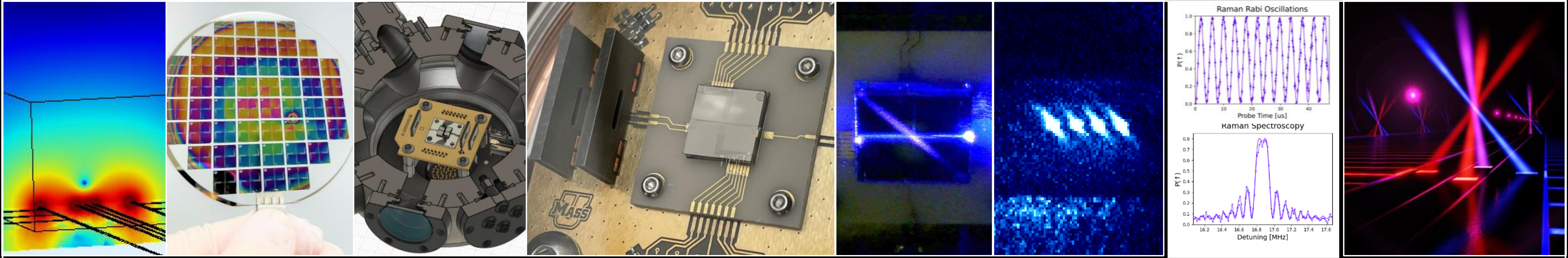
ECE 550/650 – Intro to Quantum Computing

WW06 Lecture 02

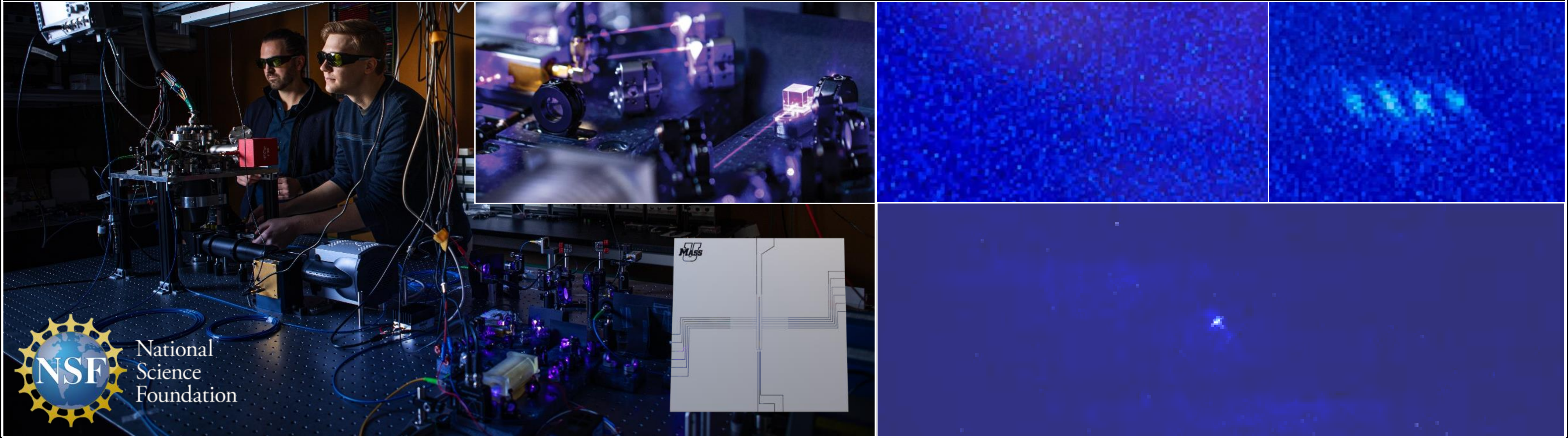
Robert Niffenegger

UMass Amherst | College of Engineering

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



Outline of the course

- Quantum Optics
  - What is interference (classical vs. single particle)
  - Superposition of states
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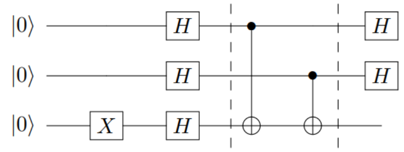


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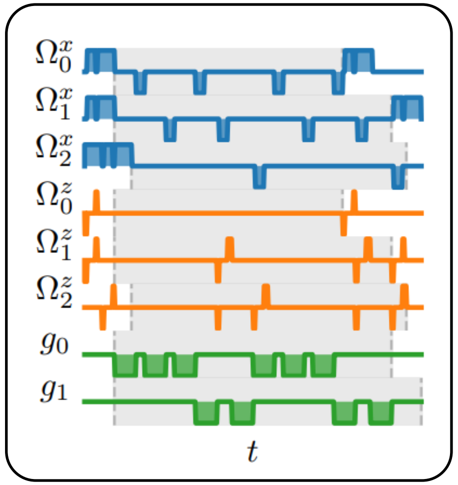

- Quantum Hardware
  - Photonics – nonlinear phase shifts
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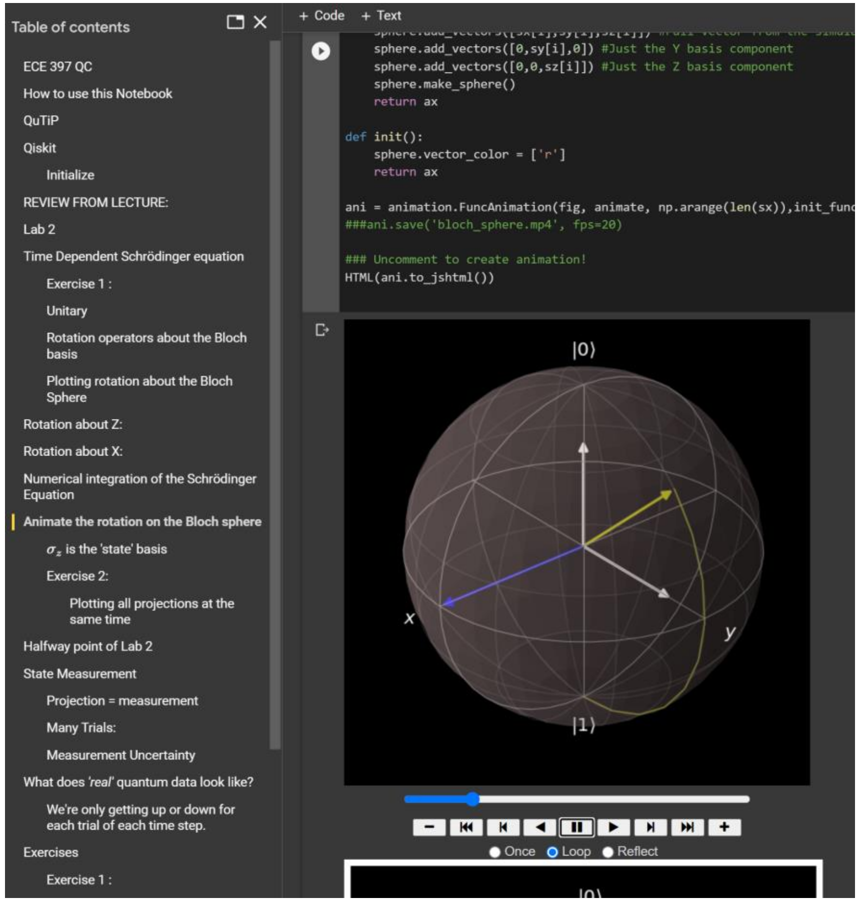
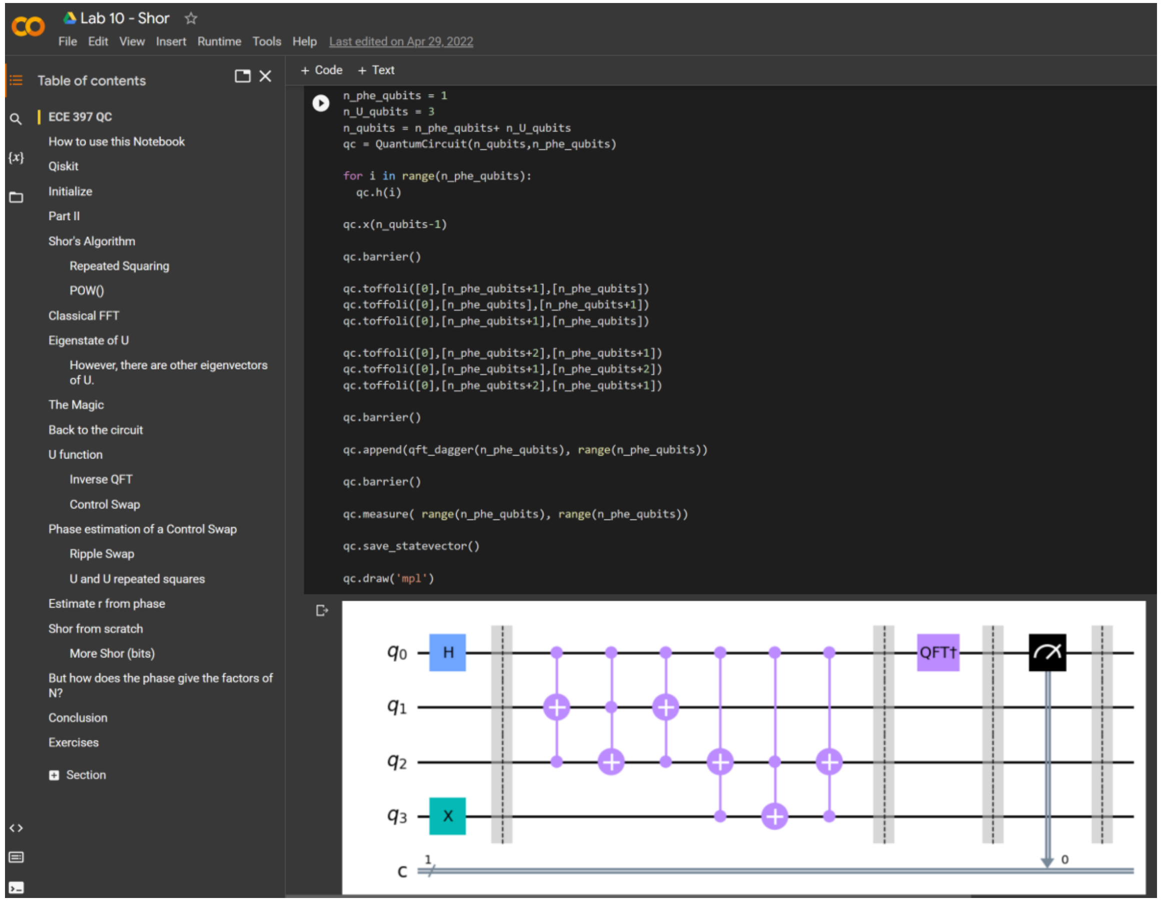
- Quantum Circuits
  - Single and two qubit gates
  - Hadamard gate , CNOT gate
- Quantum Algorithms
  - Amplitude amplification
  - Grover's Search
  - Oracle - Deutsch Jozsa
  - Bernstein Vazirani
  - Quantum Fourier Transform and period finding
  - Shor's algorithm

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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Why compute with qubits?

‘Each ~~photon~~ qubit then interferes ~~only~~ with itself’
 - Dirac

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

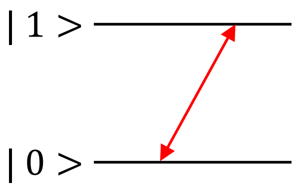
Until you entangle them

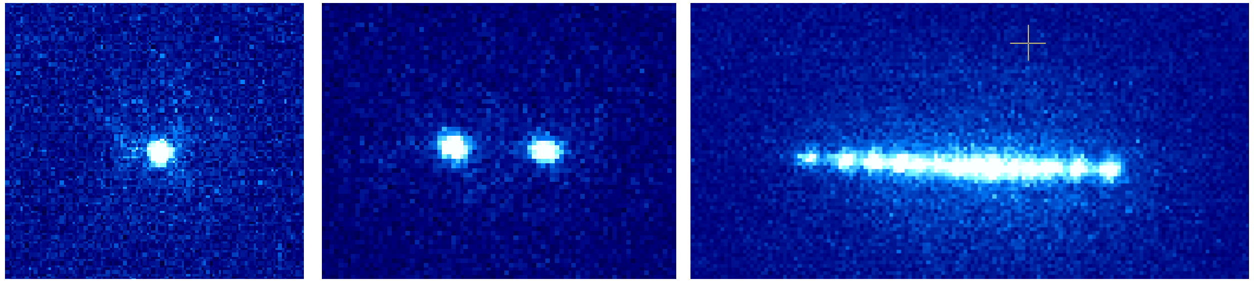
Each additional entangled two-level qubit adds those two states to the permutation

→ 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

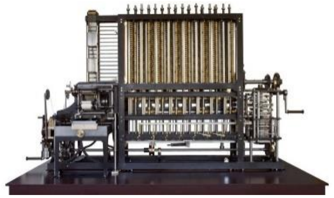




Trapped ion

Classical

32 bits in SRAM store just one number at a time



0000000 00000001 = 1
0000000 00000010 = 2
0000000 00000011 = 3
0000000 00000100 = 4

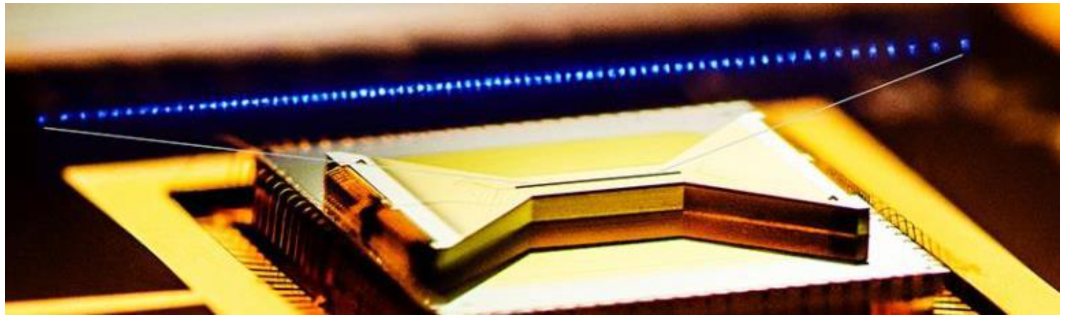
’01’ or ’10’

Quantum

32 qubits can represent all permutations

’01’ **and** ’10’

