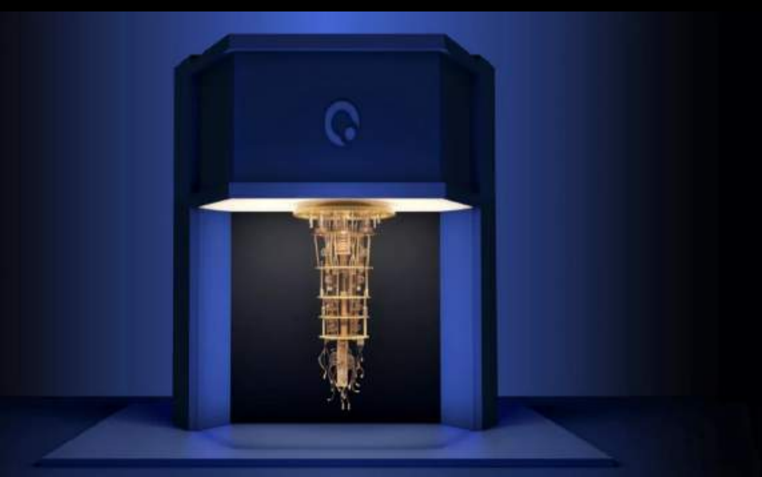
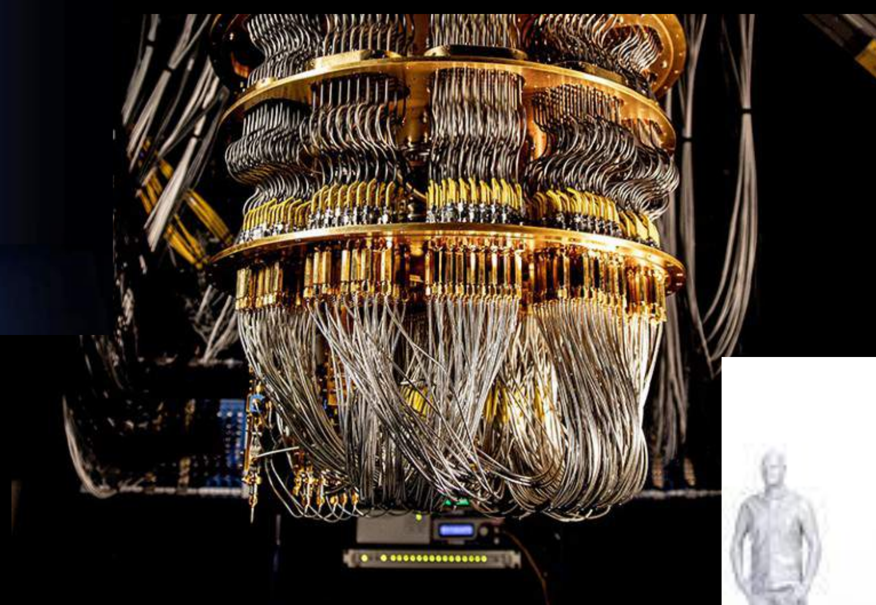
Quelle technologie pour la construction d'un ordinateur quantique?

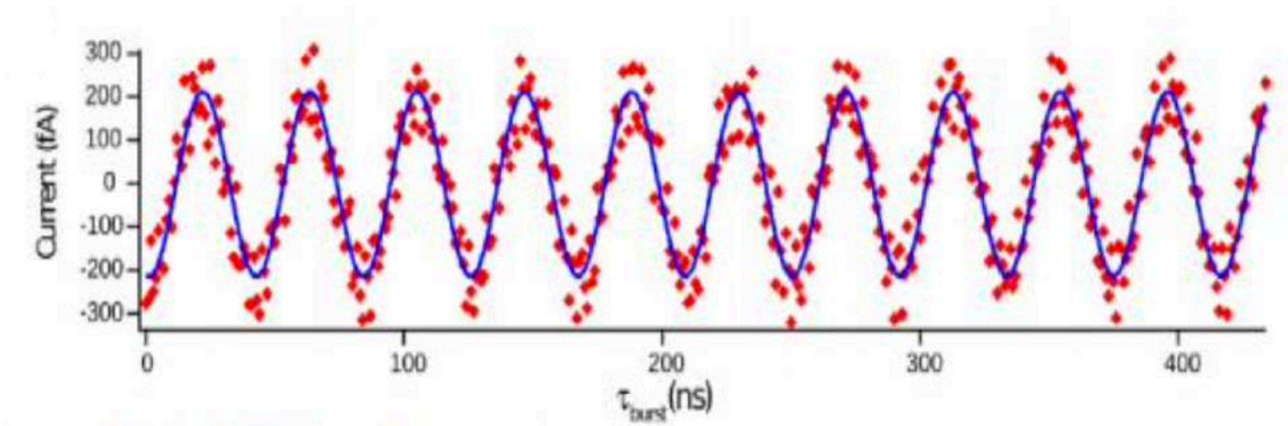
F. Balestro, UGA-CNRS, Néel Institut, QuantECA
Quantum Electronics Circuits Alps

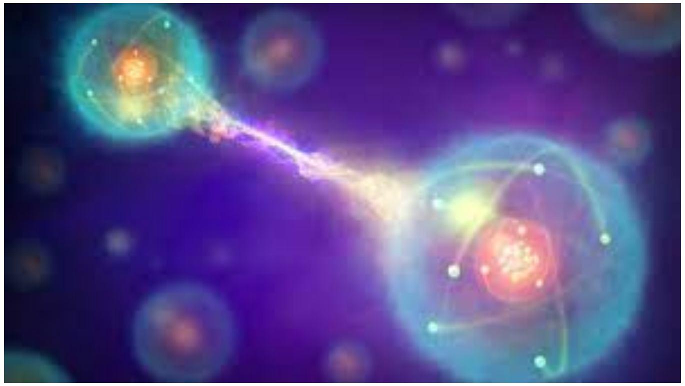




What are Quantum Technologies ?

Quantum technology is a class of technology that works by using the principles of quantum mechanics (the physics of sub-atomic particles), including quantum superposition and quantum entanglement .





Ability to control quantum entanglement and quantum superposition. That means quantum technology promises improvements to a vast range of NOT everyday applications, including:

- more reliable navigation and timing systems
- more secure communications
- more accurate healthcare imaging through quantum sensing
- more powerful computing.

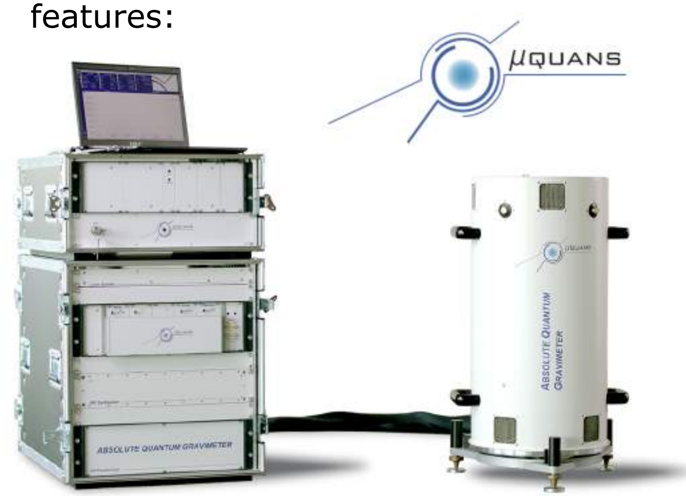
What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???

What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !

The Absolute Quantum Gravimeter is the only quantum gravity sensor available on the market place. Thanks to its disruptive technology, this instrument offers unique features:



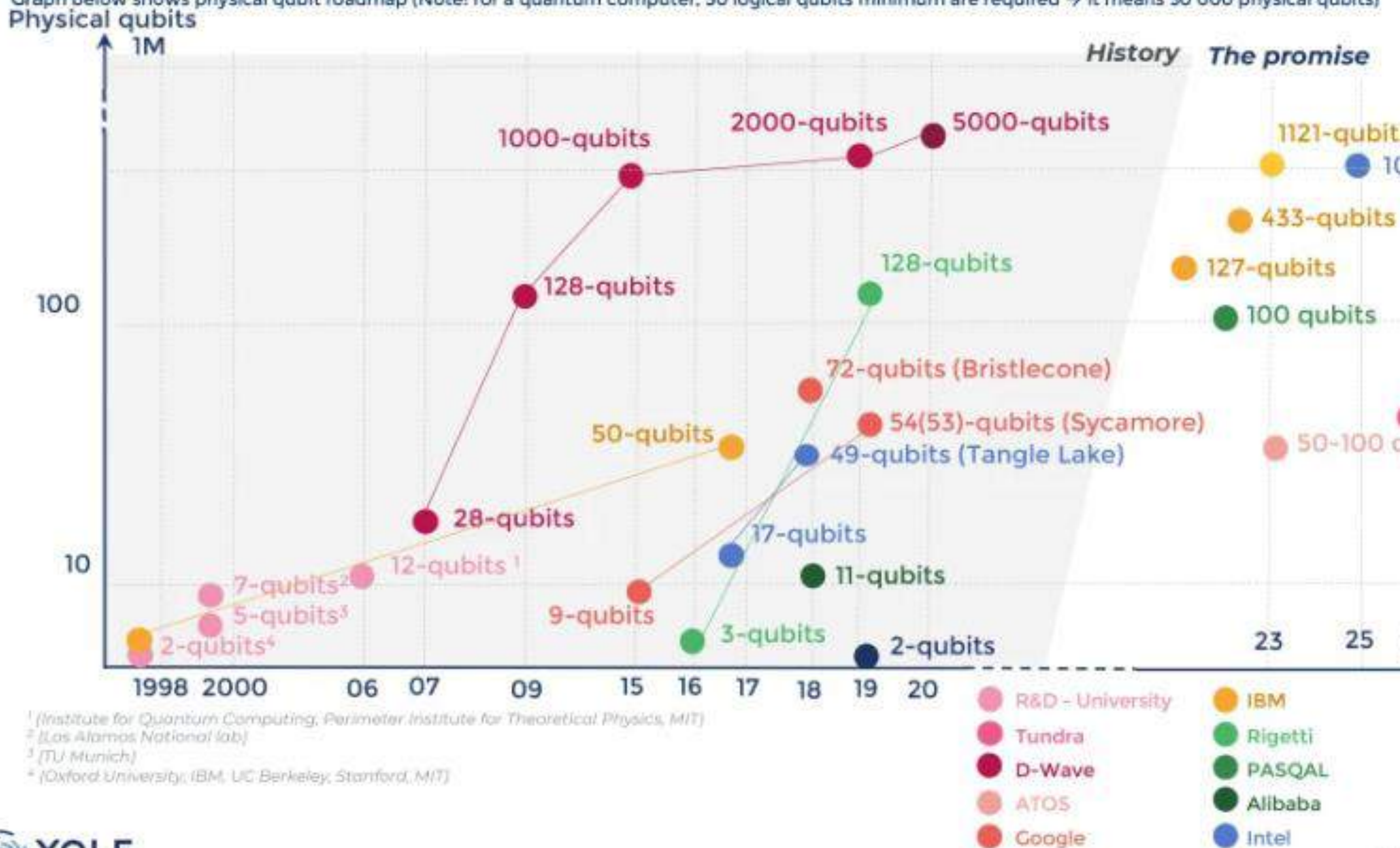
qutools

wainvam

PHYSICAL QUBIT ROADMAP FOR QUANTUM COM
– HISTORY AND FUTURE

Source: Quantum Technologies report, Yole Développement, 2021

Graph below shows physical qubit roadmap (Note: for a quantum computer, 50 logical qubits minimum are required → it means 50 000 physical qubits)



[1] (Institute for Quantum Computing, Perimeter Institute for Theoretical Physics, MIT)
[2] (Los Alamos National lab)
[3] (TU Munich)
[4] (Oxford University, IBM, UC Berkeley, Stanford, MIT)

YOLE Intelligence

What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

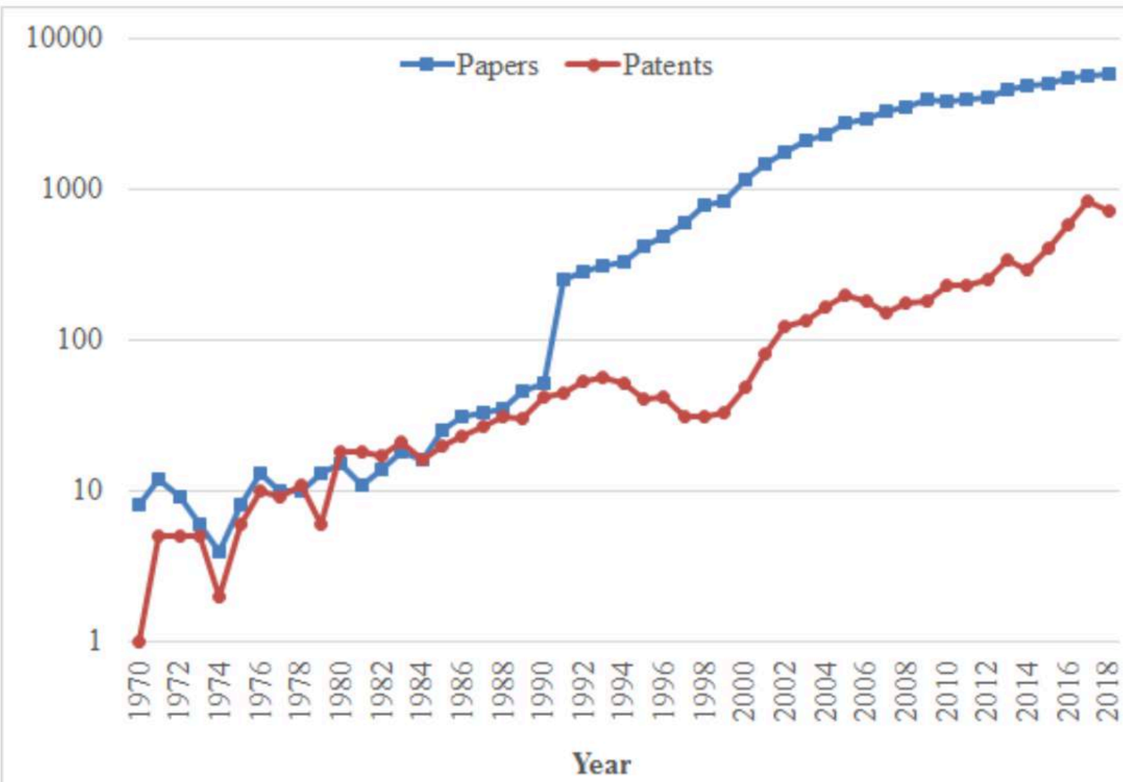
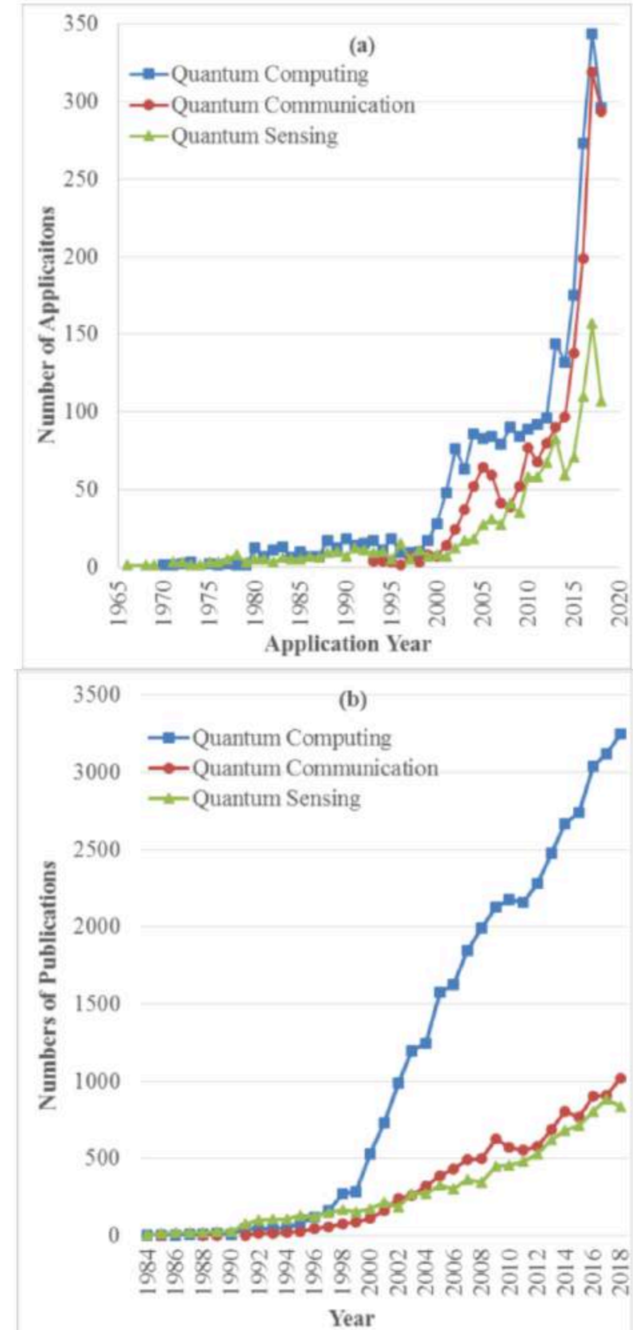
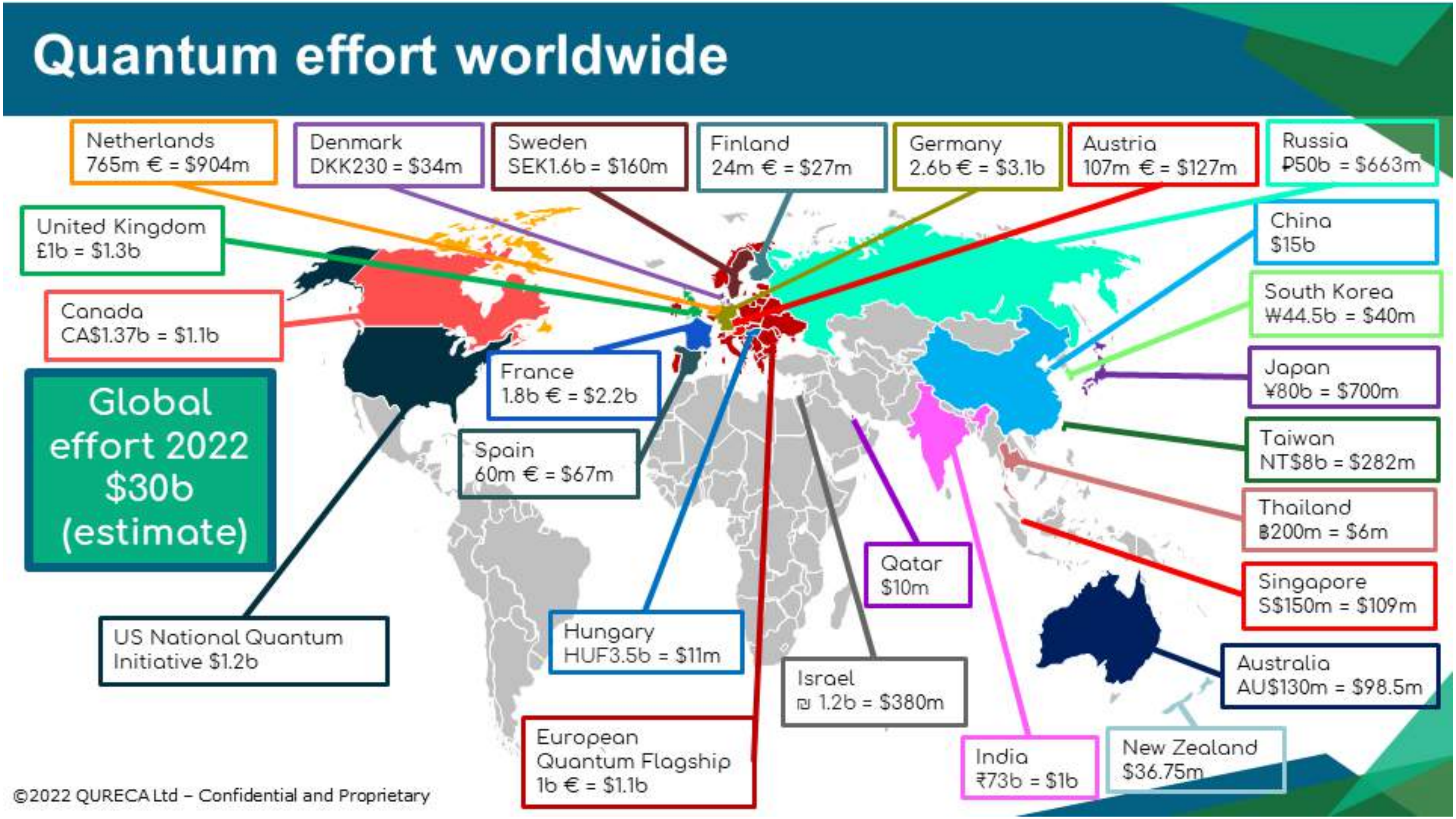


Fig. 1. Overall quantum technologies development trend based on publication by year.
(Note: the patent application publishing has almost 18-month delay from their earliest filing date, so there may have not the whole patent data in 2018 and 2019.)



What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?



https://qureca.com/overview-on-quantum-initiatives-worldwide-update-2022/

What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

January 21th 2021 the 1.8 billion euros "French Quantum Strategy"

- nearly 800 M€ over 5 years, would allow to develop a hybrid computer, including for chemistry, logistics, artificial intelligence by 2023.
- 320 M€ will be devoted to quantum communication systems
- 250 M€ to quantum sensors
- 150 M€ to post-quantum cryptography
- 290 M€ to related technologies around quantum (lasers, cryogenics,…).

What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

EDUCATION

QuanTEdu-France : Technologies quantiques :
Education et formation pour répondre aux besoins en compétences stratégiques de la recherche et de l’industrie en France.

21 Universities/Schools + 4 industrials partners

One of the major challenges is to support the emergence of talent and to accelerate the adaptation of training to the skill requirements of new sectors and professions of the future:

- Anticipate employment and skills needs as much as possible.
- Accelerate the implementation of training programs to prepare for them.
- Inventing new solutions to meet the challenges of attractiveness, vocations, adaptation, transformation, massification and skills upgrading.

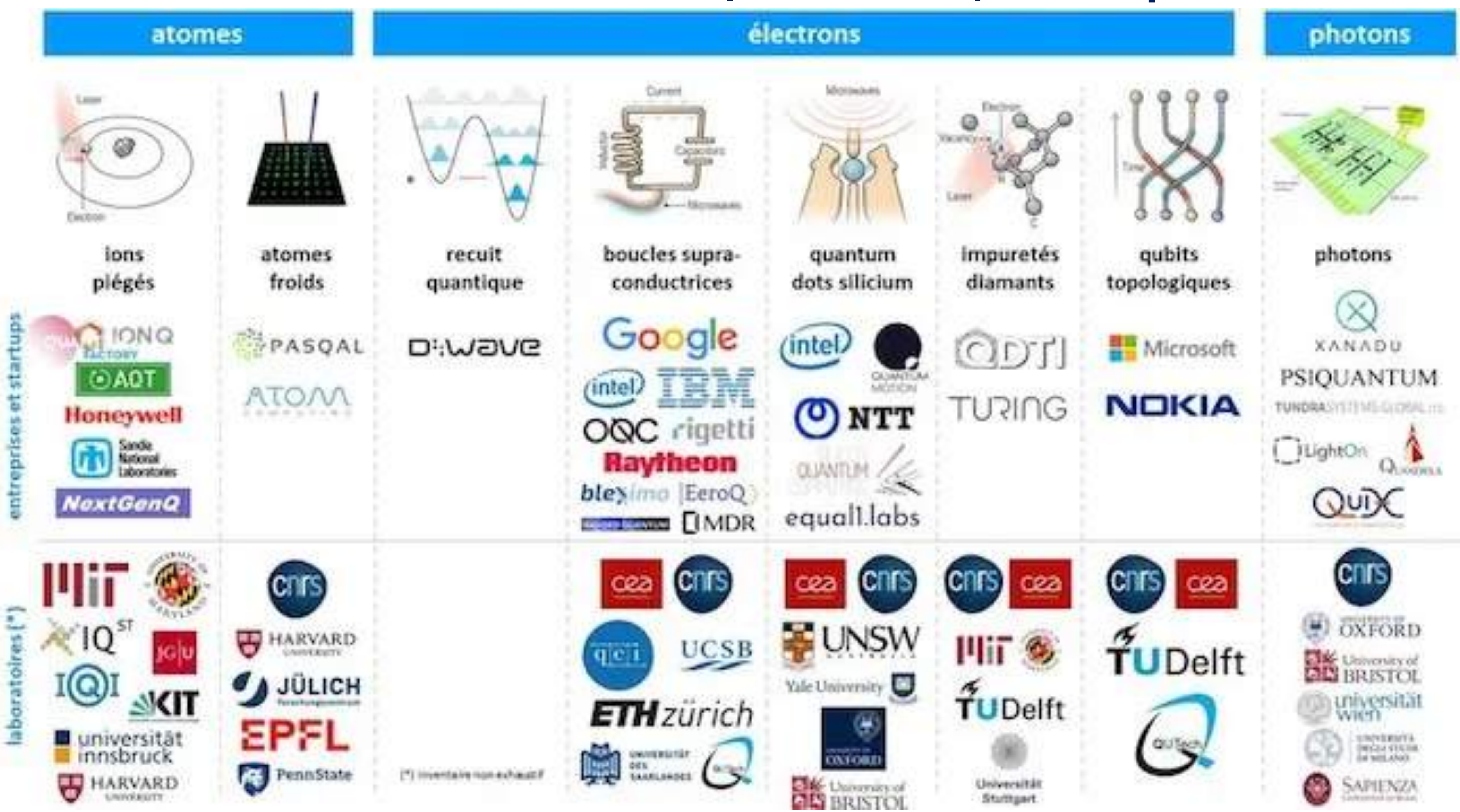
Quantum strategy goal:

16,000 direct and indirect jobs by 2030.

What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

Research Laboratories/Industries/start-ups !!

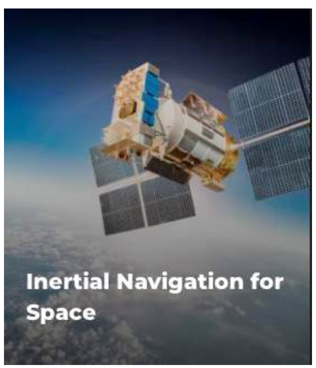


What are Quantum Technologies ?

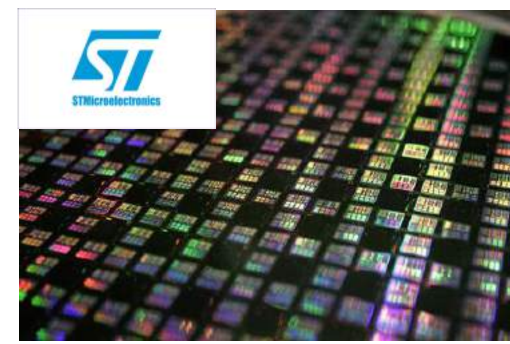
Do Quantum Technologies have a future ?
How do you answer this "simple" question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

Research Laboratories/Industries/start-ups !!

iXBlue, Thales, Atos, Airbus, Alice&Bob, AUREA, ColibrITD, EDF, MYCYOFIRM, ORANGE, Pasqal, Quandela, VeriQloud, Silent Waves, Siquance, ….



siquance



QUANDELA

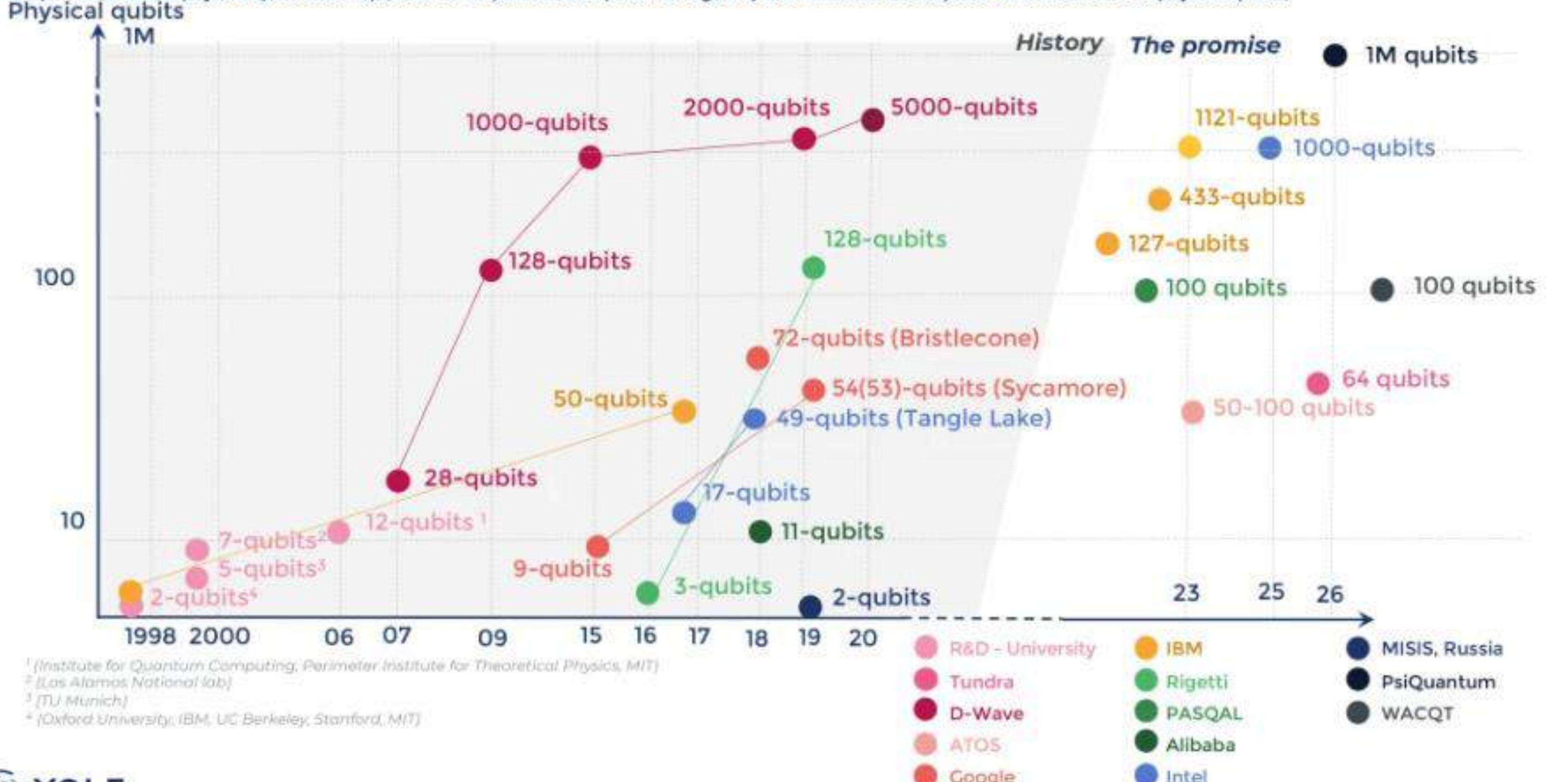
ColibrITD

ONERA
THE FRENCH AEROSPACE LAB

PHYSICAL QUBIT ROADMAP FOR QUANTUM COMPUTER – HISTORY AND FUTURE

Source: Quantum Technologies report, Yole Développement, 2021

Graph below shows physical qubit roadmap (Note: for a quantum computer, 50 logical qubits minimum are required → it means 50 000 physical qubits)



1 (Institute for Quantum Computing, Perimeter Institute for Theoretical Physics, MIT)
2 (Los Alamos National lab)
3 (TU Munich)
4 (Oxford University, IBM, UC Berkeley, Stanford, MIT)

YOLE Intelligence

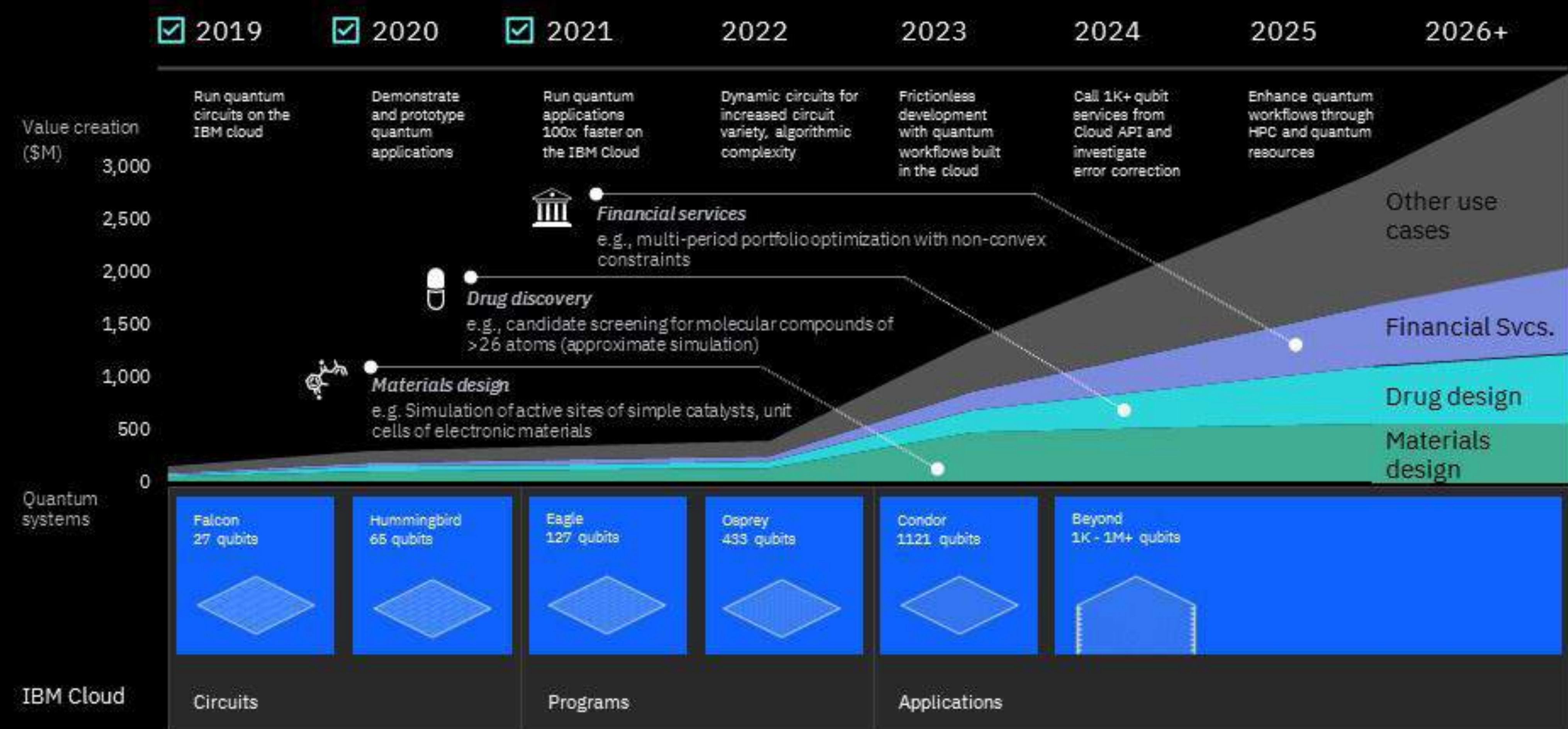
Market Analysis by Boston Consulting Group

BCG predicts Quantum computing's inflection point around the corner

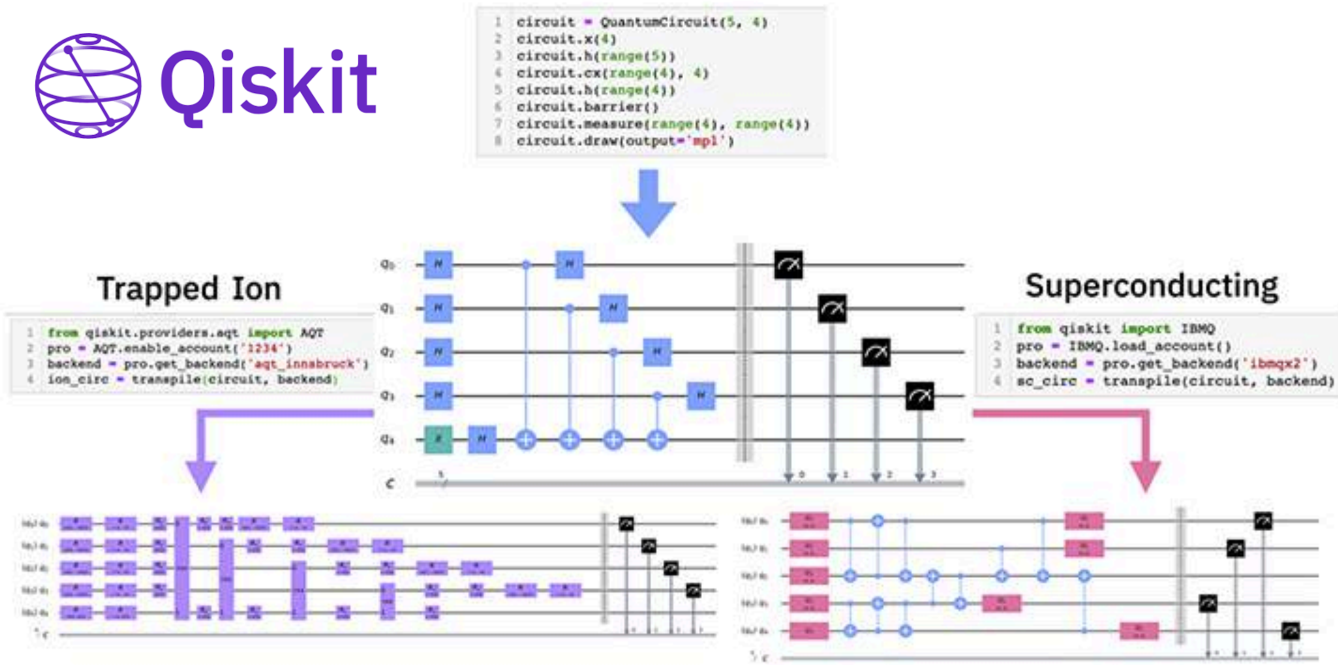
→ **poised to create $3B+ value by 2024**

IBM Quantum

BCG BOSTON CONSULTING GROUP



Qiskit



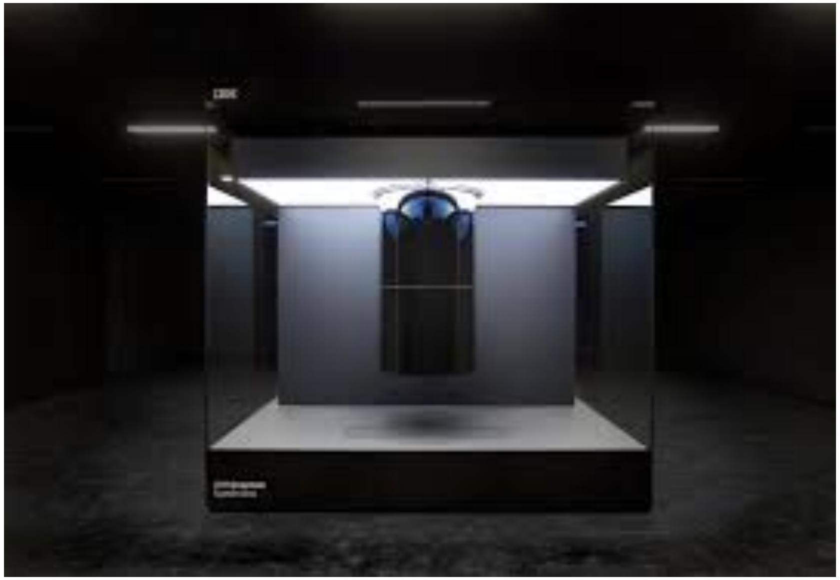
Amazon Braket

Accélérer la recherche en informatique quantique

rigetti

En savoir plus sur les processeurs superconducteurs basés sur les portes Rigetti »

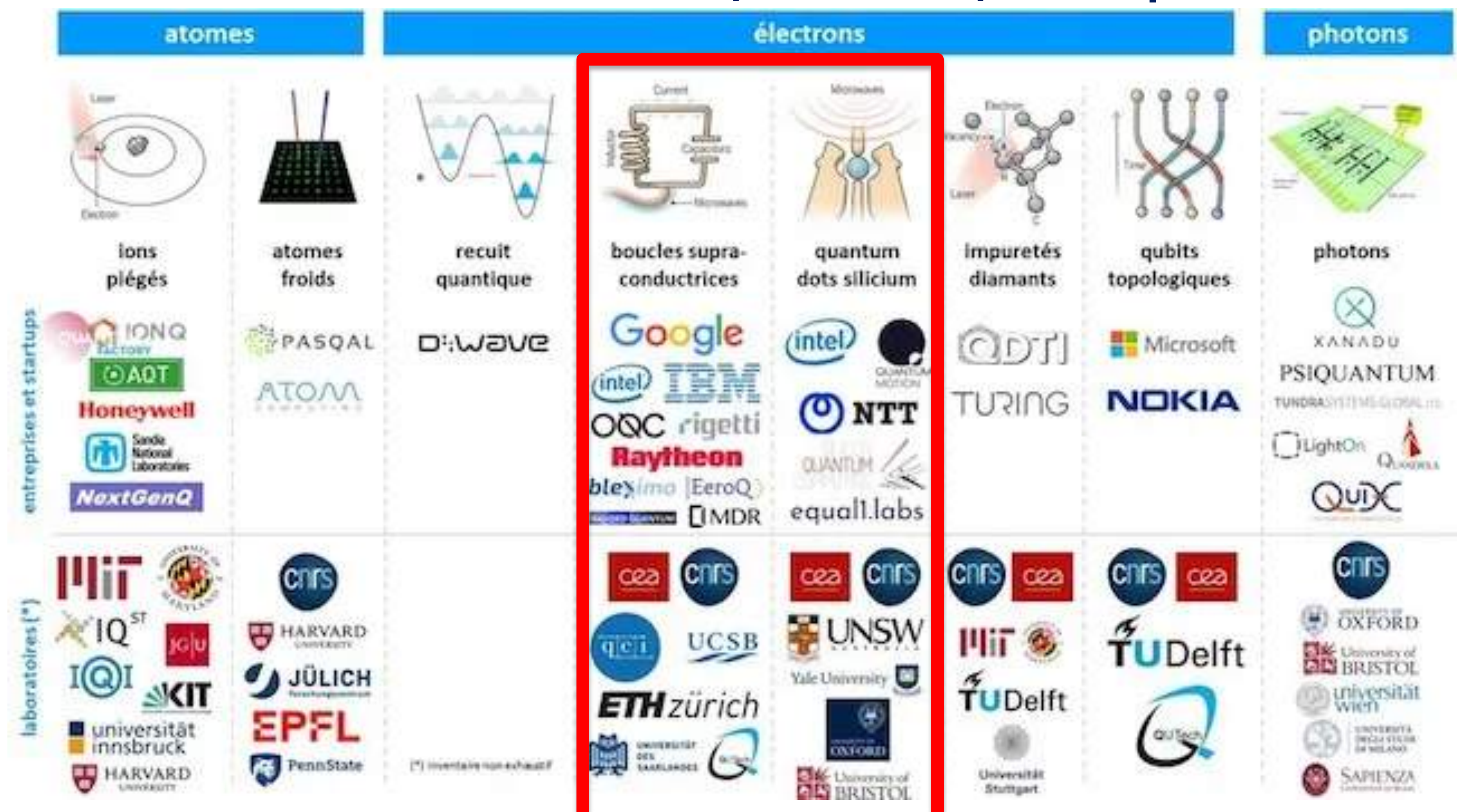
PASQAL



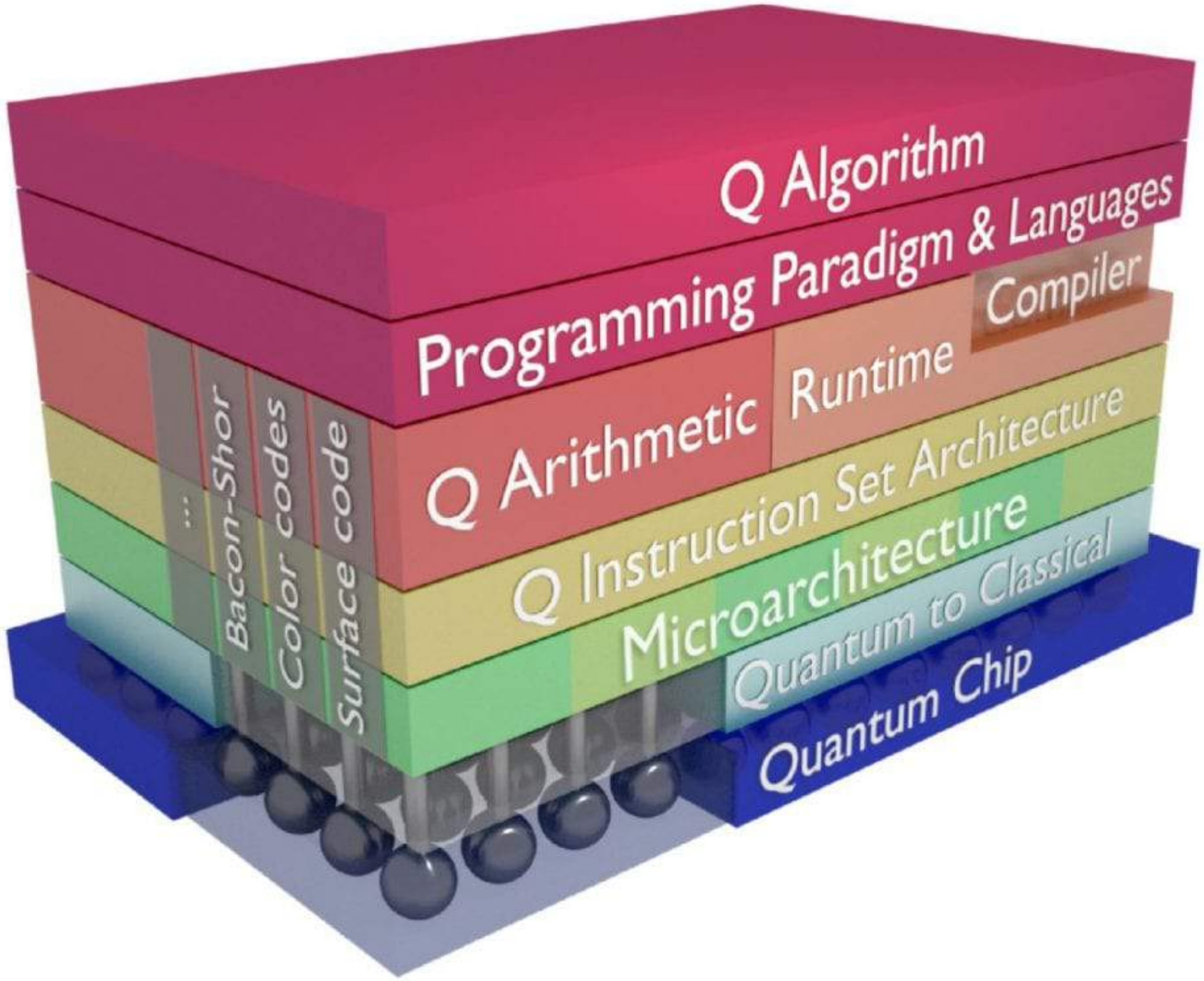
What are Quantum Technologies ?

