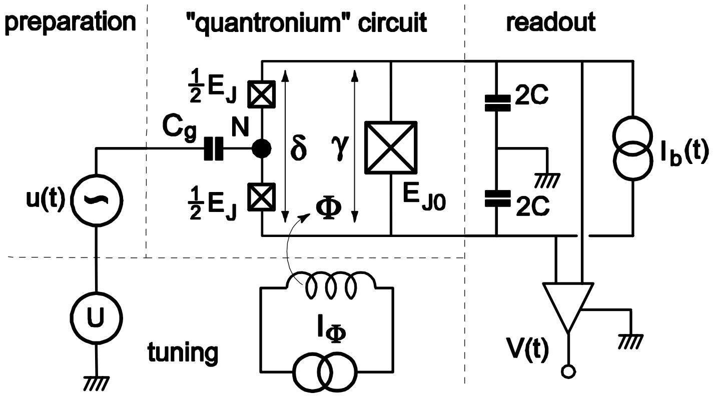
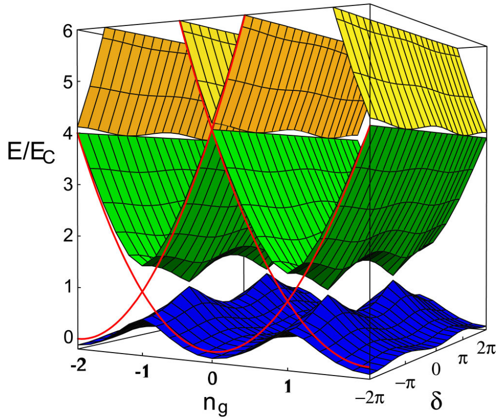
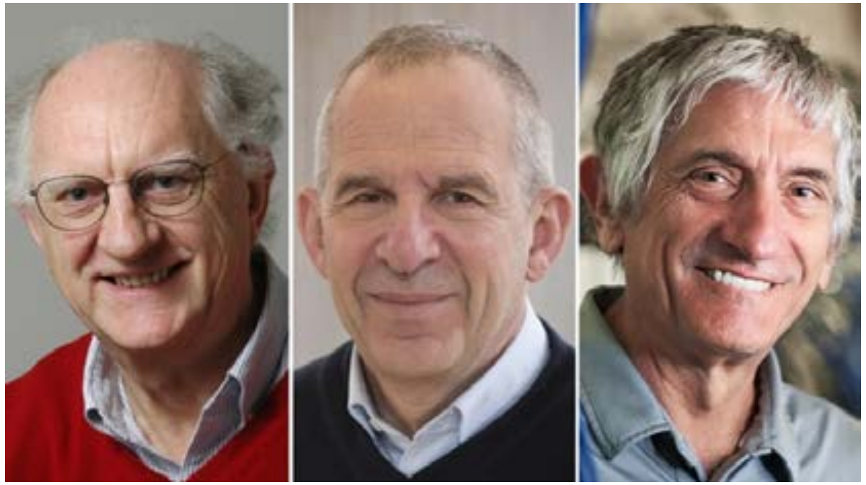




From qubits 2000 to Nobel Prize 2025

Göran Wendin
RISE & Chalmers



But this Nobel Prize story began 1913

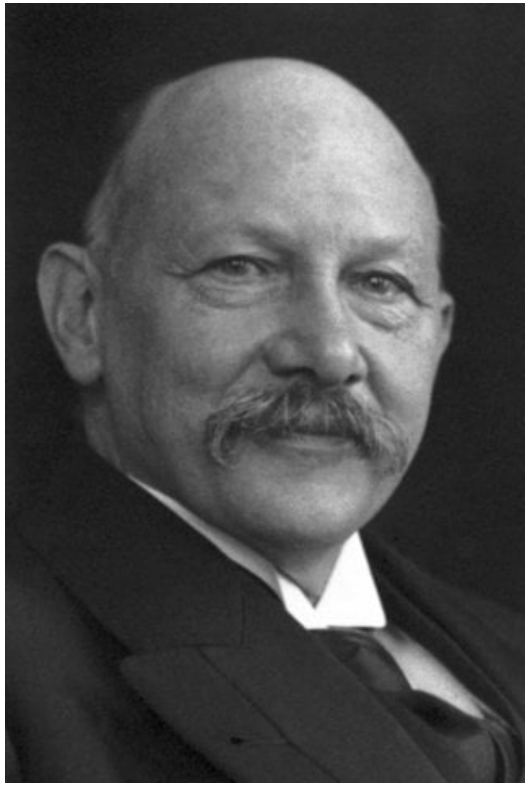
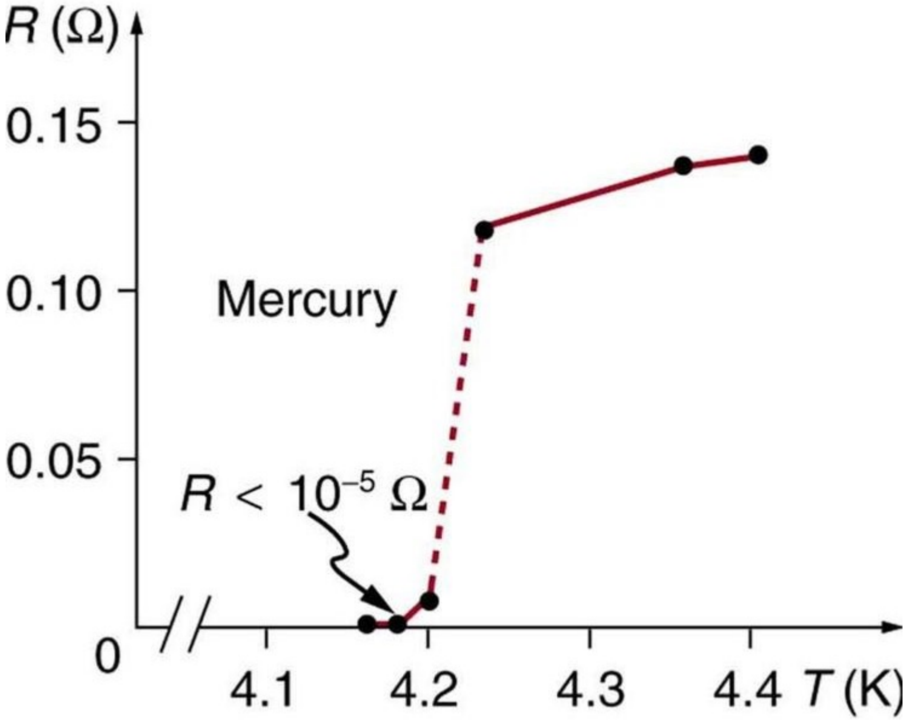


Photo from the Nobel Foundation archive.

Heike Kamerlingh Onnes

The Nobel Prize in Physics 1913 was awarded to Heike Kamerlingh Onnes "for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"



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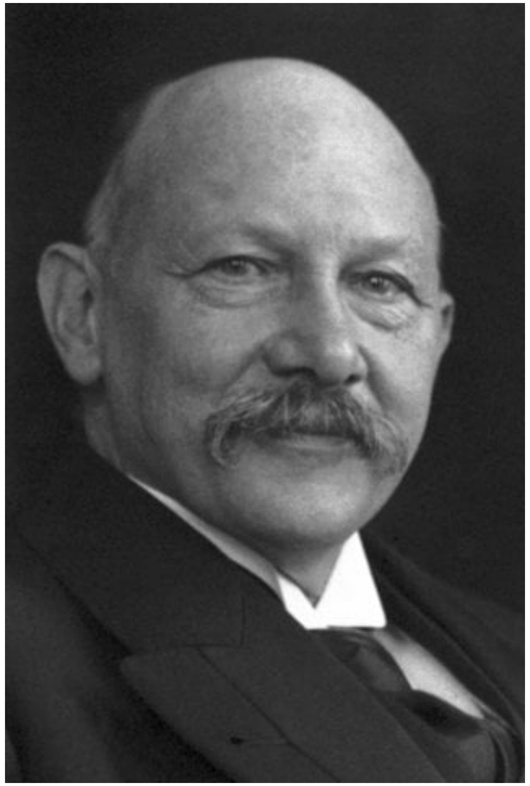

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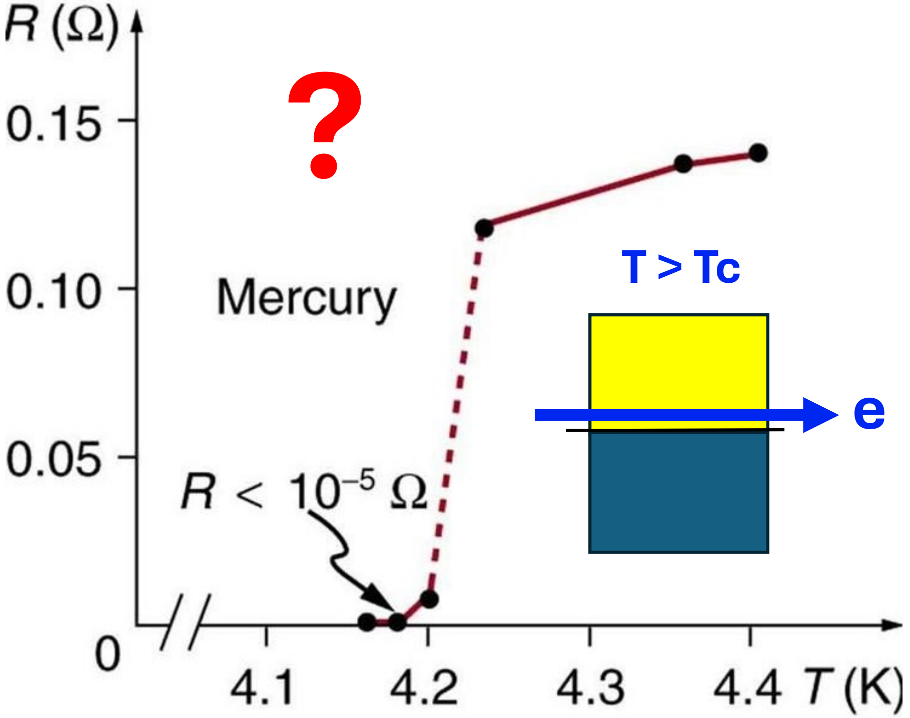

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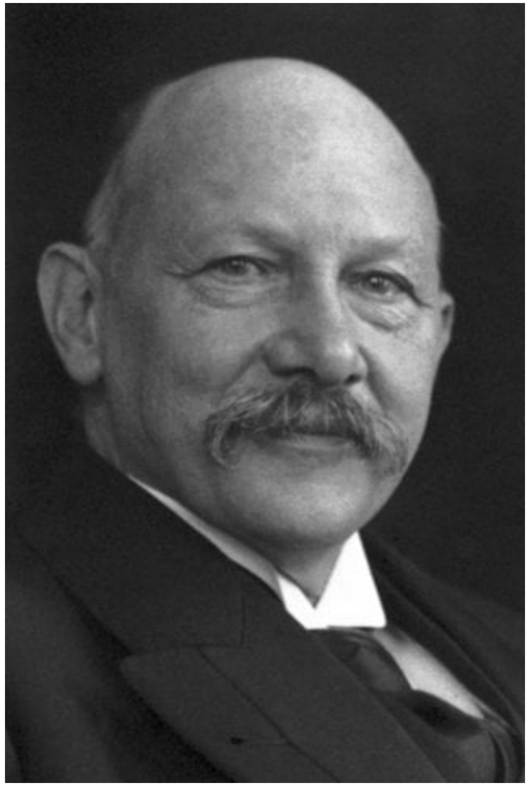

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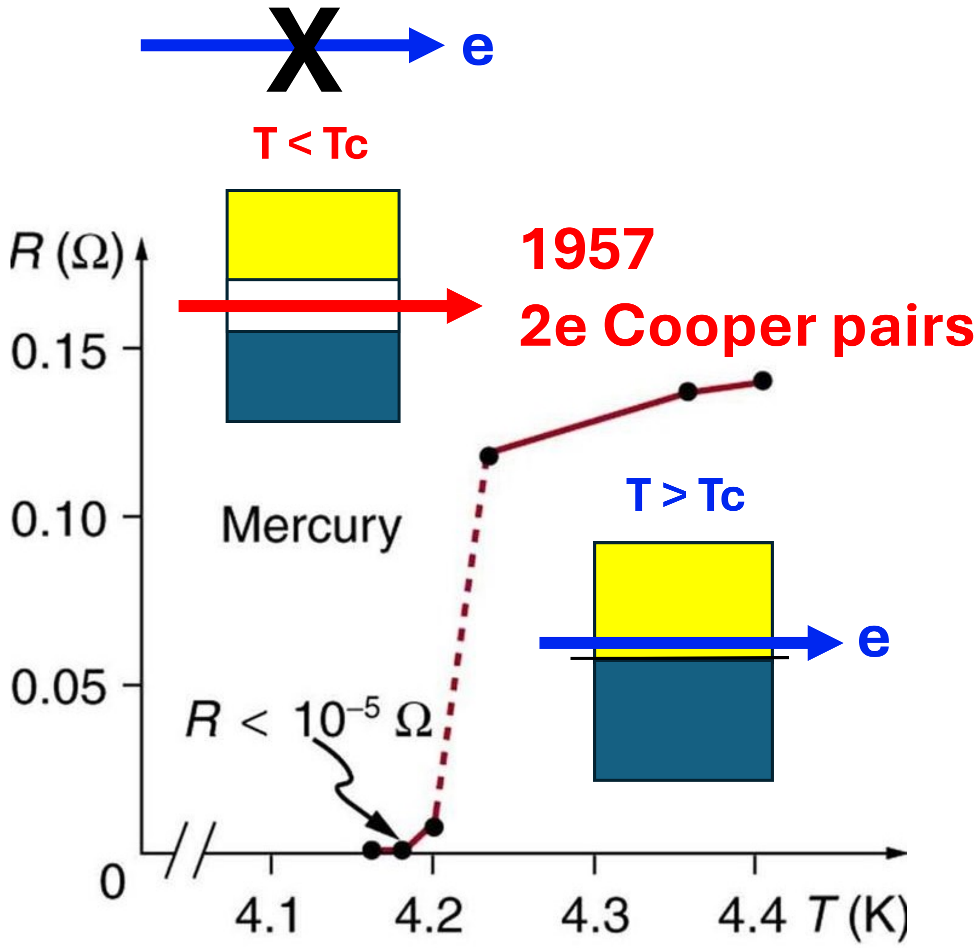
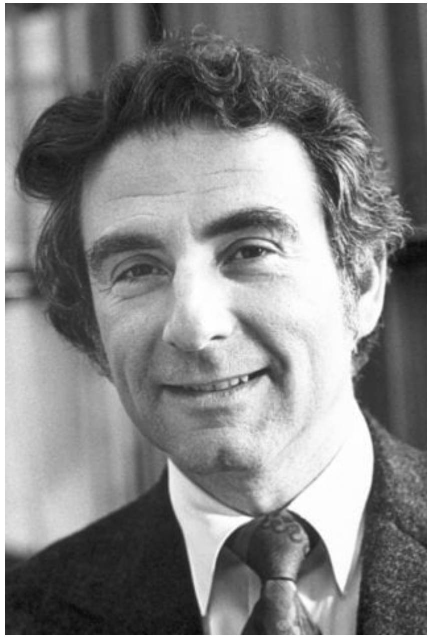
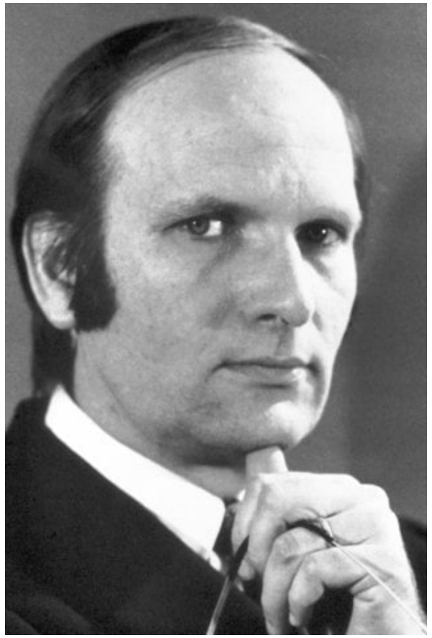


