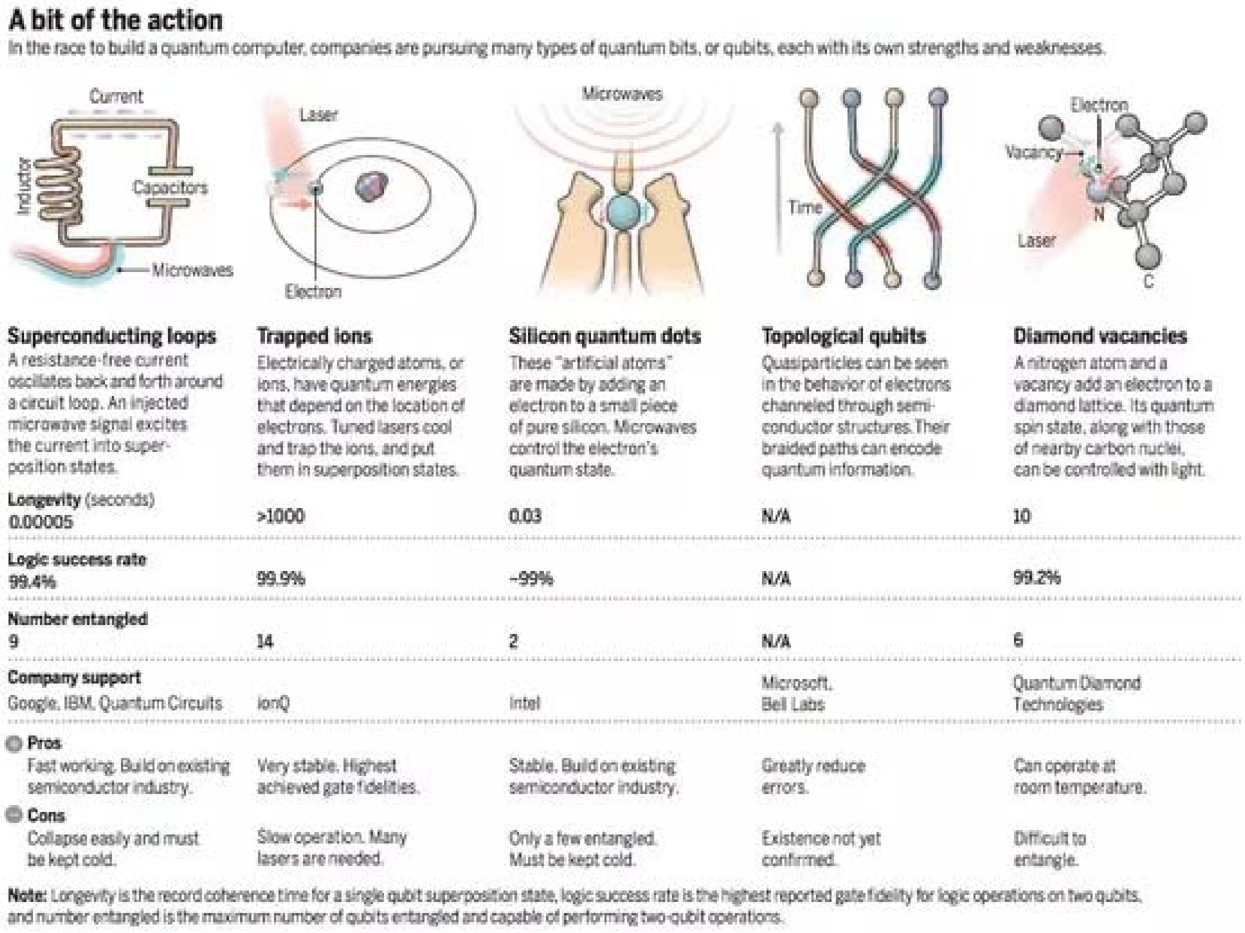
QS^3 School Summary

June 16, 2017

"Scientists are close to building a quantum computer that can beat a conventional one"

Science 2016



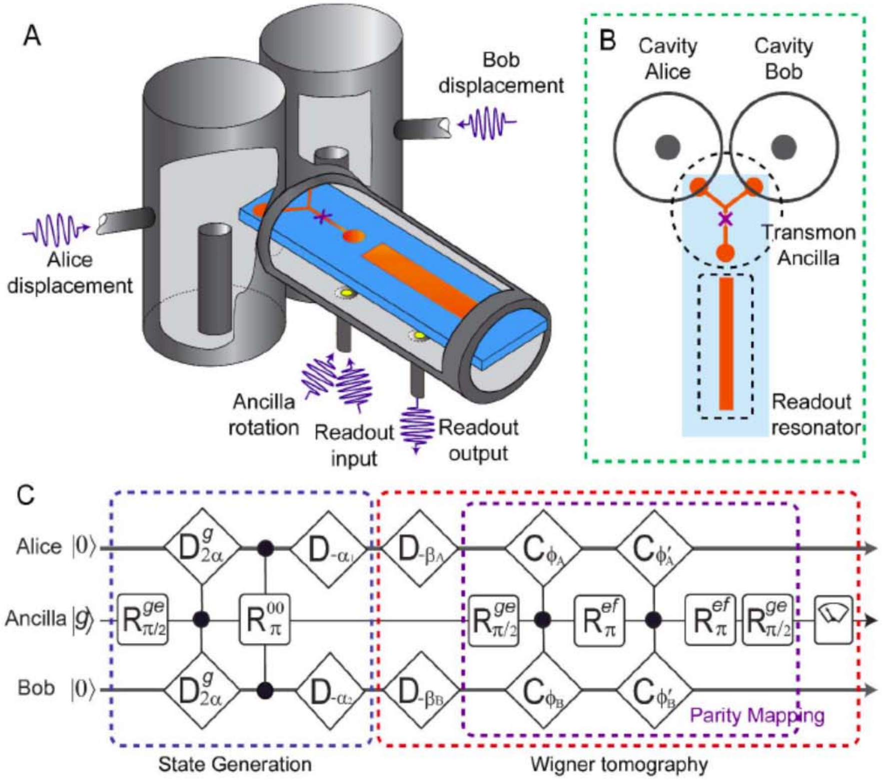
A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into superposition 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.	Quasiparticles can be seen in the behavior of electrons channeled through semiconductor structures. Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6
Company support	Google, IBM, Quantum Circuits	ionQ	Intel	Microsoft, Bell Labs	Quantum Diamond Technologies
● **Pros**	Fast working. Build on existing semiconductor industry.	Very stable. Highest achieved gate fidelities.	Stable. Build on existing semiconductor industry.	Greatly reduce errors.	Can operate at room temperature.
● **Cons**	Collapse easily and must be kept cold.	Slow operation. Many lasers are needed.	Only a few entangled. Must be kept cold.	Existence not yet confirmed.	Difficult to entangle.

Note: Longevity is the record coherence time for a single qubit superposition state, logic success rate is the highest reported gate fidelity for logic operations on two qubits, and number entangled is the maximum number of qubits entangled and capable of performing two-qubit operations.

