ECE 550/650 – Intro to Quantum Computing

Robert Niffenegger

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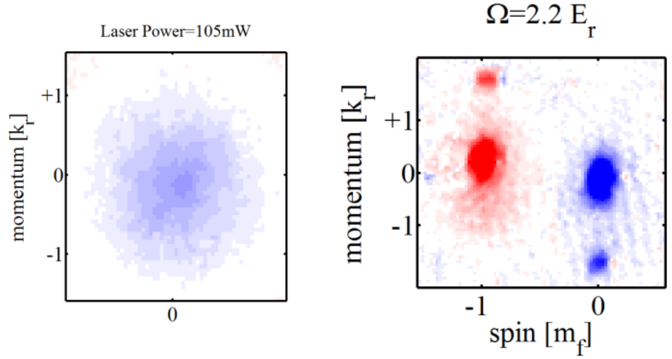
Introductions – Robert Niffenegger

PURDUE UNIVERSITY

Physics PhD (2015)

Quantum simulation experiments

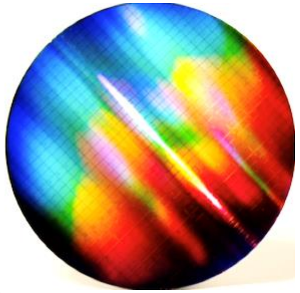
BECs with synthetic spin orbit coupling

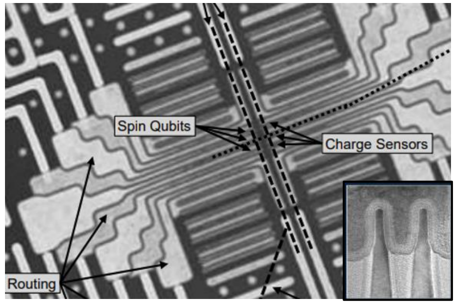


~~7nm~~ → ‘Intel 4nm’ (2019)

Process development: CMOS and qubits

7nm process technology patent



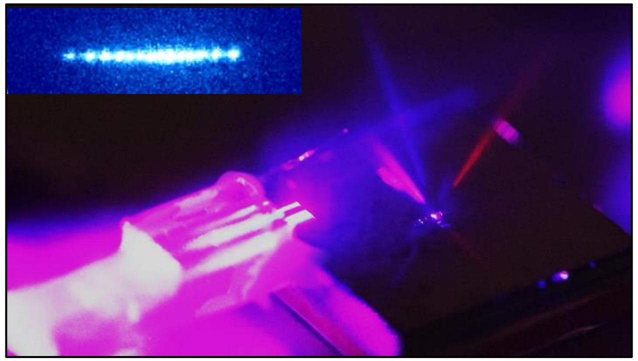


LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

MIT Lincoln Labs
Quantum Computing Group

Trapped Ions & Photonics

(2021)



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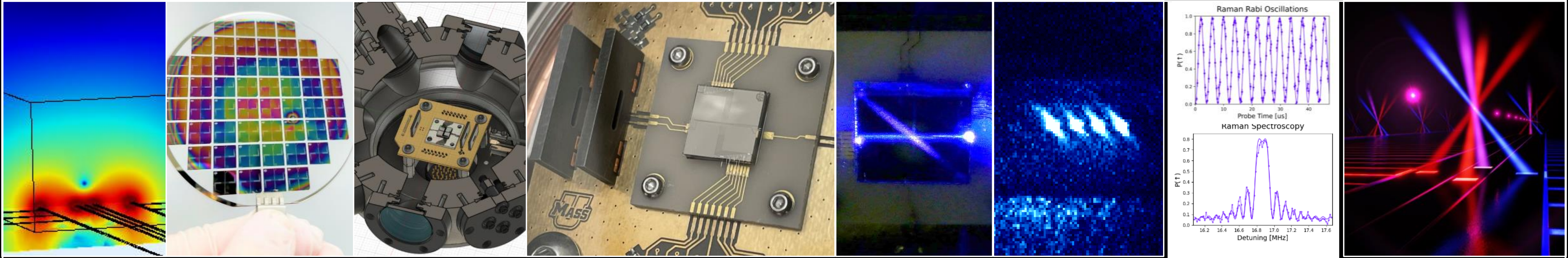
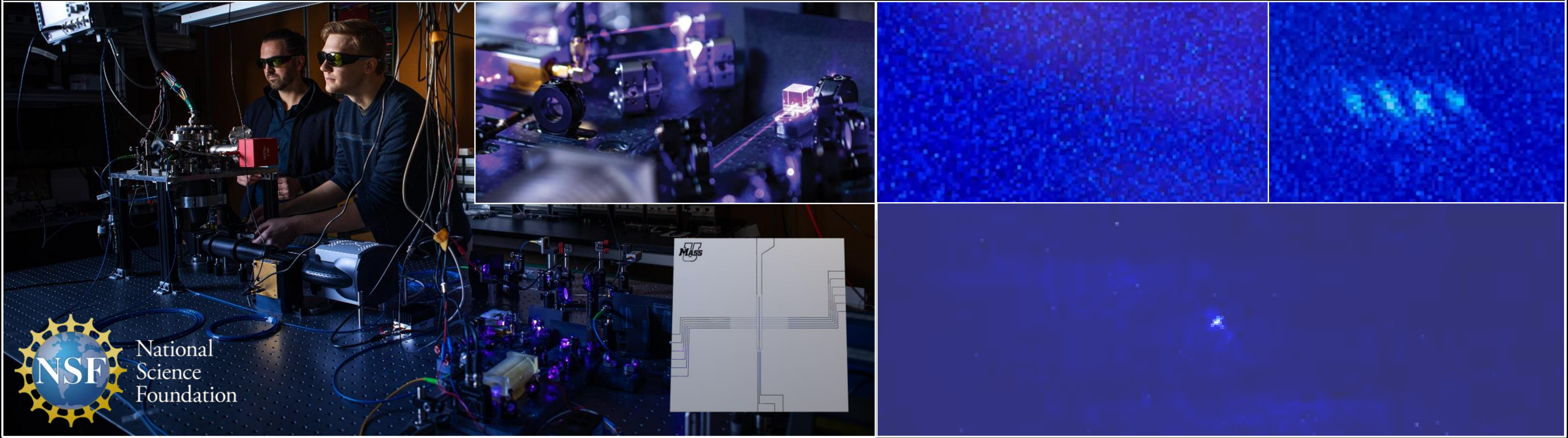
Niffenegger Lab - Developing Integrated Technologies for Trapped Ion Qubits and Optical Clocks



Design → Layout → Fabrication → Packaging → Ultra High Vacuum → Optics → Lasers → Trapped Ions→ Zeeman Qubits→ Integrated Photonics

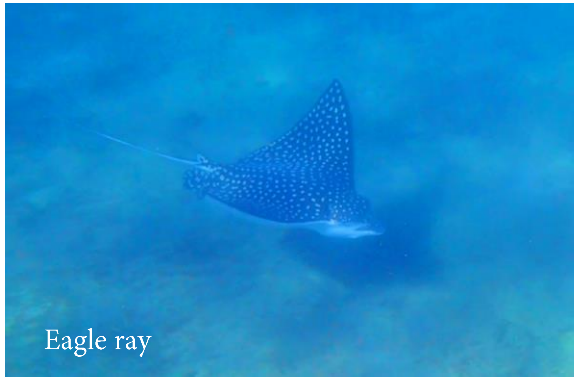


Introductions


Intel - Process Development Headquarters – Portland, OR

Robert Niffenegger
Assistant Professor ECE

B.S.	Physics - Michigan Tech
PhD	Physics - Purdue
Intel	7nm process
Postdoc	Quantum Computing MIT


Eagle ray

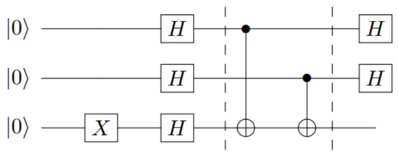
UMass Amherst Trapped ion quantum computing lab

Introductions

- Electrical or Computer Engineers?
- Why are you taking intro to Quantum Computing?
- Plans for after graduation?
- Python programming?
- Phasors and $e^{i\theta}$ Euler notation?
- Linear algebra? Rotations?
- What is a qubit?
- What is superposition?
- What is entanglement?

Outline of the course

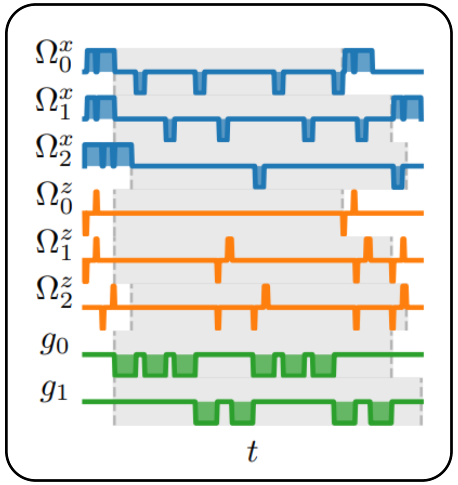
- Quantum Optics
  - What is interference (classical vs. single particle)
  - Superposition of states
  - Measurement and measurement basis
- Atomic physics
  - Spin states in magnetic fields and spin transitions
  - Transitions between atomic states (Rabi oscillations of qubits)
- Single qubits
  - Single qubit gates (electro-magnetic pulses, RF, MW, phase)
  - Error sources (dephasing, spontaneous decay)
  - Ramsey pulses and Spin echo pulse sequences
  - Calibration (finding resonance and verifying pulse time and amplitudes)
- Two qubit gates
  - Two qubit interactions – gate speed vs. error rates
  - Entanglement – correlation at a distance
  - Bell states and the Bell basis
  - XX gates, Controlled Phase gates, Swap




```
qc = QubitCircuit(3)
qc.add_gate("X", targets=2)
qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
qc.add_gate("SNOT", targets=2)

# Oracle function f(x)
qc.add_gate(
    "CNOT", controls=0, targets=2)
qc.add_gate(
    "CNOT", controls=1, targets=2)

qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
```

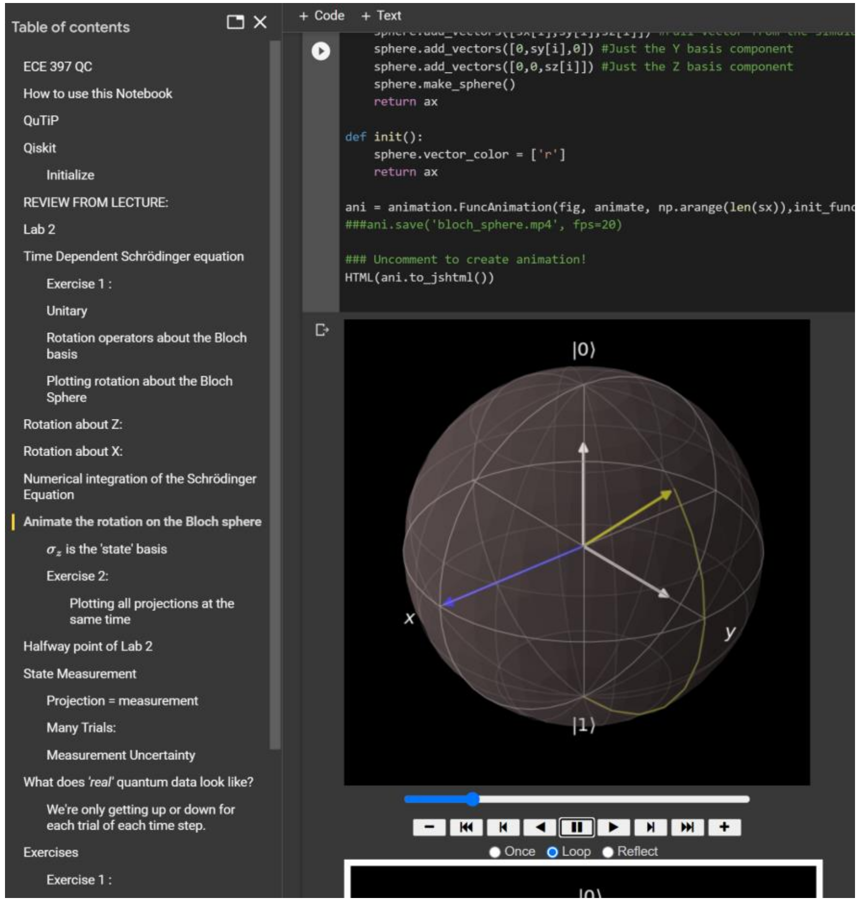


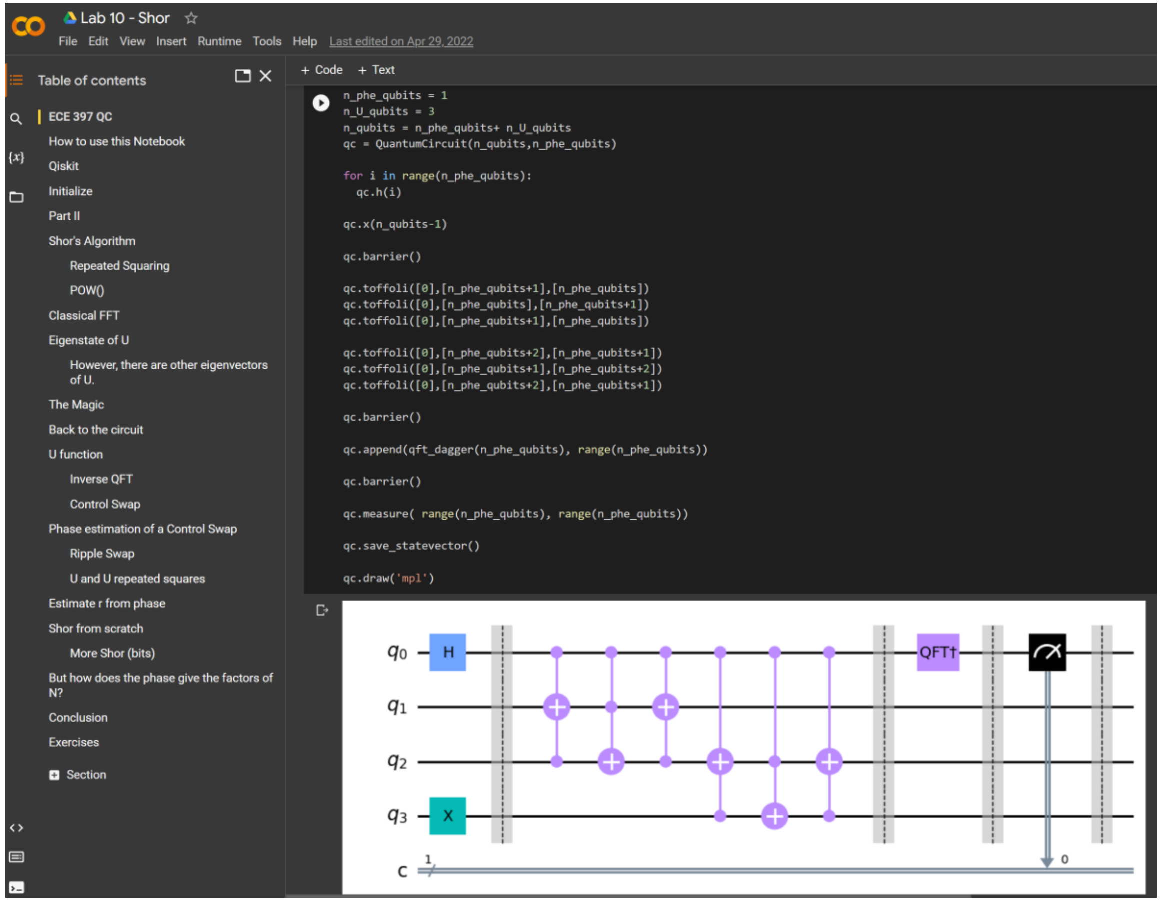
- Quantum Hardware
  - Photonics – nonlinear phase shifts
  - Transmons – charge noise, SWAP gate
- Quantum Circuits
  - Single and two qubit gates
  - Hadamard gate , CNOT gate
- Quantum Algorithms
  - Amplitude amplification
  - Grover's Search
  - Oracle - Deutsch Jozsa
  - Bernstein Vazirani
  - Quantum Fourier Transform and period finding
  - Shor's algorithm

