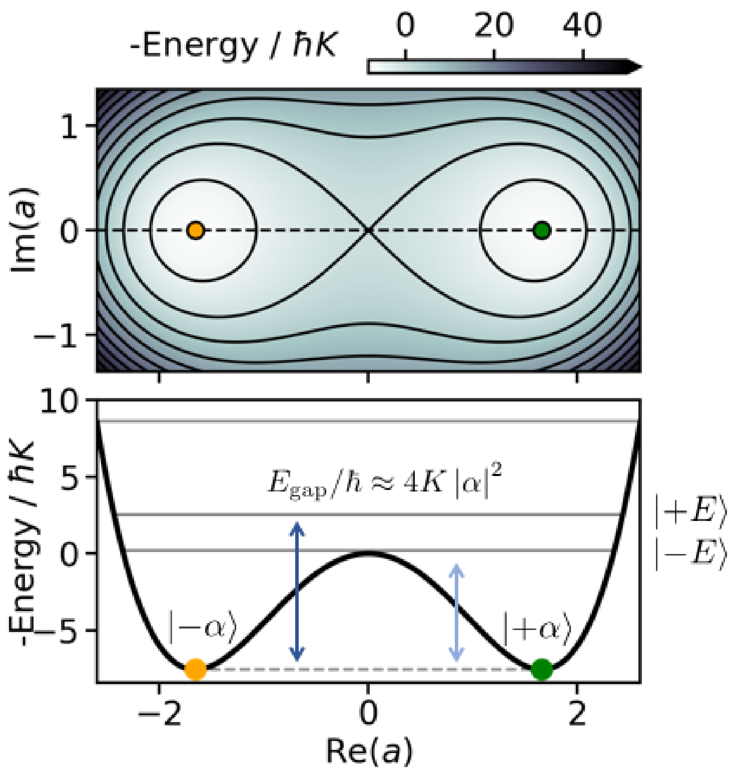




Krinner et al., arXiv 2112.03708

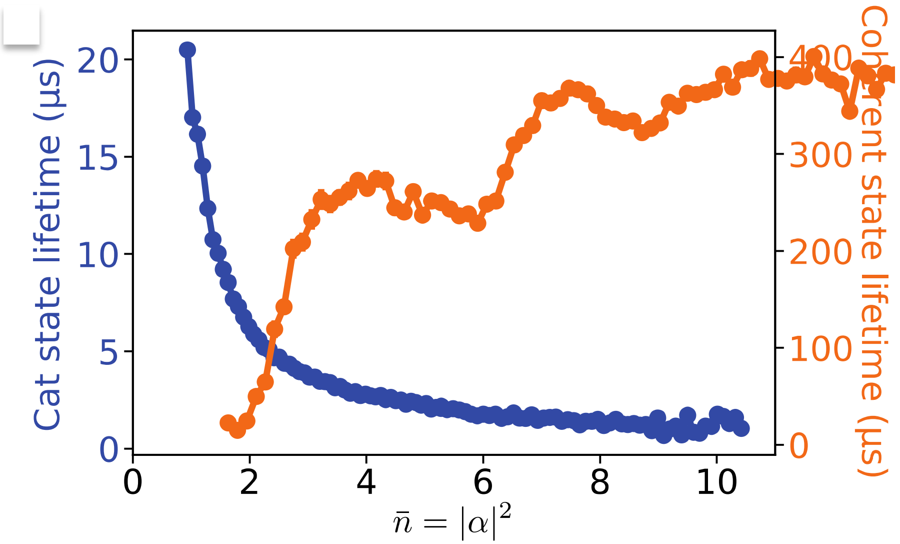
New Approaches: Biased Noise

“Kerr-cat” stabilized qubit



Puri *et al.*, NPJ Quantum Inf. (2017).
Grimm and **NEF** *et al.*, Nature (2020).

Demonstration of biased noise



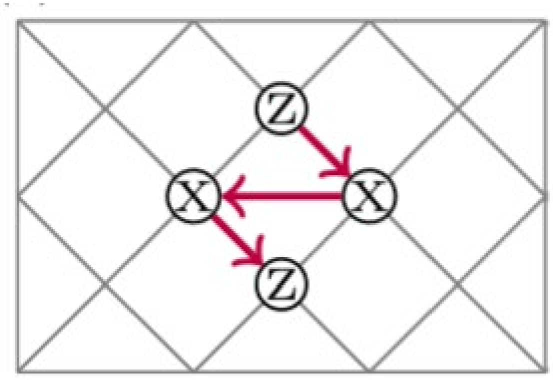
Frattini et al., in prep (2022)

Error protection when in cat-manifold:

