# Quantum Computing:

## State of Play

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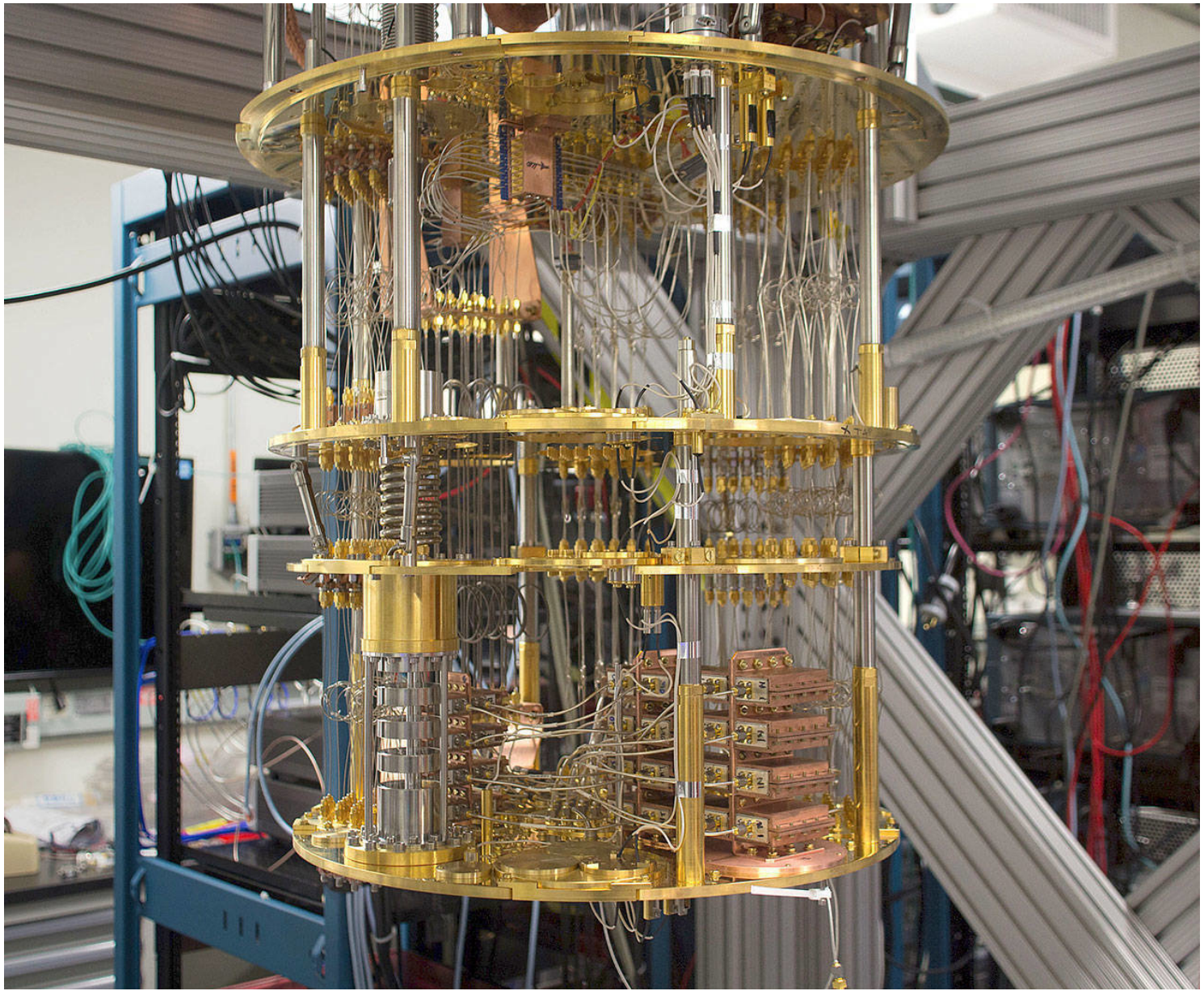
OC ACM Chapter Meeting, May 16th, 2018

# Quantum Computing : Media Hype

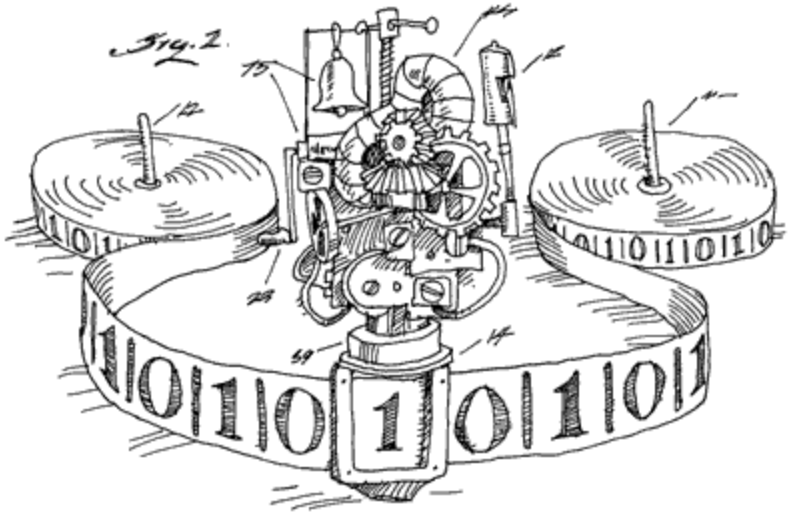
# What is a "Quantum" Computer?



IBM, Superconducting quantum computer

# Main Idea : **Computation is Physics**

- **Traditional computation uses classical physics**
  - *Turing Machines* : data tape and a moving read/write head for *bits*




Anything "Turing Complete" can simulate a Turing Machine, and thus all classical computation.

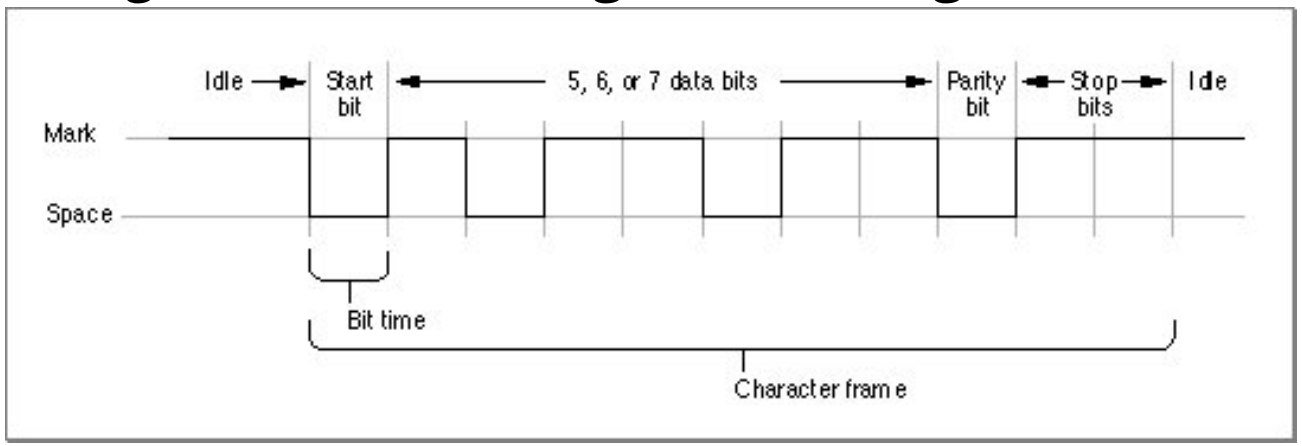
Even Microsoft Excel or Minecraft

- **The physical world is better described by quantum physics**
  - *Atoms, Molecules* : do not generally behave like Turing Machines

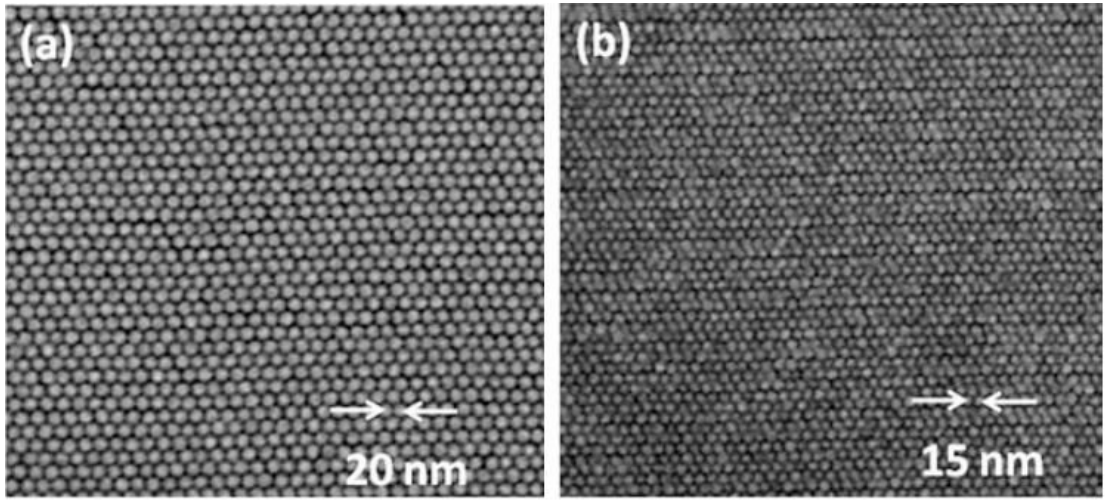
- **Does quantum physics change the possibilities of computation?**
  - **Yes.** The theory of computation must be extended

# Classical Physics & Bits

- **Classical Bits**
  - *Electrical signals* : bits are high/low voltages on metallic wires




  - *Magnetic domains* : bits are spin configurations in arrays of atoms




Bits are **definite** physical configurations (0 **or** 1)

# Quantum Physics and Qubits

## New "coherent" features for quantum bits (qubits)

- ***Superpositions*** of 0 and 1 can also be *definite*

  A bit has two possible definite states.

  A qubit has a definite state for each point on the surface of a unit sphere.

- ***Entanglement*** breaks modularity : *More is different*

  1 qubit requires 2 continuous angles to cover its spherical state space

  N qubits require 2^N continuous angles to cover their state space (not 2N)

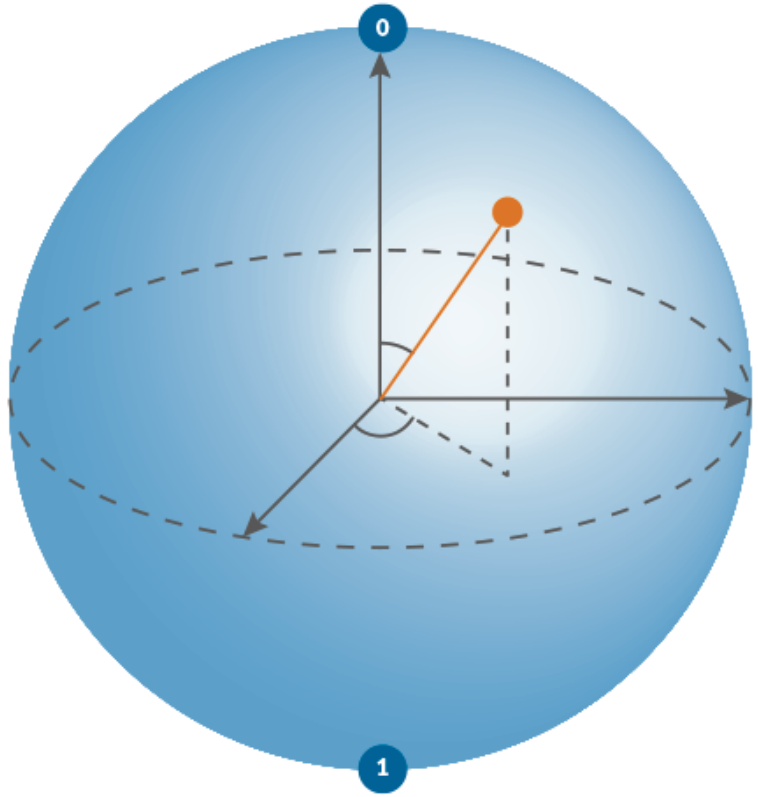
  *Exponential scaling* of parameters with qubit number, not linear!

- ***Time-symmetry*** : logic gates must be *reversible*

  Qubit states follow *smooth continuous orbits* on the unit sphere

- ***Measurement*** forces *probabilistic* description

  When measured, qubit *randomly* collapses to 0 or 1 based on state proximity



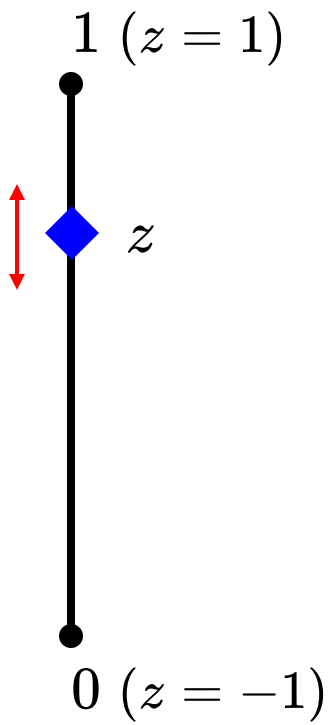

**These coherent features wash out (or "decohere") on the macro-scale to produce the classical picture**

# Probabilistic Bits vs. Quantum Bits

## Classical Bit

Only 2 *definite* states: 0 or 1

z-axis connecting them is *indefinite*, or probabilistic



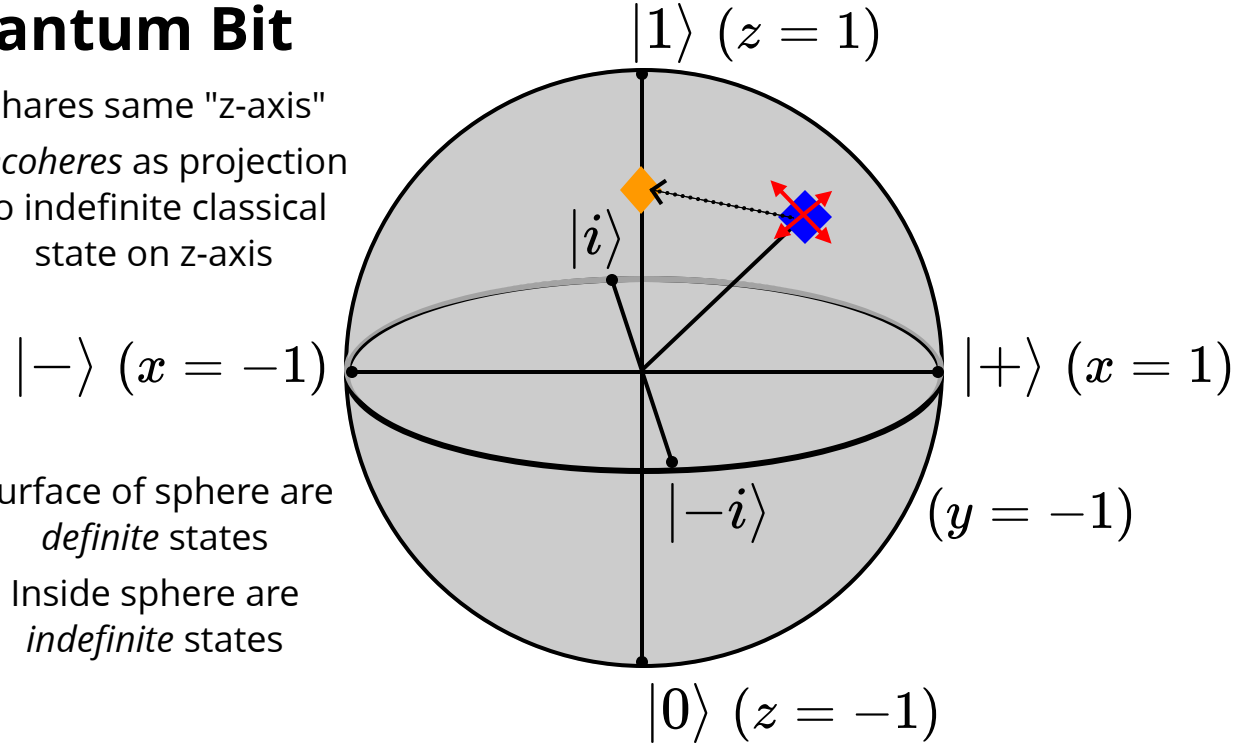

## Quantum Bit

Shares same "z-axis"