If time permits

- Error Correction
  - Repetition codes
  - Color Codes
  - Surface code

Labs – Colab notebooks QuTiP then QISKIT





https://github.com/UMassIonTrappers/quantum-computing-labs

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Quick intro

Brief overview of quantum computing

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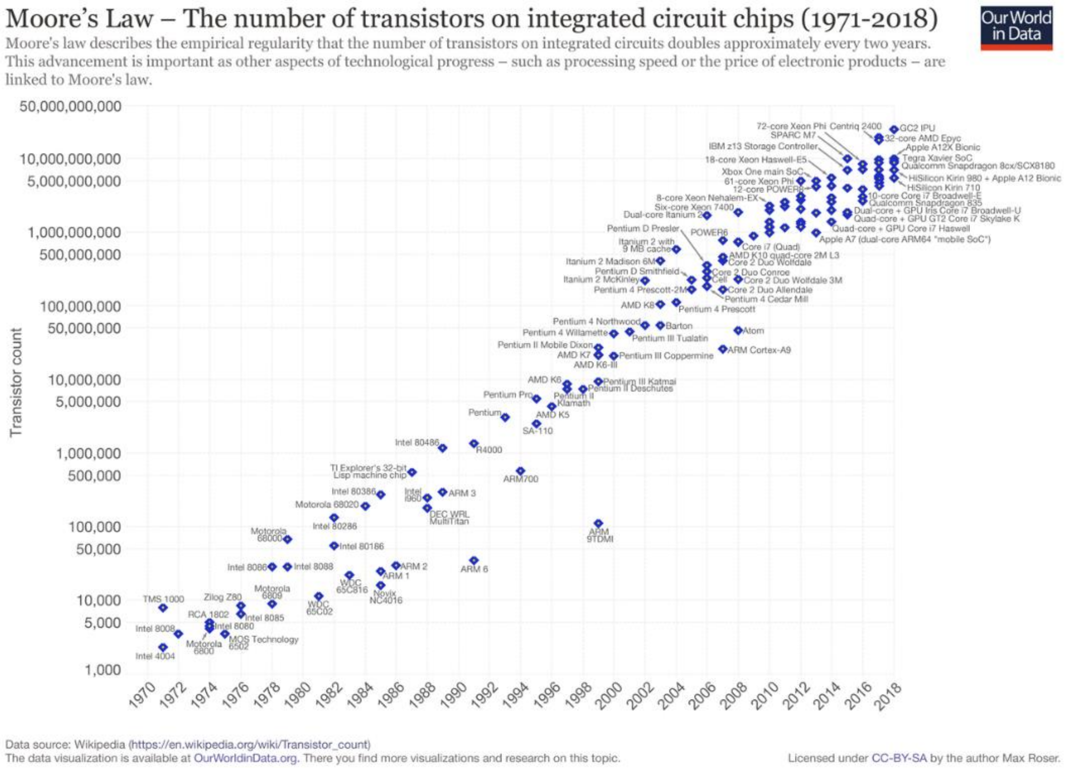
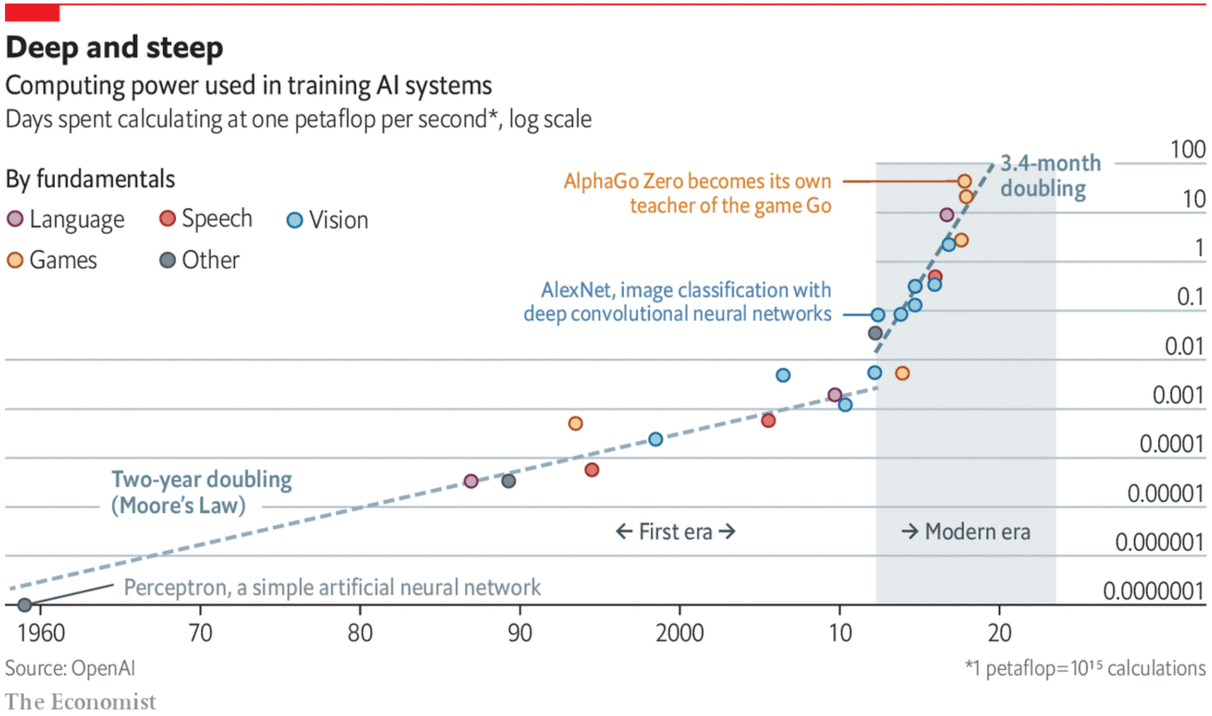
Computing - Supply & Demand

As Moore's law has 'ended'



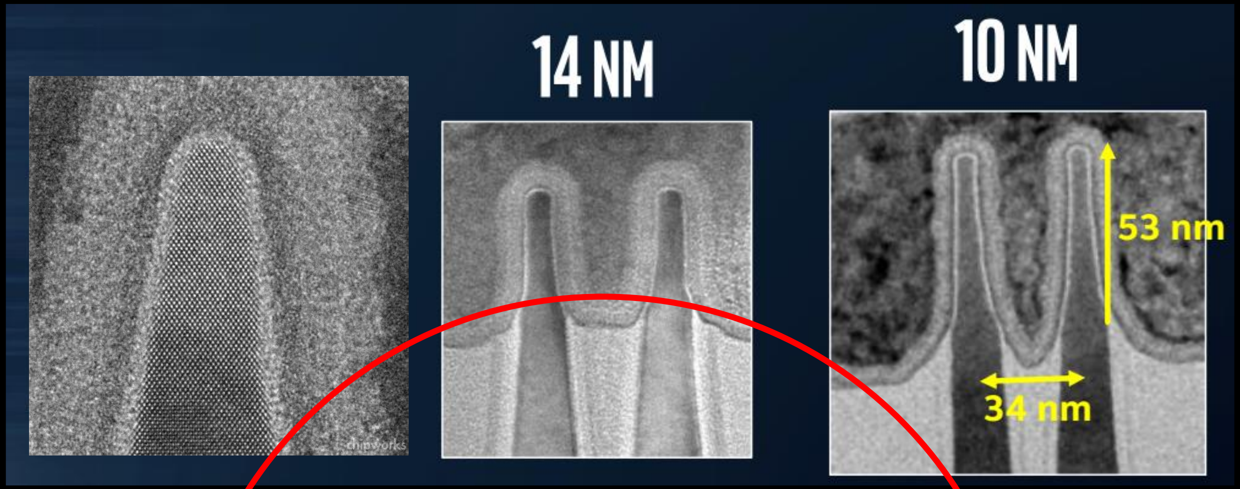
Computational demand has accelerated*
(deepseek*?)



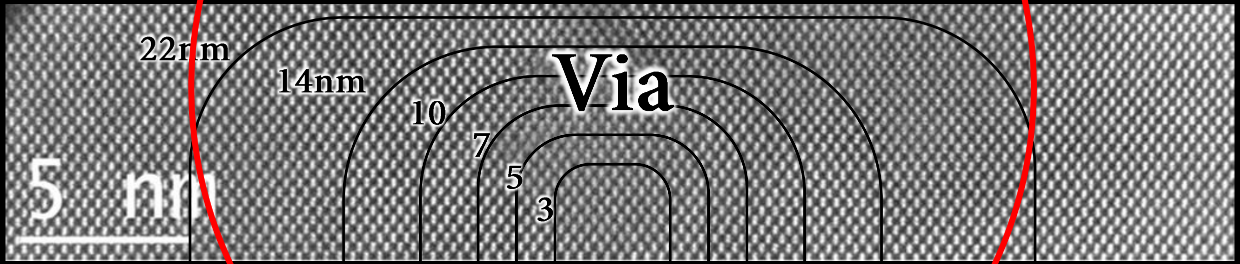
The world needs more 'compute'!

Physical Constraints to Scaling CMOS

FinFETs down to handful of Silicon atoms

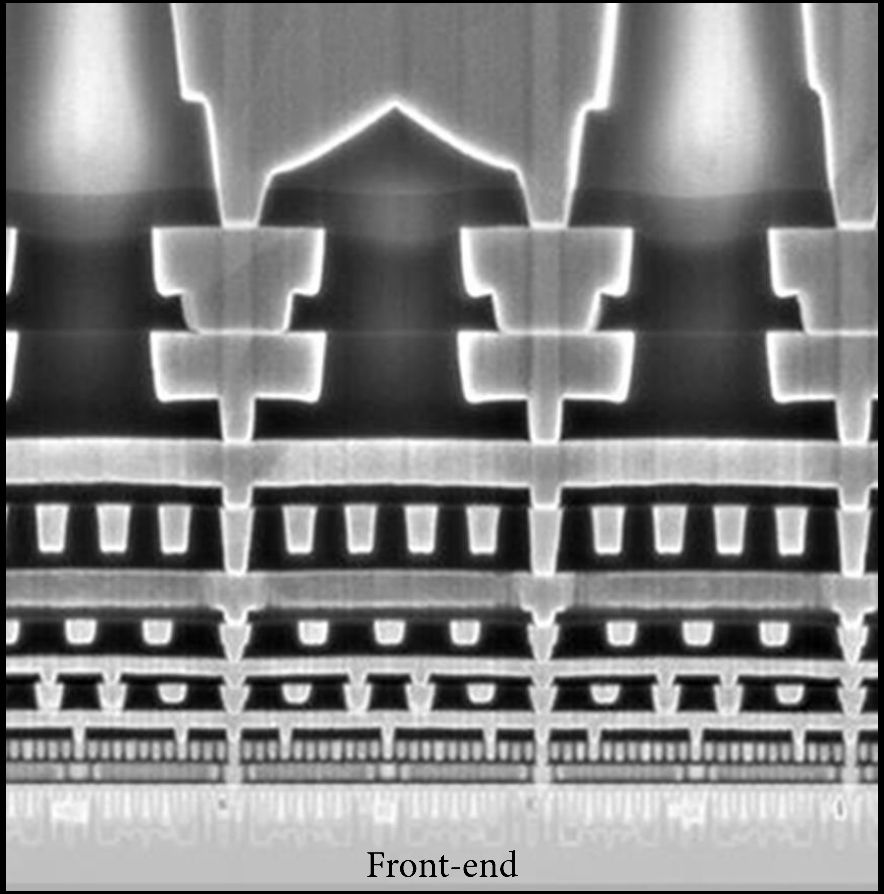


Silicon atoms



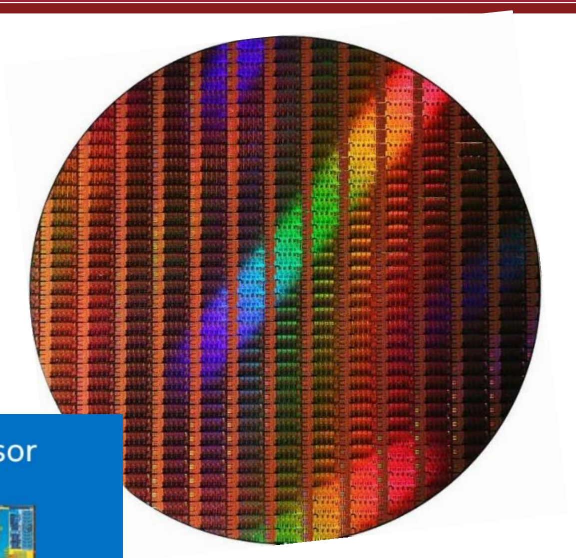
Interconnects too

M0



CMOS – Quality *and* Quantity ➔ sCALE

Full wafer - 1 Trillion T



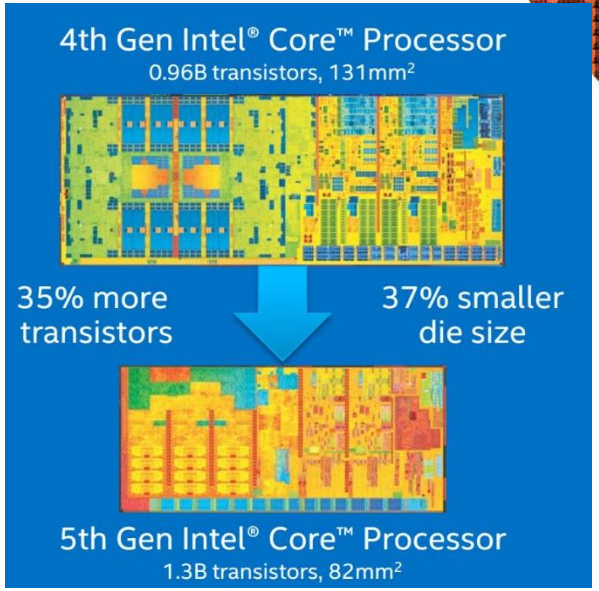
7nm CMOS Integrated technology process development
- Moore's law front lines
- Fixing yield limiters while not breaking anything else

Reliability = Scalability

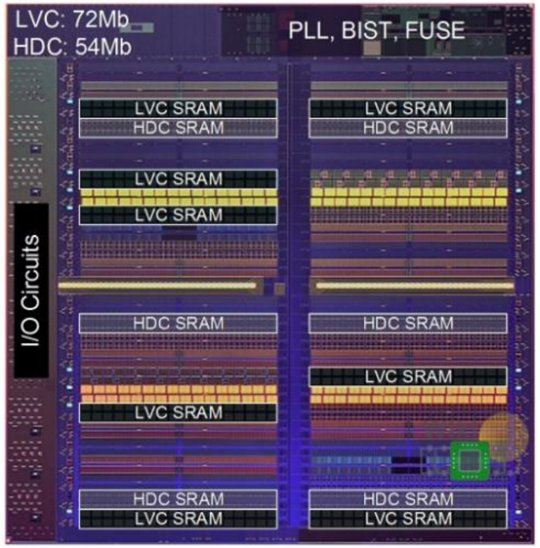
1T - Single CMOS transistors
10T - Simple logic/inverters
100T - Logic Chains
1,000T - SRAM bypass
1,000,000 T - SRAM addressability
1,000,000,000 T - Full die
1,000,000,000,000 T - Full wafer

6T SRAM bit flip errors $< 10^{-18}$
(i.e. >99.9999999999999999%)

Full Core - 1 Billion T

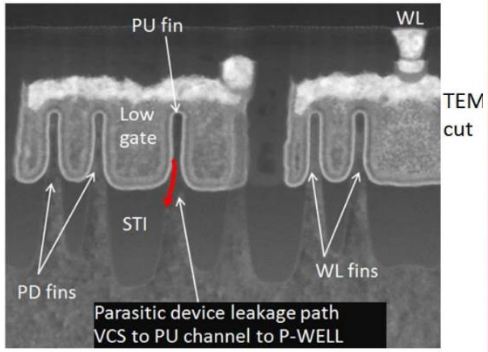


Full SRAM - 1 Million T



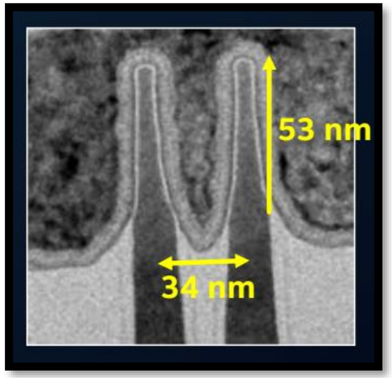
Die shot of Intel's 10nm shuttle. (ISSCC 2018)

6-Transistor SRAM cell



R. Mann, et al.,"An Extrinsic Device and Leakage Mechanism in Advanced Bulk FinFET SRAM"

Dual Fin-FET transistor



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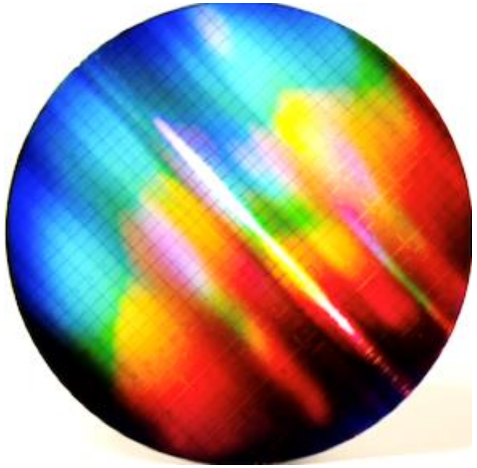
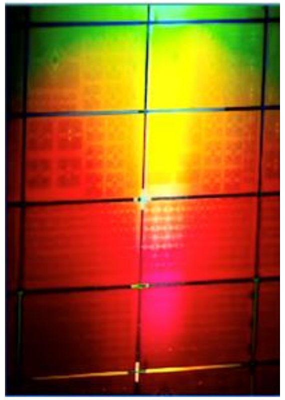
FinFET at 20mK = Spin Qubit

- Embrace the Quantum!
  - If FinFETs are becoming quantum → make them qubits
- Inherently scalable based on VLSI CMOS