Phase-flips suppressed by: $\approx e^{-2\bar{n}}$

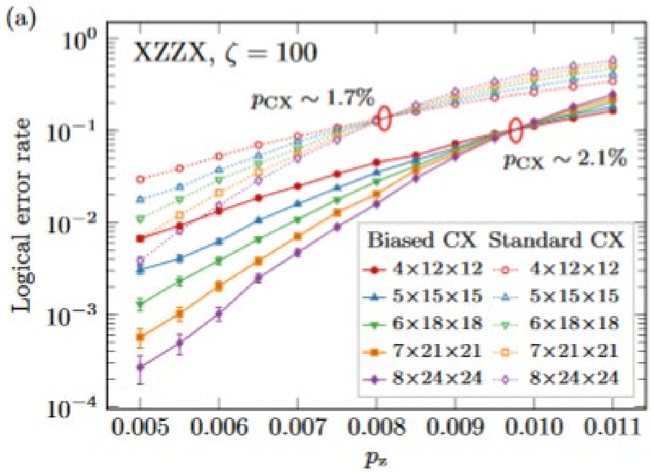
Bit-flip rate: $2\bar{n}\kappa_1$

XZZX optimized surface code



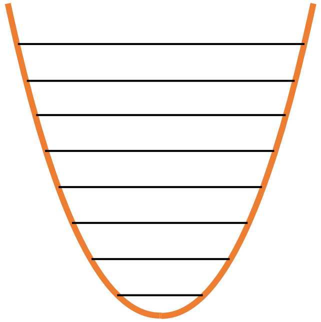
Bonilla Ataides *et al.*,
Nat. Commun. **12**, 2172 (2021)

Biased noise can increase threshold

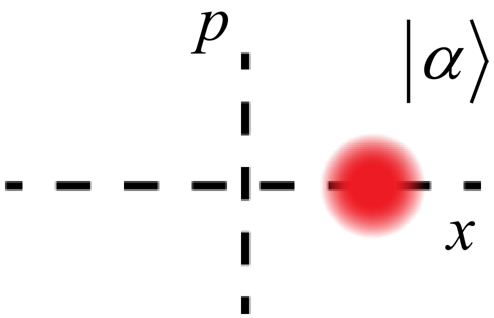


Darmawan *et al.*,
PRX Quantum **2**, 030345 (2021)

Controlling and Encoding Information in the Oscillator



Continuous variables:



1) "GKP" codes

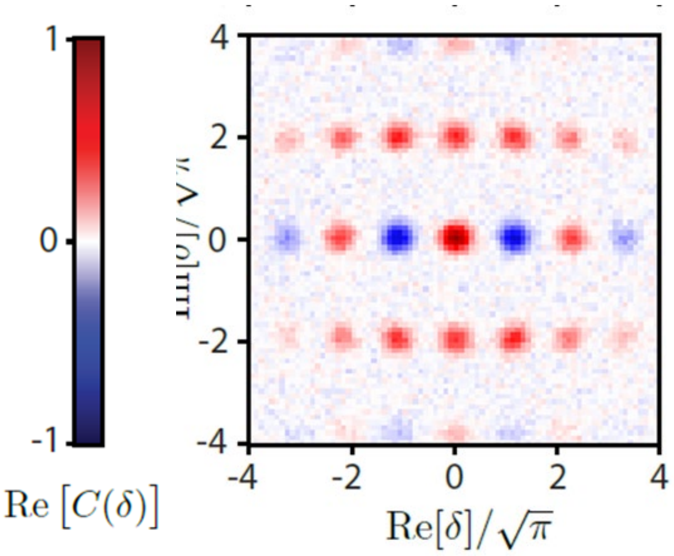
(Gottesman, Kitaev, and Preskill, 2001)

2) "cat" codes

(Mirrahimi, Leghtas, MD, RS, 2013)

3) "binomial" codes

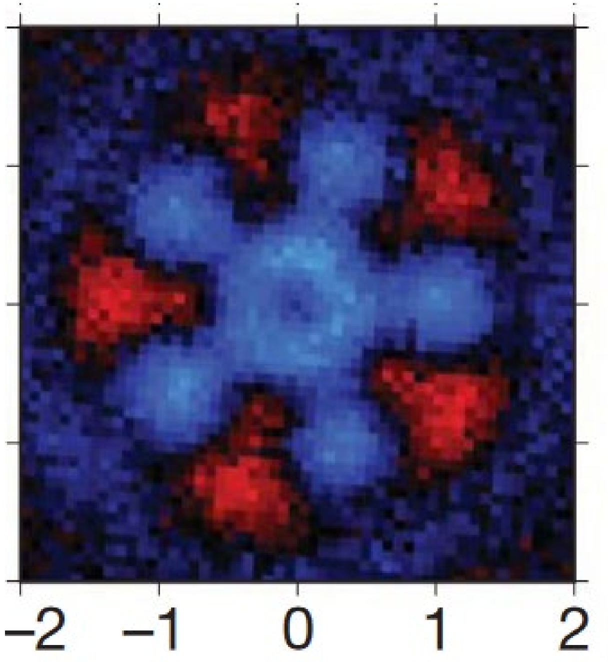
(M. Michael, …, Jiang, Girvin, 2016)



P. Campagne-Ibarcq et al., *Nature* **584**, 368 (2020)

Measured Wigner function

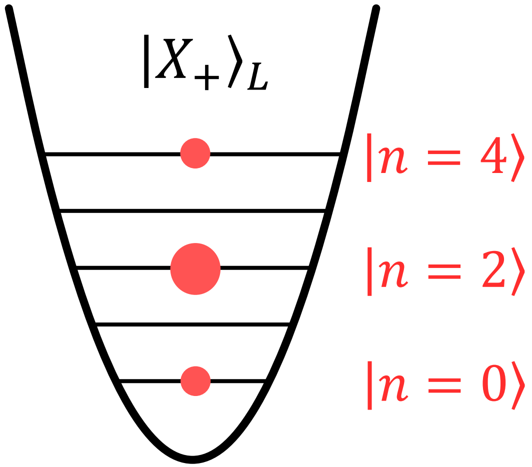
$$|\psi_{osc}\rangle = |0\rangle + |5\rangle$$



