'Quantum Fluctuation'
by Artist-in-Residence
Martha Lewis

The Second Quantum Revolution: From Macroscopic Quantum Tunneling to the 'Impossible' Computer

Luigi Frunzio

External interest disclosure:
LF is a founder and equity holder of Quantum Circuits, Inc.

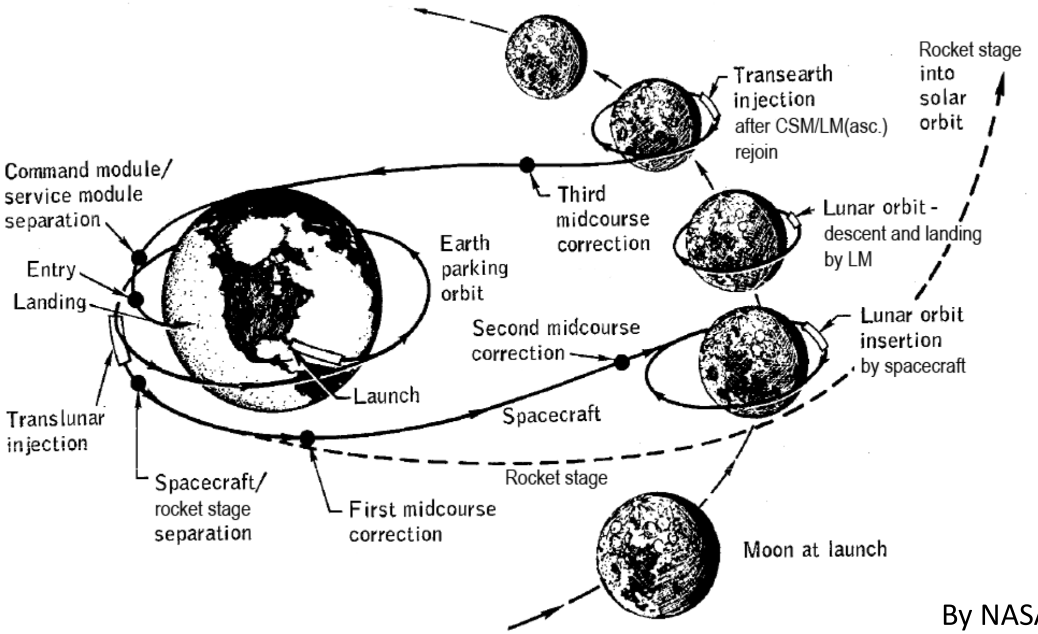
Universita' Milano-Bicocca – November 17th, 2025

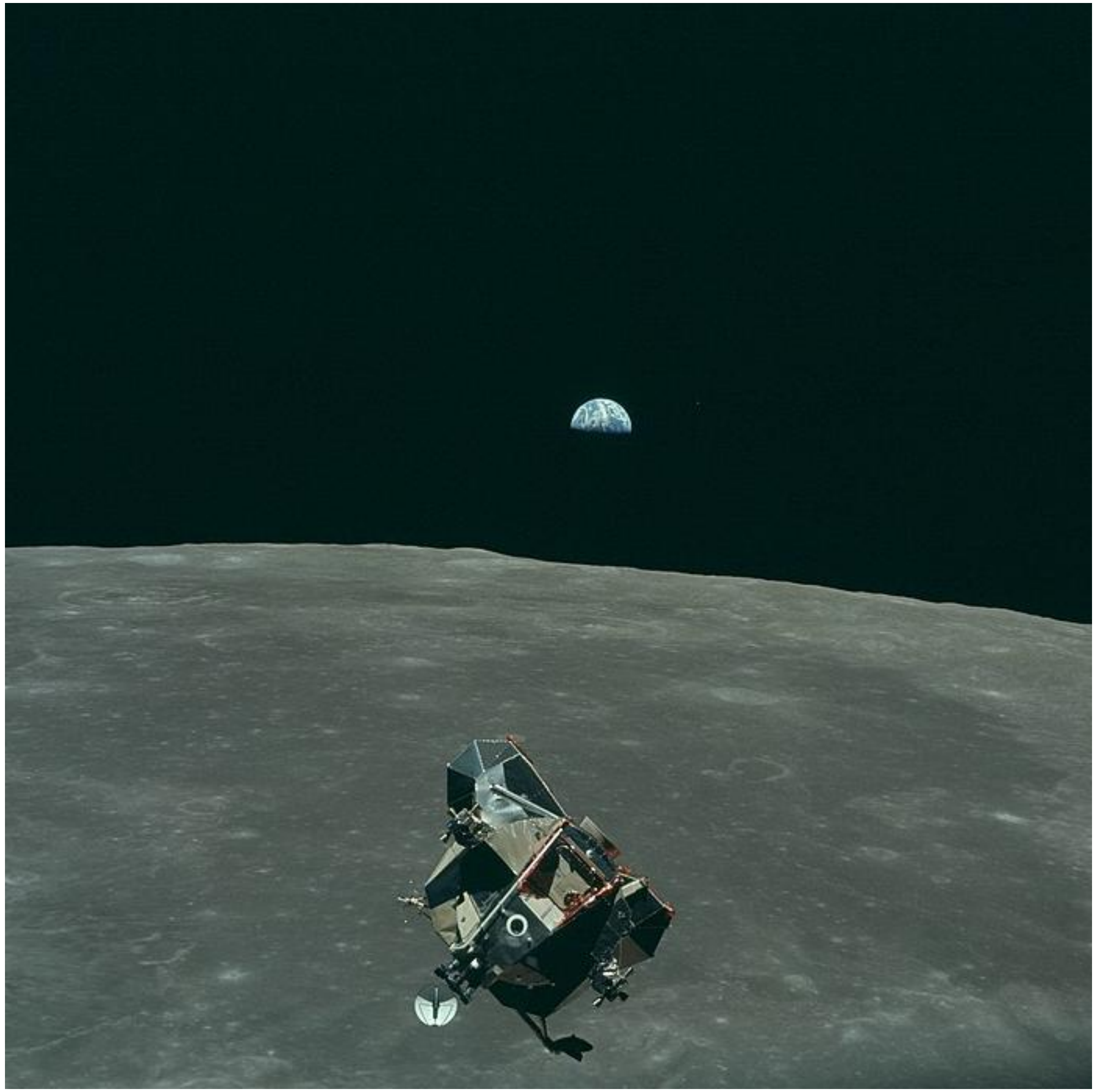
Vocabulary for this talk:

Classical Mechanics: (Galileo & Newton-> Lagrange & Hamilton)

Objects move along well-defined (and completely predictable) trajectories determined by the forces (e.g. gravity) acting on them.

This theory works perfectly for large objects
(sand grains, baseballs, satellites, planets, galaxies).





Apollo 11 Lunar Module. Credit: Michael Collins

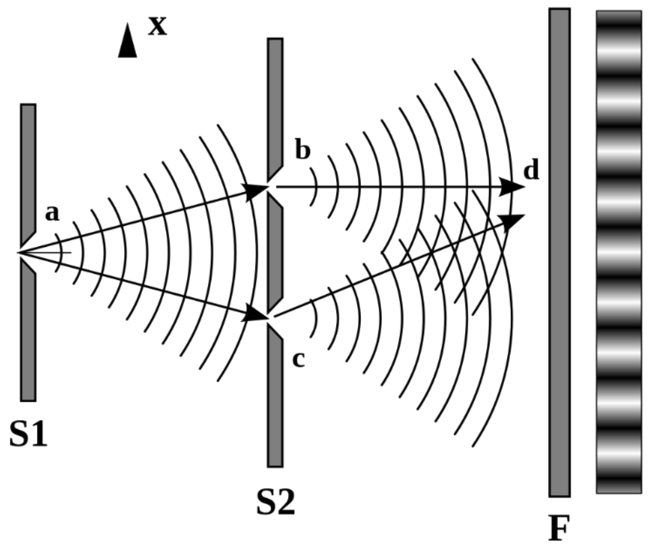
By NASA - http://www.hq.nasa.gov/alsj/a410/A08_MissionReport.pdf, Public Domain, https://commons.wikimedia.org/w/index.php?curid=19587968

Vocabulary for this talk:

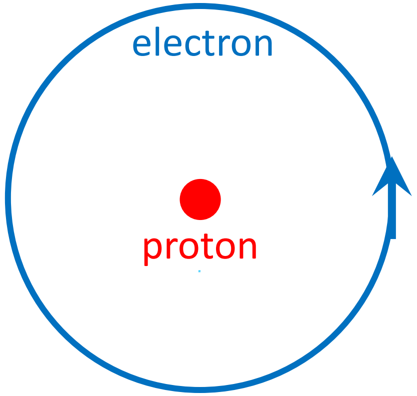
Classical Mechanics: fails in certain extreme limits (e.g., small size: electrons, atoms, …)

Quantum Mechanics: Same predictions as classical mechanics for large objects, but very different (and correct) at the atomic scale. The most accurate theory in all of the physical sciences.

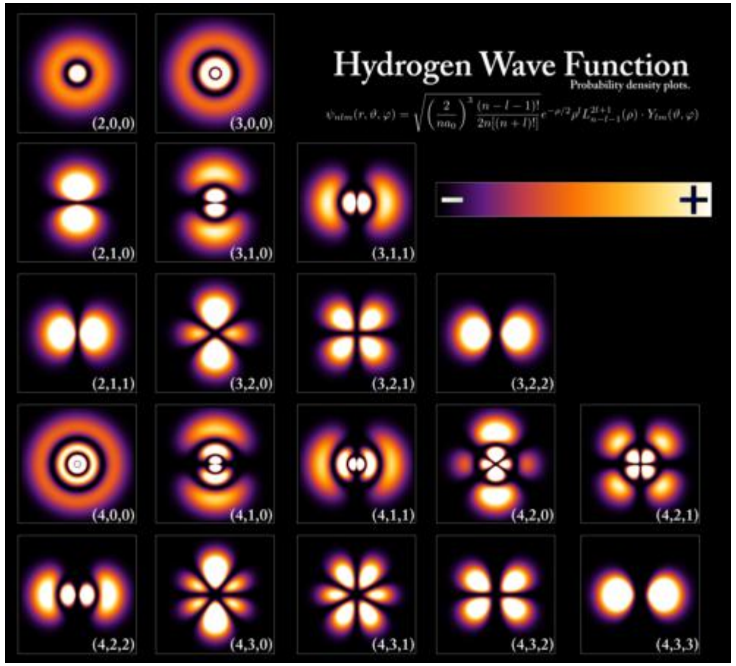
Particles do NOT have well-defined trajectories—they take all possible trajectories!
Particles act like waves.



Old quantum theory: Bohr's electron 'planetary orbit' around proton in hydrogen



Quantum wave picture of electrons



Vocabulary for this talk:

Classical Mechanics: fails in certain extreme limits (e.g., small size: electrons, atoms, …)

Quantum Mechanics: Same predictions as classical mechanics for large objects, but very different (and correct) at the atomic scale. The most accurate theory in all of the physical sciences.

Particles do NOT have well-defined trajectories—they take all possible trajectories!
Particles act like waves.

Classical Computers: Ordinary electrical/mechanical devices that follow the laws of classical mechanics.

Quantum Computers: A completely new type of computer based on the laws of quantum mechanics.

Feynman, Int. J. Theor. Phys. 21, 467 (1982)

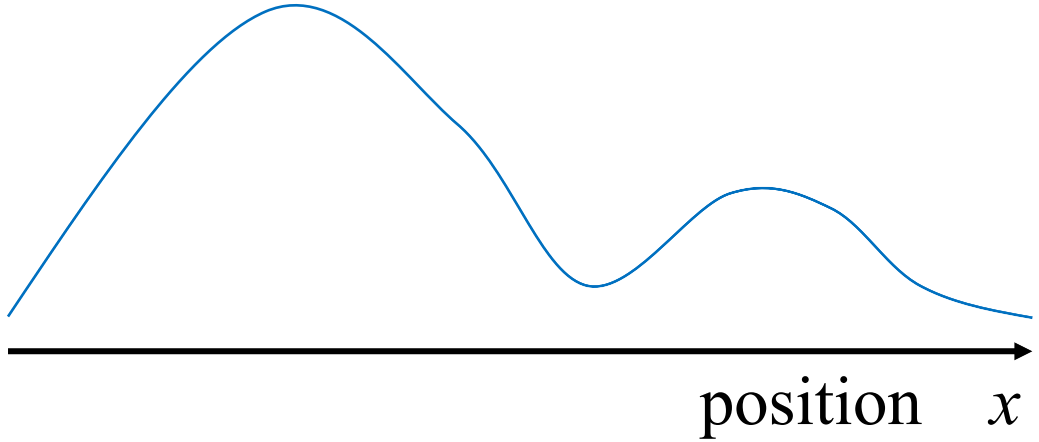
Quick Review on Quantum Mechanics - I

- Quantum theory describes behavior at atomic (and now larger) scales.
  - Particles act like waves (e.g. electrons).
  - Waves act like particles (e.g. photons).

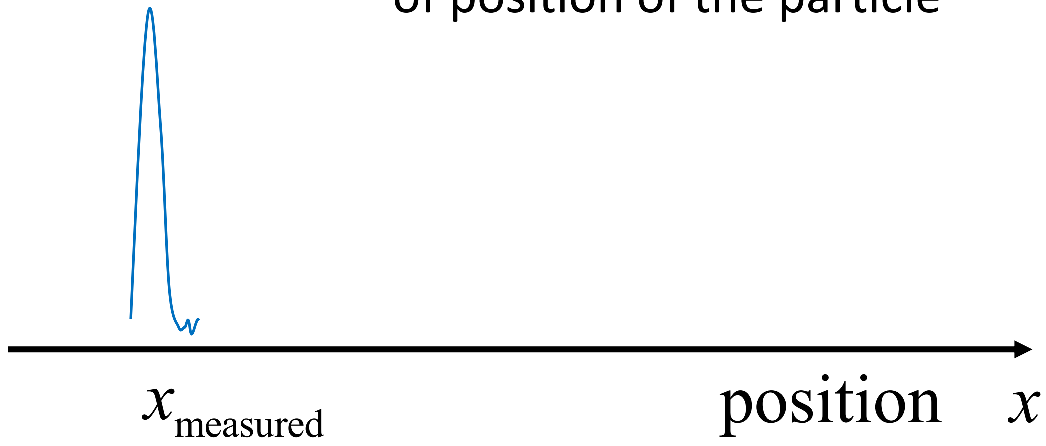
  - Counter-intuitive effects involving
    - uncertainty and ineluctable randomness ('superposition')
    - act of measurement affects the quantum state
    - 'spooky action at a distance' ('entanglement')

$$|\rightarrow\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle$$

Quantum wave <u>before</u> measurement.
Particle does not have a definite position.



Quantum wave <u>after</u> measurement of position of the particle



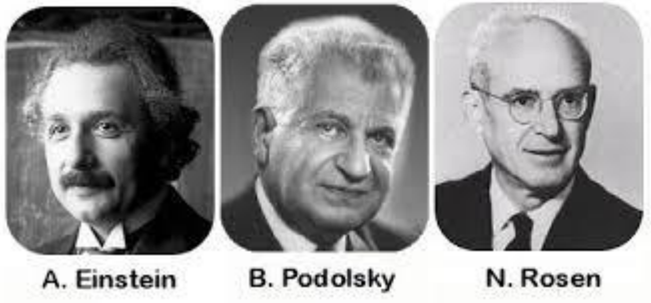
Quick Review on Quantum Mechanics - II

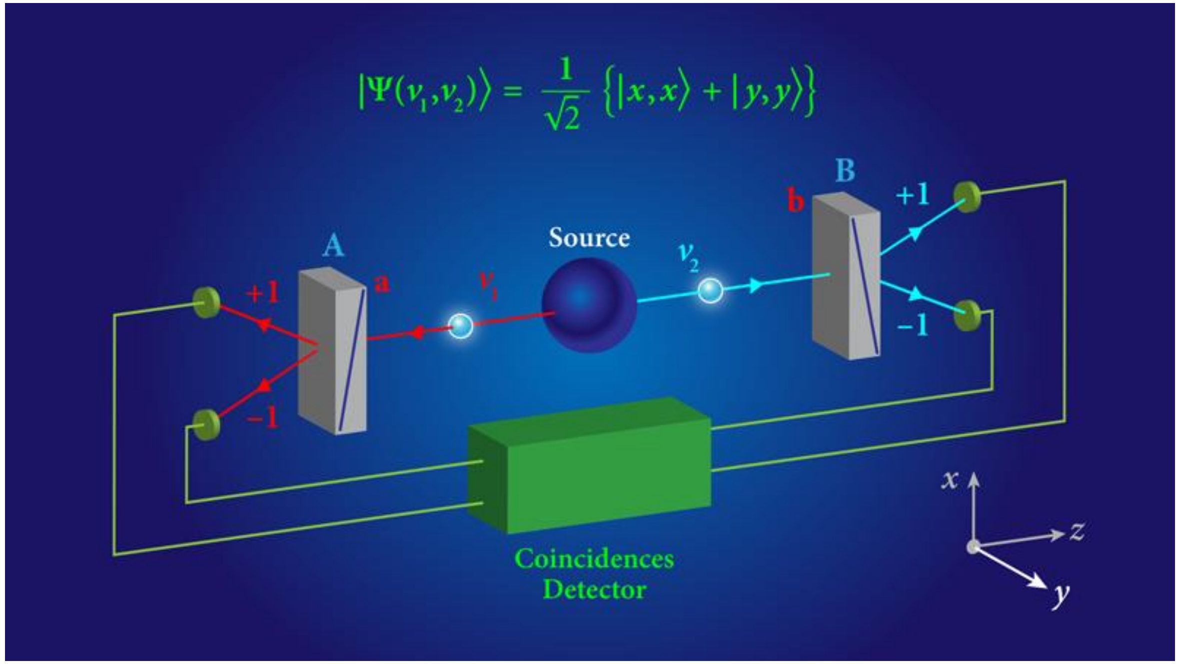
Bell's states

$$|\psi_{1,2}\rangle = \frac{1}{\sqrt{2}}(|01\rangle \pm |10\rangle)$$

$$|\varphi_{1,2}\rangle = \frac{1}{\sqrt{2}}(|00\rangle \pm |11\rangle)$$

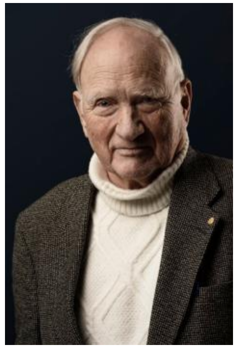
1936





Bell's inequality
local realism vs non-locality

1972

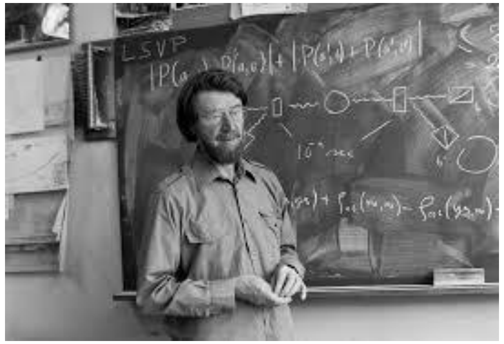


John Clauser

1982

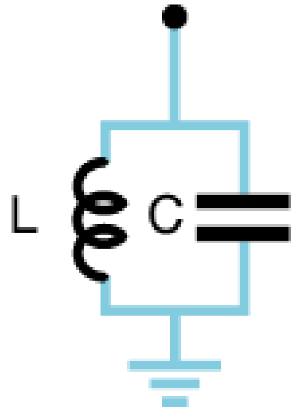
Alain Aspect

1964



John Bell

Quantizing Circuits



Leggett, J. Phys. Colloques ***39,*** *C6-1264 (1978)*
Progr. Theor. Phys. **69**, 80 (1980)

Are there Macroscopic Quantum Coherence Effects such that large visible object have their macroscopic Parameters quantized?

Are V and I ever quantum?

