# QY4. Qubit Devices

- Ion trap Qubits
- Neutral atoms

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## Lesson #2

DEMOCRITUS UNIVERSITY OF THRACE
DEPARTMENT OF ELECTRICAL & COMPUTER ENGINEERING

MSc in QUANTUM COMPUTING AND QUANTUM TECNNOLOGIES

NATIONAL CENTRE FOR SCIENTIFIC RESEARCH "DEMOKRITOS"

# Ion Trap Qubits

## The optical alternative

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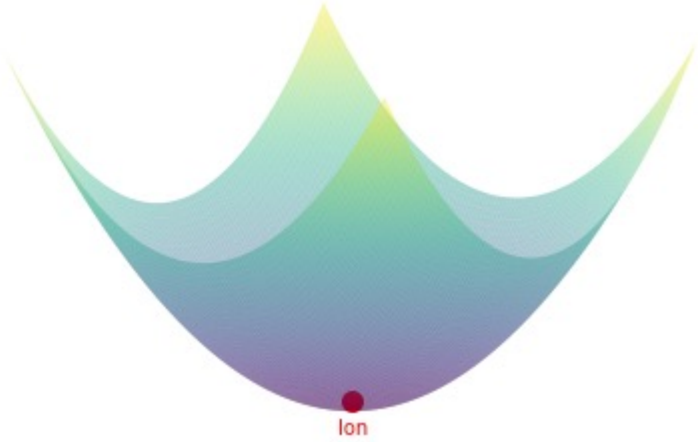
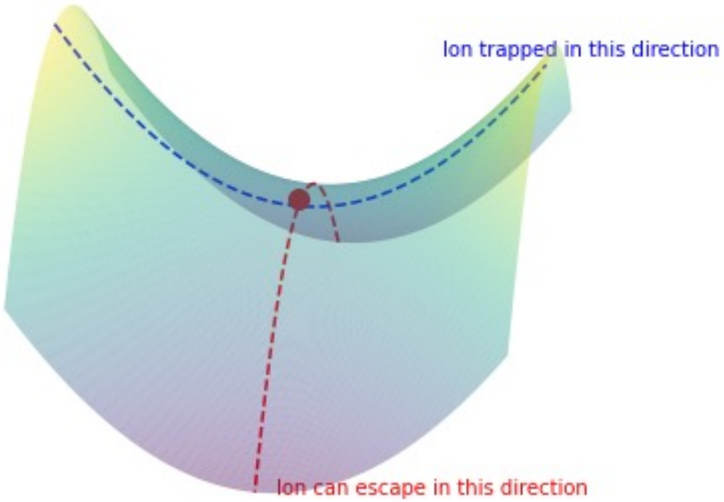
# Ion-traps History

**1953** : Wolfgang Paul proposed his now-called Paul trap [W. Paul, H. Steinwedel. (1953) “Ein neues Massenspektrometer ohne Magnetfeld”, RZeitschrift für Naturforschung A 8 (7): 448-450]. For this invention, Paul and Dehmelt were awarded the 1989 Physics Nobel Prize, since it is used to make highly precise atomic clocks.

**Current trapped ion** quantum computers extensively use the Paul trap, but Paul won the prize six years before such an application was proposed [J. Cirac, P. Zoller. (1995) “Quantum Computations with Cold Trapped Ions”. Physical Review Letters 74 (20): 4091–4094]!

# Trapping Electric Field / Potential





Using the laws of electrostatics, we can show that it is impossible to create a confining potential with only static electric fields.

# But

…if the saddle potential rotates at a specific frequency, the wall will catch the ion as it tries to escape in the downhill direction. Explicitly, the electric potential that we generate is given by

$$\Phi = \frac{1}{2}\left(u_x x^2 + u_y y^2 + u_z z^2\right) + \frac{1}{2}\left(v_x x^2 + v_y y^2 + v_z z^2\right)\cos(\omega t + \phi)$$

The parameters $u$, $v$, and need to be adjusted to the charge and mass of the ion and to the potential's angular frequency . We have to tune these parameters very carefully, since the ion could escape if we do not apply the right forces at the right time.

https://ethz.ch/content/dam/ethz/special-interest/phys/quantum-electronics/tiqi-dam/documents/phd_theses/Thesis-Maciej-Malinowski

# Ion chain in a trap

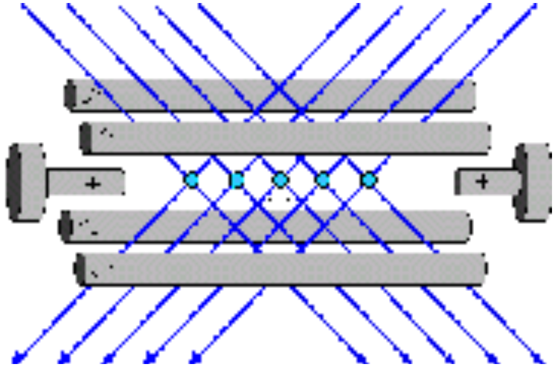
We have the technology to trap many ions and put them close together in a one-dimensional array, called an ion chain.

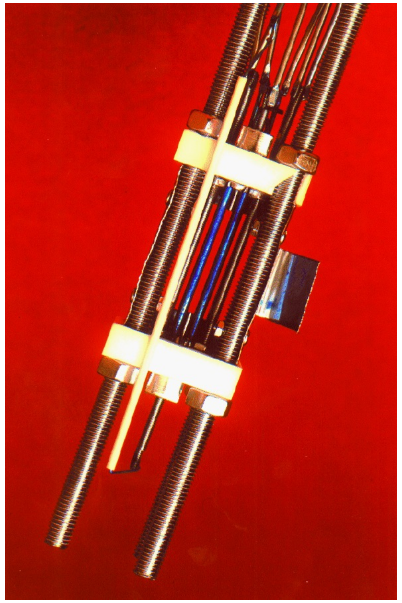
Shooting a photon at an ion can cause relative motion between ions. The proximity between qubits will cause unwanted interactions, which could modify their state.

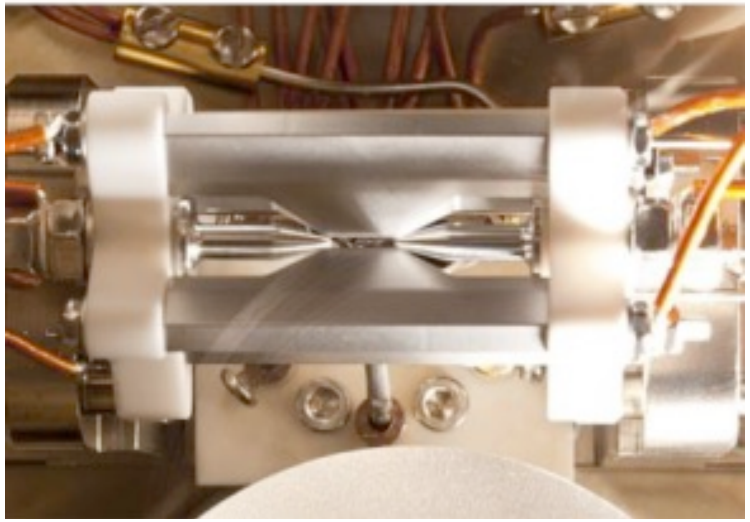
We place the ions in a sufficiently spaced one-dimensional array and cool them all down to the point where their motion in space is quantized. By carefully tuning the laser frequency, we can control both the excitations of the ions and the motion of the ion chain.

