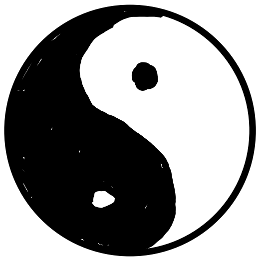
Introduction and Overview (Preskills Notes)

Inherent Contradictions

2. Gates vs **4. Isolation**

↑ coupling between qubits

↑ no coupling to environment



To build a Quantum Computer

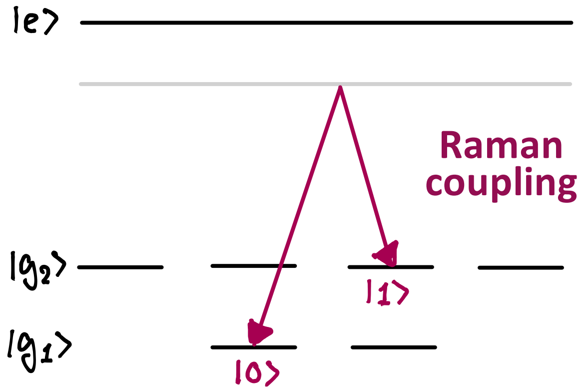
⇩

Choose, find or invent a system with acceptable tradeoffs

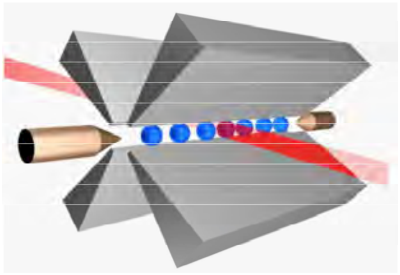
Ion Trap Quantum Computing

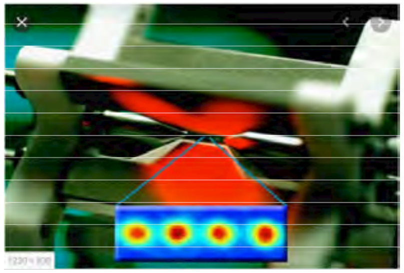
First to demonstrate a Quantum Gate

- **Qubit is encoded in the electronic ground state of an atomic ion**



- **Early design with a few ions in trap**

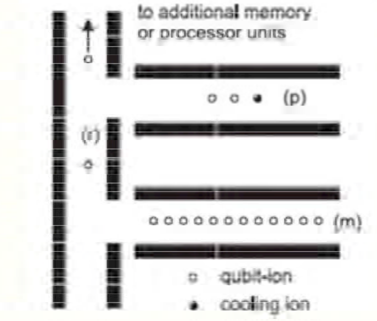




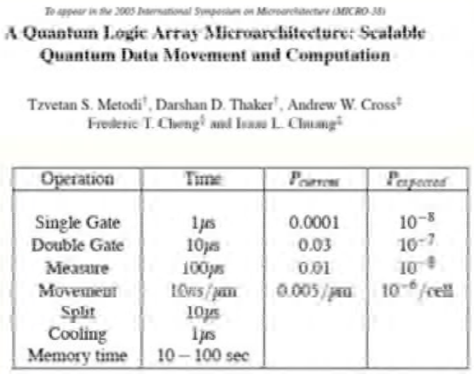
Introduction and Overview (Preskills Notes)

- Major challenges today – same as in 1998 !
- “Clock speed” set by vibrational freqs microfabricated traps do better
- More ions -> harder to cool motion, harder to individually address ions in linear trap.
- Scaling up to 1000’s of ions is an enormous challenge

Scalable Ion Trap Quantum Processor – one vision



D. Kielpinski, C. Monroe, and D. J. Wineland, Nature 417, 709 (2002).



To appear in the 2005 International Symposium on Microarchitecture (MICRO-38)

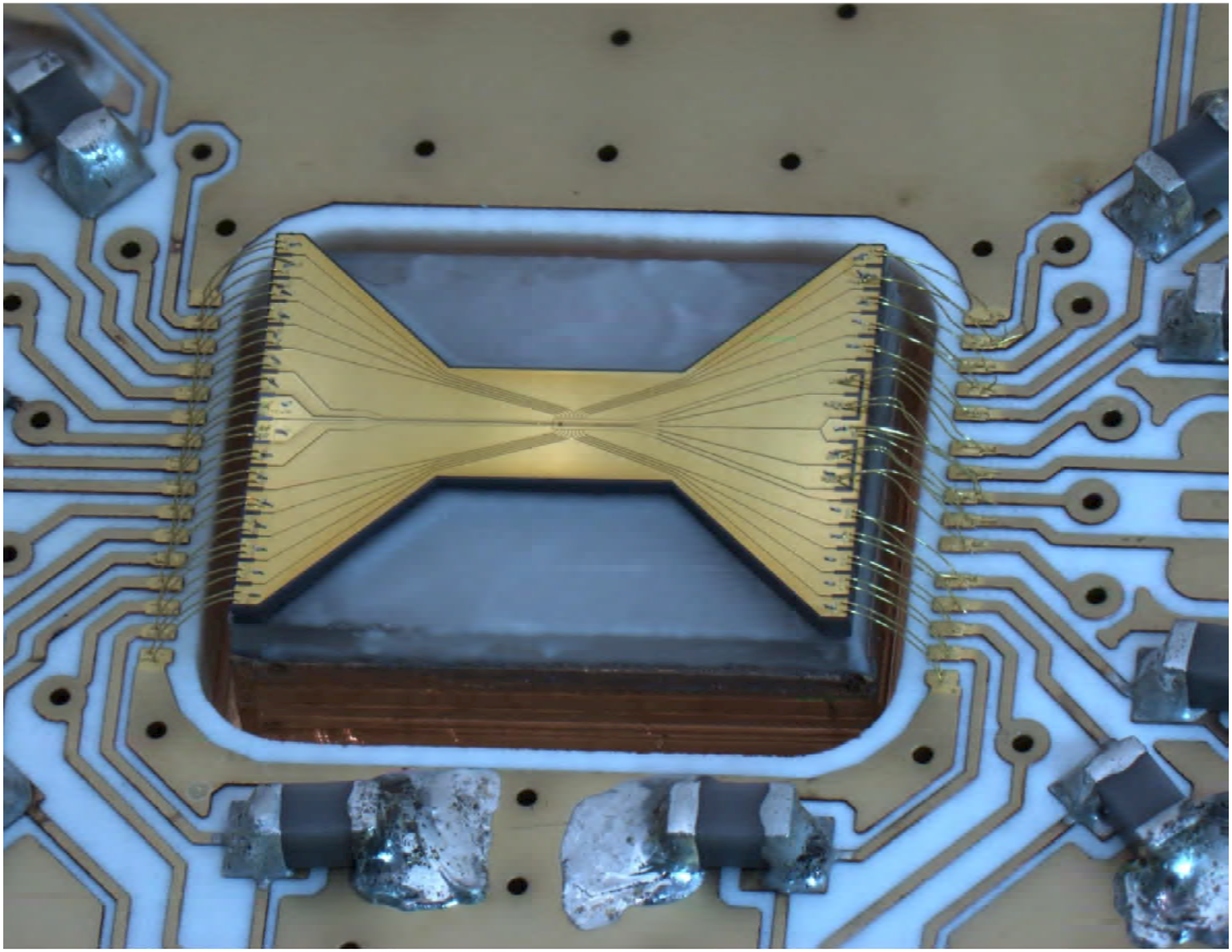
A Quantum Logic Array Microarchitecture: Scalable Quantum Data Movement and Computation

