Introduction of an introduction to quantum technology and quantum computing. Understanding the meaning of quantum supremacy claimed in Nature 574 (2019) 504

Gines MARTINEZ
Directeur de Recherche du CNRS
Subatech

On en parle partout !

La France fonce dans la révolution quantique

Puissante et mystérieuse, la physique quantique a donné naissance à l'électronique, au laser, à l'IRM. Elle provoque aujourd'hui une nouvelle révolution, que la France ne veut pas manquer.

Dans l'univers quantique, un chat peut être à la fois mort et vivant, un

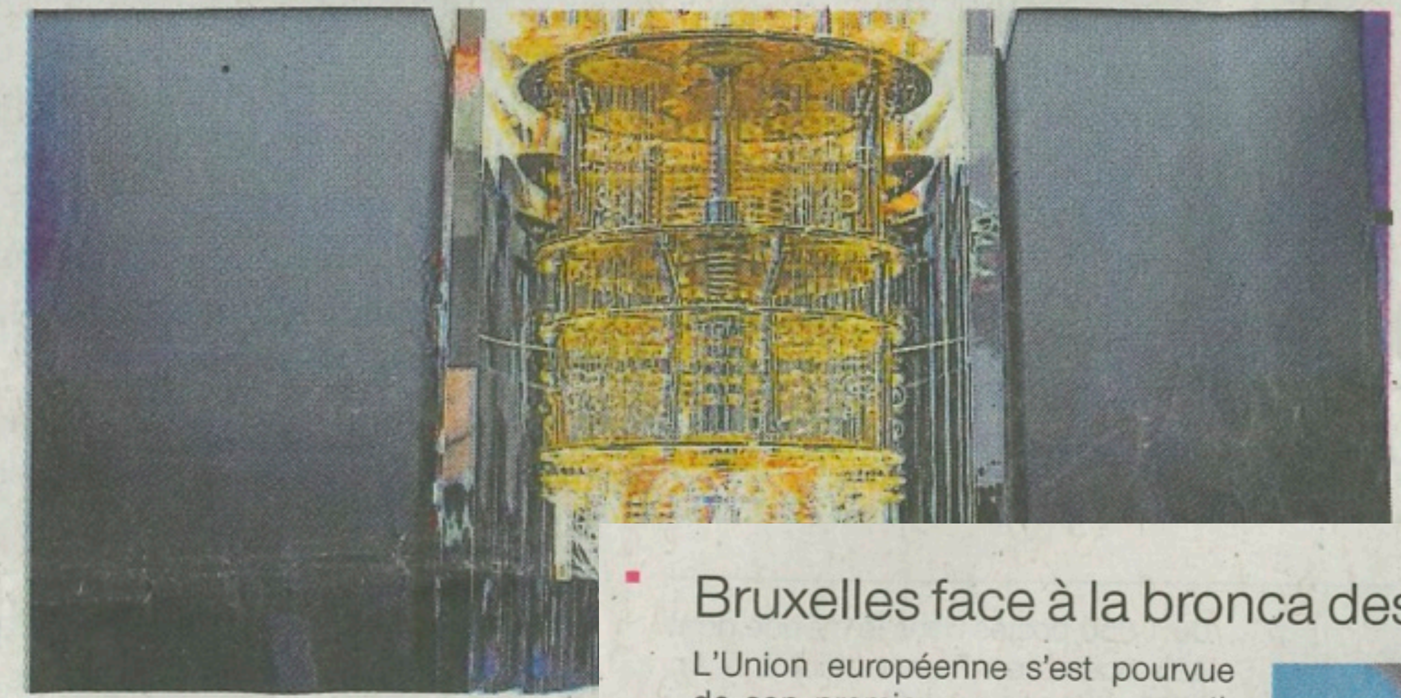
solaires...

« Après celle des années 1950-

déjà créé des antennes d'un centimètre carré aux performances supé-

Exploiter les superpouvoirs des particules

En 1900, un génie allemand nommé Max Planck a conclu que la physique classique n'expliquait pas certains phénomènes. Depuis, par petites touches, des générations de physiciens ont mis au jour une physique alternative. Elle est parfaitement claire en langage mathématique. Mais elle est impossible à formuler, et même à imaginer, par le commun des mortels. Il faut dire que cette nouvelle physique a découvert que les particules qui composent la matière ont des superpouvoirs. Leur énergie ne varie pas en continu, comme un moteur de voiture, mais par petits paquets, les quantas (d'où le nom de physique quantique) qui lui permettent de se trouver simultanément dans plusieurs états différents. Comme si elles



System One est présenté par IBM ... opérationnel au monde.

une lampe était la lumière. De elles peuvent se trouver en plus

« La technologie française a besoin d'investisseurs »

Google annonçait, en 2019, avoir atteint la « suprématie » avec son premier ordinateur quantique doté de 53 Qbits (unité de puissance propre à cette technologie). Mais le calcul réalisé par la machine de Google en quelques minutes aurait-il pris 10 000 ans sur un ordinateur classique, selon Google ? Ou trois jours, selon IBM ? Ce dernier a promis, en mai dernier, de proposer, dès cette

instables. « **Les perspectives sont formidables. Mais il faut des conditions favorables et obtenir des Qbits parfaits, fiables et en grand nombre.** »

Pour Cyril Allouche, « **ce qu'on a fait, jusqu'à présent, c'est prouver le concept. On sait que l'on peut envoyer des instructions et réaliser des calculs. Outre-Atlantique, on nous annonce des ordinateurs fonc-**

Bruxelles face à la bronca des scientifiques

L'Union européenne s'est pourvue de son premier programme quantique en 2018. « Quantum flagship » n'est doté que d'un modeste milliard d'euros sur dix ans.

Lorsqu'elle prend la tête de la nouvelle Commission en 2019, Ursula von der Leyen, ex-ministre de la Défense de l'Allemagne, affiche d'autres ambitions. Dans son premier discours sur « l'état de l'Union », en septembre 2020, elle annonce que 20 % des 750 milliards du plan de relance européen iront au numérique.

La feuille de route est tracée pour le commissaire au Marché intérieur, Thierry Breton. Ancien ministre de l'Économie de Jacques Chirac, l'ingénieur Thierry Breton a surtout dirigé Thomson CSF (ancêtre de Thales), France Télécoms et le géant informatique Atos. Il est exaspéré par les fragilités de l'Europe dans certaines technologies clés : semi-conducteurs, communications par satellites, supercalculateurs, cloud (centres de données utilisés à distance) et, le 9 mars, quantique. Depuis lors, il multiplie plans et appels à projet. Objectif : sortir l'Europe de sa dépendance et de son retard face aux États-Unis et à la Chine.

En mars, la Commission annonce

Le 3 juin, Thierry Breton exposait la politique numérique européenne.

| Photo : Stéphanie Lecocq, AFP

qu'elle exclura de ses soutiens les labos d'États non-membres. Royaume-Uni, Suisse et Israël sont visés. Trop patriote ? C'est en tout cas l'indignation chez tout ce que l'Europe compte de sommités scientifiques, y compris le responsable du programme quantique européen lui-même, Tommaso Calarco. La Commission aurait fait marche arrière début juin.

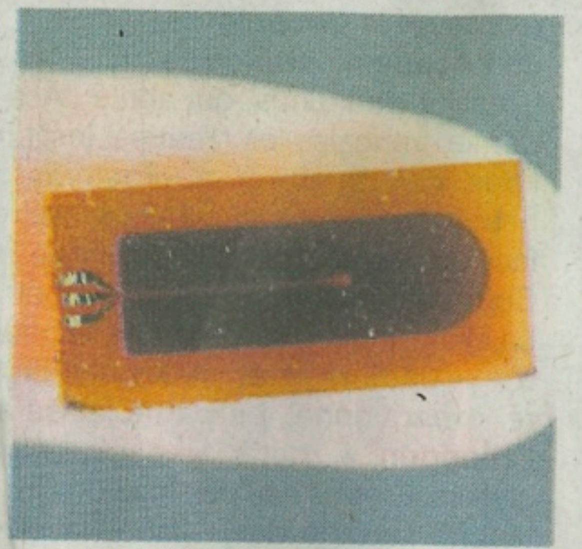
Il faut dire que tous les projets de recherche européens d'ici à 2027, prévus au sein du grand programme Horizon 2020 – avec 95 milliards de budget – étaient menacés de paralysie.

Une richesse française née des prix Nobel

La France ne part pas de rien en matière de physique quantique. Depuis les pères de la discipline, il y a un siècle, comme Henri Poincaré, elle compte des dizaines de physiciens de rang mondial, dont une lignée de titulaires du prix Nobel : Pierre et Marie Curie, Henri Becquerel, Louis de Broglie, Louis Néel, Jean Perrin, Alfred Kastler, Albert Fert, Pierre-Gilles de Gennes, Georges Charpak, Claude Cohen-Tannoudji, Serge Haroche, et Gérard Mourou.

Issue de leurs travaux, la France dispose d'une solide recherche académique menée notamment par le CNRS, le CEA, l'université de Paris-Saclay, l'Institut polytechnique. Les travaux d'application sont menés par de grands groupes comme Airbus et Orange (systèmes de communication protégés), Thales (capteurs quantiques), Atos (émulateurs et systèmes de contrôle), STMicroelectronics (silicium) ou encore Air Liquide (froid extrême). Autour d'eux, un tissu d'une vingtaine de jeunes pousses, encore peu connues, dont Quandela, Pasqal, Muquans, Alice & Bob, C12 Nanotech, VeriQloud, Quantfi, Qubit Pharma.

Soutenues par Bpifrance (la banque de l'État), les subventions du « plan quantique » et le fonds d'inves-



Une antenne quantique réalisée par Thales, aussi efficace qu'un modèle conventionnel mille fois plus grand.

| Photo : Thales

tissement privé, Quantonation, créé par l'homme d'affaires Charles Beigbeder, elles travaillent sur des sujets austères : les semi-conducteurs et supraconducteurs, les photons, les atomes froids, les ions de terres rares... Pour réaliser, un jour, un ordinateur quantique, et, avant cela, un ordinateur hybride, il faudra maîtriser ces technologies obscures.

La finalité, elle, est lumineuse : éviter que la France devienne, comme dans d'autres domaines, une colonie numérique d'IBM, Google et Microsoft.

Un milliard pour une recherche appauvrie

Il n'est pas si fréquent que la présidente de la Commission européenne se rende en France. Lorsqu'Ursula von der Leyen est venue, le 23 juin, à Paris, confirmer les 40 milliards accordés à la France dans le plan de relance européen, elle a pourtant fait un détour par Bruyères-le-Châtel (Essonne) pour visiter un laboratoire du Commissariat à l'énergie atomique et aux énergies alternatives (CEA). C'est là qu'un consortium européen comprenant la France et l'Allemagne, élabore ce qui pourrait devenir le premier prototype d'ordinateur hybride doté d'un accélérateur quantique. Il est attendu d'ici à 2023.