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

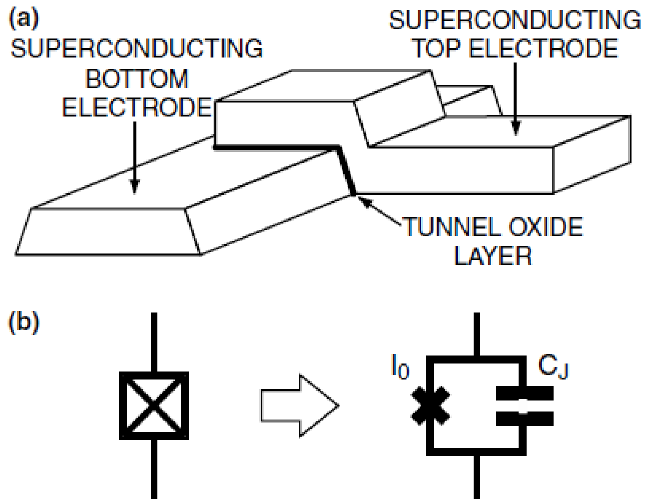
"p"

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

"x"

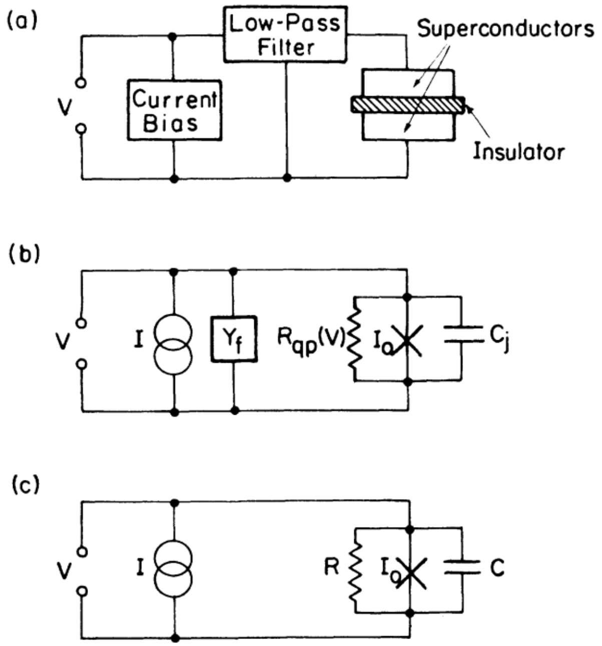
$$\varphi = \sqrt{\frac{\hbar Z_0}{2}}(a + a^\dagger)$$

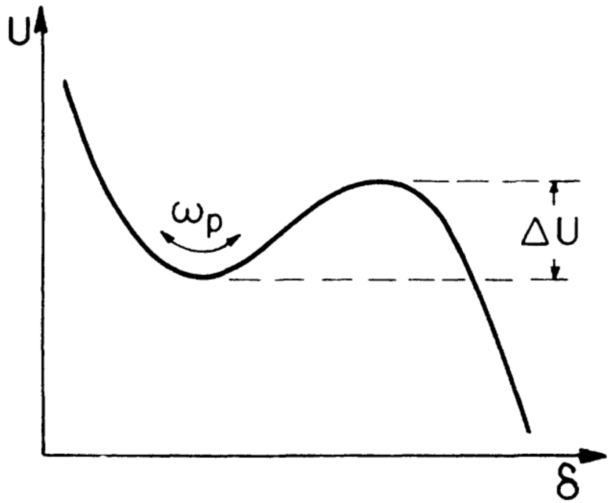
Josephson junction

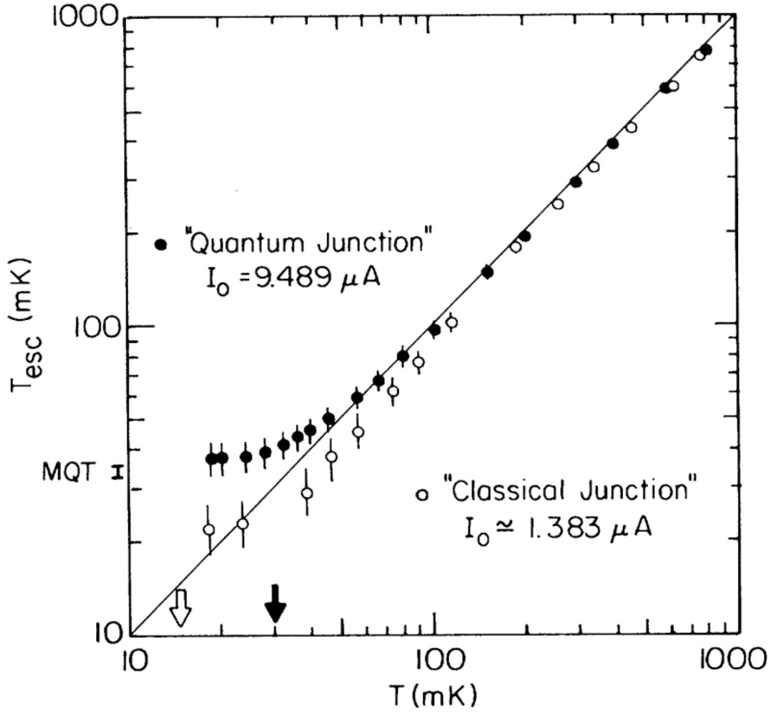


$$H = \frac{Q^2}{2C} + E_J\cos(\phi)$$

The Nobel Prize in Physics 2025







JohnClarke

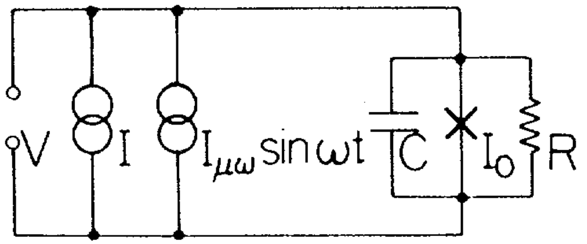
Michel Devoret

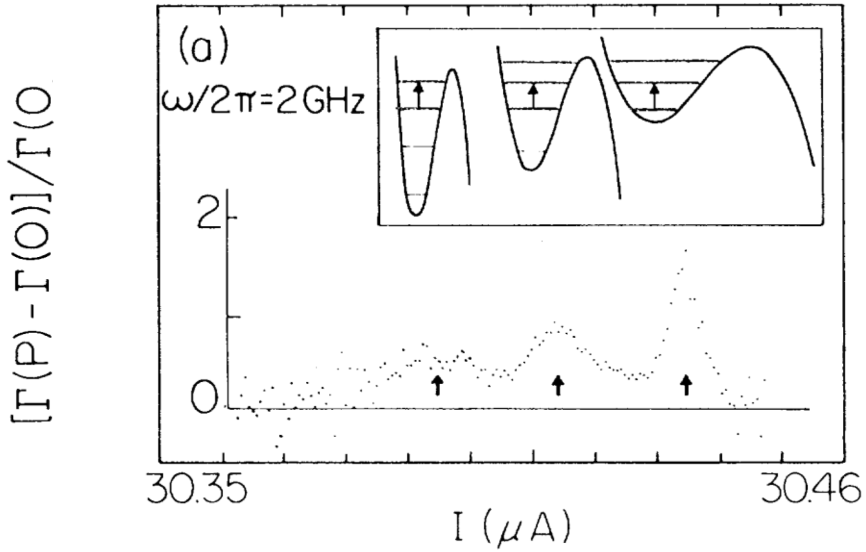
John Martinis

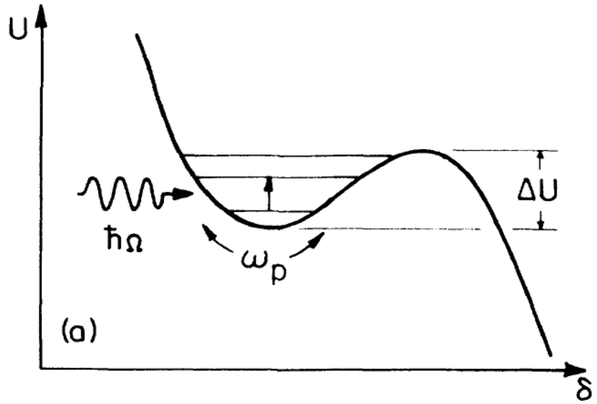
"for the discovery of macroscopic quantum mechanical tunneling and energy quantisation in an electrical circuit"

Devoret, Martinis, Clarke
Physical Review Letters 55, 1908
(28 October 1985)

The Nobel Prize in Physics 2025








JohnClarke


Michel Devoret


John Martinis

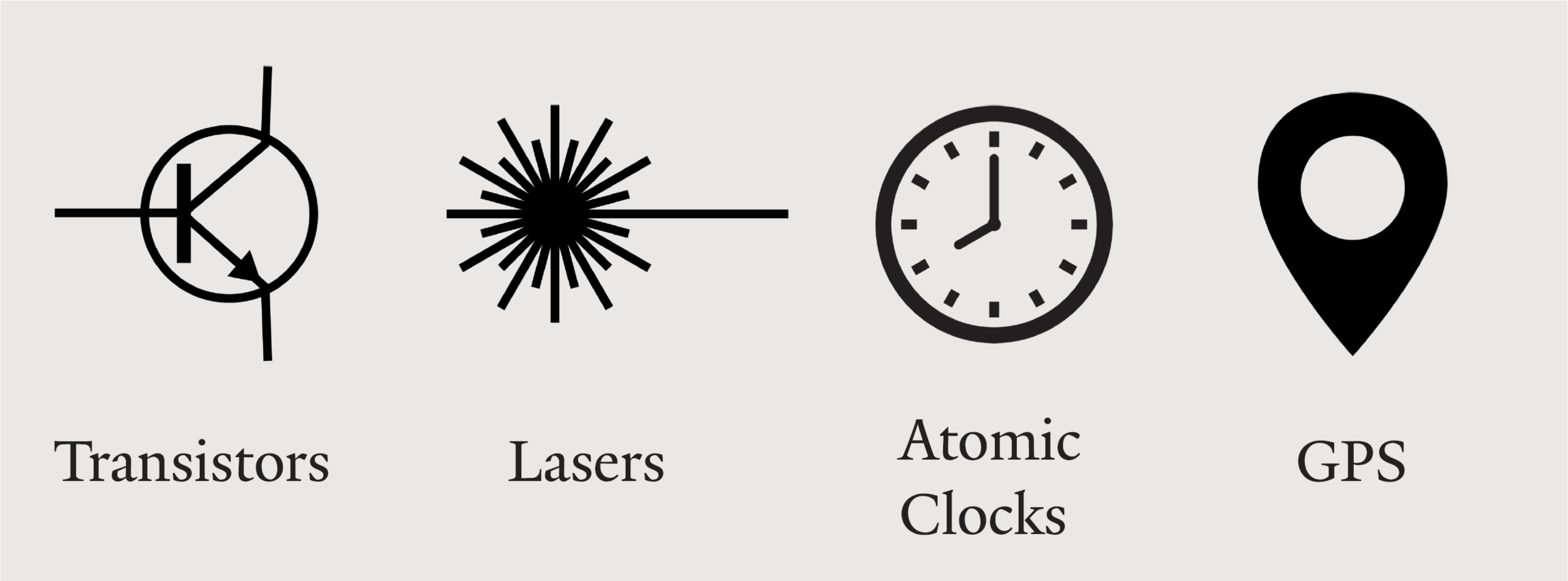
"for the discovery of macroscopic quantum mechanical tunneling and energy quantisation in an electrical circuit"

Devoret, Martinis, Clarke
Physical Review Letters 55, 1908
(28 October 1985)

Martinis, Devoret and Clarke
Physical Review Letters 55, 1543
(7 October 1985)

The First Quantum Revolution 1900-1964

The inventors of quantum mechanics did not foresee any of these quantum devices.



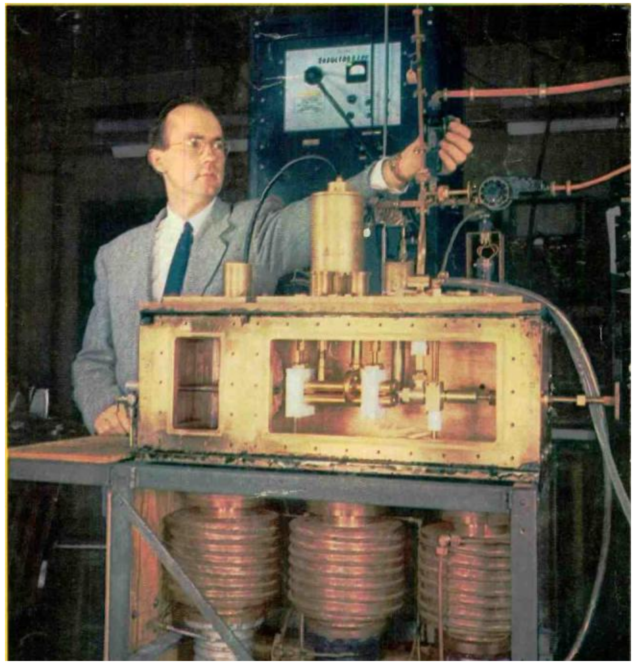
The inventors of these quantum devices did not foresee their applications.

These quantum devices do **not** use the full power of quantum mechanics.

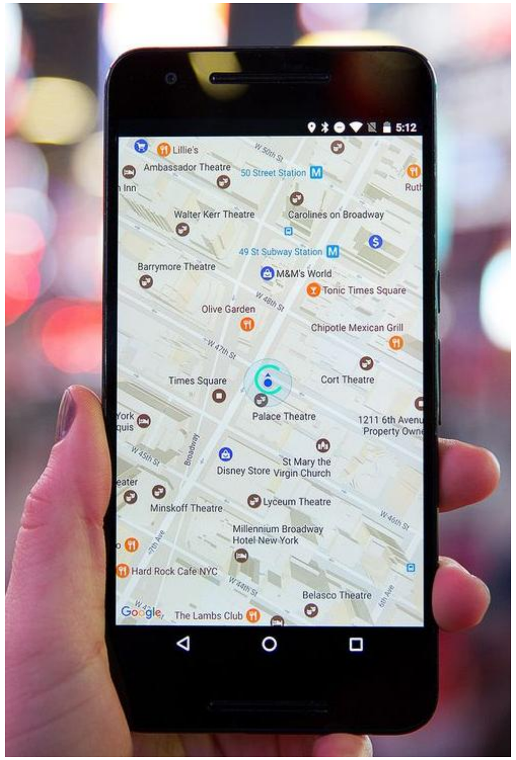
The material parameter values (e.g. frequency of laser, threshold voltage for transistor) are predicted by quantum mechanics **but** the collective variables are largely classical.

20th Century Tech Revolution

Charles Townes



1953
Atomic Clocks

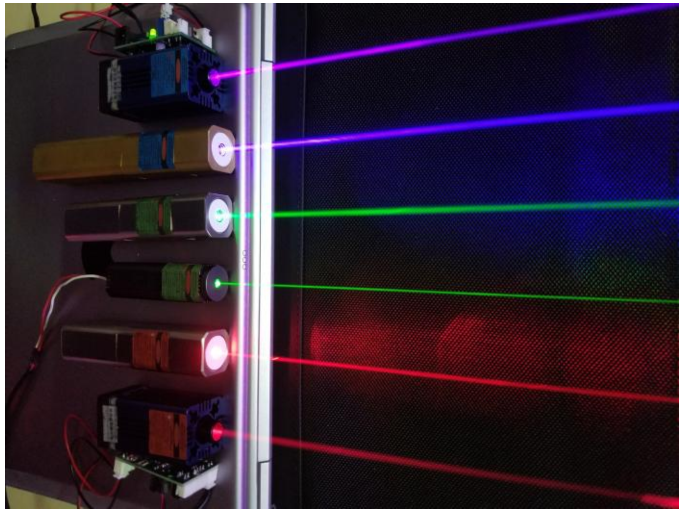


GPS

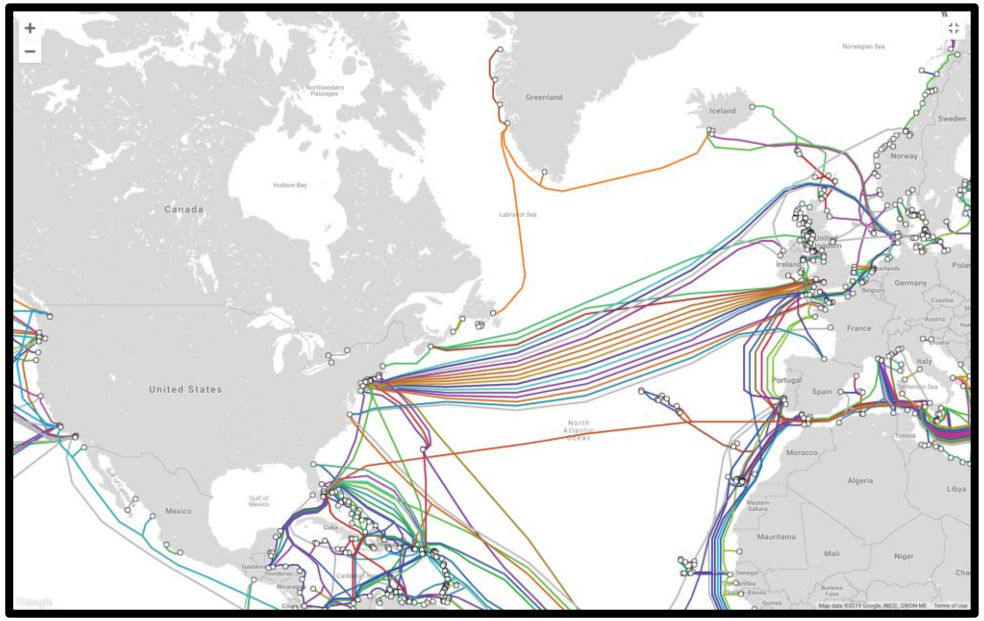
20th Century Tech Revolution

1960
Lasers

Theodore Maiman

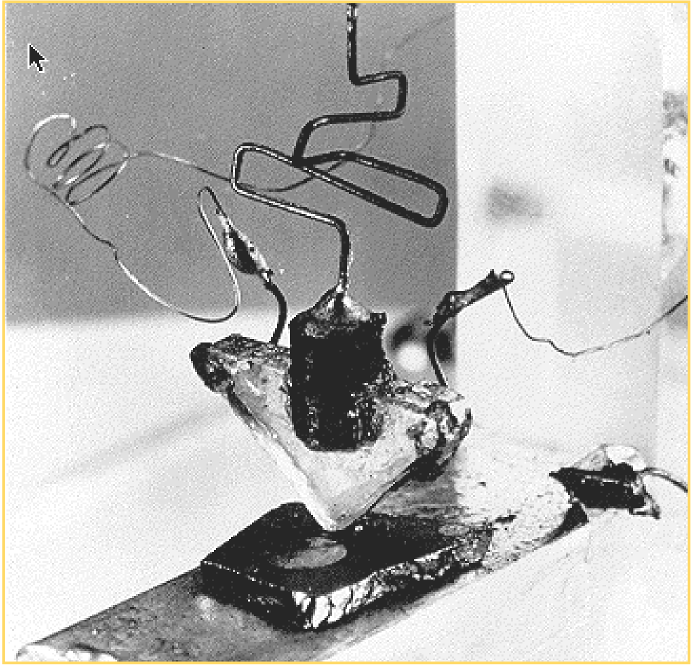


CD-player laser



Transoceanic fiber-optic communication

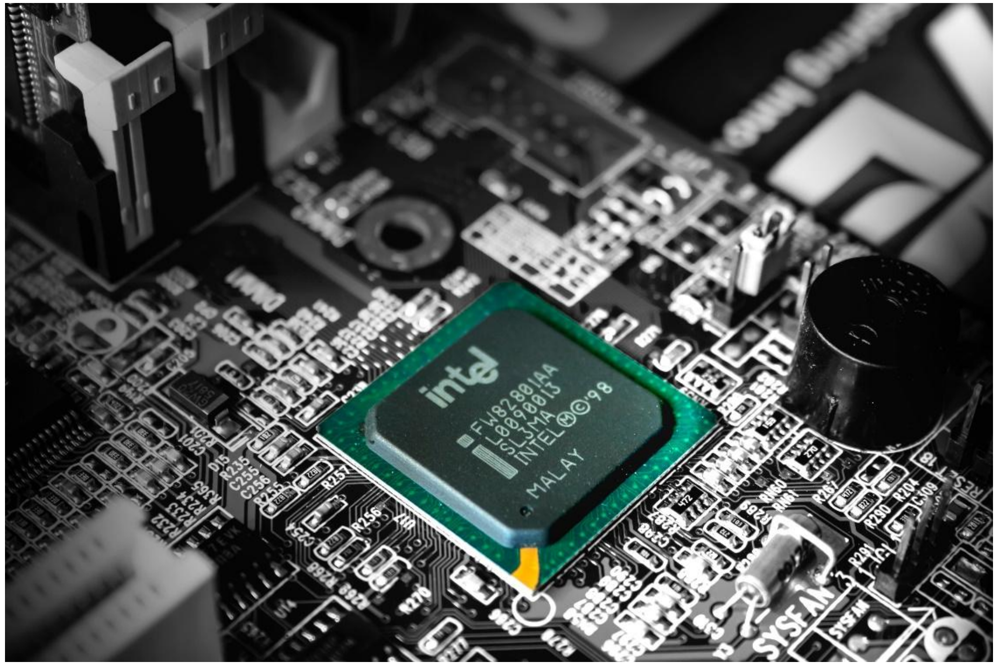
20th Century Tech Revolution



1947

Transistor

Bardeen, Brattain, Shockley



Current rate of transistor production?