# Ion Trap

Number of atoms that can be controlled is limited, and each requires its own laser. Probably <100 ions max.







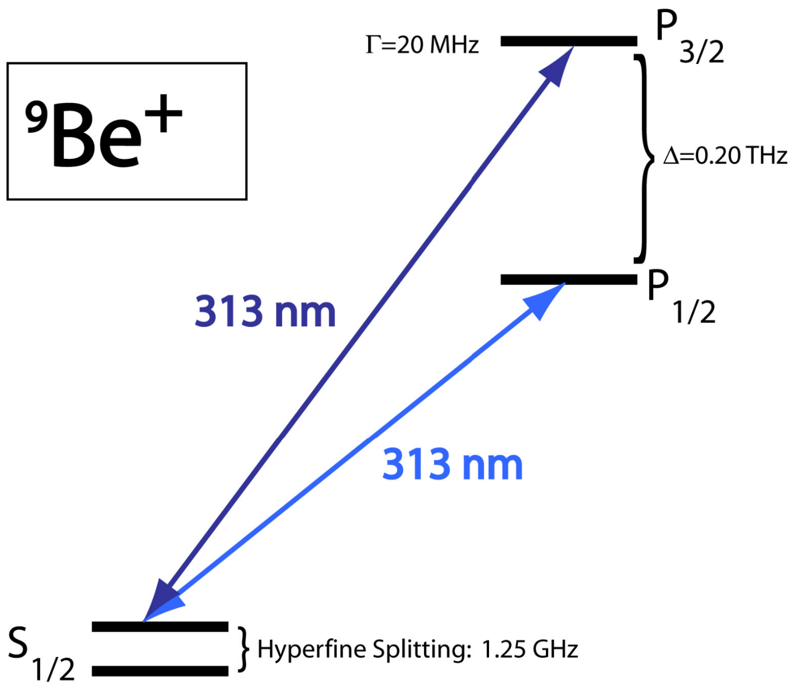
# Which atom?

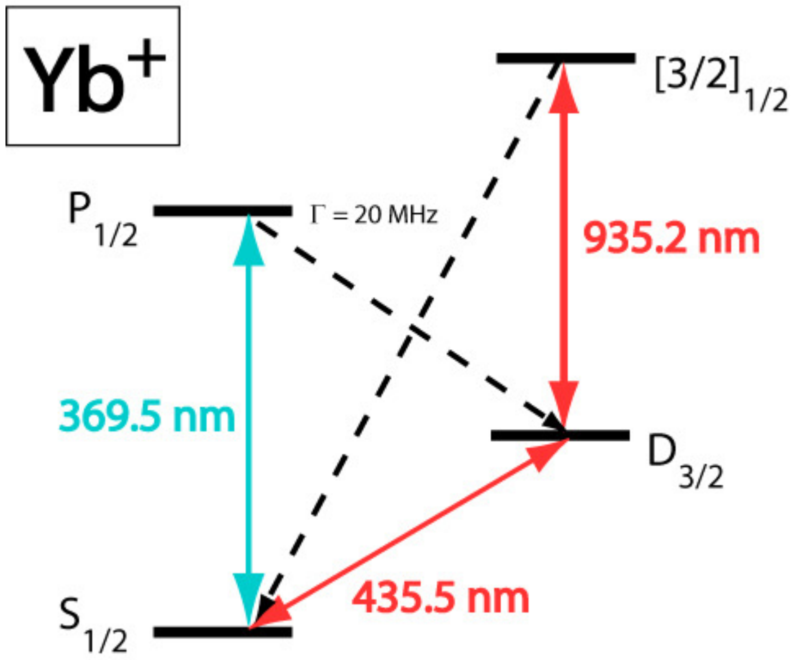
We would like the atom to
(1) Have an excited state that is long-lived, and
(2) manipulate using frequencies that lasers can produce.

Semiconductor laser technology: a wide range of frequencies that we can use in the visible and infrared ranges

The best ions for our purposes are single-charged ions in **Group II** of the periodic table, such as Calcium-40 ($^{40}\text{Ca}$), Beryllium-9 ($^{9}\text{Be}$), and Barium-138 ($^{138}\text{Ba}$). The rare earth Ytterbium-171 ($^{171}\text{Yb}$) is used by IonQ and Honeywell. These elements have two valence electrons, but their ionized version only has one. The valence electron is not so tightly bound to the atom, so it is the one whose state we use to represent a qubit.

# Energy-level diagram for Sodium Be and Yb

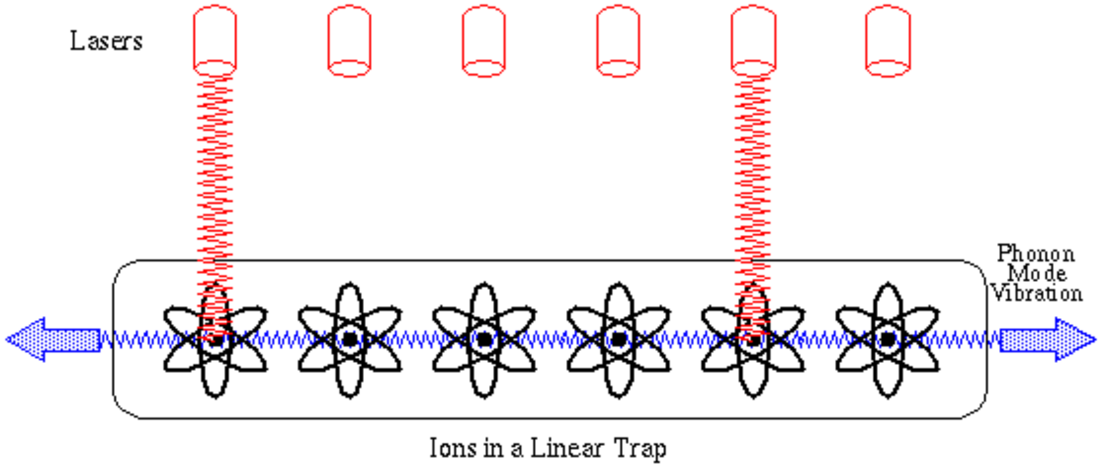


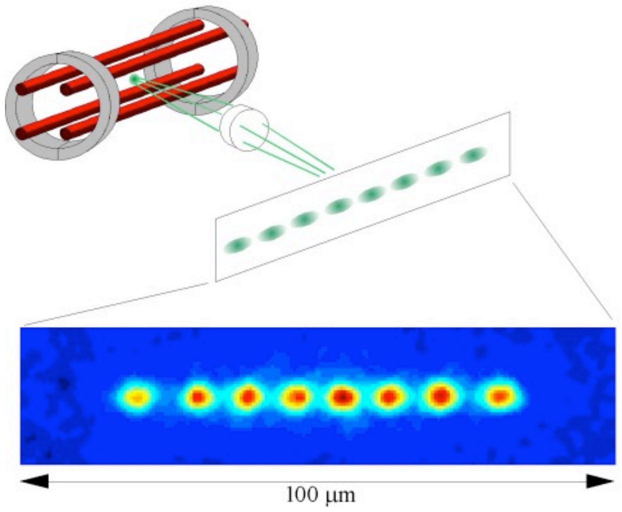


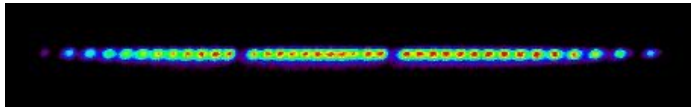
https://iontrap.umd.edu/resources-2/periodic-table/

# Control of trapped atoms

Ions (charged atoms) are suspended in space in an oscillating electric field.  Each atom is controlled by a laser.