Dans les technologies quantiques, la France entend se placer juste derrière les États-Unis et la Chine. Emmanuel Macron l'a dit le 21 janvier, dans un laboratoire du CNRS à Paris-Saclay, lorsqu'il a présenté son « plan quantique » doté de 1,8 milliard d'euros.

Si le montant est flatteur, il n'y a qu'un milliard qui viendra de l'État, dont 594 millions seulement sont vraiment nouveaux. Les 800 millions restants sont apportés par l'Union européenne et des entreprises.

Interrogé en mai par nos confrères des *Échos* sur cet élan politique nouveau, le prix Nobel de physique Serge

Emmanuel Macron lors de l'annonce du « plan quantique » le 21 janvier.

| Photo : Archives Yoan Valat, AFP

Haroche a tempéré les enthousiasmes. « **La France a pris du retard et ne consacre plus que 2,2 % de son produit intérieur brut à la recherche** », du fait d'une réduction constante « **au cours des trente dernières années** ».

Dénonçant « **le faible nombre de postes ouverts au CNRS** » autant que « **le salaire de misère des jeunes chercheurs qui parviennent à y entrer** » et leurs « **mauvaises conditions de travail** », il a estimé « **qu'on ne peut blâmer ceux qui acceptent des postes à l'étranger** ».

Ouest-France du 19 juillet 2021

Quelques formulations utilisées

- *Revolution quantique*
- *Superpouvoirs de particules*
- *Puissance et mystérieuse*
- *Dans l'Univers quantique un chat peut être mort et vivant*
- *Physique Alternative*
- *Le qubit est une puissance propre à cette technologie*
- *Elle est parfaitement claire en langage mathématique mais impossible à formuler …*
- *…*

What is hidden behind all this excitation about the quantum world?
«*capteurs, ordinateur quantique, crypto-quantique*»

By the way, in the next years, we will celebrated the first 100 years of the quantum physics, with the theoretical developments of Niels Bohr, Erwin Schrödinger, Werner Heisenberg et al. in the middle of the 1920's.

Only 5 generations of physicists since the birth of the quantum physics!

Caveats and Outlook

- I am not an expert in quantum computing. I know quantum mechanics
- This is not an exhaustive talk
- Introducing what is the idea behind quantum computing
- Introducing one of the quantum technology developments that has lead to artificial quantum complex system
- Understanding what it has been achieved with the quantum processor «Sycamore» programmable superconductor processor of Google AI Quantum laboratory

Publication in 2019

- Sycamore programmable superconducting processor
- Quantum algorithms
- 200 seconds of millions of times quantum sampling
- 10 thousand years for a «classical» supercomputer
- Quantum supremacy for this very specific computational task
- Acclaiming a much-anticipated computing paradigm

Nature 574 (2019) 505 https://inspirehep.net/literature/1760347

Article

Quantum supremacy using a programmable superconducting processor

https://doi.org/10.1038/s41586-019-1666-5

Received: 22 July 2019

Accepted: 20 September 2019

Published online: 23 October 2019

Frank Arute[1], Kunal Arya[1], Ryan Babbush[1], Dave Bacon[1], Joseph C. Bardin[1,2], Rami Barends[1], Rupak Biswas[3], Sergio Boixo[1], Fernando G. S. L. Brandao[1,4], David A. Buell[1], Brian Burkett[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[5], Roberto Collins[1], William Courtney[1], Andrew Dunsworth[1], Edward Farhi[1], Brooks Foxen[1,5], Austin Fowler[1], Craig Gidney[1], Marissa Giustina[1], Rob Graff[1], Keith Guerin[1], Steve Habegger[1], Matthew P. Harrigan[1], Michael J. Hartmann[1,6], Alan Ho[1], Markus Hoffmann[1], Trent Huang[1], Travis S. Humble[7], Sergei V. Isakov[1], Evan Jeffrey[1], Zhang Jiang[1], Dvir Kafri[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Paul V. Klimov[1], Sergey Knysh[1], Alexander Korotkov[1,8], Fedor Kostritsa[1], David Landhuis[1], Mike Lindmark[1], Erik Lucero[1], Dmitry Lyakh[9], Salvatore Mandrà[3,10], Jarrod R. McClean[1], Matthew McEwen[5], Anthony Megrant[1], Xiao Mi[1], Kristel Michielsen[11,12], Masoud Mohseni[1], Josh Mutus[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Murphy Yuezhen Niu[1], Eric Ostby[1], Andre Petukhov[1], John C. Platt[1], Chris Quintana[1], Eleanor G. Rieffel[3], Pedram Roushan[1], Nicholas C. Rubin[1], Daniel Sank[1], Kevin J. Satzinger[1], Vadim Smelyanskiy[1], Kevin J. Sung[1,13], Matthew D. Trevithick[1], Amit Vainsencher[1], Benjamin Villalonga[1,14], Theodore White[1], Z. Jamie Yao[1], Ping Yeh[1], Adam Zalcman[1], Hartmut Neven[1] & John M. Martinis[1,5*]

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension 2^{53} (about 10^{16}). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in speed compared to all known classical algorithms is an experimental realization of quantum supremacy[8–14] for this specific computational task, heralding a much-anticipated computing paradigm.

Back to 1982

I. Simulating a classical system

II. Time for simulating a probability

III. Quantum computers

IV. Quantum system simulated by a classical computer?

V. Negative probabilities

VI. Polarisation of photons

VII. Two photon correlation experiment

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

https://inspirehep.net/literature/1115226

Simulating Physics with Computers

Richard P. Feynman

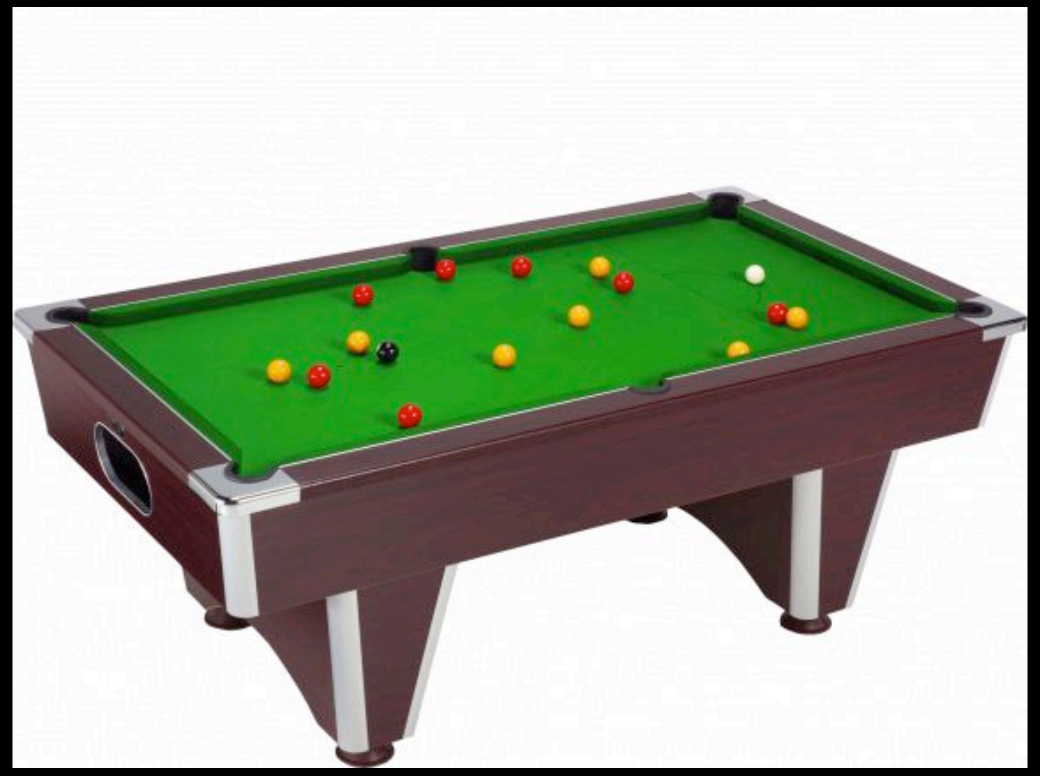
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981

1. INTRODUCTION

On the program it says this is a keynote speech—and I don't know what a keynote speech is. I do not intend in any way to suggest what should be in this meeting as a keynote of the subjects or anything like that. I have my own things to say and to talk about and there's no implication that anybody needs to talk about the same thing or anything like it. So what I want to talk about is what Mike Dertouzos suggested that nobody would talk about. I want to talk about the problem of simulating physics with

Simulating a classical system



- Time has to be discrete
- A kind of cellular automaton (Game of life is another kind of known cellular automaton) from a classical state to new classical state in discrete time jumps

$$s_i = F_i(s_j, s_k, \ldots .)$$

- Classical physics is causal : future is calculated from past

$$s_j, s_k, \ldots \text{past of } i$$

- Classical physics is reversible
- Classical physics is local : only few points in the neighborhood of a point contribute to its evolution in time

$$s_j, s_k, \ldots \text{neighborhood of } i$$

- Classical physics is quite adaptable to computing calculation
- Computing complexity increases «proportional to" (polynomially with) N (number of space points, number of particles, …)

Richard Feynman, International Journal of Theoretical Physics 21 (1982) 467

Simulating probabilities

- For each particle P(x,t). Space and time has to be discrete
- If one takes k bits, since P is between 0 and 1, the smallest probability is 2^{-k}.
- Computing complexity increases exponentially. For R particles in N space-time points, we need N^R configurations. Considering that somehow R is proportional to N, one get N^N configurations
- Simulating probabilities becomes imposible as N increases.
- Imaging a probabilistic computer. « randomisation of the last to digits of a number or what ever you could imaginate», but you do it following the probability evolution laws.
- Same input (t=0) can result in several outputs at the final time. One has to repeat the calculation by a large number of times (n) to build the probability distribution and the final time, with an error related to square of n
- However, such a probabilistic computer is not adapted to simulate quantum systems. Why?