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



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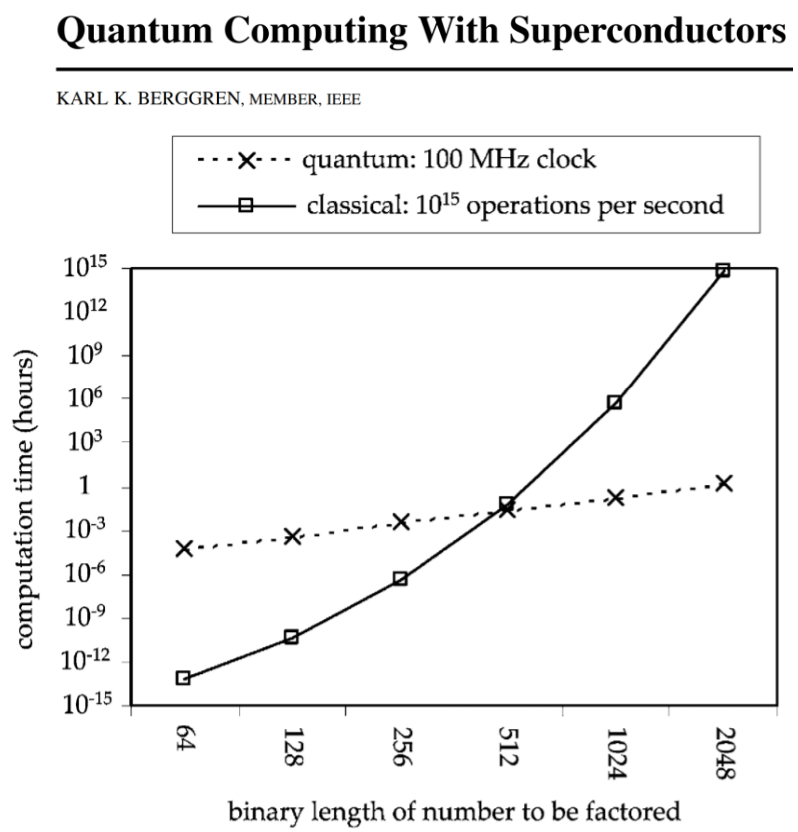
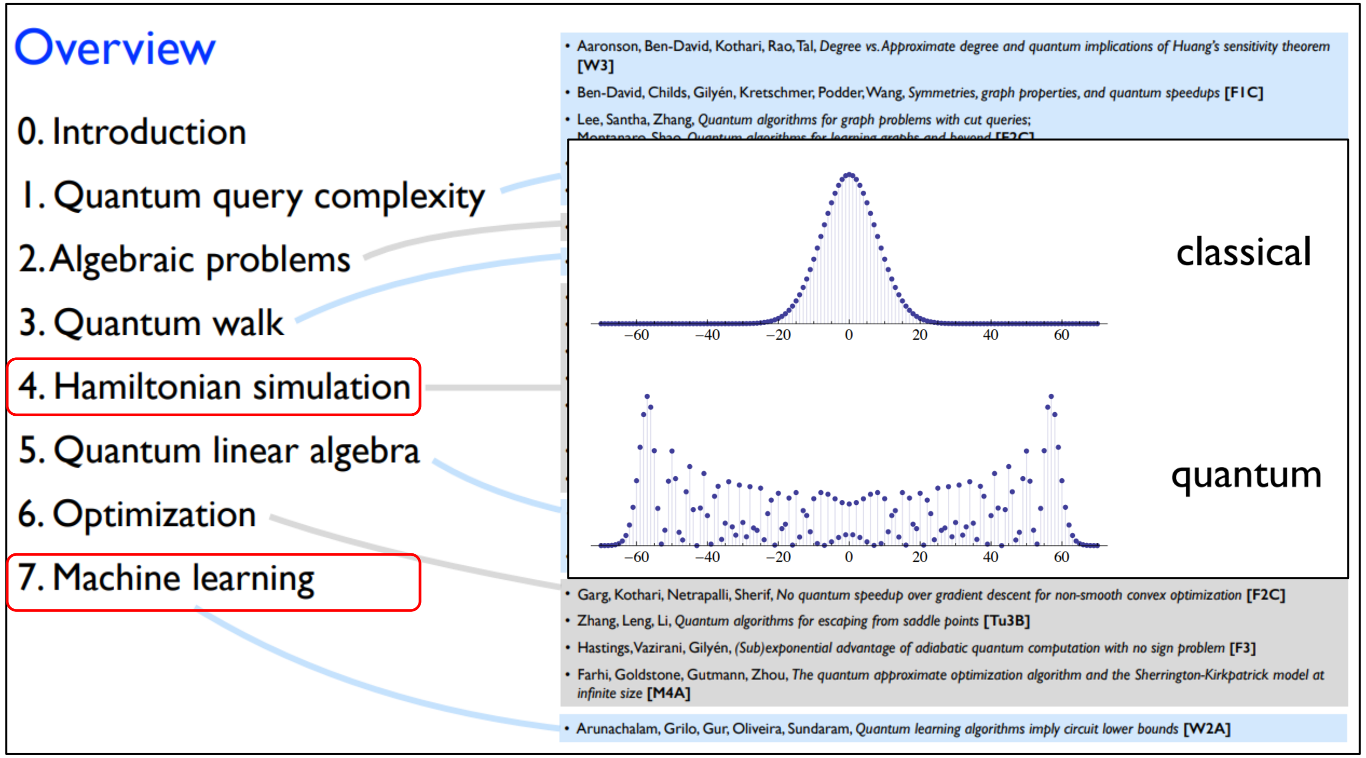
Quantum speedups?

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

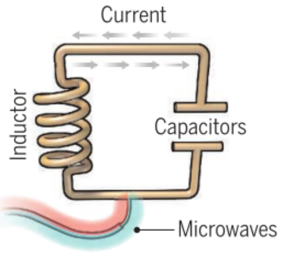
David P. DiVincenzo
IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA
(February 1, 2008)

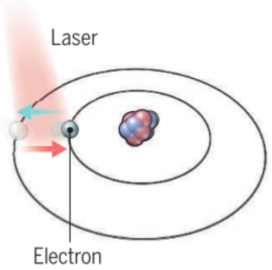
1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits
3. Long relevant coherence times (vs. gate time)
4. A “universal” set of quantum gates
5. A qubit-specific measurement capability

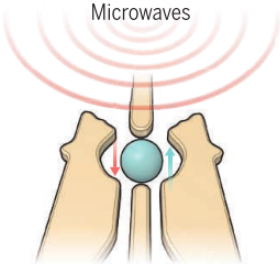
Many viable qubits but all have challenges scaling

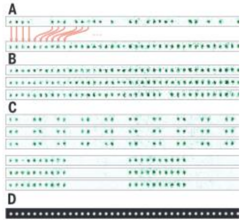
(Increasing qubit number without loss in performance)

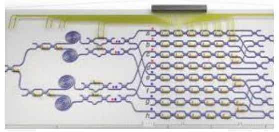
‘New qubits’











	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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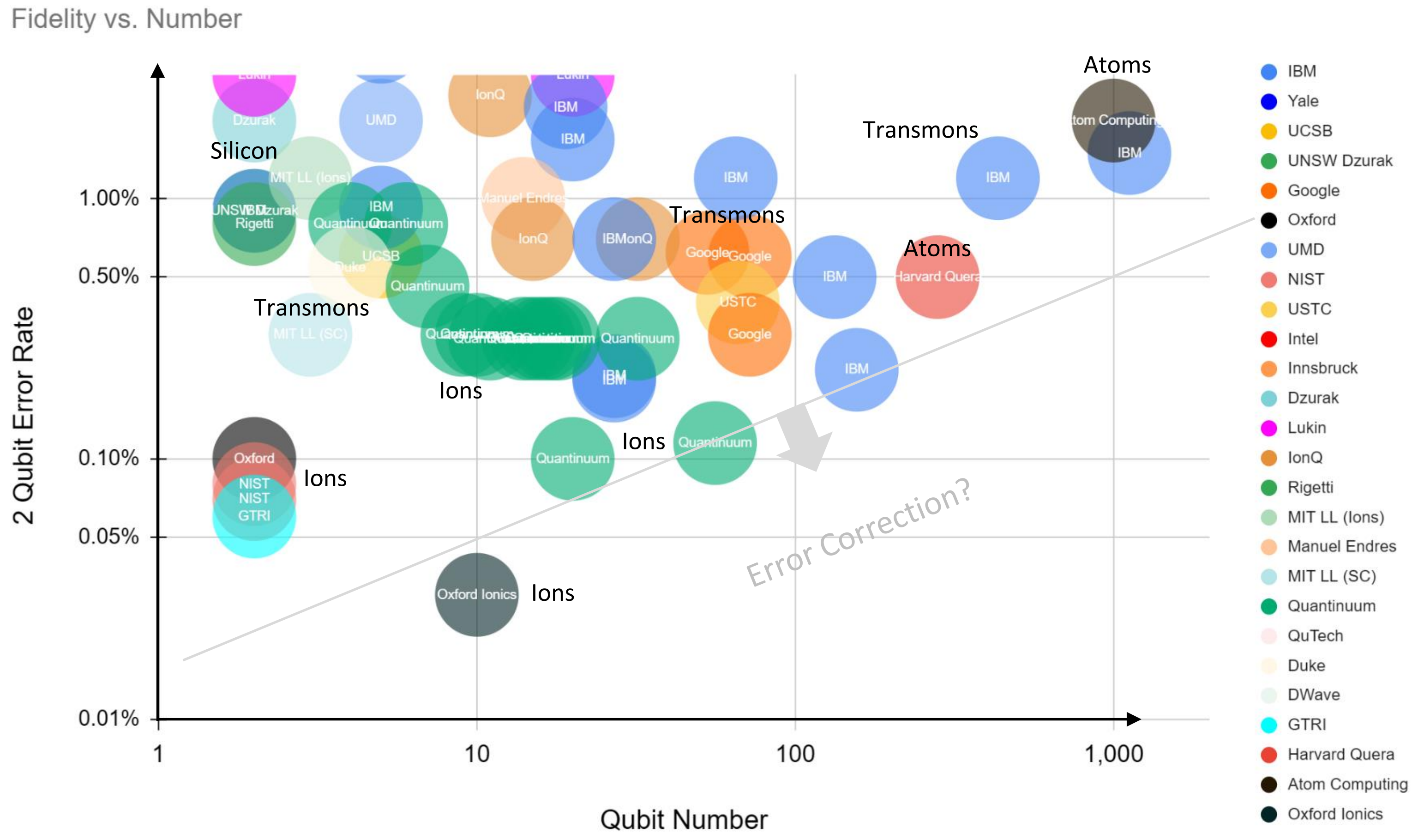
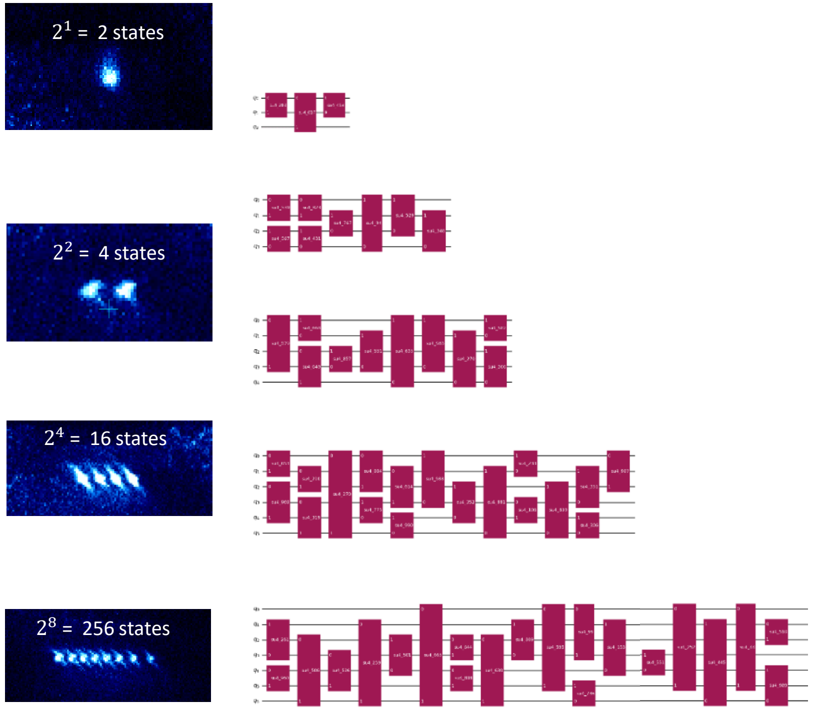
Comparing Quantum Computers

Quantum Volume

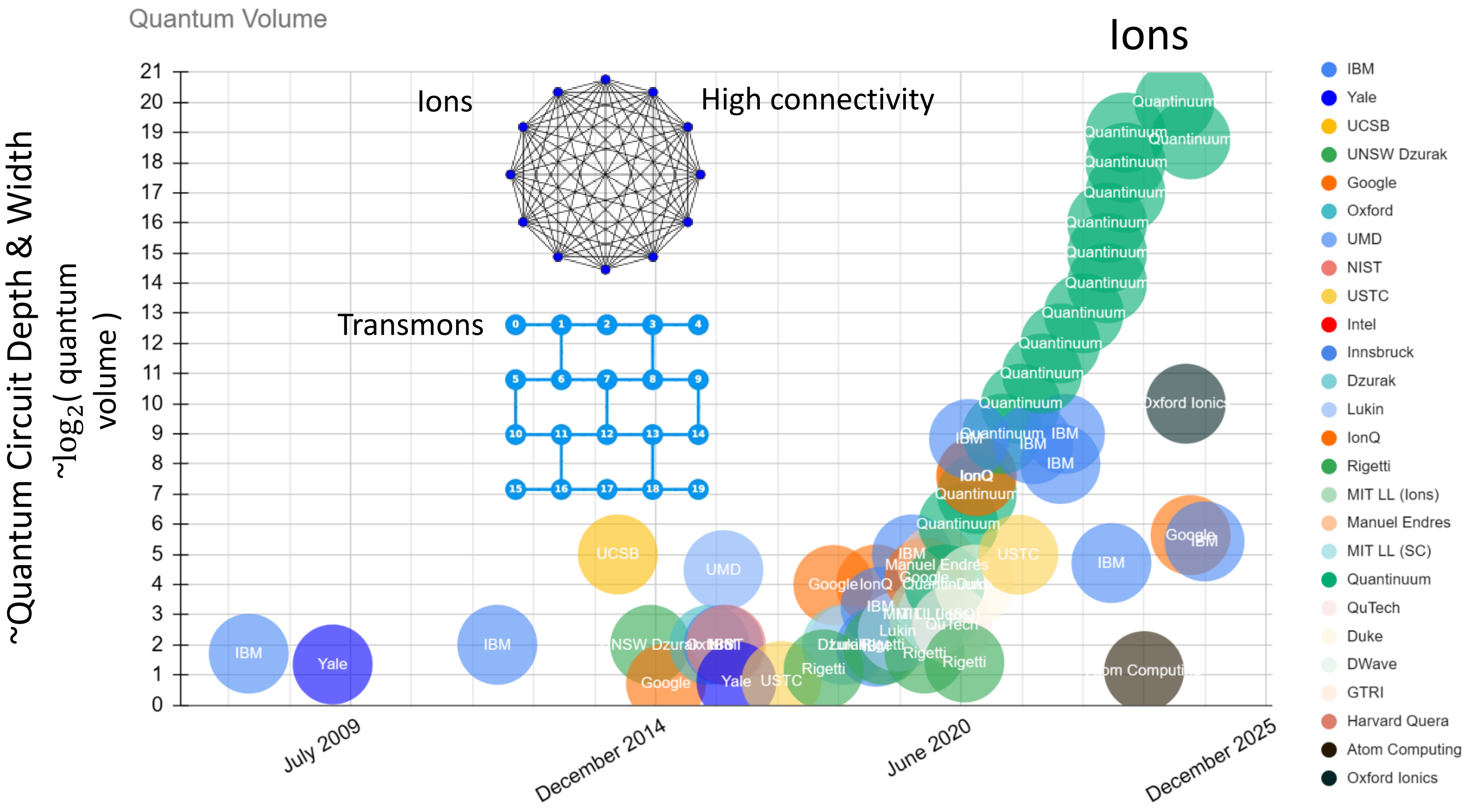




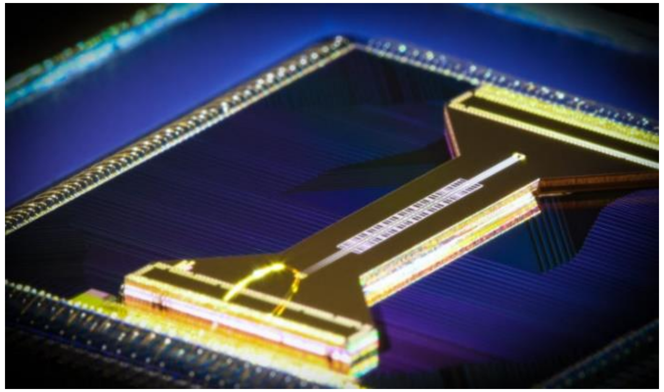
Qubit number &
Circuit depth
Both increasing

Quantum Volume

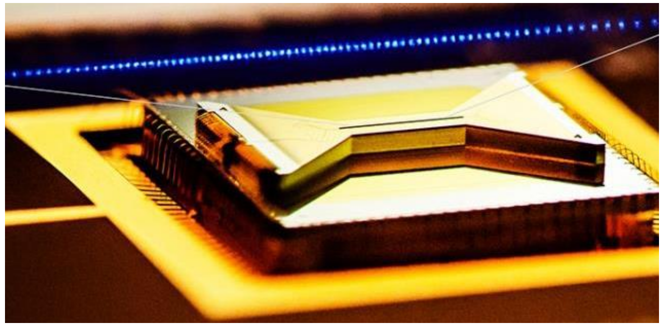
$\log_2$(QV) of various qubit modalities (estimates)



Quantinuum (Honeywell)