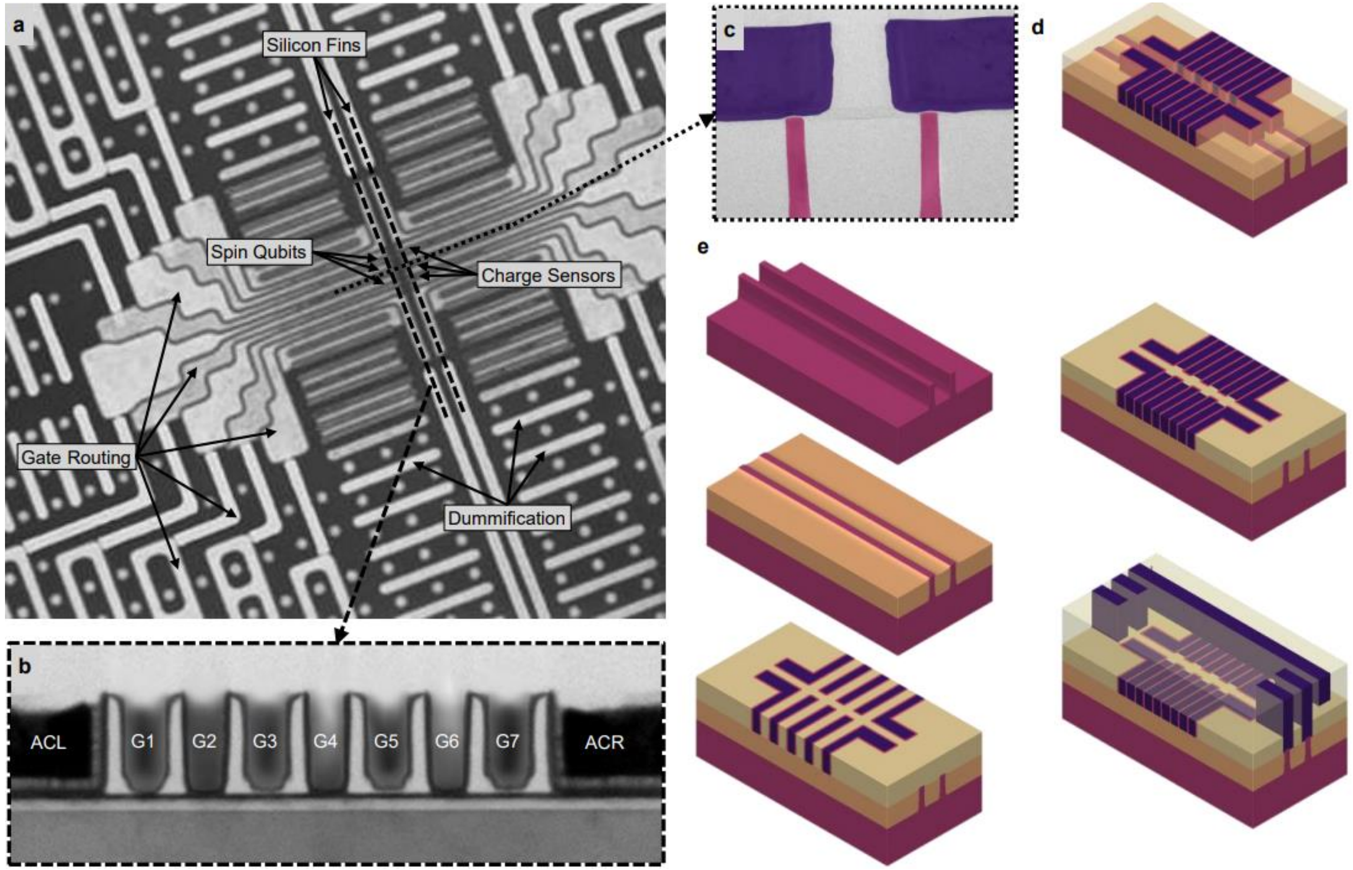
However,

- Difficult to protect from decoherence and tune
- Preventing demonstration of a small QC or QV





Jim Clarke and Hubert George (Intel CR)



Zwerver, A. M. J., et al. "Qubits made by advanced semiconductor manufacturing." *arXiv preprint arXiv:2101.12650* (2021).

Why compute with qubits?

qubit
'Each ~~photon t~~hen interferes on~~ly wi~~th itself'
- Dirac

A qubit can experience multiple 'paths' simultaneously (superposition, double slit)

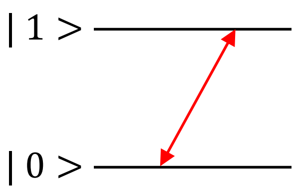
Until you entangle them

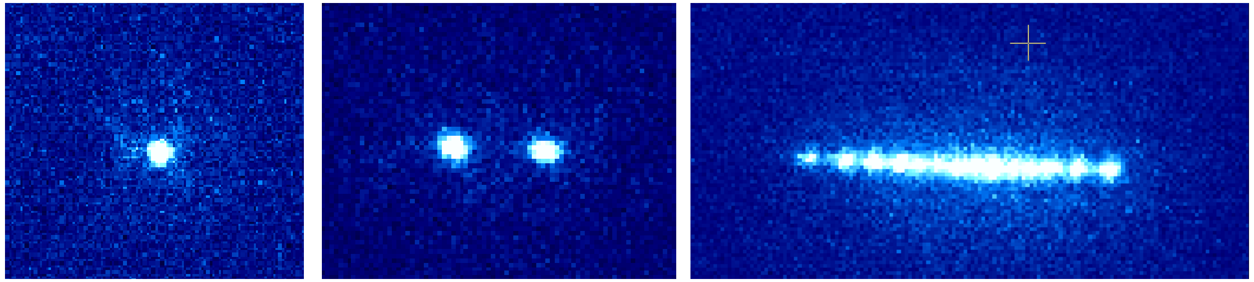
Each additional entangled two-level qubit adds those two states to the permutation

→ Qubits explore twice as many paths for each additional qubit

2^n possible states (for n qubits with two levels)

➔ Higher dimensional interference is the 'power' of quantum computation

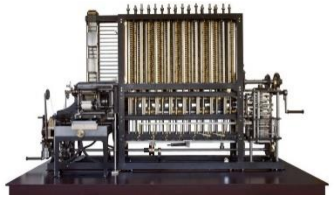




Trapped ion

Classical

32 bits in SRAM store just one number at a time



000000 00000001 = 1
000000 00000010 = 2
000000 00000011 = 3
000000 00000100 = 4

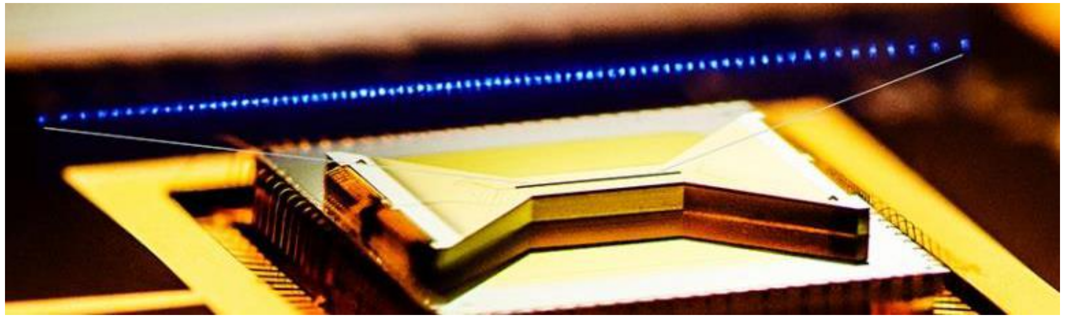
'01' or '10'

Quantum

32 qubits can represent all permutations

'01' **and** '10'

2^{32} > 4 Billion (~Quantum volume)



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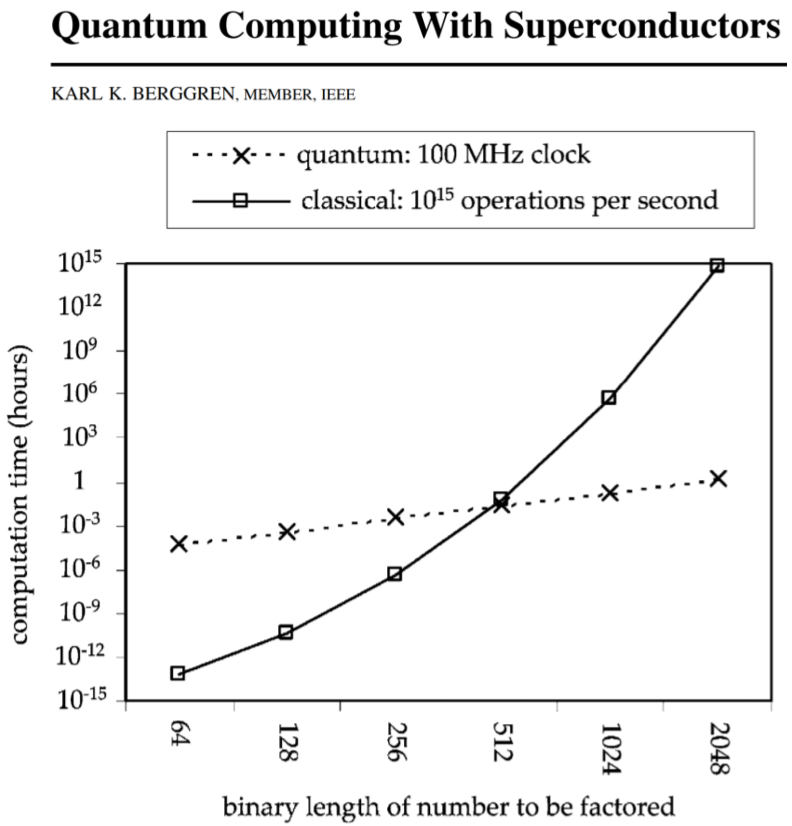
Quantum speedups?

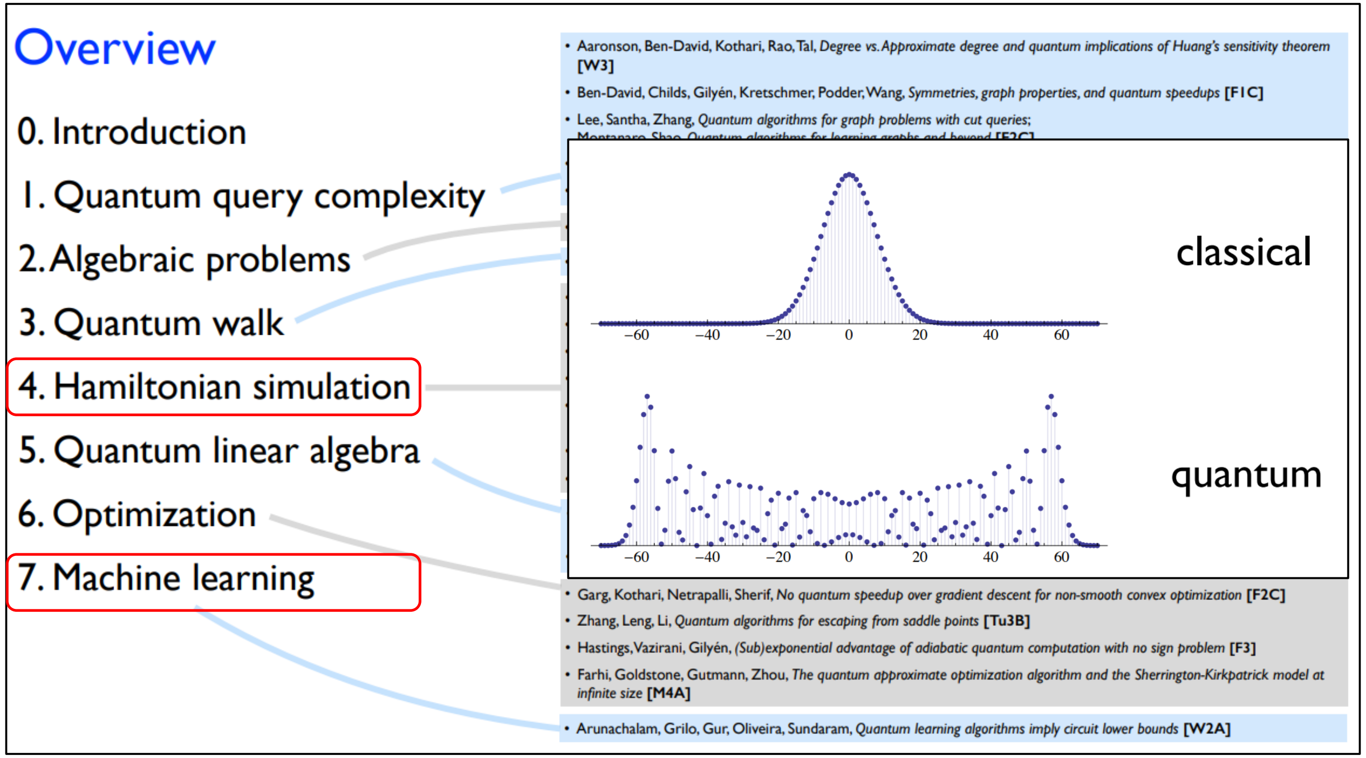
Shor's Algorithm

(Quantum Fourier Transform → period finding → factoring)



Andrew Childs

University of Maryland



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How do you build a quantum computer?

The Physical Implementation of Quantum Computation

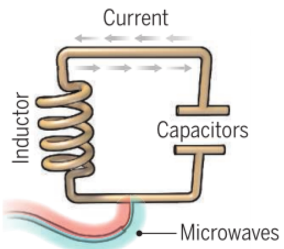
David P. DiVincenzo
IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA
(February 1, 2008)

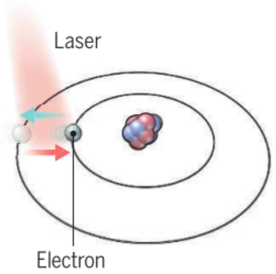
1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits
3. Long relevant coherence times (vs. gate time)
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

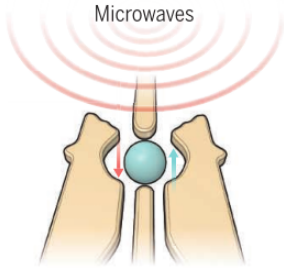
Many viable qubits but all have challenges scaling

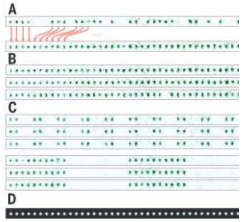
(Increasing qubit number without loss in performance)

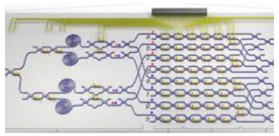
'New qubits'











	Superconducting loops	Trapped ions	Silicon quantum dots	Neutral atoms	Photonics
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Like ions but atoms are trapped with lasers and interact via Rydberg (nearly ionized) excitations	Single photons are guided along integrated pathways and interact via phase shifts during interference
Longevity (seconds)	0.00005	>1000	0.03	1	
Logic success rate	99.4%	99.9%	~99%	97%	97%* (heralded)
Number entangled	27	24	3	20	12
Company support	Google, IBM, Rigetti ...	IonQ, Honeywell, AlpineQ, UniversalQ	Intel, HRL/Boeing, SiliconQuantum	Quera , Atom Computing Cold Quanta	Xanadu, PsiQuantum
Pros	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	2D arrays becoming possible, faster gates	CMOS compatible photonics waveguide technology
Cons	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Gate fidelity	Cryogenic single photon sources and detectors

Science, Dec 2016 (modified)