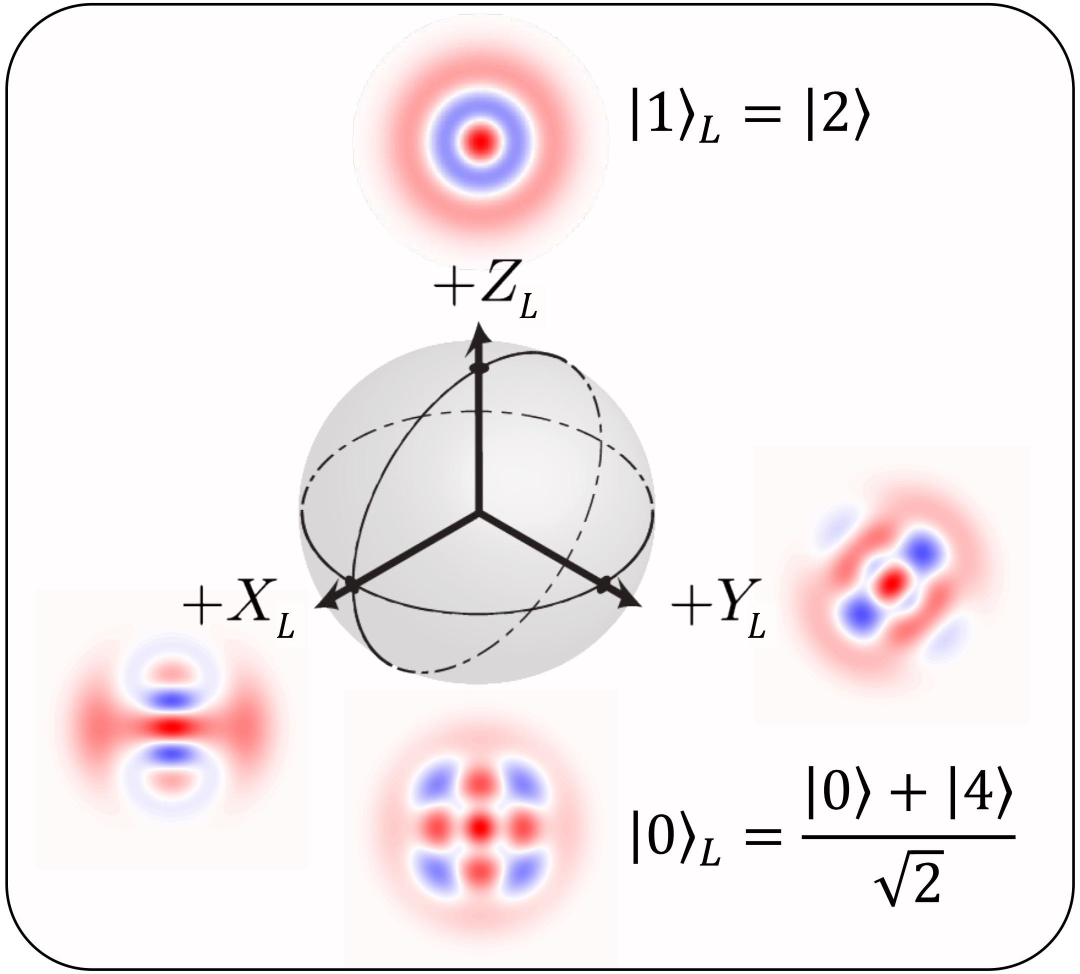
Hofheinz et al., *Nature* **459**, 546 (2009)

Hardware-efficient QEC: Bosonic Codes

- Photon parity check bit
- Equal decay probability



code space (even)