Cat in Two Boxes



IBM: Supercondcuting Qubits and QX

QX demo: *m*-qubit QFT, *m* = 2

For each frequency $f < 2^m$ Hz:

1. Prepare each qubit q_n in $(|0\rangle + e^{2\pi i f t}|1\rangle)/\sqrt{2}$, $t = 1/2^{(m-n)}$

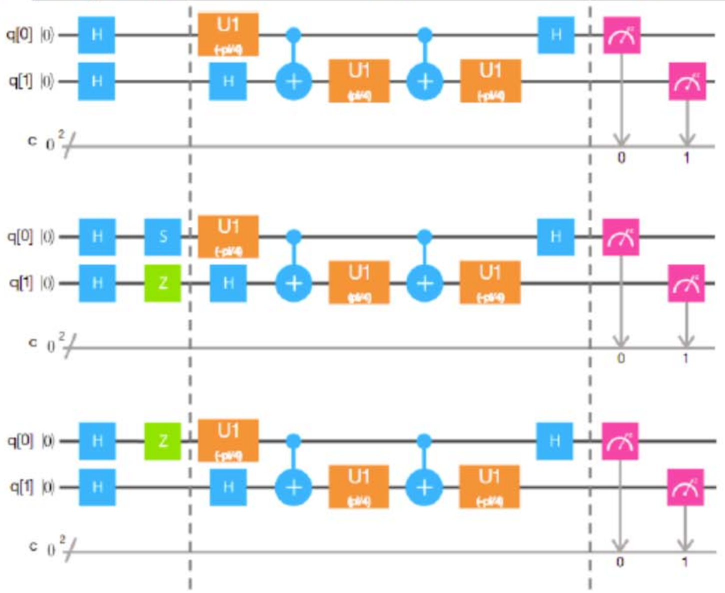
2. Perform QFT

3. Measure all q_n

4. Reverse the bit order (in principle this could be done with a series of SWAP gates prior to measurement)

5. Convert binary to decimal; should recover *f*

Freq. **Step: 1 2 3 4 5**



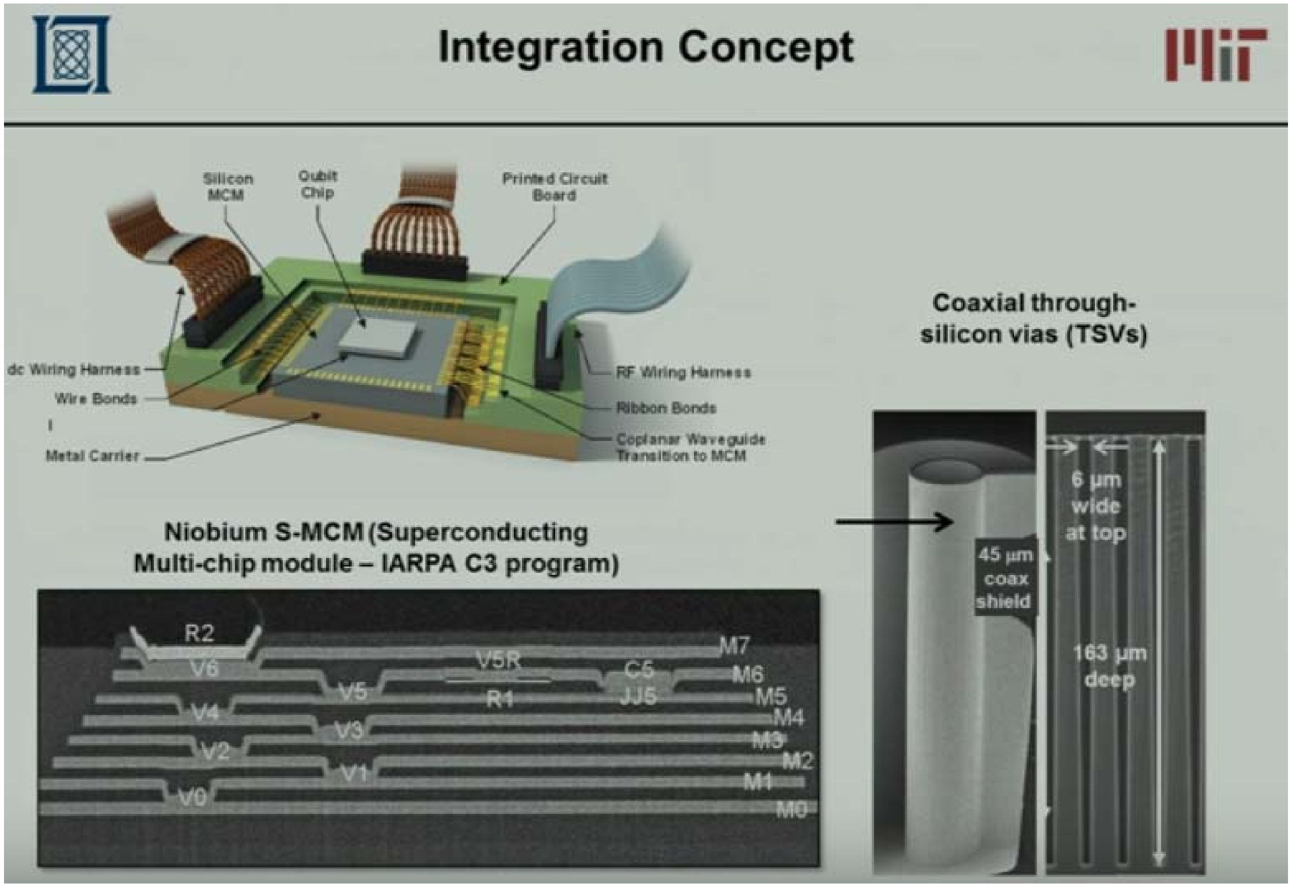
0 Hz: 00 → 00 → **0**

1 Hz: 10 → 01 → **1**

2 Hz: 01 → 10 → **2**

3 Hz: (left as an exercise)

Oliver: Superconducting Qubits & 3D Integration



Integration Concept

Coaxial through-silicon vias (TSVs)

Niobium S-MCM (Superconducting Multi-chip module – IARPA C3 program)

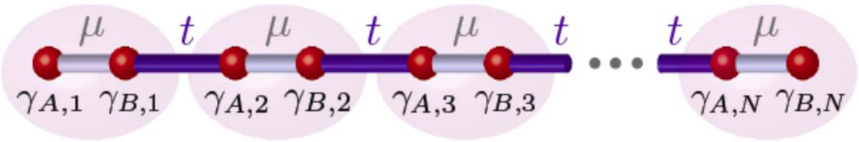
Pakin: Quantum Annealing

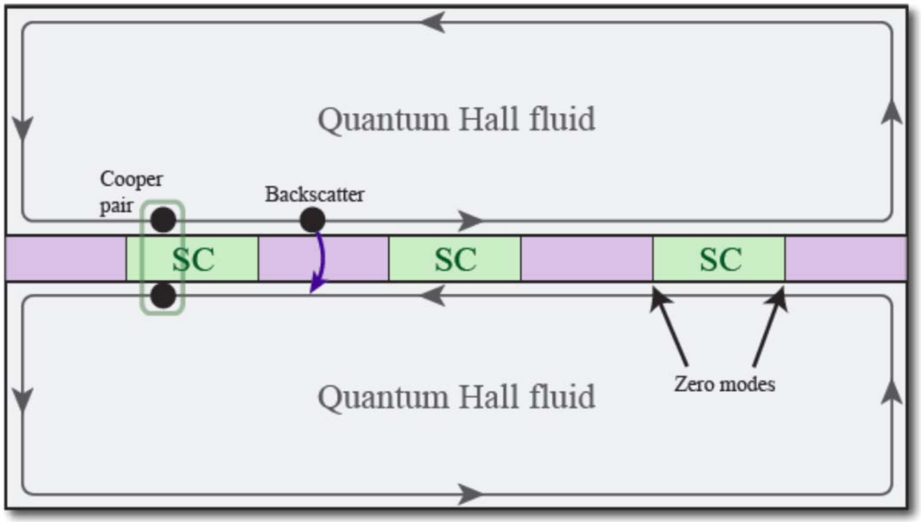
$$\mathcal{H}(t) = -\overbrace{\underbrace{\sum_{i=0}^{N-2}\sum_{j=i+1}^{N-1} J_{i,j}\sigma_i^z\sigma_j^z}_{\text{Longitudinal interactions}} - \underbrace{\sum_{i=0}^{N-1} h_i\sigma_i^z}_{\text{Longitudinal field}}}^{\mathcal{H}_0\ \text{(classical part)}} - \underbrace{\Gamma(t)\sum_{i=0}^{N-1}\sigma_i^x}_{\text{Transverse field}}$$