>20 trillion/sec !!

The Second Quantum Revolution

The new idea:

Take the strangest aspects of the quantum theory (uncertainty, randomness and 'spooky action at a distance')

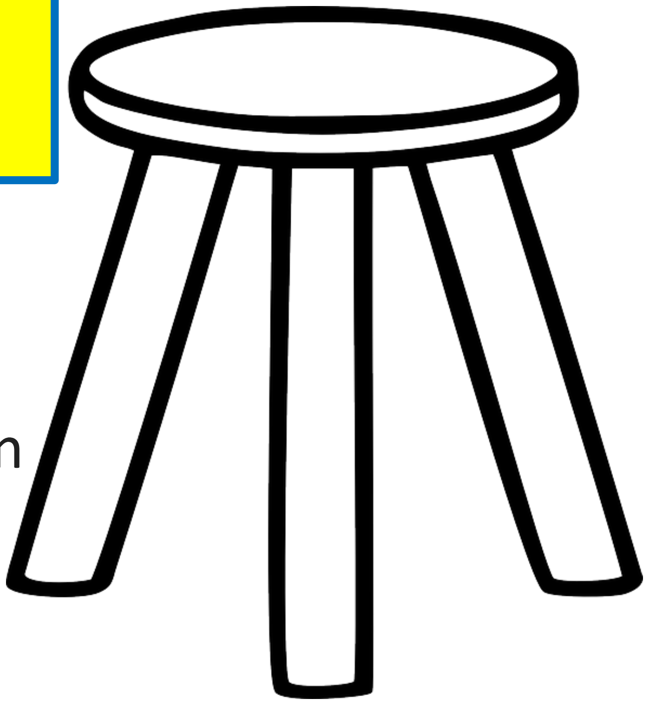
and consider them not as **bugs**, but rather as **features**

and **harness** them in new technologies.

A second revolution is underway for the 21st Century

We cannot foresee its consequences.

- We are well in the "NISQ Computer" era.
- Rudimentary quantum computers exist but do not yet work well.
- We have invented the quantum abacus or maybe the quantum vacuum tube.



- Quantum Computing
  Quantum Simulation
  Quantum Communication

- Quantum Materials
  - 2D Superconductors
  - Topological insulators
  - Twisted bilayer graphene
  - Majorana fermions?

Bad!

Quantum states are extremely sensitive to external perturbations

Good!

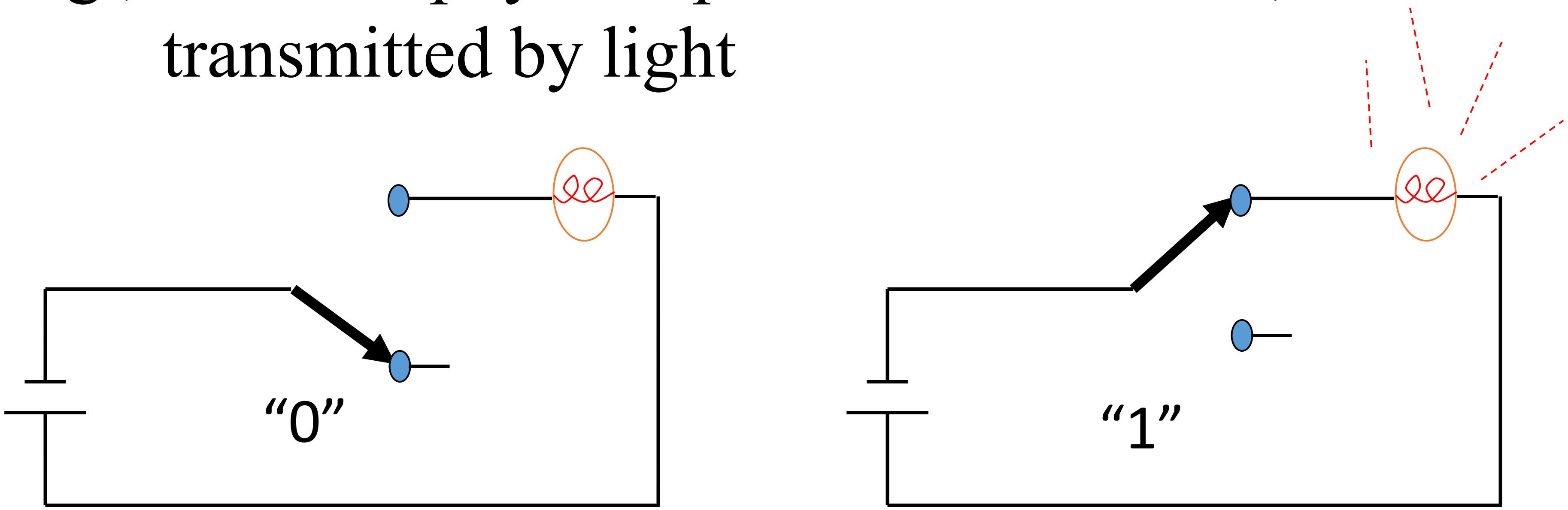
- Quantum Sensing (new understanding of quantum measurements)
  - Gravitational waves (LIGO)
  - Axion Dark Matter searches (HAYSTAC and ALPHA @ Yale)
  - Single-molecule NMR

Classical bits

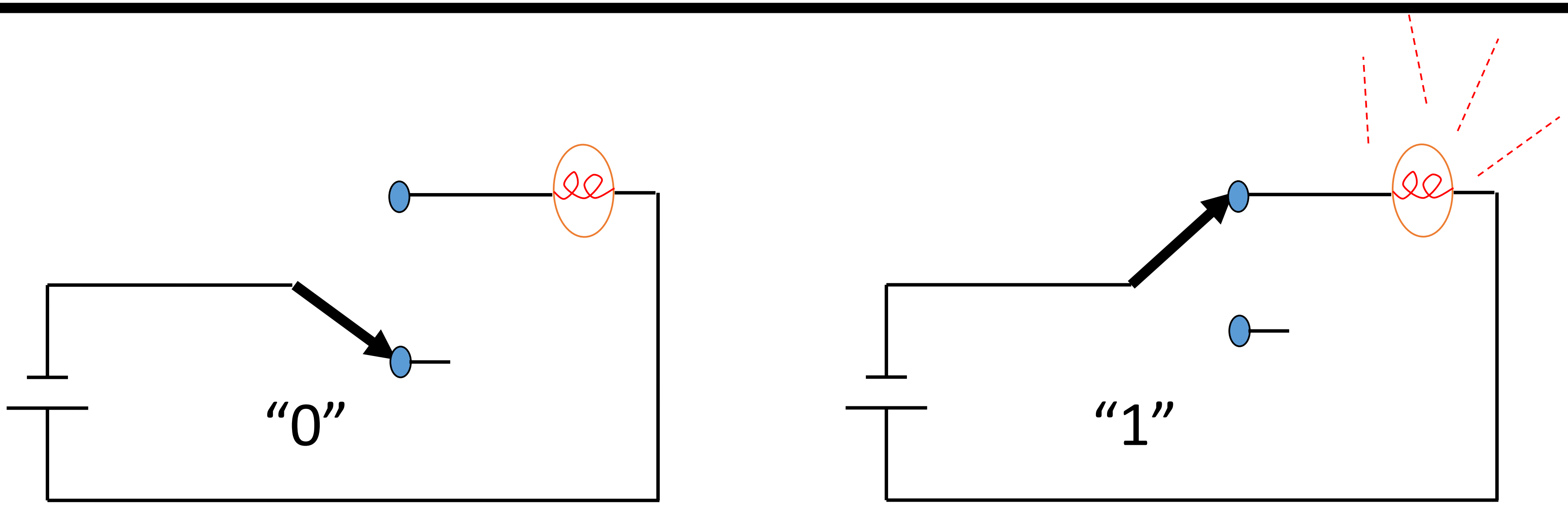
Information is physical.

Information is stored in, and transmitted by, physical systems

e.g., stored in physical position of a switch;
transmitted by light

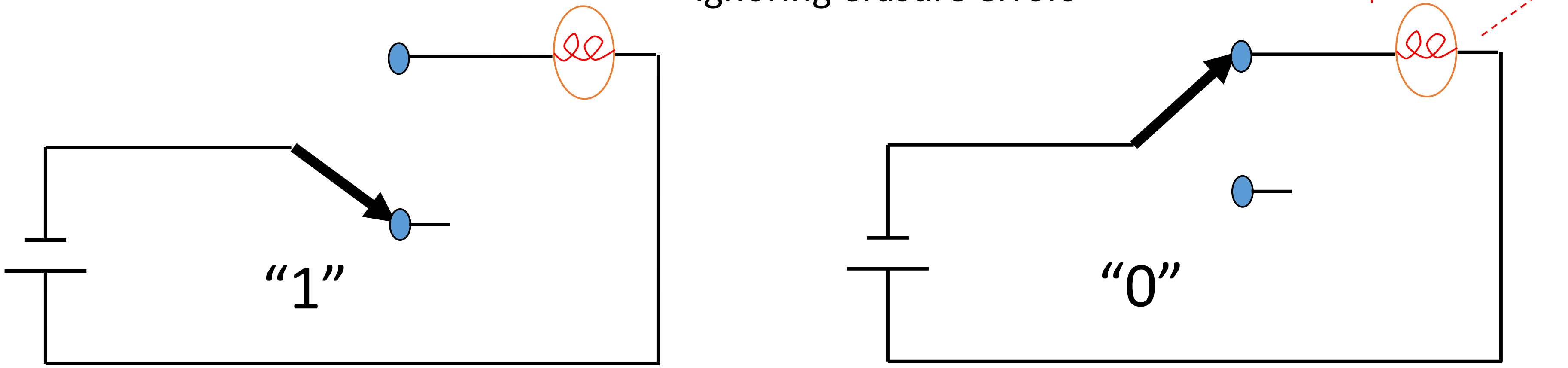


There exist (only) two possible encodings for classical bits.



Thus there exists only one* kind of error for a classical bit: bit flip.

*ignoring erasure errors



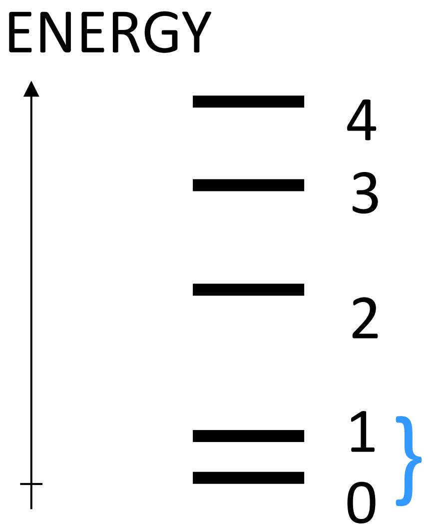
Quantum bits (‘qubits’)

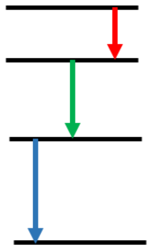
Information is physical.

Quantum information is stored in the physical states of a quantum system:

- atoms, molecules, ions …
- photons
- superconducting circuits
- mechanical oscillators, …

Discrete quantized energy levels



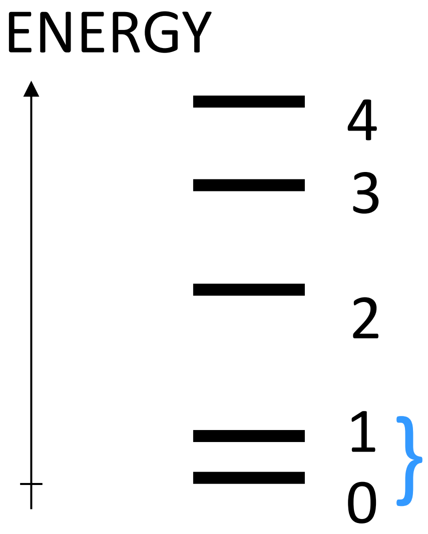


Quantum information is digital:

Energy levels of a quantum system are discrete.

We (typically) use only the lowest two.

Measurement of the state of a qubit yields one classical bit of information: Measurement result is always 0 or 1.



Four important notations:

CS, Physics, NMR:

$$\text{excited state } 1 = |e\rangle = |\downarrow\rangle, Z = -1$$

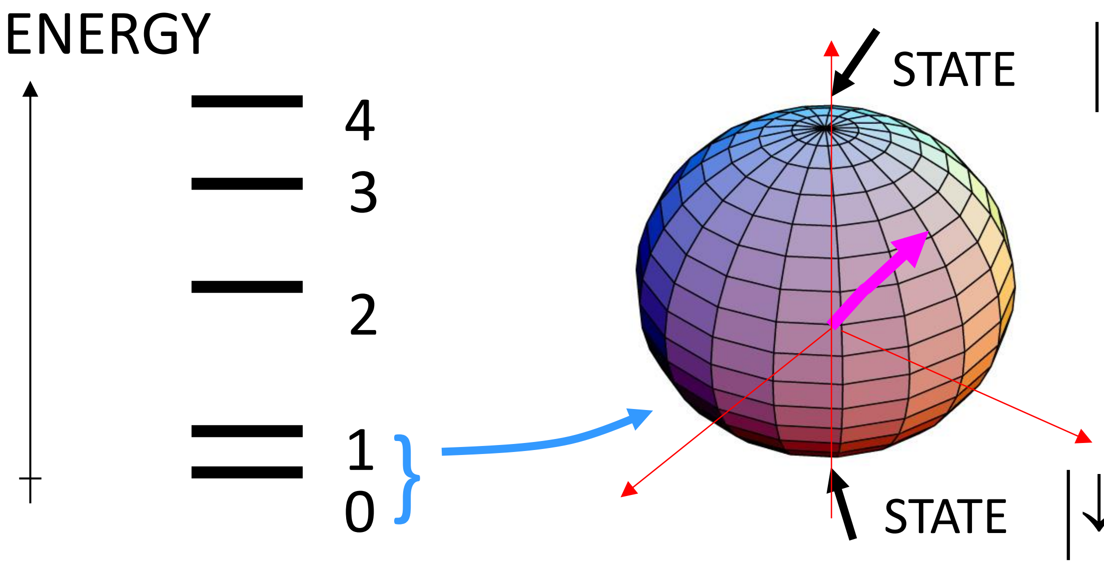
$$\text{ground state } 0 = |g\rangle = |\uparrow\rangle, Z = +1$$

Quantum information is analog:

A quantum system with two distinct states can exist in an Infinite number of physical states ('superpositions') *intermediate* between $|\downarrow\rangle$ and $|\uparrow\rangle$.

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

Unlike classical bits, qubit states (and errors) are continuous!



$|\uparrow\rangle = |0\rangle$

$|\downarrow\rangle = |1\rangle$

$\theta =$ co-latitude

$\varphi =$ longitude

State defined by 'spin polarization vector' on Bloch sphere

Feature:
Qubit is in 'both states at once,' [sort of…] so we can do parallel processing. Potential exponential speed up.

A classical register of N bits can be in 1 of 2^N states:

$$|000\rangle, |001\rangle, |010\rangle, |011\rangle, |100\rangle, |101\rangle, |110\rangle, |111\rangle$$

A quantum register can hold an exponentially large superposition of all possible 2^N states

Arbitrary complex coefficients

$$|000\rangle \Rightarrow |000\rangle + |001\rangle - |010\rangle - |011\rangle + |100\rangle + |101\rangle + |110\rangle - |111\rangle$$

that can be created in one time step!

Even a small quantum computer of 53 qubits has a state space so large (1 petabyte) that its operation is difficult to simulate on a conventional supercomputer.

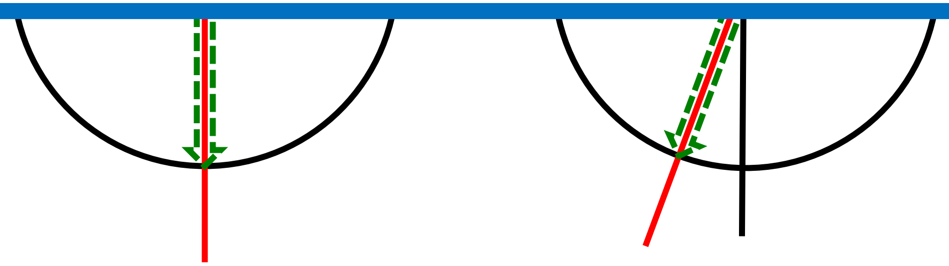
Quantum information is analog/digital:

Equivalently: a quantum bit is like a classical bit except there are an infinite number of encodings (aka 'quantization axes').

If Bob gives Alice a $Z' = +1$,

"In quantum mechanics you don't see what you get, you get what you see."