*Decoheres* as projection to indefinite classical state on z-axis

Surface of sphere are *definite* states

Inside sphere are *indefinite* states




- Probabilistic *state*: 1 parameter

$$z = P(1) - P(0) \in [-1, 1], \quad (P(1) + P(0) = 1)$$

- Evolution can only flip: $0 \leftrightarrow 1,\ (z \to -z)$
- Measurement obeys Bayes' rule:

$$P(1|r) = \frac{P(r|1)P(1)}{P(r|1)P(1)+P(r|0)P(0)}$$

- Probabilistic *state*: 3 parameters

$$\vec{\rho} = (x, y, z) \in [-1, 1]^{\times 3}, \quad (x^2 + y^2 + z^2 \leq 1)$$

$$x + iy = e^{-(i\phi+d)/2}\, 2\sqrt{P(1)P(0)}$$

- Evolution precesses in circle: $\partial_t \vec{\rho} = \vec{\Omega} \times \vec{\rho}$
- Measurement obeys Bayes' rule

# Gate-based Quantum Computation

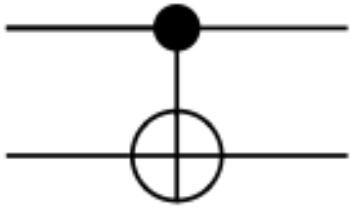
**Idea : Treat quantum logic as superset of reversible logic**

- Use *reversible classical computation* as a starting point
  Quantum computation should "decohere" to this classical model
  - Usual AND, OR, NAND gates are not reversible
  - Reversible logic gates : **NOT, CNOT, Toffoli**

$x \mapsto 1 \oplus x$

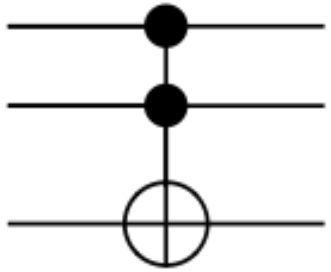
NOT

$(x, y) \mapsto (x, x \oplus y)$



CNOT (controlled-NOT)

$(x, y, z) \mapsto (x, y, xy \oplus z)$



Toffoli (controlled-controlled-NOT)

- Upgrade the bits in these gates to ***qubits***

# Gate-based Quantum Computation

**3 new features in quantum generalization**

1. *Parallelism* of gates over superpositions of qubit states

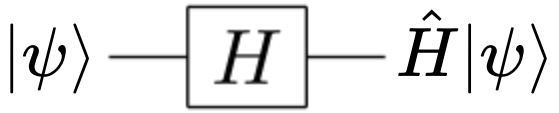

NOT

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \mapsto \hat{X}|\psi\rangle = \alpha|1\rangle + \beta|0\rangle$$

2. *Random* classical bits obtained when measuring qubits

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \Rightarrow \begin{cases} 0, & P(0) = |\alpha|^2 \\ 1, & P(1) = |\beta|^2 \end{cases}$$

3. *New gates* to produce superpositions from classical bit states




Hadamard

$$|\psi\rangle = |1\rangle \mapsto \hat{H}|\psi\rangle = \frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle$$

Negatives in the "probability amplitudes" for the superpositions allow for "destructive interference" since they can cancel positives

# Is a quantum computer more powerful?

- The answer to this is ***unknown***. However there are ***strong indications it is***.

- Rough logic of why it *likely* to be more powerful:
  - ***(+) Parallelization*** of computations over superpositions
    - This parallelization can *exponentially speed up* a single computation

  - ***(-) Randomness*** of measurement kills the parallelization speedup
    - Computations generally are *exponentially repeated* due to uncertainty

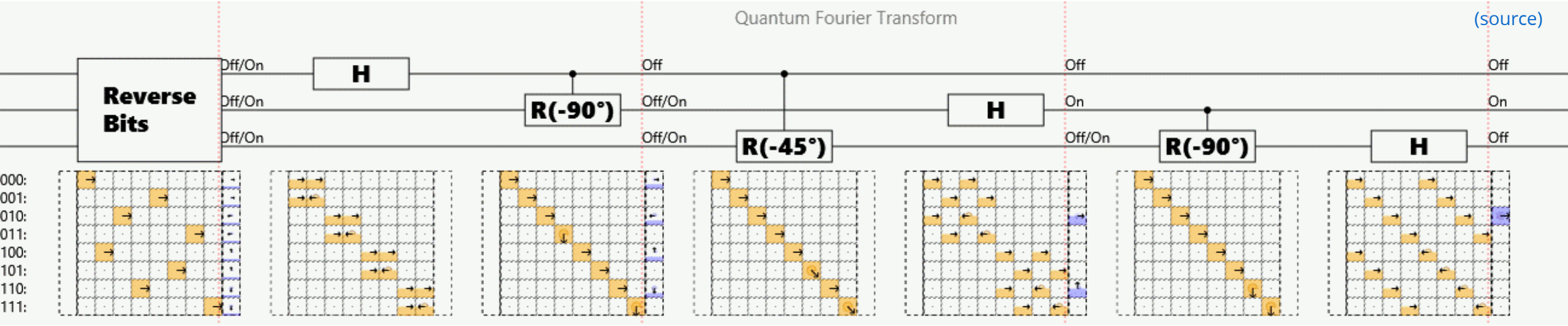
  - **(+) D*estructive interference*** can eliminate most uncertainty
    - Prior to measurement, *interference can reduce most outcomes to zero probability*, leaving only a few information-dense possibilities
    - This can at least partially restore the speedup expected from parallelism

# Example: Quantum (Fast) Fourier Transform

Suppose a periodic sequence can be encoded as the amplitudes of a superposition

The quantum Fourier transform (QFT) finds periodicity in polynomial operations

# steps per n bits: $2^n(2^{n+1}-1)\,(\mathrm{DFT}) \longrightarrow 3n2^n\,(\mathrm{FFT}) \longrightarrow (n^2+n)/2\,(\mathrm{QFT})$




$$|\psi\rangle = |000\rangle + i|001\rangle - |010\rangle - i|011\rangle + |100\rangle + i|101\rangle - |110\rangle - i|111\rangle$$

$$\Rightarrow \hat{F}|\psi\rangle = |010\rangle$$

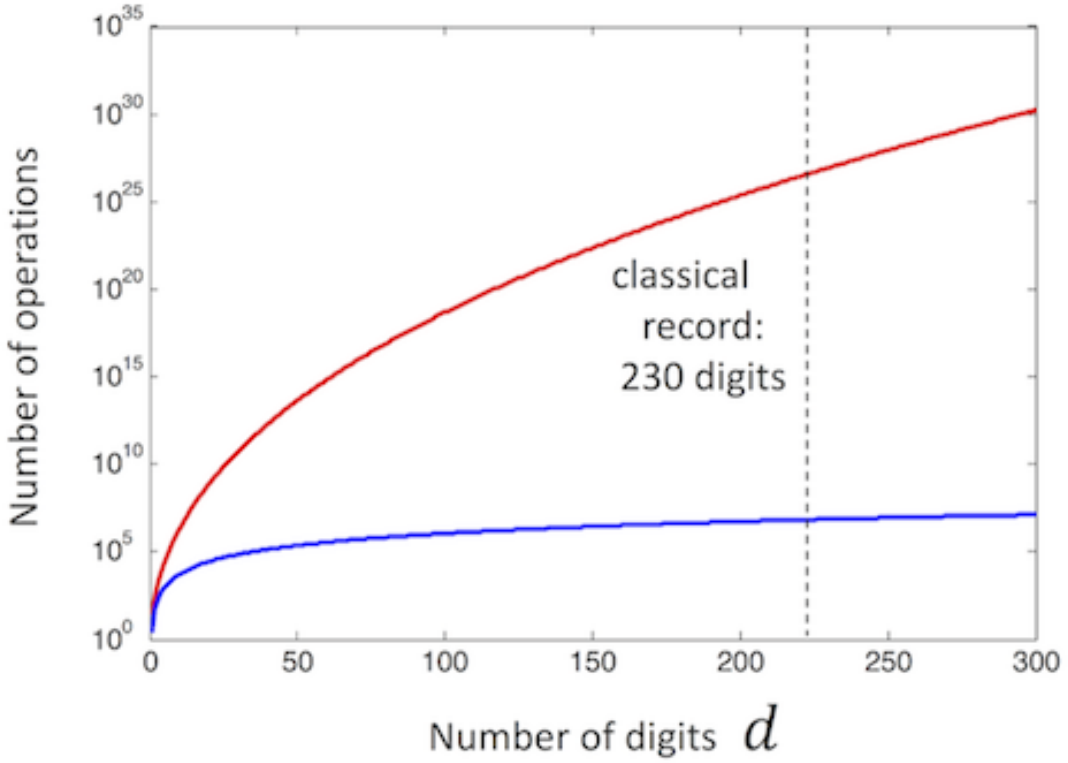
Detects that each successive phase factor is: $(e^{2\pi i/8})^2$

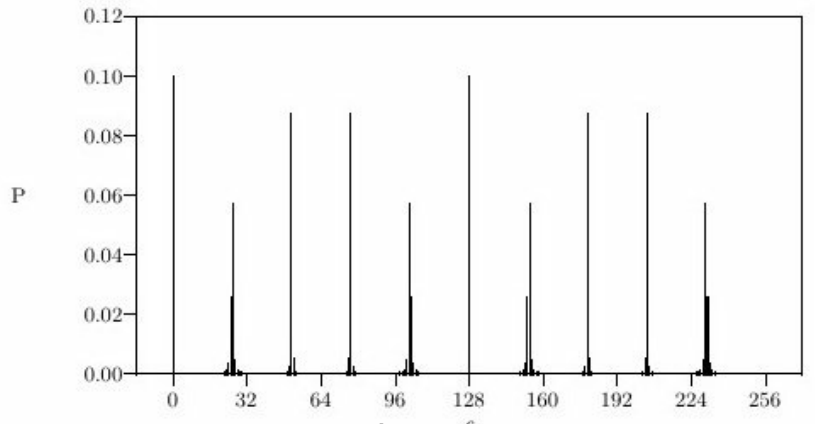
**Caveat**: Answer stored as *superposition*. Must *randomly sample outputs* to measure.

# Example: Shor's Algorithm

To **factorize an n-bit integer**, reduce the problem to a period-finding problem, then apply the quantum Fourier transform to exponentially speed it up. Since the resulting superpositions are periodic by construction, the main caveat of the QFT is mitigated.

$$O(e^{1.7(\log n)^{1/3}(\log\log n)^{2/3}})\ (\text{number sieve}) \longrightarrow O((\log n)^2(\log\log n)(\log\log\log n))\ (\text{Shor})$$




Measured output : sparse, easy to sample

**Useful for breaking encryption!**

Public key encryption (RSA) relies on the factoring of integers to be difficult

# How close are we to practical quantum computers?

**We already have them!  … sort of**

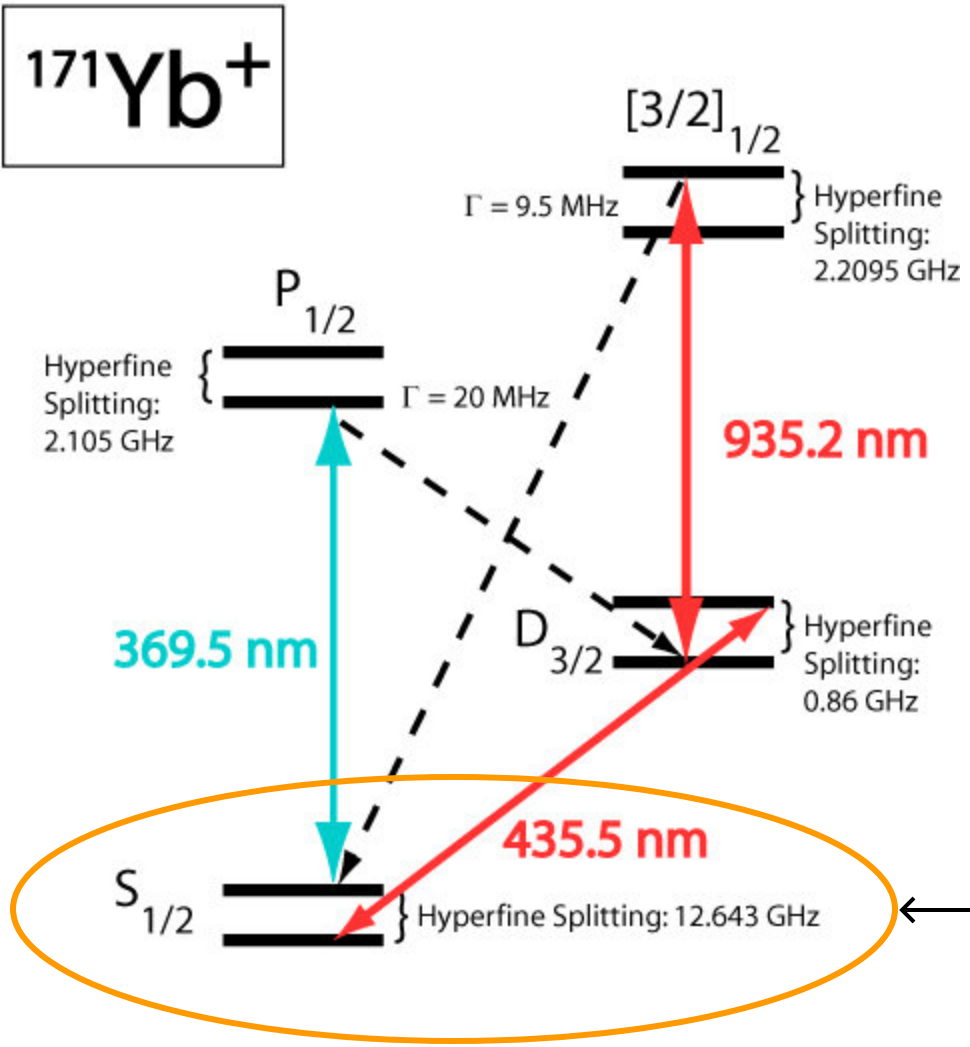
2 main competing implementations (others in development):