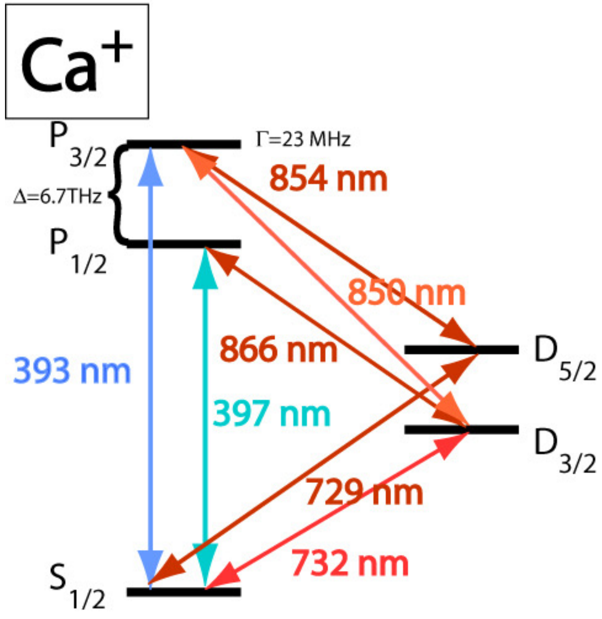


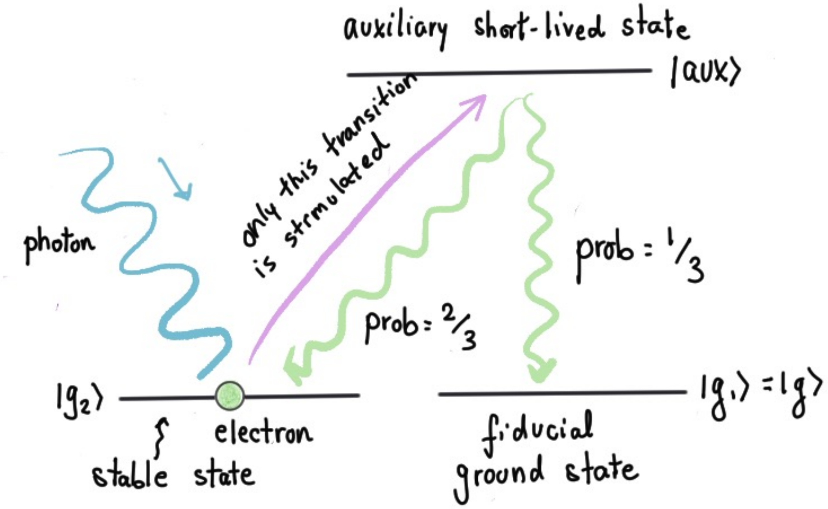


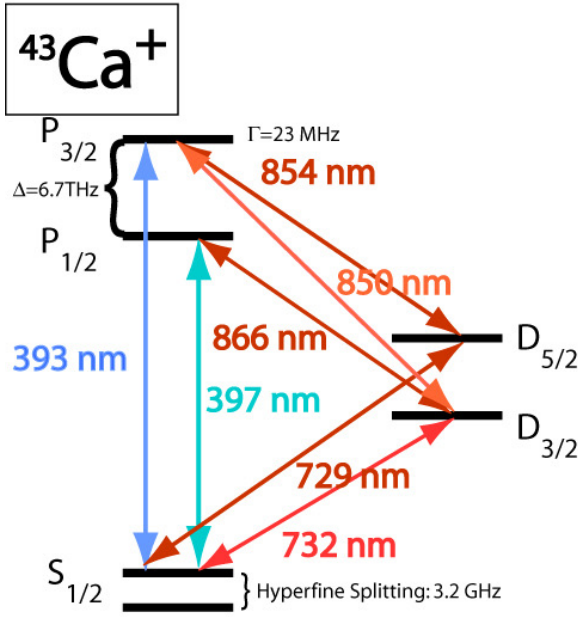


# Optical pumping: qubit preparation

Criteria 1, 2 and 3 of DiVicenzo are satisfied

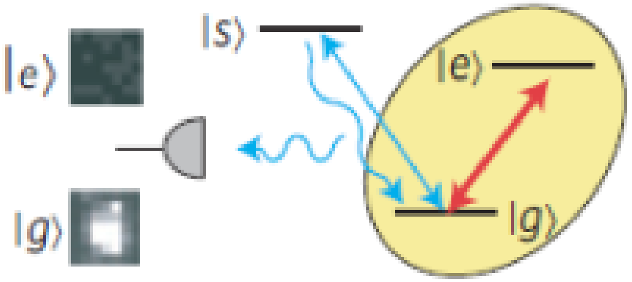






g : ground state, e: excited state, aux or s: short-lived state,

# Read out mechanism: non-demolition measurements



g: ground state, e: excited state, aux or s: short-lived state

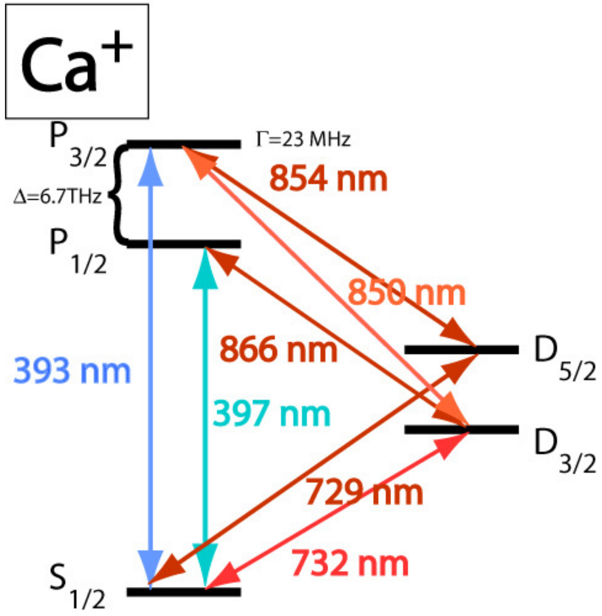
At low T, the entire ion chain acts as a quantum harmonic oscillator, meaning that it can vibrate with energies that are multiples of Planck's constant times a fundamental frequency :

