QUANTUM COMPUTERS: THE R&D CHALLENGES

Pol Forn-Díaz, IFAE

INFIERI Summer School

Madrid, September 2nd 2021

INTRODUCTION QUANTUM COMPUTING TECHNOLOGY GROUP AT IFAE

A little bit about me (and the QC environment in BCN)

- Group established in 2019
- First serious effort in experimental quantum computing nationwide
- Group leading several European efforts (FET Open AVaQus, Quantera SiUCs) to develop superconducting quantum computing technology
- First quantum algorithm with 1 qubit implemented: A. Pérez-Salinas et al., Physical Review A 104 (1), 012405

Dilution refrigerators

Josephson junction technology

Metal deposition system

https://qct.ifae.es/

QILIMANJARO QUANTUM TECH SL

Introduction

- Qilimanjaro Quantum Tech SL: established in April 2019, Barcelona. **One** of the **few European companies** in quantum computing, the **only one** based on quantum annealing.
- Current status: Signed **two international contracts** of services in quantum computing. Member of a European **consortium** funded by the **EC**.

http://www.qilimanjaro.tech/

QILIMANJARO QUANTUM TECH SL

EXCELENCIA SEVERO OCHOA

BIST Barcelona Institute of Science and Technology

Complete team: 5 Founders, 2 Admin/Comms, 4 Hardware, 6 Theory/Software

Víctor Canivell (CBO)

José Ignacio Latorre

Pol Forn-Díaz (QHA)

Artur Garcia (QSA)

Jordi Blasco (CFO)

QILIMANJARO

QUANTUM · TECH

http://www.qilimanjaro.tech/

QILIMANJARO QUANTUM TECH SL

Expectations

- **Today:** Qilimanjaro offers consultancy services in quantum algorithms and technology transfer. Available funding for 24 months.
- **Mid-term** (1-3 years): access to quantum platform Qibo and licensed technologies to providers of QC. Looking for additional funding.
- **Long-term** (>3 years): Large-scale annealer prototypes, available platform for clients and academics, quantum computing services.

Developing a new open-source language to control quantum computers: QIBO

- https://github.com/Quantum-TII/qibo
- arxiv.org/abs/2009.01845

OUTLINE

Block 1: Overview of Quantum Computing Platforms

- A brief history of experimental QC
- How to build a quantum computer?
- Digital/analog quantum computers
- Leading experimental platforms

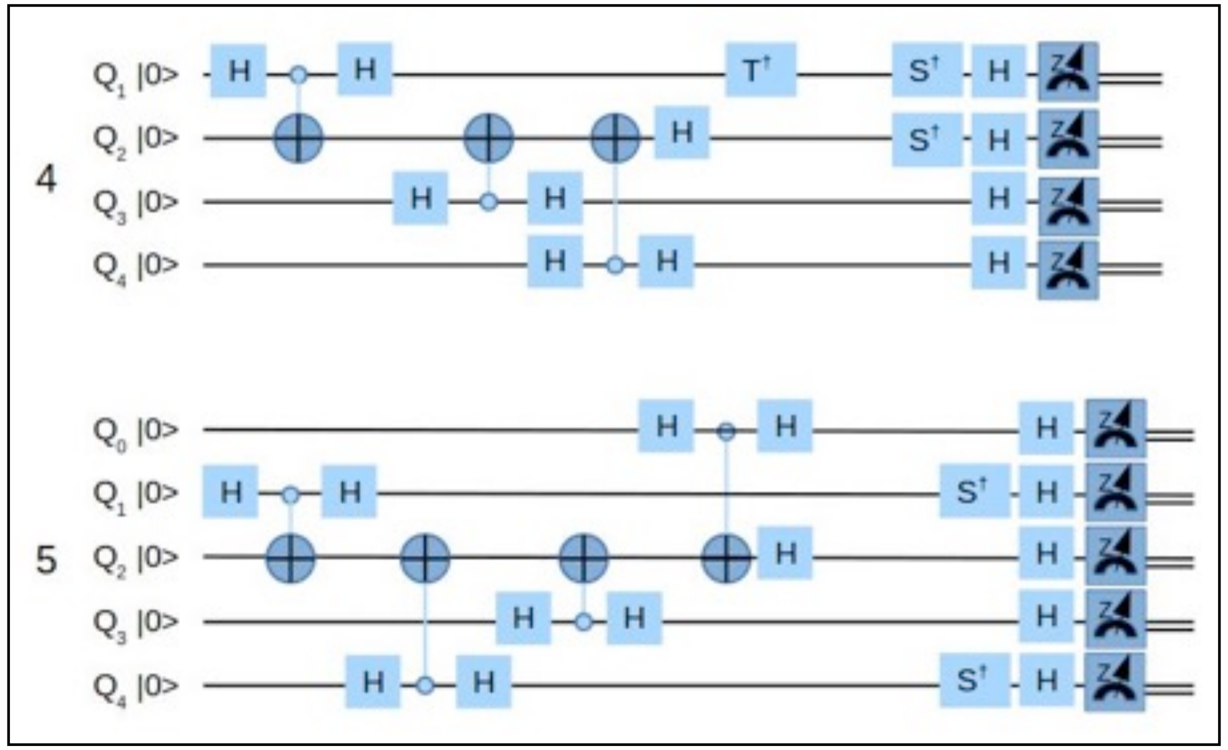
Block 2: Experimental quantum computing + Quantum industry

- 1-qubit manipulation: Rabi, Ramsey, echo
- Noise and decoherence
- Examples of quantum algorithms implemented

(extra) Block 3: What can HEP do for QC?

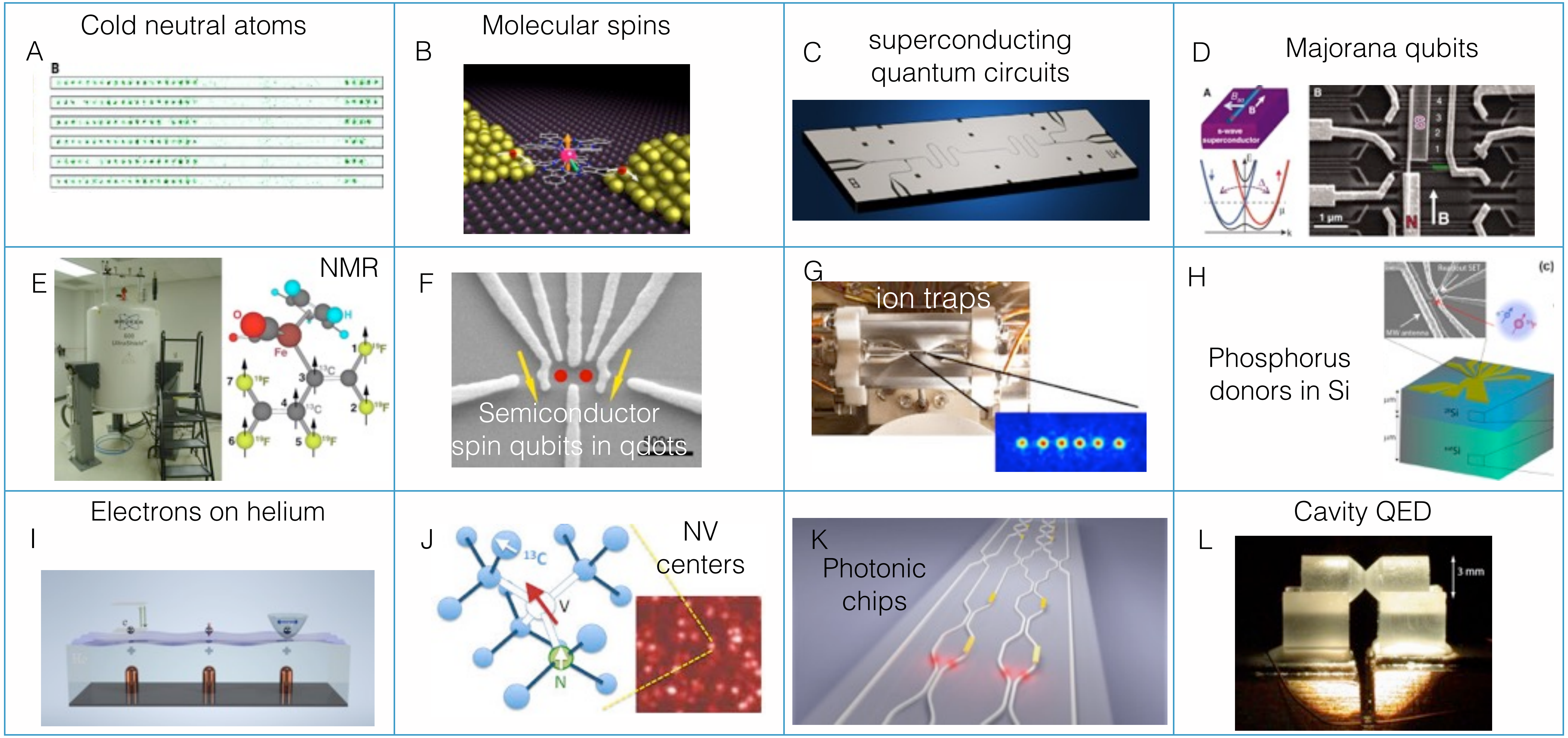
Block 1: Overview of Quantum Computing Platforms

- A brief history of experimental QC
- How to build a quantum computer?
- Digital/analog quantum computers
- Leading experimental platforms



Quiz: How much do you know about real quantum computers?

Candidate quantum processors tried so far:



* Many images taken from Wikipedia

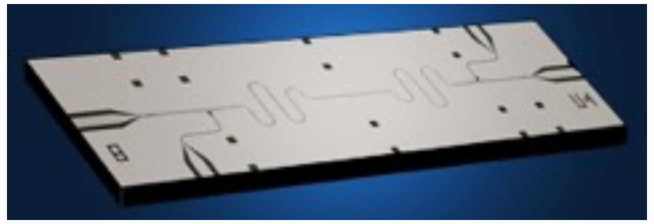
Quiz: How much do you know about real quantum computers?

Candidate quantum processors tried so far:

A Cold neutral atoms

B Molecular spins

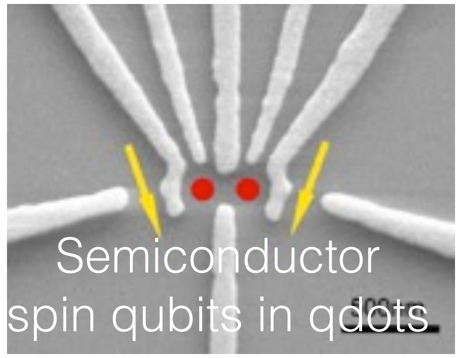
C superconducting quantum circuits



D Majorana qubits

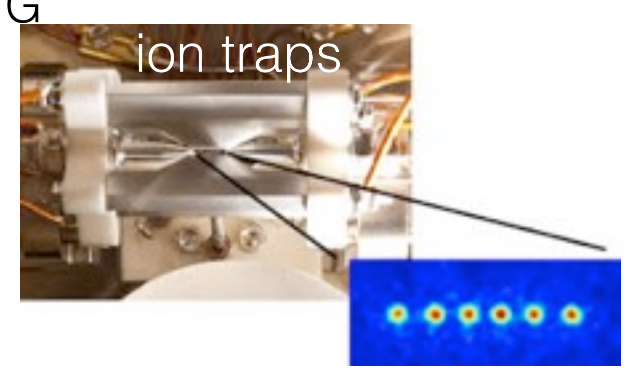
E NMR

F



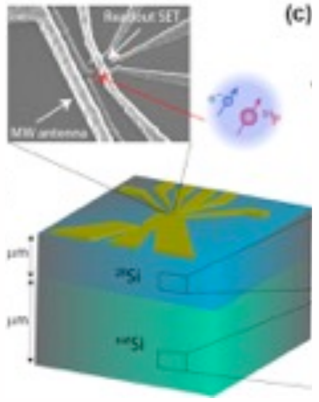
Semiconductor spin qubits in qdots

G



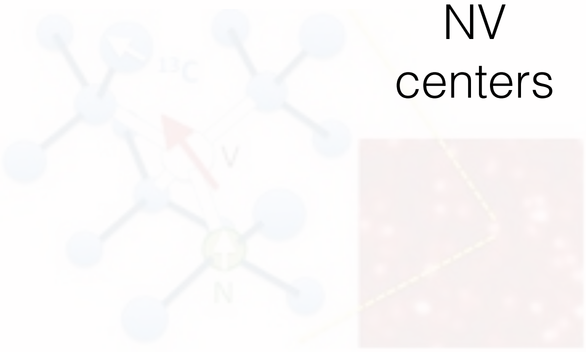
ion traps

H Phosphorus donors in Si



I Electrons on helium

J NV centers



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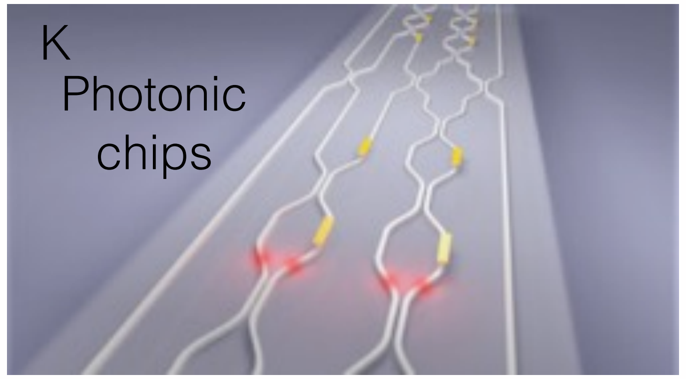


Photonic chips

L Cavity QED

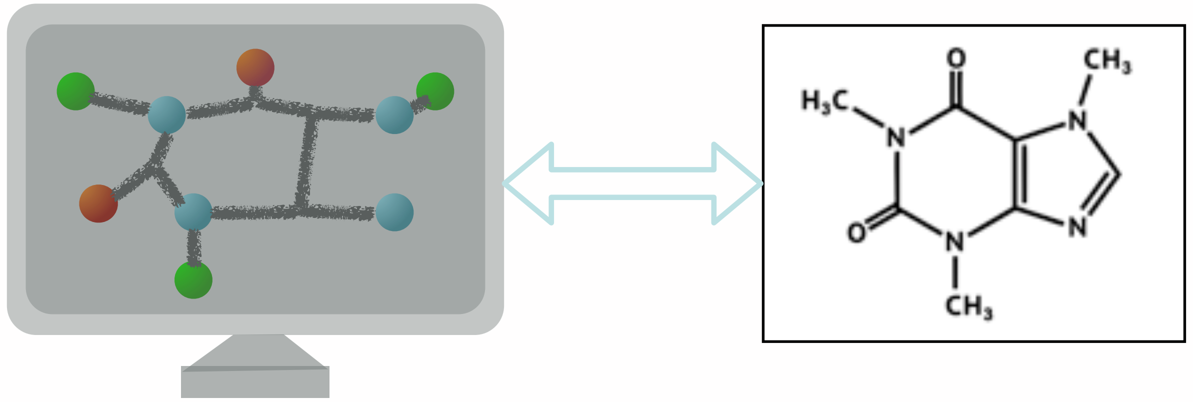
* Many images taken from Wikipedia

A BRIEF HISTORY OF EXPERIMENTAL QC

1980 | 1990 | 2000 | 2010 | 2020

Birth of the idea | Proofs | Begin experiments | Industry enters | Quantum supremacy

- 1980: Paul Benioff proposes quantum mechanical model of a Turing machine
- 1980: Yuri Manin proposes computations a classical computer cannot perform
- 1982: Richard P. Feynman introduces the concept of a quantum simulator



Using intrinsic properties of quantum systems can we map **and compute** complex problems?

R. P. Feynman, *Simulating physics with computers, Int. J. Theor. Phys.* **21**, 467 (1982)

- 1985: David Deutsch proposes the first quantum algorithm, in 1992 refined by Richard Josza as the Deutsch-Josza algorithm. No practical use.

D. Deutsch, *Quantum theory, the Church-Turing principle and the universal quantum computer*. Proceedings of the Royal Society A. 400 (1818): 97–117

A BRIEF HISTORY OF EXPERIMENTAL QC

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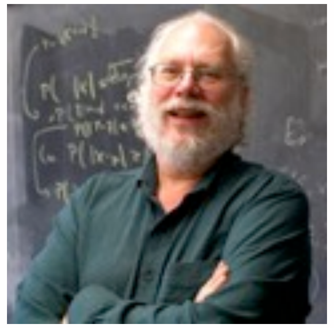
- 1992: Bernstein-Vazirani algorithm. First algorithm more efficient than classical computers.
- 1994: Shor's prime factoring algorithm*. Most powerful so far discovered, exponentially faster than best known classical algorithm. In 1995 he proposes a quantum error correcting code.

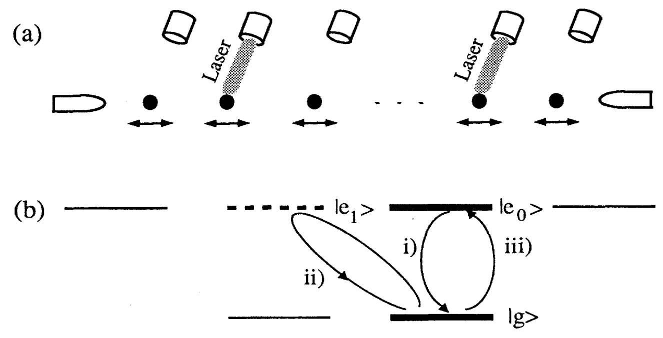
This algorithm made the world realize that **quantum computers were something else**. It raised many expectations and triggered the race to propose candidates for QCs.



The algorithm poses a **threat to RSA encryption**, use today in communications security: military and government interests. Quantum computers as **geopolitical weapons**, in analogy to nuclear bombs.

Shor, P.W. (1994). "Algorithms for quantum computation: discrete logarithms and factoring". Proceedings 35th Annual Symposium on Foundations of Computer Science. IEEE Comput. Soc. Press: 124–134

- 1995: Cirac-Zoller C-NOT proposal with ion traps. First real proposal for a quantum computer.



Paper proposes trapping ions with electrical potentials and address its internal energy states as qubits. Coupling mediated by collective oscillations

J. I. Cirac and P. Zoller. Quantum Computations with cold trapped ions. Phys. Rev. Lett. **74**, 4091 (1995)

- 1996: Grover's algorithm: Next best algorithm known so far. Polynomially faster search.

Grover L.K.: A fast quantum mechanical algorithm for database search, Proceedings, 28th Annual ACM Symposium on the Theory of Computing, (May 1996) p. 212

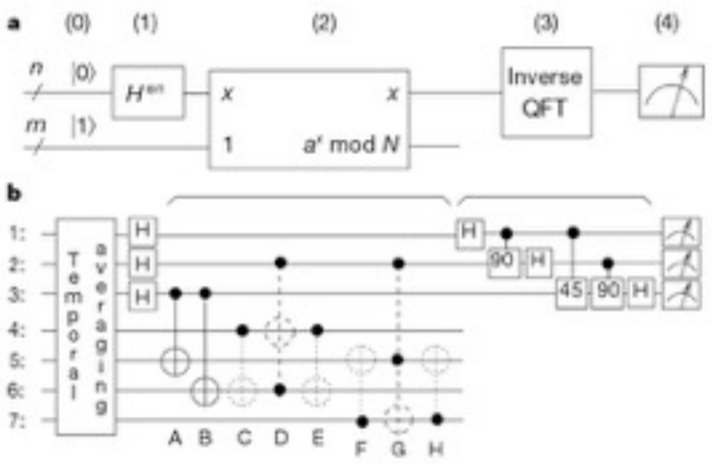
A BRIEF HISTORY OF EXPERIMENTAL QC

1980 | 1990 | 2000 | 2010 | 2020

Birth of the idea | Proofs | **Begin experiments** | Industry enters | Quantum supremacy

- 1998: Deutsch-Josza algorithm on an NMR system.
  I. L. Chuang et al., Nature **393**, 143 (1998). Stanford University
- 2000: Di-Vincenzo criteria formulated.
  DiVincenzo, David P. (2000-04-13). "The Physical Implementation of Quantum Computation". Fortschritte der Physik. 48 (9–11): 771–783
- 2001: Shor's algorithm implemented on an NMR system [A]
  Lieven K. Vandersypen et al., Nature **414**, 883 (2001). Stanford University
- 2003: CNOT gate implemented on an ion trap [B]
  Ferdinand Schmidt Kahler et al., Nature **422**, 408 (2003). University of Innsbruck
- 2005: Coherent oscillations between electron spins in a quantum dot [C]
  J. Petta et al., Science **309**, 2180 (2005). Harvard University
- 2007: CNOT gate implemented on a superconducting circuit [D]
  Jelle Plantenberg et al., Nature **447**, 836 (2007). Delft University of Technology

A



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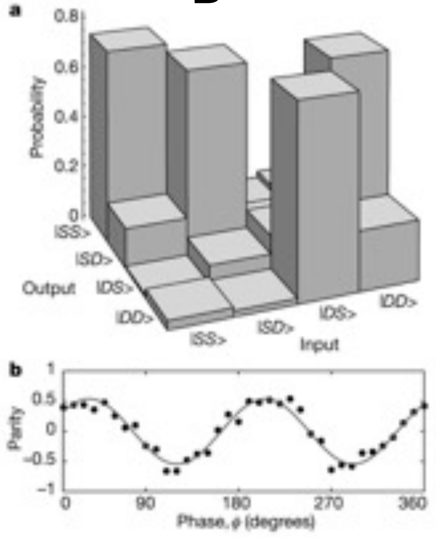
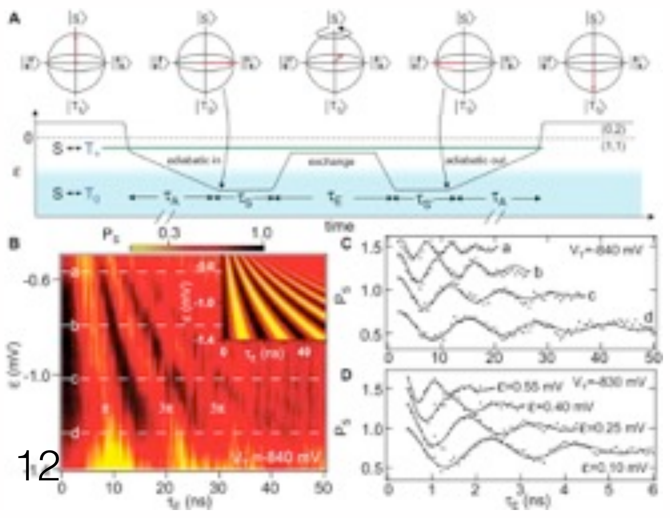
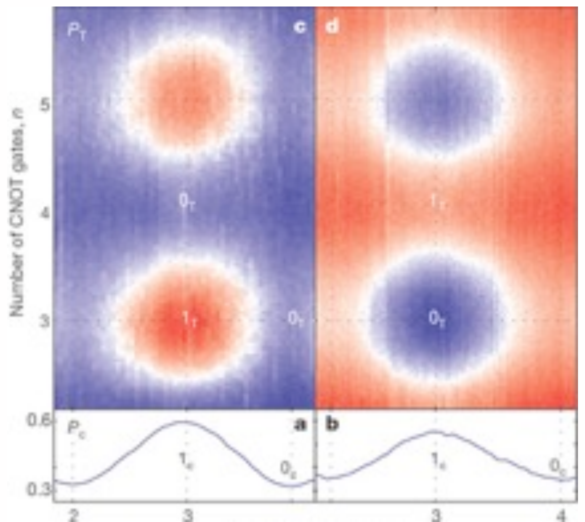


C



D



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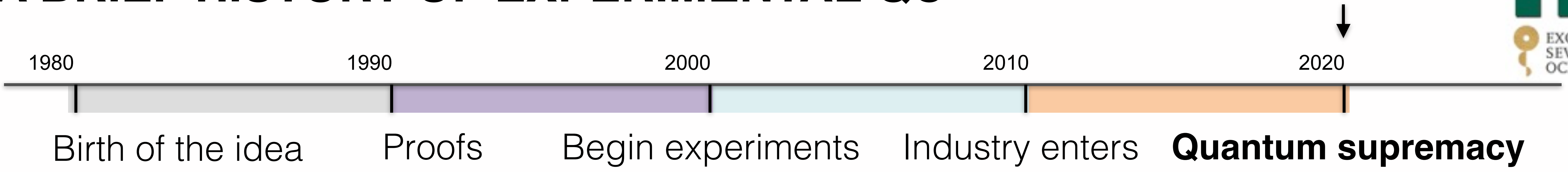
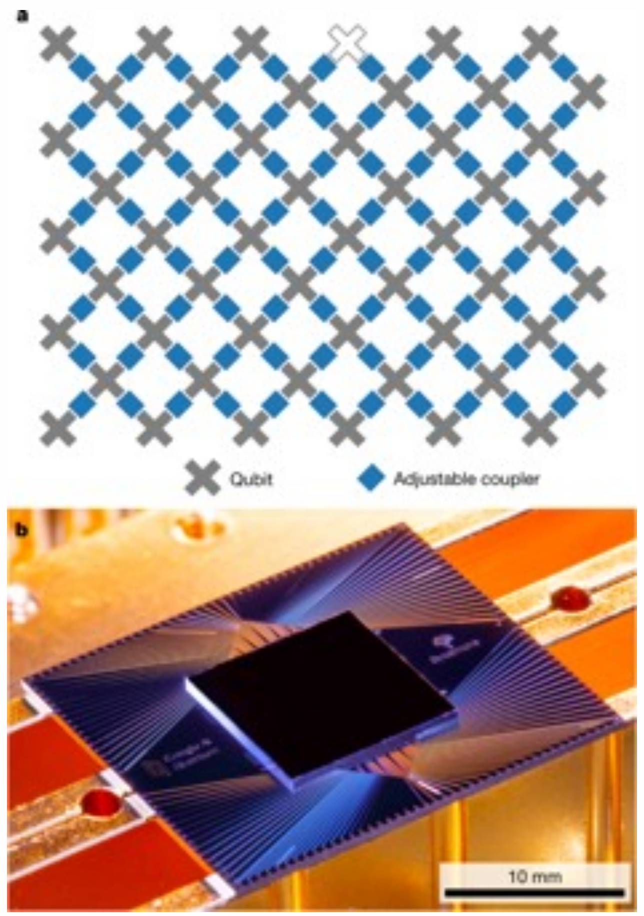
- 2011: IBM launches its quantum computing program
- 2011: D-Wave presents its first commercial product
- 2013: Rigetti quantum computing founded as first experimental quantum computing startup
- 2013: Google acquires research team from UC Santa Barbara
- 2015: IonQ is founded
- 2016: The Quantum Manifesto is published to boost efforts in Europe
- 2017: Zapata computing founded to focus on Quantum Software
- 2018: EU Quantum Flagship is launched
- 2017-18: First European Quantum computing companies founded: OxfordQC, Alpine QTech, IQM
- 2018: John Preskill coins 'NISQ' concept: near-term intermediate scale quantum processors.
- 2019: First Spanish quantum computing company founded: Qilimanjaro
- 2021: IonQ becomes first quantum startup to become public.

