Quantum computing
- climbing Mount Entanglement

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UWM retirement association 2022.01.04

Classical and quantum mechanics

Macroscopic everyday phenomena are well described by classical physics.

Newton’s laws
Maxwell Equations

At the microscopic level classical physics no longer works well.

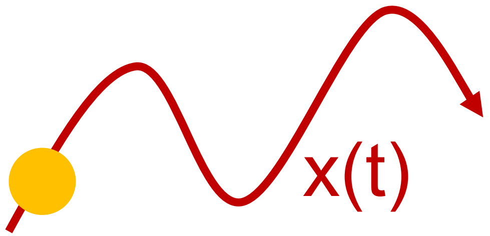
Quantum mechanics takes over.

What is the difference between classical and quantum mechanics?

Quantum mechanics gives up on certainty and describes the world with amplitudes and probabilities.

Quantum uncertainty

Classical particles follow a path.



If we know $x(t_{init})$, and $p(t_{init})=m\ v(t_{init})$

we can use Newton's laws of motion to calculate

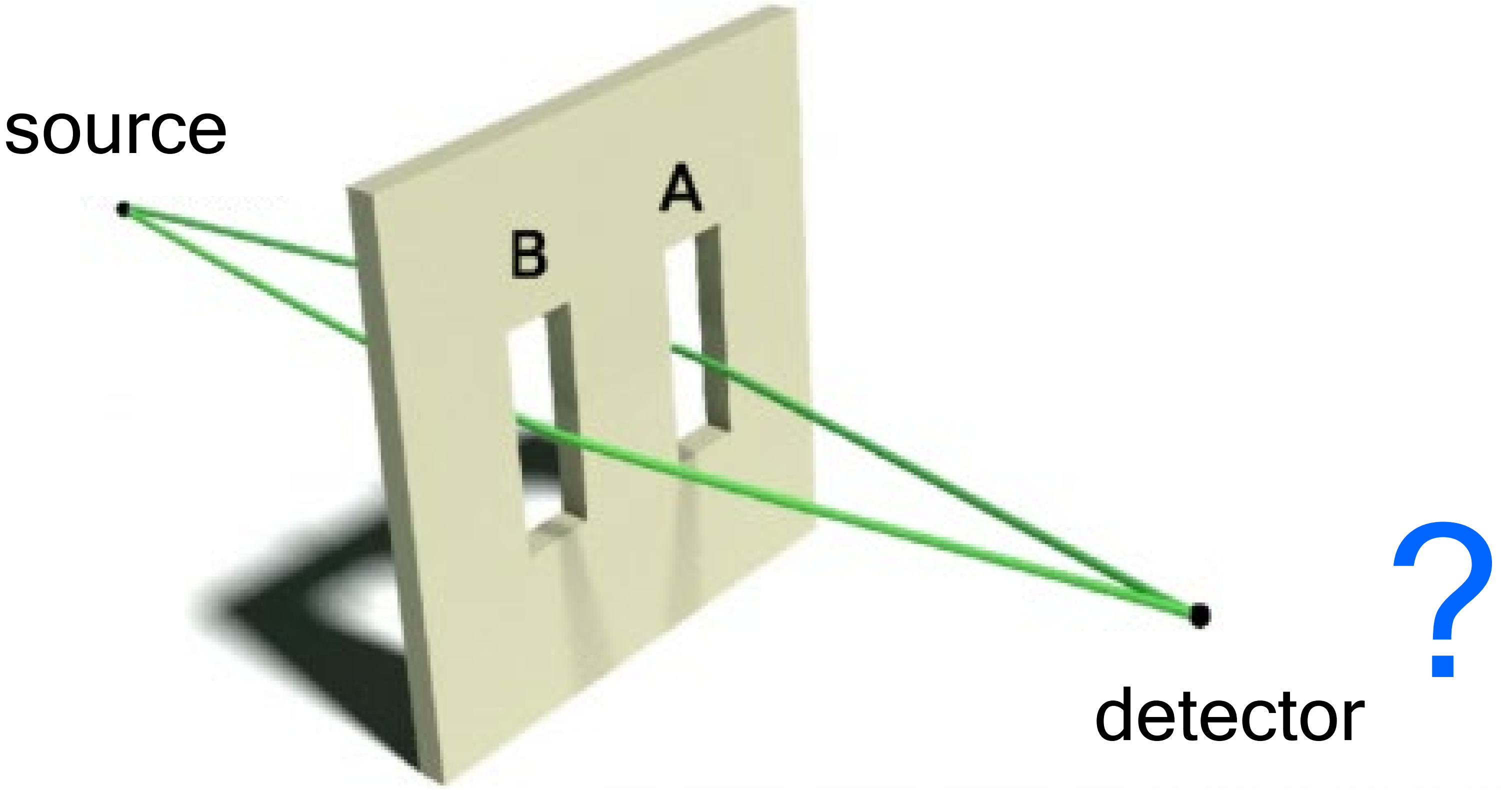
$x(t)$ and $p(t) = m\ v(t)$ for all $t > t_{init}$.

The motion is deterministic.

In quantum mechanics it is in principle NOT possible to know $x(t)$ AND $p(t)$ simultaneously.

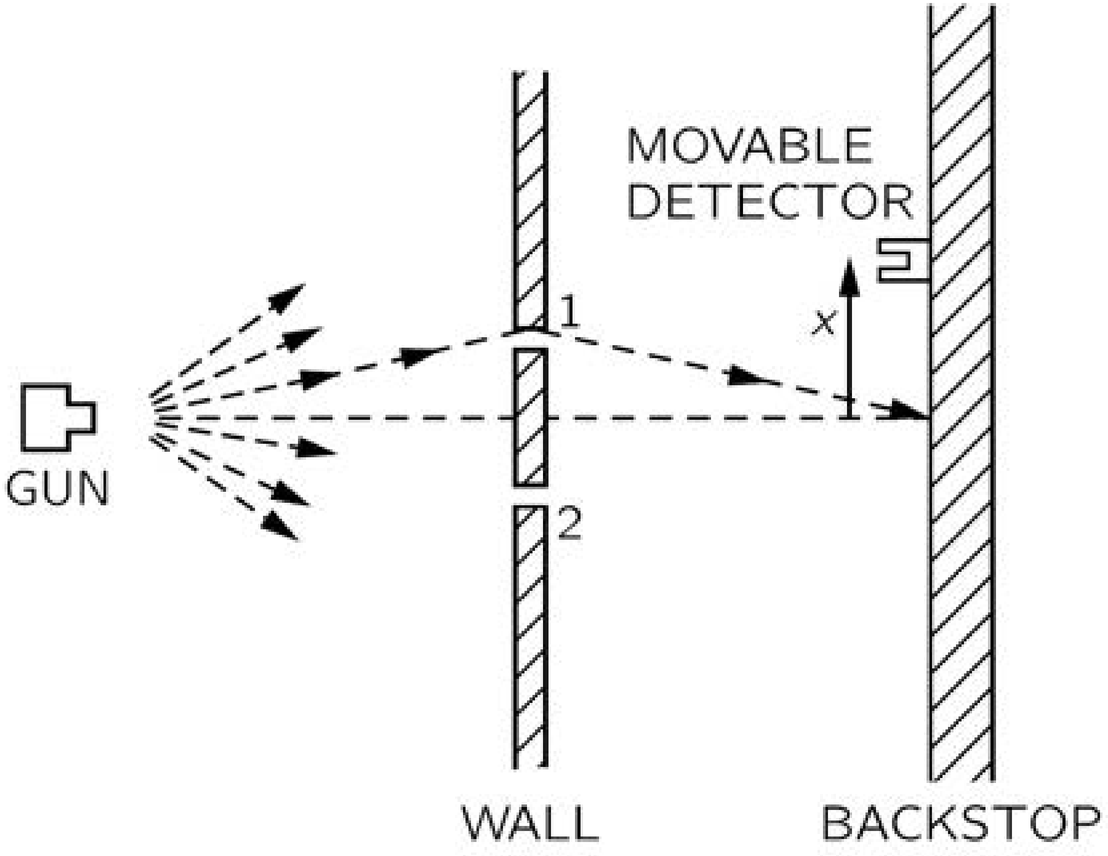
Heisenberg uncertainty principle $\boxed{\Delta x \Delta p > \hbar / 2}$

Two slit experiment



Two slit experiment

With classical particles:



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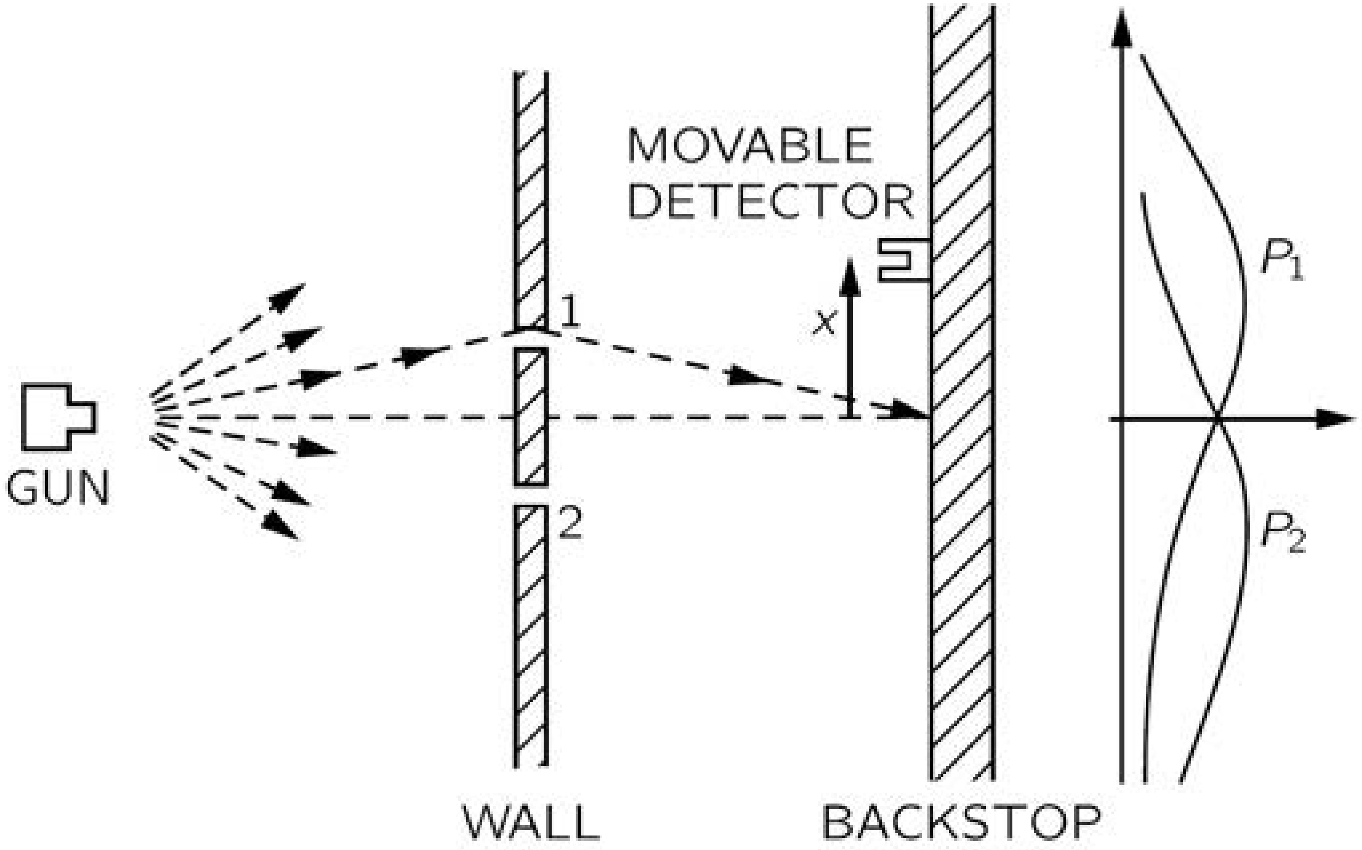
Feynman Lectures on Physics 1963

Two slit experiment

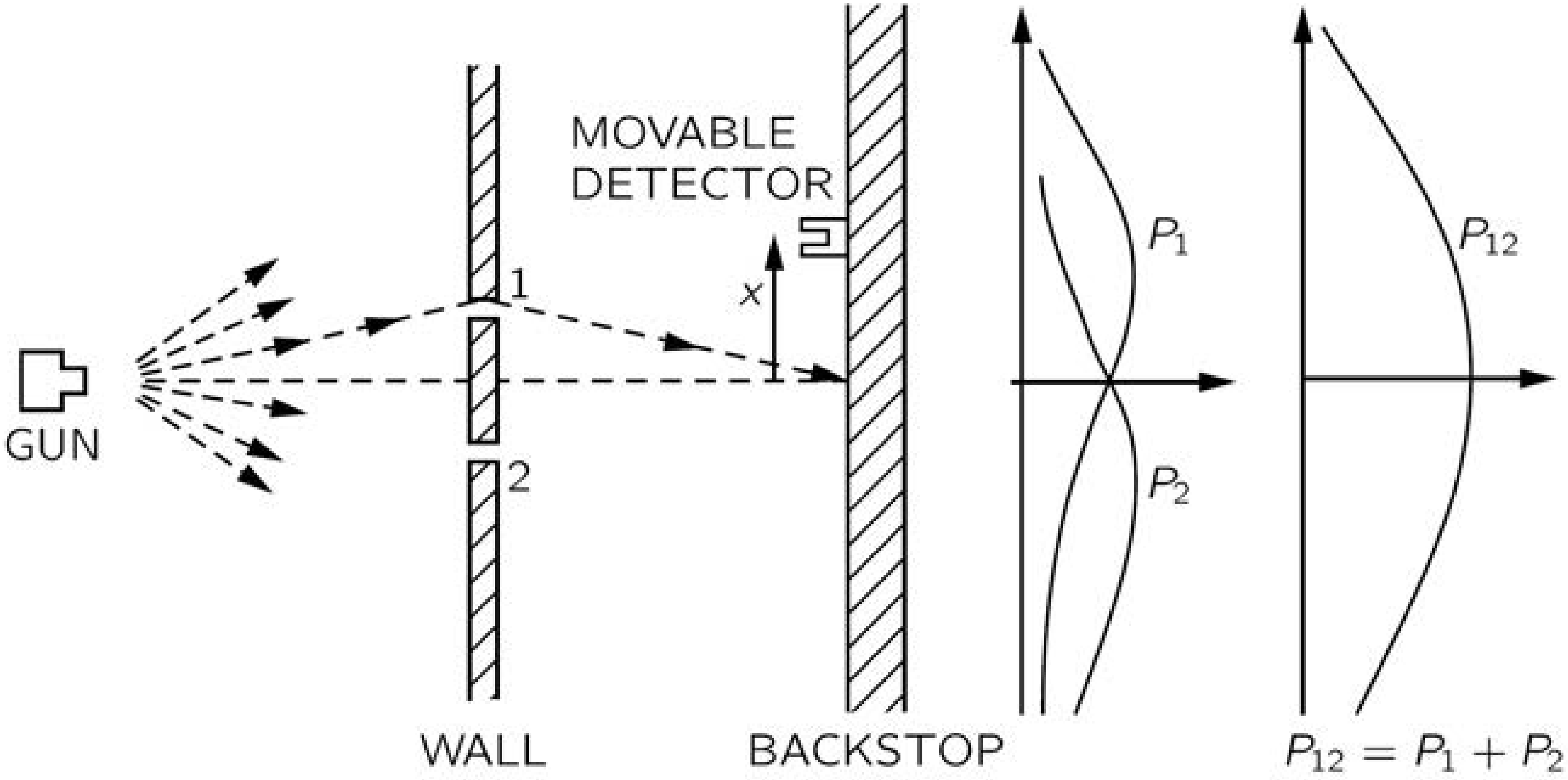
With classical particles:



Feynman Lectures on Physics 1963

Two slit experiment

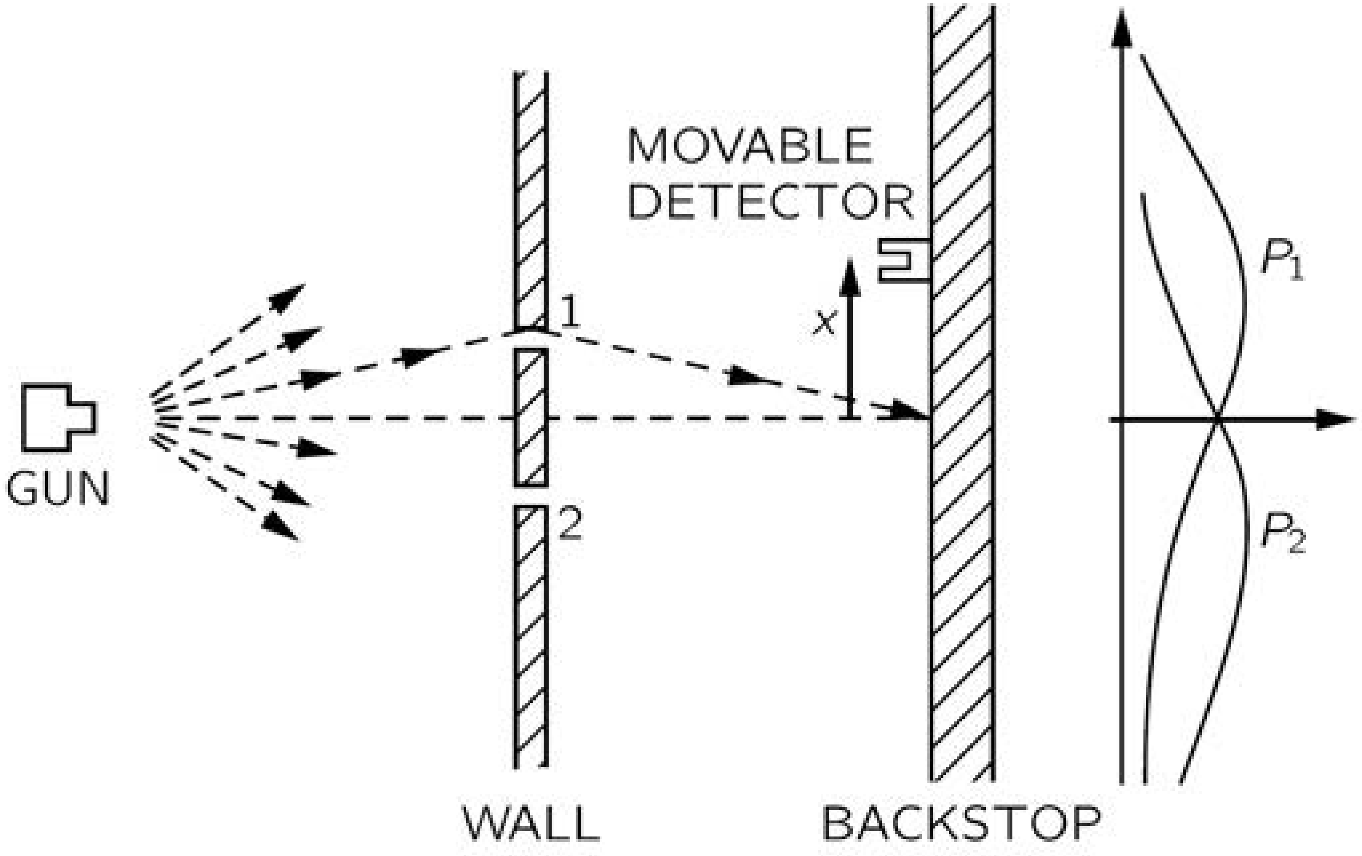
With classical particles:



Feynman Lectures on Physics 1963

Two slit experiment

With quantum particles:



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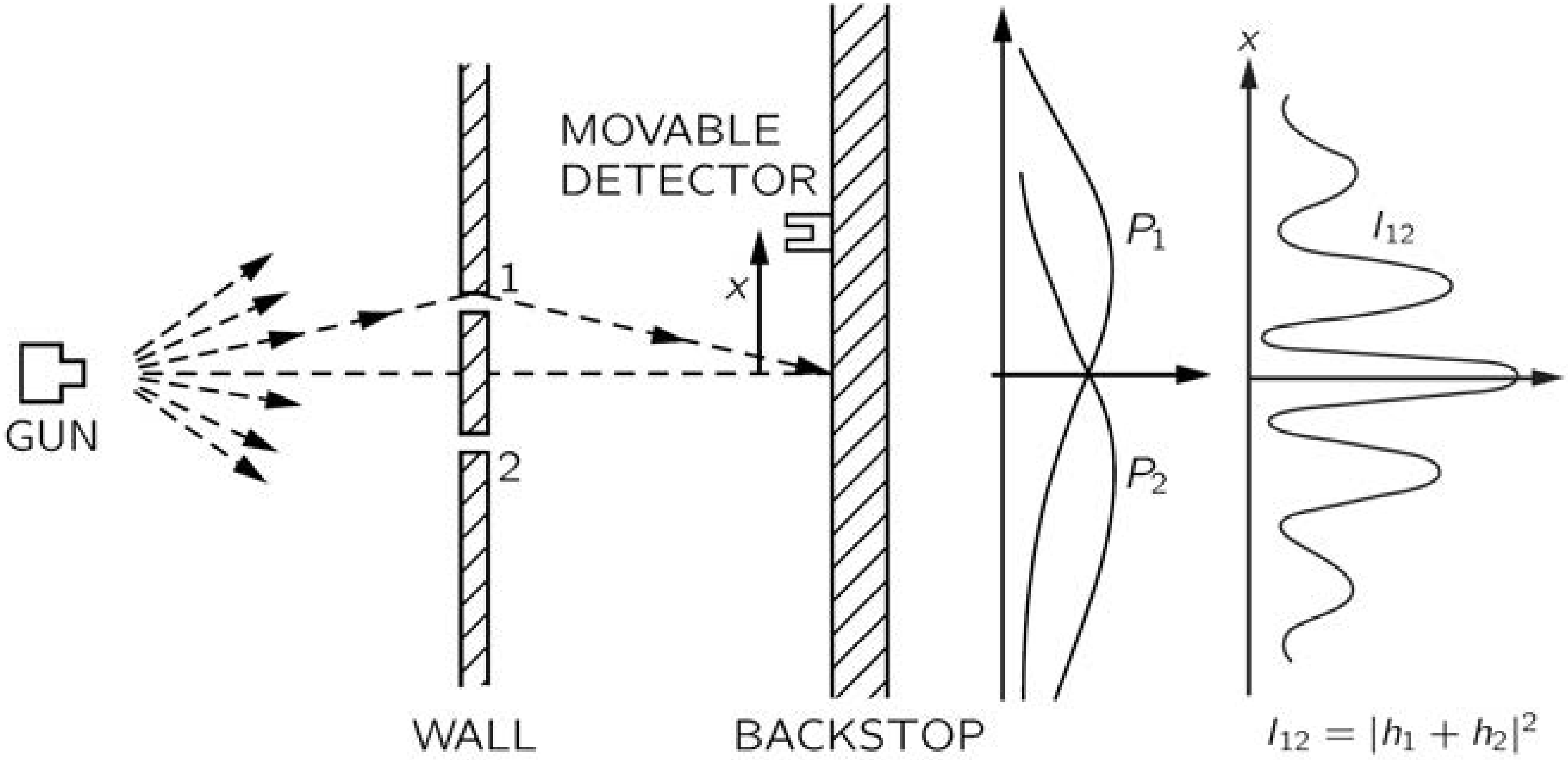
Feynman Lectures on Physics 1963

Two slit experiment

With quantum particles:

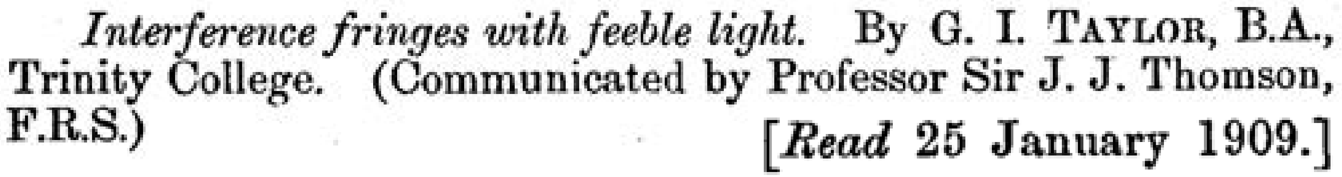


Feynman Lectures on Physics 1963

Two slit experiment

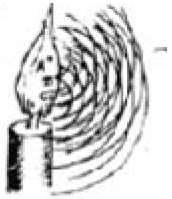
The experiment has been done.