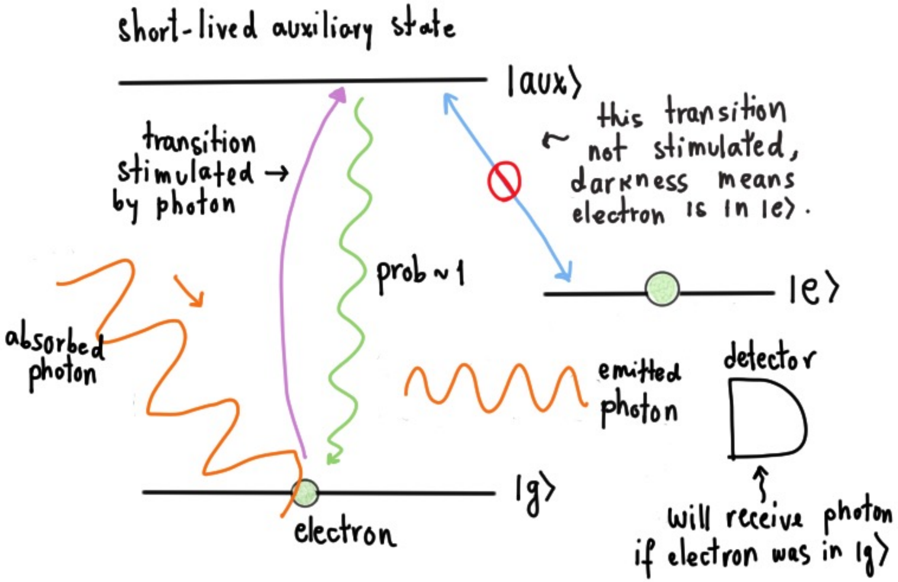
$$E = n\,(h/2\pi)\omega$$

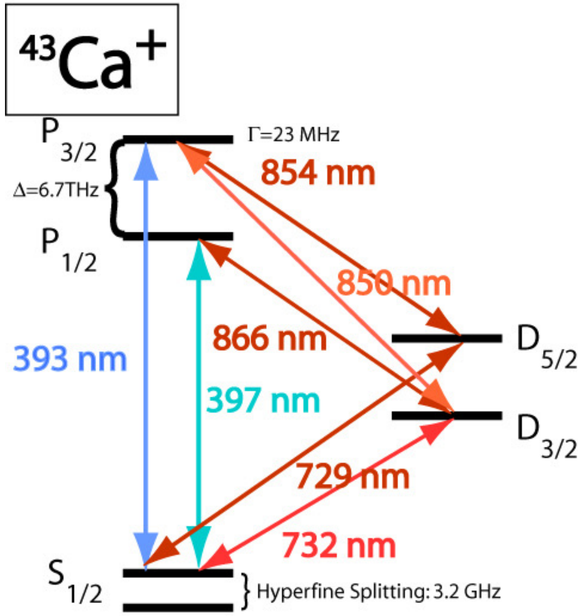
When the chain is oscillating with energy E, we denote the harmonic oscillator state, also known as phonon state or motional state, by $|n>$.

The harmonic oscillator can absorb and emit energy in multiples of hω, in packets of energy known as phonons. When we shine laser light on a particular atom of the ion chain, the entire chain could absorb the energy of the photons and start oscillating. However, this does not happen when the atoms are cooled down and the light frequency matches the energy gap. Instead, the atom changes energy level, and we can manipulate a single qubit.

# Read out mechanism: non-demolition measurements (not loosing chain atoms)







We shine a laser light wavelength of 397 nm that drives the transition from to the auxiliary state s. The transition is short-lived; it will quickly go back to g, emitting a photon of the same wavelength. The state is not affected. Conversely, if the ion is dark, we will have measured the result corresponding to state e. To see the photons emitted by the ions, we need to collect the photons using a lens and a photomultiplier, a device that transforms weak light signals into electric currents.

# Measuring the qubits: the 5th criterion

We can detect the emission of photons of each atom individually, so we are on the right track. But in reality, there is also some uncertainty in the measurement. In many quantum computing algorithms, we only measure the state of a pre-chosen set of ions called the **ancilla**. If these ions emit light, they can accidentally excite other ions on the chain, causing decoherence.

A way to avoid this source of uncertainty is to use two species of ions: one for the ancilla and one for the qubits that are not measured, or logical qubits. In this case, the photons emitted by the ancilla ions would not excite the logical qubits. However, using two different species of ions causes extra trouble when we want to implement arbitrary qubit operations.

# Sum-up

**Criterion 1** is only met partially: we do have robust qubits, but there seems to be a hard technological limit for scalability.

**Criterion 2** does not present too much of a problem thanks to optical pumping technology.

**Criterion 3** also becomes an issue when the ion chain is too long since coherence times for motional states become shorter.

**Criterion 4** is related to this decoherence problem since multi-qubit gates can take too long to implement accurately in a long ion chain.

**Criterion 5** also has a problem.

# Prons & Cons

## Prons (+)

- Their operations are much less prone to errors
- Their delicate quantum states of individual ions last longer than those in superconducting qubits, which, although small, are still made of a very large number of atoms.
- Trapped ions can interact with many others, which makes it easier to run some complex calculations, whereas superconducting qubits tend to interact only with their nearest neighbours.

## Cons (-)

- They are slower at interacting than superconducting qubits, which will be important when it comes to accounting for real-time errors coming out of the system.
- There are limits to how many ions can fit in a single trap and be made to interact.

# Current SotA

**IonQ**’s latest model contains 32 (~64) trapped ions sitting in a chain; plucking any 2 using lasers causes them to interact. To scale up to hundreds of qubits, the company is working on ways to link up multiple chains of qubits using photons.

**Honeywell** plans to interconnect all the ions by physically shuttling them around a giant chip *( J. M. Pino et al. Preprint at https://arxiv.org/abs/2003.01293; 2020*). The latest system by the firm’s **Honeywell Quantum Solutions (HQS)** division, called H1, consists of just 20 qubits. In particular, Honeywell has achieved a **quantum volume** of 128, the largest in the market!

The **challenge** is to keep the quality and precision of qubits, while controlling dozens, or even hundreds, at once — which neither Honeywell nor IonQ has yet shown it can do. Although many of the necessary components have been mastered individually.

# Spectroscopic notation

The value of $n$ is written as a prefix and the value of the total angular momentum quantum number $j$ by a subscript. The magnitude of the total spin quantum number $s$ appears as a left superscript in the form $2s+1$. Thus, a state with $n=2$ $l=1$ , a **P** state, would be written as

$$n^{2s+1}\,P_j$$

For example, the ground state of the hydrogen atom ($n = 1$, $l=0$, $s=1/2$) is written $1^2\,S_{1/2}$, read “**one doublet S one-half.**”

The $n=2$ state can have $l=0$ or $l=1$, so the spectroscopic notation for these states is $2^2S_{1/2}$, $2^2P_{1/2}$, and $2^2P_{3/2}$.