Tzvetan S. Metodi†, Darshan D. Thaker†, Andrew W. Cross‡
Frederic T. Chong† and Isaac L. Chuang‡

Operation	Time	$P_{current}$	$P_{expected}$
Single Gate	1μs	0.0001	10^{-8}
Double Gate	10μs	0.03	10^{-7}
Measure	100μs	0.01	10^{-8}
Movement	10ns/μm	0.005/μm	10^{-6}/cell
Split	10μs		
Cooling	1μs		
Memory time	10 – 100 sec		

Introduction and Overview (Preskills Notes)

NIST Group, Current as of 2023



Introduction and Overview (Preskills Notes)

Status: Many important milestones achieved

- Entanglement of ≥ 20 ions (2018)
- Highest gate & readout fidelities, longest coherence times
- Error Correction, Fault Tolerance proof of principle demonstrations
- Complex algorithms on few ions, quantum simulations with ≥ 50
- Research groups in academia, National Labs, Industry

Some leading groups

NIST **Quantinuum** **IonQ**

Sandia NL **Duke U**

Many, many others

Some links to get started

Amazon Braket (IonQ, other Technologies)
https://aws.amazon.com/braket/

Quantinuum (Ion Trap Quantum Computing
https://www.quantinuum.com

IonQ https://ionq.com

NIST https://www.nist.gov/pml/time-and-frequency-division/ion-storage

Challenge: Do a web search and look for the largest GHZ state made in the lab

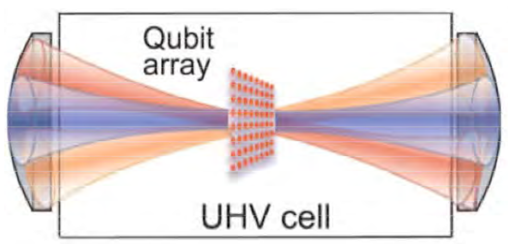
$$|GHZ\rangle = \frac{1}{\sqrt{N}}\left(|00\ldots00\rangle + |11\ldots11\rangle\right)$$

Note: What is the fidelity of the state ?

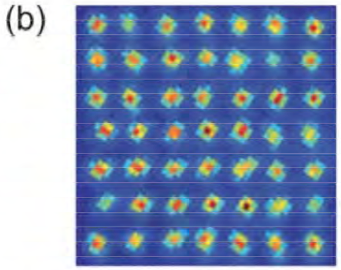
Introduction and Overview (Preskills Notes)