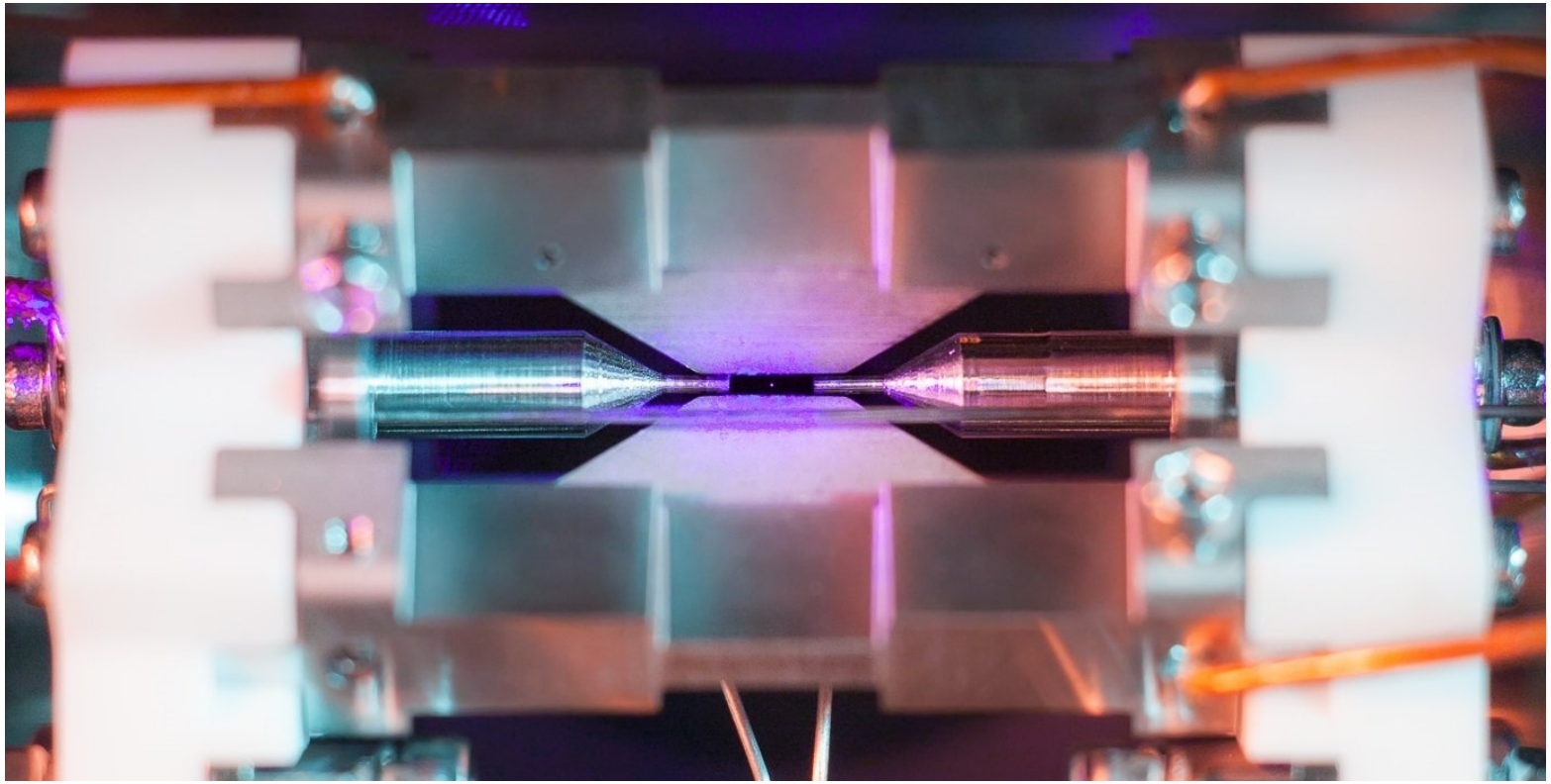
1. Trapped ions
   - UMD : 53 qubits

2. Superconducting circuits
   - Google : 72 qubits
   - IBM : 50 qubits
   - Rigetti Computing : 19 qubits
   - UC Berkeley : 10 qubits

**But these numbers do not tell the complete story**

# Technology 1 : Trapped Ions



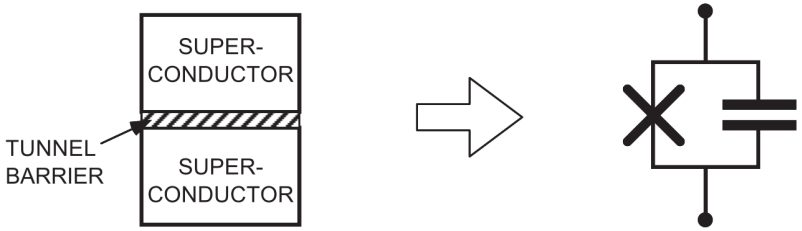



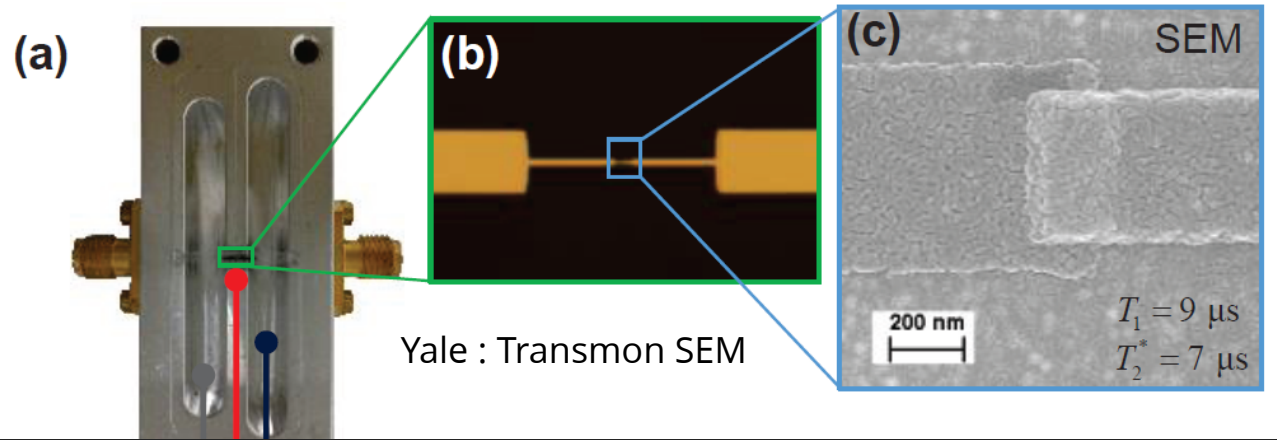
A trapped ion qubit is a superposition of the lowest two magnetic hyperfine energy levels of an ion (like Ytterbium or Calcium)

Such ions are trapped and cooled with lasers, then manipulated with more lasers

# Technology 2 : Superconducting Qubits

A superconducting (transmon) qubit is a superposition of the lowest two energy levels of a charge oscillation (an "artificial atom") across a nonlinear inductive tunnel barrier attached to a capacitive antenna

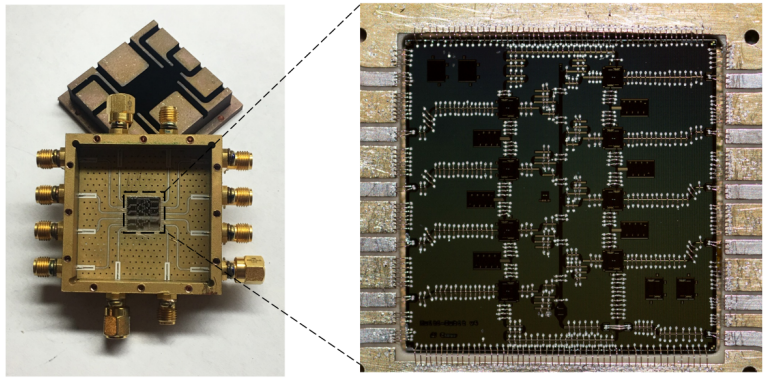


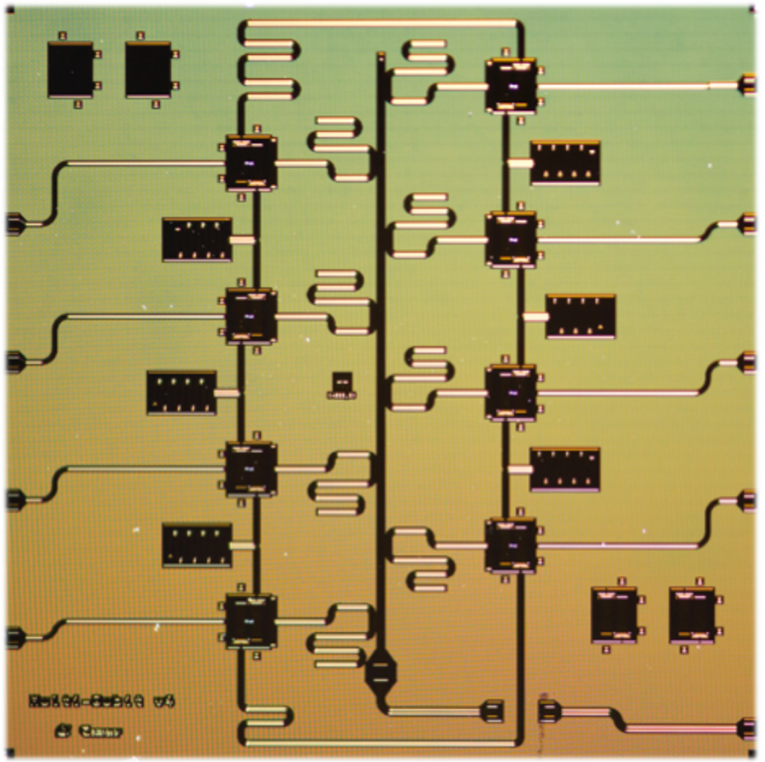

Yale : Transmon SEM

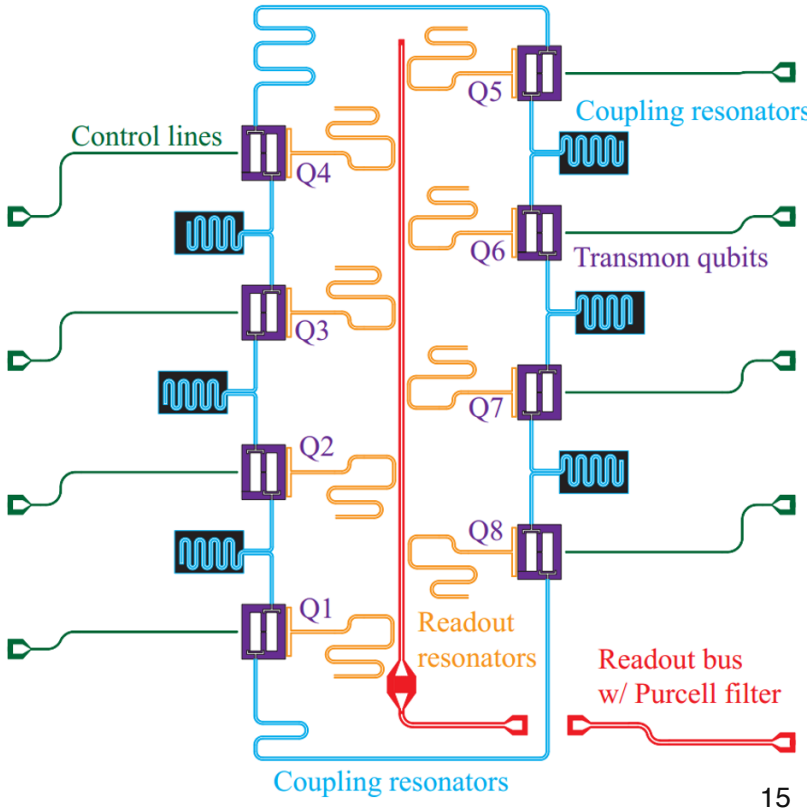
Controlled with all electrical AC signals at microwave frequencies