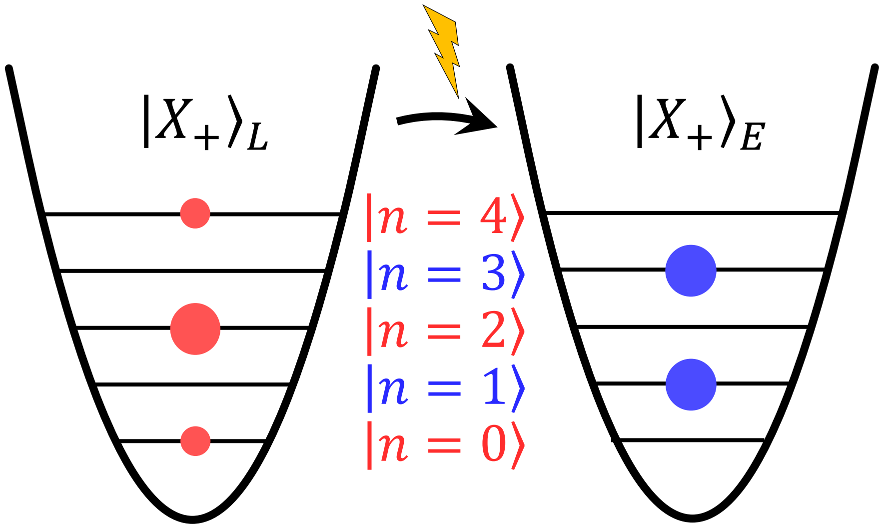
Michael et al., PRX 2016

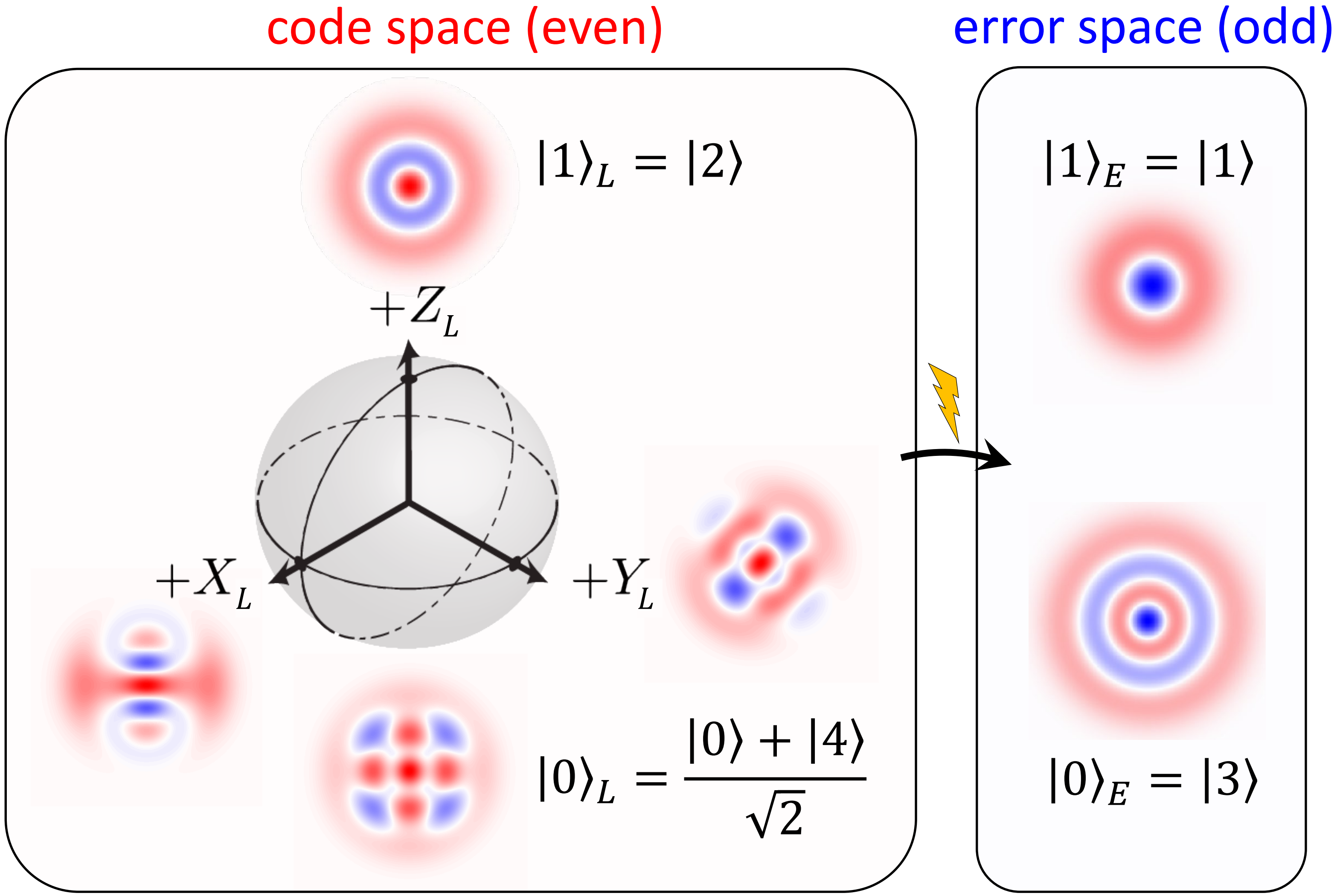
Hardware-efficient QEC: Bosonic Codes

- Photon parity check bit
- Equal decay probability

- After photon loss:
  $|0\rangle_E$, $|1\rangle_E$ still orthogonal

  → **Error-Correctable**





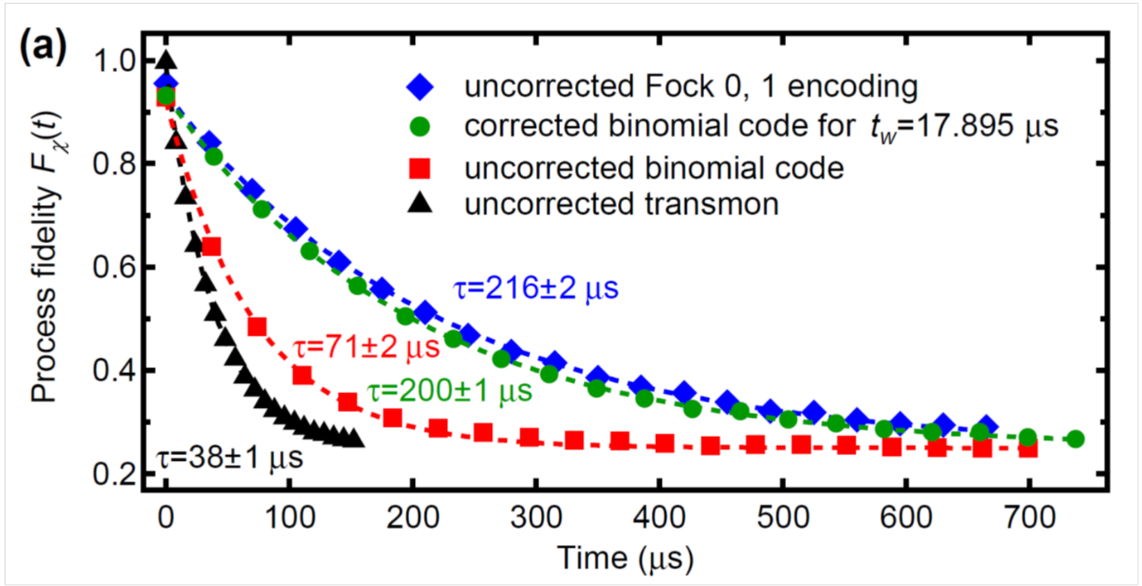
Michael et al., PRX 2016

Reaching Breakeven with Bosonic Qubits

Only approach to reach breakeven for error correction so far!

First breakeven: (4-fold cat code) Ofek et al., Nature **536**, 441 (2016)

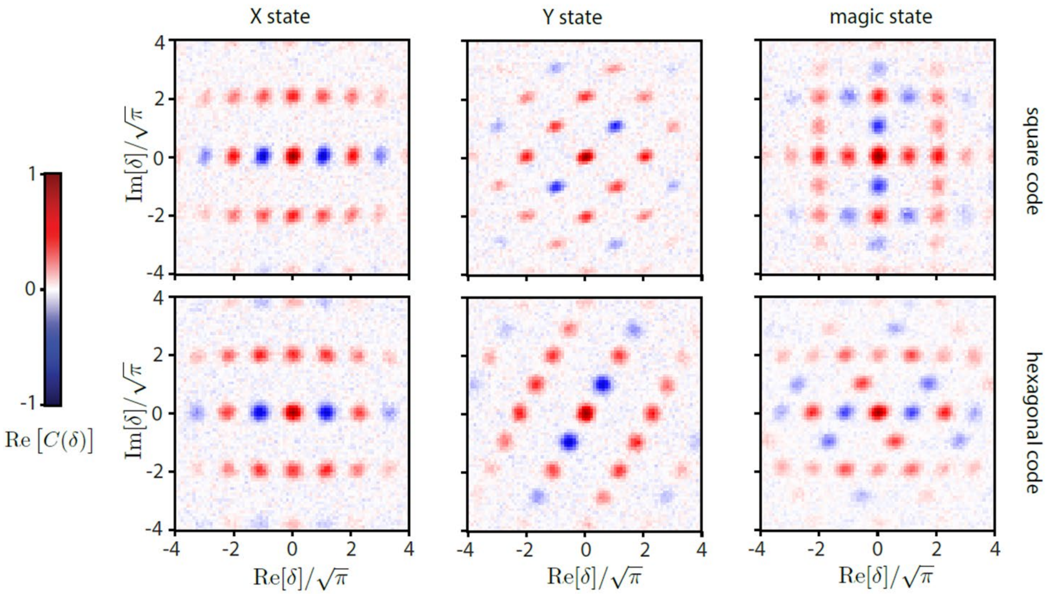
Kitten or binomial code



QEC and operations: (L. Sun group@ Tsinghua)
Nature Physics **15**, 503 (2019)