Do Quantum Technologies have a future ?
How do you answer this “simple” question ???
- Quantum Technologies already exist !
- What are the ingredients to answer this question ?

Research Laboratories/Industries/start-ups !!



What is a Quantum Computer ...?

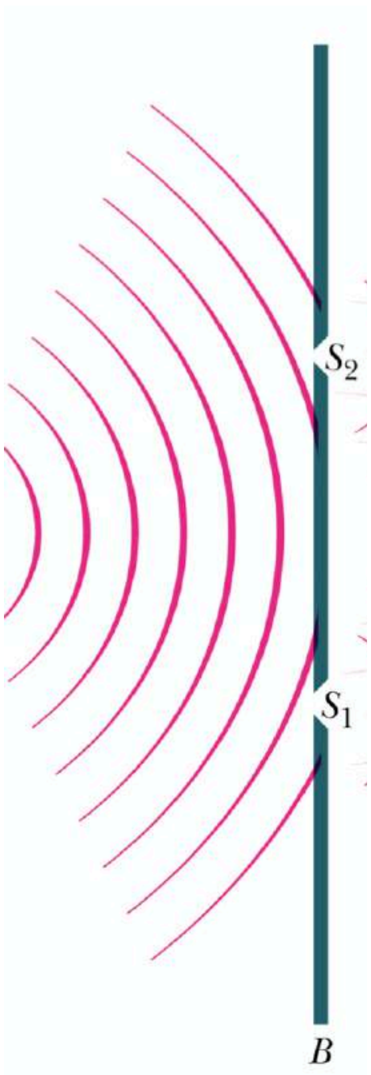


Introduction : concepts de base de la mécanique quantique

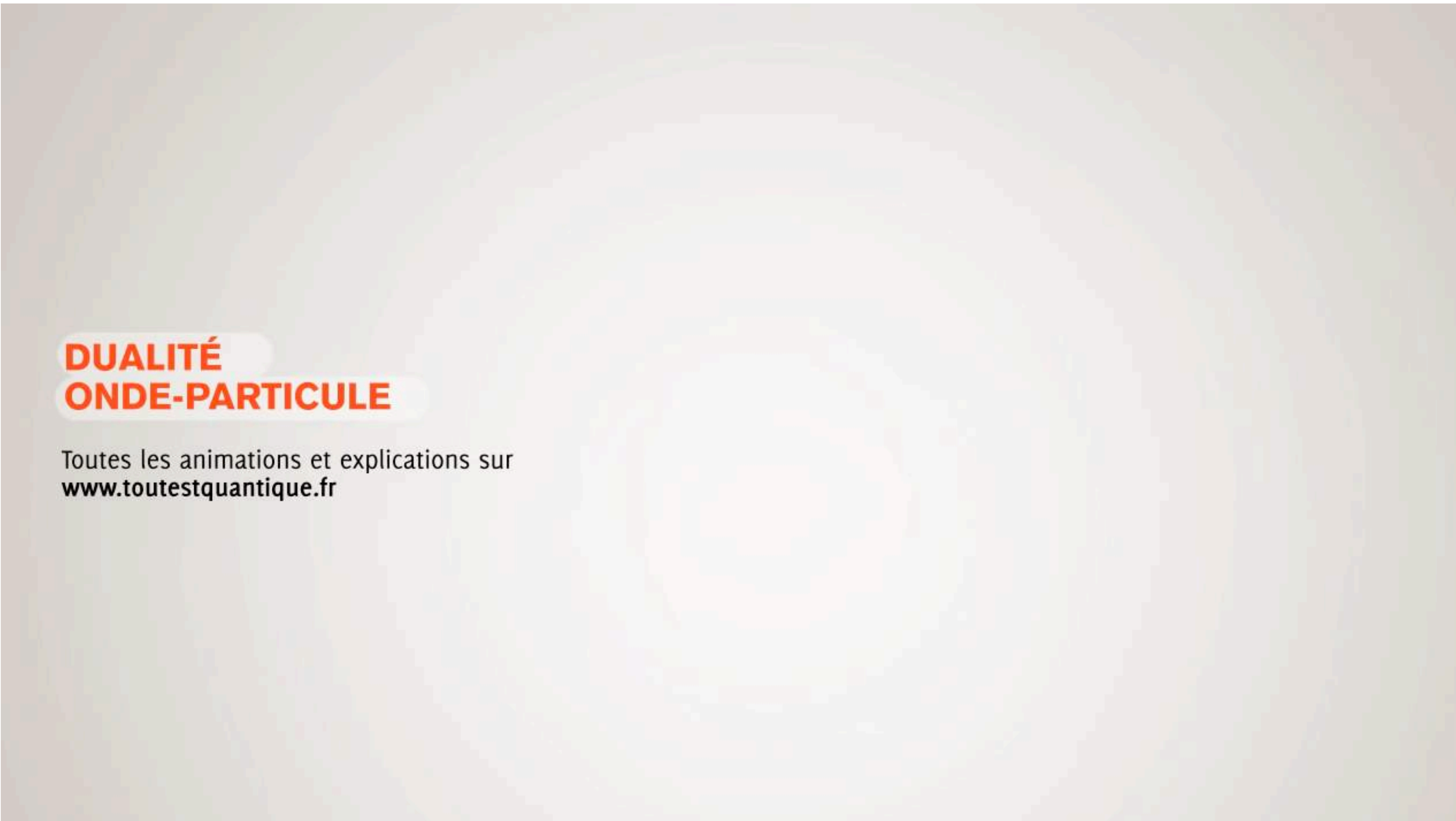
Très largement inspiré de « Suprématie Quantique » - Julien Bobroff
https://www.youtube.com/watch?v=CTu2uvTconE

- Dualité onde – corpuscule
- Quantification
- Intrication

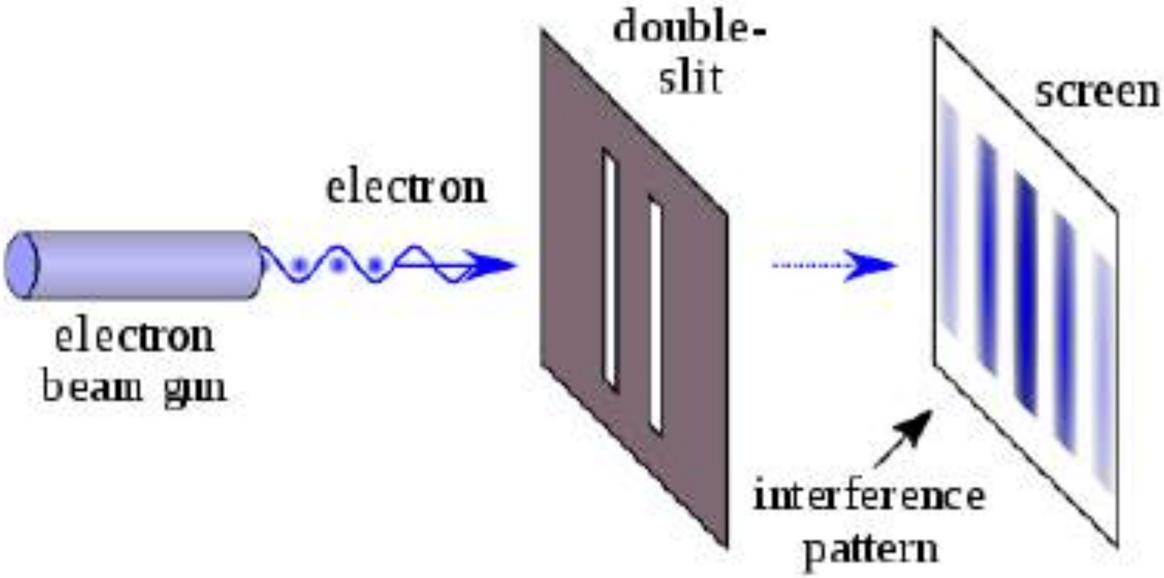
- Dualité onde – corpuscule

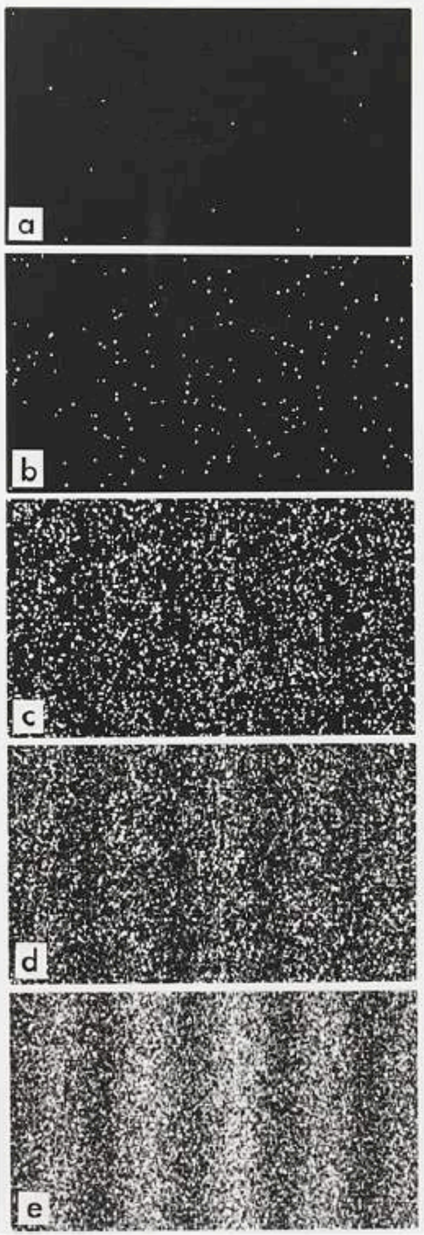


- Dualité onde – corpuscule



- Dualité onde – corpuscule

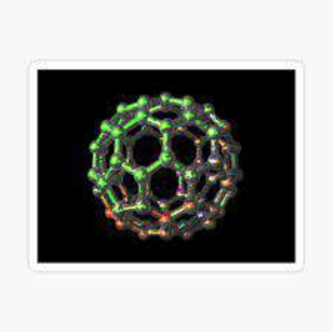




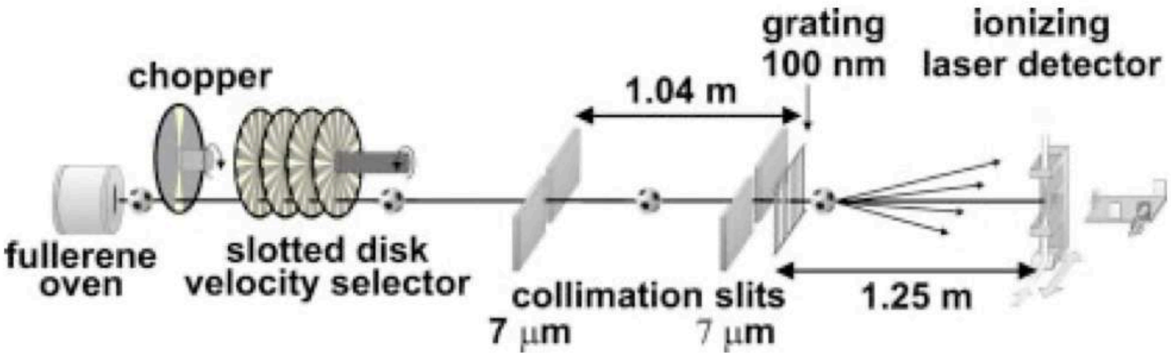
AMERICAN JOURNAL of PHYSICS

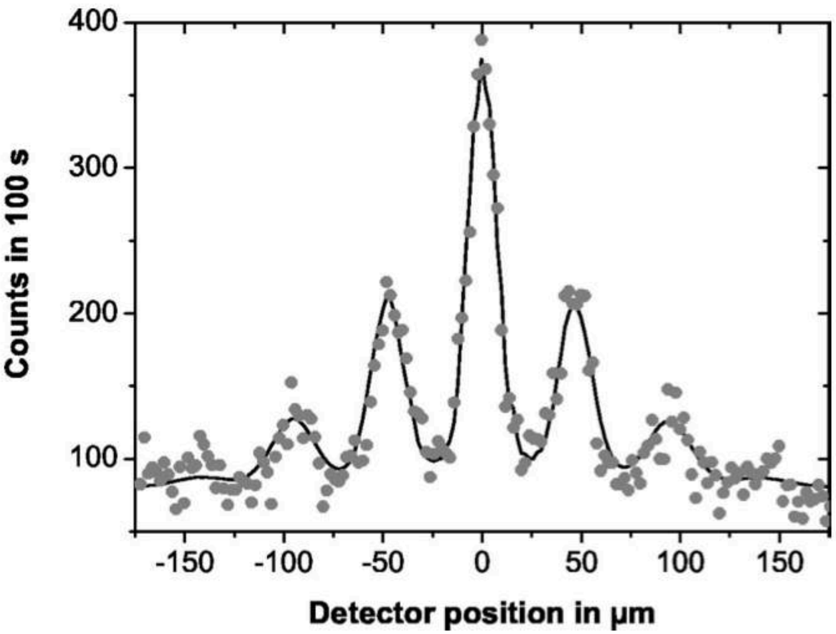
Quantum interference experiments with large molecules

Olaf Nairz, Markus Arndt, and Anton Zeilinger



Citation: Am. J. Phys. 71, 319 (2003); doi: 10.1119/1.1531580

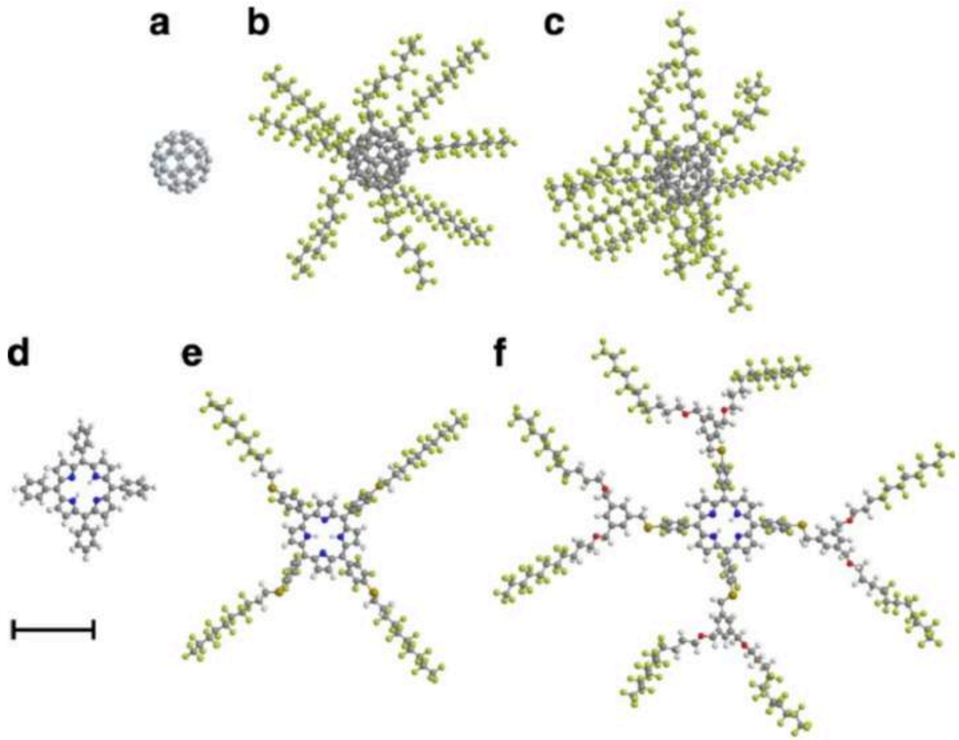


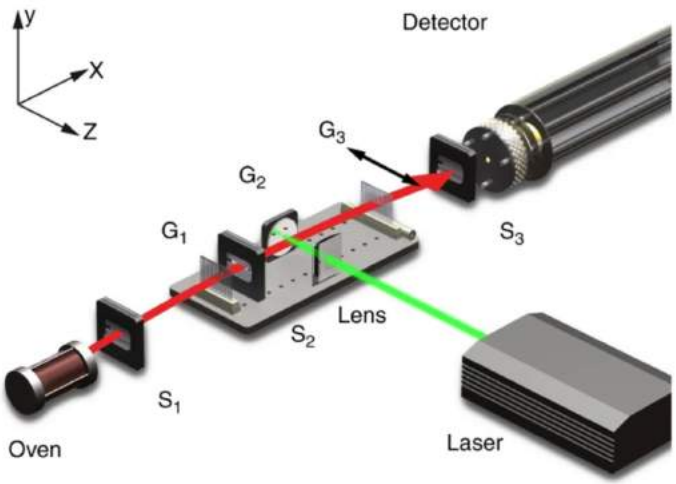


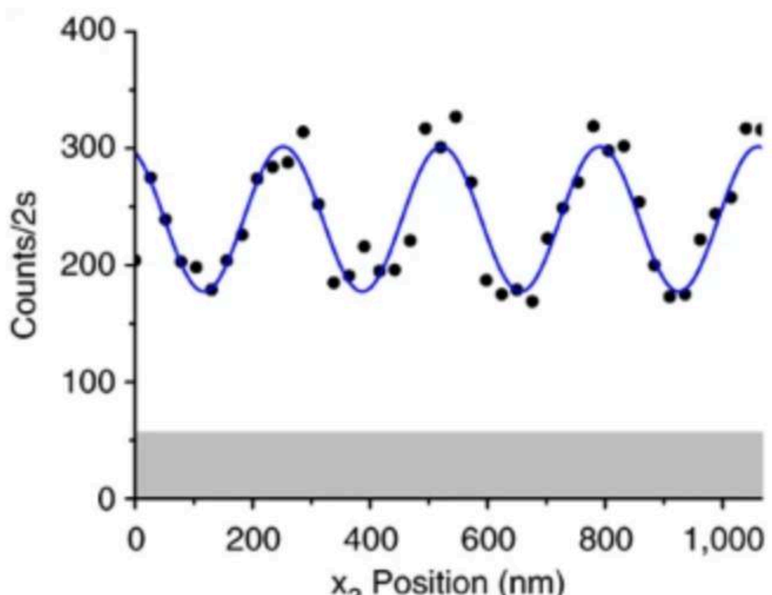
Quantum interference of large organic molecules

Stefan Gerlich, Sandra Eibenberger, Mathias Tomandl, Stefan Nimmrichter, Klaus Hornberger, Paul J. Fagan, Jens Tüxen, Marcel Mayor & Markus Arndt

Nature Communications **2**, Article number: 263 (2011) | Cite this article

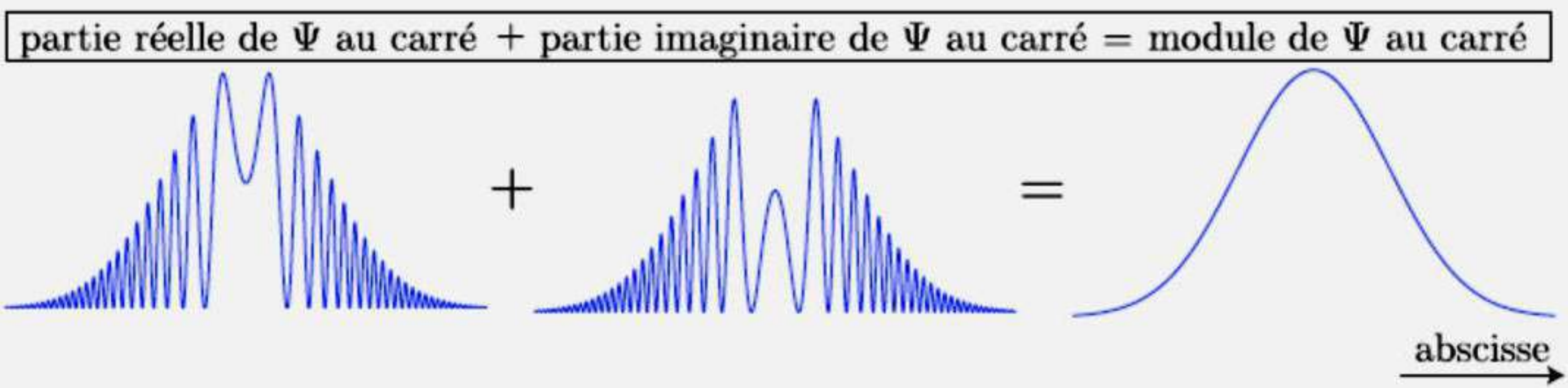




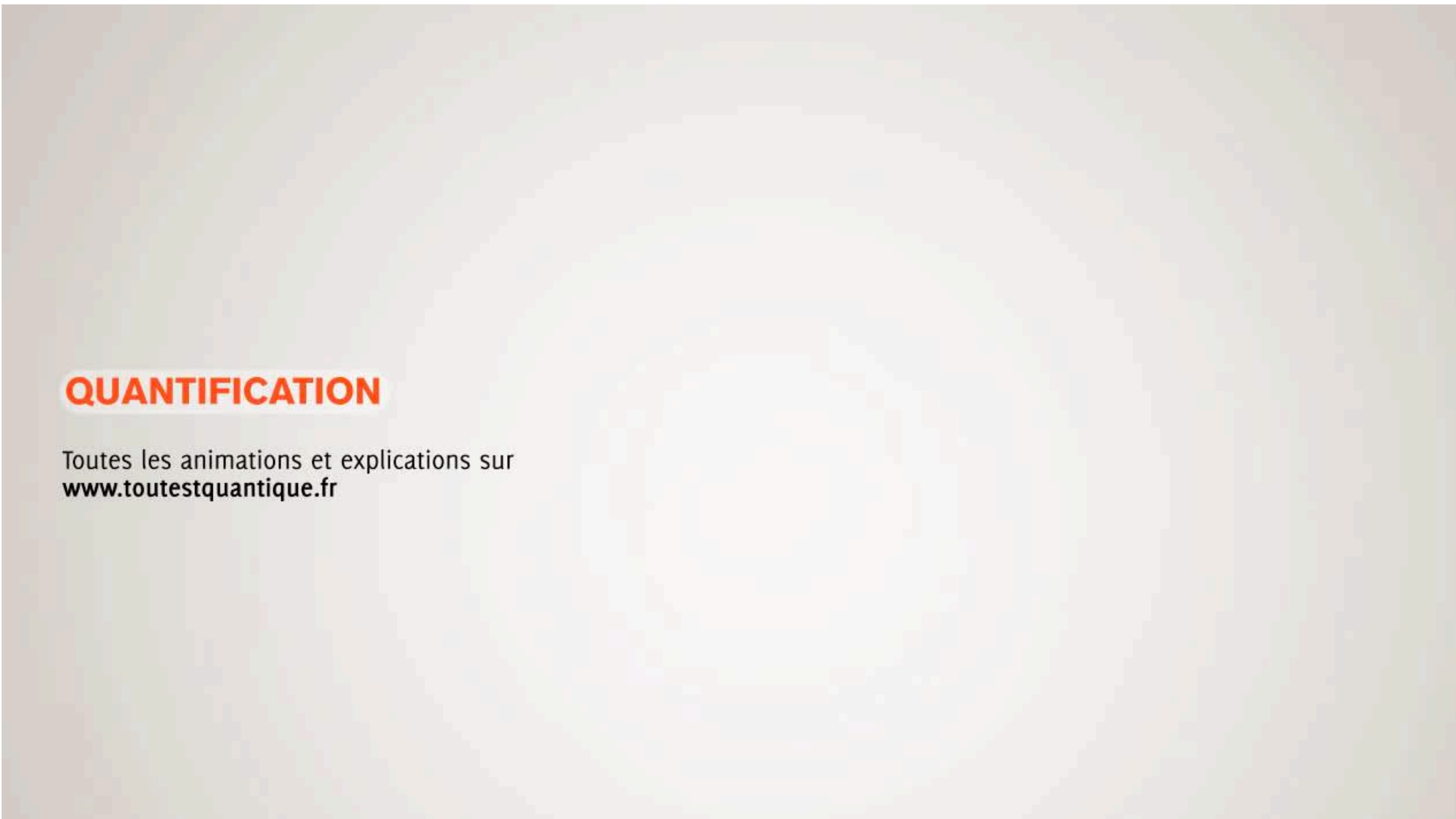


- Dualité onde – corpuscule

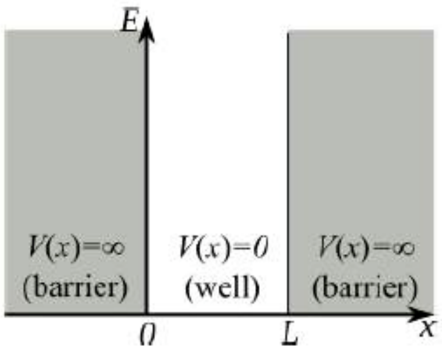
$$i\hbar\frac{\partial}{\partial t}\left|\Psi\right\rangle = \hat{H}\left|\Psi\right\rangle \qquad \psi(\vec{r},t)$$

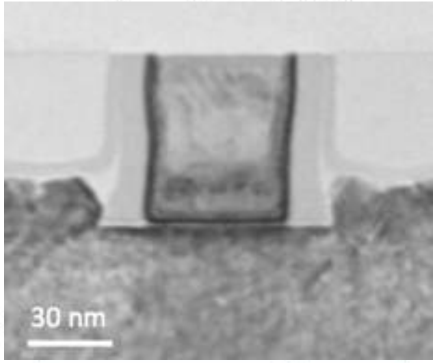


- Quantification

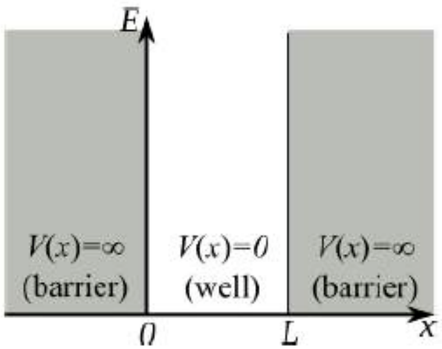


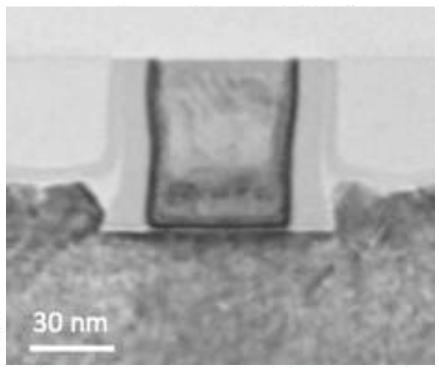
- Quantification





- Quantification

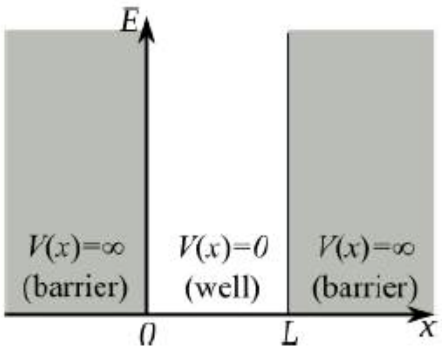


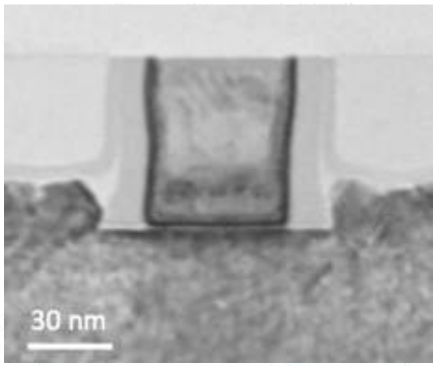


$$V(x) = \begin{cases} 0 & 0 < x < L \\ +\infty & x \leq 0\,;\ x \geq L \end{cases}$$

$$\begin{aligned} \int_0^L |\Phi_n(x)|^2 dx &= 1 \\ |B|^2 \int_0^L \sin^2(k_n.x) dx &= 1 \\ |B|^2 \tfrac{L}{2} &= 1 \\ |B| &= \sqrt{\tfrac{2}{L}} \end{aligned}$$

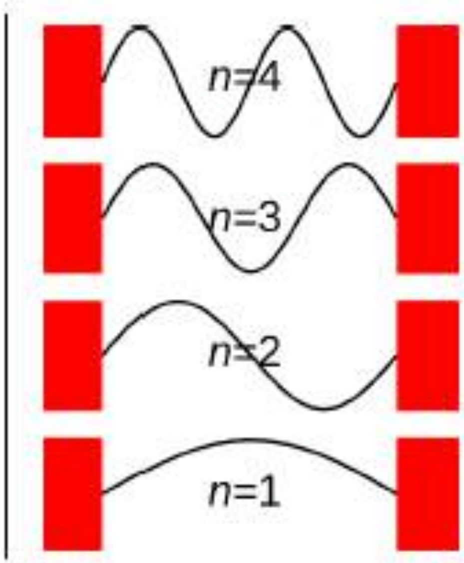
- Quantification





$$V(x) = \begin{cases} 0 & 0 < x < L \\ +\infty & x \leq 0\,;\ x \geq L \end{cases}$$

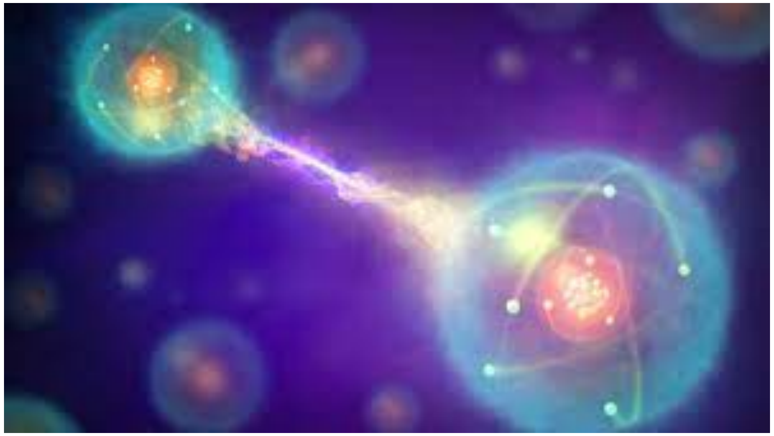
$$\begin{aligned} \int_0^L |\Phi_n(x)|^2 dx &= 1 \\ |B|^2 \int_0^L \sin^2(k_n.x)dx &= 1 \\ |B|^2 \tfrac{L}{2} &= 1 \\ |B| &= \sqrt{\tfrac{2}{L}} \end{aligned}$$



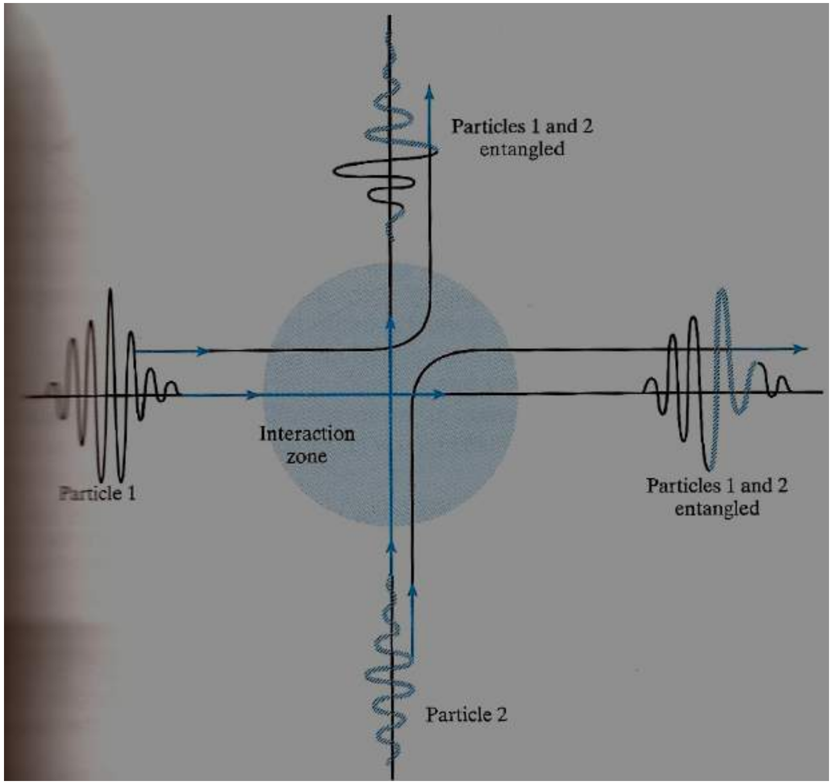
$$E_n = \frac{(n\pi\hbar)^2}{2mL^2}$$

$$\Phi(x) = \sqrt{\frac{2}{L}} \sin\left(n\frac{\pi}{L}x\right)$$

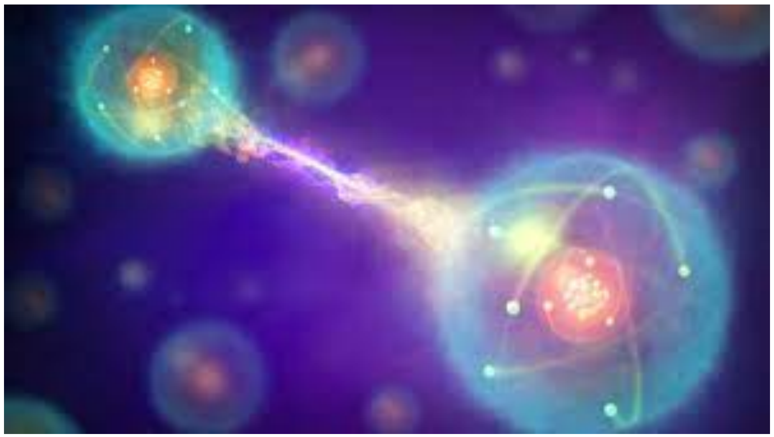
- Intrication



$c_1|00> + c_2|01> + c_3|10> + c_4|11>$



- Intrication



$$c_1|00\rangle + c_2|01\rangle + c_3|10\rangle + c_4|11\rangle$$

Quantum bits

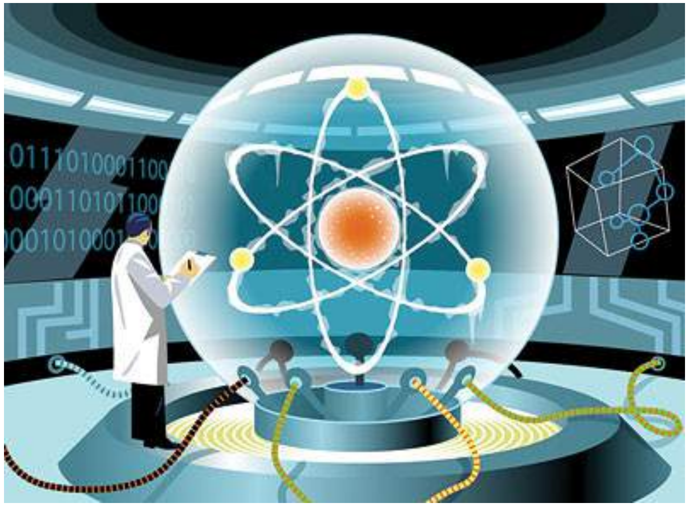
Classical computation

Bit

1

0

Quantum computation

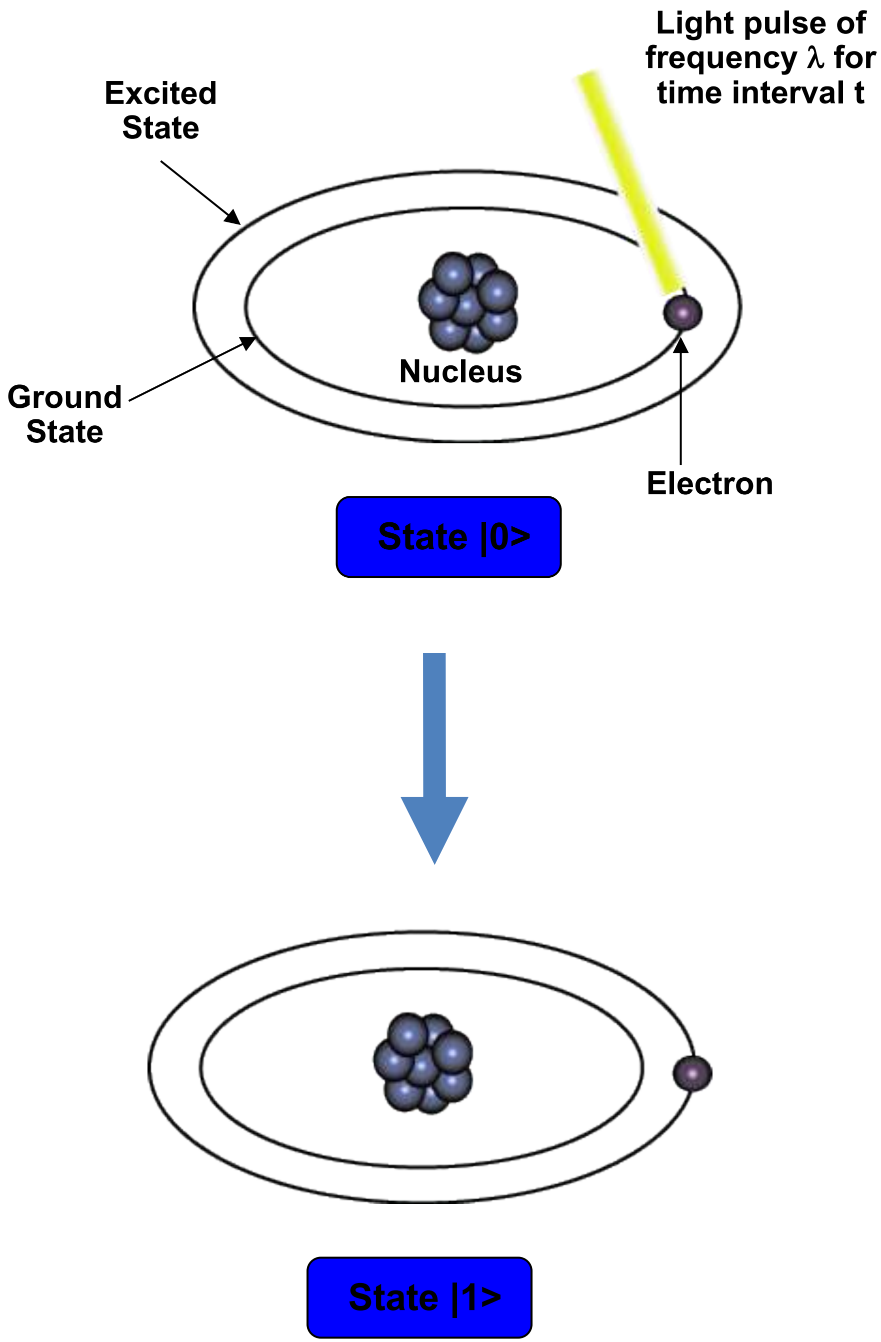


Qubit

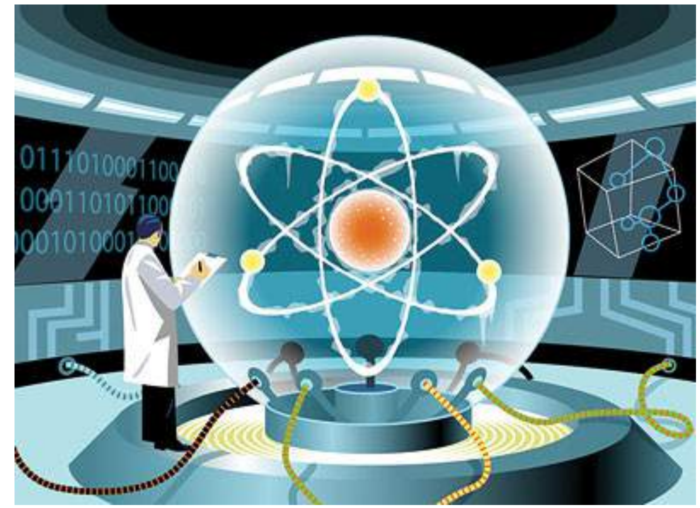
$|1\rangle$

$|0\rangle$

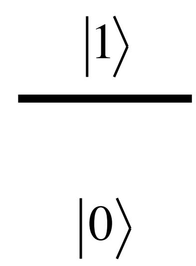
Quantum bits



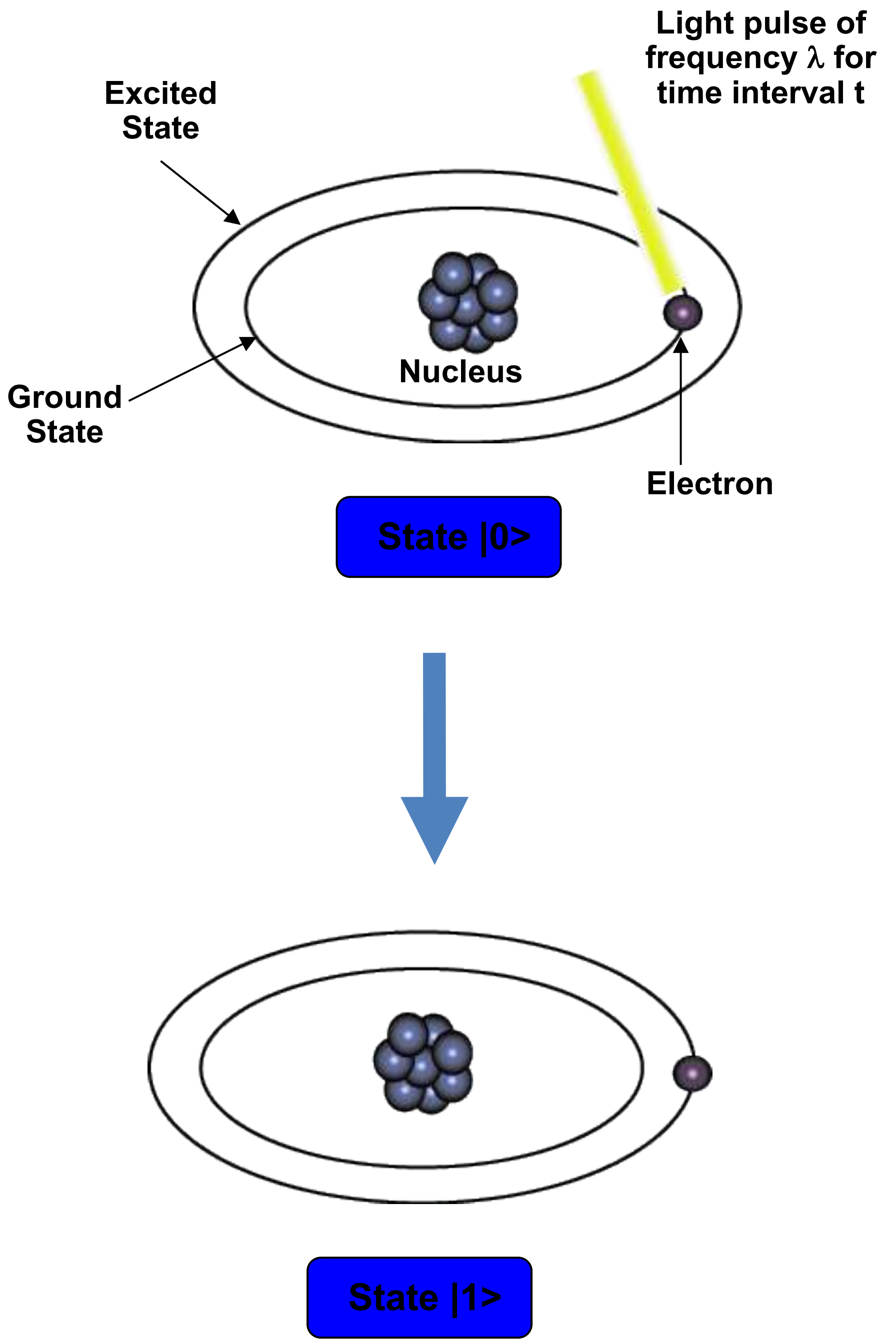
Quantum computation



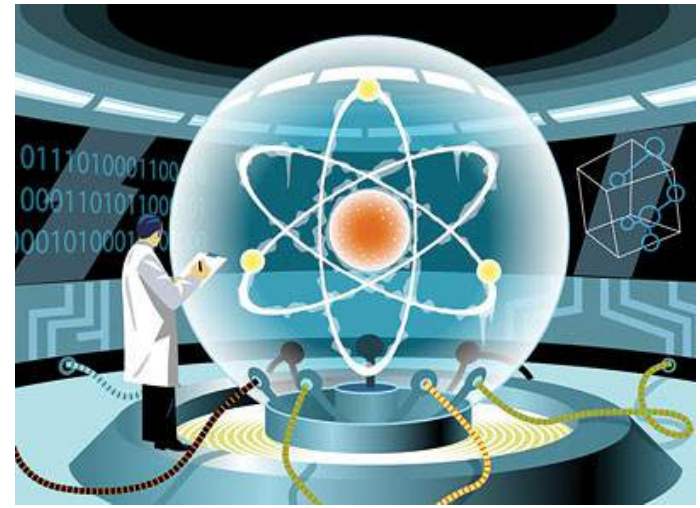
Qubit



Quantum bits



Quantum computation



Qubit

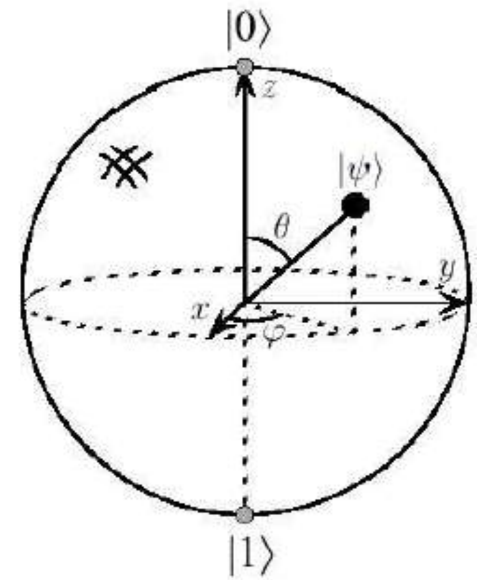
$$|1\rangle$$

$$|0\rangle$$

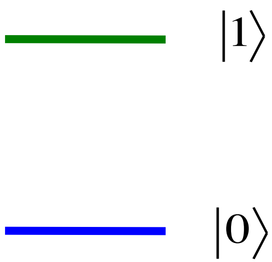
$$|\psi\rangle = \alpha_0 |0\rangle + \beta_1 |1\rangle$$