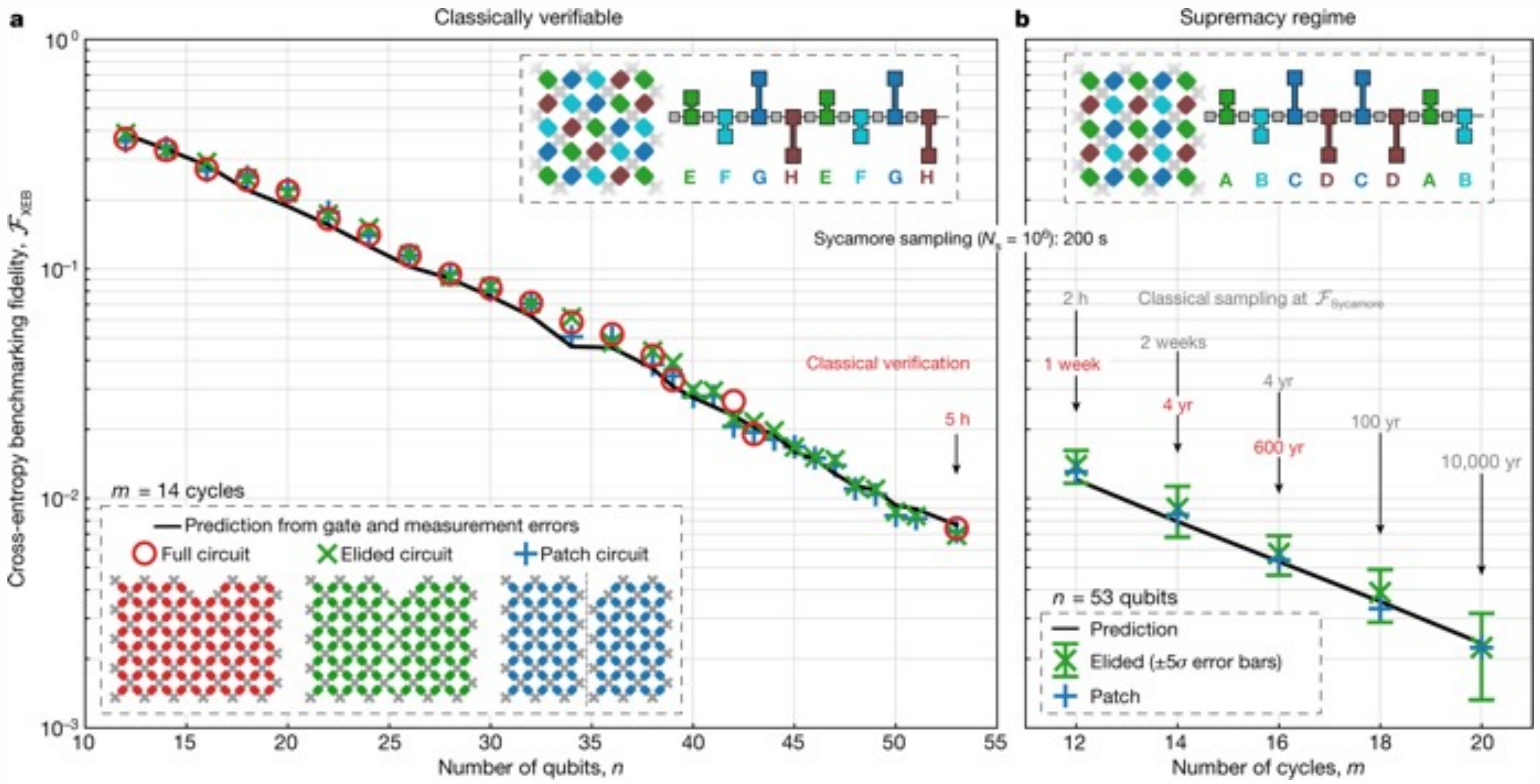
Quantum Computing in the NISQ era and beyond. John Preskill. Quantum 2, 79 (2018)

A BRIEF HISTORY OF EXPERIMENTAL QC



- 2019: Google announces the achievement of quantum supremacy with a superconducting quantum processor of 53 qubits led by John Martinis.





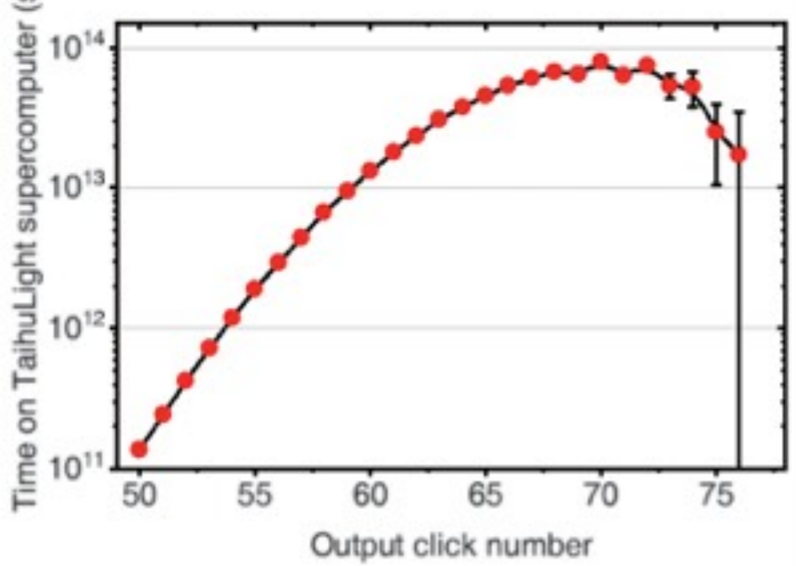
F. Arute et al., Quantum Supremacy using a programmable superconducting processor. Nature **574**, 505 (2019).

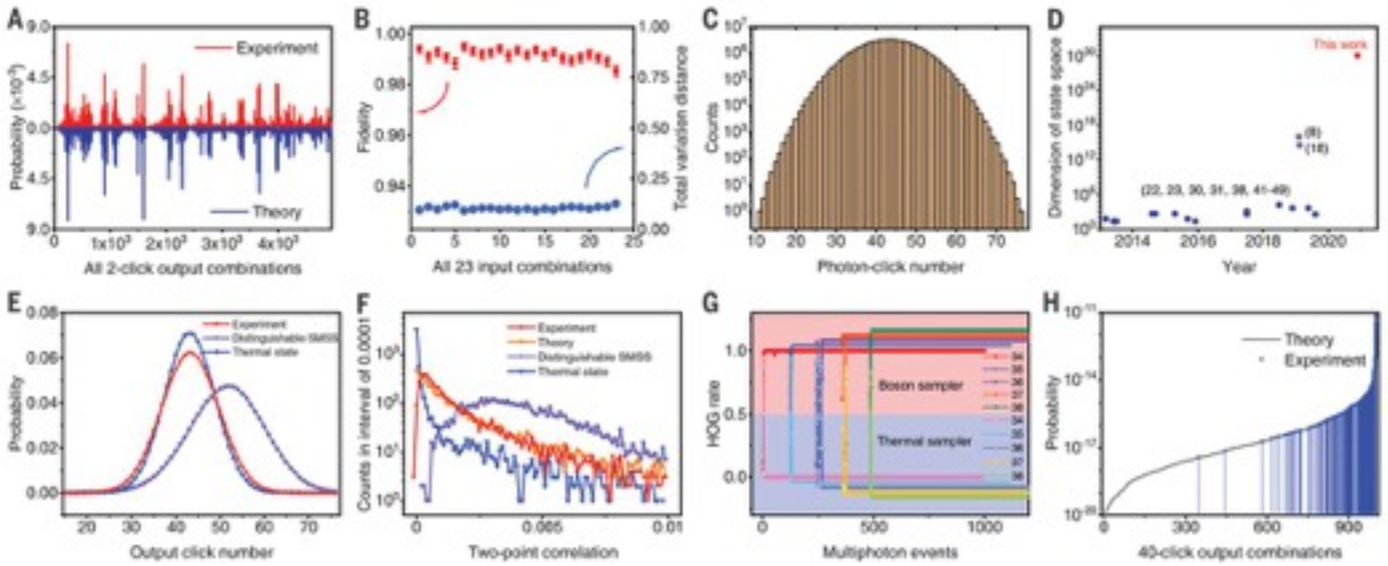
A BRIEF HISTORY OF EXPERIMENTAL QC

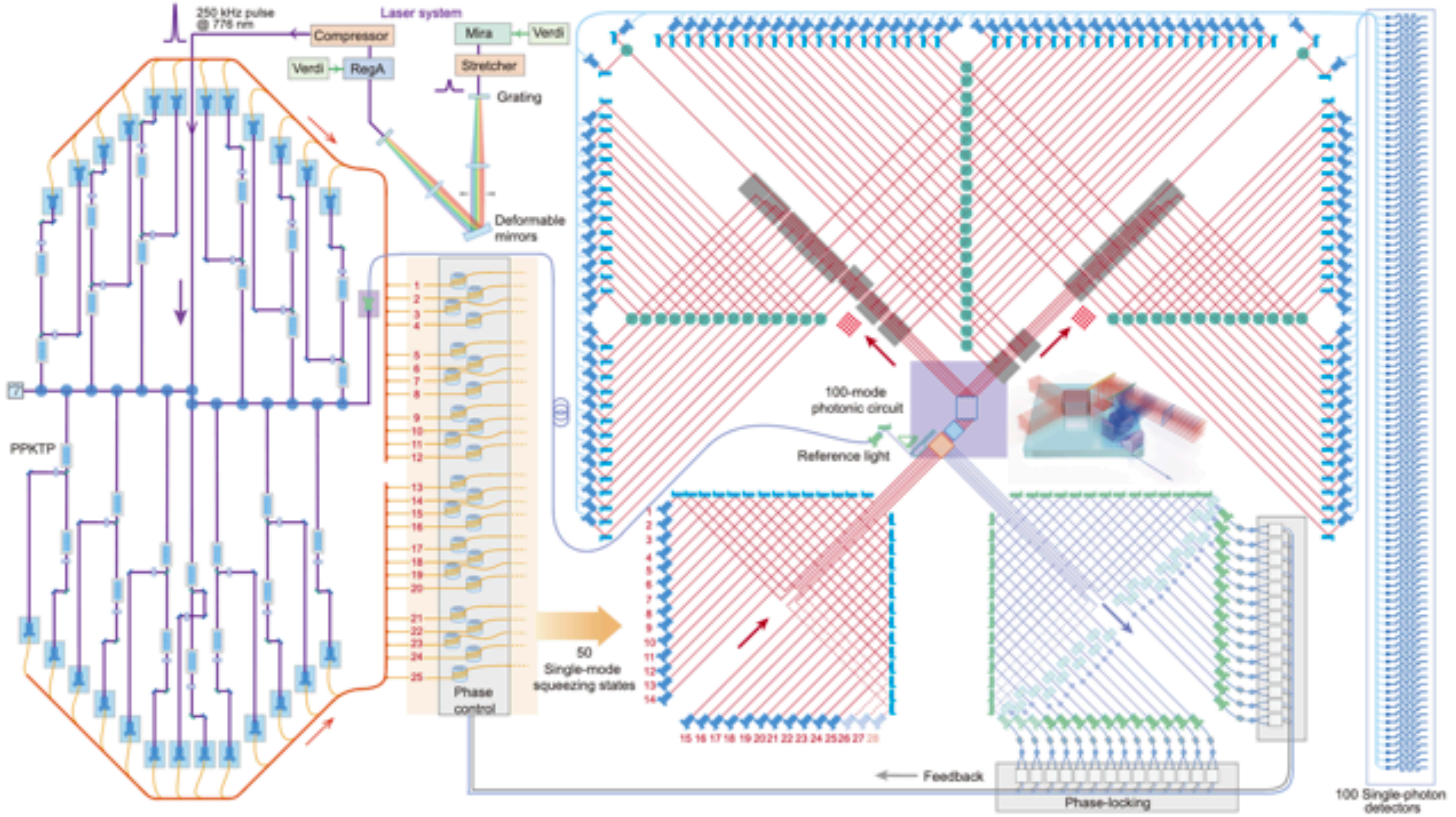
1980 | 1990 | 2000 | 2010 | 2020

Birth of the idea | Proofs | Begin experiments | Industry enters | **Quantum supremacy**

- 2020: Chinese team led by Jian Wei Pan demonstrates quantum supremacy with a photonic quantum processor using 50 photonic modes.





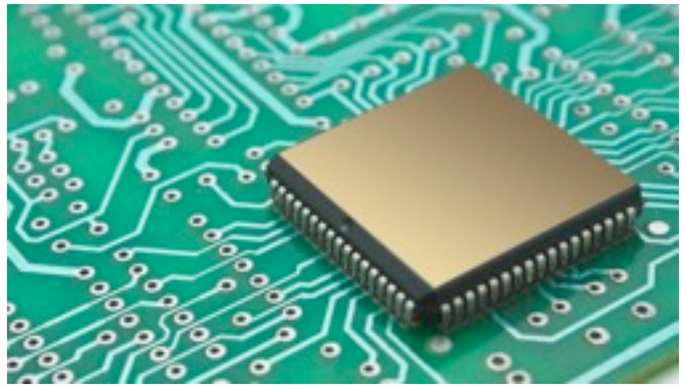


Han-Sen Zhong et al., Quantum Computational Advantage using photons. Science **370**, 1460 (2020).

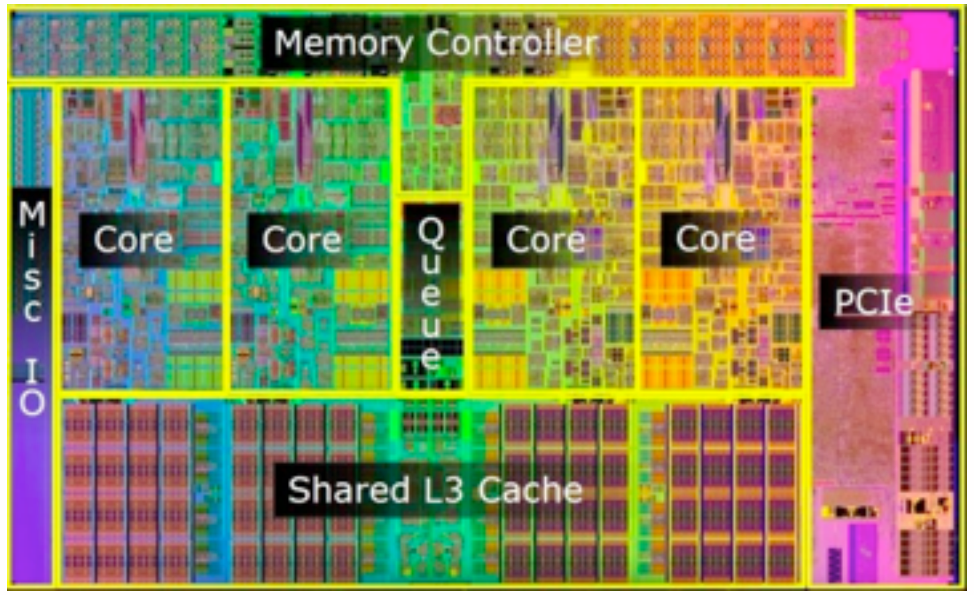
HOW TO BUILD A QUANTUM COMPUTER?

Computers consists of various elements: processors, memory, wiring, buses, connections, etc.

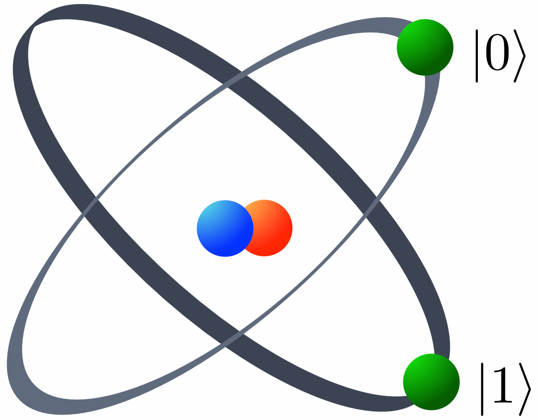
Classical information: bits



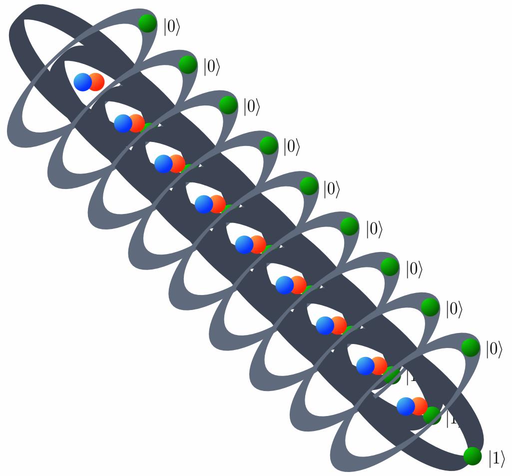
Intel Core i7 ~10^9 transistors



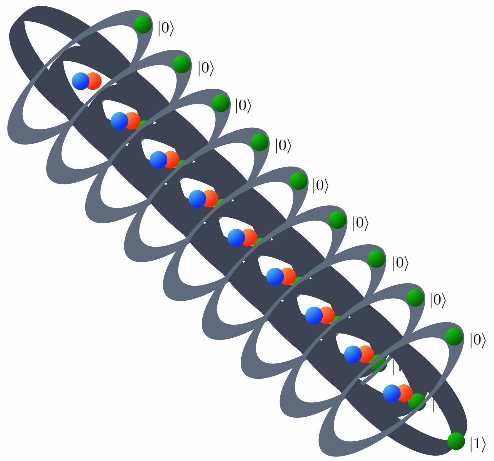
Quantum information: qubits



Quantum processor?



HOW TO BUILD A QUANTUM COMPUTER?



Initialized state

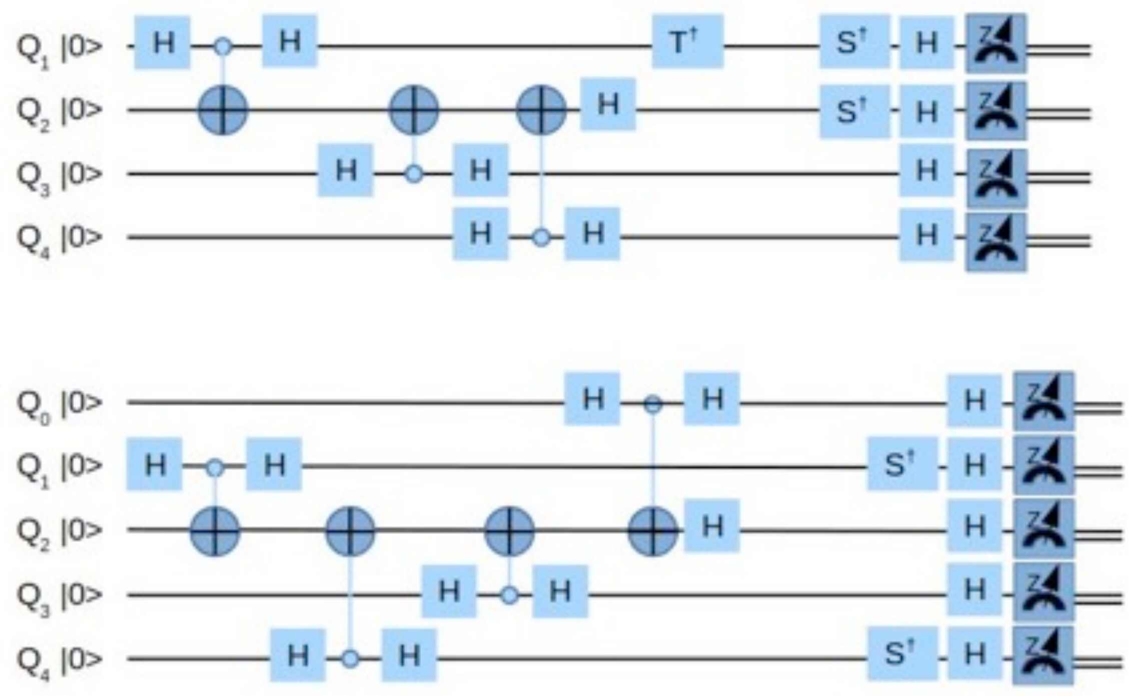
$$|\Psi(0)\rangle$$

$$\hat{U}$$

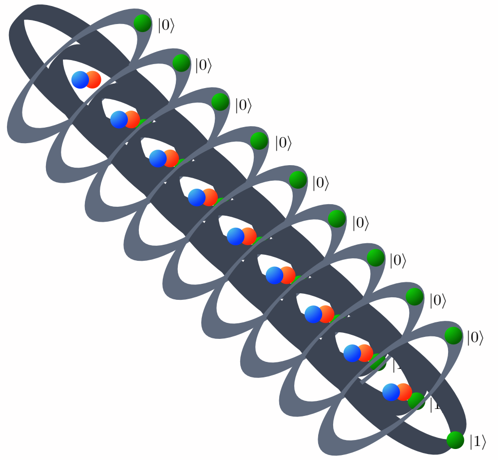
Operation decomposed in 1-, 2-qubit gates

4

5



Examples 4/5, qubit sequences from D. Alsina, J.I. Latorre. Physical Review A **94** (1), 012314 (2016)

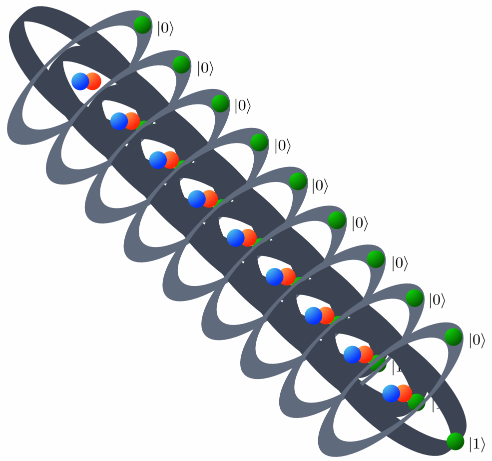


Processing 2^N states simultaneously

$$|\Psi(T)\rangle$$

Nielsen and Chuang, Quantum Computation and Quantum Information Processing

HOW TO BUILD A QUANTUM COMPUTER?



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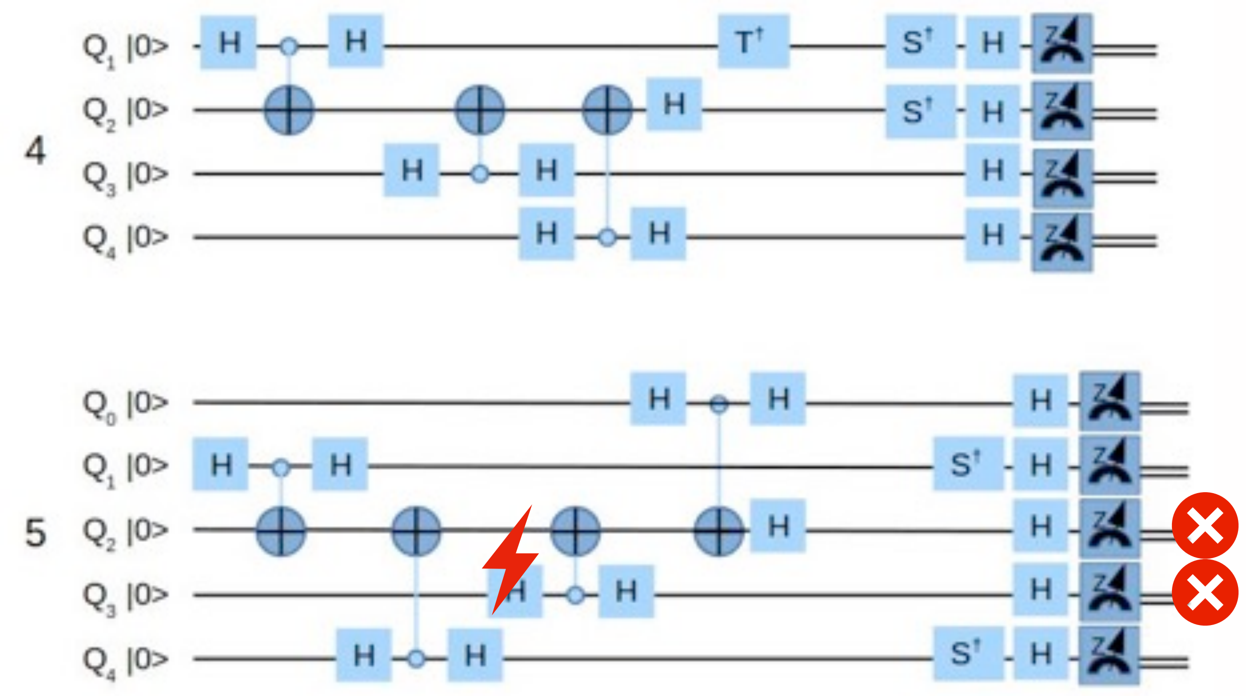

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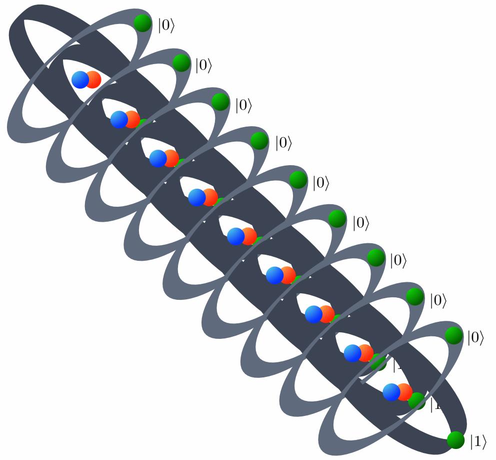

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Nielsen and Chuang, Quantum Computation and Quantum Information Processing

HOW TO BUILD A QUANTUM COMPUTER?
THE DIVINCENZO CRITERIA

In 2020, D. Divincenzo formulated the following criteria to implement quantum computation:

1. A scalable physical system with well characterized qubits
2. The ability to initialize the state of the qubits to a simple fiducial state, such as
3. Long relevant decoherence times, much longer than the gate operation time. Introduce Quantum Error Correction (QEC).
4. A "universal" set of quantum gates: 1-, 2-qubit gates
5. A qubit-specific measurement capability

Desiderata for quantum communication:

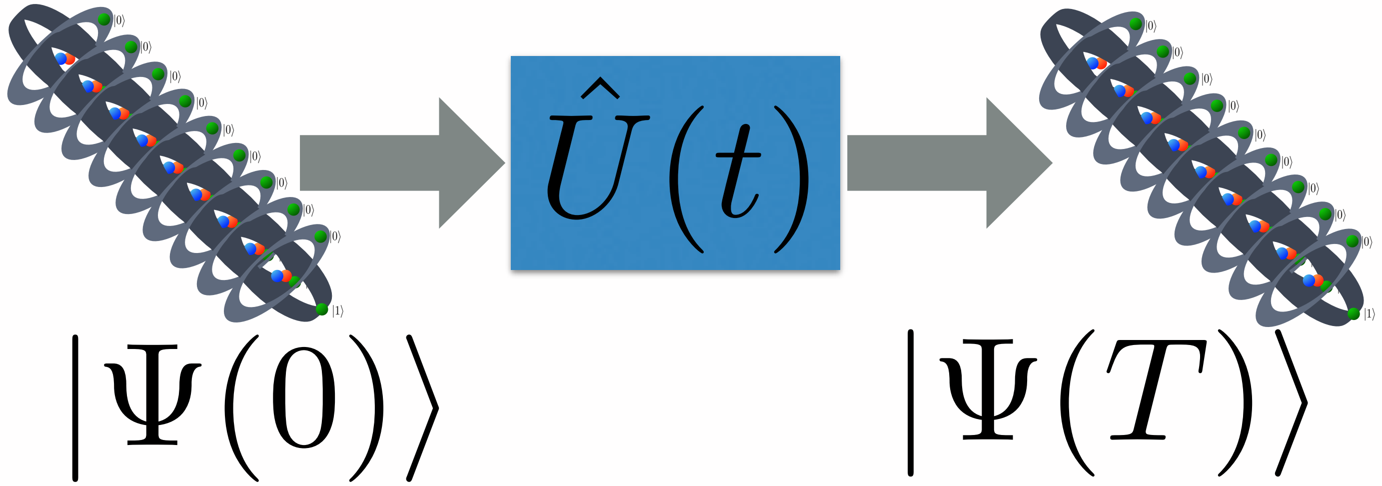
1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations

The Physical Implementation of Quantum Computation. D. Divincenzo. Fortschritte der Physik. 48 (9–11): 771–783
arXiv:quant-ph/0002077

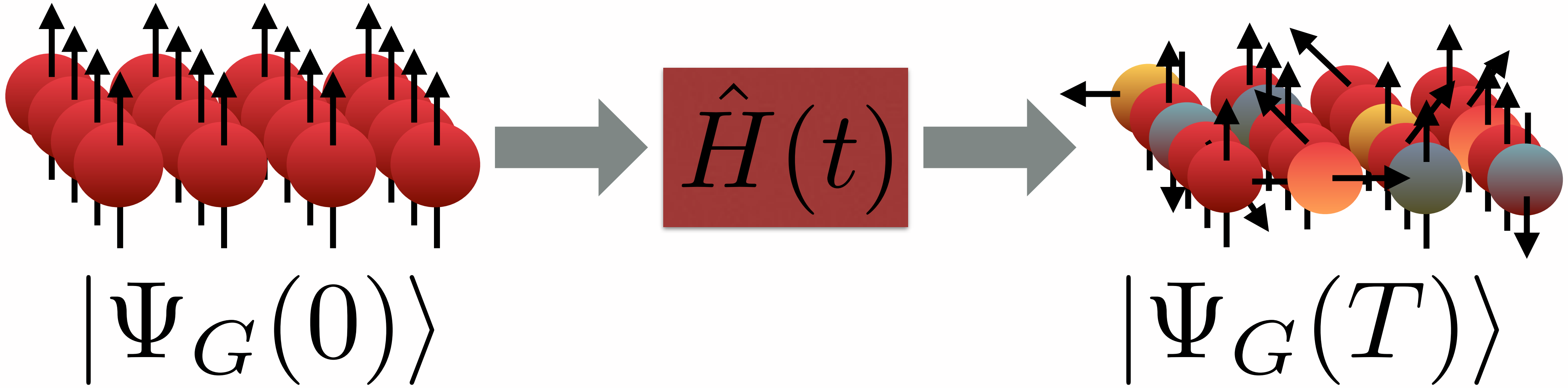
DIGITAL/ANALOG QUANTUM COMPUTERS

Digital quantum computers are most well-known. Alternative approach is by using analog quantum processors, also known as quantum annealers.