Neutral Atom based Quantum Processors

Optical tweezer array



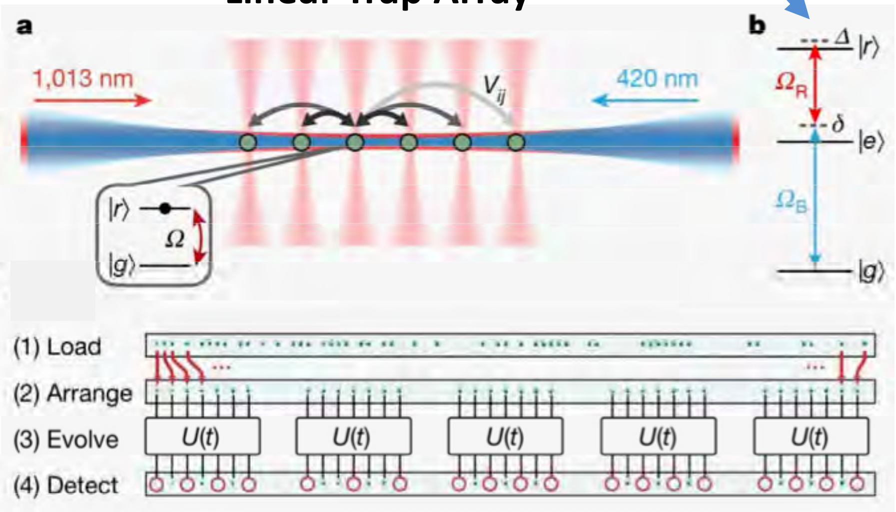
Fluorescing atoms



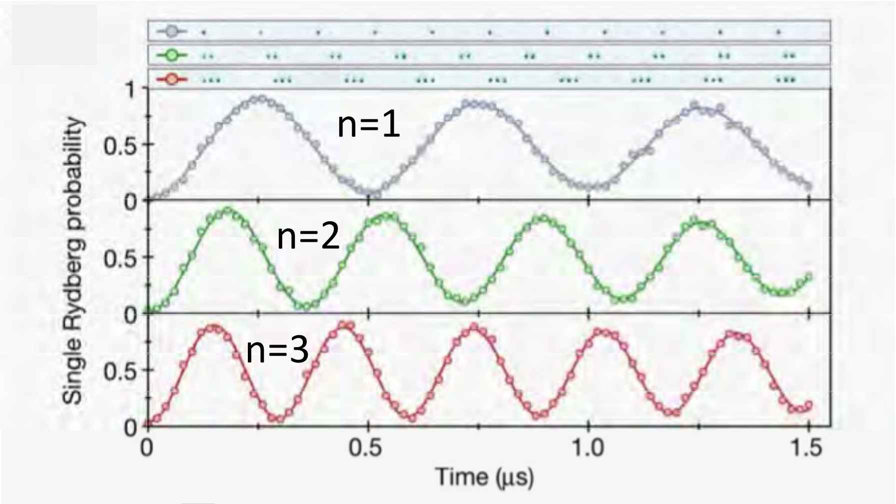
- Large numbers of non-interacting qubits, (≥ 100) trapped in 2D or 3D arrays.
- Qubits interact when excited into Rydberg states with large dipole moments
- Major advantage: Weak coupling to the environment when not doing gates
  ➡ excellent quantum memory
- Favorite platform for quantum simulation of quantum manybody physics
- BEC's in optical lattices as analog simulators of superconductivity, quantum magnetism and more.

Linear Trap Array

2-photon transition to a Rydberg state



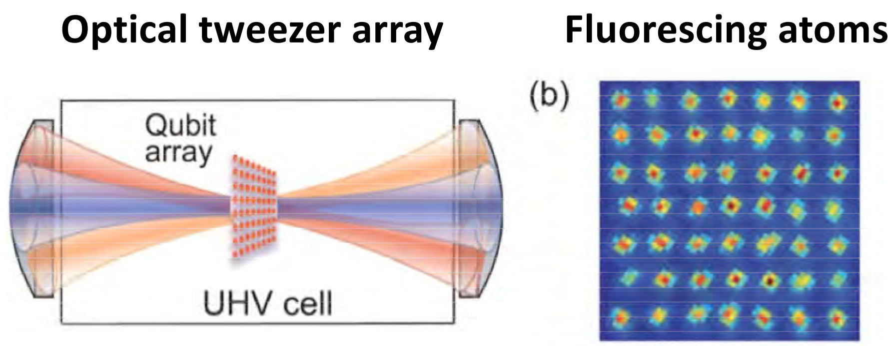
Sorted into groups of n ➡ $\sqrt{n}$ enhancement



$\sqrt{n}$ enhancement of Rabi frequency

Introduction and Overview (Preskills Notes)

Neutral Atom based Quantum Processors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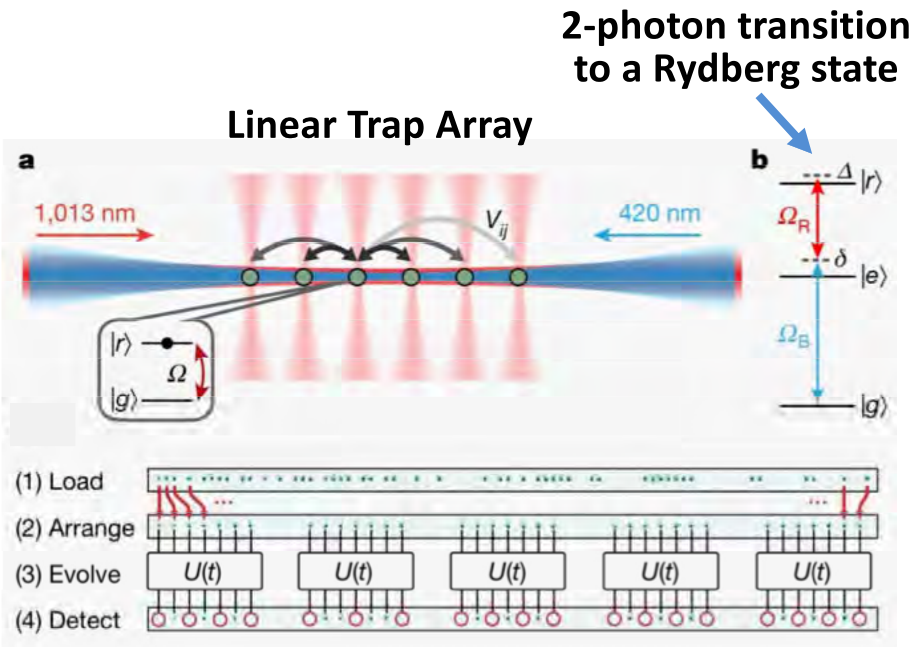

Linear Trap Array

2-photon transition to a Rydberg state

Sorted into groups of *n* ⇨ $\sqrt{n}$ enhancement

If we have *n* uniformly driven atoms in a group and only one of them can be excited into the Rydberg state at any time, the Rabi frequency is

$$n = 1 \quad \langle r | H_{int} | 1 \rangle = \hbar\Omega$$

$$n = 2 \quad \langle r | H_{int} \frac{1}{\sqrt{2}} (|01\rangle + |10\rangle) = \sqrt{2}\,\hbar\Omega$$

$$n = 3 \quad \langle r | H_{int} \frac{1}{\sqrt{2}} (|001\rangle + |010\rangle + |100\rangle) \sqrt{3}\,\hbar\Omega$$

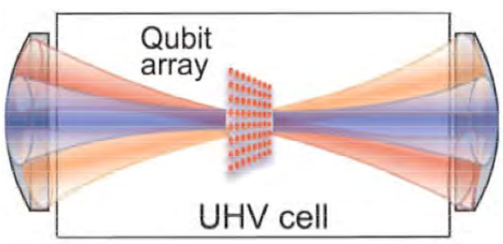
$$\vdots$$

$$n \quad \langle r | H_{int} \frac{1}{\sqrt{n}} \underbrace{(|0\ldots01\rangle + |1\ldots0\rangle)}_{n \text{ ways to excite one atom}} = \sqrt{n}\,\hbar\Omega$$

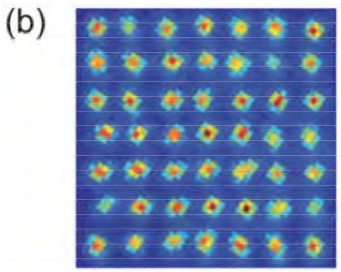
Introduction and Overview (Preskills Notes)