(Sasha Korotkov)



Not probabilities

Alice

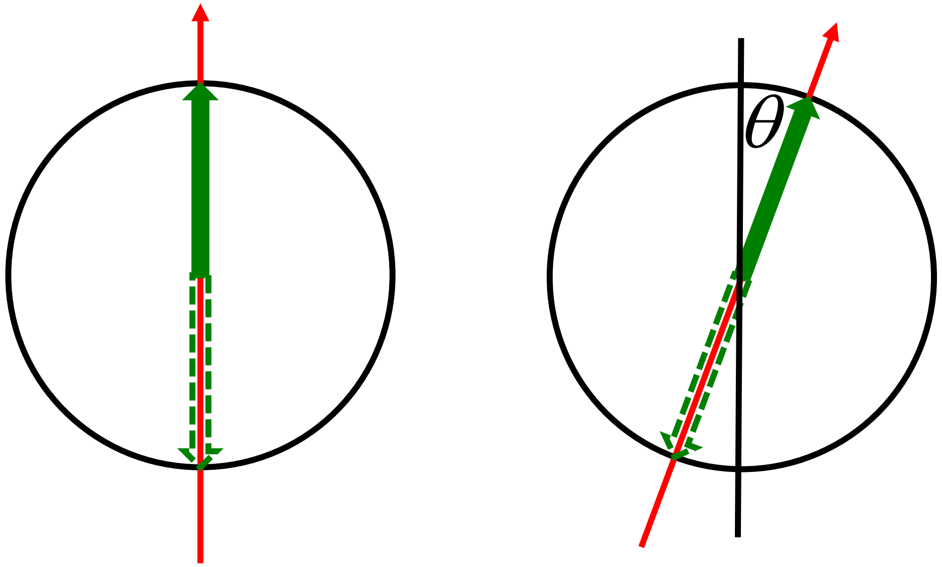
Bob

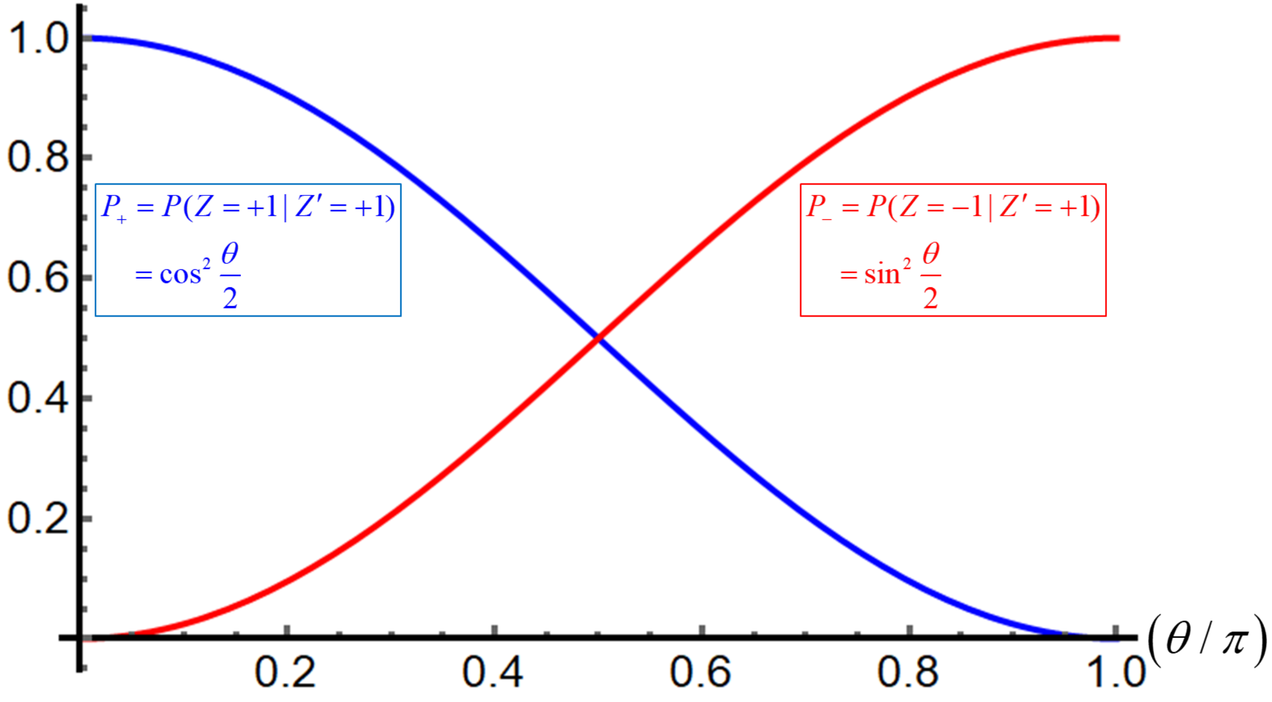
'Back action' (aka 'state collapse') of Alice's measurement changes the state, but this is invisible to Alice.

Why are quantum measurement results random?

Q: How do we reconcile discrete (digital) measurement results and continuous (analog) quantum states (encodings)?

A: Randomness is the only solution!





Measurement results are discrete but the probability distribution of random results is continuous.

A quantum register can hold an exponentially large superposition of

all possible 2^N states

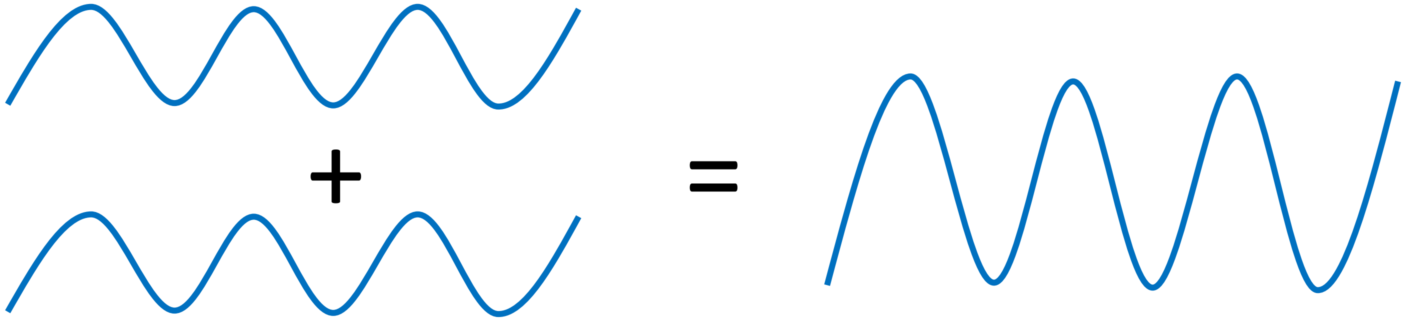
$$|000\rangle \Rightarrow |000\rangle + |001\rangle - |010\rangle - |011\rangle + |100\rangle + |101\rangle + |110\rangle - |111\rangle$$

Feature: Since this includes all possibilities, the answer to our calculation is in here!

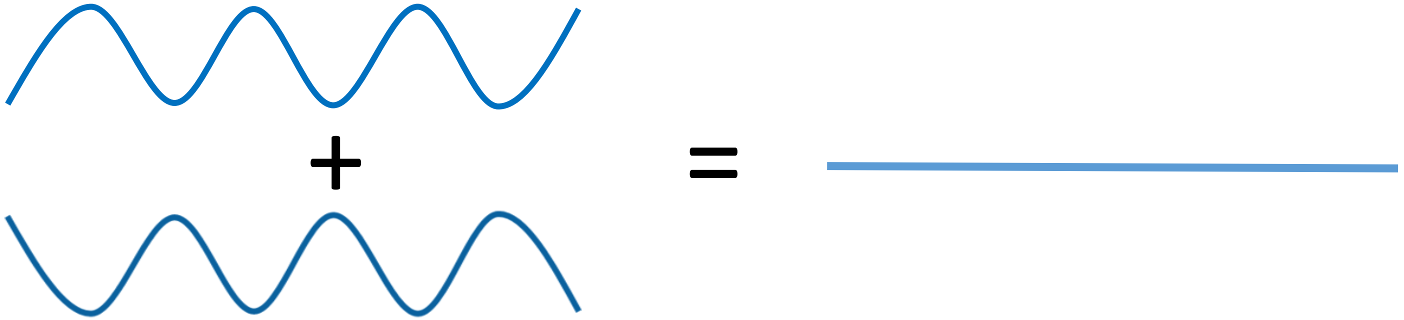
Bug: Measurement yields an almost completely random bit string.
(Not likely to be the correct answer.)

Q: How can quantum algorithms produce useful results instead of random noise?

A: Quantum particles (and qubits) have wave-like properties. Use wave interference.



Constructive interference: Higher intensity means higher probability of seeing this in the answer.



Destructive interference: Lower intensity means lower probability of seeing this in the answer.

Quantum register

$$|000\rangle \Rightarrow |000\rangle + |001\rangle + |010\rangle + |011\rangle + |100\rangle + |101\rangle + |110\rangle + |111\rangle$$

1994

Peter Shor

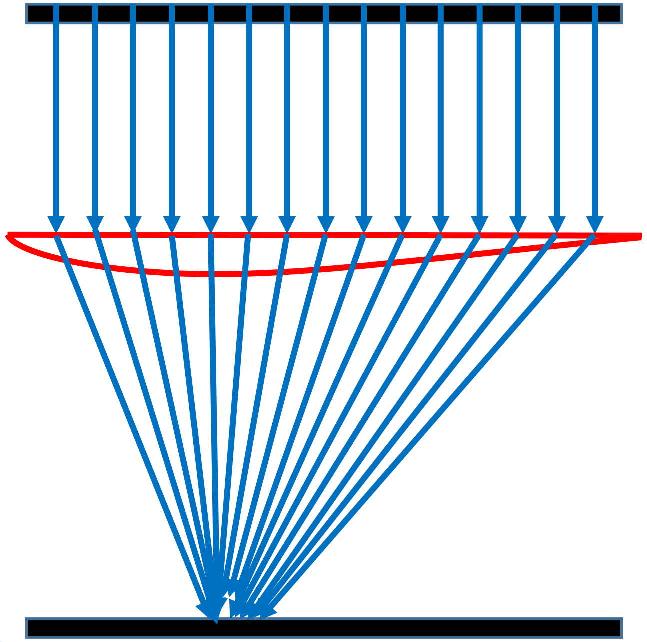
Quantum computer program

Apply wave-like destructive interference to eliminate (many of) the “wrong” answers.

$$\cancel{|000\rangle} + \cancel{|001\rangle} + |010\rangle + |011\rangle + \cancel{|100\rangle} + \cancel{|101\rangle} + \cancel{|110\rangle} + \cancel{|111\rangle}$$

Measurement then yields the correct answer with high probability.

INPUT (superposition)



OUTPUT “focused” on correct answer

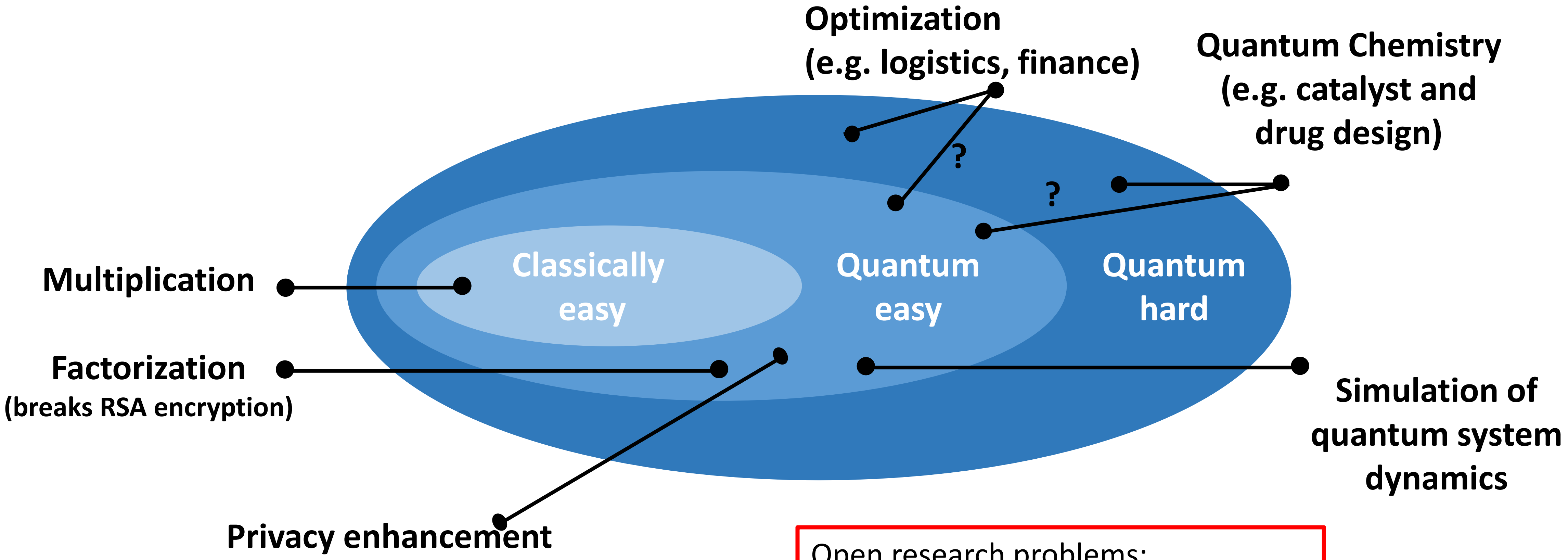
Grand Challenge of quantum algorithm development:
How do we make the right shape for the “focusing lens” for problems where we don’t yet know the answer?
What is the ‘killer app’ that will offer quantum utility assuming the hardware is nearly perfect?

We still aren’t sure, but quantum chemistry and materials science look promising even though technically these are <u>quantum hard</u>.

What powers do quantum machines have?

We aren't actually sure…still a partially open problem in quantum CS.

The realization that quantum information processors can be vastly more powerful than traditional computers has overturned the foundations of theoretical computer science established nearly a century ago by Church and Turing.



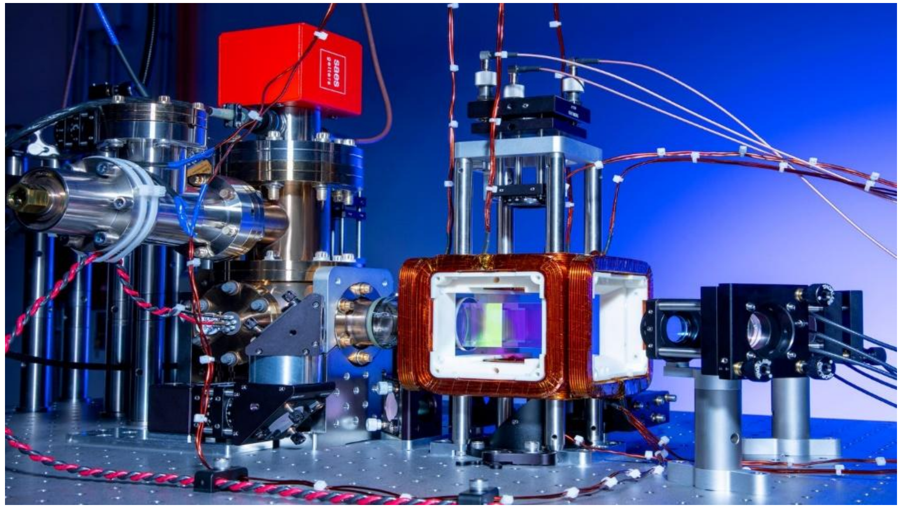
Open research problems:
- quantum complexity classification
- quantum heuristics

Quantum Hardware

NMR

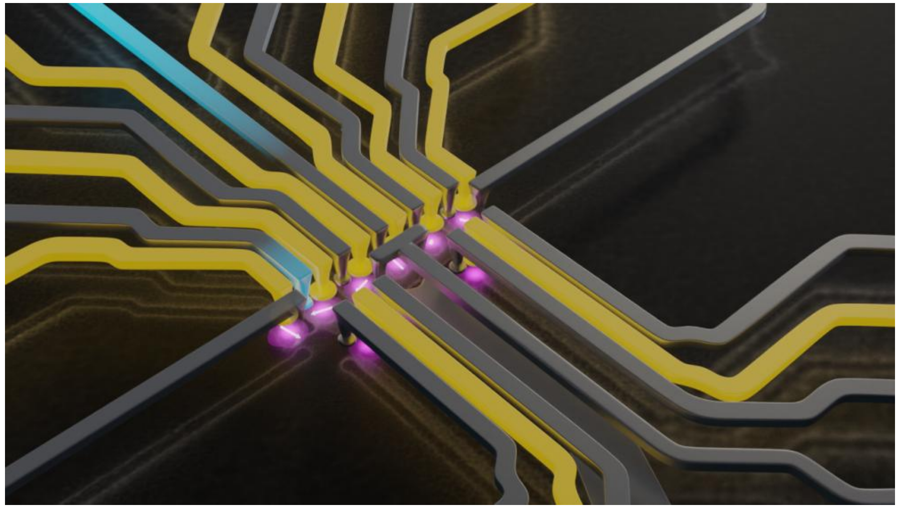
PC: Volker Steger/ Science Photo Library

Neutral atoms



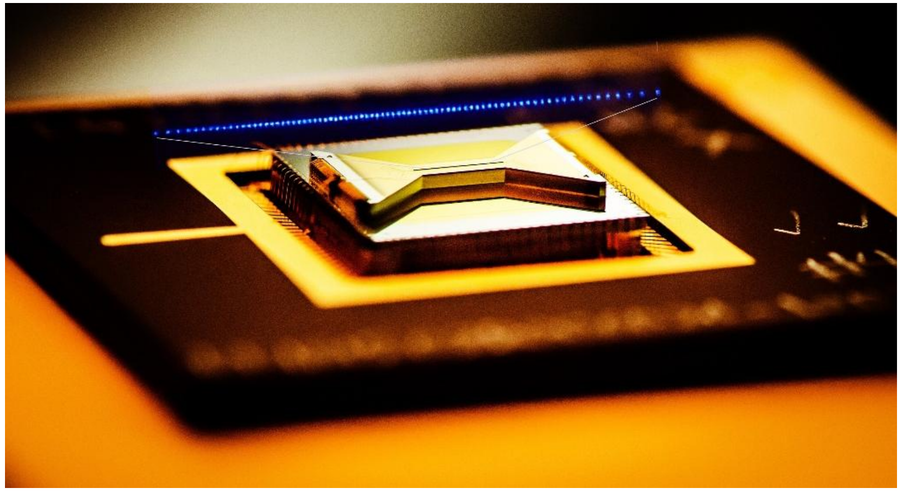
PC: QuEra

Electron spins



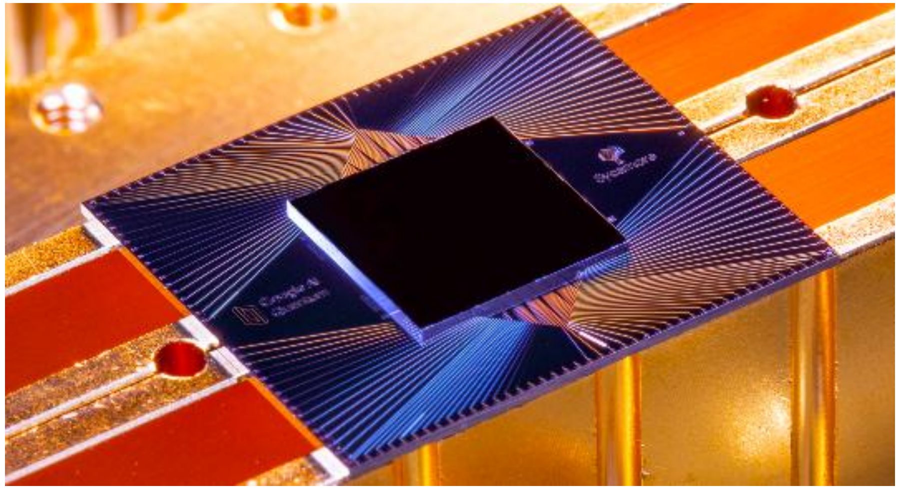
PC: HRL Laboratories

Trapped ions



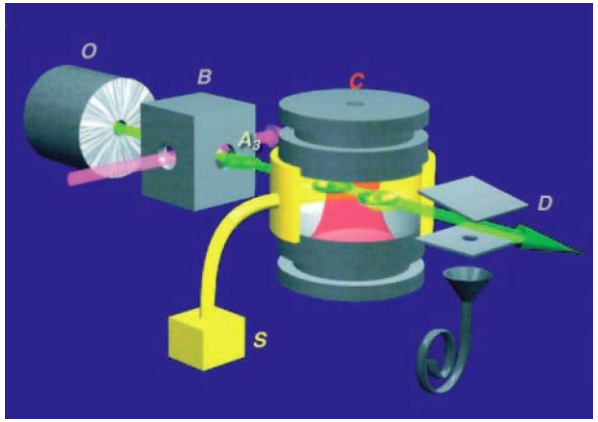
PC: IonQ

Superconducting circuits/cQED



Arute *et al*. 2019

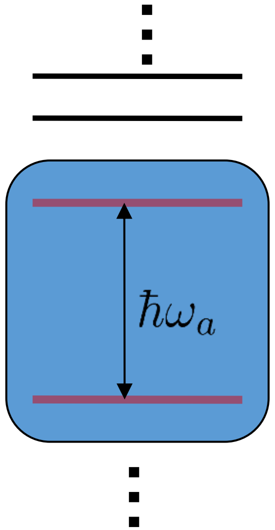
Atoms for 2-level systems



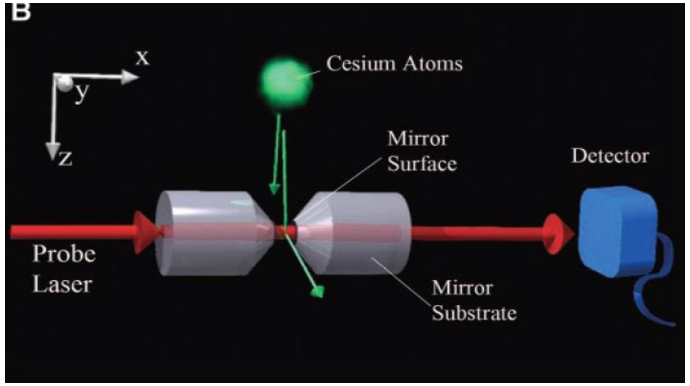
Rydberg atoms
RMP **73**, 565 (2001)

Requirements:

- anharmonicity (natural!)
- long-lived states
- good coupling to EM field
- preparation, trapping etc.



$$\hat{H} = \frac{1}{2}\hbar\omega_a\hat{\sigma}_z$$



alkali atoms
Science **287**, 1447 (2000)

Rydberg atoms & microwave cavities (Haroche et al.)