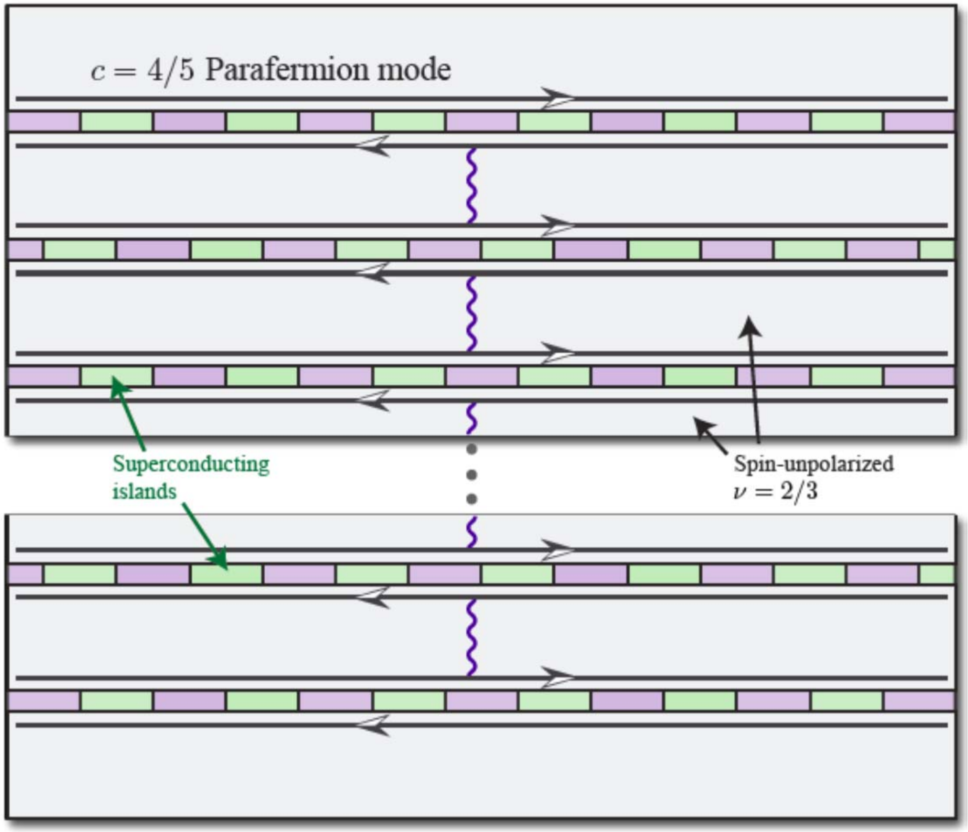
$$\mathcal{H}_S(s) = \frac{\varepsilon(s)}{2}\left(\sum_{\langle i,j\rangle} J_{i,j}\sigma_i^z\sigma_j^z + \sum_{\langle i\rangle} h_i\sigma_i^z\right) - \frac{\Delta(s)}{2}\sum_{\langle i\rangle} h_i\sigma_i^x + \mathcal{H}_?(s)$$

- **in which $\mathcal{H}_?(s)$ encapsulates the interaction with the environment**

Alicea: Topological Quantum Computing





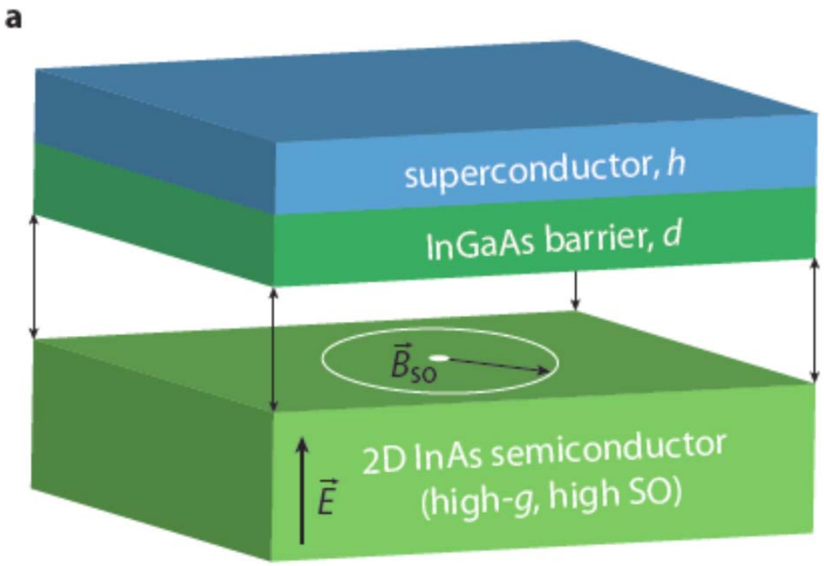


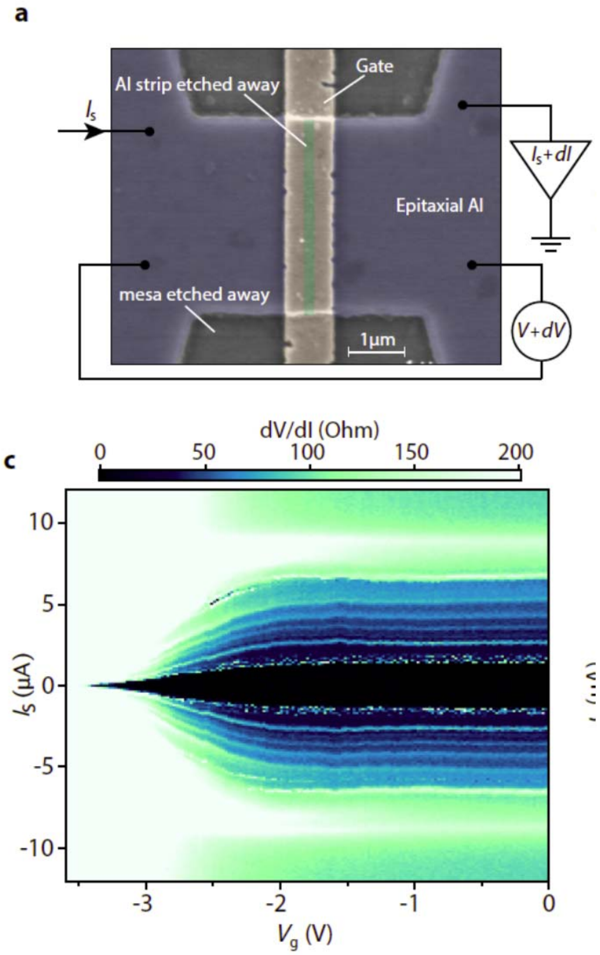
Designer non-Abelian anyon platforms: from Majorana to Fibonacci

Jason Alicea[1] and Ady Stern[2]