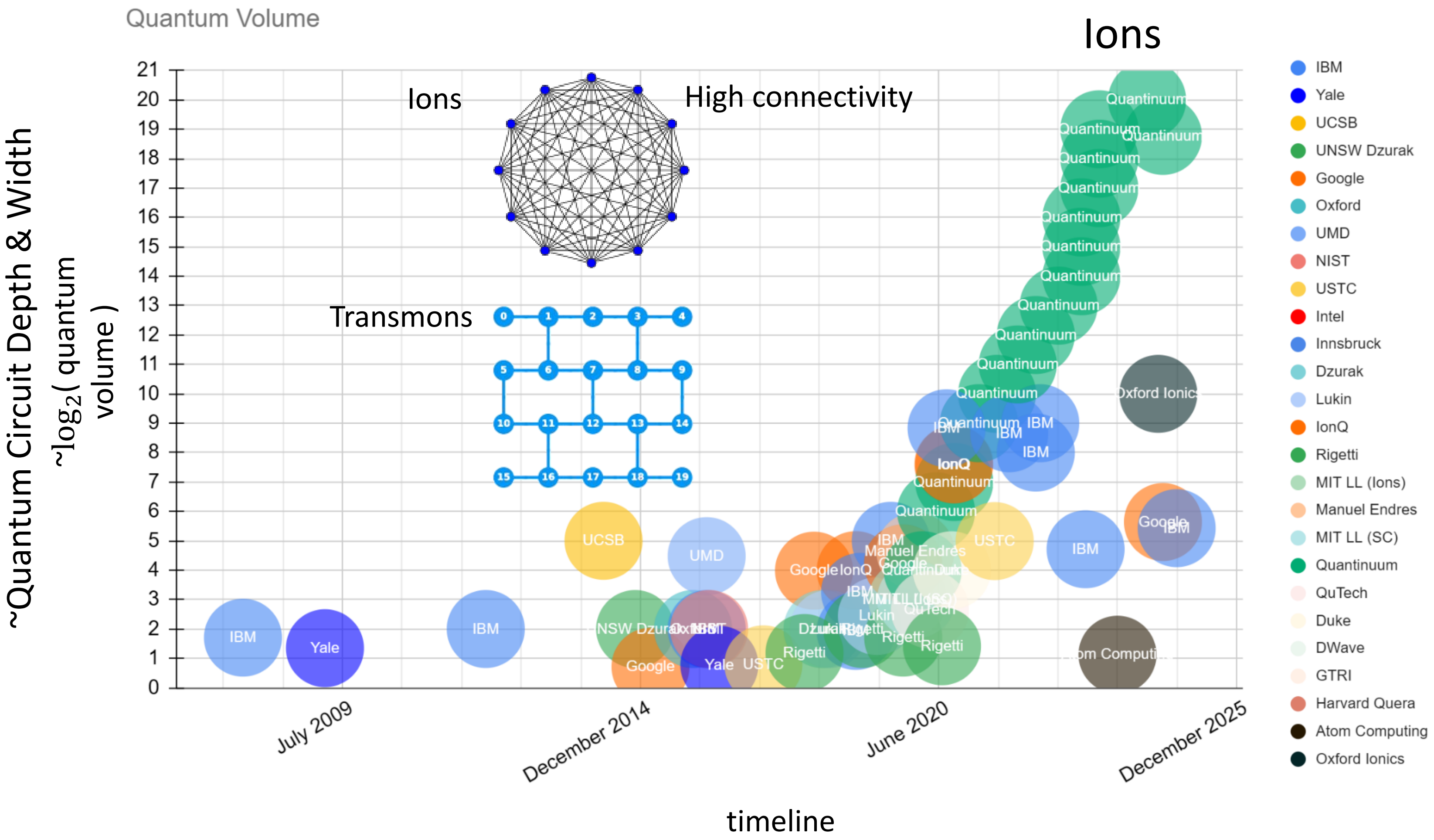


IonQ



Quantum Volume – Trapped ions in the lead

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



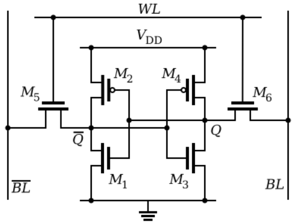
<u>Trapped Ion Qubit Advantages</u>

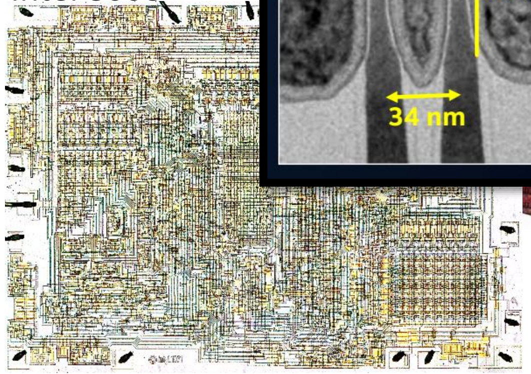
1. High fidelity operations
   - 2Q gates > 99.97%
   - 1Q gates > 99.9999%
   - Readout > 99.99%
   - State Preparation & Measurement > 99.97%
2. Long coherence time
   - 200ms → 600 seconds
   - Ratio to gate time > 1,000,000
3. Atoms are identical (less tuning)
4. High connectivity
5. Low crosstalk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

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

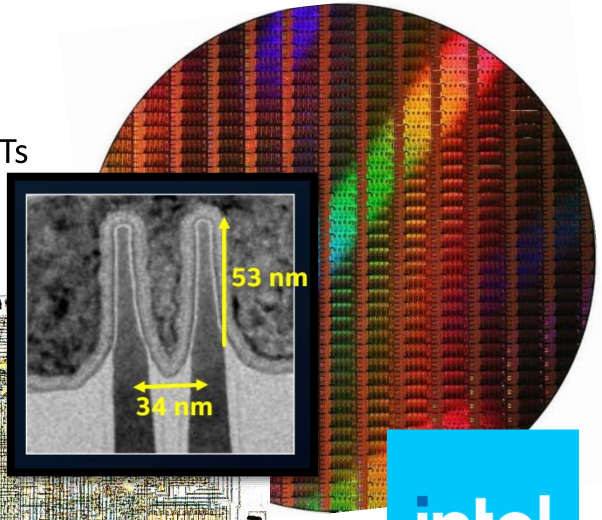
Scaling towards Quantum Error Correction

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





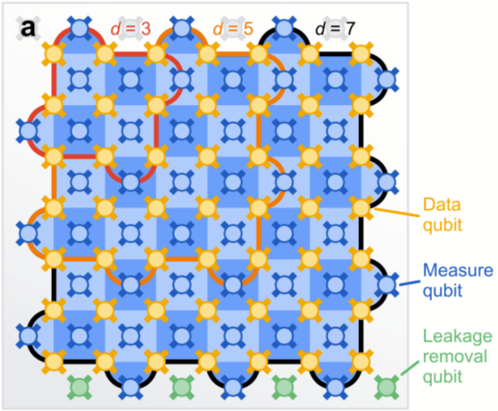
FinFETs



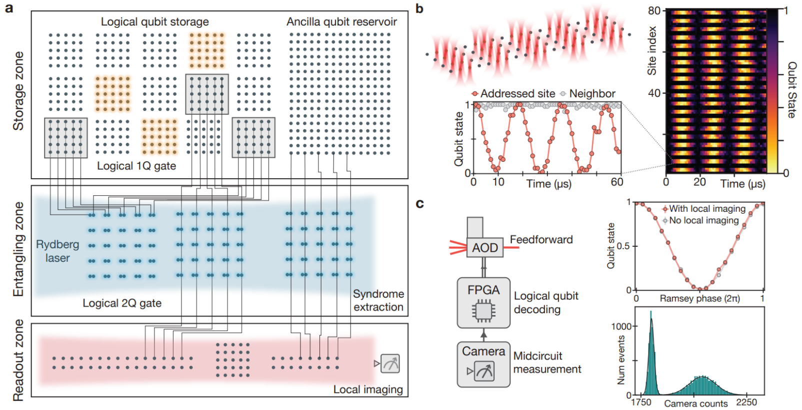
Intel 8008

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?

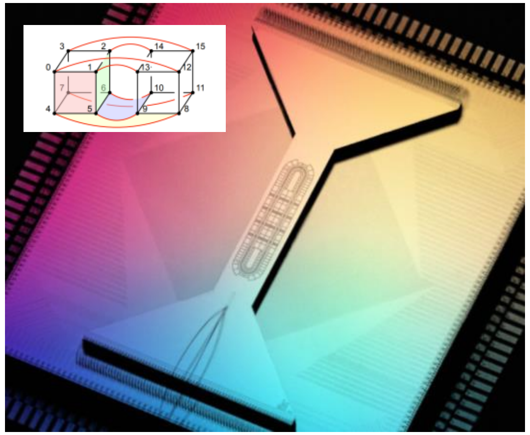
Google - arXiv:2408.13687



Rydberg atoms - Lukin Harvard 2023



Quantinuum - arXiv:2409.04628



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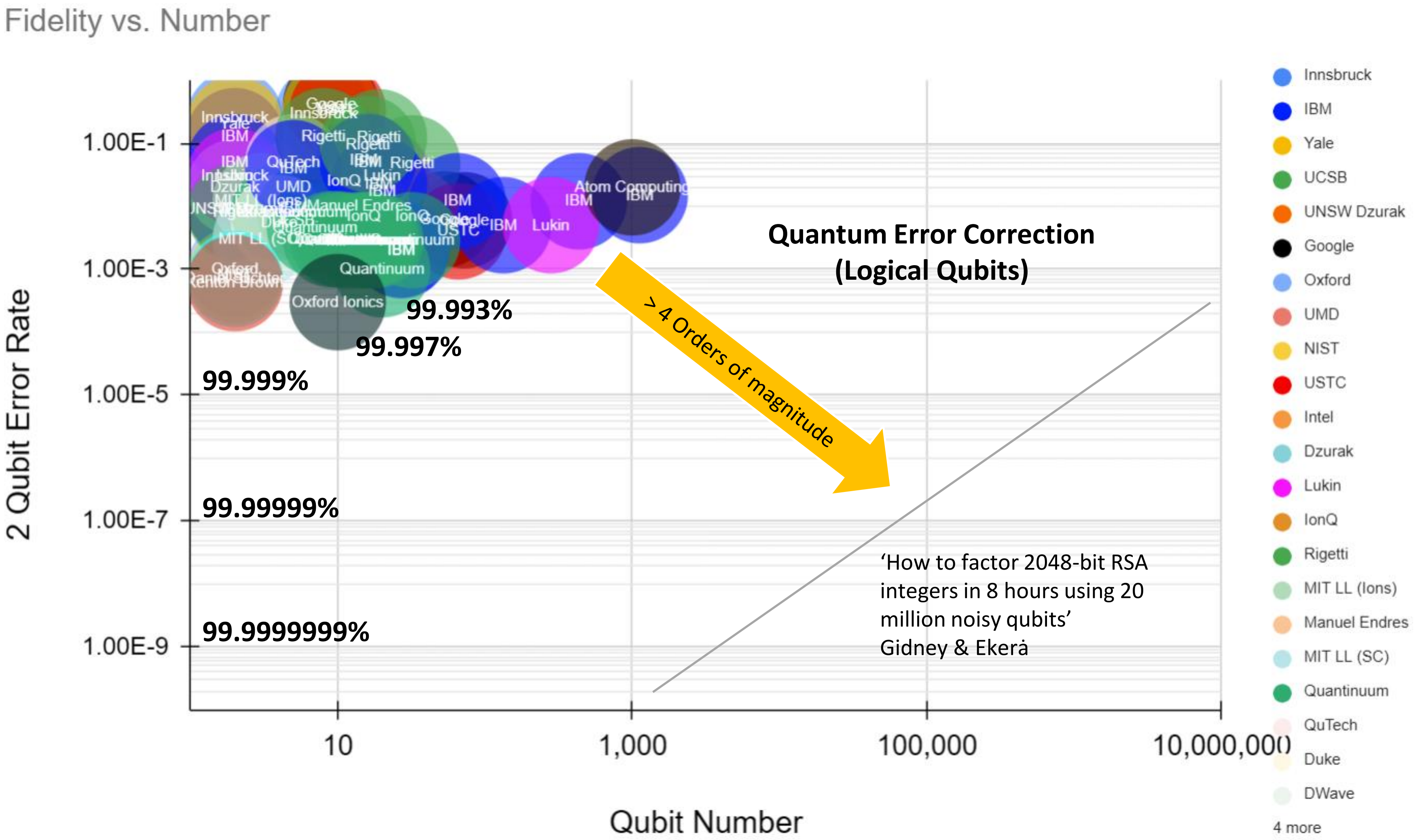
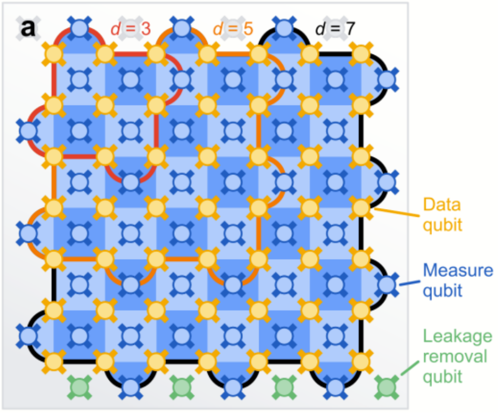
Scaling towards Error Correction