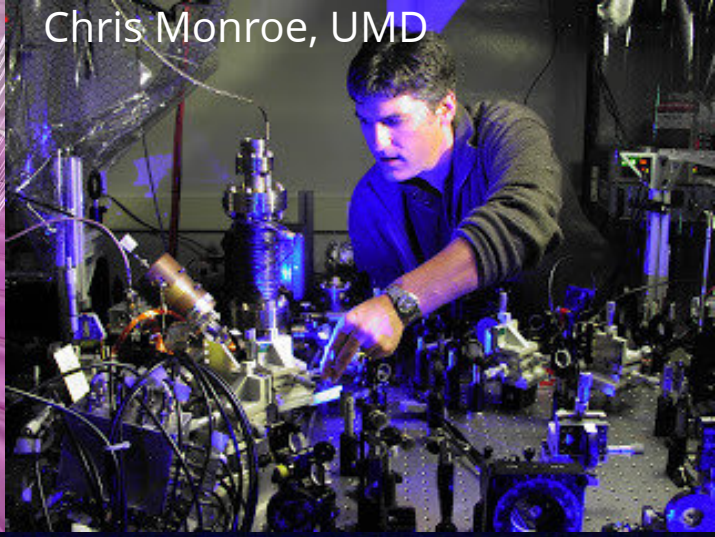
Cooled to mK temperatures



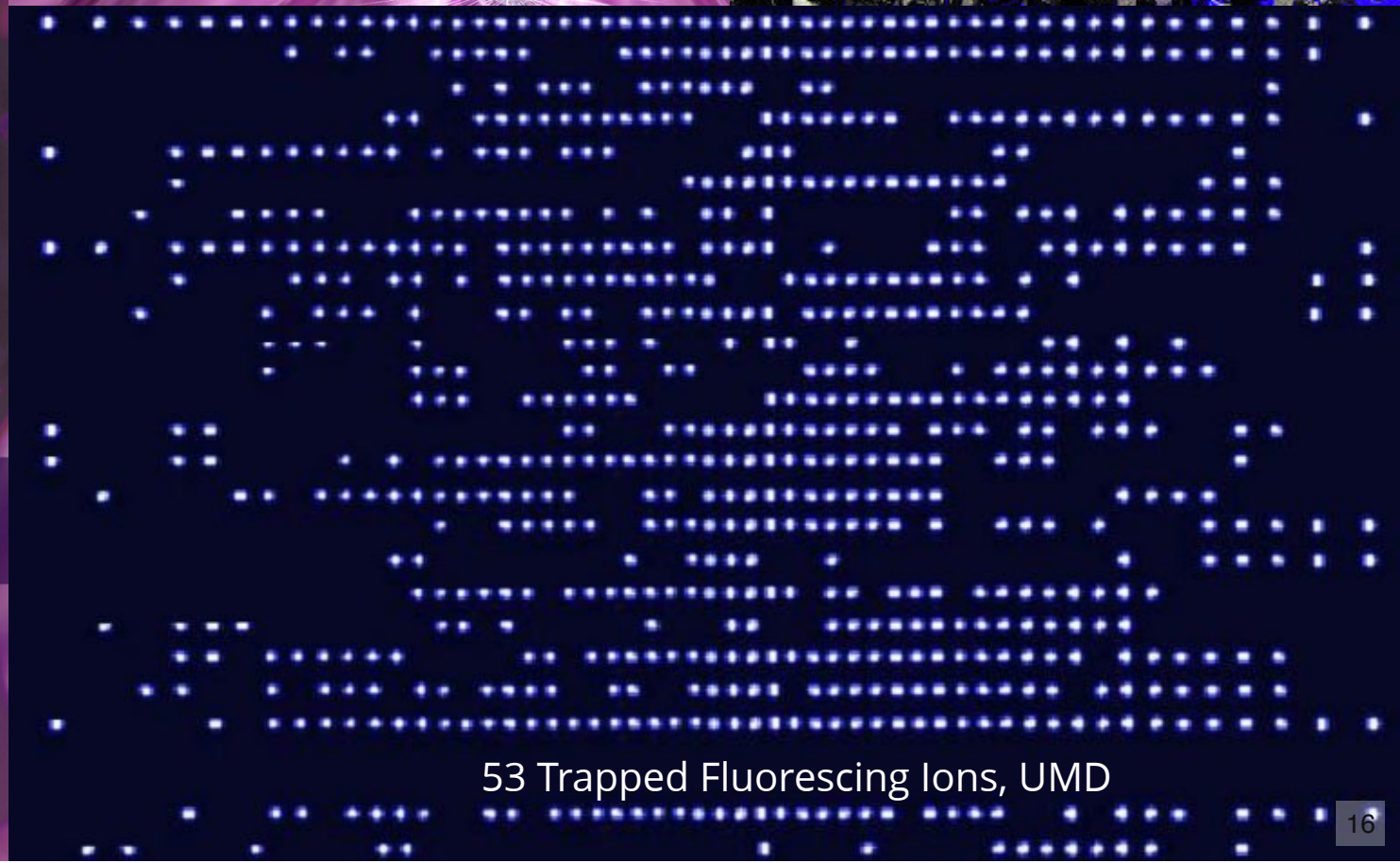
UC Berkeley : 8 qubit chip





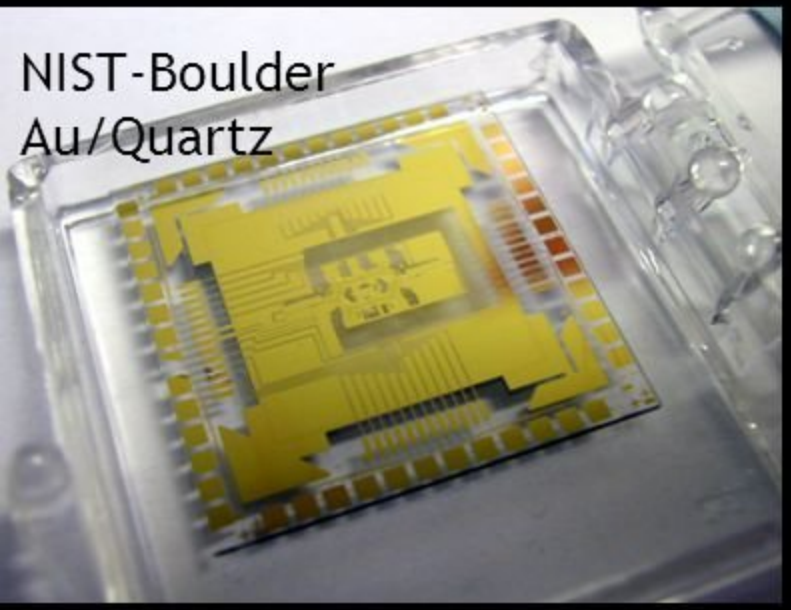



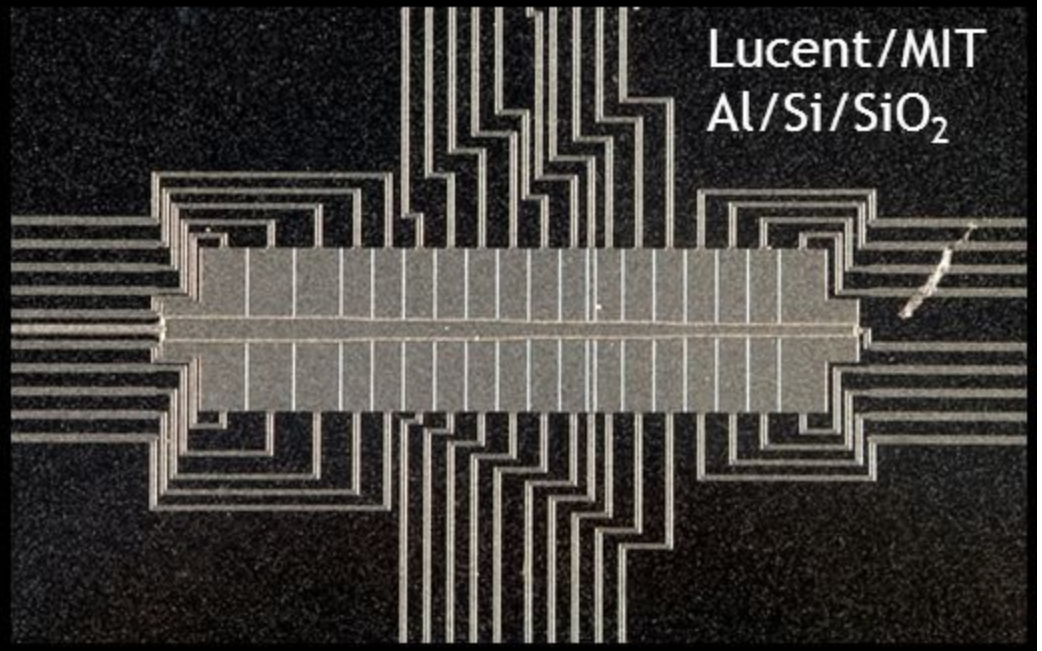
Chris Monroe, UMD

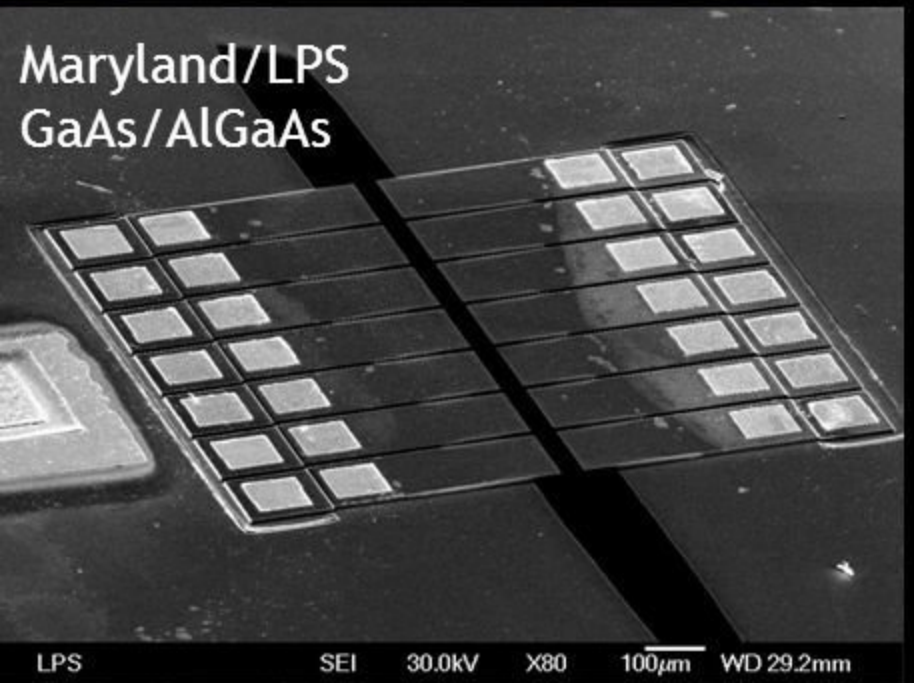


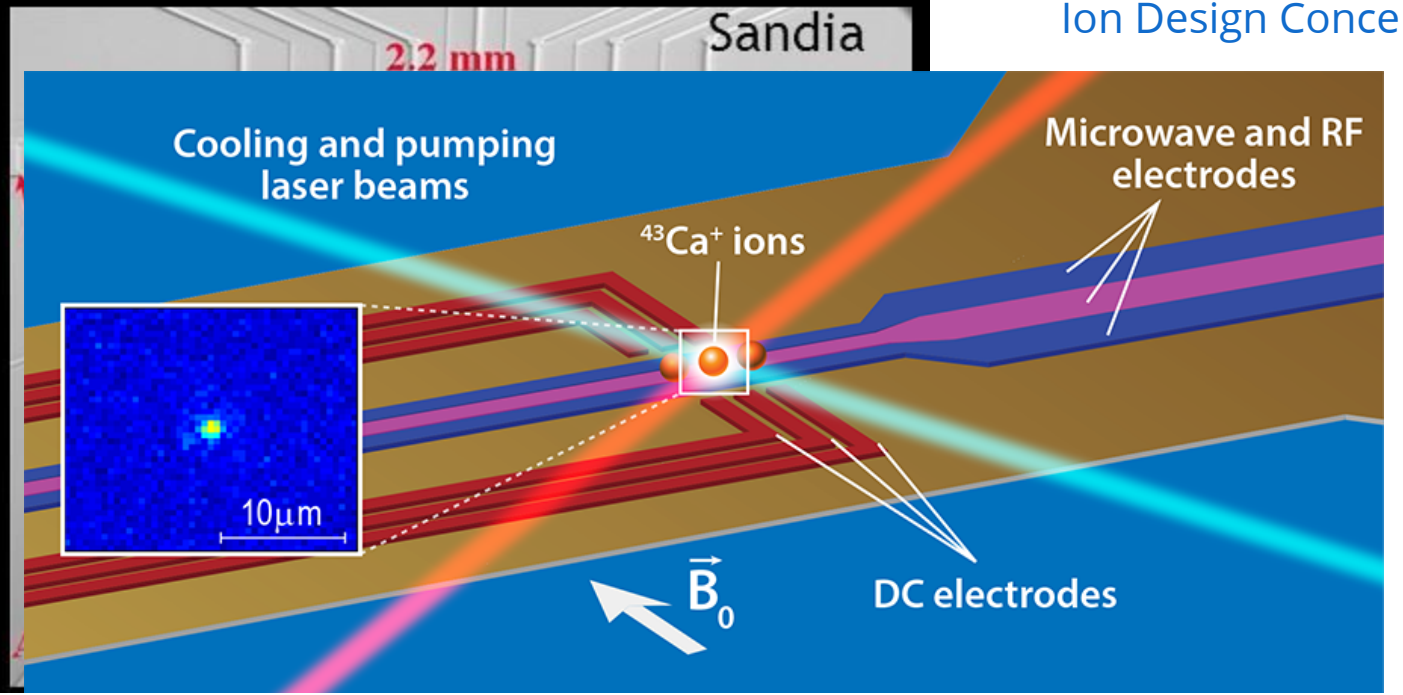
53 Trapped Fluorescing Ions, UMD

# Ion Trap Chips



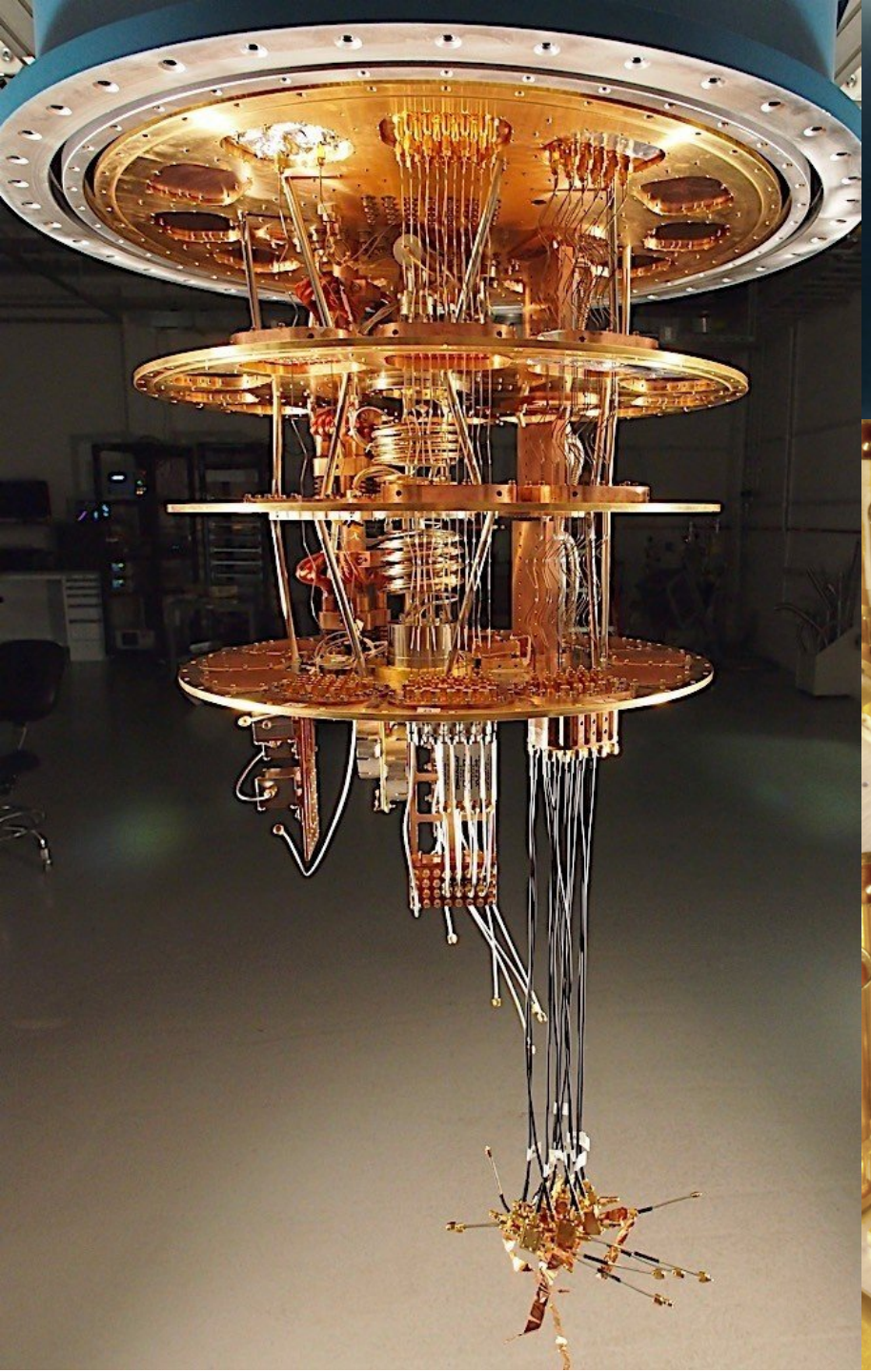



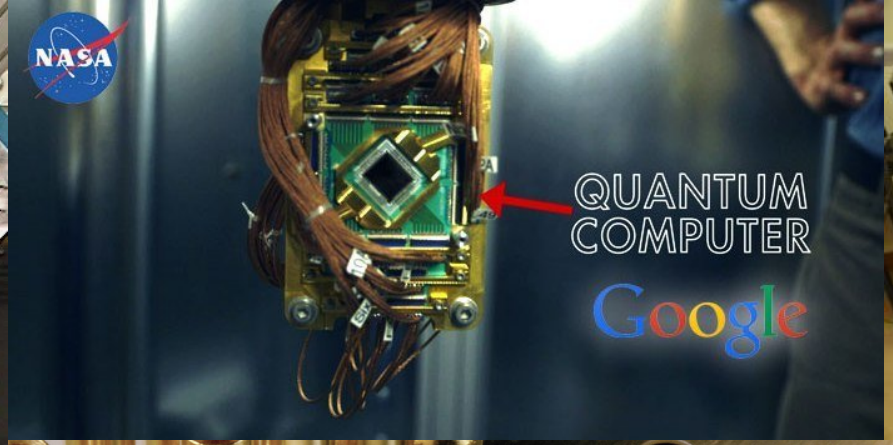



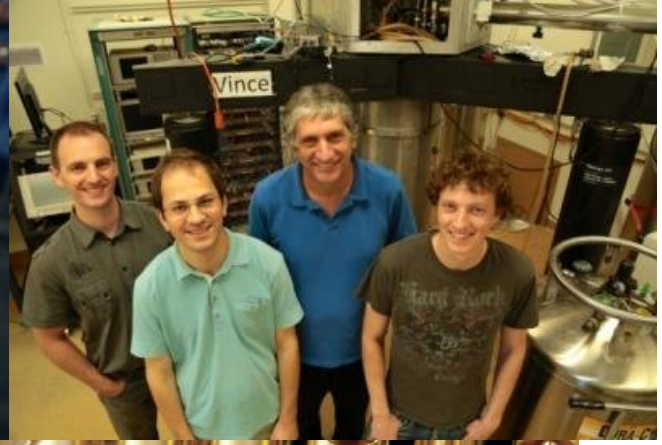

**Government Labs**
(MIT Lincoln Labs, Sandia National Labs, Laboratory for the Physical Sciences, NIST)

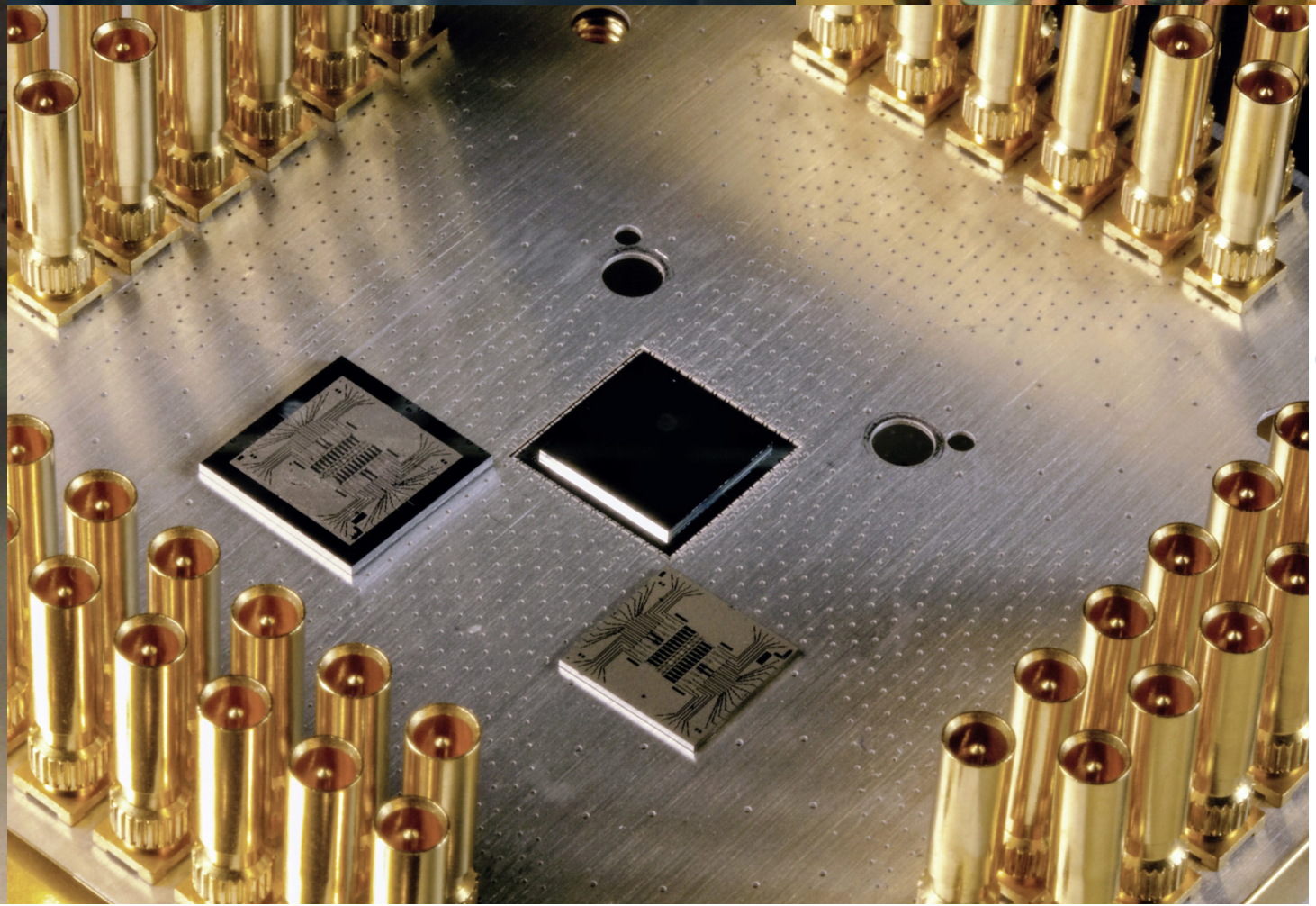
Levitating trapped ions as qubits

YouTube video of Trapped Ion Design Concept