Remote entanglement: (RS group@ Yale)
Burkhart et al. , PRX Quantum **2**, 030321 (2021)

GKP code



State preparation: C. Flühmann et al. (ions in Home group)
Nature **566**, 513 (2019)

QEC: P. Campagne-Ibarcq et al. (Devoret group@ Yale)
Nature **584**, 368 (2020)

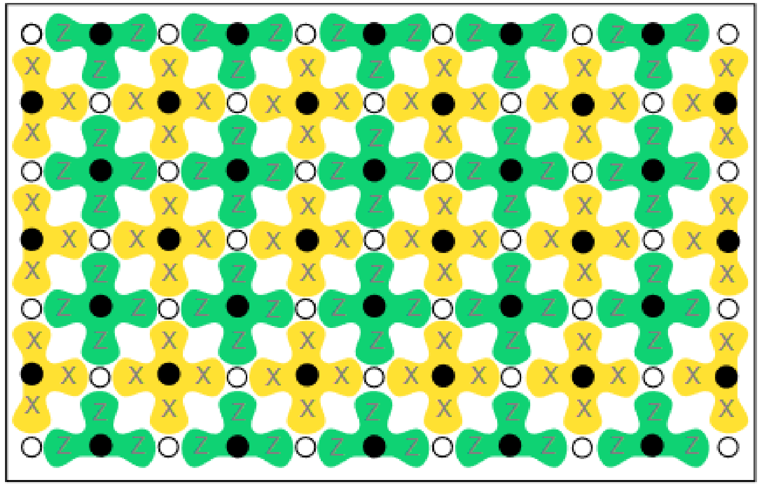
Error correction considerations

“Codesign”

- What are the ways to reduce the overhead?
- How much can we gain by implementing first layer “in hardware”?
- What types of errors matter most – adapt the code to qubit or vice-versa?
- How does error-correction scheme affect architecture & algorithms?
- What comes between NISQ and full FT scaling…
  can we benefit from a little bit of error correction or detection now?