Google - arXiv:2408.13687



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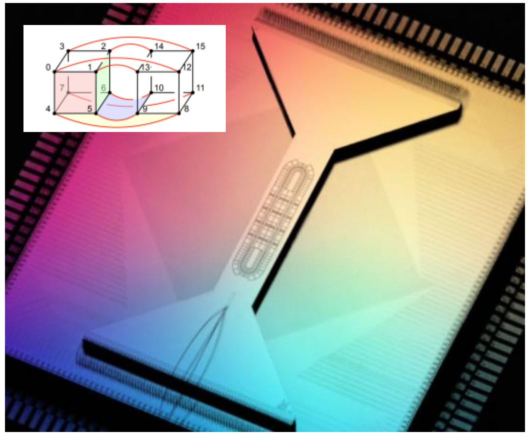
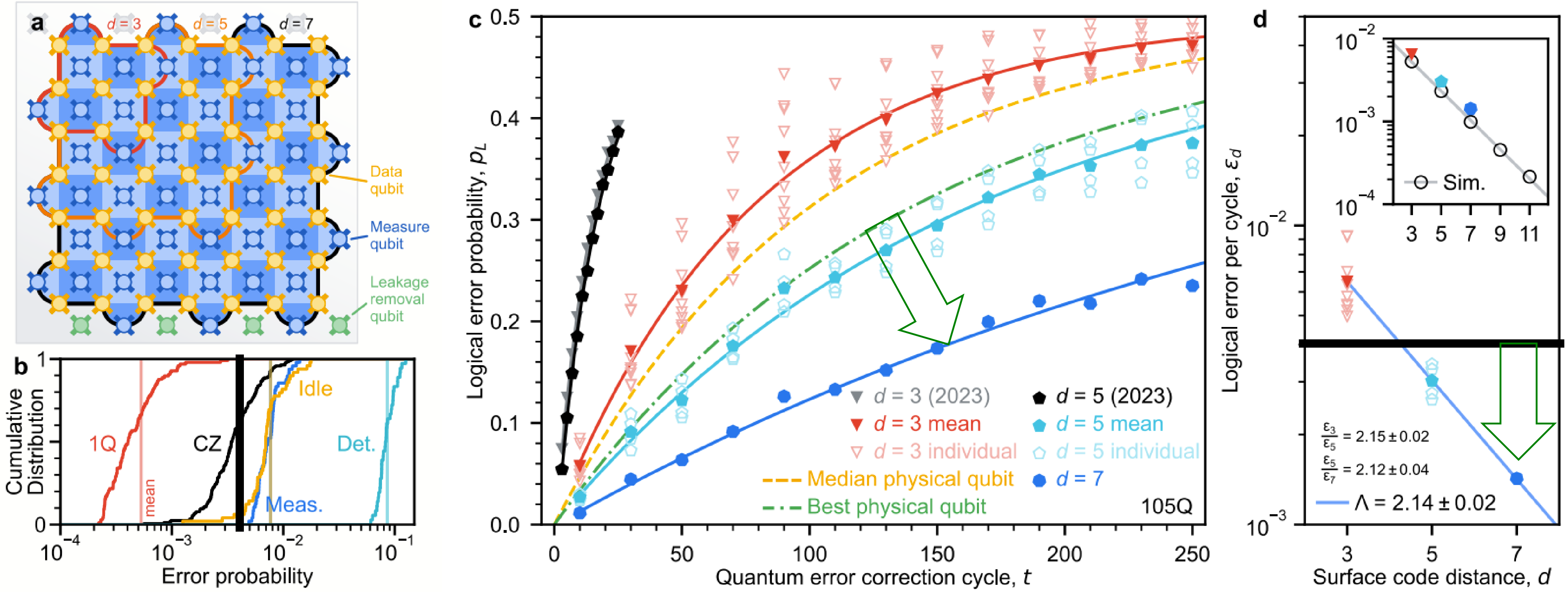
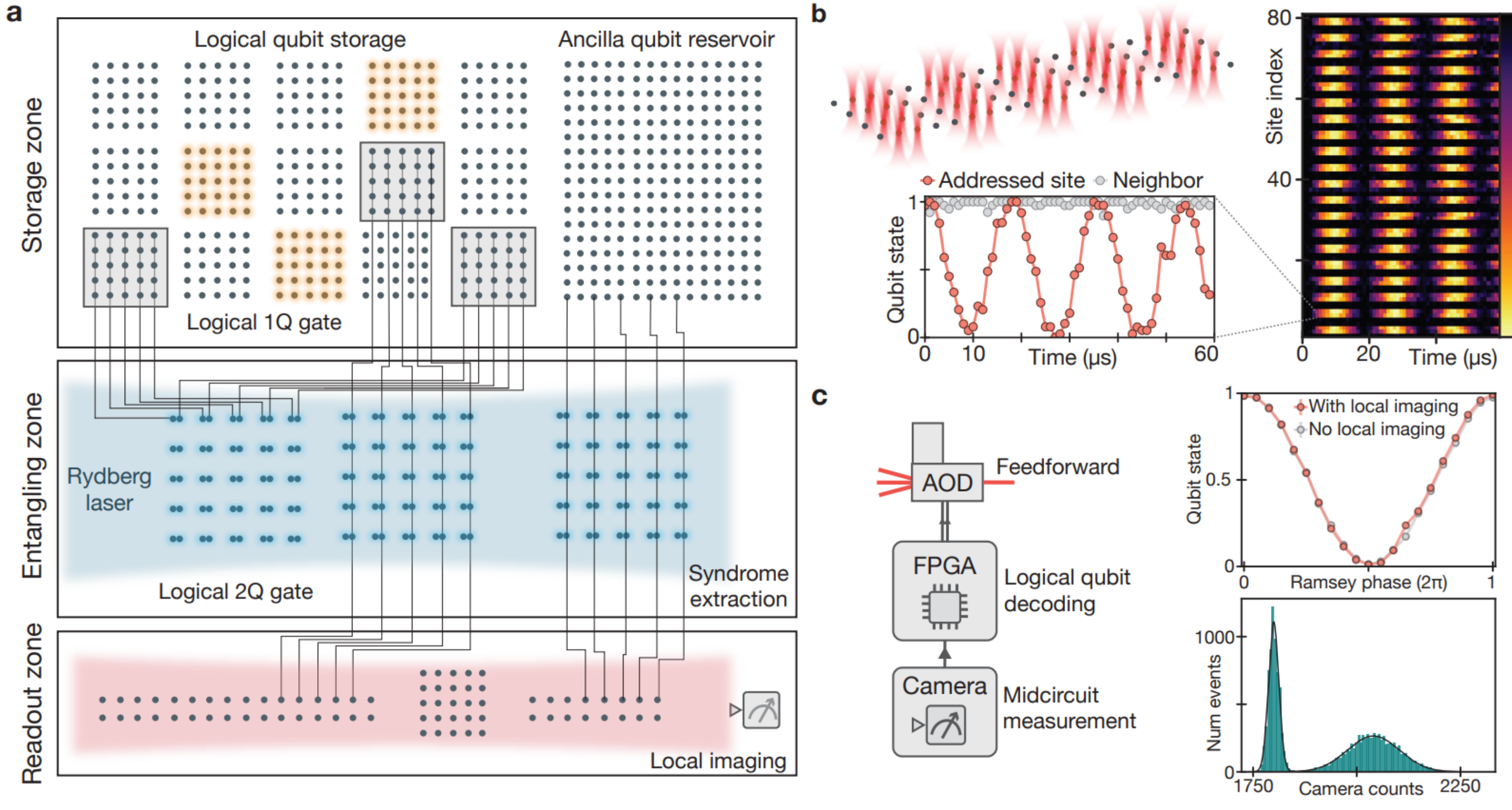


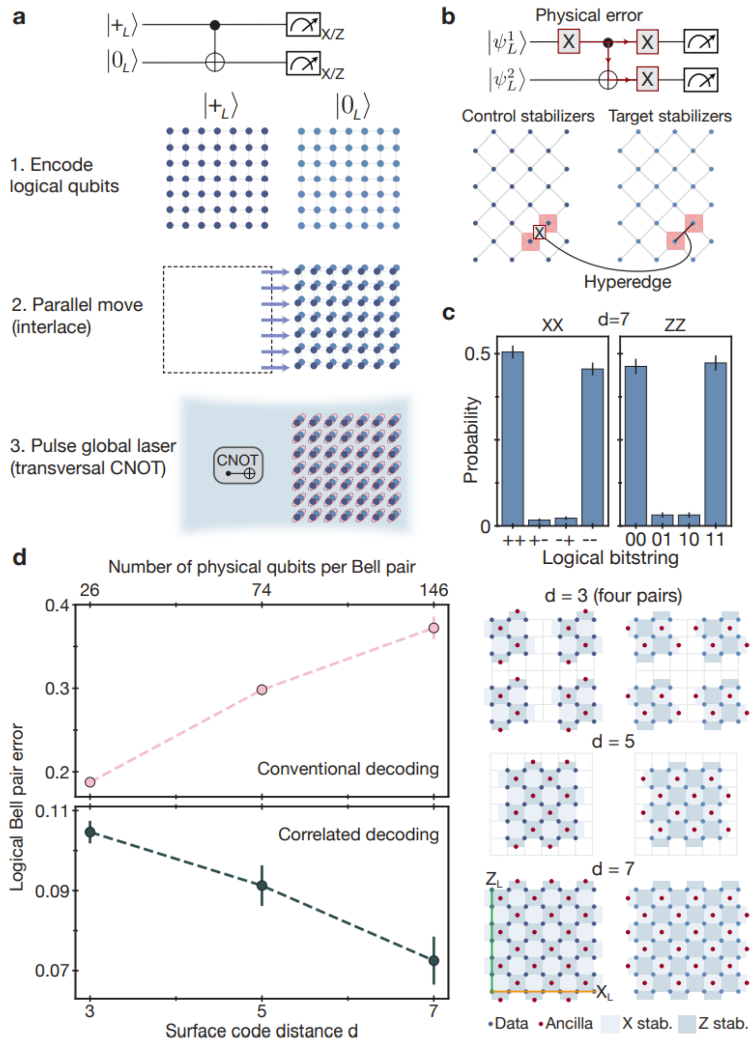
Google – Surface Code Threshold



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

Rydberg Atoms – Entangling of multiple Logical Qubits





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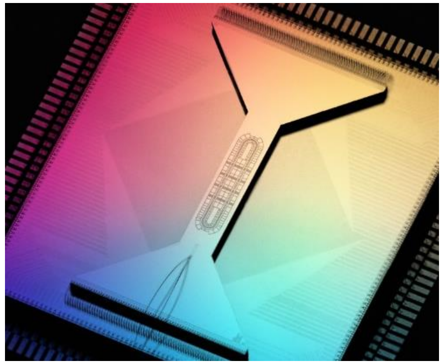
Trapped Ions – Error correction & entangling of Logical Qubits



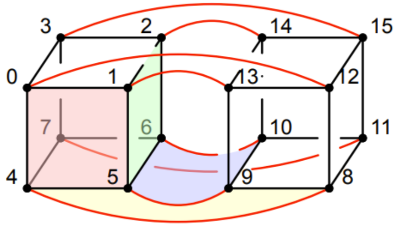
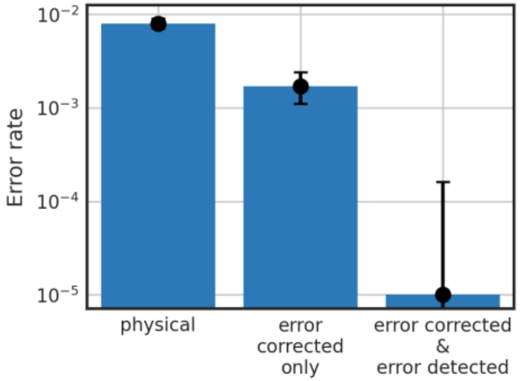
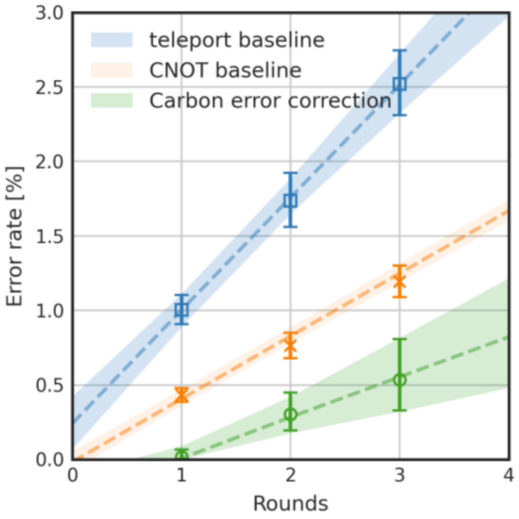


FIG. 1. The [[16, 6, 4]] color code on the 4D hypercube, or tesseract. Each of the 16 vertices is a qubit. Cubes are X and Z stabilizers, and squares are logical operators, e.g., 0145.



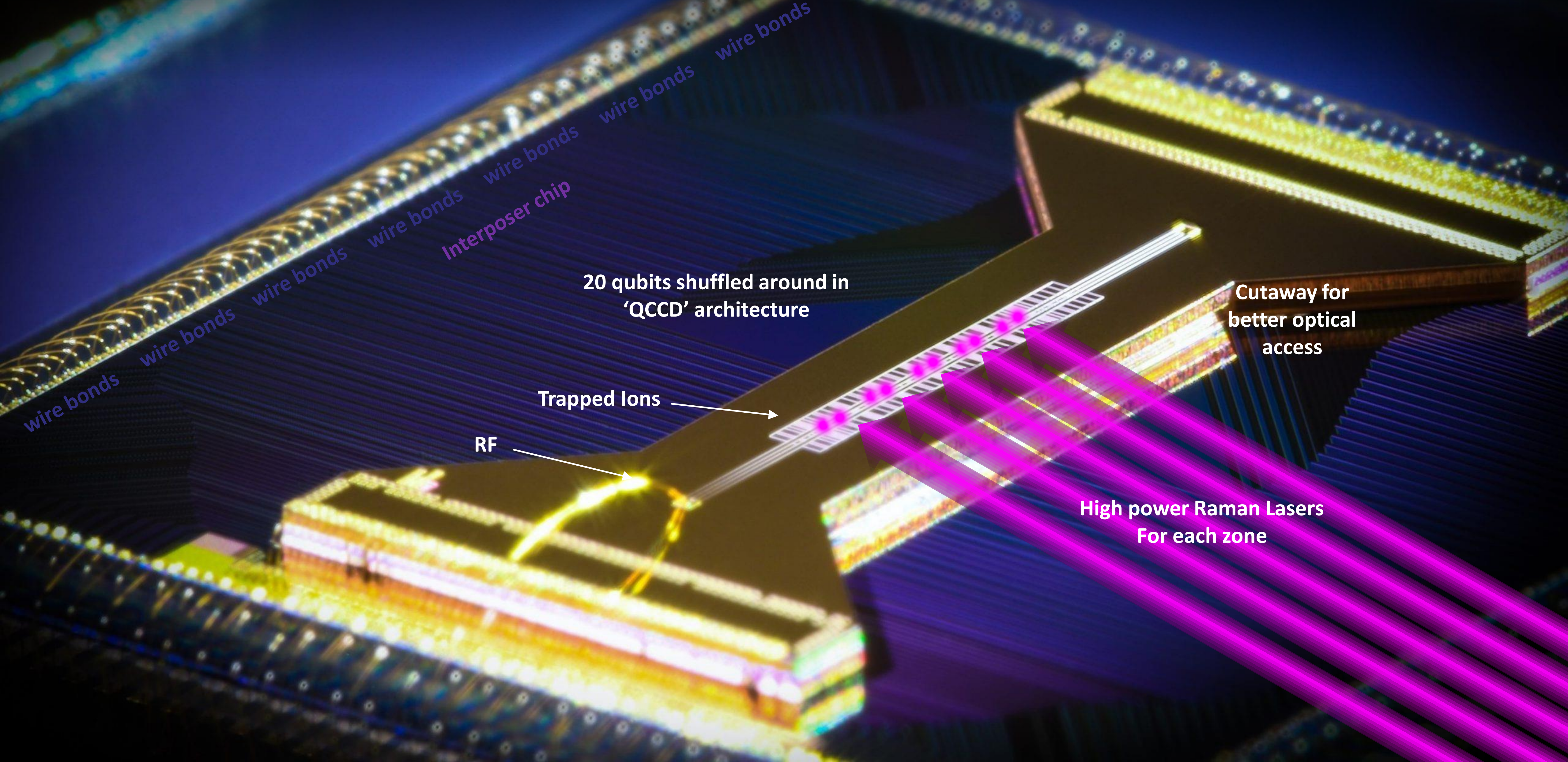


Experiment	Qubits	Baseline error rate	Encoded error rate	Gain
Path-4	4	1.5(2)%	$0.10^{+0.11}_{-0.06}$%	15×
Cube-8	8	2.3(3)%	$0.2^{+0.2}_{-0.1}$%	11×
$\|0^{12}\rangle + \|1^{12}\rangle$ Cat-12	12	2.4(3)%	$0.11^{+0.16}_{-0.08}$%	22×
Error correction 5×	4	2.7(4)%	$0.11^{+0.21}_{-0.09}$%	24×
	8	5.6(6)%	$0.7^{+0.7}_{-0.4}$%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

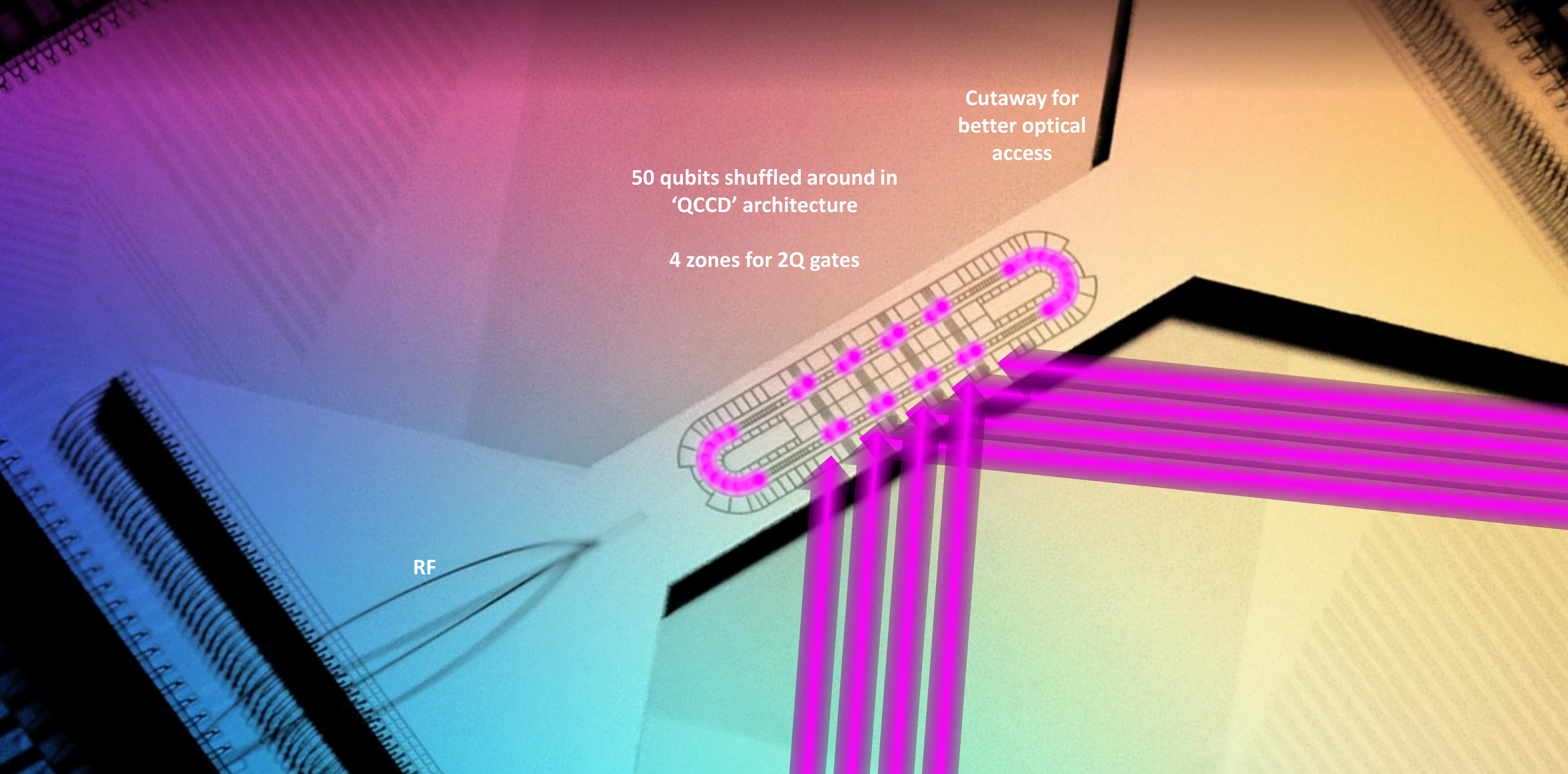
TABLE II. Experiments preparing encoded cat states.