Neutral Atom based Quantum Processors

Optical tweezer array



Fluorescing atoms



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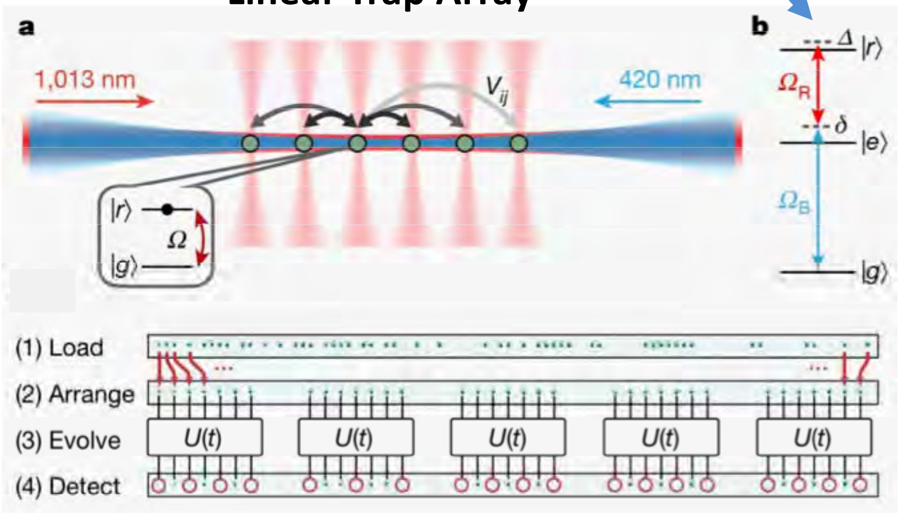
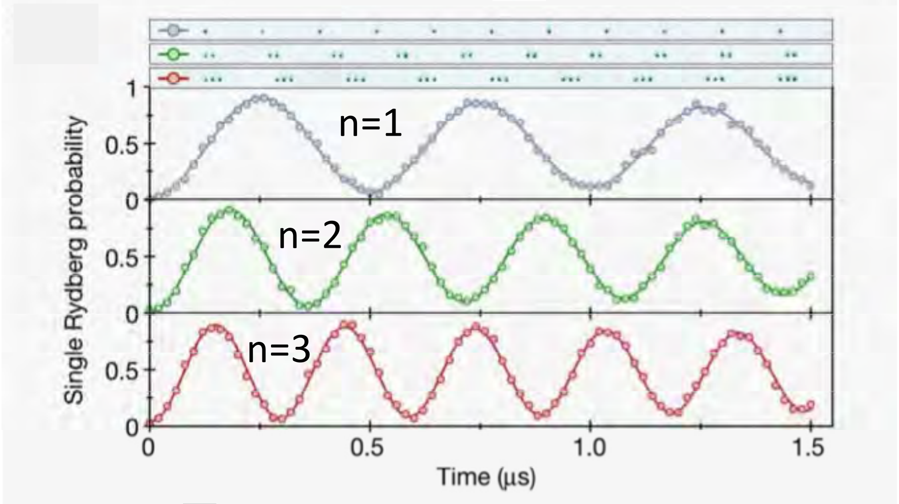


Sorted into groups of *n* ⇨ $\sqrt{n}$ enhancement

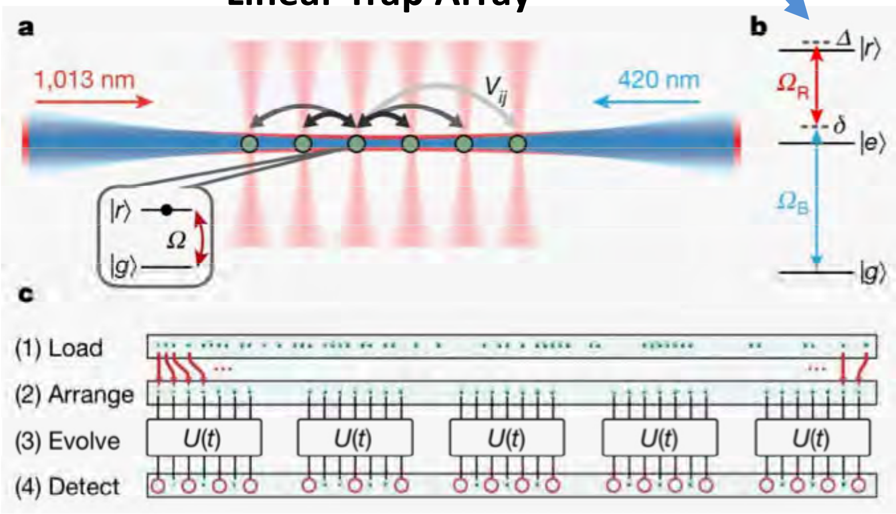


$\sqrt{n}$ enhancement of Rabi frequency

Introduction and Overview (Preskills Notes)

2-photon transition to a Rydberg state

Linear Trap Array



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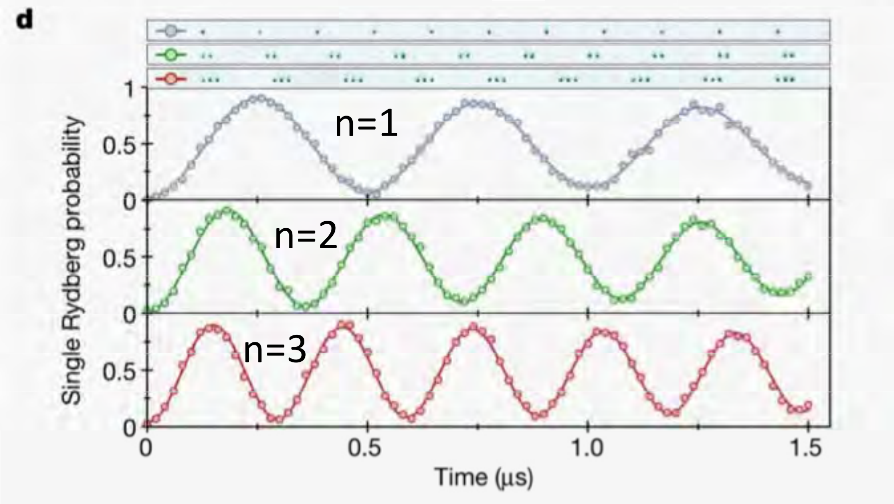
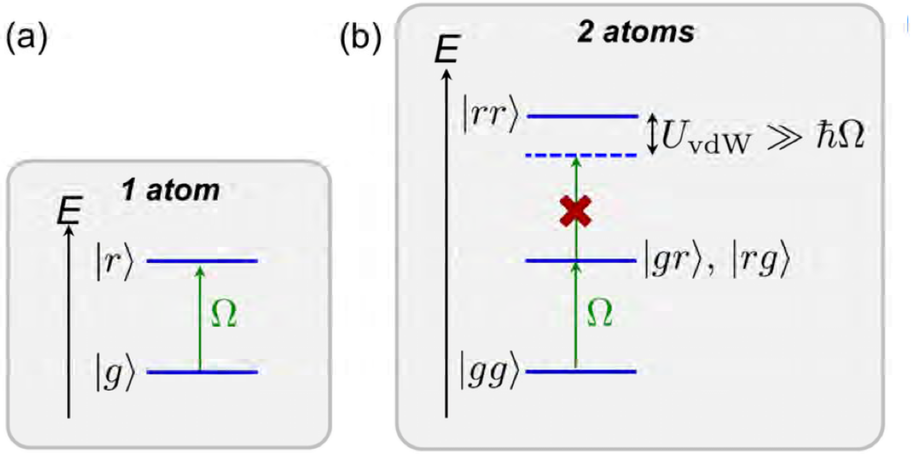