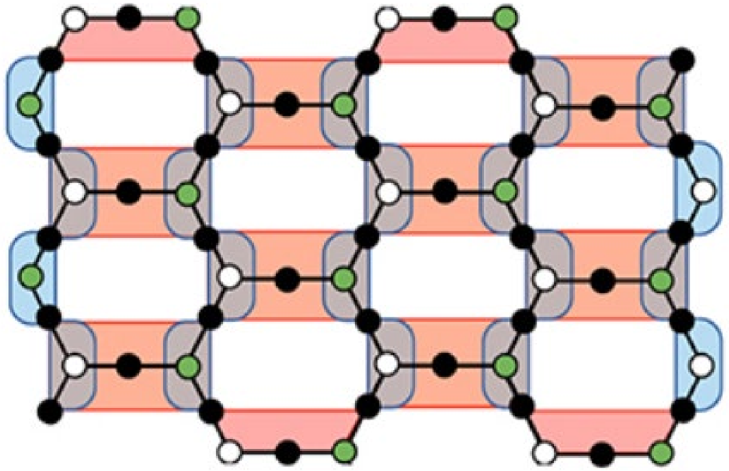
Computing Architectures

Nearest neighbor grid



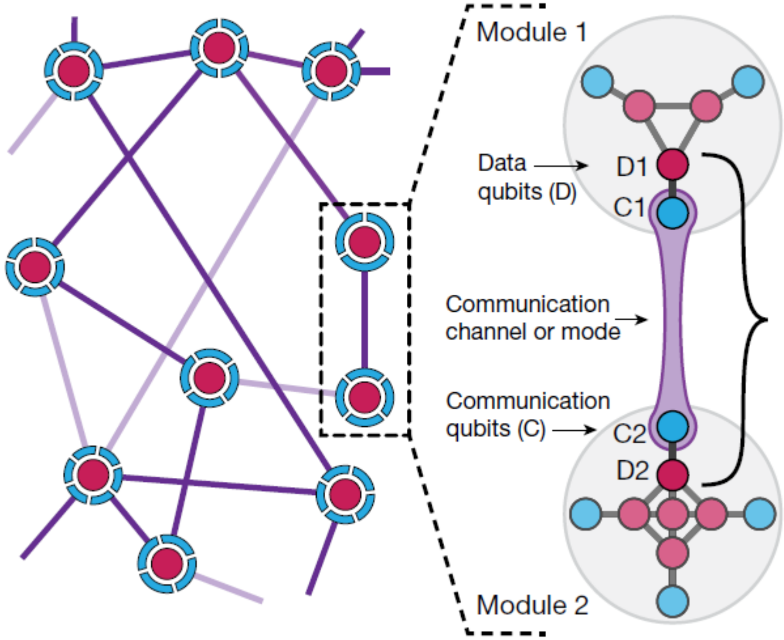
Fowler et al.,
PRA **86**, 032324 (2012)

Heavy hexagon



Chamberland et al.,
PRX **10**, 011022 (2020)

Modular architecture



Chou et al.,
Nature 561, 368 (2018)

Architecture considerations

- Should every qubit be the same – or specialized devices for various tasks?
  - “Hybrid” quantum systems, e.g. spin for memory, SC for processing?

- Nearest neighbor or longer range coupling?
  - What is the tradeoff of performance vs. degree of branching

- Precision Hamiltonian design
  - The off state is as important as the on-state!

- Modular or monolithic?

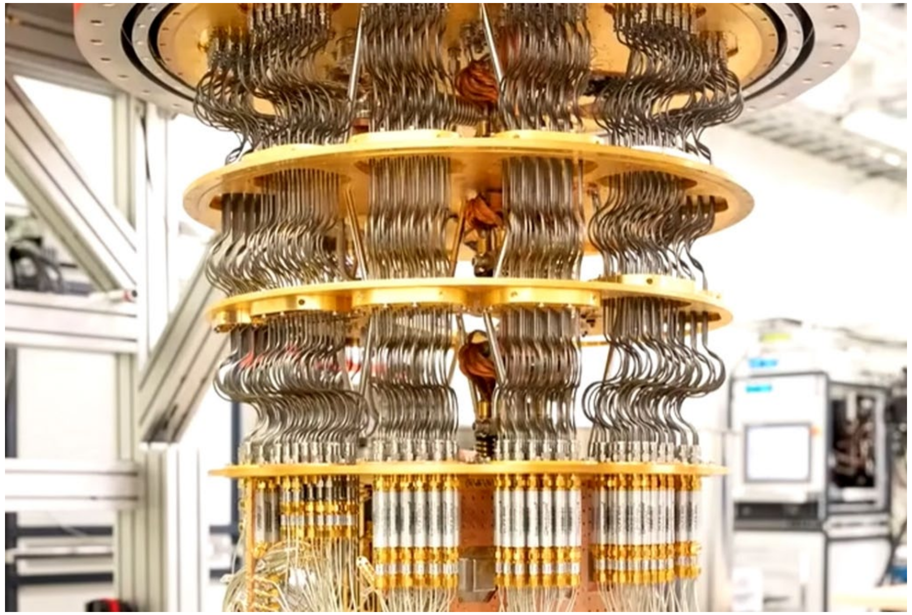
- Communication – what do you gain with some long range links?
  - Tradeoffs of link length, bit rate, fidelity?