Digital: Evolution of quantum state by change of state:



Analogue: Evolution of quantum state by change of H. Also known as AQC.



DIGITAL/ANALOG QUANTUM COMPUTERS

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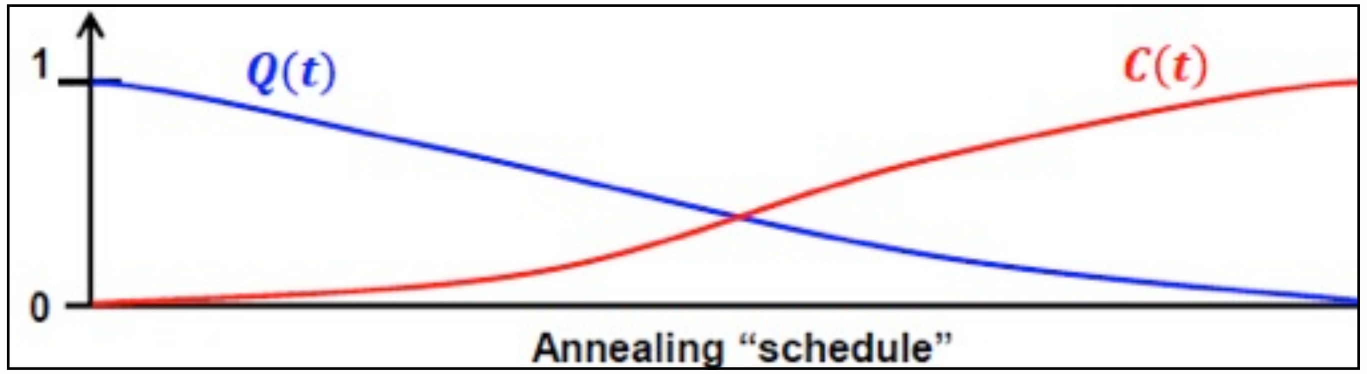
Annealing (Analog Quantum Processor)	Quantum Gates (Digital Quantum Processor)
Not universal*	Universal**
Does **not** require QEC	Requires QEC
Scalable in the **mid-term**	Scalable in the long term

* Ideas exist to make it universal
** There exist non-universal versions (NISQ), not clear they may show advantage

- **Adiabatic theorem** of Quantum Mechanics guarantees arriving at desired solution in the ground state.
- Annealers are not proven to be more efficient to classical quantum processors, it's a **heuristic method** (much like Monte Carlo).
- Annealing schedule starts from a **trivial system** to prepare and evolves into a nontrivial configuration that provides the solution to the problem in case.
- Quantum annealing is particularly suited to address optimization problems, which are societally very relevant.



$$\mathcal{H}(t) = Q(t)\mathcal{H}_D + C(t)\mathcal{H}_P$$

Trivial — Problem

E. Farhi et al., arxiv:quant-ph/0001106
T. Albash and D. Lidar, Rev. Mod. Phys. 90, 015002 (2018)

DIGITAL/ANALOG QUANTUM COMPUTERS

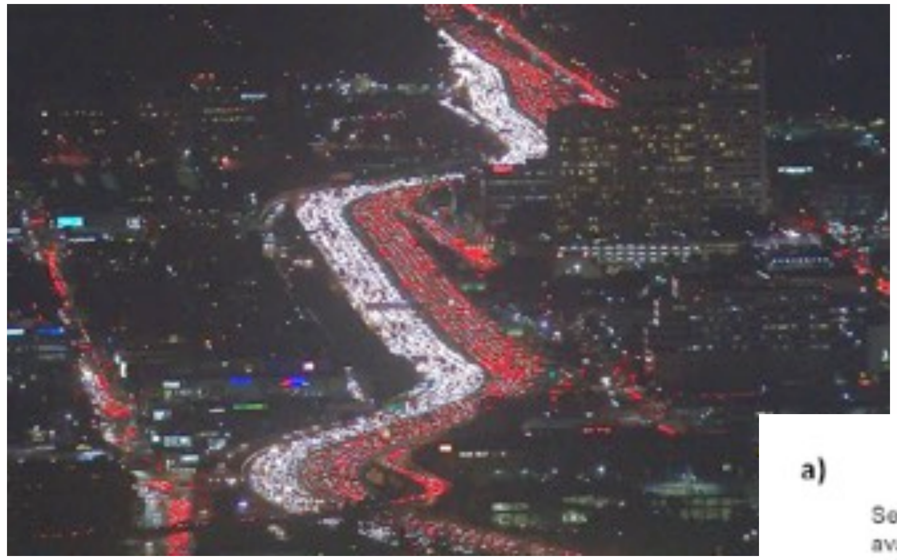
EXCELENCIA SEVERO OCHOA
BIST Barcelona Institute of Science and Technology

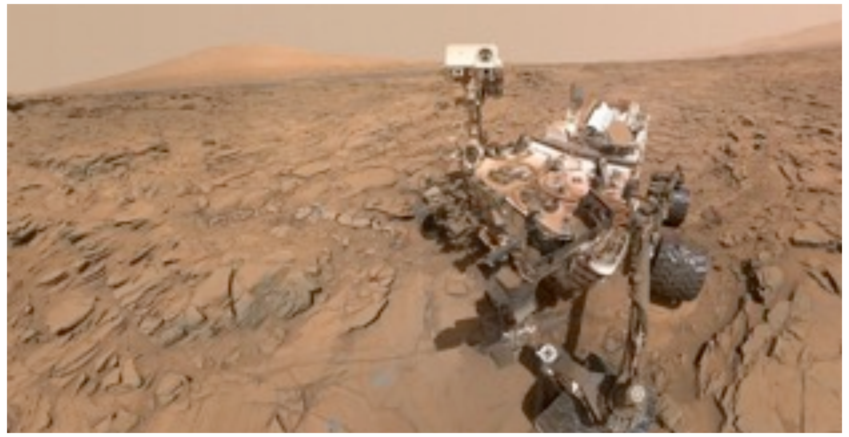
Why do we need small Quantum Annealers?

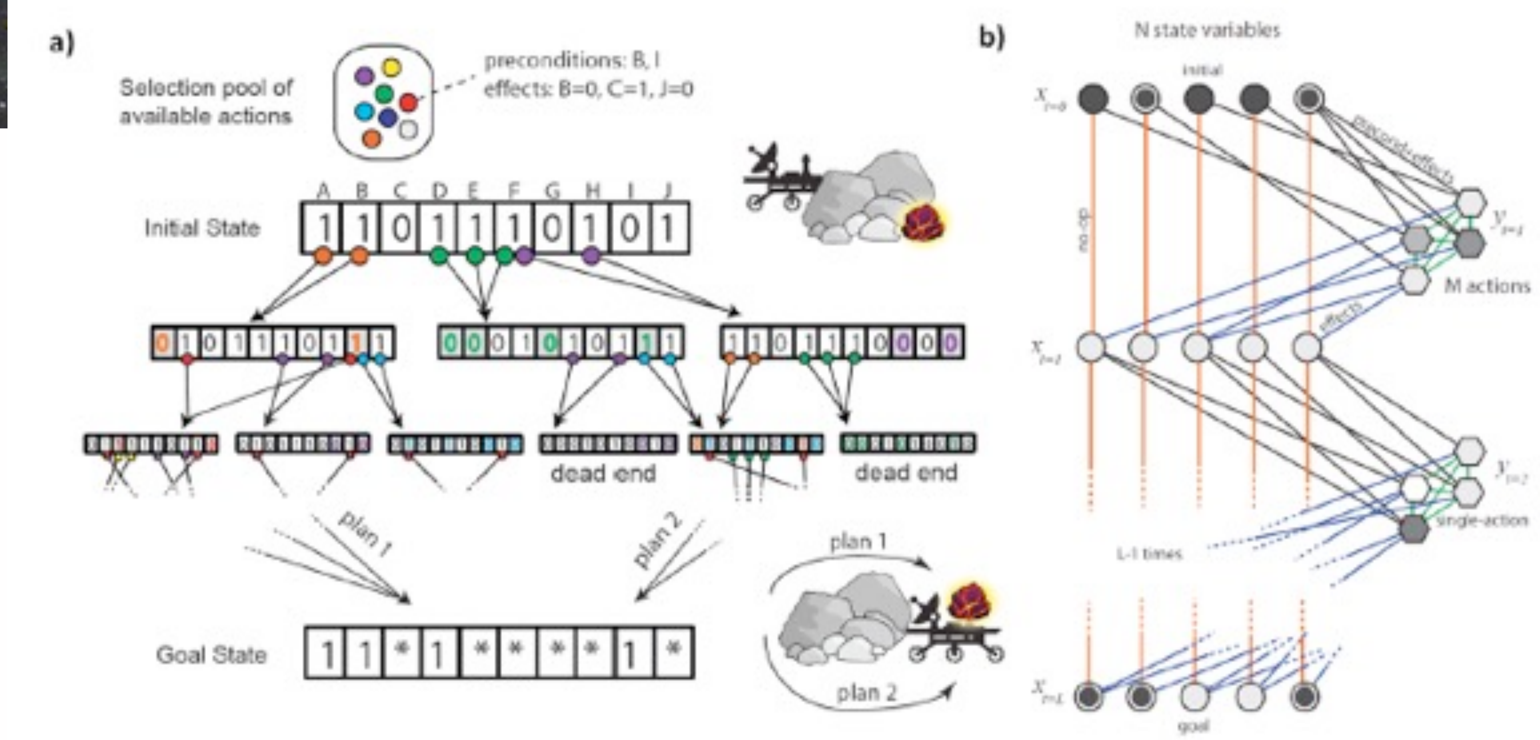
- Applications where small-sized quantum processors can outperform classical computers

1. Optimization: traffic, navigation, scheduling, machine learning, etc.

2. Quantum Simulation: chemistry, materials

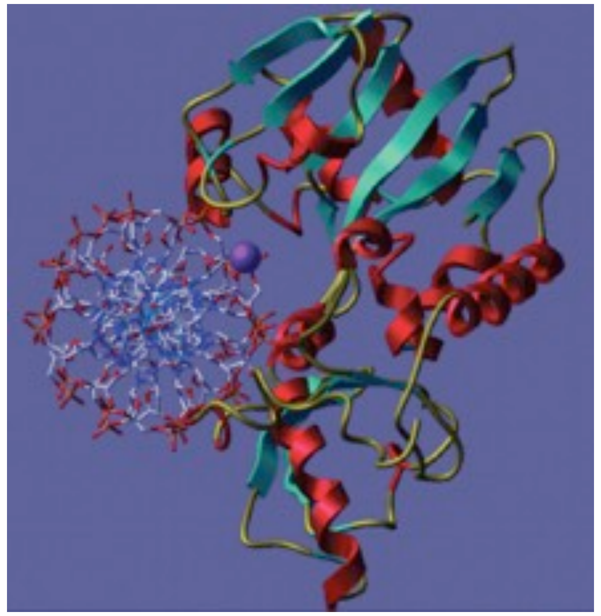






Navigation, scheduling, portfolio management in finance, etc.

Neural networks trained more efficiently by quantum annealers



(Bio-)chemistry

Study complex molecules to yield new drugs, fertilizers, CO_2 capture, etc.

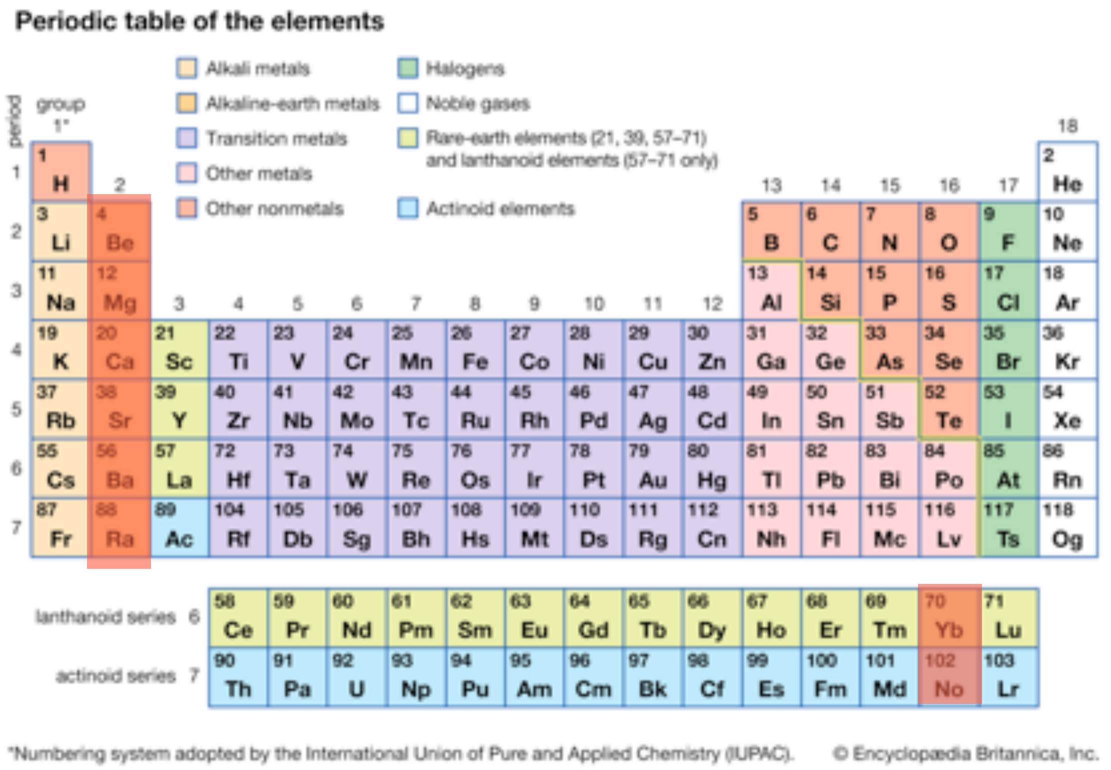
LEADING EXPERIMENTAL PLATFORMS

ION TRAPS

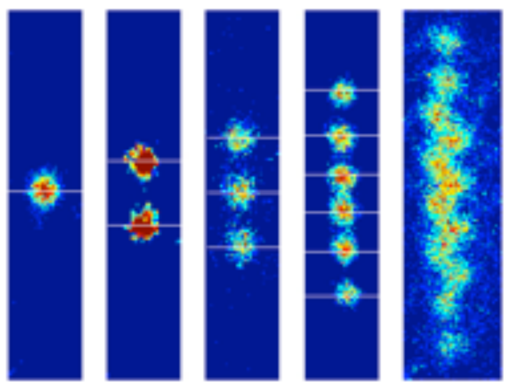
Charged ions can be trapped in non-stationary electrical potentials. Proposed by Ignacio Cirac and Peter Zoller in 1995.

J. I. Cirac and P. Zoller. Phys. Rev. Lett. **74**, 4091 (1995)

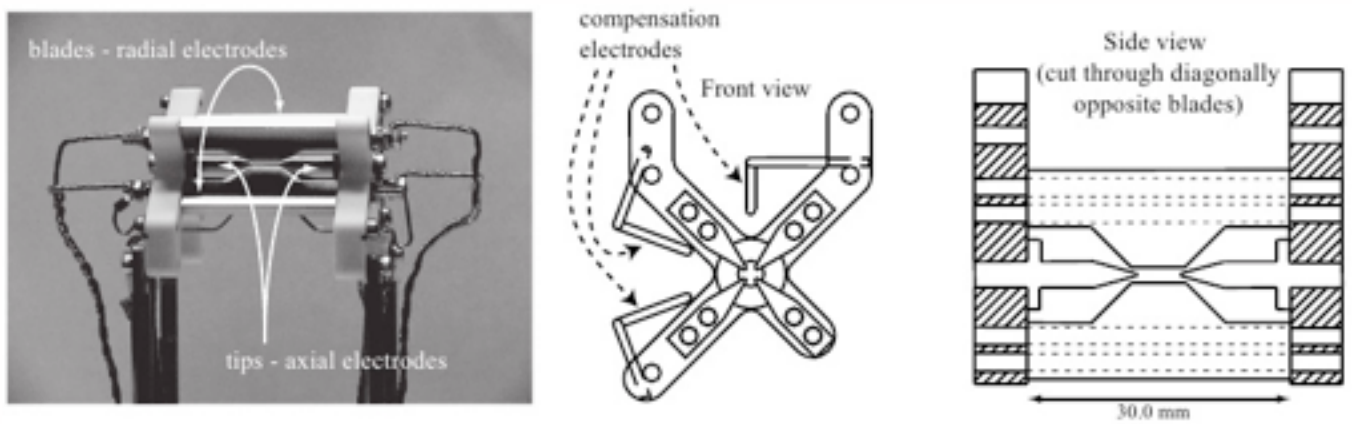
- Ionize gas (Ca, Be, Yb, Sr, Ba, Ra*, Yb, No*)
- Rotating electrical potential (Paul trap)
- Internal electronic states addressable with laser beams
- Ions repel each other, creating array



Fluorescence imaging from single Be ion chains



Linear Paul trap



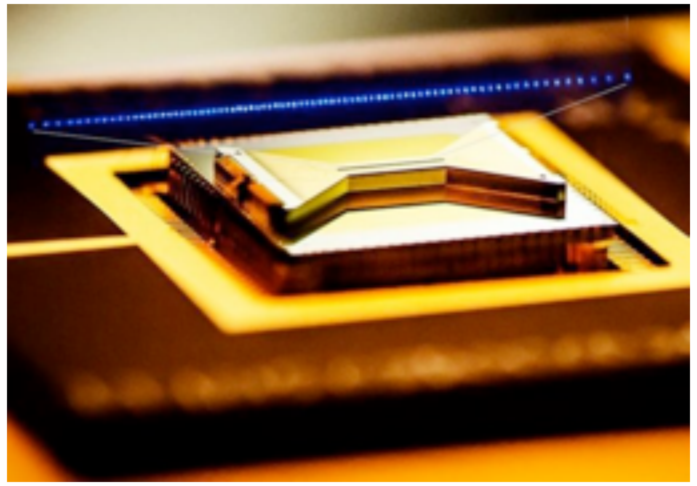
LEADING EXPERIMENTAL PLATFORMS

ION TRAPS

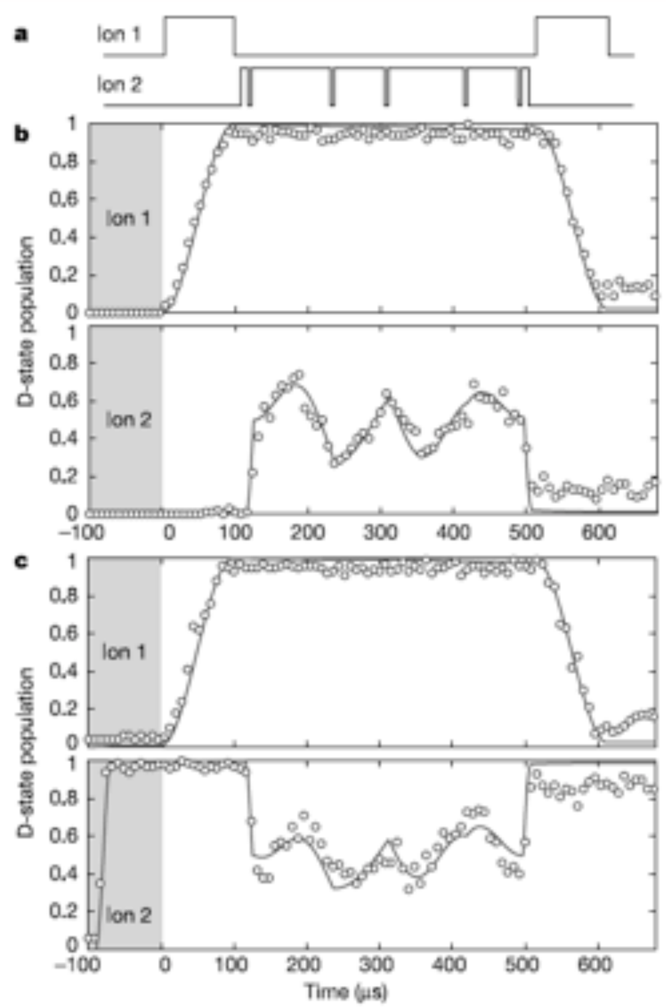
DiVincenzo criteria:

- Coherence times: natural atoms are **extremely coherent**, on the order of 1s.
- Initialization: **sideband cooling** to motional ground state (LD regime)
- Readout specific: **electron shelving**, CCD with dark state
- Universal gate set: Red/Blue sideband with motional degree of freedom
- Scalability: within Paul trap, limited. **On a chip**, unlimited but very challenging
- Conversion to flying qubits: **built-in**, as atoms emit photons by flourescence. Efficiency is low.

Atom trap for ions on-chip (from IonQ)



Implementing CZ CNOT gate (Innbruck):



Ferdinand Schmidt Kahler et al., Nature **422**, 408 (2003).

LEADING EXPERIMENTAL PLATFORMS

PHOTONIC CIRCUITS

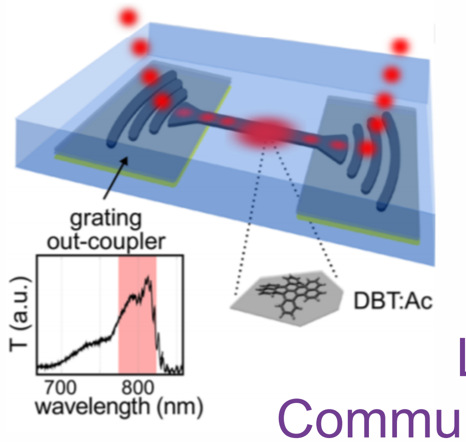
Photons contain a polarization degree of freedom (left-/right-) which acts as a qubit.

- Photons can be **guided** on dielectrics (aka optical fibers). The same principle can be translated on chips.
- **Nonlinear materials** produce a net photon-photon interaction, leading to 2-qubit gates. This requires physically bringing in closer any number of waveguides that require interaction between photons. Alternatively, one can use measurement-based QC.
- **Single photon sources** can be generated using natural atoms or (most preferable) semiconducting optically active quantum dots, which act on demand.
- Optical photons can be counted using **photon counters** that operate at room temperature, with very high efficiencies. Using polarizers, this allows distinguishing polarization states.