Qubit and Bloch Sphere

Bloch sphere [from Nielson&Chuang]



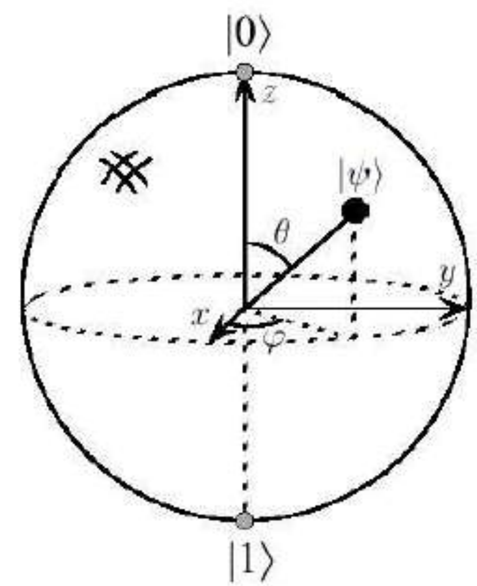
<u>Bloch sphere :</u> We can write our state with phase factors



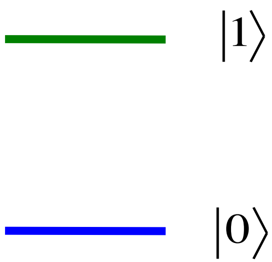
$$|\Psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$

Qubit and Bloch Sphere

Bloch sphere [from Nielson&Chuang]

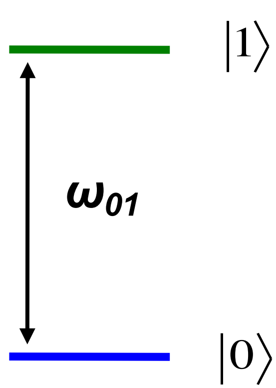


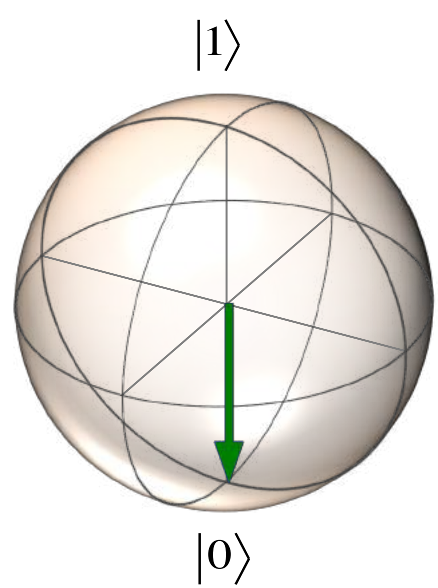
<u>Bloch sphere :</u> We can write our state with phase factors



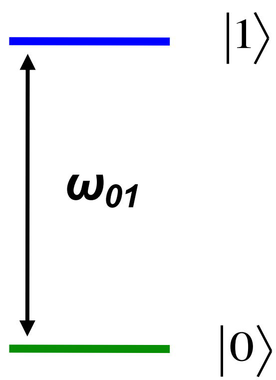
$$|\Psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$

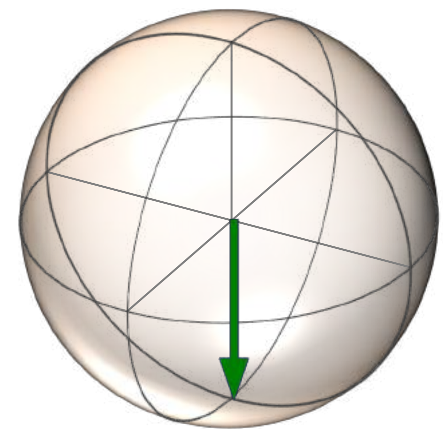
A 2-level system + an RF oscillating field at angular frequency ω matching the resonance frequency ω_{01}





2-level system = qubit

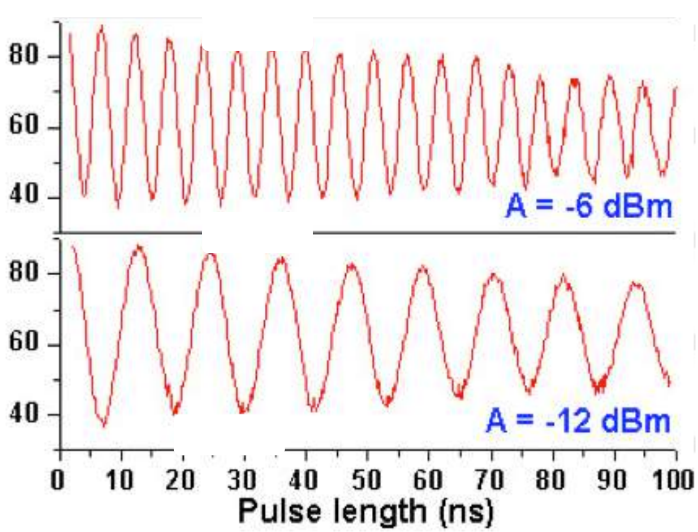




$$P_e(t) = \frac{\Omega^2}{\Omega^2 + \hbar^2 \Delta^2/4} \sin^2\left[t\sqrt{\Omega^2/\hbar^2 + \Delta^2/4}\right]$$

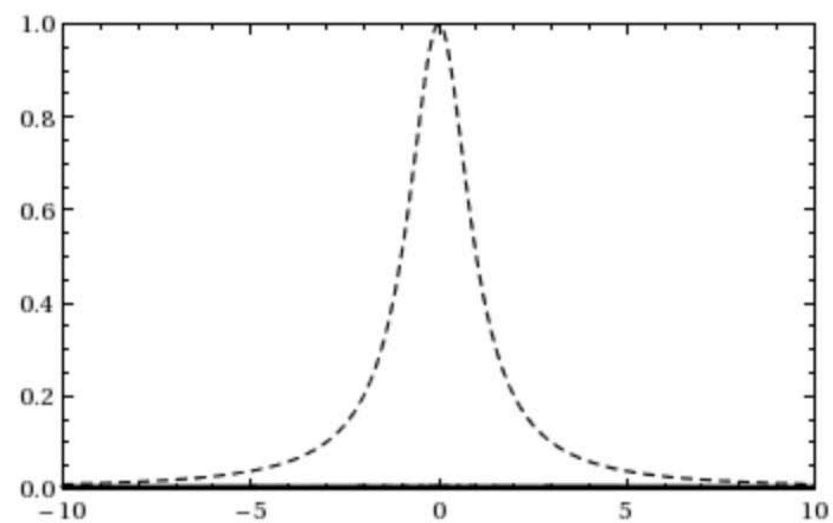
$$\Delta = \omega - \omega_{01}$$

$P_e(t)$



Chiorescu et al., *Science* 299 (2003)

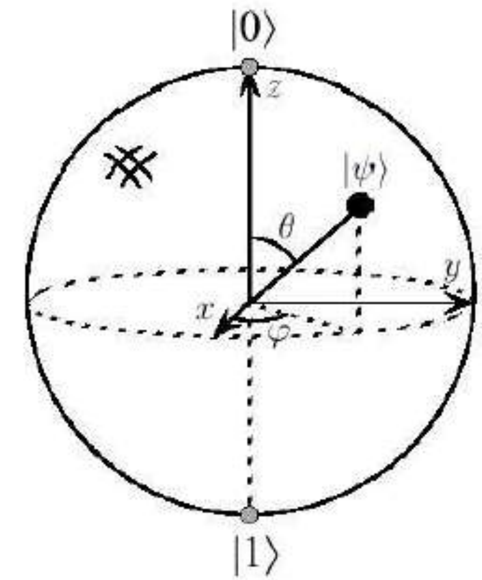
P_e



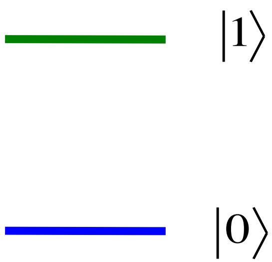
$\Delta = \omega - \omega_{01}$

2-level system = qubit

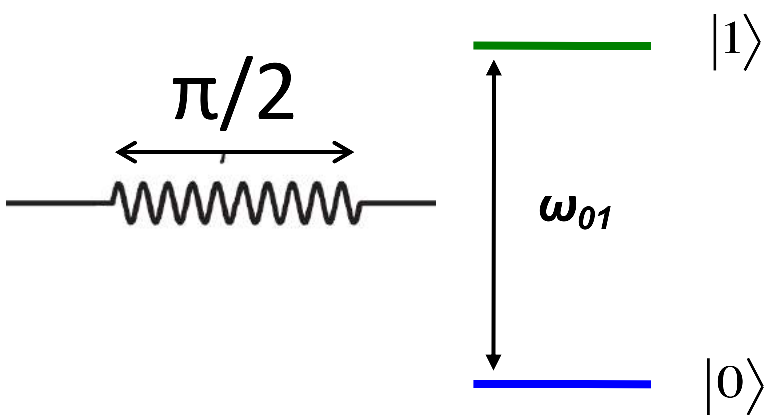
Bloch sphere [from Nielson&Chuang]

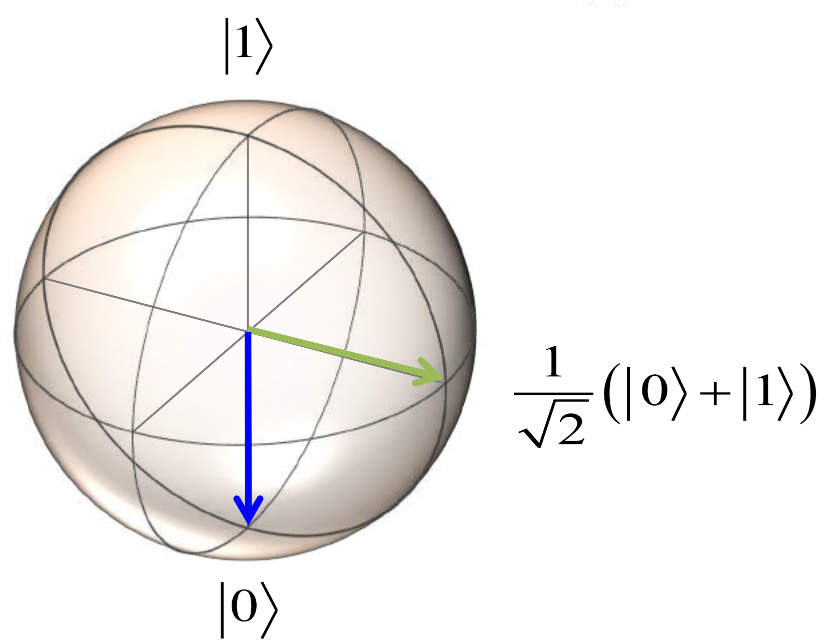


<u>Bloch sphere:</u> We can write our state with phase factors



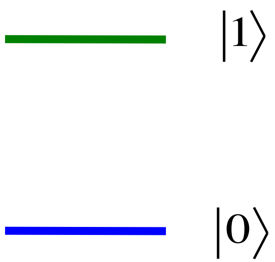
$$|\Psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$



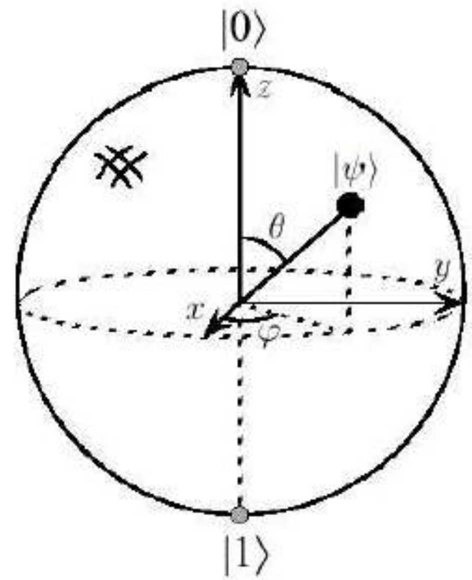


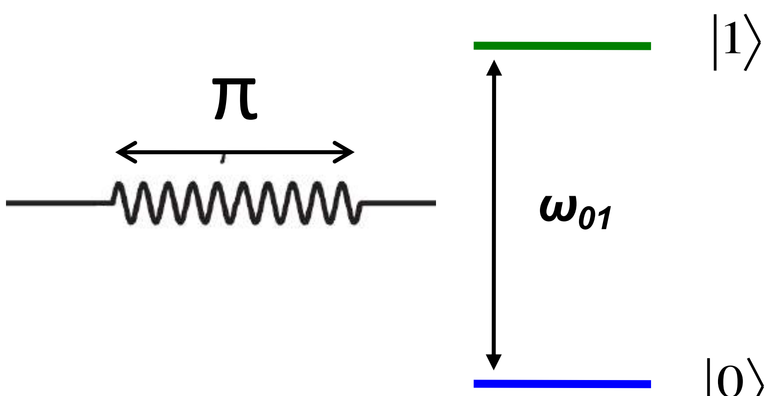
Bloch sphere [from Nielson&Chuang]

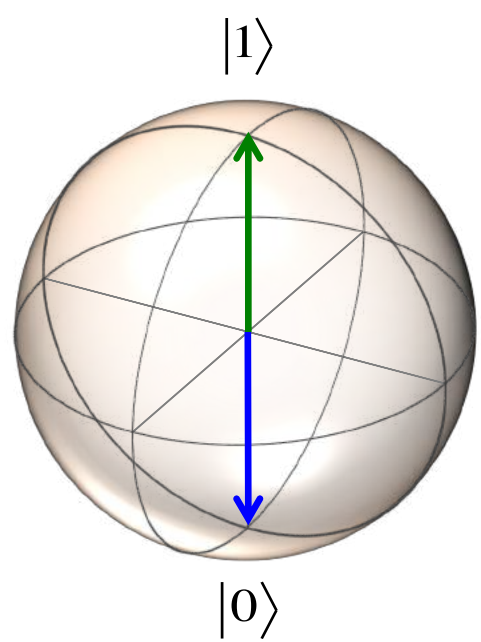
Bloch sphere: We can write our state with phase factors



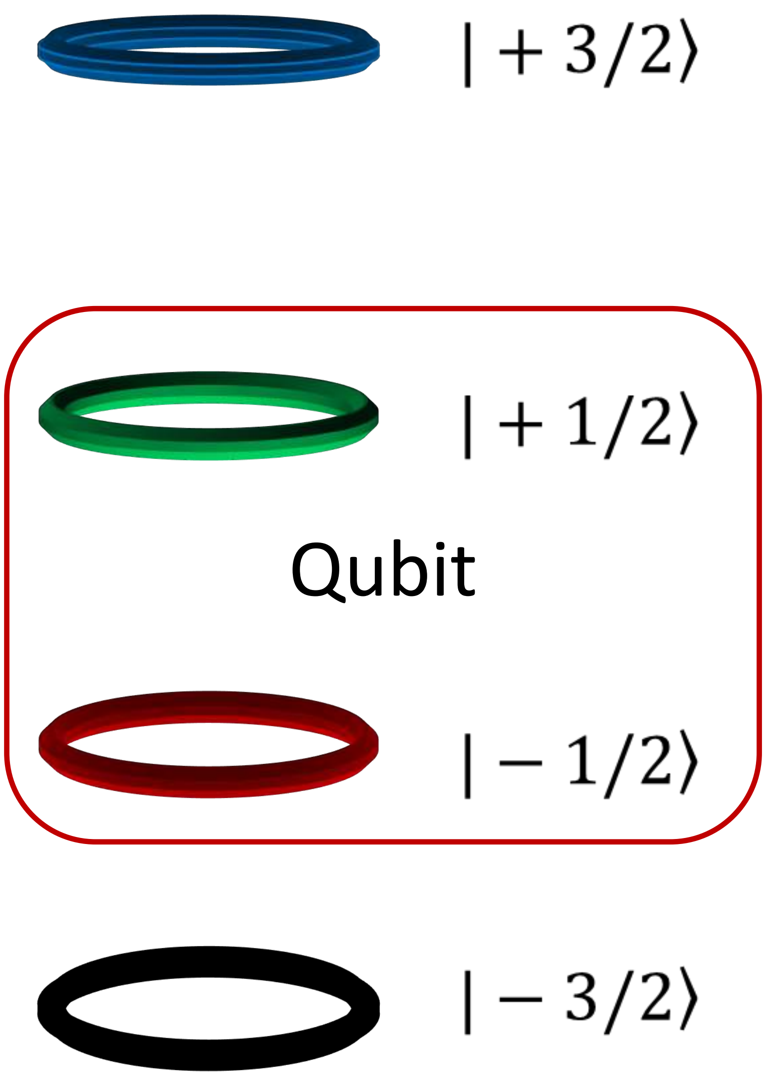
$$|\Psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$







Single Nuclear Spin Manipulation



Single Nuclear Spin Manipulation

Energy : E

Population : α β

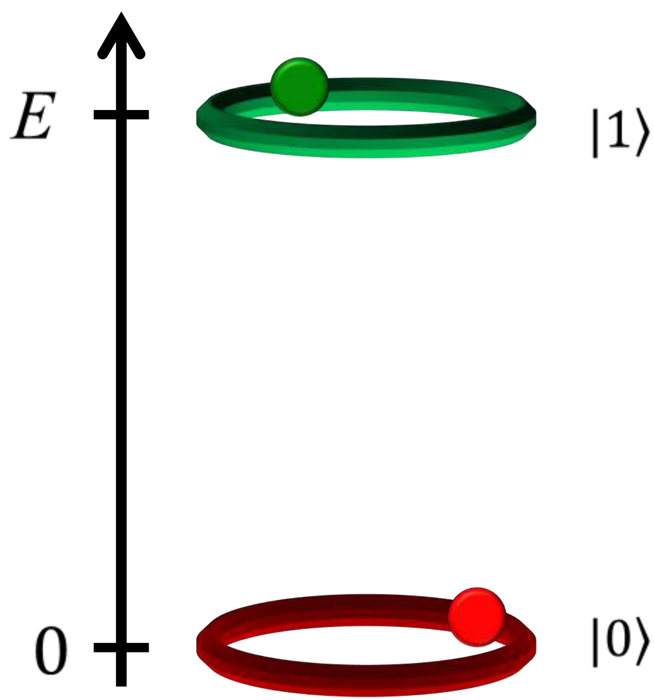
Phase : ρ

Amplitude : A

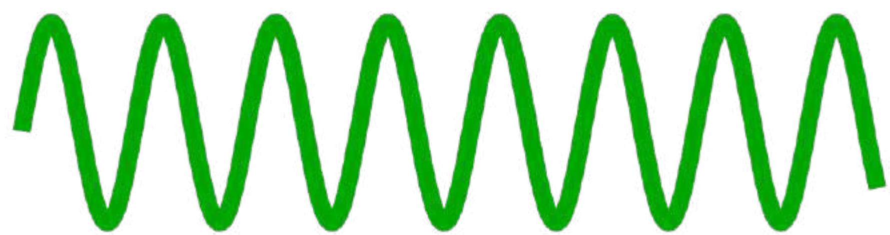
Frequency : f

Length : τ

Phase : Φ



$$|\Psi\rangle = \alpha|0\rangle + \beta e^{i\rho}\,|1\rangle$$



$$P = A \sin\,(2\,\pi\, f\, \tau + \Phi)$$

Single Nuclear Spin Manipulation

Energy : E

Population : $\alpha \;\; \beta$

Phase : ρ

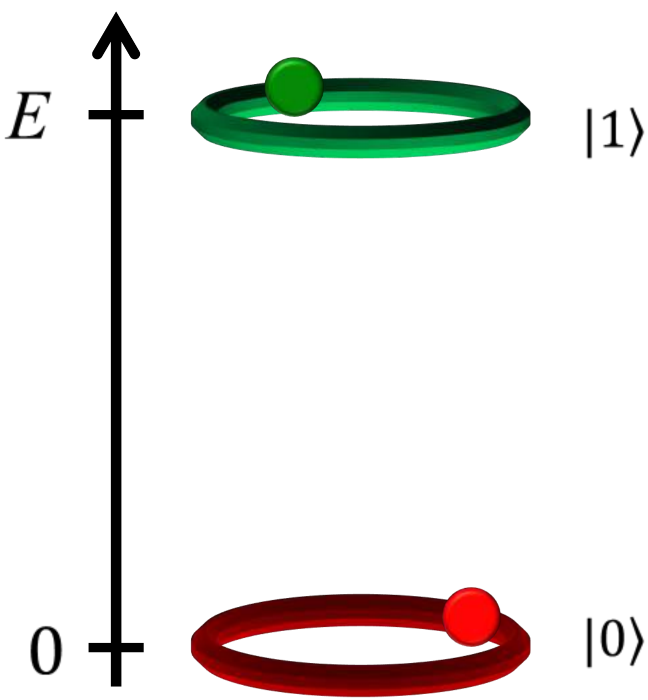
Coupling : g

Amplitude : A

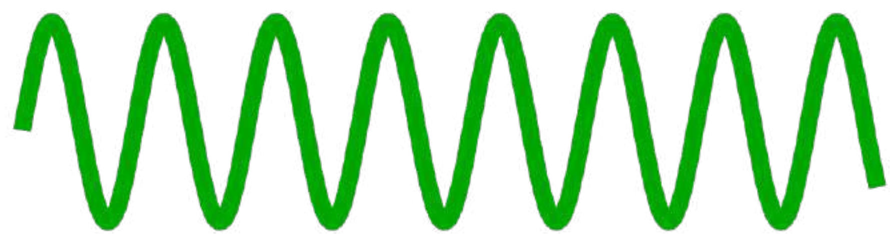
Frequency : f

Length : τ

Phase : Φ



$$|\Psi\rangle = \alpha|0\rangle + \beta e^{i\rho}\,|1\rangle$$



$$P = A \sin\,(2\,\pi\, f\, \tau + \Phi)$$

Single Nuclear Spin Manipulation

Energy : E

Population : $\alpha \;\; \beta$

Phase : ρ

Coupling : g

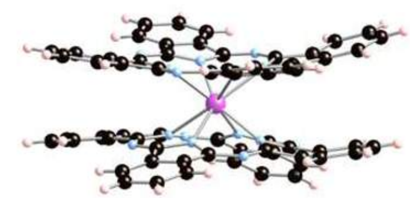
Amplitude : A

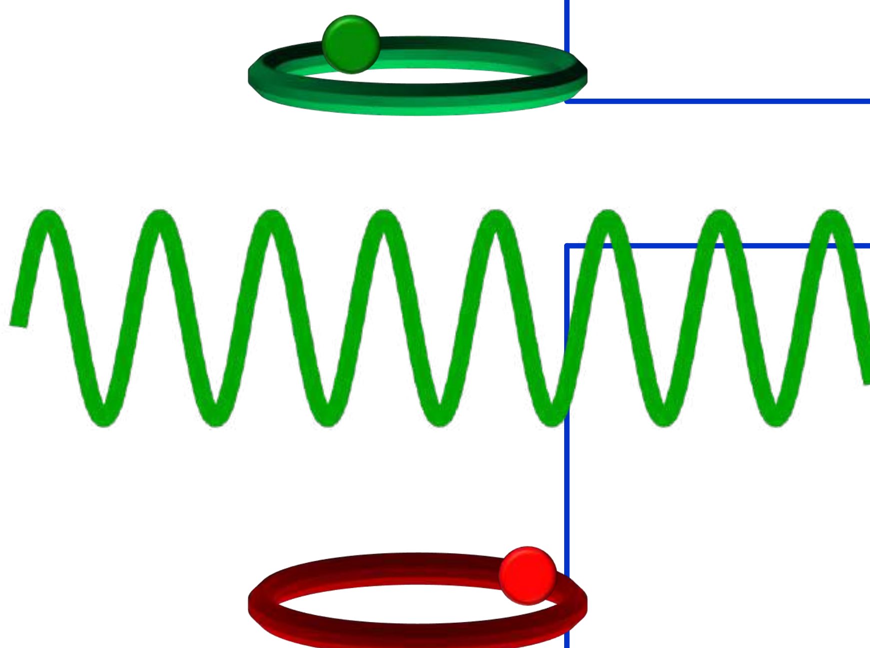
Frequency : f

Length : τ

Phase : Φ

What we measure

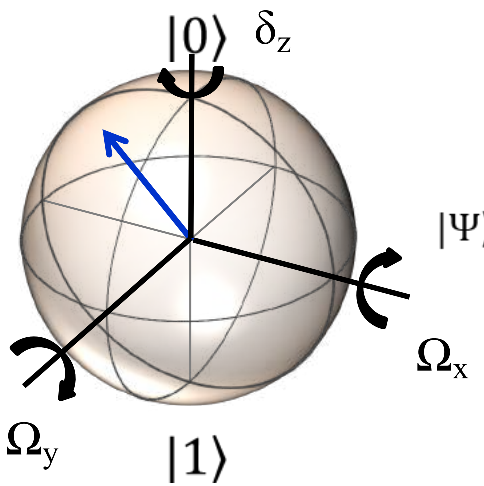




What we tune

Single Nuclear Spin Manipulation

State representation: Bloch Sphere



$$|\Psi\rangle = \cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,e^{i\rho}\,|1\rangle$$

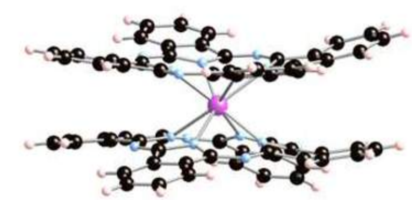
Energy : E

Population : α β

Phase : ρ

Coupling : g

What we measure



State dynamic: Hamiltonian

$$\Omega_x = g\,A\,\cos(\Phi)\,\mu_N/h$$

$$\Omega_y = g\,A\,\sin(\Phi)\,\mu_N/h$$

$$\delta_z = f - E/h$$

$$\mathcal{H} = \frac{h}{2}\begin{pmatrix} \delta_z & \Omega_x - i\Omega_y \\ \Omega_x + i\Omega_y & -\delta_z \end{pmatrix}$$

$$|\Psi(\tau)\rangle = e^{-i\mathcal{H}\tau/h}\,|\Psi(0)\rangle$$

Amplitude : A

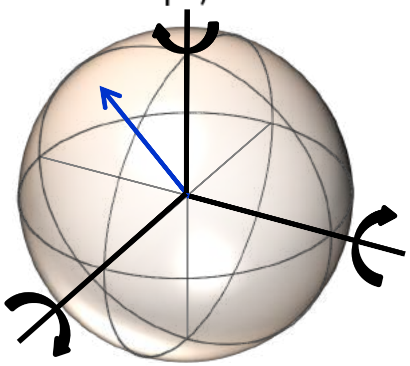
Frequency : f

Length : τ

Phase : Φ

What we tune

State representation: Bloch Sphere



= 7 MHz

= 0 MHz

= 0 MHz

$|\Psi\rangle = \cos(\theta/2)\,|0\rangle + \sin(\theta/2)\,e^{i\rho}\,|1\rangle$

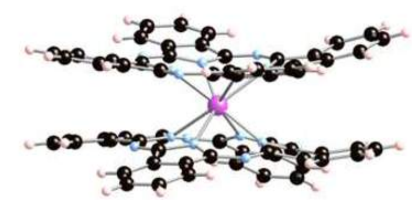
Energy : E

Population : α β

Phase : ρ

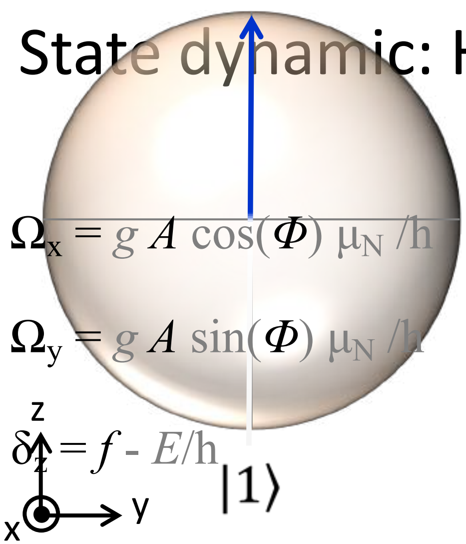
Coupling : g

What we measure



Length dependence

State dynamic: Hamiltonian



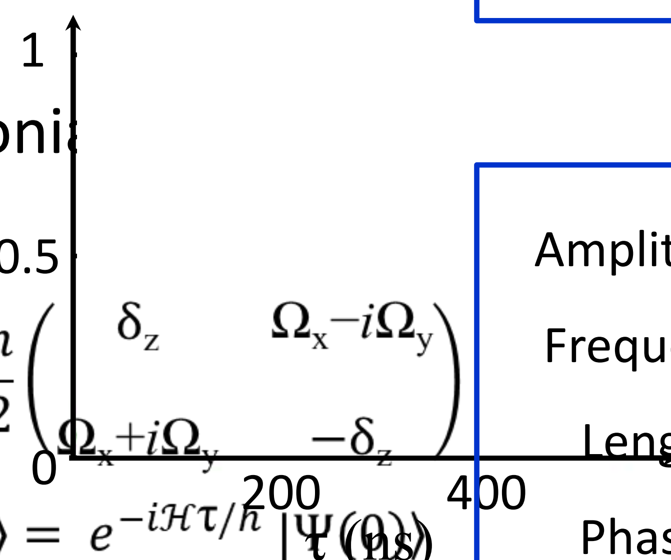
$\Omega_x = g\,A\cos(\Phi)\,\mu_N/h$

$\Omega_y = g\,A\sin(\Phi)\,\mu_N/h$

$\delta_z = f - E/h$

$$\mathcal{H} = \frac{h}{2}\begin{pmatrix} \delta_z & \Omega_x - i\Omega_y \\ \Omega_x + i\Omega_y & -\delta_z \end{pmatrix}$$

$$|\Psi(\tau)\rangle = e^{-i\mathcal{H}\tau/\hbar}\,|\Psi(0)\rangle$$



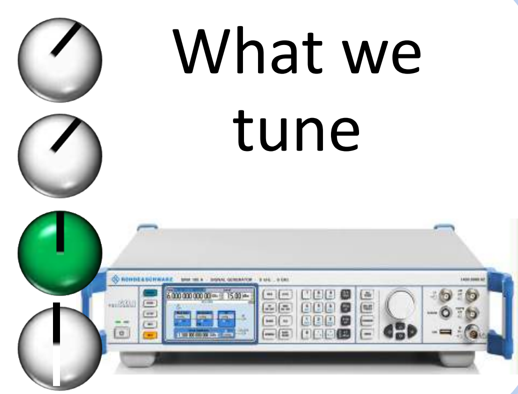
Amplitude : A

Frequency : f

Length : τ

Phase : Φ

What we tune



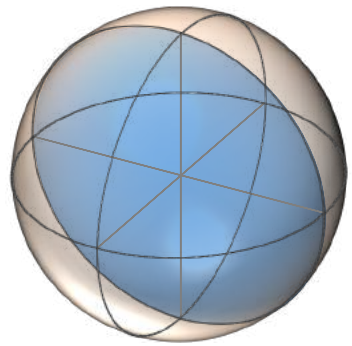
Single Nuclear Spin Manipulation

$\Omega_x = g\,A\cos(\Phi)\,\mu_N/h \quad = 4\ \text{MHz}$

$\Omega_y = g\,A\sin(\Phi)\,\mu_N/h \quad = 0\ \text{MHz}$

$\delta_z = f - E/h \quad = 0\ \text{MHz}$

$$|\Psi(\tau)\rangle = e^{-i\mathcal{H}\tau/h}\,|\Psi(0)\rangle$$

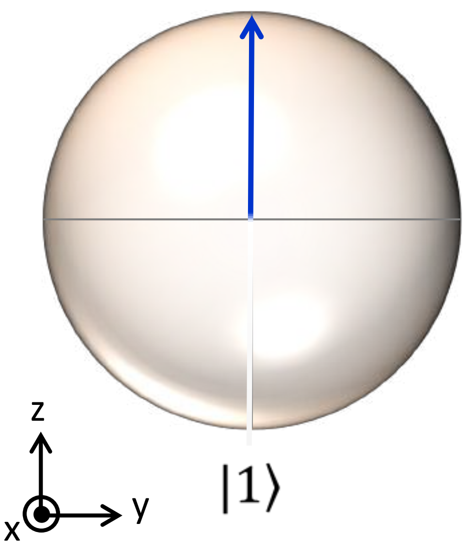


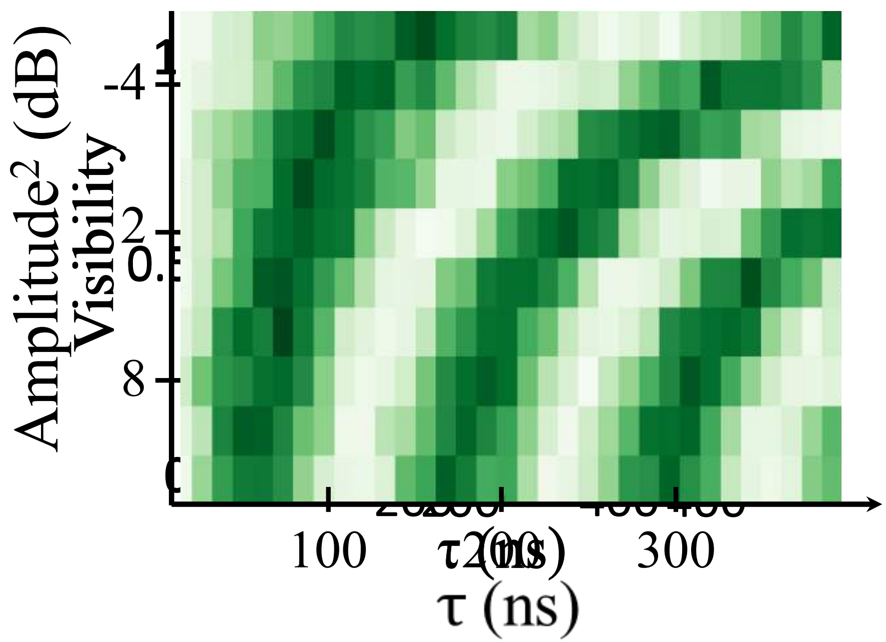
Energy : E

Population : α β

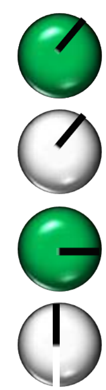
Phase : ρ

Coupling : g





Amplitude Length dependence



Amplitude : A

Frequency : f

Length : τ

Phase : Φ

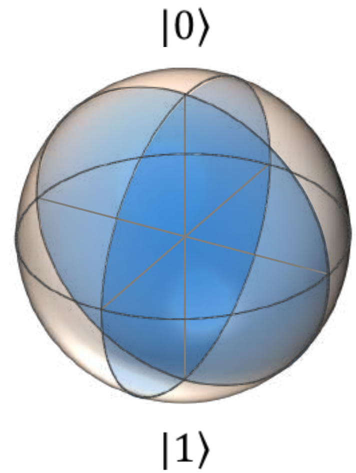
Single Nuclear Spin Manipulation

$\Omega_x = g\,A\cos(\Phi)\,\mu_N/h \quad = 8\ \text{MHz}$

$\Omega_y = g\,A\sin(\Phi)\,\mu_N/h \quad = 0\ \text{MHz}$

$\delta_z = f - E/h \quad = 0\ \text{MHz}$

$$|\Psi(\tau)\rangle = e^{-i\mathcal{H}\tau/h}\,|\Psi(0)\rangle$$

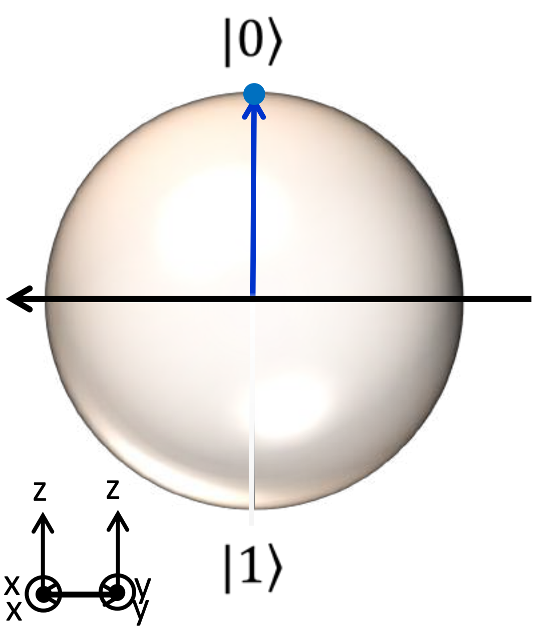


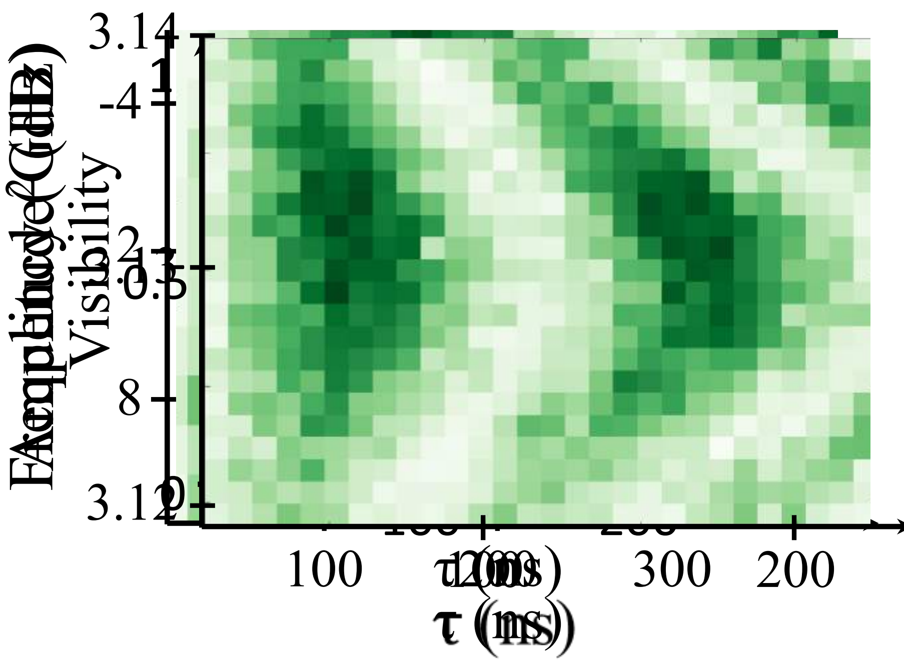
Energy : E

Population : α β

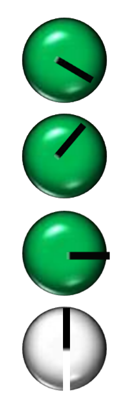
Phase : ρ

Coupling : g





Amplitude dependence



Amplitude : A

Frequency : f

Length : τ

Phase : Φ

Single Nuclear Spin Manipulation

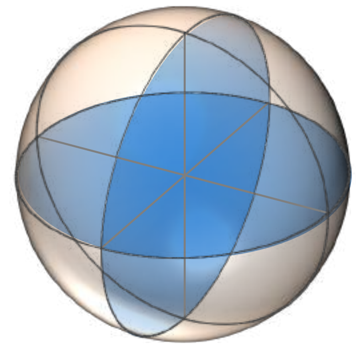
$\Omega_x = g\,A\cos(\Phi)\,\mu_N/h$ = 5 MHz