Shabani: Topological Qubits

https://arxiv.org/pdf/1511.01127.pdf

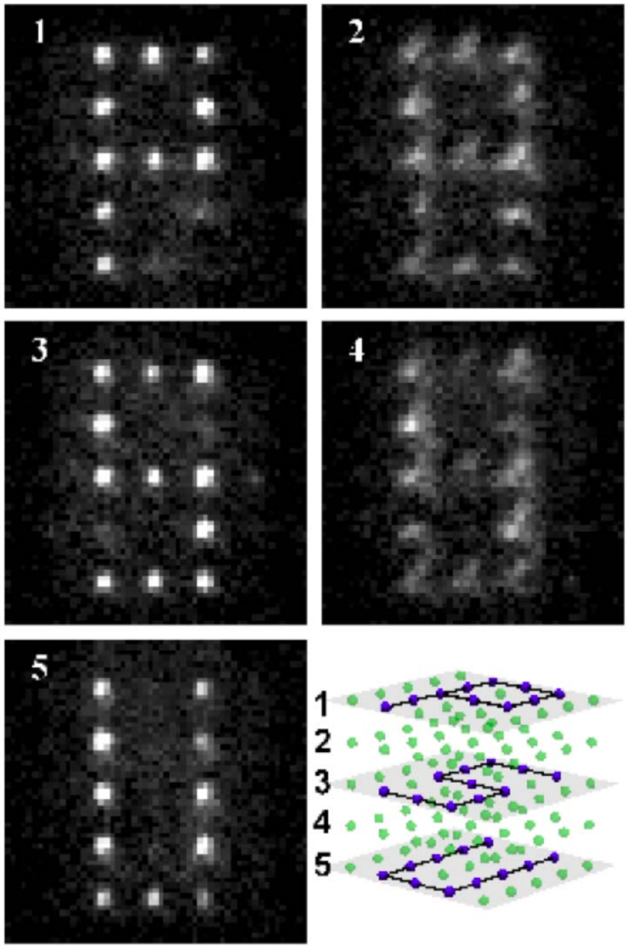




Weiss: Neutral Atom Quantum Computing

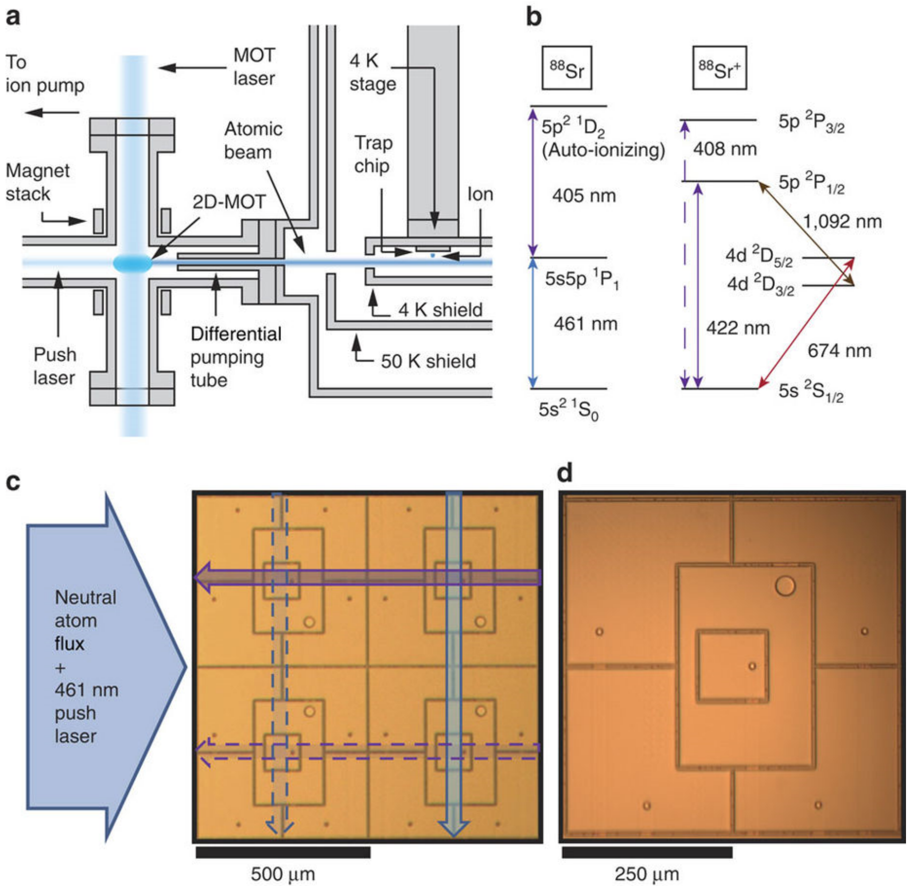
There are a lot of ways to manipulate the internal and external states of atoms.

10^6 atomic qubits in < 5 mm^2 or <0.5 mm^3

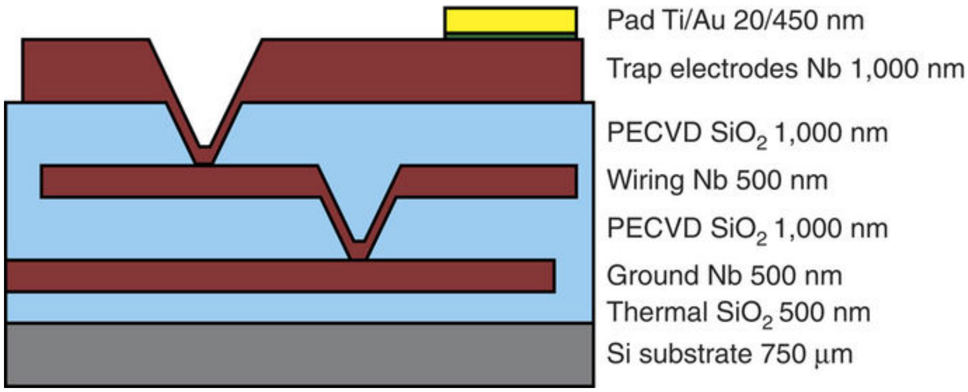


Sage: Ion Traps & 3D Integration

Strontium ion loading and trapping.

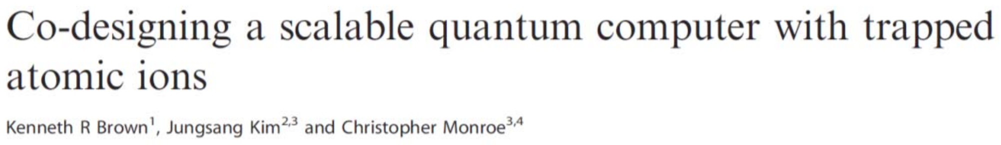


Multilayer stack of trap chip (not drawn to scale).



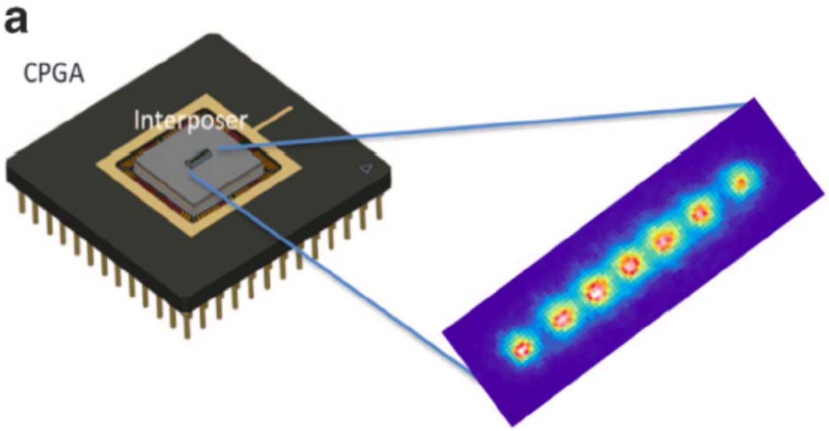
- *Nature Communications* **7**, Article number: 13005 (2016)