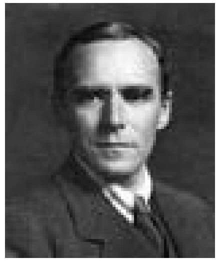
Proceedings of the Cambridge Philosophical Society

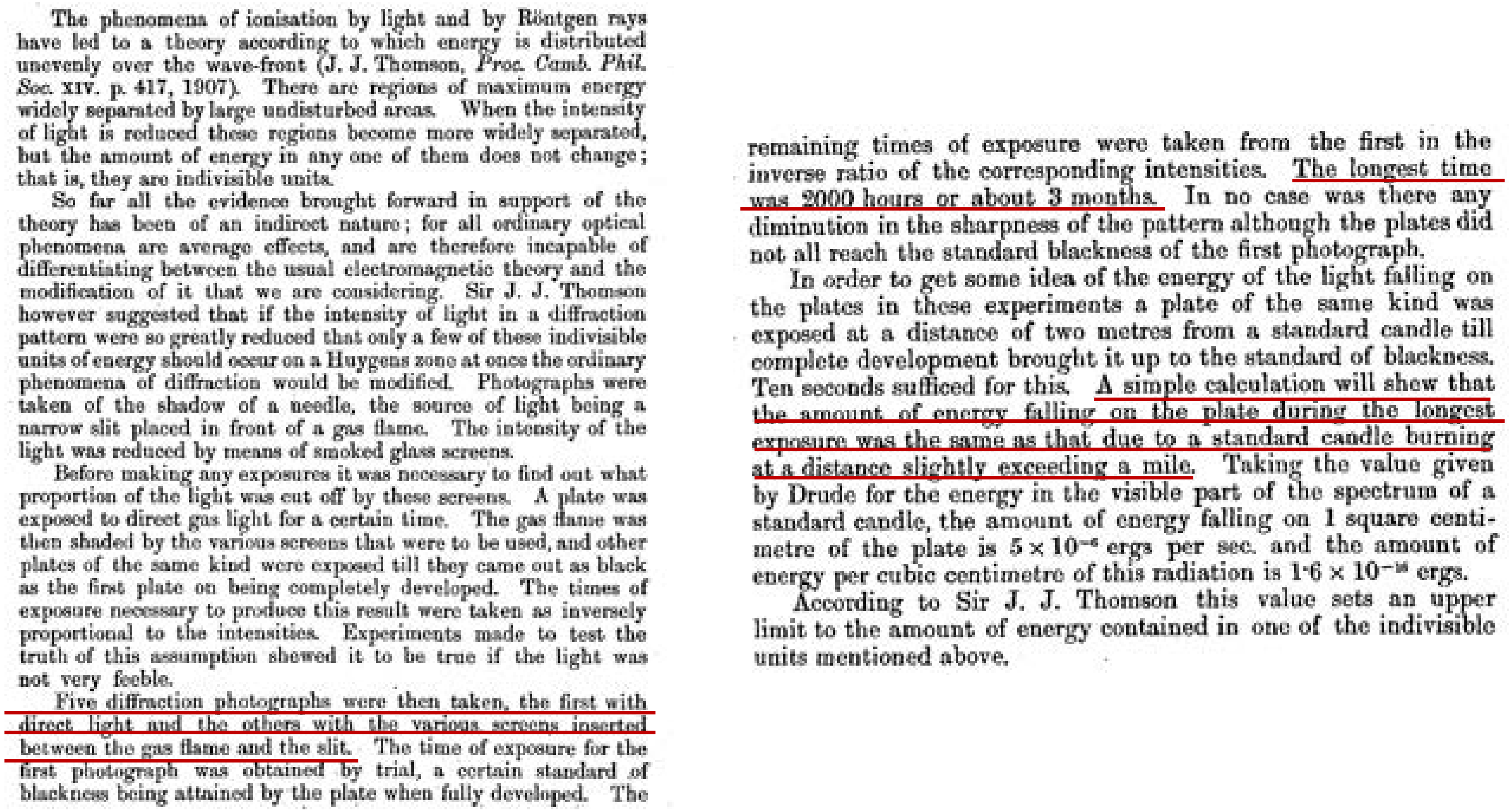


Interference fringes with feeble light. By G. I. Taylor, B.A., Trinity College. (Communicated by Professor Sir J. J. Thomson, F.R.S.)

[*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.

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.

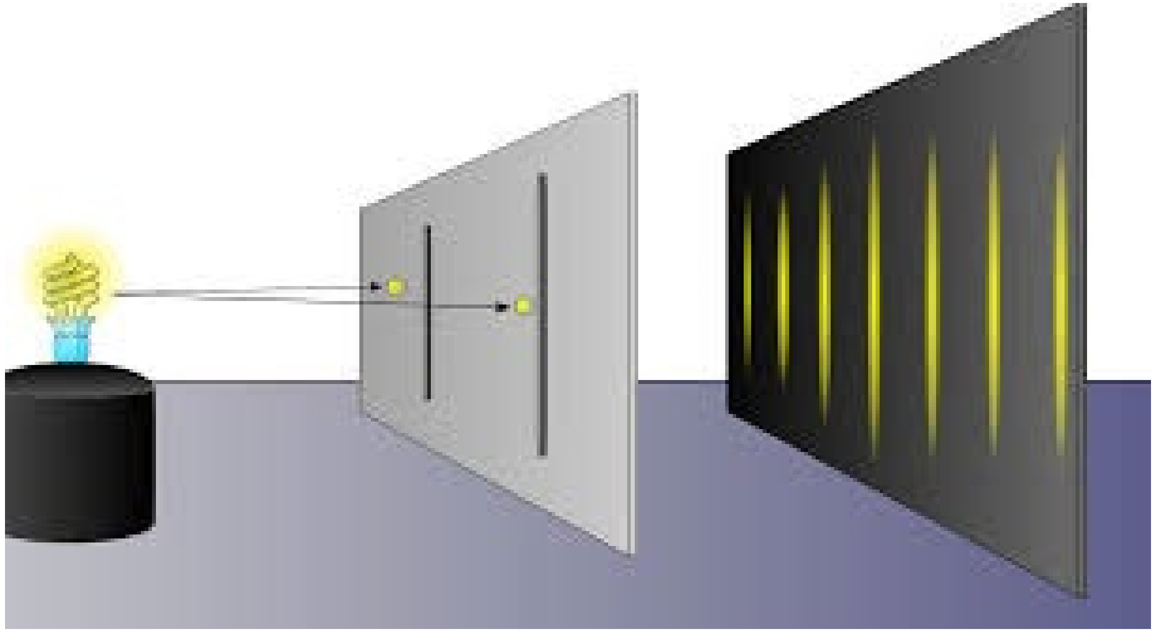
Five diffraction photographs were then taken, the first with direct light and the others with the various screens inserted between the gas flame and the slit. The time of exposure for the first photograph was obtained by trial, a certain standard of blackness being attained by the plate when fully developed.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

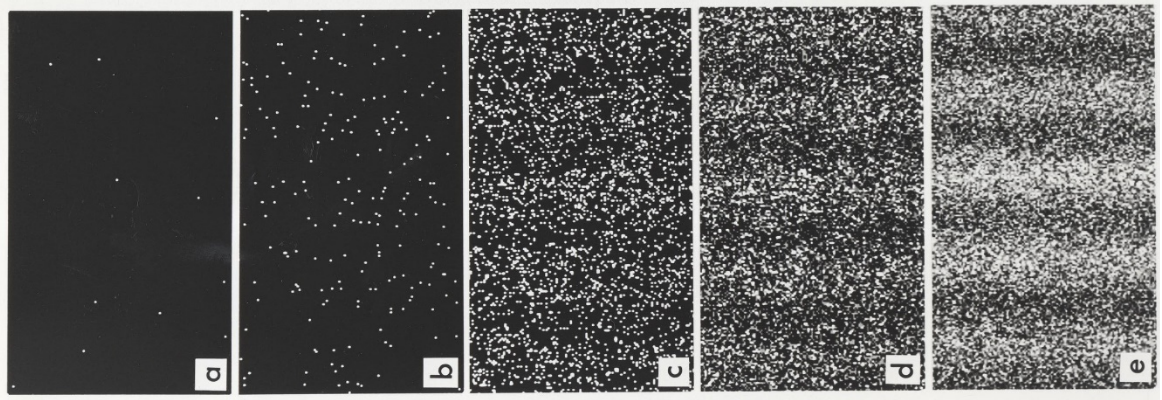
According to Sir J. J. Thomson this value sets an upper limit to the amount of energy contained in one of the indivisible units mentioned above.

Two slit interference with light

interference with light waves



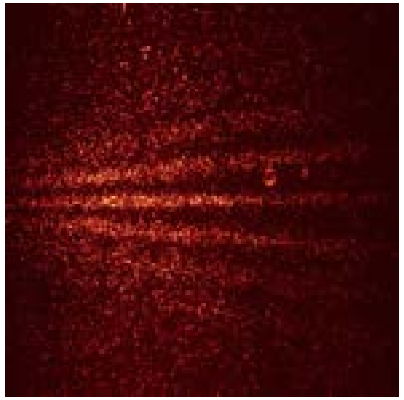
interference is seen even when only one photon at a time passes the slits

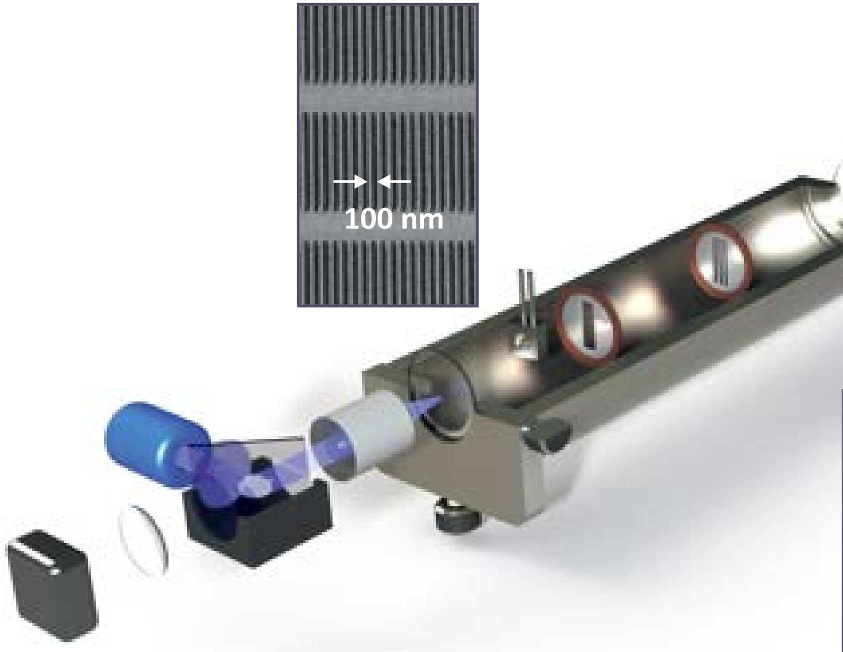


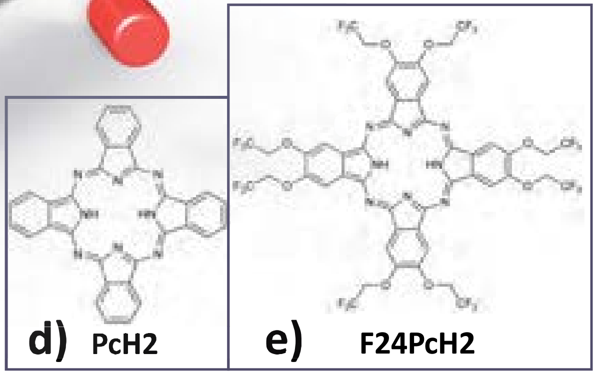
G.I. Taylor 1909

Quantum Spatial Superposition with Molecules

Interference fringes are observed.
Apparently each molecule propagates through both slits. Quantum superposition of matter!





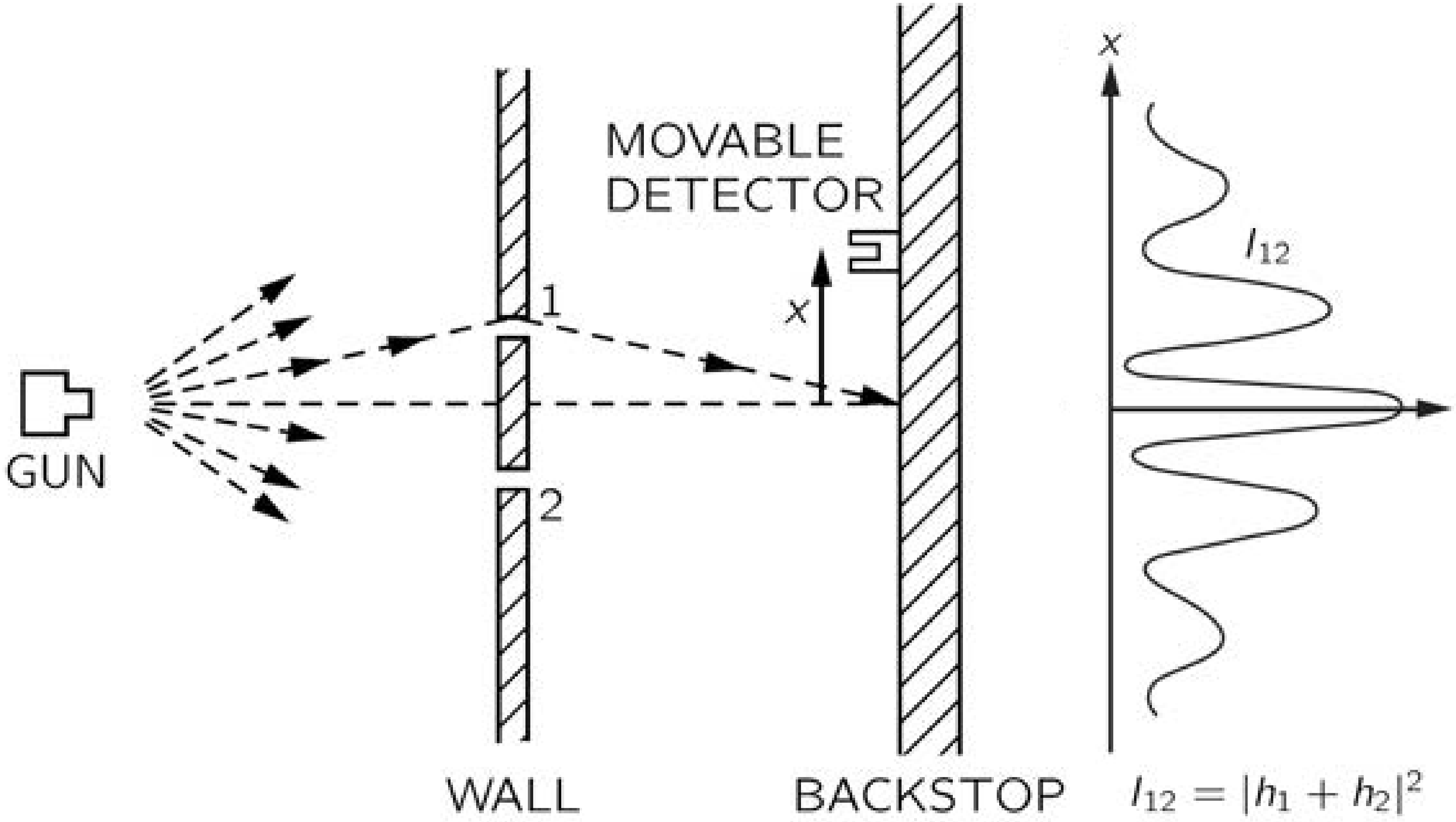

d) PcH2
e) F24PcH2

Phthalocyanine derivatives

Nature Nanotech. 7, 297 (2012)

Two slit experiment

Experiment confirms interference.
How does the particle go through both slits?



$I_{12} = |h_1 + h_2|^2$

Feynman Lectures on Physics 1963

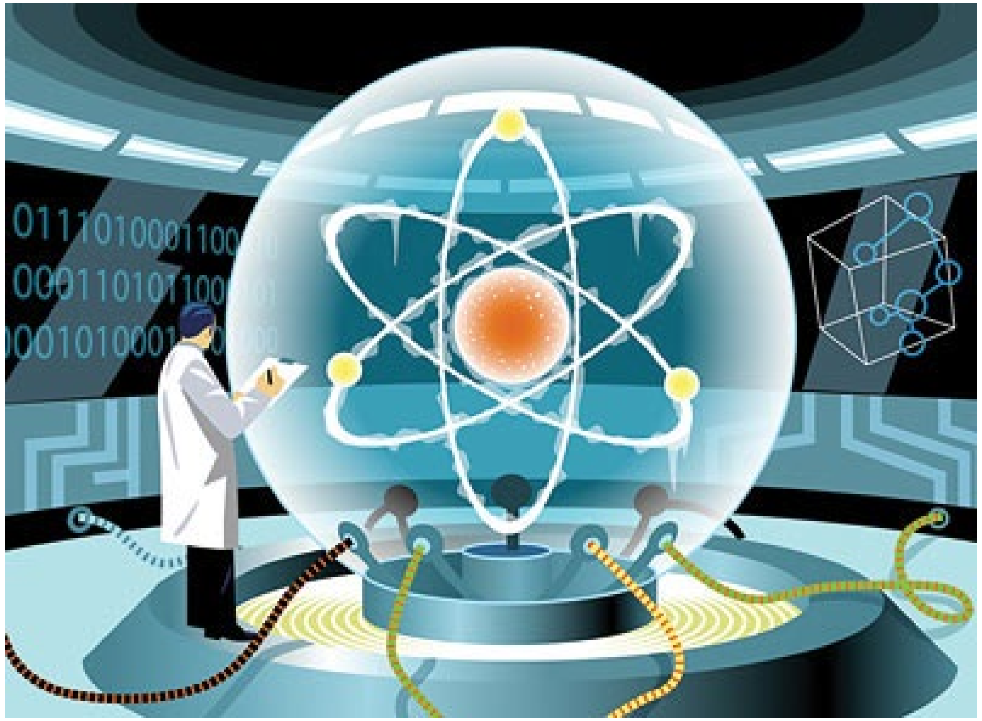
Quantum mystery....

Quantum data

Not only can particles be in two places at once
they can be used to represent two data values at once.

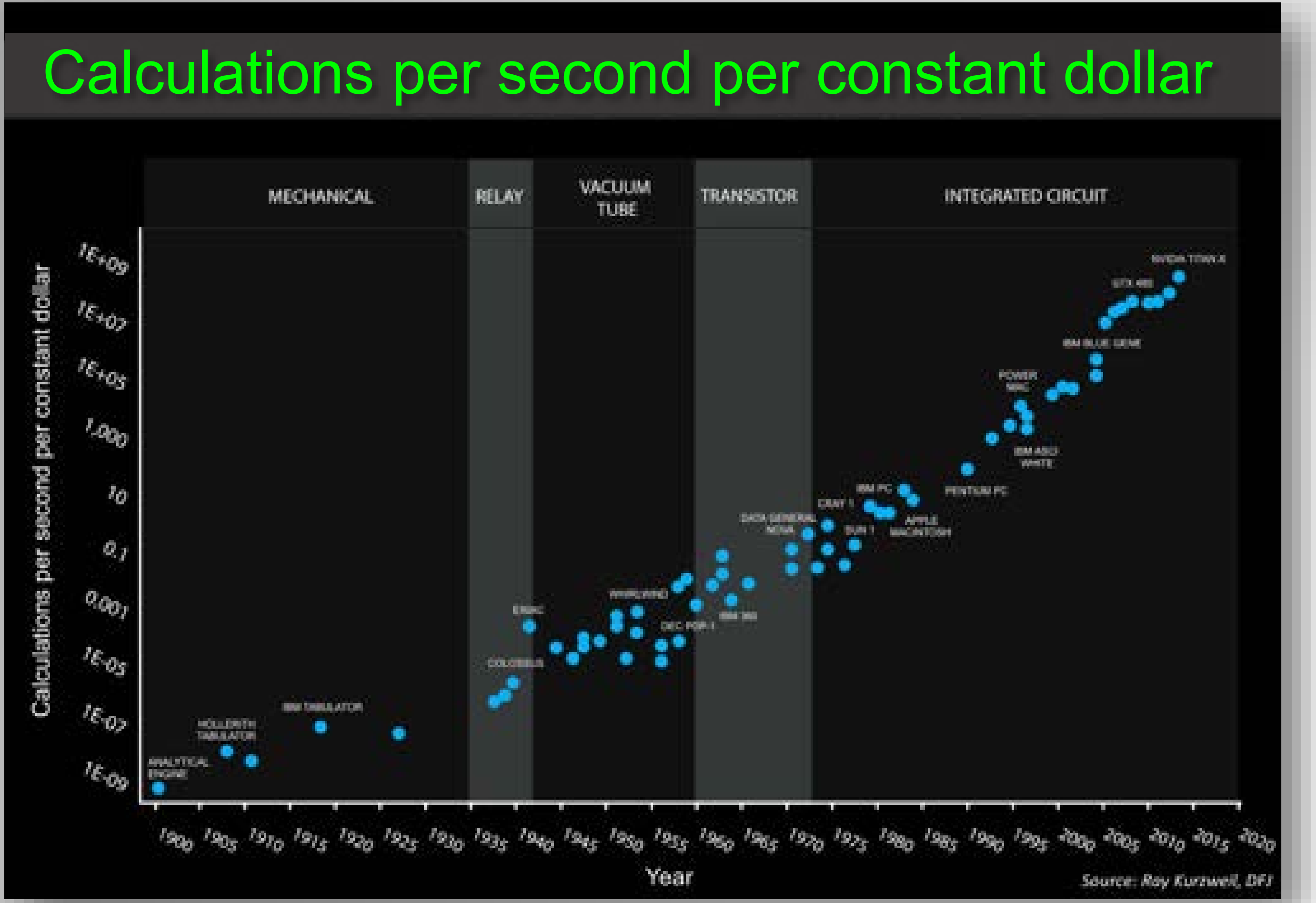
Qubits

Quantum computers



Moore’s Law

- 5+ decades of exponential growth in computing power are drawing to a close.
- Quantum computers hold the promise of a new exponential advance over classical machines.
- Large government investments:
  - UK Quantum technology hubs **£**350M
  - European Union Quantum Flagship €1B
  - China National Lab for Quantum Information $10B
  - US National Quantum Initiative $1.25B
- Fortune 500 investments:
  Google, Microsoft, IBM, Intel, Honeywell, Lockheed Martin, Raytheon, ….
- Startups:
  DWave, Rigetti, Quantum Circuits, IonQ, Silicon Quantum Computing, ColdQuanta,…



Source: Ray Kurzweil, DFJ

Quantum computing timeline

Theory

1982

s. cond. macro coherence

Deutsch problem

1990

Shor factoring

1994

Cirac/Zoller trapped ion gate

Shor error correction

1995

q.dot qubits

Neutral Atom gate

2000

dissipative entanglement

Surface Code architecture

2010

Universal protected codes

2015

Early 1980s: Richard Feynman and others propose quantum computers for tackling physics problems

1994: Peter Shor discovers a fast method to factor numbers on a quantum computer

Quantum: a new era in computing

EU invests 1 billion Euros to make quantum computing practical

The project will help everything from networking to gravity sensors.

Jon Fingas , @jonfingas
04.25.16 in Personal Computing

Comments

Shares

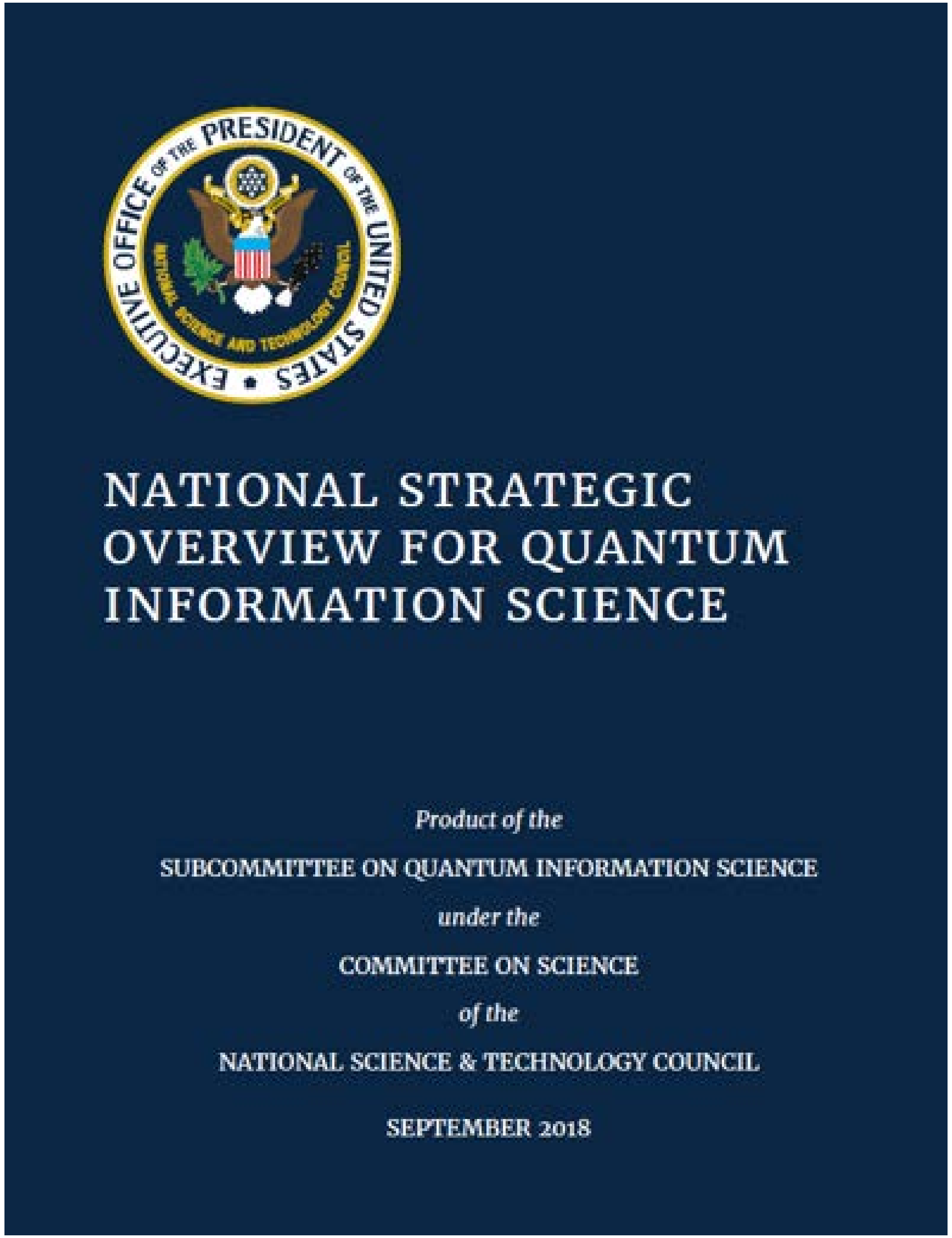
Alfred Pasieka/Science Photo Library via Getty Images

Major investments on Quantum Computing research programmes from 2010 to 2016.