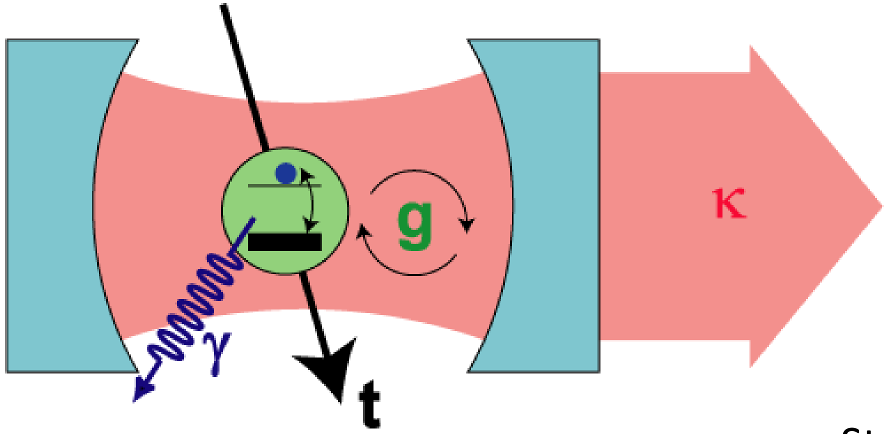
Excited atoms with one (or several) e⁻ in very high principal quantum number (n)
► long radiative decay time ($\sim 3\times 10^{-2}\mathrm{sec}$),
► very large dipole moments
► well-defined preparation procedure

Alkali atoms trapped in optical cavities (Kimble et al.)

can trap single atom inside optical cavity,
manipulate and read out its state with lasers!

Cavity Quantum Electrodynamics (CQED)

- coupling atom / discrete mode(s) of EM field
- central paradigm for study of open quantum systems



2g = vacuum Rabi freq.

κ = cavity decay rate

γ = "transverse" decay rate

t = transit time

Strong Coupling = $g > \kappa, \gamma, 1/t$

Jaynes-Cummings Hamiltonian

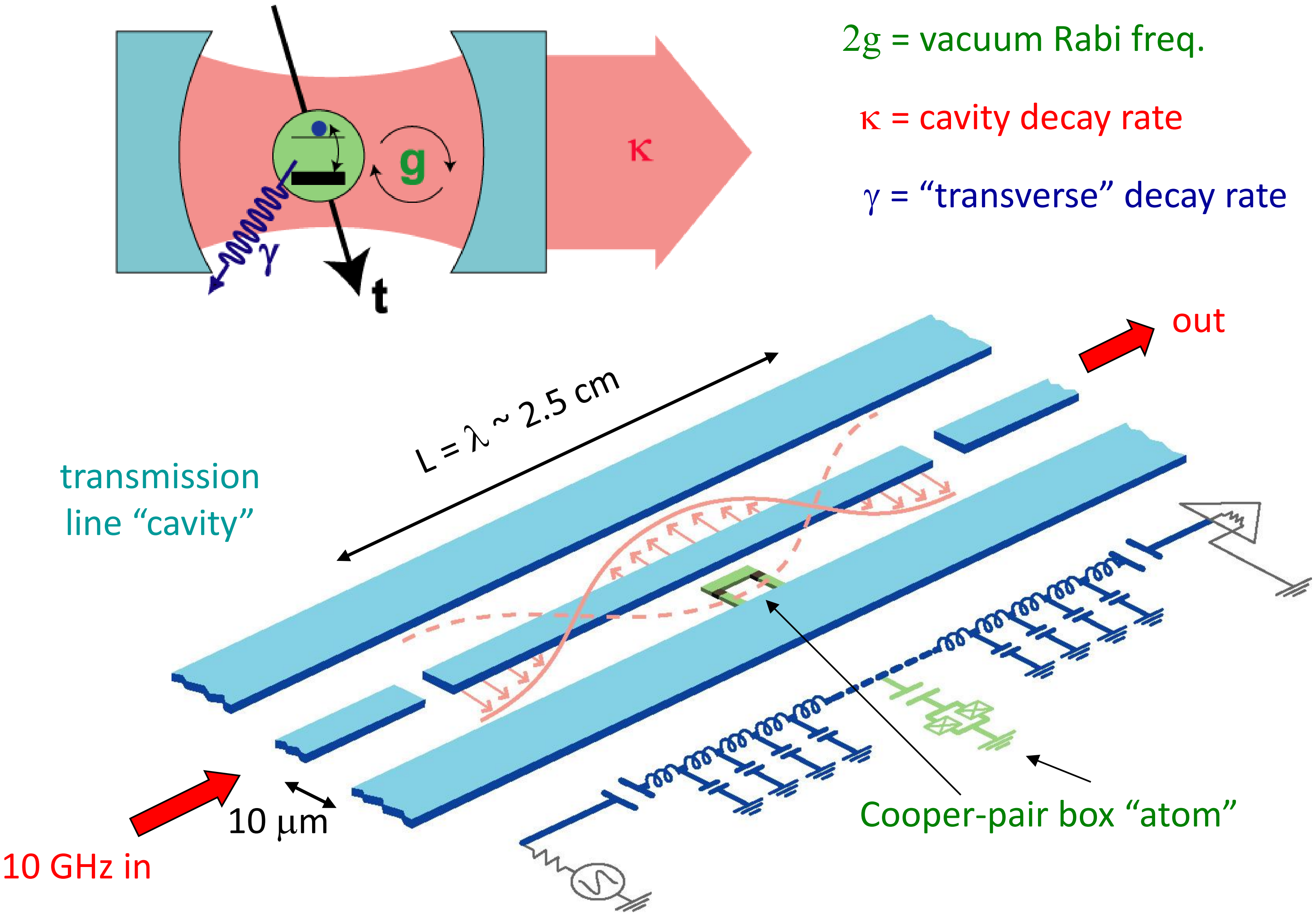
$$\hat{H} = \hbar\omega_r(a^\dagger a + \tfrac{1}{2}) + \frac{E_{el}}{2}\hat{\sigma}_x - \frac{E_J}{2}\hat{\sigma}_z - \hbar g(a^\dagger\sigma^- + \sigma^+ a)$$

Quantized Field

2-level system

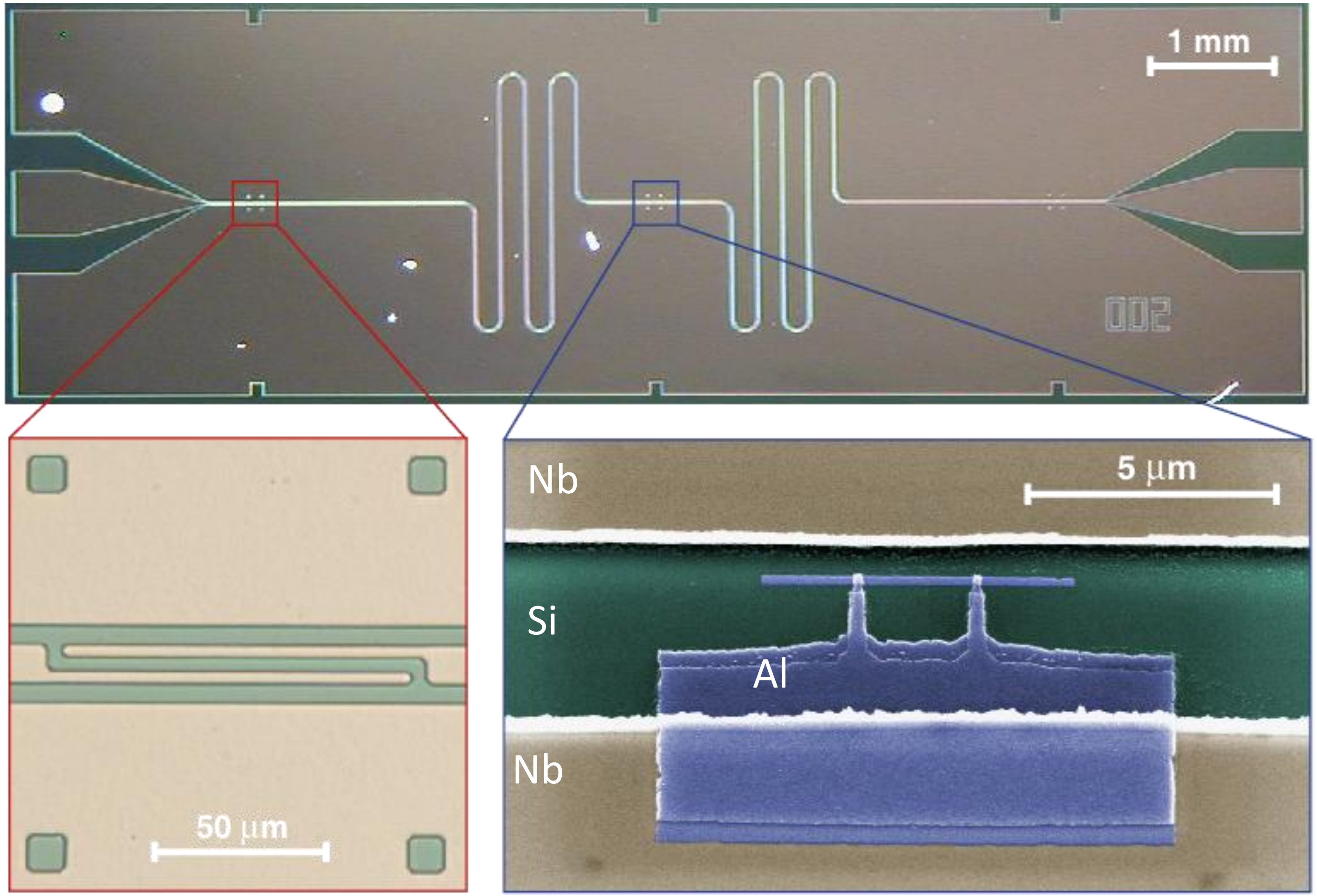
Electric dipole Interaction

A circuit Implementation of CQED



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

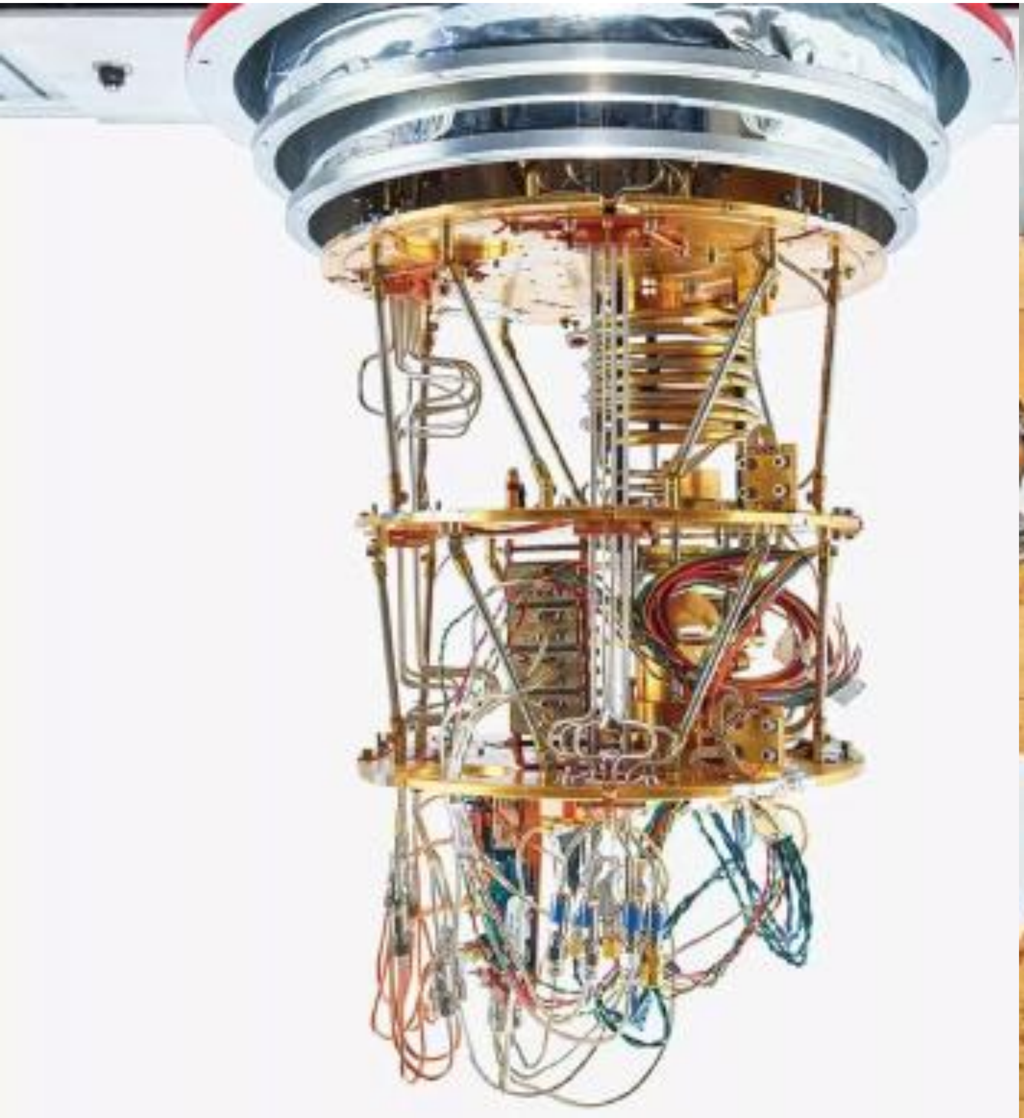
The Chip for circuit QED (cQED)



No wires attached to qubit!

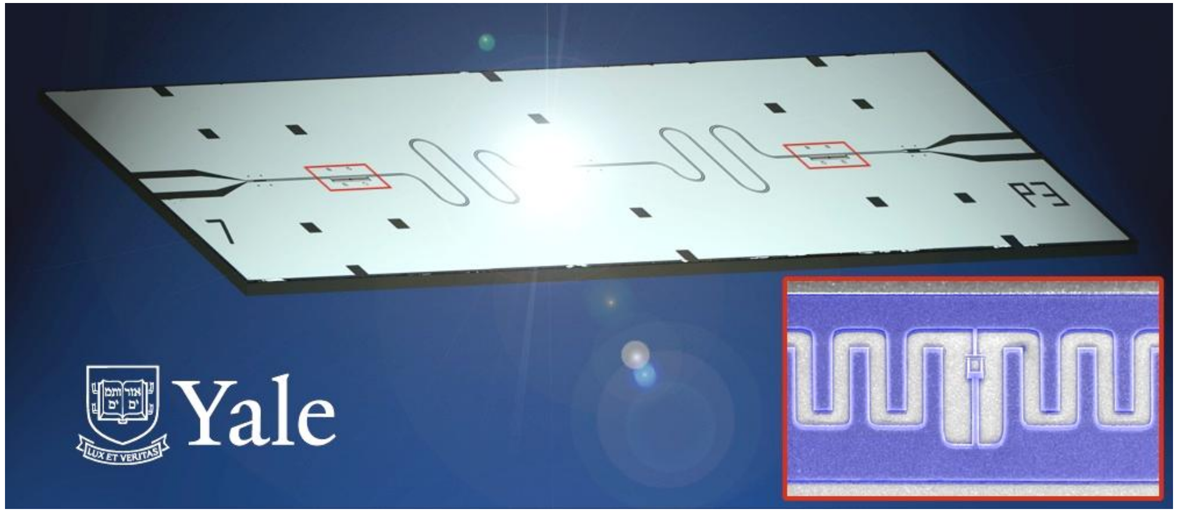
Experiment: Wallraff et al., *Nature* **431**, 162 (2004)

Building a (superconducting) quantum computer



The first all-electronic quantum processor (2008)

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



"Circuit QED:" artificial atoms coupled to microwave photons

Lithographically produced integrated circuit with semiconductors replaced by superconductors.

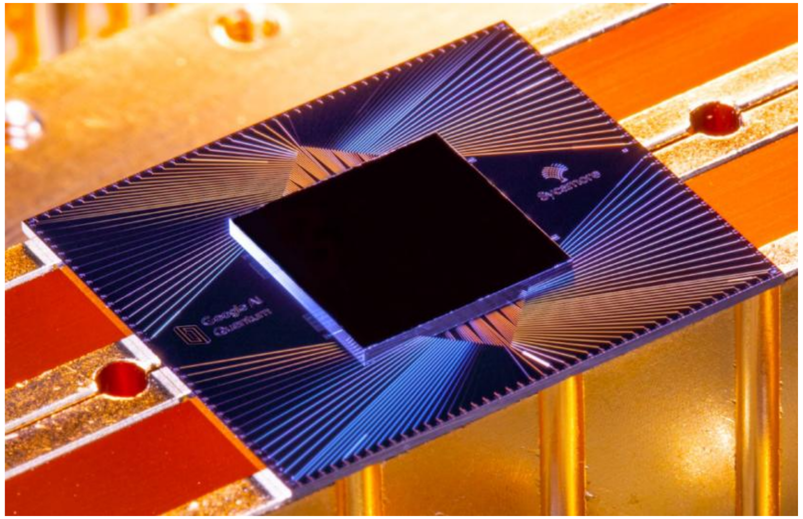
Rob Schoelkopf Michel Devoret

Current industrial systems are direct massive engineering scale-ups of this first device.