2-photon gate with tunable knob

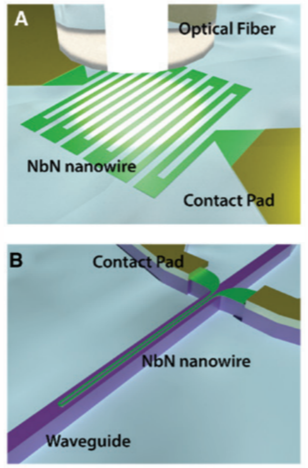
Qiang et al., Optics Letters **41** 5318 (2016)

Single photon source with grating



Lin et al., Nature Communications **8** 1132 (2017)

Superconducting nanowire single photon detector



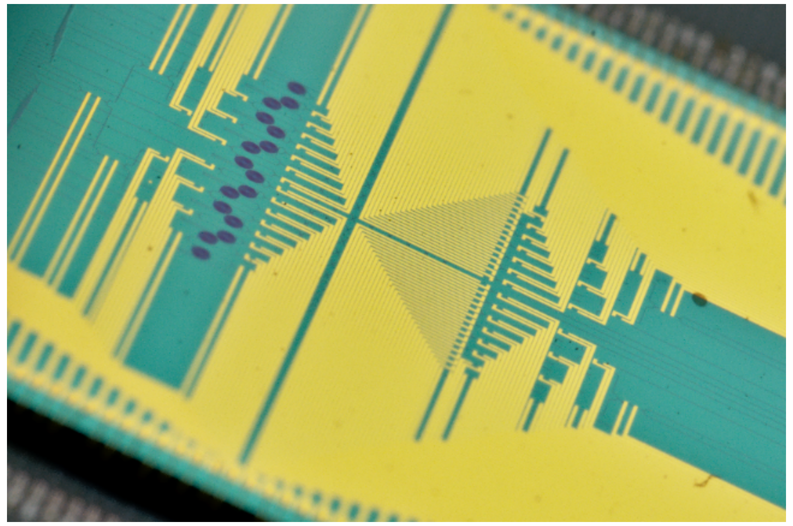
Vetter et al., Nano Letters **16** 11 (2016)

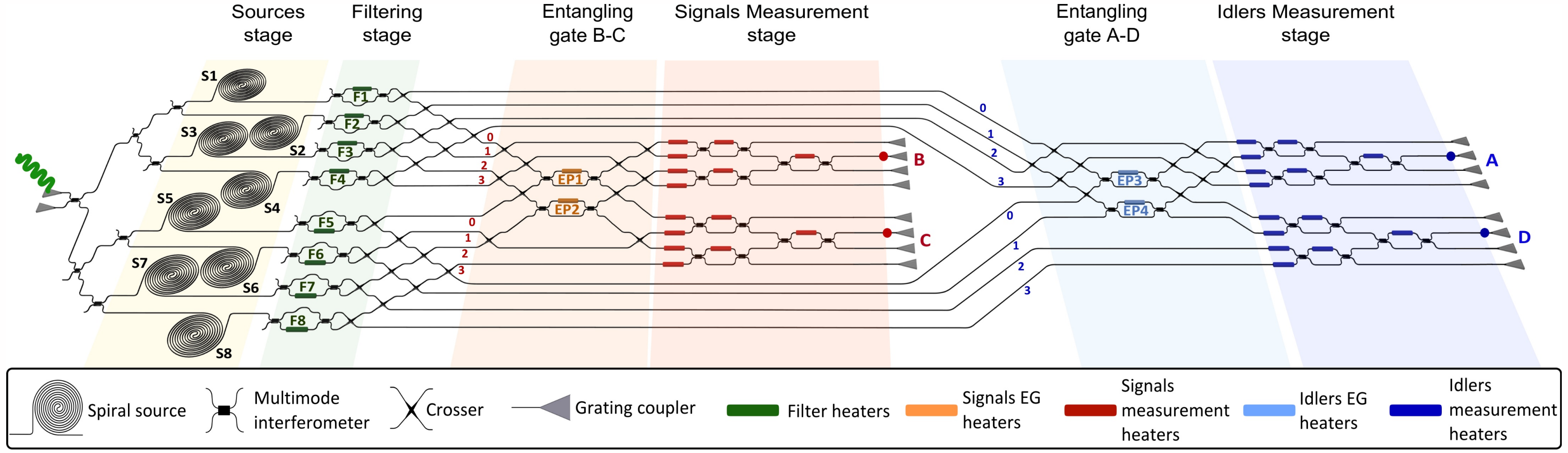
LEADING EXPERIMENTAL PLATFORMS

PHOTONIC CIRCUITS

DiVincenzo criteria:

- Coherence times: photons **do not directly interact**. Waveguides are very low loss (~dB/km). **Decoherence is not relevant**.
- Initialization: **Challenging**, as one needs to prepare a single photon every time the experiment runs. Good single photon sources are **not 100% faithful**.
- Readout specific: **Photon counters are very efficient**, especially the superconducting type, with low dark counts and fast recovery time (sub-ns).
- Scalability: Chips can be **patterned** with UV light on a table-top setup. Scaling to many photons is a technological challenge in many fronts: sources, detectors, waveguides. Main obstable: chips can be made **programmable**, with limitations.
- Conversion to flying qubits: Photons ***are* flying qubits**





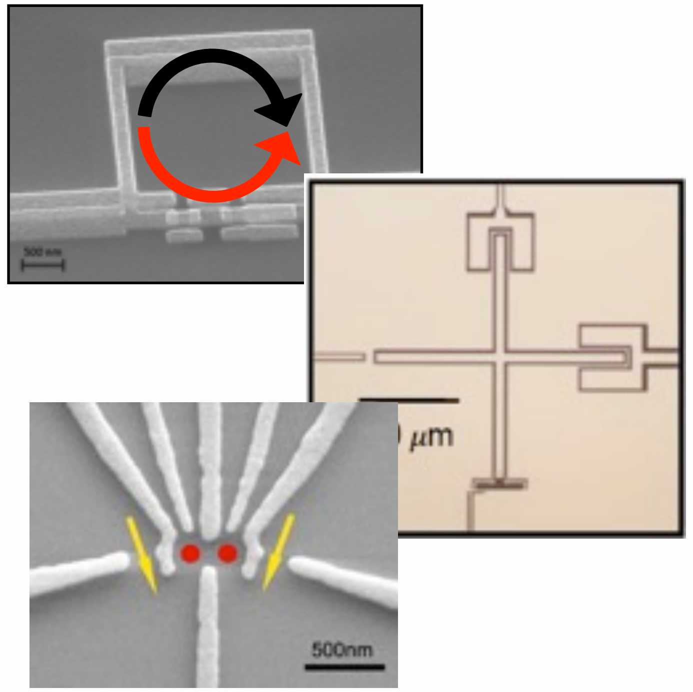
Wang et al., Science **360** 285 (2018)

SOLID-STATE QUANTUM COMPUTING PLATFORMS

Microscopic

$$i\hbar\frac{\partial\psi(\vec{r},t)}{\partial t} = \mathcal{H}(\vec{r},t)\psi(\vec{r},t)$$

Mesoscopic



Large number of particles

Artificial, man-made

Quantum collective degrees of freedom

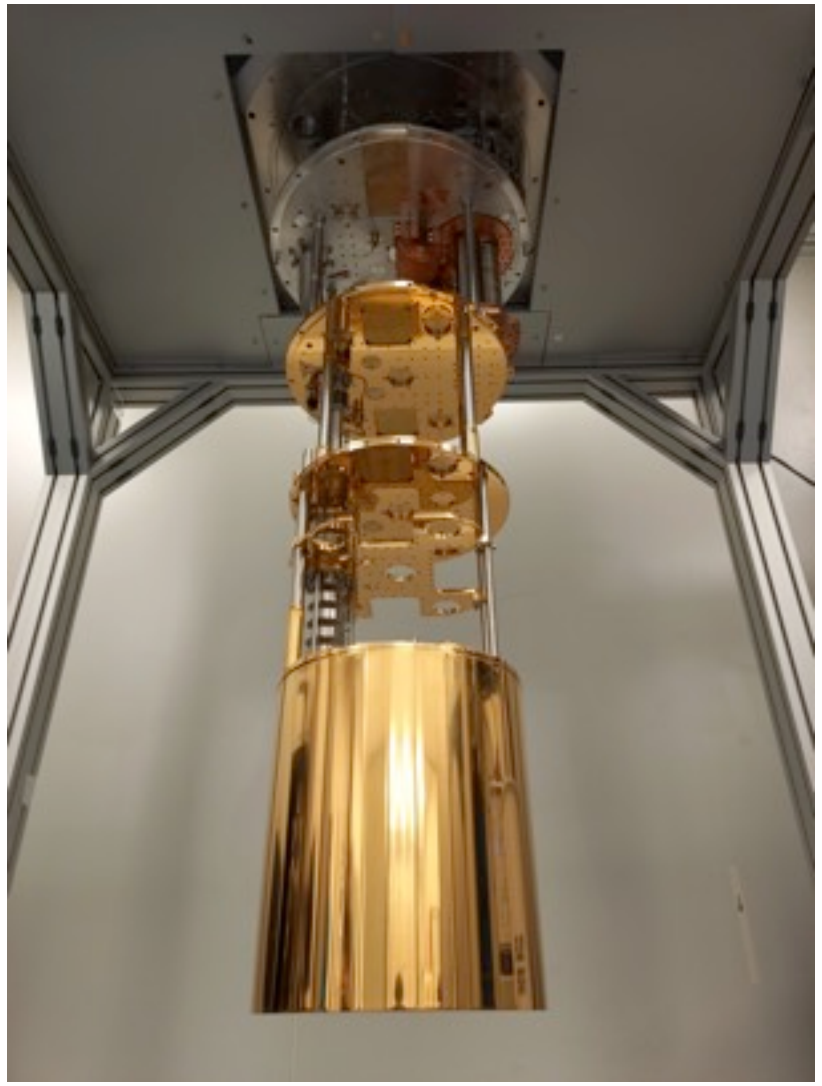
Macroscopic

$$\vec{F} = m\vec{a}$$

INFRASTRUCTURE FOR SOLID-STATE QUANTUM COMPUTING PLATFORMS

Dilution refrigerators

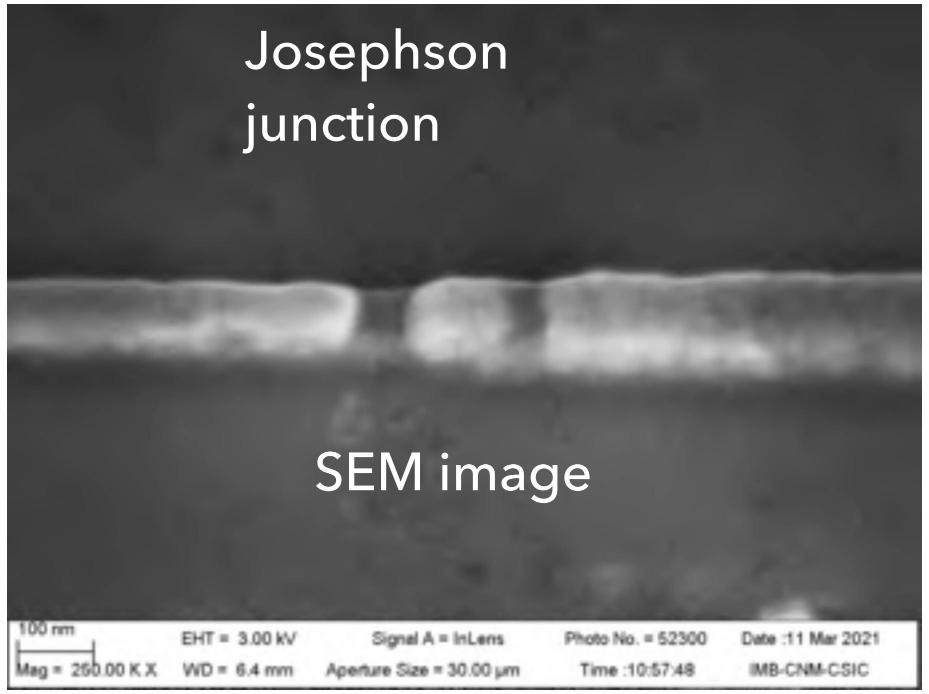
T = 0.01 K (-273.13 C)
Power consumption: 10kW



Solid-state systems achieve state initialization automatically

$$k_B T \ll \hbar \omega_q$$

Use of nano-lithography techniques conventionally used in CMOS technology to pattern superconductor/semiconductor nanostructures

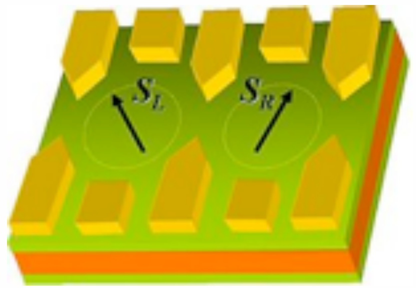


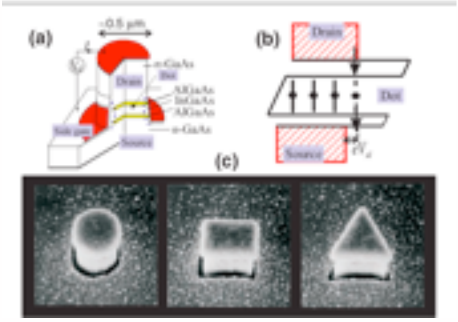
LEADING EXPERIMENTAL PLATFORMS

SEMICONDUCTOR SPIN QUBITS IN LATERAL QUANTUM DOTS

Electrons are charged particles that can be confined. Electron spin reacts to magnetic fields. Proposed by Daniel Loss and David Divincenzo in 1998.

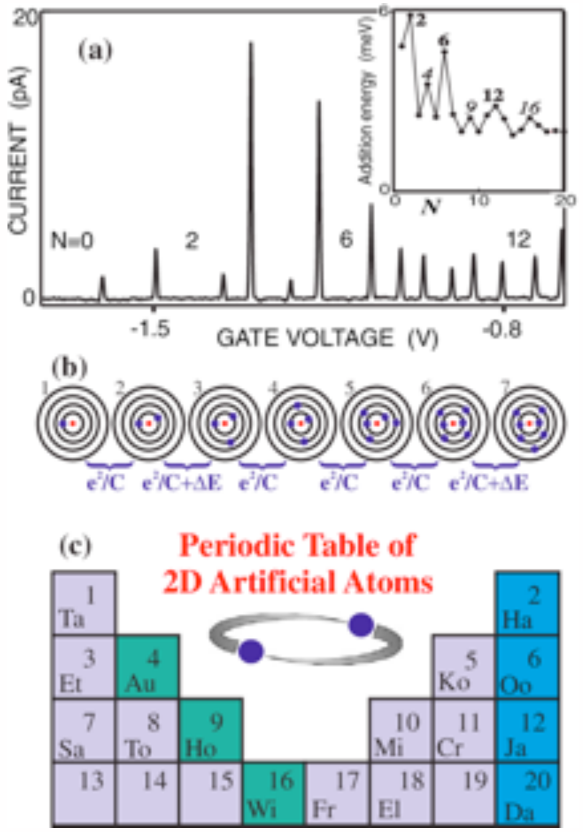
- Semiconductor heterostructures define a **free 2D electron gas**
- Electrostatic potentials can be patterned by lithographic techniques to define 0-dimensional regions known as **quantum dots**
- Electrons in quantum dots have their **energies quantize**d, just like atoms
- Electrons are pure **spin-1/2 particle** and thus react to magnetic fields: fixed fields produce **Zeeman splitting** (between 0 and 1), oscillating fields excite transitions.
- **Electron charge** can also be used to detect qubit state, as charge and spin can be correlated by tunneling out of the quantum dot.





Quantum computation with quantum dots. Daniel Loss and David P. DiVincenzo. Phys. Rev. A 57, 120 (1998).

Periodic table of quantum dots



Few-electron quantum dots. L P Kouwenhoven, et al., Reports on Progress in Physics **64**, 6 (2001)

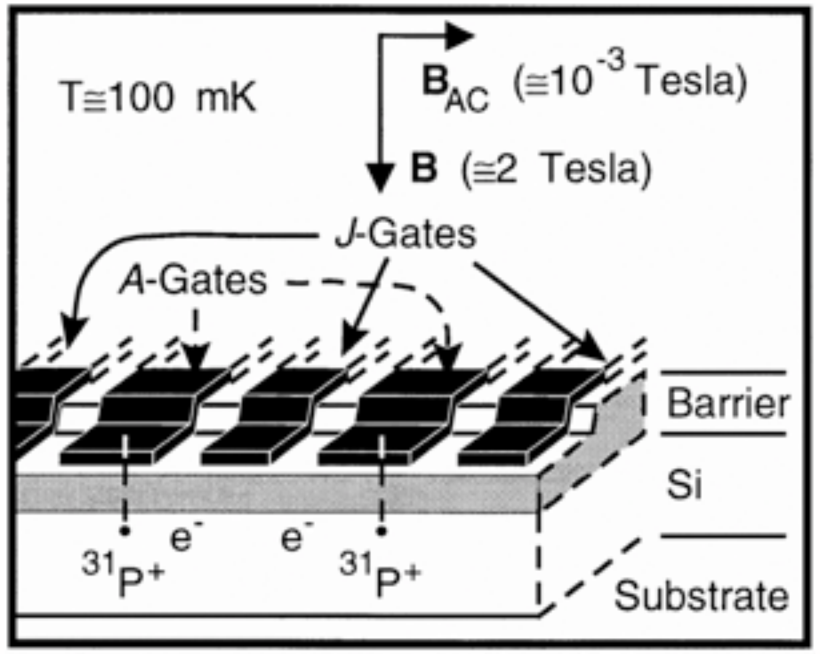
LEADING EXPERIMENTAL PLATFORMS

PHOSPHOROUS DONORS IN SILICON

Impurity atoms can be trapped in other materials, like natural ion traps. Especially in IV-materials. Proposed by Bruce Kane in 1998.

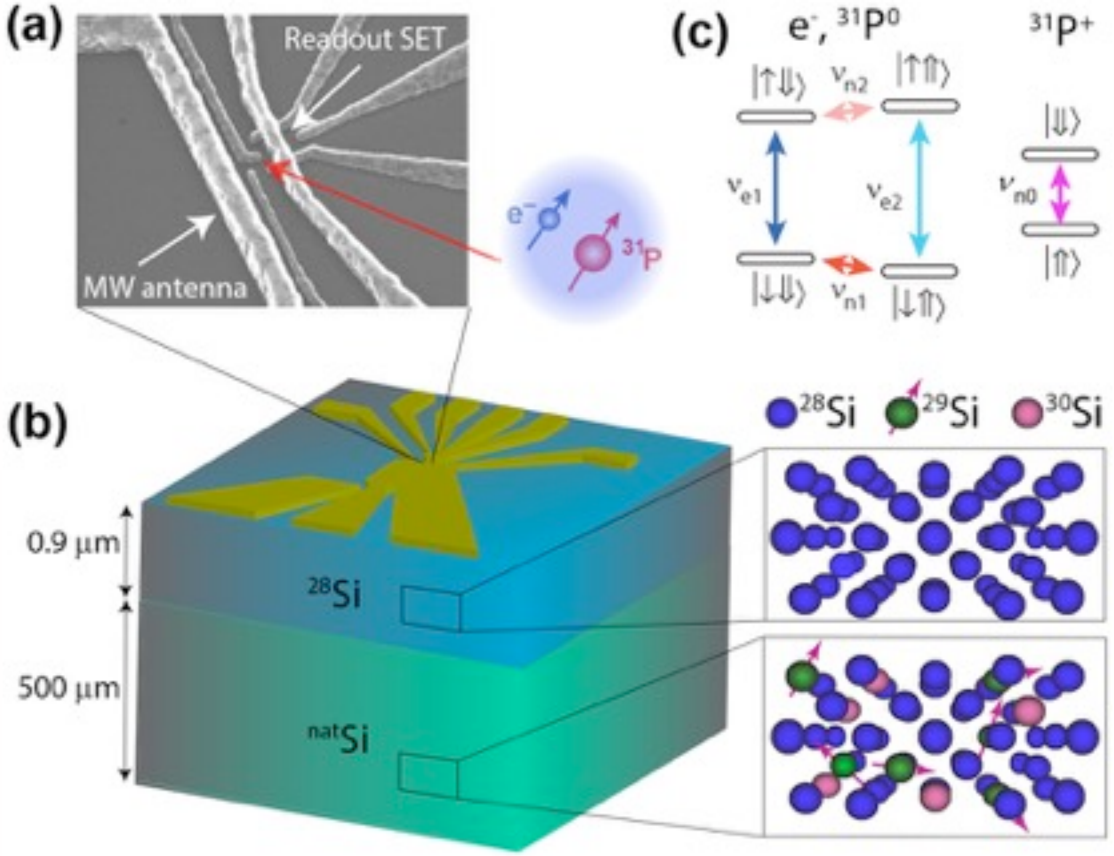
- Phosphorous atoms have **long lived** electronic states (phosphorescence)
- **Ion implantation** technology has evolved in the last 2 decades
- Control and readout techniques from **lateral quantum dot** technology

Proposal to implant dopants in Si



A silicon-based nuclear spin quantum computer. B. E. Kane. *Nature* volume 393, pages133–137(1998)

Implementation in a real experiment, with phosphorous energy levels

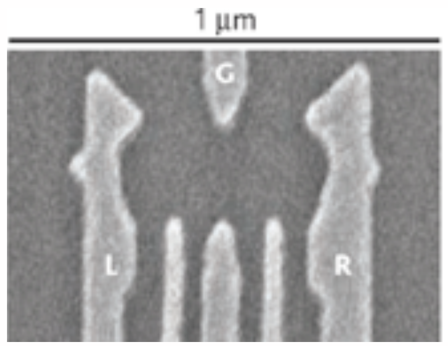


LEADING EXPERIMENTAL PLATFORMS

SEMICONDUCTOR SPIN QUBITS (QUANTUM DOTS/PHOSPHOROUS DONORS)

DiVincenzo criteria:

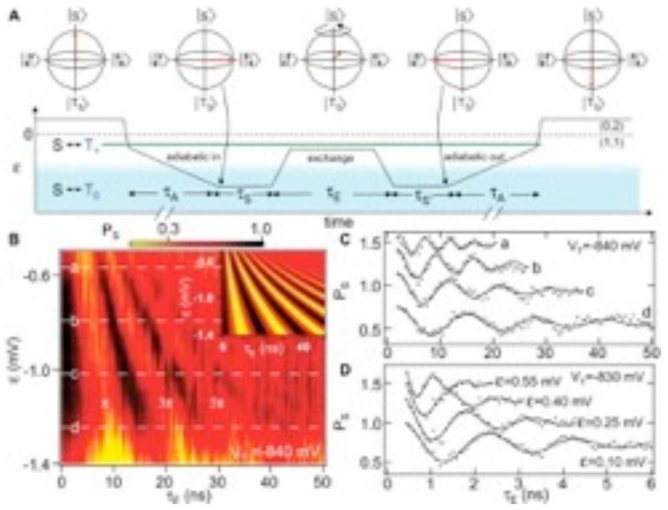
- Coherence times: electron spins are very well decoupled from their environment, leading to **very long** coherence times (order millisecond).
- Initialization: at **cryogenic temperatures**, with a magnetic field applied, Zeeman splitting larger than thermal energy $k_B T \ll \hbar\omega_Z = \hbar g_e \mu_B B$
- Readout specific: electrons are charged, **charged-based sensors** (quantum point contact, SET), or with superconducting **resonators** like superconducting qubits.
- Universal gate set: spins interact (as in magnets) via **exchange** interaction. Single qubits in the microwave regime.
- Scalability: **nearest neighbor** arrays may be produced (many electrodes to be controlled), resonator-mediated interactions allow long-range interactions, or shuttling electrons between traps. **Big plus**: CMOS technology will kick in eventually, leading to a huge boost in scalability.
- Conversion to flying qubits: Semiconductors have **transitions** into the **optical** domain



Double quantum dot geometry with gates indicated “L”, “R”, “G”

2-qubit oscillations induced by exchange

$$\hat{H}_{\text{int}} = g\hat{S}_1 \cdot \hat{S}_2$$



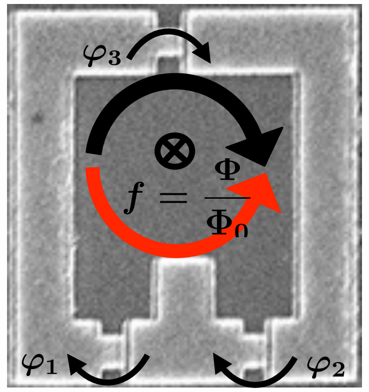
J. Petta et al., Science **309**, 2180 (2005)

LEADING EXPERIMENTAL PLATFORMS

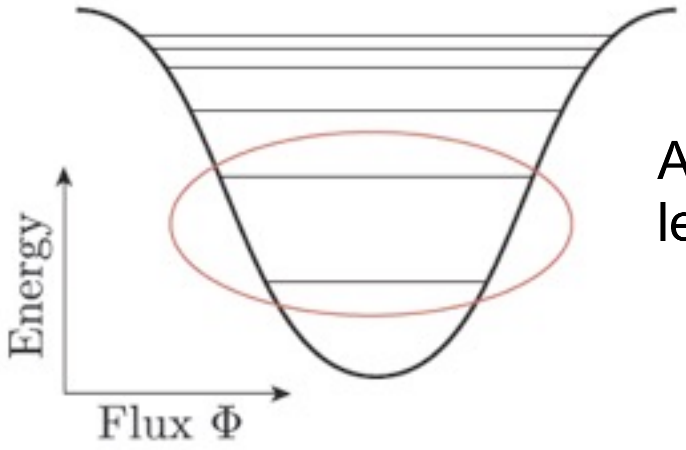
SUPERCONDUCTING QUBITS

Superconducting circuits exhibit **no dissipation** and contain **nonlinear elements (Josephson junctions)** enabling non-harmonic potentials (as in atoms) to address internal energy states. Suggested by **A. Leggett in the 1980s.**

- Superconductivity provides **loss-free electronic circuitry** to produce resonators in the microwave (gigaherz) frequency domain
- The **Josephson effect** is a constriction/insulating barrier that behaves as a **nonlinear inductance**, giving resonators an anharmonic potential
- Qubit design has evolved to be as simple as a **junction in parallel to a capacitor** (the transmon qubit)
- **Many qubit types** exist: charge, flux, phase, hybrids. Best candidates are charge-insensitive qubits and flux-like qubits

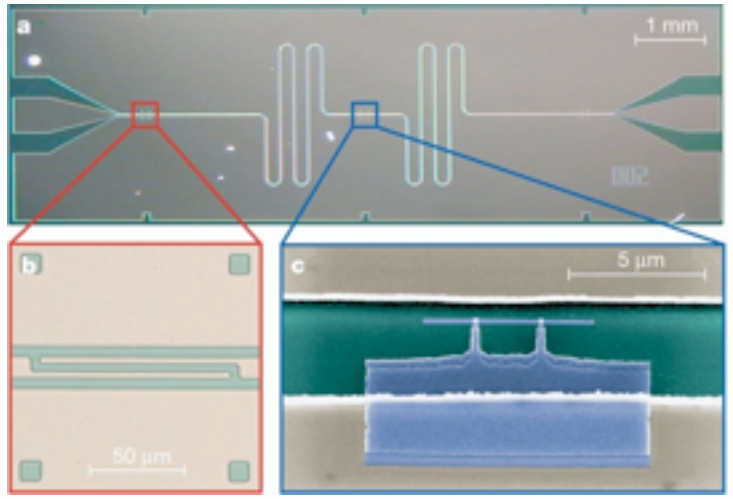


Flux qubit from Delft

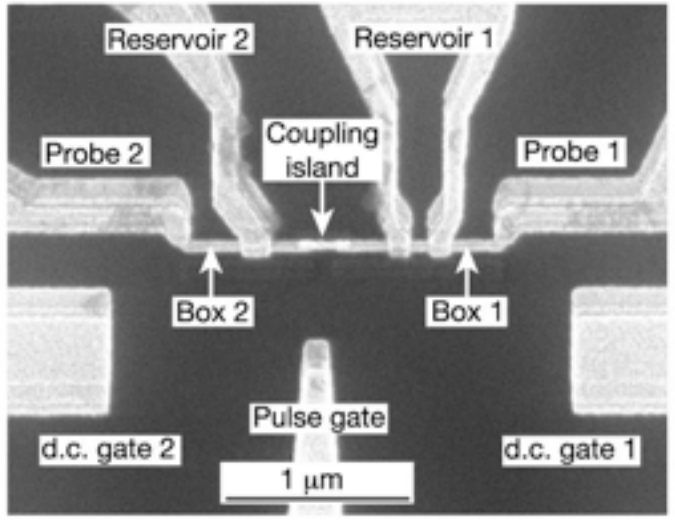


Anharmonic potential: level addressing

Transmon qubit from ETH Zurich



Circuit QED: resonator-qubit platform Yale



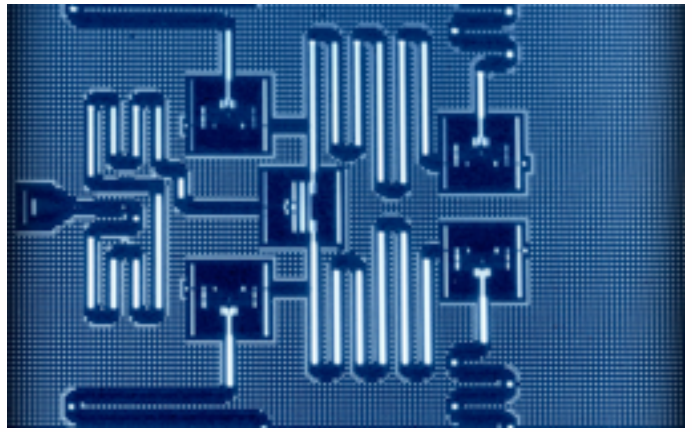
Frist charge qubit from NEC

LEADING EXPERIMENTAL PLATFORMS

SUPERCONDUCTING QUBITS

DiVincenzo criteria:

- Coherence times: Qubits are large and are solids. Many noise sources couple to their fields. After 2 decades of engineering circuits, improvements by 5-6 orders of magnitude have been achieved, with room for more improvement. Still, it's **their biggest downside**.
- Initialization: operate circuits at **cryogenic temperatures** $k_B T \ll \hbar\omega_q$
- Readout specific: using **resonators** and heterodyning techniques, and quantum limited amplifiers leads to even single shot readout.
- Universal gate set: circuits are large and interact **capacitively** and/or **inductively**, very **strongly**
- Scalability: being electrical circuits, **scalability is more easily implemented** than in atomic-based platforms. Integration with CMOS-like electronics plausible.
- Conversion to flying qubits: requires microwave-to-photon converters (in development), or directly using microwaves for short (in-house) distances. **Hard.**

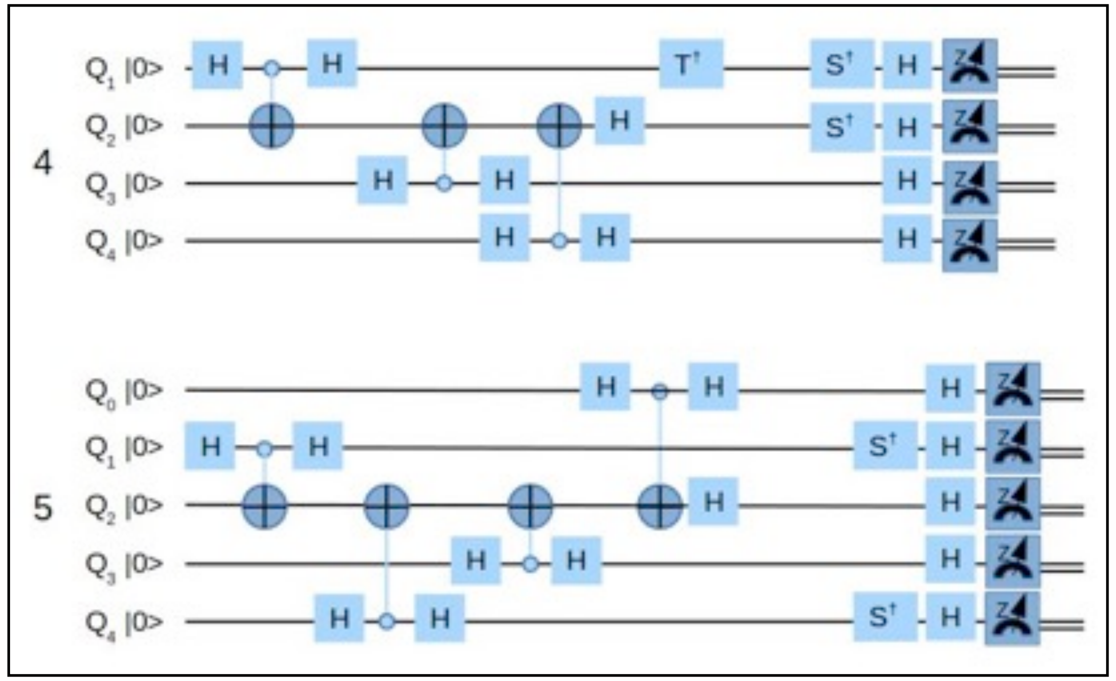


IBM 5-qubit's first online device

Google's dilution fridge cabling

Block 1: Overview of Quantum Computing Platforms

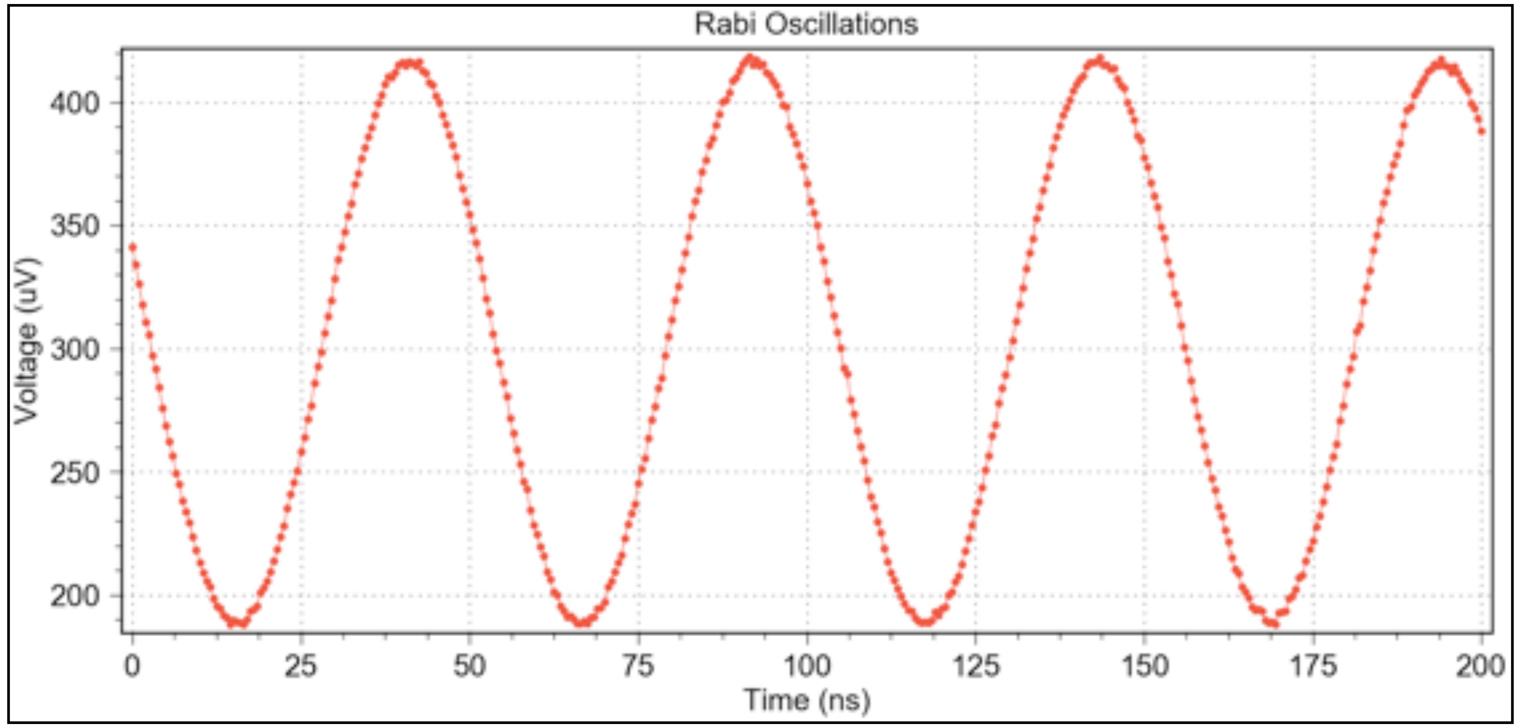
- A brief history of experimental QC
- How to build a quantum computer?
- Digital/analog quantum computers
- Leading experimental platforms



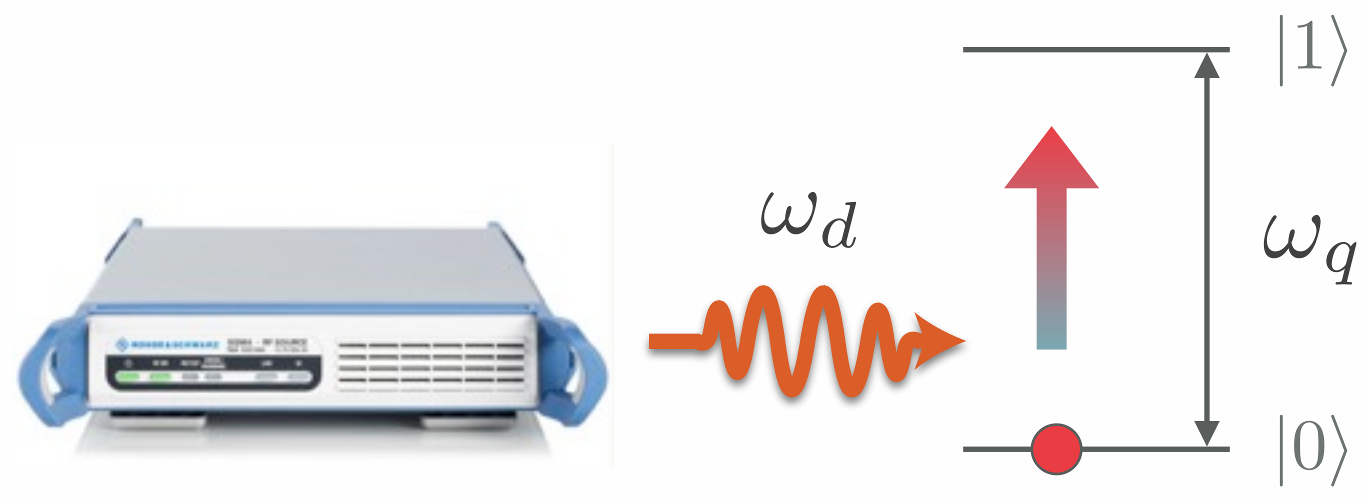
END OF BLOCK 1!

Block 2: Experimental quantum computing + Quantum industry

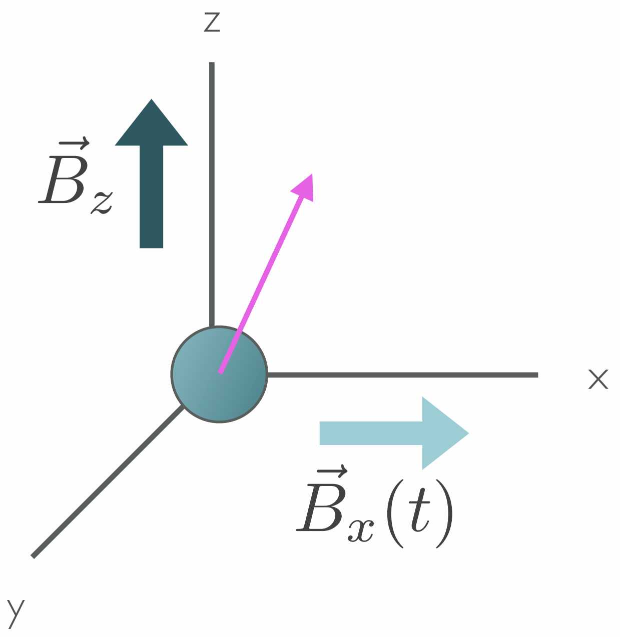
- 1-qubit manipulation: Rabi, Ramsey, echo
- Noise and decoherence
- Quantum algorithms implemented and outlook



1-QUBIT MANIPULATION: RABI, RAMSEY, ECHO



Analogy with spin-1/2



Import all NMR techniques for qubit state control…

Rabi formula

$$P_{0\to 1} = \frac{\Omega_R^2}{\Delta^2 + \Omega_R^2} \sin^2\left(\sqrt{(\Delta^2 + \Omega_R^2)}t/\hbar\right)$$

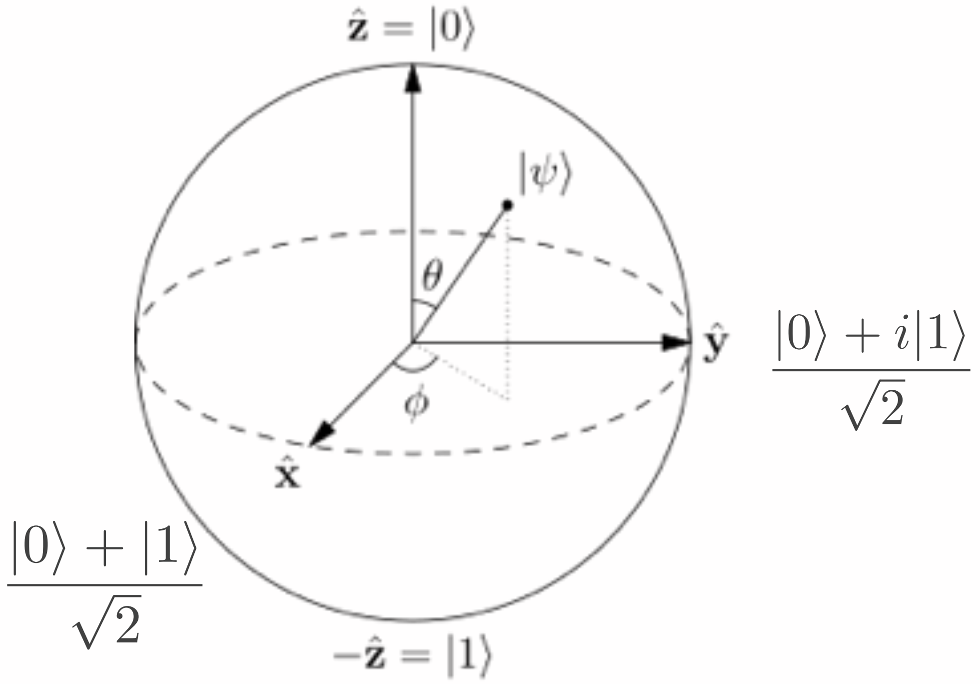
Ω_R Rabi frequency “bare”

$\Delta \equiv \omega_q - \omega_d$ Detuning

Quantum Mechanics, C. Tannoudji

Nielsen and Chuang, Quantum computation and Quantum information

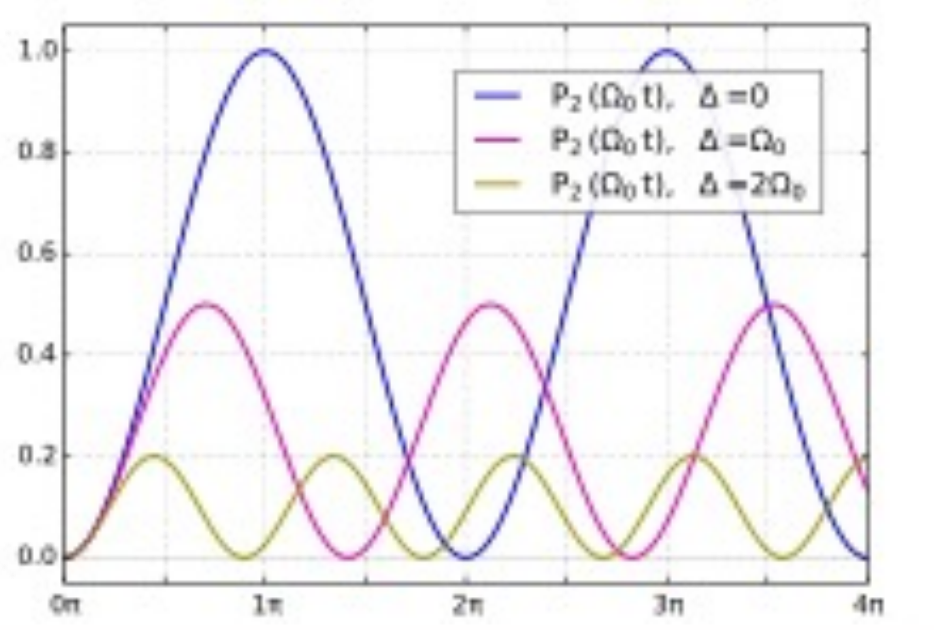
1-QUBIT MANIPULATION: RABI, RAMSEY, ECHO



$$|\Psi\rangle = \cos\theta|0\rangle + \sin\theta e^{i\phi} e^{-iE_{01}t/\hbar}|1\rangle$$

In lab frame, spin precesses (Larmor frequency),
z-axis control

Rabi oscillations **x-y axes control**



Wikipedia

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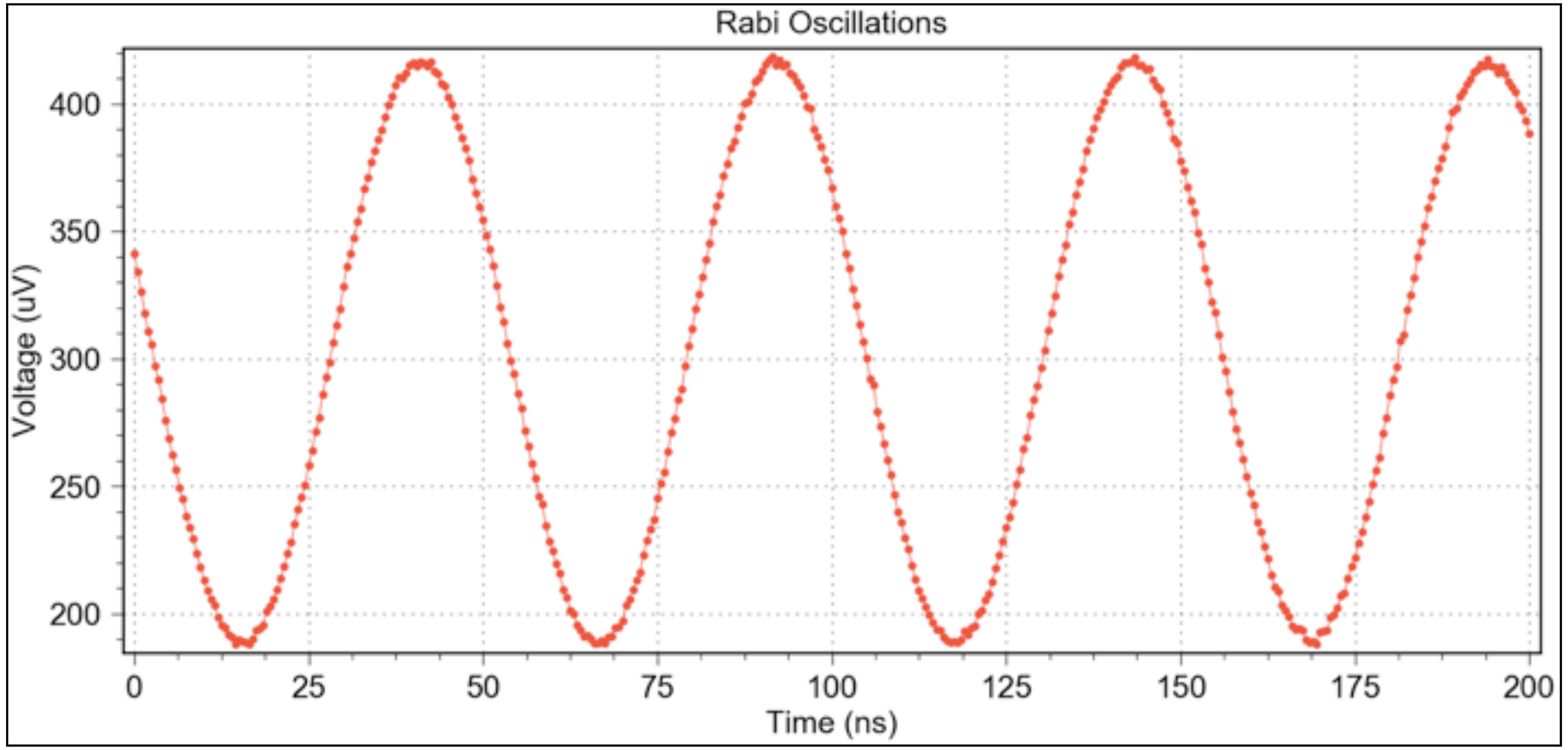
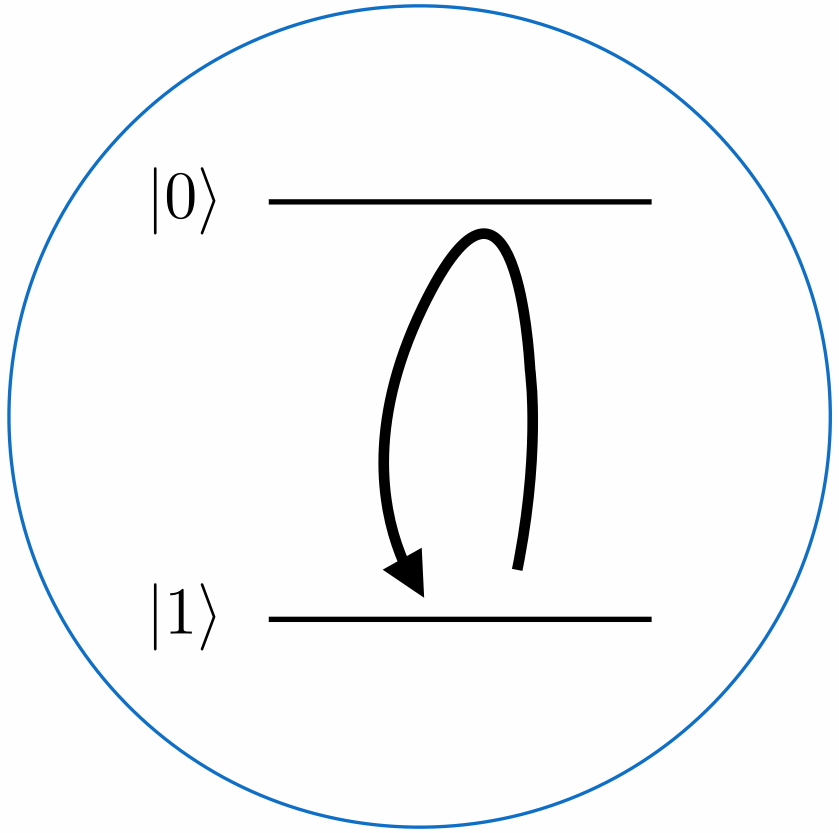
Quantum Mechanics, C. Tannoudji

Nielsen and Chuang, Quantum computation and Quantum information

1-QUBIT MANIPULATION: RABI, RAMSEY, ECHO

Driven, coherent Rabi oscillations of a superconducting qubit



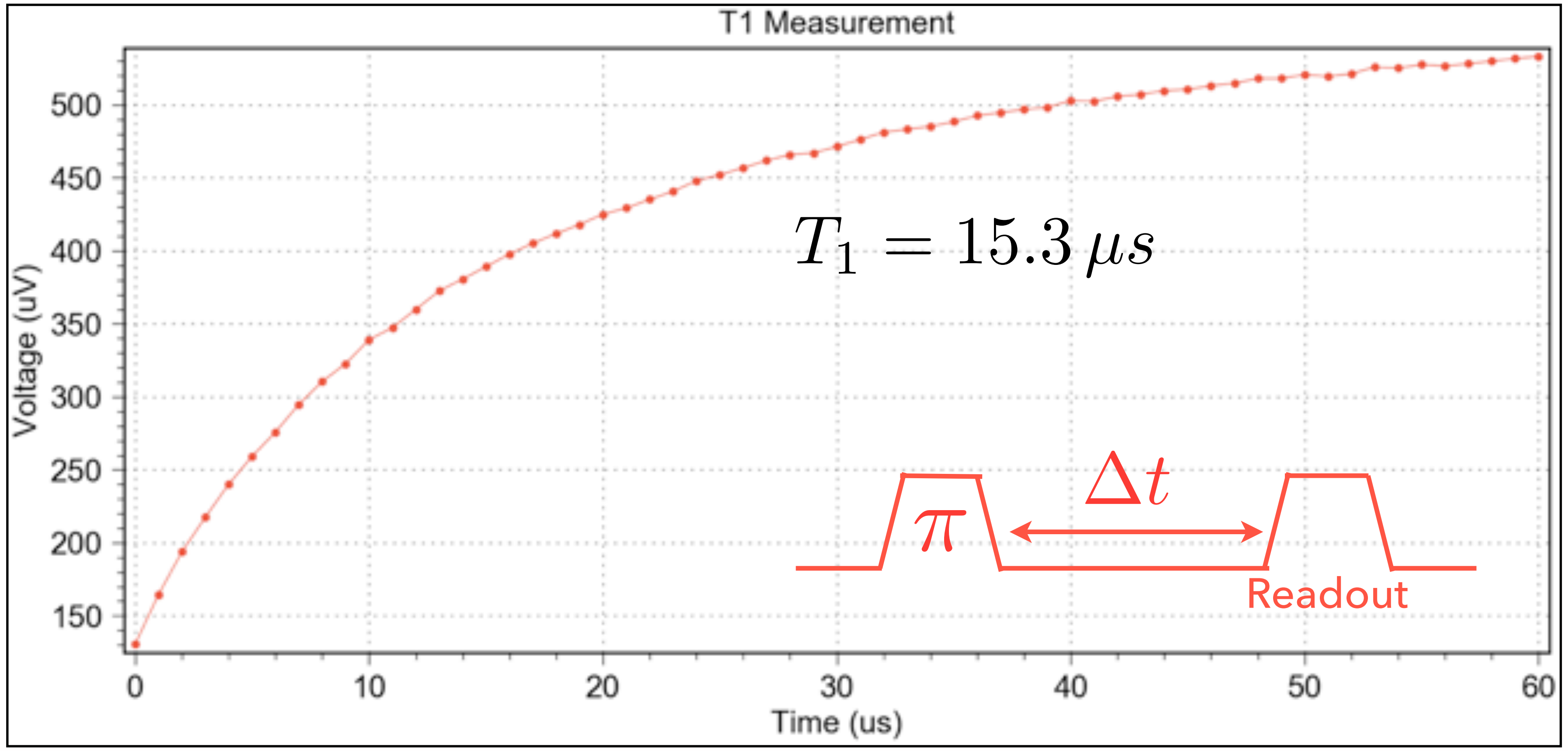


Data taken from a superconducting qubit at the IFAE QCT lab

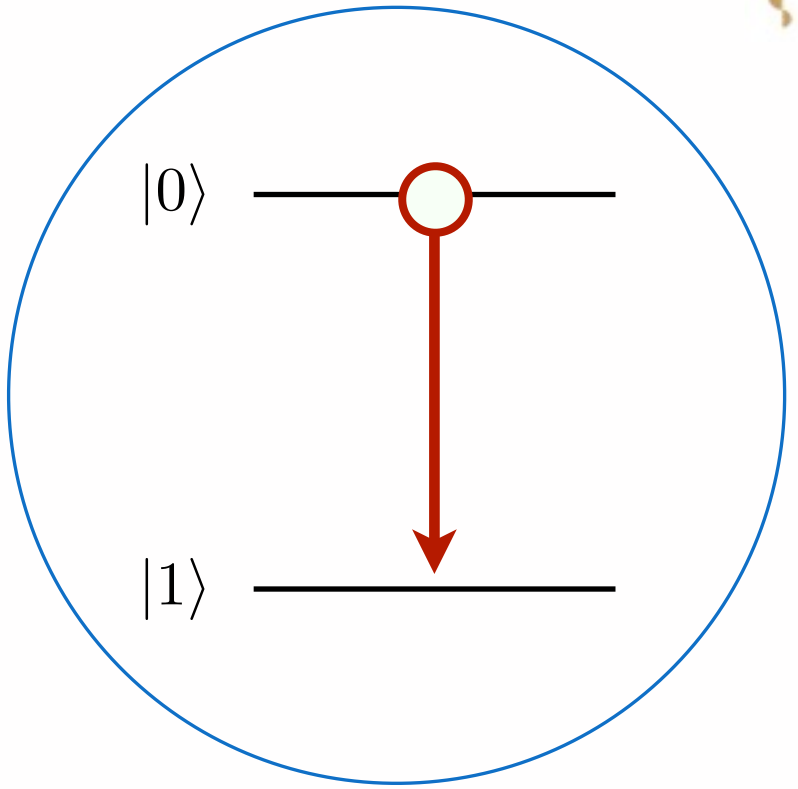
Spin-1/2-like control of qubits allows us to characterize qubit properties borrowing techniques from NMR