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

US National Strategy - NQI

A $1.3B, five year investment in Quantum Information Science.



EXECUTIVE OFFICE OF THE PRESIDENT OF THE UNITED STATES

NATIONAL STRATEGIC
OVERVIEW FOR QUANTUM
INFORMATION SCIENCE

Product of the
SUBCOMMITTEE ON QUANTUM INFORMATION SCIENCE
under the
COMMITTEE ON SCIENCE
of the
NATIONAL SCIENCE & TECHNOLOGY COUNCIL

SEPTEMBER 2018

Quantum: a new era in computing

intel

IBM Q™

Microsoft
Quantum Computer

rigetti

qci
Quantum Circuits, Inc

ColdQuanta

What makes a quantum computer tick?

Quantum bits

Classical bits

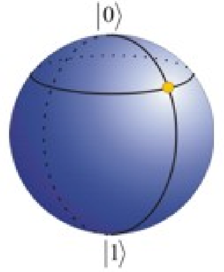
0

1

N classical bits can store a single data value out of 2^N possibilities.

Qubits

data= $a|0>+b|1>$



N qubits can store 2^N different values simultaneously. 2^{100} is more than the number of particles in the universe.

Quantum superposition !

Superposition and entanglement

Two qubits: $|\psi\rangle_1 = a_0|0\rangle + a_1|1\rangle, \quad |\psi\rangle_2 = b_0|0\rangle + b_1|1\rangle$

Product State:

$$\begin{aligned}|\psi\rangle &= \left(a_0|0\rangle + a_1|1\rangle\right)\otimes\left(b_0|0\rangle + b_1|1\rangle\right)\\ &= \boxed{a_0b_0|00\rangle + a_0b_1|01\rangle + a_1b_0|10\rangle + a_1b_1|11\rangle}\end{aligned}$$

Classically we can only store one of four states at a time in a 2 bit memory: 00 or 01 or 10 or 11

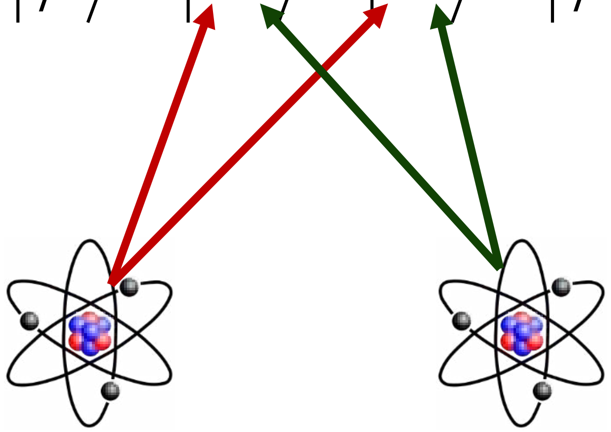
$|\psi\rangle$ encodes four different states at one time.

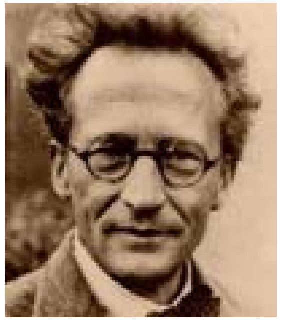
With N qubits we can encode 2^N states at one time.

Superposition and entanglement

It is also possible to create states that are not product states:

$$|\psi\rangle = |00\rangle + |11\rangle \neq |\psi\rangle_1 |\psi\rangle_2$$





Verschränkung
”entanglement”

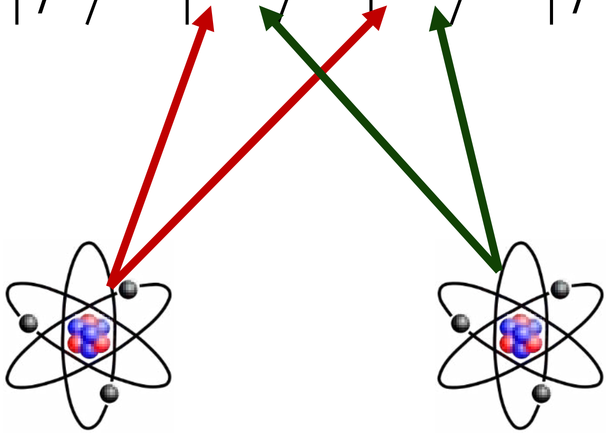
Such a state is entangled, and cannot be described in terms of classical bits – there is no local and realistic description of entangled states, Einstein, Podolsky, Rosen 1935 (EPR paradox).

Quantum computers provide a speedup over classical machines.
It is not clear exactly where the speedup comes from.
The power of quantum computers appears to be intimately related to the presence of entanglement. If there was no entanglement, we could use a classical description of the machine.

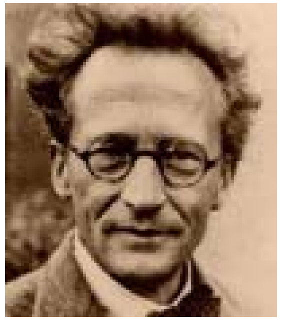
Superposition and entanglement

It is also possible to create states that are not product states:

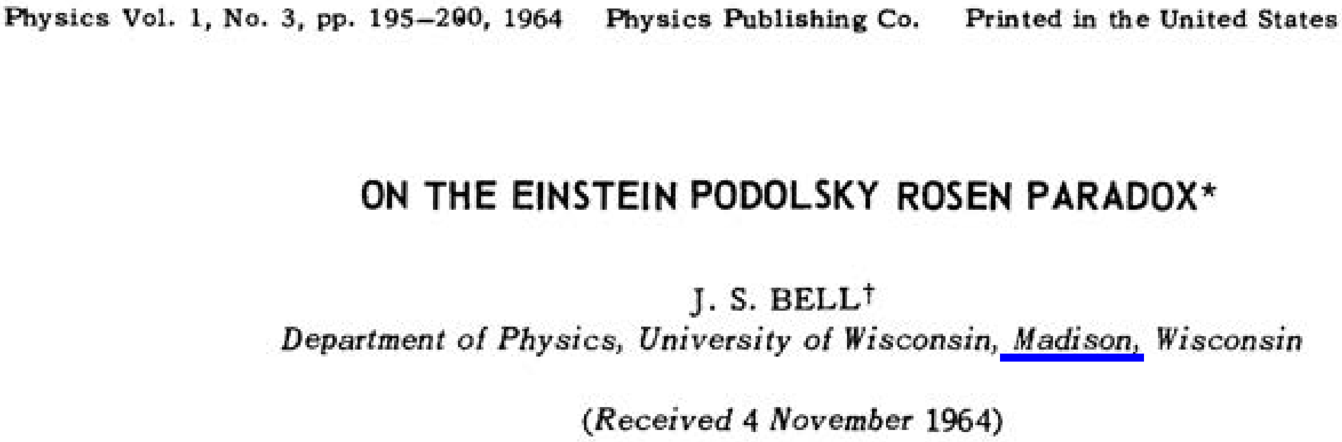
$$|\psi\rangle = |00\rangle + |11\rangle \neq |\psi\rangle_1 |\psi\rangle_2$$



Maximally entangled 2-qubit state "Bell" state.



Verschränkung
"entanglement"



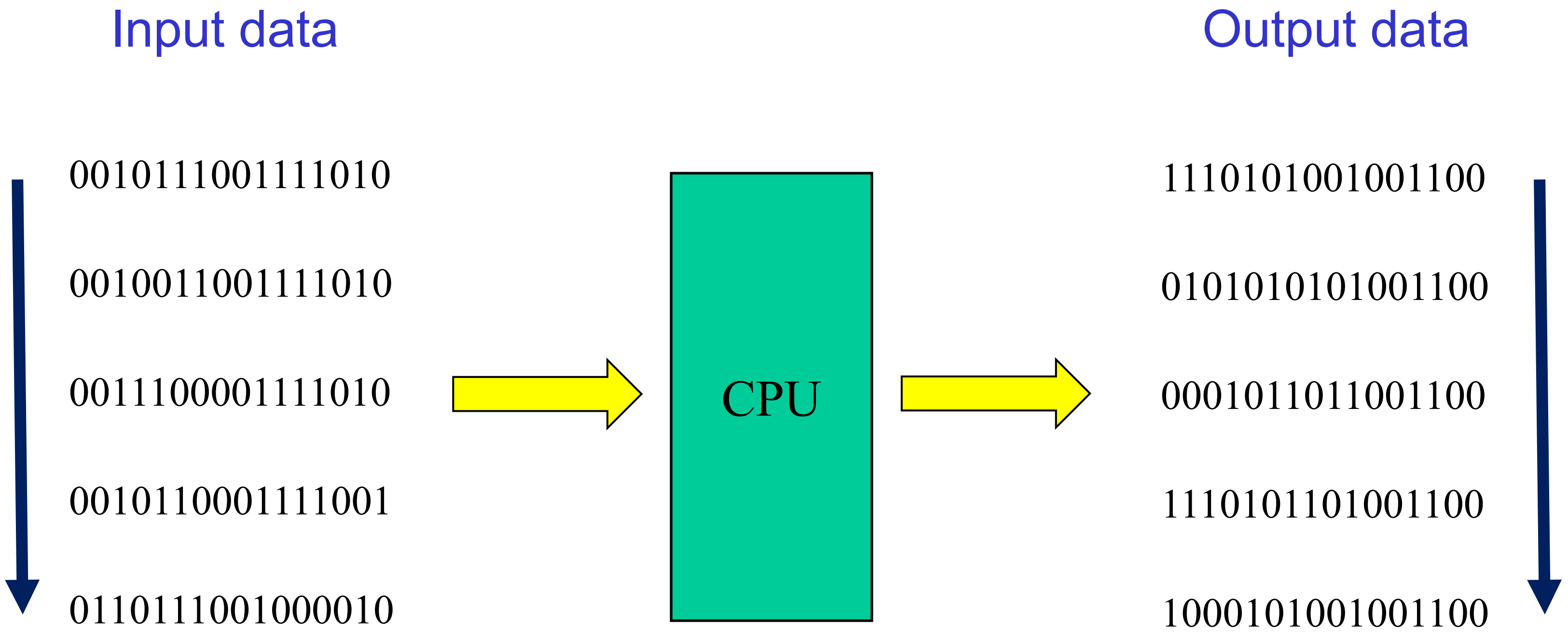
Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†
Department of Physics, University of Wisconsin, Madison, Wisconsin

(*Received* 4 *November* 1964)

Classical data processing



Input data

0010111001111010

0010011001111010

0011100001111010

0010110001111001

0110111001000010

CPU

Output data

1110101001001100

0101010101001100

0001011011001100

1110101101001100

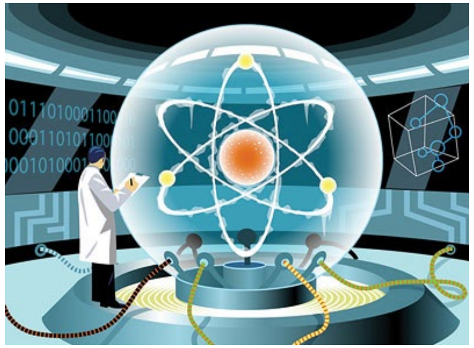
1000101001001100

Sequential data processing

Quantum data processing

Input data

$$|\psi\rangle = a|00...00\rangle + b|00...01\rangle + c|00...10\rangle + d|00...11\rangle + ...|11...11\rangle$$



Quantum CPU

Output data

$$|\psi\rangle \rightarrow |\psi'\rangle = f(|\psi\rangle)$$

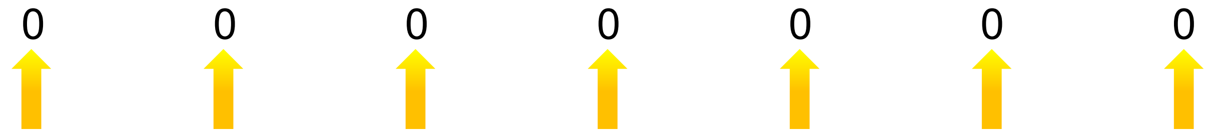
$$|\psi'\rangle = a'|00...00\rangle + b'|00...01\rangle + c'|00...10\rangle + d'|00...11\rangle + ...|11...11\rangle$$

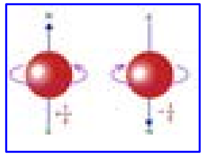
The results for all possible input data are computed in parallel

But the result is only determined probabilistically

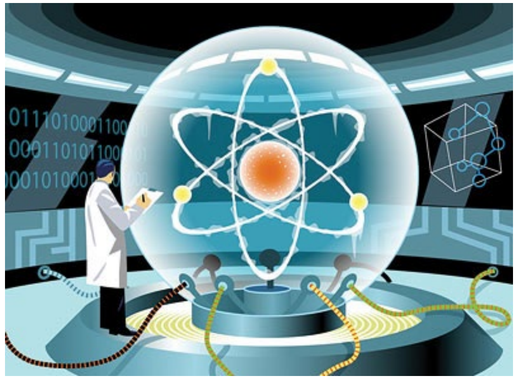
Running the computer

input





computation



Output state
(deterministic)

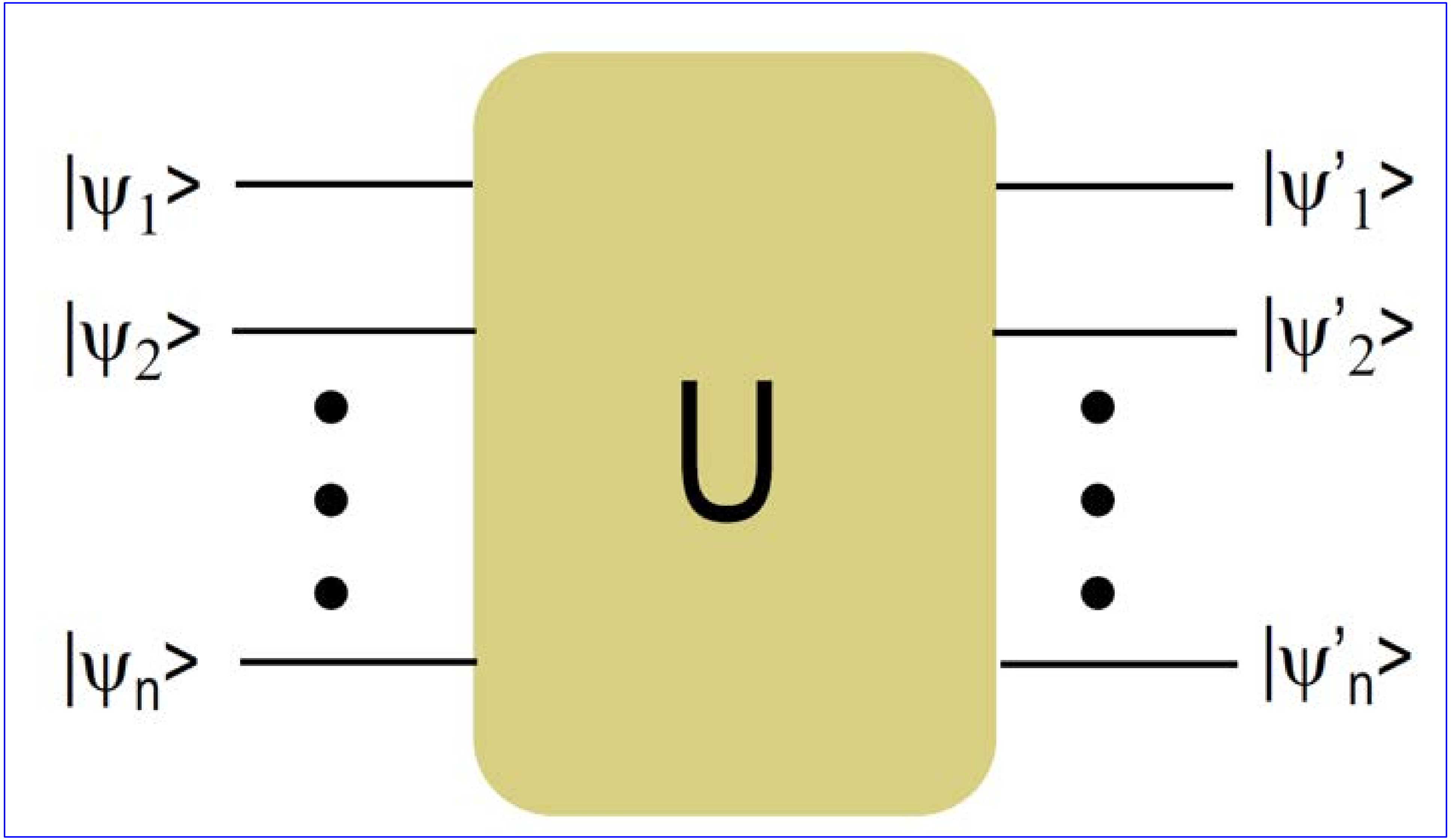
measurement
(probabilistic)

0	1	0	0	0	0	1
1	1	0	0	1	1	1
0	0	0	0	1	1	0
0	0	1	0	1	0	1
0	1	0	0	1	0	0

Quantum algorithms extract useful information from uncertain data.

Circuit model of Quantum Computing

input



output

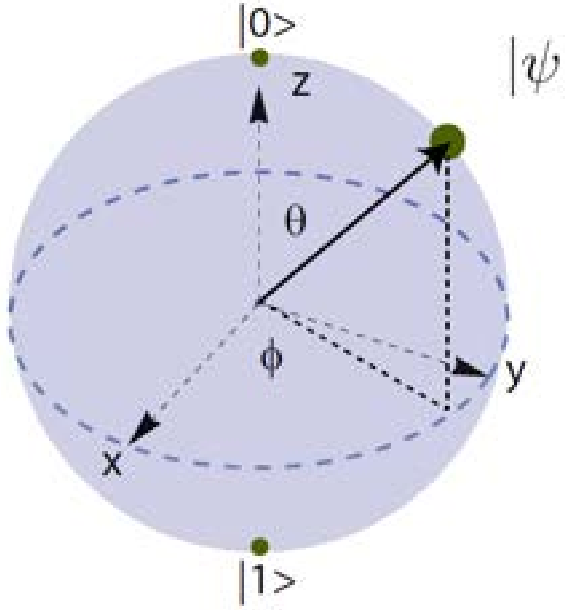
Arbitrary U can be decomposed into one- and two- qubit gates.

One-qubit gates

Qubit state can be parameterized by two angles on the Bloch sphere.

One-qubit gates rotate on the sphere.

X gates rotate about x
Y gates rotate about y
Z gates rotate about z



$$|\psi\rangle = \cos(\theta/2)|0\rangle + \sin(\theta/2)e^{\imath\phi}|1\rangle$$

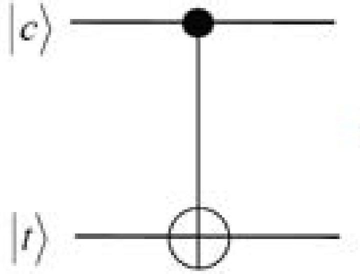
Figure 1.3: Bloch sphere representation of a qubit.

Two-qubit gates

Two-qubit gates are required to create entanglement.

input	output
ct	ct
00	00
01	01
10	11
11	10

CNOT gate

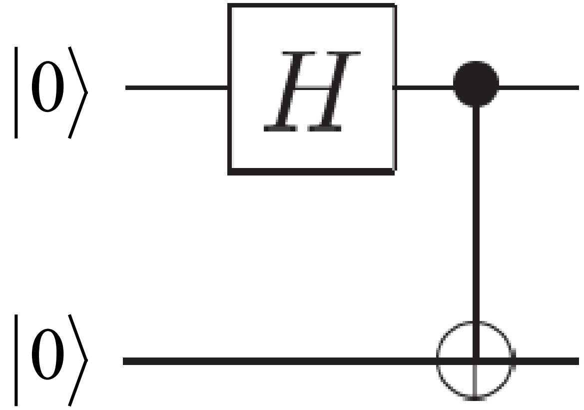


c+t mod(2)

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

Entanglement on demand

We can create entanglement with a simple quantum circuit.



$$|00\rangle \xrightarrow[\text{H}]{} \left(|0\rangle + i|1\rangle\right)|0\rangle = |00\rangle + i|10\rangle \xrightarrow[\text{CNOT}]{} \boxed{|00\rangle + i|11\rangle}$$

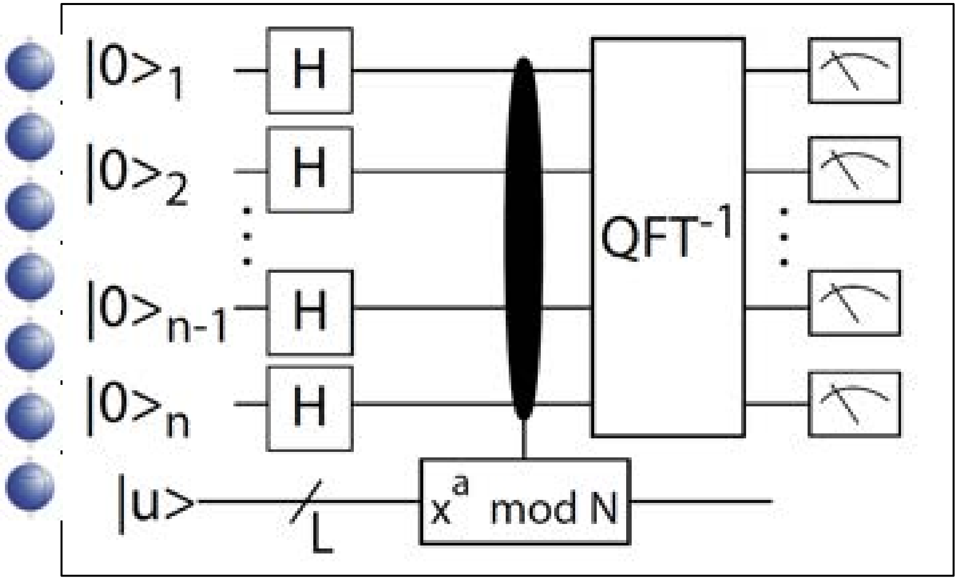
entanglement

Quantum Factoring algorithm

Peter Shor (1994 Bell labs)

Best known classical algorithm: $time \sim e^{(\log N \log^2 N)^{1/3}}$.

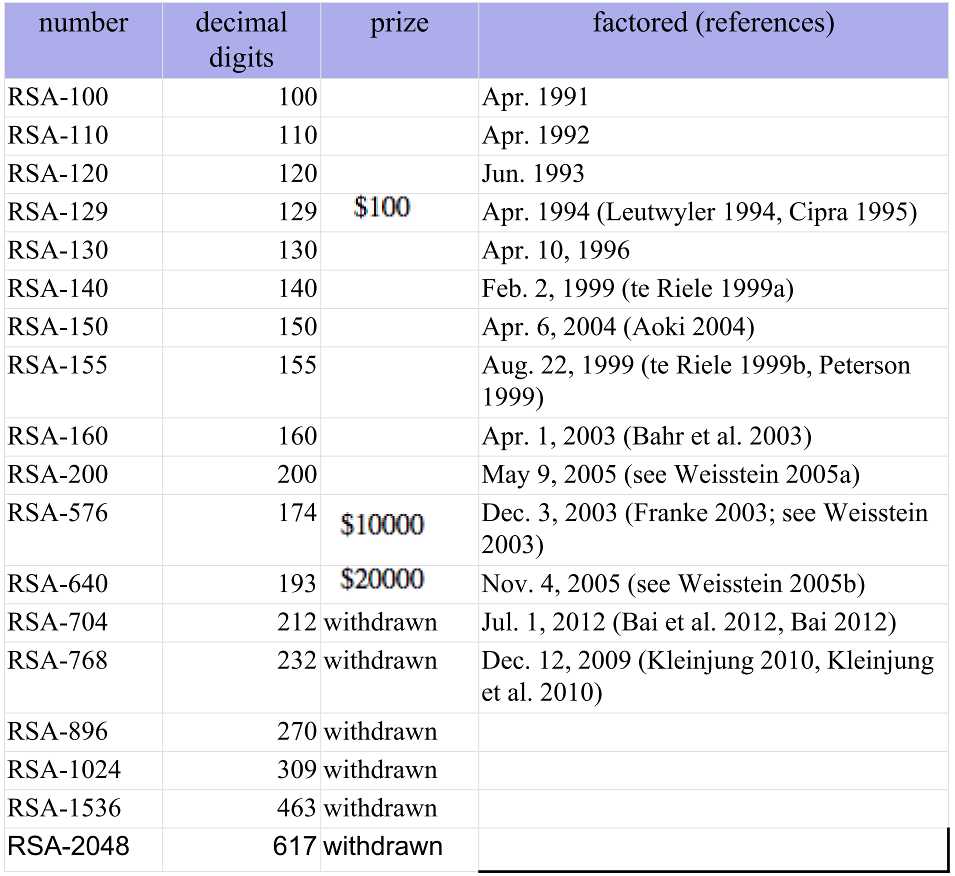
Shor's quantum algorithm: $time \sim (\log N)^3$



RSA Public key cryptography

- Rivest, Shamir, Adleman (RSA) invented a public key cryptosystem in 1977.
- Independently invented by C. Cocks in England in 1973 but kept secret.
- There is a public key known to everyone and a private key.
- Messages are encrypted with the public key and broadcast.
- Only recipients who know the private key can decrypt the message.
- This is widely used to protect personal data on the internet, e.g. online shopping.
- The security of RSA relies on the difficulty of factoring large numbers.