# Silicon ion-traps (I)

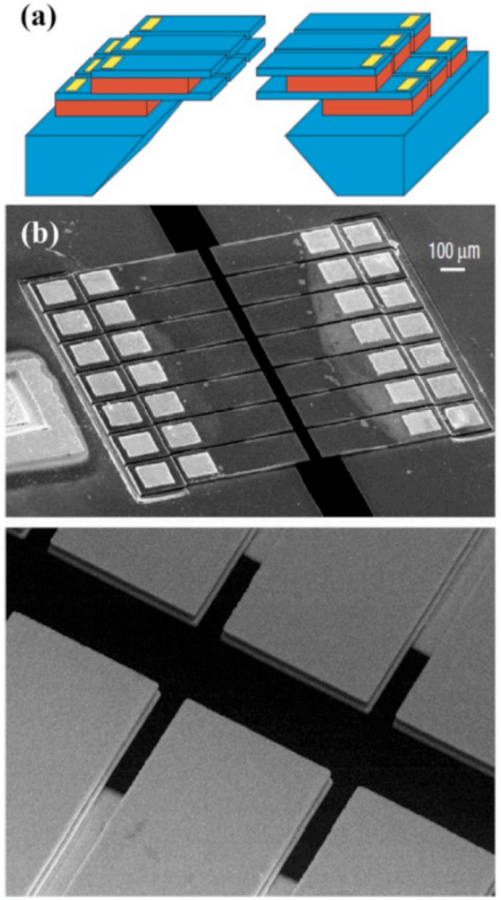
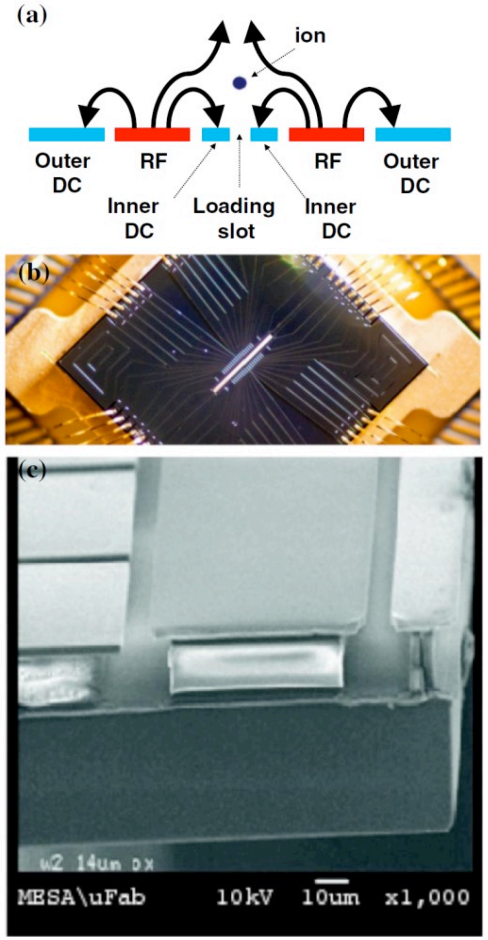
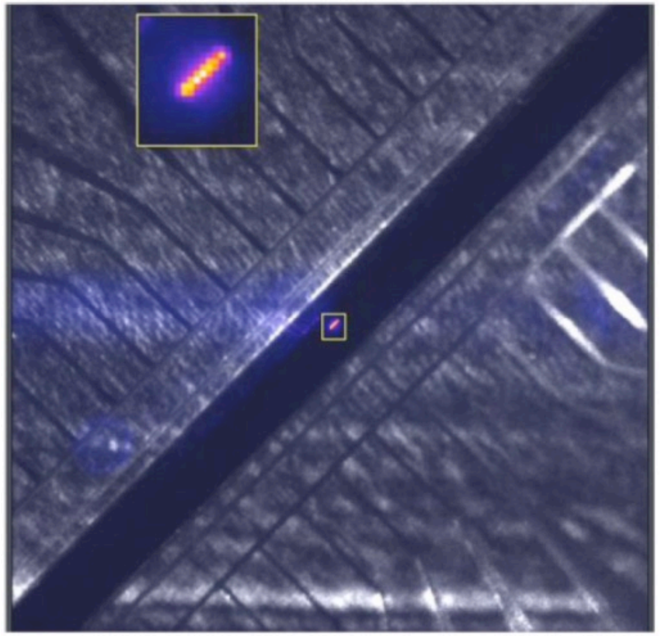


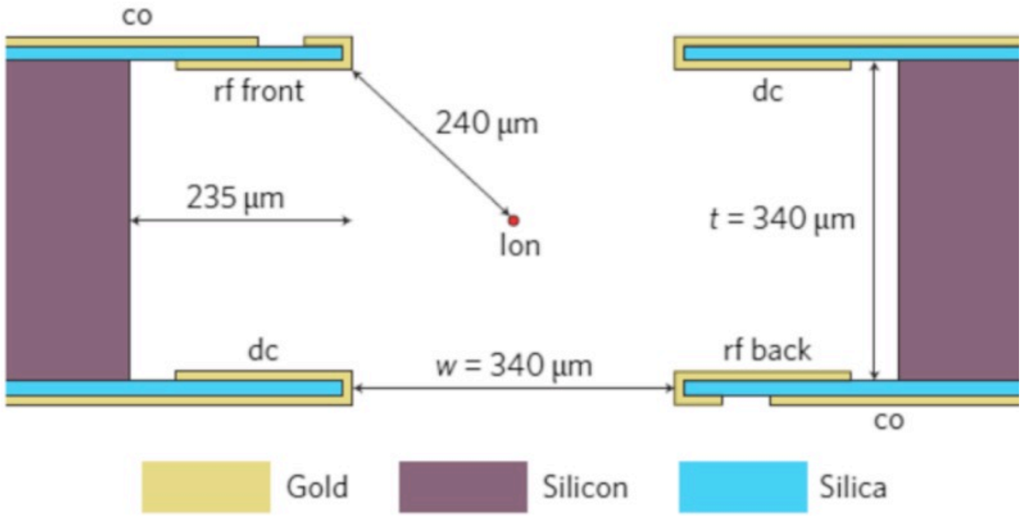
**Figure 3** **Schematic and picture of the first ion trap fabricated by a semiconductor fabrication process.** **(a)** Schematic of the ion trap [53]. **(b)** Scanning electron micrograph of the ion trap [53].

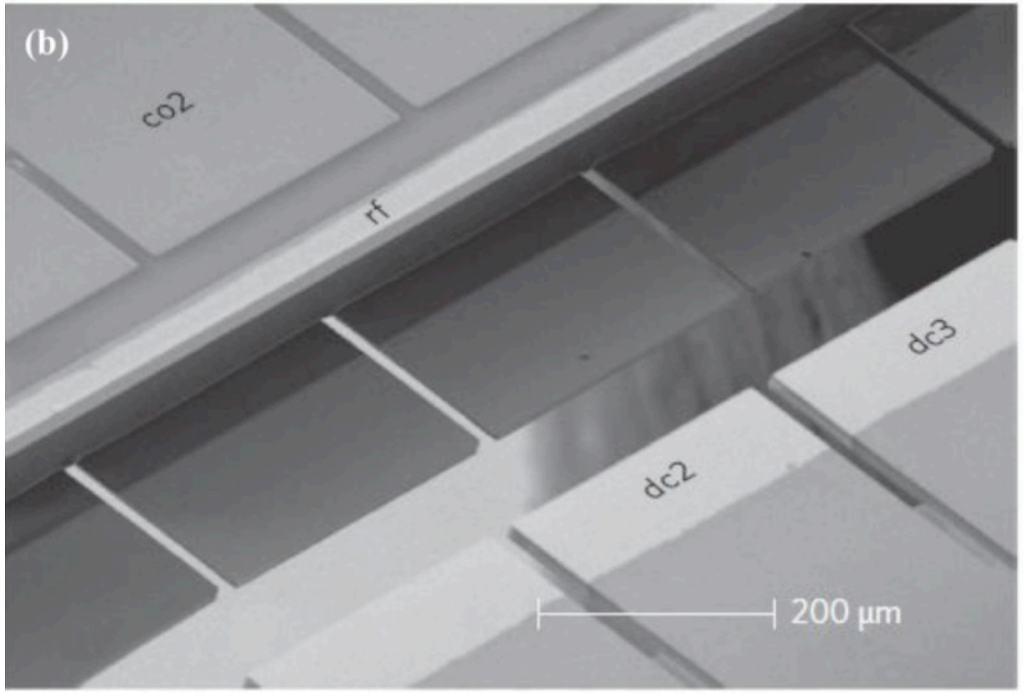




Cho et al. Micro and Nano Systems Letters (2015) 3:2
DOI 10.1186/s40486-015-0013-3