$\Omega_y = g\,A\sin(\Phi)\,\mu_N/h$ = 0 MHz

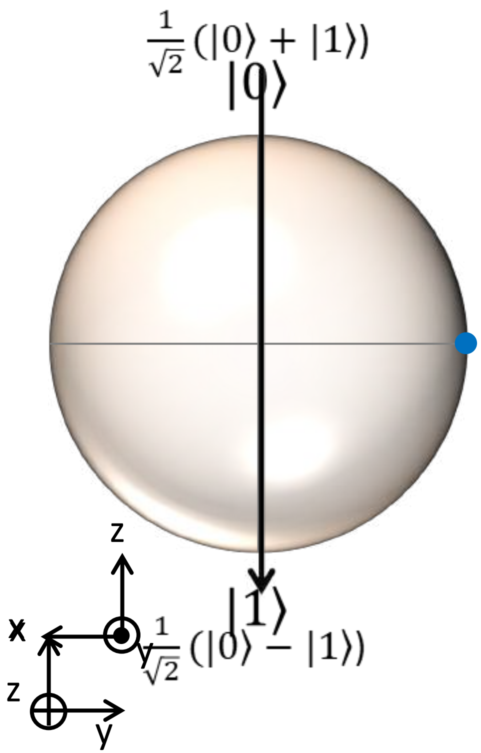
$\delta_z = f - E/h$ = 0 MHz

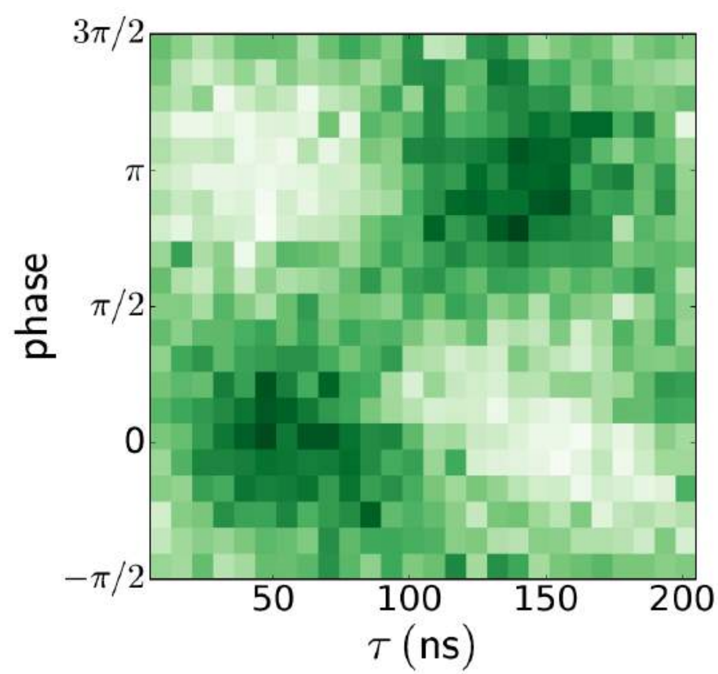
$$|\Psi(\tau)\rangle = e^{-i\mathcal{H}\tau/h}\,|\Psi(0)\rangle$$

$|0\rangle$



$|1\rangle$





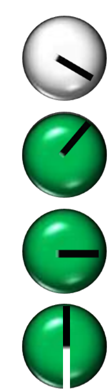
Energy : E

Population : α β

Phase : ρ

Coupling : g

Frequency / Phase dependence



Amplitude : A

Frequency : f

Length : τ

Phase : Φ

Single Nuclear Spin Manipulation

$|+3/2\rangle$

$T_1 = 34$ s

Hahn echo $T_2 = 2.6$ ms
Ramsey $T_2 = 330$ µs

$|+1/2\rangle$

$T_1 = 18$ s

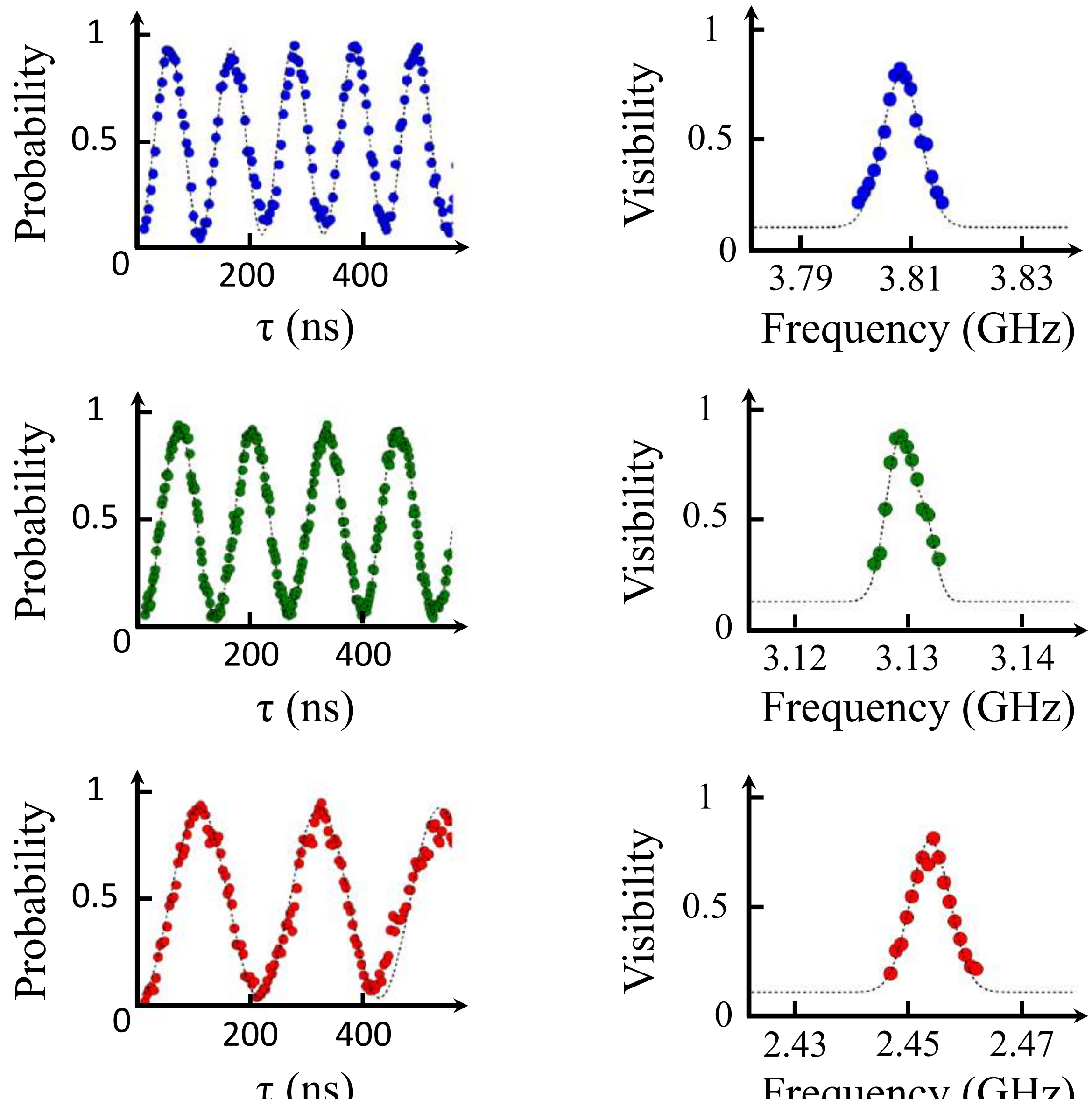
Hahn echo $T_2 = 1.6$ ms
Ramsey $T_2 = 330$ µs

$|-1/2\rangle$

$T_1 = 34$ s

Hahn echo $T_2 = 2.4$ ms
Ramsey $T_2 = 250$ µs

$|-3/2\rangle$



Operating Quantum States in Single Magnetic Molecules : Implementation of Grover's algorithm.
C. Godfrin et al. *Phys. Rev. Lett.* **119**, 187702 (2017).
Electrically driven nuclear spin resonance in single-molecule magnets
S. Thiele et al. *Science* **344**, 1135 (2014).

Entanglement

Entanglement is the ability of quantum systems to exhibit correlations between states within a superposition.

Imagine two qubits, each in the state |0> + |1> (a superposition of the 0 and 1.) We can entangle the two qubits such that the measurement of one qubit is always correlated to the measurement of the other qubit.

Multiple qubits can be written as products of states of individual q-bits:

$(c_1|0> + c_2|1>)\ (c_3|0> + c_4|1>)\ldots(c_n|0> + c_{n+1}|1>)$

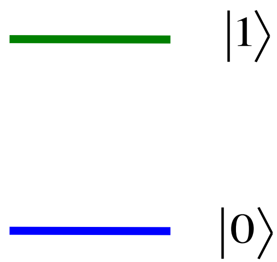
2 Entangled qubits :

$c_1|00> + c_2|01> + c_3|10> + c_4|11>$

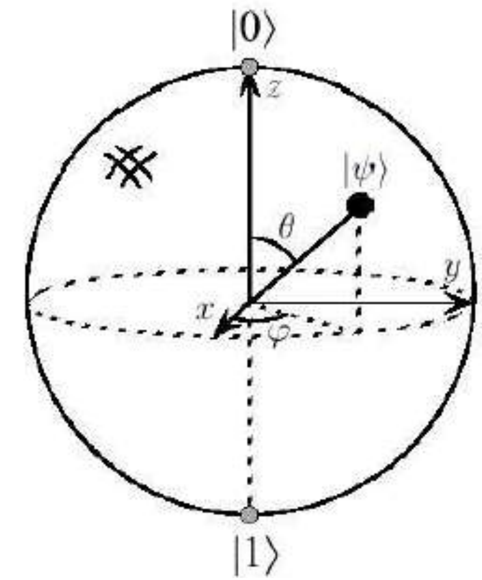
Quantum parallelism

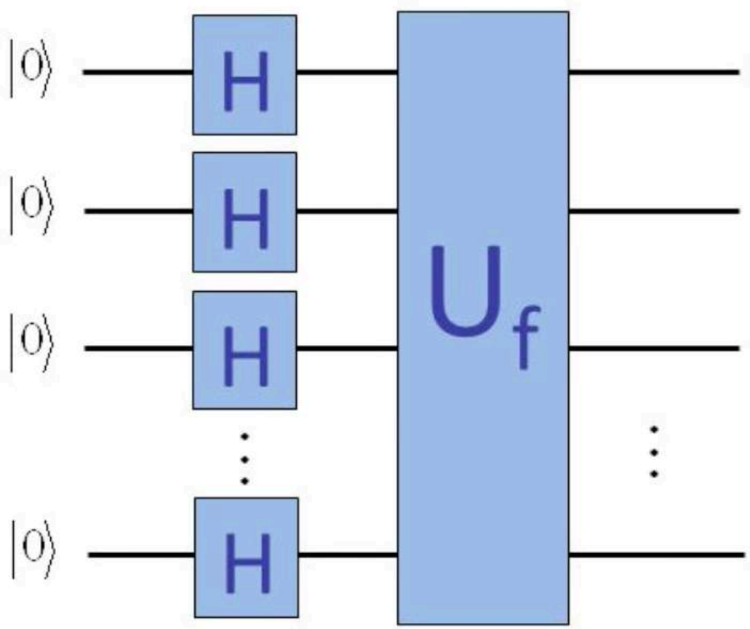
Bloch sphere [from Nielson&Chuang]

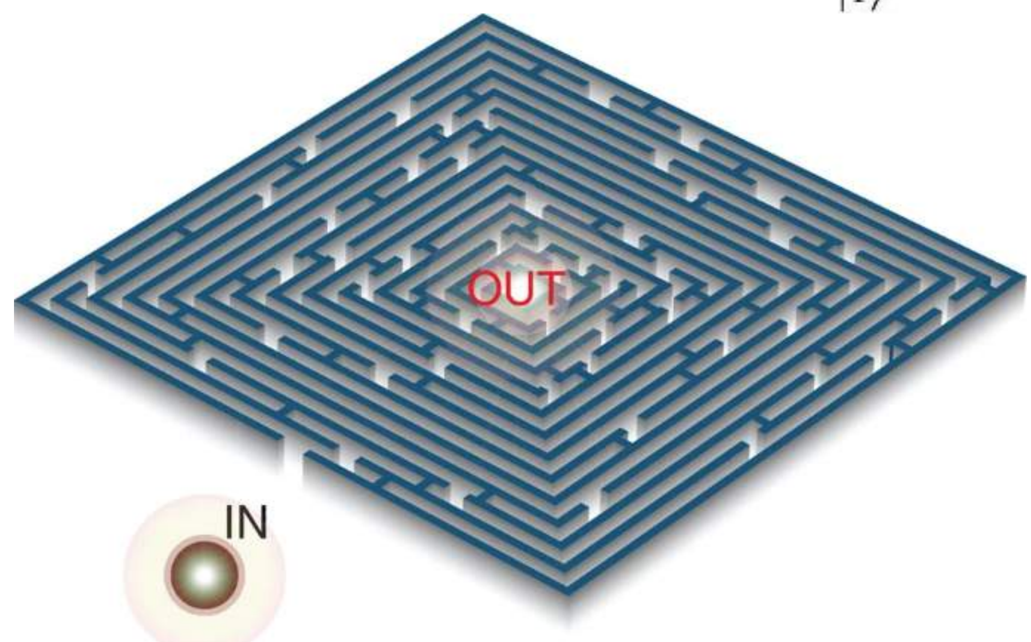
Bloch sphere: We can write our state with phase factors



$$|\Psi\rangle = e^{i\gamma}\left(\cos\frac{\theta}{2}|0\rangle + e^{i\varphi}\sin\frac{\theta}{2}|1\rangle\right)$$



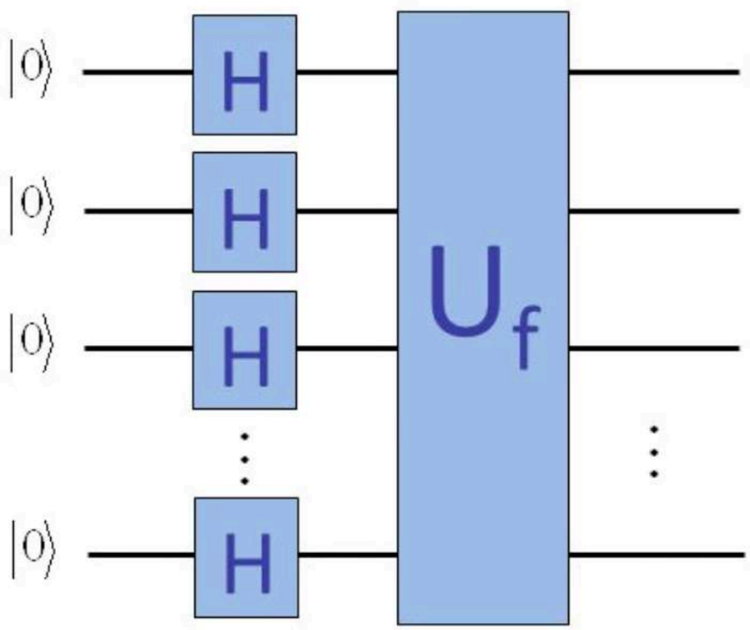


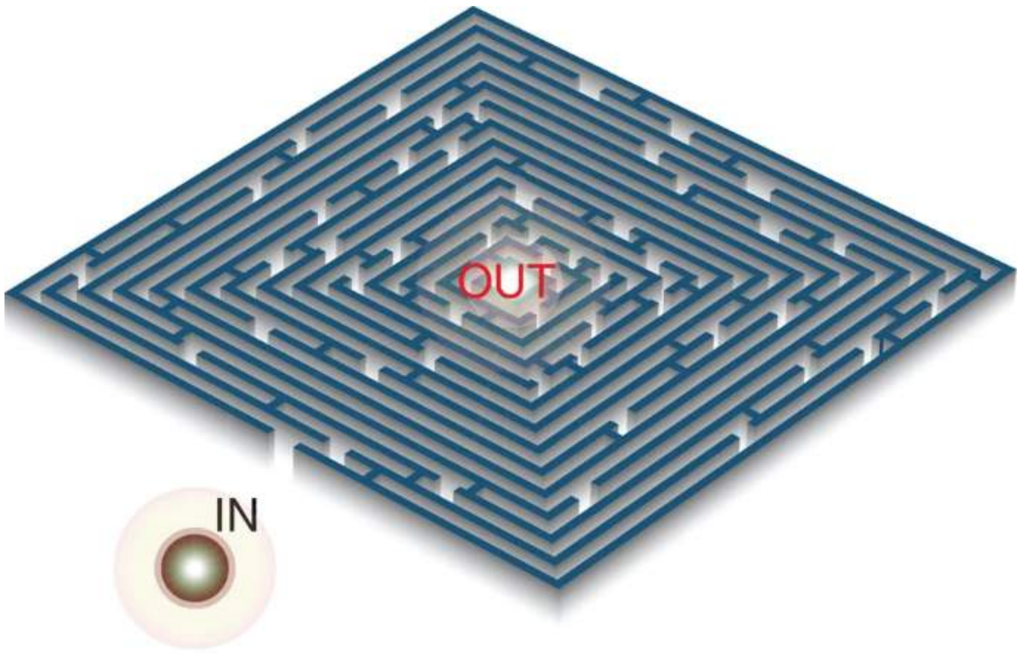


Quantum parallelism

- The machine should have a collection of bits. (~10^3 qubits)
- It should be possible to set all the memory bits to 0 before the start of each computation.
- The error rate should be sufficiently low. (less 10^{-4})
- Reliable output of the final result should be possible.

D. P. DiVincenzo, G. Burkard, D. Loss, E. V. Sukhorukov, cond-mat/9911245





Quantum computation

A quantum computer is a machine that performs calculations based on the laws of quantum mechanics.

1982 - Feynman proposed the idea of creating machines based on the laws of quantum mechanics instead of the laws of classical physics.

Richard P. Feynman, Simulating Physics with Computers
International Journal of Theoretical Physics, VoL 21, Nos. 6/7, 1982

1994 - Peter Shor came up with a quantum algorithm to factor very large numbers in polynomial time.

Shor, P. W. in Proc. 35th Annu. Symp. Foundations of Computer Science (ed. Goldwasser, S.) 124–134 (IEEE Computer Society, Los Alamitos, CA, 1994).

Ekert, A. & Jozsa, R.
Quantum computation and Shor's factoring algorithm. Rev. Mod. Phys. 68, 733–753 (1996).

1997 - Lov Grover develops a quantum search algorithm with O(√N) complexity

Grover, L. K. Quantum mechanics helps in searching for a needle in a haystack. Phys. Rev. Lett. 79, 325–328 (1997).

DiVincenzo Criteria

- **Information storage on qubits:**
the information is encoded on a quantum property of a scalable physical system which lives long enough to perform computations

- **Initial state preparation:**
the state of the qubit needs to be prepared before each computation

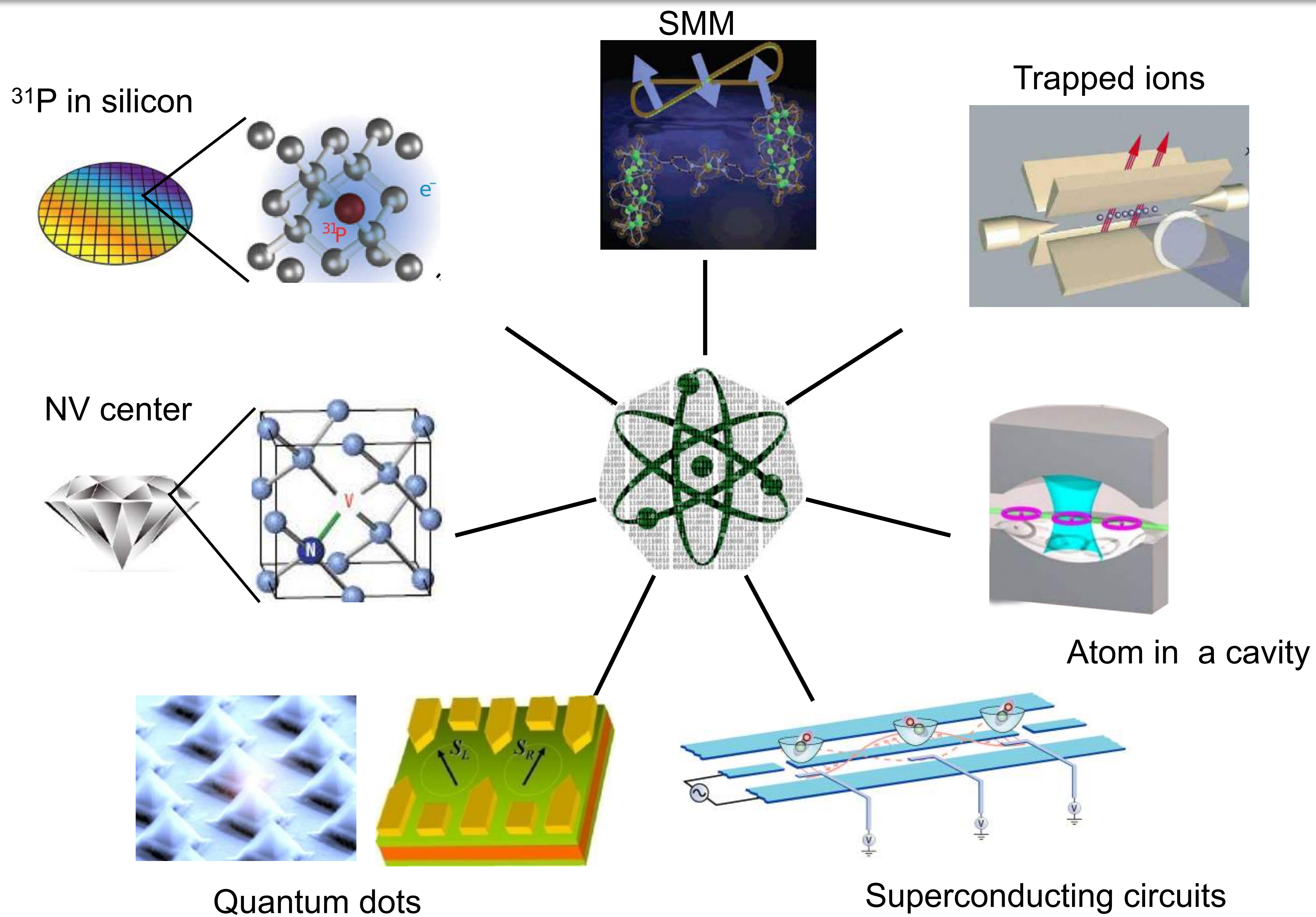
- **Isolation:**
the qubit must be protected from decoherence by isolation from the environment

- **Gate implementation:**
the manipulation of a quantum state must be performed with reasonable precision and much faster than the decoherence time T_2

- **Read-out:**
the final state of the qubit must be read-out with a sufficiently high precision

D. P. DiVincenzo, Topics in Quantum Computers, NATO Advanced Study Institute, Series E: Applied Sciences, 345 (1996).

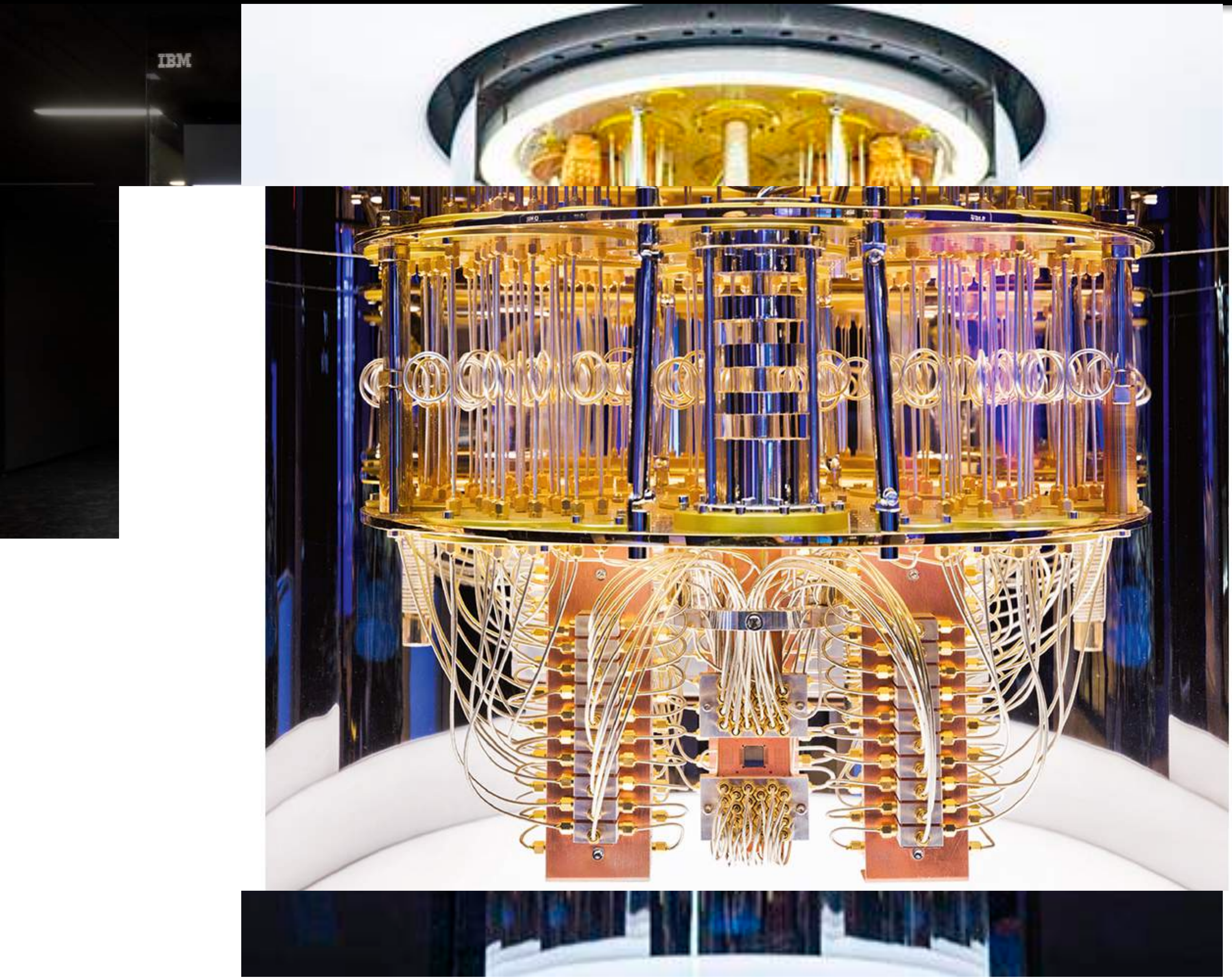
Different qubits



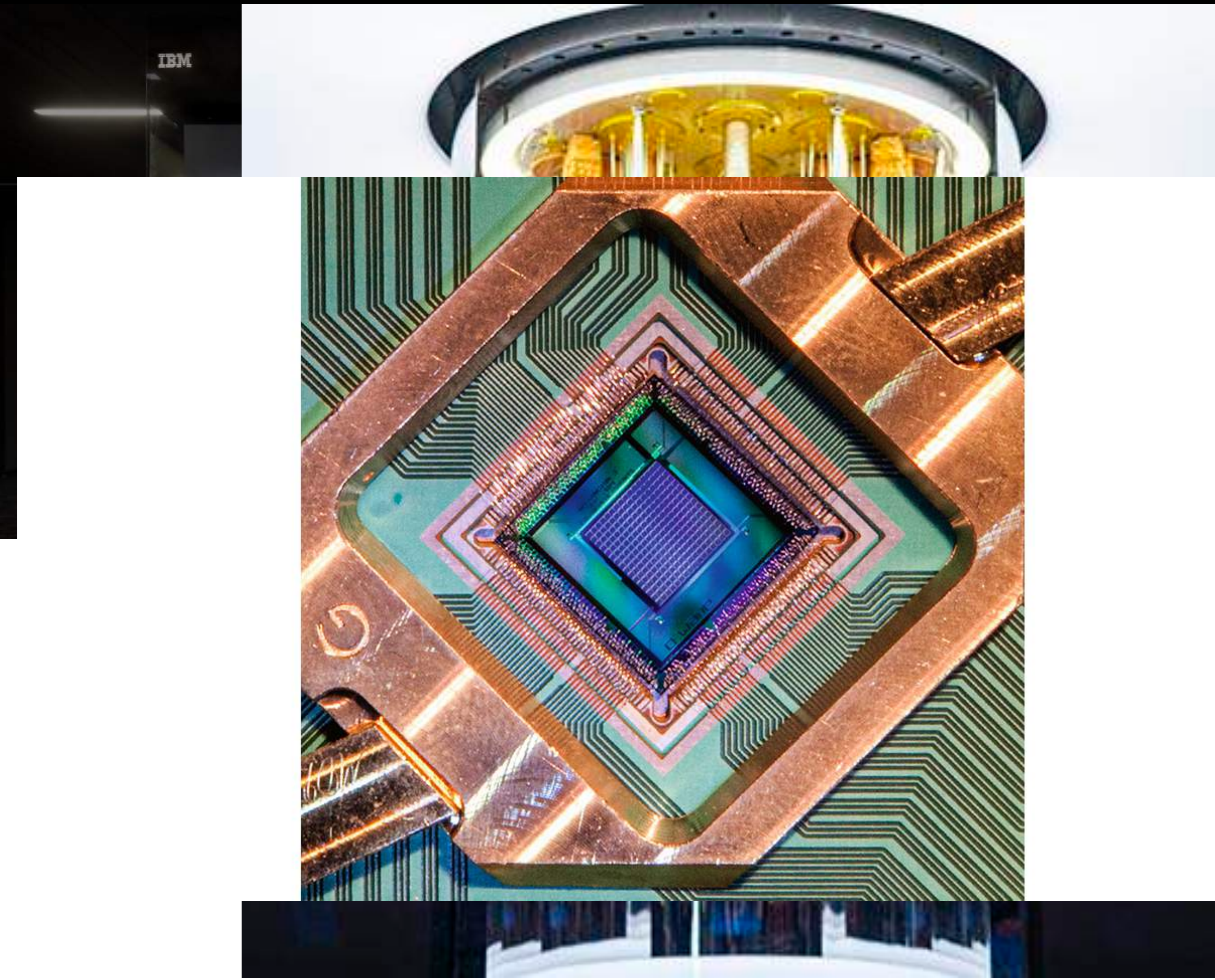
A quantum Computer

A quantum Computer

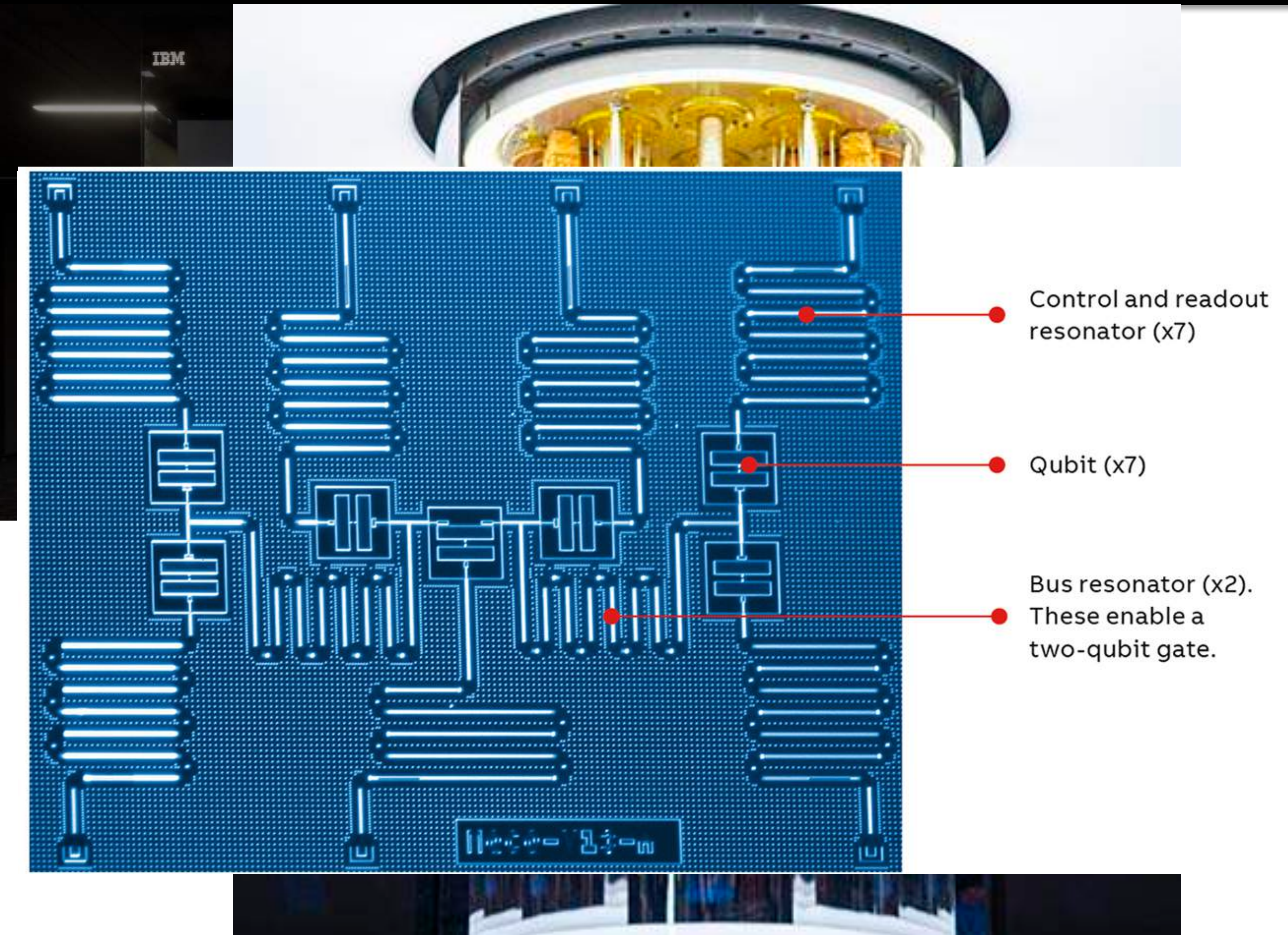
A quantum Computer



A quantum Computer



A quantum Computer

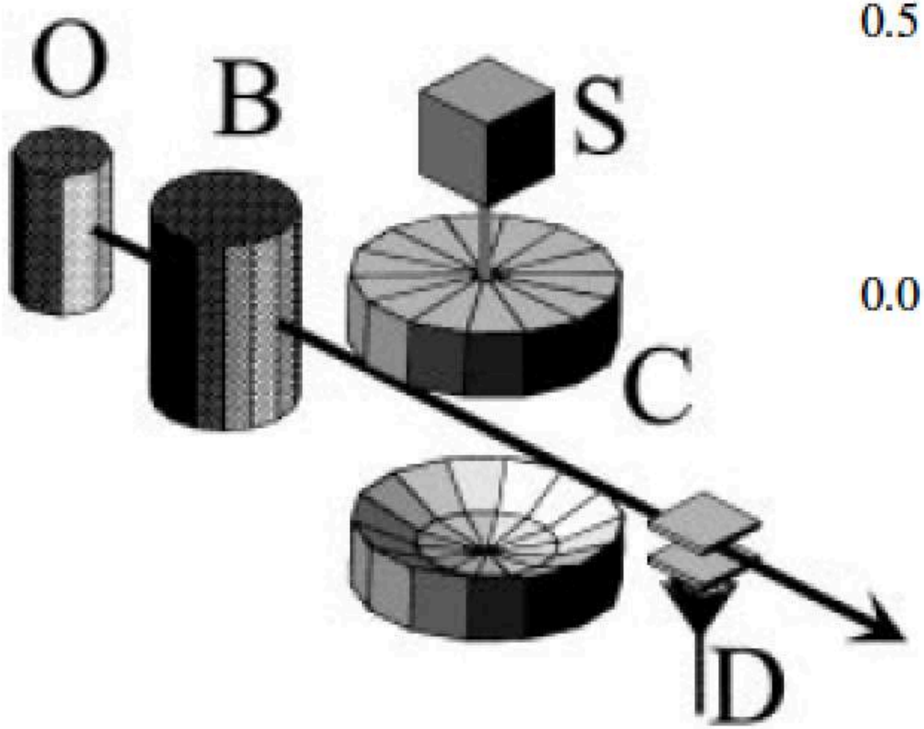


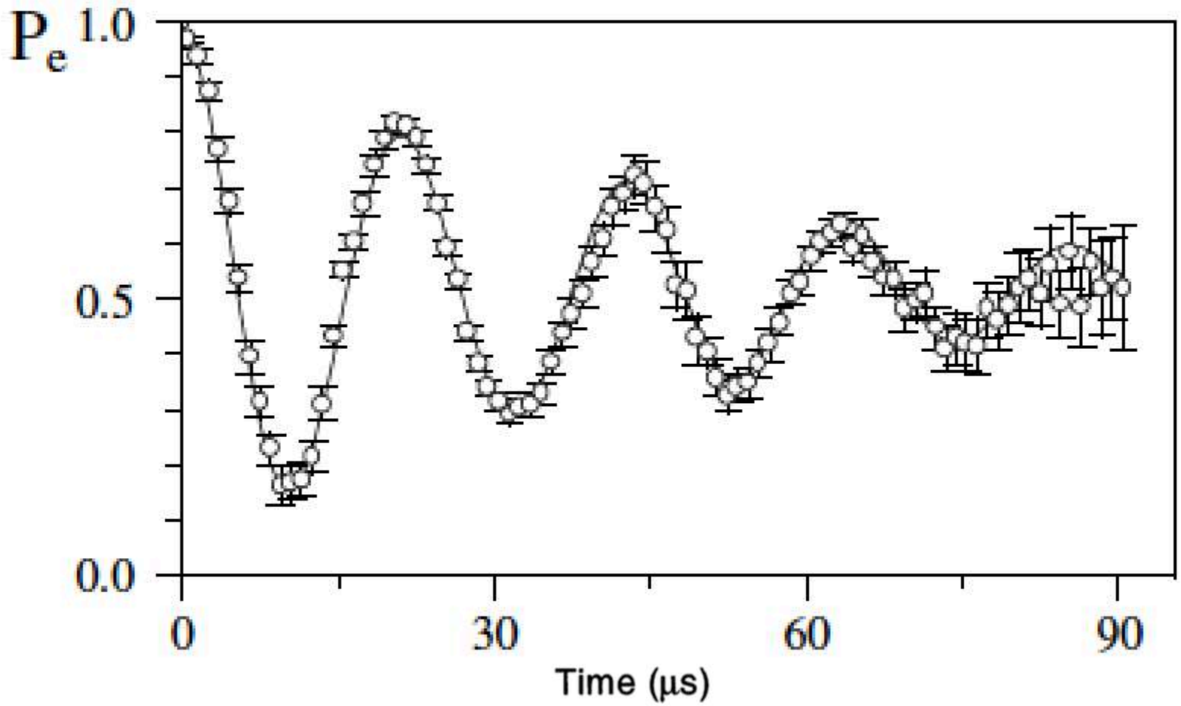
Rydberg Atom

VOLUME 76, NUMBER 11 PHYSICAL REVIEW LETTERS 11 MARCH 1996

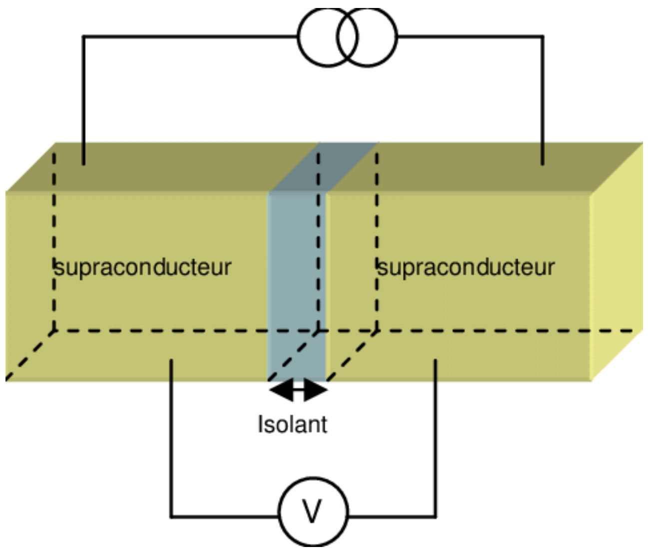
Quantum Rabi Oscillation: A Direct Test of Field Quantization in a Cavity

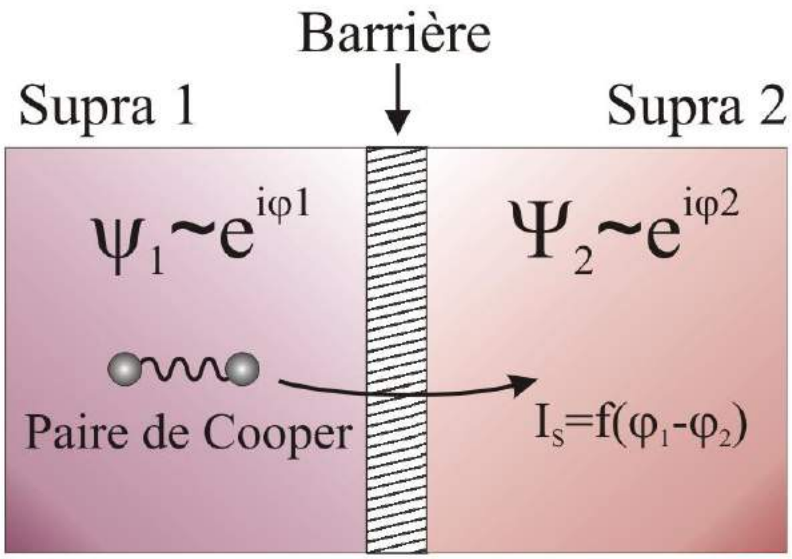
M. Brune, F. Schmidt-Kaler, A. Maali, J. Dreyer, E. Hagley, J.M. Raimond, and S. Haroche
Laboratoire Kastler Brossel, Département de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, F-75231 Paris Cedex 05, France*
(Received 9 November 1995)



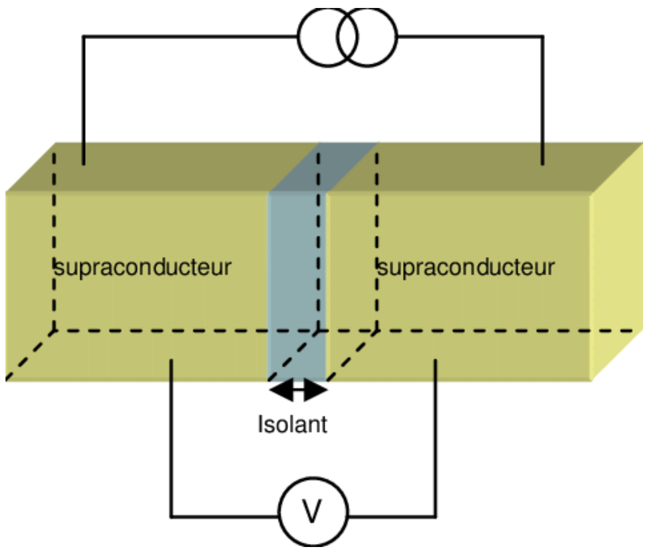


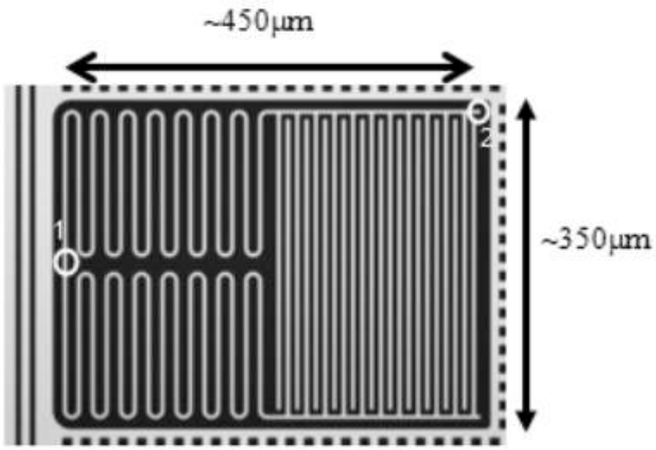
Superconducting qubits



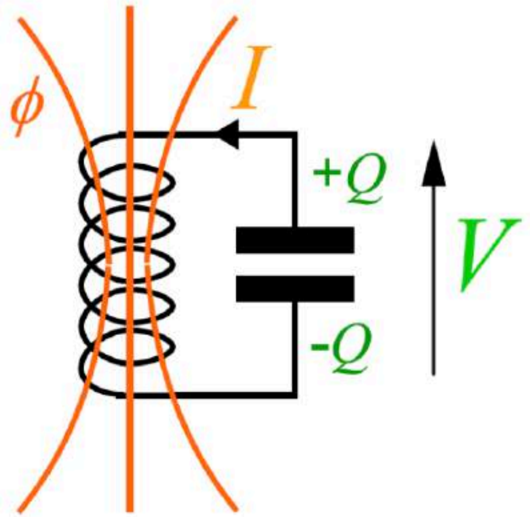


Superconducting qubits

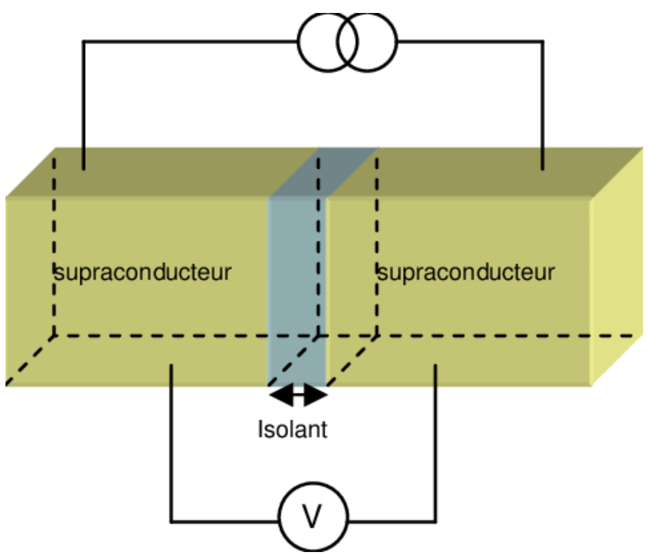


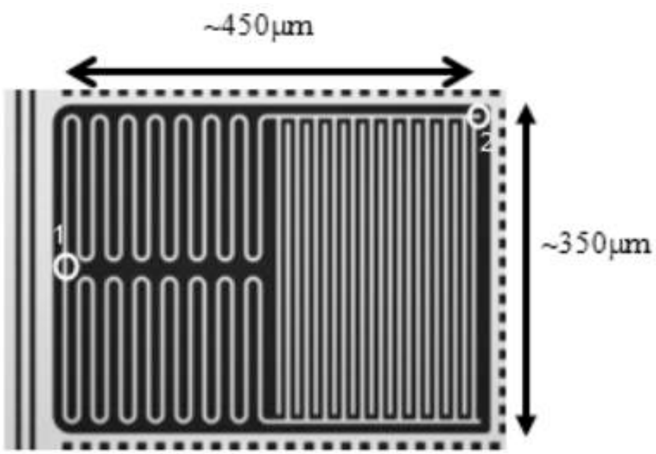


Khalil, M., et al. , *Applied Superconductivity (2011).*

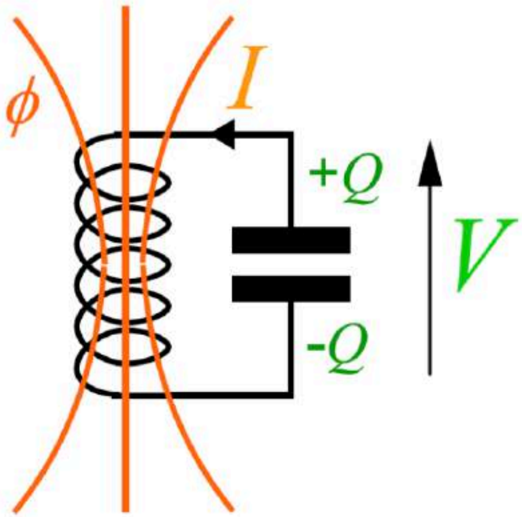


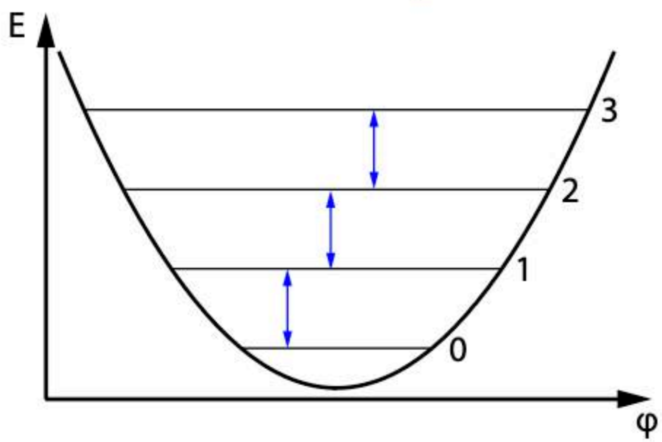
Superconducting qubits





Khalil, M., et al. , *Applied Superconductivity (2011)*.