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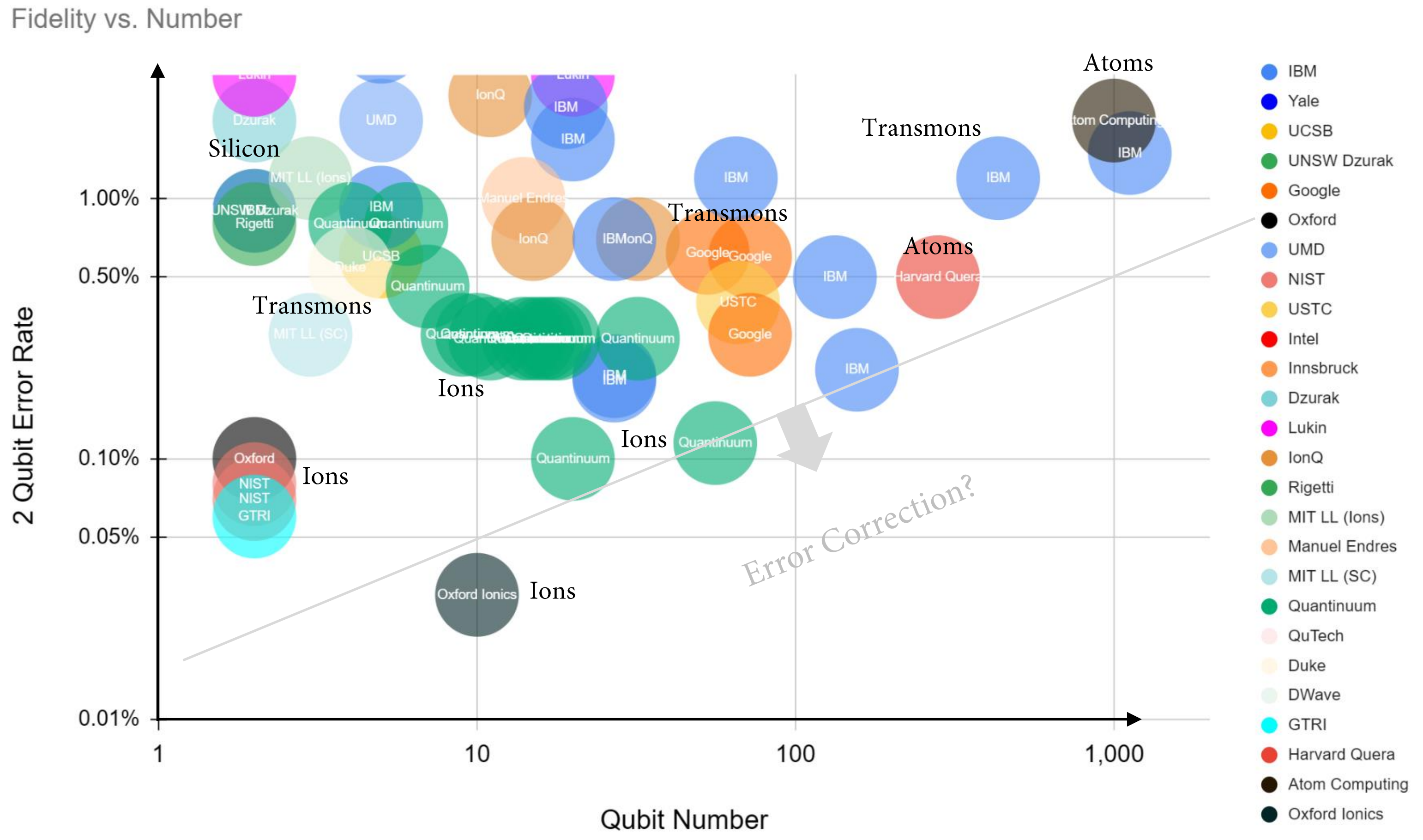
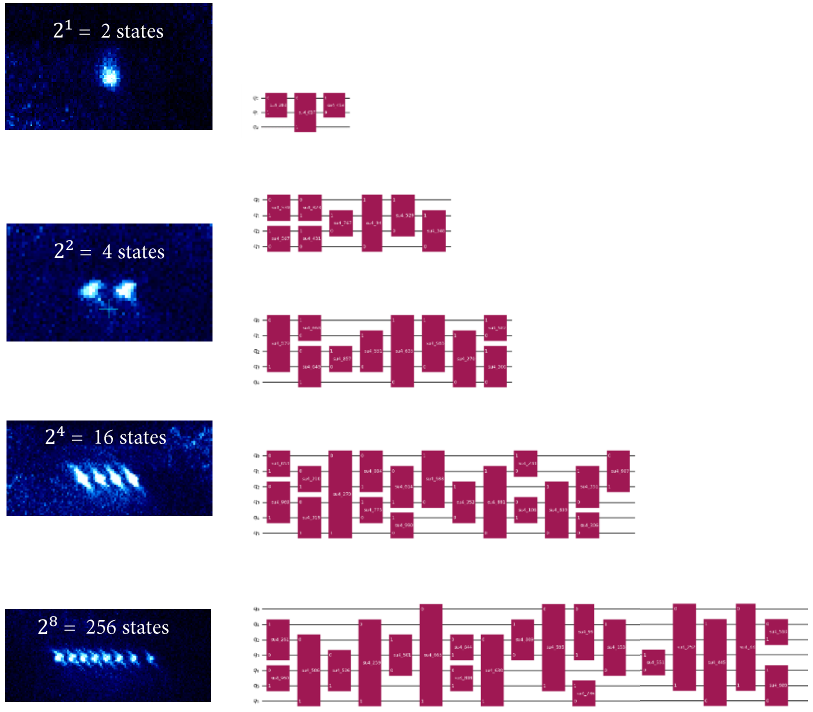
Comparing Quantum Computers



Quantum Volume



Qubit number &
Circuit depth
Both increasing

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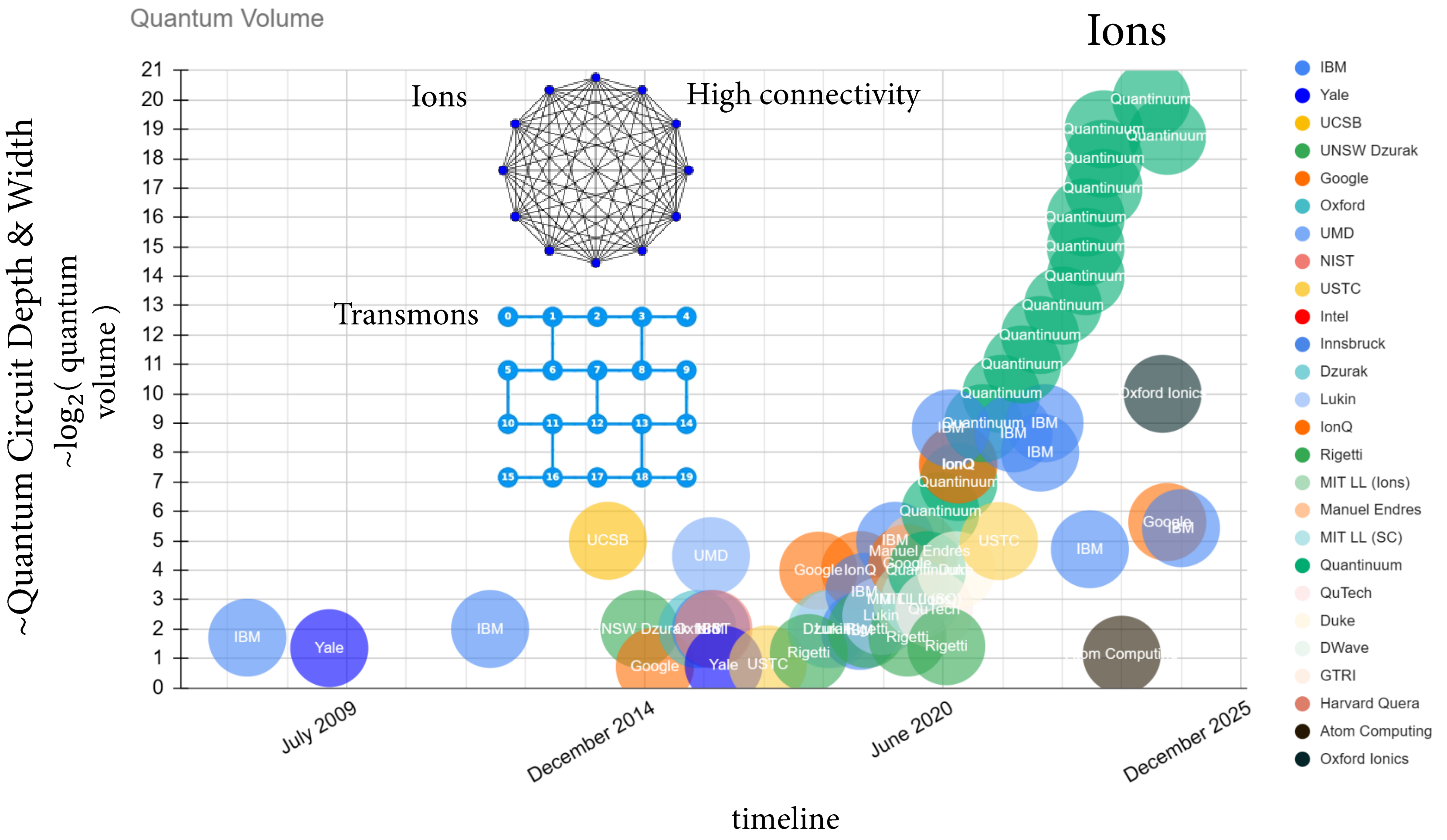
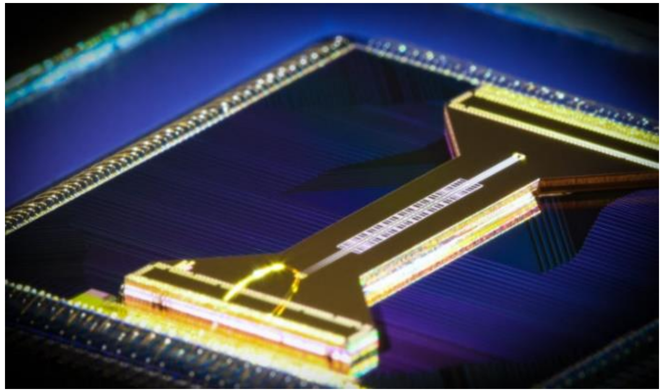
Quantum Volume

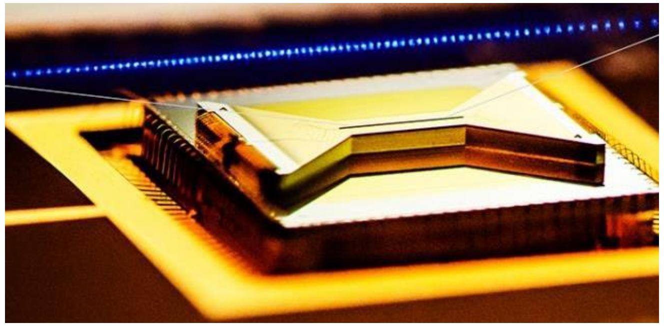
$\log_2(\mathrm{QV})$ of various qubit modalities (estimates)



Quantinuum (Honeywell)



IonQ



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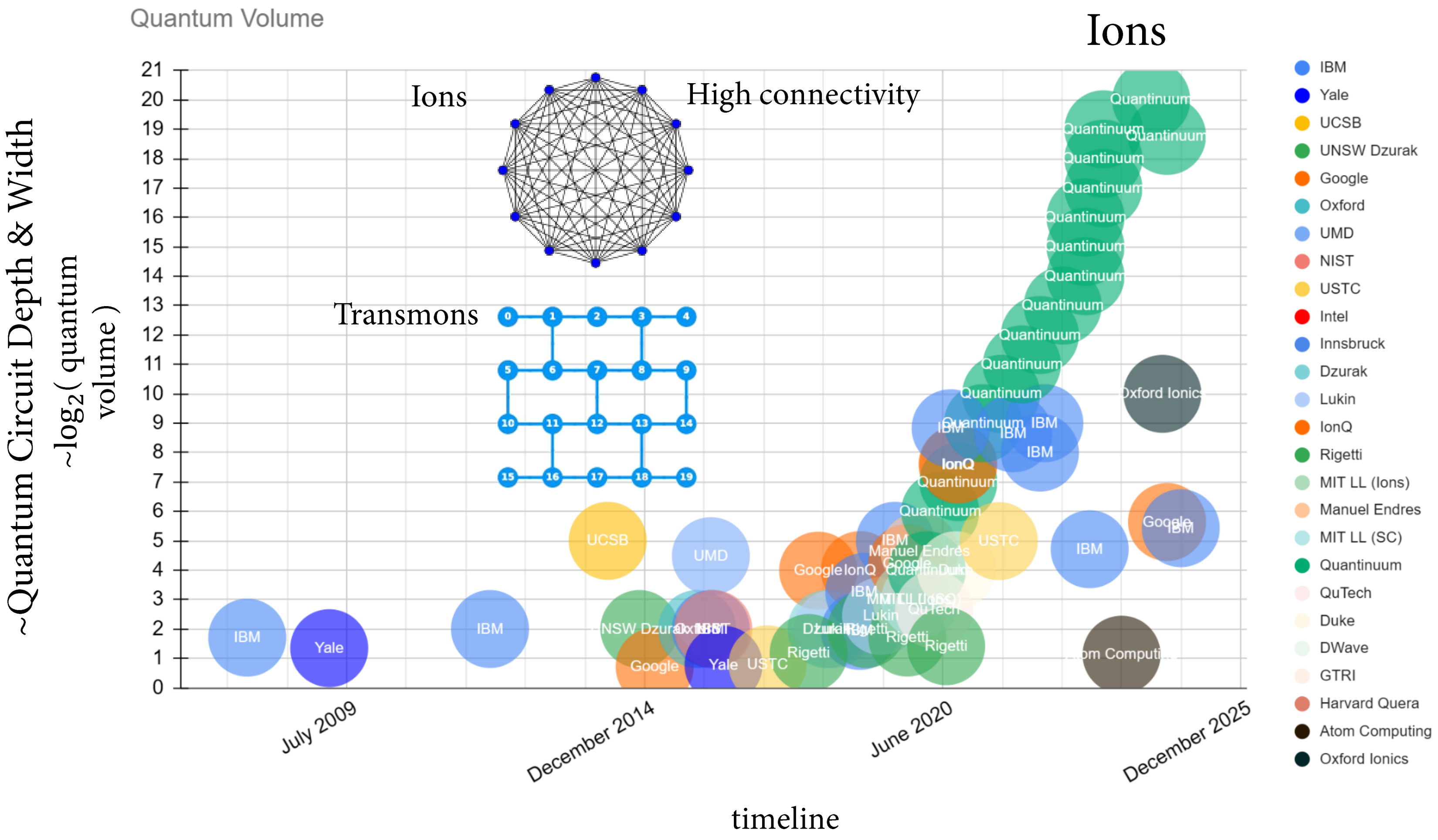
Quantum Volume – Trapped ions in the lead

$\log_2$(QV) of various qubit modalities (estimates)



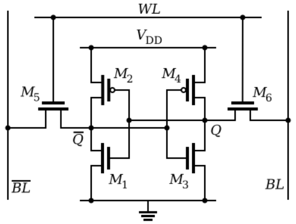
Trapped Ion Qubit Advantages

1. High fidelity operations
   - 2Q gates > 99.97%
   - 1Q gates > 99.9999%
   - Readout > 99.99%
   - State Preparation & Measurement > 99.97%
2. Long coherence time
   - 200ms → 600 seconds
   - Ratio to gate time > 1,000,000
3. Atoms are identical (less tuning)
4. High connectivity
5. Low crosstalk (w/ focused lasers)

6T SRAM bit flip errors $< 10^{-18}$
(i.e. >99.9999999999999999%)

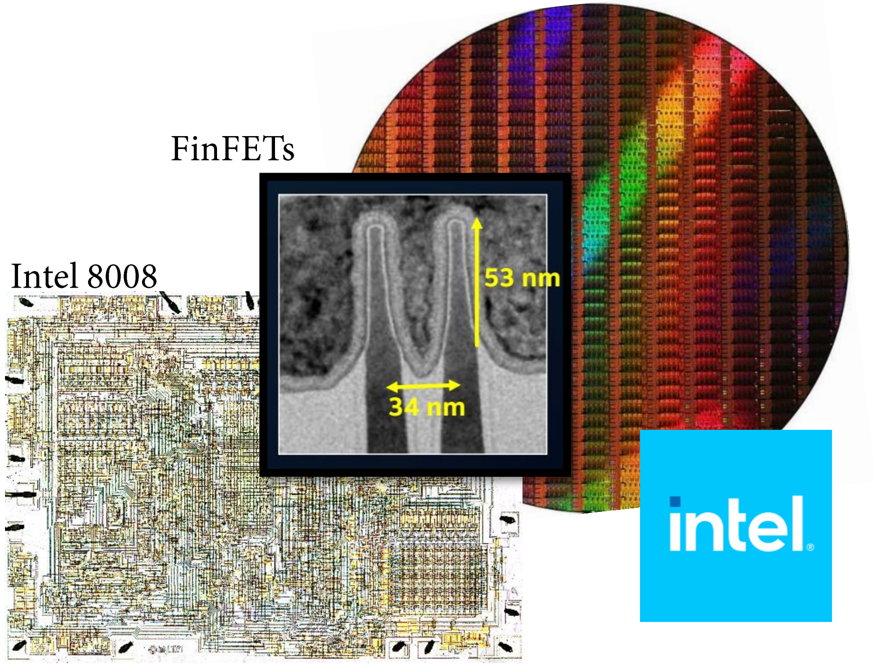
Scaling towards Quantum Error Correction

1 T – Transistor
6 T - SRAM (error correction)
100 T - Logic Chains
3,100 T – Intel 8008 (1971)
285,000 T – Intel 386 (1985)
1,000,000,000 T – Modern CPU
1,000,000,000,000 T - Full wafer



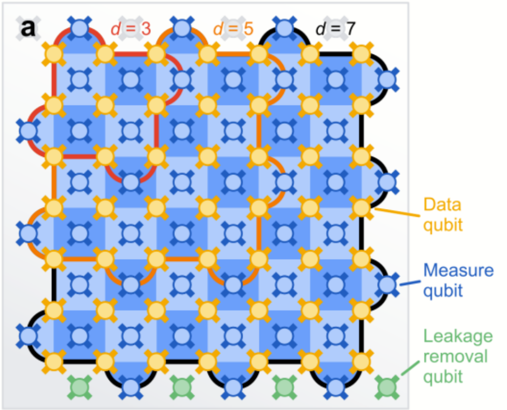
FinFETs

Intel 8008

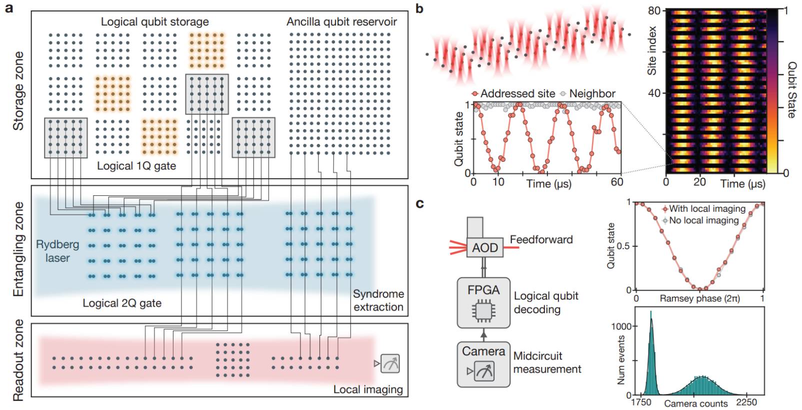


1 Q – Qubit
7-101 Q = 1 Logical Qubit (LQ)
56 Q – 12 Logical Qubits (12 LGHZ)
280 Q - 40 Logical Qubits (4 LGHZ)
1,000 Q – 100 Logic qubits (?)
10,000 Q – 100 Fault tolerant LQ
100,000 Q - 1000 FT LQ
1,000,000 Q – Shor's Algorithm?