Factoring RSA Numbers



number	decimal digits	prize	factored (references)
RSA-100	100		Apr. 1991
RSA-110	110		Apr. 1992
RSA-120	120		Jun. 1993
RSA-129	129	$100	Apr. 1994 (Leutwyler 1994, Cipra 1995)
RSA-130	130		Apr. 10, 1996
RSA-140	140		Feb. 2, 1999 (te Riele 1999a)
RSA-150	150		Apr. 6, 2004 (Aoki 2004)
RSA-155	155		Aug. 22, 1999 (te Riele 1999b, Peterson 1999)
RSA-160	160		Apr. 1, 2003 (Bahr et al. 2003)
RSA-200	200		May 9, 2005 (see Weisstein 2005a)
RSA-576	174	$10000	Dec. 3, 2003 (Franke 2003; see Weisstein 2003)
RSA-640	193	$20000	Nov. 4, 2005 (see Weisstein 2005b)
RSA-704	212	withdrawn	Jul. 1, 2012 (Bai et al. 2012, Bai 2012)
RSA-768	232	withdrawn	Dec. 12, 2009 (Kleinjung 2010, Kleinjung et al. 2010)
RSA-896	270	withdrawn	
RSA-1024	309	withdrawn	
RSA-1536	463	withdrawn	
RSA-2048	617	withdrawn	

Largest number known to have been factored:
RSA-768
=1230186684530117755130494958384962720772853569595334792197322452151726400507263657518
745202199786469389956474942774063845925192557326303453731548268507917026122142913461670429214311602221240479274737794080665351419597459856902143413
=
334780716989568987860441698482126908177047949837137685689124338898288379387800228761471165253174308773781446799949
x
3674604366679959042824463379962795263227915816434308764267603228381573966651127923337341714339681027009279873630 8917

Classical number field sieve algorithm

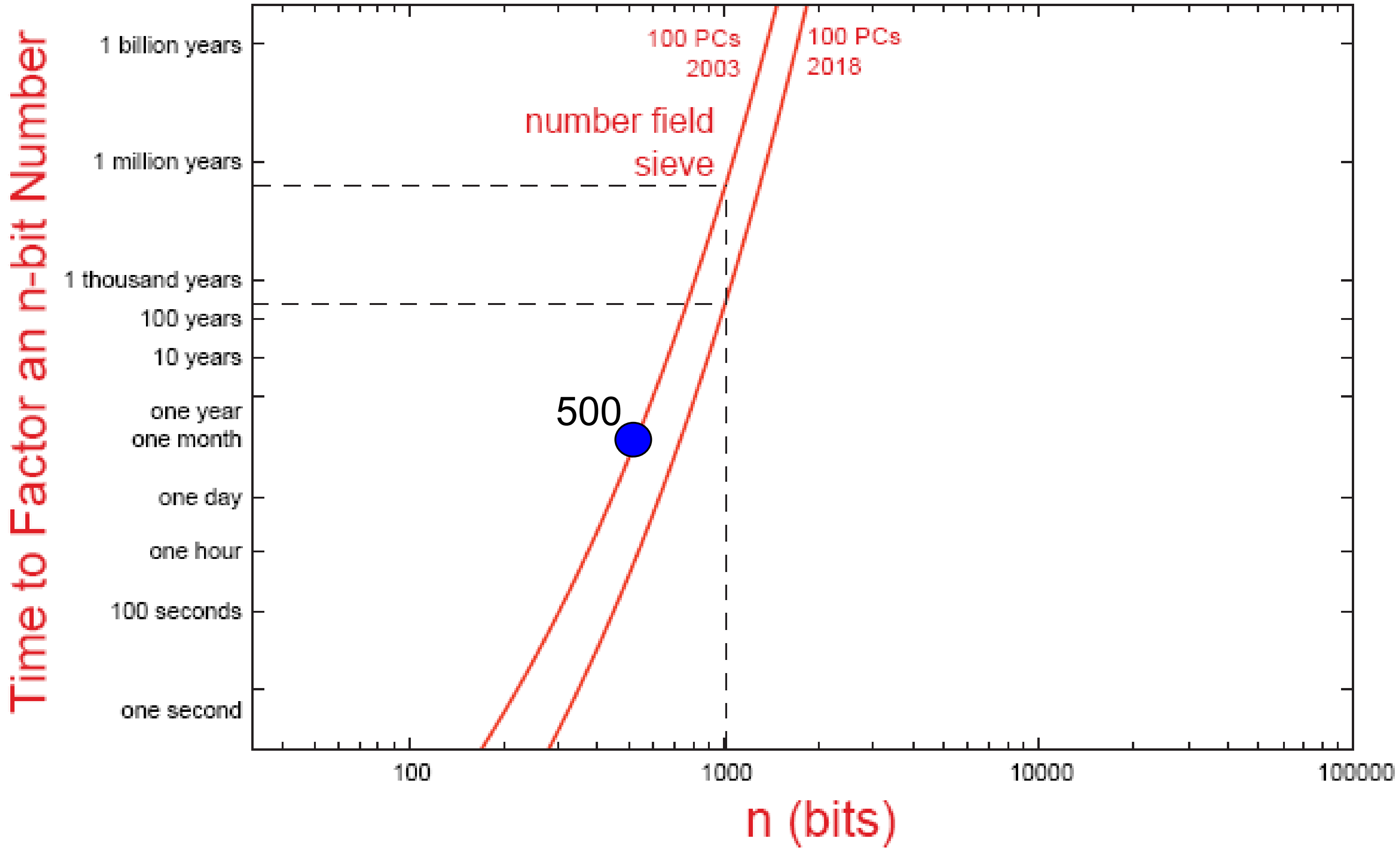
$$time \sim e^{1.9(\ln n)^{1/3}(\ln \ln n)^{2/3}}$$

RSA 768 took 1500 AMD64 years to factor.

RSA 1536 would take 200 billion AMD64 years

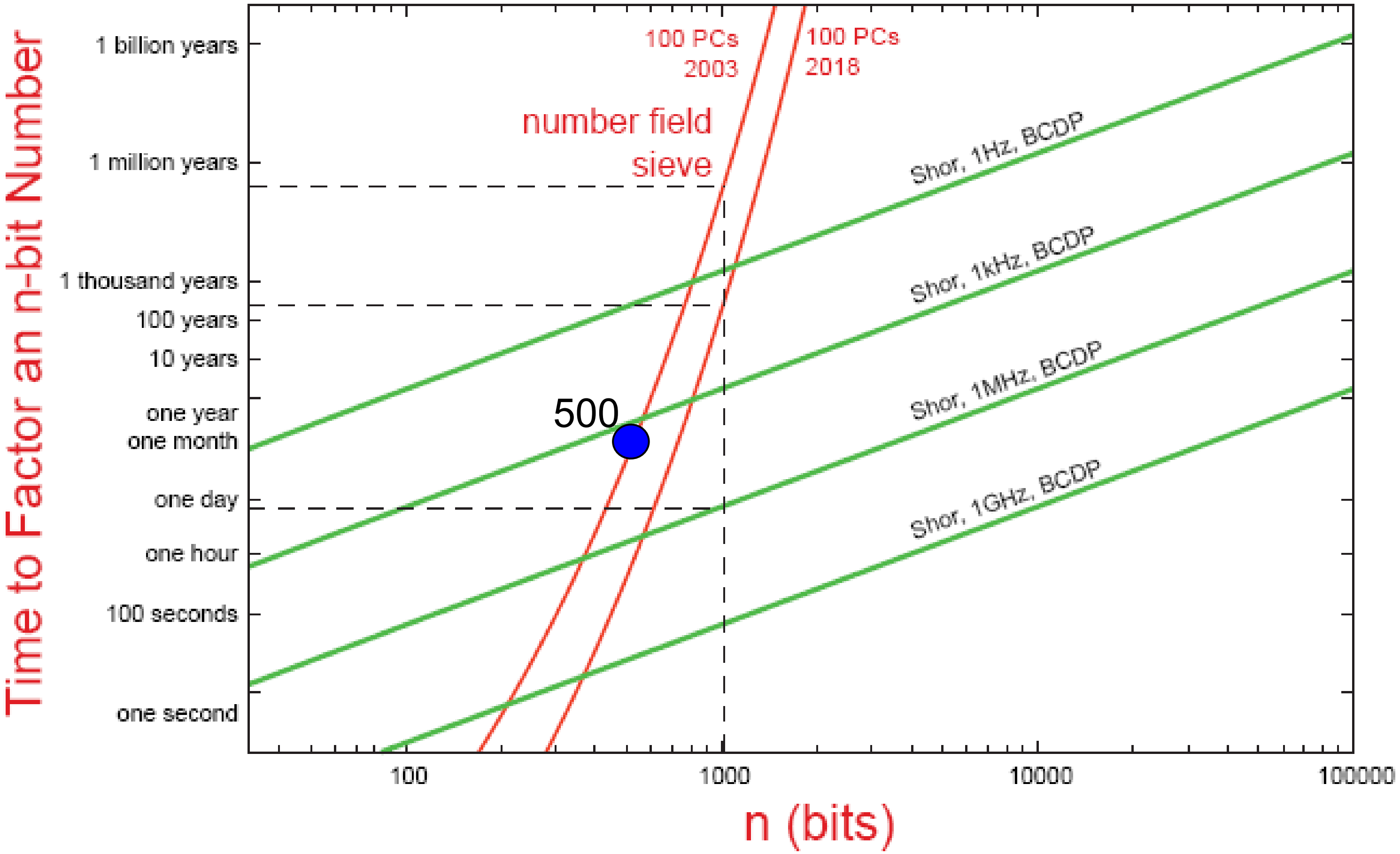
Factoring algorithms

vanMeter, et al. arXiv:quant-ph/0507023



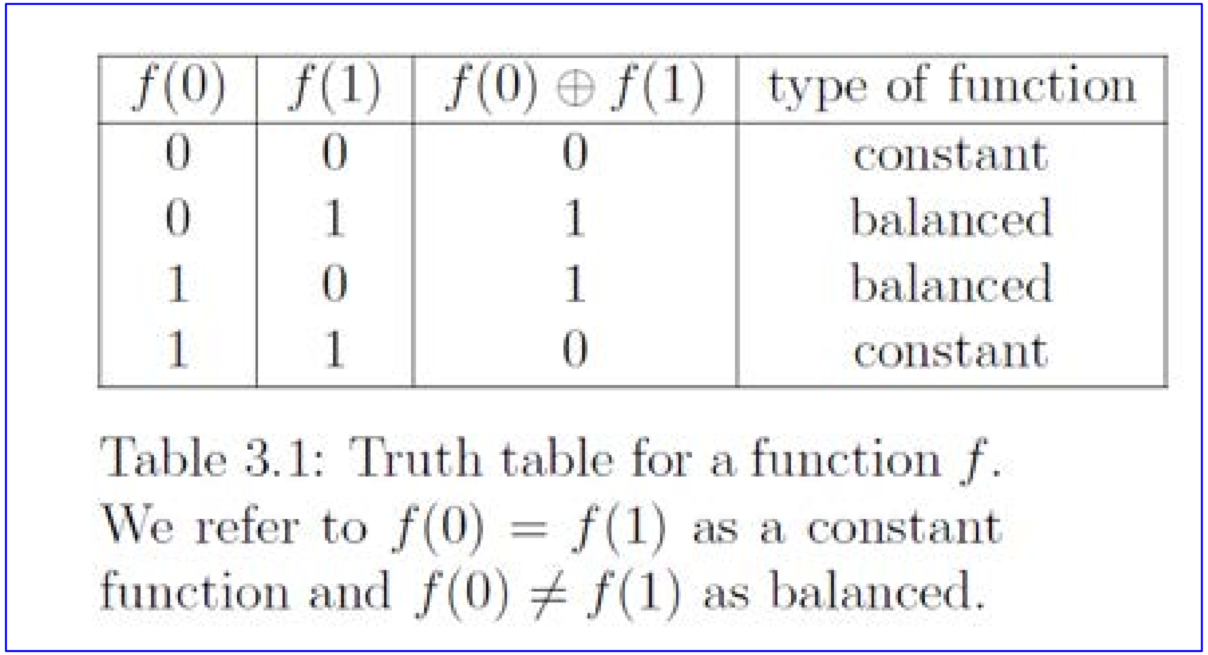
Factoring algorithms

vanMeter, et al. arXiv:quant-ph/0507023



A simpler example: Deutsch-Jozsa

Consider the following problem. The function f takes a one bit input with value 0 or 1 and maps it to a one bit output, 0 or 1. There are four possibilities given in Table 3.1. The problem is to determine $f(0) \oplus f(1)$ which tells us whether the function is constant or balanced.



$f(0)$	$f(1)$	$f(0) \oplus f(1)$	type of function
0	0	0	constant
0	1	1	balanced
1	0	1	balanced
1	1	0	constant

Table 3.1: Truth table for a function f. We refer to $f(0) = f(1)$ as a constant function and $f(0) \neq f(1)$ as balanced.

Classically this requires two evaluations of the function f. Using a quantum circuit we need only a single evaluation.

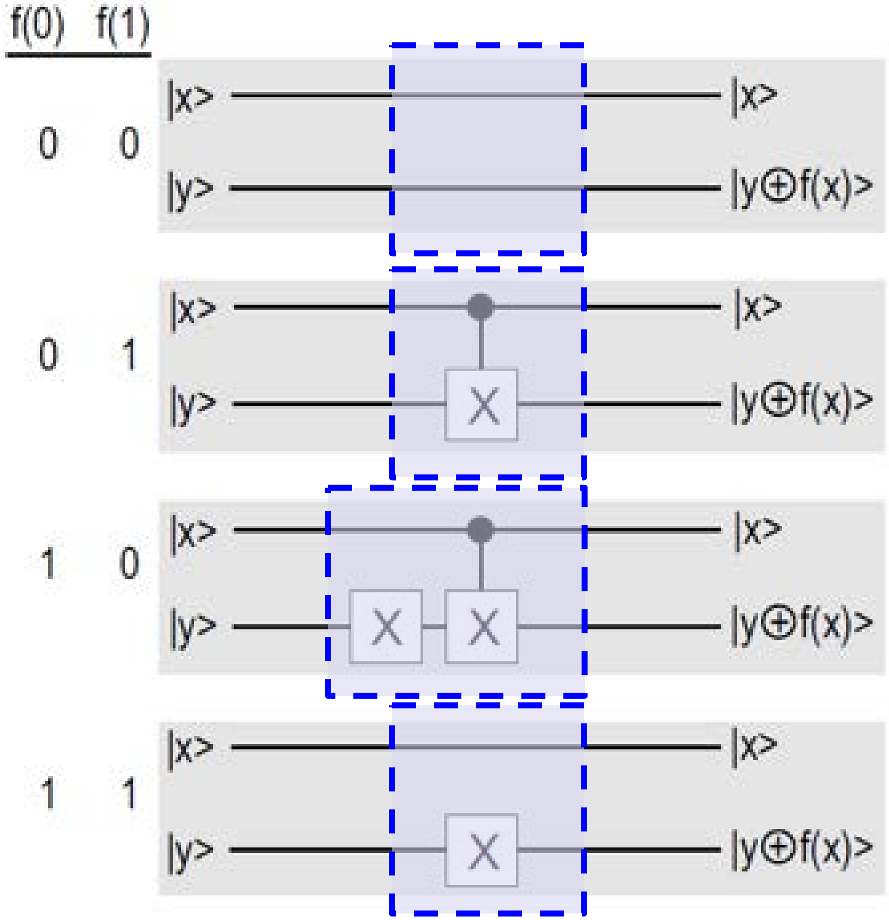
A simpler example: Deutsch-Jozsa

Classically this requires two evaluations of the function f. Using a quantum circuit we need only a single evaluation. The function evaluation can be expressed as a unitary operator

$$|x\rangle|y\rangle \xrightarrow{U_f} |x\rangle|y \oplus f(x)\rangle$$

Different f(x) correspond to different quantum circuits.

Has been demonstrated in the lab.



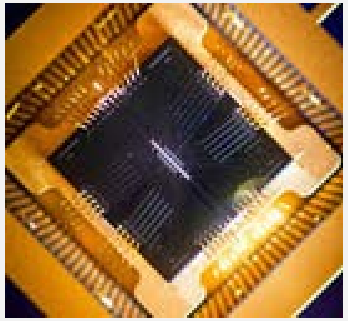
mount entanglement

How long is the road ?

Quantum Computing Platforms

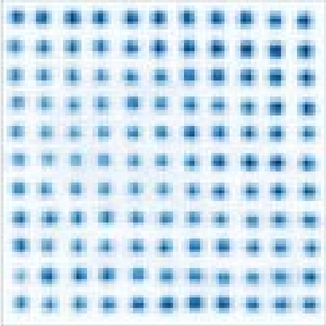
Atomic qubits (identical)
Room T apparatus (or 4K)
Optical interface/qu. networking
Laser cooling and control

trapped ions



~20Q demonstrated

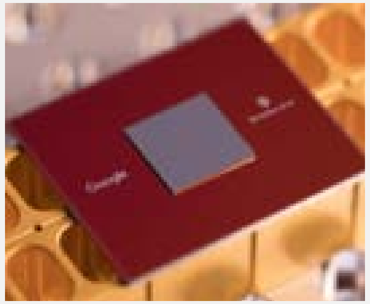
neutral atoms



100Q arrays

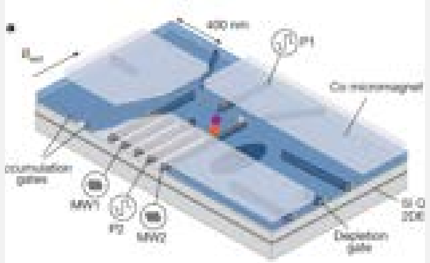
Engineered qubits (not identical)
Requires cryogenic cooling
No optical interface
Microwave electronics

superconductors



60Q chips

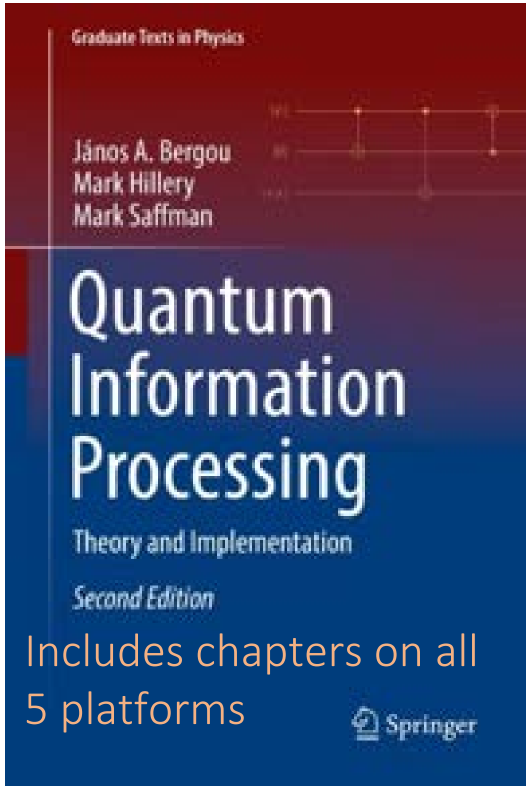
quantum dots



2Q devices

optical

Scalability challenging



Graduate Texts in Physics

János A. Bergou
Mark Hillery
Mark Saffman

Quantum Information Processing

Theory and Implementation

Second Edition

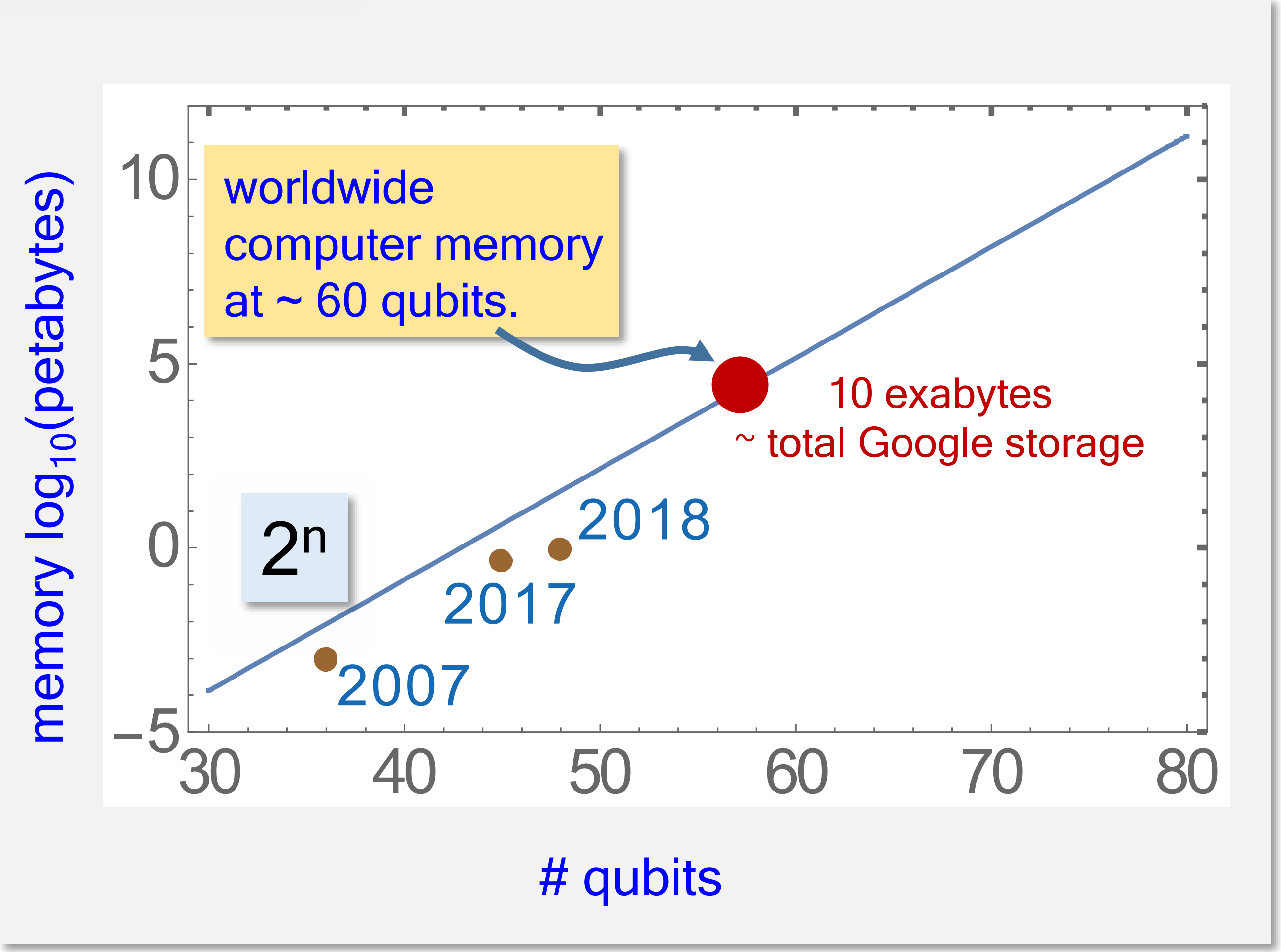
Springer

Includes chapters on all 5 platforms

Classical Simulation of Quantum Circuits

Large scale classical simulators are memory or time limited.