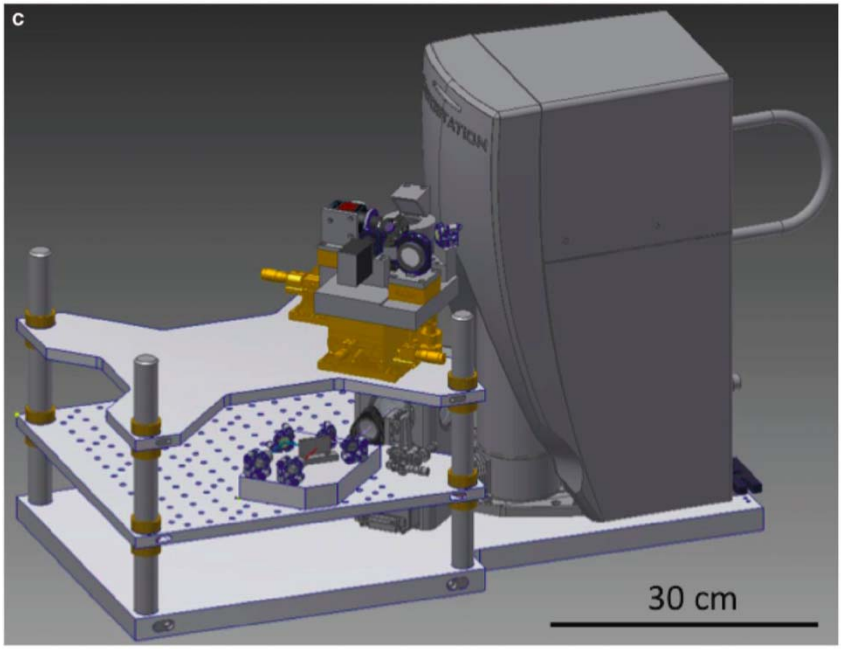
Monroe: Trapped Ion Quantum Informatoin



Co-designing a scalable quantum computer with trapped atomic ions

Kenneth R Brown[1], Jungsang Kim[2,3] and Christopher Monroe[3,4]





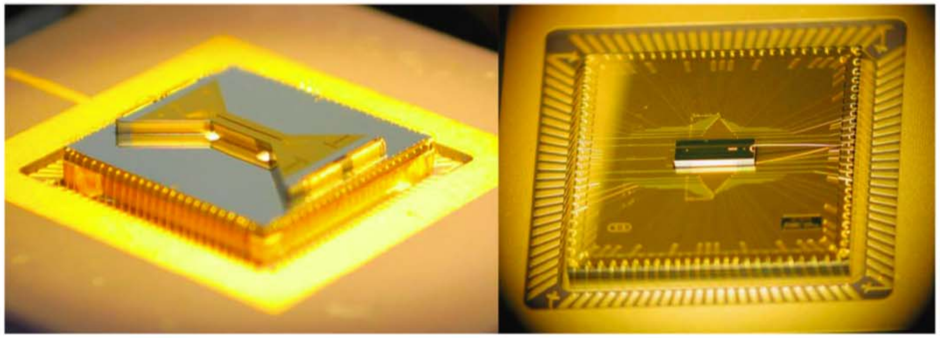


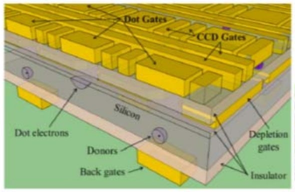
Figure 3. Advanced microfabricated ion traps. LEFT: High-optical access (HOA) trap from Sandia National Laboratories (Image courtesy of Duke University). RIGHT: Ball-grid array (BGA) trap from GTRI/Honeywell (Image courtesy of Honeywell).

Lyon: Spin Qubits

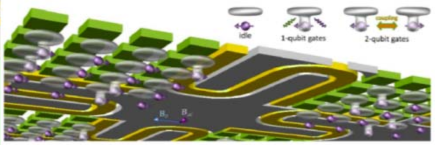
Why Electron Spins?

$\sim 10^9$ Qubits

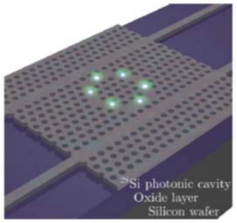
for full-scale Quantum Computer



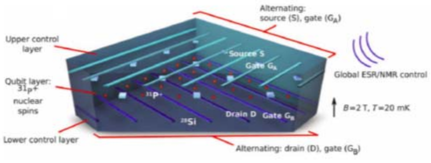
Pica, PRB **93**, 035306 (2016)



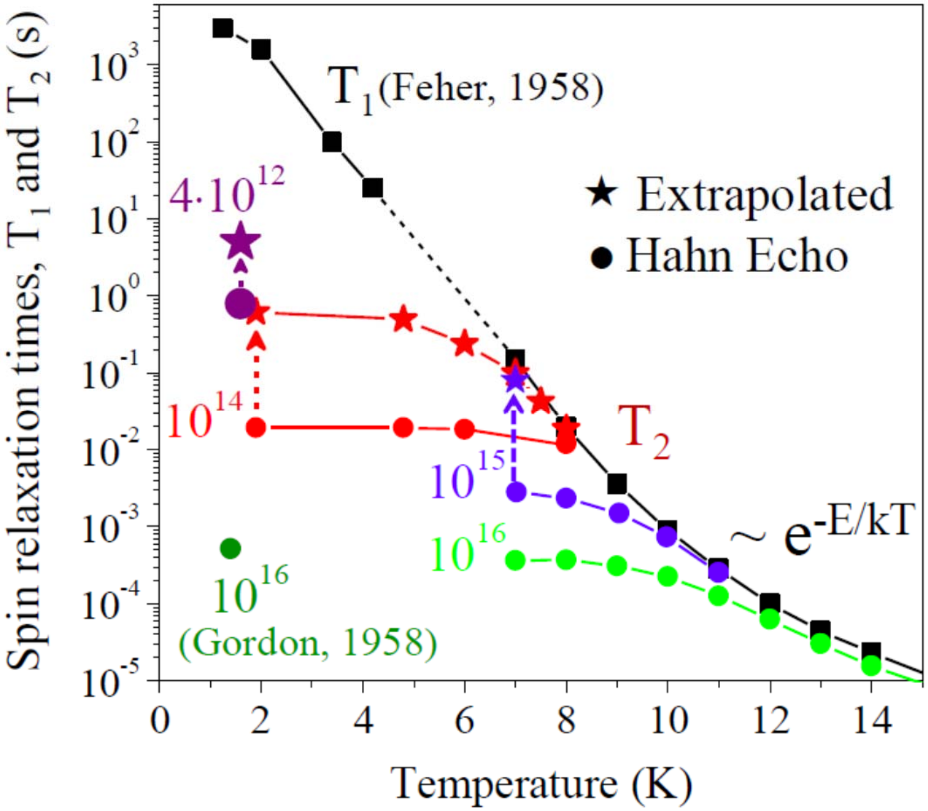
Tosi, ArXiv:1509.08538 (2105)