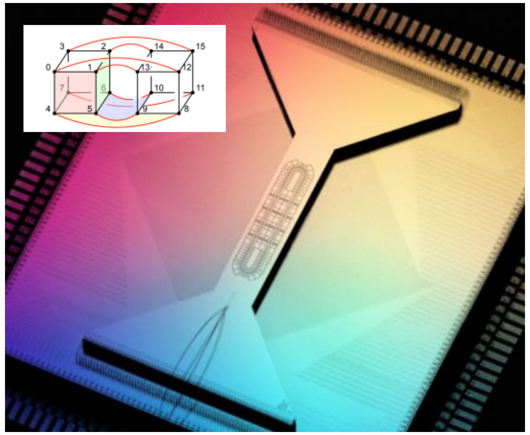
Google - arXiv:2408.13687



Rydberg atoms - Lukin Harvard 2023

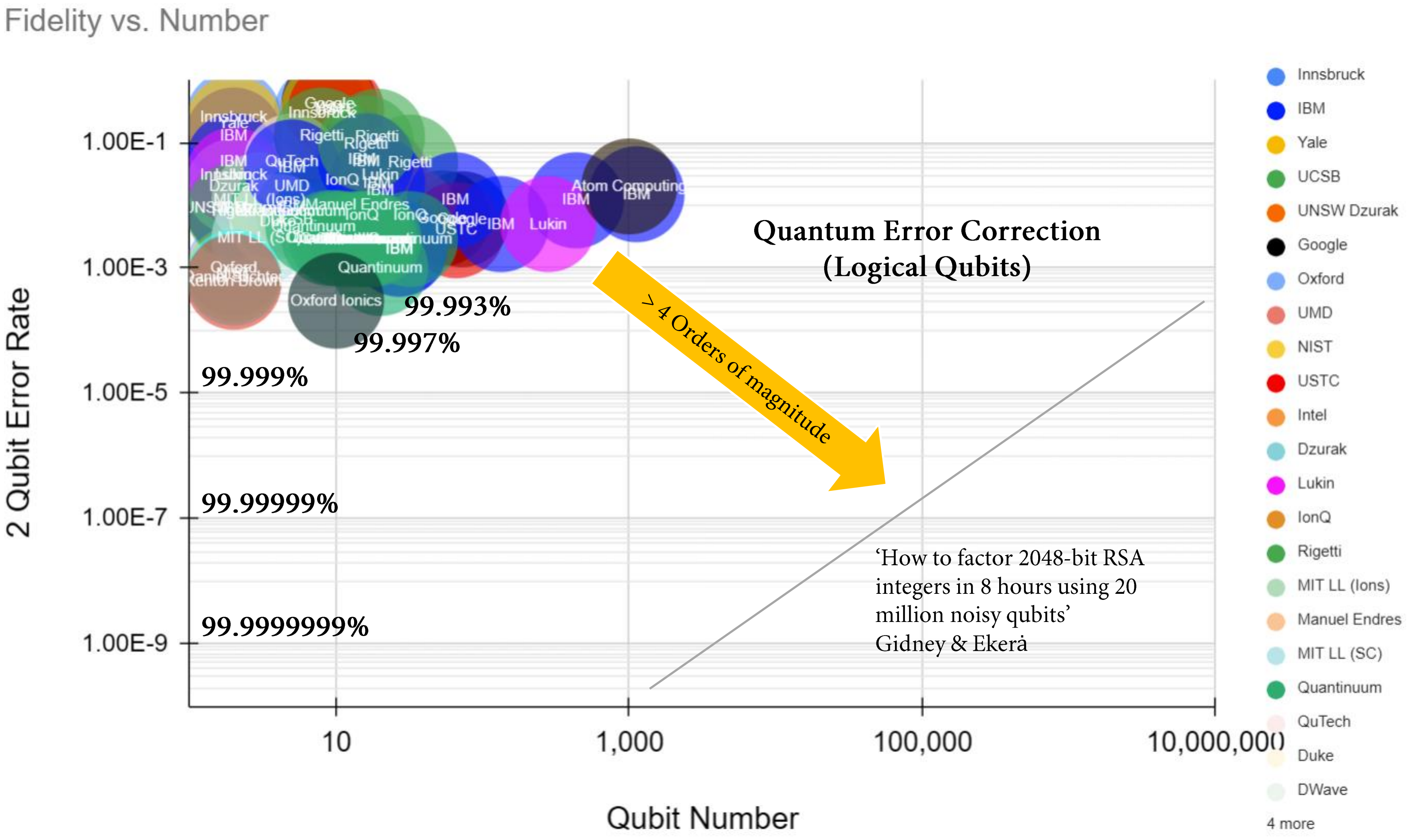


Quantinuum - arXiv:2409.04628

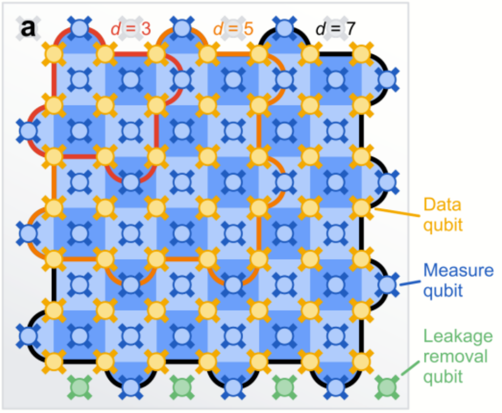


6T SRAM bit flip errors < 10^{-18}
(i.e. >99.9999999999999999%)

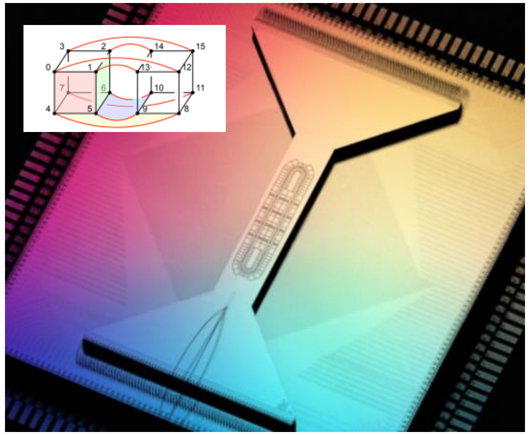
Scaling towards Error Correction



Google - arXiv:2408.13687



Quantinuum - arXiv:2409.04628



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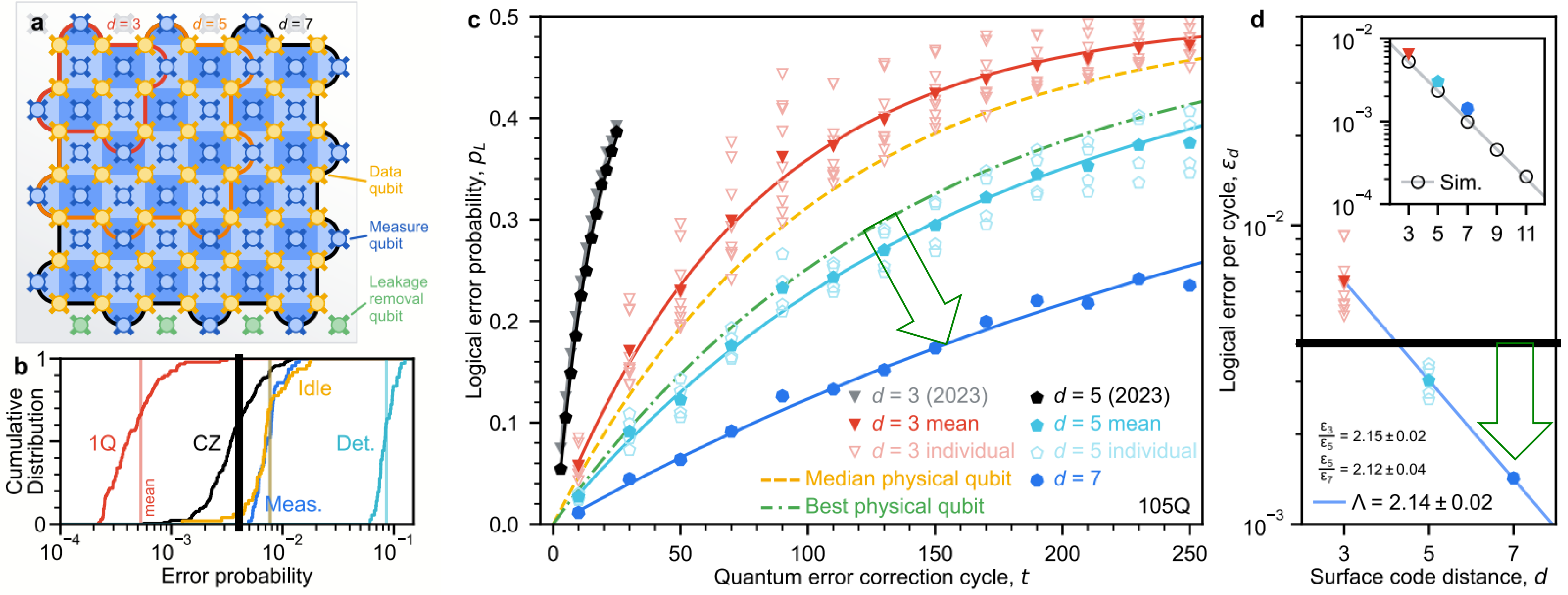
Google – Surface Code Threshold



A single, large, logical qubit (surface code) – with fidelity that scales

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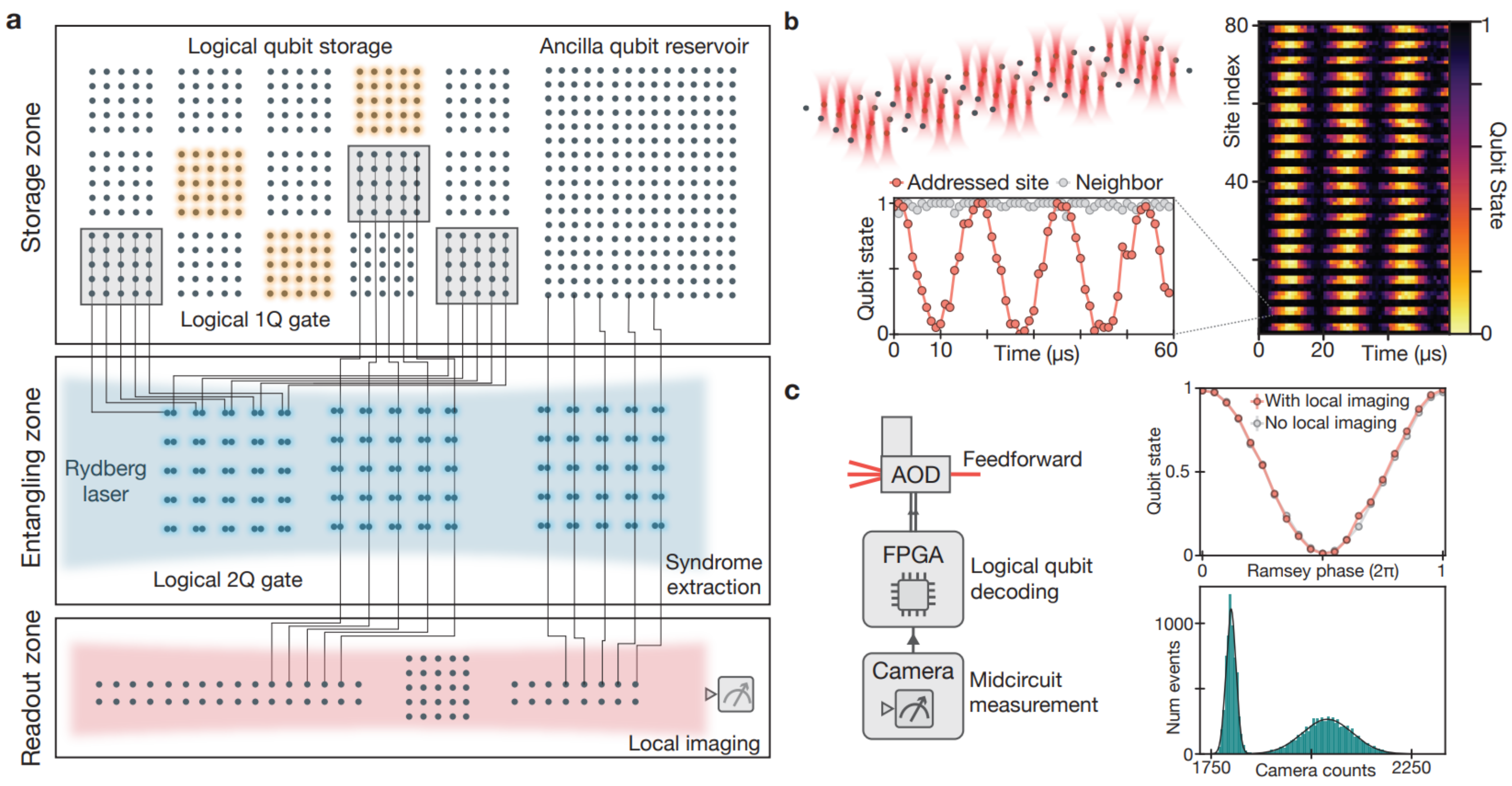
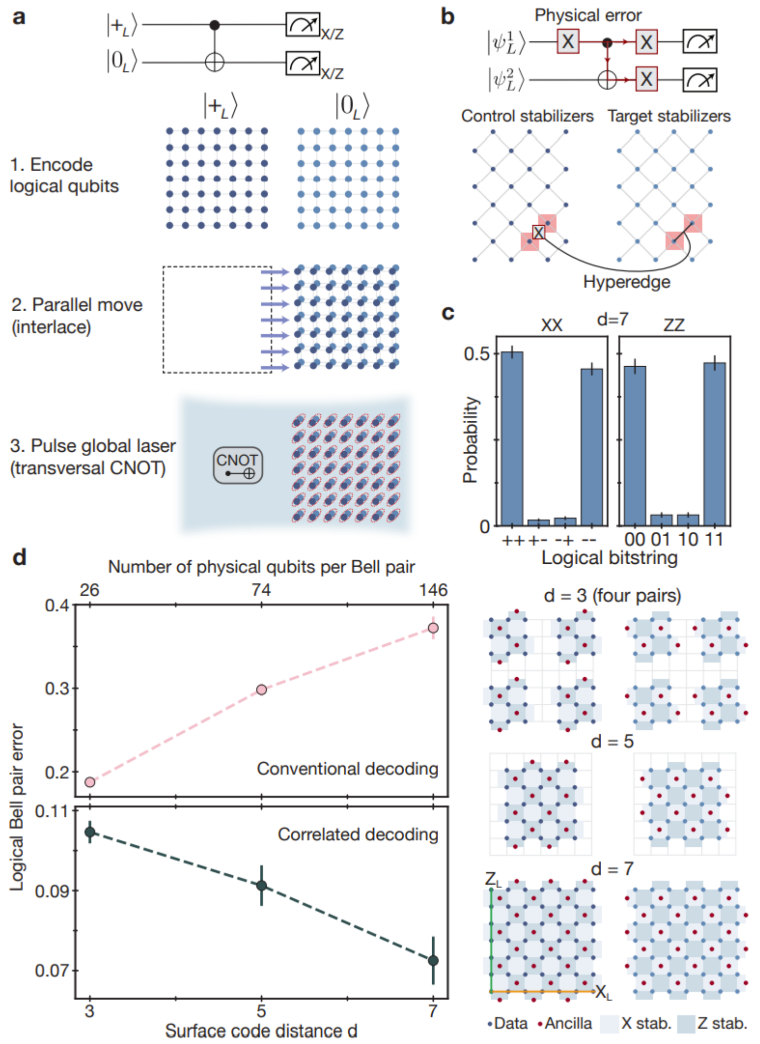
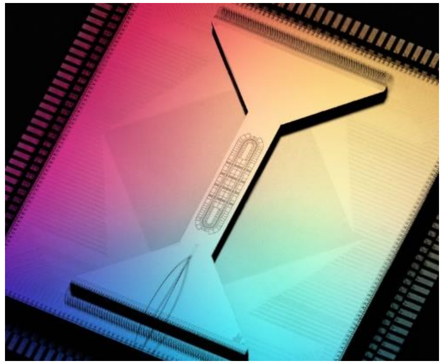
Rydberg Atoms – Entangling of multiple Logical Qubits





Trapped Ions – Error correction & entangling of Logical Qubits



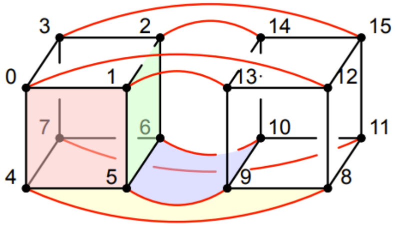
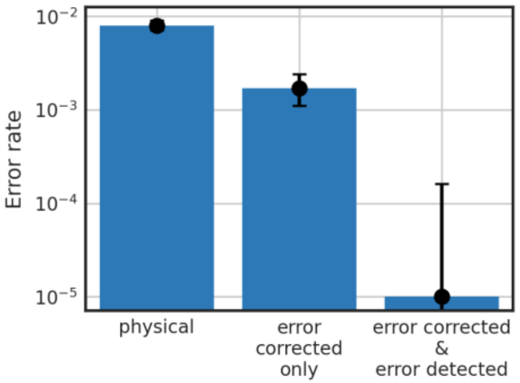
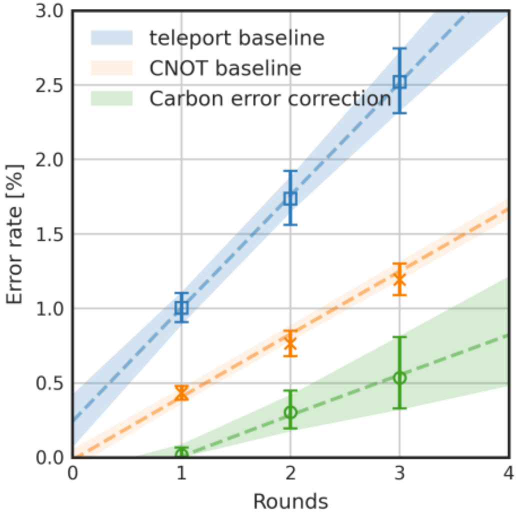


FIG. 1. The [[16, 6, 4]] color code on the 4D hypercube, or tesseract. Each of the 16 vertices is a qubit. Cubes are X and Z stabilizers, and squares are logical operators, e.g., 0145.