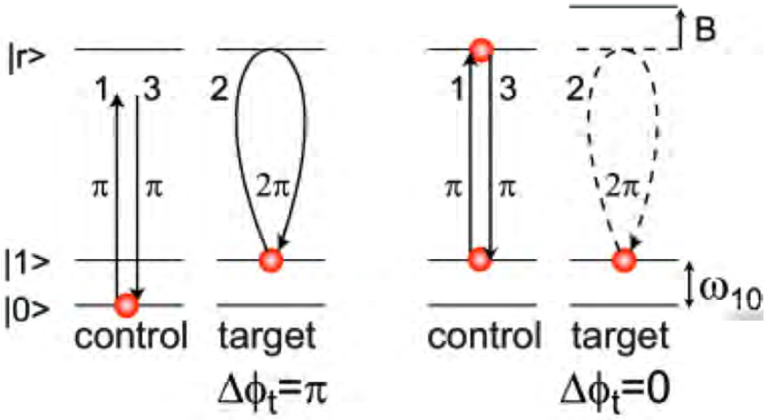
$\sqrt{n}$ enhancement of Rabi frequency

Rydberg Blockade



Principle of the Rydberg blockade. (a) A resonant laser couples, with strength Ω, the Rydberg state |r and the ground state |g of an atom. (b) For two nearby atoms, interactions U vdW shift the doubly excited state |rr, preventing the double excitation of the atom pair when U vdW Ω.

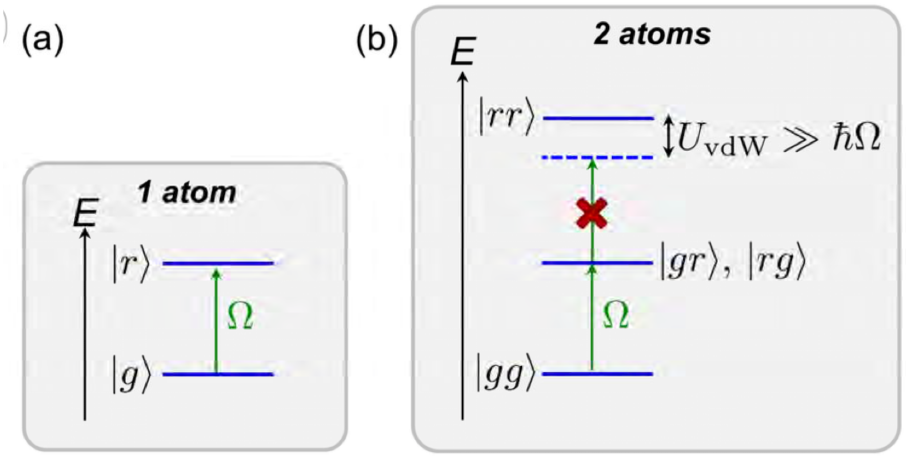
Controlled-Phase Gate



π phase shift of Target conditioned on Control

Introduction and Overview (Preskills Notes)

Rydberg Blockade



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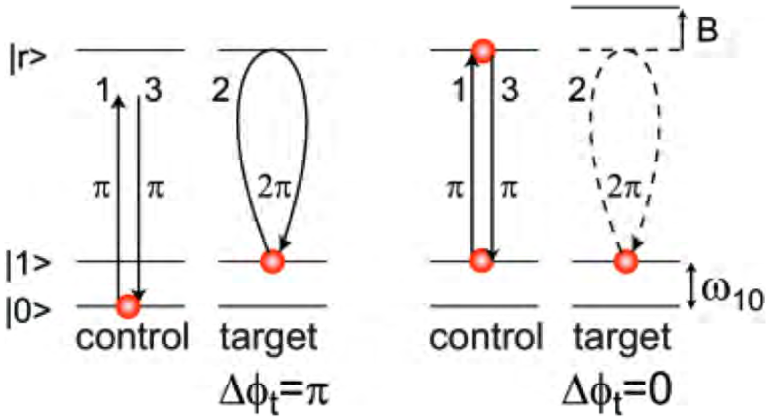