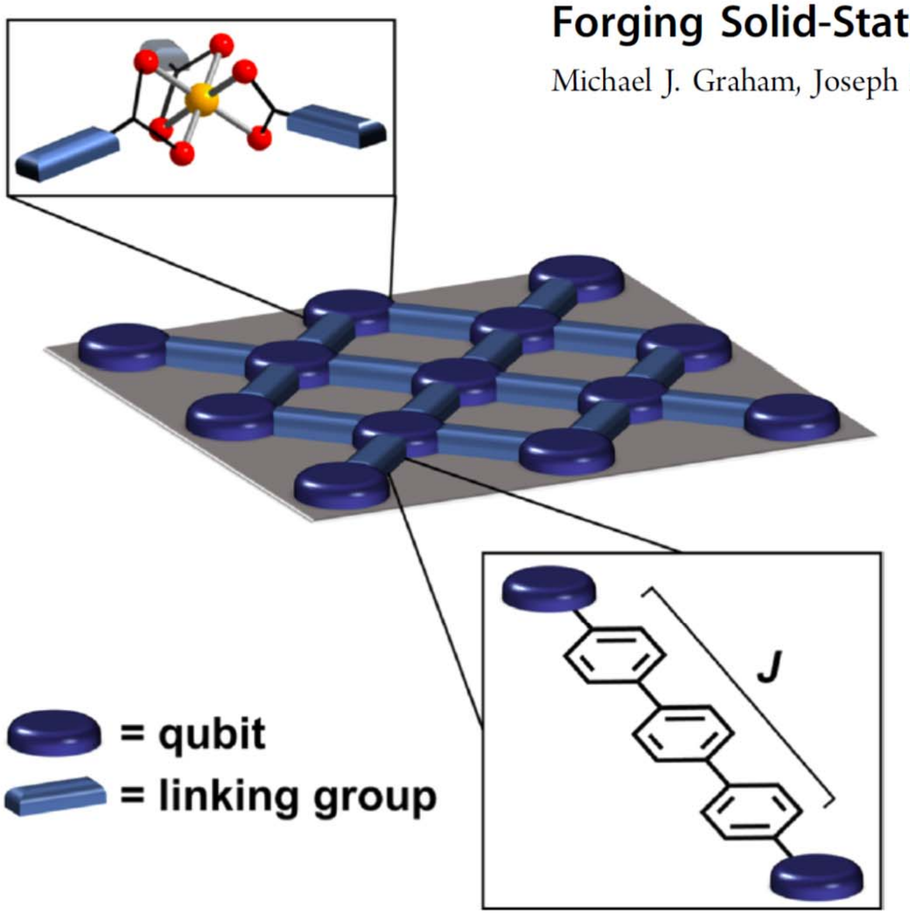
Morse, arXiv:1606.03488 (2016)



Hill, Sci Adv **1**, e1500707 (2015)

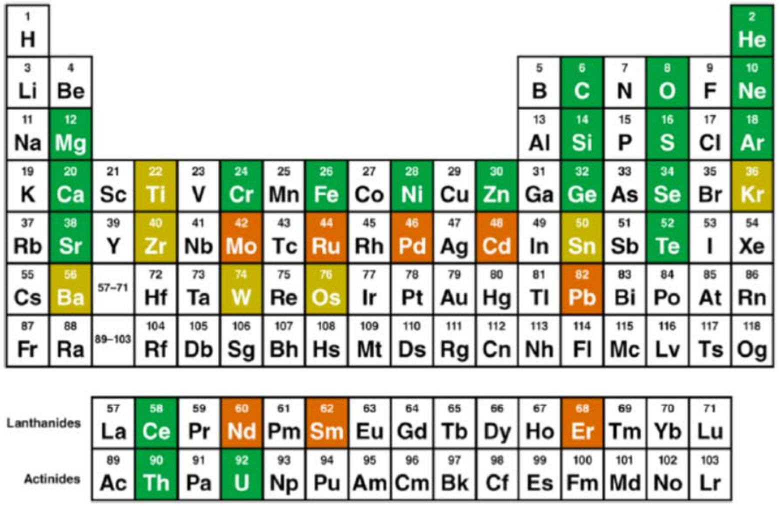


Freedman: Chemistry and Quantum Computing



Forging Solid-State Qubit Design Principles in a Molecular Furnace

Michael J. Graham, Joseph M. Zadrozny, Majed S. Fataftah, and Danna E. Freedman*



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 🟨	57–71	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	89–103	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

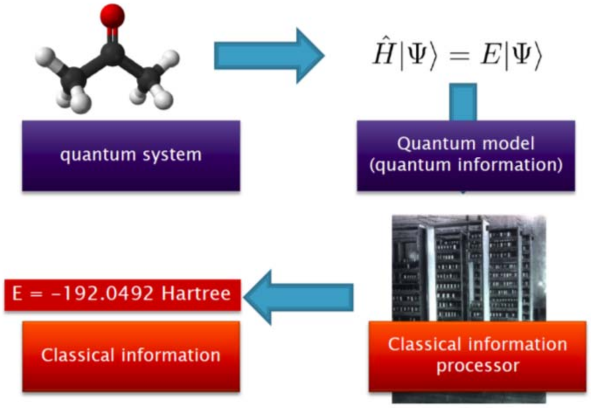
Lanthanides	57 La	58 Ce 🟩	59 Pr	60 Nd 🟧	61 Pm	62 Sm 🟧	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er 🟧	69 Tm	70 Yb	71 Lu
Actinides	89 Ac	90 Th 🟩	91 Pa	92 U 🟩	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

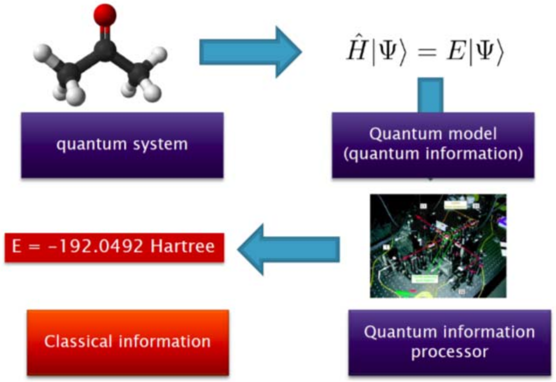
Figure 5. Periodic table with elements highlighted according to the natural abundance of zero-spin isotopes. Green: ≥90% abundance, yellow: ≥80% abundance, orange: ≥70% abundance, and white: <70% abundance.

Aspuru-Guzik: Quantum Simulation

https://quantum.nasa.gov/materials/2012-01-17-B3-Aspuru.pdf

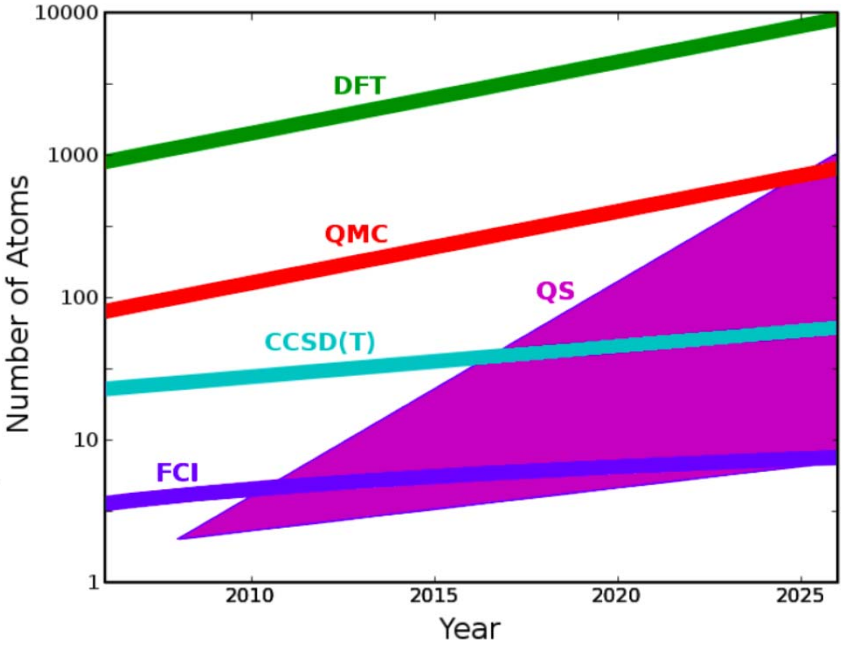
R. P. Feynman, *Int. J. Theor. Phys.* (1982)