And continued - 1972

BCS-theory (1957)
Cooper pairs – 2e

Bardeen
Cooper
Schrieffer

The Nobel Prize in Physics 1972 was awarded jointly to John Bardeen, Leon Neil Cooper and John Robert Schrieffer "for their jointly developed theory of superconductivity, usually called the BCS-theory"

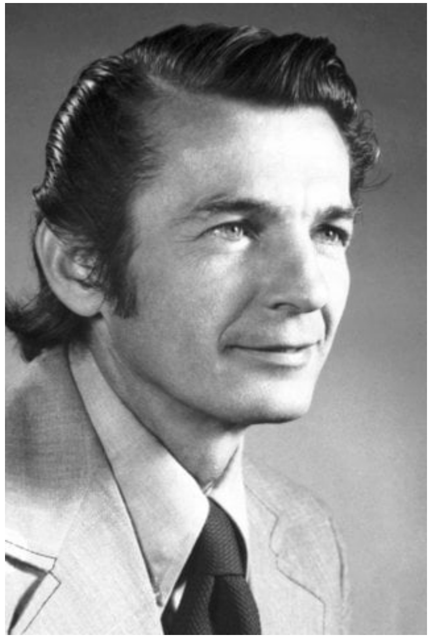
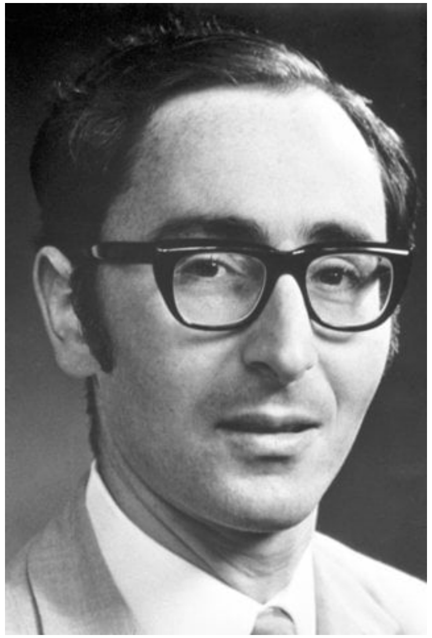
And was celebrated - 1973

Collective properties of physical systems

24-th Nobel Symposium

June 12-16, 1973
Aspenäsgården,
Lerum, Sweden.

And continued - 1973

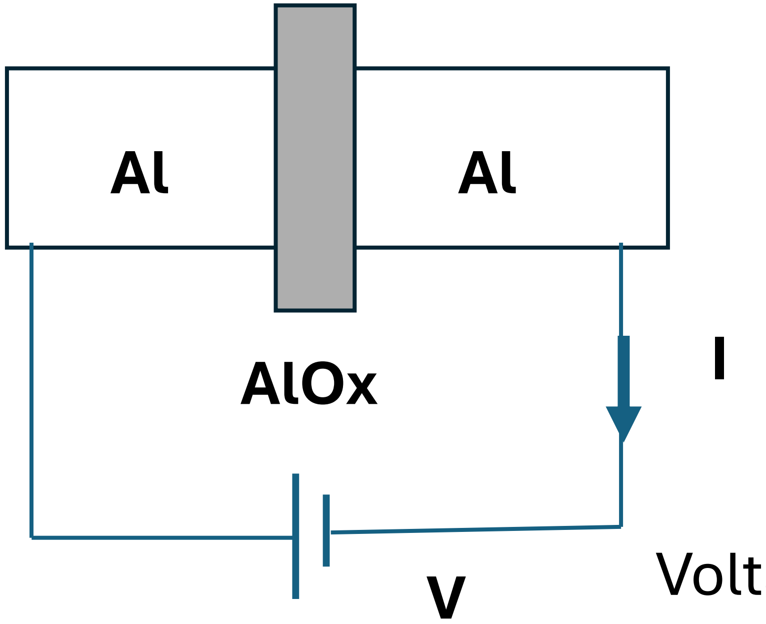


Electron tunneling in **semiconductors**
(Leo Esaki)
superconductors (Ivar Giaever)
Josephson effect
(Brian Josephson)

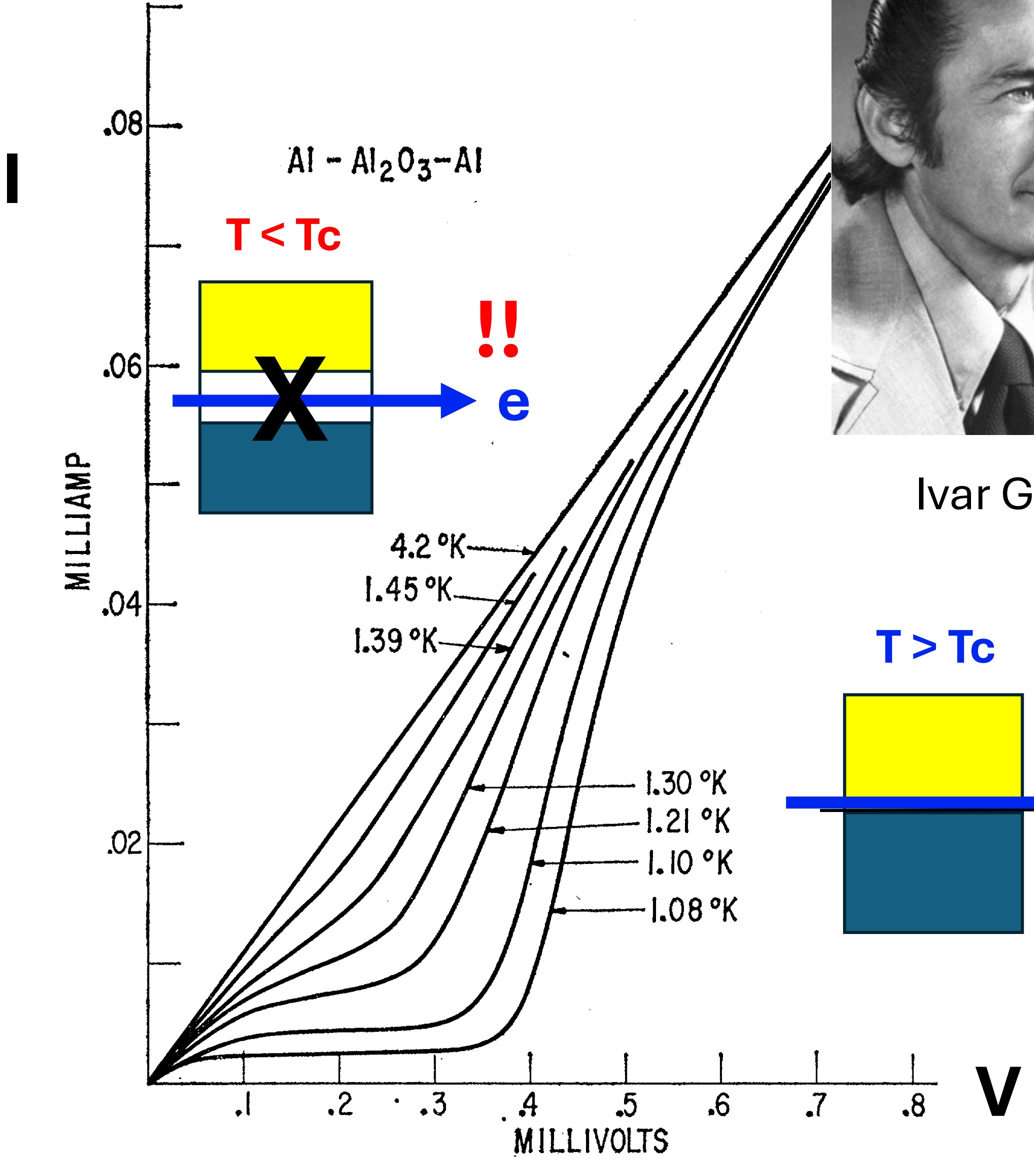
The Nobel Prize in Physics 1973 was divided, one half jointly to Leo Esaki and Ivar Giaever "for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors, respectively" and the other half to Brian David Josephson "for his theoretical predictions of the properties of a supercurrent through a tunnel barrier, in particular those phenomena which are generally known as the Josephson effects"

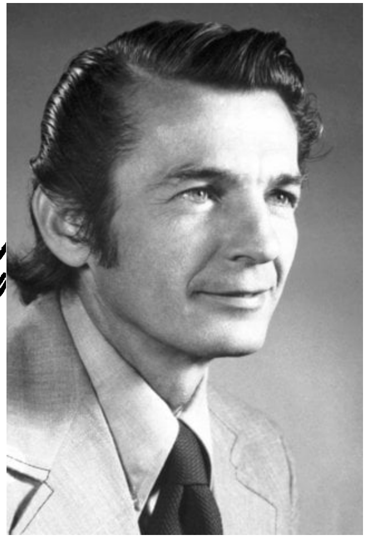
Tunnelling & the superconducting gap - 1961

Measuring the
I-V characteristic



Voltage source

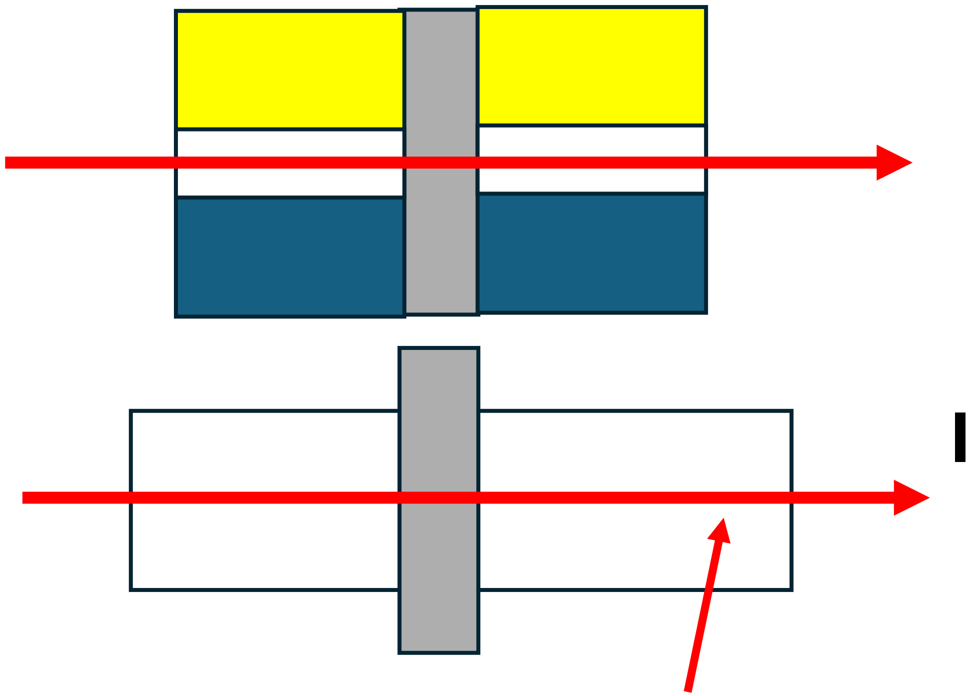




Ivar Giaever

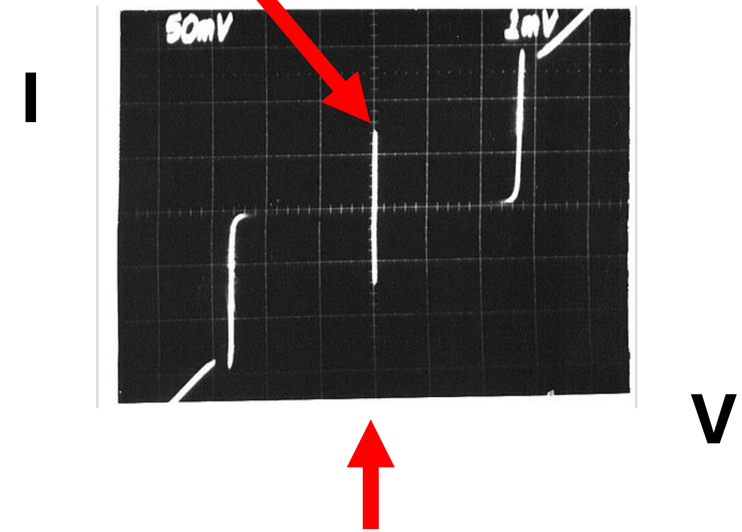
Josephson current – measured 1963

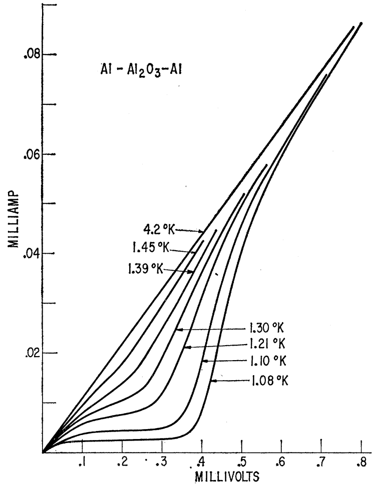
T < Tc



Current source ∞
Setting the current and
measuring the voltage

T < Tc





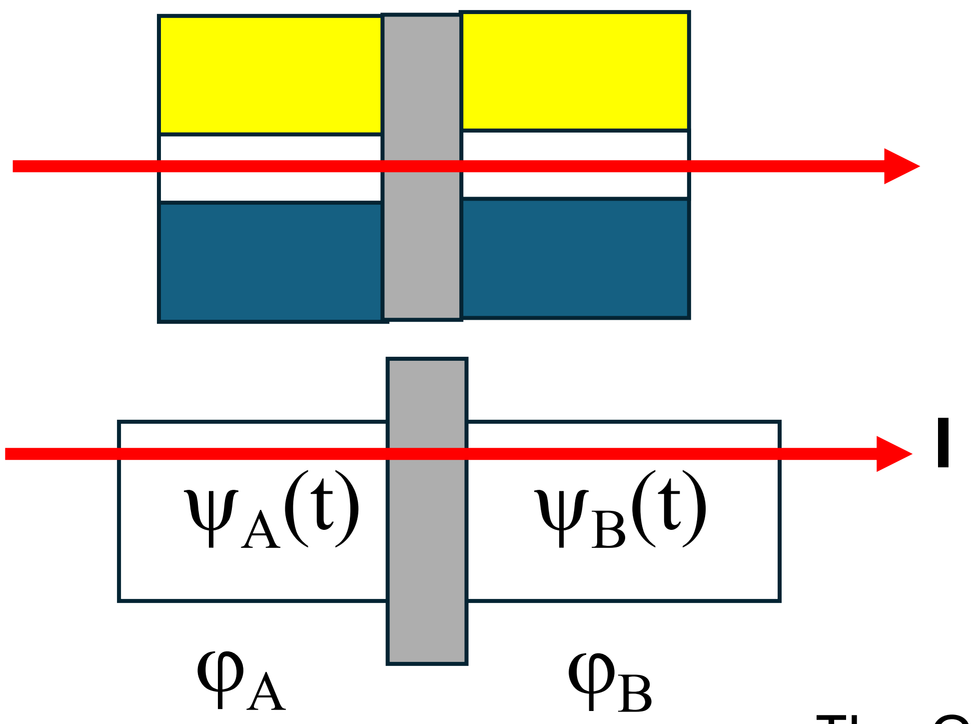
V = 0

Zero-voltage state.