# Silicon ion-traps (II)

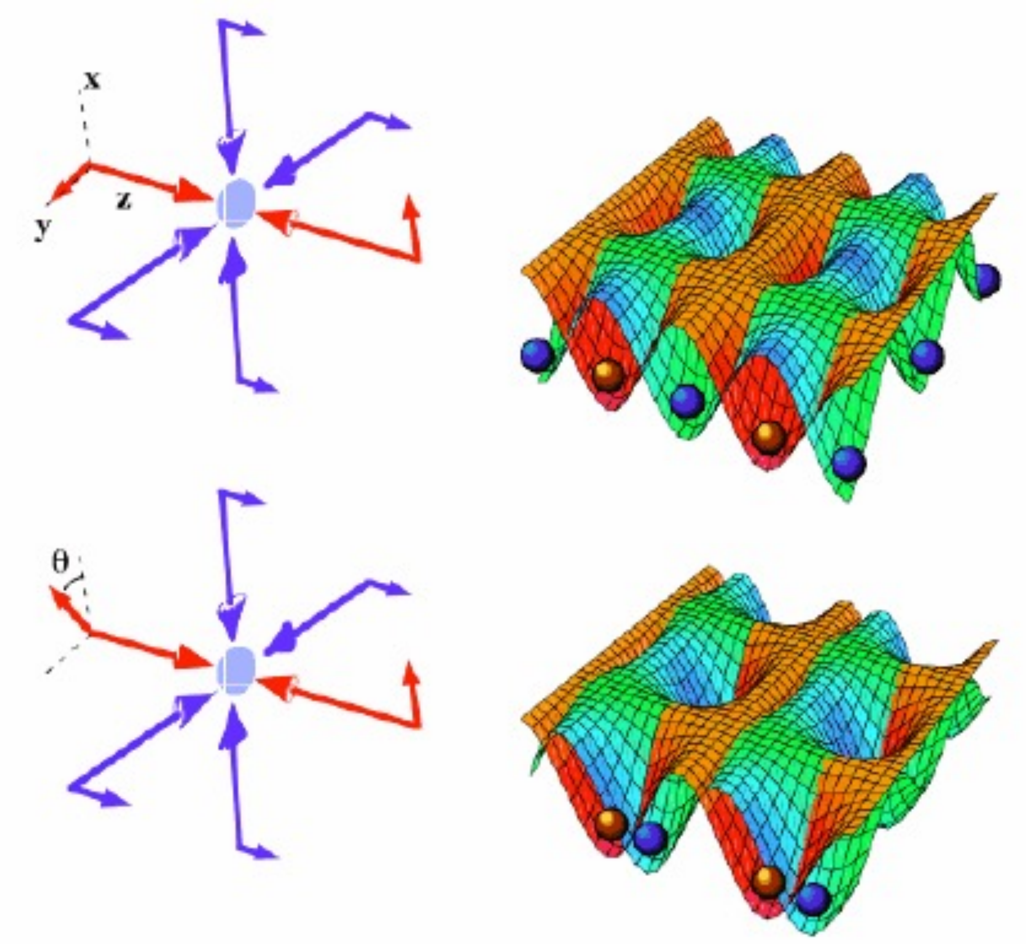




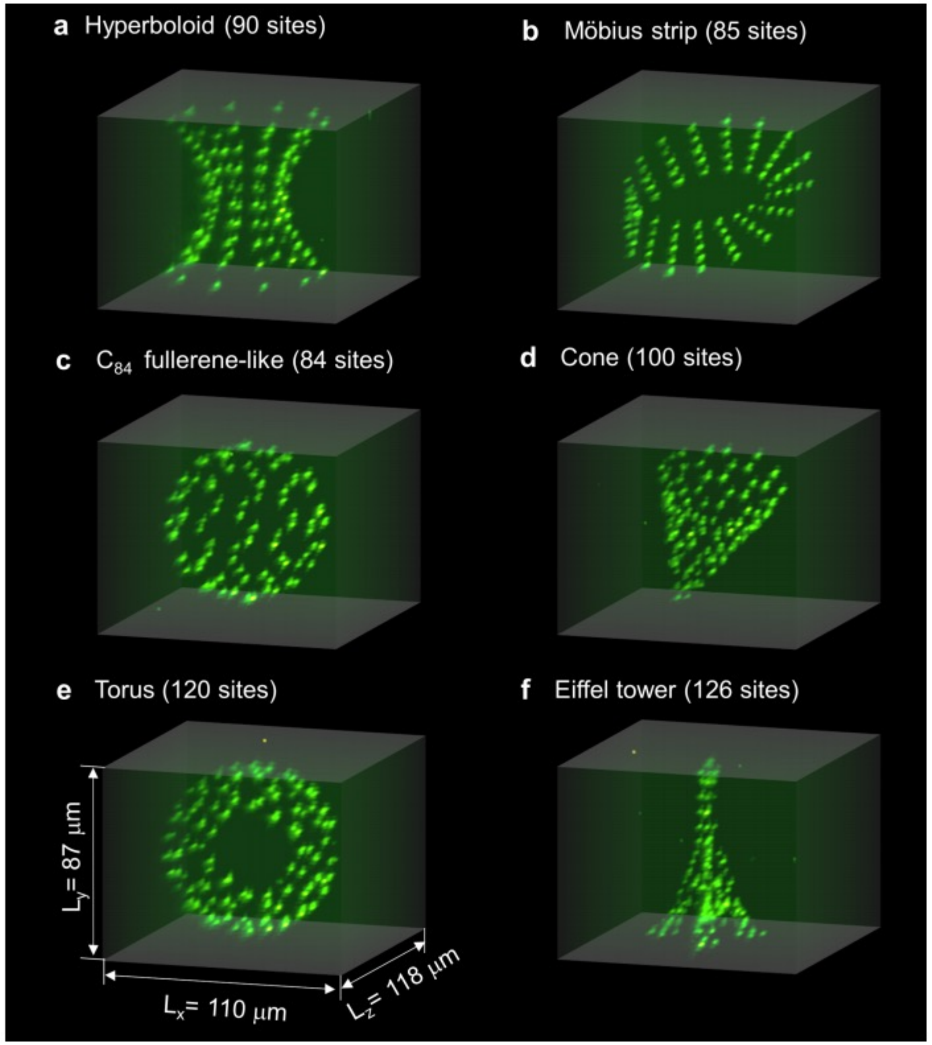
# Neutral Atoms

# Optical Lattice (Atoms)

Neutral atoms are held in place by standing waves from several lasers.
Atoms can be brought together to execute gates by changing the waves slightly.
Also used to make high-precision atomic clocks.