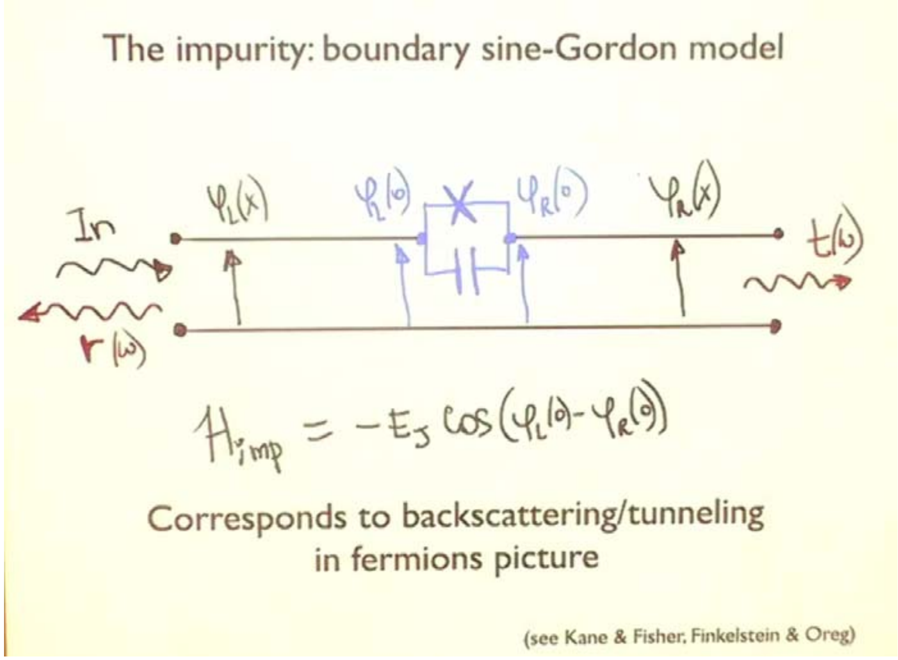
Optimistic prospects?

A quantum “Moore’s law?”



Manucharyan: Simulation with Superconducting Qubits

http://online.kitp.ucsb.edu/online/synquant16/manucharyan/

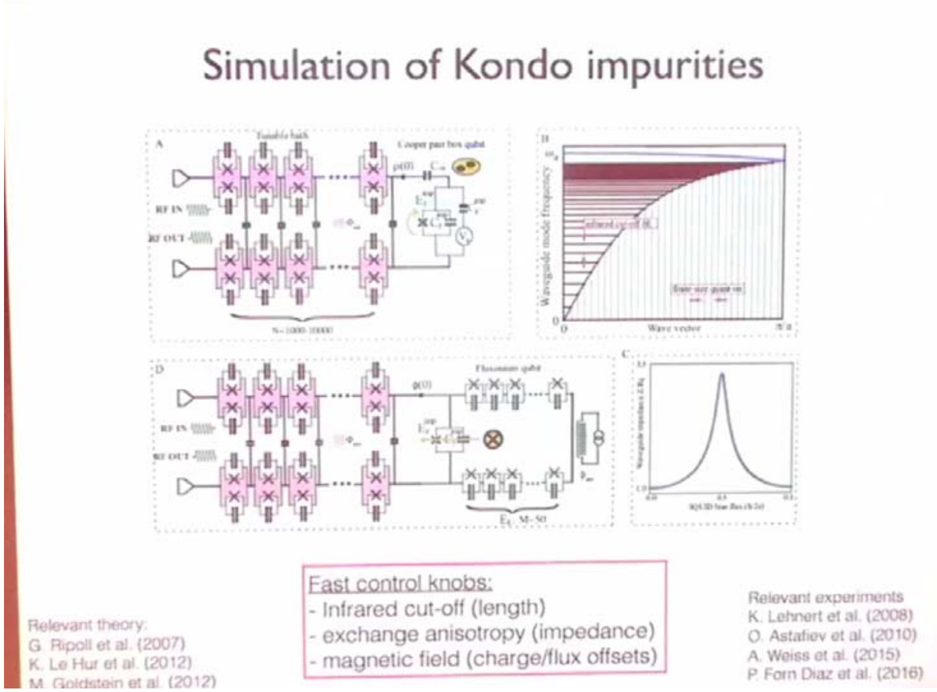


The impurity: boundary sine-Gordon model

$$H_{imp} = -E_J \cos(\varphi_L(0) - \varphi_R(0))$$

Corresponds to backscattering/tunneling
in fermions picture

(see Kane & Fisher, Finkelstein & Oreg)



Simulation of Kondo impurities

Fast control knobs:
- Infrared cut-off (length)
- exchange anisotropy (impedance)
- magnetic field (charge/flux offsets)

Relevant theory:
G. Ripoll et al. (2007)
K. Le Hur et al. (2012)
M. Goldstein et al. (2012)

Relevant experiments
K. Lehnert et al. (2008)
O. Astafiev et al. (2010)
A. Weiss et al. (2015)
P. Forn Diaz et al. (2016)

Mosca: Broad Views of Quantum Computing

https://www.youtube.com/watch?v=vWP4LF2hz80

New paradigm brings new possibilities

- Designing new materials, drugs, etc.
- Optimizing
- Sensing and measuring
- Secure communication
- What else???

McQueen: Quantum Materials

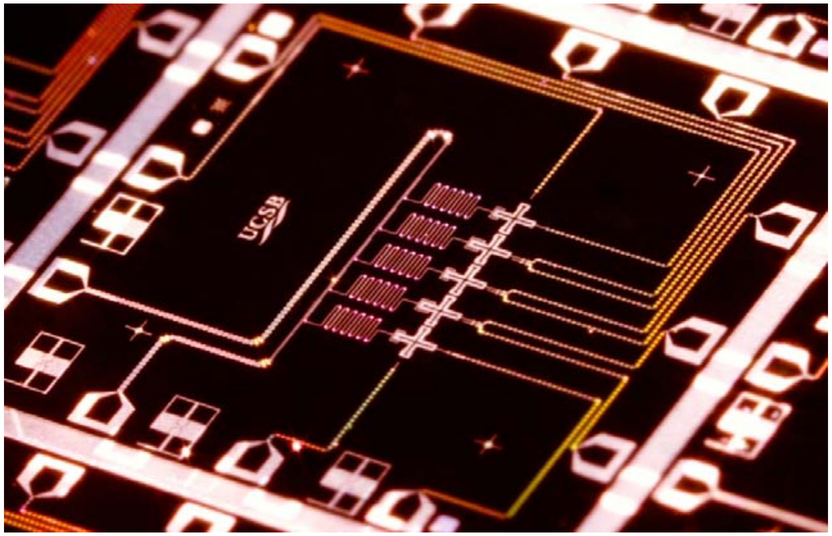
Superconducting Qubits

Superconducting qubits:

Theory (S. Girvin)

Experiment (V. Manucharyan)

Working prototypes demonstrated
at QS3 :



IBM Quantum Experience (4 physical qubits)

D-Wave
Scott Pakin LANL

Trapped Ions and neutral atoms

Trapped Ions
Theoretical background and experiment
Demonstration of 5 physical qubits working