The current crosses a **resistive barrier**, but **no voltage drop!**

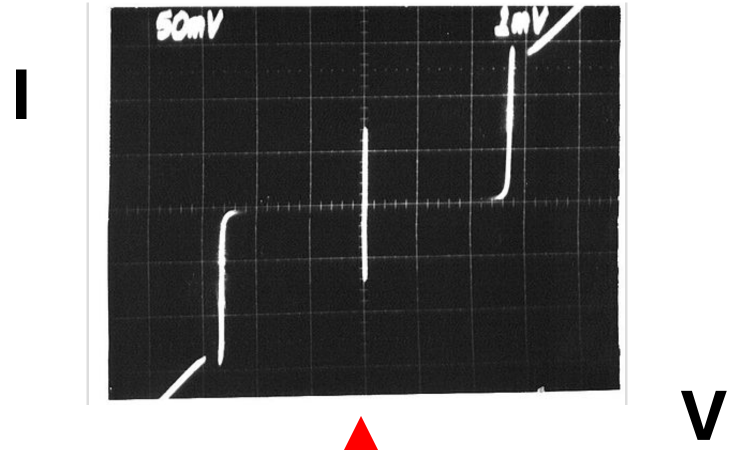
The Josephson effect - predicted 1962

T < Tc



$\varphi = \varphi_A - \varphi_A$

T < Tc

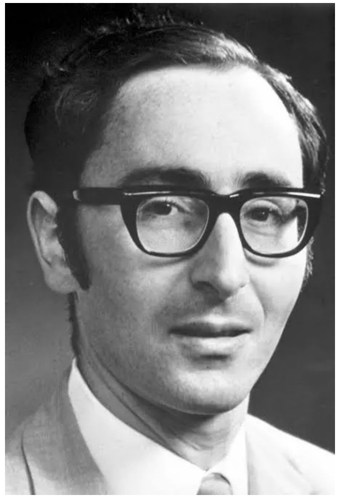


V = 0 → tunneling of Cooper pairs

Current flows without resistance

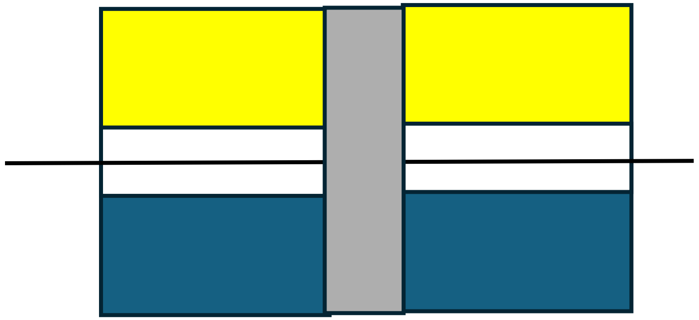
The Cooper pairs ("bosons") live in a superconducting condensate that is described by an order parameter ψ, similar to a wave function, with amplitude and phase:

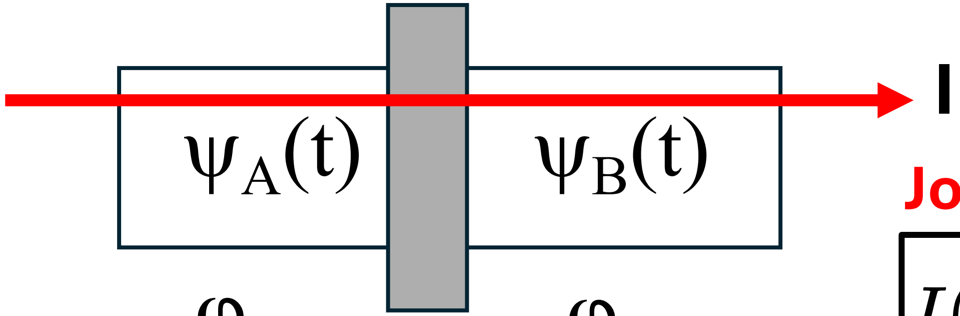
$\Psi = |\Psi| \exp(i\varphi)$



Nobel Prize 1973

The Josephson effect - 1962

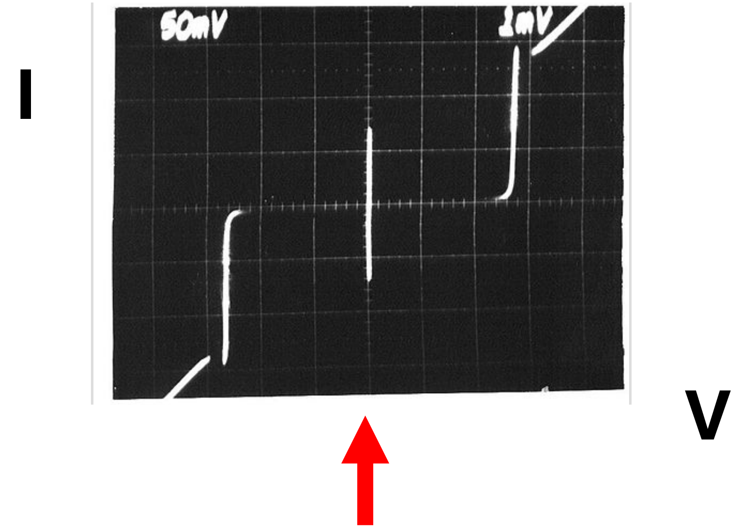


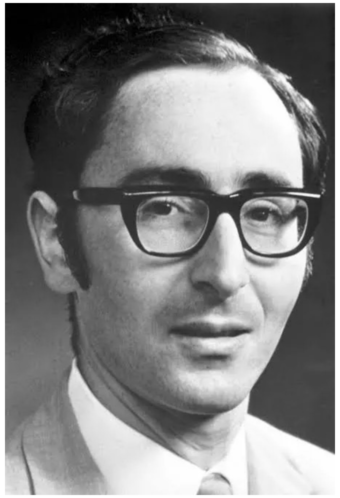


φ_A φ_B

$\varphi = \varphi_A - \varphi_A$

$\Psi = |\Psi| \exp(i\varphi)$





Nobel Prize 1973

Josephson relations

$$\boxed{\begin{aligned} I(t) &= I_c \sin(\varphi(t)) \\ \frac{\partial\varphi}{\partial t} &= \frac{2eV(t)}{\hbar} \end{aligned}}$$

V = 0 → φ constant

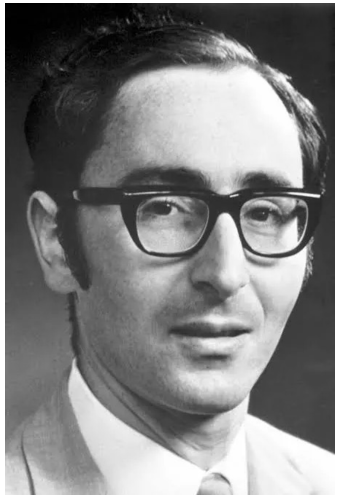
$I(\varphi) = Ic \sin(\varphi)$

V =constant ≠ 0

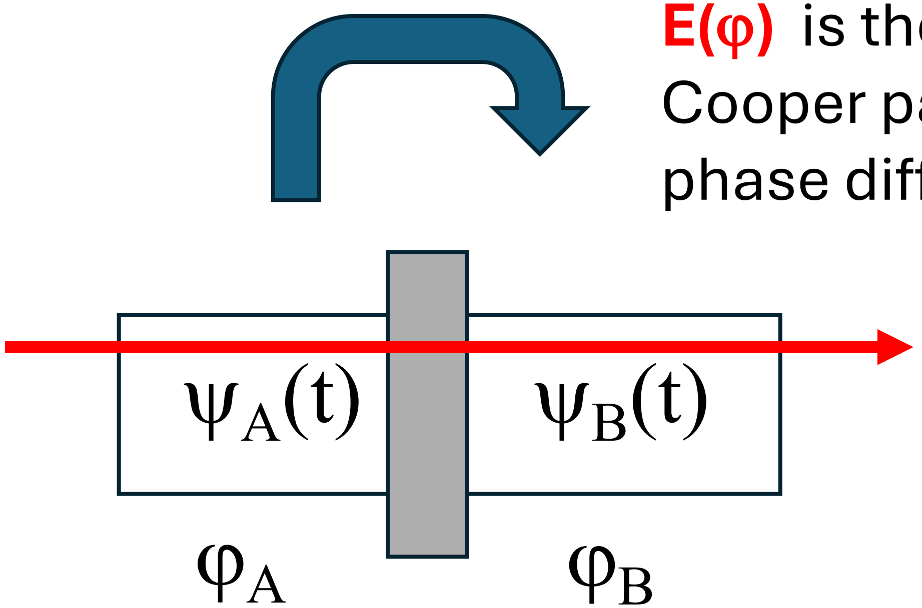
→ $I = Ic \sin(\omega t)$ $\quad \boldsymbol{\omega} = \frac{2eV}{\hbar}$

Josephson frequency → voltage-to-frequency converter

The Josephson energy E(φ)



Nobel Prize 1973



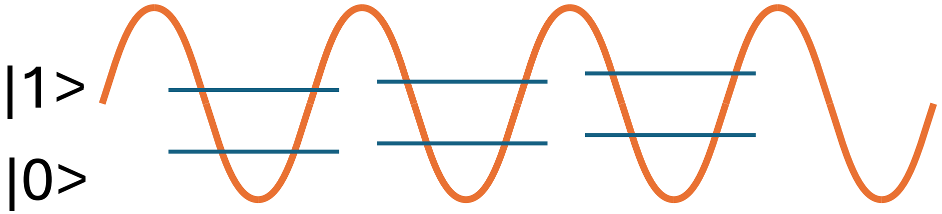
E(φ) is the energy needed to transfer a Cooper pair charge (- 2e) across the phase difference φ.

$$\Phi_0 = \frac{h}{2e}$$ Magnetic flux quantum

$$E(\varphi) = -\frac{\Phi_0 I_c}{2\pi}\cos\varphi = -E_J \cos\varphi$$

$\varphi = \varphi_A - \varphi_A$

E(φ) is the “potential energy” of a Cooper pair



It can trap the system in quasi-bound states

The potential energy of a current-biased (I_e) Josephson Junction (JJ)

$$U(\phi) = E_J(1 - \cos\phi) - \Phi_0 I_e \phi$$

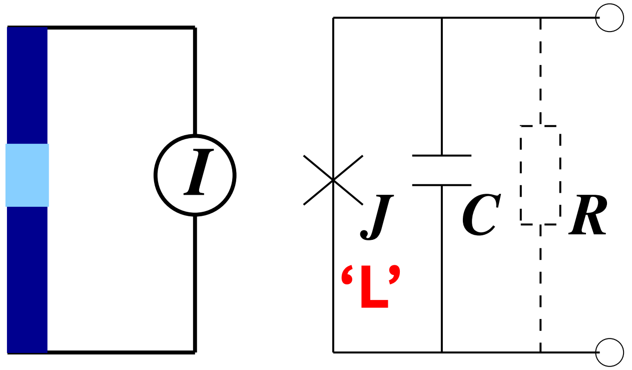
$$E_J = \frac{\Phi_0 I_c}{2\pi}$$

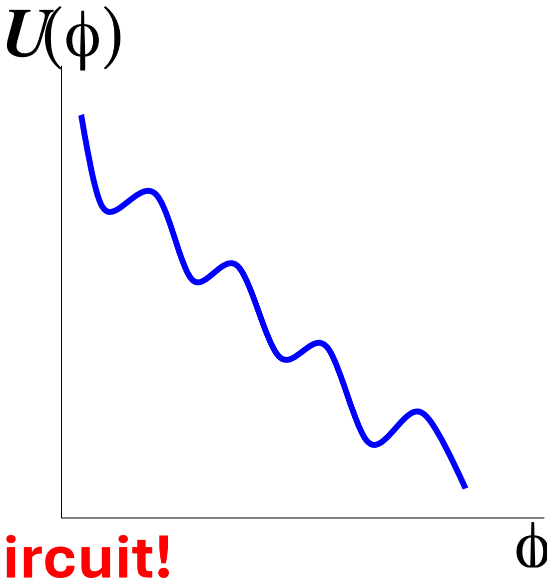
Large JJ critical current Ic

→ Deep potential energy well

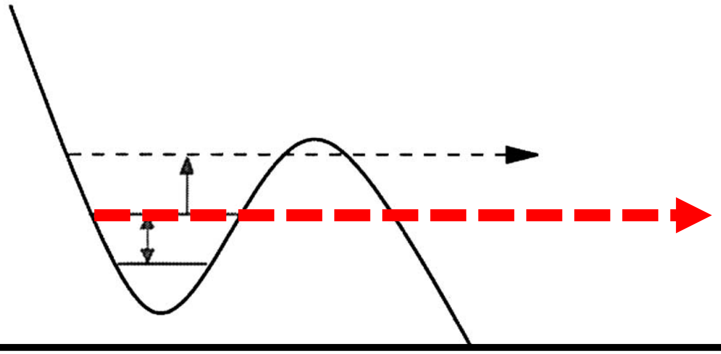
→ Can create bound quantum states !!