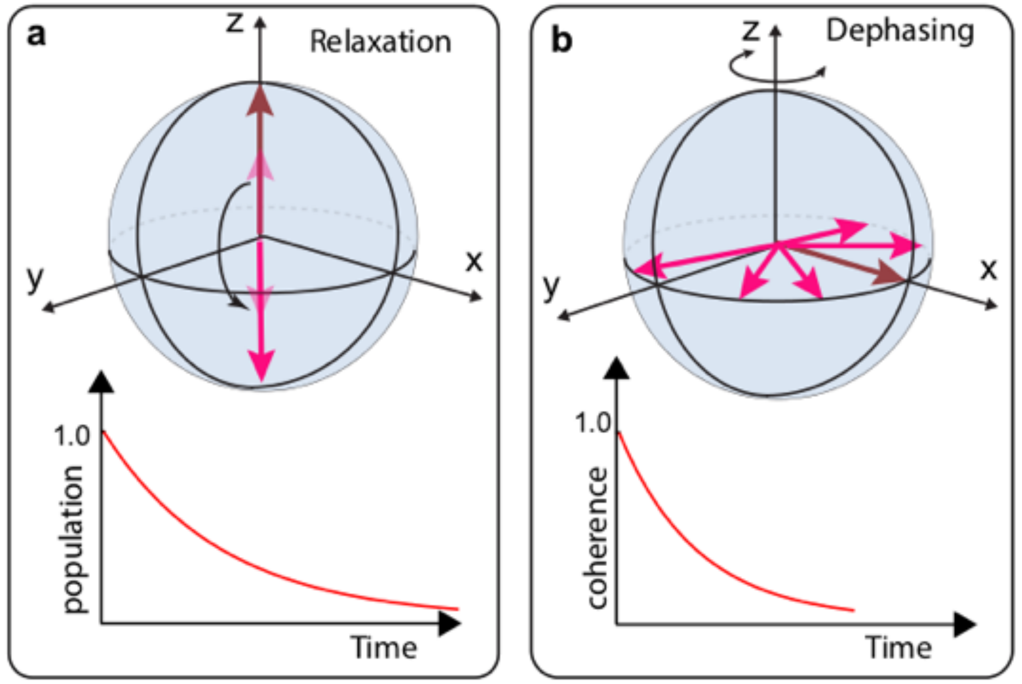
1-QUBIT MANIPULATION: RABI, RAMSEY, ECHO

Energy decay of a superconducting qubit

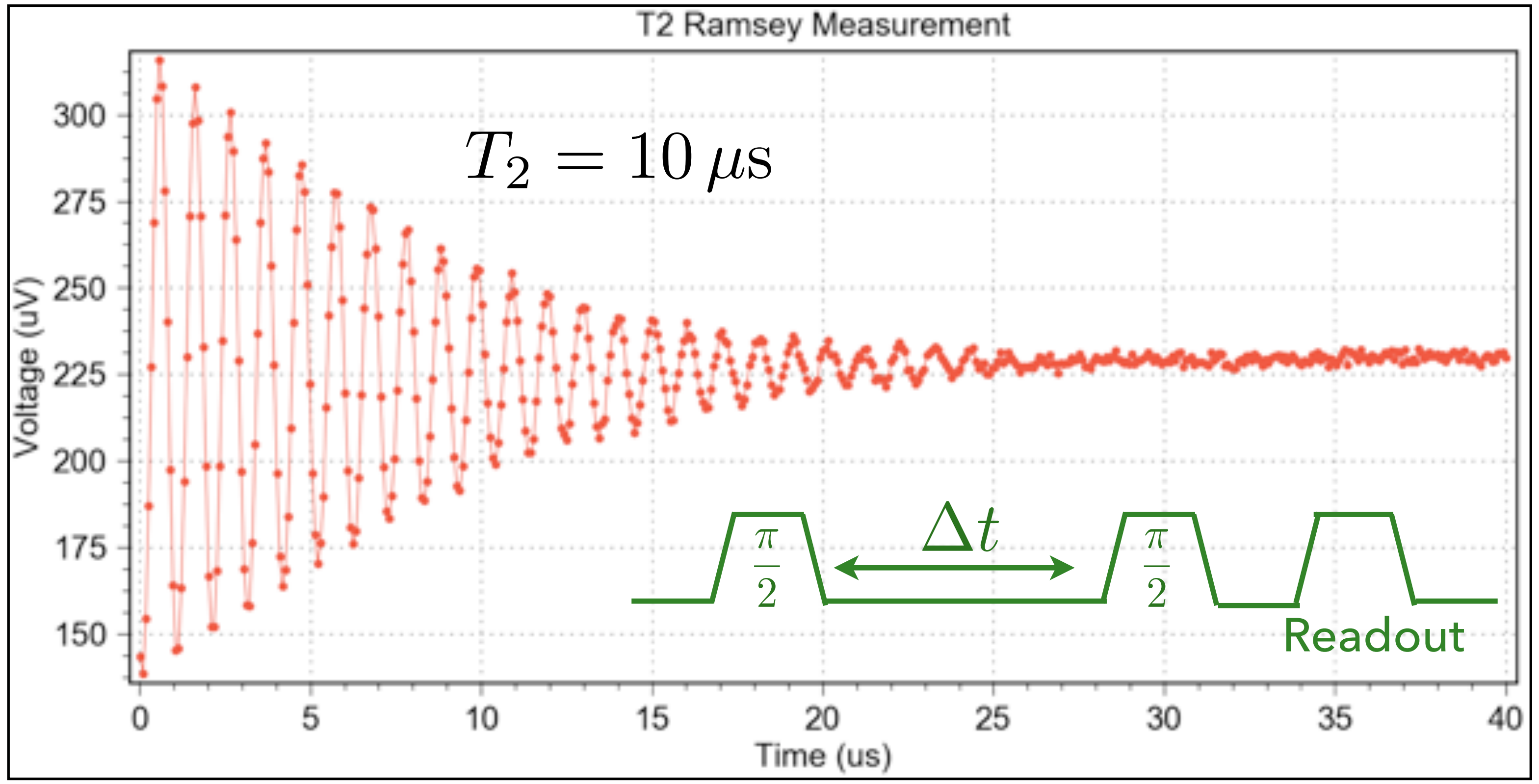


$$P_e(t) = P_e(0)e^{-t/T_1}$$





1-QUBIT MANIPULATION: RABI, RAMSEY, ECHO



Decay of a superposition state: Ramsey fringes

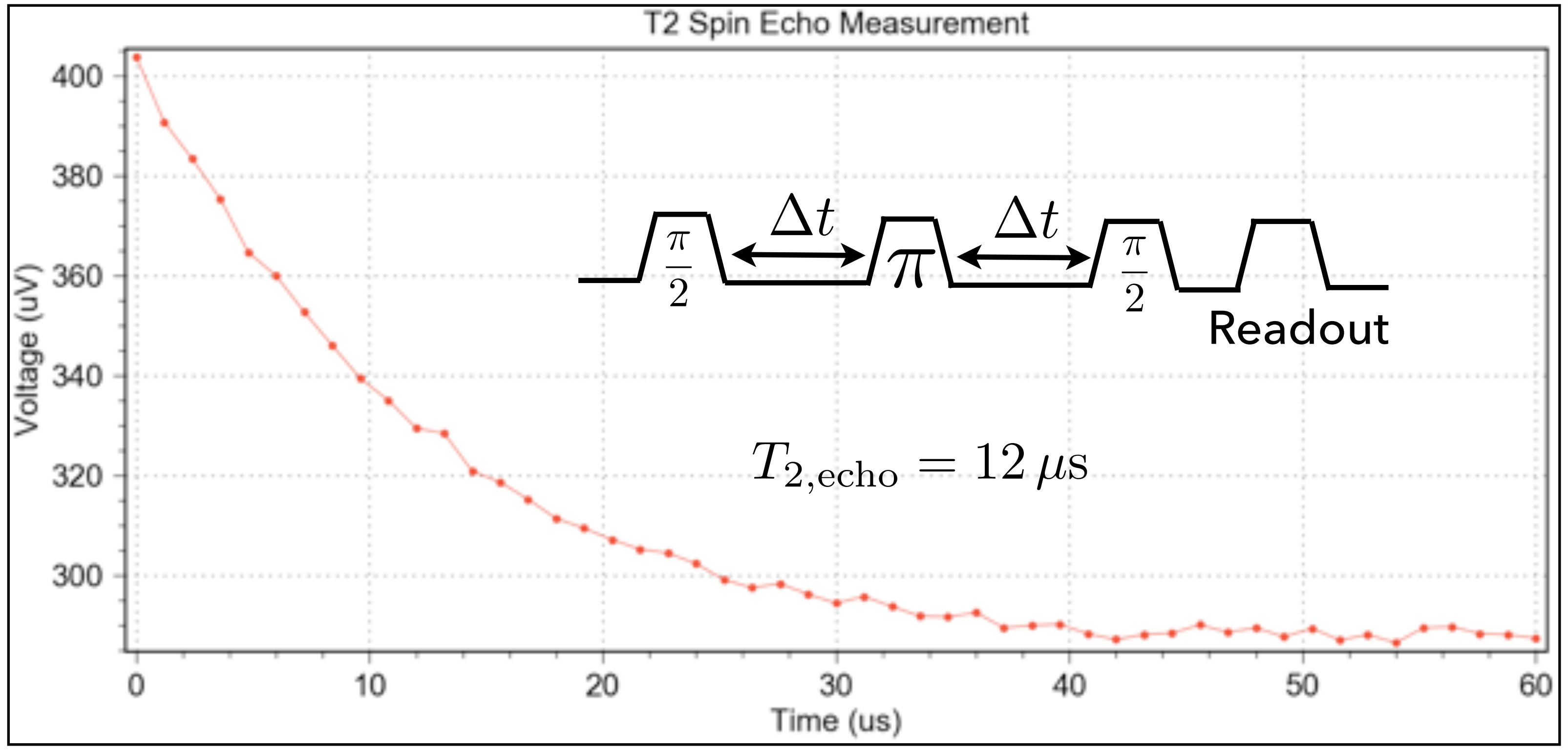
$$P(t) = P(0)e^{-t/T_2}\sin(\omega t)$$

Definition of decoherence time:

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\varphi}$$

T_φ Pure dephasing, non-resonant, low-frequency processes

Dynamical correction: Hahn spin-echo. Corrects effect of low frequencies



NOISE AND DECOHERENCE

Multiple sources of noise:

- Control/readout circuit noise (white)
- Infrared radiation (Planck)
- Microscopic (solid state): Two-level systems (1/f), quasiparticles (Poisson)
- High energy: Cosmic rays, environmental radiation

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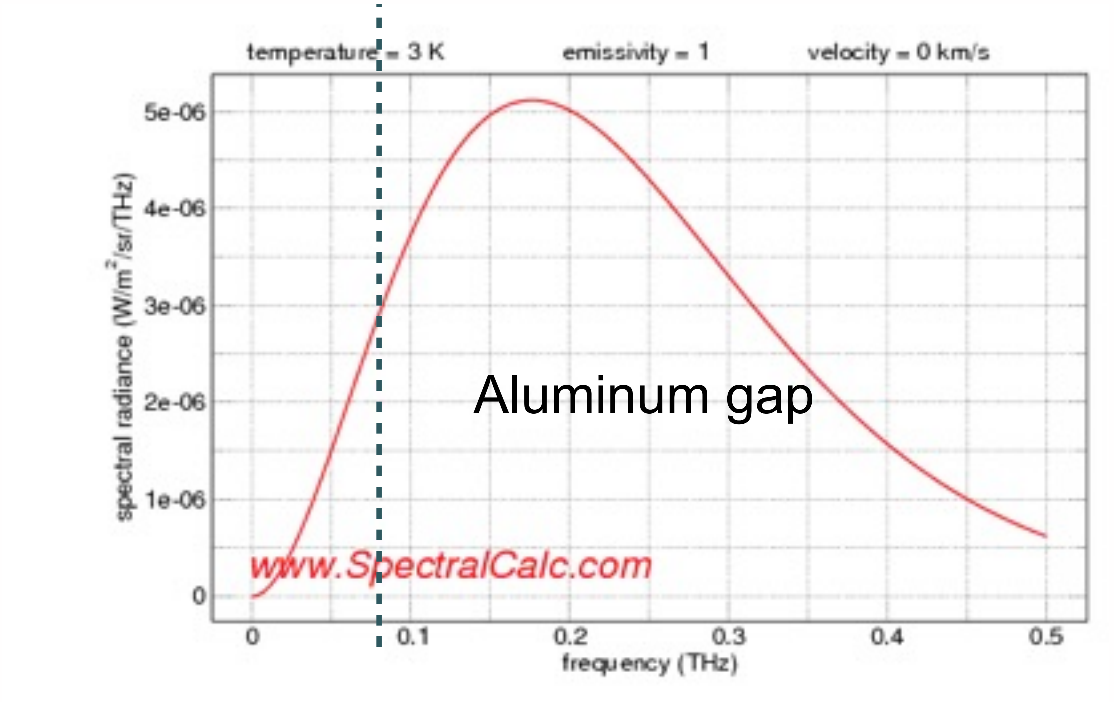
Fridge background thermal photons



IR absorptive material (SiC) in MCh can, 90% absorption

Picture courtesy of R. Barends

NOISE AND DECOHERENCE

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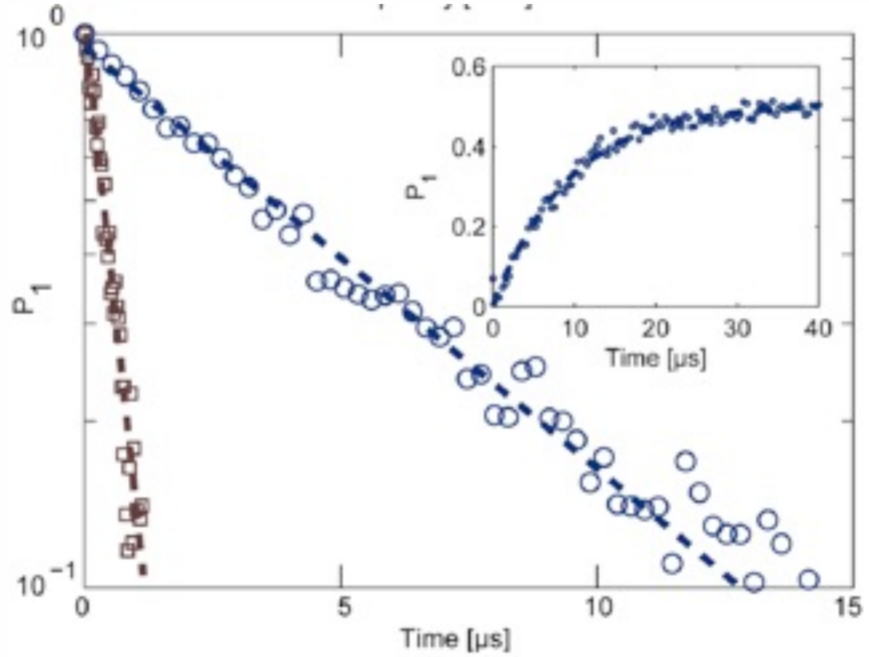
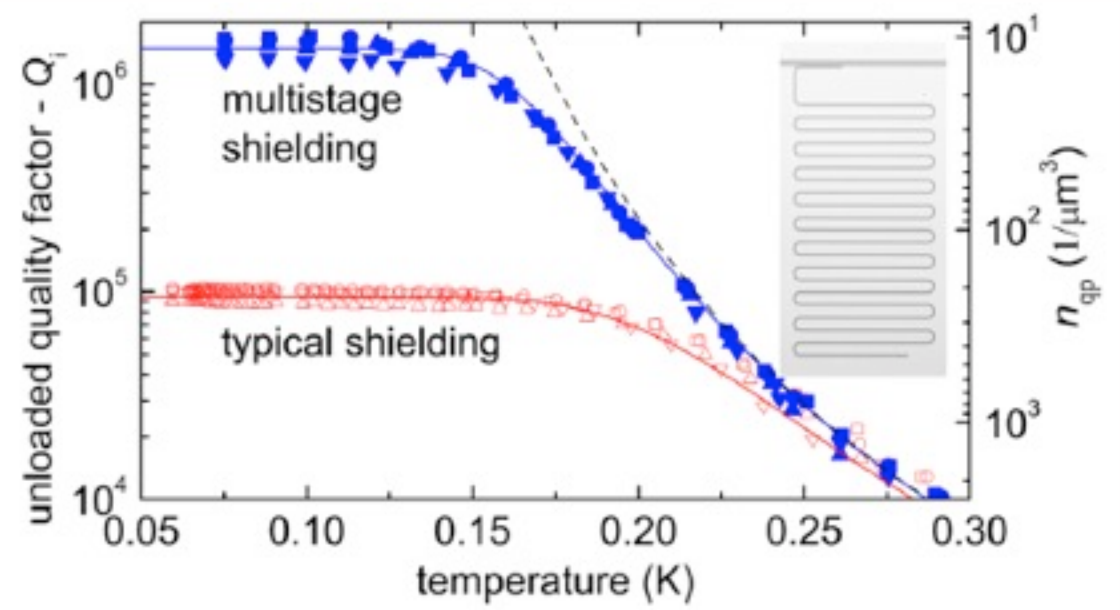
Qubit improvement



Córcoles et al., APL 99, 181906 (2011)

Resonator improvement



Barends et al., APL 99, 113507 (2011)

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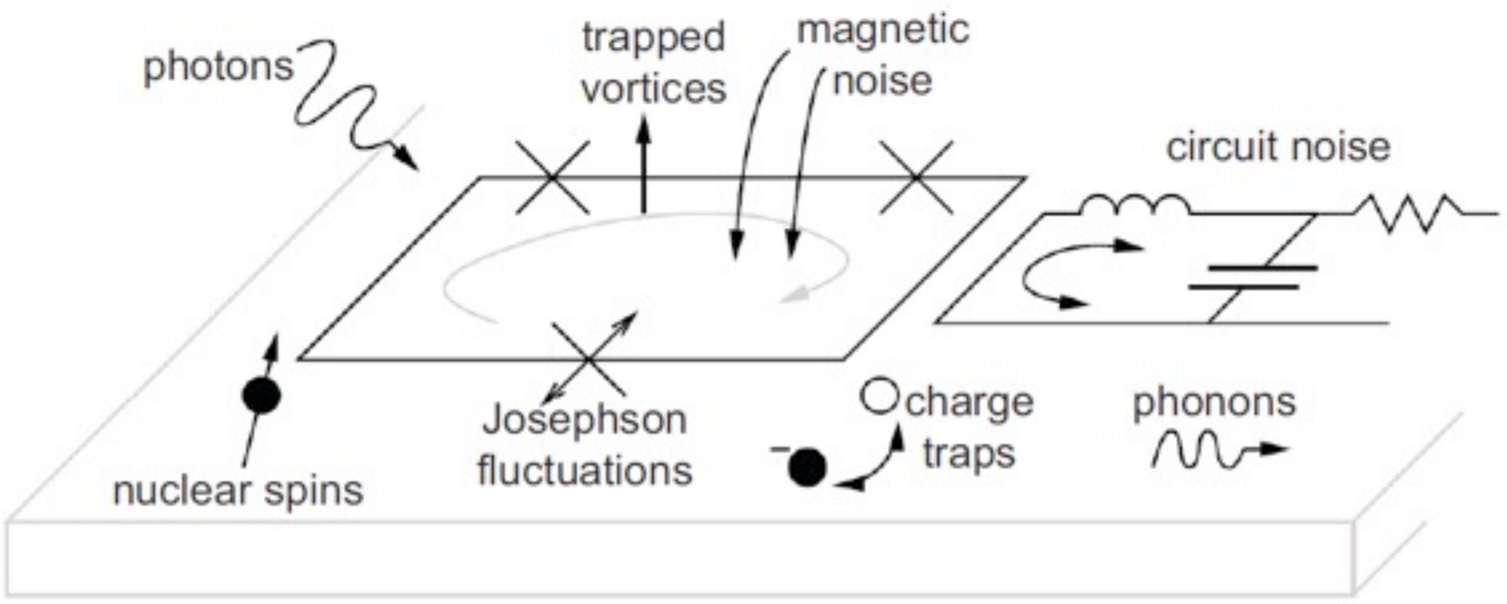
Particularly bad for solid-state qubits, but also trapped ions using atomic chips!



- Low frequency fluctuations produce 1/f noise and dephasing + relaxation
- Fast-moving particles (electrons) produce Poissonian noise and relaxation.

Plantenberg, PhD thesis (Delft)

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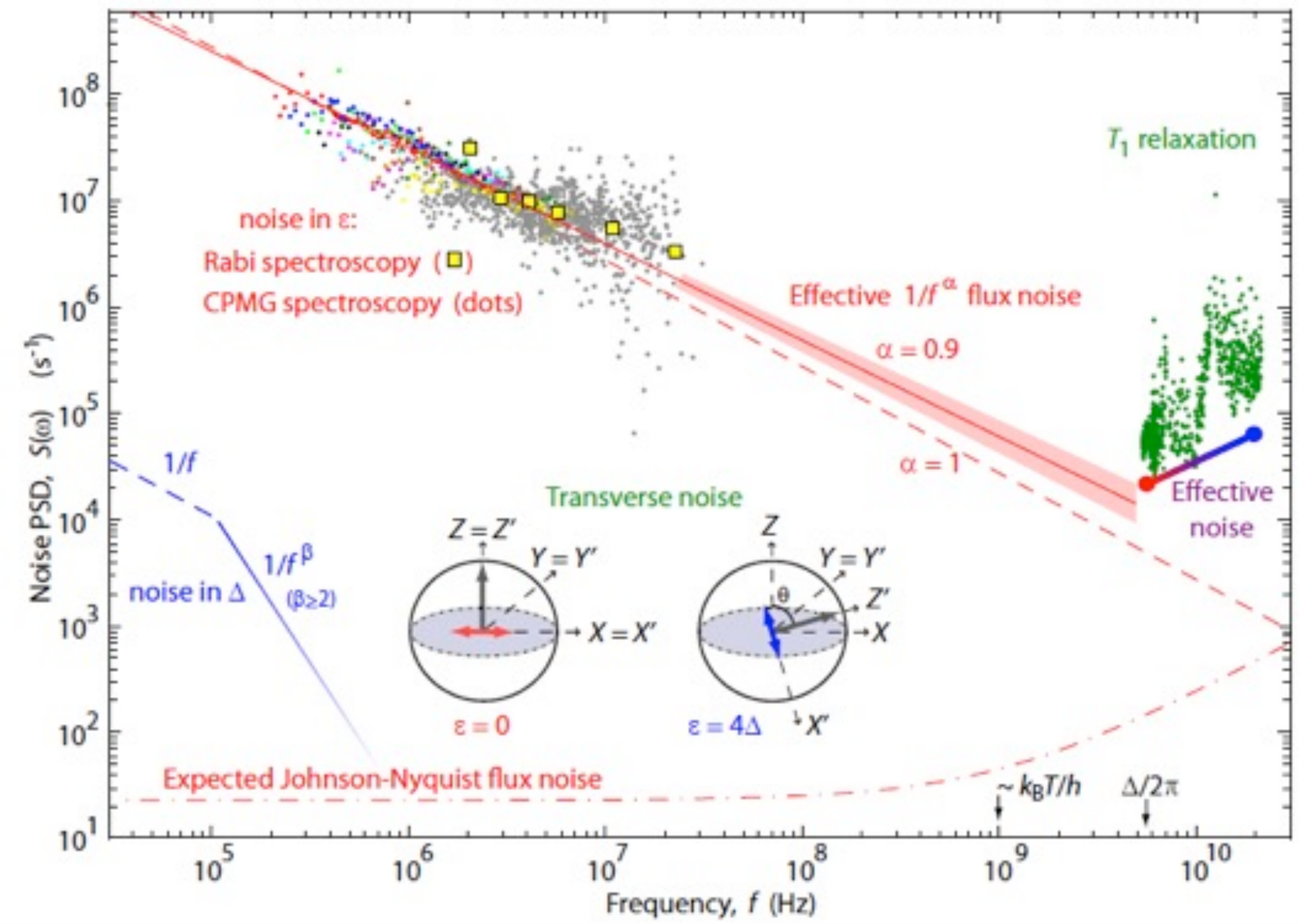
1/f noise in superconducting qubis. Same type of flux noise observed in SQUIDs!

$$S_\Phi(f) = \frac{\mu\Phi_0}{f}$$



Bylander et al., Nature Phys. vol. 7, pp. 565-570 (2011)

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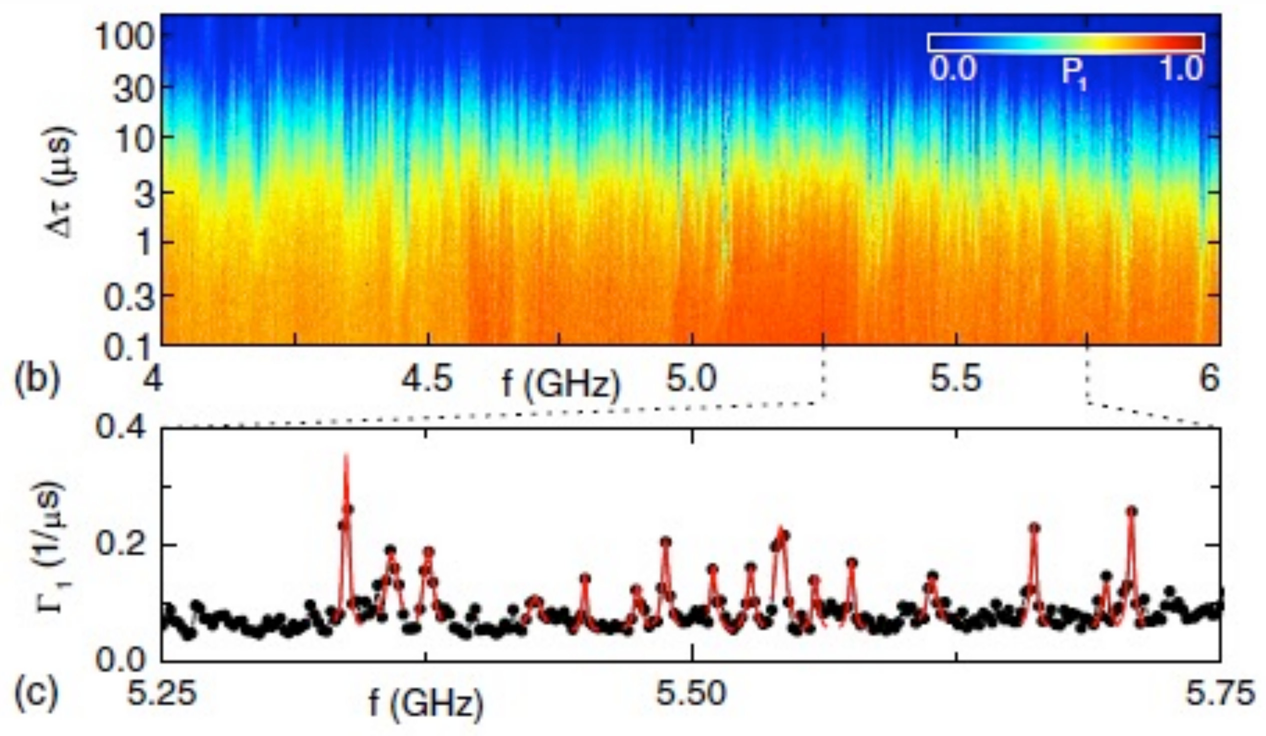
T1 fluctuations, consistent with TLSs



Barends et al., PRL 111, 080502 (2013)