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 $99.90^{+0.1}_{-0.3}$%

Surface Electrode Trap
Honeywell (Quantinuum) H1 – linear trap



Quantinuum H2 – Racetrack Ion Trap



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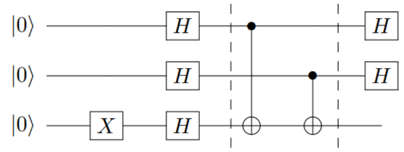


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qc.add_gate(
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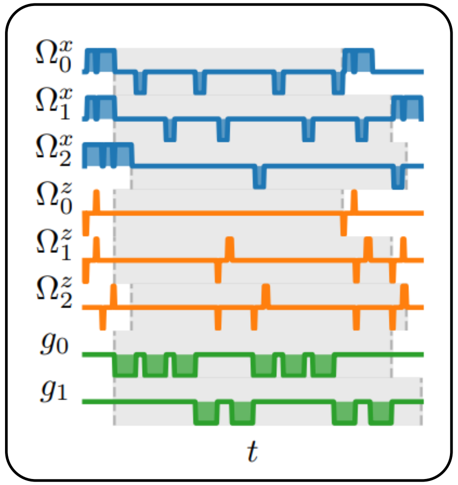
```



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  - Quantum Fourier Transform and period finding
  - Shor's algorithm

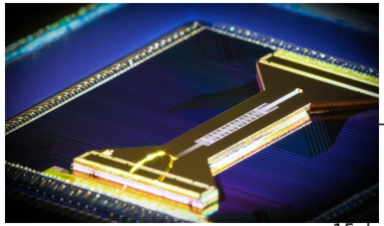
If time permits

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

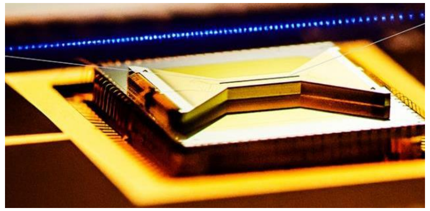
Benchmarking Quantum Hardware with Algorithms

"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



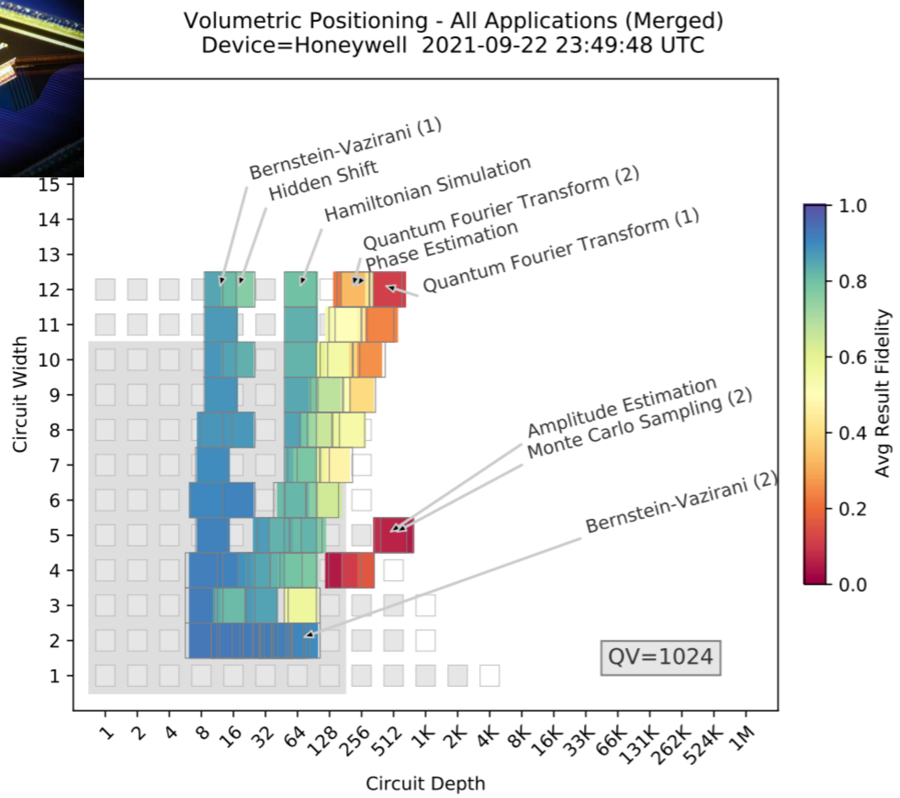


FIG. 12. **Benchmark results on Honeywell System Model H1.** The

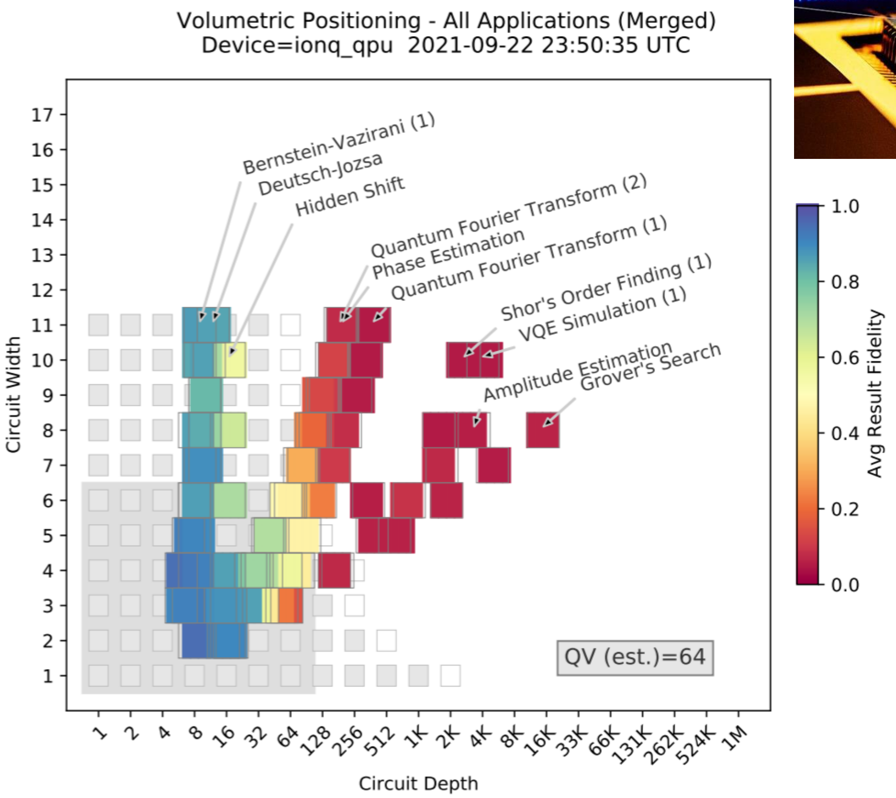


FIG. 13. **Benchmark results on IonQ's cloud-accessible system.**

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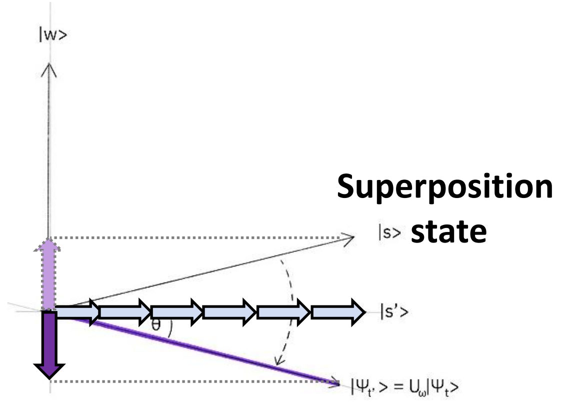
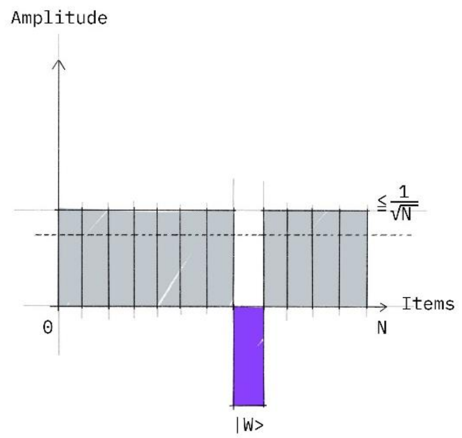
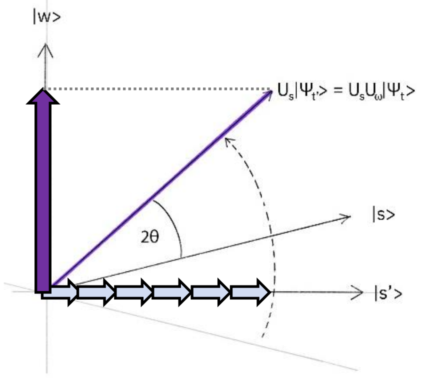
Grover Search (amplitude amplification)

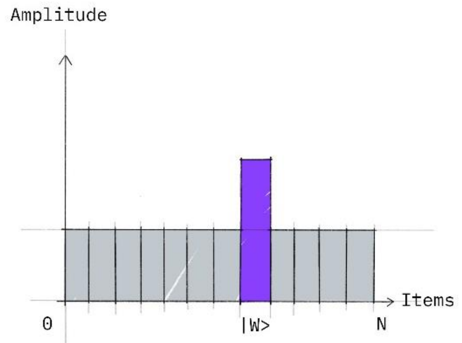