π phase shift of Target conditioned on Control

Some links to get started

QuEra	https://www.quera.com/aquila
Cold Quanta	https://coldquanta.com

Sandia, Los Alamos National Labs

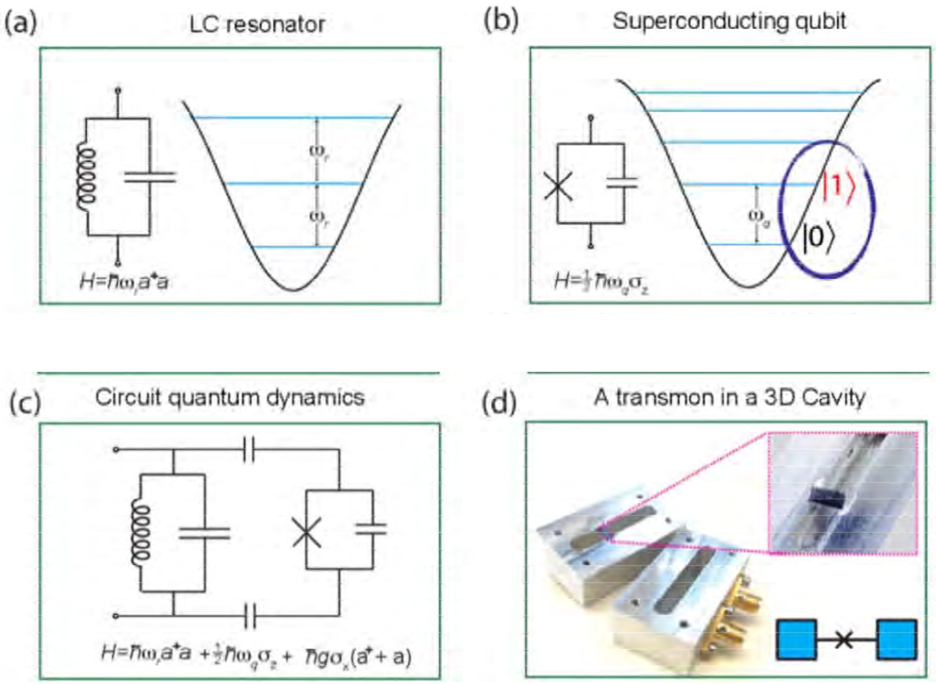
Individual PI's – Quantum Simulation

Lukin, Vuletic, Greiner, Endres, Bloch, Saffman, Biederman, Browaeys, Weiss, and many others…

Introduction and Overview (Preskills Notes)

Superconducting Qubits

- The basic building block is the so-called Transmon Qubit
- A Transmon is a nonlinear oscillator made from a Josephson Junction and other circuit elements

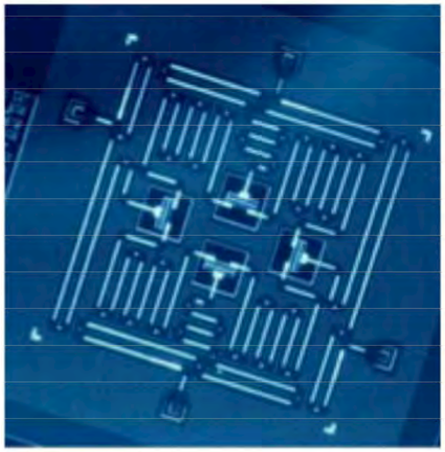


↑

Jaynes-Cummings Hamiltonian

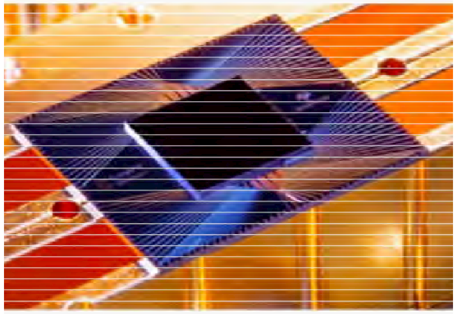
Superconducting Qubits

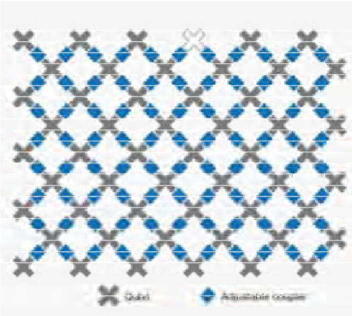
IBM 4–Transmon device (2017)



A device consisting of four transmon qubits, four quantum busses, and four readout resonators fabricated by IBM and published in npj Quantum Information in January 2017.[4]

Google 54–Transmon device (2019)





Introduction and Overview (Preskills Notes)

Superconducting Qubits

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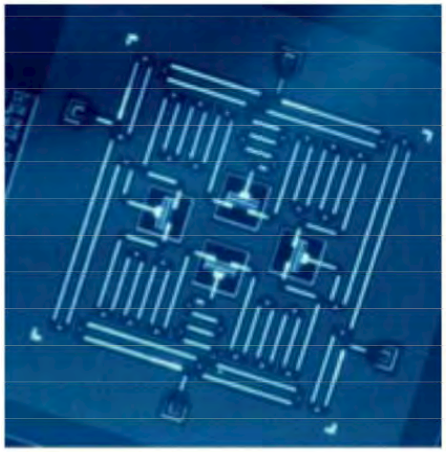

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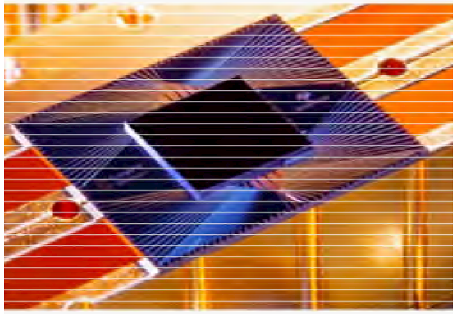
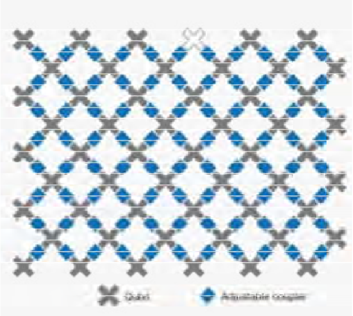




Advantages

- **Solid State platform, looks like electronics**
- **Clearer path to scale up to many qubits?**

Challenges

- **Gates, coherence times not as good as atomic platforms, but gap is closing**
- **Requires dilution refrigerator**