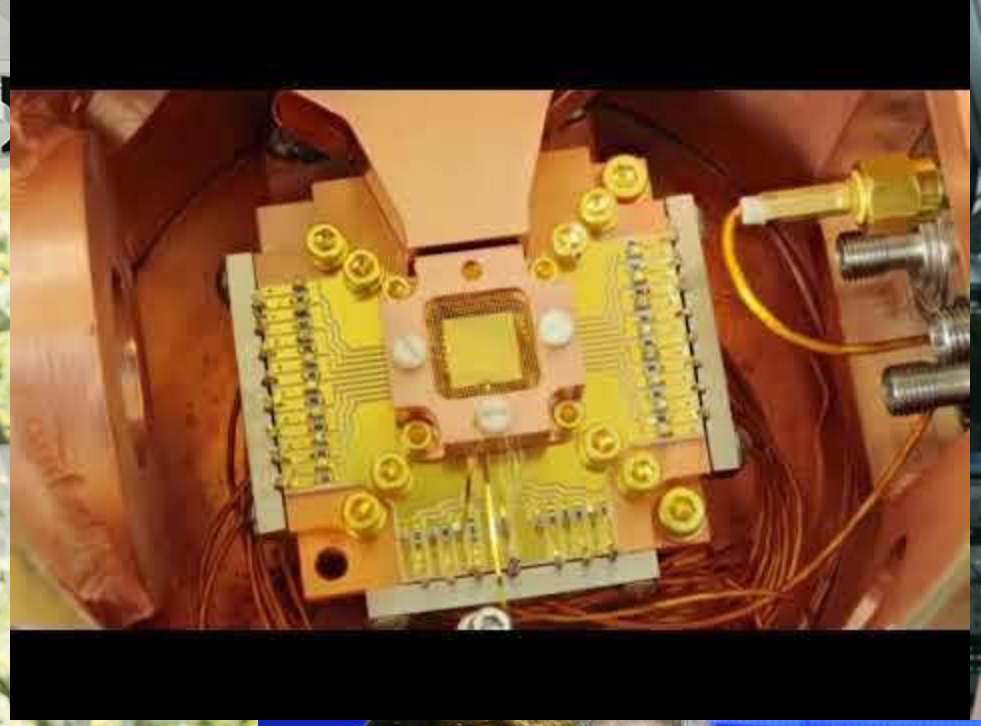
Hartmut Neven,

John Martinis,

Google Quantum AI Lab

Bristlecone Chip

72 qubits



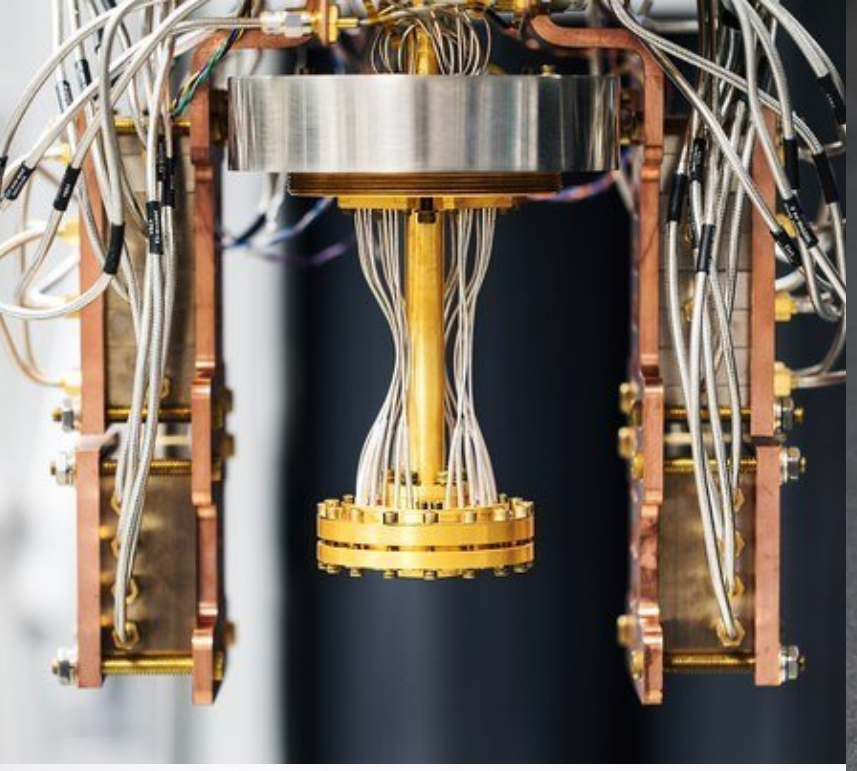

Jay Gambetta,

Jerry Chow

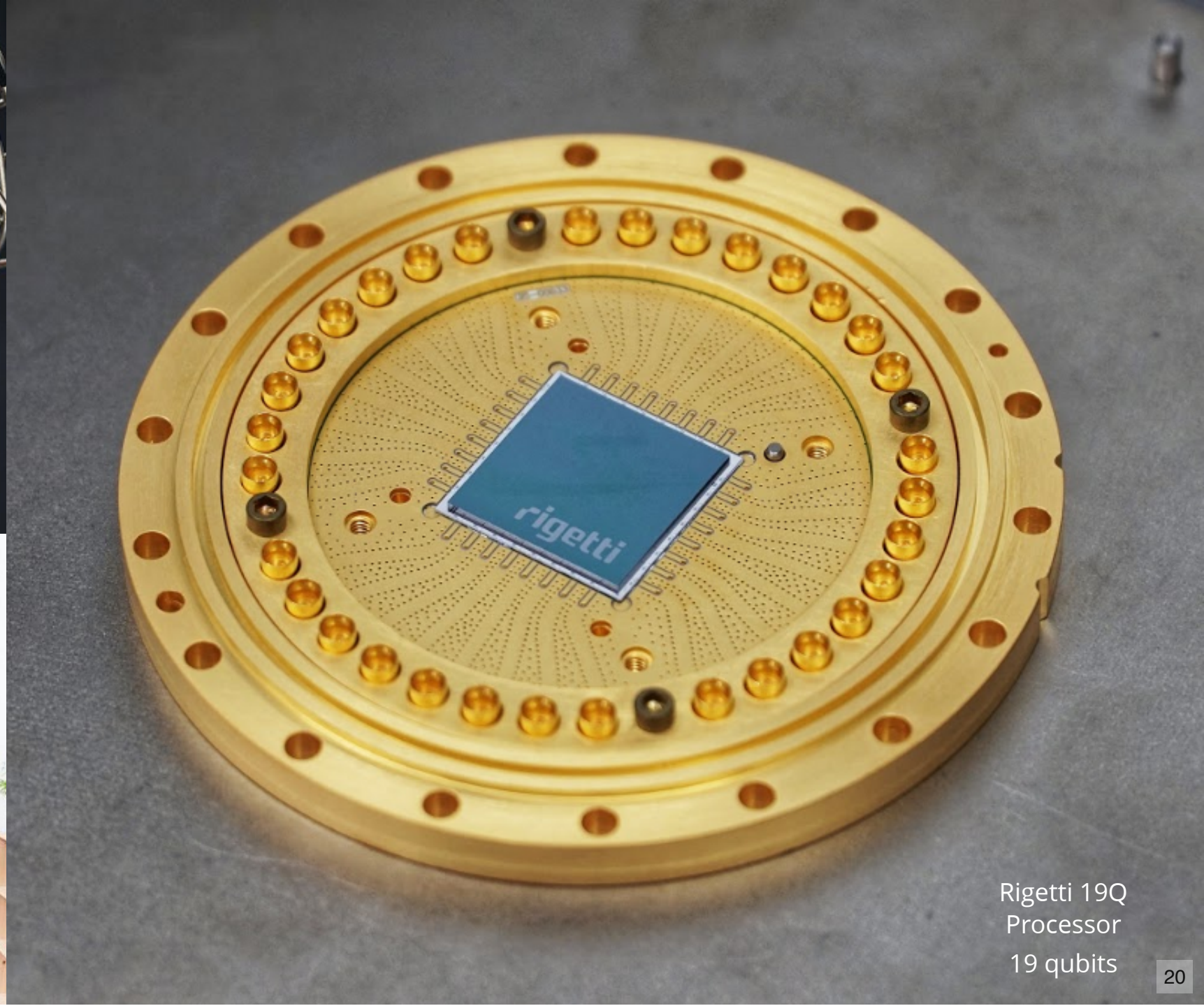
IBM Q

IBM Q Prototype

50 qubits




Rigetti
Computing




Rigetti 19Q
Processor
19 qubits

# How Many Qubits is "Enough"?

- Suppose our goal is to implement **Shor's Algorithm** to factor an **n-bit** integer.  For example, strong RSA encryption uses 2048-bit keys.
  - Need: **2n** qubits minimum to implement algorithm
    - RSA needs 4096 qubits - about 2 orders of magnitude more than state-of-the-art quantum computing hardware (a few years away)
  - **Caveat: qubits need to be perfect - no laboratory qubit is perfect**