Experiment	Qubits	Baseline error rate	Encoded error rate	Gain
Path-4	4	1.5(2)%	$0.10^{+0.11}_{-0.06}$%	15×
Cube-8	8	2.3(3)%	$0.2^{+0.2}_{-0.1}$%	11×
$\|0^{12}\rangle + \|1^{12}\rangle$ Cat-12	12	2.4(3)%	$0.11^{+0.16}_{-0.08}$%	22×
Error correction 5×	4	2.7(4)%	$0.11^{+0.21}_{-0.09}$%	24×
	8	5.6(6)%	$0.7^{+0.7}_{-0.4}$%	8×

TABLE II. Experiments preparing encoded cat states.

Reference	Logical qubits	Fidelity
[HDHL24]	4 in [[25, 4, 3]] code	$99.5^{+0.2}_{-0.4}$% to $99.7^{+0.2}_{-0.3}$%
[BEG+24]	4 in [[7, 1, 3]] code	72(2)% error correction; $99.85^{+0.1}_{-1.0}$% error detection
This work	12 in [[16, 4, 4]] code	$99.82^{+0.12}_{-0.4}$% to $99.90^{+0.1}_{-0.3}$%

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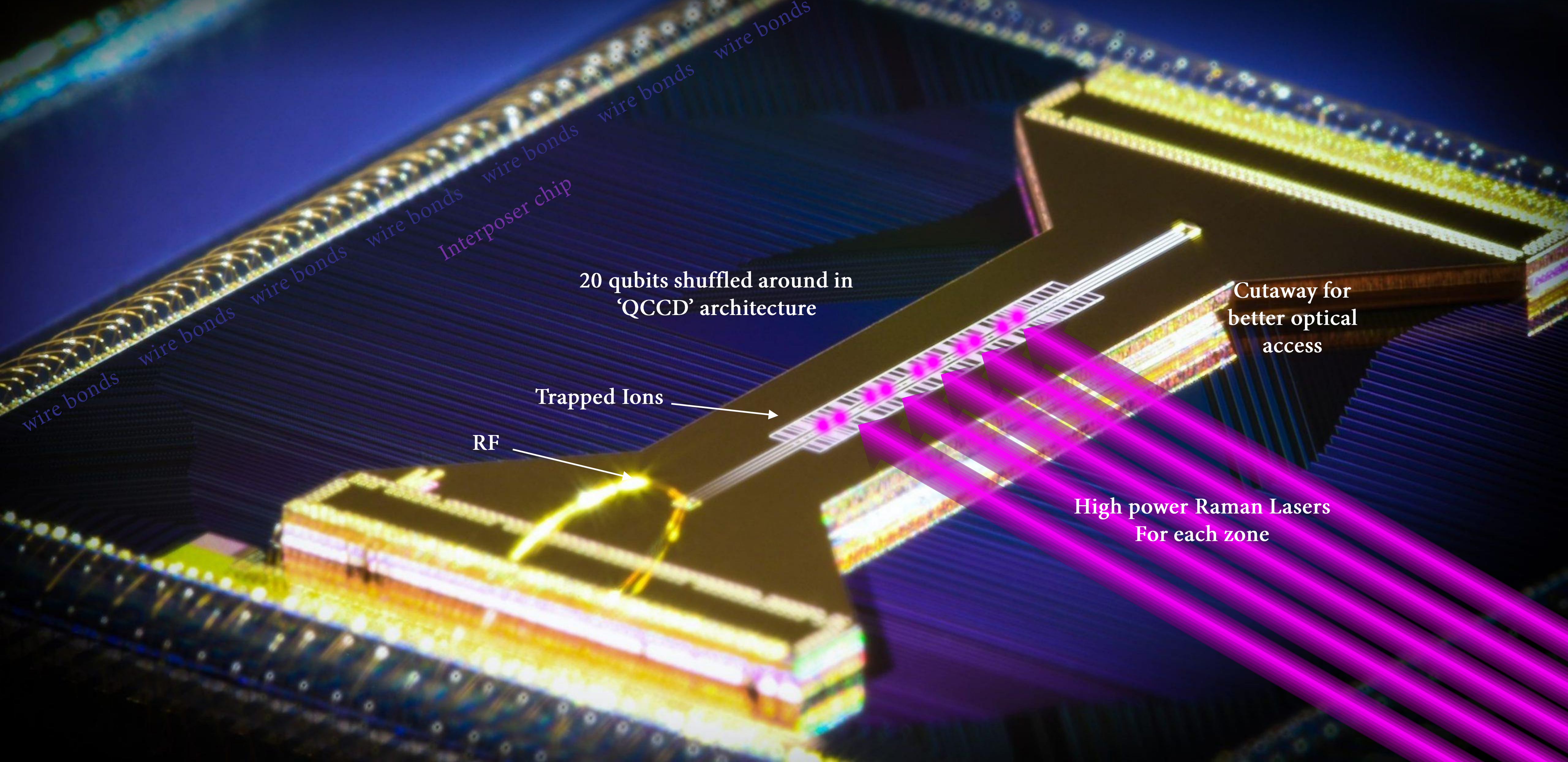
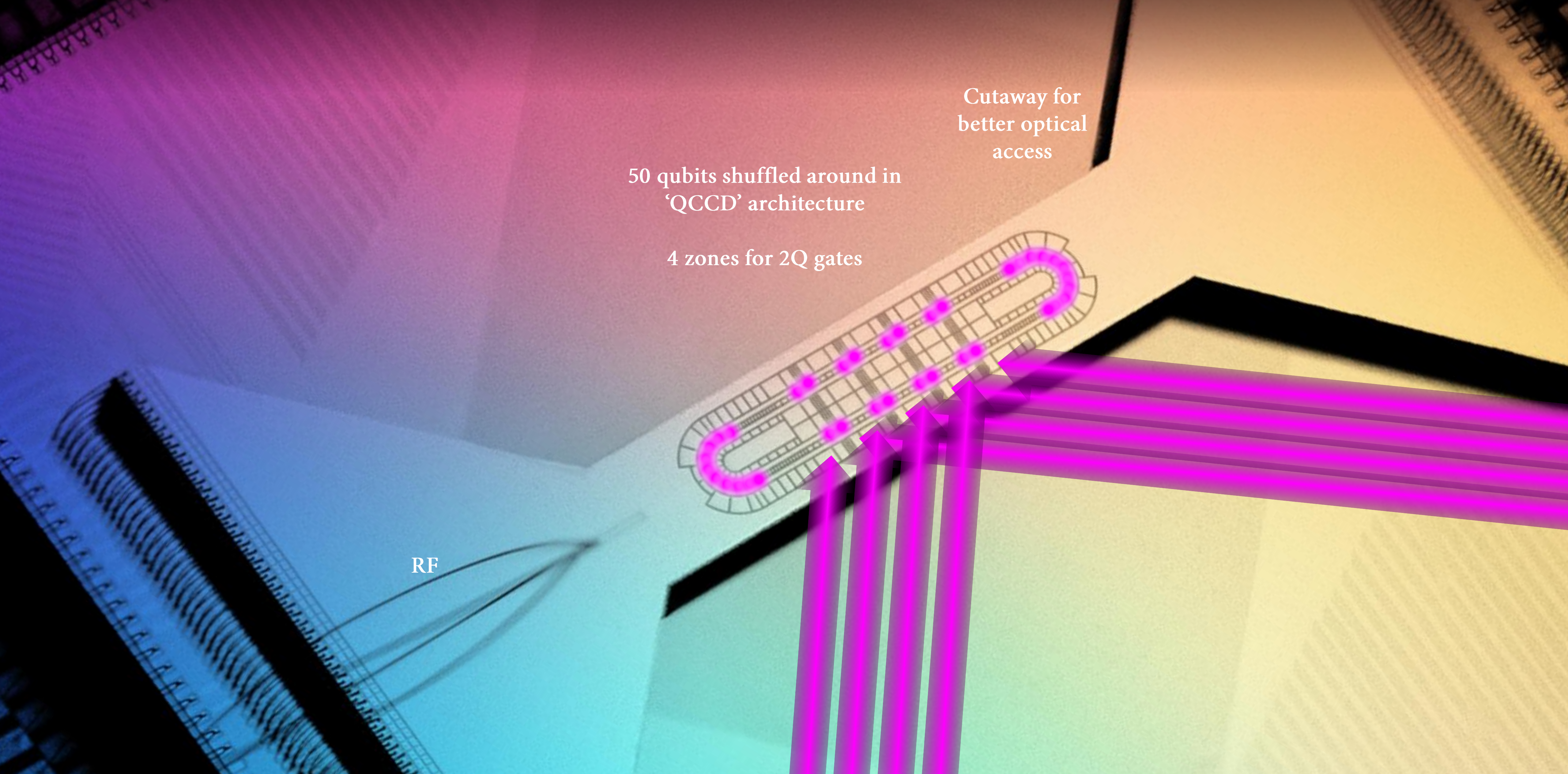
Surface Electrode Trap
Honeywell (Quantinuum) H1 – linear trap



Quantinuum H2 – Racetrack Ion Trap



Outline of the course

- Quantum Optics
  - What is interference (classical vs. single particle)
  - Superposition of states
  - Measurement and measurement basis
- Atomic physics
  - Spin states in magnetic fields and spin transitions
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  - Two qubit interactions – gate speed vs. error rates
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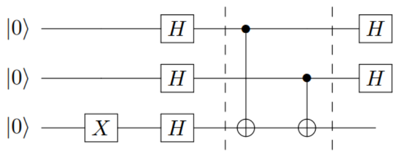
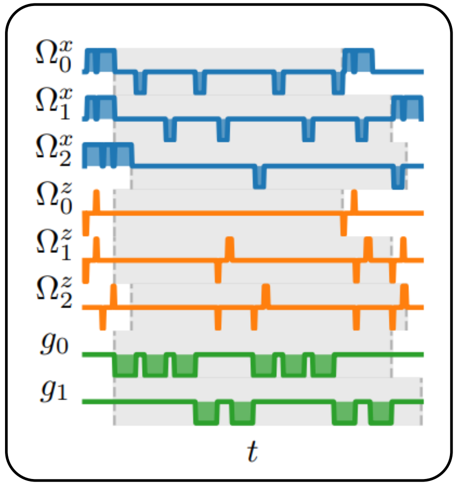
  - Bell states and the Bell basis
  - XX gates, Controlled Phase gates, Swap




```
qc = QubitCircuit(3)
qc.add_gate("X", targets=2)
qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
qc.add_gate("SNOT", targets=2)

# Oracle function f(x)
qc.add_gate(
    "CNOT", controls=0, targets=2)
qc.add_gate(
    "CNOT", controls=1, targets=2)

qc.add_gate("SNOT", targets=0)
qc.add_gate("SNOT", targets=1)
```



- Quantum Hardware
  - Photonics – nonlinear phase shifts
  - Transmons – charge noise, SWAP gate
- Quantum Circuits
  - Single and two qubit gates
  - Hadamard gate , CNOT gate
- Quantum Algorithms
  - Amplitude amplification
  - Grover’s Search
  - Oracle - Deutsch Jozsa
  - Bernstein Vazirani
  - Quantum Fourier Transform and period finding
  - Shor’s algorithm

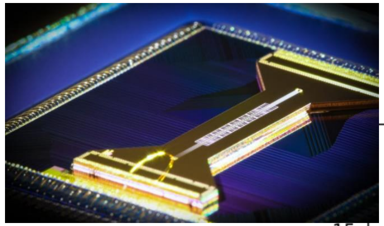
If time permits

- Error Correction
  - Repetition codes
  - Color Codes
  - Surface code

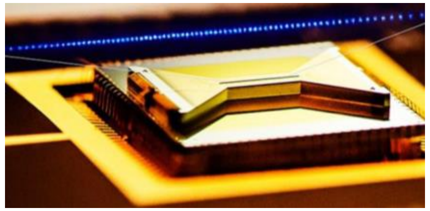
Benchmarking Quantum Hardware with Algorithms

"Application-Oriented Performance Benchmarks for Quantum Computing."
Lubinski, Thomas, et al. *arXiv preprint arXiv:2110.03137* (2021).
QED-C Technical Advisory Committee on Standards and Performance Benchmarks Chairman

Honeywell



IonQ



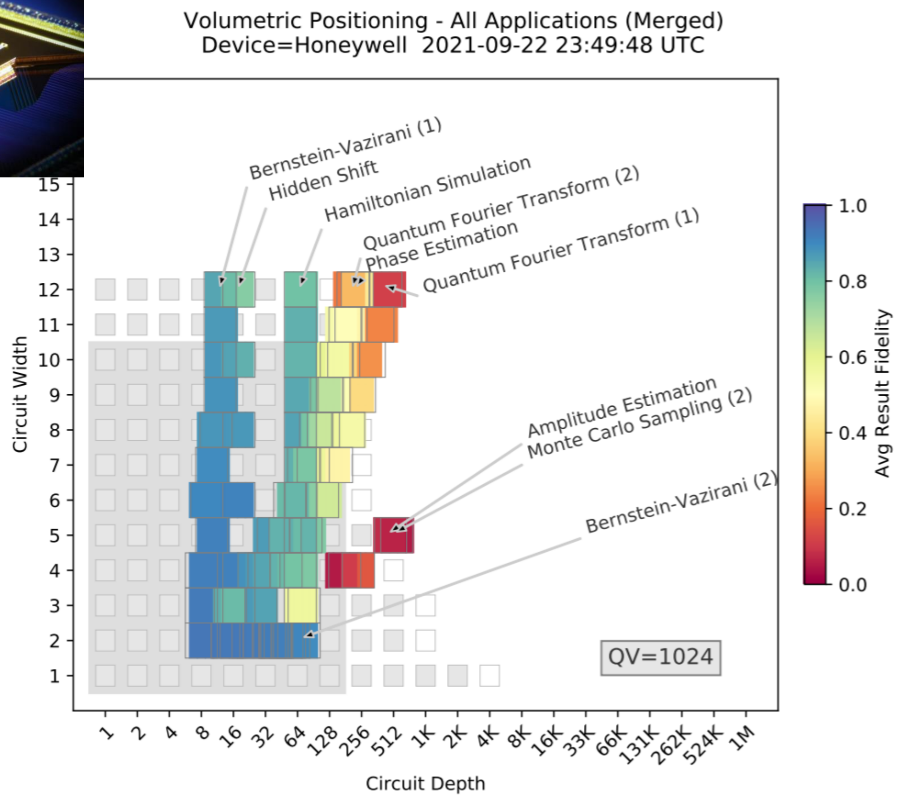


FIG. 12. **Benchmark results on Honeywell System Model H1.** The

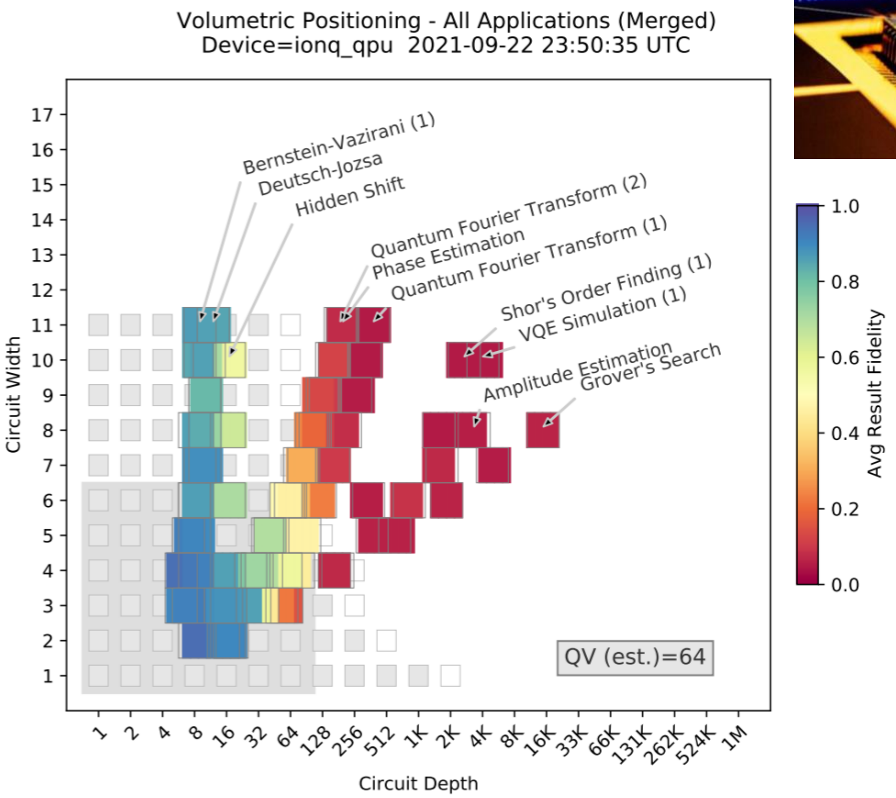
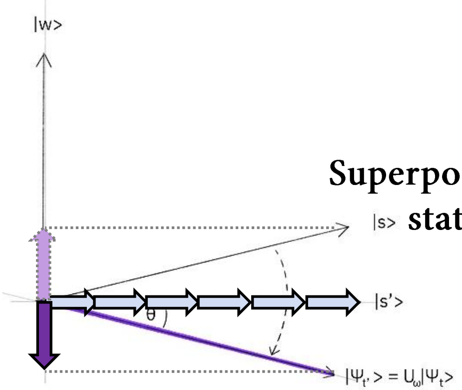