Richard Feynman, International Journal of Theoretical Physics 21 (1982) 467

Quantum physics is not probability

- In quantum physics, linearity is respected at the amplitud of the wave function
- The amplitud consist in a module and in a phase
- The sum of two probabilities 1/2 can result in a probability between 0 and 1 depending on the phase.
- Two extreme results are destructive (0) and constructive (1) interference of the amplitude
- Quantum physics is not local due to intrication

Quantum computing

E_1

E_0

- Basic element : a quantum system with two stationary states

$$\psi = a_0\psi_0 + a_1\psi_1$$

- It is possible to set at t=0 the state of the basic element two any state. a_i are imaginary (amplitude and phase) numbers

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle$$

- You have N basic elements. The total number of posible states of such es system is 2^N. All the linear combinations of those 2^N states are stationary states of the system

$$|0101111001\cdots 0\rangle$$

- During a time Δt you can make interactions between the basic element represented by a $\mathcal{H}_i$

$$\psi(t_i + \Delta t) = \mathcal{U}_i\psi(t_i) = e^{\frac{i}{\hbar}\mathcal{H}_i\Delta t}\psi(t_i)$$

- Any quantum system could be then simulated with the right choice of $\mathcal{H}_i$

$$\psi_f = \Pi_{i=1}^{i=m} e^{\frac{i}{\hbar}\mathcal{H}_i\Delta t}\psi(t=0)$$

- Computing increase proportional to the size of the system, while in a classical computing the increase is exponential.

Linearity and quantum parallelisation

- The final state «read-out» is the result of one single simulation. One needs to perform many simulations to determine (read) the final state

In the 80's this was science fiction

Richard Feynman, International Journal of Theoretical Physics 21 (1982) 467

Several Caveats

- Basic element is called qubit. One cannot clone a qubit. C’est le théorème de non-clonage quantique
- Extremely large number of possibilities does exists for the choice of $\mathscr{H}_i$. Basis choices of $\mathscr{H}_i$ are $\mathscr{H}_s$ for setting a qubit to a precise state and $\mathscr{H}_g$ to interact two qubits (a quantum gate)
- The interaction can results in the intrication of the information in two different qubits. Non-locality, which is projected at the end of the calculation when the final state is measured
- You cannot distinguish two qubit (quantum) states with one single measurement of the qubit. In order to determine the finale state one has to perform several simulations
- One assumes that there is no errors during each quantum simulation (NISQ, see later)
- A quantum calculation consists on n qubits, m cycles ($\mathscr{H}_i$) and N simulations

Michel LE BELLAC, Reflets de la Physique, n.67 (2020) 4

Quantum calculation

- n qubits
- m cycles with a Hamiltonian $\mathscr{H}_i$ from $i = 1$ to m
- The choice of $\mathscr{H}_i$ is given by the quantum algorithm
- Hilbert space of dimension 2^n
- Projection (reading) of the n qubits state at the end of each cycle
- N samples of the quantum calculation to determine the final n-qubit state
- Each cycle need fully coherence of the quantum process

Preparing the initial state of the qbit

- After setting the bit tow let's state $|0\rangle$, one can be able to set the qubit to any required state, combination of the two states : $a_0|0\rangle + a_1|1\rangle$

- Mathematically this can be represented by a 2D unitary (conjugate transposed is equal to its inverse) matrix $\mathscr{U}_s = e^{\frac{i}{\hbar}\mathscr{H}_s \Delta t}$: $|\psi\rangle = \mathscr{U}_s|0\rangle$

- The possibilities of $\mathscr{U}_s$ are infinite (there is the question of the resolution of a_i factor here. If it can be read with a precision of k-bit, therefore one has 2^k possibilities of $|a_i|$. But the factor a_i is imaginary, therefore one has to consider the precision on the phase, so the total number of possibilities is 2^{k+m} (module of the amplitude precision in k-nits and for the phase in m-bits)

- For a classical bit, one two possibilities of the initial state are possible 0 or 1

- Example of $\mathscr{U}_s$ could be $\mathscr{U}_s = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$ $\quad |0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + |1\rangle\right)$ Hadamard gate

- Another different exemple $\mathscr{U}_s = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & i \\ -i & 1 \end{pmatrix}$ $\quad |0\rangle \rightarrow \frac{1}{\sqrt{2}}\left(|0\rangle + i|1\rangle\right)$

Quantum Gates

- The basic gate in a quantum computing (the equivalent of a AND, OR, NOT logical gates) is a Hamiltonian $\mathscr{H}_g$ involving two qbits

- The 2-qubit states are $|00\rangle$, $|01\rangle$, $|10\rangle$ and $|11\rangle$

- This transformation can be represented by a 4D unitary matrix $\mathscr{U}_g = e^{\frac{i}{\hbar}\mathscr{H}_g \Delta t}$

- Exemple :

$$\mathscr{U}_g = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ 0 & 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\frac{1}{\sqrt{2}}\Big(|10\rangle - |11\rangle\Big) \longrightarrow |11\rangle$$

$$\frac{1}{\sqrt{2}}\Big(|10\rangle + |11\rangle\Big) \longrightarrow |10\rangle$$

Quantum interference is rich

Back to 1994

- Quantum algorithm for prime factorization
- Shor Algorithm that could be used in a quantum computer to break the RSA

RSA (Rivest–Shamir–Adleman) is a public-key cryptosystem that is widely used for secure data transmission

A Method for Obtaining Digital Signatures and Public Key Cryptosystems (Formerly on Digital Signatures and Public Key Cryptosystems)

Ronald L. Rivest (MIT), Adi Shamir (MIT), Len Adelman (MIT)
Apr, 1977

15 pages
Report number: MIT/LCS/TM-82

Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer*

Peter W. Shor†

Abstract

A digital computer is generally believed to be an efficient universal computing device; that is, it is believed able to simulate any physical computing device with an increase in computation time by at most a polynomial factor. This may not be true when quantum mechanics is taken into consideration. This paper considers factoring integers and finding discrete logarithms, two problems which are generally thought to be hard on a classical computer and which have been used as the basis of several proposed cryptosystems. Efficient randomized algorithms are given for these two problems on a hypothetical quantum computer. These algorithms take a number of steps polynomial in the input size, e.g., the number of digits of the integer to be factored.

Keywords: algorithmic number theory, prime factorization, discrete logarithms, Church's thesis, quantum computers, foundations of quantum mechanics, spin systems, Fourier transforms

AMS subject classifications: 81P10, 11Y05, 68Q10, 03D10

Peter W. Shor, SIAM J.Sci.Statist.Comput. 26 (1997) 1484
https://arxiv.org/abs/quant-ph/9508027

Shor Algortihm

$$\mathcal{U}_i^{HG} = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$

- n qubits are need :
- Initialization via the Hadamard gate $\mathcal{U}_i^{HG}$
- 2-qubit gates $\longrightarrow$ $\mathcal{U}_{jk}^{G} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & e^{i\theta_{jk}} \end{pmatrix}$ $\quad \theta_{jk} = \frac{\pi}{2^{k-j}}$ avec $k > j$

  Relative phase θ_{jk} to the state $|11\rangle$
- Process n single gate and $\frac{n(n-1)}{2}$ double gates :

$$\left(\mathcal{U}_{n-1}^{HG}\right)\left(\mathcal{U}_{(n-1)(n-1)}^{G}\mathcal{U}_{n-2}^{HG}\right)\cdots\left(\mathcal{U}_{1(n-1)}^{G}\cdots\mathcal{U}_{12}^{G}\mathcal{U}_{1}^{HG}\right)\left(\mathcal{U}_{0(n-1)}^{G}\cdots\mathcal{U}_{02}^{G}\mathcal{U}_{01}^{G}\mathcal{U}_{0}^{HG}\right)$$

Quantum Fourier transform

In few words :

A quantum computer :

- with N qubits
- with Hadamard single gates
- with two-qubits gate setting a phase in the state $|11\rangle$

could break the RSA encryption !!!

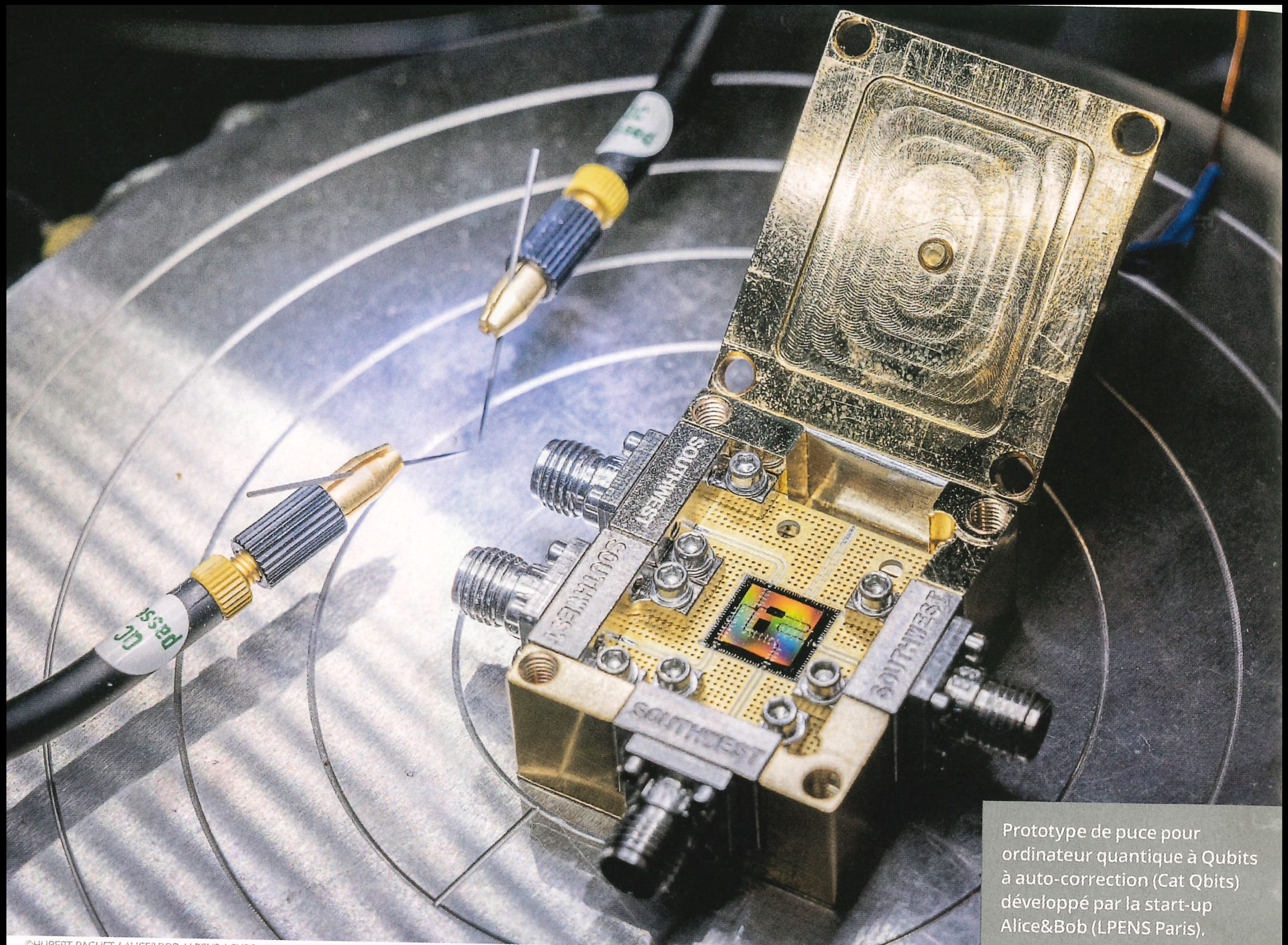
Quantum technology is going very quickly !