- Hidden resource cost : **Quantum Error Correction**
  - **Quantum coherence is very sensitive**
  - To protect against decoherence, **need to encode quantum information redundantly**

  - **Idea : compose "Logical" qubits out of many "Physical" qubits**

## Classical Bit Error Correction

$$0 \mapsto 000 \qquad 1 \mapsto 111$$

If one bit flips, can detect and correct via majority-voting

## Qubit Error Correction

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

Same basic idea, but now applied to *superpositions*

**Main problem**: cannot "look" at the bits directly due to measurement collapse

**Resolution**: measure *parities* of bits instead

## Qubit Error Correction

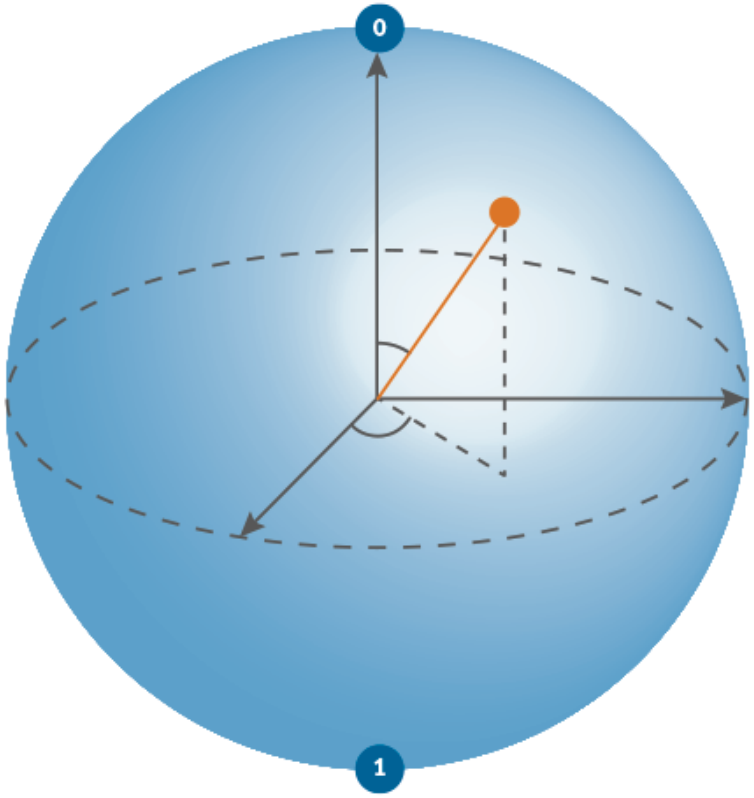
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \mapsto \alpha|000\rangle + \beta|111\rangle$$

**Simple bitflip protection is not quite enough.**

**Problem**: qubits can do more than just flip - more can go wrong

**Resolution**: redundantly encode several types of information at once (e.g., multiple axes of the sphere), and measure several types of *parities* to fully detect and correct errors

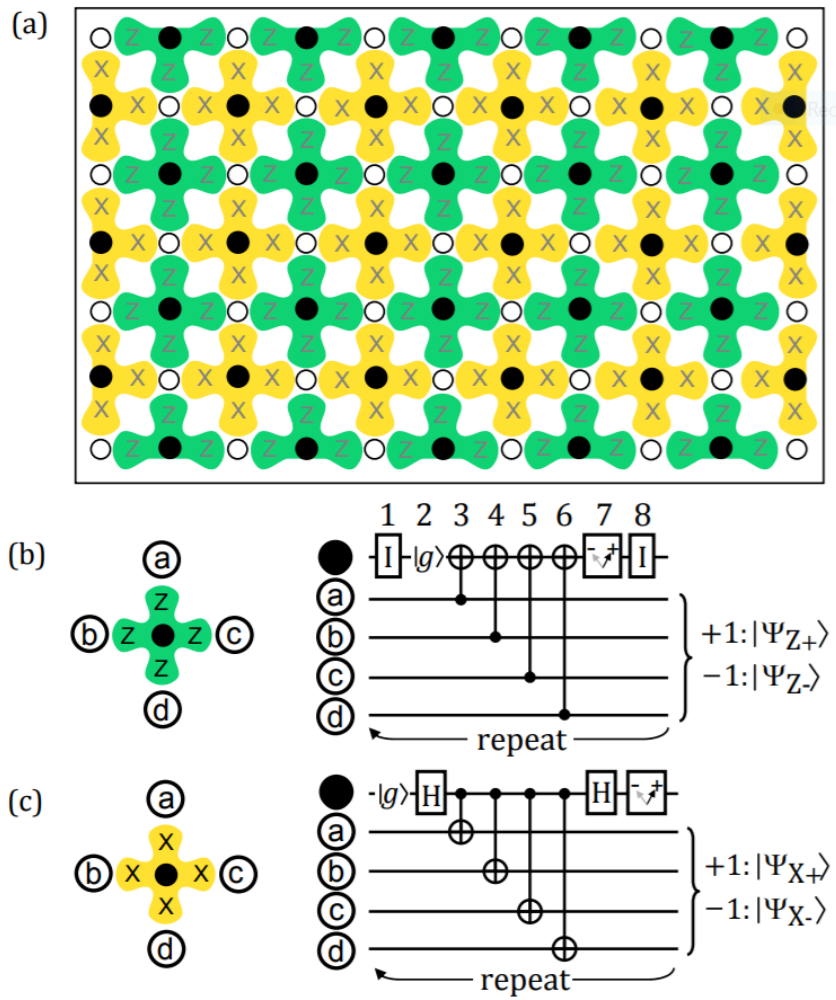
Remarkably, protecting two independent types of error is sufficient to protect against all errors



# The "Surface Code"

Phys. Rev. A 86, 032324 (2012)

A very clever way to implement full quantum error correction for a **2D lattice** of nearest-neighbor-coupled qubits is the "surface code"




**Idea** : Create **three** interspersed lattices

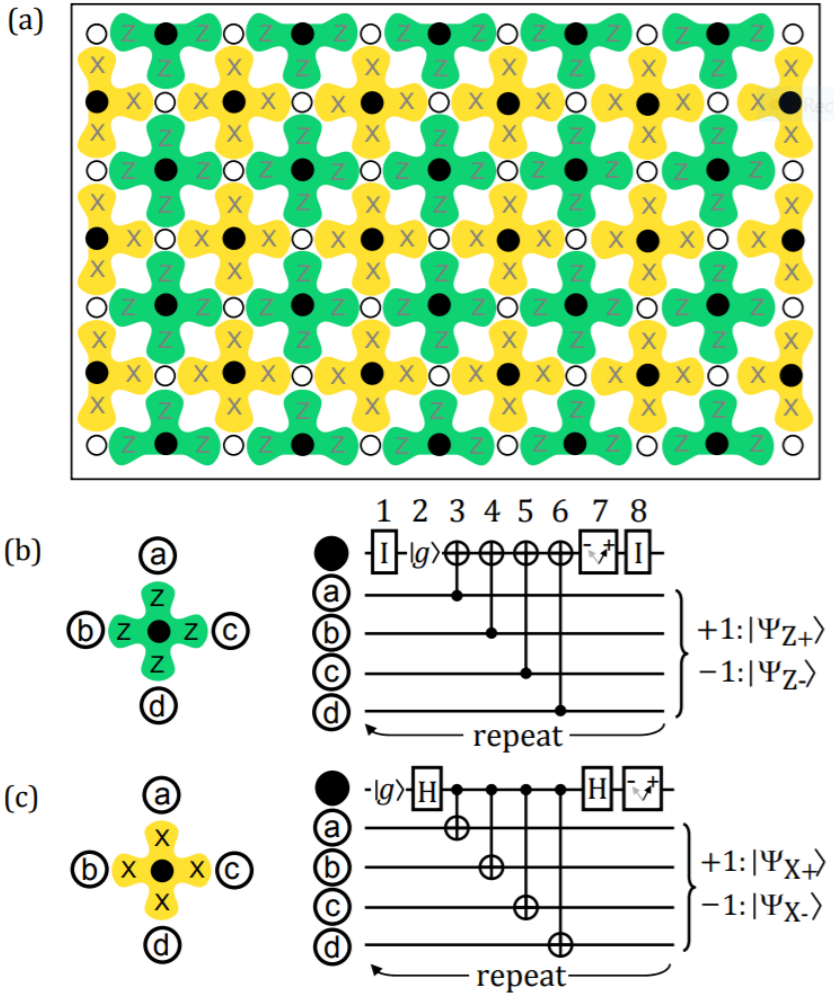
1. **Data qubit lattice** - white dots (stores quantum info.)

2. **X qubit lattice** - black dots, yellow (measures XXXX parities)

3. **Z qubit lattice** - black dots, green (measures ZZZZ parities)

Can **encode** redundant information across entire **area of the lattice** to reduce error rate for the resulting logical qubit

# "Surface Code" Logical Qubit

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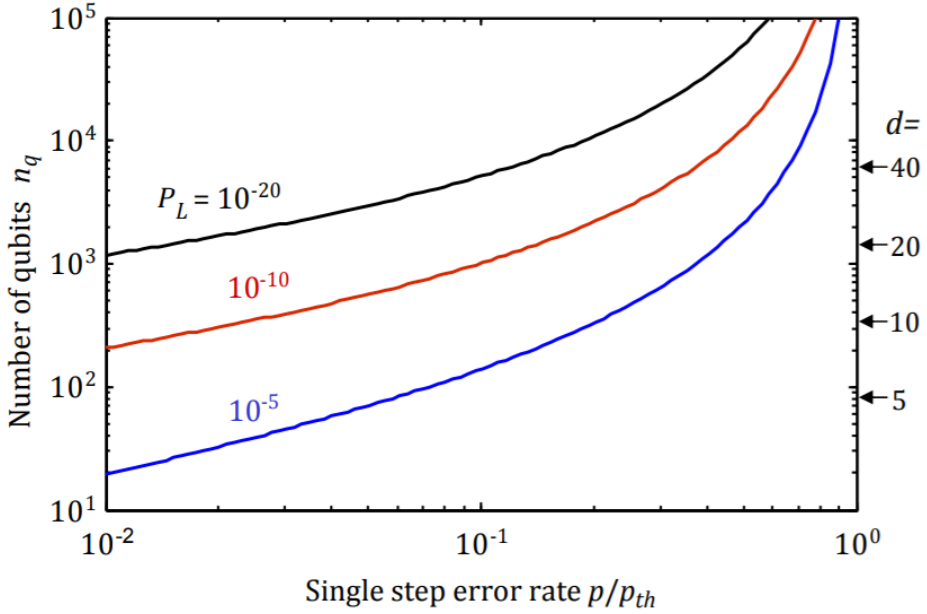



**Shor's Algorithm** needs a logical error rate of around **1e-20 per step**

If each step has an error rate ~1e-3 (typical in very good hardware), then **about 1e4 physical qubits will be needed to encode each logical qubit!**

# Updated Estimate for Shor's Algorithm

- **n = 2048 bits** for secure RSA encryption
- Need a minimum of **2n logical qubits** for n bits
- Need **1e4 physical qubits** per logical qubit
- Need another **factor of 15 overhead** for algorithmic details (state purification)

**Minimum qubit number :** $10^9$

- Adding in the time-axis:
  - Algorithm requires **3e11 Toffoli gates**
  - For superconducting qubits **~100ns per Toffoli gate**

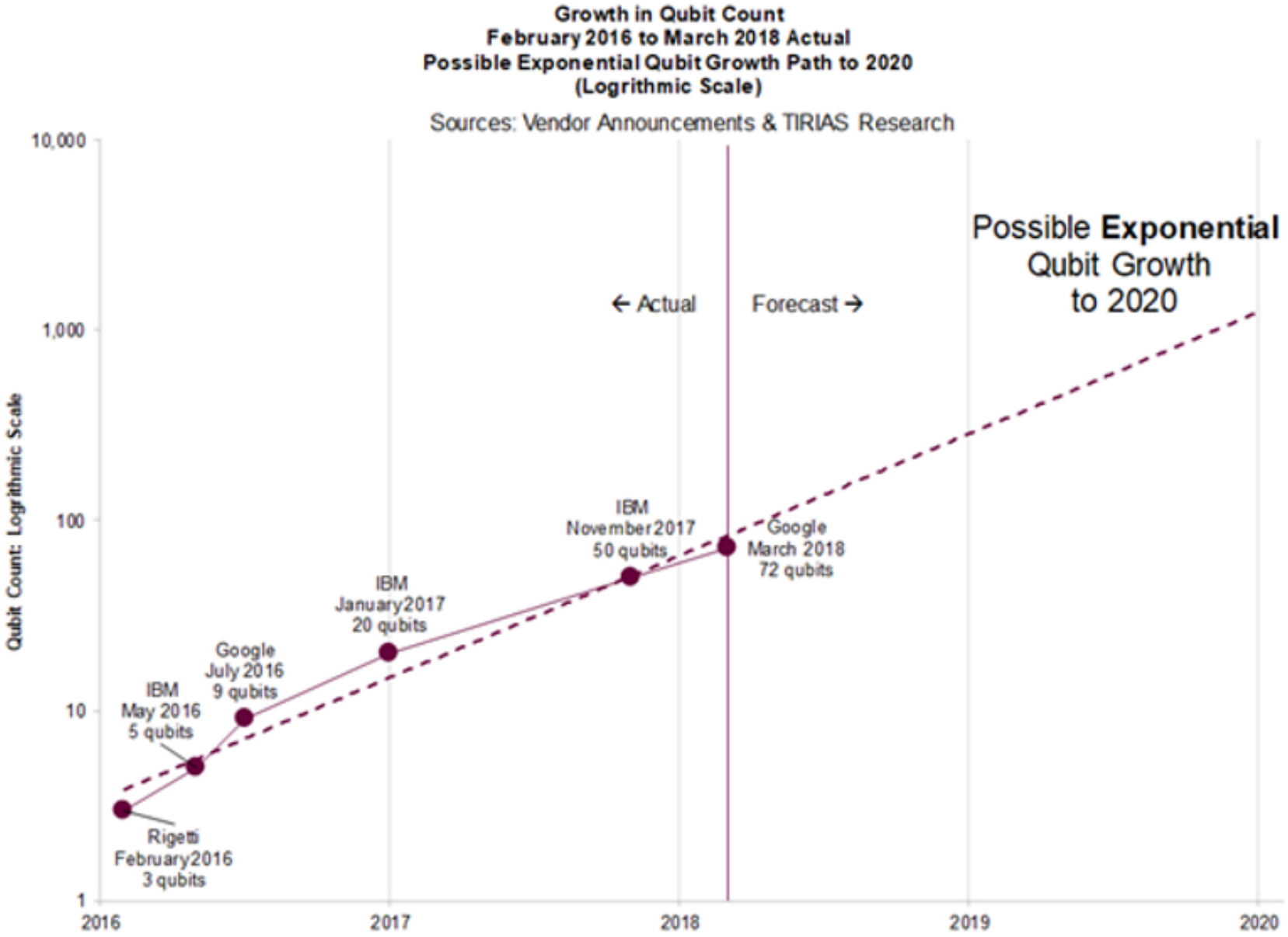
**Factoring run-time :** $27\ \mathrm{hr}$