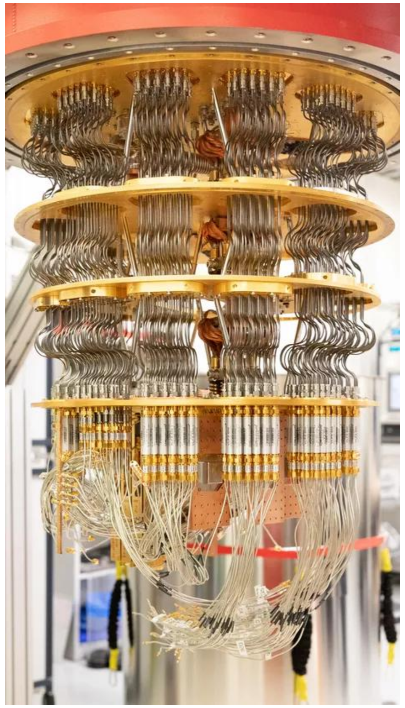
Out of the Yale lab and into industry:

- circuit QED architecture
- Transmon qubits
- Dispersive readout
- Quantum bus

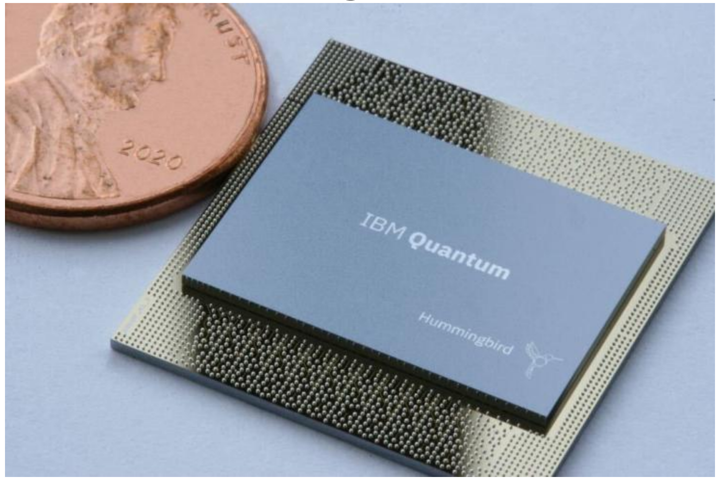
Google
IBM
Intel
Amazon
Northrup-Grumman
Microsoft
Rigetti
Samsung
Alice&Bob
NordQuantique
Alibaba
……
Quantum Circuits, Inc.
of New Haven, CT

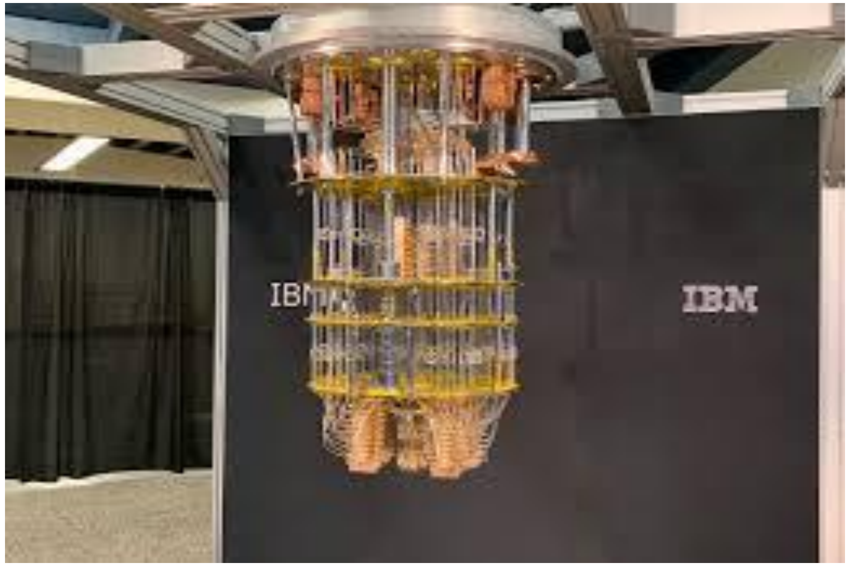


2019 Google AI Sycamore

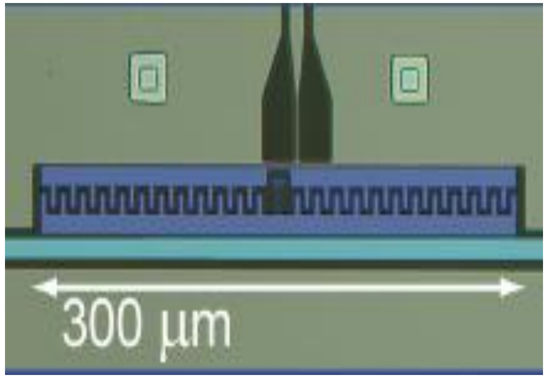


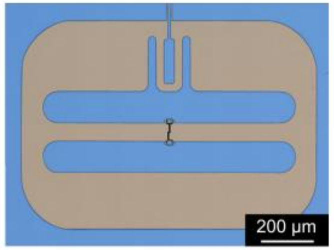
IBM Q Hummingbird 2020

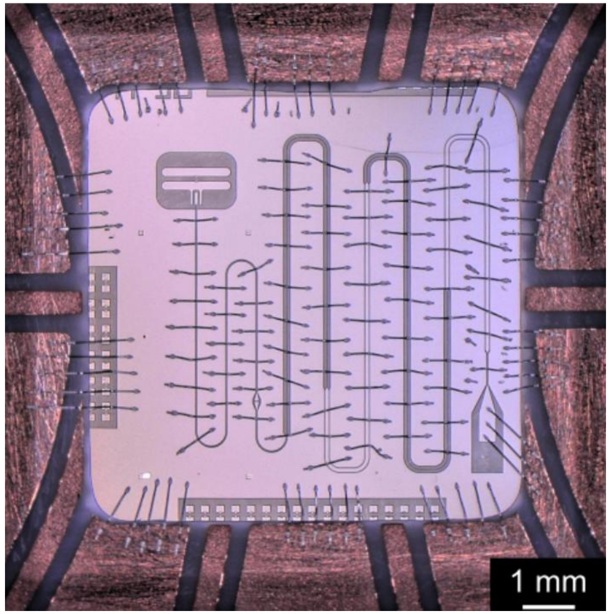


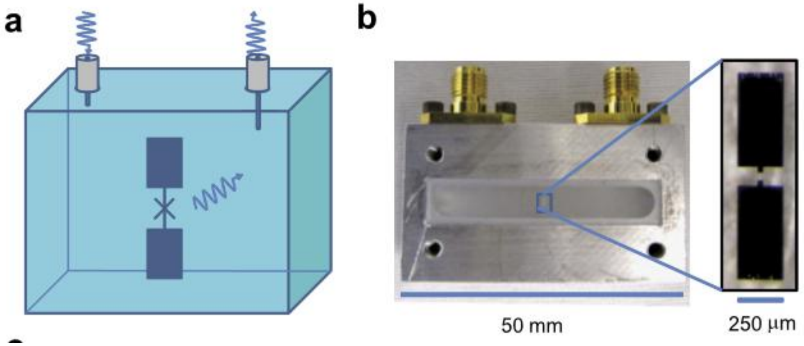


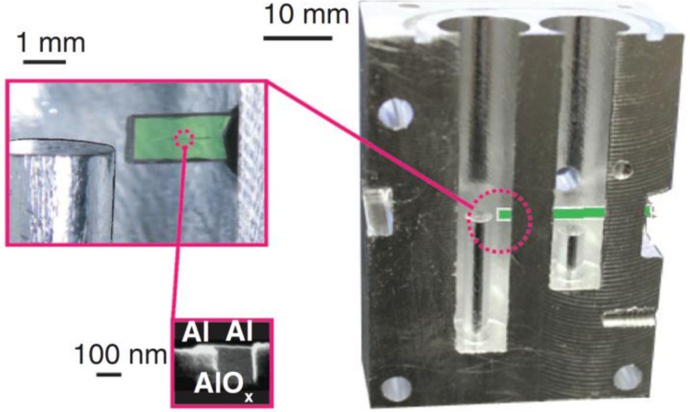
2D vs 3D cQED architecture

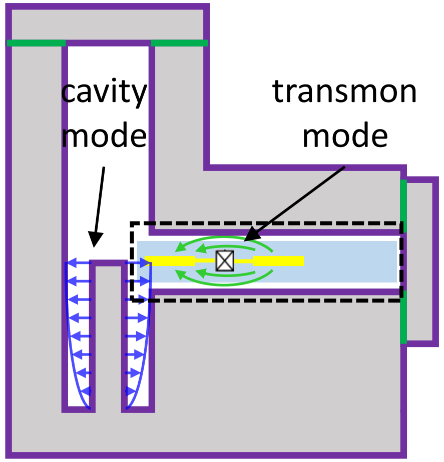


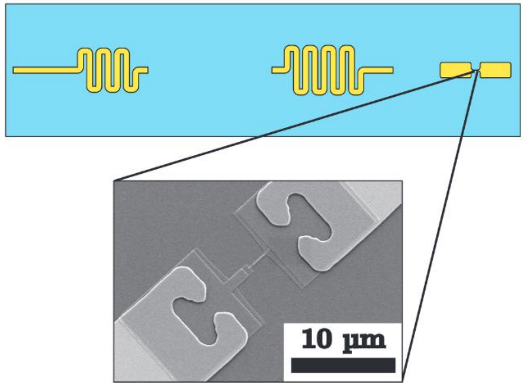






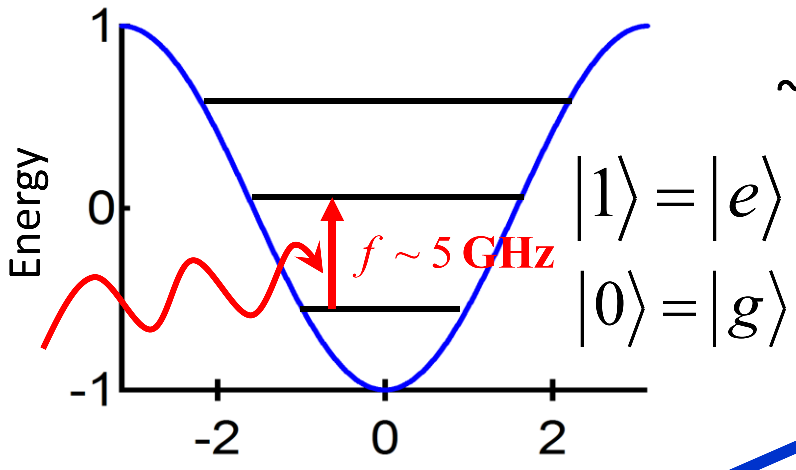


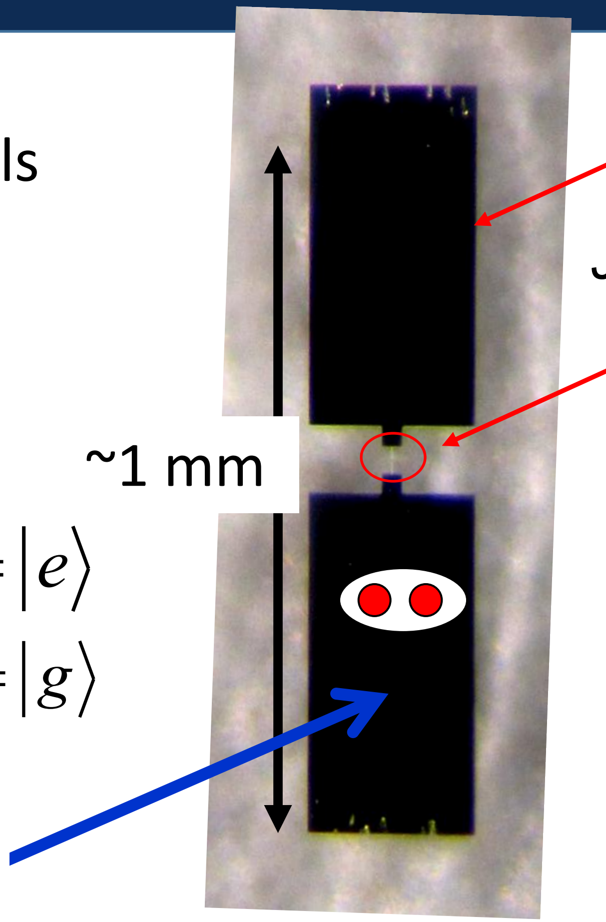


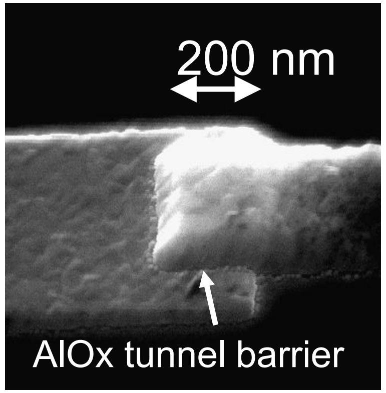


‘Transmon’ Qubit = ‘artificial atom’
with quantized energy levels

Emits and absorbs microwave ‘light’







‘transistor of
quantum computing’

Superconductivity eliminates single-particle excitations—only collective motion

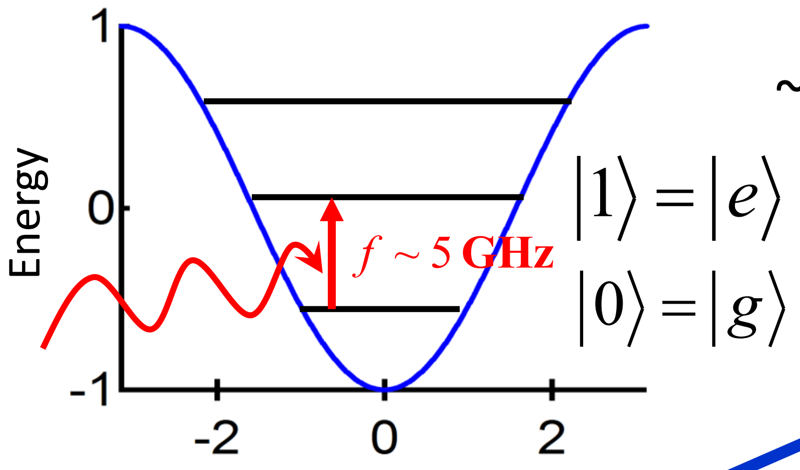
Quantized energy level spectrum is *simpler* than the hydrogen one

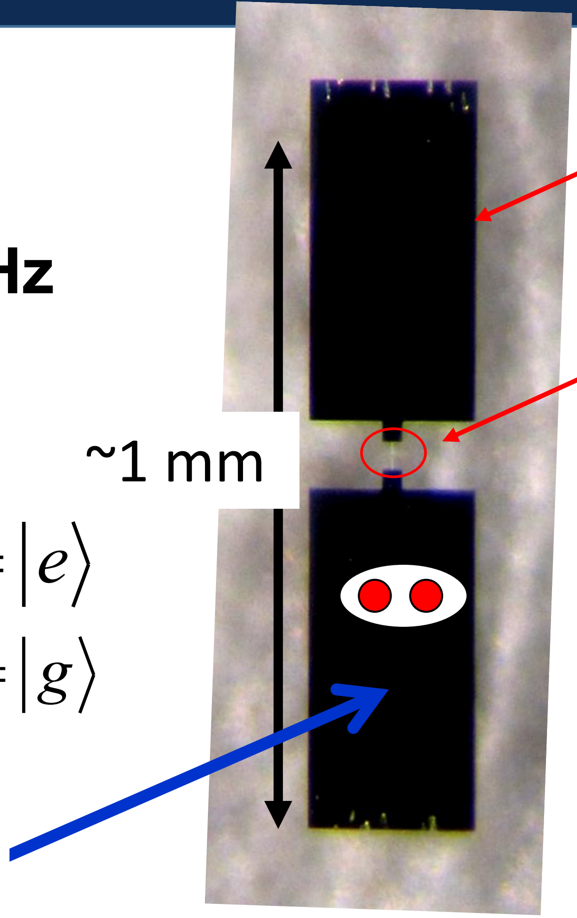
Quality factor $Q = \omega T_1$=2.5*10^7 *comparable to* that of hydrogen 1s-2p

Enormous transition dipole moment, atom has its own antenna: ultra-strong coupling to microwave photons

Transmon Qubit

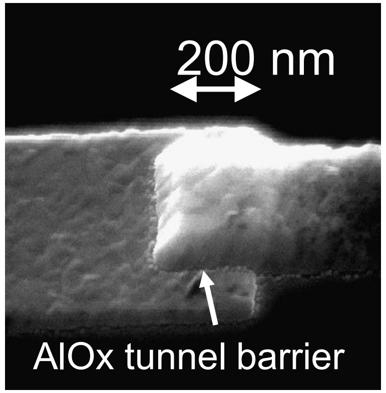
$\omega_{01} \sim (2\pi)\ 2 - 10\ \mathrm{GHz}$





Antenna pads are capacitor plates

Josephson tunnel junction



'transistor of quantum computing'

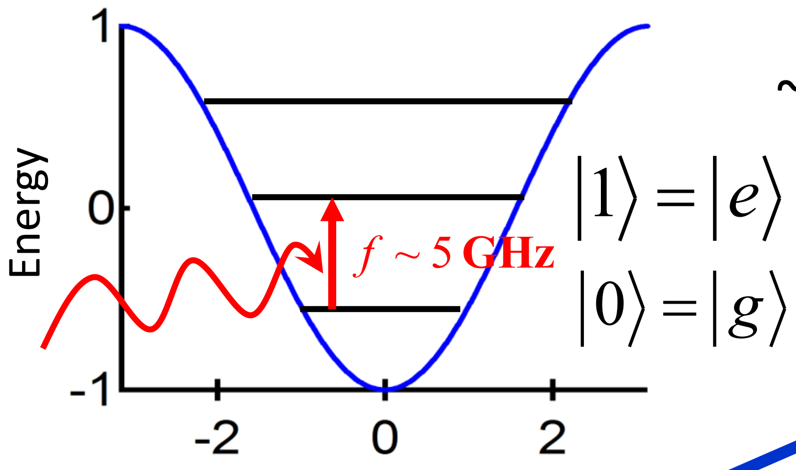
Why must these atoms be cooled to near absolute zero?

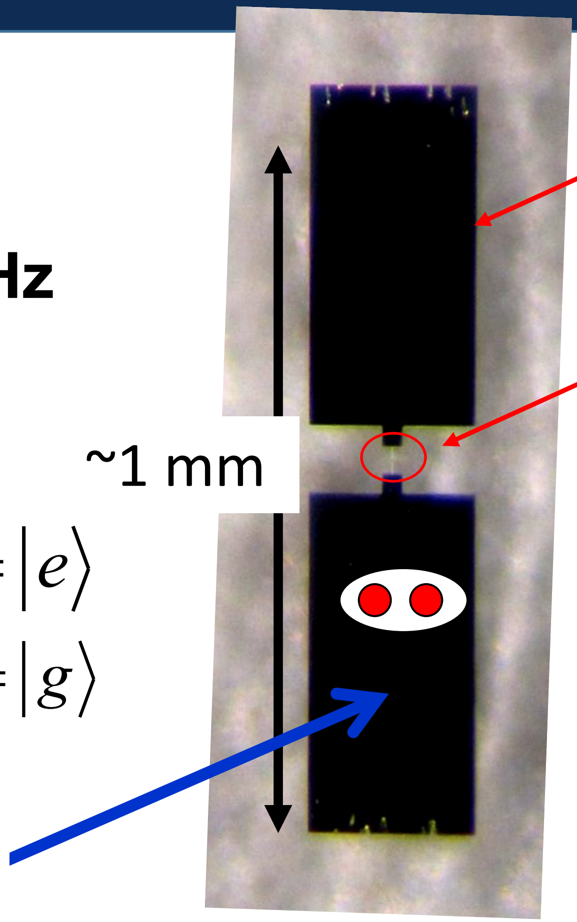
Superconductivity (zero-resistance current flow) only below ~1 Kelvin.

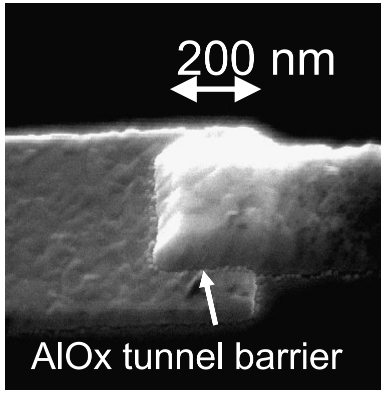
Energy of microwave photons at 5 GHz: $h \times 5\ \mathrm{GHz} \approx \mathrm{k_B} \times 0.25\ \mathrm{Kelvin}$

Transmon Qubit

$$\omega_{01} \sim (2\pi)\ 2 - 10\ \text{GHz}$$





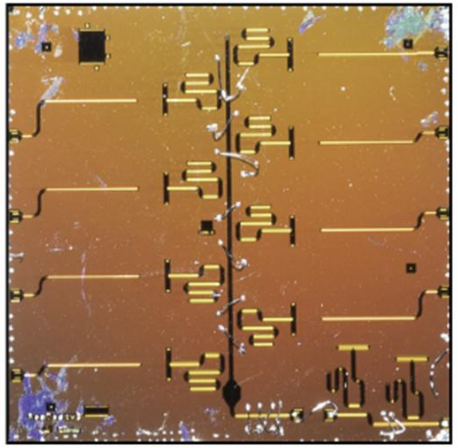


'transistor of
quantum computing'

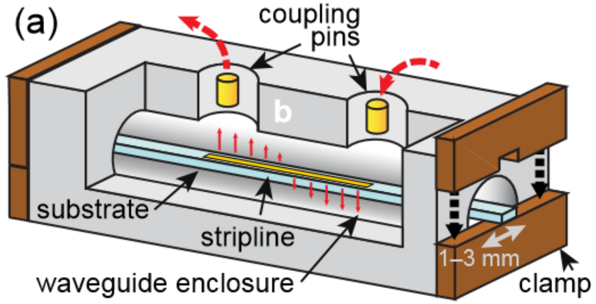
Why microwave instead of optical transition frequencies as in 'real' atoms?