Oracle → Flips sign of 'answer'



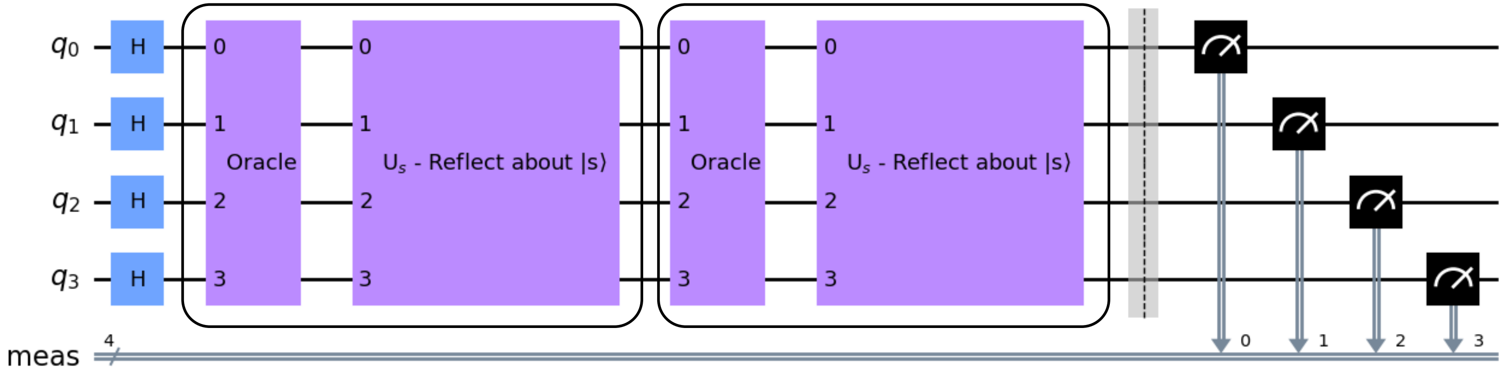


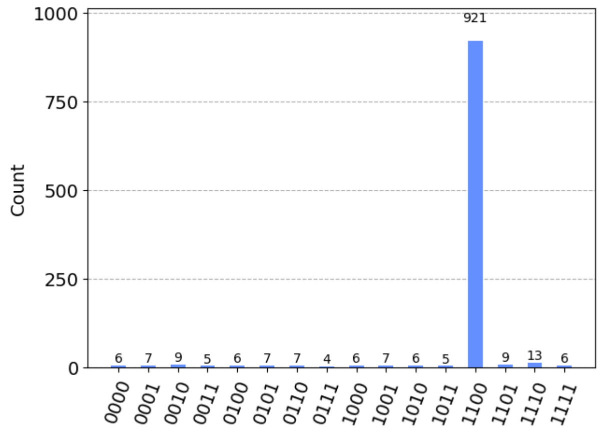
Amplitude Amplification → Answer more probable



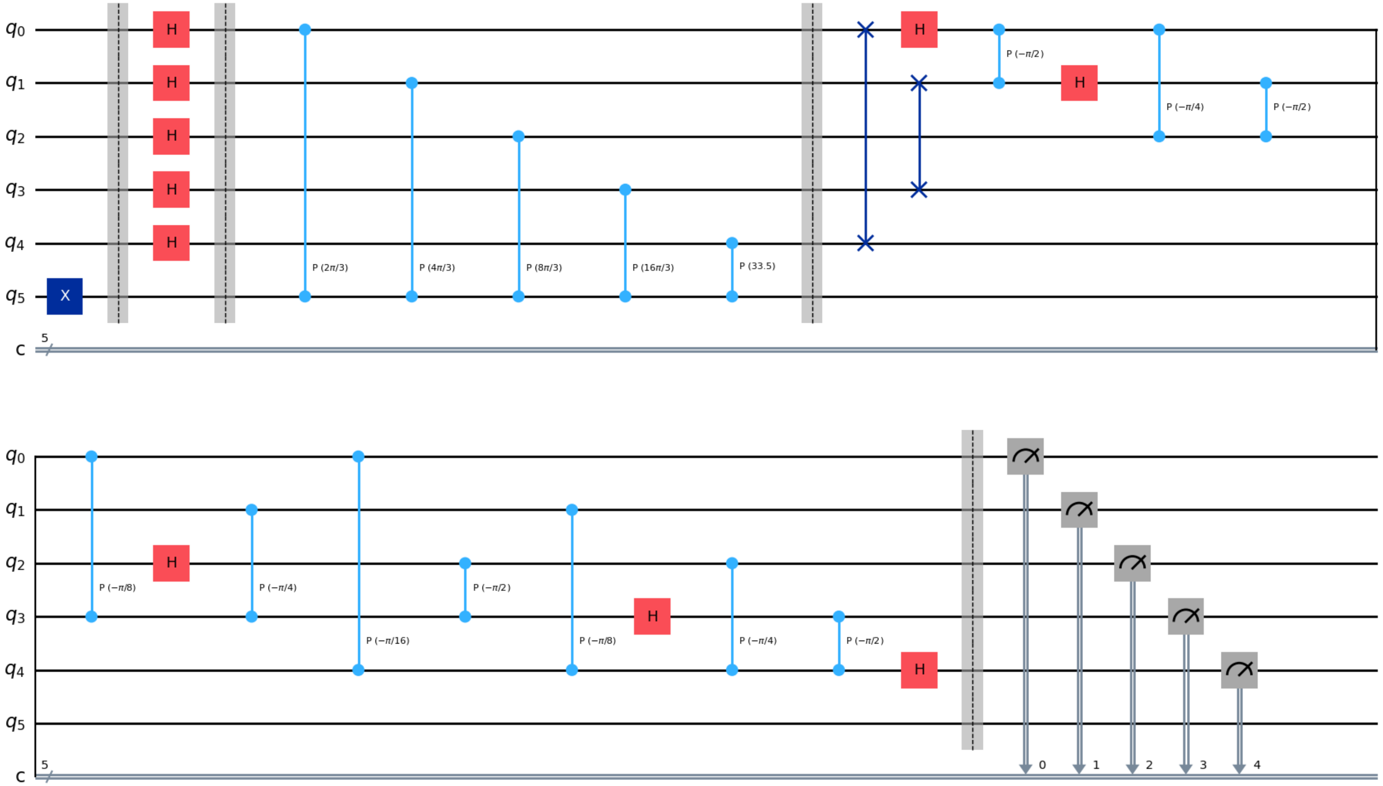


Repeat $\sqrt{N}$ times (twice for 4 bits)

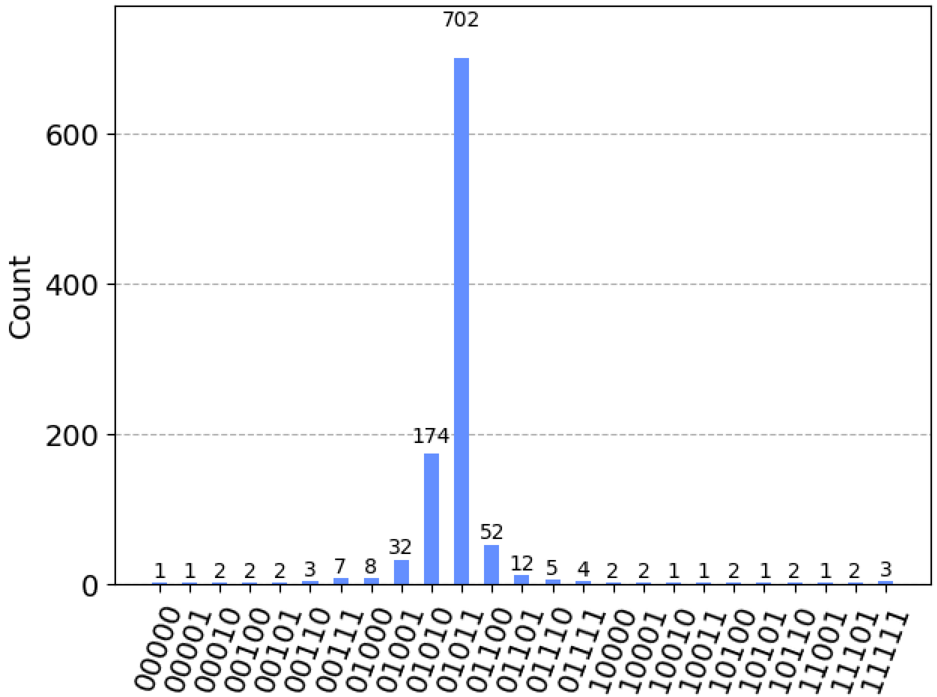




Quantum Phase Estimation



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



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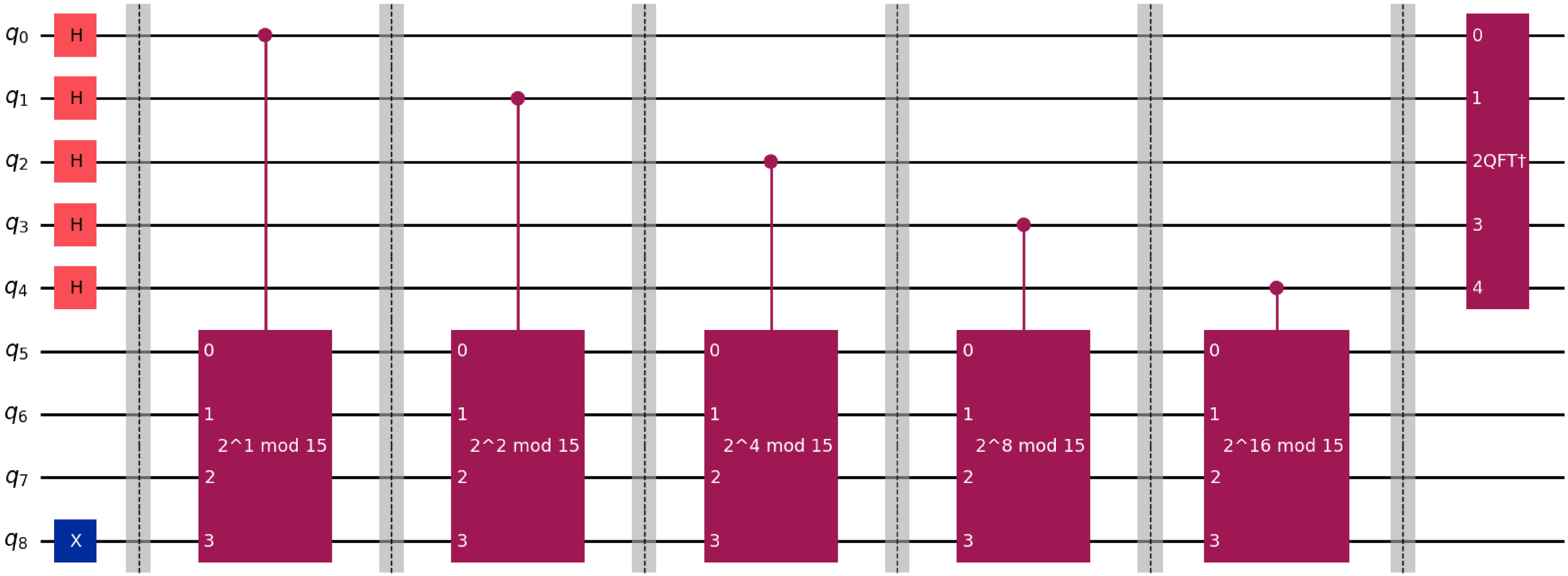
Shor's Algorithm



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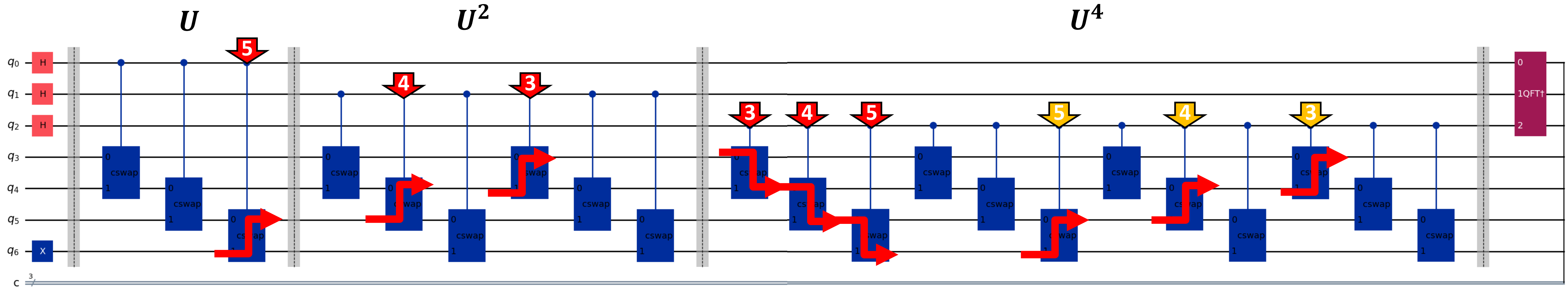
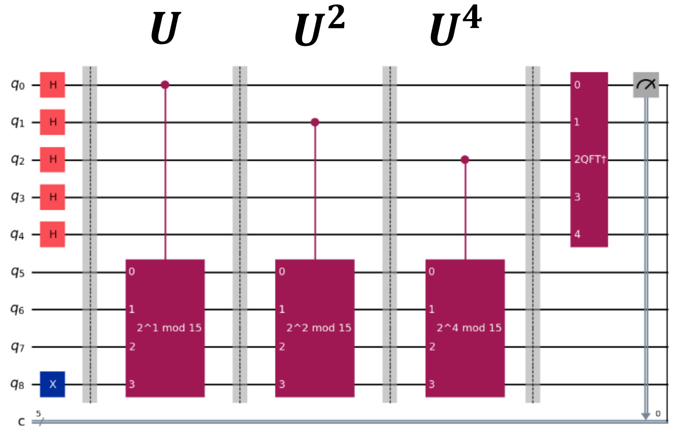
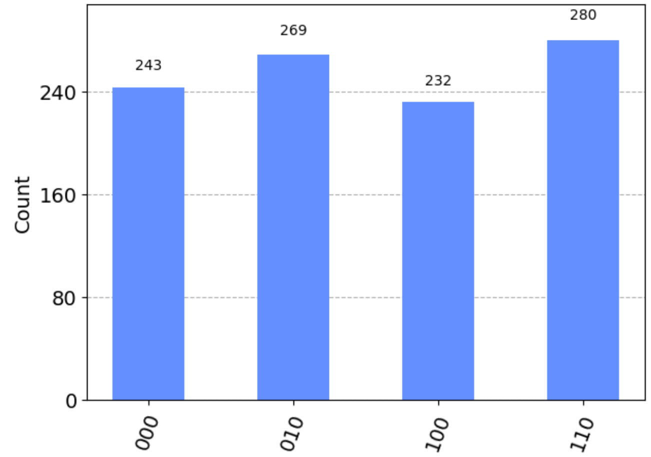
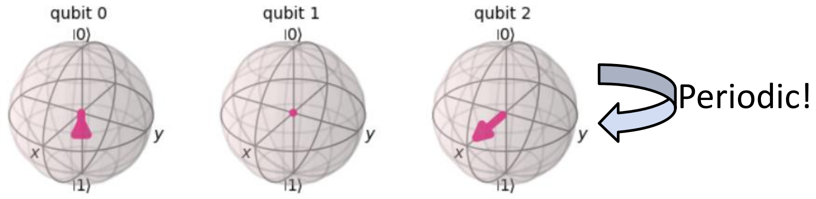
Shor's Algorithm - Repeated Squares!







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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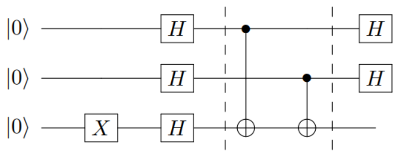
Outline of the course

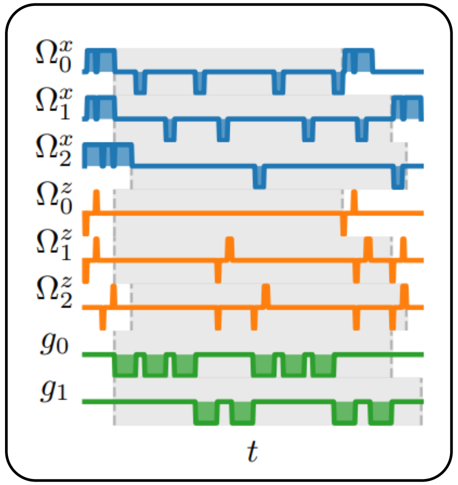
- Quantum Optics
  - What is interference (classical vs. single particle)
  - Superposition of states
  - Measurement and measurement basis
- Atomic physics
  - Spin states in magnetic fields and spin transitions
  - Transitions between atomic states (Rabi oscillations of qubits)
- Single qubits
  - 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)
```