Brute force requires exponential memory



2007 Massively parallel quantum computer simulator Comp. Phys. Commun. 176, 121 (2007) 1 terabyte

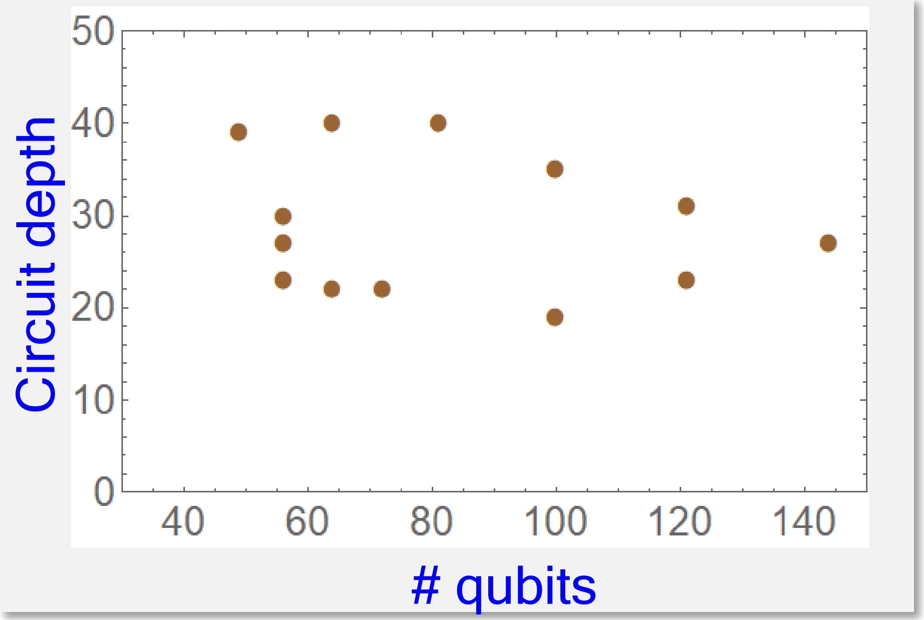
2017 0.5 Petabyte Simulation of a 45-Qubit Quantum Circuit arXiv: 1704.01127 0.5 petabytes

2018 Massively parallel quantum computer simulator, eleven years later arXiv: 1805.04708 1.0 petabytes

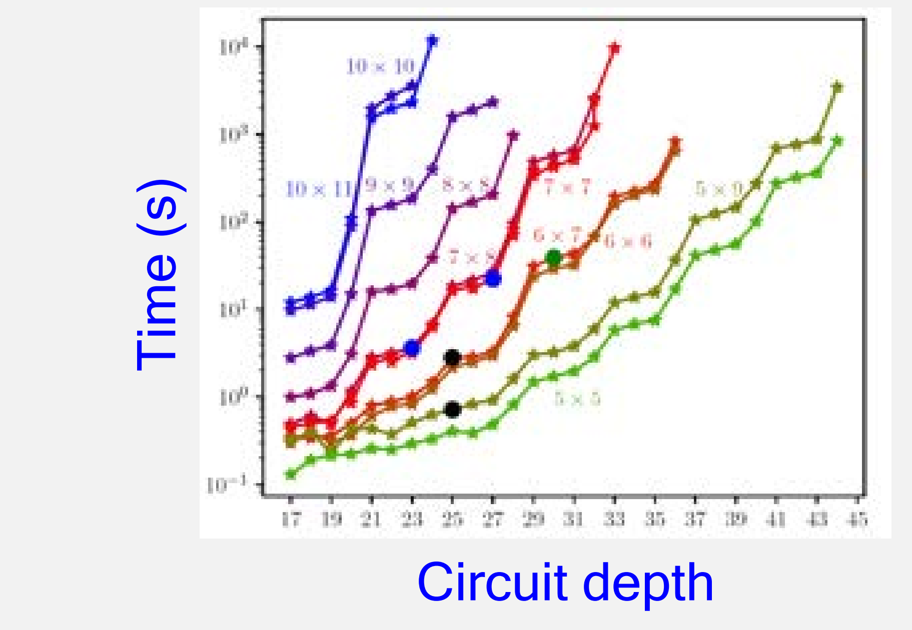
Classical Simulation of Quantum Circuits

Can trade memory for time to simulate more qubits

arXiv:1710.05867, 1712.05384, 1707.00865, 1805.01450



Deep circuits require exponential time



Near term algorithms

- There is still a big gap between the promise of quantum computing and the reality of today's hardware.

- Sometimes referred to as the NISQ era -
  Noisy Intermediate Scale Quantum

- A great deal of current effort on hybrid approaches:
  classical optimization coupled with a quantum co-processor.

  VQE – Variational quantum eigensolver
  QAOA – Quantum Approximate Optimization Algorithm

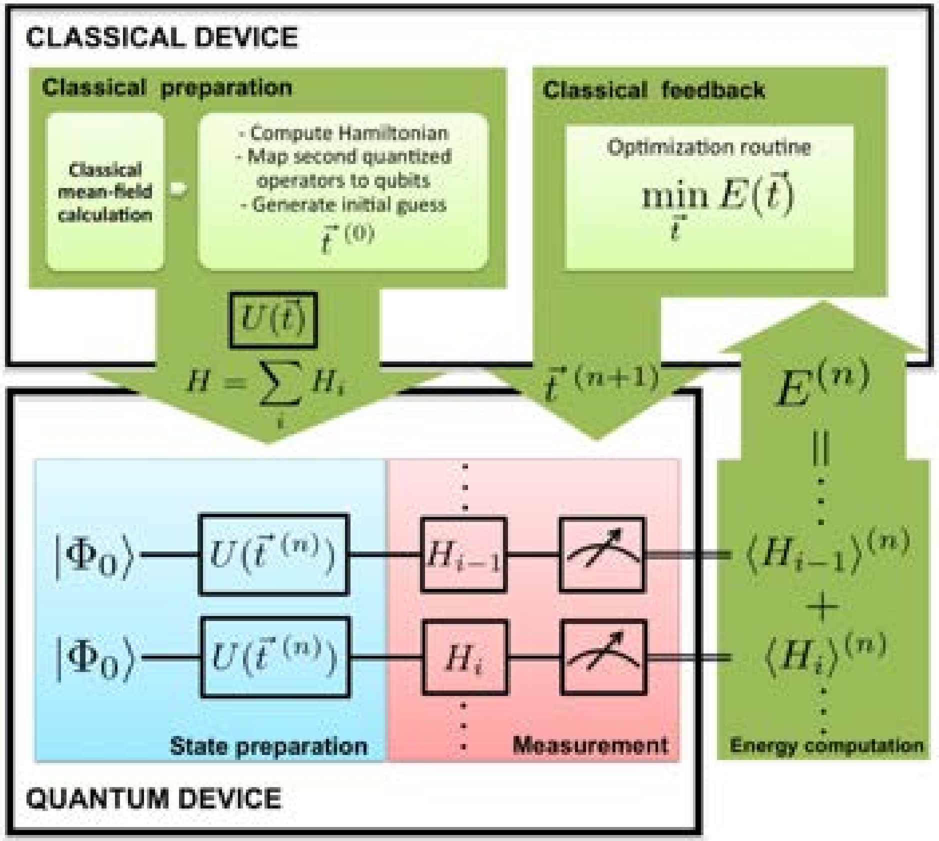
- These approaches can be used for quantum machine learning.

VQE

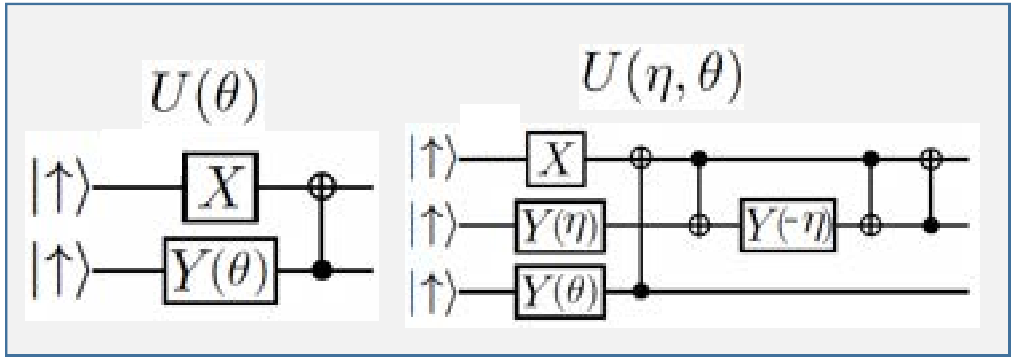
Peruzzo, et al. *Nat. Commun.* **5**, 4213 (2014)

- Quantum hardware for state preparation and measurement of observables.

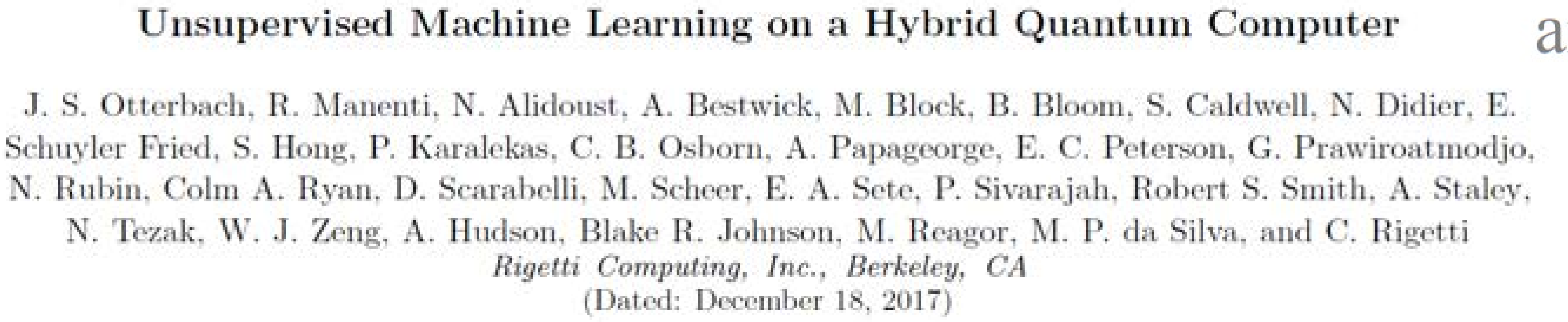
- Classical processing for analysis of the quantum measurements and optimal choice of the state ansatz to find a variational optimal.



Dumitrescu, et al. Cloud Quantum Computing of an Atomic Nucleus, PRL **120**, 201501 (2018)



Quantum Machine Learning



Unsupervised Machine Learning on a Hybrid Quantum Computer

J. S. Otterbach, R. Manenti, N. Alidoust, A. Bestwick, M. Block, B. Bloom, S. Caldwell, N. Didier, E. Schuyler Fried, S. Hong, P. Karalekas, C. B. Osborn, A. Papageorge, E. C. Peterson, G. Prawiroatmodjo, N. Rubin, Colm A. Ryan, D. Scarabelli, M. Scheer, E. A. Sete, P. Sivarajah, Robert S. Smith, A. Staley, N. Tezak, W. J. Zeng, A. Hudson, Blake R. Johnson, M. Reagor, M. P. da Silva, and C. Rigetti

Rigetti Computing, Inc., Berkeley, CA

(Dated: December 18, 2017)

arXiv:1712.05771v1

Clustering of input data is a well known unsupervised learning task.

This can be mapped onto a combinatorial optimization problem called MaxCut.

Given a graph divide the vertices into two sets such that the number of connections between vertices in different sets is maximized.

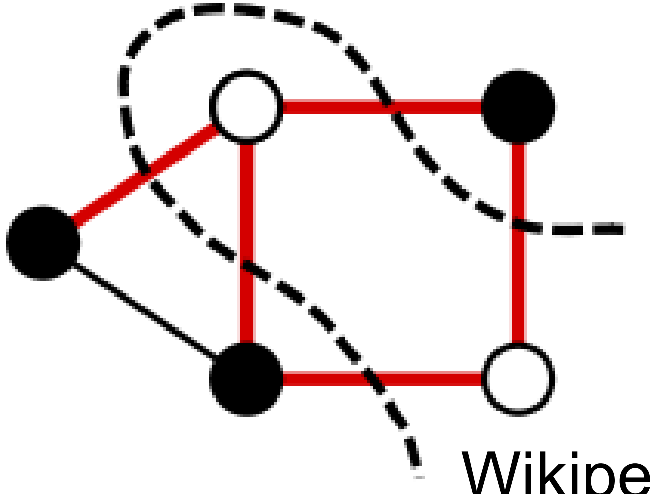
MaxCut

Example of MaxCut for a 5 vertex graph.

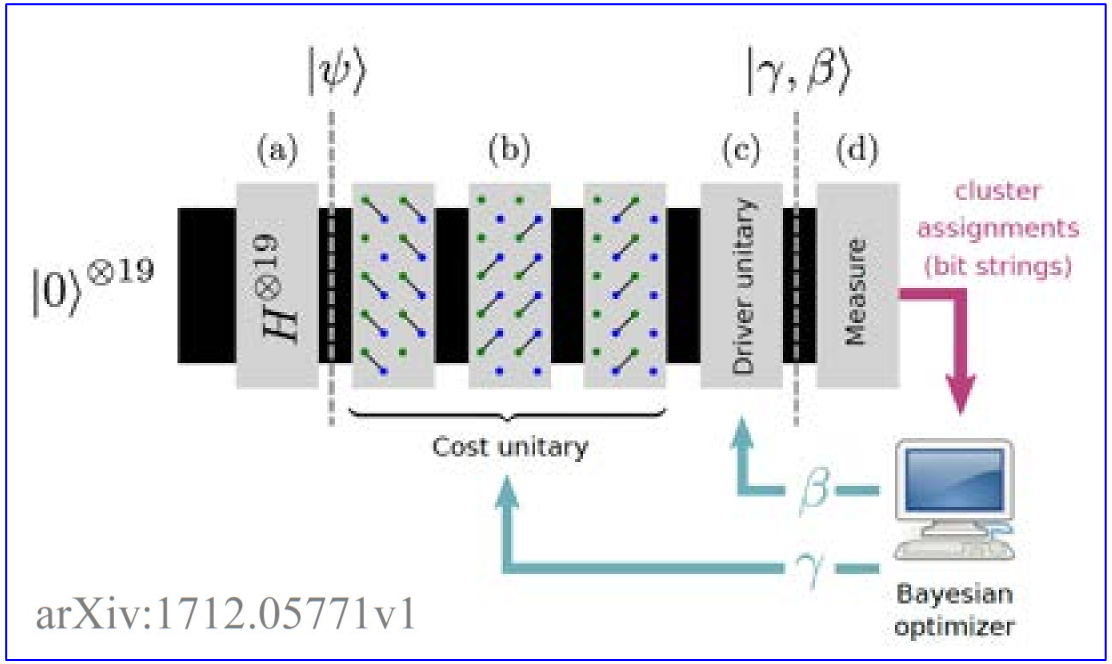
For the clustering application – weighted MaxCut is used where the weight function is a distance metric between objects.

MaxCut is NP hard, but there are efficient classical heuristics.

QAOA (generalization of VQE) can be used to directly solve MaxCut on quantum hardware.



Wikipedia

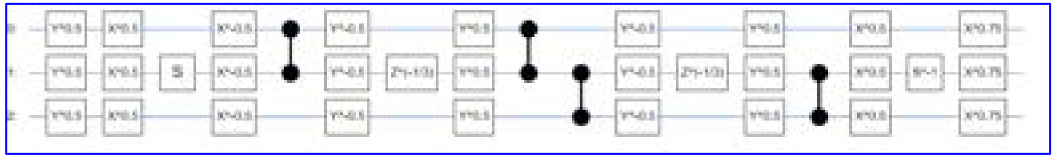


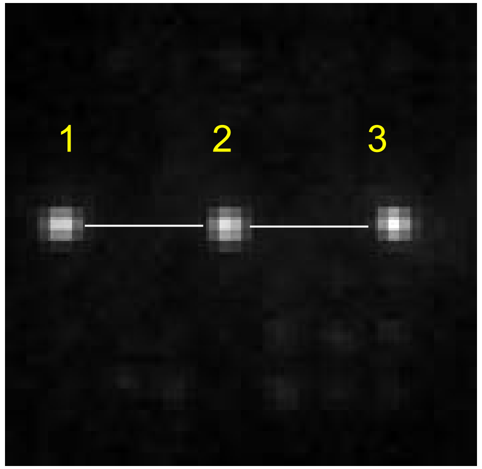
arXiv:1712.05771v1

QAOA MaxCut – 3 qubits

arXiv: 2112.14589

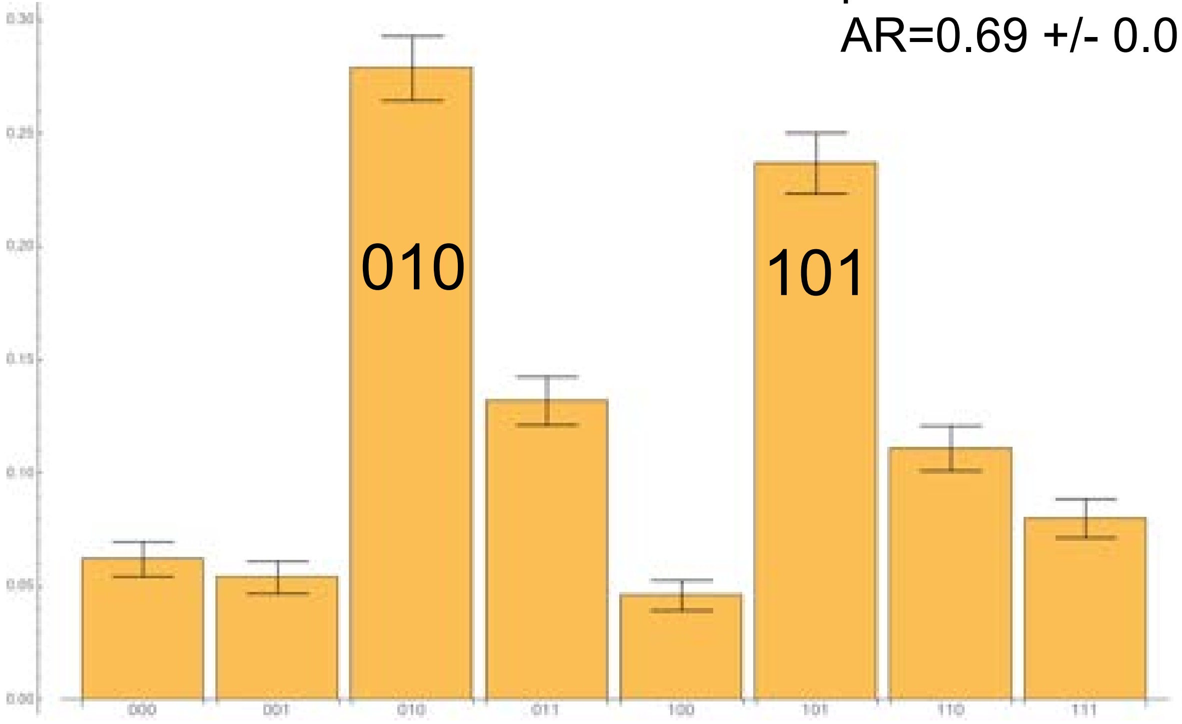
- QAOA for 3 node MaxCut



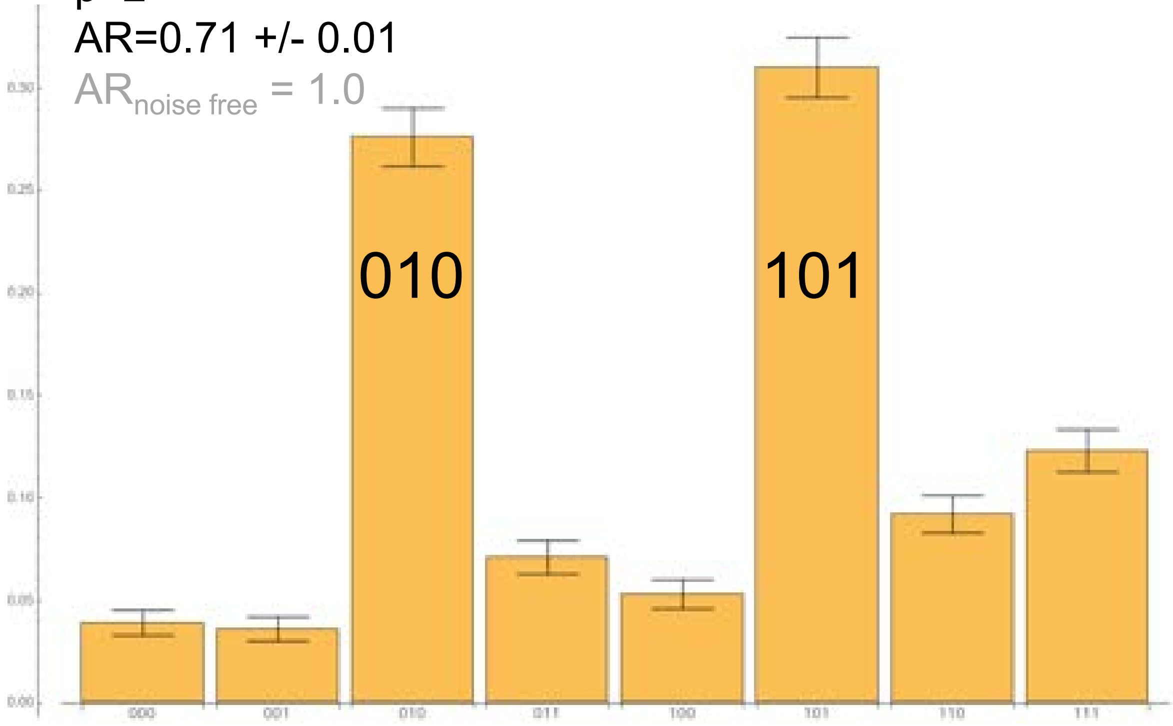


MaxCut solutions are 010 and 101

p=1
AR=0.69 +/- 0.01



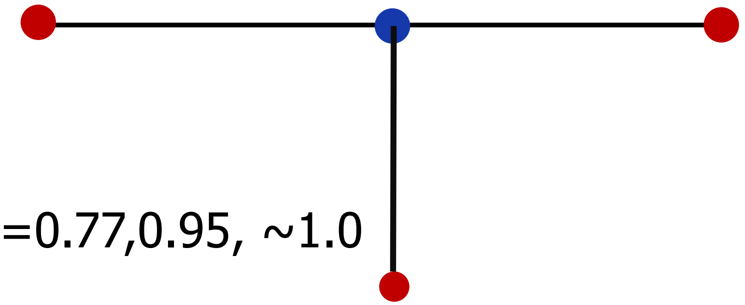
p=2
AR=0.71 +/- 0.01
$AR_{\text{noise free}}$ = 1.0

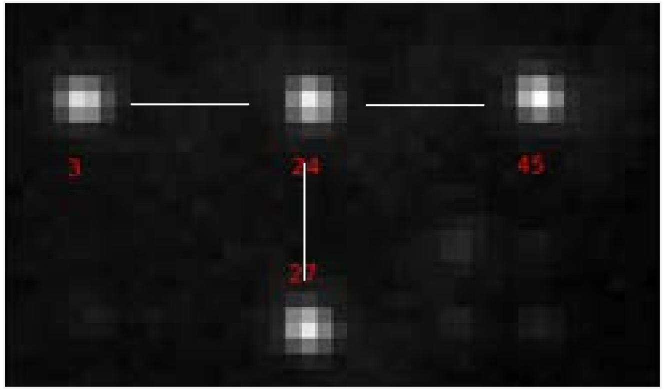


QAOA MaxCut – 4 qubits

arXiv: 2112.14589

- QAOA for 4 node MaxCut



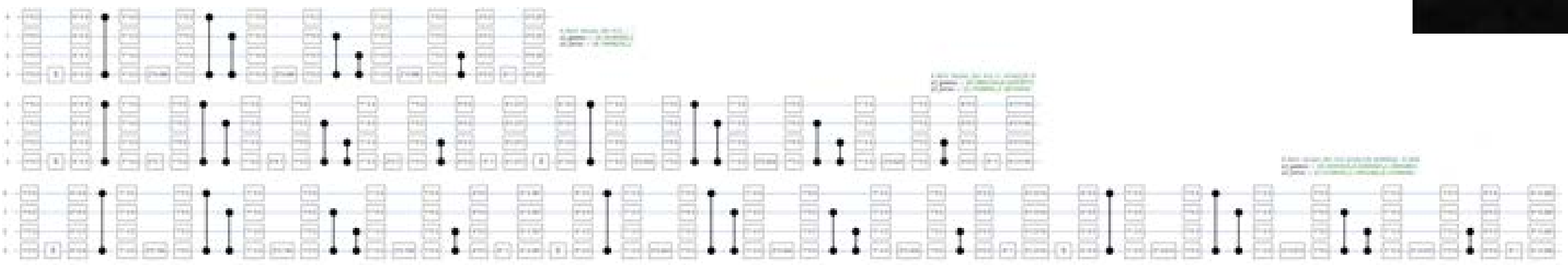


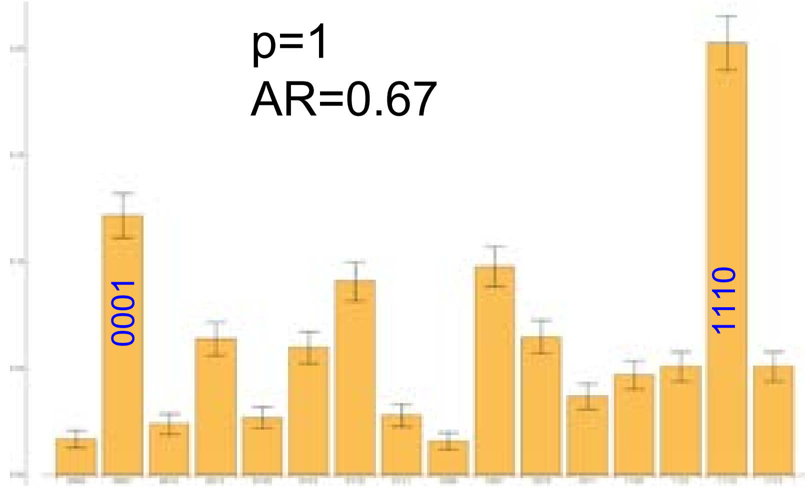
MaxCut solutions are 0001 and 1110
Noise free prediction for p=1,2,3 is AR=0.77,0.95, ~1.0