# Optical Lattice (Atoms)



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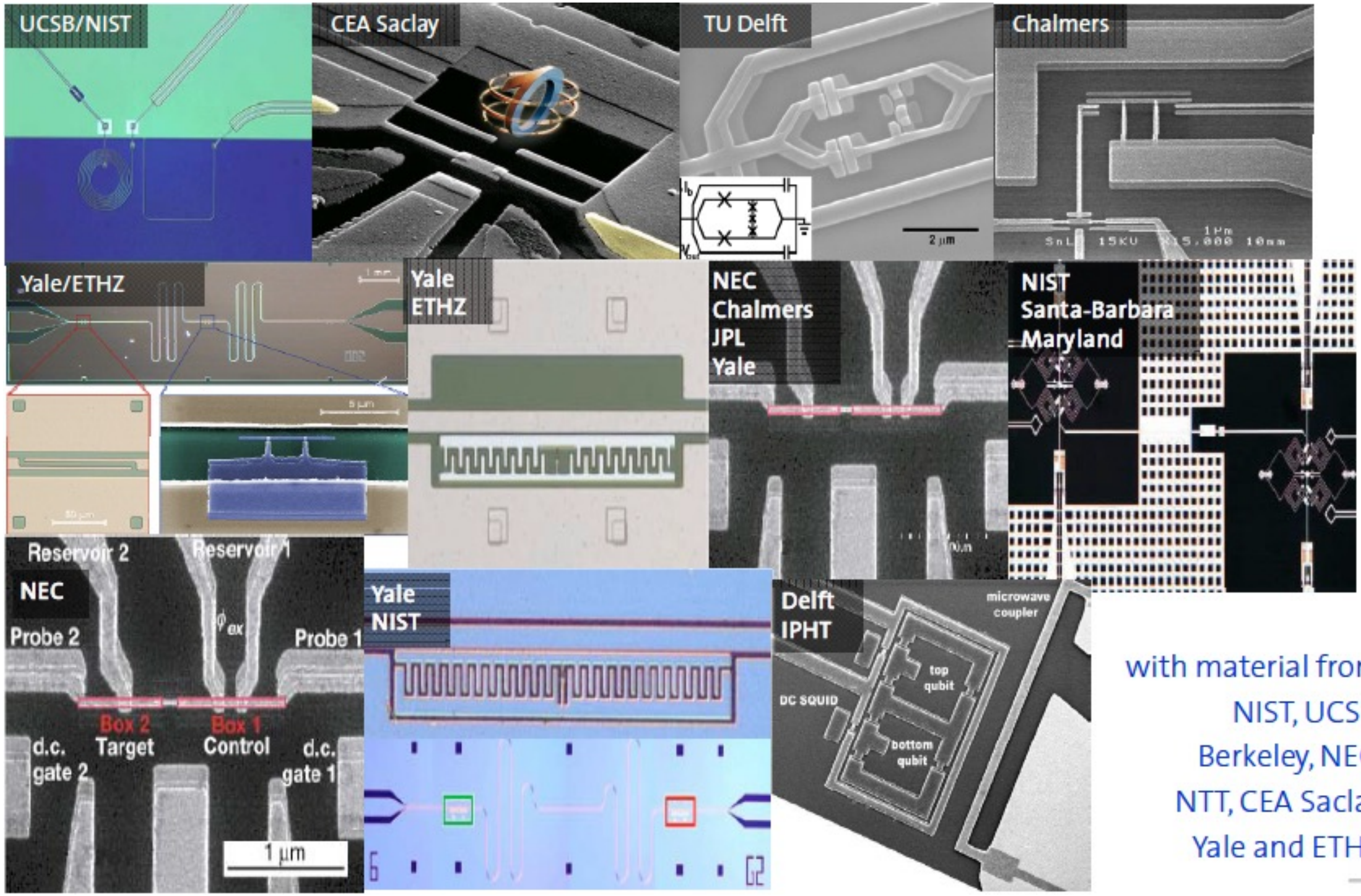
# Technology Comparison