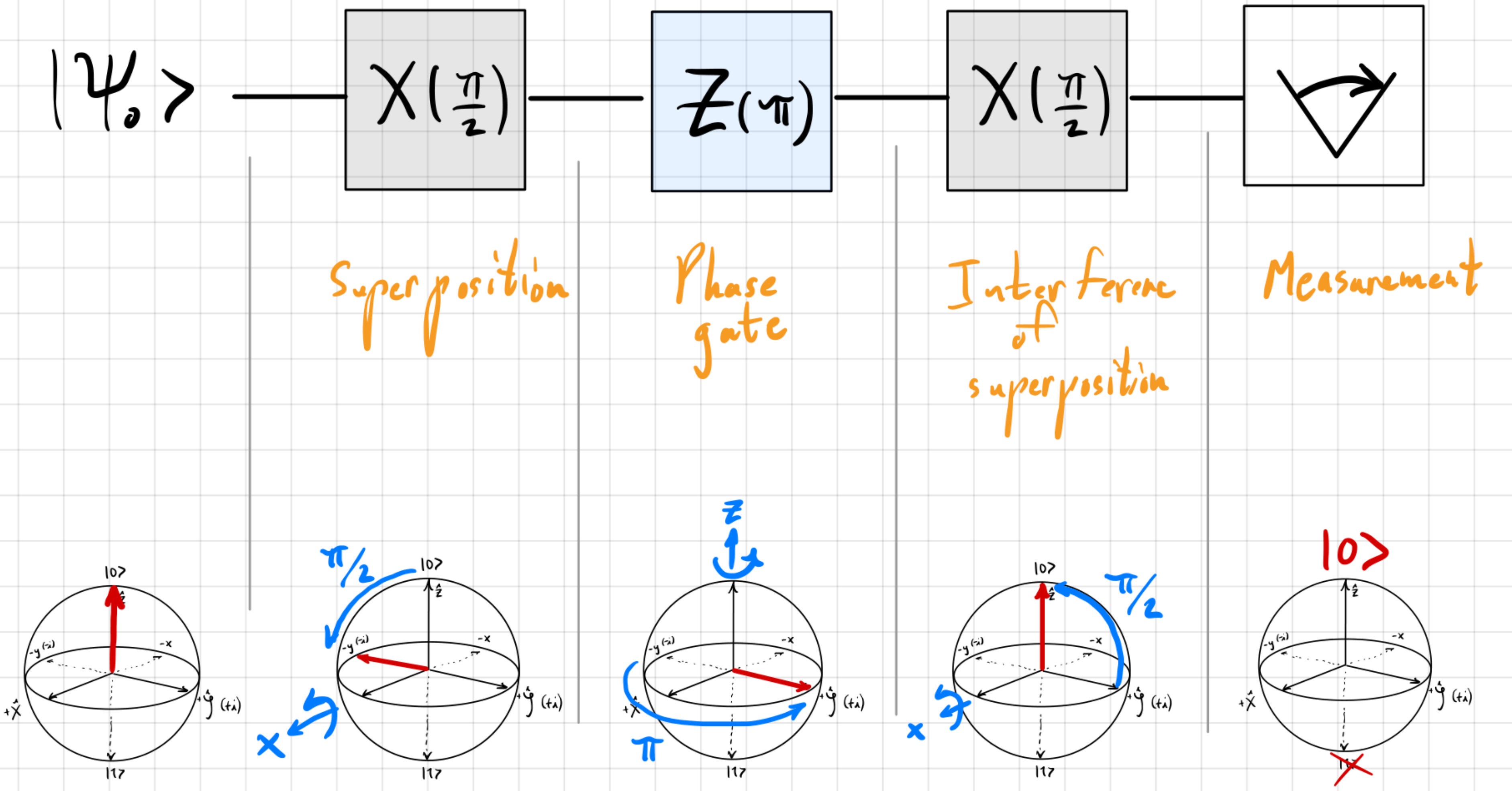


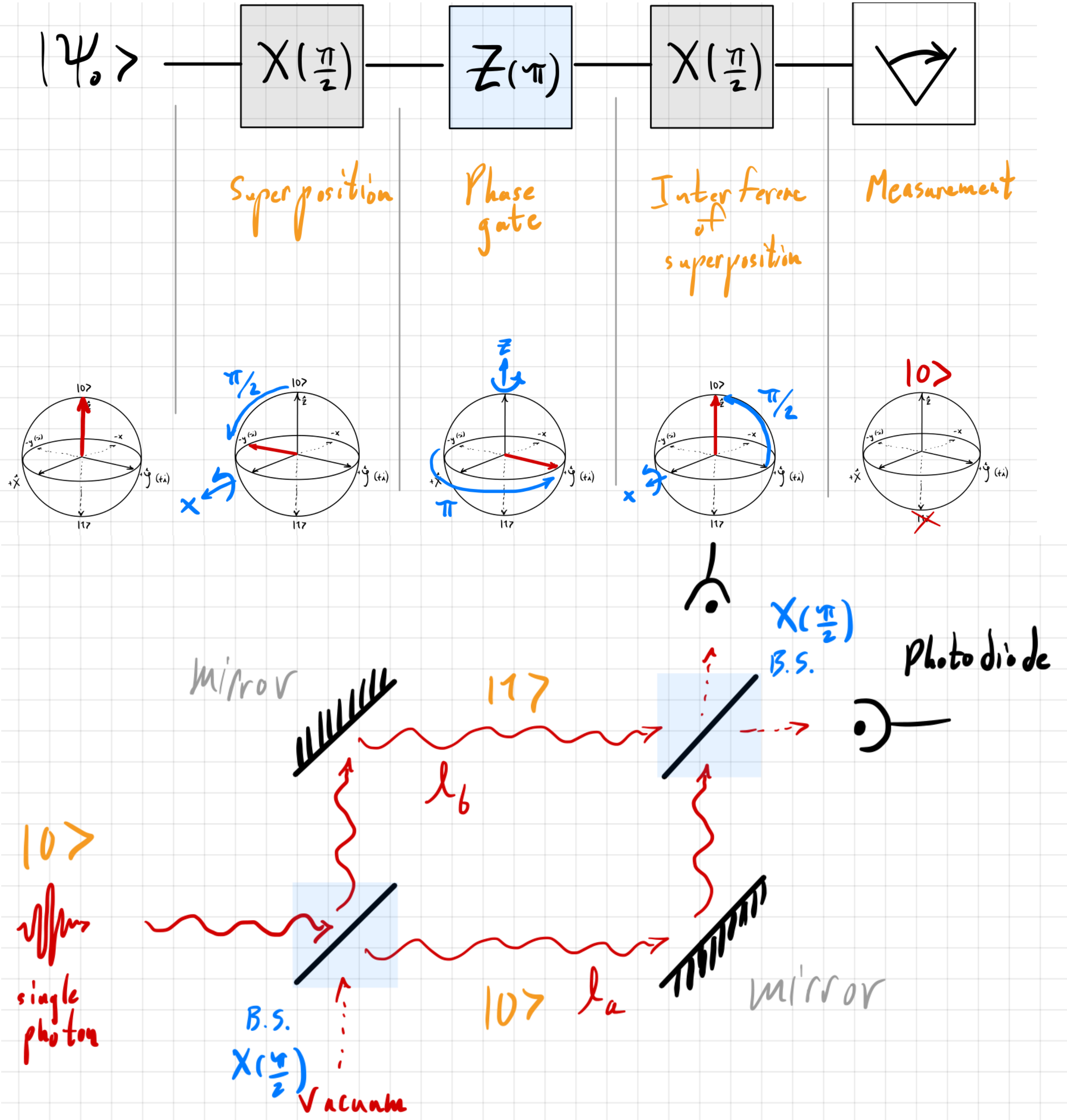
- Quantum Hardware
  - Photonics – nonlinear phase shifts
  - Transmons – charge noise, SWAP gate
- Quantum Circuits
  - Single and two qubit gates
  - Hadamard gate , CNOT gate
- Quantum Algorithms
  - Amplitude amplification
  - Grover's Search
  - Oracle - Deutsch Jozsa
  - Bernstein Vazirani
  -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

If time permits

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

Quantum Computing

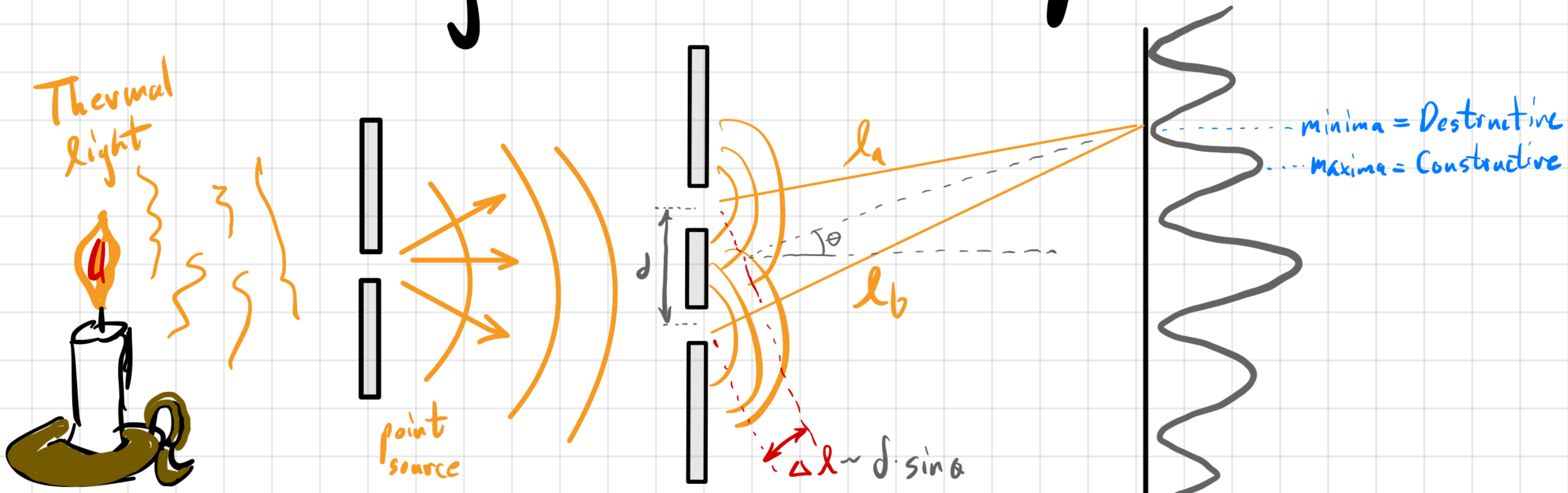




|ψ₀>
X(π/2)
Z(π)
X(π/2)
Superposition
Phase gate
Interference of superposition
Measurement
|0>
|1>
π/2
π
z
x
|0>
mirror
|1>
X(π/2)
B.S.
Photodiode
l_b
|0>
single photon
B.S.
X(π/2)
Vacuum
|0>
l_a
mirror

Interference – Young's Double Slit 1803

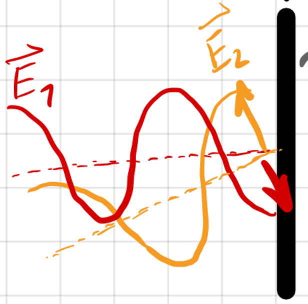
1803 Young's Double Slit Experiment



Maxima : $\Delta l = m \cdot \lambda$ $\quad m = 1, 2, 3, \ldots$

Minima : $\Delta l = (m + 1/2) \cdot \lambda$

Half wavelength out-of-phase

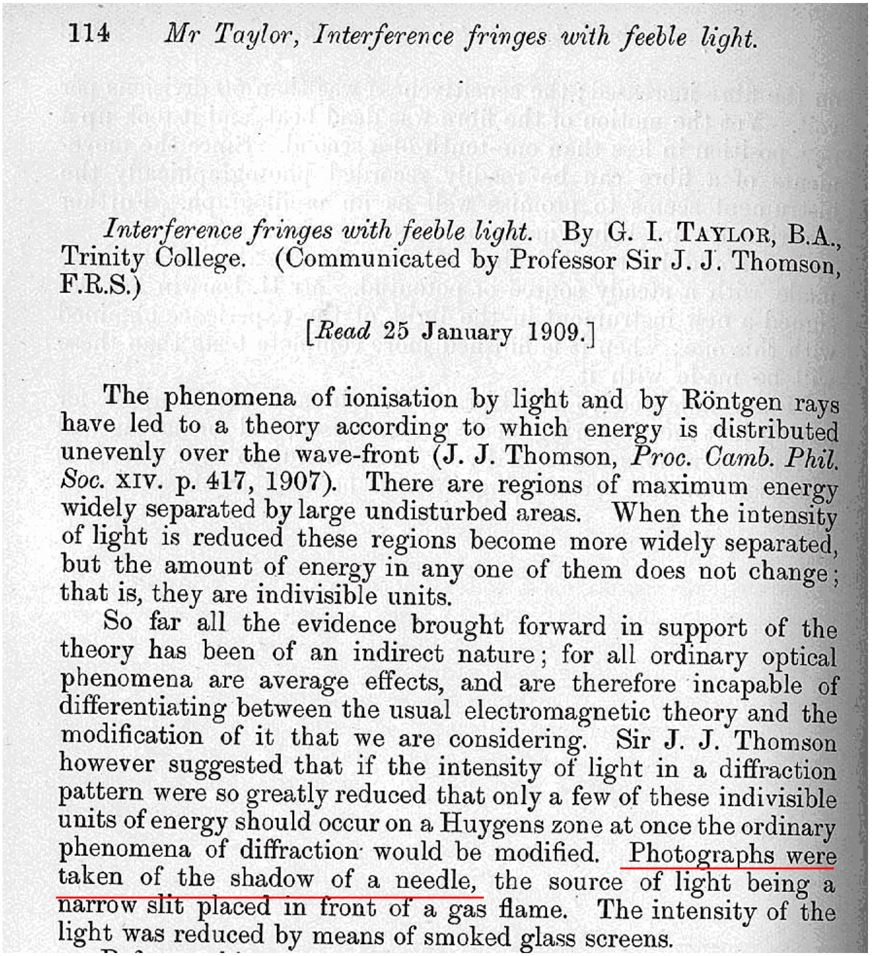


$\vec{E} = \vec{E}_1 + \vec{E}_2$ Classical superposition

$= -E_1 + E_2$ out of phase

$= 0$ Destructive

Interference with feeble light



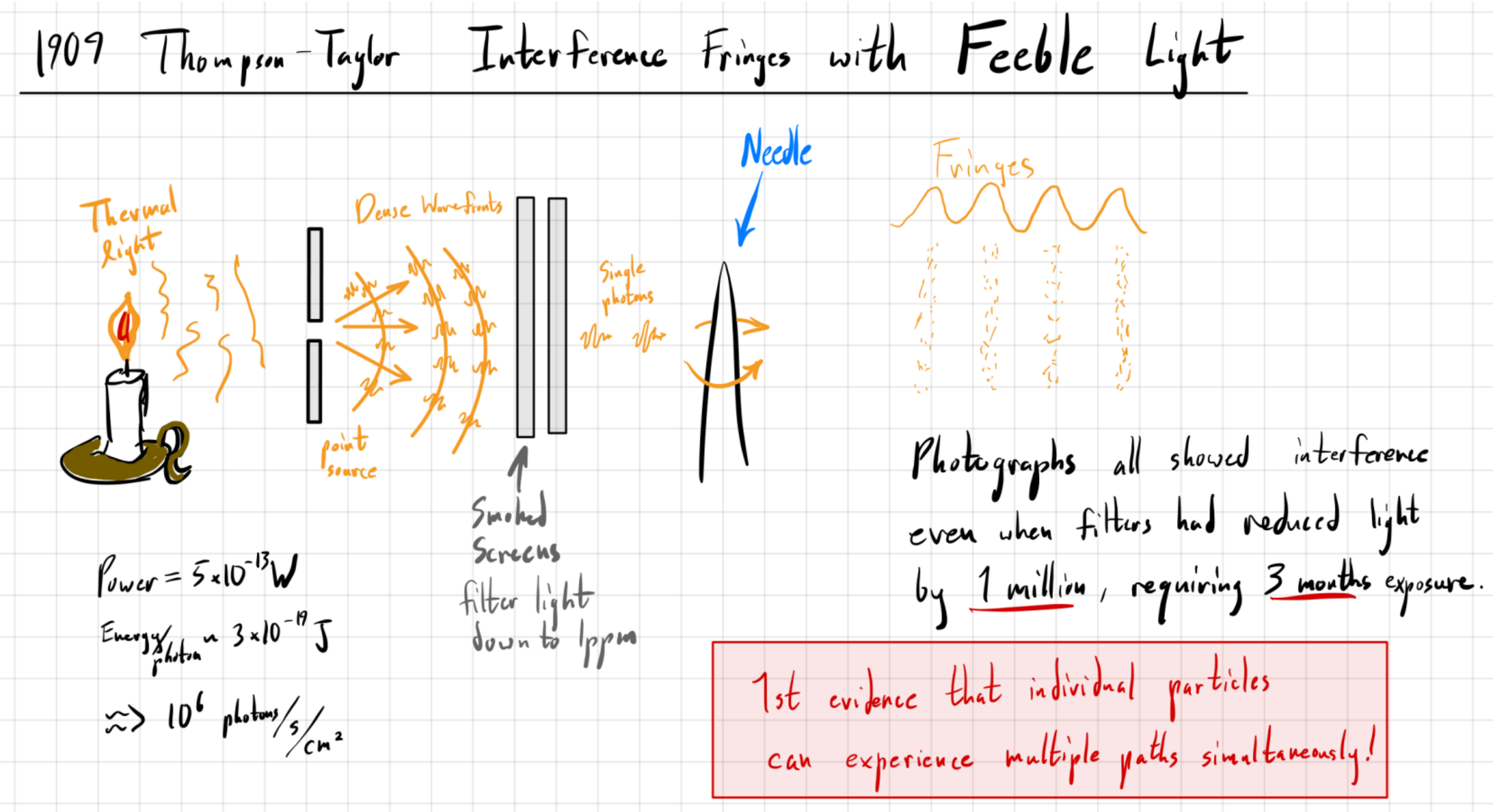
114 *Mr Taylor, Interference fringes with feeble light.*

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.



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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.

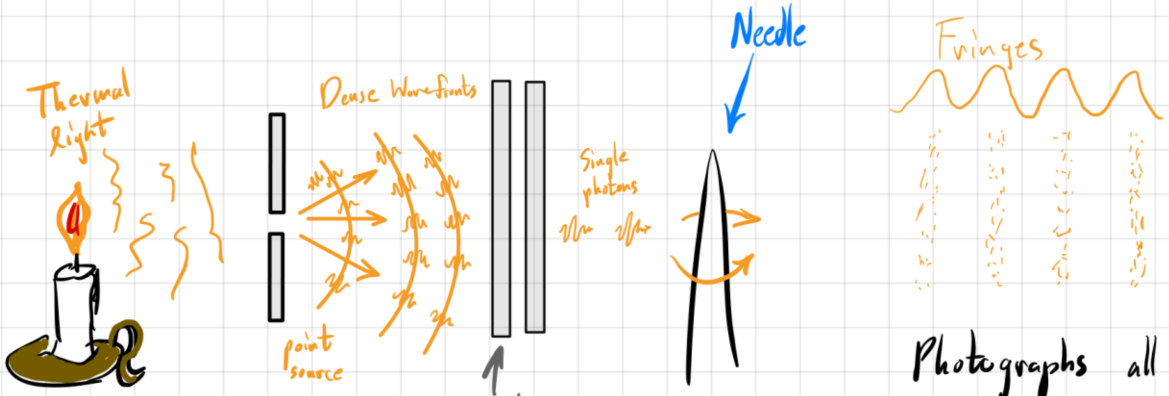
Five diffraction photographs were then taken, the first with direct light and the others with the various screens inserted between the gas flame and the slit. The time of exposure for the first photograph was obtained by trial, a certain standard of blackness being attained by the plate when fully developed.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