(Compare to **6.4 quadrillion years** for a classical desktop computer running the number sieve)

Side note : Can reduce run-time by adding more qubits

Phys. Rev. A 86, 032324 (2012)

# How Long Until A Billion Qubits?

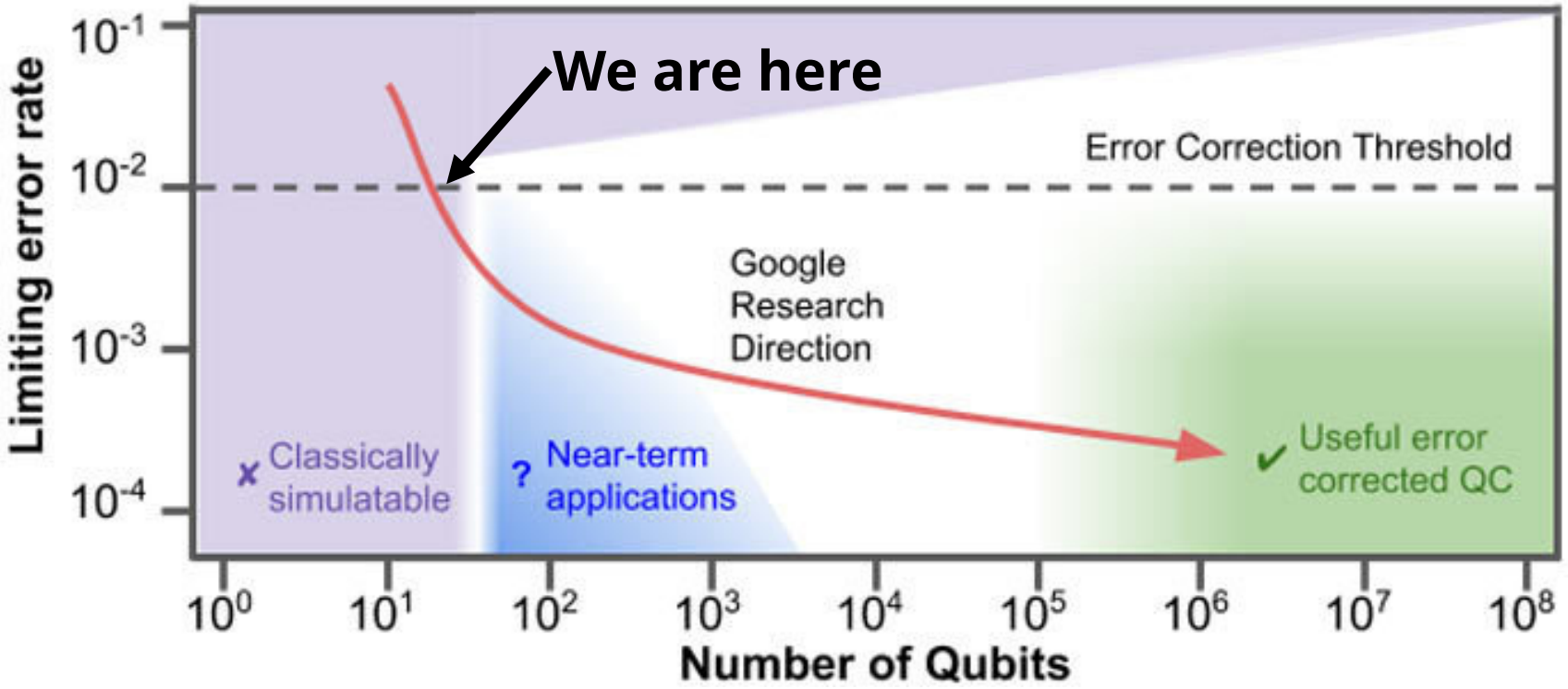



Growth in qubit number is currently **exponential**

If growth continues exponentially (with both fidelity and technical substrate scaling favorably) then we can expect chips with one billion qubits in:

**~10-15 years**

# What can we do until then?




Google Slides

We are now reaching the scale that is no longer possible to simulate using classical supercomputers.

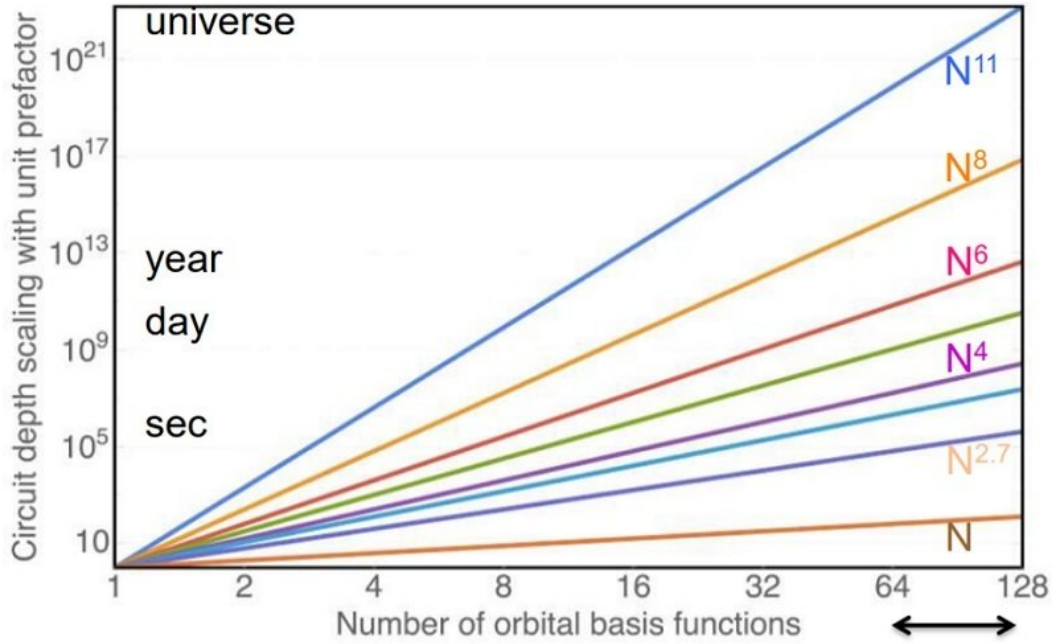
The current challenge is to find "near-term" applications for the existing quantum devices.

# Quantum Simulation

**Idea** : Quantum systems more easily simulate other quantum systems
(Proposed by Feynman in 1985)

## Huge Progress in Algorithms (Quantum Chemistry)

| Year | Reference | Total Depth |
|---|---|---|
| 1985 | Feynman | (proposal) |
| 2005 | Aspuru-Guzik [1] | $\mathcal{O}(\text{poly}(N))$ |
| 2010 | Whitfield [2] | $\mathcal{O}(\text{poly}(N))$ |
| 2012 | Seeley [3] | $\mathcal{O}(\text{poly}(N))$ |
| 2013 | Perruzzo [4] | $\mathcal{O}(\text{poly}(N))$ |
| 2013 | Toloui [5] | $\mathcal{O}(\text{poly}(N))$ |
| 2013 | Wecker [6] | $\mathcal{O}(N^{11})$ |
| 2014 | Hastings [7] | $\mathcal{O}(N^{8})$ |
| 2014 | Poulin [8] | $\sim N^{6}$ |
| 2014 | McClean [9] | $\sim N^{6}$ |
| 2014 | Babbush [10] | $\sim N^{5}$ |
| 2015 | Babbush [11] | $\tilde{\mathcal{O}}(N^{5})$ |
| 2015 | Babbush [12] | $\tilde{\mathcal{O}}(\eta^{2}N^{3})$ |
| 2015 | Wecker [13] | $\mathcal{O}(N^{4})$ |
| 2016 | McClean [14] | $\mathcal{O}(\eta^{2}N^{2})$ |
| 2017 | Babbush [15] | $\mathcal{O}(\eta^{1.83}N^{1.67})$ |
| 2017 | Babbush [15] | $\tilde{\mathcal{O}}(N^{2.67})$ → Exact: 100 logical qubits (error corrected) |
| 2017 | Babbush [15] | $\mathcal{O}(N)$ → Approximate: 100 physical qubits (?) |

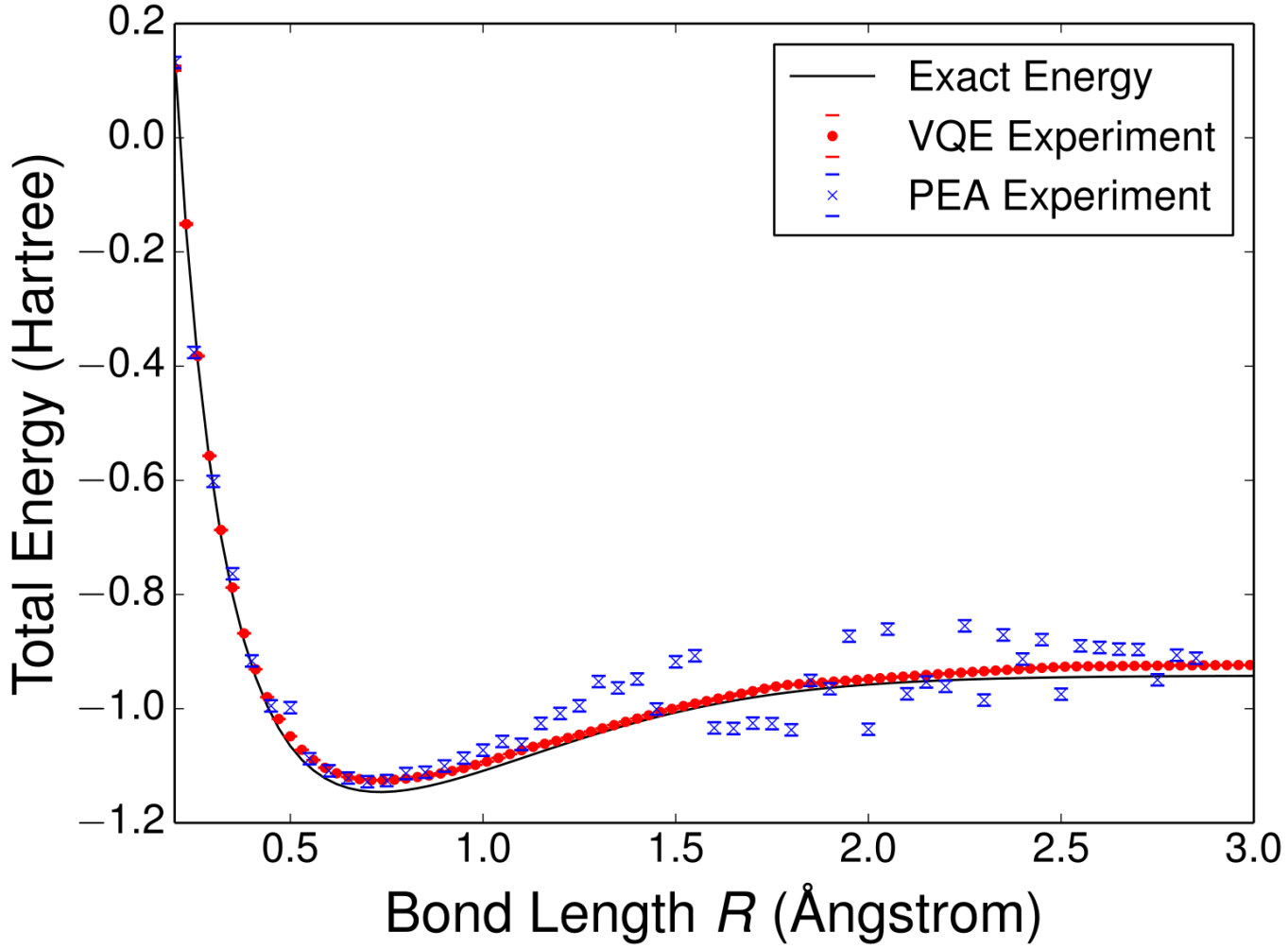



**Quantum Chemistry** is an obvious application

Recent algorithms need only
**~1e2 physical qubits** for **approximate** solutions,
or
**~1e2 logical qubits** for **exact** solutions