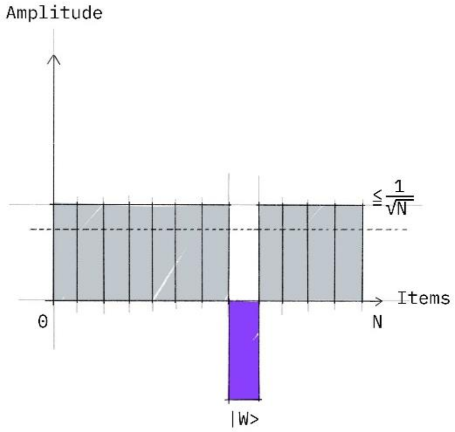
FIG. 13. **Benchmark results on IonQ's cloud-accessible system.**

Grover Search (amplitude amplification)

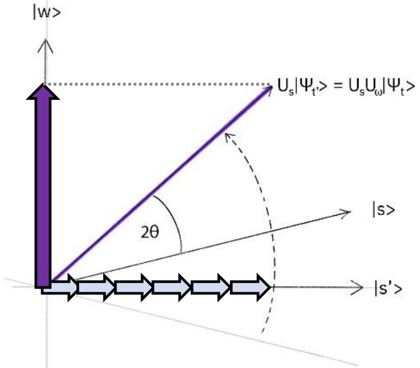
Oracle → Flips sign of 'answer'

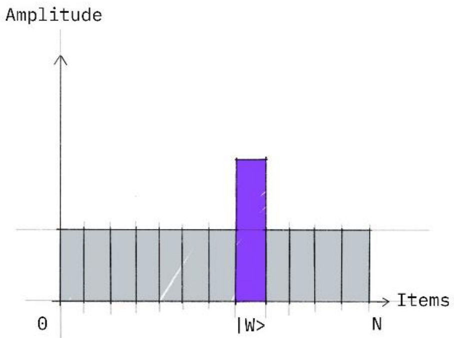
Superposition state



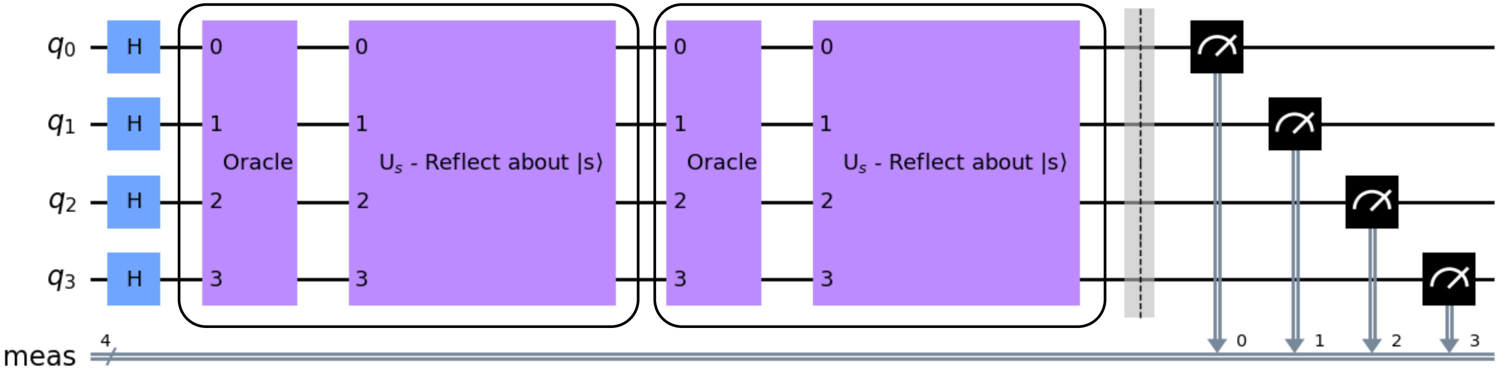


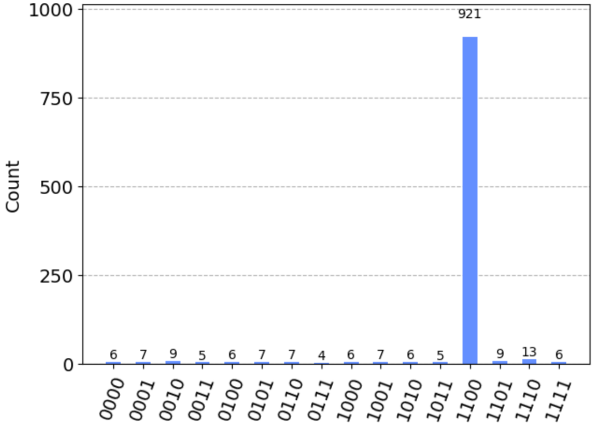
Amplitude Amplification → Answer more probable



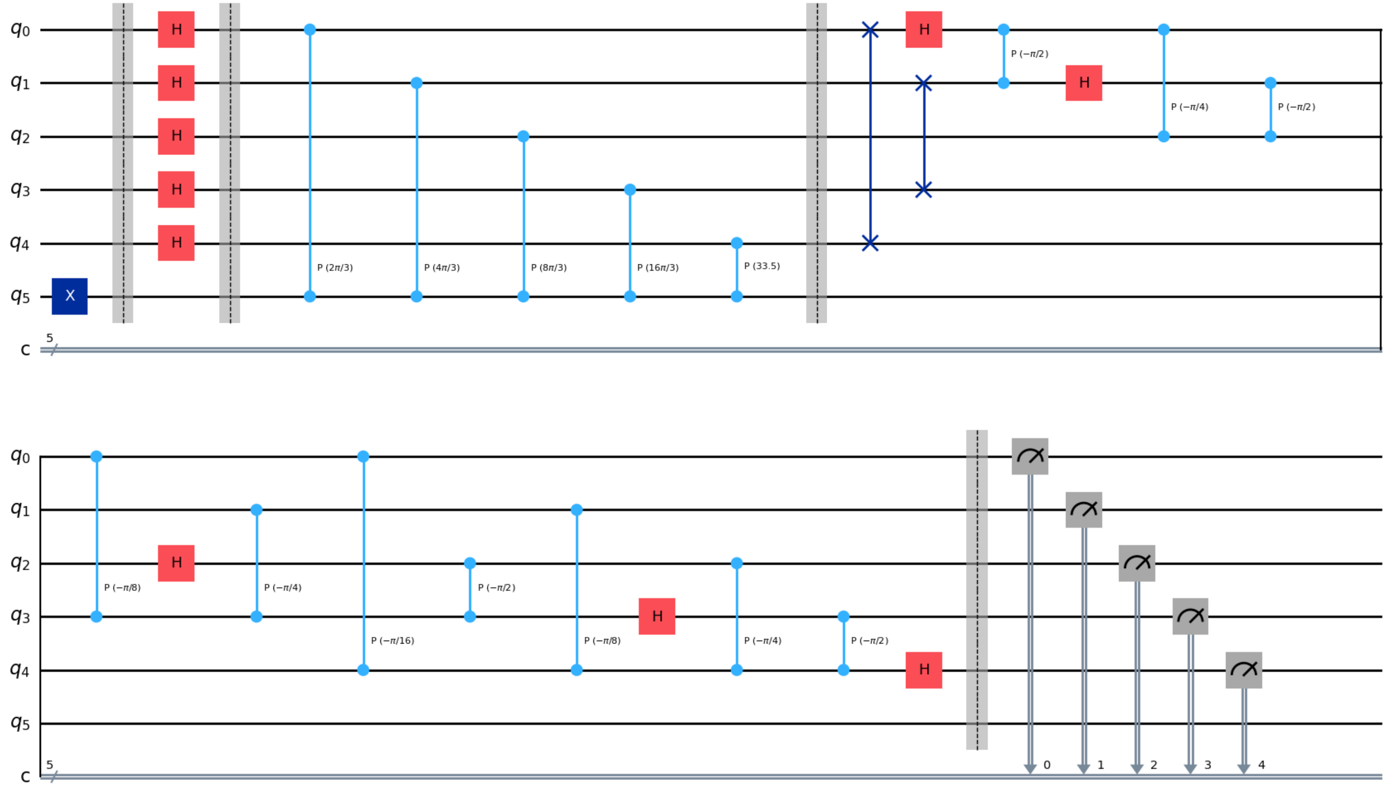


Repeat $\sqrt{N}$ times (twice for 4 bits)

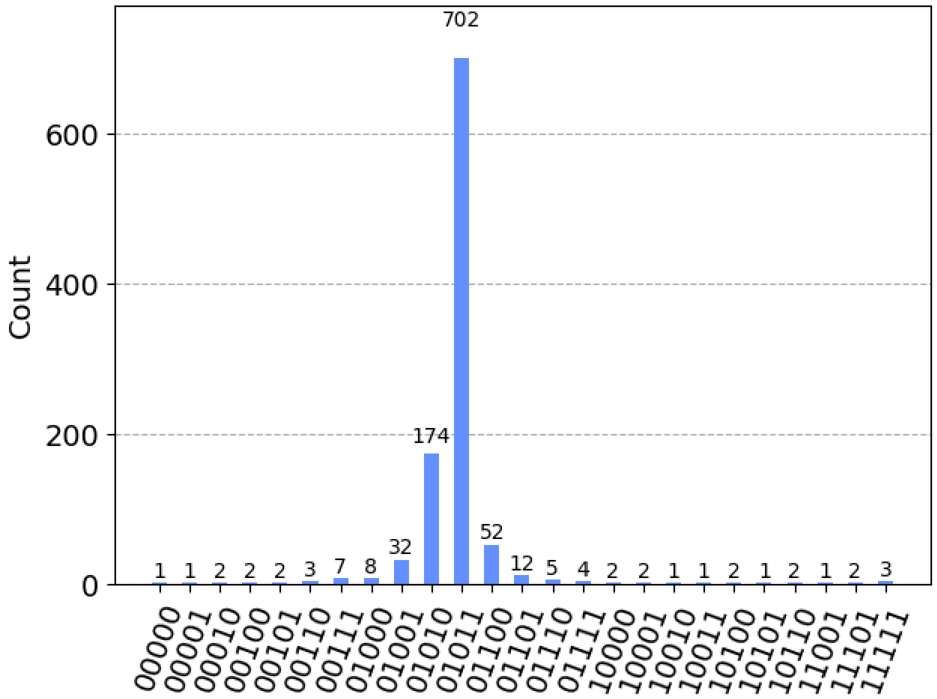




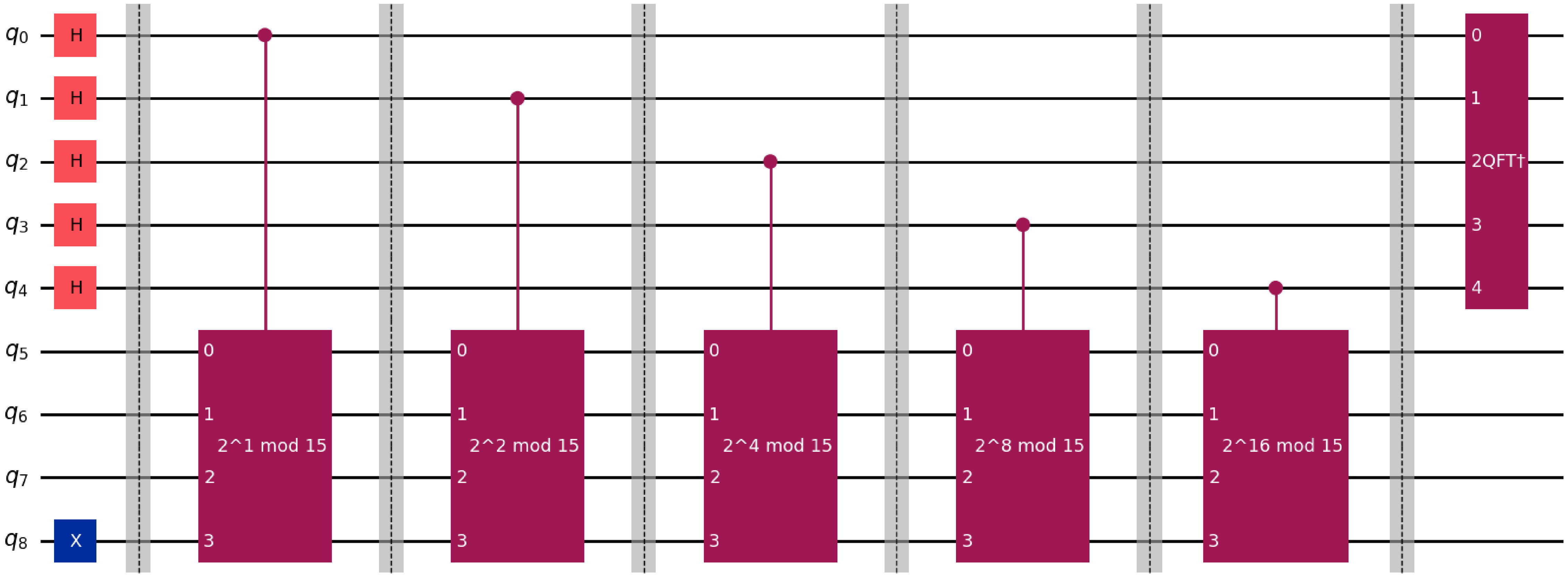
Quantum Phase Estimation



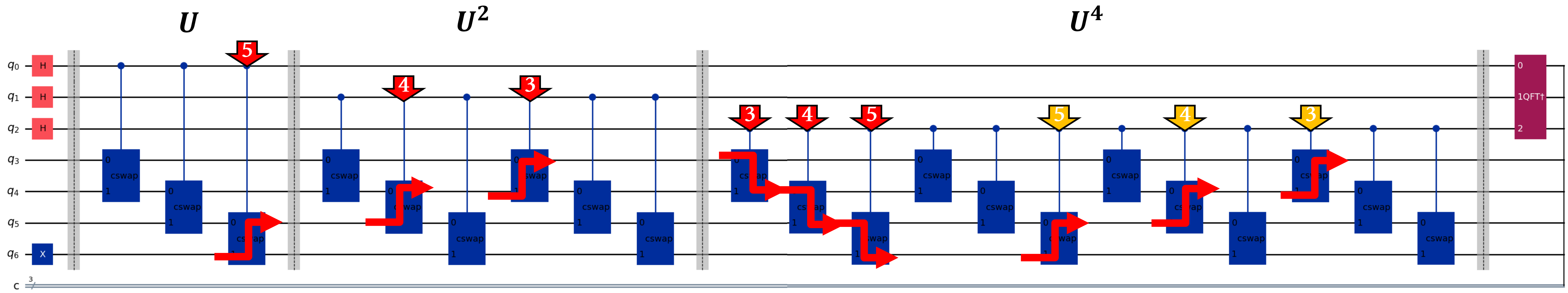
$$01011 = 11\,,\ 11 \cdot \frac{1}{2^5} = \frac{11}{32} = 0.34375$$

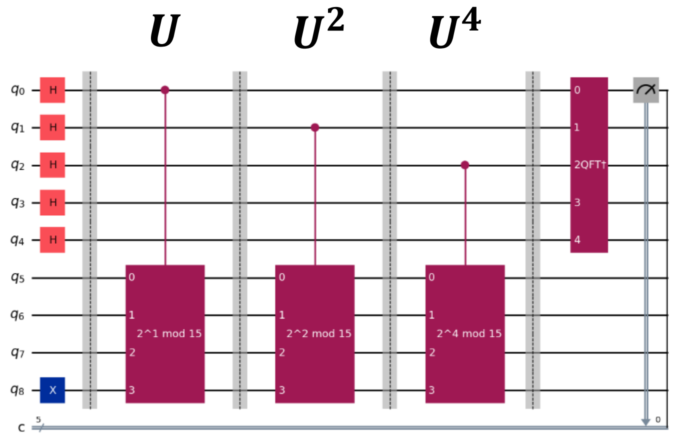


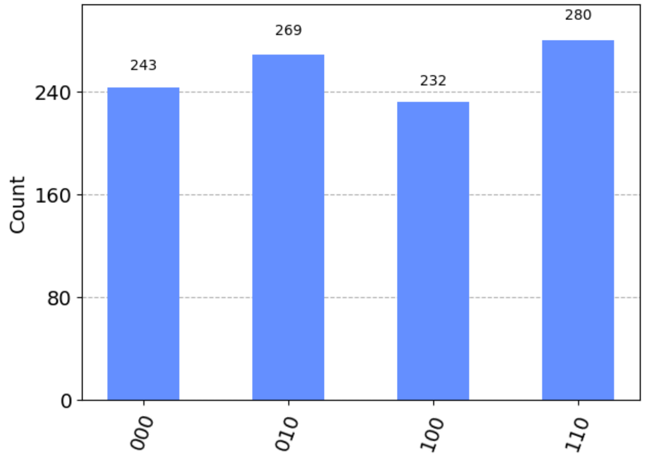
Shor's Algorithm



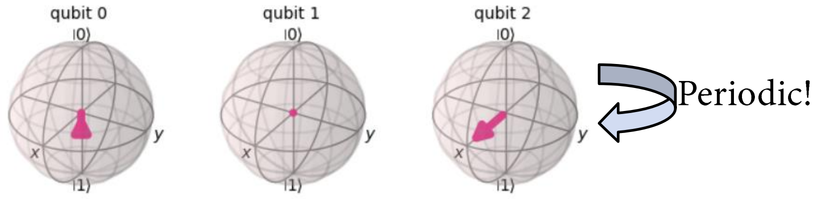
Shor’s Algorithm - Repeated Squares!