Closing Thoughts

- Coherence times have plateaued – is 0.1 – 1 millisecond long enough?
- Scale up and correct, or correct and then scale?
- What are the first real use cases – commercial or scientific?
- What does progress on error-correction and fault-tolerance look like?
- How do we best employ partially corrected machines?
- What can we learn through quantum co-design?

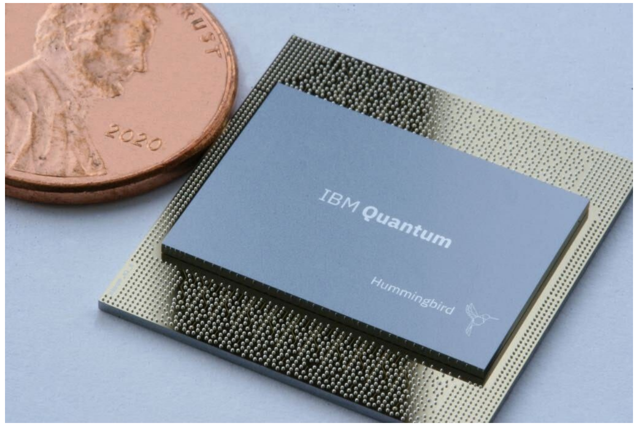
Supporting Technologies

Wiring



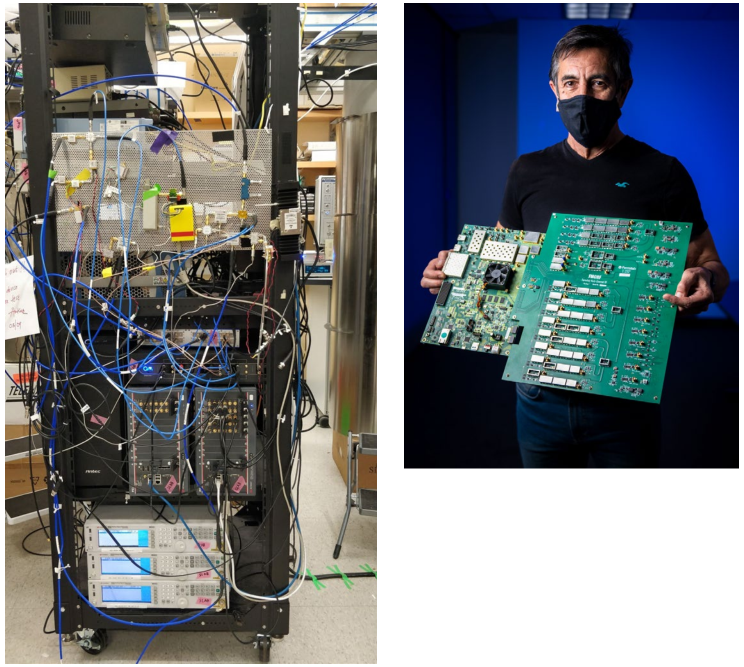
Cryostat for 50 qubits
(Google supremacy experiment)

Packaging/Integration



Chips with multiple
layers for wiring access
(IBM shown here)

Control systems



https://news.fnal.gov

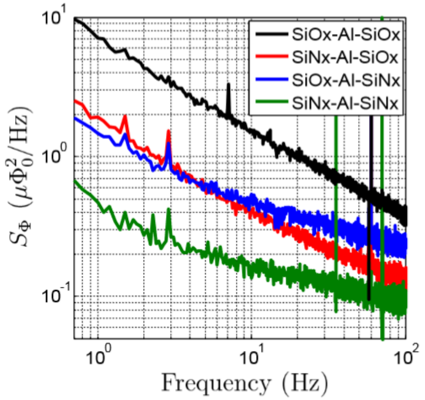
Simplifying and making
control electronic scalable
(Fermilab)

Enabling technology considerations

- Role of materials and fabrication
- Size/density versus performance!
  Coherence is better if devices are bigger…
- Scalability of wiring and filtering
- Control systems – any fundamental limits?
  Warm vs. cold? Overall power of this?