Specialists said that «quantum computer technology is today as computer technology was in 1945»

Michel LE BELLAC, Reflets de la Physique, n.67 (2020) 4

Le Plan Quantique Français

Journal du CNRS, 303 (2021) 12



Prototype de puce pour ordinateur quantique à Qubits à auto-correction (Cat Qbits) développé par la start-up Alice&Bob (LPENS Paris).

Un plan pour la recherche française

Annoncé le 21 janvier 2021 au Centre de nanosciences et de nanotechnologies, le Plan Quantique entend organiser les forces industrielles et de recherche du pays pour faire de la France un acteur majeur des technologies quantiques.

Les prix Nobel de physique Albert Fert et Serge Haroche, qui développèrent la spintronique et l'électrodynamique quantique en cavité, le lauréat de la médaille d'or du CNRS en 2005, Alain Aspect, et ses travaux pionniers sur l'intrication quantique, les simulateurs quantiques d'Atos… La France possède des compétences reconnues dans le domaine des technologies quantiques et entend bien conserver un rôle majeur dans la compétition internationale. Pour cela, le président Emmanuel Macron a dévoilé le 21 janvier un grand Plan Quantique, fortement attendu des communautés scientifiques françaises mais dont l'annonce avait longtemps été repoussée à cause de la crise sanitaire et économique.

1,8 milliard d'euros

Ce plan s'appuie en partie sur le rapport[1] rendu par la députée Paula Forteza, le chercheur Iordanis Kerenidis (CNRS) et l'ancien PDG de Safran, Jean-Paul Herteman, en janvier 2020, et qui mettait en avant l'excellence de la recherche française. Mais aussi le retard du pays en termes d'investissements, notamment pour le transfert vers l'industrie. Il proposait 37 mesures visant à définir une *« stratégie nationale ambitieuse »*, dont plusieurs ont été reprises.

Investissements des grands acteurs internationaux du quantique

UE : *Flagship quantique* **1 Md€** sur 10 ans lancé en 2018	Royaume-Uni **1 Md£** sur 10 ans lancé en 2014
Chine **10 Md€** lancé en 2015	France : *Plan Quantique* **1,8 Md€** sur 5 ans lancé en 2021
États-Unis **1,3 Md$** sur 5 ans lancé en 2018 **+ 800 M$** sur 2 ans en mars 2020	Allemagne **650 M€** sur 5 ans lancé en 2018 **+ 2 Md€** en 2020

1.8 Md€

Capteurs quantiques, Calcul quantique, Communications quantiques

Transfer vers l'industrie

Aboutir à un marché d'ici a 5 ans

Technologies «habilitantes" : comme la cryogénie et les matériaux de pointe

Josephson Junction

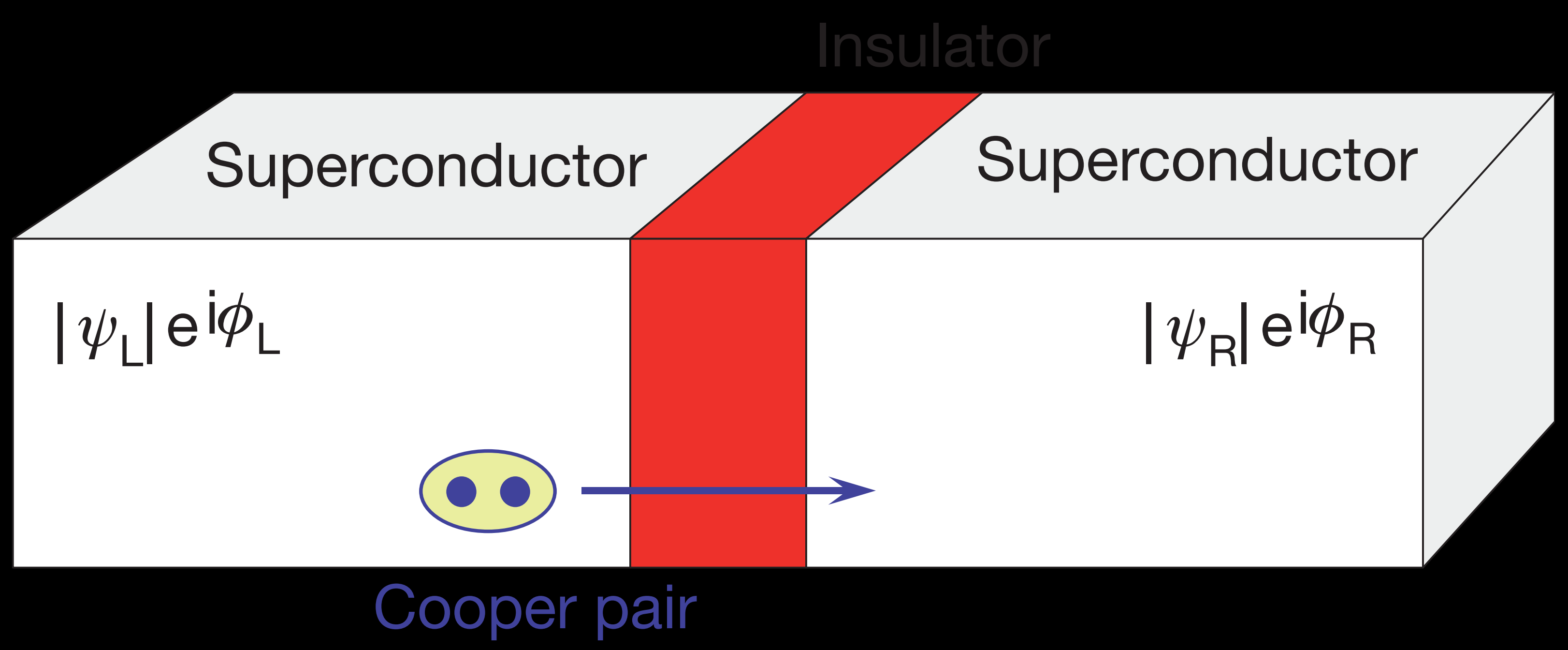
VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

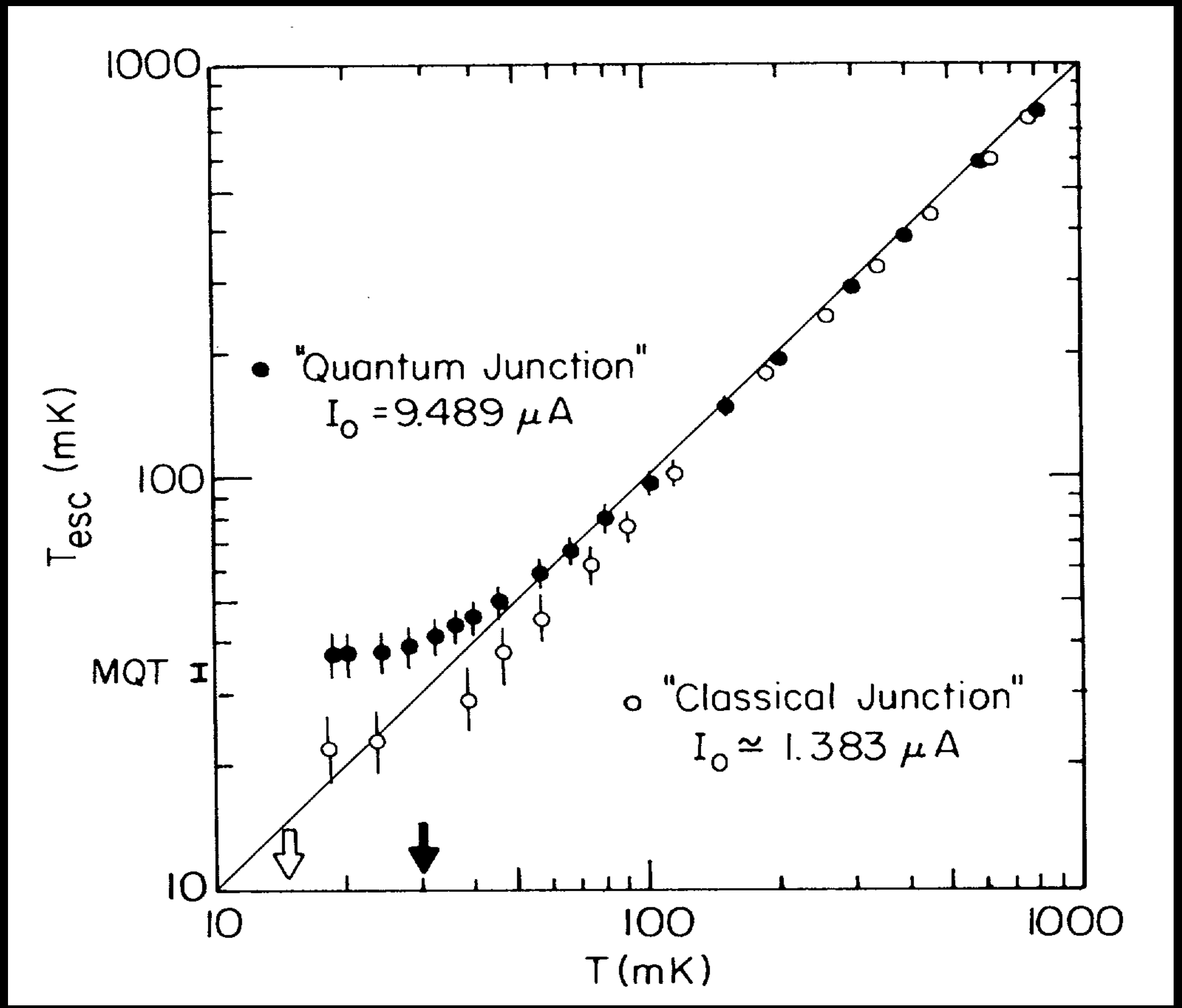
Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,[a] John M. Martinis, and John Clarke
Department of Physics, University of California, Berkeley, California 94720, and Materials and Molecular Research Division, Lawrence Berkeley Laboratory, Berkeley, California 94720

(Received 26 July 1985)

- Josephson Junction : two superconductor separated by an insulator
- Macroscopic quantum tunneling
- Macroscopic variable : Phase difference between two superconducting wave function
- Transition : from zero-voltage to nonzero-voltage state