Smoked Screens filter light down to 1ppm

Power = 5×10^{-13} W

Energy/photon ~ 3×10^{-19} J

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

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

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

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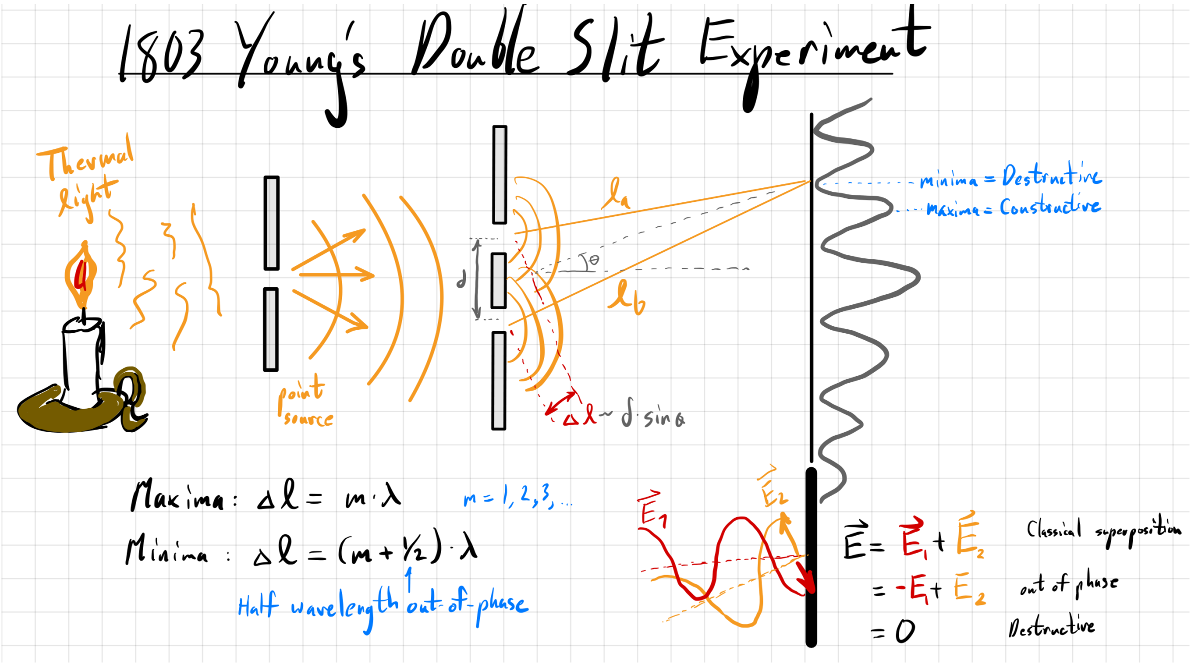
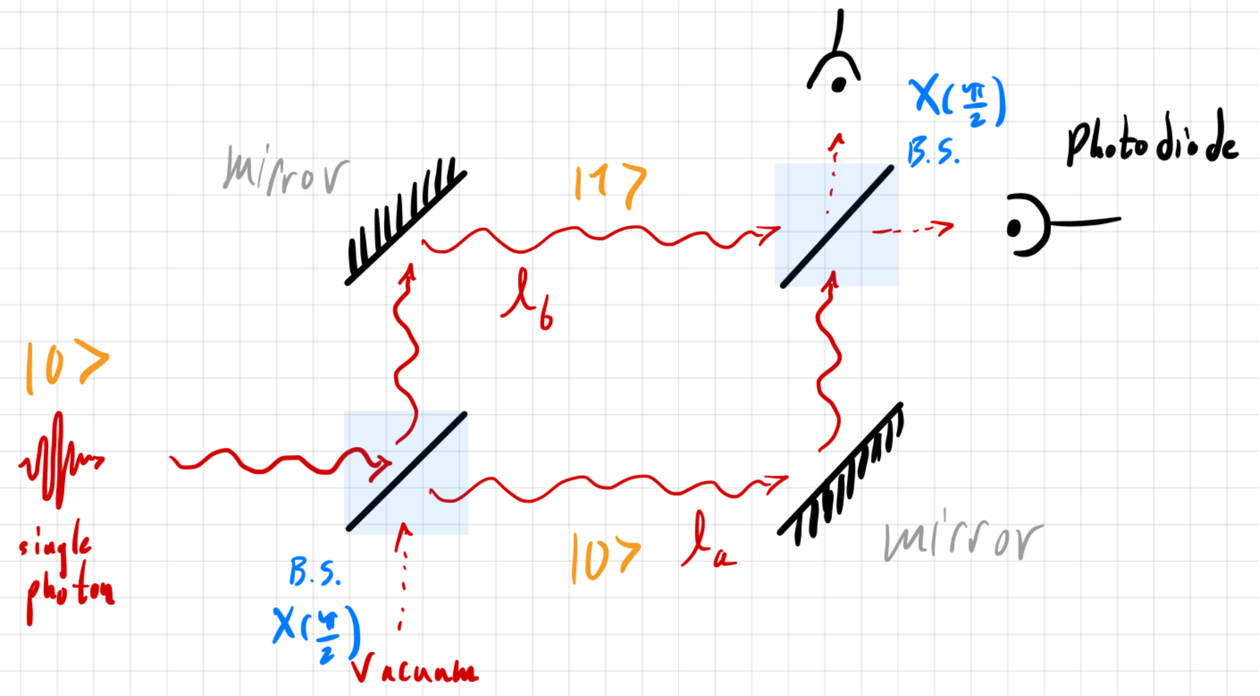
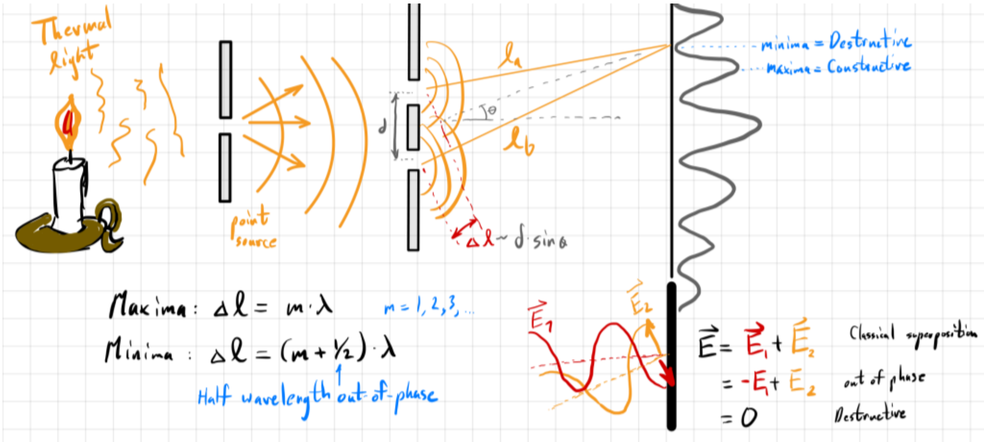
Mach Zehnder Interferometer



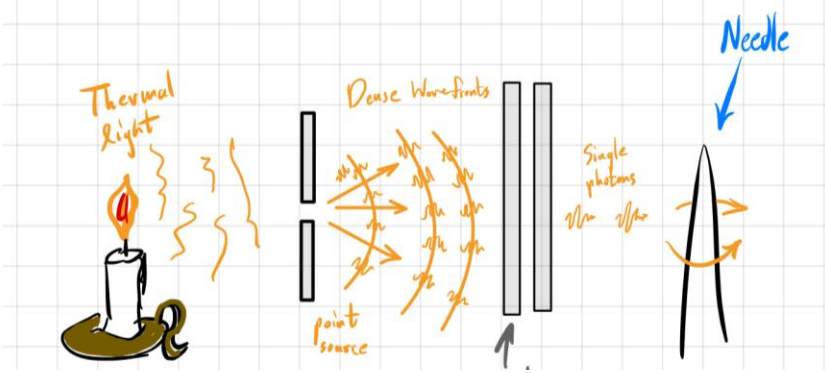


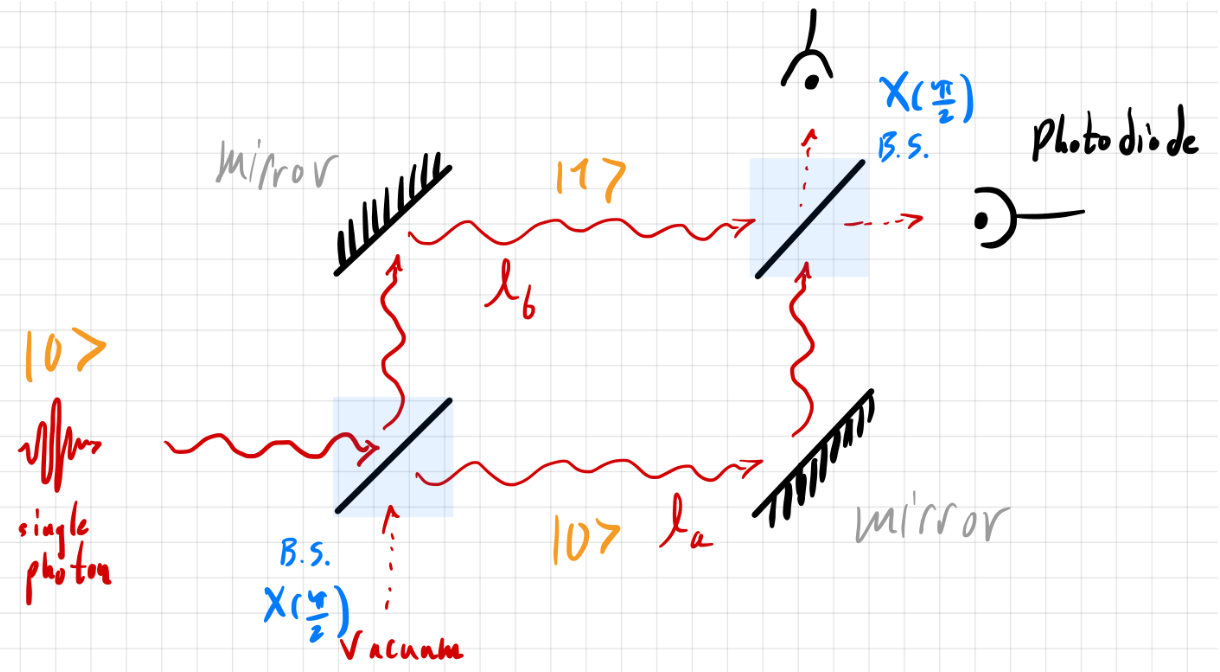
Mach Zehnder Interferometer

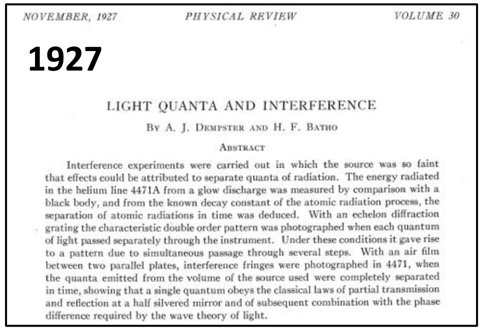
1803 Classical Interference



1909 Quantum* Interference (single photons)







NOVEMBER, 1927 PHYSICAL REVIEW VOLUME 30

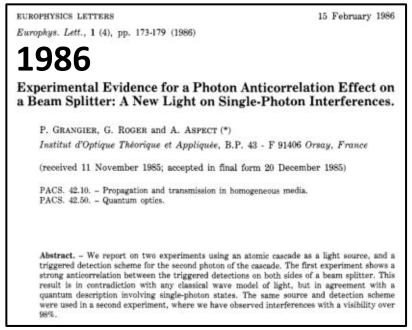
1927

LIGHT QUANTA AND INTERFERENCE

By A. J. Dempster and H. F. Batho

Abstract

Interference experiments were carried out in which the source was so faint that effects could be attributed to separate quanta of radiation. The energy radiated in the helium line 4471A from a glow discharge was measured by comparison with a black body, and from the known decay constant of the atomic radiation process, the separation of atomic radiations in time was deduced. With an echelon diffraction grating the characteristic double order pattern was photographed when each quantum of light passed separately through the instrument. Under these conditions it gave rise to a pattern due to simultaneous passage through several steps. With an air film between two parallel plates, interference fringes were photographed in 4471, when the quanta emitted from the volume of the source used were completely separated in time, showing that a single quantum obeys the classical laws of partial transmission and reflection at a half silvered mirror and of subsequent combination with the phase difference required by the wave theory of light.



EUROPHYSICS LETTERS 15 February 1986
Europhys. Lett., 1 (4), pp. 173-179 (1986)

1986

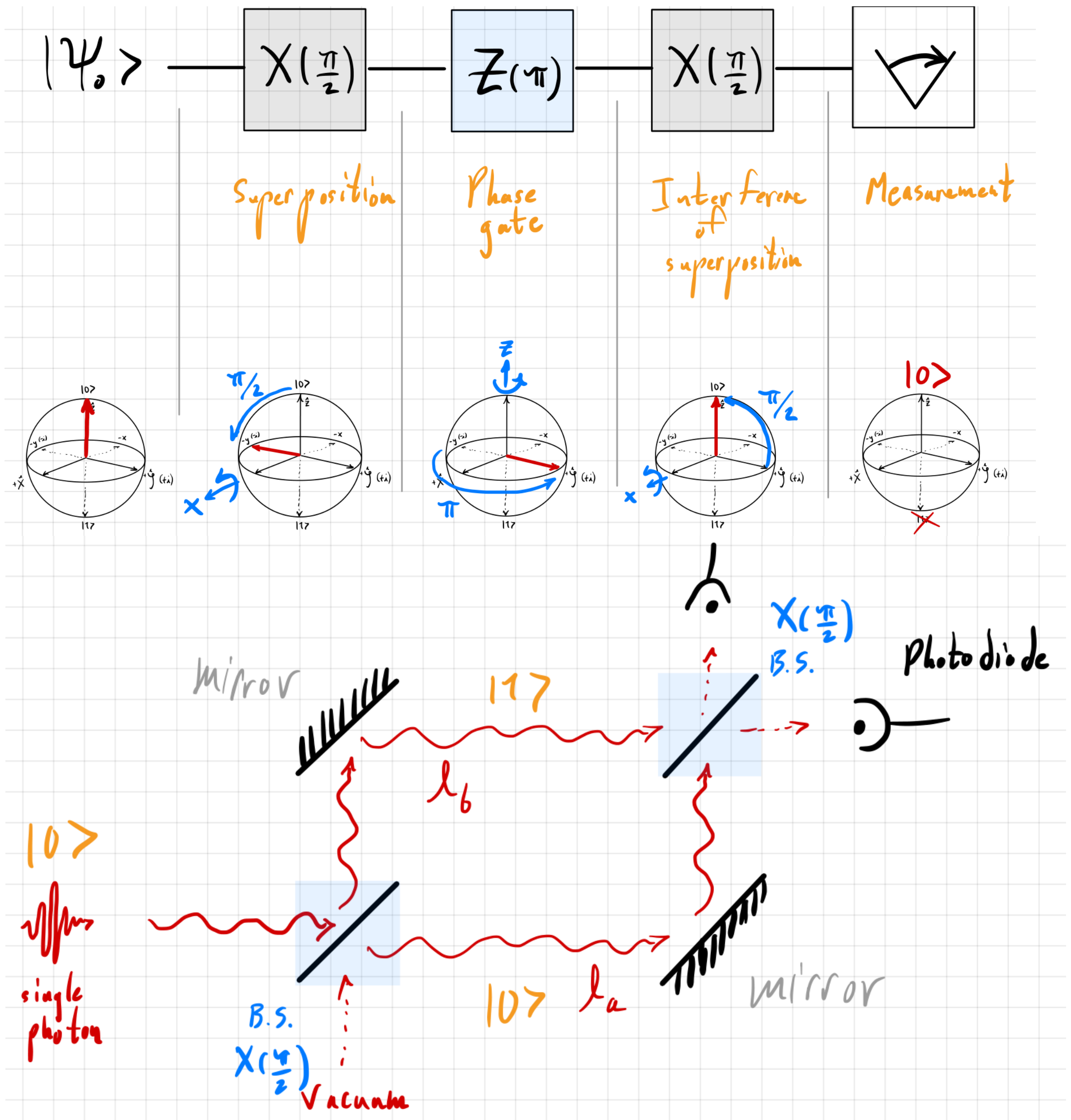
Experimental Evidence for a Photon Anticorrelation Effect on a Beam Splitter: A New Light on Single-Photon Interferences.

P. Grangier, G. Roger and A. Aspect (*)
Institut d'Optique Théorique et Appliquée, B.P. 43 - F 91406 *Orsay, France*

(received 11 November 1985; accepted in final form 20 December 1985)

PACS. 42.10. – Propagation and transmission in homogeneous media.
PACS. 42.50. – Quantum optics.

Abstract. – We report on two experiments using an atomic cascade as a light source, and a triggered detection scheme for the second photon of the cascade. The first experiment shows a strong anticorrelation between the triggered detections on both sides of a beam splitter. This result is in contradiction with any classical wave model of light, but in agreement with a quantum description involving single-photon states. The same source and detection scheme were used in a second experiment, where we have observed interferences with a visibility over 98%.



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