Phase kickbacks before InvQFT



Outputs		Phase	r=
110(bin) =	6(dec)	6/8 =3/4	4
000(bin) =	0(dec)	0/8 = 0	0
010(bin) =	2(dec)	2/8 = 1/4	4
100(bin) =	4(dec)	4/8 = 2/4	2

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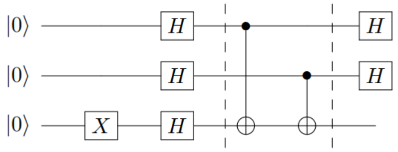


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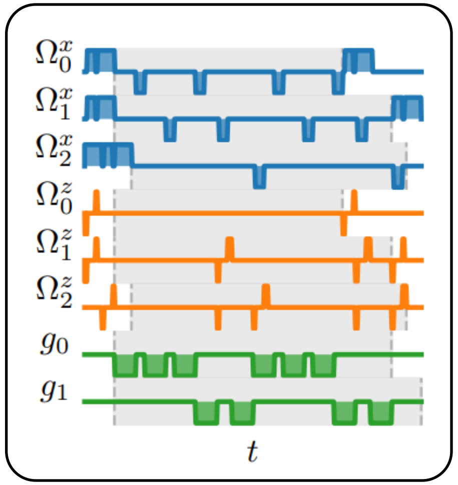

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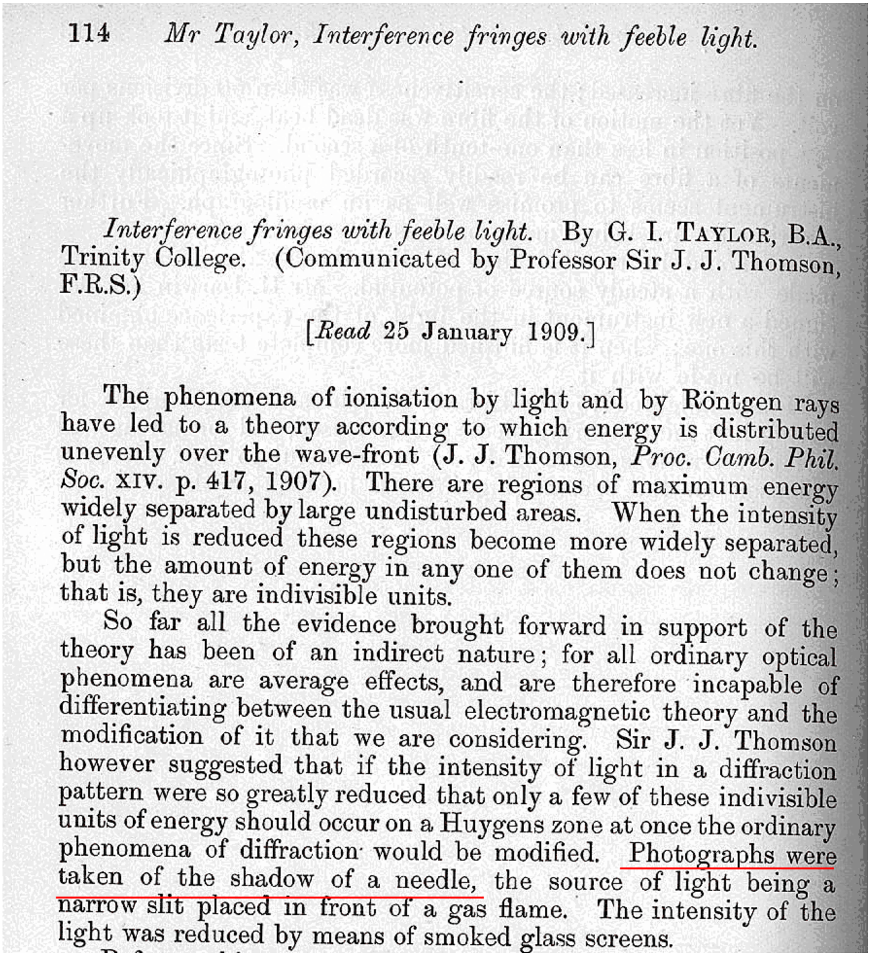
Interference with feeble light



114 *Mr Taylor, Interference fringes with feeble light.*

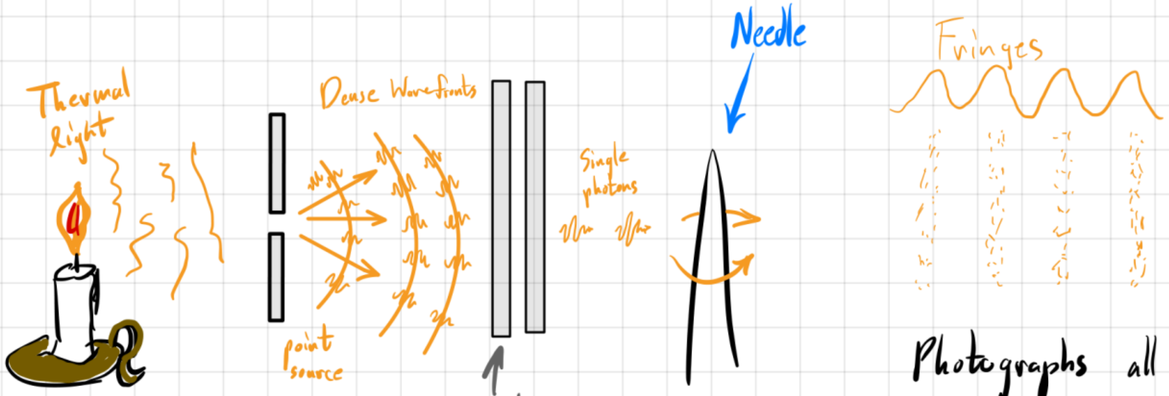
Interference fringes with feeble light. By G. I. TAYLOR, B.A., Trinity College. (Communicated by Professor Sir J. J. Thomson, F.R.S.)

[*Read* 25 January 1909.]

The phenomena of ionisation by light and by Röntgen rays have led to a theory according to which energy is distributed unevenly over the wave-front (J. J. Thomson, *Proc. Camb. Phil. Soc.* XIV. p. 417, 1907). There are regions of maximum energy widely separated by large undisturbed areas. When the intensity of light is reduced these regions become more widely separated, but the amount of energy in any one of them does not change; that is, they are indivisible units.

So far all the evidence brought forward in support of the theory has been of an indirect nature; for all ordinary optical phenomena are average effects, and are therefore incapable of differentiating between the usual electromagnetic theory and the modification of it that we are considering. Sir J. J. Thomson however suggested that if the intensity of light in a diffraction pattern were so greatly reduced that only a few of these indivisible units of energy should occur on a Huygens zone at once the ordinary phenomena of diffraction would be modified. Photographs were taken of the shadow of a needle, the source of light being a narrow slit placed in front of a gas flame. The intensity of the light was reduced by means of smoked glass screens.

1909 Thompson-Taylor Interference Fringes with Feeble Light



Smoked Screens filter light down to 1ppm

Power = 5×10^{-13} W

Energy/photon ~ 3×10^{-19} J

$\Rightarrow 10^6$ photons/s/cm²

Photographs all showed interference even when filters had reduced light by 1 million, requiring 3 months exposure.

$\boxed{\text{1st evidence that individual particles can experience multiple paths simultaneously!}}$

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Interference with feeble light

Before making any exposures it was necessary to find out what proportion of the light was cut off by these screens. A plate was exposed to direct gas light for a certain time. The gas flame was then shaded by the various screens that were to be used, and other plates of the same kind were exposed till they came out as black as the first plate on being completely developed. The times of exposure necessary to produce this result were taken as inversely proportional to the intensities. Experiments made to test the truth of this assumption shewed it to be true if the light was not very feeble.

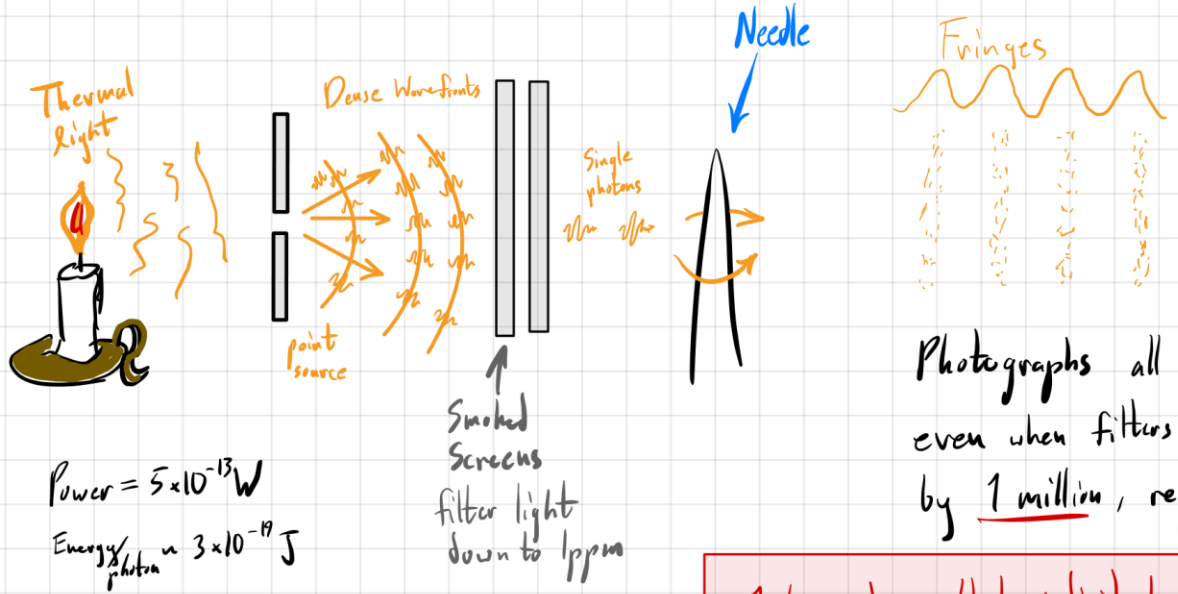
Five diffraction photographs were then taken, the first with direct light and the others with the various screens inserted between the gas flame and the slit. The time of exposure for the first photograph was obtained by trial, a certain standard of blackness being attained by the plate when fully developed. The

remaining times of exposure were taken from the first in the inverse ratio of the corresponding intensities. The longest time was 2000 hours or about 3 months. In no case was there any diminution in the sharpness of the pattern although the plates did not all reach the standard blackness of the first photograph.

In order to get some idea of the energy of the light falling on the plates in these experiments a plate of the same kind was exposed at a distance of two metres from a standard candle till complete development brought it up to the standard of blackness. Ten seconds sufficed for this. A simple calculation will shew that the amount of energy falling on the plate during the longest exposure was the same as that due to a standard candle burning at a distance slightly exceeding a mile. Taking the value given by Drude for the energy in the visible part of the spectrum of a standard candle, the amount of energy falling on 1 square centimetre of the plate is 5×10^{-6} ergs per sec. and the amount of energy per cubic centimetre of this radiation is $1{\cdot}6 \times 10^{-16}$ ergs.

According to Sir J. J. Thomson this value sets an upper limit to the amount of energy contained in one of the indivisible units mentioned above.

1909 Thompson-Taylor Interference Fringes with Feeble Light



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Energy/photon ~ 3×10^{-19} J

$\approx> 10^6$ photons/s/cm^2

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1st evidence that individual particles can experience multiple paths simultaneously!

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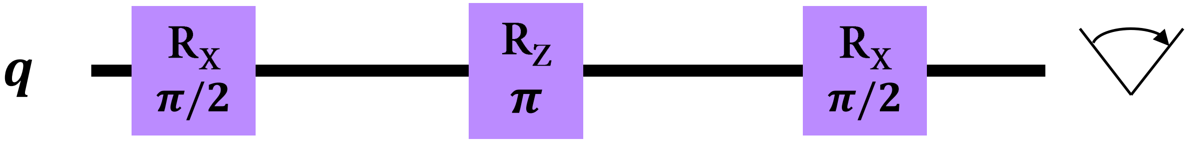
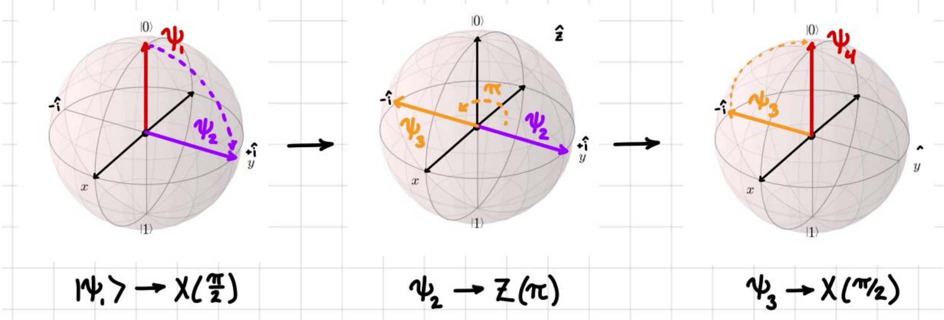
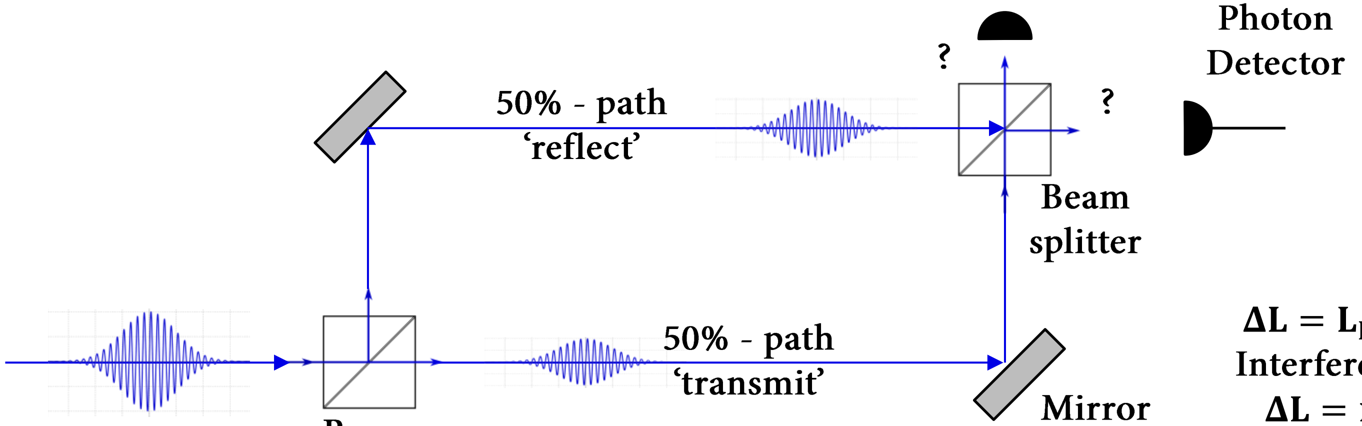
Qubits – Mach Zehnder Interferometer



Bit rotation | Phase rotation | Bit rotation | Measure



$\Delta\Phi = \Phi_0 - \Phi_1$
coherence if:
$\Delta\Phi = m \cdot 2\pi$



$\Delta L = L_R - L_T$
Interference if:
$\Delta L = m \cdot \lambda$