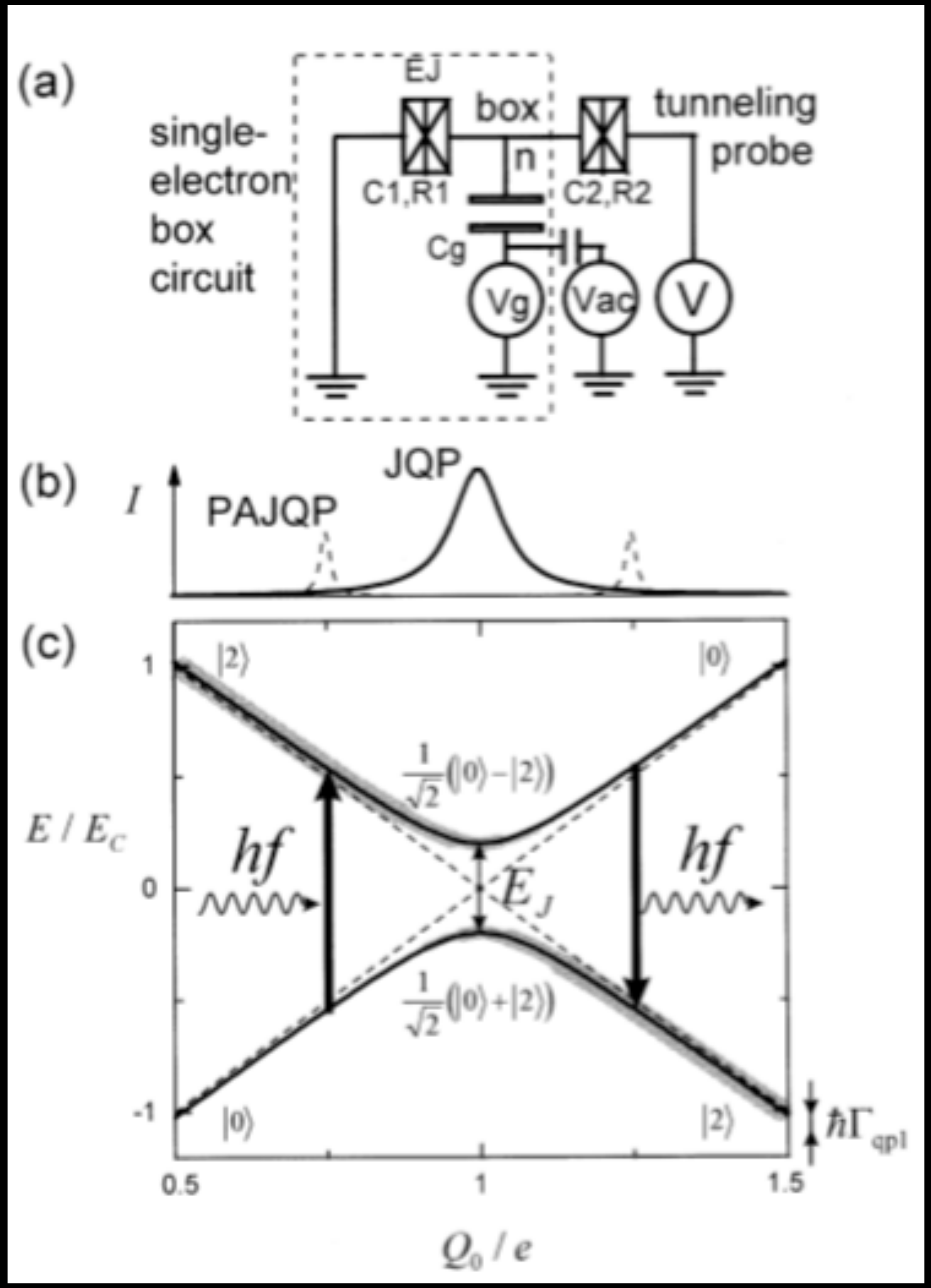
Energy levels in a Josephson junction

VOLUME 79, NUMBER 12 PHYSICAL REVIEW LETTERS 22 SEPTEMBER 1997

Spectroscopy of Energy-Level Splitting between Two Macroscopic Quantum States of Charge Coherently Superposed by Josephson Coupling

Y. Nakamura, C. D. Chen, and J. S. Tsai
NEC Fundamental Research Laboratories, Tsukuba, Ibaraki 305, Japan
(Received 16 April 1997)

- Stydy of the first excited state $|2\rangle$, in addition to the ground state $|0\rangle$
- Dégéneration of both states with V_g : $Q_0 = C_g V_g + Qb = me$
- Effective Hamiltonian $\mathscr{H} = E_C(\hat{n} - Q_0/e)^2 - \frac{E_J}{2}\left\{ |0\rangle\langle 2| |2\rangle\langle 0| \right\}$
- State $|2\rangle$ is read by the tunneling probe by sequential tunneling ($|2\rangle \rightarrow |1\rangle \rightarrow |0\rangle$) ==> Josephson-QuasiParticle-current (JQP). $Q_0 = C_g V_g + C_2 V + Qb$
- Microwave irradiation (V_{ac}) as photon-assisted Cooper pair tunneling ($|0\rangle \rightarrow |2\rangle$)



Single photon strong coupling

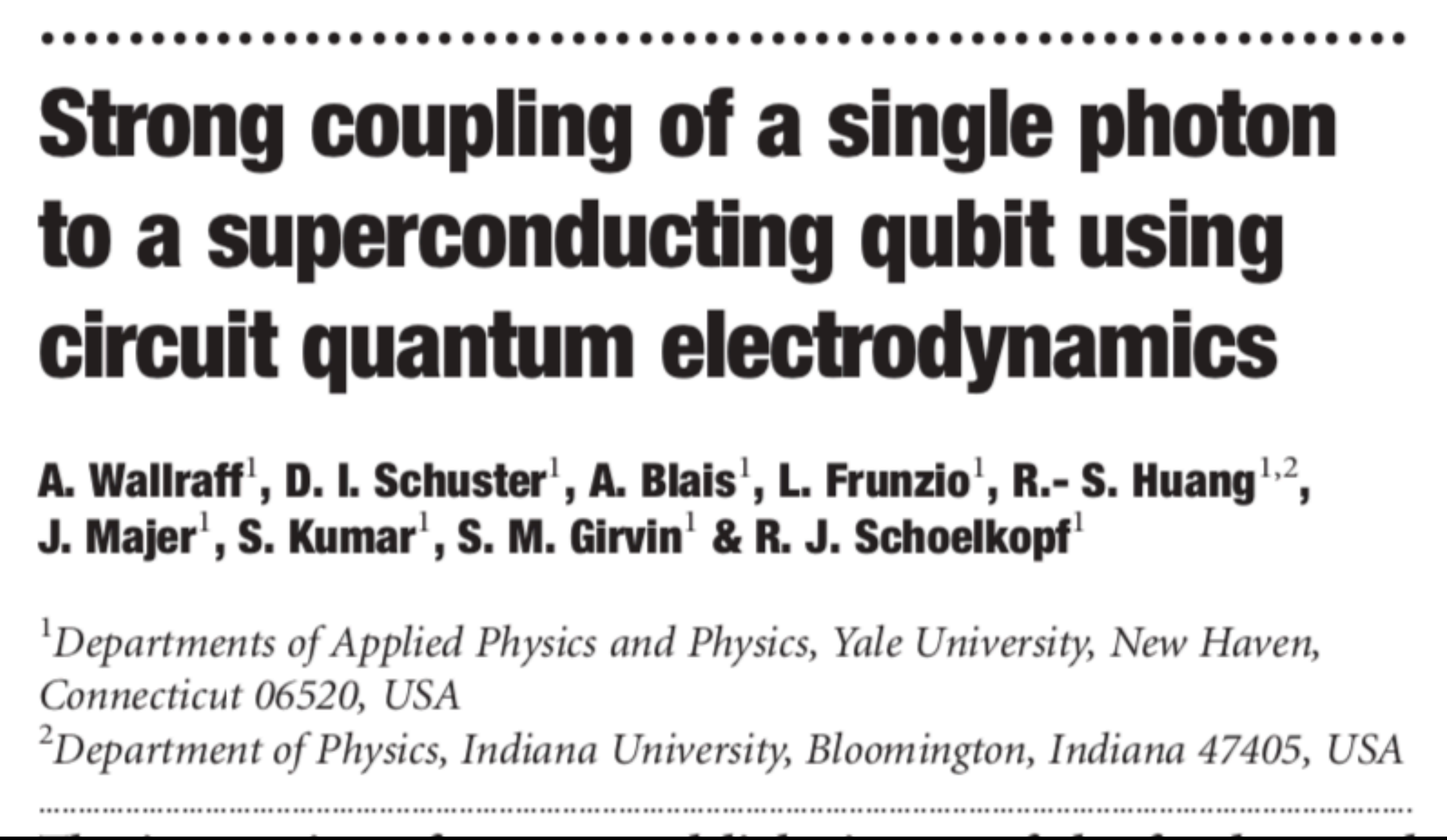
Nature 431 (2004) 162

Coherent interaction of a superconducting (Josephson junctions) two level system with a single microwave photon

Analougus to atome-photon interaction in a cavity (Rabi coherent oscillations $|0\rangle \leftrightarrow |1\rangle$)

Studying strong interaction of light and matter

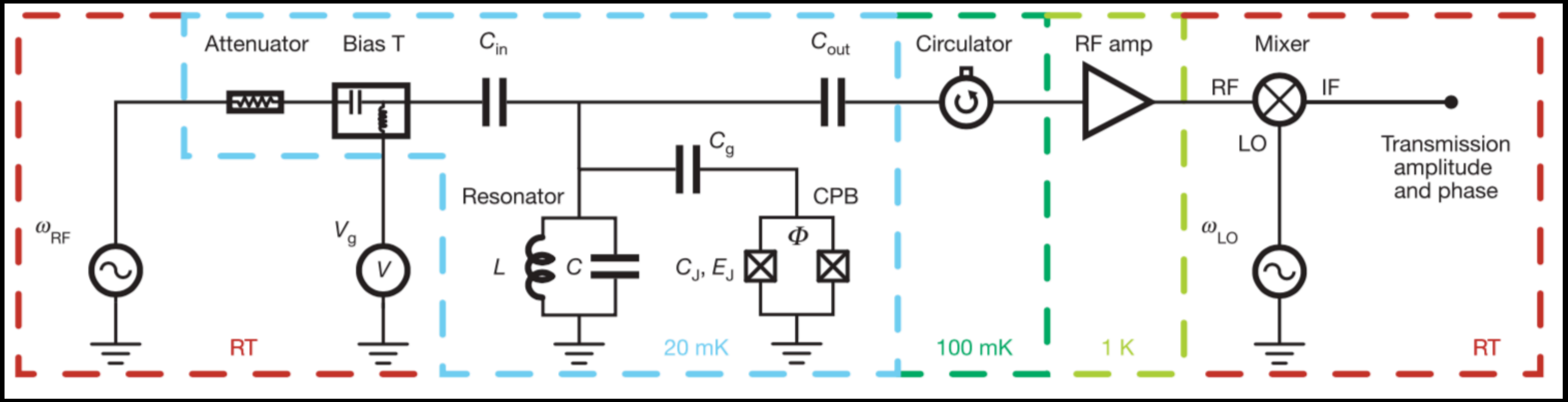
Quantum information processing



Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics

A. Wallraff[1], D. I. Schuster[1], A. Blais[1], L. Frunzio[1], R.- S. Huang[1,2], J. Majer[1], S. Kumar[1], S. M. Girvin[1] & R. J. Schoelkopf[1]