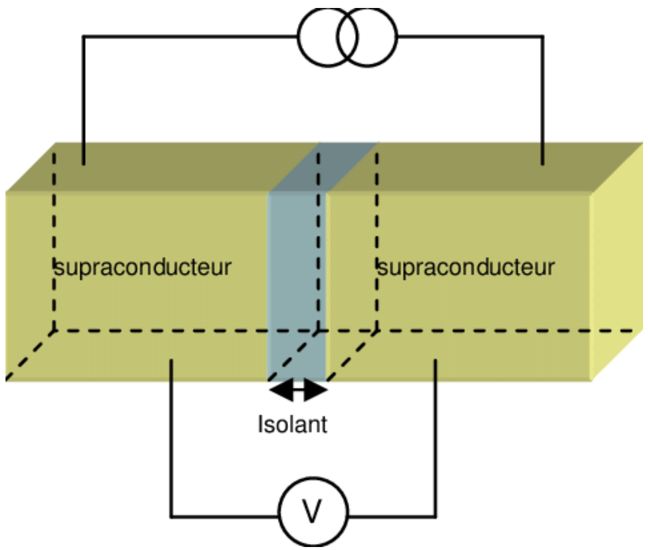


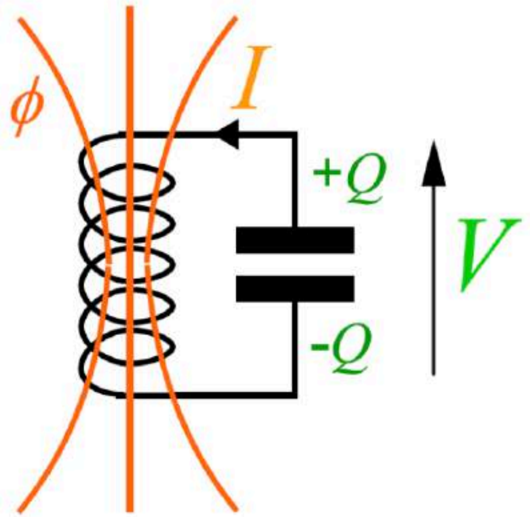


$$\hbar\omega \gg k_B T$$

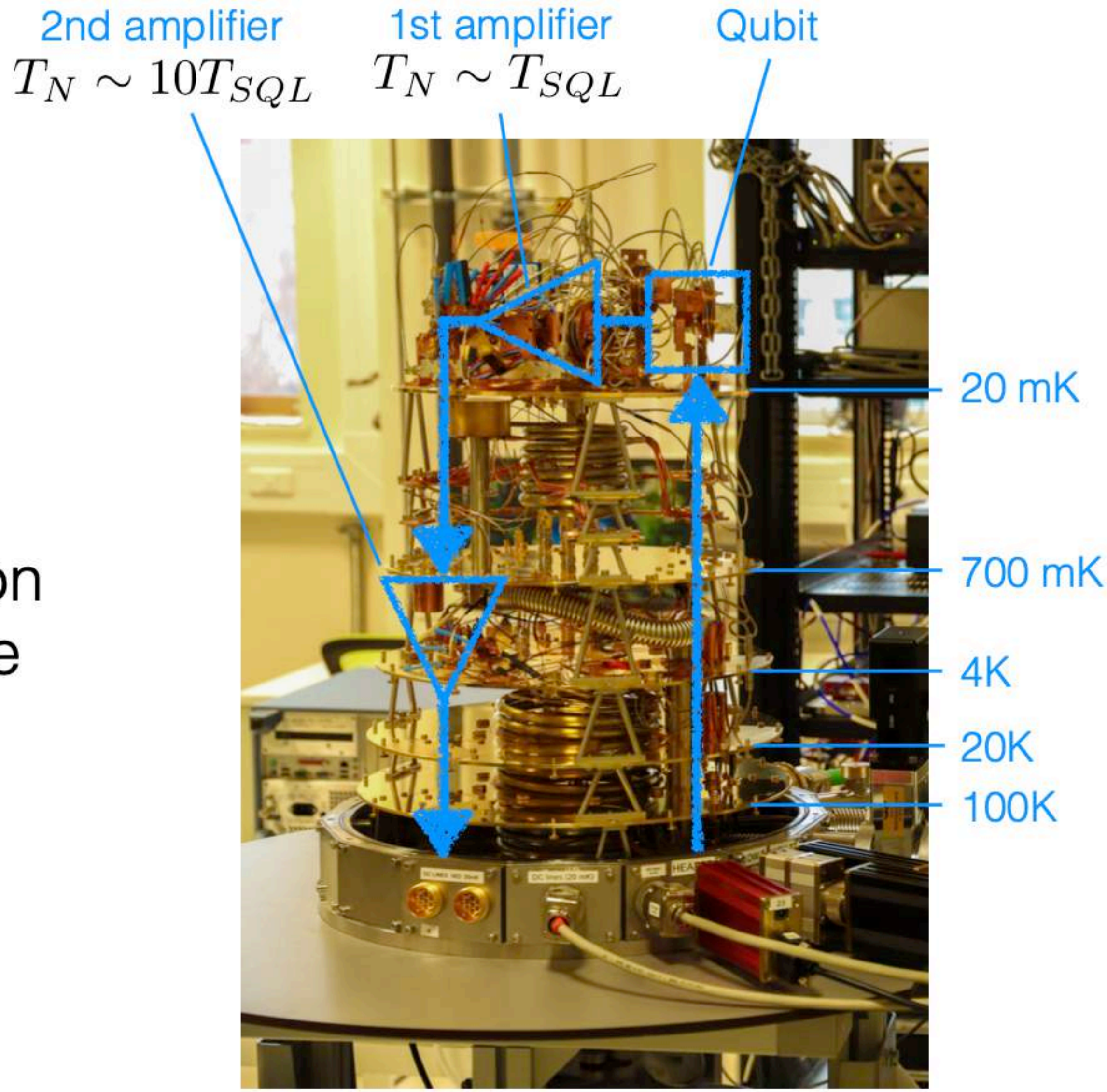
$\frac{\hbar\omega}{k_B} \sim 500$ mK $T \sim 20$ mK

Superconducting qubits

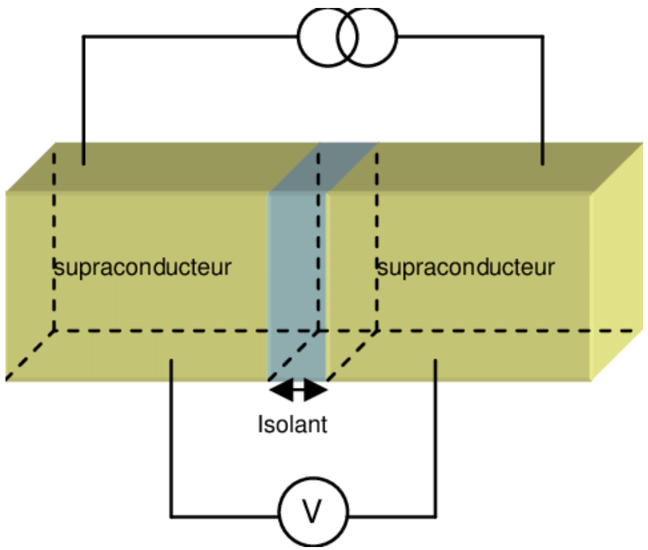


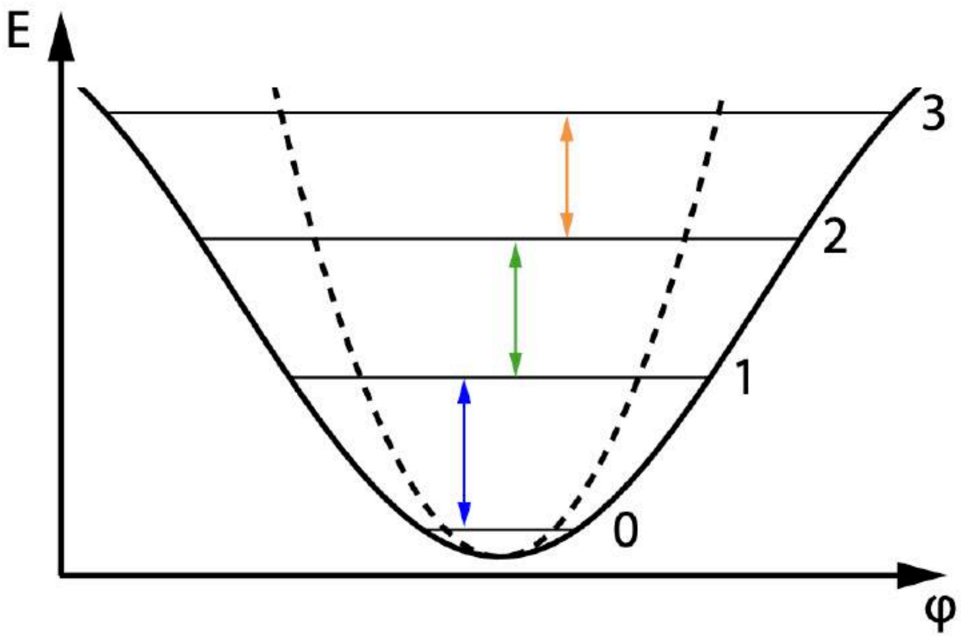


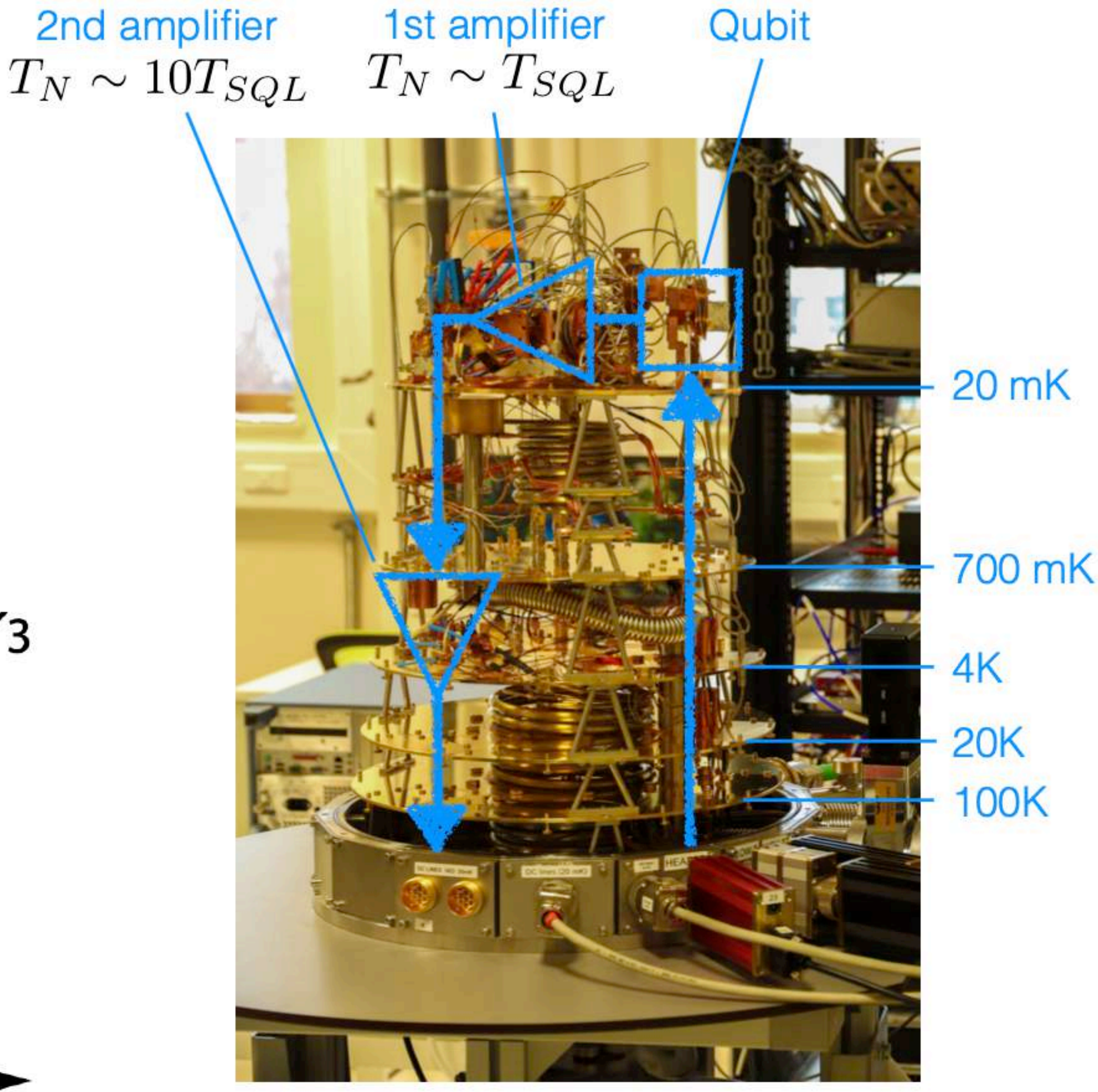
Dilution fridge



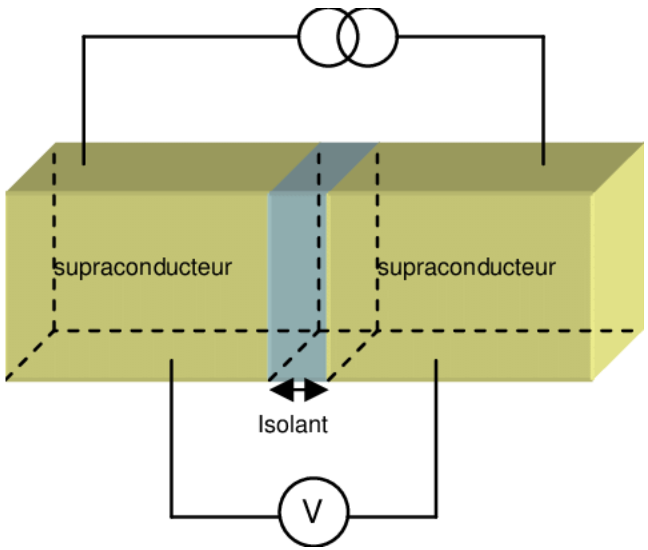
Superconducting qubits

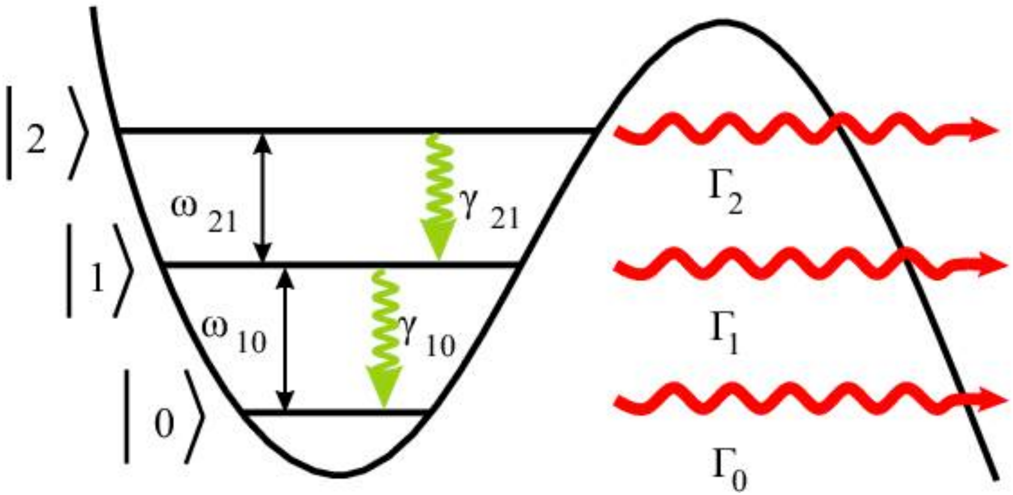


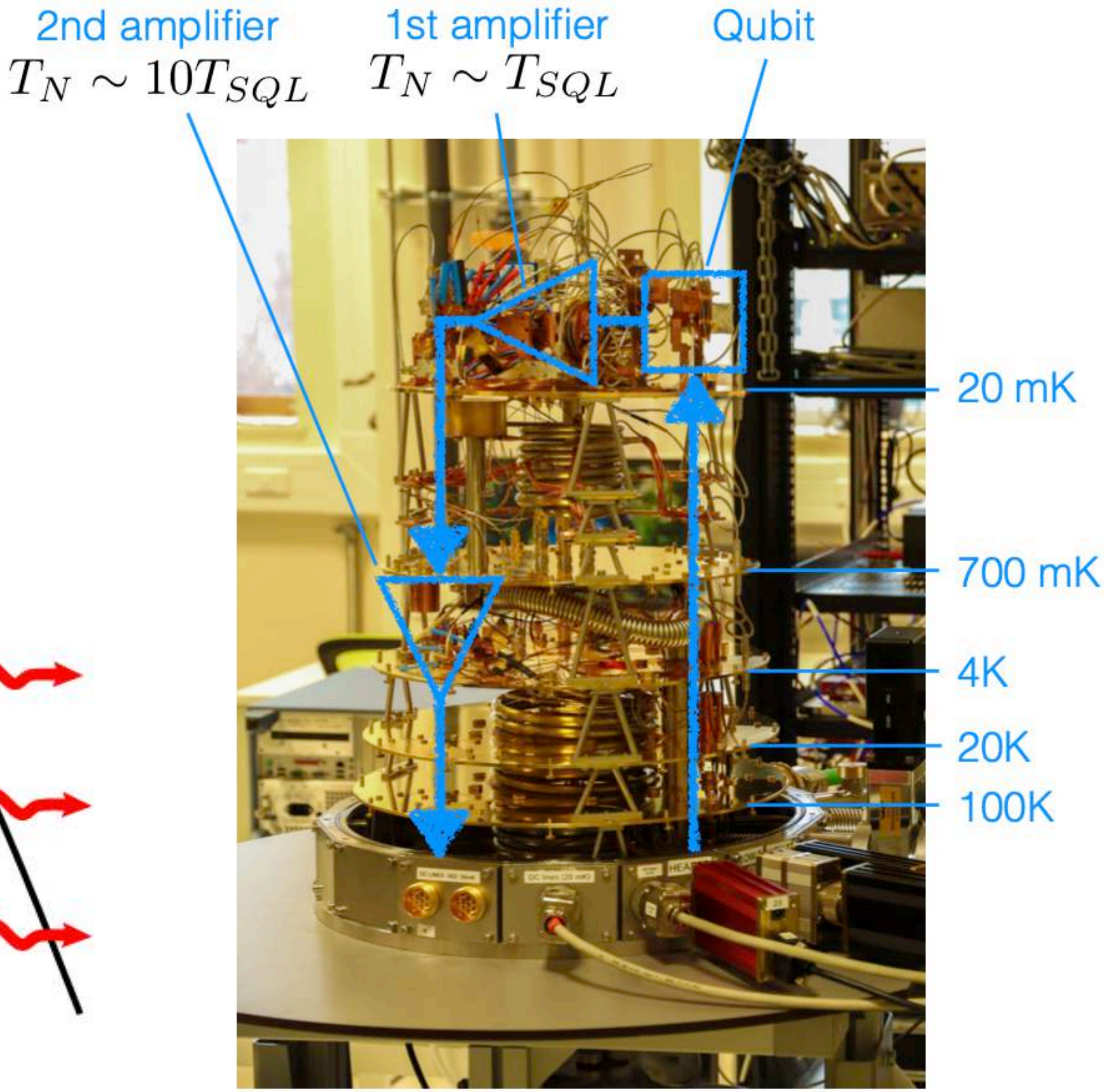




Superconducting qubits







Superconducting qubits

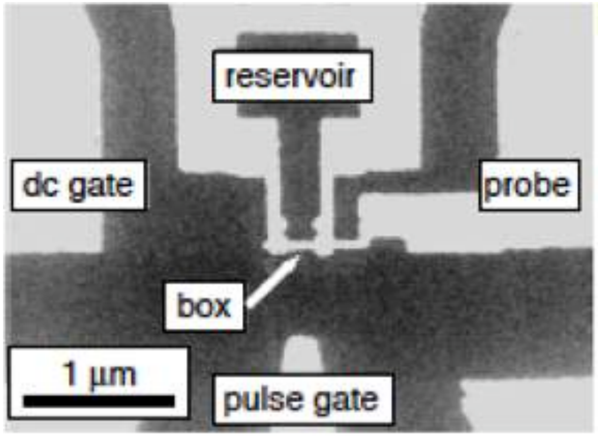
letters to nature

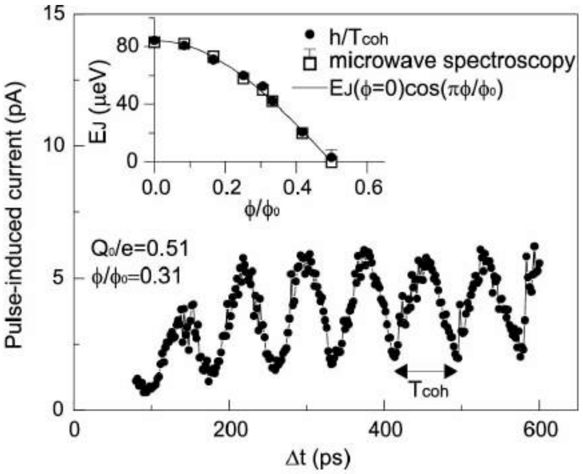
Nature 398 786 (1999)

Coherent control of macroscopic quantum states in a single-Cooper-pair box

Y. Nakamura*, Yu. A. Pashkin† & J. S. Tsai*

* *NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† *CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan*





Superconducting qubits

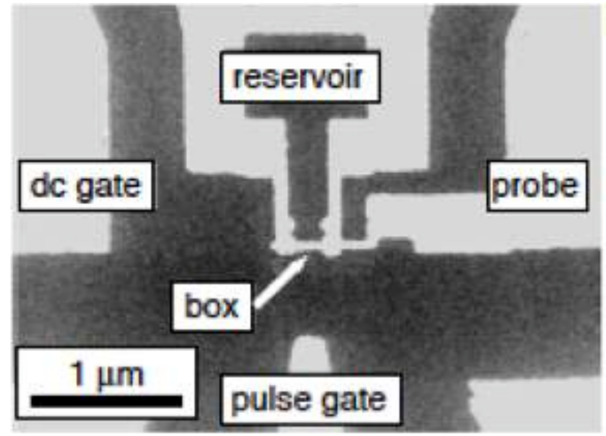
letters to nature

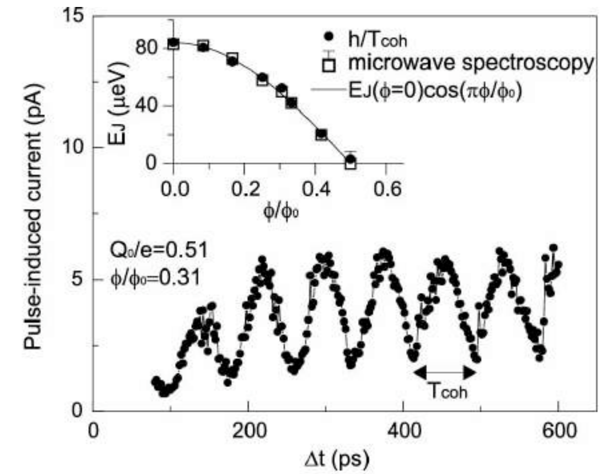
Nature 398 786 (1999)

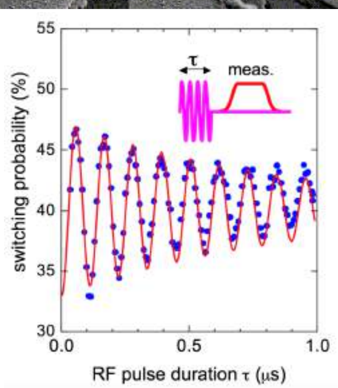
Coherent control of macroscopic quantum states in a single-Cooper-pair box

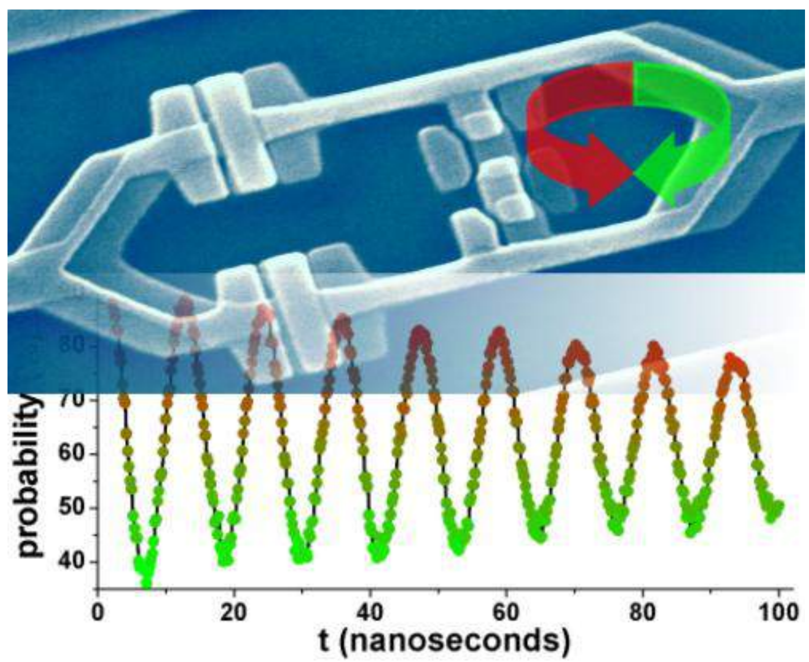
Y. Nakamura*, **Yu. A. Pashkin†** & **J. S. Tsai***

* *NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305-8051, Japan*
† *CREST, Japan Science and Technology Corporation (JST), Kawaguchi, Saitama 332-0012, Japan*

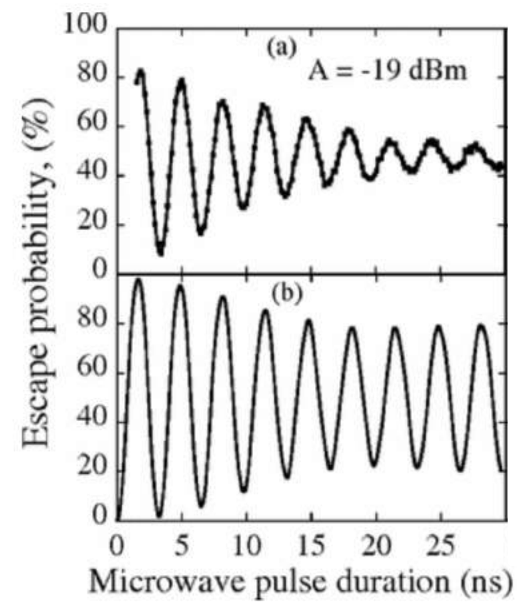






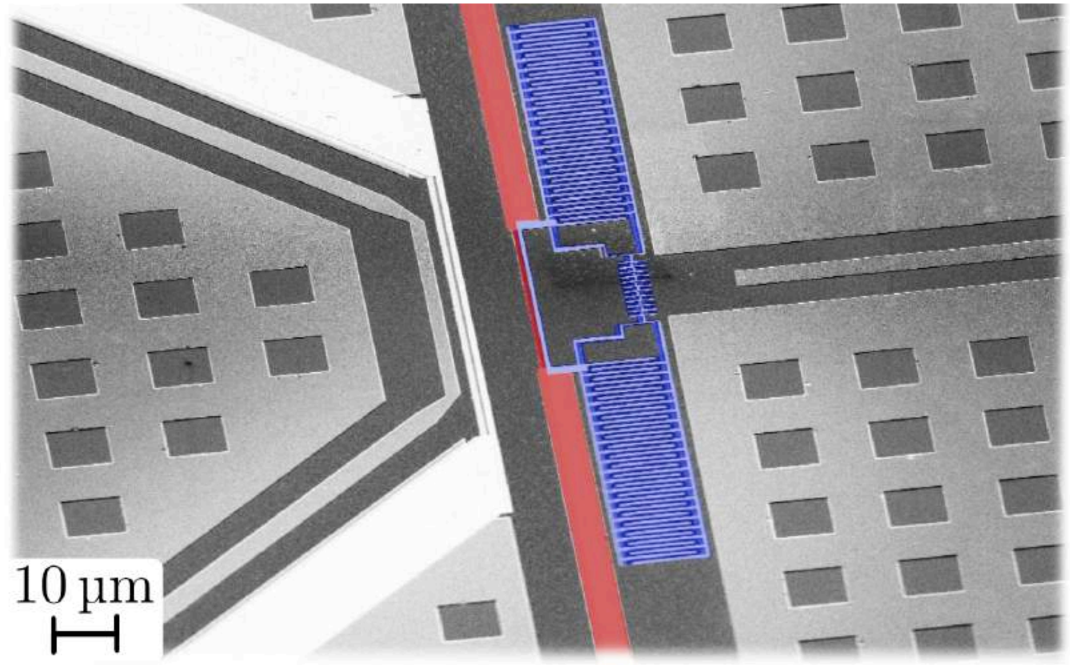


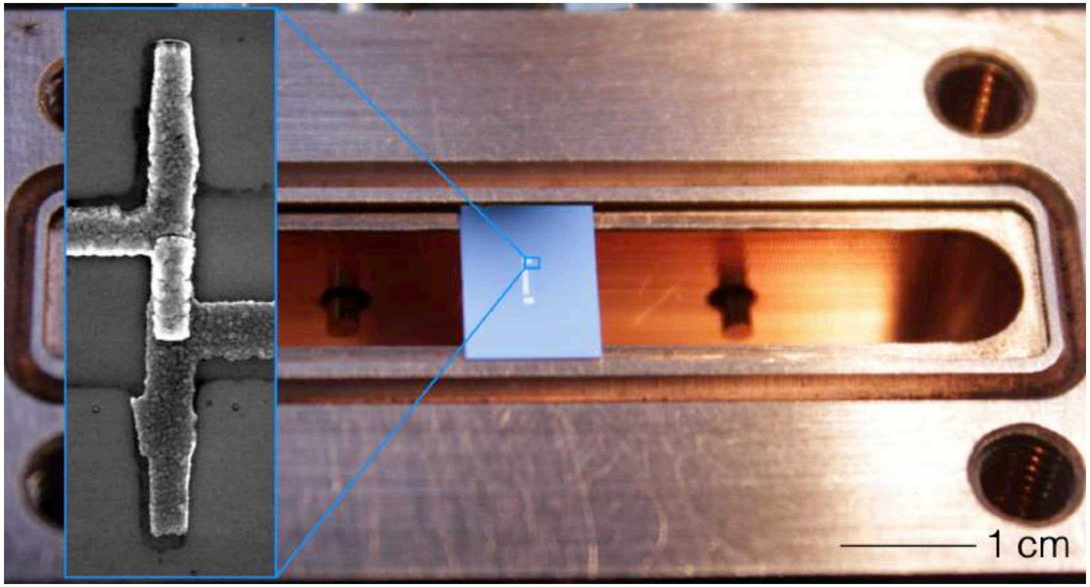
I. Chiorescu et al. Science 299, 1869 (2003)
Delft University



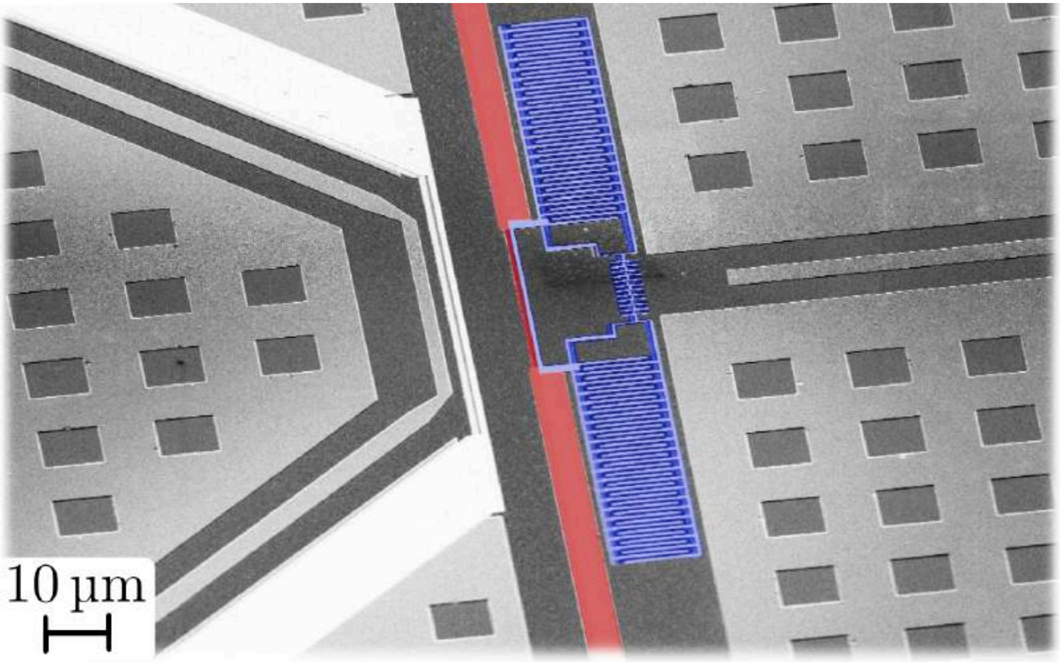
J. Claudon et al. PRL 93, 187003 (2004)
Grenoble