→ MQC; MQT





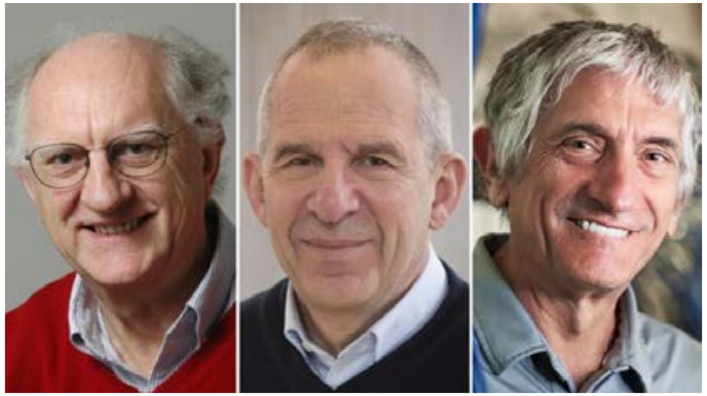
Non-linear LC circuit!

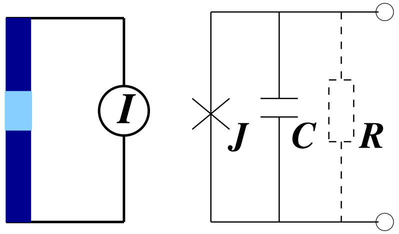


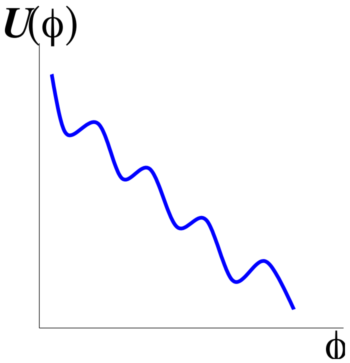
→Macroscopic quantum coherence MQC

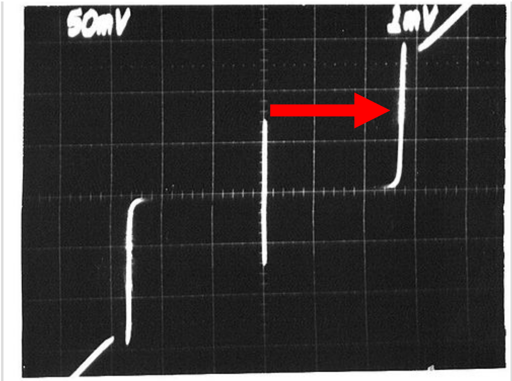
→ Macroscopic quantum tunneling MQT

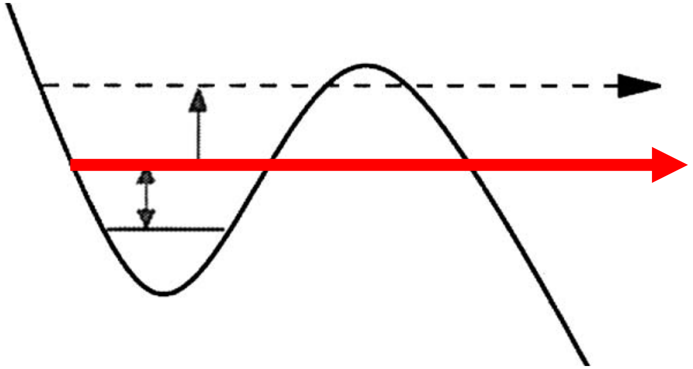
Now is finally 1985 –
the origin of the 2025 Nobel Prize



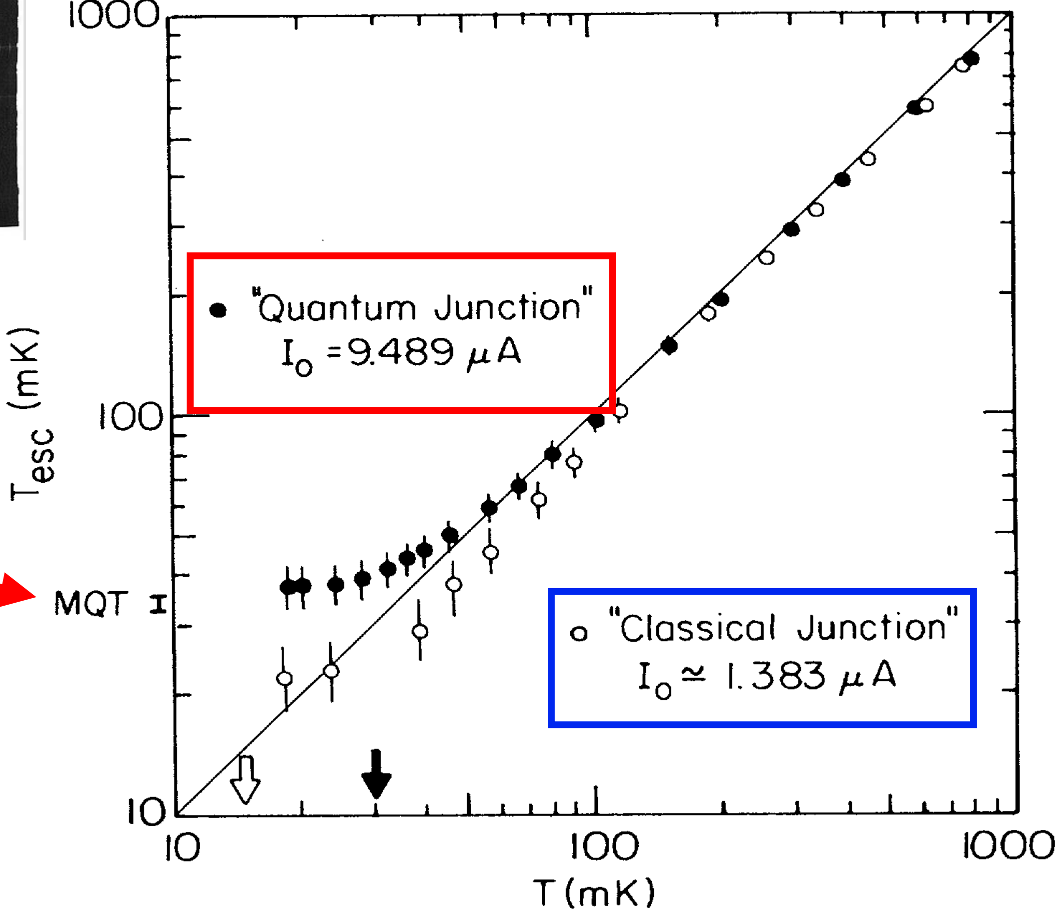








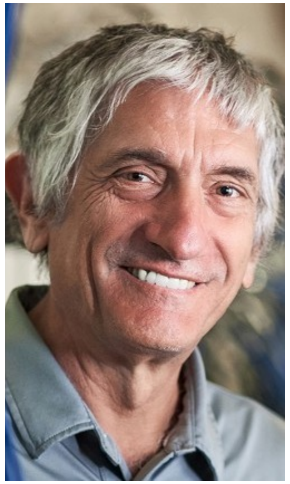
Caldeira-
Leggett 1981

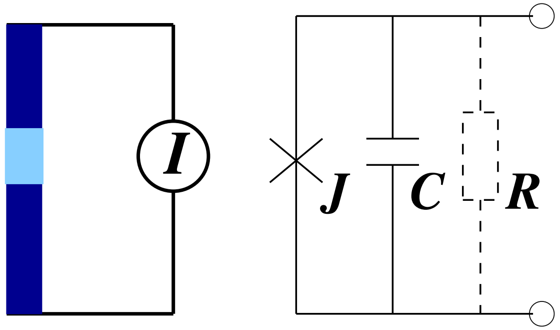


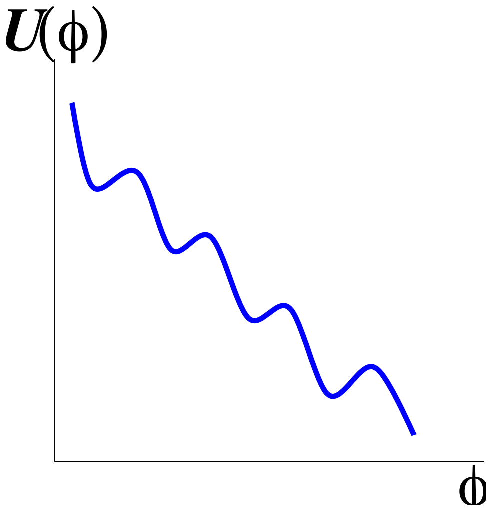
When **T → 0**

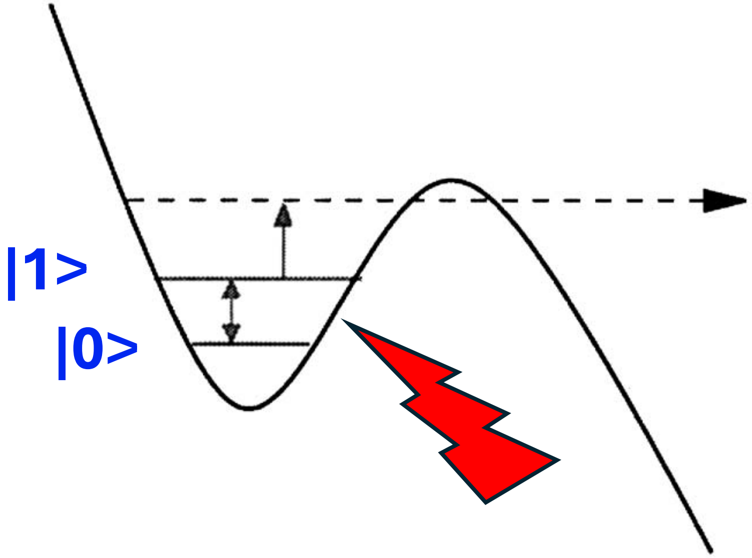
the **energy levels become sharp** and the "particle" can be trapped (MQC) before tunneling out through the JJ barrier (MQT)

John Martinis' qubit (2003-2007)

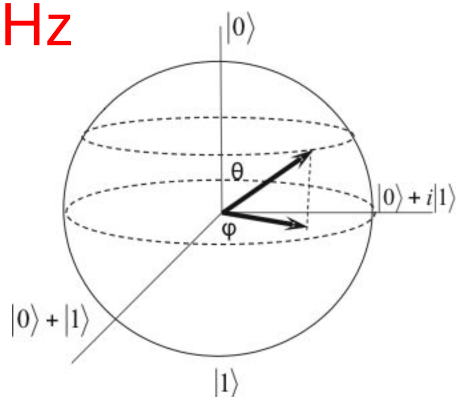






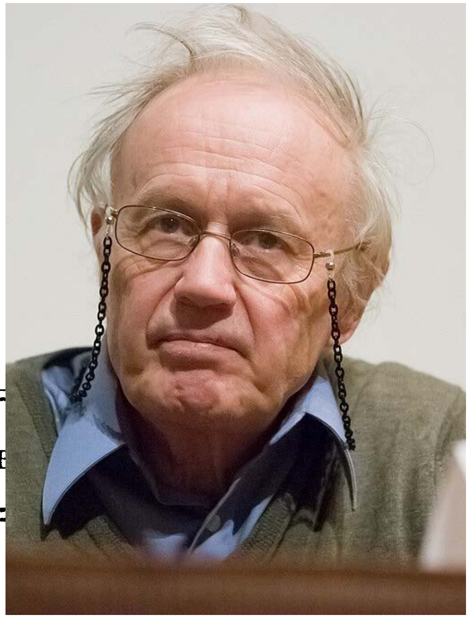


Microwaves ≈ 3 GHz



When **T → 0**
the **energy levels become sharp** and the "particle" can be trapped (MQC) before tunneling out through the JJ barrier (MQT)

Nobel Prize – 2003: Anthony Leggett →



Leggett in 2007

VOLUME 46 26 JANUARY 1981 NUME

Physical Review Letters

Liquid He_3

Influence of Dissipation on $\boxed{\text{Quantum Tunneling in Macroscopic Systems}}$

A. O. Caldeira and A. J. Leggett

School of Mathematical and Physical Sciences, University of Sussex, Brighton BN1 9QH, Sussex, United Kingdom

(Received 28 July 1980)

A quantum system which can tunnel, at $T = 0$, out of a metastable state and whose interaction with its environment is adequately described in the classically accessible region by a phenomenological friction coefficient η, is considered. By only assuming that the environment response is linear, it is found that dissipation multiplies the tunneling probability by the factor $\exp[-A\eta(\Delta q)^2/\hbar]$, where Δq is the "distance under the barrier" and A is a numerical factor which is generally of order unity.

Physica Scripta. Vol. T76, 165–170, 1998

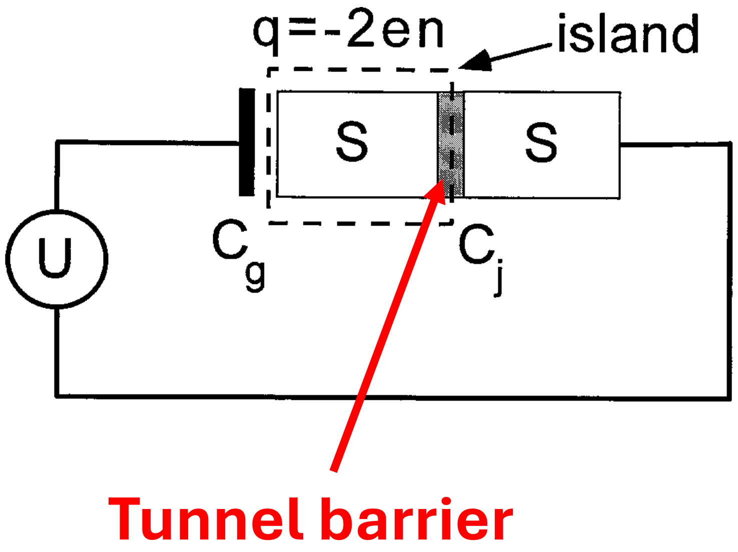
Quantum Coherence with a Single Cooper Pair

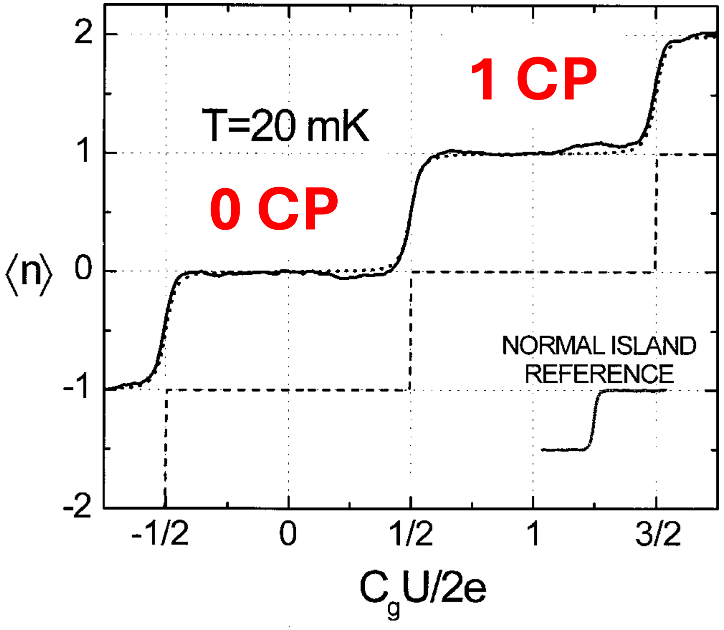
V. Bouchiat,* D. Vion, P. Joyez, D. Esteve and M. H. Devoret