Chris Monroe

Trapped ions, 3D integration
J. Sage

Optical lattices: neutral atoms

Davis Weiss

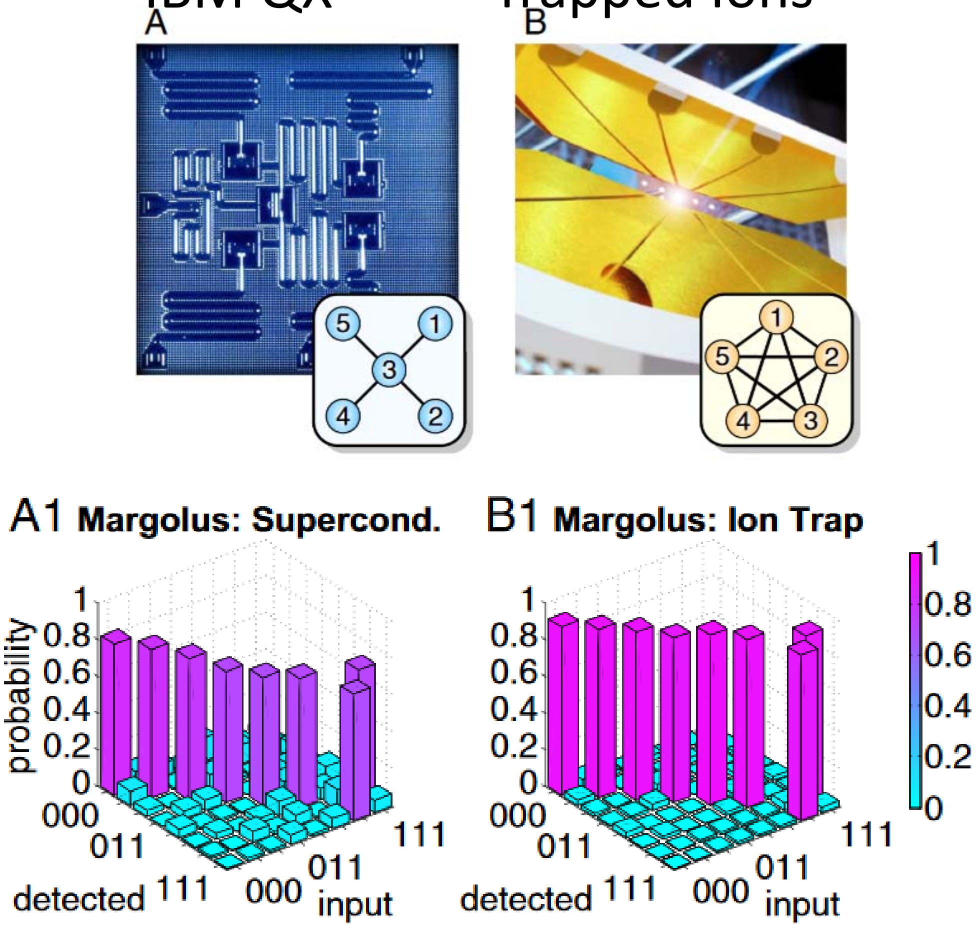
Positive: large coherence times, higher temperatures than SC qubits
Identical qubits

month of trapped ion life time
not getting lost

seconds of qubit (trapped atom) life time

Functioning of a QC

IBM QX Trapped Ions



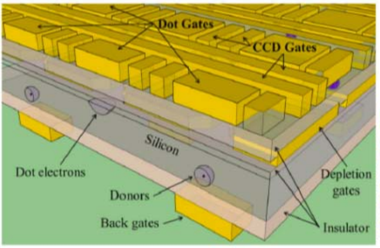
Chris Monroe
published
28 March 2017

- Developing algorithms
- Communicating with the hardware

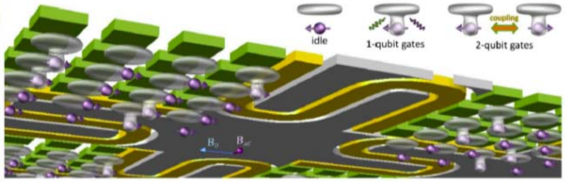
Spin Qubits

Putting many qubits together to build QC

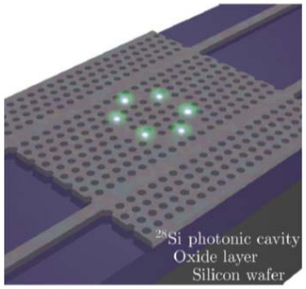
Si- based: S. Lyons



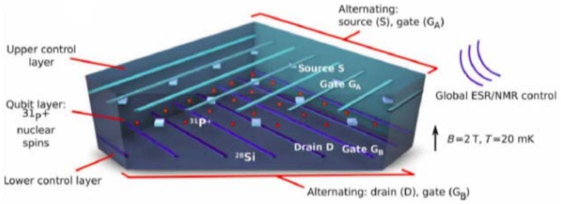
Pica, PRB **93**, 035306 (2016)



Tosi, ArXiv:1509.08538 (2105)



Morse, arXiv:1606.03488 (2016)



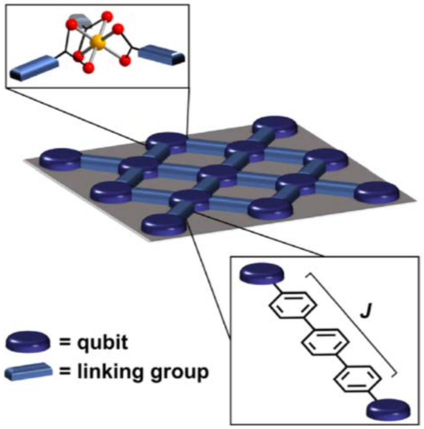
Hill, Sci Adv **1**, e1500707 (2015)

No working QC yet

Molecular magnets
Danna Freedman

only principle ideas
bad coherence times

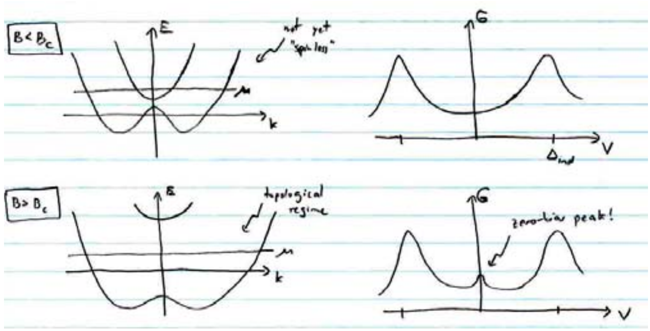
quantum sensors possible



Topological Quantum Computing

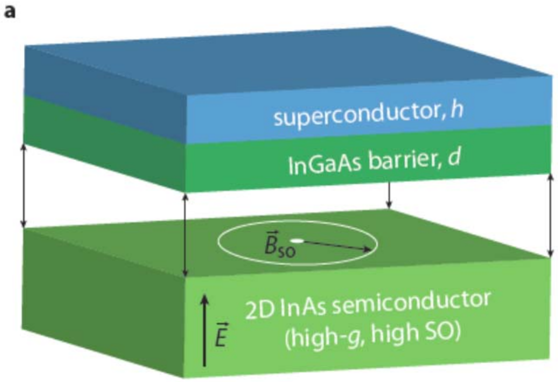
Right now on the level of cool theoretical proposal

Basic theory of topological computation
J. Alicea



Topological Quantum Computing: Experiment

J. Shabani: topological qubits in 1000 years?



Not mentioned at QS3:
many experimental publications about zero-bias peak

Braiding not yet demonstrated

Materials point of view

- All functioning and close to functioning devices
  are based on well-known and industrially produced materials
  Si
  InAs, InGaAs, etc
  Al-based Josephson Junctions

- Molecular magnets: ideas (unrealistic?) about making qubits
  Quantum sensors

- New "quantum materials", "materials by design":
  interesting properties
  not used for QC