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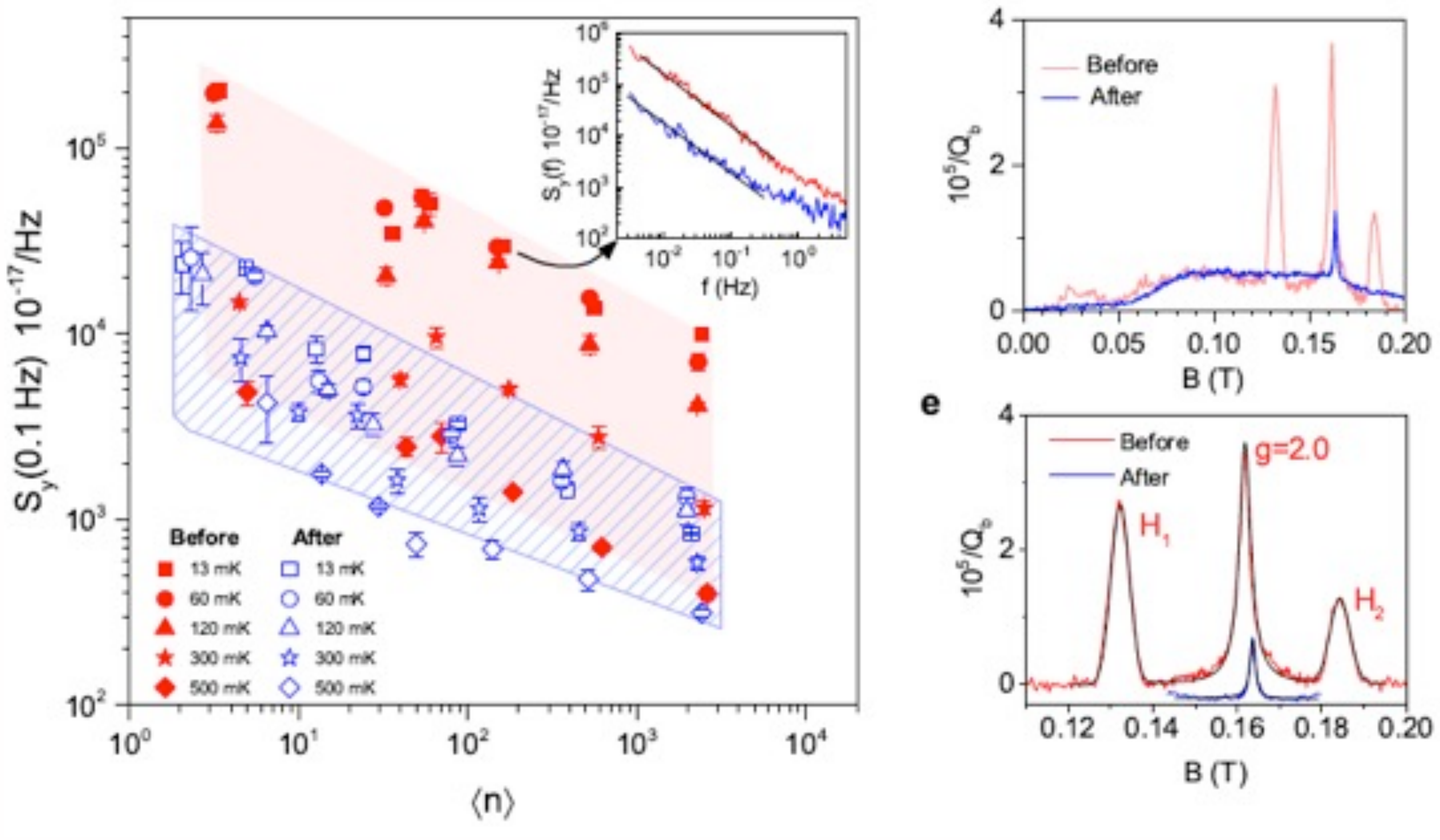
Solution is right surface treatment to eliminate chemical residues (esp. water) from fabrication, as shown to work with resonators

Remains a **BIG** problem



S. E. de Graaf et al., Nature Communications, 9:1143 (2018)

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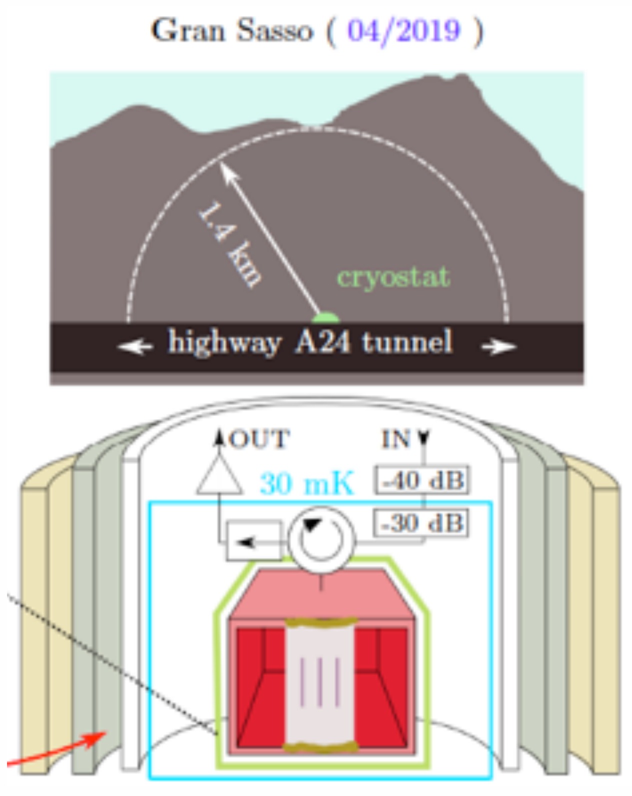
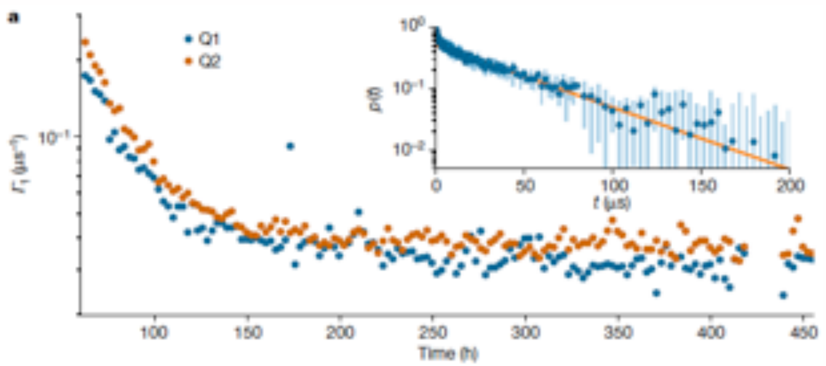
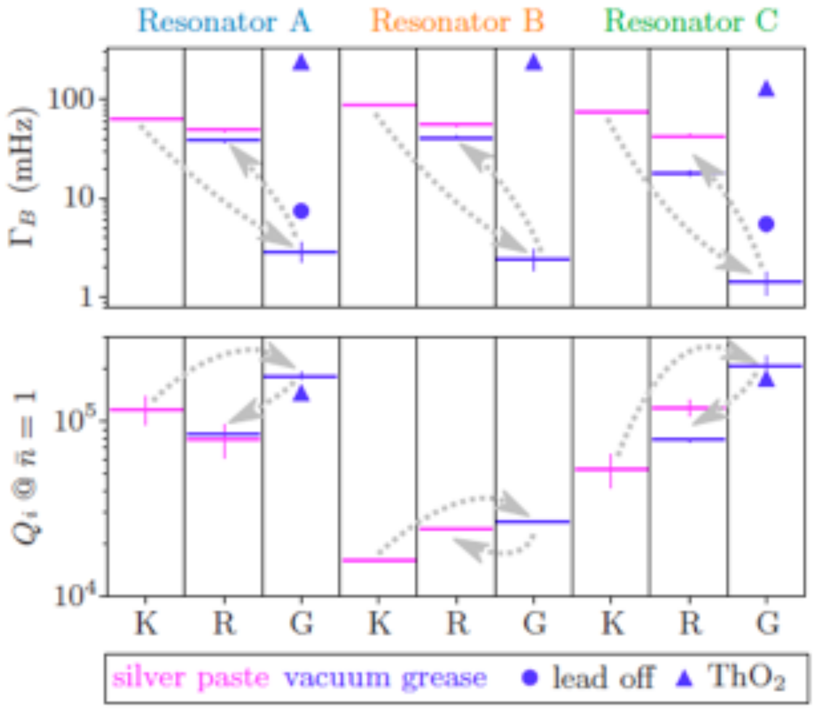
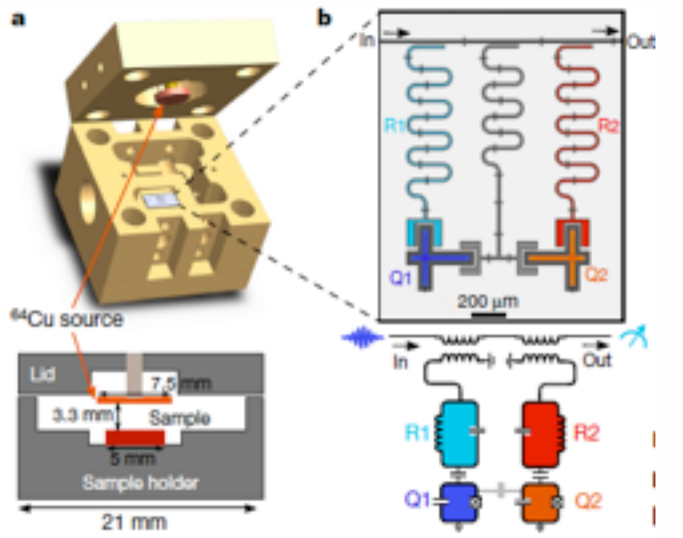




Superconducting resonators exhibit improved quality factors in an underground research station. **Cosmic rays** do impact qubits in consequence. Environmental radiation damps qubit energy. May be **inducing microscopic noise** in the qubit.



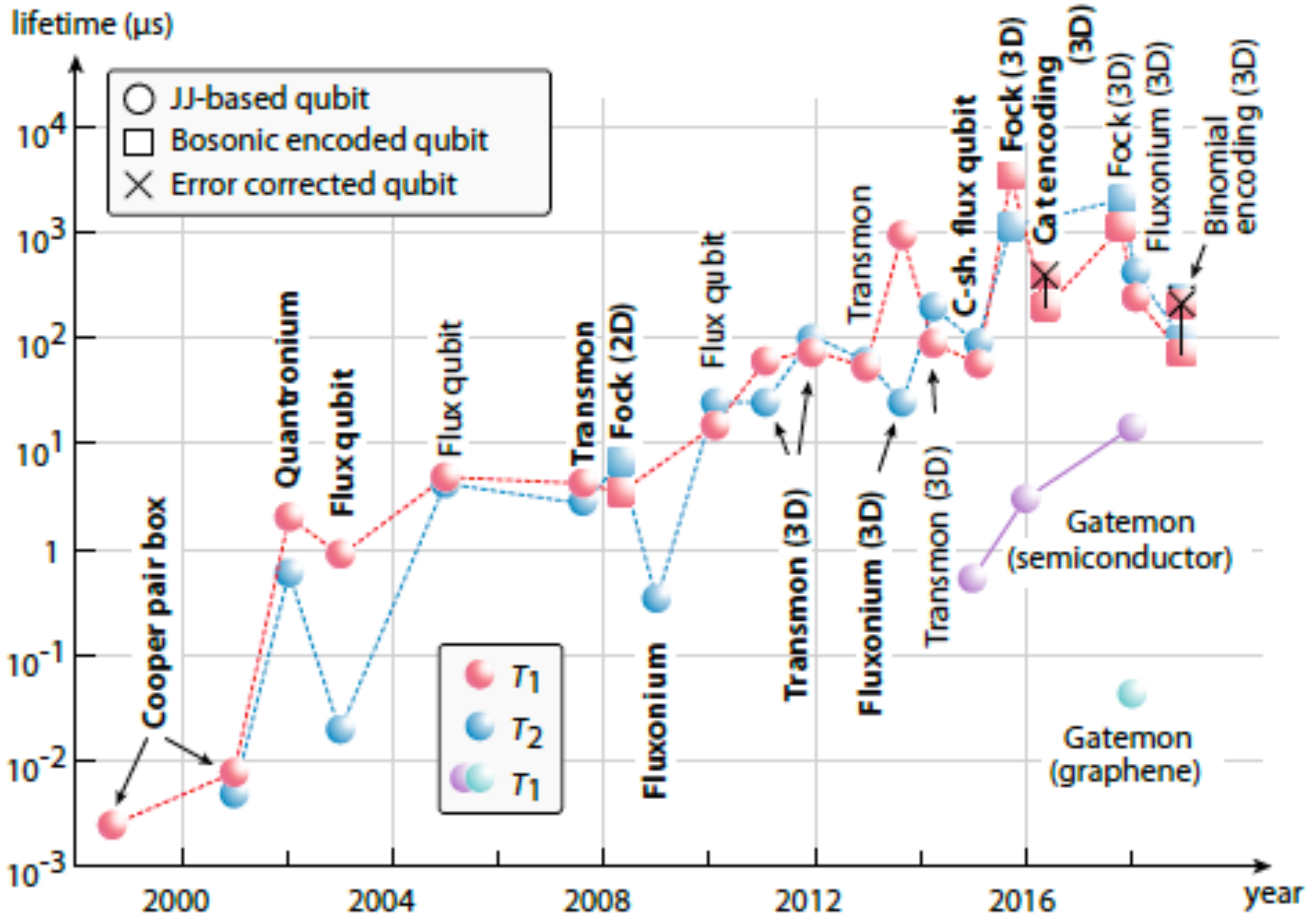


A. Vepsäläinen et al., *Nature* **volume 584**, pages 551–556 (2020)

Reducing the impact of radioactivity on quantum circuits in a deep-underground facility
Laura Cardani. NATURE COMMUNICATIONS | (2021) 12:2733

NOISE AND DECOHERENCE

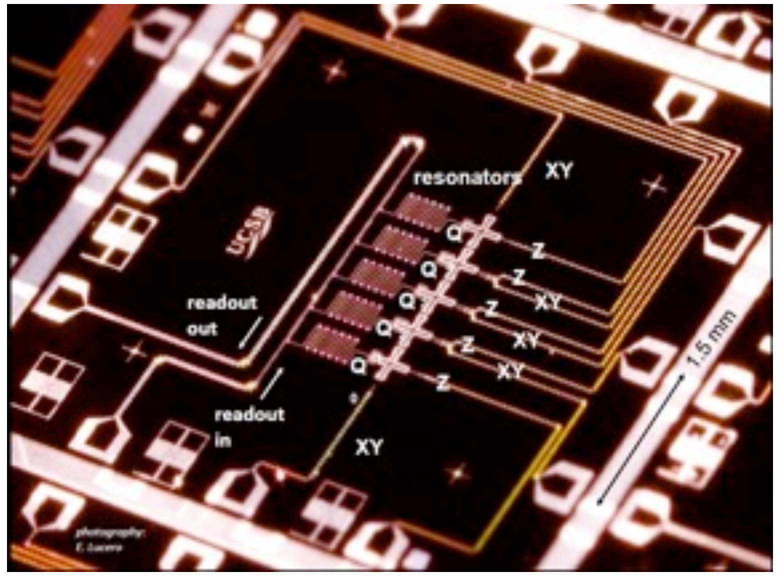
Moore-like law for superconducting qubit coherence times



M. Kjaergaard et al., Annual Reviews of Condensed Matter Physics 11, 369-395 (2020)

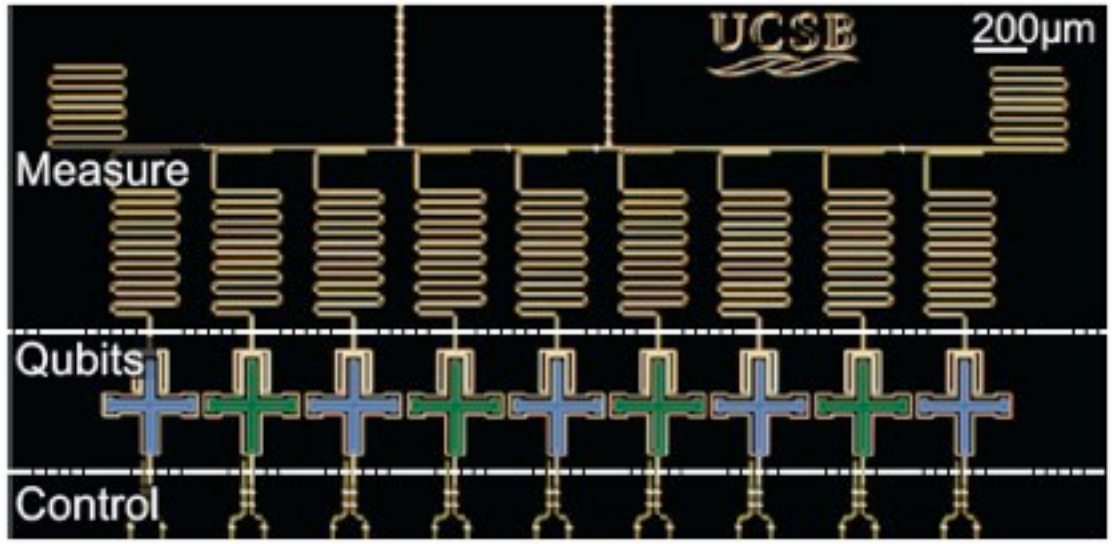
SUPERCONDUCTING DEVICE SIZE EVOLUTION

5-qubit (2013) UCSB



Nature 508, 500-503 (2014)

9-qubit (2015) UCSB

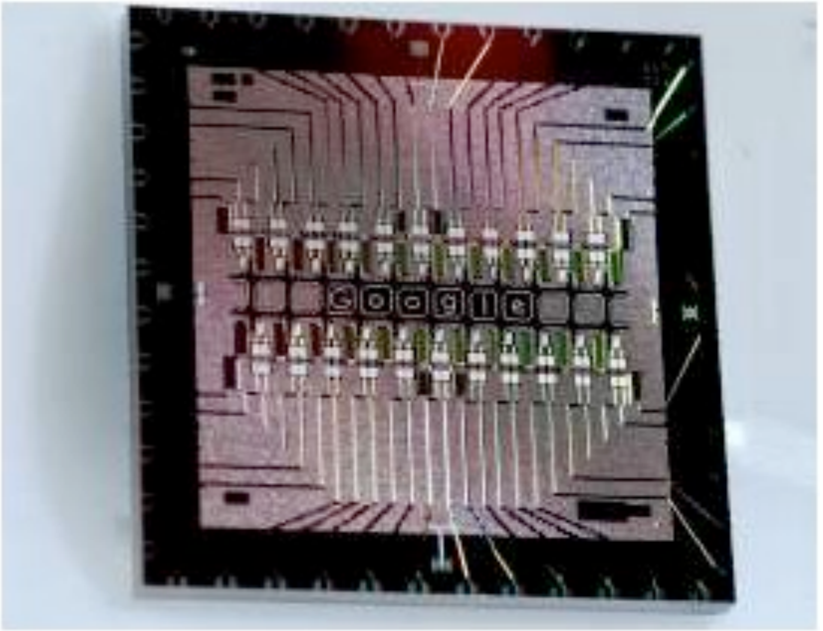


Nature 519, 66-69 (2015)

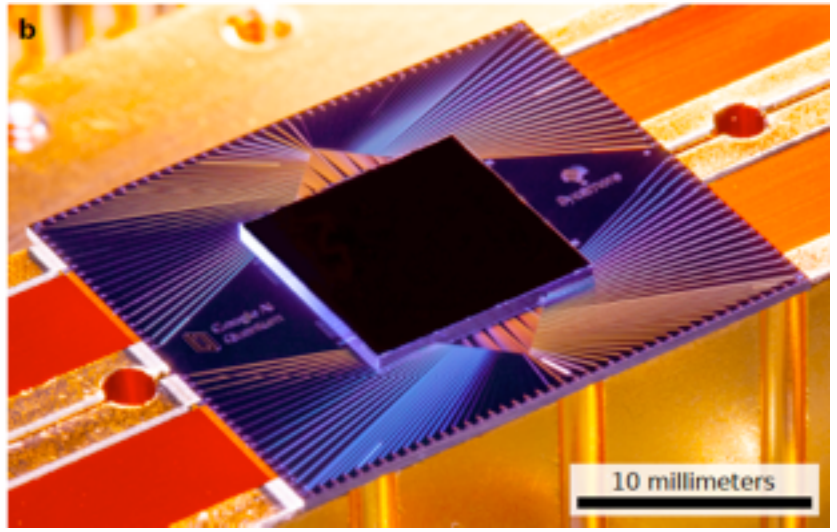
2000+ qubits (2016) D-Wave

Quantum annealer, no proof of quantum advantage

22-qubit (2017) Google



54-qubit (2019) Google

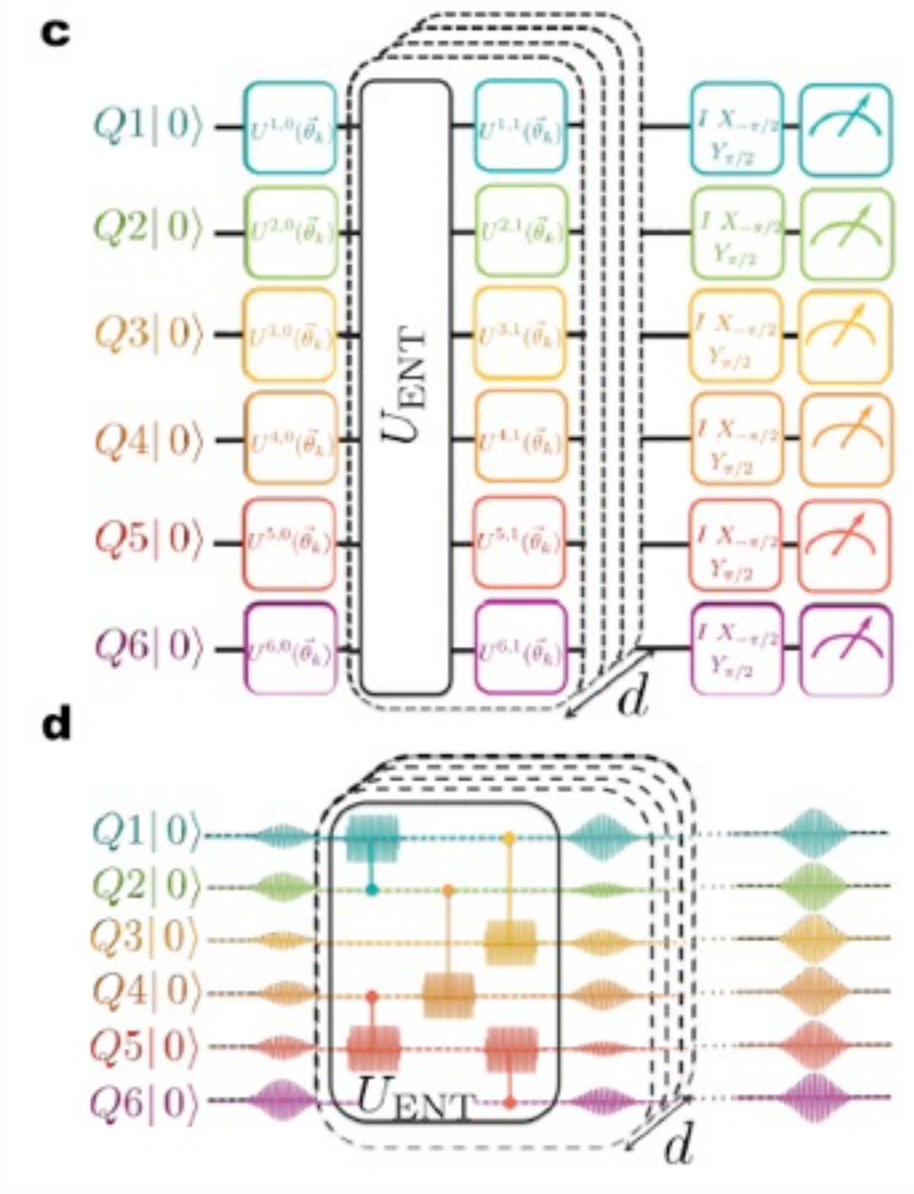


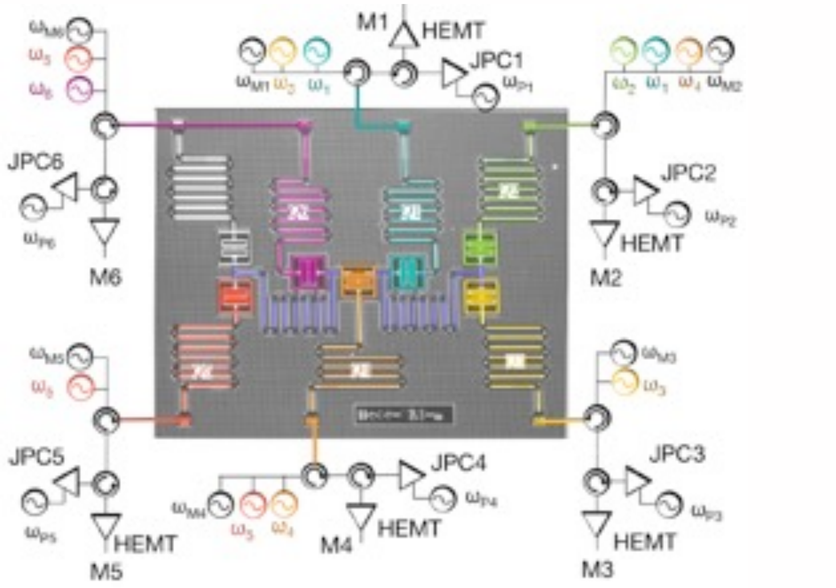
Nature 574, 505 (2019)

60-qubit (2021) China
5000+ (2021) D-Wave

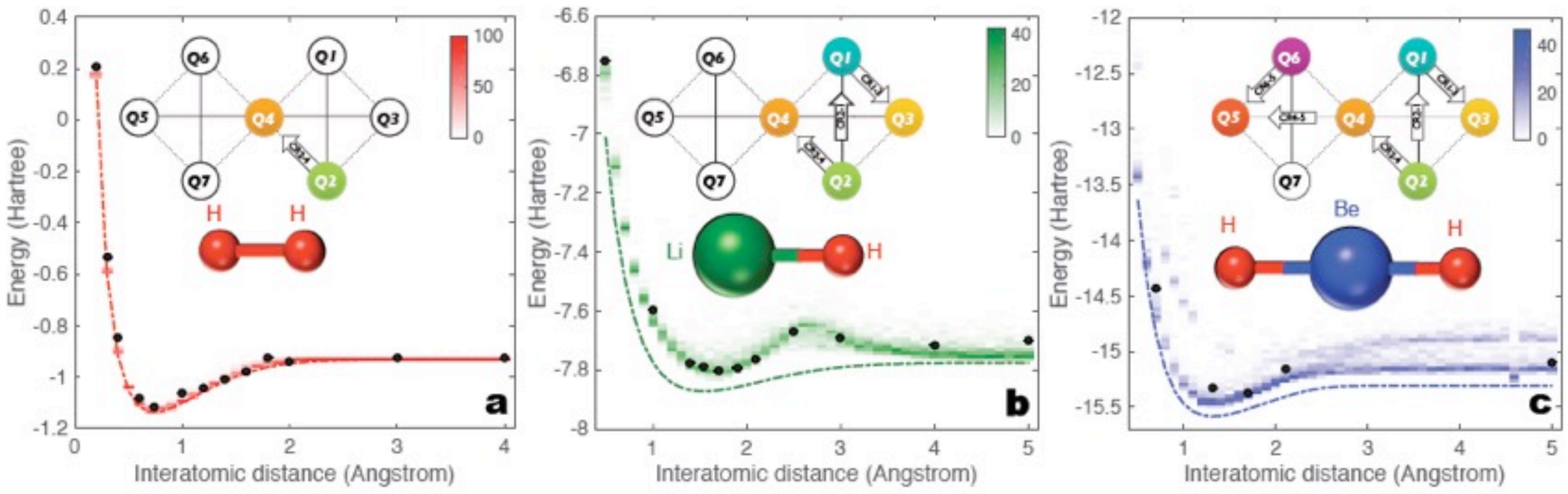
EXAMPLES OF QUANTUM ALGORITHMS IMPLEMENTED