[1]*Departments of Applied Physics and Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*



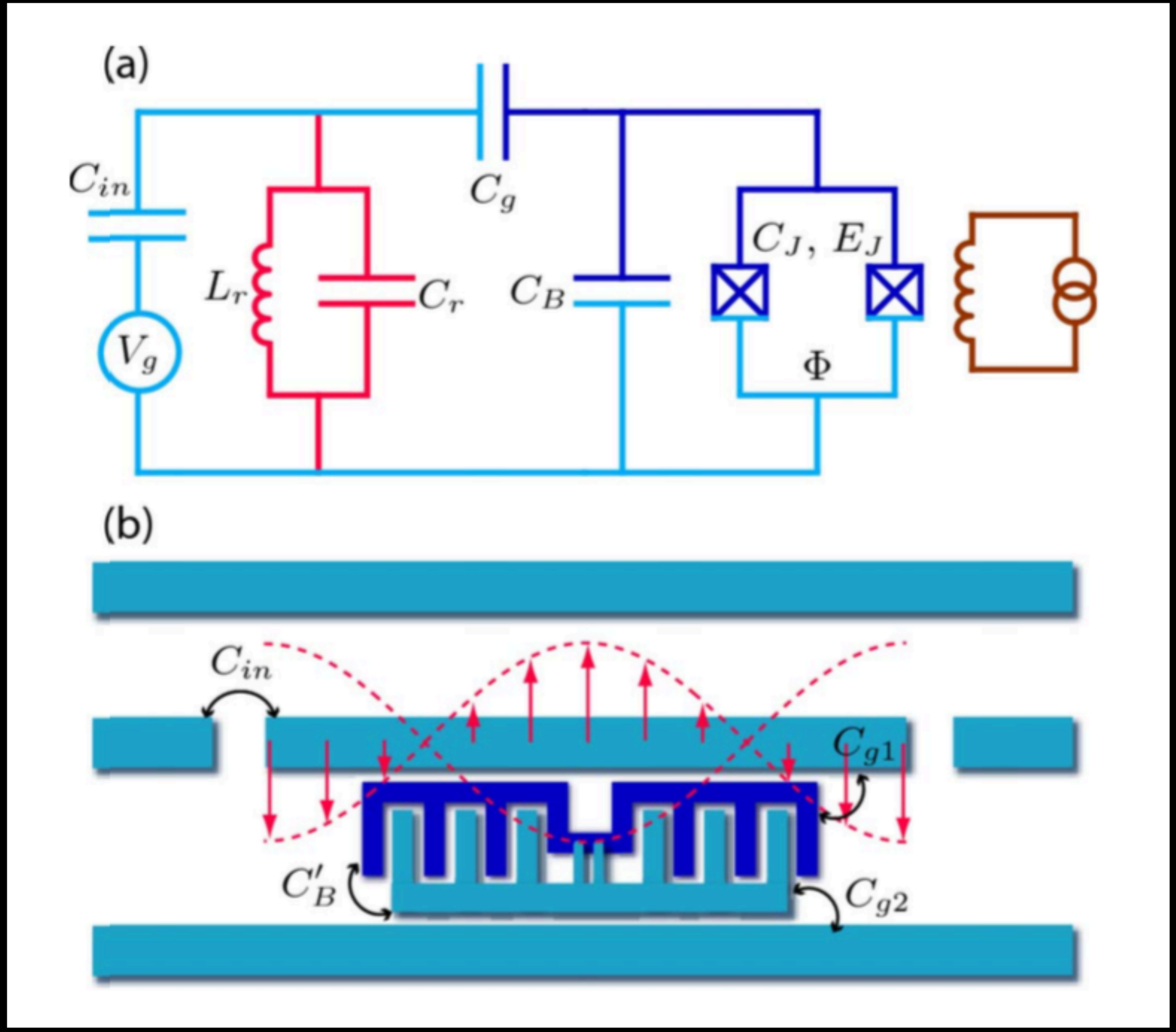
«Transmon» qubits

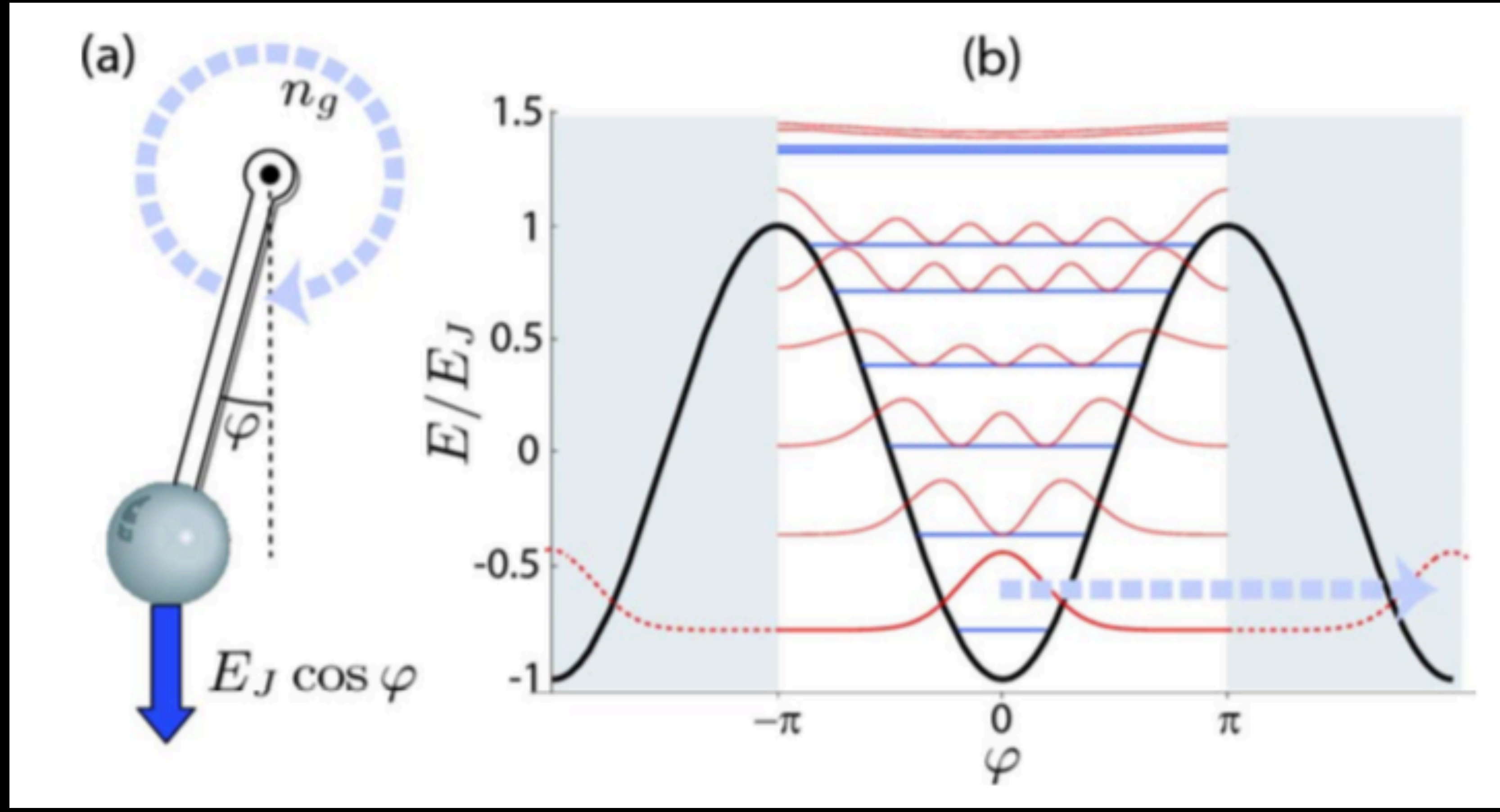
- Reduction of the to charge noise
- increase of the qubit-photon coupling
- Mantaining sufficient anharmonicity for selective quit control
- Transmon cubits are used by Ai Google «sycamore» quantum processor

PHYSICAL REVIEW A **76**, 042319 (2007)

Charge-insensitive qubit design derived from the Cooper pair box

Jens Koch,[1] Terri M. Yu,[1] Jay Gambetta,[1] A. A. Houck,[1] D. I. Schuster,[1] J. Majer,[1] Alexandre Blais,[2] M. H. Devoret,[1] S. M. Girvin,[1] and R. J. Schoelkopf[1]
[1]*Departments of Physics and Applied Physics, Yale University, New Haven, Connecticut 06520, USA*
[2]*Département de Physique et Regroupement Québécois sur les Matériaux de Pointe, Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1*





Rotor analogy

$$\mathscr{H}_{\text{rot}} = \frac{\mathscr{L}_z^2}{2ml^2} - mgl\cos\varphi$$

First quantum processors

- Putting about 50-100 qubits together
- Applying a serie of gates on one or two qubits. Each gate about tens of ns. Full serie about microseconds
- Reading the final quantum states and repeating the process many times.
- The question of errors is a major issue not addressed in this first quantum processors. We are in the NISQ era. NISQ for Noisy Intermediate Scale Quantum Technologies.
- Radioactivity is an issue for these quantum processors