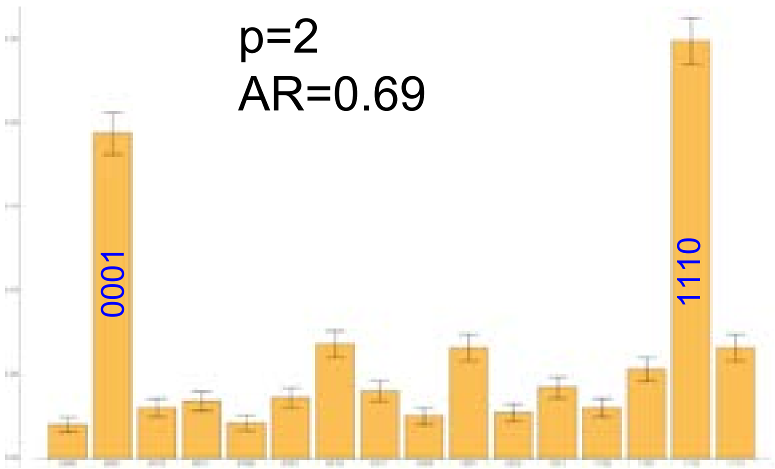
6 CZ

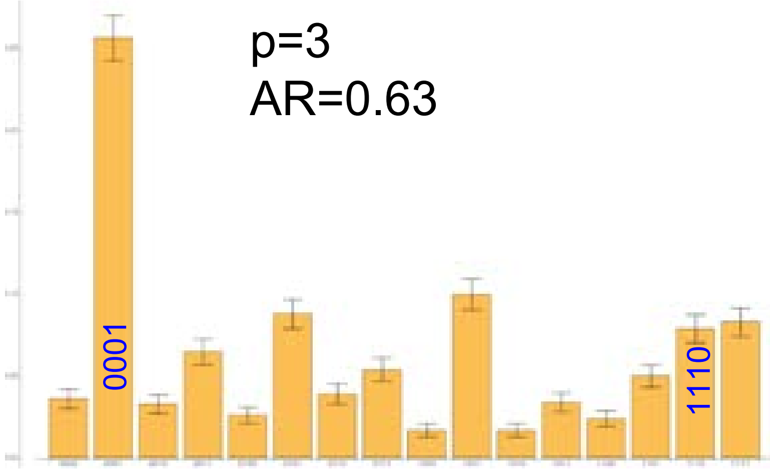
12 CZ

18 CZ









Quantum Science and Engineering at UWM

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

WISCONSIN QUANTUM INSTITUTE
Quantum Science and Engineering at UW–Madison

Chicago Quantum Exchange

WARF
Wisconsin Alumni Research Foundation

NSF

Department of Energy
United States of America

Army Research Office
1951

ARL

Air Force Office of Scientific Research
United States Air Force

Office of Naval Research
ONR
Science & Technology

DARPA

ColdQuanta

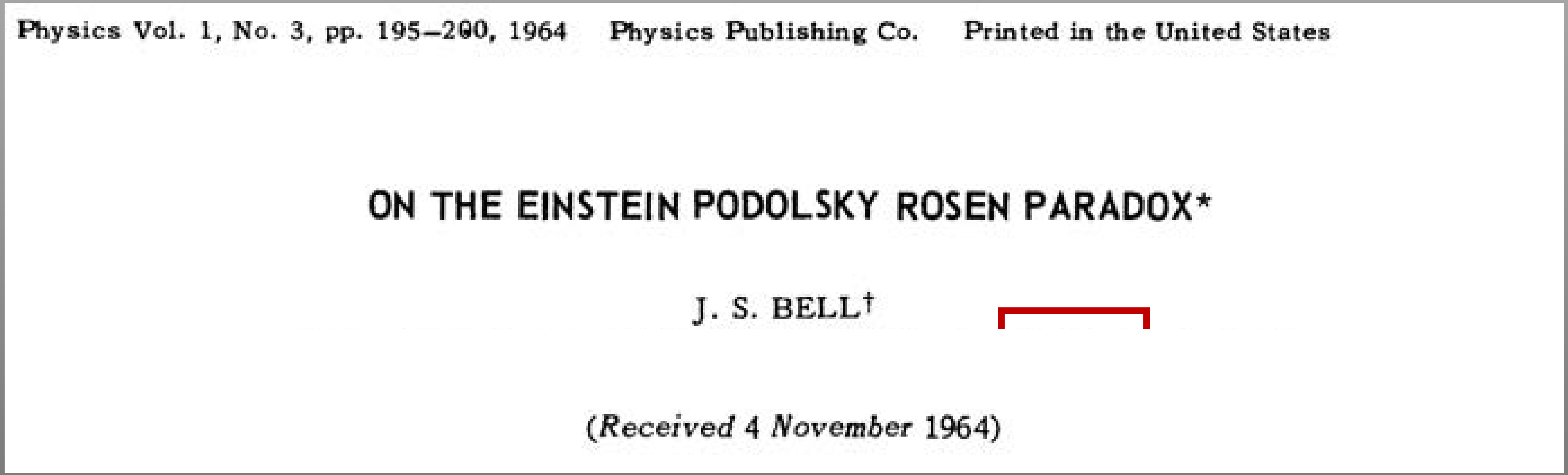
NORTHROP GRUMMAN

HRL LABORATORIES

Google

AMERICAN FAMILY INSURANCE
Insure carefully, dream fearlessly.

Early days



Physics Vol. 1, No. 3, pp. 195–200, 1964 Physics Publishing Co. Printed in the United States

ON THE EINSTEIN PODOLSKY ROSEN PARADOX*

J. S. BELL†

(*Received 4 November 1964*)

Susan Coppersmith 2001
Quantum dot qubits

Mark Eriksson 1999
Quantum dot qubits

Dieter van Melkebeek 2000
Computational complexity

Mark Saffman 1999
Neutral atom qubits

WISCONSIN QUANTUM INSTITUTE

Quantum Science and Engineering at UW-Madison

29
faculty

Physics, Chemistry, Computer Sciences, Electrical & Computer Engineering, Engineering Physics, Materials Science, Mathematics, Statistics

Research portfolio

Qubits & Quantum computing

Quantum networking

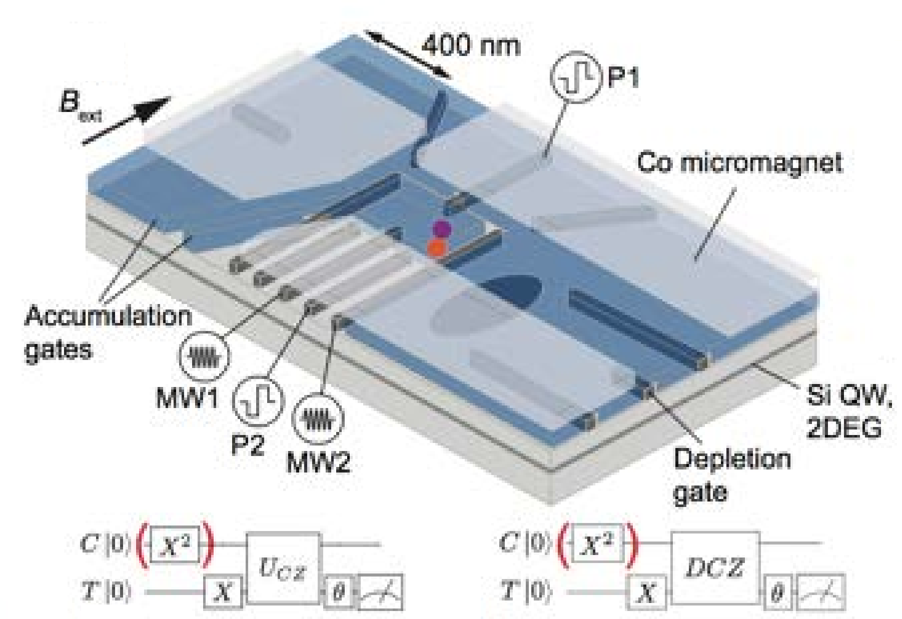
Quantum sensing & metrology

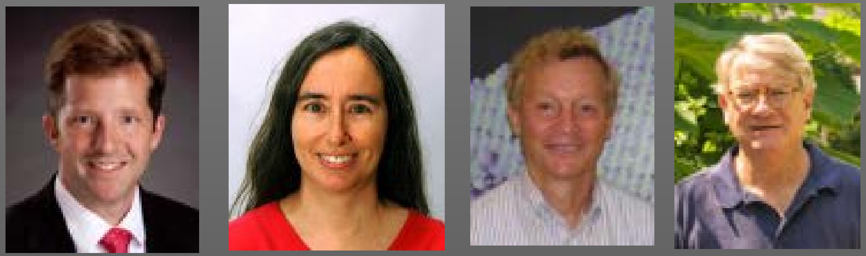
Applications

Workforce Development

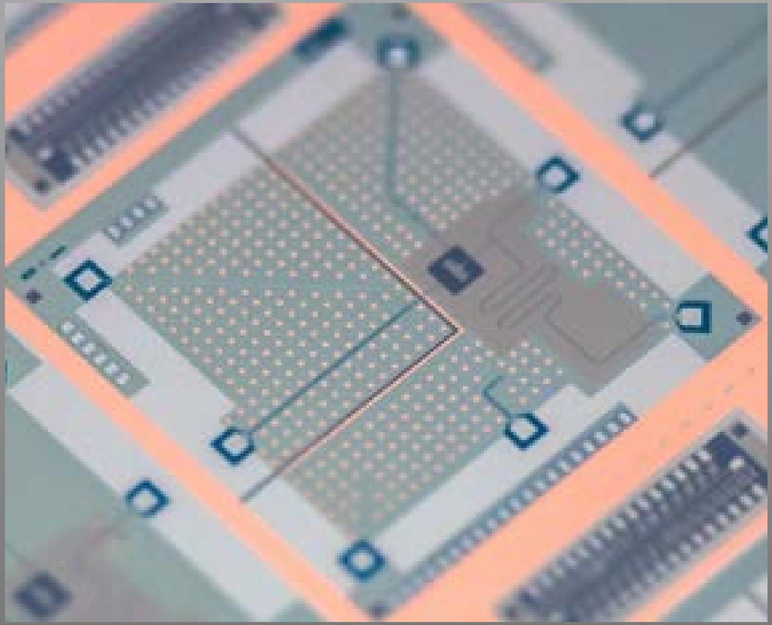
Qubit platforms

Si quantum dots

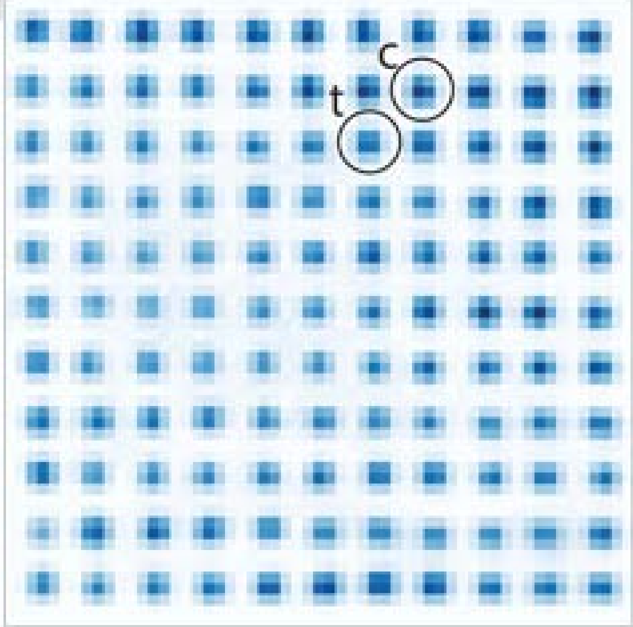


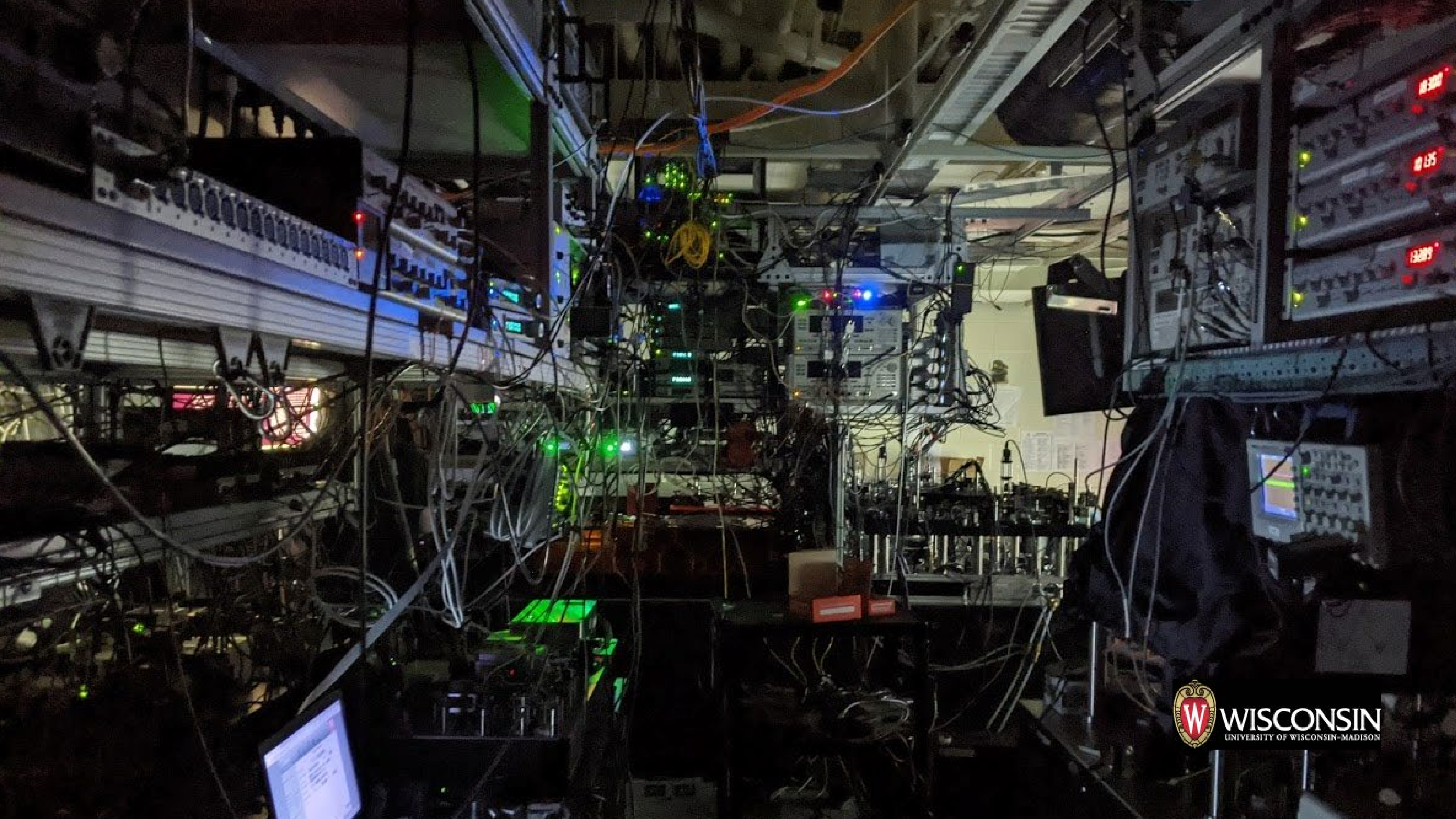


Superconducting circuits



Neutral atom arrays





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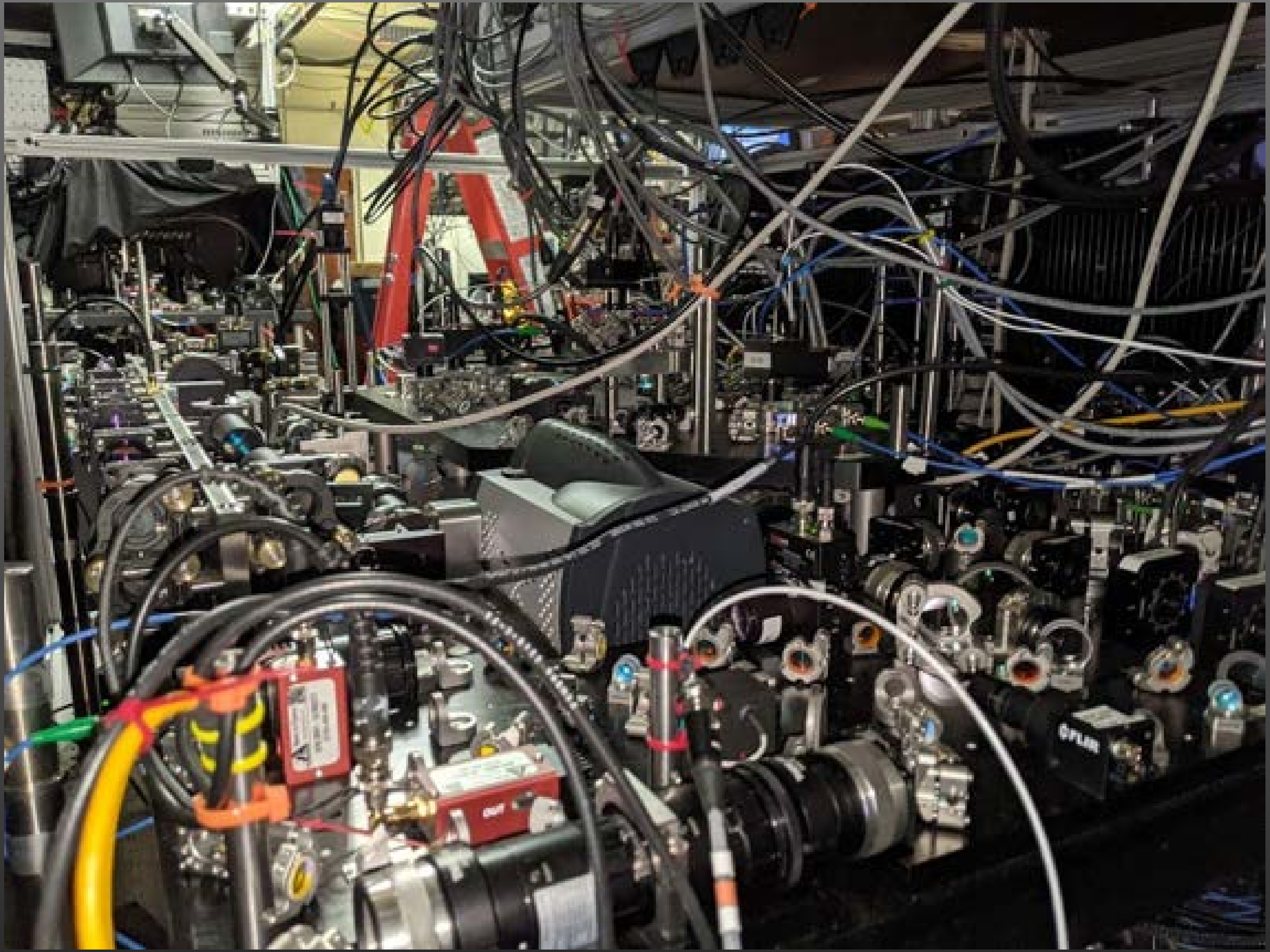
Neutral atom hardware

Inside view of the “QPU” at UWM.

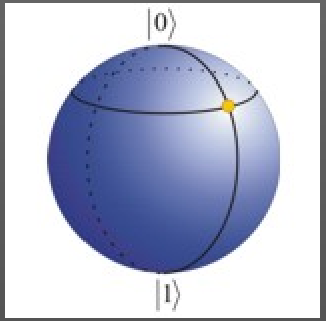
Includes optical components, optomechanics, beam steering, detectors, cameras, all in an enclosure with environmental stabilization.

Not shown are laser, optical, electronic, and computer subsystems that feed into the QPU.



Neutral atom approach

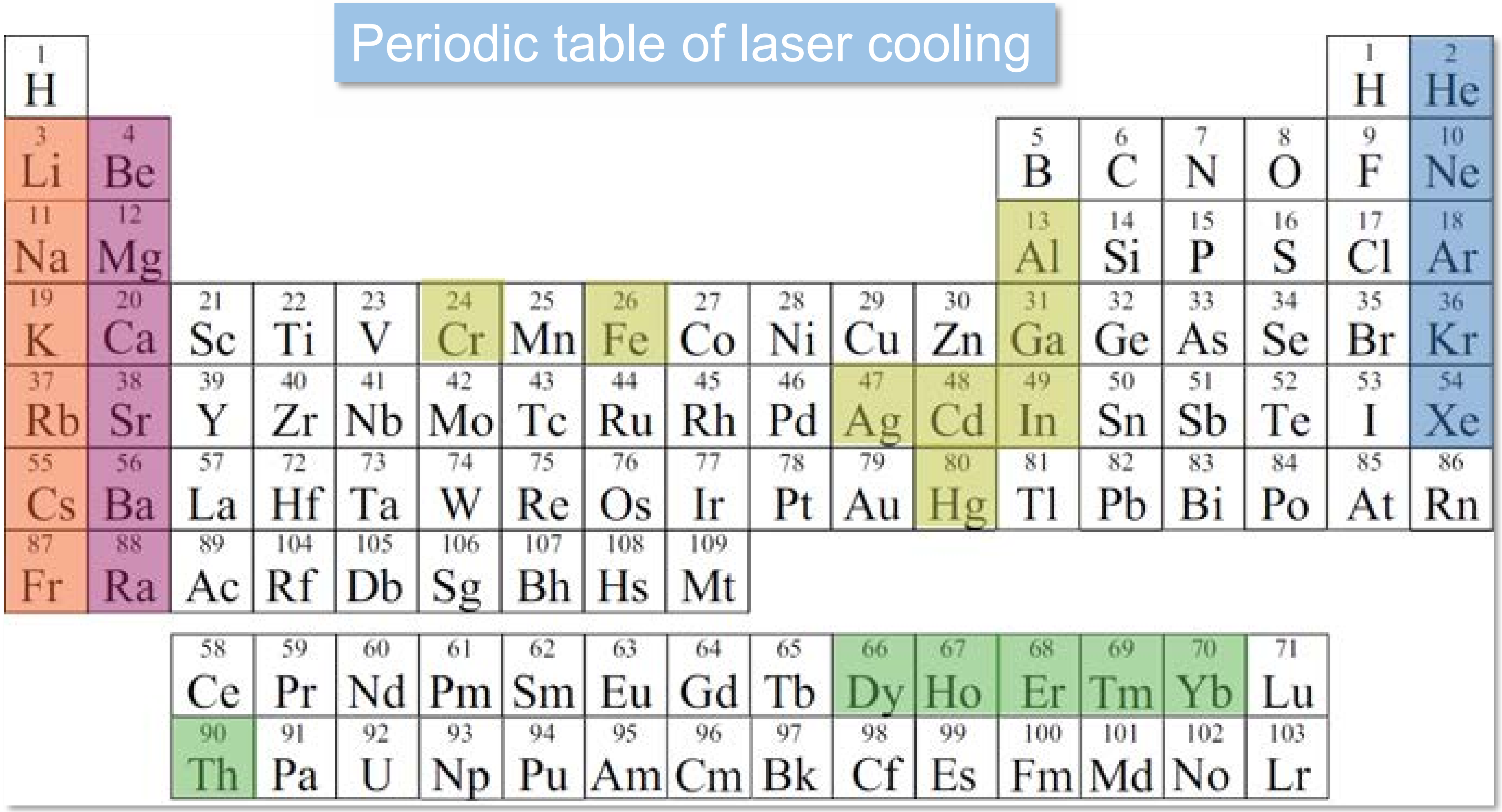
Qubits



- Initialization Laser cooling and trapping
- Coherence Hyperfine clock states. Coherence > 10s demonstrated
- Measurements Light scattering. High fidelity.
- Universal set of logical gates Microwaves/laser pulses/Rydberg states
- Scalability……. Qubit arrays demonstrated in 1D, 2D and 3D geometries. Several groups have shown arrays with >100 qubits.

DiVincenzo
Fortschr. Phys. (2000)
Qu. Inf. Comp. (2001)

Which atom should we pick ?