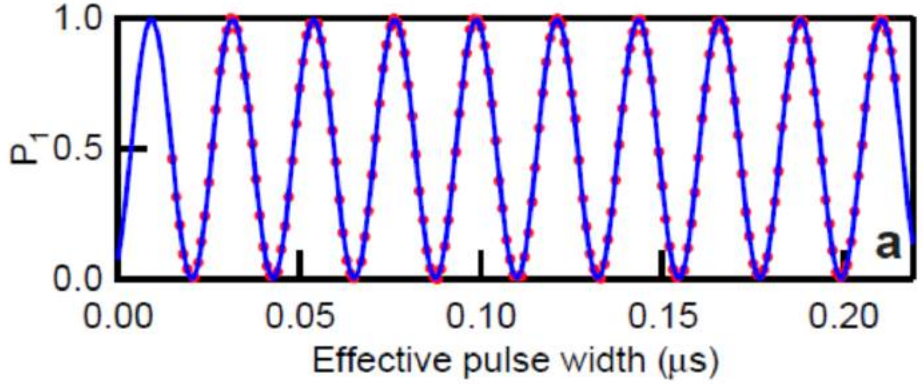
Superconducting qubits

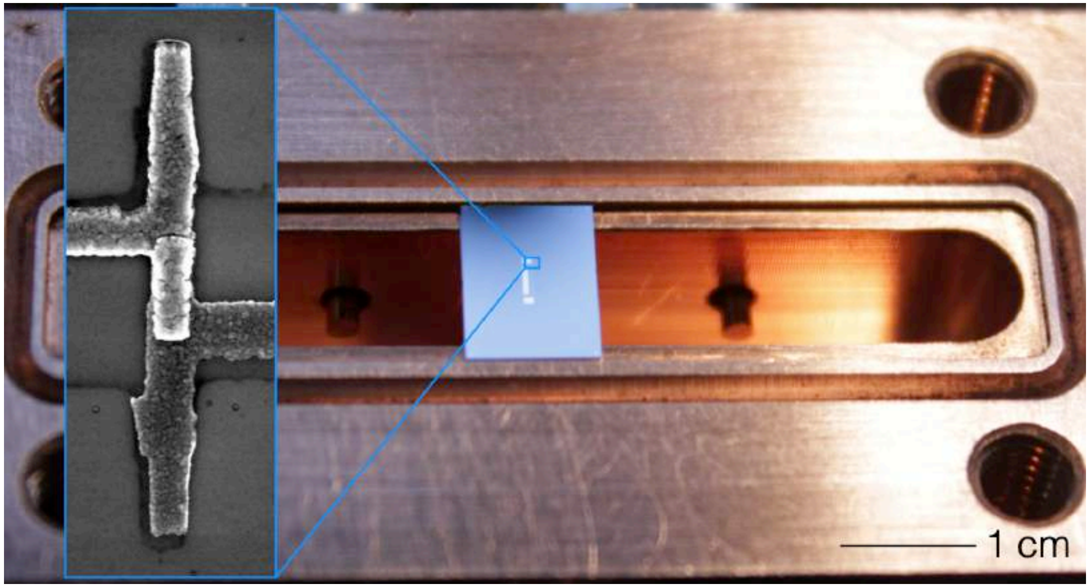




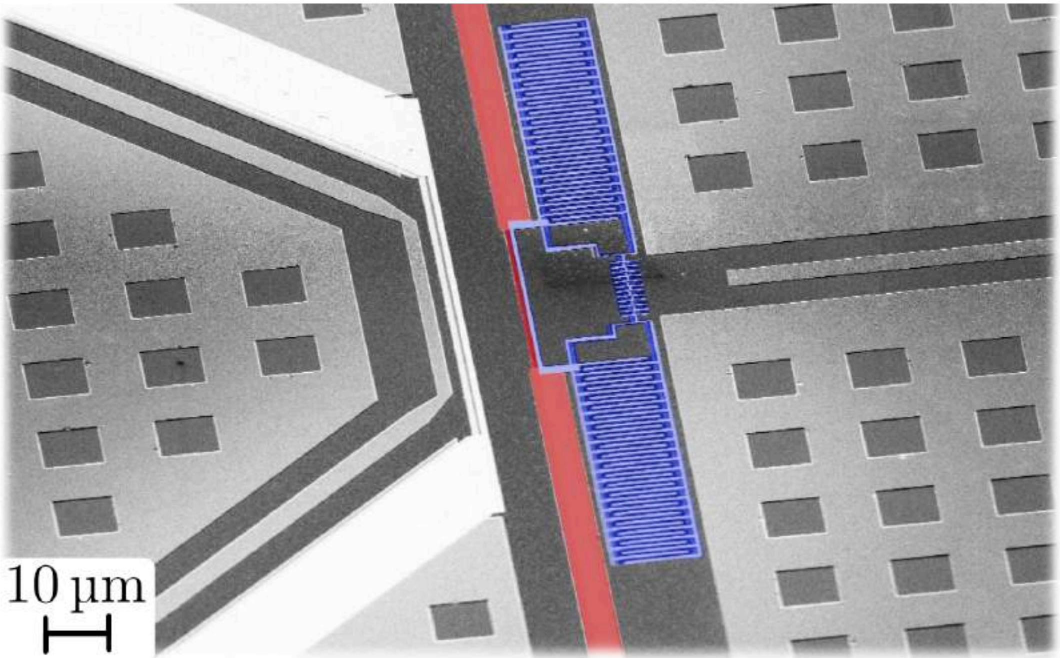
Superconducting qubits

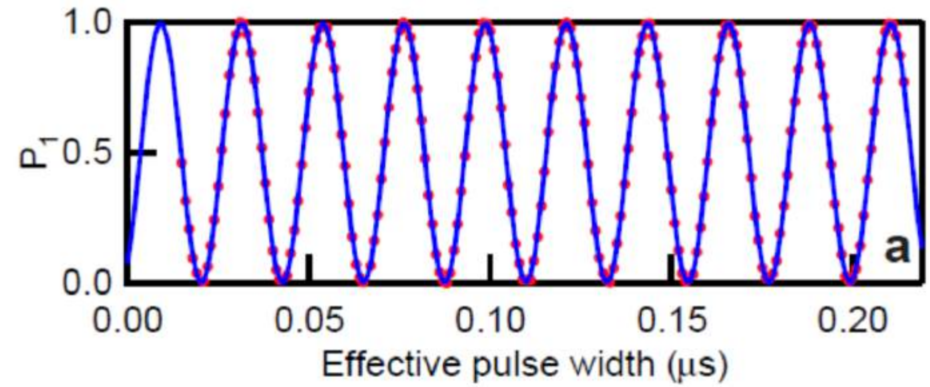


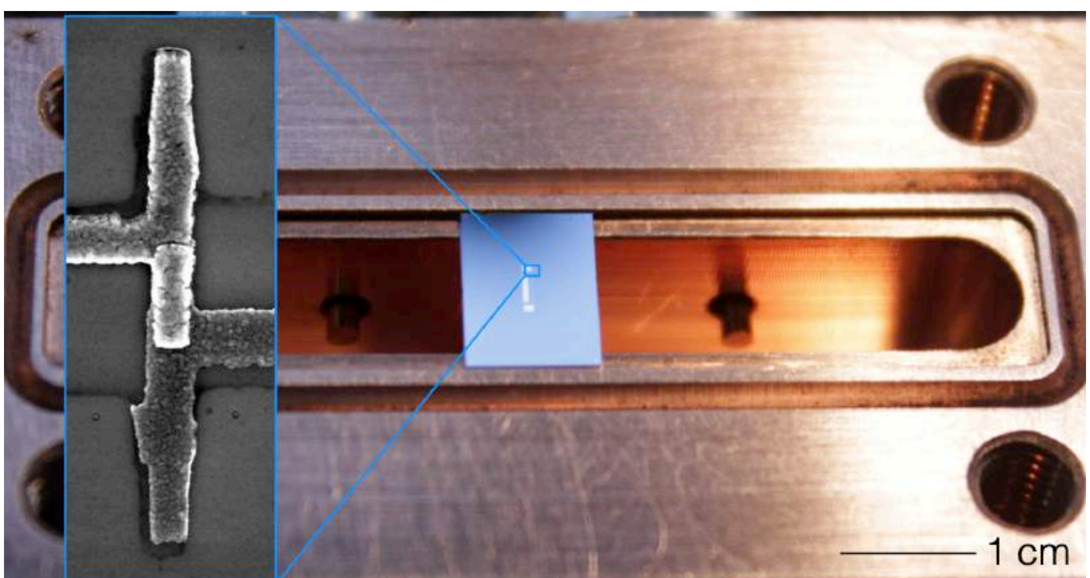


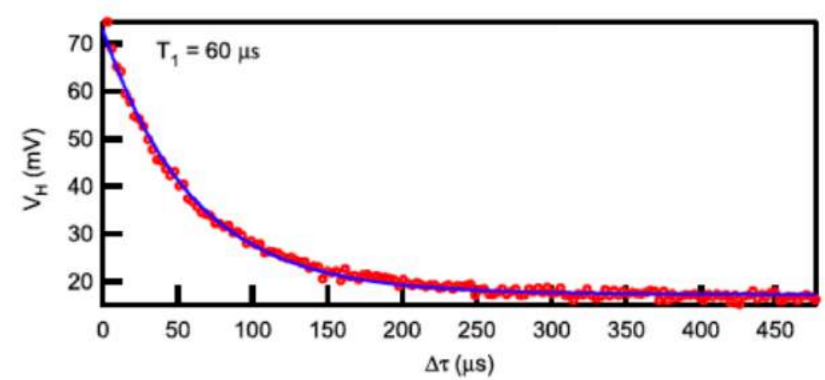


Superconducting qubits

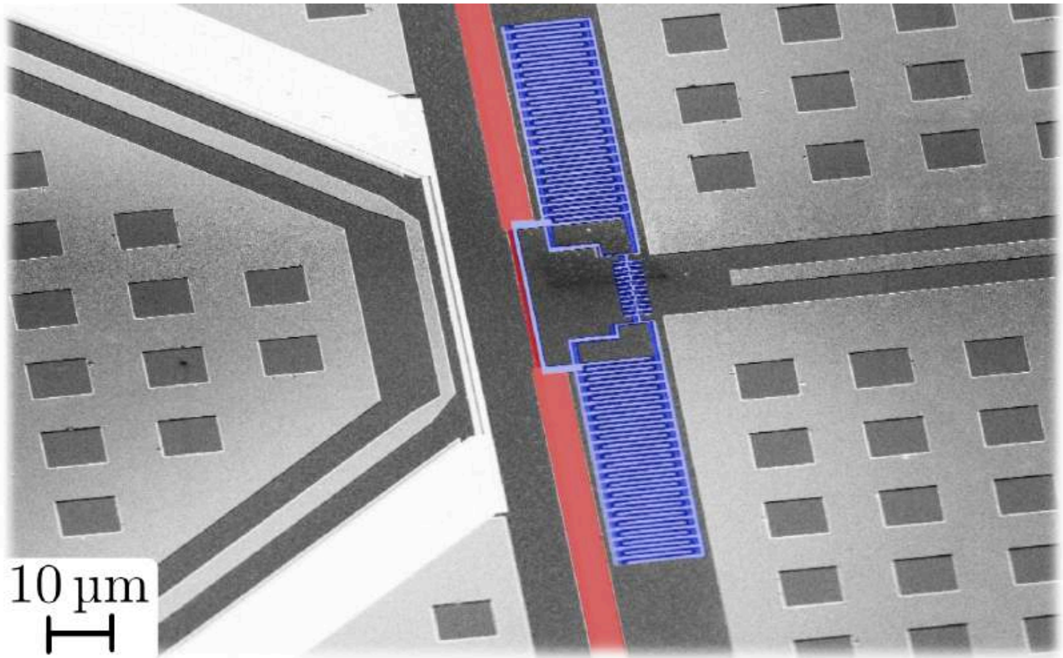


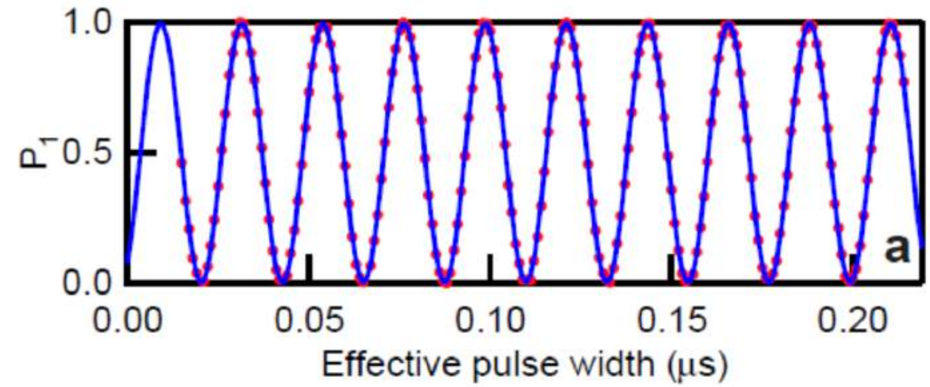


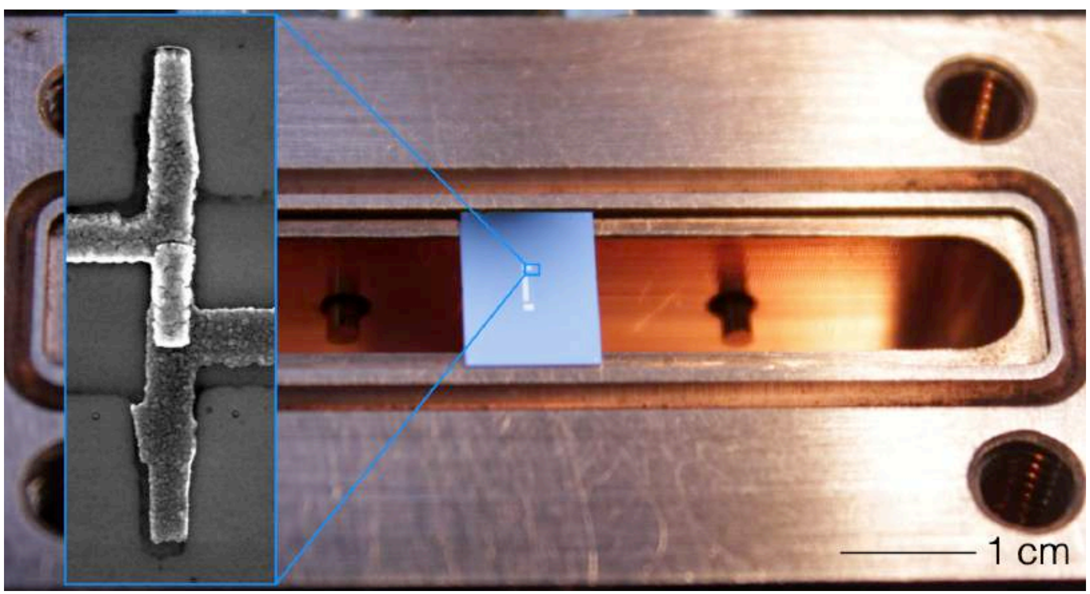




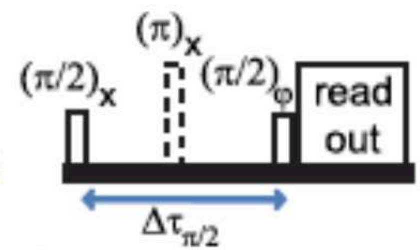
Superconducting qubits

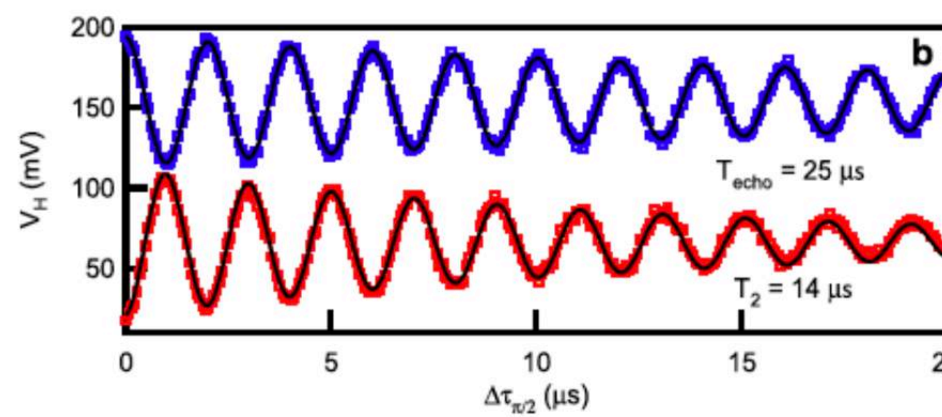




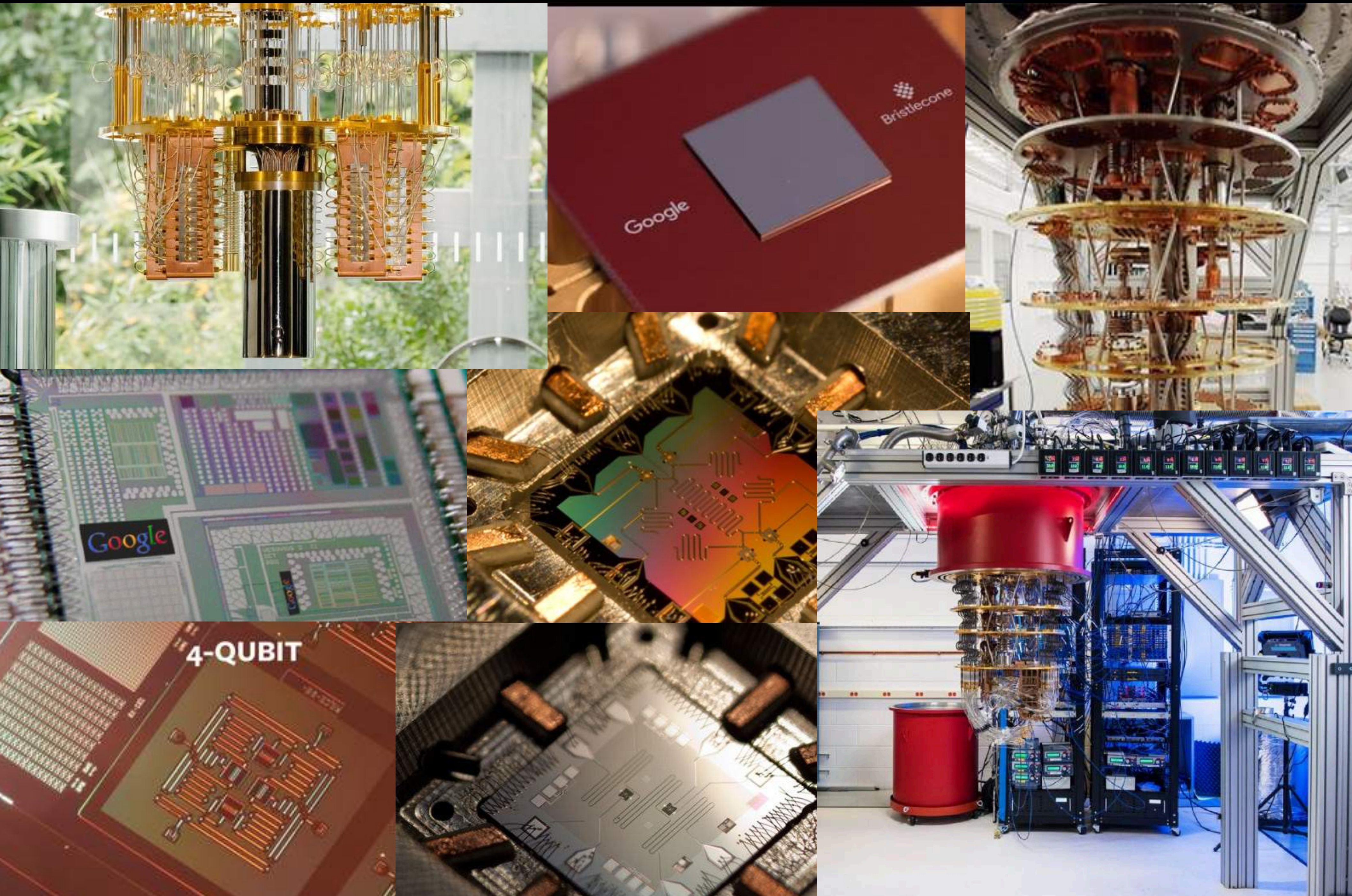


sequence





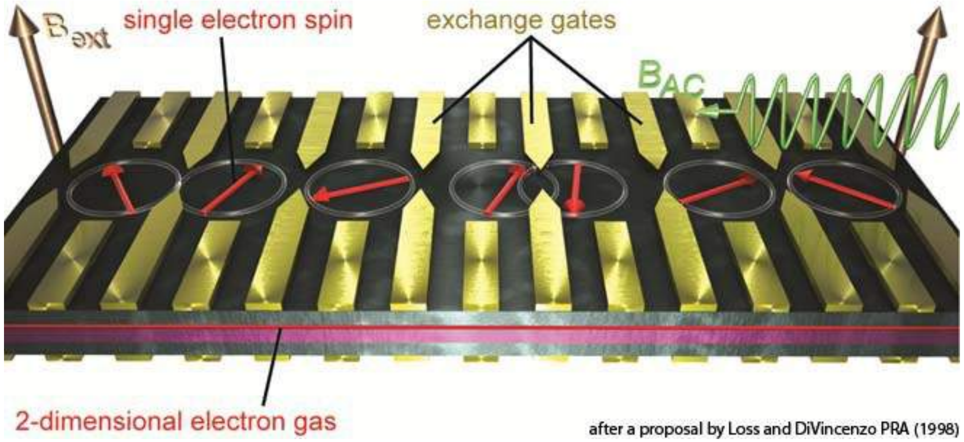
Superconducting qubits



Spin qubits

Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998

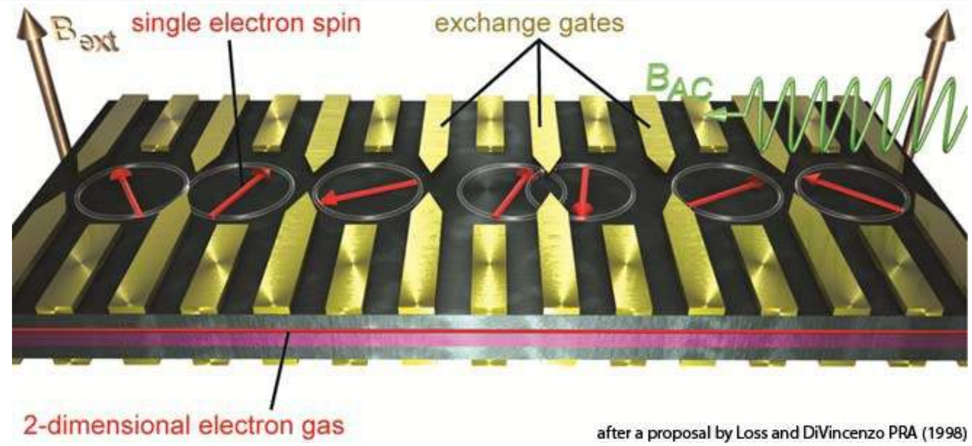


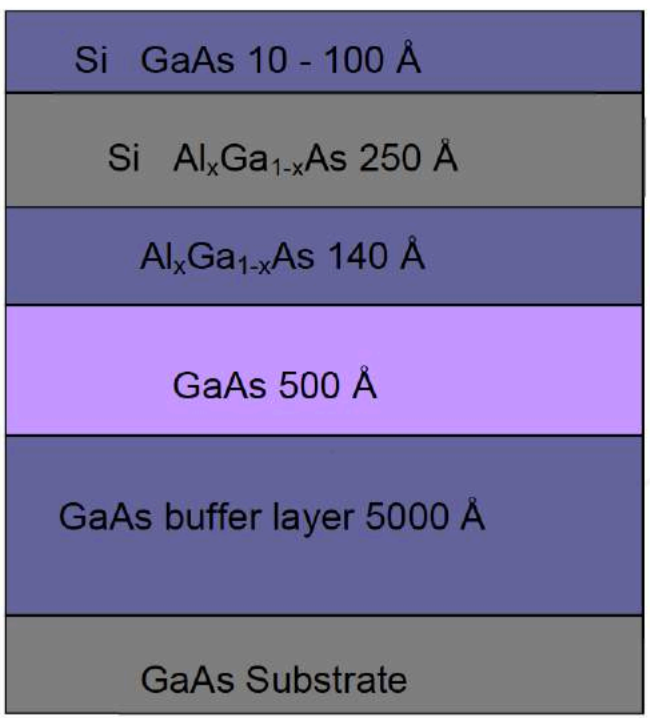
after a proposal by Loss and DiVincenzo PRA (1998)

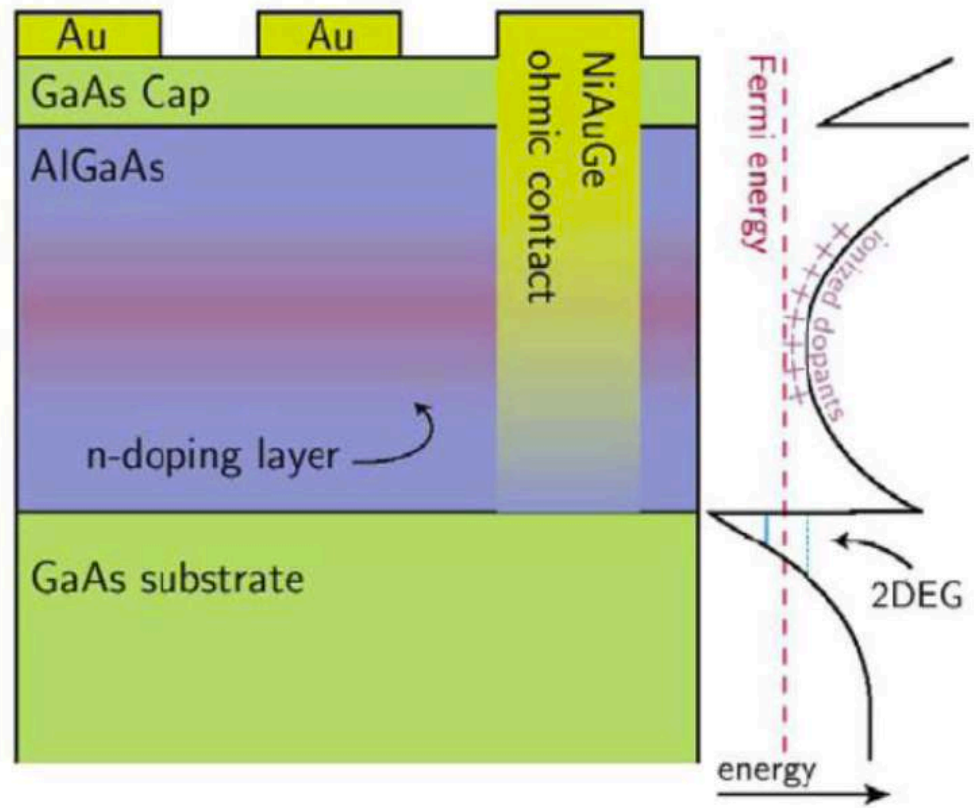
Spin qubits

Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998



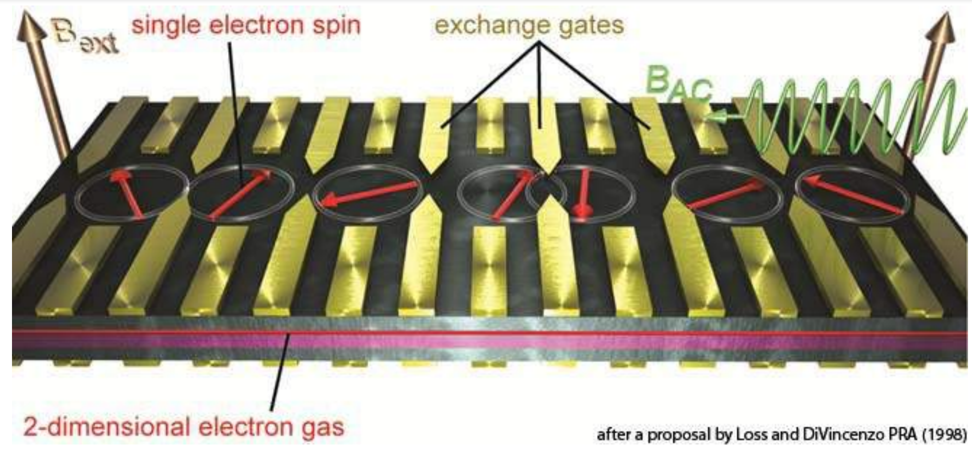


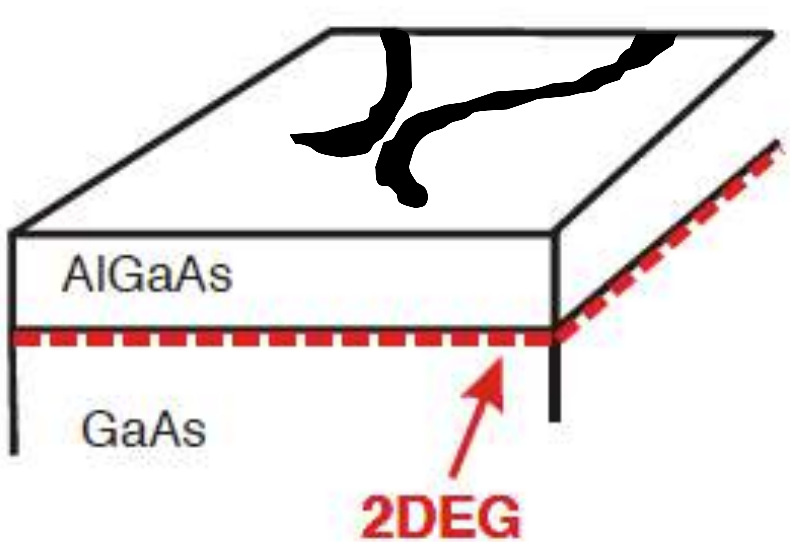


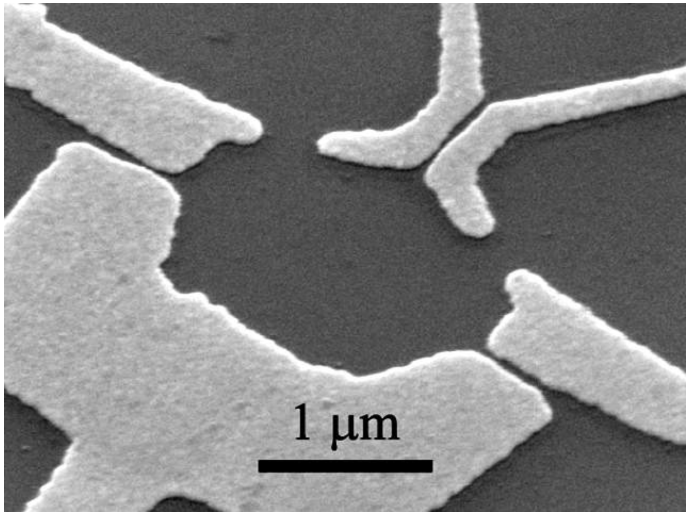
Spin qubits

Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998



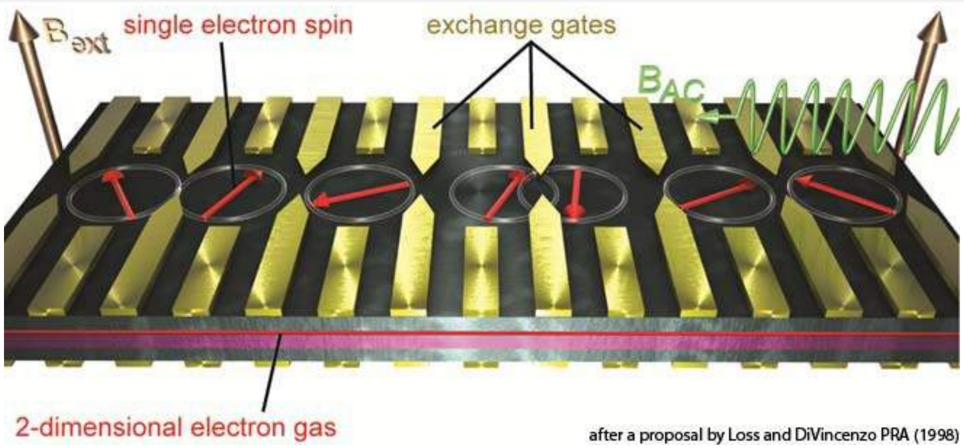


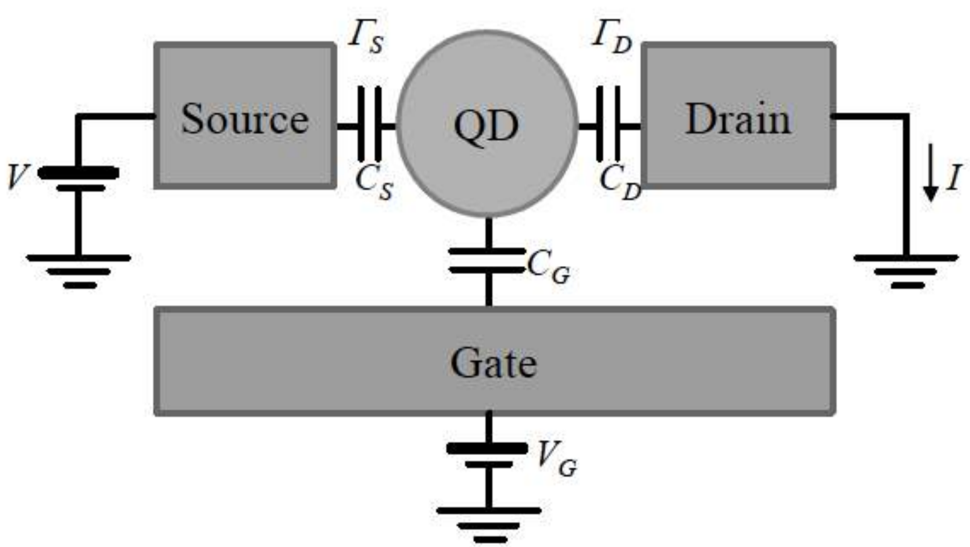


Spin qubits

Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998

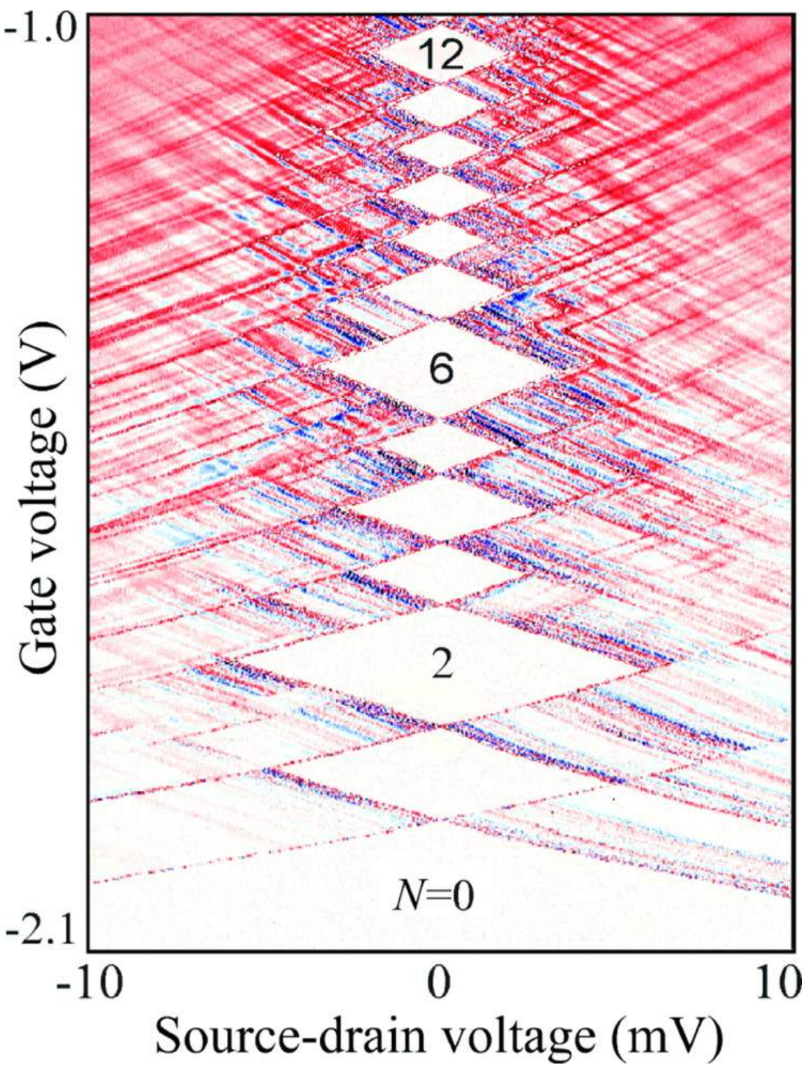


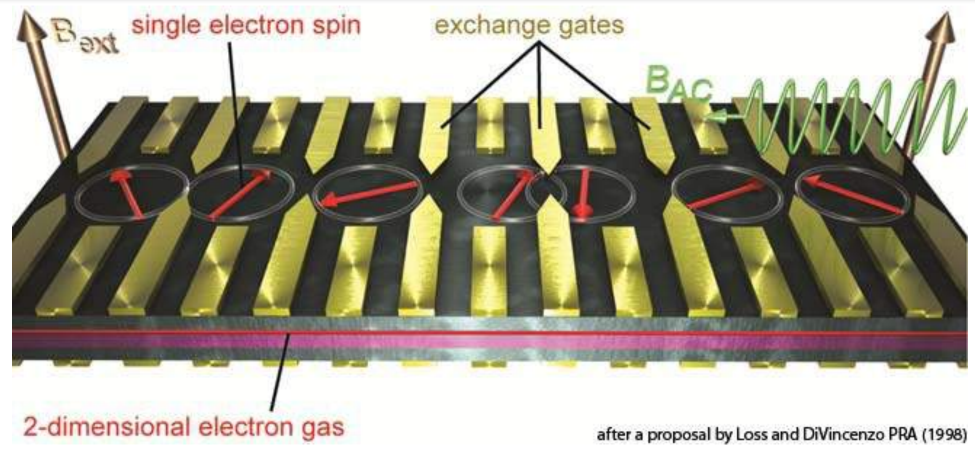


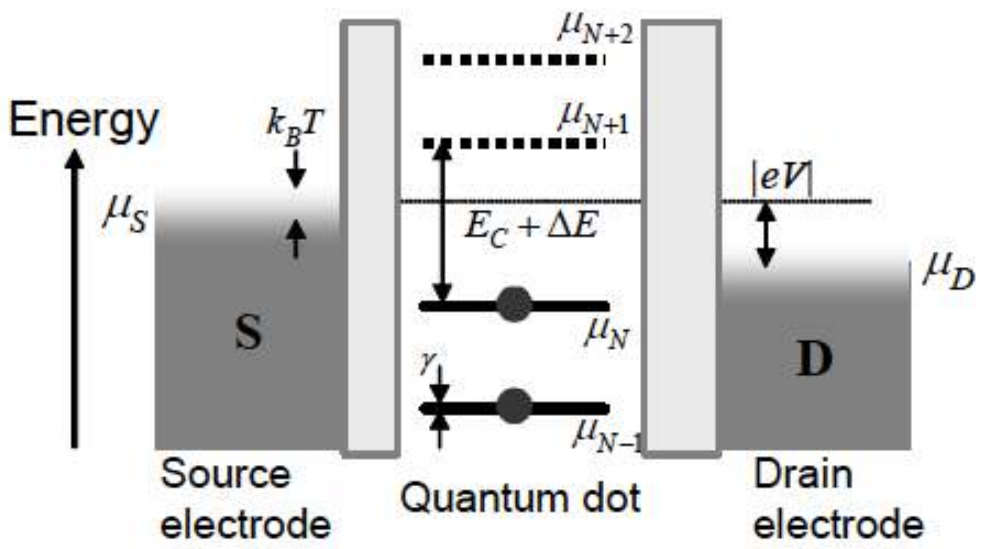
Spin qubits

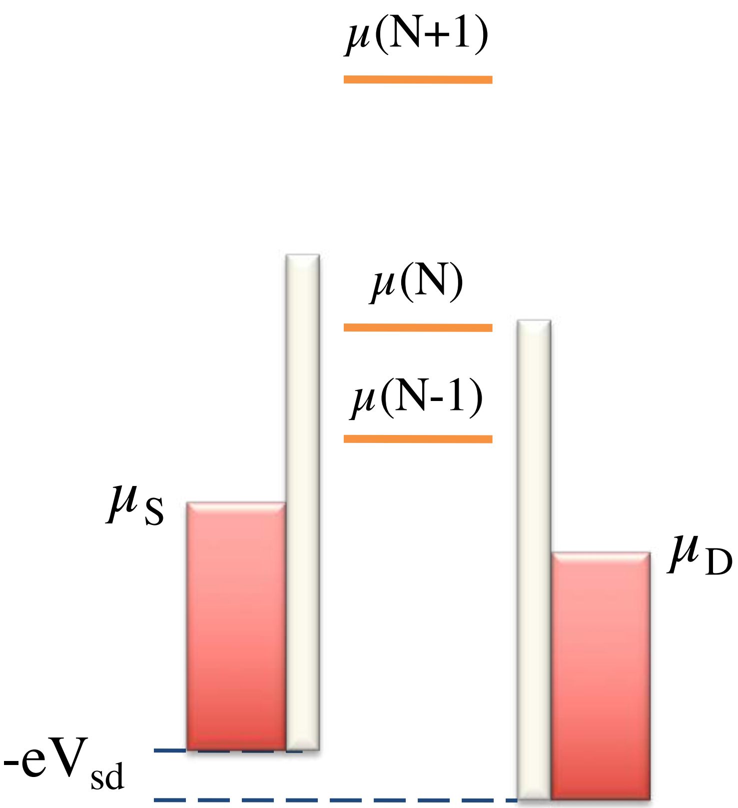
Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998

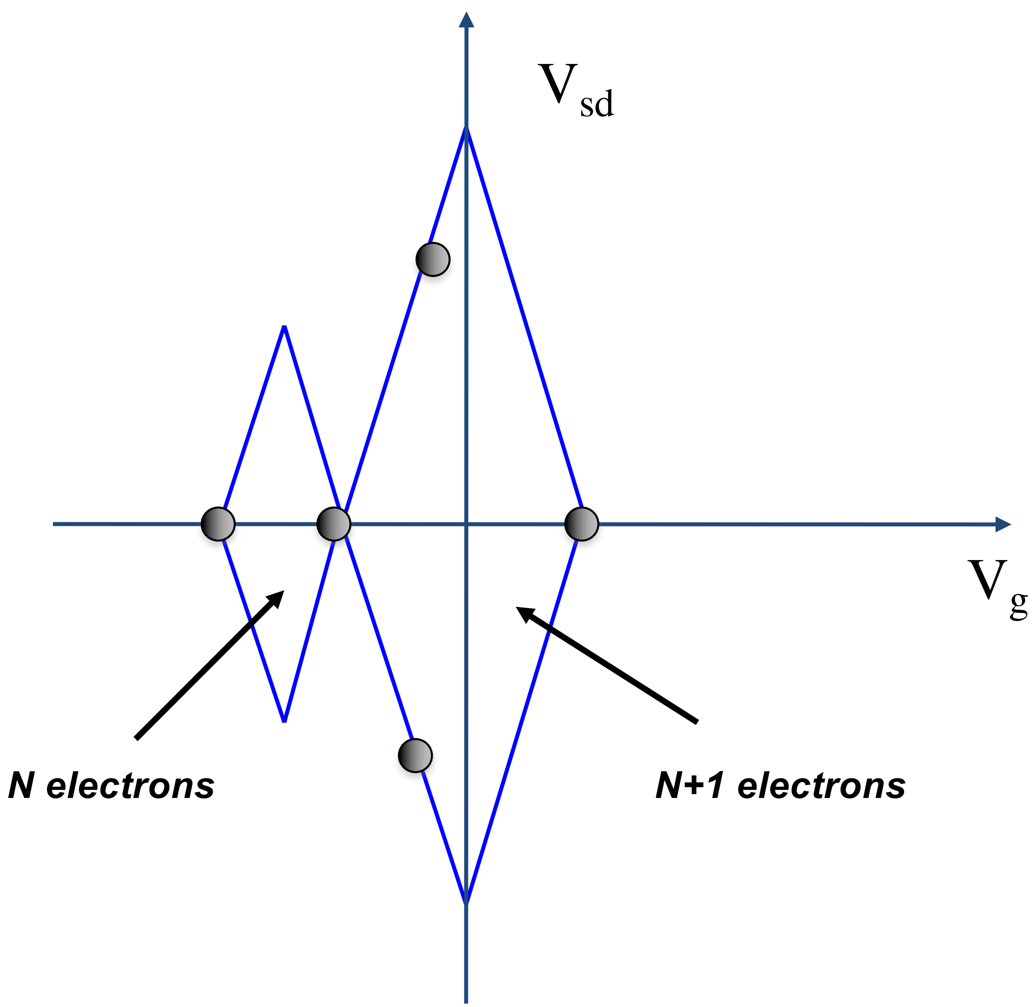








Coulomb Diamond

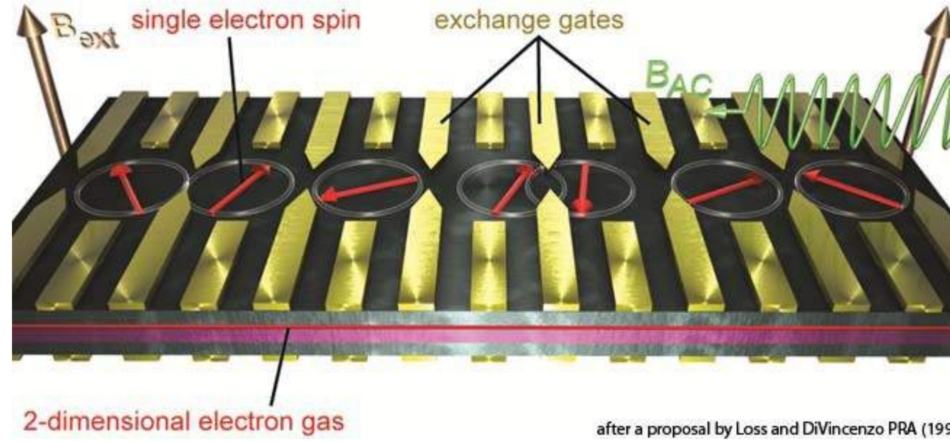


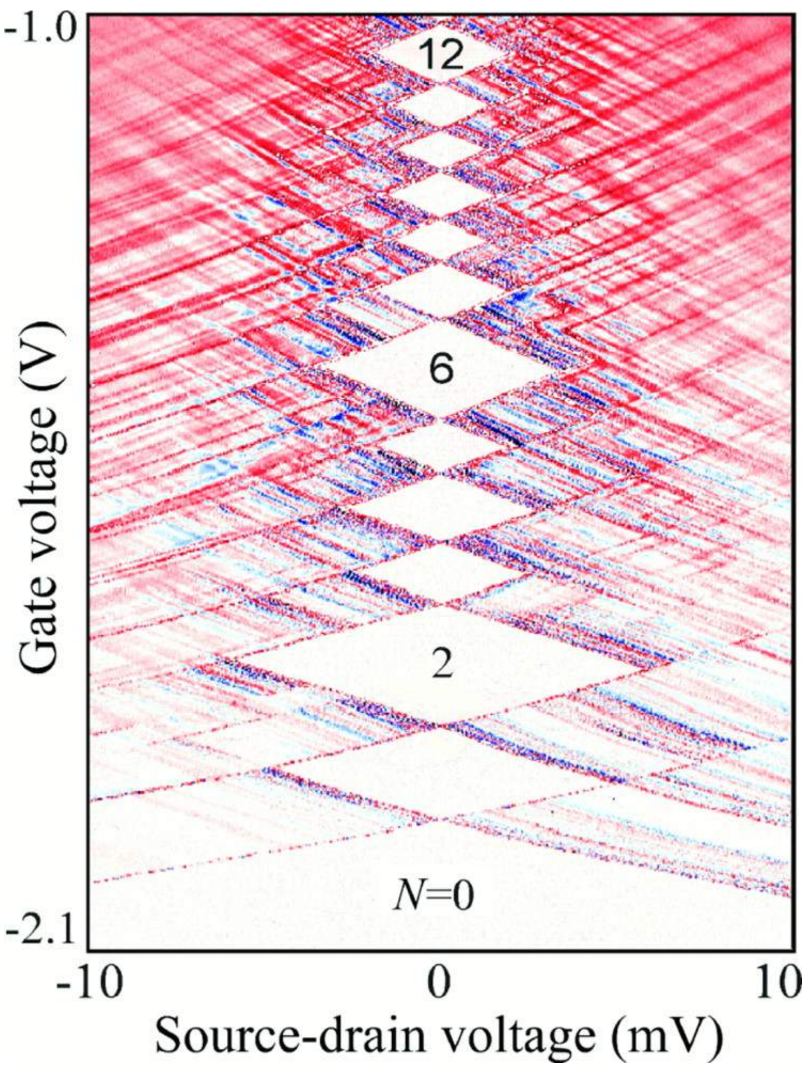
Spin qubits

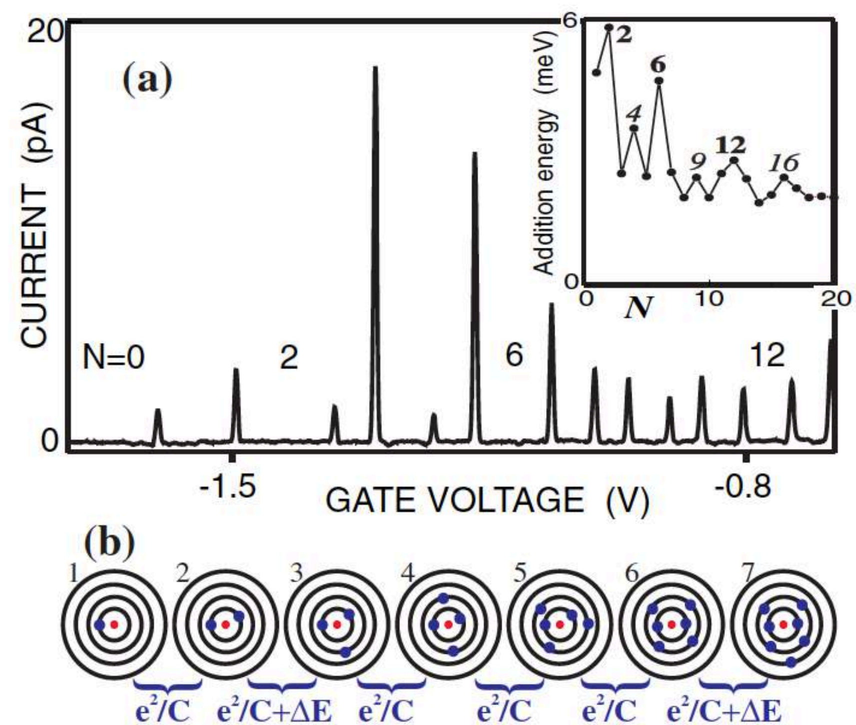
Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo

Phys. Rev. A **57**, 120 – Published 1 January 1998



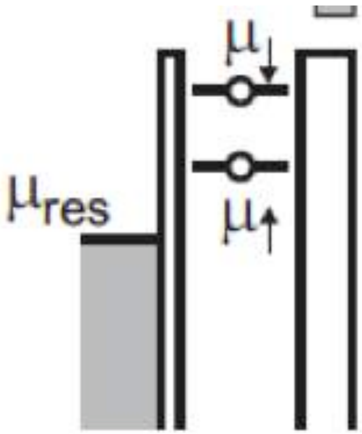


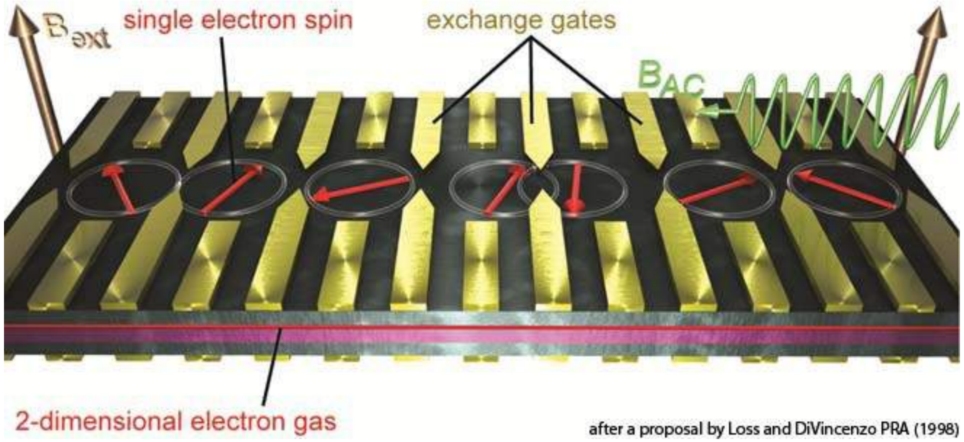


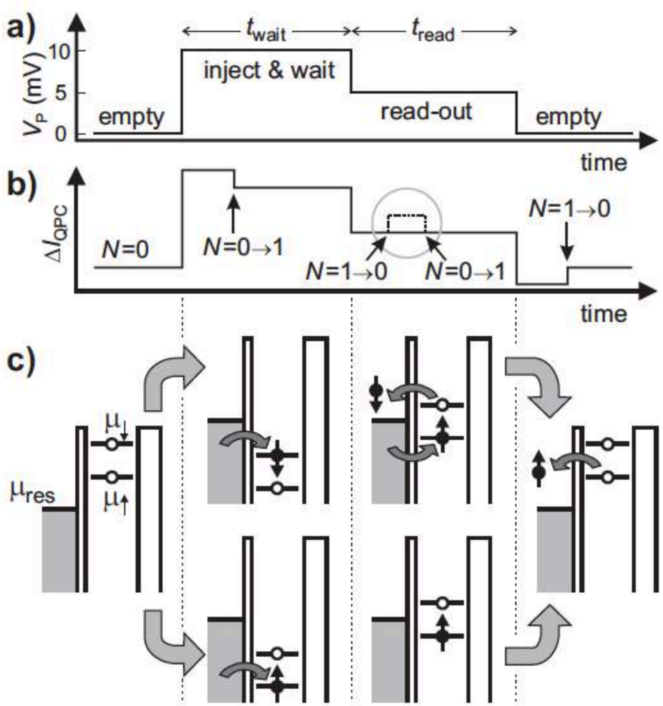
Spin qubits

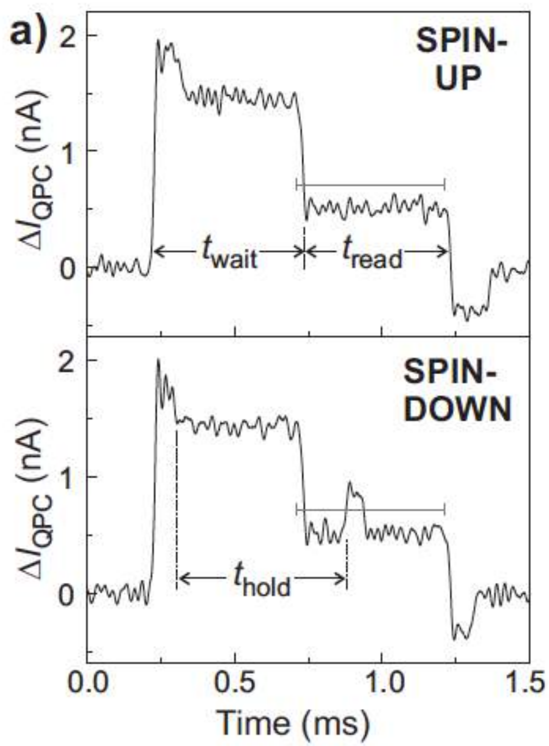
Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998





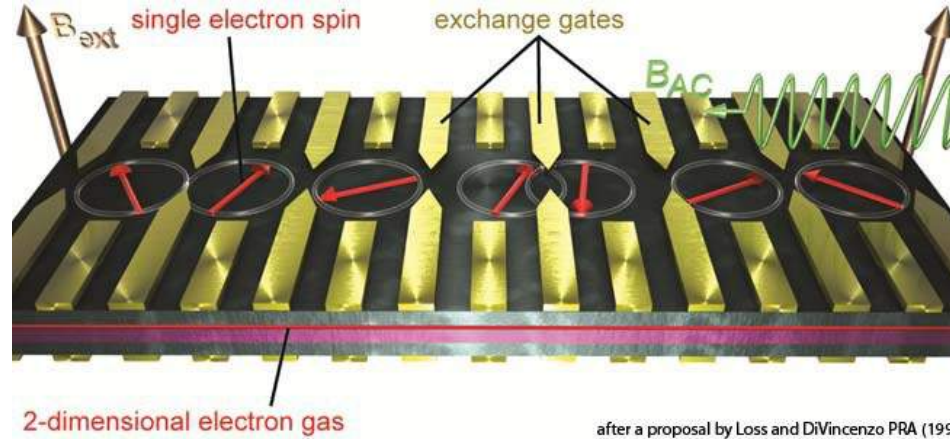


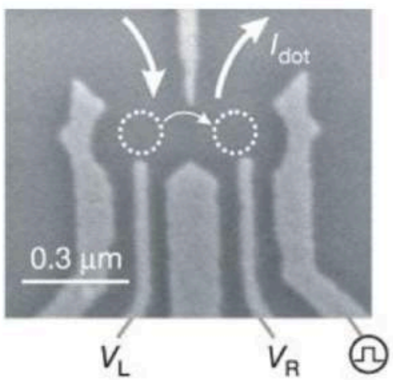


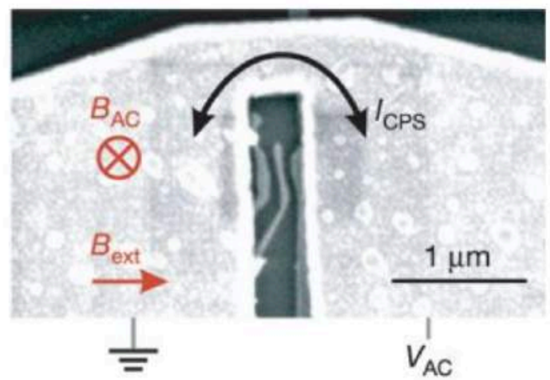
Spin qubits

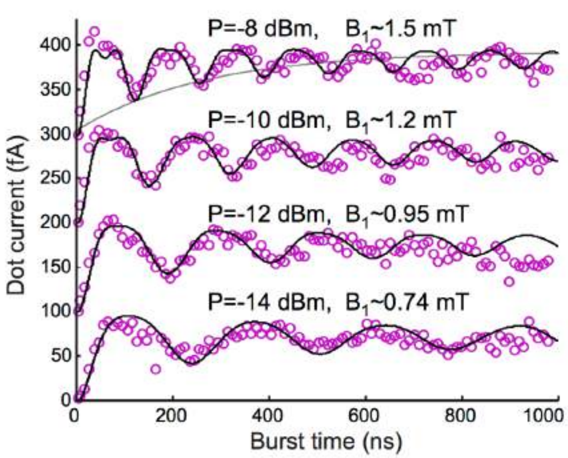
Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998

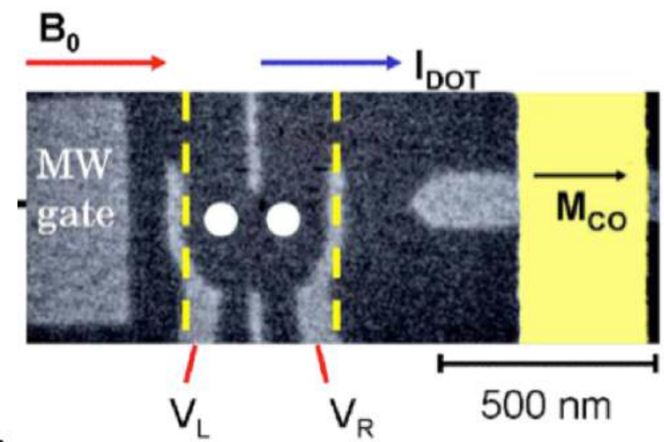


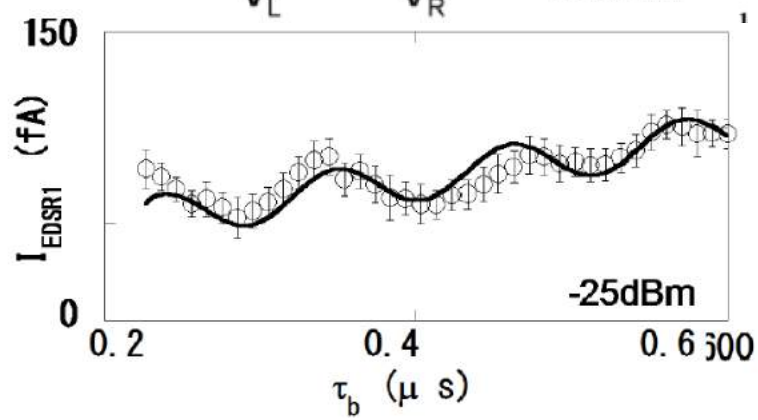






F. Koppens et al. Nature 56 (2006)
Delft University



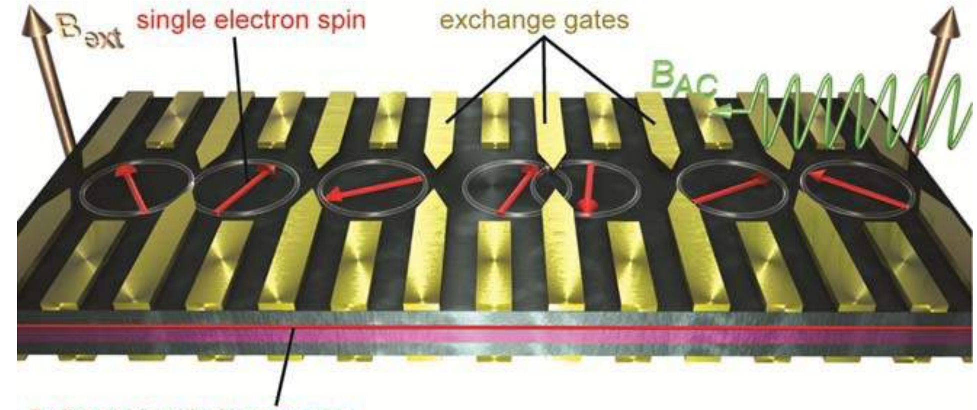


T. Obata et al. Phys. Rev. B 81, 085317
Tokyo

Spin qubits

Quantum computation with quantum dots

Daniel Loss and David P. DiVincenzo
Phys. Rev. A **57**, 120 – Published 1 January 1998



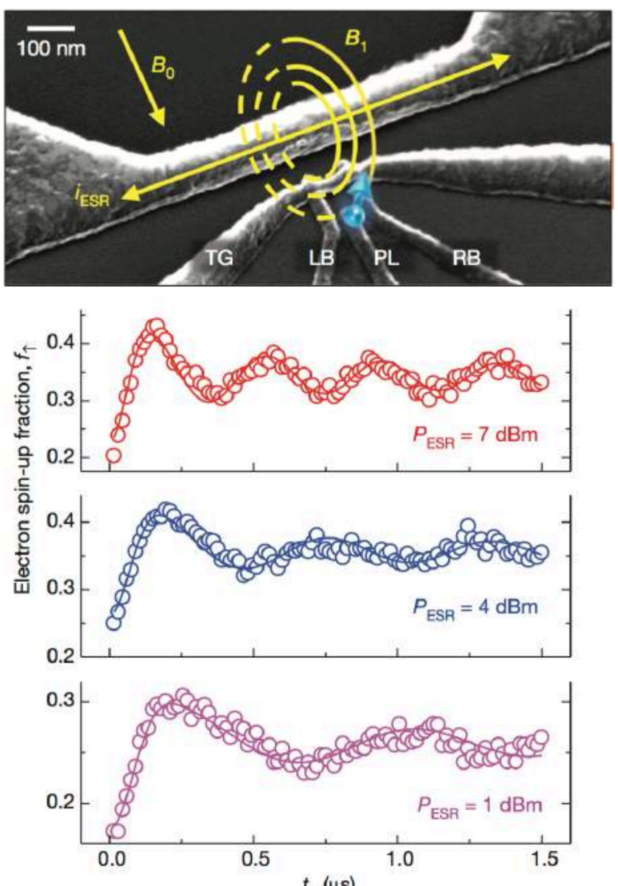
after a proposal by Loss and DiVincenzo PRA (1998)

A single-atom electron spin qubit in silicon

Jarryd J. Pla, Kuan Y. Tan, Juan P. Dehollain, Wee H. Lim, John J. L. Morton, David N. Jamieson, Andrew S. Dzurak & Andrea Morello

Nature **489**, 541–545 (27 September 2012)

Sydney



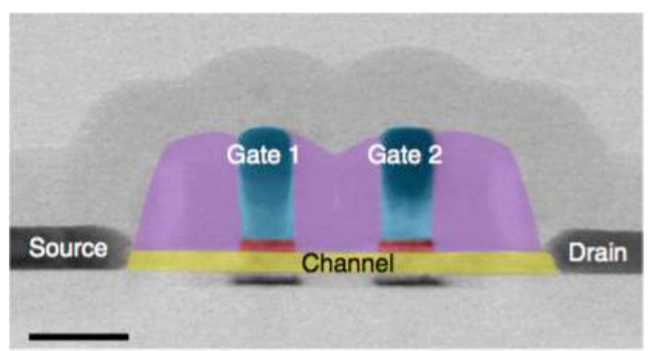
ARTICLE

Received 28 Jul 2016 | Accepted 14 Oct 2016 | Published 24 Nov 2016

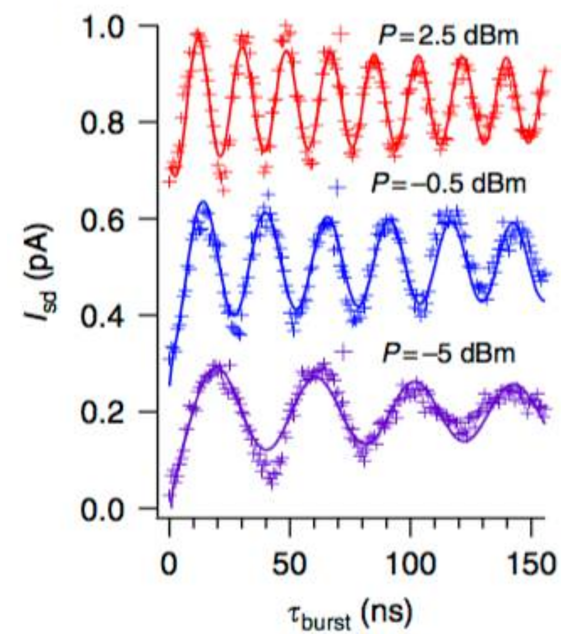
DOI: 10.1038/ncomms13575 OPEN

A CMOS silicon spin qubit

R. Maurand[1,2], X. Jehl[1,2], D. Kotekar-Patil[1,2], A. Corna[1,2], H. Bohuslavskyi[1,2], R. Laviéville[1,3], L. Hutin[1,3], S. Barraud[1,3], M. Vinet[1,3], M. Sanquer[1,2] & S. De Franceschi[1,2]



Grenoble

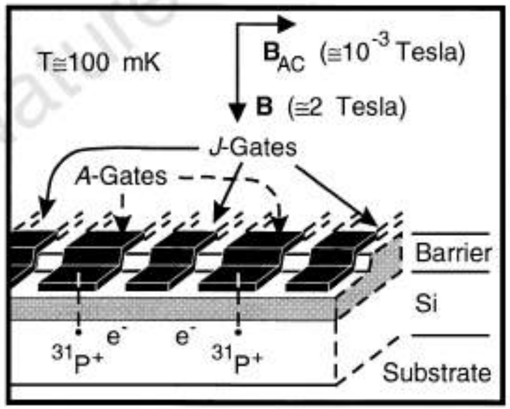


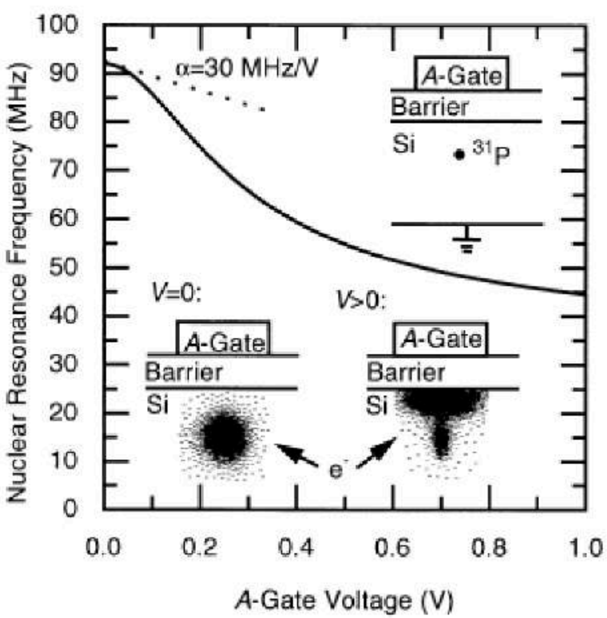
Spin qubits

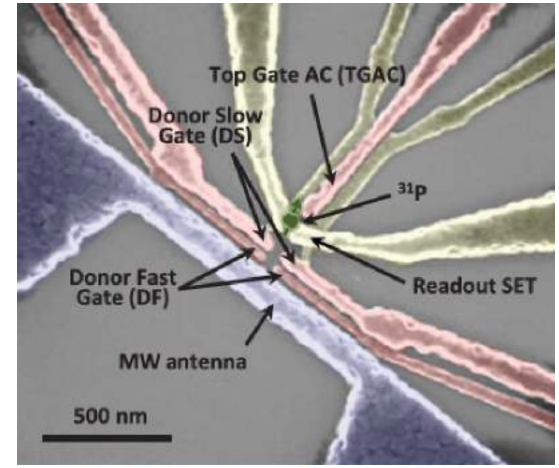
A silicon-based nuclear spin quantum computer

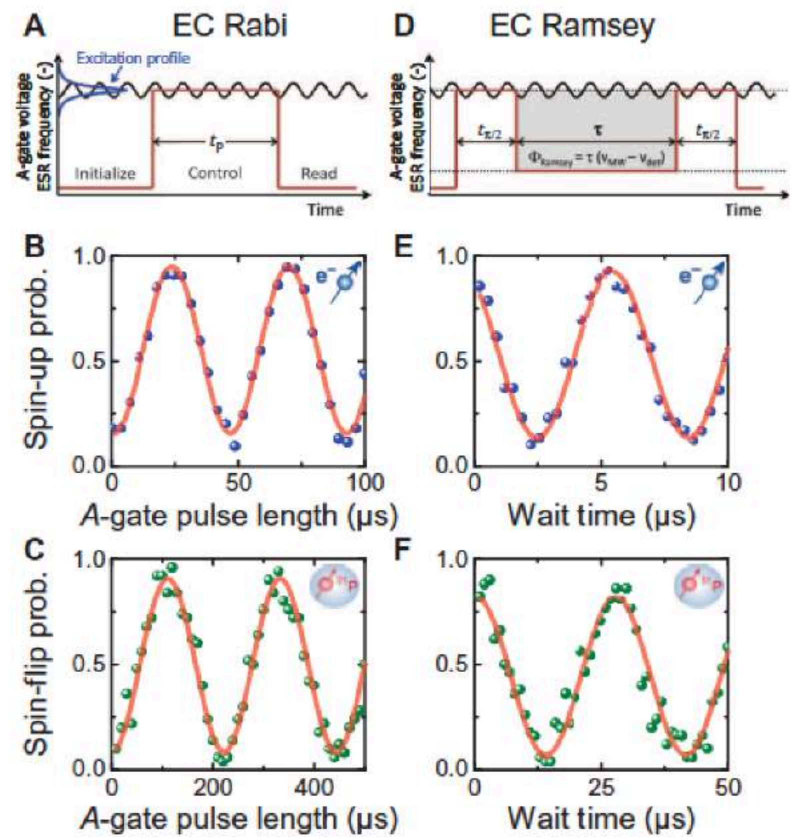
B. E. Kane
Semiconductor Nanofabrication Facility, School of Physics, University of New South Wales, Sydney 2052, Australia

NATURE | VOL 393 | 14 MAY 1998







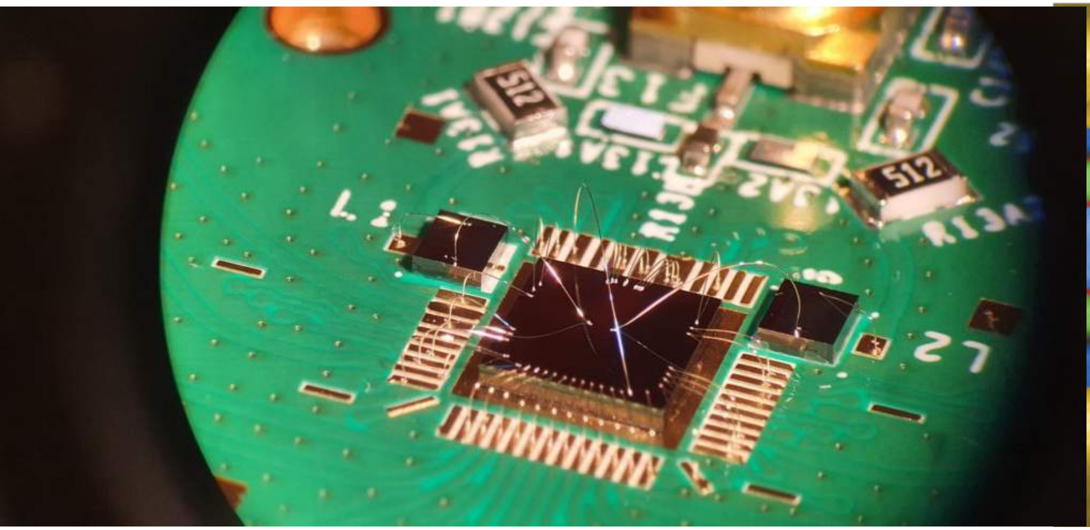


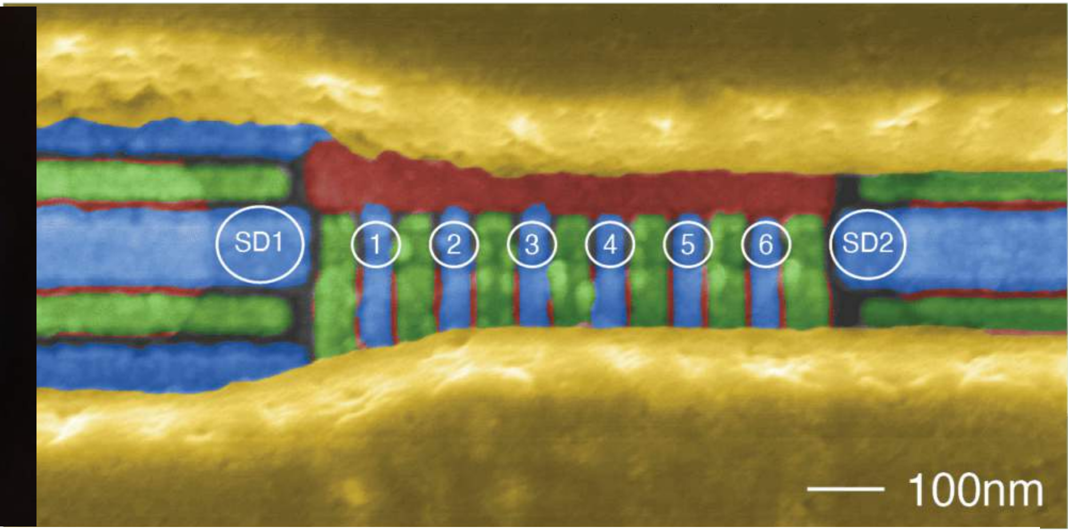
A. Laucht et al. Sci. Adv. (2015)

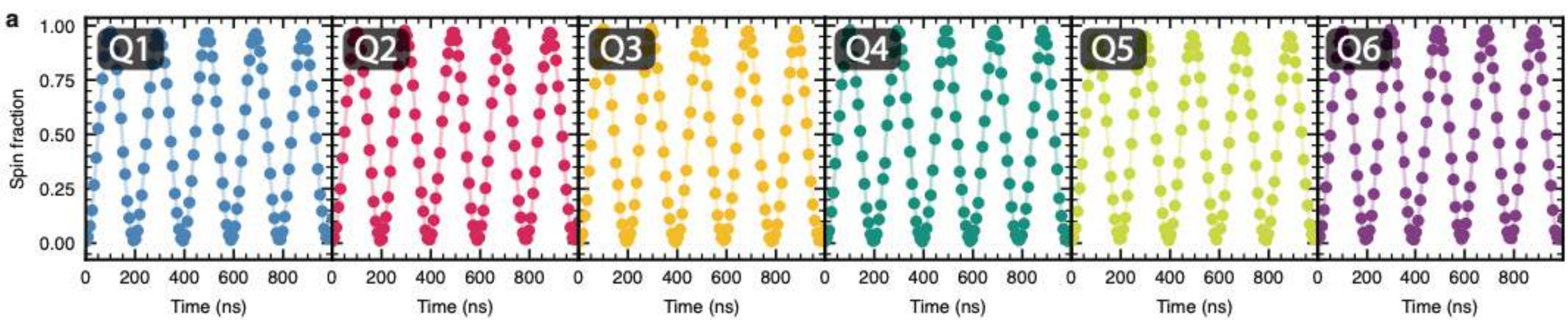
Spin qubits

Universal control of a six-qubit quantum processor in silicon

Stephan G.J. Philips*[1], Mateusz T. Mądzik*[1], Sergey V. Amitonov[1], Sander L. de Snoo[1], Maximilian Russ[1], Nima Kalhor[1], Christian Volk[1], William I.L. Lawrie[1], Delphine Brousse[2], Larysa Tryputen[2], Brian Paquelet Wuetz[1], Amir Sammak[2], Menno Veldhorst[1], Giordano Scappucci[1], and Lieven M.K. Vandersypen† [1]

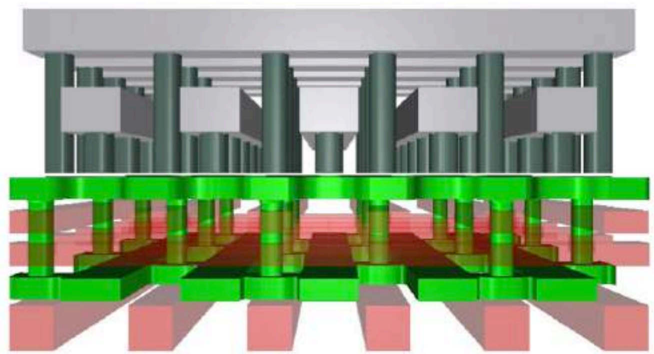




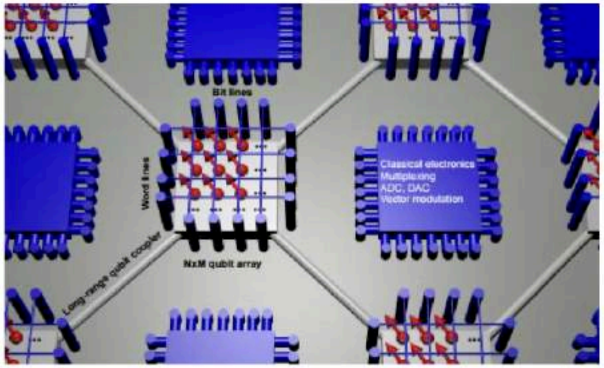


Spin qubits

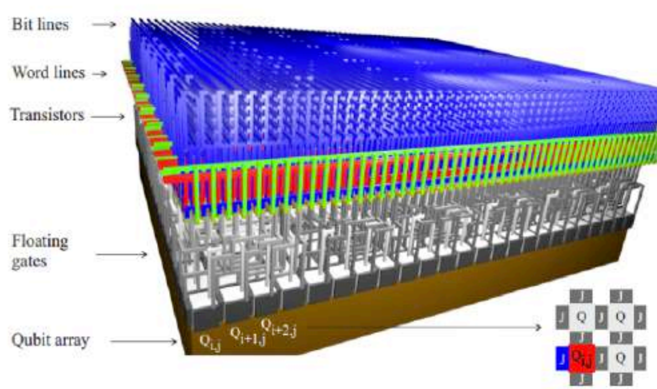
	Si spin
Size	$(100nm)^2$
Fidelity	>98%
Speed	~5 µs
Manufacturing	
Qubit Variability	0.1%-0.5%
Operation T°	1K
Connectivity	4
Entangled qubits	2



M. Vinet et al et al., IEDM (2018)
3D integration of quantum procesor and classical control system

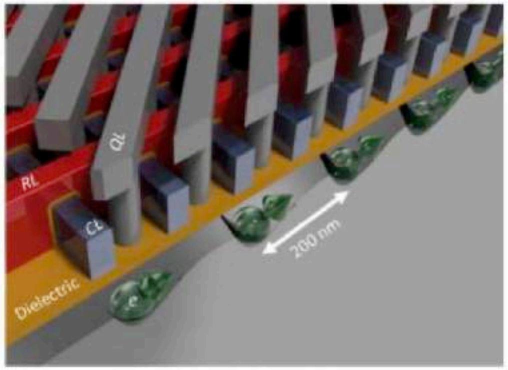


L.M.K. Vandersypen et al., npj Quant. Inf. (2017)
Monolithic coplanar integration of classical and quantum electronics + long range coupling



M. Veldhorst et al. (UNSW), Nature Comm. (2017)

10 transistors and 13 control lines per qubit

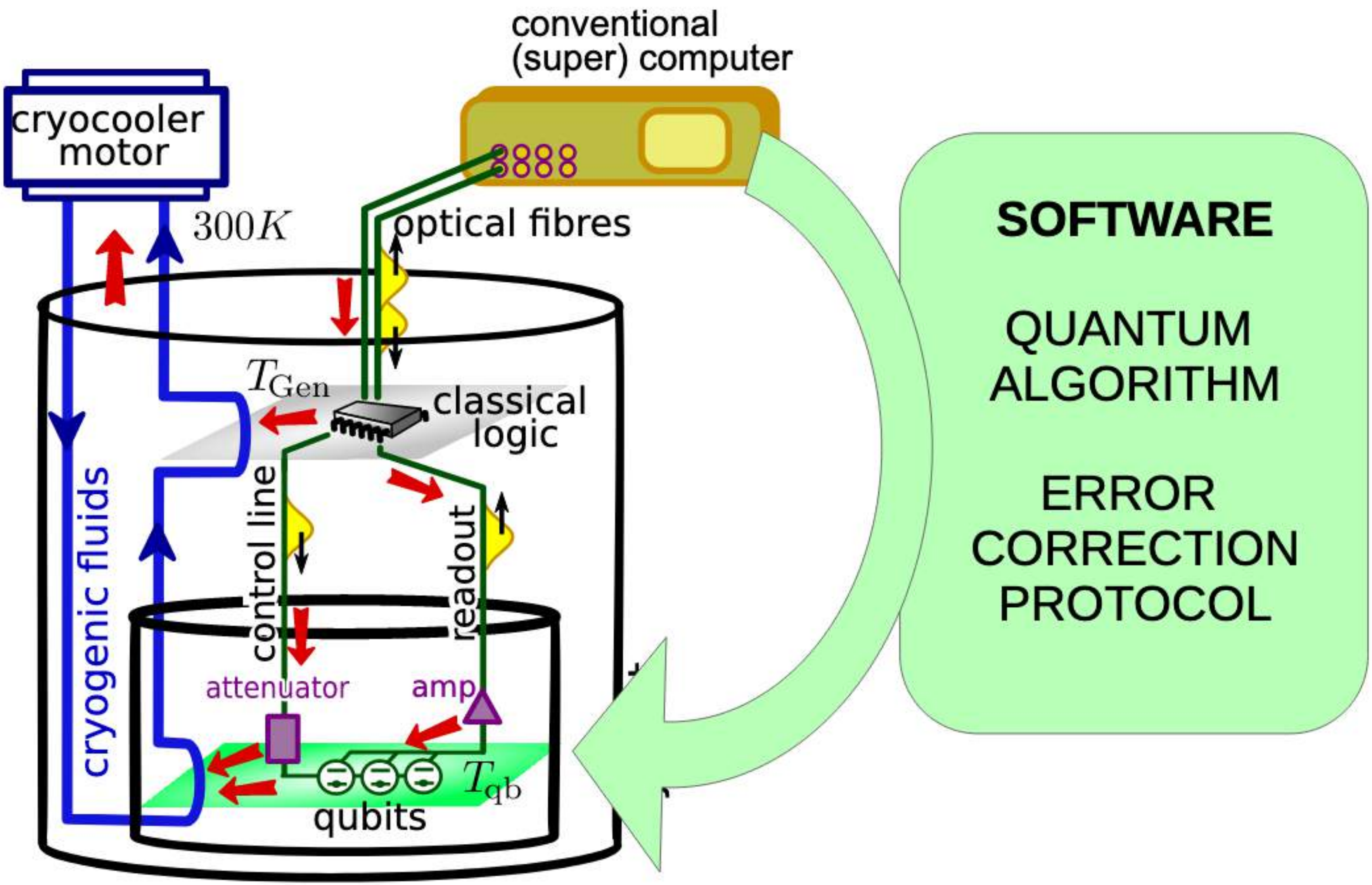


R. Li et al., Science express (2017)

Line/column/diagonal addressing of tunnel barriers and QD potentials

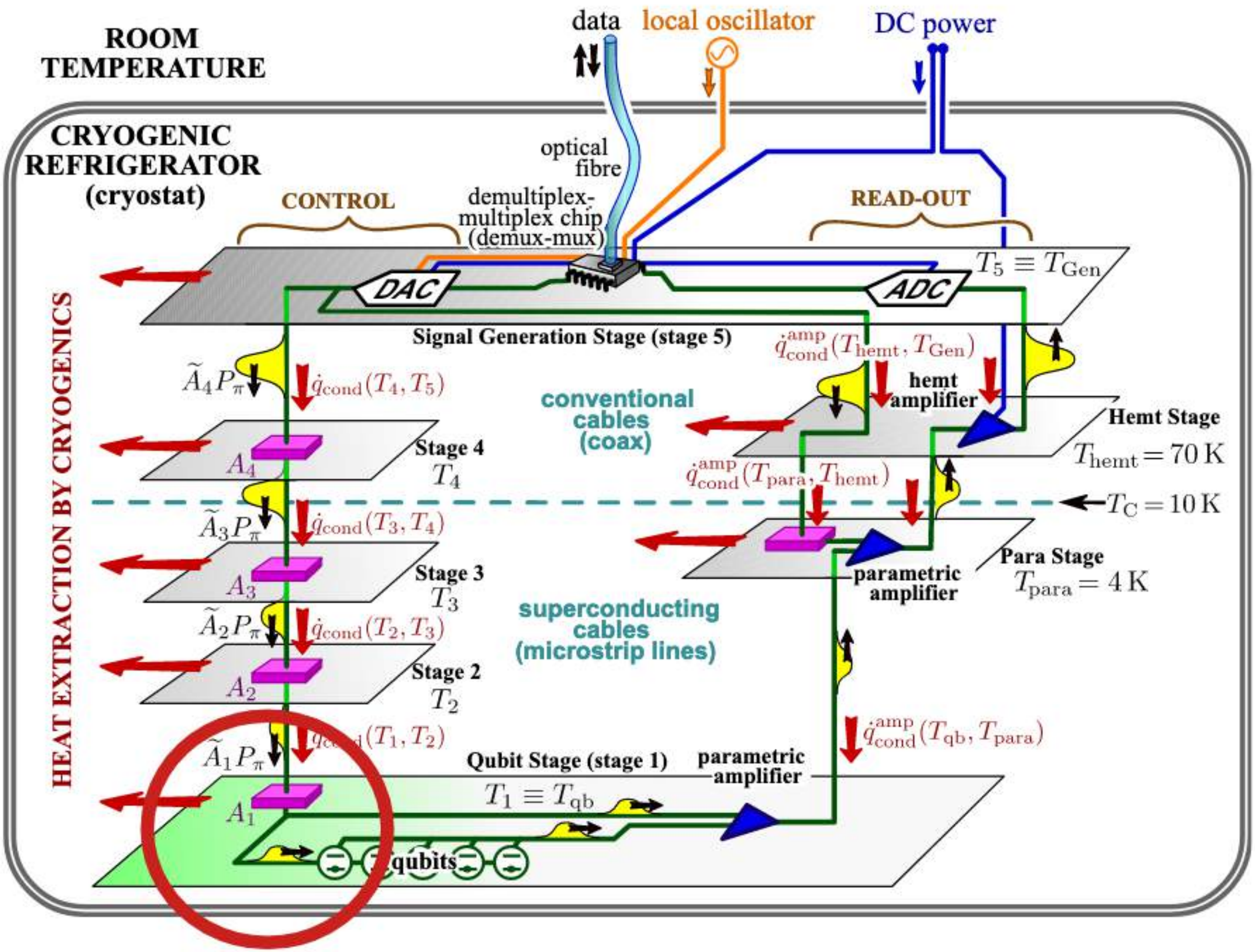
Review: F. Gonzalez-Zalba et al, Arxiv 2021

How to measure qubits



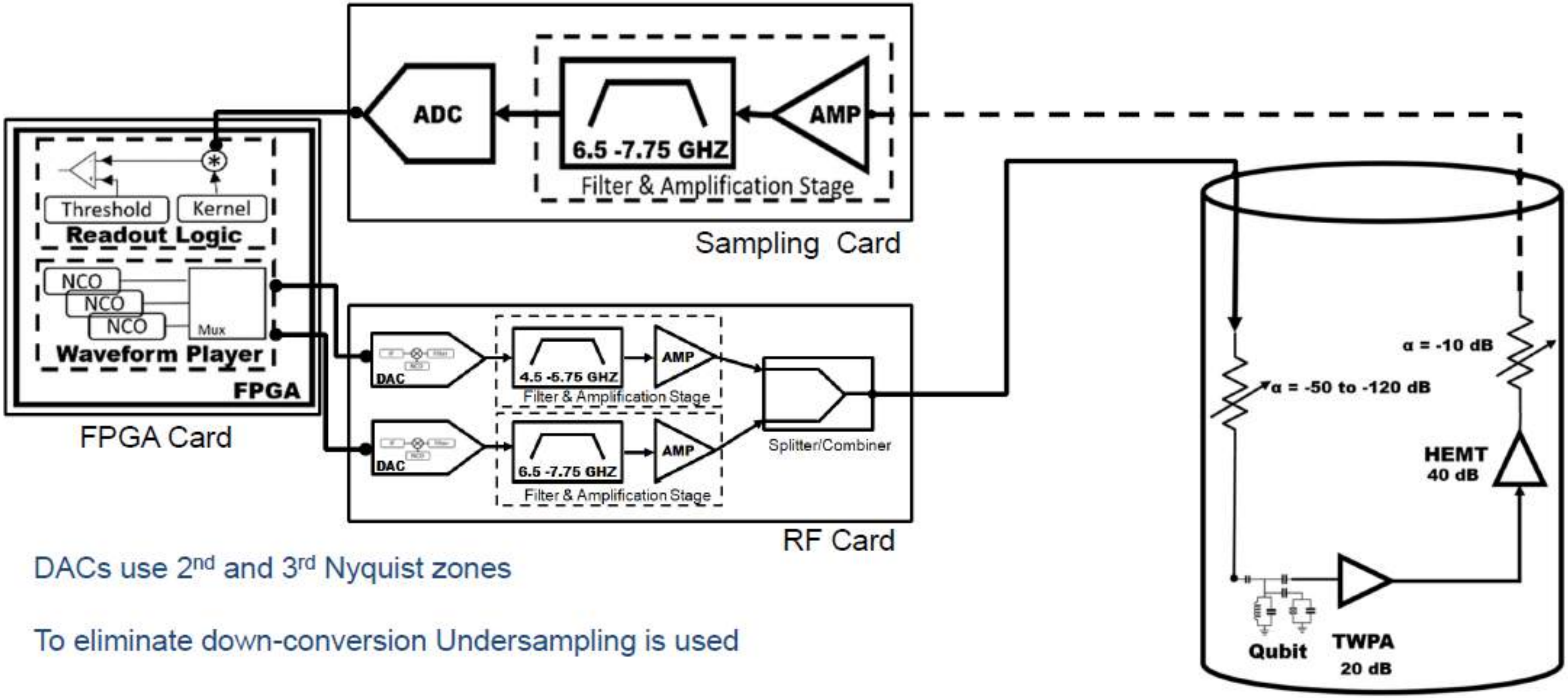
Courtesy of R. Whitney

How to measure qubits



Courtesy of R. Whitney

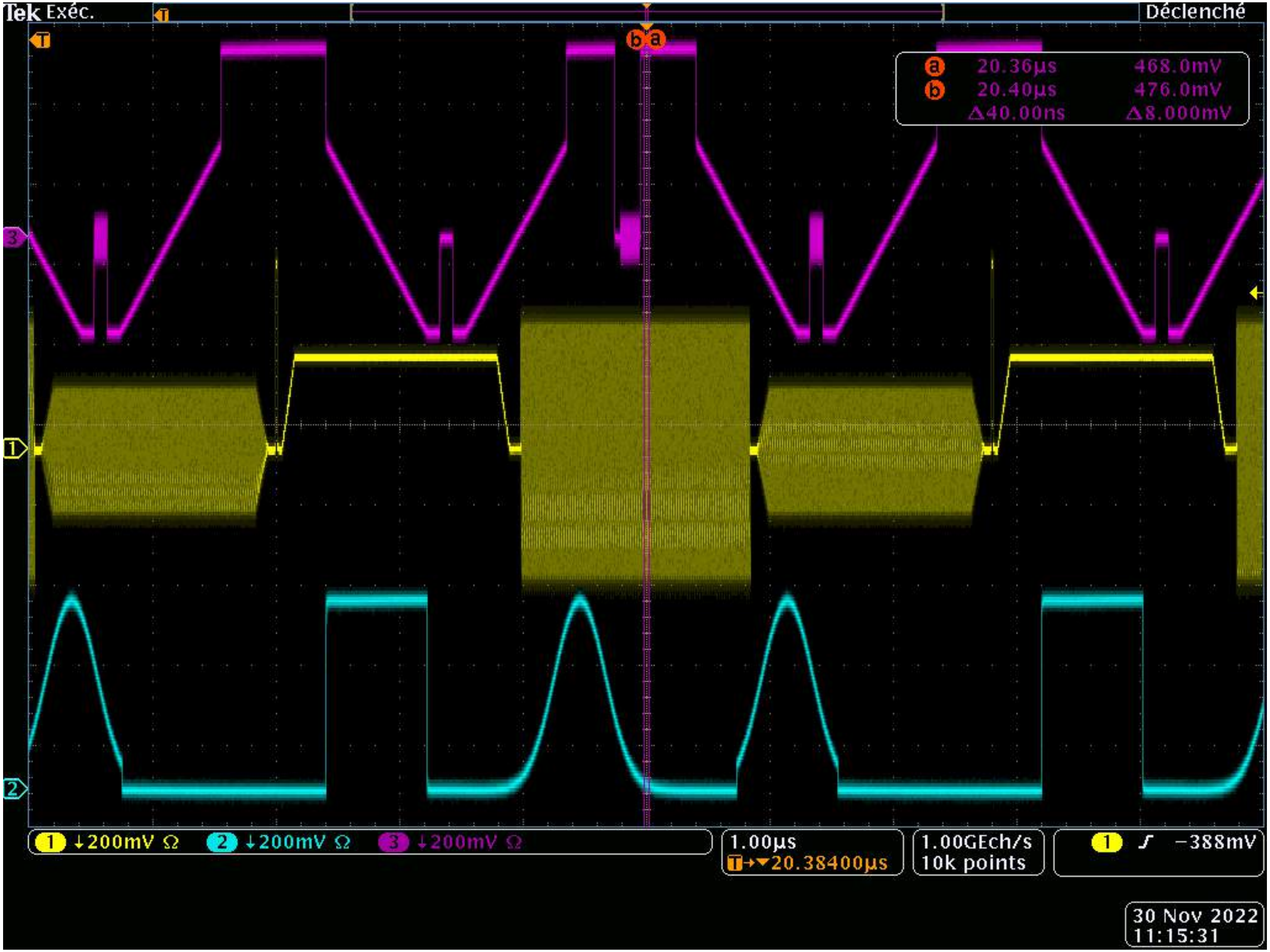
IBM condor(2022)