Because these 'atoms' are huge and 'talk' to cm wavelength light,
not sub-micron wavelength light.

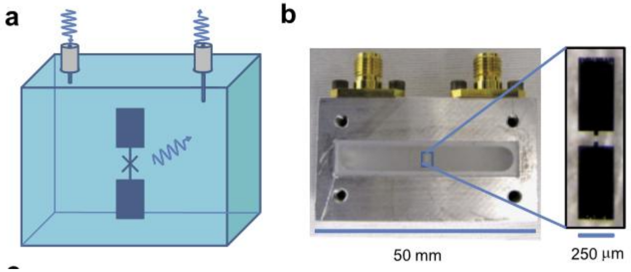
Harmonic Oscillators in the Superconducting Platform



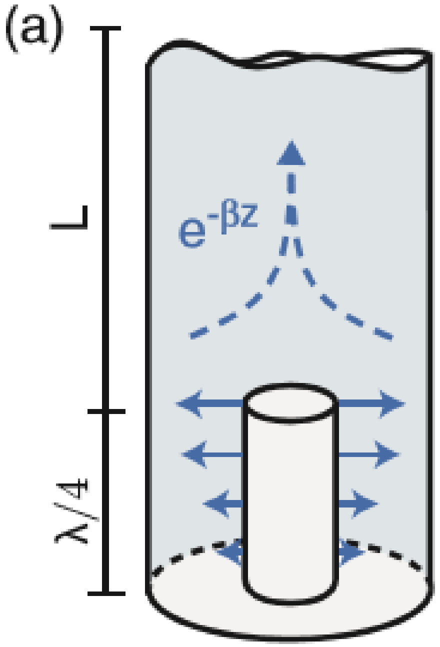
Altoé, Banerjee, Berk, Hajr *et al.* **PRX Quantum** (2022)



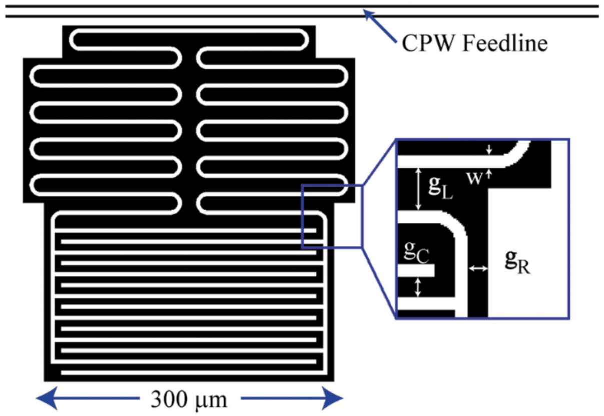
Axline *et al.*, **APL** 2016



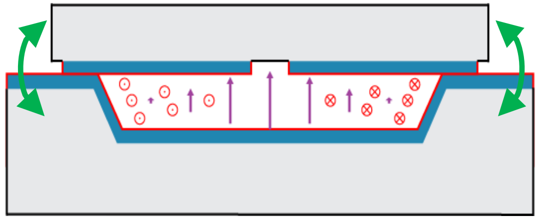
Paik *et al.*, **PRL** 2011



Reagor *et al.*, **PRB** 2016



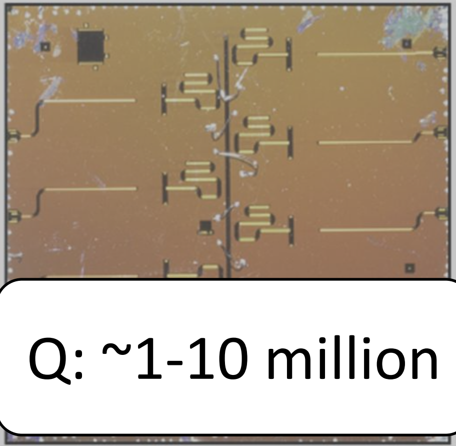
Geerlings *et al.*, **APL** 2012



Lei & **Krayzman** *et al.*, **APL** 2020

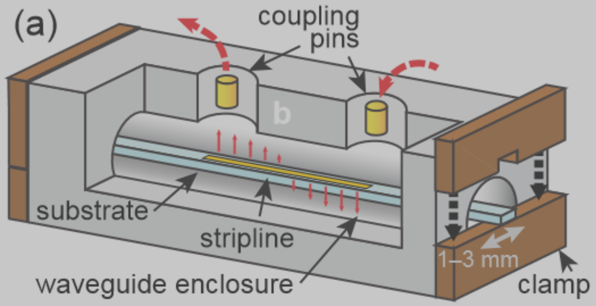
Romanenko *et al.* **PR Applied** 2020

Harmonic Oscillators in the Superconducting Platform

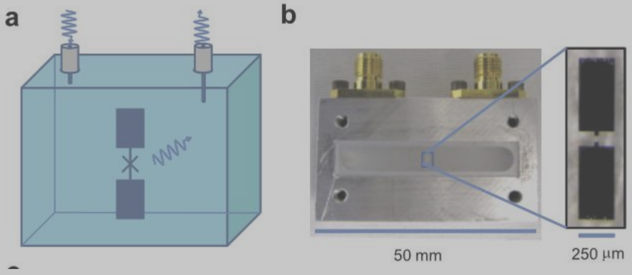


Q: ~1-10 million

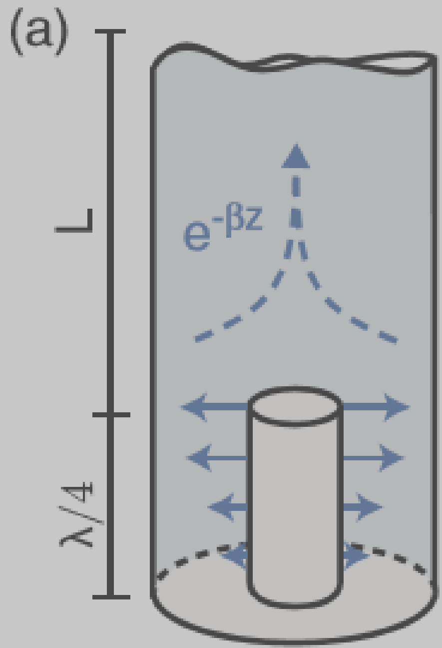
Altoé, Banerjee, Berk, Hajr *et al.* **PRX Quantum** (2022)



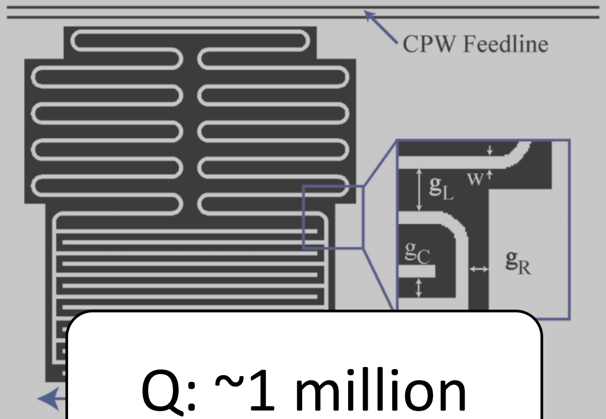
Q: ~5-10 million



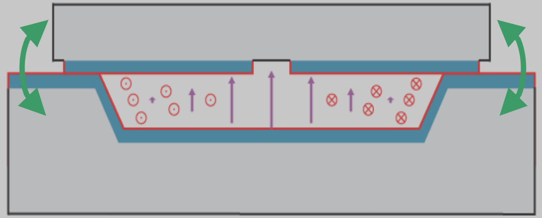
Q: ~10-100 million



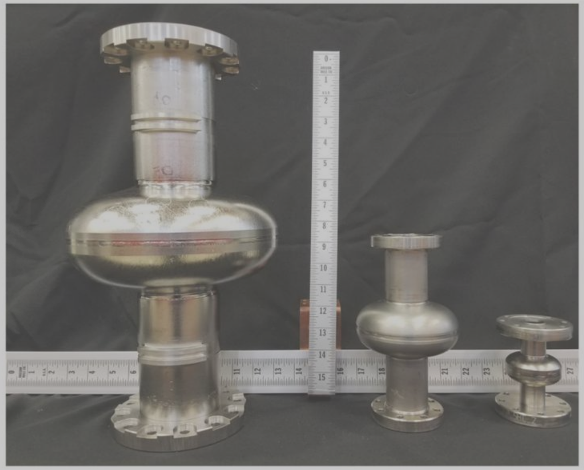
Q: ~50-100 million



Q: ~1 million



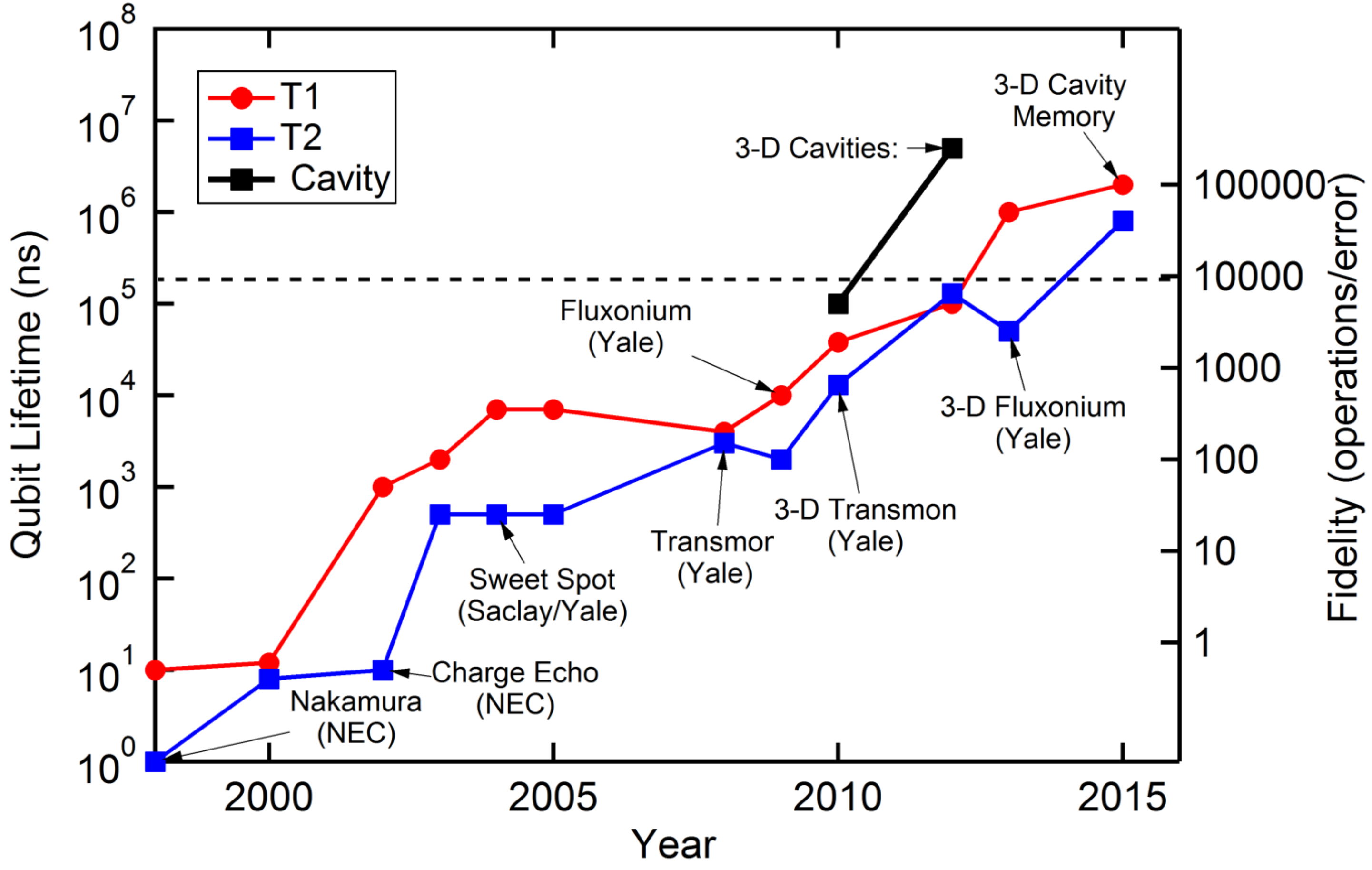
Q: ~300 million



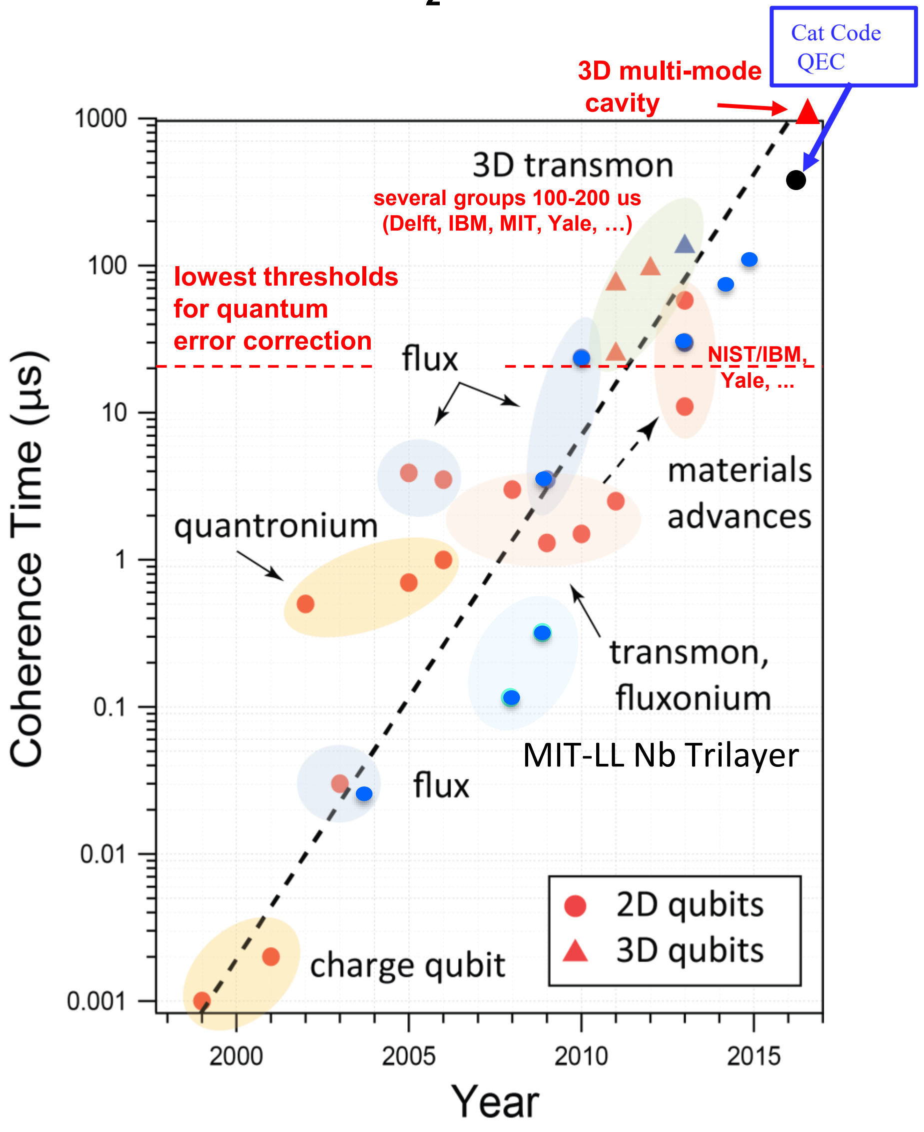
Romar 020

Q: ~1-10 billion

Exponential Growth in SC Qubit Coherence



Schoelkopf's version of "Moore's Law" for T_2



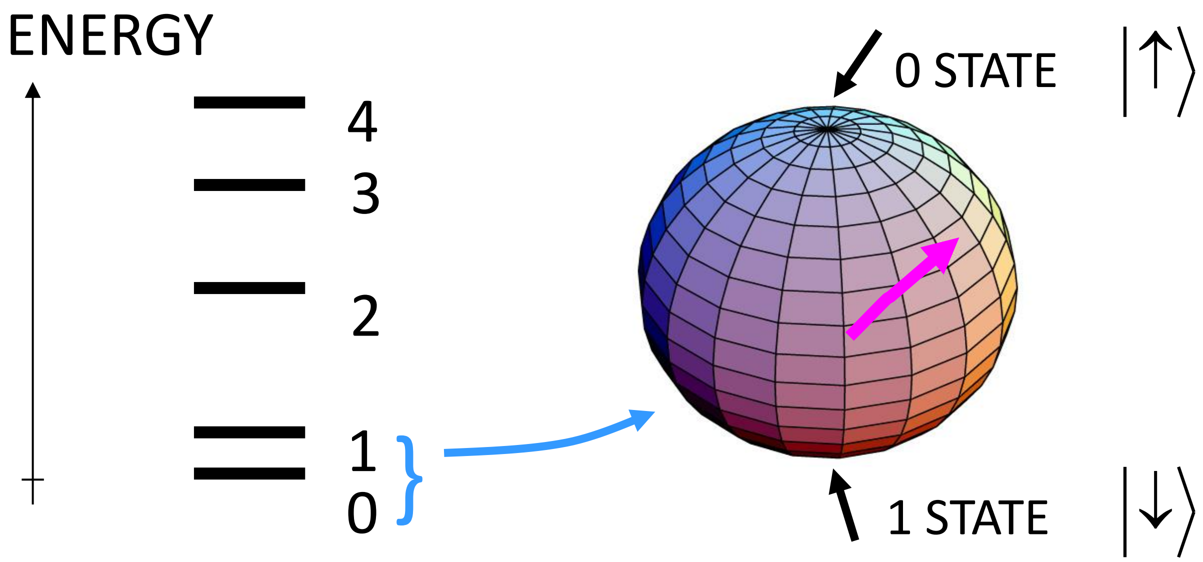
Oliver & Welander, MRS Bulletin (2013)

The huge information content of quantum superpositions comes with a price:

Great sensitivity to noise perturbations and dissipation.

Danger:
Errors are continuous!

No-Go Theorem for analog classical computation:
error correction is impossible!



The Grand Challenge: Quantum Error Correction

I am going to give you an unknown quantum state.

If you measure it, it will change randomly due to state collapse ('back action').

If it develops an error, please fix it.

***Mirable dictu*: It can be done!**

Trick is to measure what error has occurred without measuring which unknown state it occurred in and collapsing the quantum information.