Industry Favorite

- **Large efforts at IBM, Google, Rigetti**

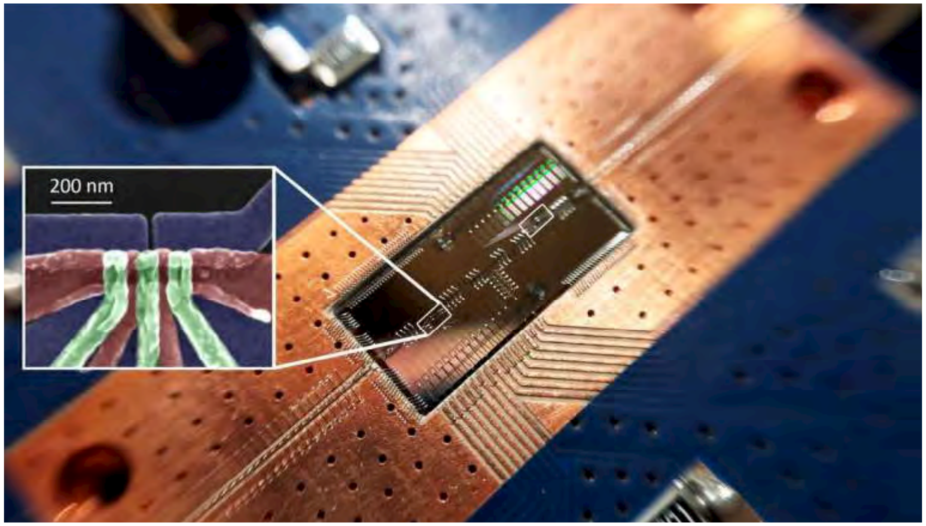
Cloud Quantum Computing

- **Amazon Braket** (IonQ, other Technology)

https://aws.amazon.com/braket/

Introduction and Overview (Preskills Notes)

Spins in Silicon Quantum Dots



- Si is highly scalable
- Qubits and Quantum Gates demonstrated
- Fidelities below State-of-the-Art
- HRL Laboratories, UNSW (Australia) group, Princeton Group, many others…

Introduction and Overview (Preskills Notes)

Comparing Physical Platforms: Status as of 2022

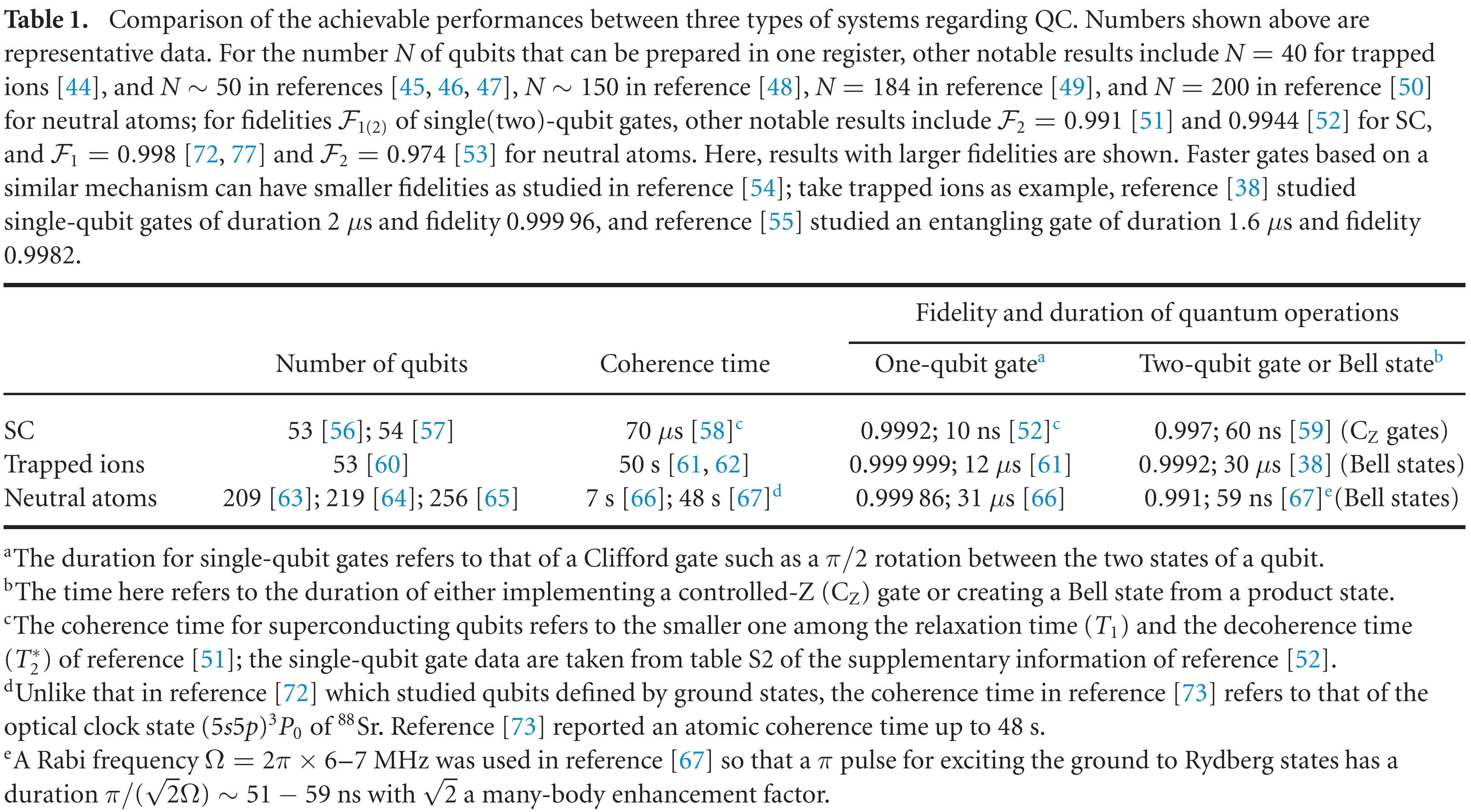


Table 1. Comparison of the achievable performances between three types of systems regarding QC. Numbers shown above are representative data. For the number N of qubits that can be prepared in one register, other notable results include $N = 40$ for trapped ions [44], and $N \sim 50$ in references [45, 46, 47], $N \sim 150$ in reference [48], $N = 184$ in reference [49], and $N = 200$ in reference [50] for neutral atoms; for fidelities $\mathcal{F}_{1(2)}$ of single(two)-qubit gates, other notable results include $\mathcal{F}_2 = 0.991$ [51] and 0.9944 [52] for SC, and $\mathcal{F}_1 = 0.998$ [72, 77] and $\mathcal{F}_2 = 0.974$ [53] for neutral atoms. Here, results with larger fidelities are shown. Faster gates based on a similar mechanism can have smaller fidelities as studied in reference [54]; take trapped ions as example, reference [38] studied single-qubit gates of duration 2 μs and fidelity 0.999 96, and reference [55] studied an entangling gate of duration 1.6 μs and fidelity 0.9982.