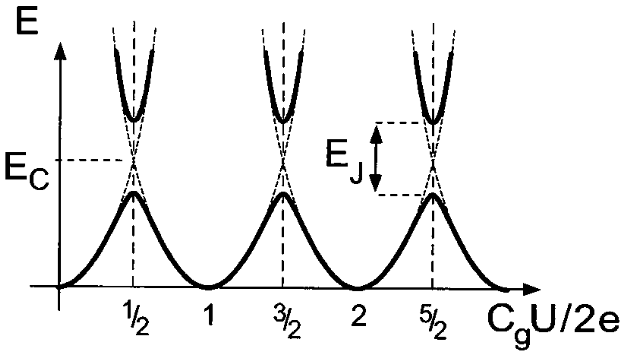
Quantronics group, Service de Physique de l'Etat Condensé CEA-Saclay, F-91191 Gif-sur-Yvette, France

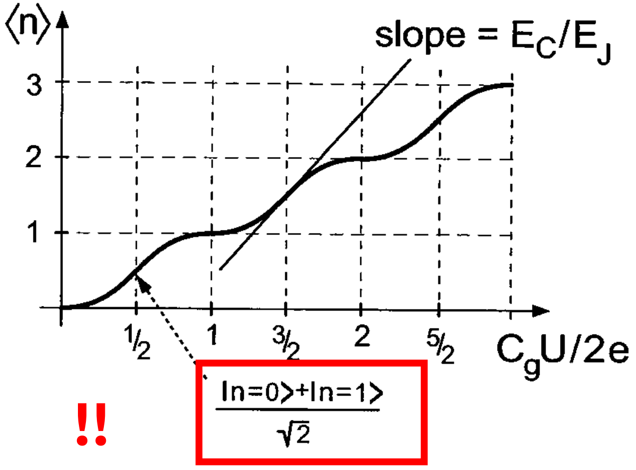
Received October 27, 1997; revised version received January 15, 1998; accepted January 23, 1998

Cooper Pair Box (CPB)









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

NATURE | VOL 398 | 29 APRIL 1999

This started the superconducting qubit technology race !!

SQUBIT

Superconducting Qubits:
Quantum Computing with Josephson Junctions

Coordinator:
Göran Wendin, Chalmers

Chalmers	P. Delsing,
	G. Wendin (coord)
Jyväskylä	J. Pekola
KTH	D. Haviland
TU Delft	H. Mooij
Karlsruhe	G. Schön
CEA Saclay	M. Devoret
ISI-Torino/Catania	R. Fazio

Project funded by the Future and Emerging Technologies arm of the IST-FET-QIPC proactive initiative

SQUBIT Go/Nogo milestone: criteria

Evidence, direct or indirect, that at least one particular realization of a qubit based on a superconducting system should be able to display a coherence time at least 1000 time longer than its switching time

There are two important (classes of) qubit lifetimes:
(1) T_1 characterizing level transitions (relaxation, mixing, saturation)
(2) T_ϕ characterizing the decoherence (dephasing) time of the two levels at fixed level population.

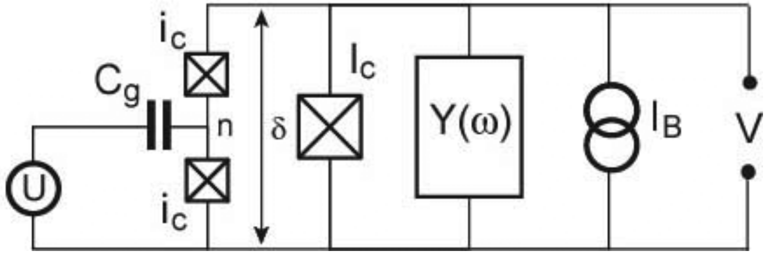
When T_ϕ dominates the lifetime, it approximately determines the line width Γ in spectroscopic experiments:

$$T_\phi \approx T_2 = h\Gamma^{-1} << T_1$$

For qubit operation to be possible, $Q_\phi = \omega_0 T_\phi >> 1$.

Quality factor must be >> 1

A NEW SUPERCONDUCTING QUBIT WITH SEPARATION OF WRITE AND READ PORTS



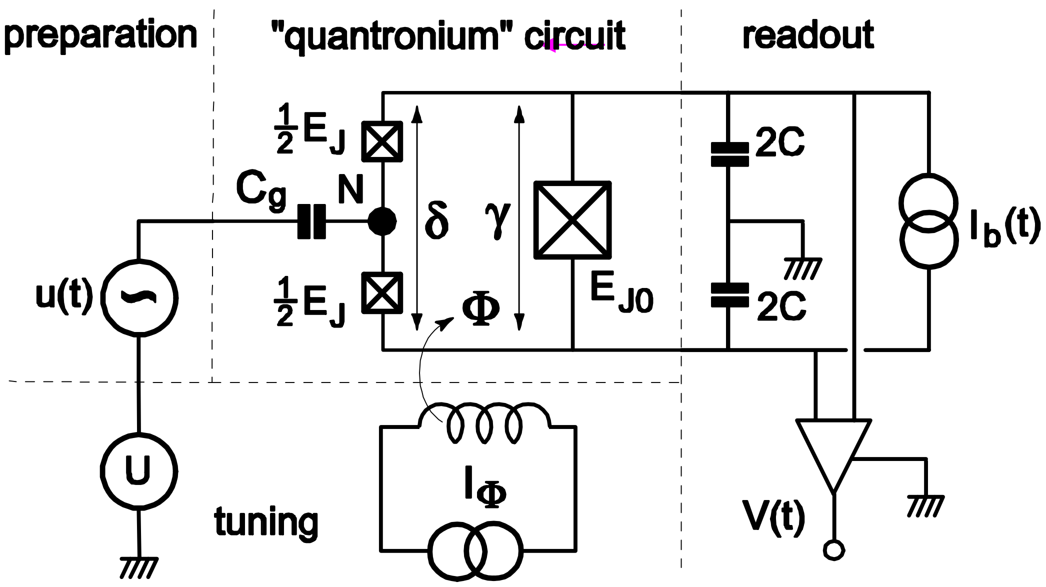
M. D.
D. ESTEVE
C. URBINA

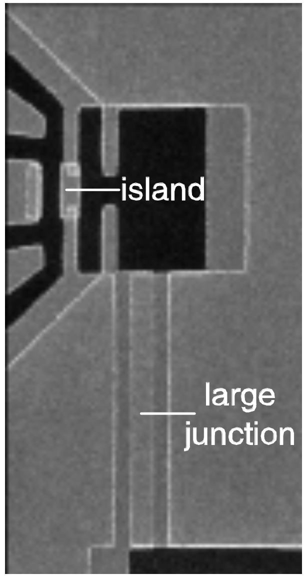
P. JOYEZ
H. POTHIER
D. VION

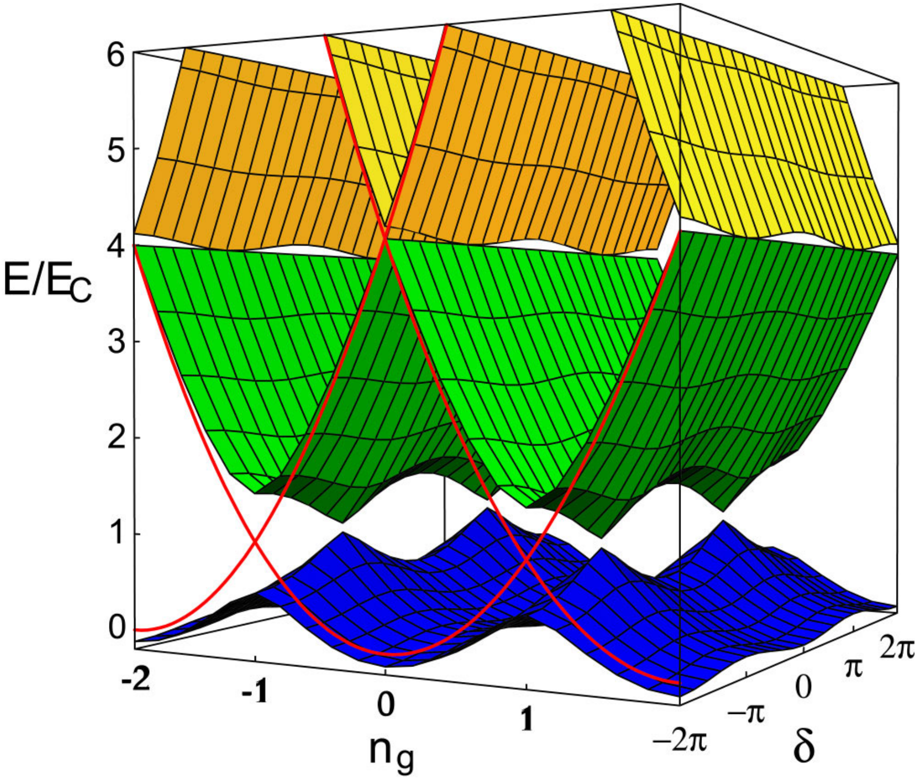
V. BOUCHIAT
A. COTTET
A. AASSIME

Delft, September 2001 **Month 20**

COOPER PAIR TRANSISTOR WITH PHASE BIAS







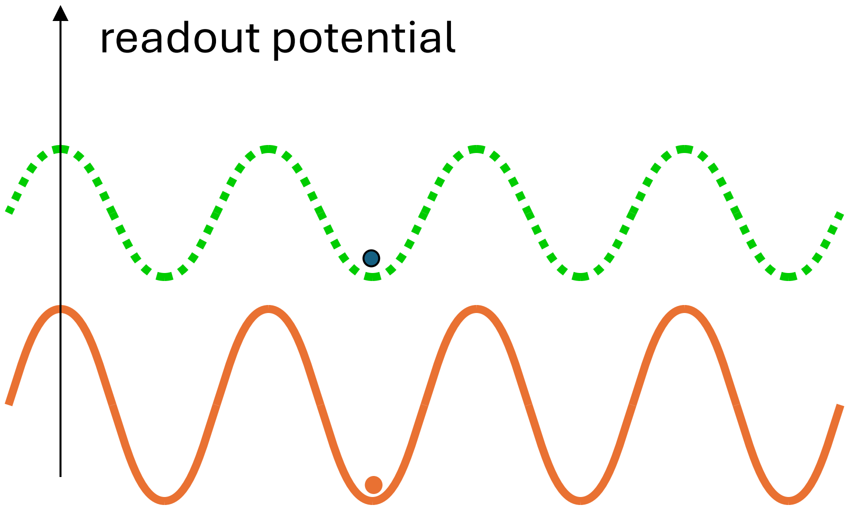
advantages:

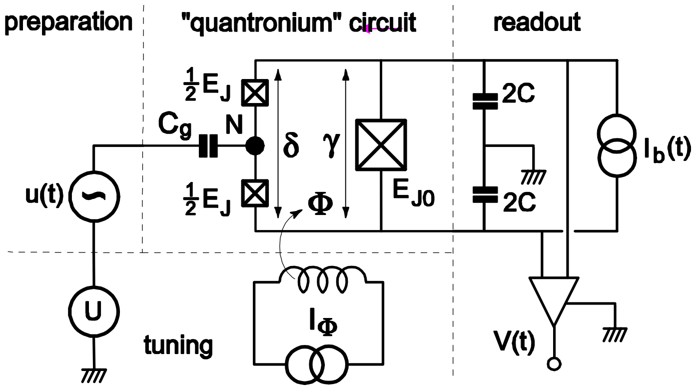
1) two knobs to tune ω_{01}

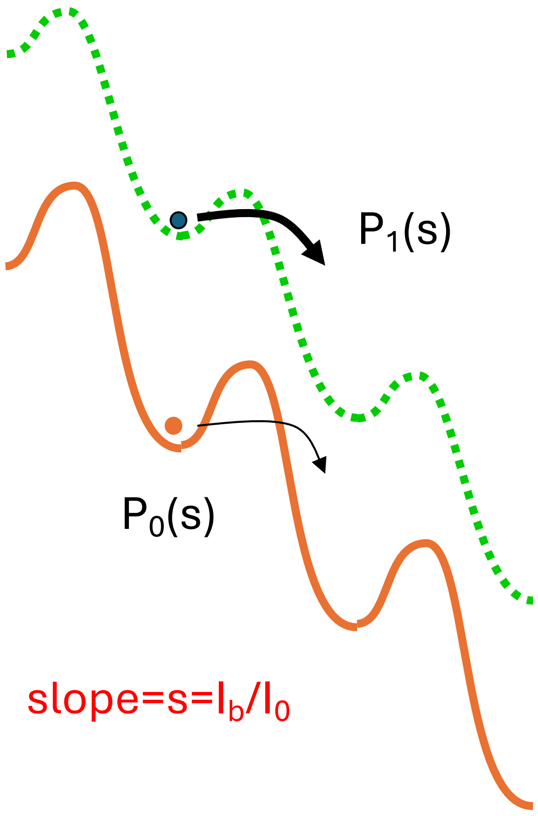
2) read-out using current I_s

$E_J/E_c=1$; $E_c=e^2/(2C_\Sigma)$

PRINCIPLE OF READ-OUT

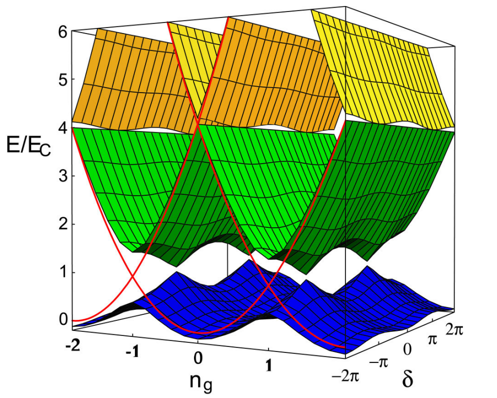


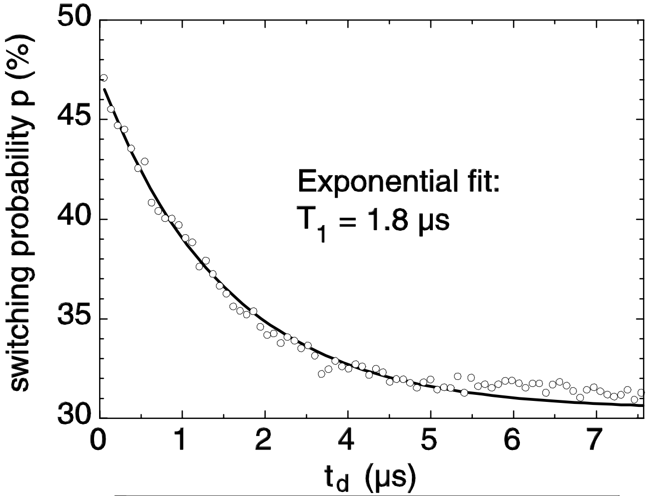


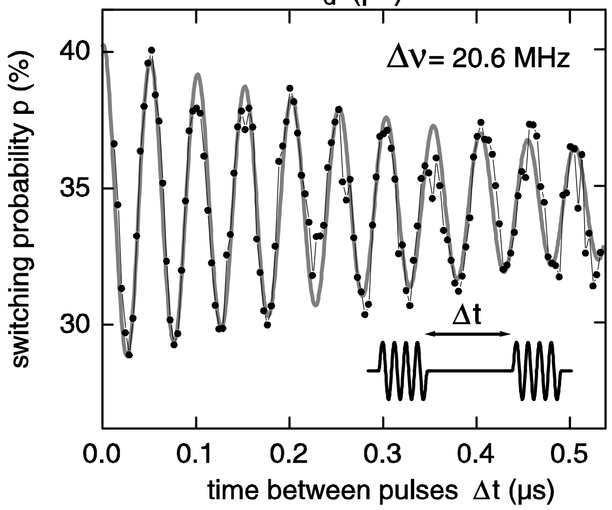


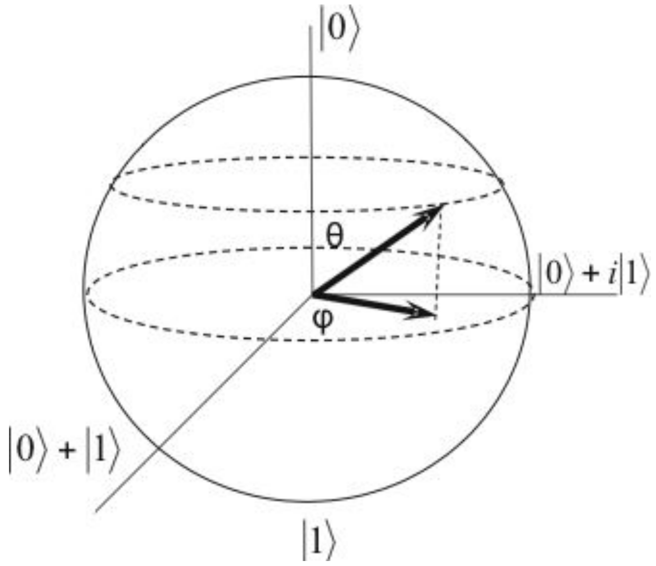
very efficient read-out since $P_1(s)$~$500P_0(s)$ when escape limited by MQT

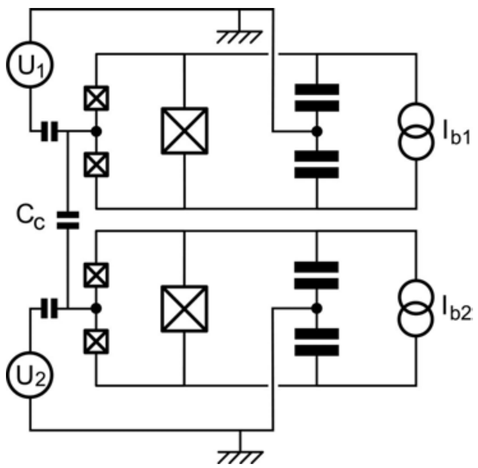
Evidence, direct or indirect, that at least one particular realization of a qubit based on a superconducting system should be able to display a coherence time at least 1000 times longer than its switching time (month 20).











$T_2 = 0.5\ \mu s$

$Q_\phi = 2.5 \times 10^4 >> 1$

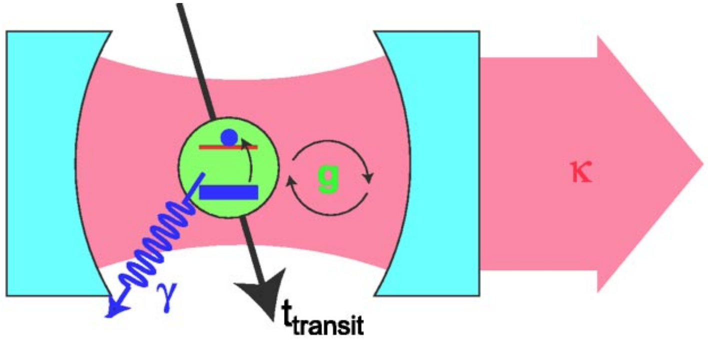
We passed! 😓 → 😁

2004 – the birth of CQED

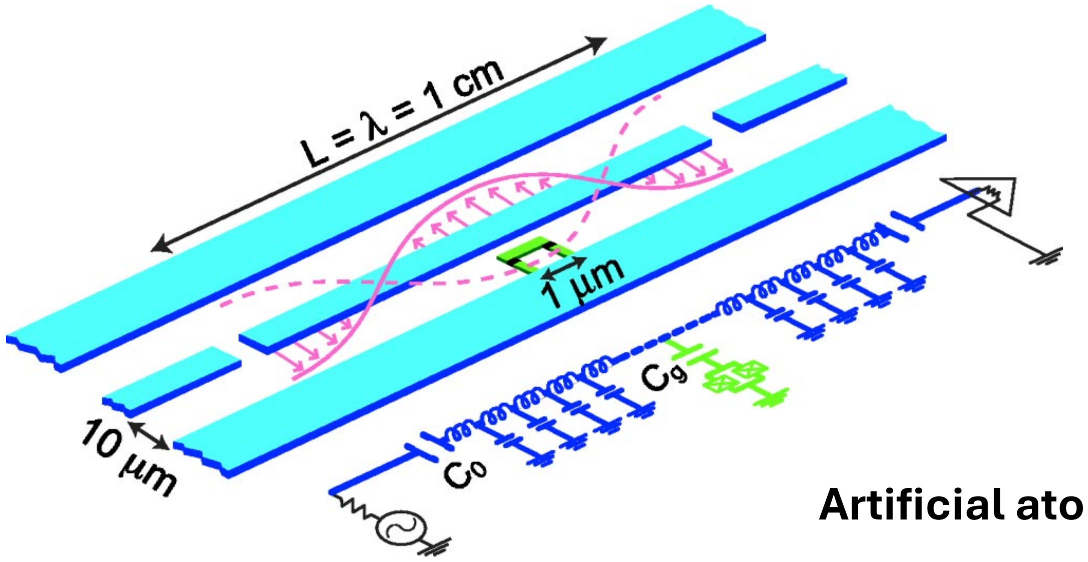
PHYSICAL REVIEW A **69**, 062320 (2004)

Cavity quantum electrodynamics for superconducting electrical circuits: An architecture for quantum computation

Alexandre Blais,[1] Ren-Shou Huang,[1,2] Andreas Wallraff,[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]*Department of Physics, Indiana University, Bloomington, Indiana 47405, USA*



Real atom



Artificial atom

2007 – the birth of the Transmon

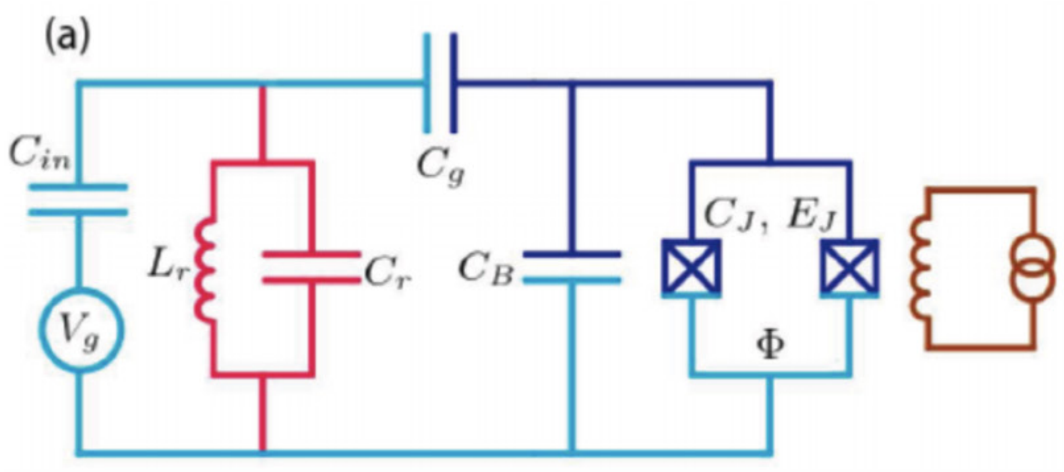
PHYSICAL REVIEW A **76**, 042319 (2007)

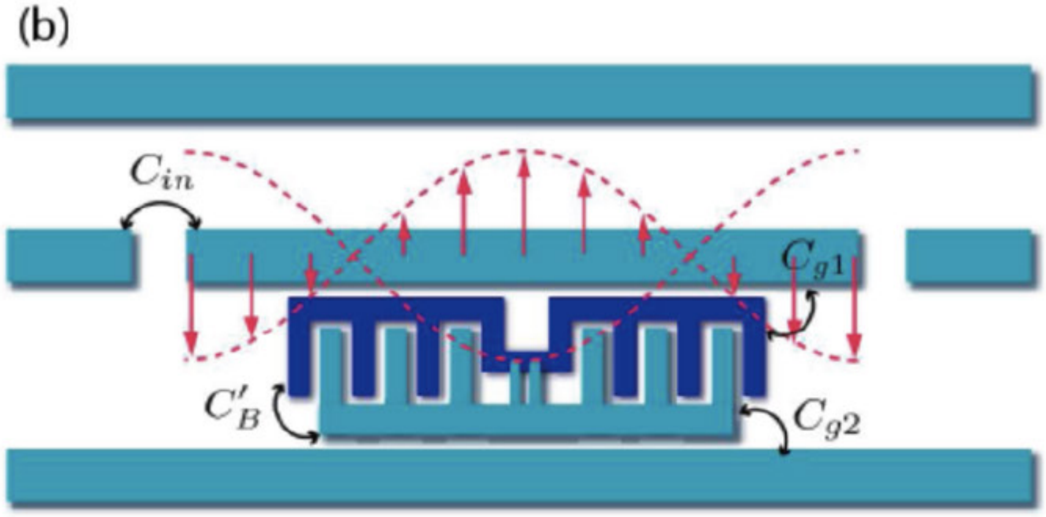
Charge-insensitive qubit design derived from the Cooper pair box

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*

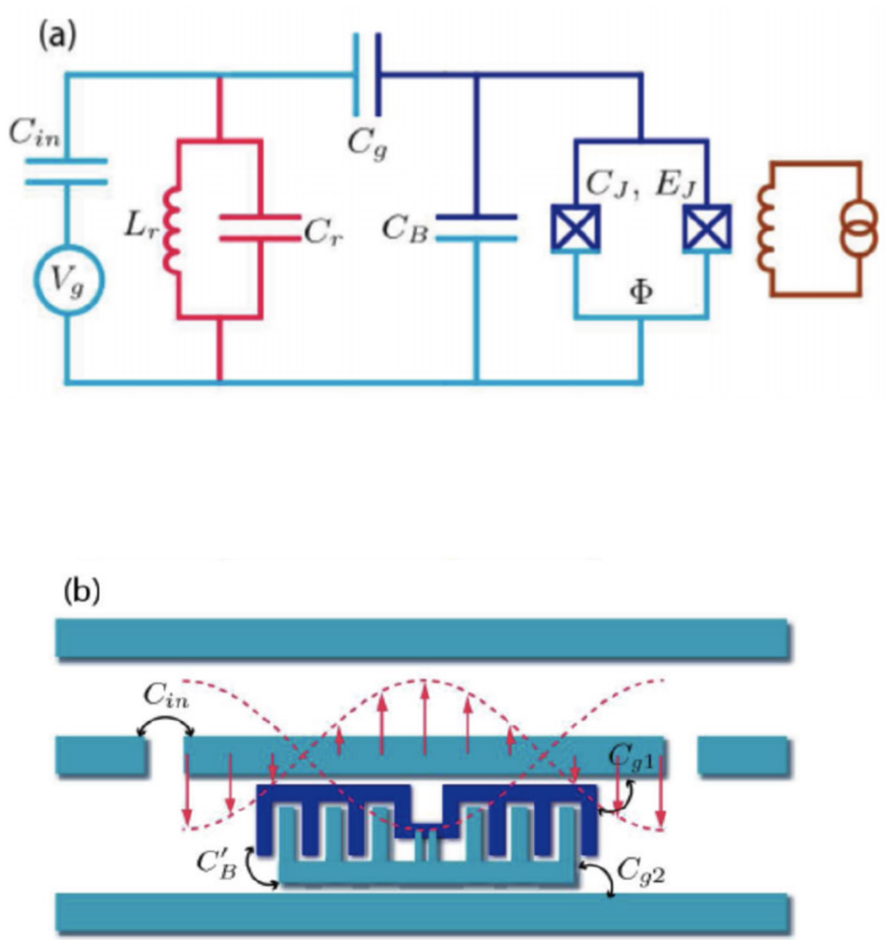
[2]*Département de Physique et Regroupement Québécois sur les Matériaux de Pointe, Université de Sherbrooke, Sherbrooke, Québec,*