Periodic table of laser cooling

1 H																1 H	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									
		58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu		
		90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr		

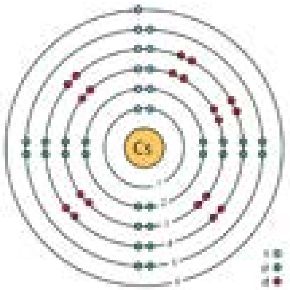
Single atom arrays:

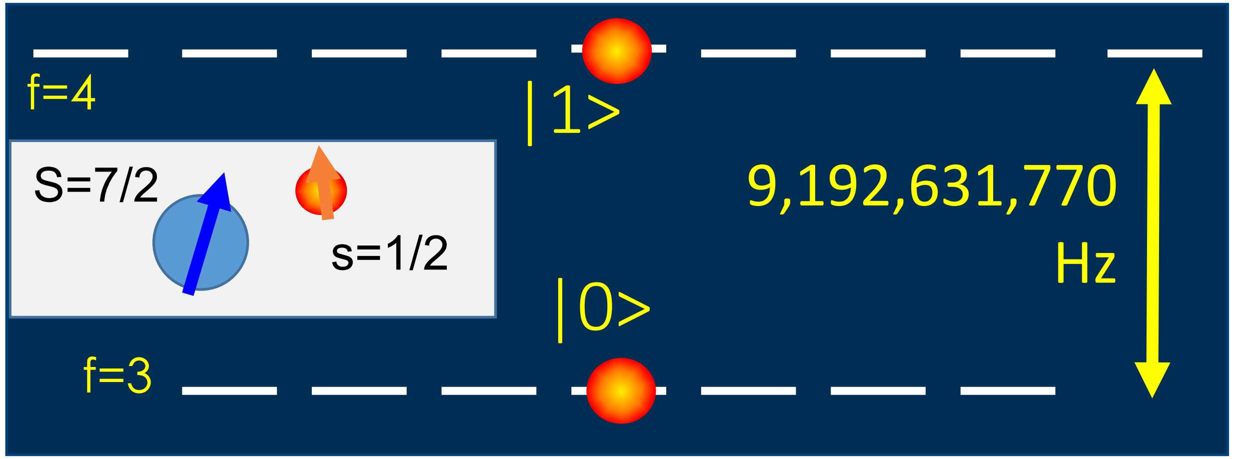
Rb, Cs,

Sr, Yb

An industry standard qubit

Cesium





- The hyperfine m=0 clock states provide the SI definition of the second.

- These states are entangled superpositions of nuclear and electronic spin projections

|1>= ↑↓ + ↓↑

|0>= ↑↓ - ↓↑

Excellent coherence properties:

- In free space hyperfine lifetime 34 years
- When optically trapped T1, T2 up to 10s has been demonstrated

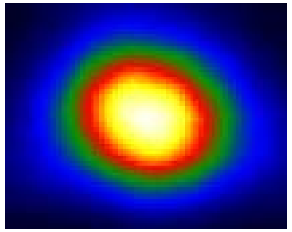
Coherence limited by finite atom temperature, trap light optical Stark shifts, magnetic fields.

Minute scale coherence appears possible.

Operational Sequence

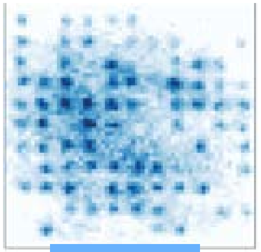
Qubit Register Preparation

Cold Atoms



Laser cooling 852,894 nm lasers

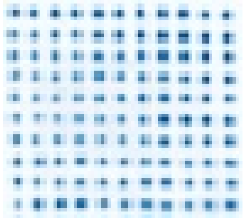
Single Atom Array



Camera

Array 825 nm lasers, Deep cooling

Filled Array



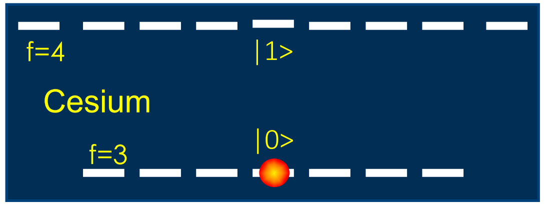
Camera

Rearrangement 1064 nm laser

Controlling the Mechanics

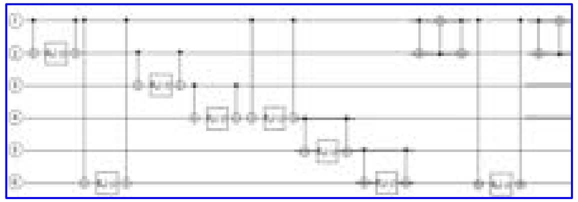
Calculation Cycle

State Initialization



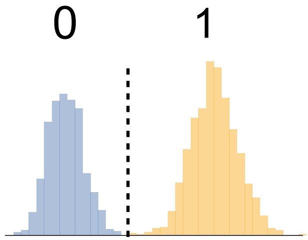
Optical Pumping 895 nm laser

Quantum Circuit



Gates 1Q, 2Q 459 nm, 1040 nm lasers, µwaves

Measure Results



Camera

852 nm lasers

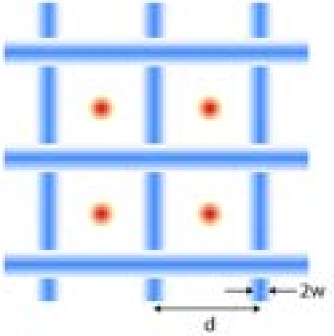
Controlling the Quantum

Blue Array Technology

a single bottle beam	Opt. Lett. **34**, 1159 (2009)
bottle beam array	SPIE **8249** (2012)
Gaussian beam array	PRA **88**, 013420 (2013)
line array	PRL **123**, 230501 (2019)

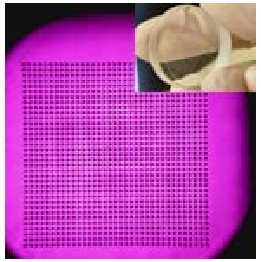
- dynamic line array

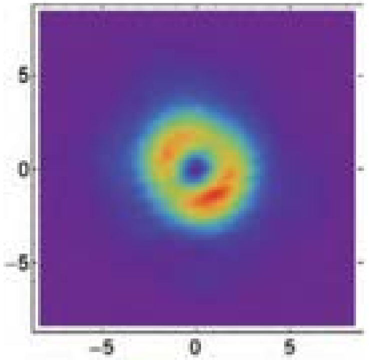
atoms trapped in
cages of light

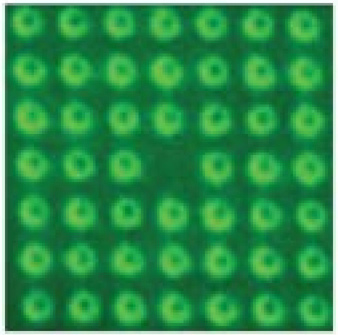


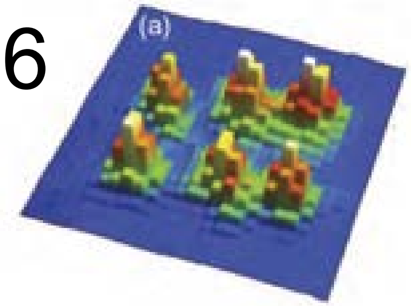
- Hole array

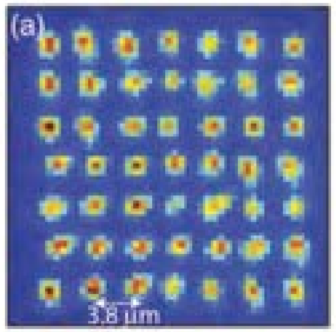
>1000 sites

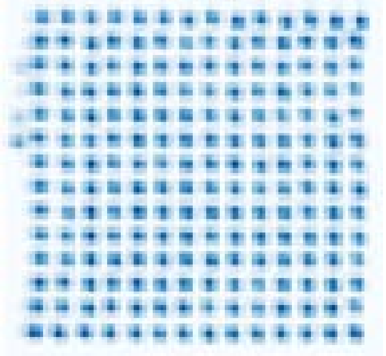












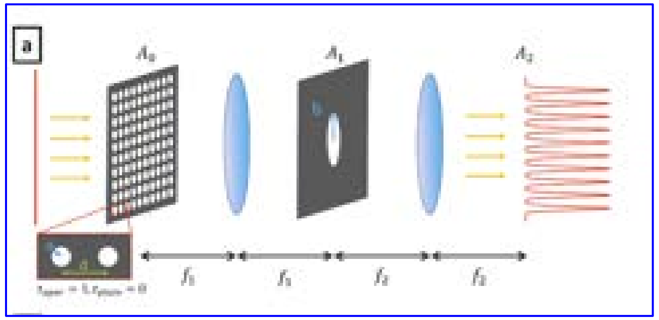
Scalable qubit registers

Dynamic line array

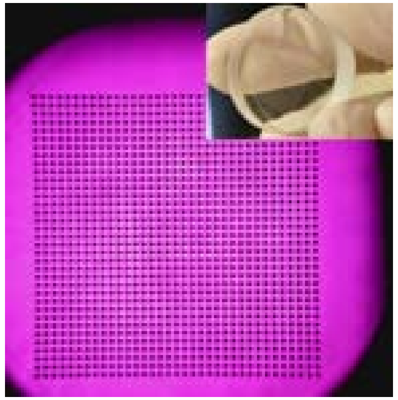
Up to 500 sites, currently in use.

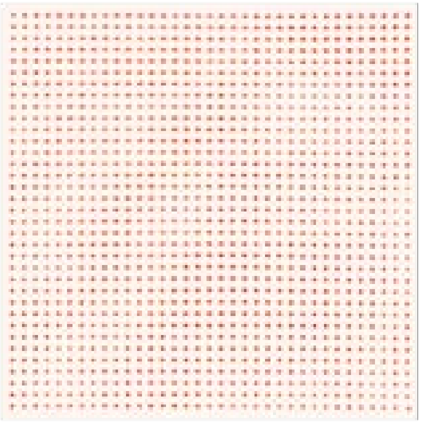
Hole array

Scalable to $>10^4$ sites



Component
1225 sites



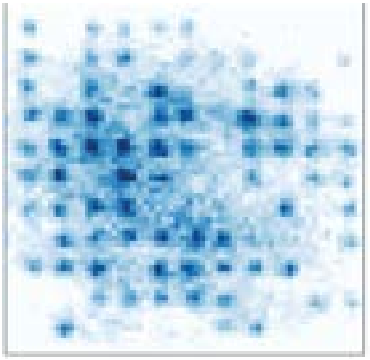


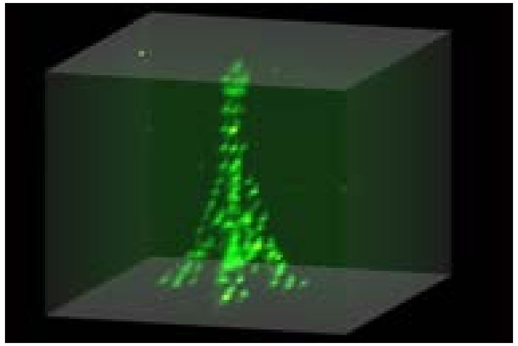
1225
Cs atoms

Atom Rearrangement

- Loading single atoms into a trap array is a stochastic process.

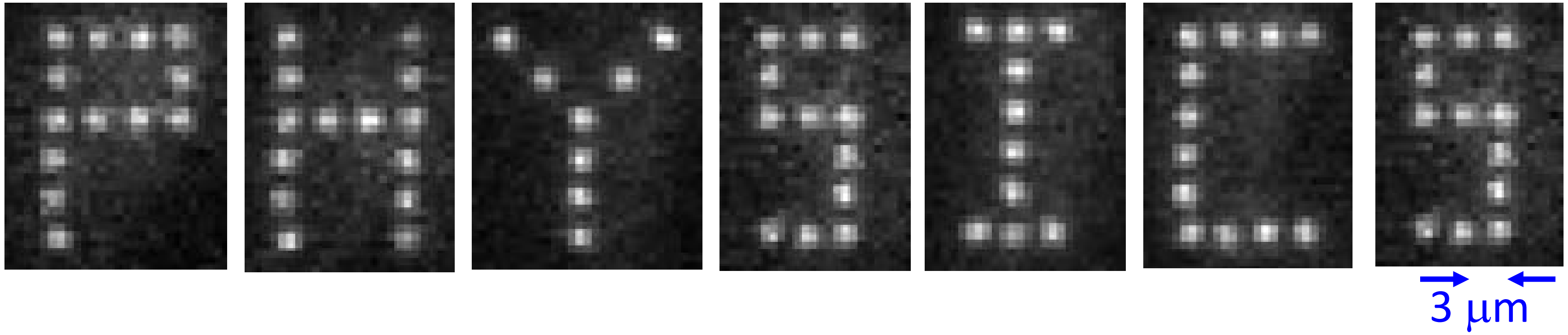
- The array is deterministically filled using "atom rearrangement".
  Works in 1D, 2D, 3D
  KAIST, Paris, Harvard, Darmstadt, Wuhan, Moscow, ….



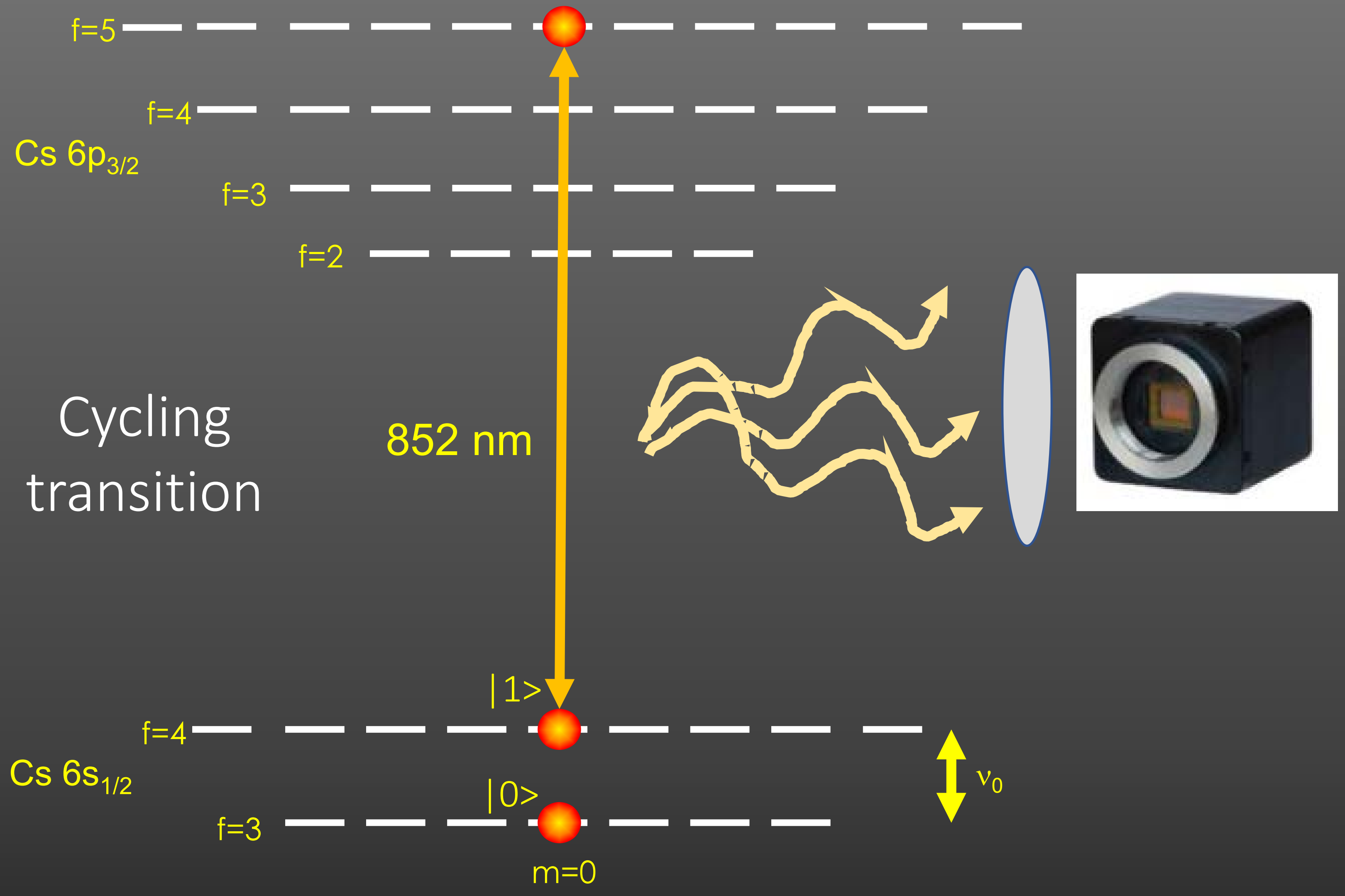


Browaeys group (2019)

2D acousto-optic scanner

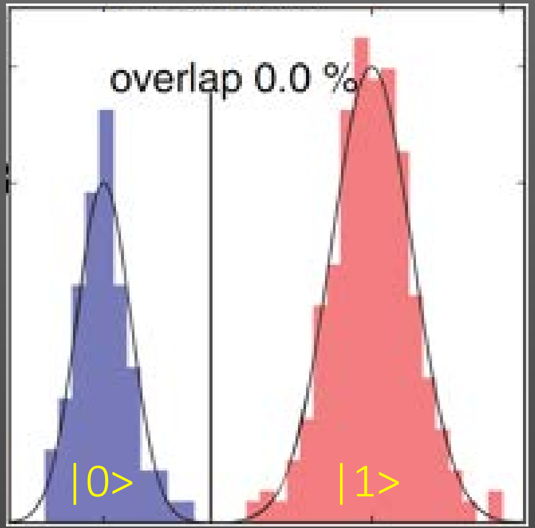


Qubit measurement



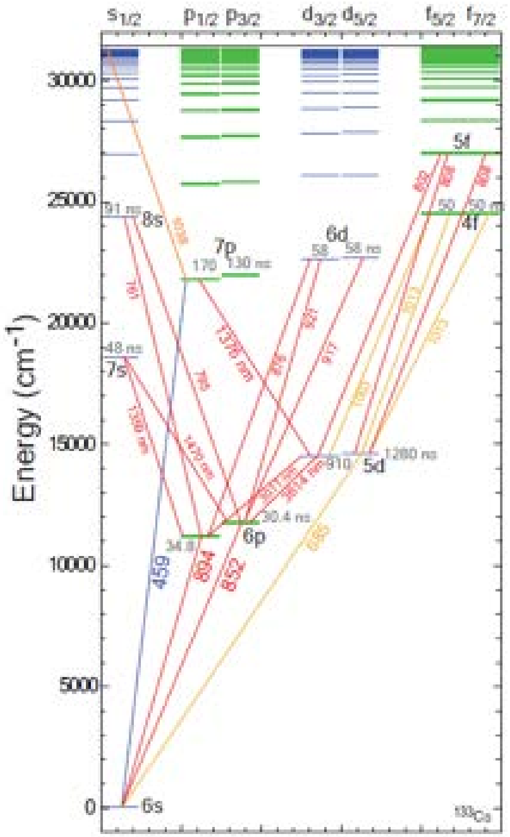
Cycling transition

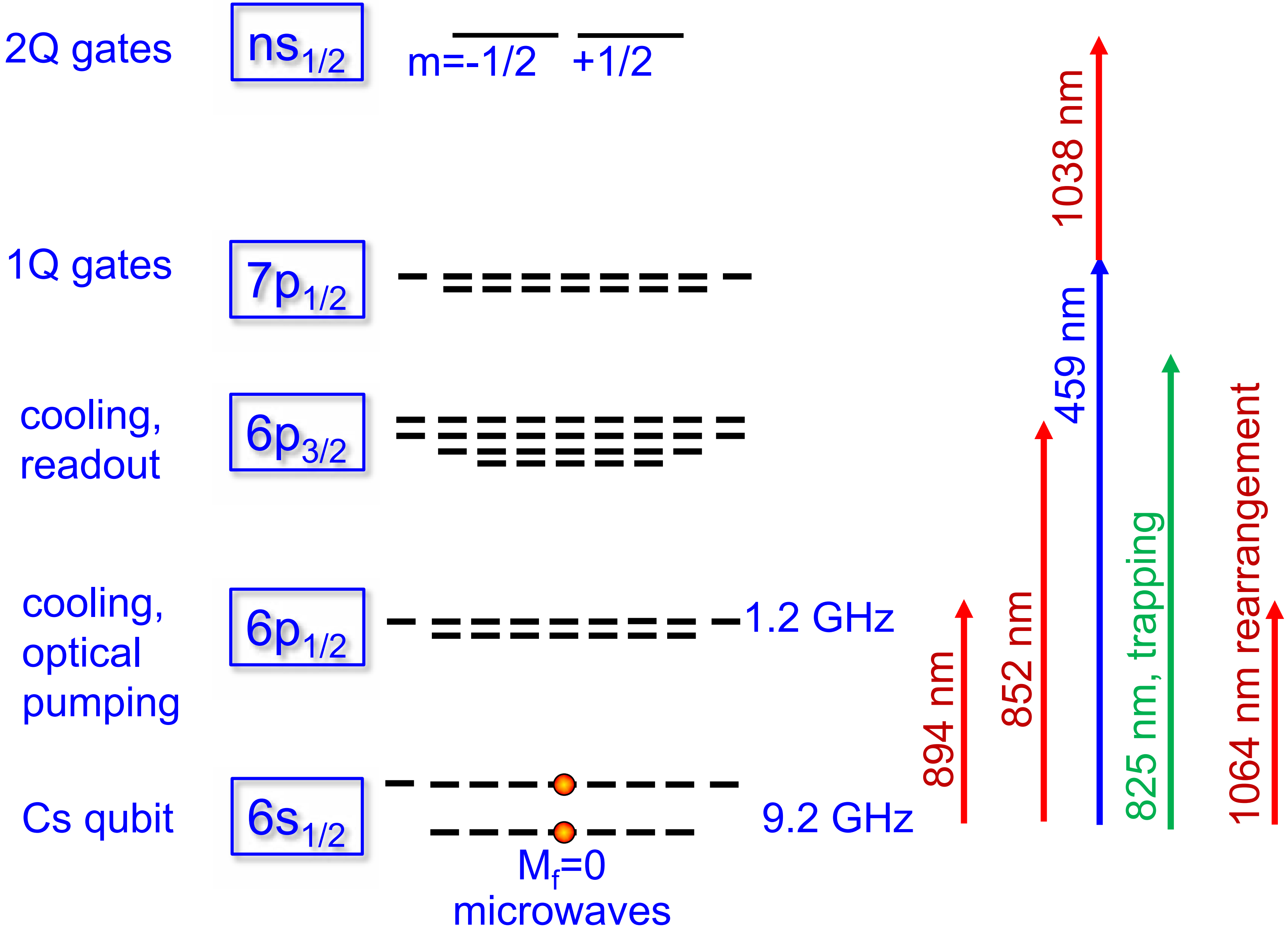
histogram



Photoelectron counts

Qubit control





2Q gates $ns_{1/2}$ m=-1/2 +1/2

1Q gates $7p_{1/2}$

cooling,
readout $6p_{3/2}$

cooling,
optical
pumping $6p_{1/2}$ 1.2 GHz

Cs qubit $6s_{1/2}$ 9.2 GHz

M_f=0
microwaves

894 nm

852 nm

459 nm

1038 nm

825 nm, trapping

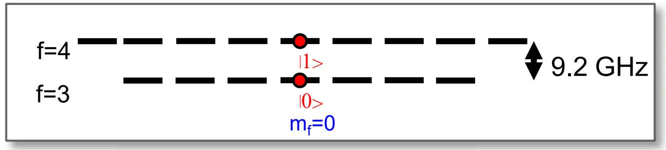
1064 nm rearrangement

- 6 different colors
- 13 lasers

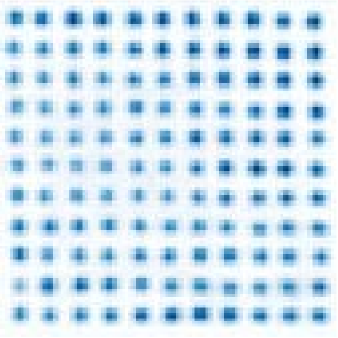
Single qubit gates - global

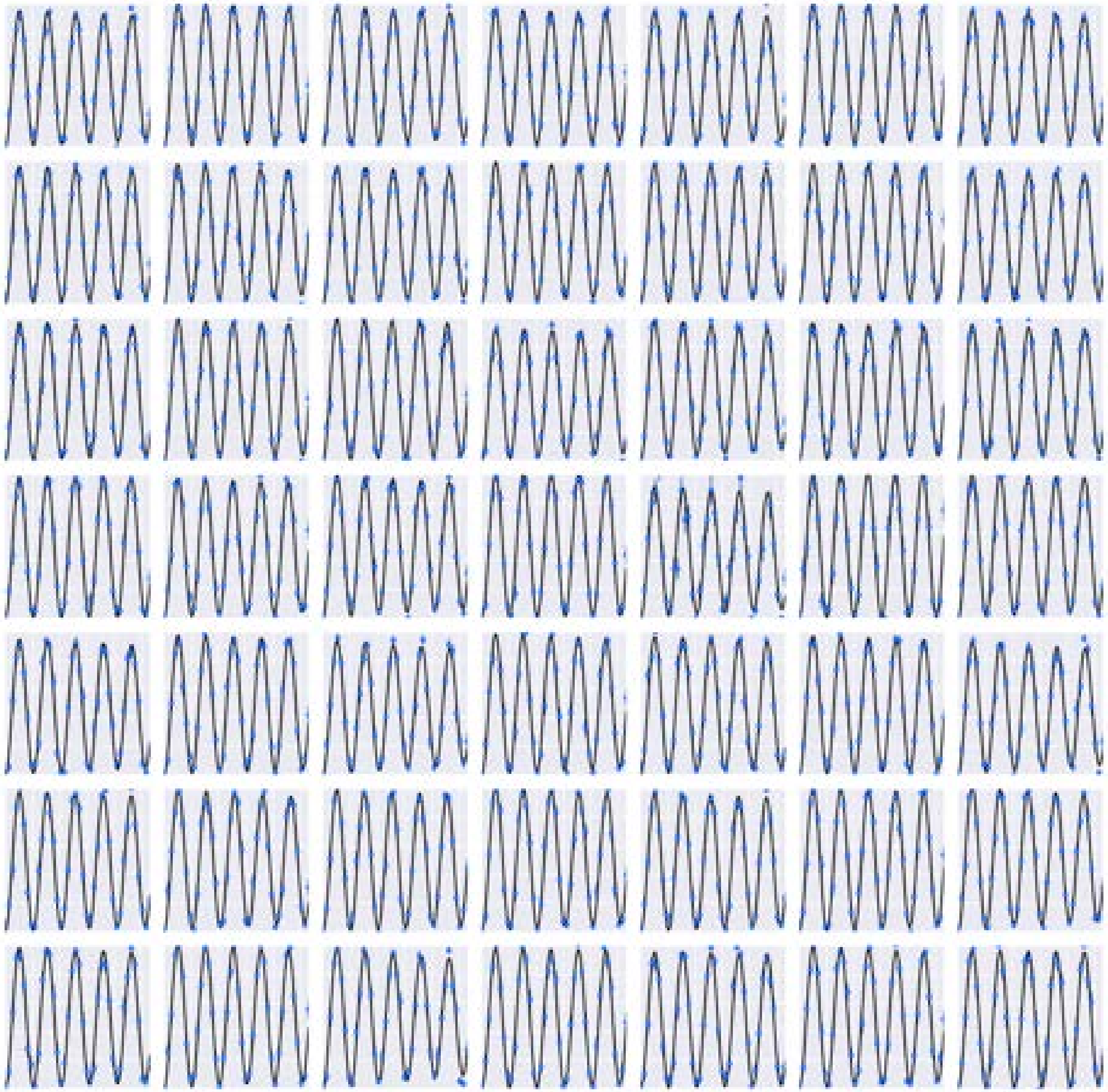
PRL 114, 100503 (2015)