	Number of qubits	Coherence time	Fidelity and duration of quantum operations	
			One-qubit gate[a]	Two-qubit gate or Bell state[b]
SC	53 [56]; 54 [57]	70 μs [58][c]	0.9992; 10 ns [52][c]	0.997; 60 ns [59] (C_Z gates)
Trapped ions	53 [60]	50 s [61, 62]	0.999 999; 12 μs [61]	0.9992; 30 μs [38] (Bell states)
Neutral atoms	209 [63]; 219 [64]; 256 [65]	7 s [66]; 48 s [67][d]	0.999 86; 31 μs [66]	0.991; 59 ns [67][e](Bell states)

[a] The duration for single-qubit gates refers to that of a Clifford gate such as a $\pi/2$ rotation between the two states of a qubit.

[b] The time here refers to the duration of either implementing a controlled-Z (C_Z) gate or creating a Bell state from a product state.

[c] The coherence time for superconducting qubits refers to the smaller one among the relaxation time (T_1) and the decoherence time (T_2^*) of reference [51]; the single-qubit gate data are taken from table S2 of the supplementary information of reference [52].

[d] Unlike that in reference [72] which studied qubits defined by ground states, the coherence time in reference [73] refers to that of the optical clock state $(5s5p)^3P_0$ of ^{88}Sr. Reference [73] reported an atomic coherence time up to 48 s.

[e] A Rabi frequency $\Omega = 2\pi \times 6$–7 MHz was used in reference [67] so that a π pulse for exciting the ground to Rydberg states has a duration $\pi/(\sqrt{2}\Omega) \sim 51 - 59$ ns with $\sqrt{2}$ a many-body enhancement factor.

Introduction and Overview (Preskills Notes)

Other Platforms

Nuclear Magnetic Resonance

- Qubits encoded in spin-1/2 nuclei in a single molecule.
- Mature technology, many early proof of principle demonstrations
- Fundamentally not scalable, many early demonstrations, largely abandoned

Photonics

- Photons can carry QI in, e. g., their polarization state.
- Great for transmitting quantum info
- Easy to make, transmit and detect
- Difficult to store ⇨ work on photon Quantum Memories
- Photon-photon gates in cavities, mediated By Rydberg polaritons, One-Way Q.C., Measurement based Quantum Computing

Haroche (ENS), Rempe (MPQ),
Schoelkopf (Yale), others

Introduction and Overview (Preskills Notes)

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Other Platforms

- NV Centers in Diamond – Good for Quantum Sensing
- Electrons floating on liquid Helium

⋮

Introduction and Overview (Preskills Notes)

ARTICLE

https://doi.org/10.1038/s41467-019-13335-7

OPEN

Coupling a single electron on superfluid helium to a superconducting resonator

Gerwin Koolstra[1], Ge Yang[1] & David I. Schuster[1*]

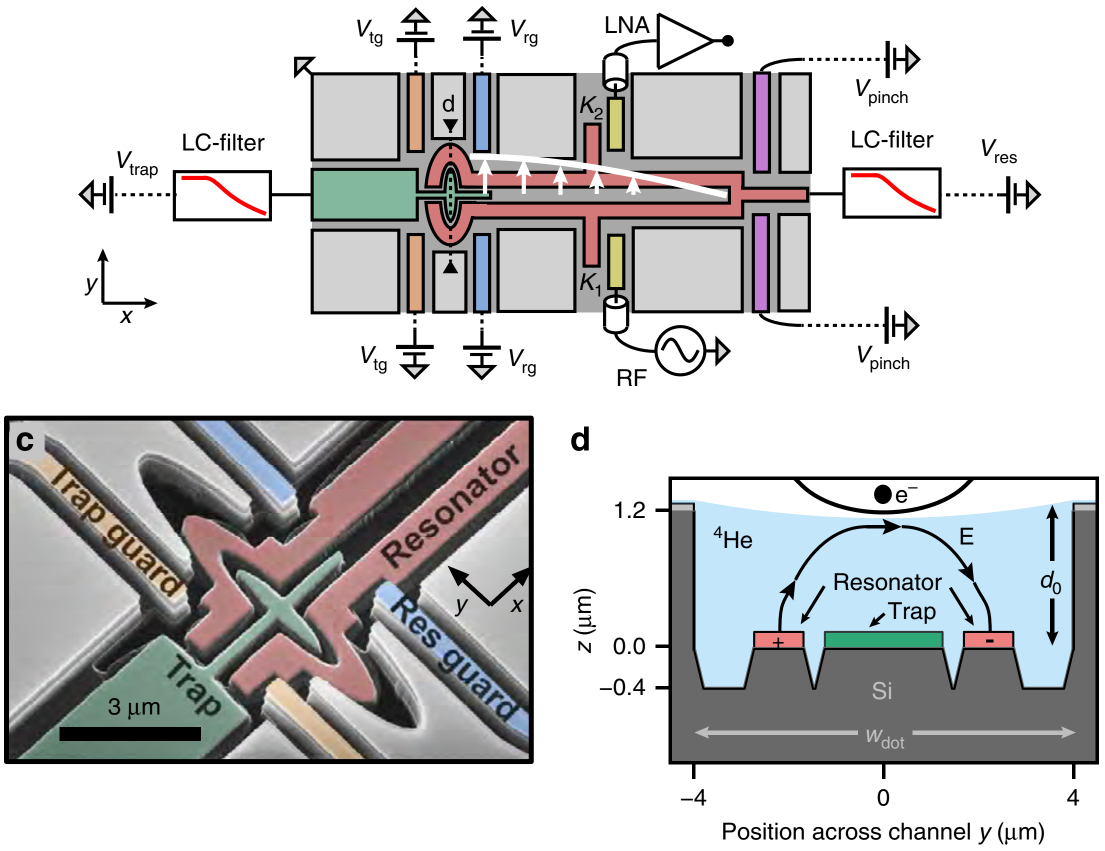

Fig. 1 An electron-on-helium dot **a** Optical micrograph and **b** schematic of the device. The resonator (red) can be probed with microwaves via coplanar waveguides

Introduction and Overview (Preskills Notes)

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⋮

Introduction and Overview (Preskills Notes)

Let’s go look at some websites…