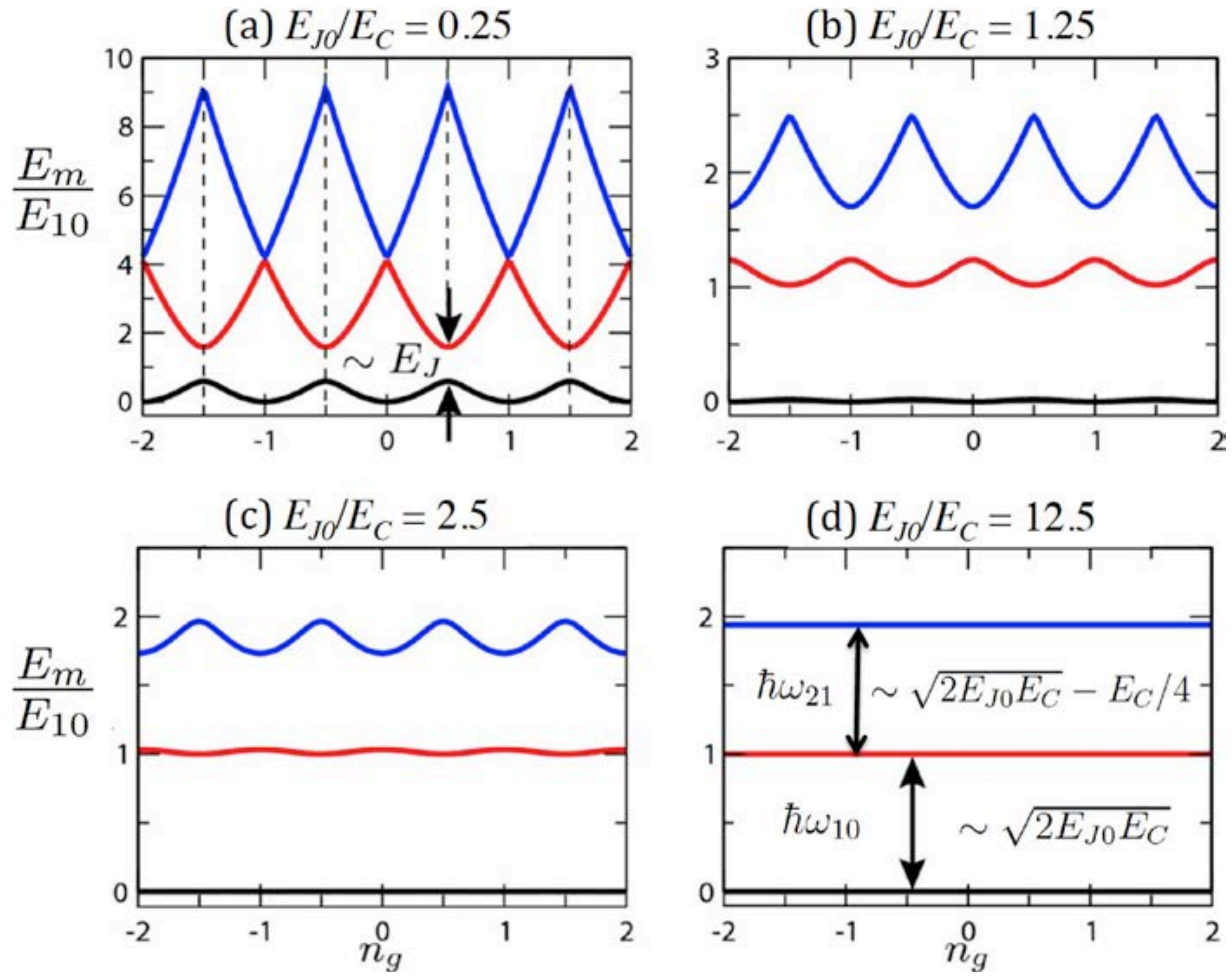




LARGE capacitance

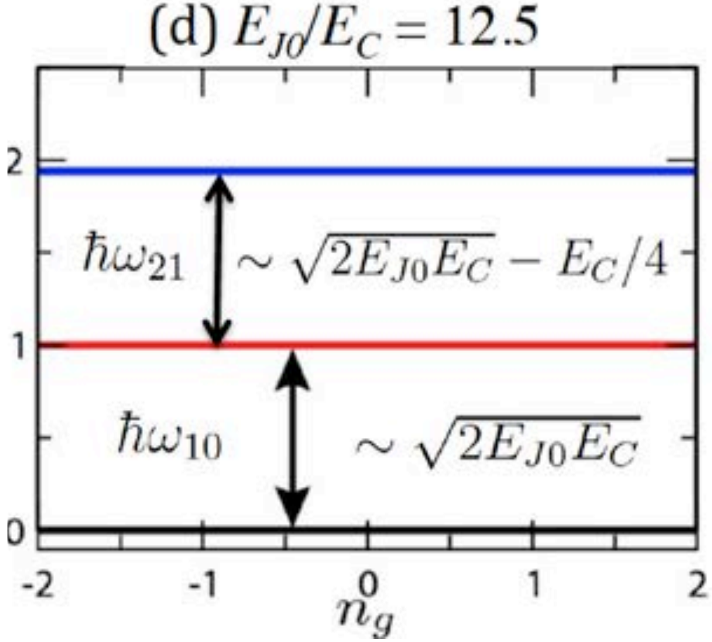
From Cooper Pair Box to Transmon – E_J/E_C >>1

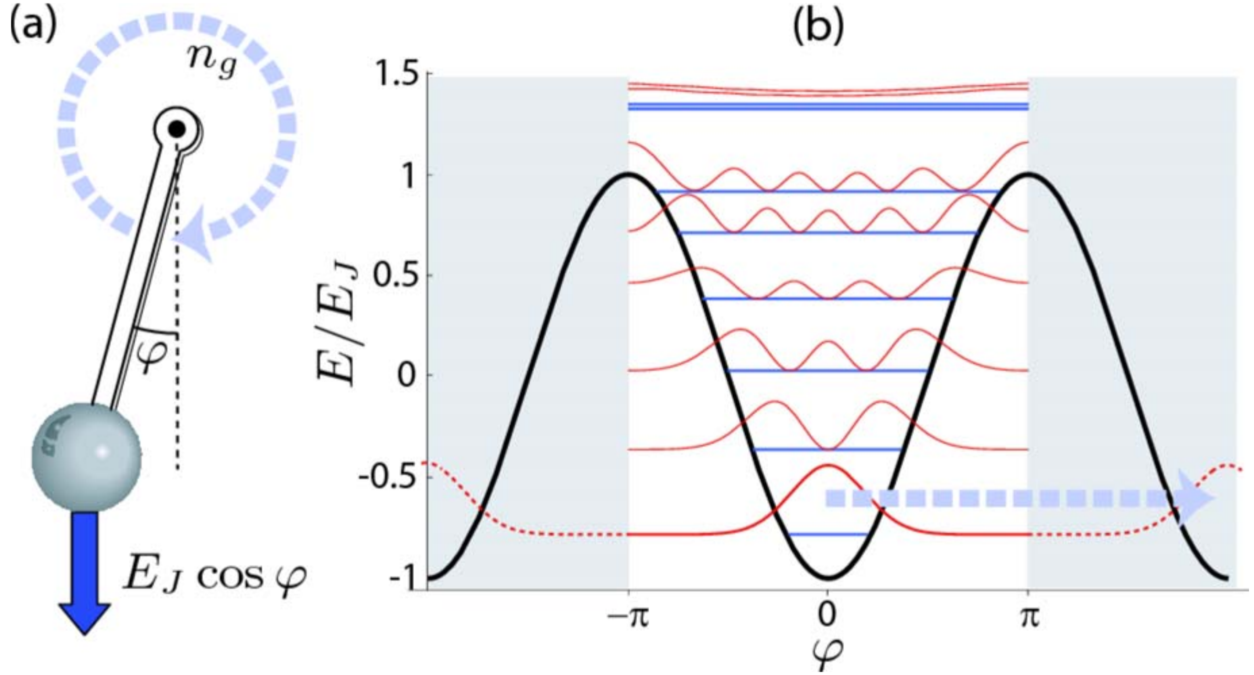




LARGE capacitance → small charging energy E_C → LARGE E_J/E_C

Transmon = Artificial atom





Anharmonic LC circuit

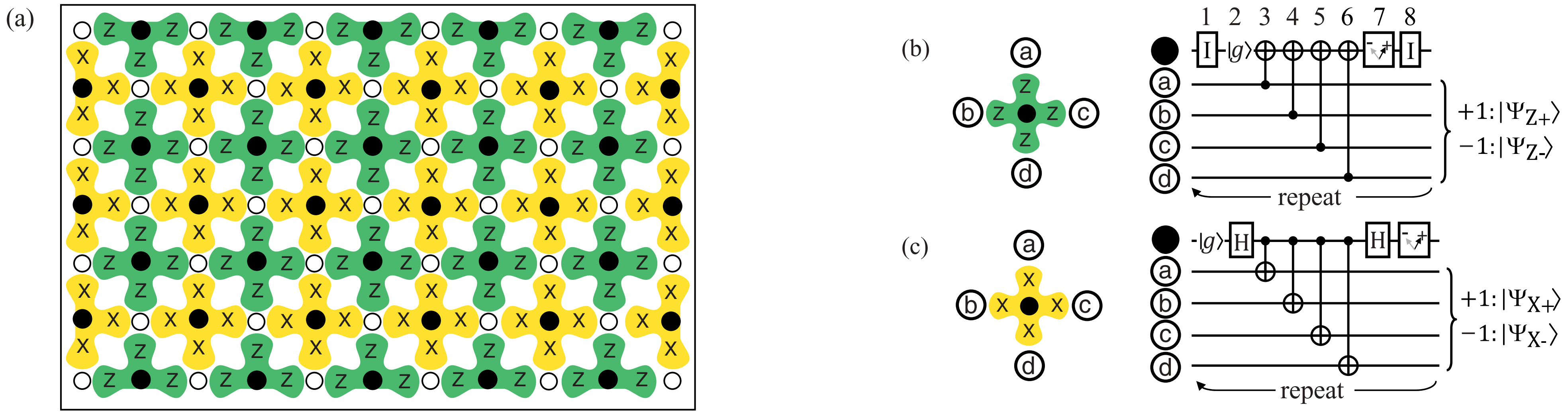
2012 – the Surface Code

PHYSICAL REVIEW A **86**, 032324 (2012)

Surface codes: Towards practical large-scale quantum computation

Austin G. Fowler
ntum Computation and Communication Technology, School of Physics, The University of Melbourne, Victoria 3

Matteo Mariantoni, John M. Martinis, and Andrew N. Cleland
Department of Physics, University of California, Santa Barbara, California 93106-9530, USA
and California Nanosystems Institute, University of California, Santa Barbara, California 93106-9530, USA



2014 – At the threshold for scaling up

Superconducting quantum circuits at the surface code threshold for fault tolerance

R. Barends[1]*, J. Kelly[1]*, A. Megrant[1], A. Veitia[2], D. Sank[1], E. Jeffrey[1], T. C. White[1], J. Mutus[1], A. G. Fowler[1,3], B. Campbell[1], Y. Chen[1], Z. Chen[1], B. Chiaro[1], A. Dunsworth[1], C. Neill[1], P. O'Malley[1], P. Roushan[1], A. Vainsencher[1], J. Wenner[1], A. N. Korotkov[2], A. N. Cleland[1] & John M. Martinis[1]

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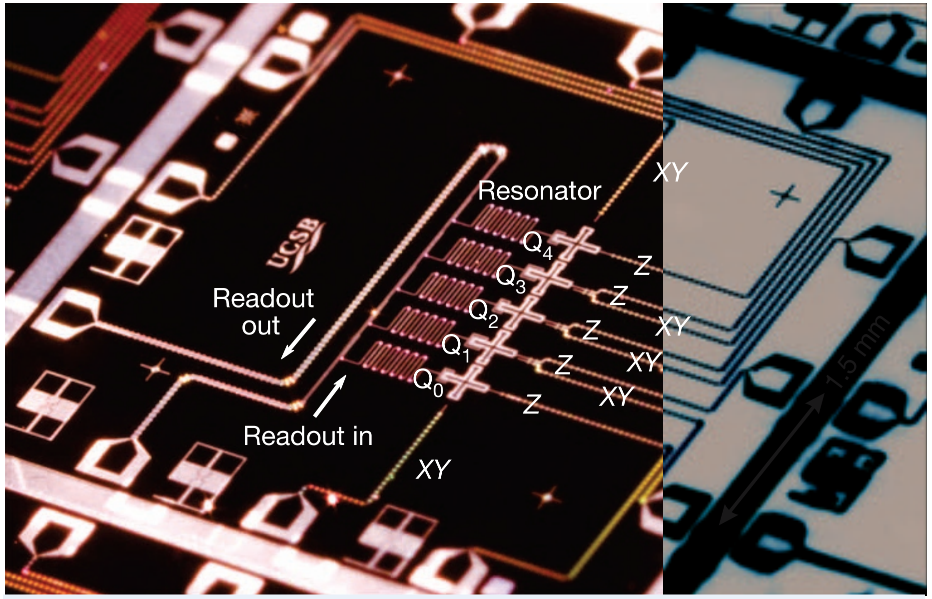
a



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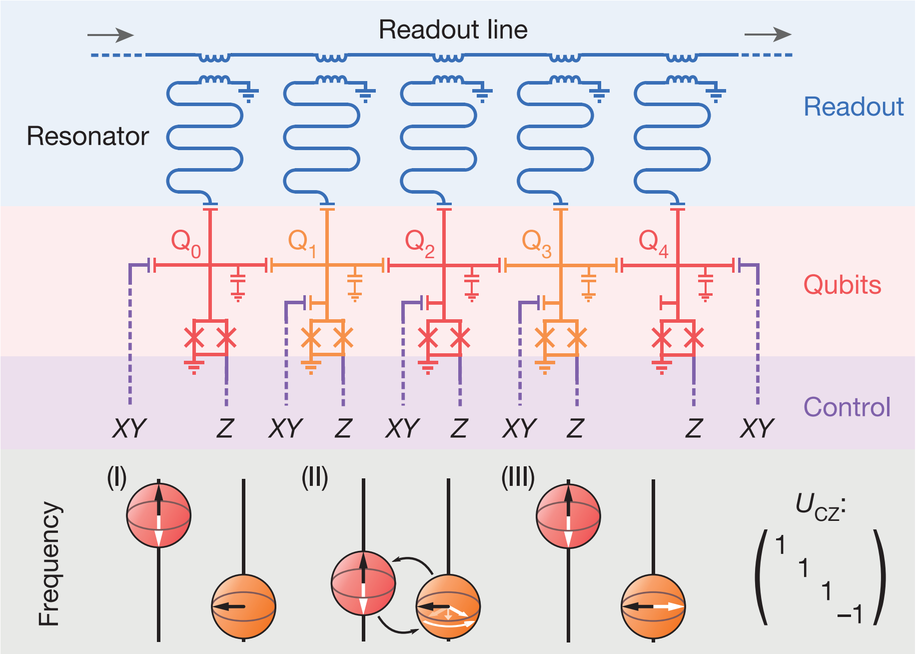