John PRESKILL
Professor of theoretical physics in CALTECH
proposed the NISQ term

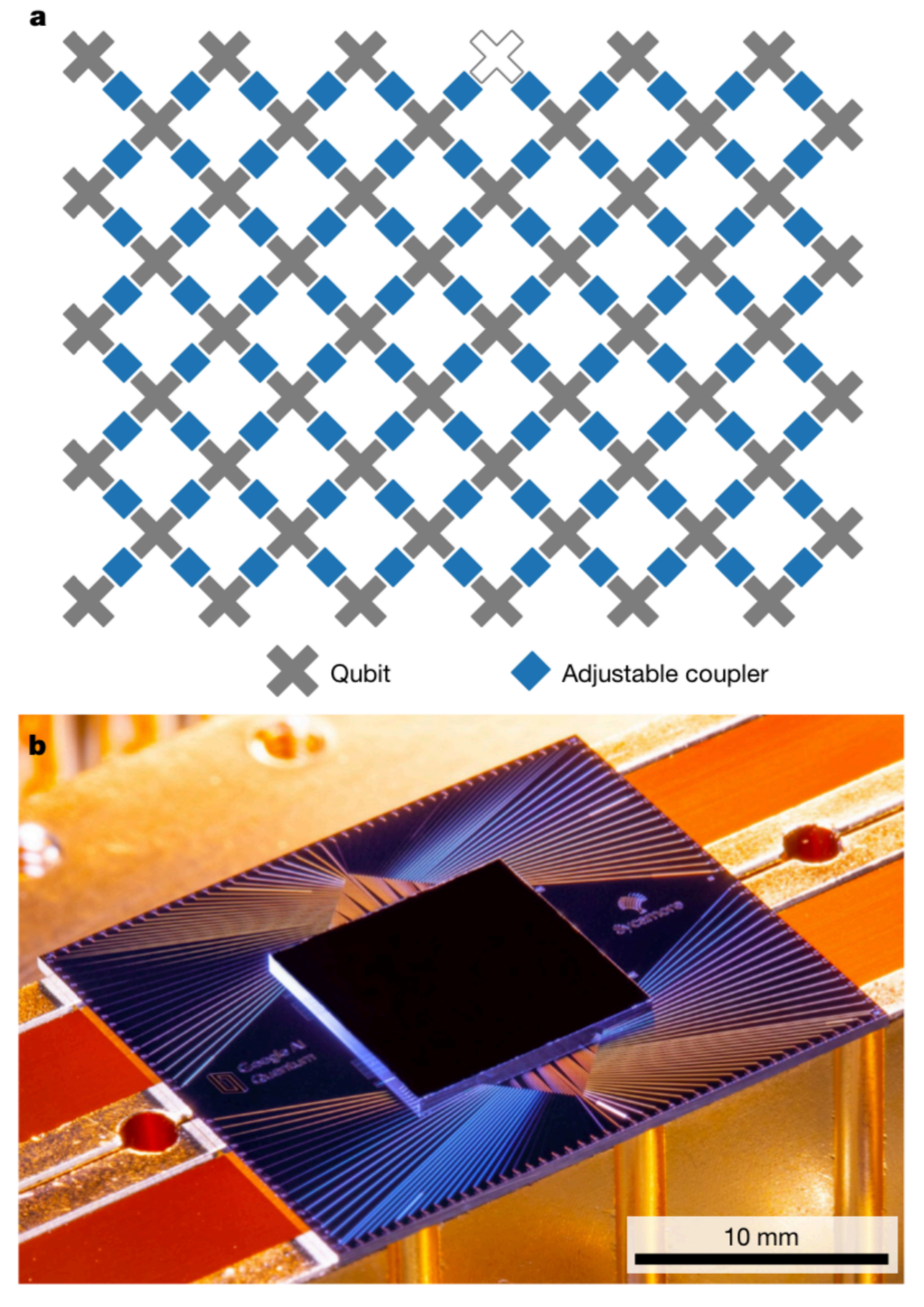
Michel LE BELLAC, Reflets de la Physique, n.67 (2020) 4

Atelier technologies quantiques des deux infinis, Marseille, juin 2021
Prospectives IN2P3

Nature 574 (2019) 505 https://inspirehep.net/literature/1760347

Sycamore quantum processor

- 54 transmon qubits (1 qubit was not working)
- Each qubit tunably coupled to up to four nearest neighbours
- Single- and Two- qubits gate
- Simultaneous gate operation on many qubits
- Microwave line to excite the qubit (two quantum levels) frequency 5-7 GHz tunable frequency via a magnetic flux control
- Each qubit is connected to a linear resonator to read the qubit state
- New design qubit-qubit coupling : quickly tuned from completely off to 40 MHz
- Processor is cooled down to 20 mK



Nature 574 (2019) 505 https://inspirehep.net/literature/1760347
and supplementary information e-print: 1910.11333

Computational task

- Pseudo random quantum circuit : good benchmark, no structure,
- Single qubit and two qubits gates for logical operations
- Sampling final state probability of a state $|x_i\rangle$
- Evaluation of $\mathcal{F}_{XEB} = 2^n \langle P(x_i) \rangle_i - 1$
- Classically $\mathcal{F}_{XEB} = 0$ since all the states are equiprobable
- Quantum interference some states are more probable than other (like a speckled intensity patter produce by light interference) : $\mathcal{F}_{XEB} = 1$
- Quantum logical gates are not perfect (there are errors) and in consequence $\mathcal{F}_{XEB} \in (0,1)$
- $\mathcal{F}_{XEB}$ can be evaluated with classical computing or with the sycamore quantum processor

$$x_i = \{0,1\}$$

$$|x_i\rangle = |x_1 x_2, x_3 \ldots x_{53}\rangle$$

$$2^n \text{ quantum states}$$

$$P(x_i)$$

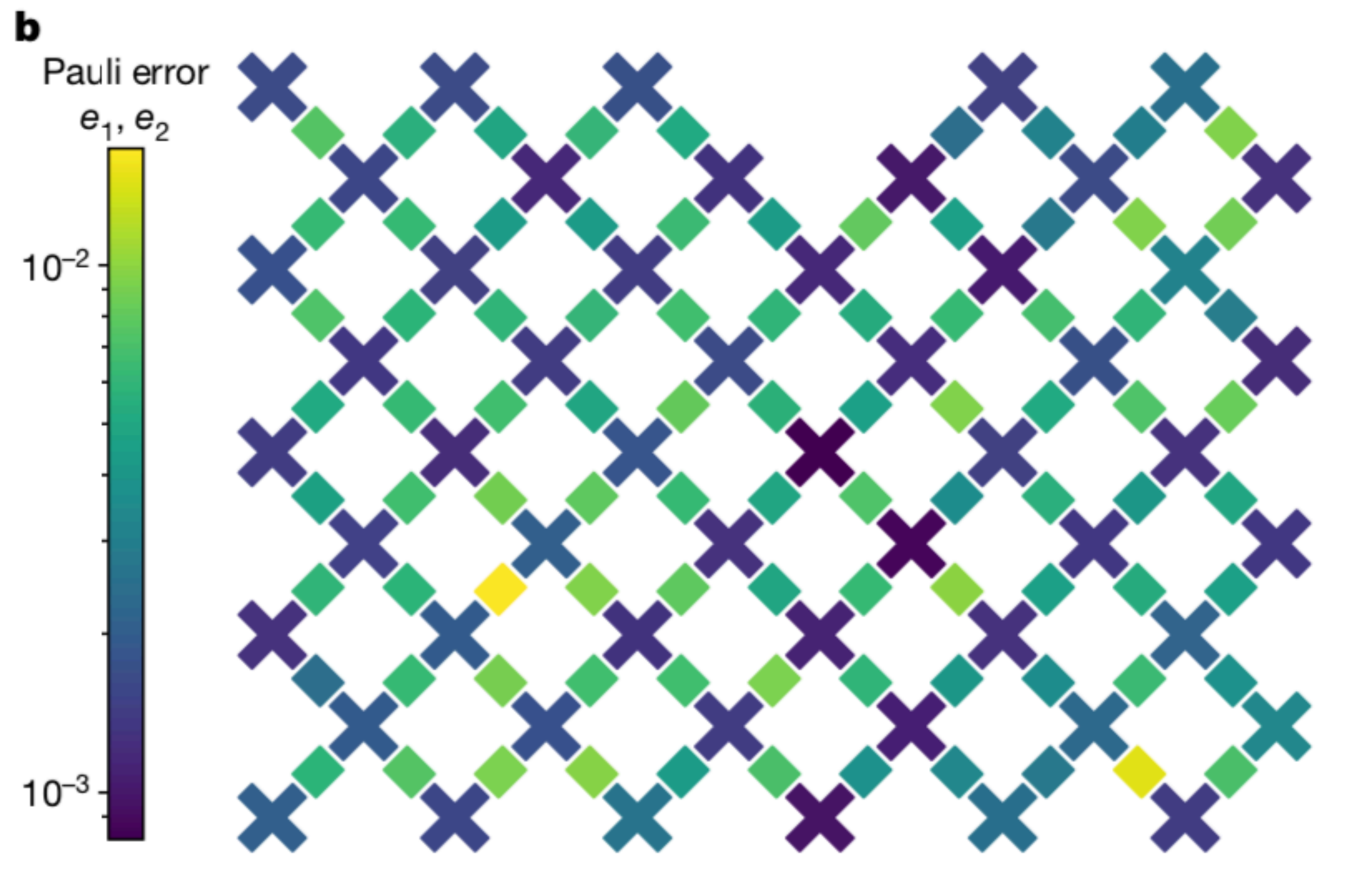
$$\mathcal{F}_{XEB} = 2^n \langle P(x_i) \rangle_i - 1$$

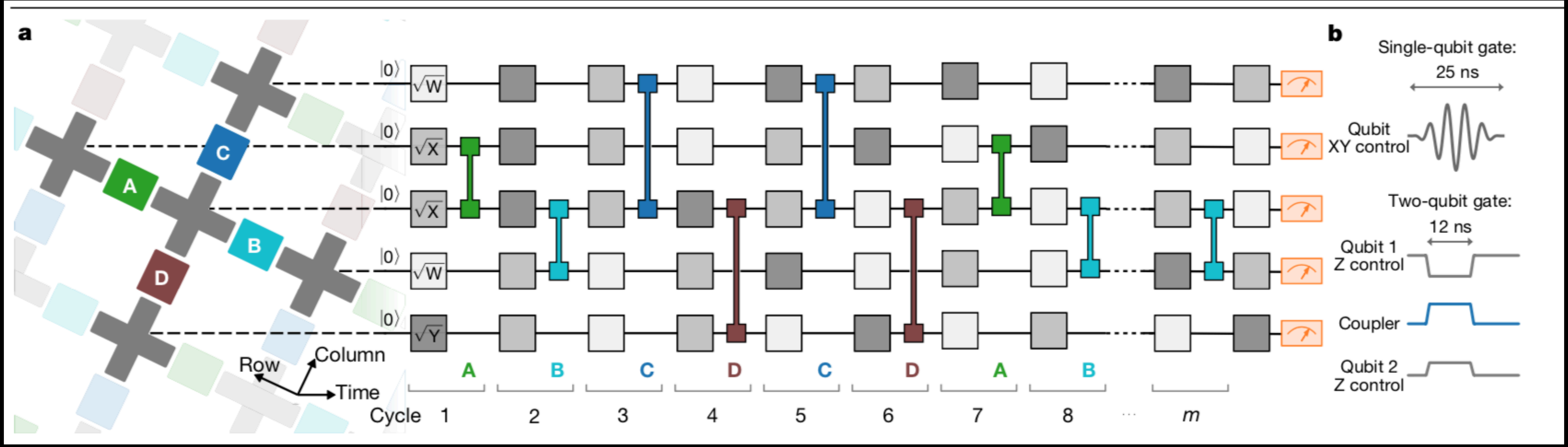
Nature 574 (2019) 505 https://inspirehep.net/literature/1760347