DACs use 2nd and 3rd Nyquist zones

To eliminate down-conversion Undersampling is used

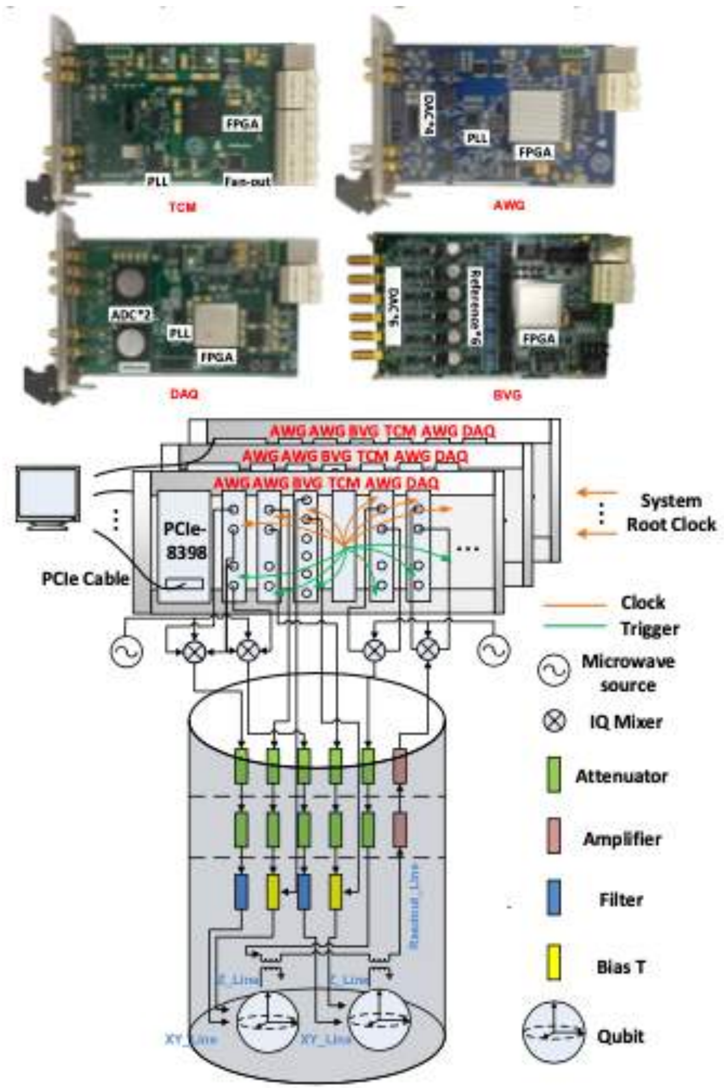
How to measure qubits



How to measure qubits

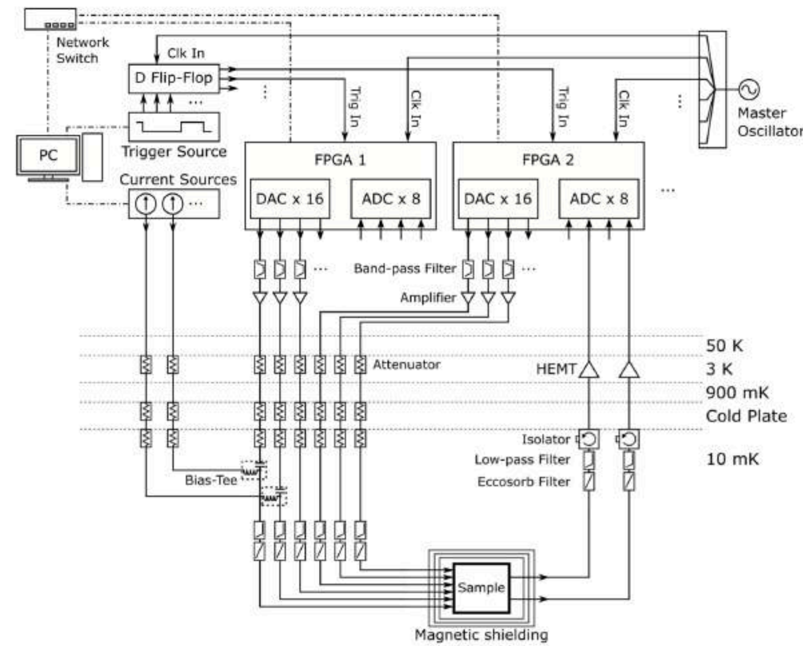
FPGA-based electronic system for the control and readout of superconducting quantum processors

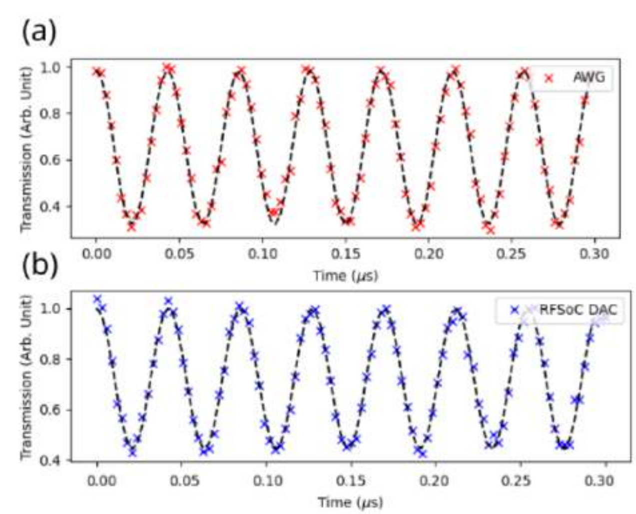
Yuchen Yang,[1,2] Zhongtao Shen,[1,2,a)] Xing Zhu,[3,a)] Ziqi Wang,[1,2] Gengyan Zhang,[3] Jingwei Zhou,[3] Xun Jiang,[3] Chunqing Deng,[3] and Shubin Liu.[1,2]



ICARUS-Q: Integrated Control and Readout Unit for Scalable Quantum Processors

Kun Hee Park,[1] Yung Szen Yap,[2,1,*] Yuanzheng Paul Tan,[3,1] Christoph Hufnagel,[1] Long Hoang Nguyen,[3] Karn Hwa Lau,[4] Patrick Bore,[1] Stavros Efthymiou,[5] Stefano Carrazza,[6,7,5] Rangga P. Budoyo,[1] and Rainer Dumke[1,3,†]





Qubits

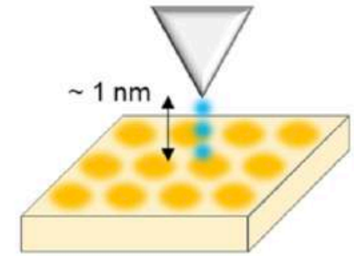
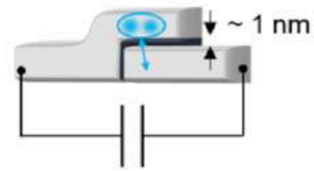
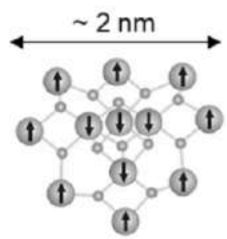
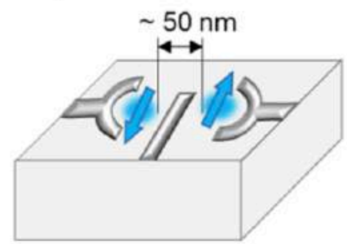
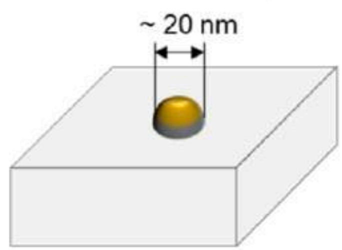
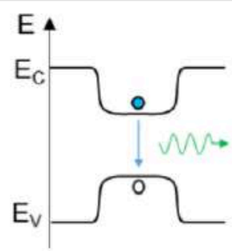
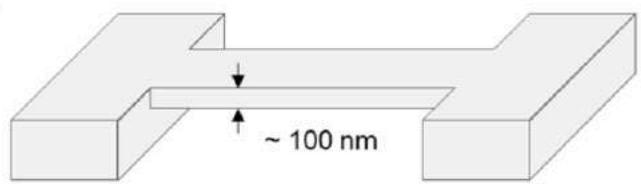
	Superconductor	Si spin	Trapped ions	Photons	NV centers
Size	$(100\mu m)^2$	$(100nm)^2$	$(1mm)^2$	$\sim(100\mu m)^2$	$\sim(100\mu m)^2$
Fidelity	~99.3%	>98%	99.9%	50% (mesure) 98% (portes)	98% (probabilistic)
Speed	250 ns	~5 µs	100 µs	1 ms	100ms
Manufacturing					
Qubit Variability	3%	0.1%-0.5%	0.0001%	0.5%	0.001%
Operation T°	50mK	1K	300K	4K	4K
Connectivity	15	4	10	2	5
Entangled qubits	53	2	20	18	20

Quelle technologie pour la construction d'un ordinateur quantique?

F. Balestro, UGA-CNRS, Néel Institut, QuantECA
Quantum Electronics Circuits Alps

Who knows ??

Qubits

charge			$f \sim 1 - 10$ GHz $Q \sim 10^4 - 10^7$ $t_{op} \sim 0.1 - 100$ ns $T_2 \sim 1 - 100$ μs (superconductors) $1 - 100$ ns (semiconductors)
spin			$f \sim 1 - 50$ GHz (electrons) $1 - 100$ MHz (nuclei) $Q \sim 10^4 - 10^7$ $t_{op} \sim 10 - 1000$ ns (electrons) $1 - 100$ μs (nuclei) $T_2 \sim 100$ ns – 1 s (electrons) 0.1 ms – 100 s (nuclei)
photons			$f \sim 10^5 - 10^6$ GHz $Q \sim 10^5 - 10^6$
mechanics			$f \sim 0.01 - 5$ GHz $Q \sim 10^6 - 10^{10}$

Nanoscience in the quantum limit

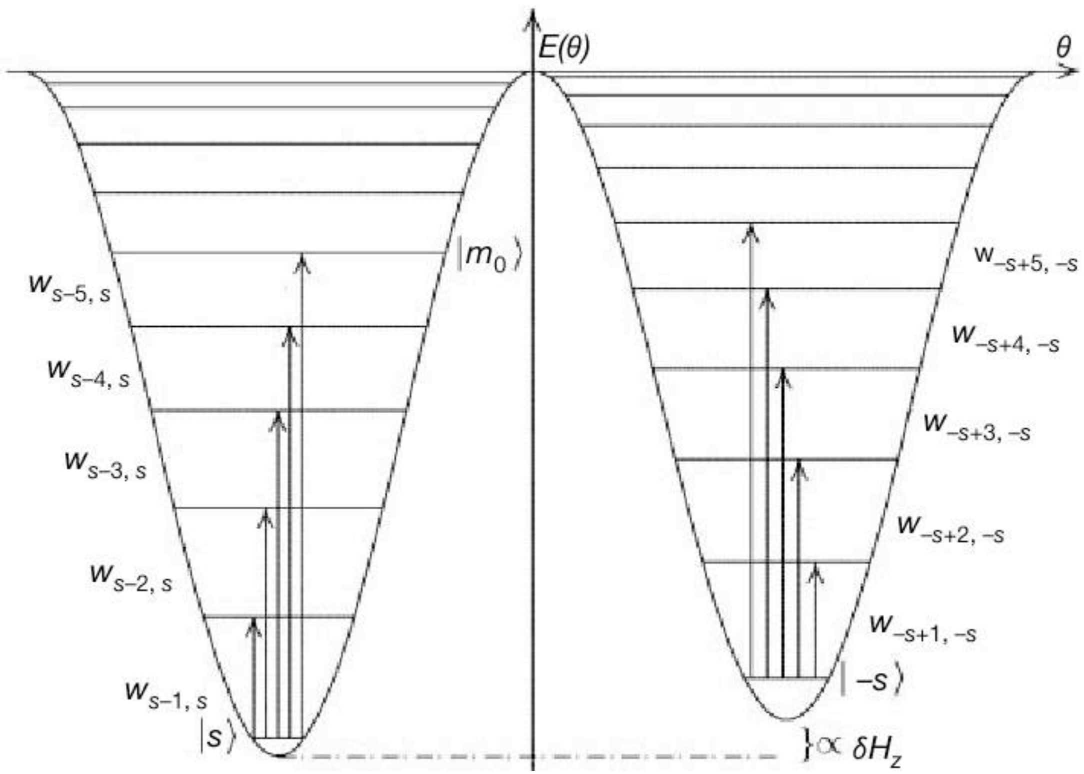
Andreas J. Heinrich[1,2], William D. Oliver[3,4], Lieven Vandersypen[5], Arzhang Ardavan[6], Roberta Sessoli[7], Daniel Loss[8], Ania Bleszynski Jayich[9], Joaquin Fernandez-Rossier[10,11], Arne Laucht[12], and Andrea Morello[12]

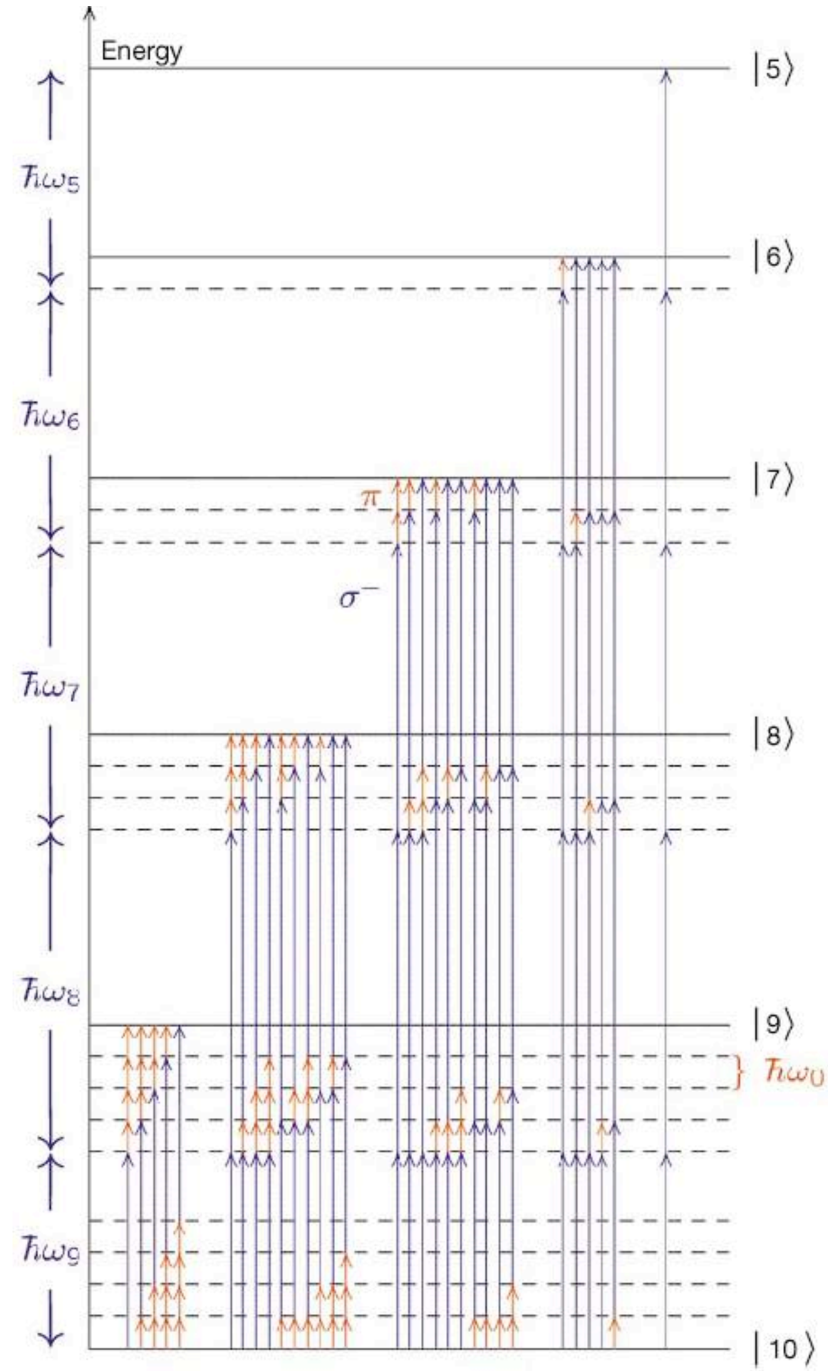
Quantum computing with multi-levels qubits

Michael N. Leuenberger & Daniel Loss
NATURE, 410, 791 (2001)

- implementation of Grover's algorithm

- fast electron spin resonance pulses can be used to decode and read out stored numbers of up to 10^5 with access times as short as 0.1 nanoseconds.



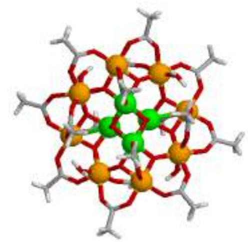


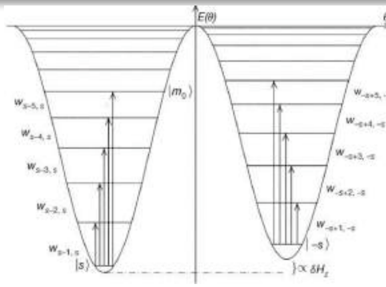
Molecular magnets as spin qubits

Quantum computing in molecular magnets

Michael N. Leuenberger & Daniel Loss

Nature **410**, 789–793 (12 April 2001)

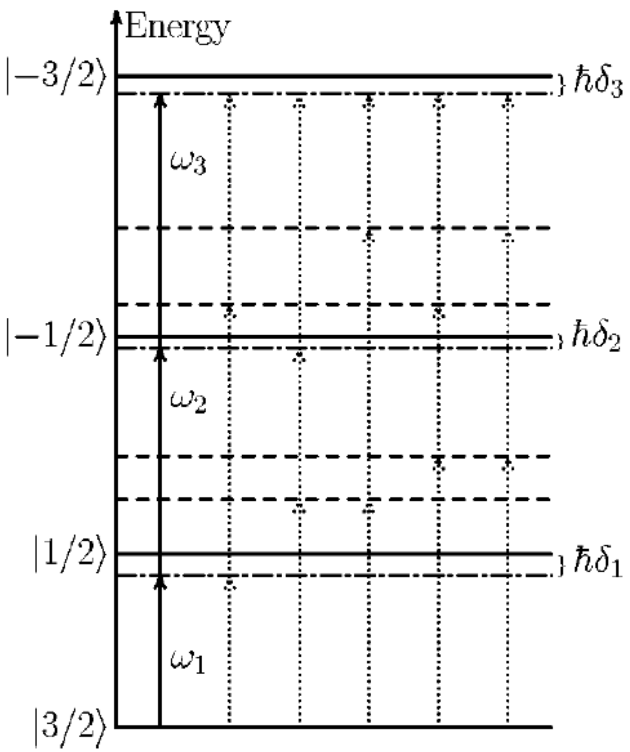




Grover, *PRL* 1997 :

As a result, the desired phone number can be obtained in only $O(\sqrt{N})$ accesses to the database.

« Grover algorithm for large nuclear spin in semiconductors » Leuenberger *et al.* PRB 2003



Grover

Find 1 among N elements :
Classically : N/2 in average
Grover algorithm : Sqrt (N)

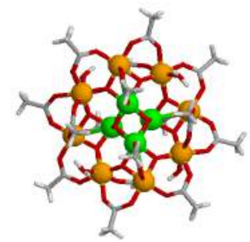
- **4 level quantum system**
- **Quadrupolar term**
- **Coherent manipulation of each transition**
- **Rabi frequency ≈ Resonance width**

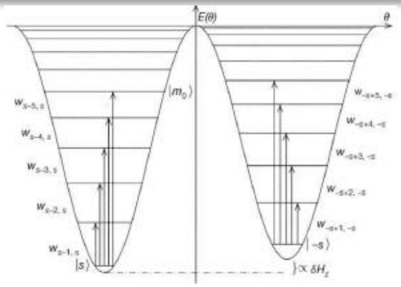
Grover algorithm

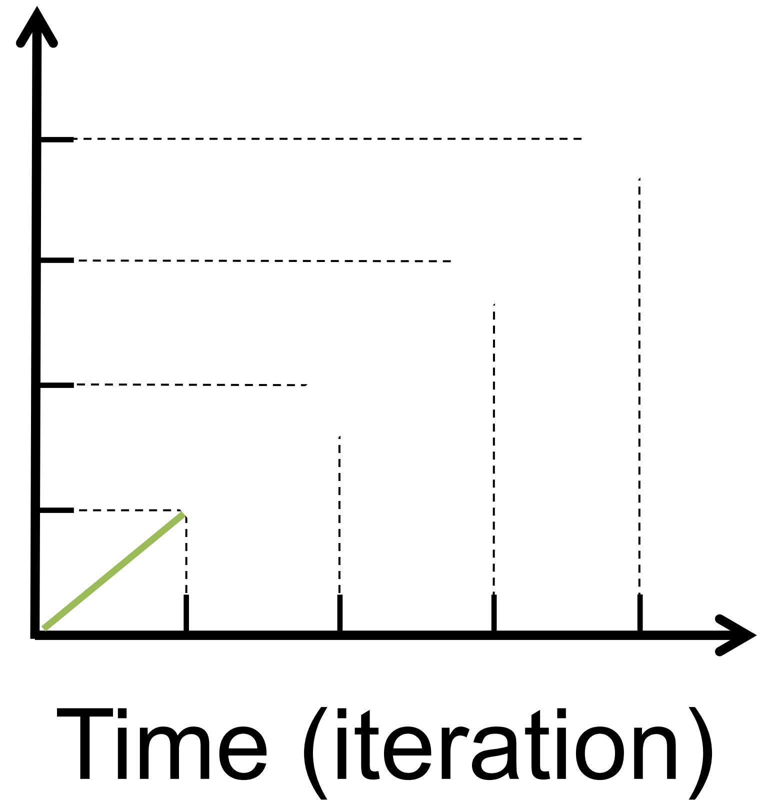
Quantum computing in molecular magnets

Michael N. Leuenberger & Daniel Loss

Nature **410**, 789–793 (12 April 2001)





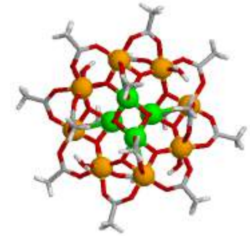


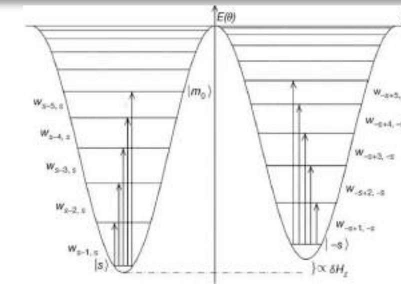
Grover algorithm

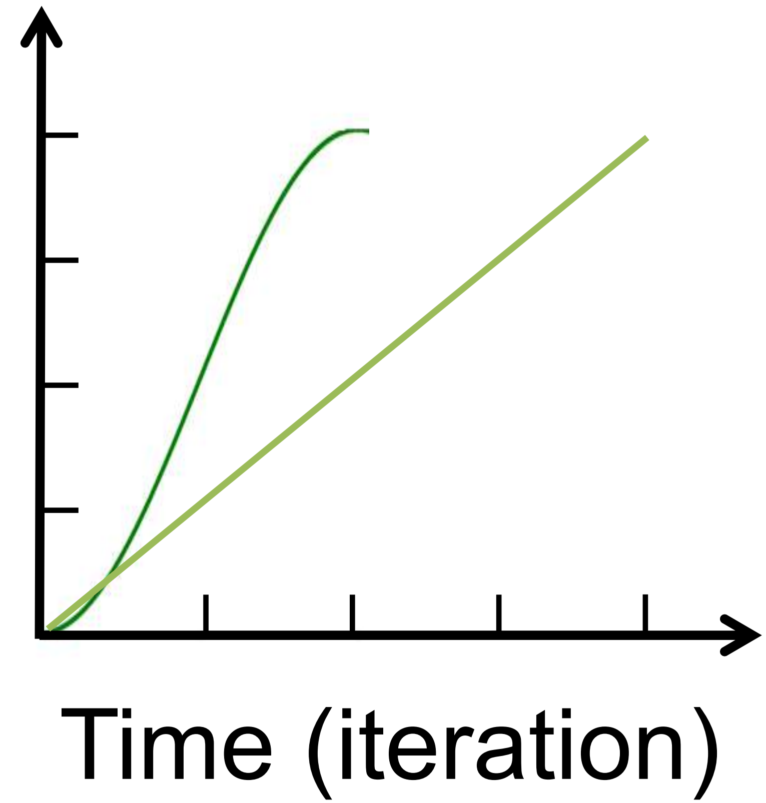
Quantum computing in molecular magnets

Michael N. Leuenberger & Daniel Loss

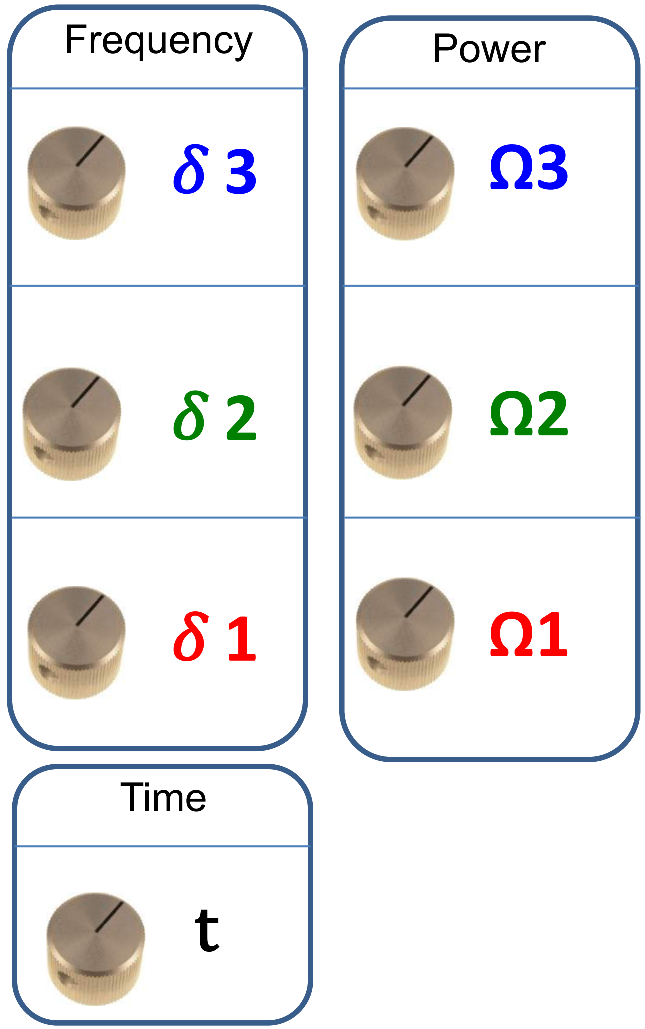
Nature **410**, 789–793 (12 April 2001)

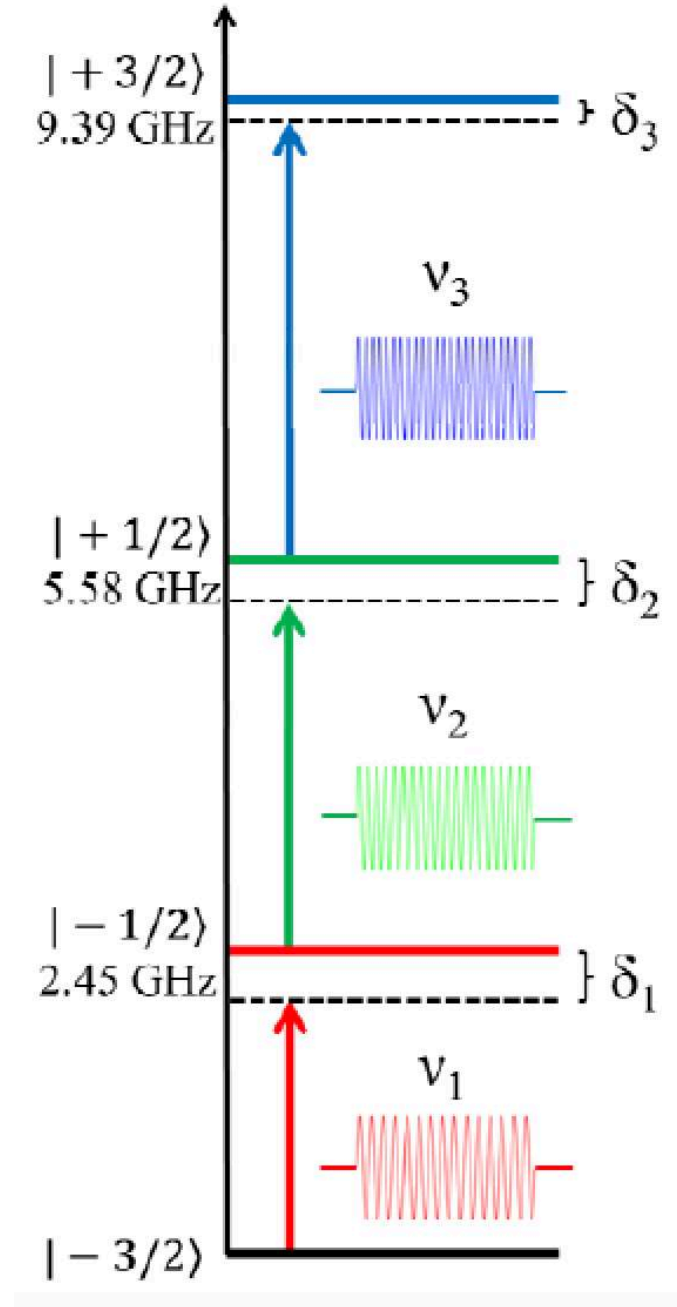






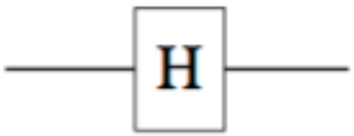
Single Nuclear Spin Manipulation

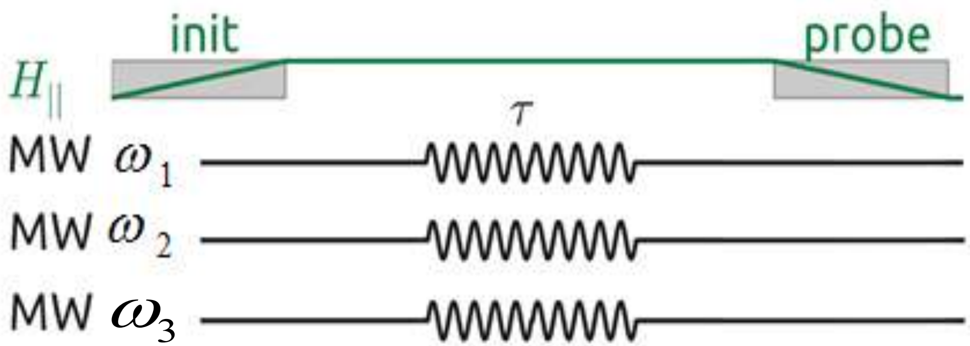


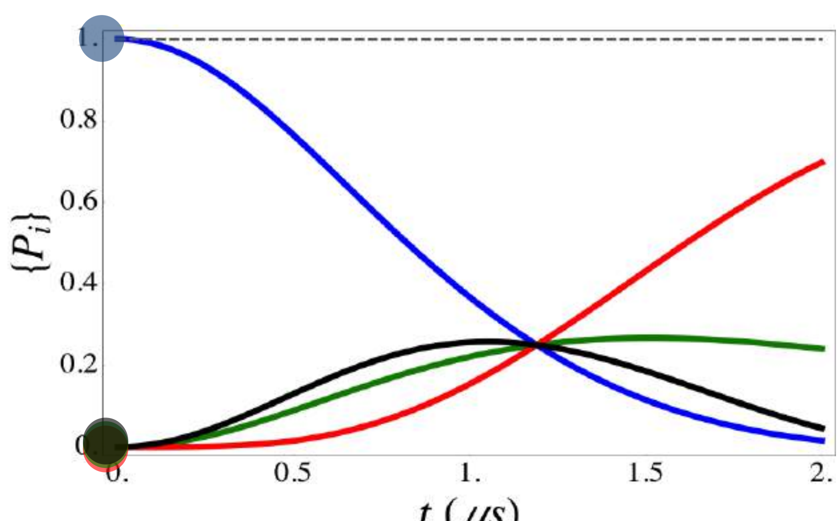


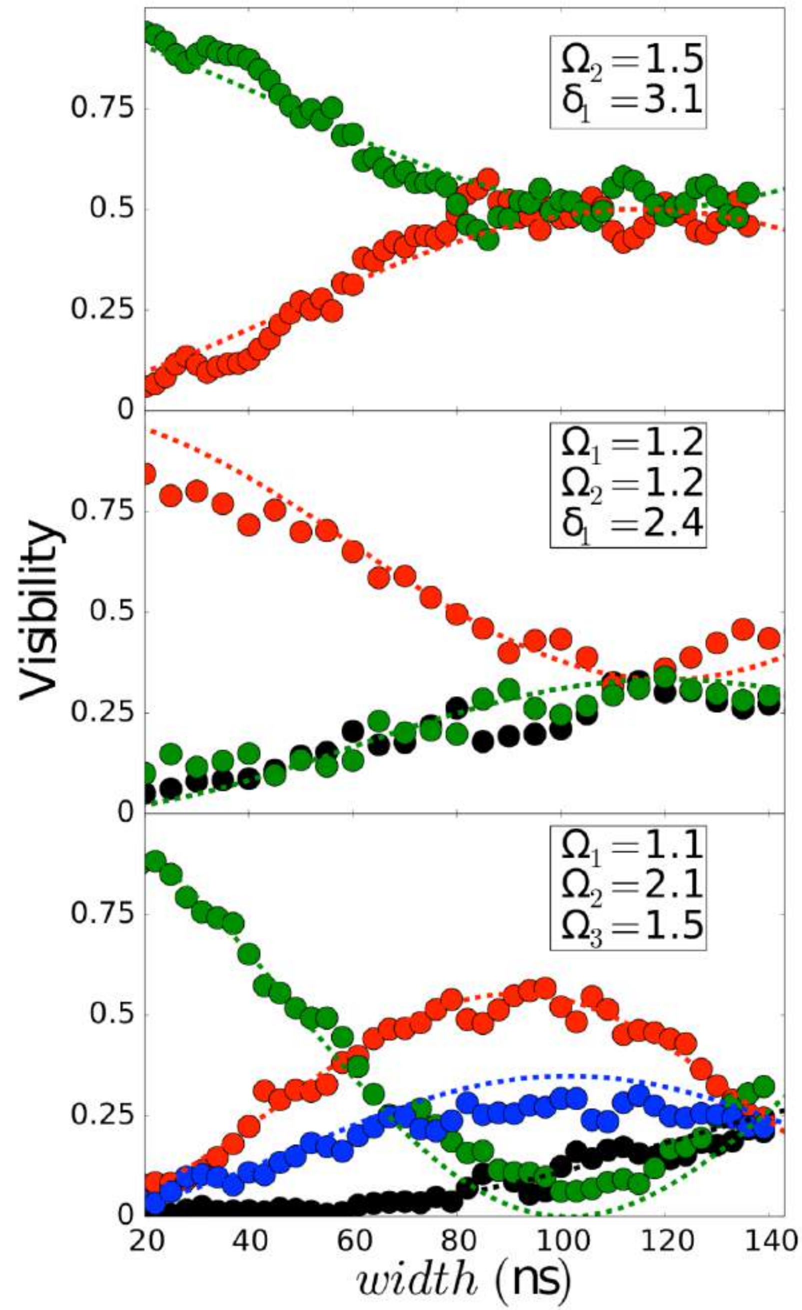
C. Godfrin *et al.* *Phys. Rev. Lett.* **119**, 187702 (2017).
E. Moreno-Pineda *et al.* *Chem. Soc. Rev.* **47**, 501 (2018)

Hadamard gate



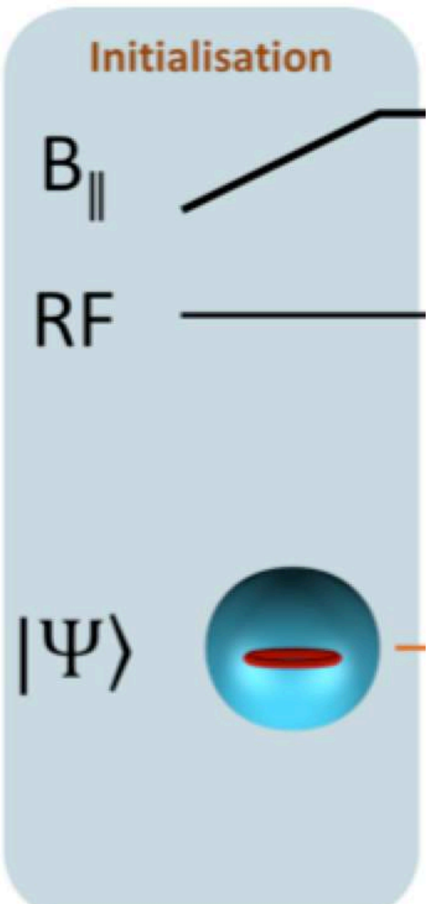






C. Godfrin *et al.* *Phys. Rev. Lett.* **119**, 187702 (2017).

Grover Algorithm



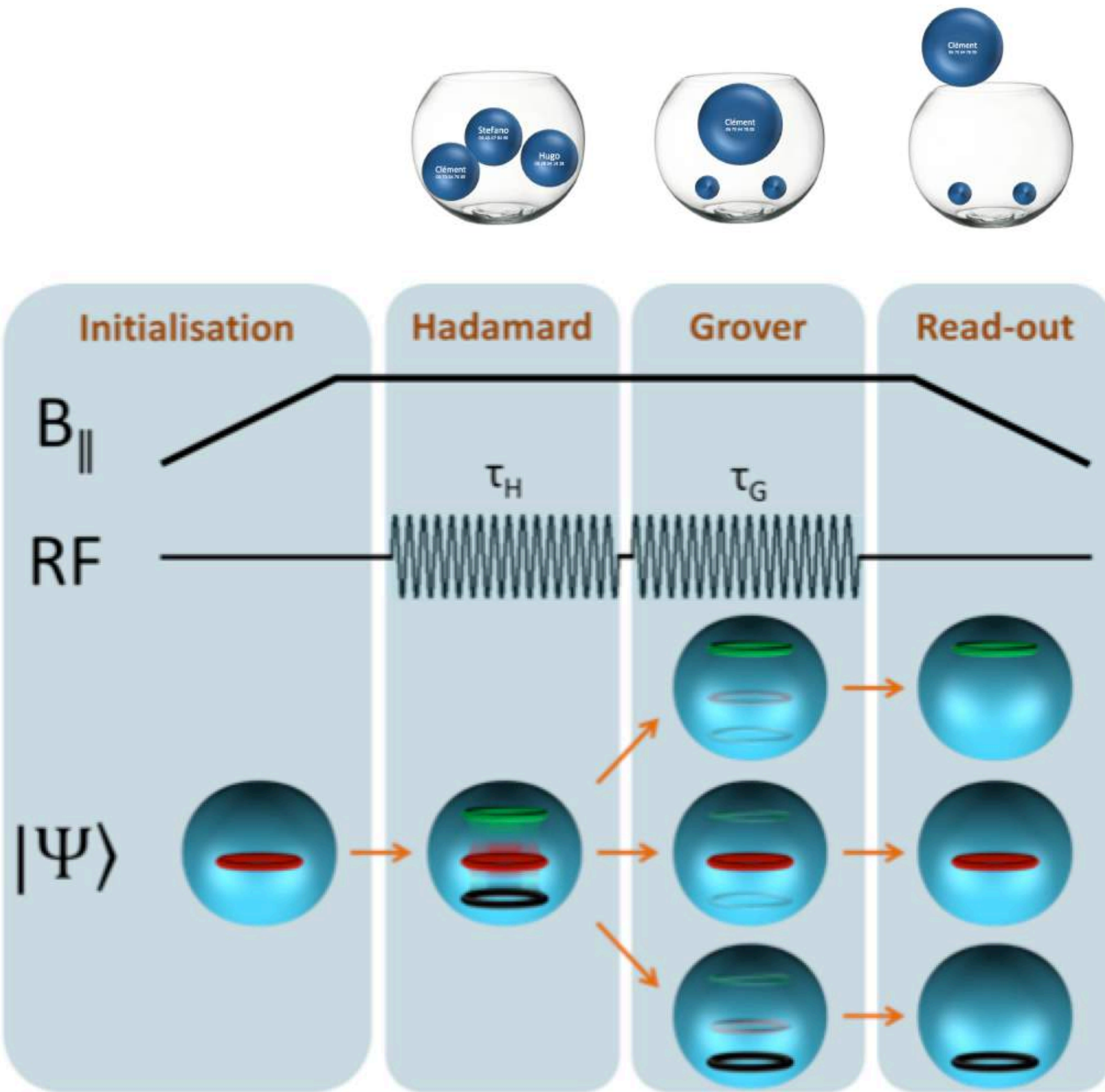
$$\begin{pmatrix} 0 & \Omega 1 & 0 & 0 \\ \Omega 1 & 0 & \Omega 2 & 0 \\ 0 & \Omega 2 & \delta g & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

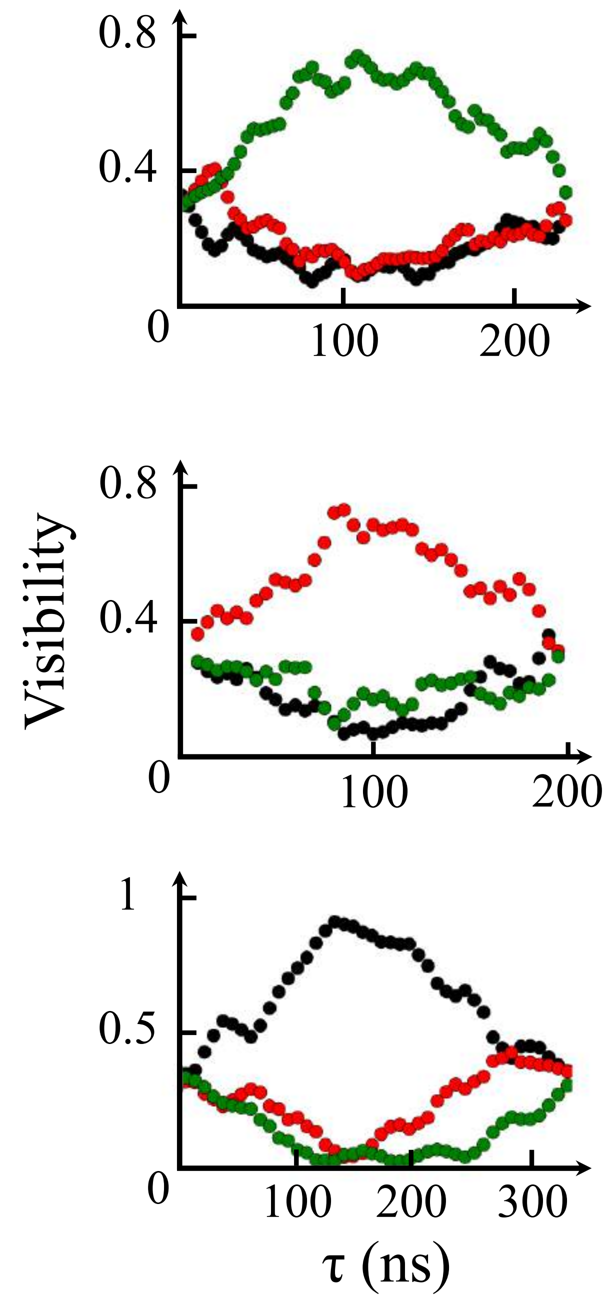
$$\begin{pmatrix} 0 & \Omega 1 & 0 & 0 \\ \Omega 1 & \delta g & \Omega 2 & 0 \\ 0 & \Omega 2 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

$$\begin{pmatrix} \delta g & \Omega 1 & 0 & 0 \\ \Omega 1 & 0 & \Omega 2 & 0 \\ 0 & \Omega 2 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

C. Godfrin *et al.* *Phys. Rev. Lett.* **119**, 187702 (2017).
E. Moreno-Pineda *et al.* *Chem. Soc. Rev.* **47**, 501 (2018)

Grover Algorithm





C. Godfrin *et al.* *Phys. Rev. Lett.* **119**, 187702 (2017).
E. Moreno-Pineda *et al.* *Chem. Soc. Rev.* **47**, 501 (2018)