Google Slides

# Experimental Progress already Underway



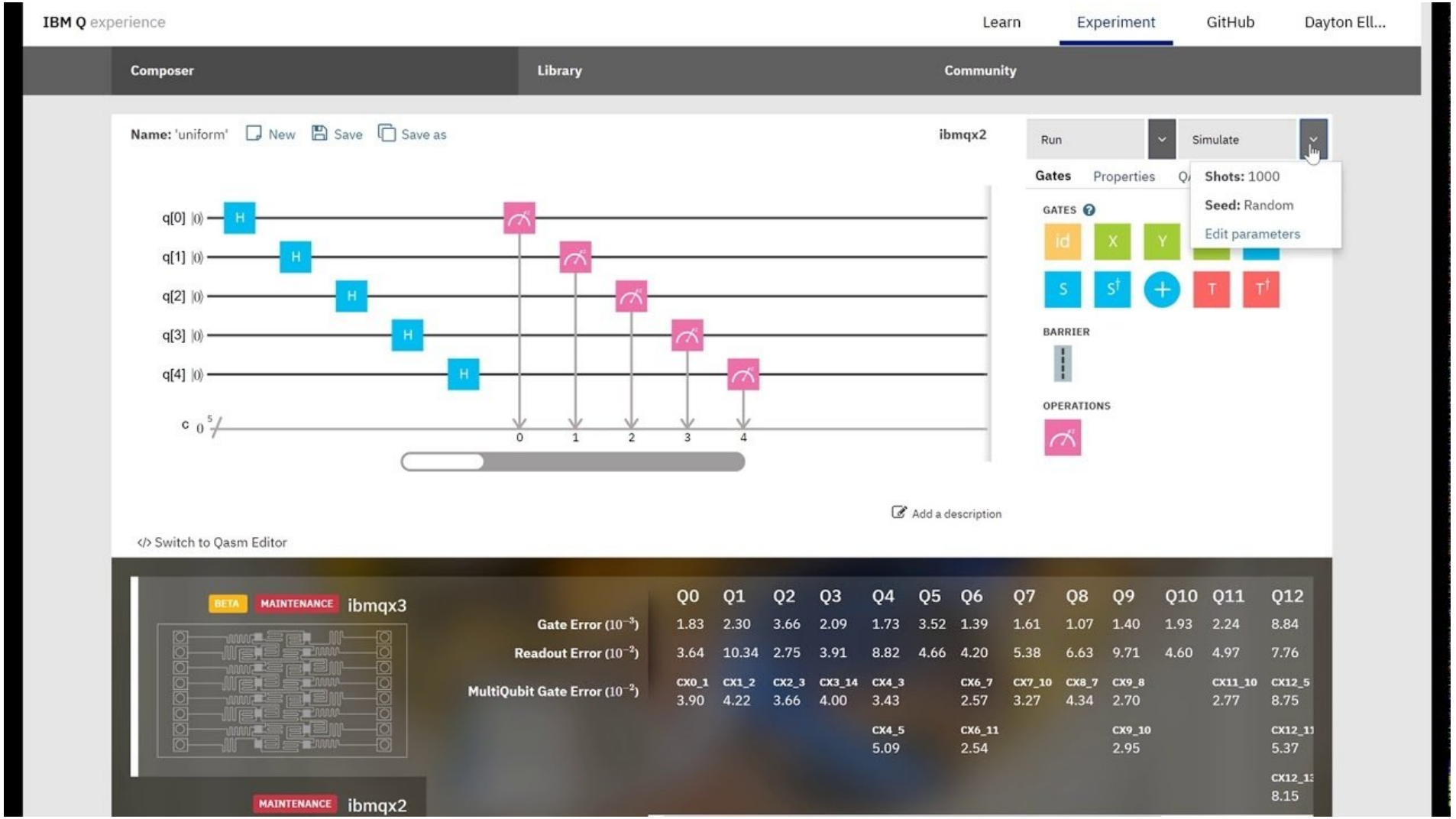

2016 Google Experiment

Two quantum algorithms for computing the bond energy for an H2 molecule using **3 qubits**, compared to the numerical calculation using a classical computer

Experimental data already viable

For larger molecules, classical computers will no longer be able to numerically calculate these energies

# Program a Quantum Computer Now

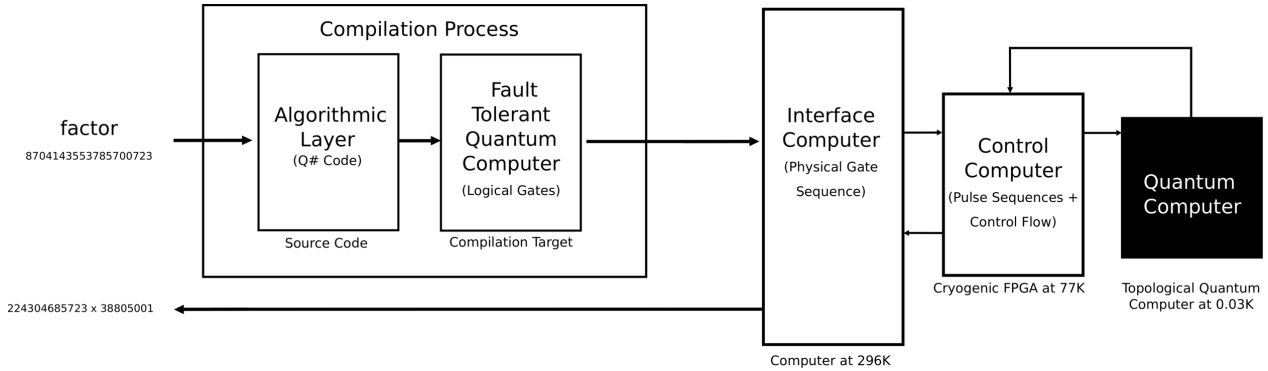



**IBM Quantum Experience : Cloud Computer**

(16 qubits free, 20+ paid)

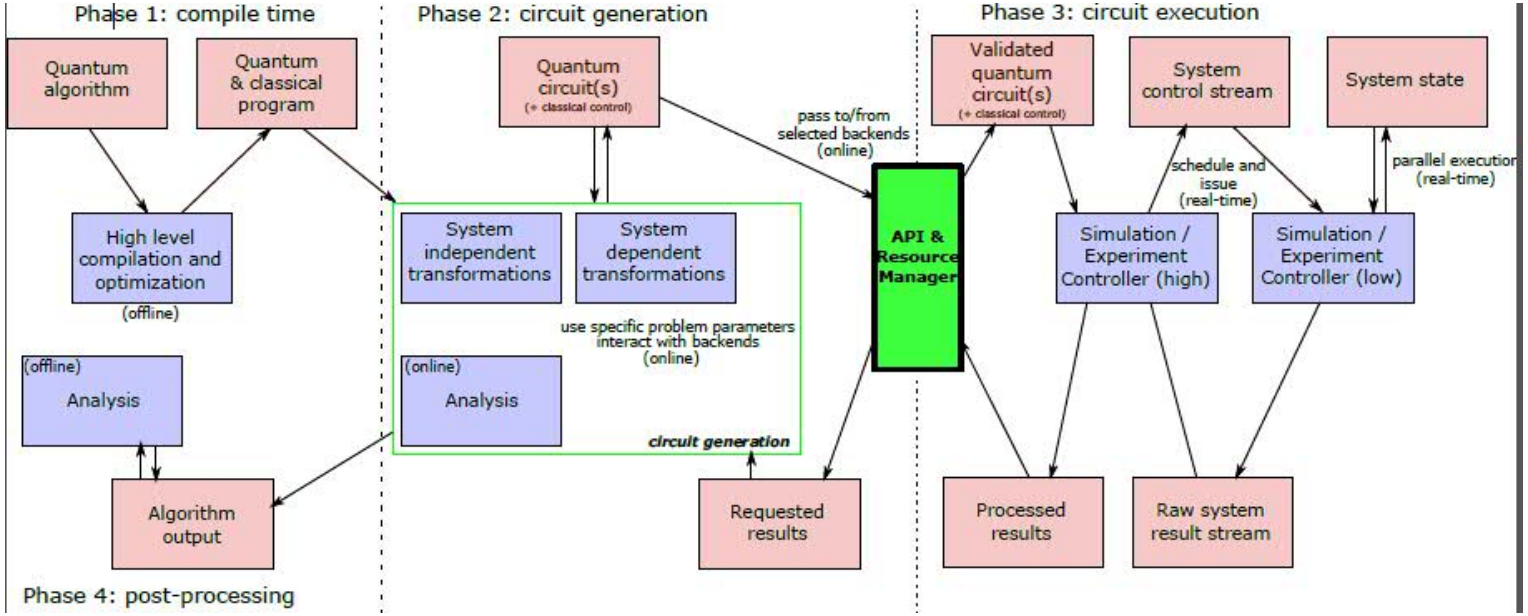
# Quantum Software Stacks

## Microsoft : Q#, Quantum Dev Kit, LiQui|>




```
operation Teleport(msg : Qubit, there : Qubit) : (
    body {
        using (register = Qubit[1]) {
            let here = register[0];
            H(here);
            CNOT(here, there);
            CNOT(msg, here);
            H(msg);
            // Measure out the entanglement.
            if (M(msg) == One)  { Z(there); }
            if (M(here) == One) { X(there); }
        }
    }
}
```

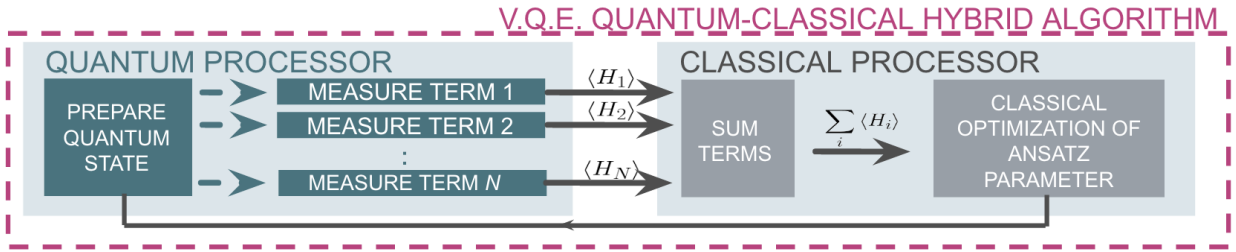
## IBM : QISKit SDK




```
from qiskit import ClassicalRegister, QuantumRegiste
from qiskit import QuantumCircuit, execute
from qiskit.tools.visualization import plot_histogra

# set up registers and program
qr = QuantumRegister(16)
cr = ClassicalRegister(16)
qc = QuantumCircuit(qr, cr)

# rightmost eight (qu)bits have ')' = 00101001
qc.x(qr[0])
qc.x(qr[3])
qc.x(qr[5])

# second eight (qu)bits have superposition of
# '8' = 00111000
# ';' = 00111011
# these differ only on the rightmost two bits
qc.h(qr[9]) # create superposition on 9
qc.cx(qr[9],qr[8]) # spread it to 8 with a CNOT
qc.x(qr[11])
qc.x(qr[12])
qc.x(qr[13])

# measure
for j in range(16):
    qc.measure(qr[j], cr[j])
```

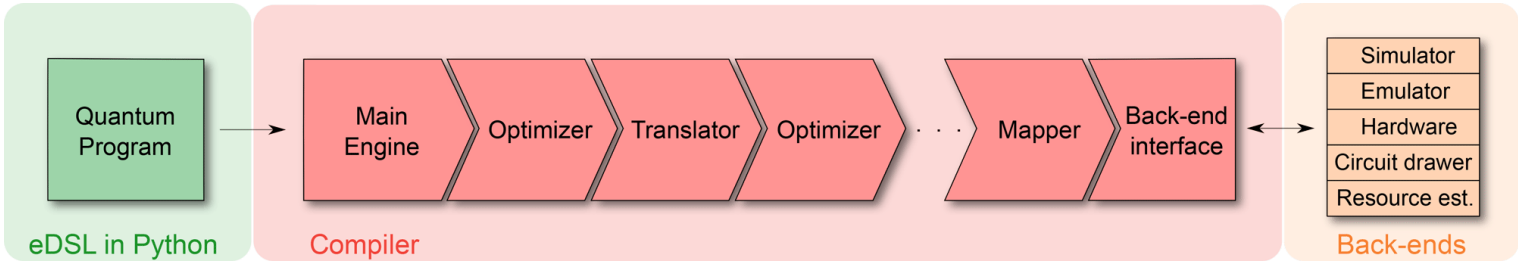
# More Quantum Software Stacks

## Rigetti Computing : Forest, Quil, PyQuil



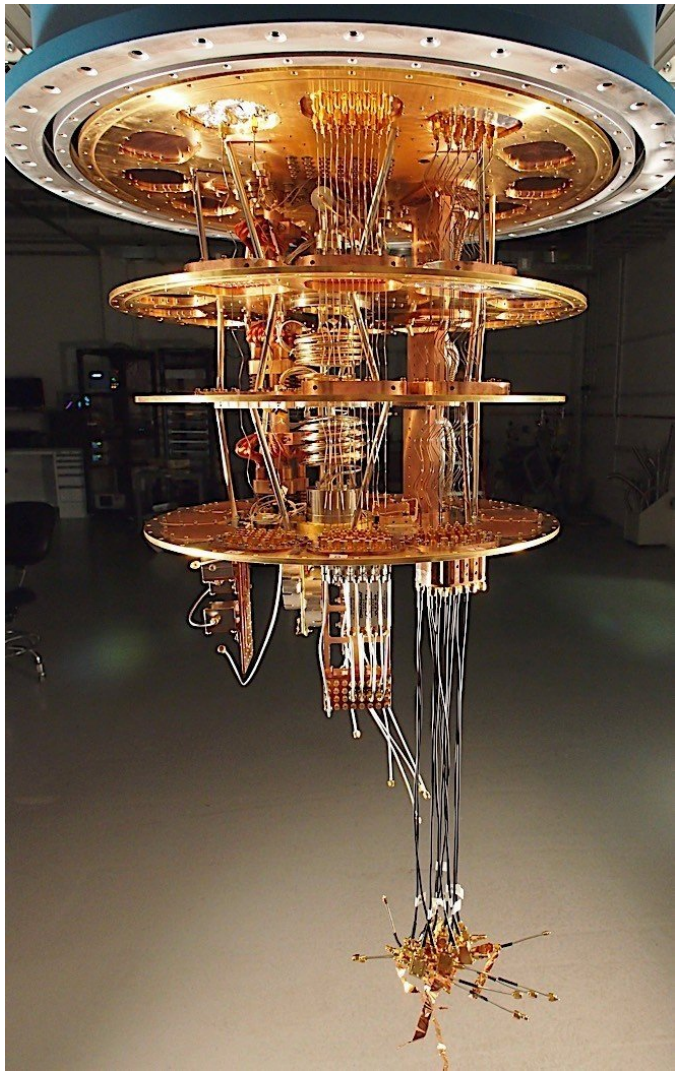

```
from math import pi

def qft3(q0, q1, q2):
    p = Program()
    p.inst( H(q2),
            CPHASE(pi/2.0, q1, q2),
            H(q1),
            CPHASE(pi/4.0, q0, q2),
            CPHASE(pi/2.0, q0, q1),
            H(q0),
            SWAP(q0, q2) )
    return p
```

## Opensource : ProjectQ




```
from projectq import MainEngine
from projectq.backends import CircuitDraw

from teleport import create_bell_pair

# create a main compiler engine
drawing_engine = CircuitDrawer()
eng = MainEngine(drawing_engine)

create_bell_pair(eng)

eng.flush()
print(drawing_engine.get_latex())
```

# Conclusions



Quantum computing is already here (mostly).

It is only a matter of time before a quantum computer accomplishes a task that is currently impossible on any classical computer.

**Thank you!**

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