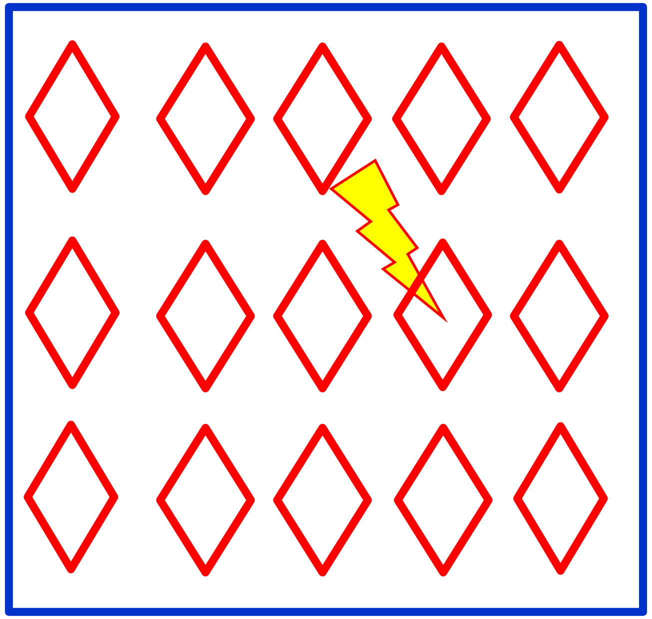
1995

Peter Shor

Quantum Error Correction for an unknown state requires storing the quantum information *non-locally* in (non-classical) *correlations* over multiple physical qubits.

‘Logical’ qubit

N ‘Physical’ qubits



Non-locality
No single physical qubit can “know” the state of the logical qubit.

Special multi-qubit measurements can tell you about errors without telling you the logical state in which the error occurred.

N qubits have errors *N* times faster.
We must fight the noise to overcome this factor of *N – and not introduce more errors! (or at least not uncorrectable errors).*

Miracle: Quantum errors are analog (i.e. continuous).
Measured errors are discrete (i.e. digital). State collapse is our friend!

Break-even point: logical qubit lifetime = lifetime of best single physical qubit.

2016: First true Error Correction Engine that worked: Schrödinger Cat Code (barely)

$$|\Psi\rangle = \psi_0 |0_L\rangle + \psi_1 |1_L\rangle$$

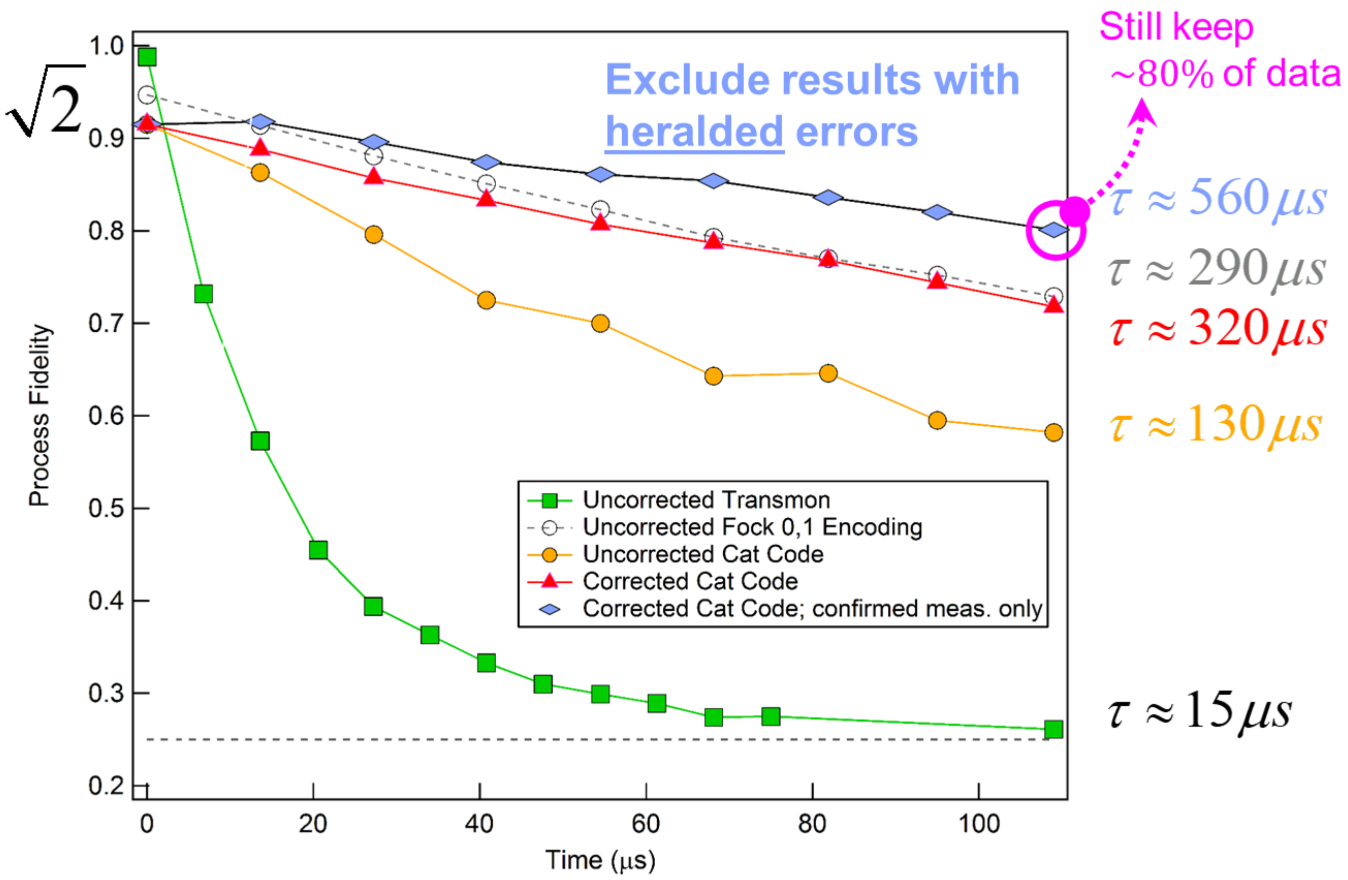
$$|0_L\rangle = |\alpha\rangle + |-\alpha\rangle$$

$$|1_L\rangle = |i\alpha\rangle + |-i\alpha\rangle$$

$|0_L\rangle$ $|1_L\rangle$ $|X_L\rangle$

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

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

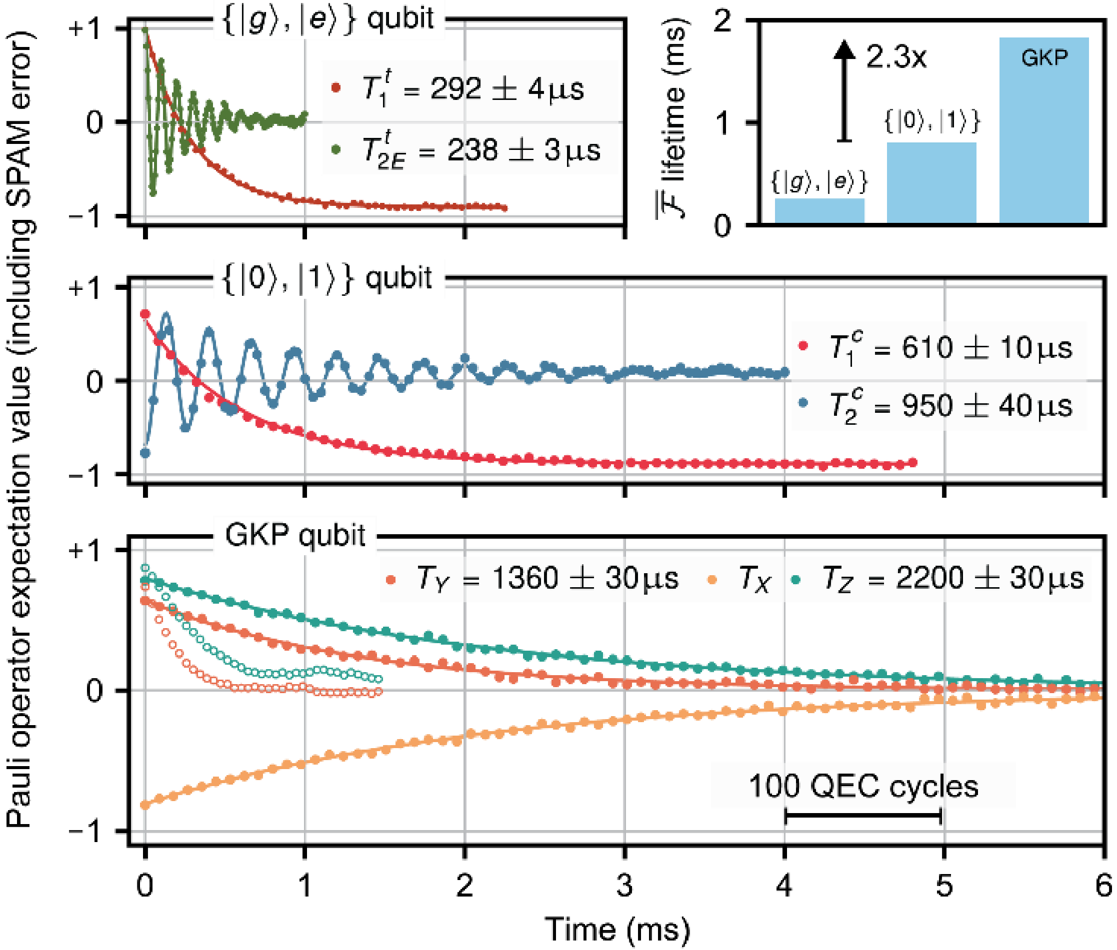


1.1x break even (unheralded)
1.75x break even (heralded)

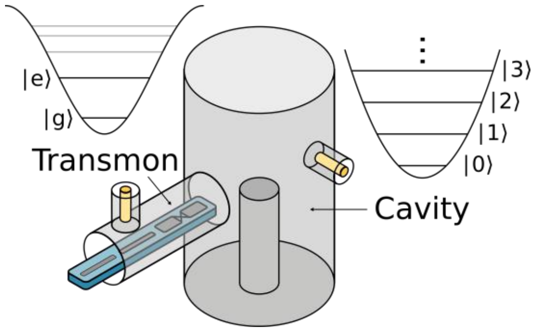
Theory: Leghtas, Mirrahimi, et al., *PRL* **111**, 120501 (2013)
Experiment: Ofek et al. *Nature* **536**, 441 (2016)

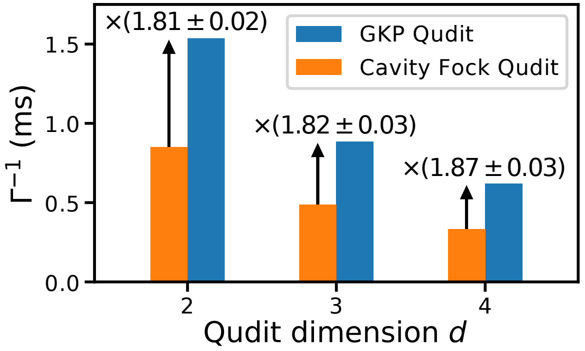
Beyond break-even QEC with the GKP code for qubits and qudits

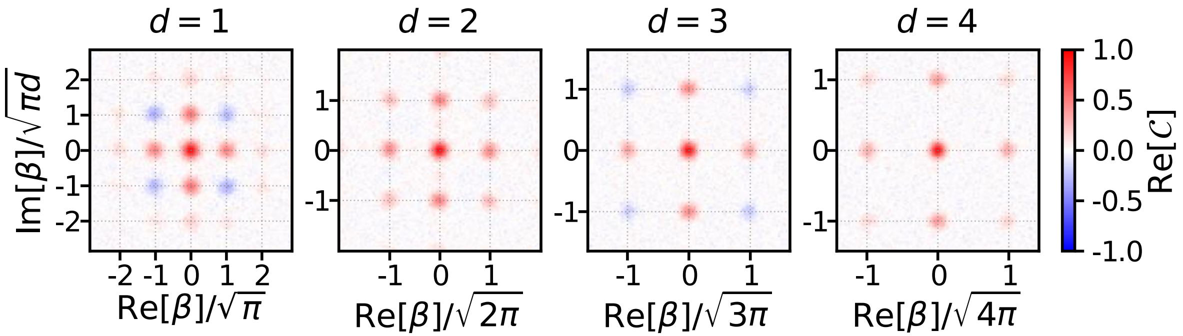
Sivak et al., Nature **616**, 50 (2023)



Brock et al., Nature **641**, 612 (2025)

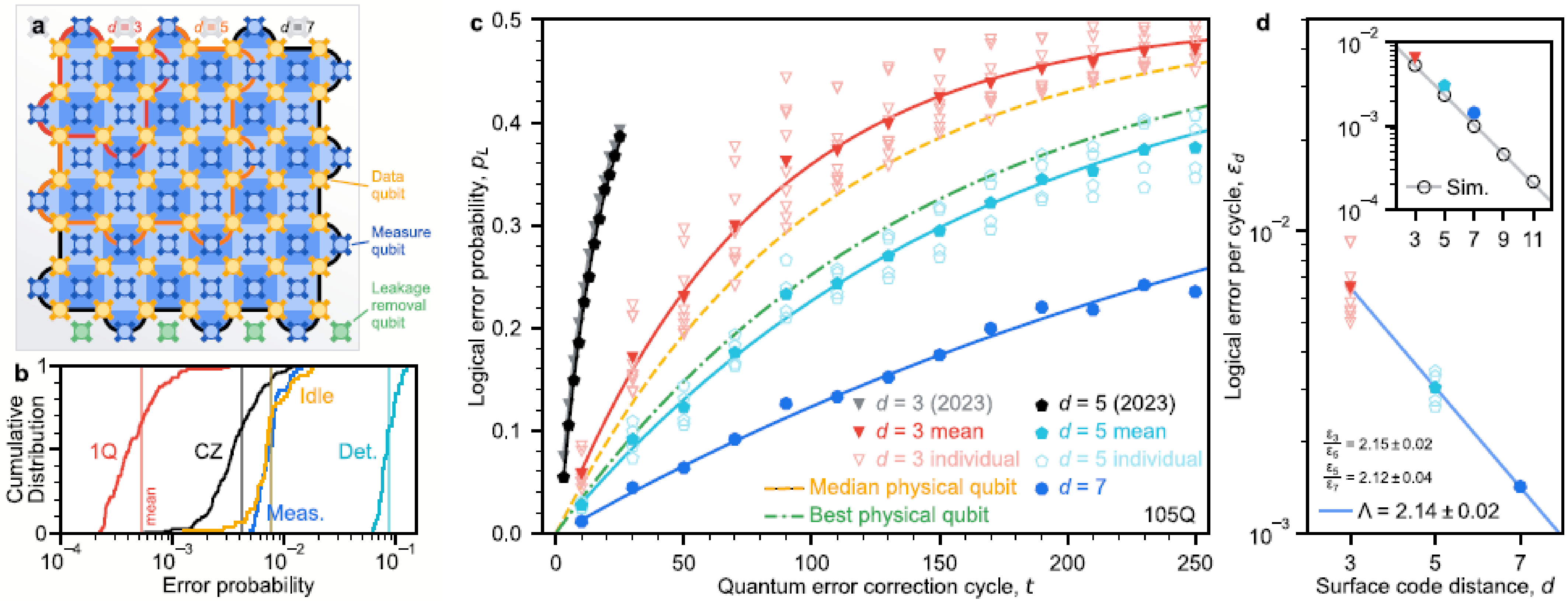






Beyond break-even QEC with surface code below threshold

2



Google Quantum AI, Nature **638**, 920 (2025)

We are on the way!

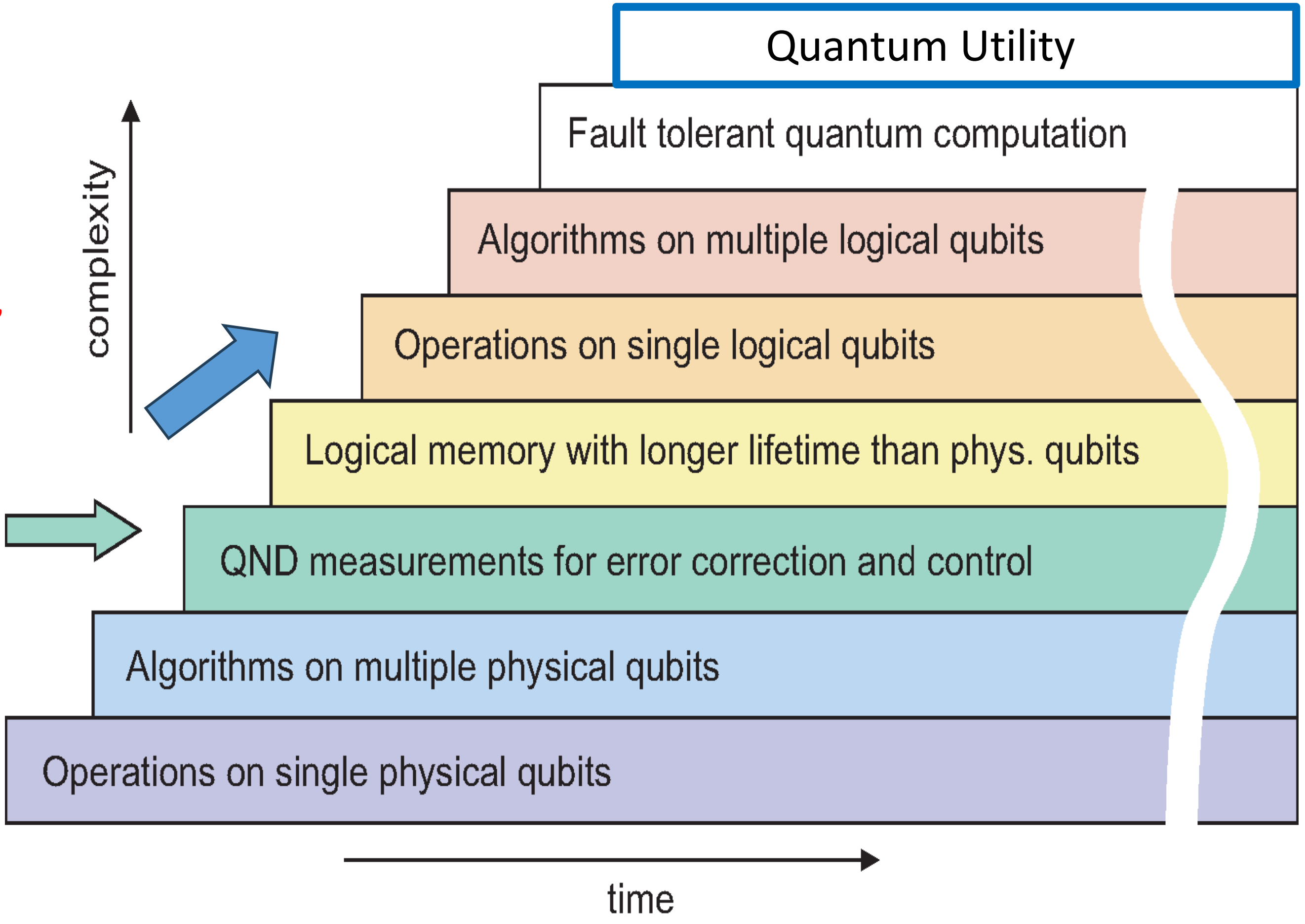
"Age of Qu. Error Correction."

"Age of Quantum Feedback"

"Age of Measurement"

"Age of Entanglement"

"Age of Coherence"



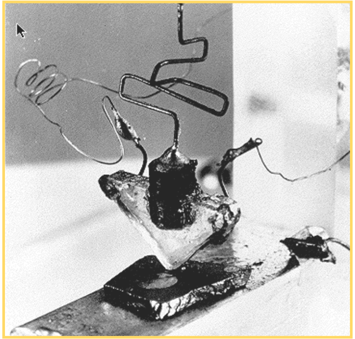
When it comes to quantum mechanics you have to 'think different'

Quantum information is carried by waves and particles.

Quantum information is analog and digital.

Quantum error correction is possible.

Hardware is still very crude…
We have long way to go!


1947 transistor

2nd Quantum Revolution:
New understanding that quantum weirdness is a feature, not a bug!