Hybrid classical-quantum algorithms:
Variational quantum eigensolvers



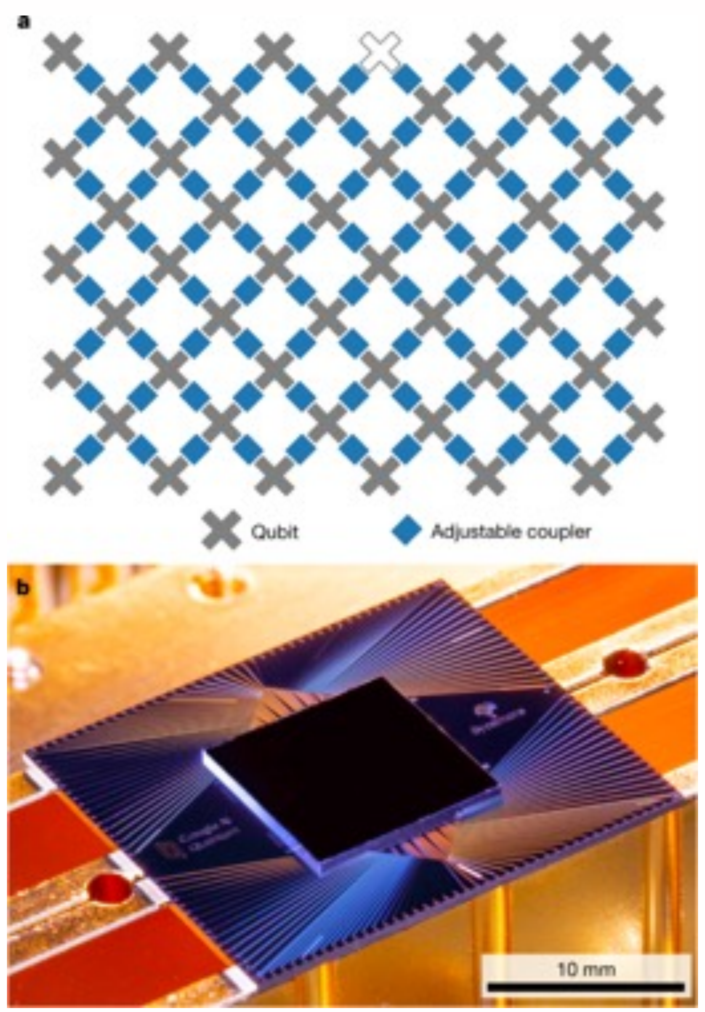


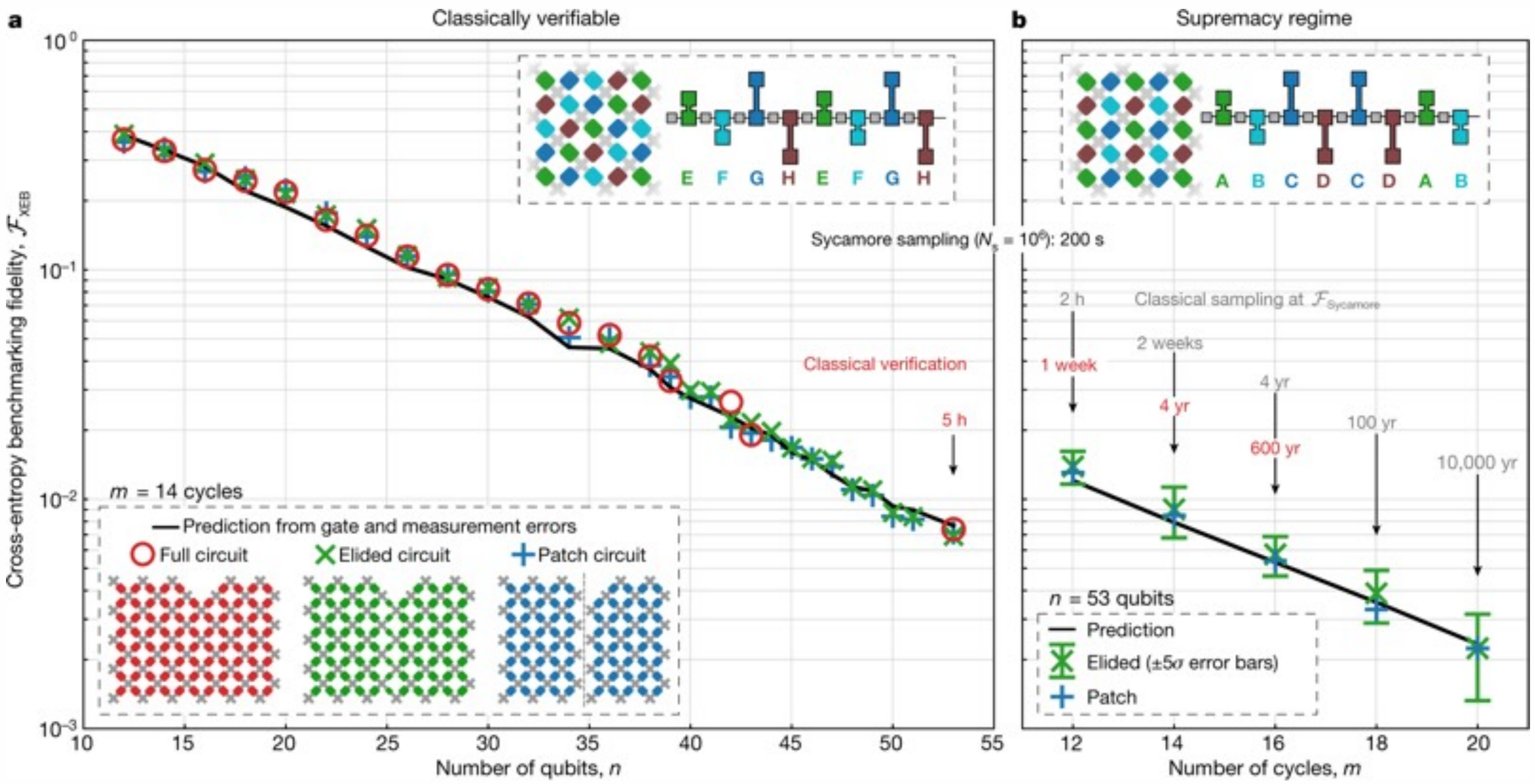
Computation of binding energy of small molecules by IBM Q team using a 6-qubit device



A. Kandala et al., Nature 549, 242 (2017)

EXAMPLES OF QUANTUM ALGORITHMS IMPLEMENTED: QUANTUM SUPREMACY





Quantum supremacy/advantage point: Operation performed with a quantum system which could not be implemented in the most powerful supercomputer in the world in a realistic time.

Achieved by Google AI team in 2019 with a 53 superconducting qubit chip generating random states with a high degree of entanglement and calculating cross-entropy.

EXPECTATIONS IN THE FIELD OF QUANTUM COMPUTATION

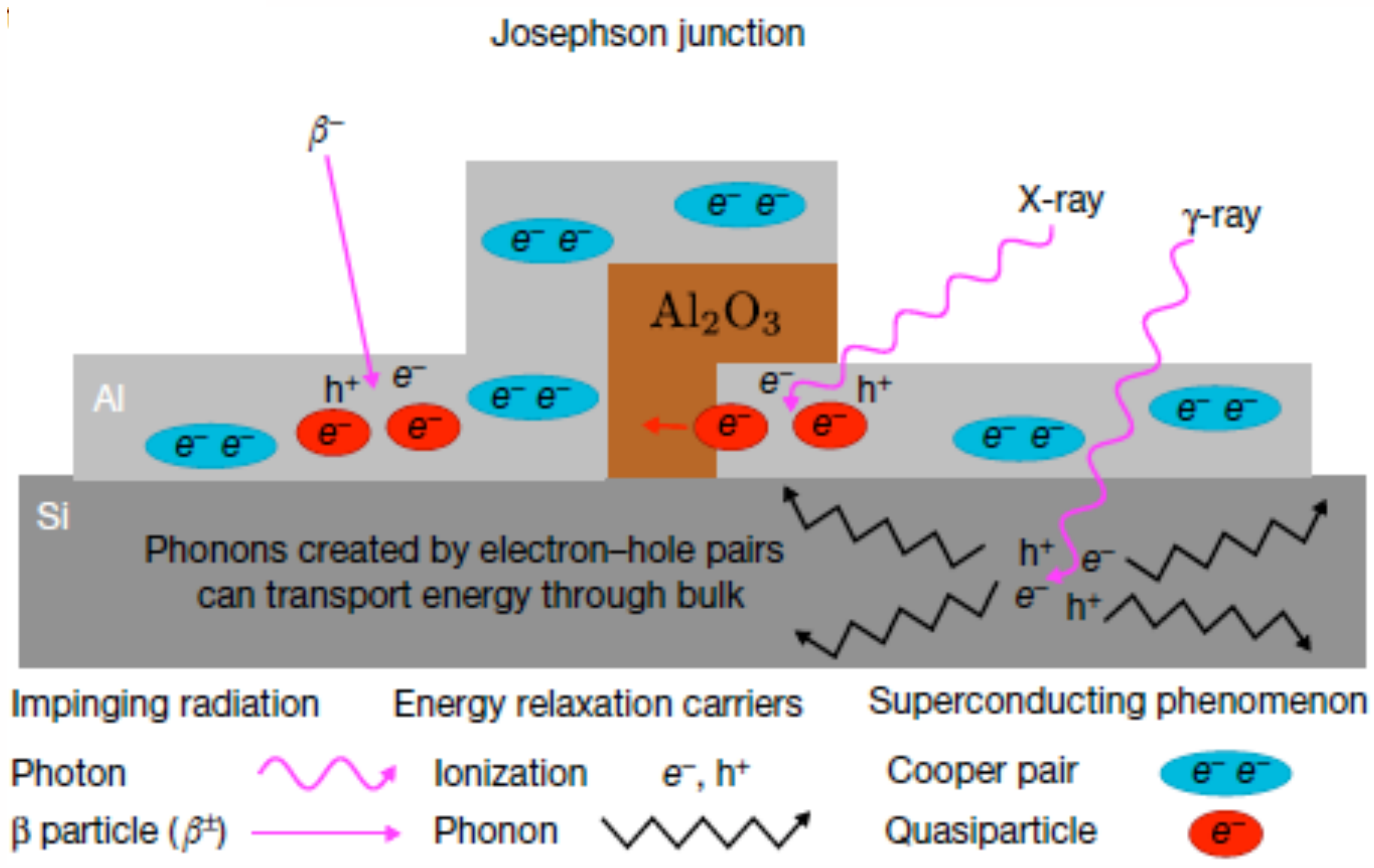
What's next?

5-10 years

- -Quantum supremacy / advantage (achieved in 2019)
- -Real world optimization problems with annealers
- -Simulation of small molecules
- -Partial error-corrected quantum computation
- -Full-sized, error-corrected, universal quantum computer

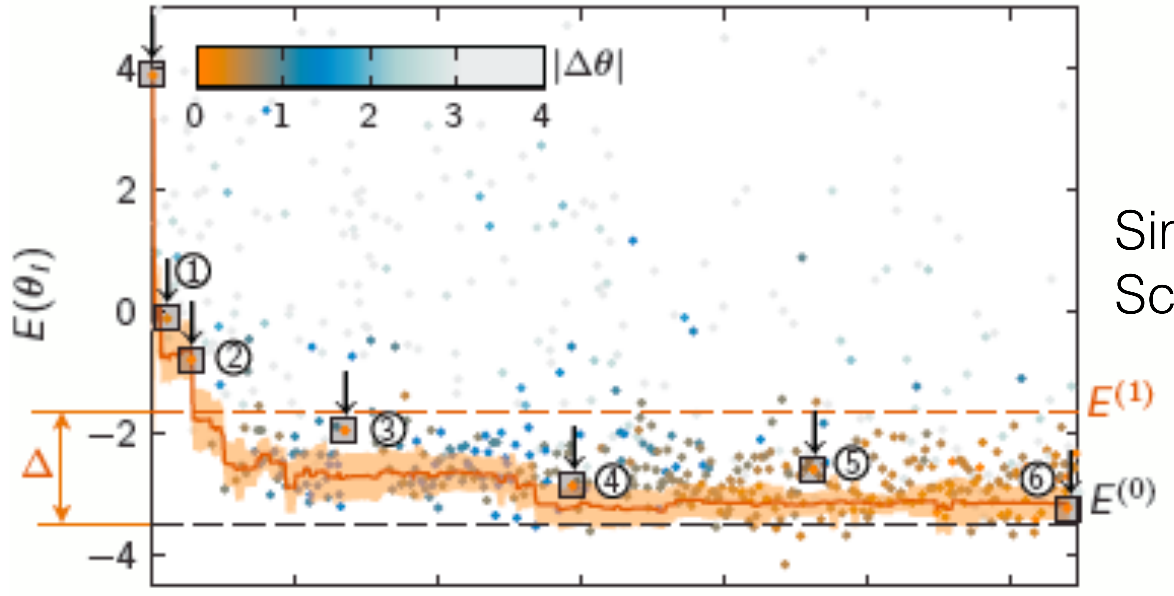
(extra) Block 3: What can HEP do for QC, and viceversa?

- Quantum algorithms for HEP
- HEP technology for qubits
- Rare event detection by qubits



Quantum algorithms for HEP

Quantum computers can accelerate the computation of many HEP problems: QCD, QFT, gravity models, etc. by simulating the exact Hamiltonian used in these problems, digitally or via analog techniques.

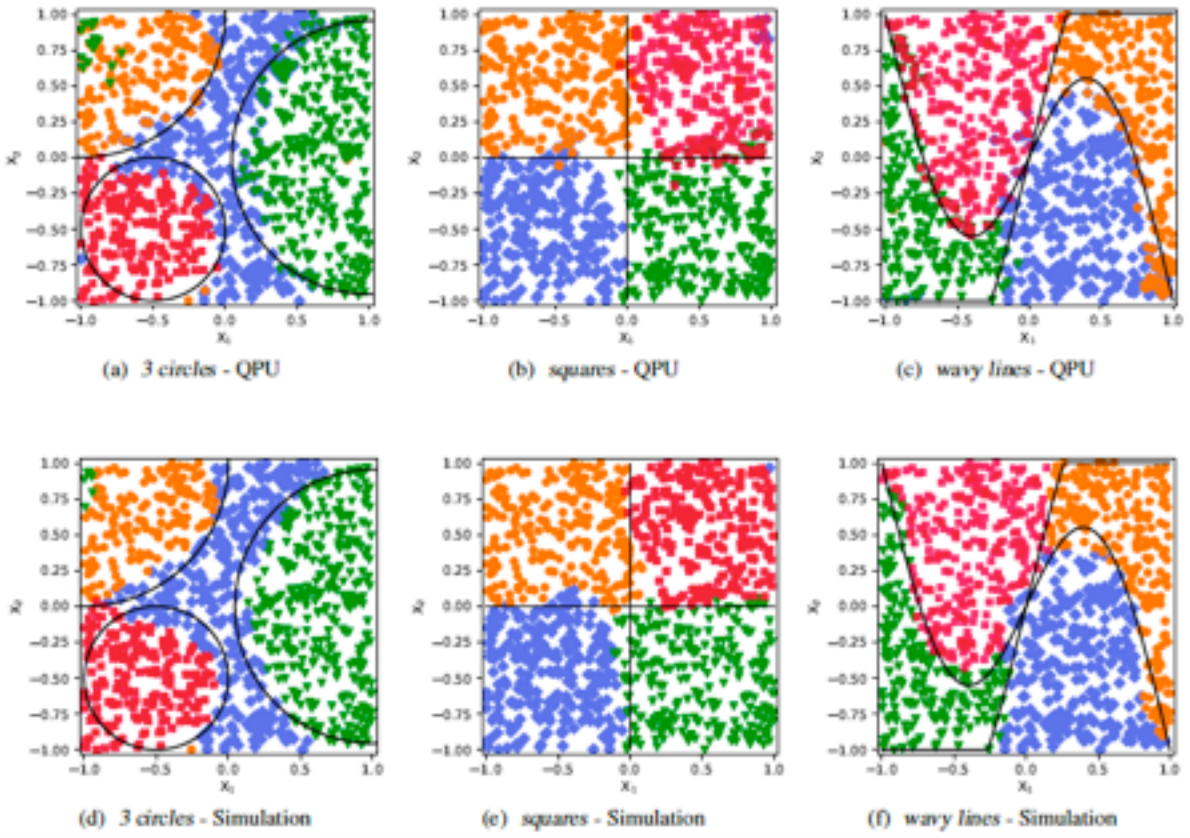


Simulation with trapped ions of Schwinger ground state

Self-Verifying Variational Quantum Simulation of the Lattice Schwinger Model, C. Kokail et al., Nature 569, 355 (2019)

Exp

Sim



Another important area of potential impact is in the **pattern recognition** to process data obtained at particle accelerators. Initial algorithms have already shown success in small-scale systems (1 qubit)

A third category is in the optimization of computation of operations related to machine learning.

Solving a Higgs optimization problem with quantum annealing for machine learning Alex Mott, Joshua Job, Jean-Roch Vlimant, Daniel Lidar & Maria Spiropulu Nature 550, 375 (2017)

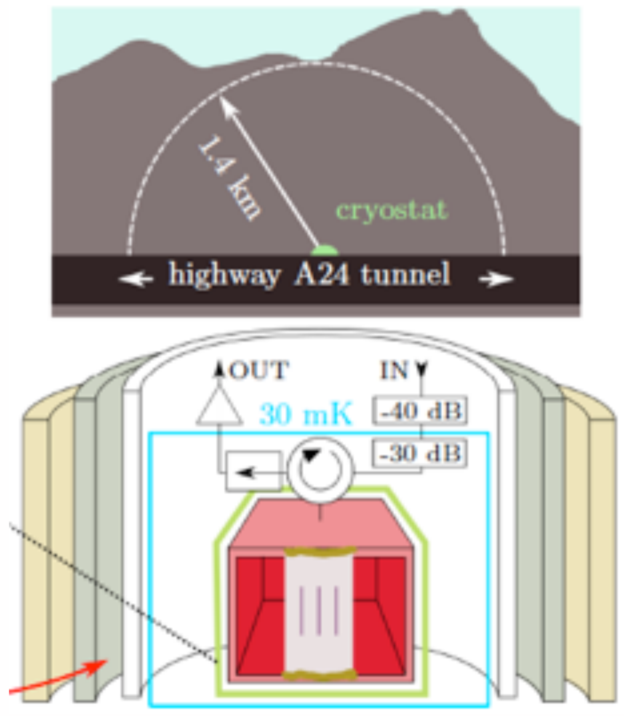
Data re-uploading for a universal quantum classifier, A. Pérez-Salinas et al., Quantum 4, 226 (2020)
Realization of an ion trap quantum classifier, T. Dutta et al., arXiv:2106.14059

HEP technology for qubits

Ionizing radiation (cosmic rays + environmental radioactivity) have been shown to be a major cause for limiting qubit **coherence**. Overcoming this important source of noise will require both reducing the impact of the source (proper shielding) as well as mitigating the effect on the chip (patterning).
This requires **good knowledge of the origin and characteristics of this kind of radiation and its effects on matter**.

Reducing the impact of radioactivity on quantum circuits in a deep-underground facility
Laura Cardani. NATURE COMMUNICATIONS | (2021) 12:2733

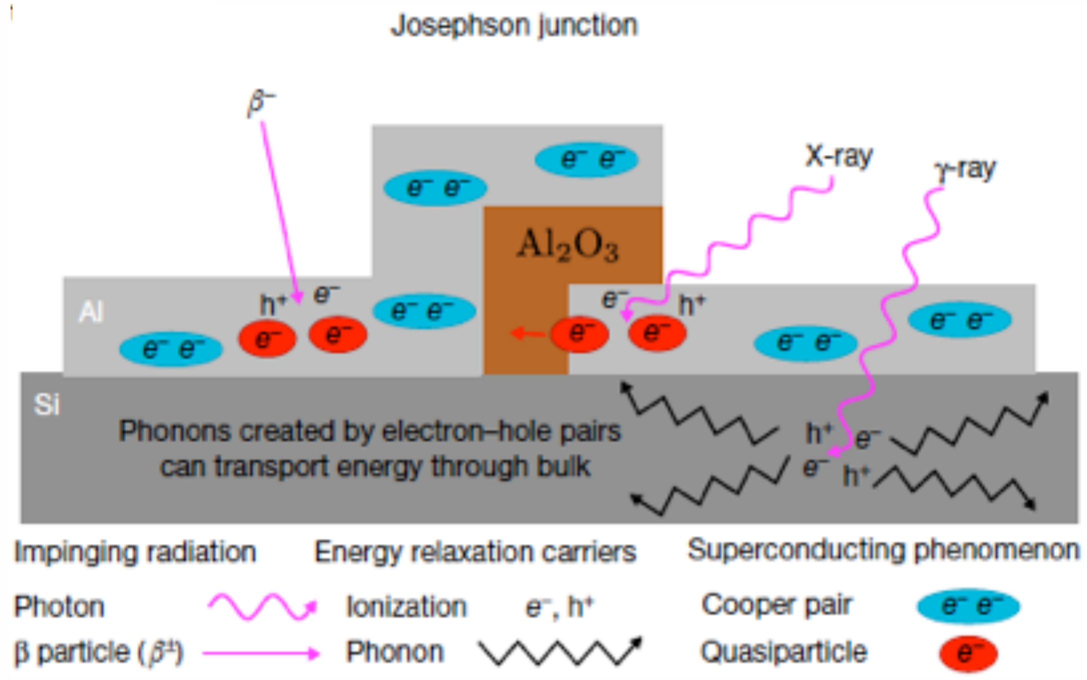
Gran Sasso (04/2019)



Cavities in accelerators have been started to be considered to store photons in qubit experiments (i.e. Fermilab).

Three-Dimensional Superconducting Resonators at T<20 mK with Photon Lifetimes up to τ=2 s A. Romanenko, et al. Phys. Rev. Applied 13, 034032

Stronger qubit-HEP interactions may open new applications of the HEP technology in qubits.

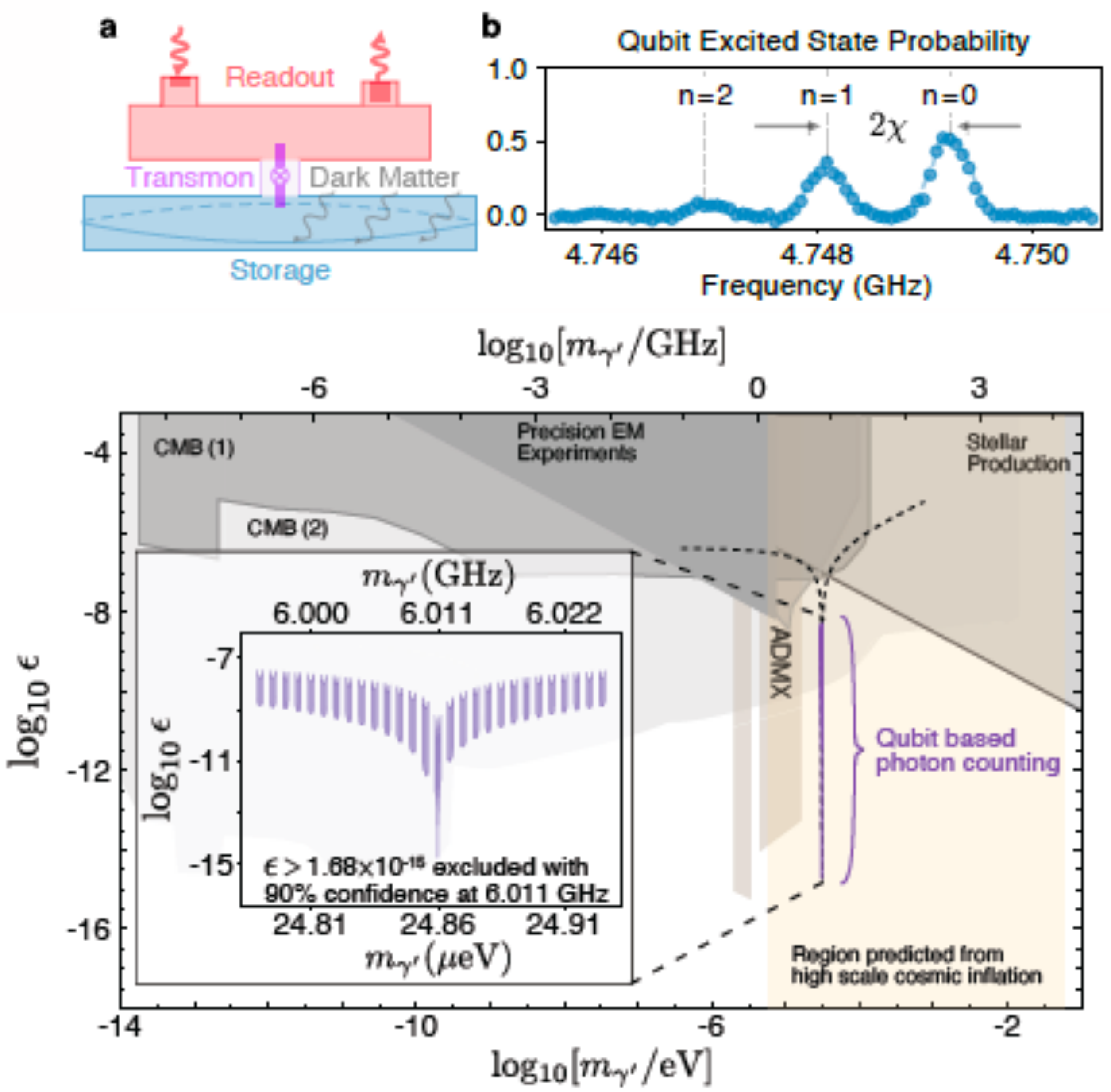


Rare event detection by qubits

Qubits are **ideal quantum spectrometers**. In addition, qubits may **interact very strongly with photons** in superconducting resonators exhibiting pristine quality factors. The result is an **incredibly sensitive** device that is able to sense the presence of photons inside the resonator with unprecedented accuracy over a certain space of parameters.

Proposals have already been put forward to use qubits combined with cavities to **detect potential dark matter signals**, including axions and dark photons.

Initial experiments are already being established in the **US** through **Fermilab**, and in **Italy at INFN**. **IFAE** is starting a collaboration with **LSC in Spain** to carry out first measurements with qubits underground.



Searching for Dark Matter with a Superconducting Qubit. Akash V. Dixit, Srivatsan Chakram, Kevin He, Ankur Agrawal, Ravi K. Naik, David I. Schuster, and Aaron Chou. Phys. Rev. Lett. 126, 141302

OUTLINE

Block 1: Overview of Quantum Computing Platforms

- A brief history of experimental QC
- How to build a quantum computer?
- Digital/analog quantum computers
- Leading experimental platforms

Block 2: Experimental quantum computing + Quantum industry

- 1 qubit manipulation: Rabi, Ramsey, echo
- Noise and decoherence
- Quantum algorithms implemented and outlook

(extra) Block 3: What can HEP do for QC?

END OF THE LECTURE!

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The Qilimanjaro team

THANK YOU!

https://qct.ifae.es/
pforndiaz@ifae.es
@pforndiaz
@_IFAE
www.qilimanjaro.tech