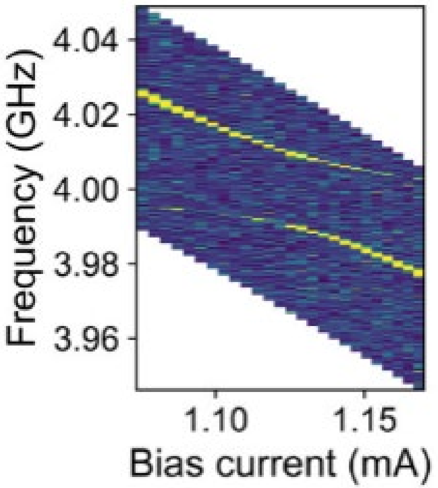
Boojums: Microscopic Physics Still Matters

1/f Flux noise



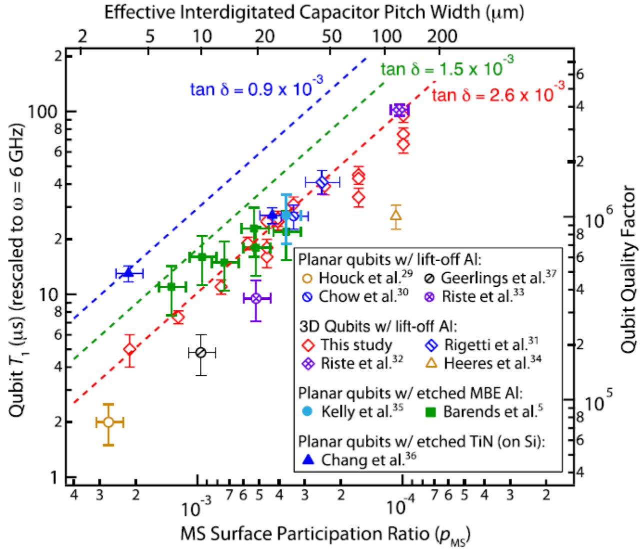
Sendelbach, PhD, U. Wisc, 2013

Coupling to TLS



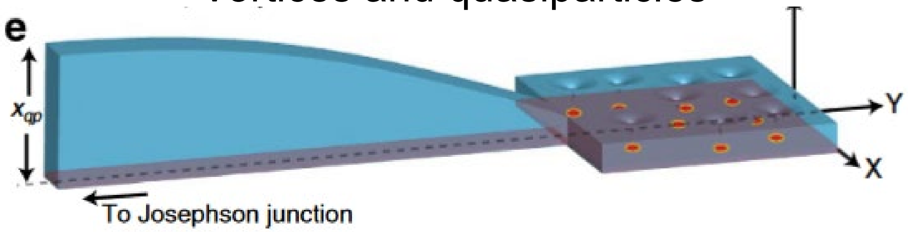
Mamin et al., PR Appl. **16**, 024023 (2021)

Surface dielectric loss



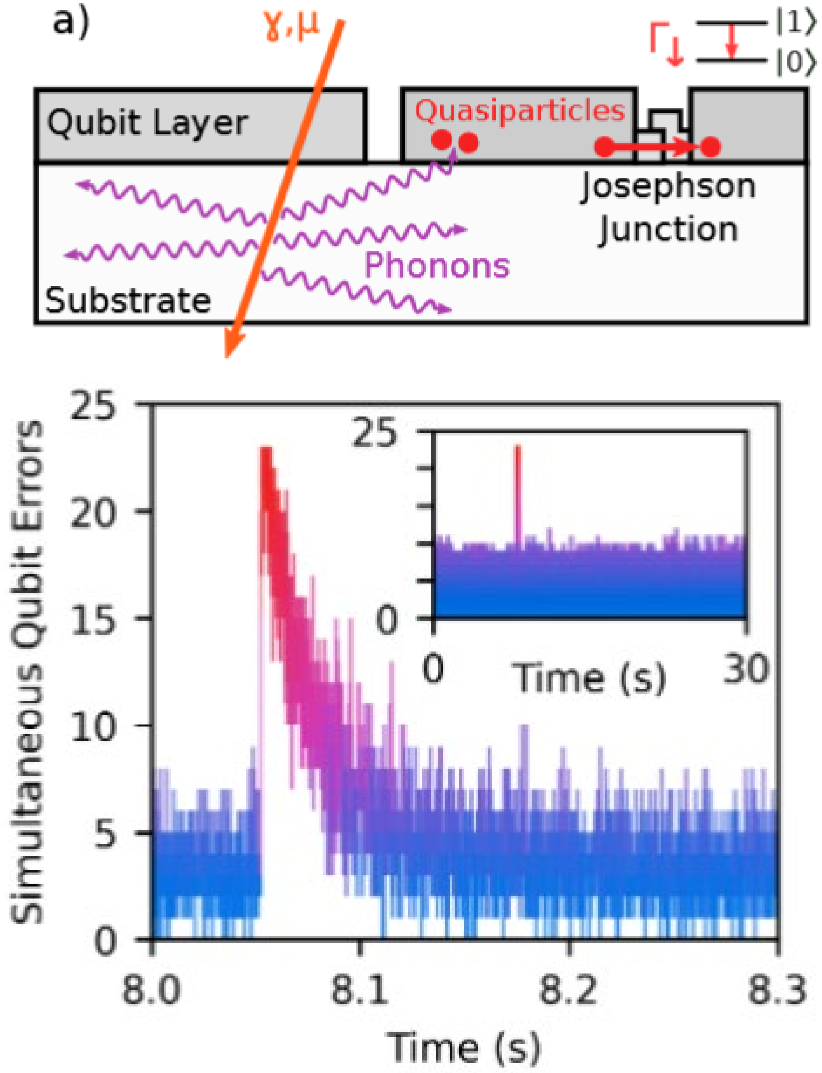
Wang et al., APL **107**, 162601 (2021)

Vortices and quasiparticles



Wang et al., Nature Comms **5**, 5836 (2014)

Cosmic ray “catastrophes”



McEwen et al., arXiv 2104.05219