c

2014 – At the threshold for scaling up

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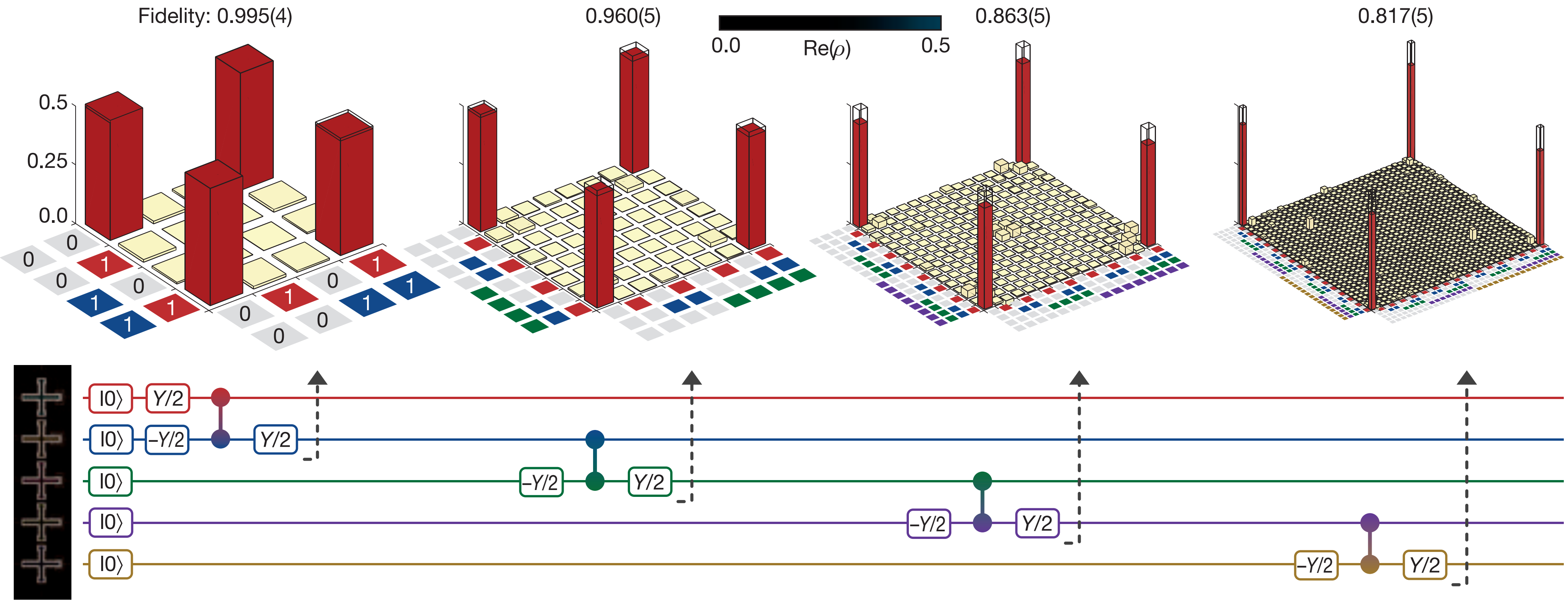
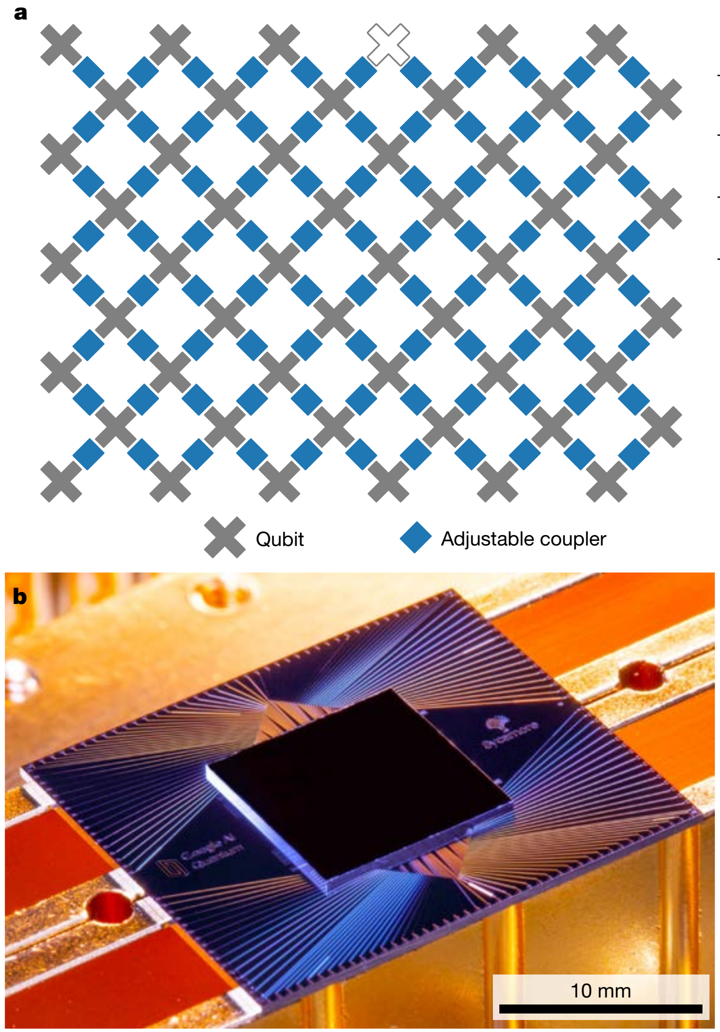


Gate fidelities: **1q, 99.92**; **2q, 99.4**

Quantum supremacy using a programmable superconducting processor



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]*

Nature | Vol 574 | 24 OCTOBER 2019 | **505**

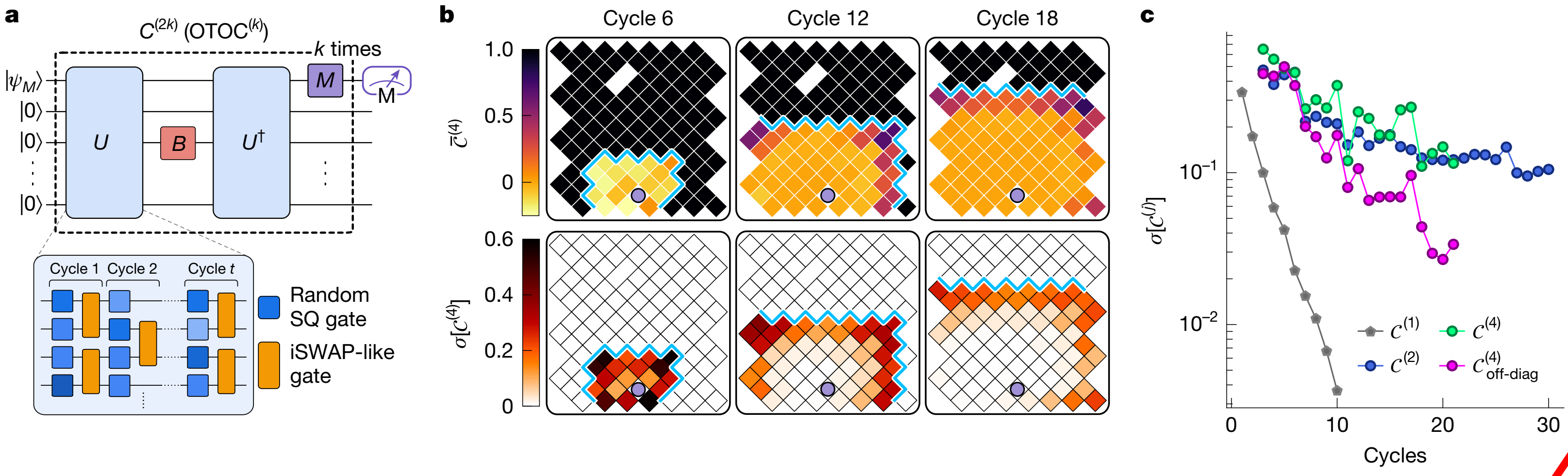
John M. Martinis, Google

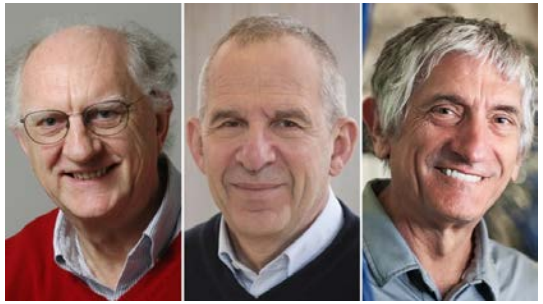
Observation of constructive interference at the edge of quantum ergodicity

Nature | Vol 646 | 23 October 2025 | **829**

Google

Frank Arute[1], Kunal Arya[1], Abraham Asfaw[1], Nikita Astrakhantsev[1], Juan Atalaya[1], Ryan Babbush[1], Dave Bacon[1], Brian Ballard[1], Joseph C. Bardin[1,6], Christian Bengs[3,4], Andreas Bengtsson[1], Alexander Bilmes[1], Sergio Boixo[1], Gina Bortoli[1], Alexandre Bourassa[1], Jenna Bovaird[1], Dylan Bowers[1], Leon Brill[1], Michael Broughton[1], David A. Browne[1], Brett Buchea[1], Bob B. Buckley[1], David A. Buell[1], Tim Burger[1], Brian Burkett[1], Nicholas Bushnell[1], Anthony Cabrera[1], Juan Campero[1], Hung-Shen Chang[1], Yu Chen[1], Zijun Chen[1], Ben Chiaro[1], Liang-Ying Chih[1], Desmond Chik[1], Charina Chou[1], Jahan Claes[1], Agnetta Y. Cleland[1], Josh Cogan[1], Saul Cohen[7], Roberto Collins[1], Paul Conner[1], William Courtney[1], Alexander L. Crook[1], Ben Curtin[1], Sayan Das[1], Laura De Lorenzo[1], Dripto M. Debroy[1], Sean Demura[1], Michel Devoret[1,8], Agustin Di Paolo[1], Paul Donohoe[1], Ilya Drozdov[1,9], Andrew Dunsworth[1], Clint Earle[1], Alec Eickbusch[1], Aviv Moshe Elbag[1], Mahmoud Elzouka[1], Catherine Erickson[1], Lara Faoro[1], Edward Farhi[1], Vinicius S. Ferreira[1], Leslie Flores Burgos[1], Ebrahim Forati[1], Austin G. Fowler[1], Brooks Foxen[1], Suhas Ganjam[1], Gonzalo Garcia[1], Robert Gasca[1], Élie Genois[1], William Giang[1], Craig Gidney[1], Dar Gilboa[1], Raja Gosula[1], Alejandro Grajales Dau[1], Dietrich Graumann[1], Alex Greene[1], Jonathan A. Gross[1], Hanfeng Gu[7], Steve Habegger[1], John Hall[1], Ikko Hamamura[7], Michael C. Hamilton[1,10], Monica Hansen[1], Matthew P. Harrigan[1], Sean D. Harrington[1], Stephen Heslin[1], Paula Heu[1], Oscar Higgott[1], Gordon Hill[1], Jeremy Hilton[1], Sabrina Hong[1], Hsin-Yuan Huang[1], Ashley Huff[1], William J. Huggins[1], Lev B. Ioffe[1], Sergei V. Isakov[1], Justin Iveland[1], Evan Jeffrey[1], Zhang Jiang[1], Xiaoxuan Jin[1], Cody Jones[1], Stephen Jordan[1], Chaitali Joshi[1], Pavol Juhas[1], Andreas Kabel[1], Dvir Kafri[1], Hui Kang[1], Amir H. Karamlou[1], Kostyantyn Kechedzhi[1], Julian Kelly[1], Trupti Khaire[1], Tanuj Khattar[1], Mostafa Khezri[1], Seon Kim[1], Robbie King[1,11,12], Paul V. Klimov[1], Andrey R. Klots[1], Bryce Kobrin[1], Alexander N. Korotkov[1], Fedor Kostritsa[1], Robin Kothari[1], John Mark Kreikebaum[1], Vladislav D. Kurilovich[1], Elica Kyoseva[7], David Landhuis[1], Tiano Lange-Dei[1], Brandon W. Langley[1], Pavel Laptev[1], Kim-Ming Lau[1], Loïck Le Guevel[1], Justin Ledford[1], Joonho Lee[1,13], Kenny Lee[1], Yuri D. Lensky[1], Shannon Leon[1], Brian J. Lester[1], Wing Yan Li[1], Alexander T. Lill[1], Wayne Liu[1], William P. Livingston[1], Aditya Locharla[1], Erik Lucero[1], Daniel Lundahl[1], Aaron Lunt[1], Sid Madhuk[1], Fionn D. Malone[1], Ashley Maloney[1], Salvatore Mandrà[1,14,15], James M. Manyika[1], Leigh S. Martin[1], Orion Martin[1], Steven Martin[1], Yossi Matias[1], Cameron Maxfield[1], Jarrod R. McClean[1], Matt McEwen[1], Seneca Meeks[1], Anthony Megrant[1], Xiao Mi[1], Kevin C. Miao[1], Amanda Mieszala[1], Zlatko Minev[1], Reza Molavi[1], Sebastian Molina[1], Shirin Montazeri[1], Alexis Morvan[1], Ramis Movassagh[1], Wojciech Mruczkiewicz[1], Ofer Naaman[1], Matthew Neeley[1], Charles Neill[1], Ani Nersisyan[1], Hartmut Neven[1] ✉, Michael Newman[1], Jiun How Ng[1], Anthony Nguyen[1], Murray Nguyen[1], Chia-Hung Ni[1], Murphy Yuezhen Niu[1,16], Logan Oas[1], Thomas E. O'Brien[1], William D. Oliver[1,17,18,19], Alex Opremcak[1], Kristoffer Ottosson[1], Andre Petukhov[1], Alex Pizzuto[1], John Platt[1], Rebecca Potter[1], Orion Pritchard[1], Leonid P. Pryadko[1,20], Chris Quintana[1], Ganesh Ramachandran[1], Chandrasekhar Ramanathan[21], Matthew J. Reagor[1], John Redding[1], David M. Rhodes[1], Gabrielle Roberts[1], Eliott Rosenberg[1], Emma Rosenfeld[1], Pedram Roushan[1], Nicholas C. Rubin[1], Negar Saei[1], Daniel Sank[1], Kannan Sankaragomathi[1], Kevin J. Satzinger[1], Alexander Schmidhuber[1], Henry F. Schurkus[1], Christopher Schuster[1], Thomas Schuster[11,22], Michael J. Shearn[1], Aaron Shorter[1], Noah Shutty[1], Vladimir Shvarts[1], Volodymyr Sivak[1], Jindra Skruzny[1], Spencer Small[1], Vadim Smelyanskiy[1], W. Clarke Smith[1], Rolando D. Somma[1], Sofia Springer[1], George Sterling[1], Doug Strain[1], Jordan Suchard[1], Philippe Suchsland[1,23], Aaron Szasz[1], Alex Sztein[1], Douglas Thor[1], Eifu Tomita[1], Alfredo Torres[1], M. Mert Torunbalci[1], Abeer Vaishnav[1], Justin Vargas[1], Sergey Vdovichev[1], Guifre Vidal[1], Benjamin Villalonga[1], Catherine Vollgraff Heidweiller[1], Steven Waltman[1], Shannon X. Wang[1], Brayden Ware[1], Kate Weber[1], Travis Weidel[1], Tom Westerhout[1], Theodore White[1], Kristi Wong[1], Bryan W. K. Woo[1], Cheng Xing[1], Z. Jamie Yao[1], Ping Yeh[1], Bicheng Ying[1], Juhwan Yoo[1], Noureldin Yosri[1], Grayson Young[1], Adam Zalcman[1], Chongwei Zhang[3], Yaxing Zhang[1], Ningfeng Zhu[1] & Nicholas Zobrist[1]





Michel Devoret

From Nobel Prize 2025
to Quantum Advantage 20xx

To be continued ......
on Wednesday in the Panel