with material from
NIST, UCSB,
Berkeley, NEC,
NTT, CEA Saclay,
Yale and ETHZ

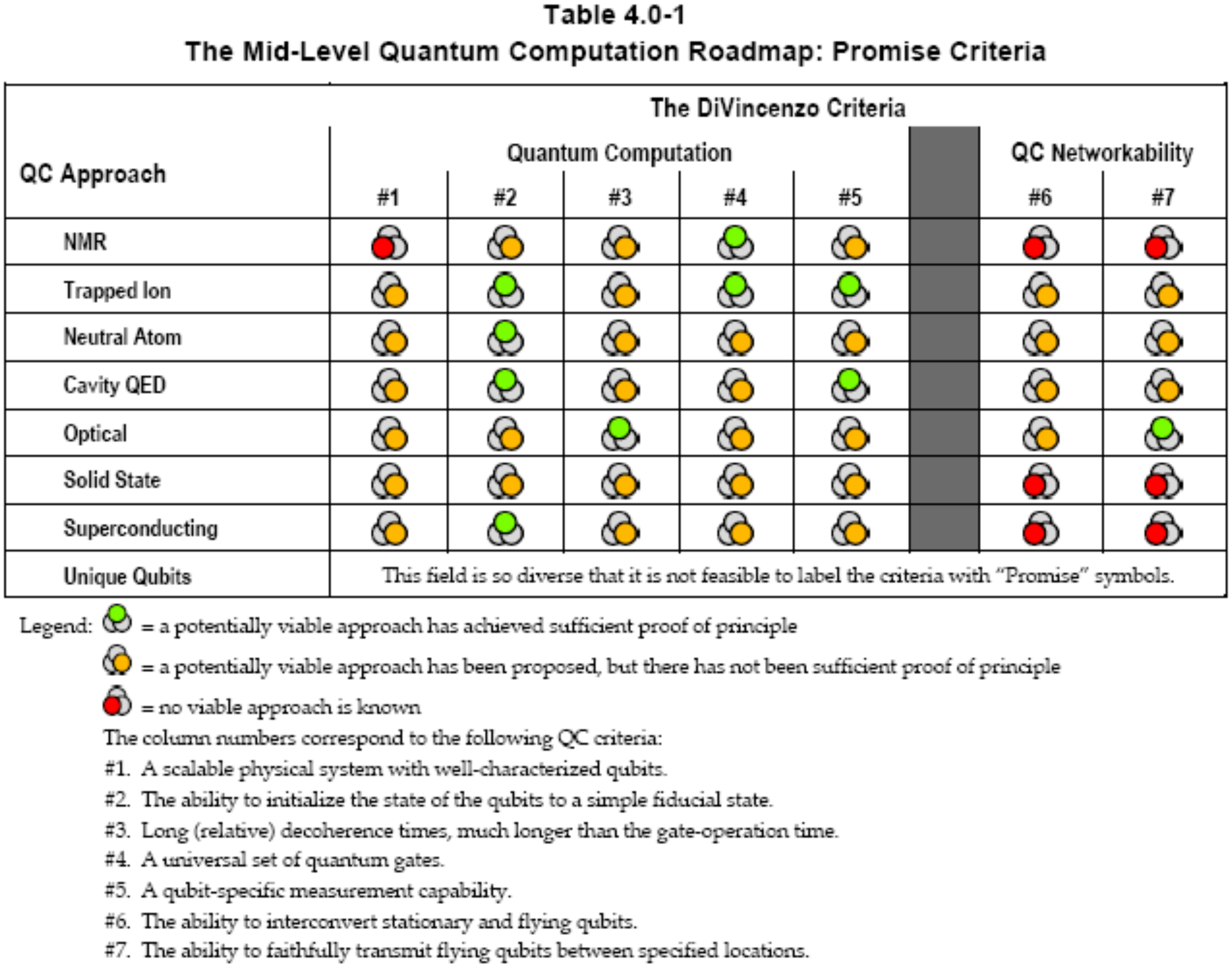


Table 4.0-1

The Mid-Level Quantum Computation Roadmap: Promise Criteria

| QC Approach | The DiVincenzo Criteria | | | | | | |
|---|---|---|---|---|---|---|---|
| | Quantum Computation | | | | | QC Networkability | |
| | #1 | #2 | #3 | #4 | #5 | #6 | #7 |
| NMR | 🔴 | 🟠 | 🟠 | 🟢 | 🟠 | 🔴 | 🔴 |
| Trapped Ion | 🟠 | 🟢 | 🟠 | 🟢 | 🟢 | 🟠 | 🟠 |
| Neutral Atom | 🟠 | 🟢 | 🟠 | 🟠 | 🟠 | 🟠 | 🟠 |
| Cavity QED | 🟠 | 🟢 | 🟠 | 🟠 | 🟢 | 🟠 | 🟠 |
| Optical | 🟠 | 🟠 | 🟢 | 🟠 | 🟠 | 🟠 | 🟢 |
| Solid State | 🟠 | 🟠 | 🟠 | 🟠 | 🟠 | 🔴 | 🔴 |
| Superconducting | 🟠 | 🟢 | 🟠 | 🟠 | 🟠 | 🔴 | 🔴 |
| Unique Qubits | This field is so diverse that it is not feasible to label the criteria with "Promise" symbols. | | | | | | |

Legend: 🟢 = a potentially viable approach has achieved sufficient proof of principle

🟠 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

🔴 = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

# The DiVincenzo criteria for a 'normal' quantum computer

According to DiVincenzo's criteria, constructing a quantum computer requires that the experimental setup meet seven conditions. The first five are necessary for quantum computation:

1. A scalable physical system with well-characterized qubit
2. The ability to initialize the state of the qubits to a simple fiducial state
3. Long relevant decoherence times
4. A "universal" set of quantum gates
5. A qubit-specific measurement capability

The remaining two are necessary for quantum communication:

6. The ability to interconvert stationary and flying qubits
7. The ability to faithfully transmit flying qubits between specified locations

# Stationary & Flying Qubits

**This is exactly what a flying qubit should be: a qubit that can be freely send from one node to the other.**

**Stationary qubits need to:**

- Be able to store quantum information reliably on a timescale of ~ms.
- Perform calculations: various gates/operations need to be reliably performed on them. This includes an operation that moves/converts the information to a flying qubit.
- Be able to be measured/read out reliably.
- Be able to be highly entangled.

**Flying qubits, however, need to:**

- Be send over macroscopic distances while keeping their encoded (quantum) information intact.
- Be operational on a macroscopic temperature scale (i.e. about room temperature).
- Perform only one single operation reliably: converting into stationary qubits.
- Be able to be entangled.

# Semi-QD Qubit: Prons and Cons

+

- Straight forward fabrication
- Easy scaling
- LHe operation (not a dilution fridge)
- Computers are made of silicon, darn it!
- Coupling to flying qubits seems possible

−

- Noise in the environment seems unavoidable
- decoherence may be a roadblock
- Fabrication very demanding (purity, precision, etc.)
- Measurement???
- Gates???

# Ion trap Qubit: Prons and Cons

- Ions are excellent quantum memories; single qubit coherence times > 10 minutes have been demonstrated

- Ions can be controlled very well

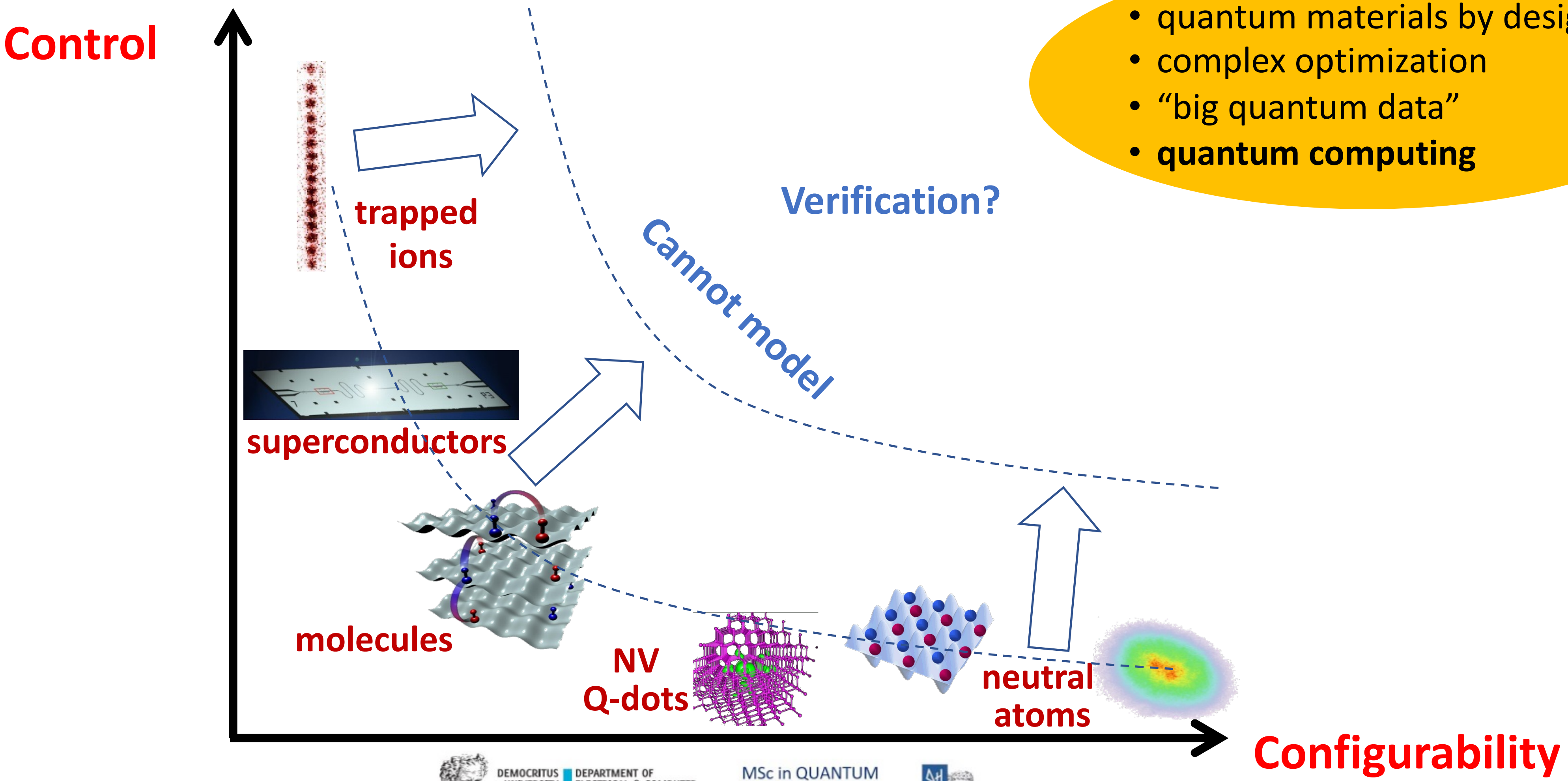
- Easier interaction with any other trapped ion

- Slow (~1 MHz)

- Technically demanding

# Qubit control & configurability

- quantum materials by design
- complex optimization
- “big quantum data”
- **quantum computing**



# The end