Analysis

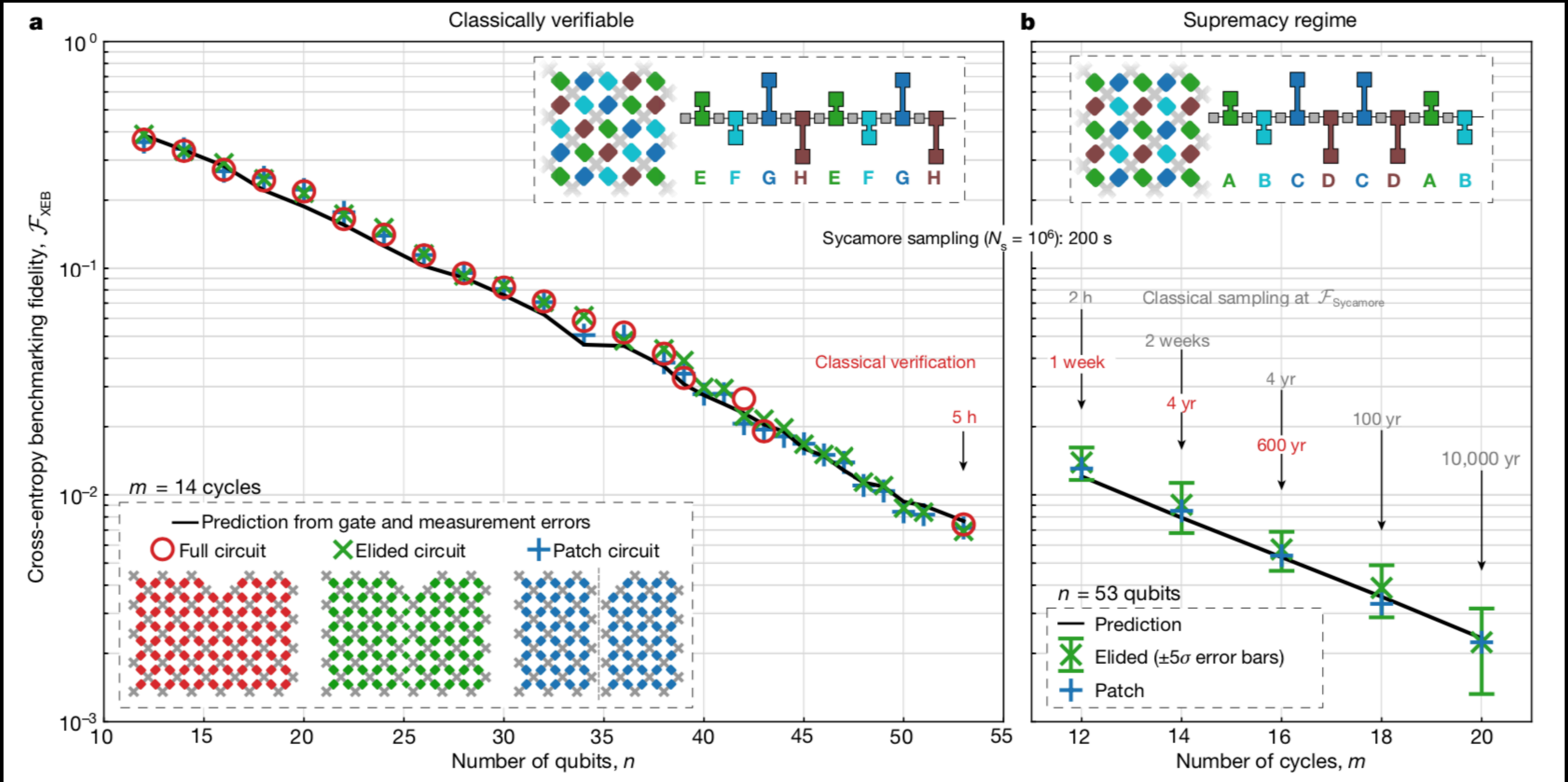
- Errors of the quantum logical gate are determine experimentally
- Single qubit gets are choses randomly $|0\rangle, |1\rangle$ and $\frac{1}{\sqrt{2}}\left\{|0\rangle + |1\rangle\right\}$
- Highly entragled states increase computational complexity
- Several quantum computations than can be classically computed are performed.

Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%





Results


a
Classically verifiable
b
Supremacy regime
Cross-entropy benchmarking fidelity, $\mathcal{F}_{XEB}$
E F G H E F G H
A B C D C D A B
Sycamore sampling ($N_s = 10^6$): 200 s
Classical sampling at $\mathcal{F}_{Sycamore}$
Classical verification
2 h
1 week
2 weeks
4 yr
4 yr
600 yr
100 yr
10,000 yr
5 h
m = 14 cycles
Prediction from gate and measurement errors
Full circuit
Elided circuit
Patch circuit
n = 53 qubits
Prediction
Elided (±5σ error bars)
Patch
Number of qubits, n
Number of cycles, m

Results

For a number of cycles m=14 :

- Perfect agreement with classical computing calculations of the quantum circuit

For a number of cycles m=20 and 53 qubits :

- $\mathcal{F}_{XEB} = (2.24 \pm 0.21) \times 10^{-3}$
- after the collection of $N_s = 30 \times 10^6$ samples (about 200 s for 10^6)
- In a classical computing (Google cloud servers), using the Schrödinger-Feynman algorithm would cost 50 trillion core-hour (10000 years in a million of cores) and consume one petawatt hour of energy (60 PWh is the world energy consumption for one years)

Quantum Suppremacy ?

Future

- A quantum computation in a Hilbert space of dimension $2^{53} = 9 \times 10^{15}$ has been achieve with sycamore processor
- Sycamore quantum processor has reached the regime of quantum supremacy
- Classical cost of simulating a quantum circuit increases exponentially
- One may expect an a Moore's Law for quantum processors during the next years
- More complex quantum algorithms like Shor algorithm could be run in a quantum processor in near future
- In this context, quatum error correction is a major priority in the field to increase the computing power of quantum processors

Nature Physics 13 Dec 2021 https://inspirehep.net/literature/1857959

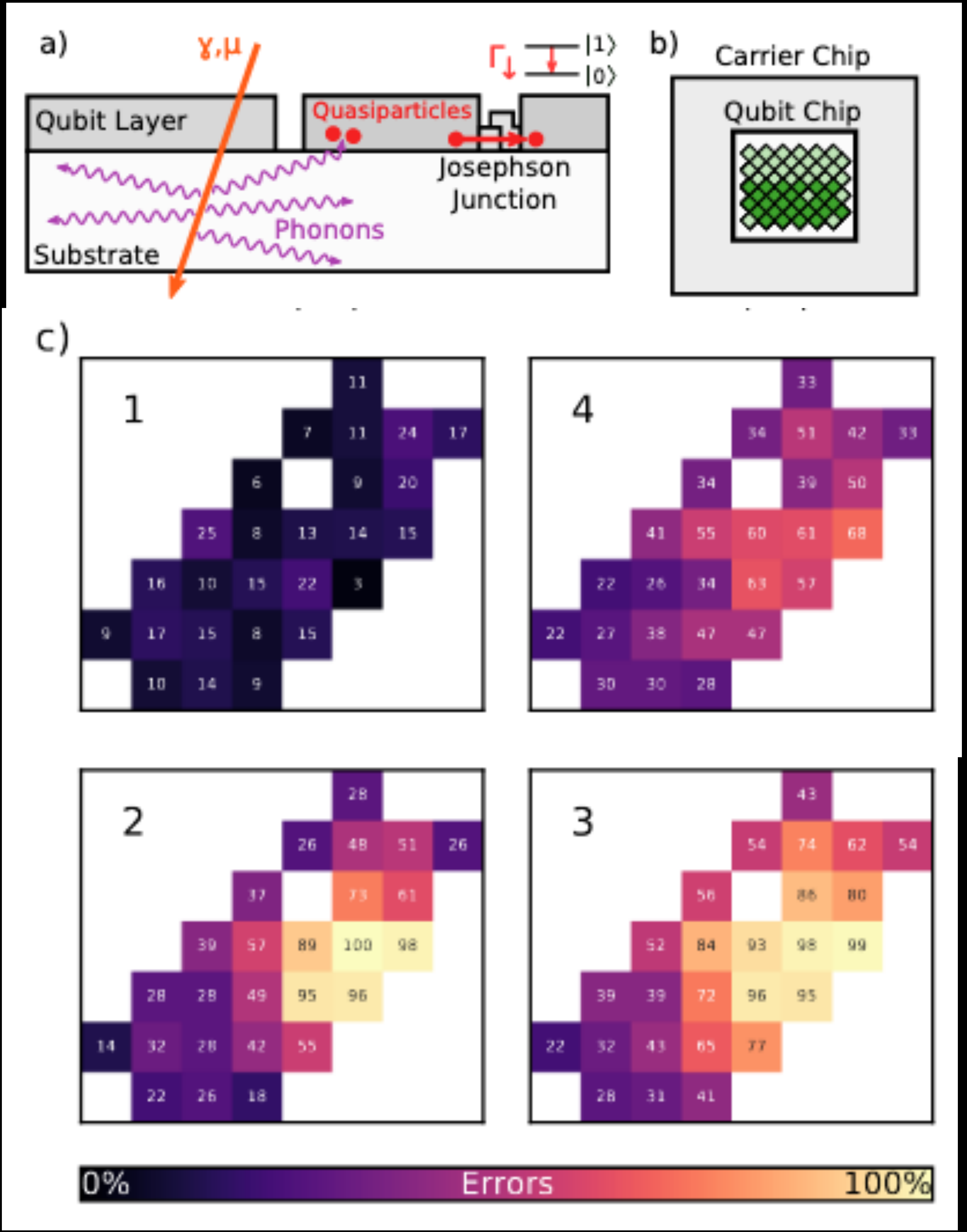
Quantum error and Comics rays and radioactivity

- Cosmic rays and latent radioactivity could be a limitation for car volume quantum processors due to the induced number of errors
- Substrat ionisation destroy qubit coherence
- Observation of high energy radiation in a quantum processor (sycamore)
- Studying the dynamics of damaging error burst due to cosmic rays and latent radioactivity
- Mitigation of these errors is a challenge for quantum computing technology


nature > nature physics > articles > article

Article | Published: 13 December 2021

Resolving catastrophic error bursts from cosmic rays in large arrays of superconducting qubits



Conclusions