Cs clock state qubits



Bias field of 1.5 G





Microwaves 10 kHz Rabi frequency

$\langle F^2\rangle_{47\ \text{sites}}$	0.9983 ± 0.0014
F^2_{min}	0.9939 ± 0.0007
F^2_{max}	0.9999 ± 0.0003

Microwaves 76 kHz Rabi frequency

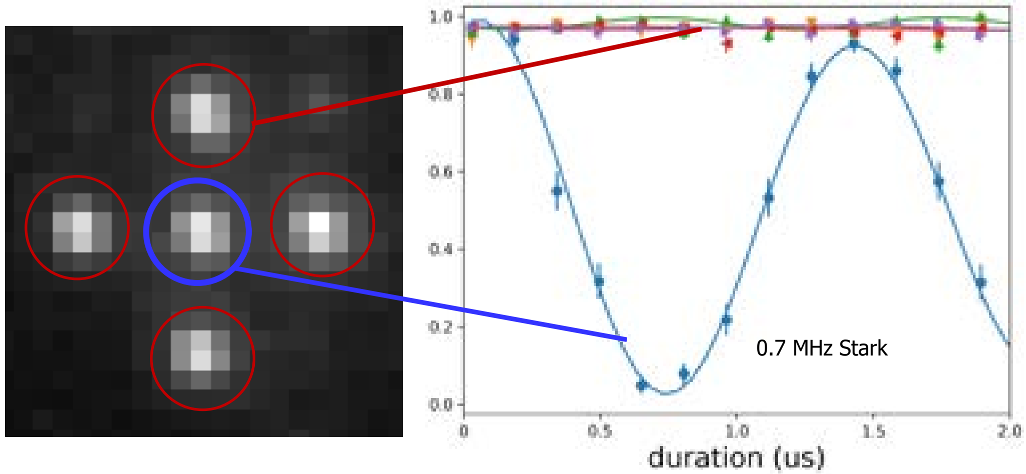
Single site control

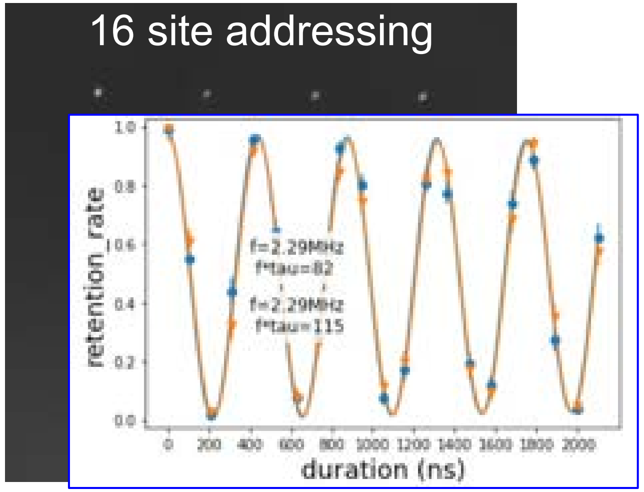
µwave 459 nm µwave

x-talk check: $R_x(\pi/2)$ $R_z(\theta)$ $R_x(-\pi/2)$

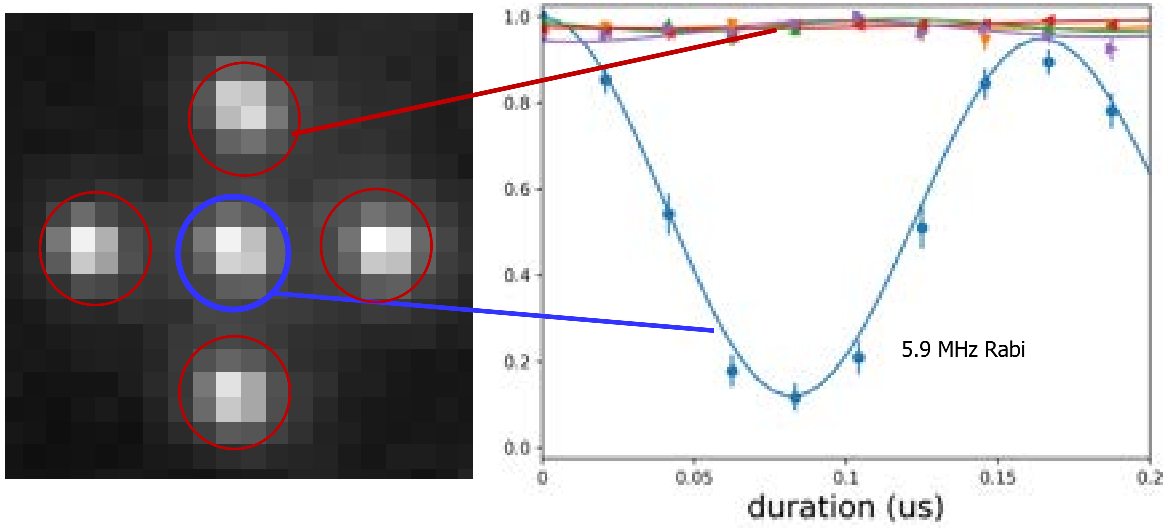
Site spacing 3 µm

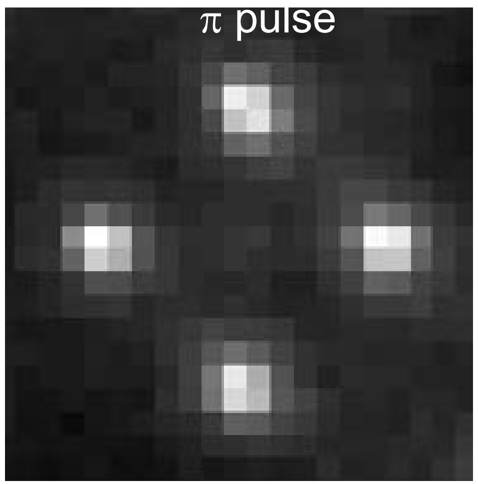
$R_x(\theta)$ rotation on single site





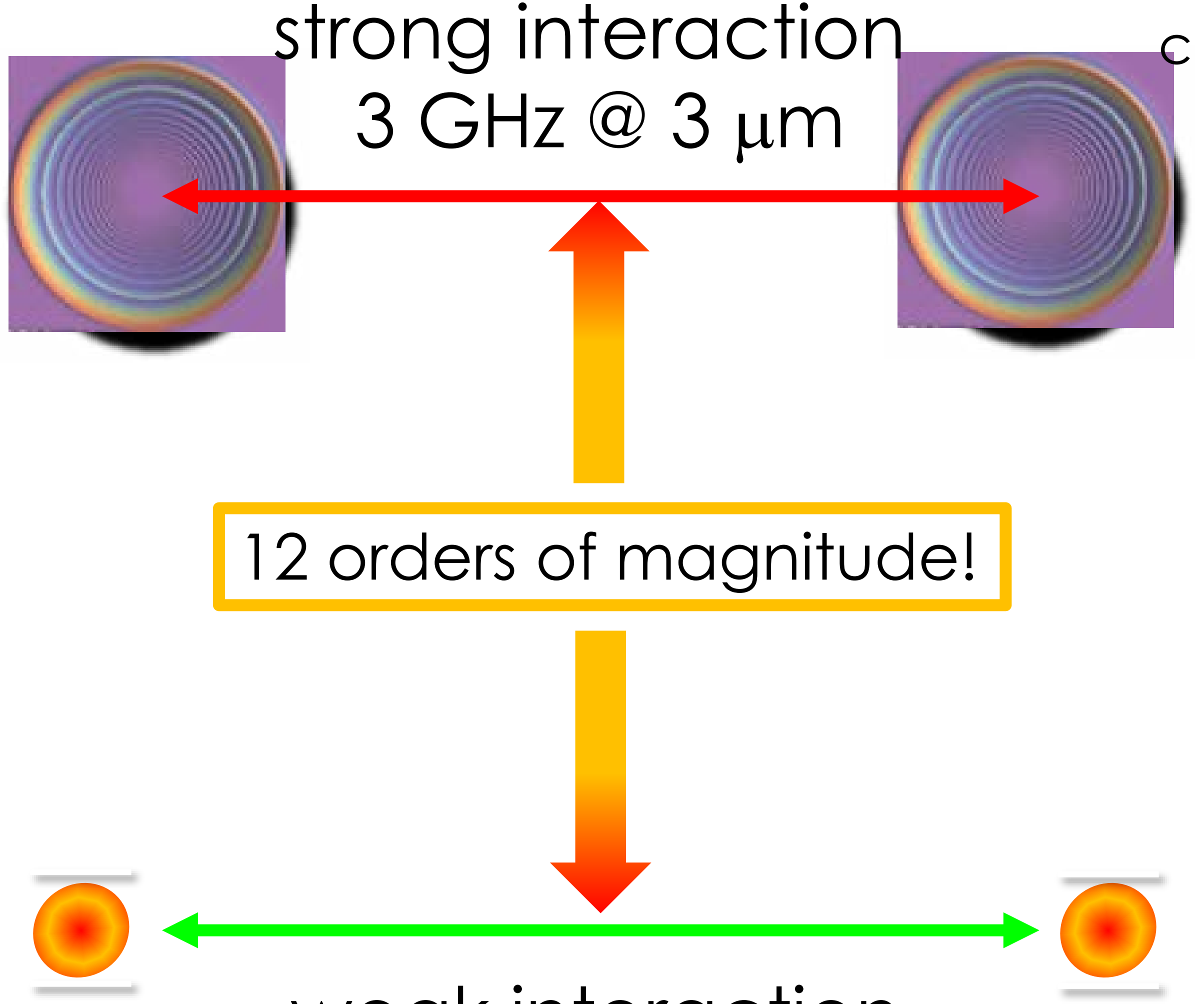
Ground-Rydberg Rabi on central site: 459+ 1040 nm





Atomic interactions and Rydberg atoms

Rydberg
Atoms
Cs 100s



strong interaction
3 GHz @ 3 μm

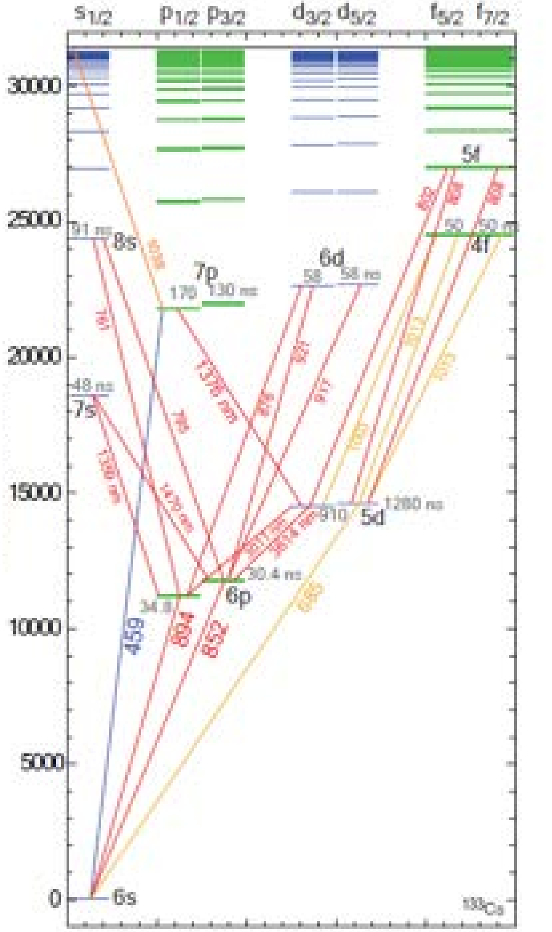
12 orders of magnitude!

weak interaction
0.001 Hz @ 3 μm

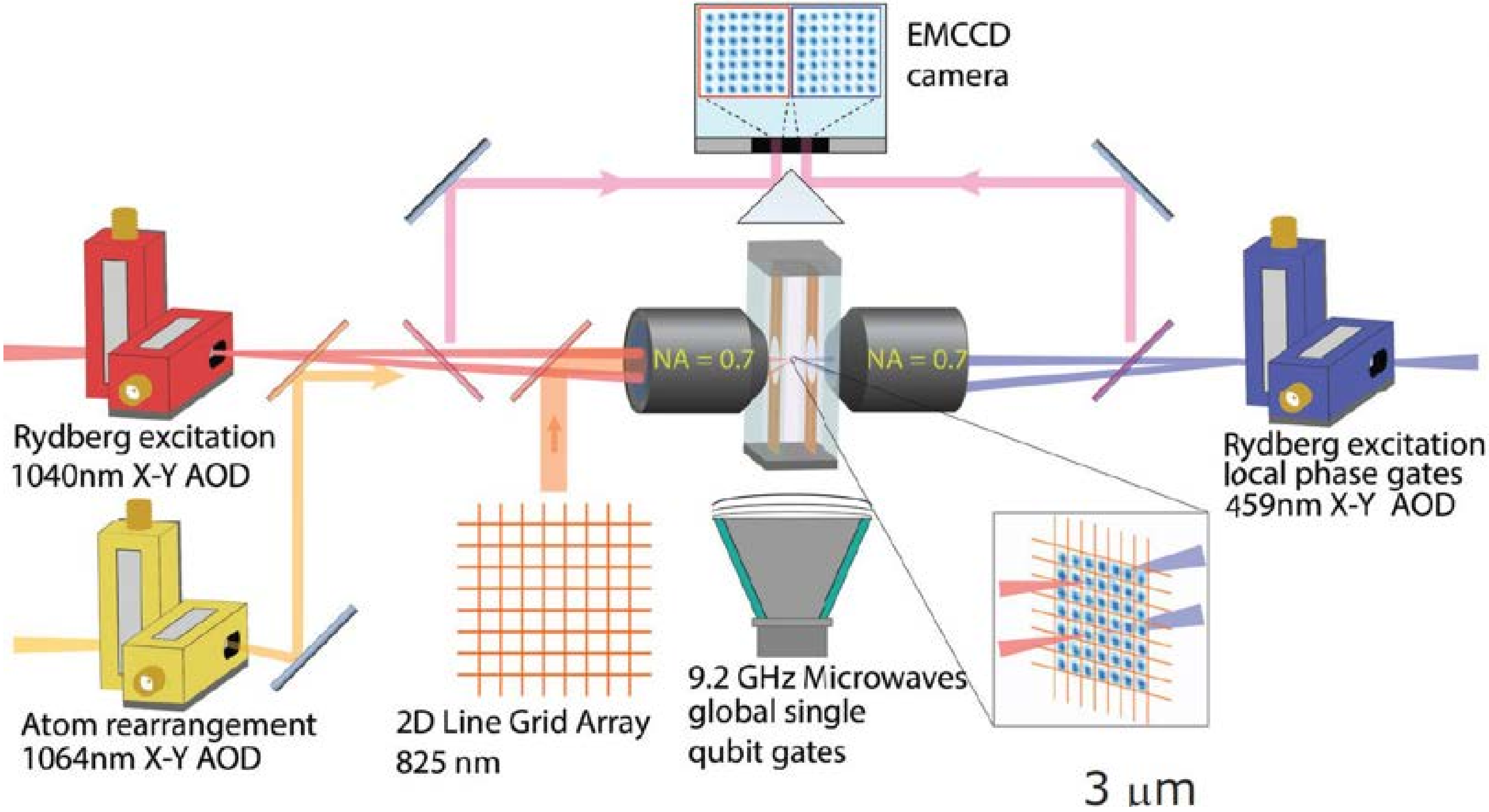
hyperfine
clock qubits

long coherence

Rydberg blockade –
cannot simultaneously
excite both atoms



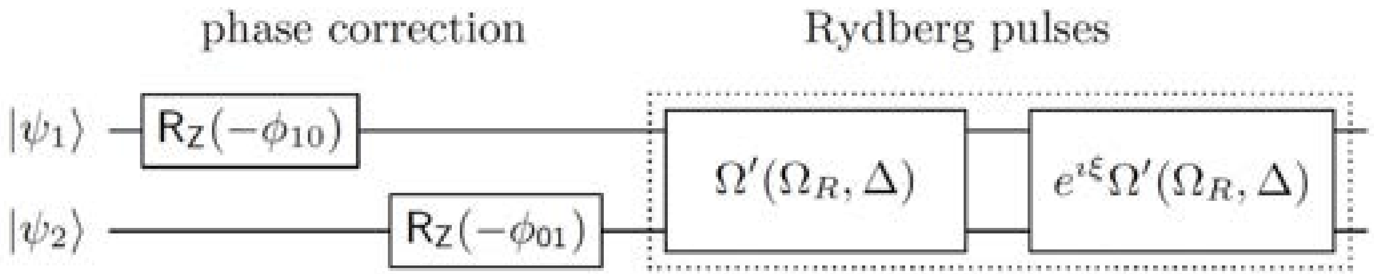
Experimental geometry

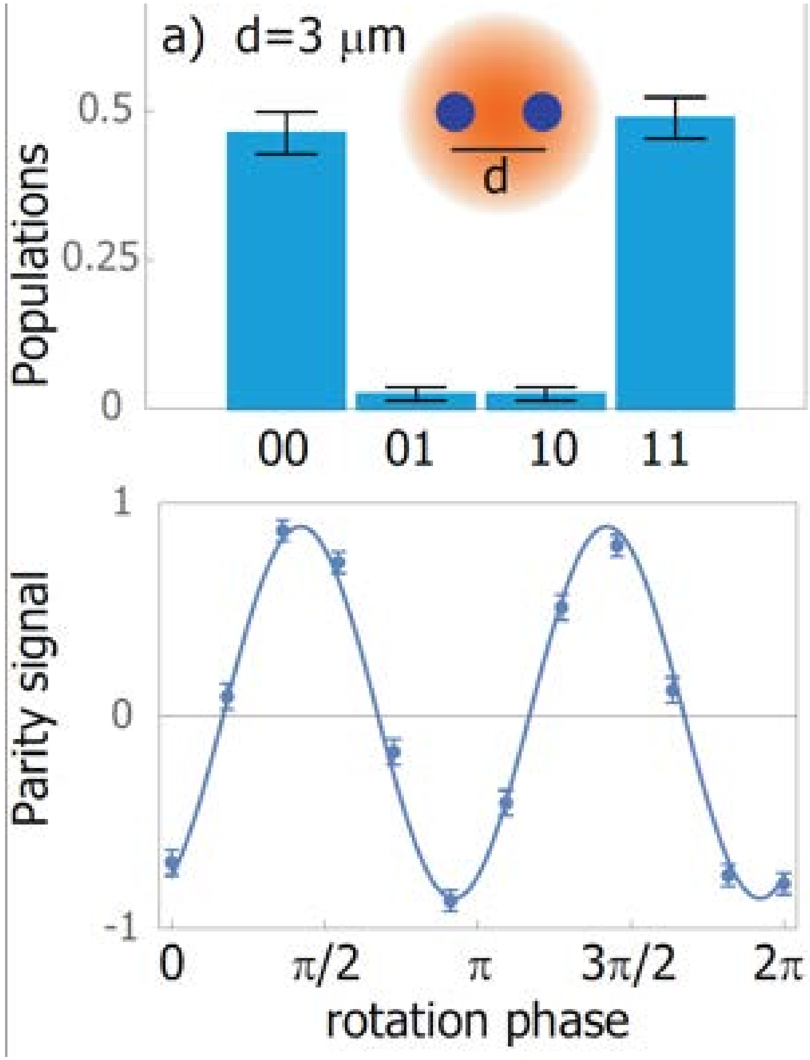


Entanglement demonstration

arXiv: 2112.14589

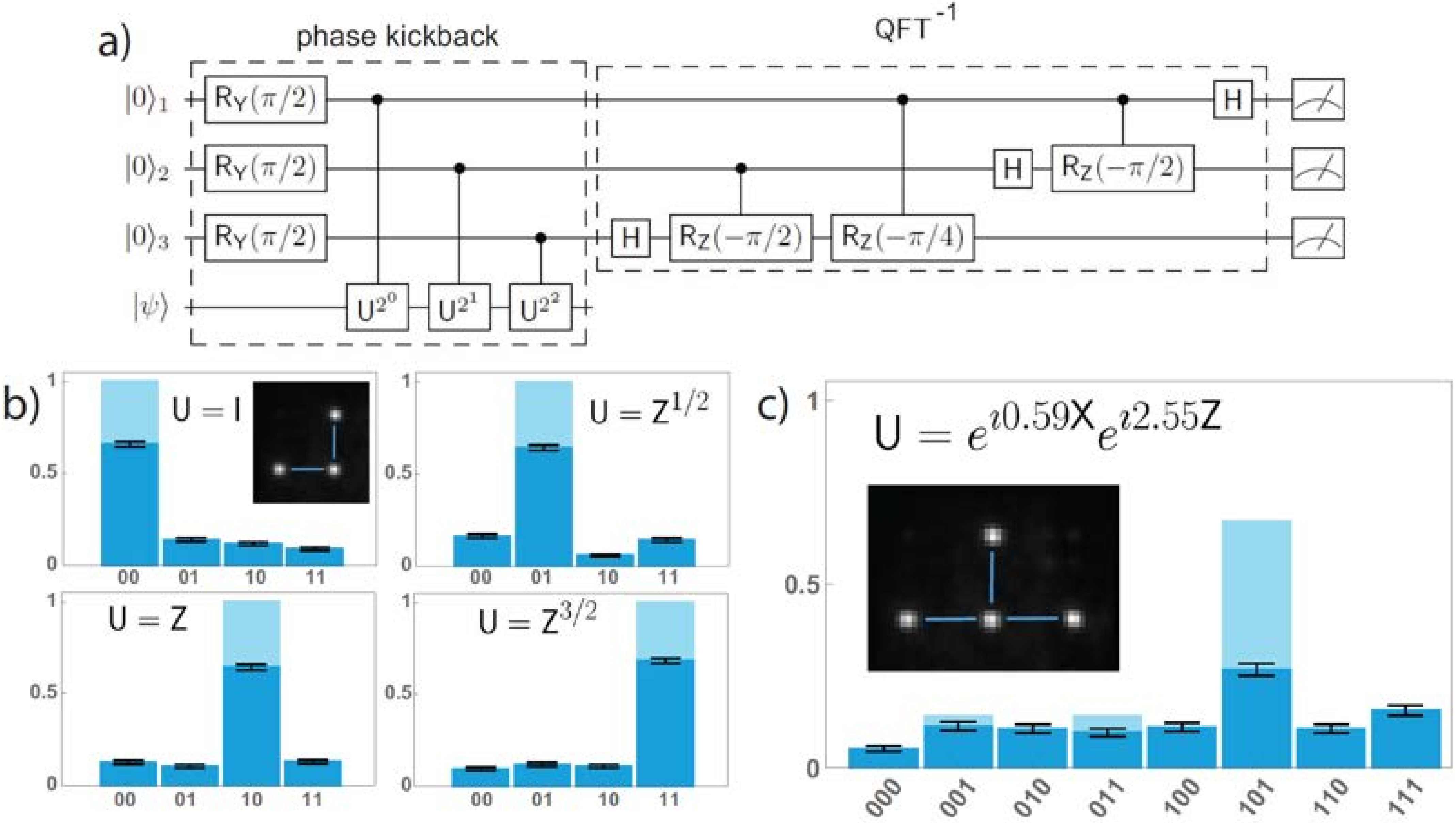
Fidelity F=0.955





Phase estimation – quantum chemistry

arXiv: 2112.14589



Summary

Quantum computing is a revolutionary approach to information processing.

There is great potential for solving hitherto intractable problems.

Quantum hardware is primitive, but under rapid development.

Hybrid approaches – classical optimizers with quantum co-processors are a near term opportunity.

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ColdQuanta

WISCONSIN QUANTUM INSTITUTE
Quantum Science and Engineering at UW–Madison

HQAN

Q-NEXT
NEXT GENERATION QUANTUM SCIENCE AND ENGINEERING

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