

The Nobel Prize in Physics 2025 for John Clarke, Michel H. Devoret and John Martinis “for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit”

Adam Rycerz

*Institute of Theoretical Physics, Jagiellonian University, ul. Stanisława Łojasiewicza 11,
PL–30348 Kraków, Poland*



JAGIELLONIAN UNIVERSITY
IN KRAKÓW

Nobel Prize in Physics 2025



Ill. Niklas Elmehed © Nobel Prize Outreach

John Clarke

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

Michel H. Devoret

Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

John M. Martinis

Prize share: 1/3

The Nobel Prize in Physics 2025 was awarded jointly to John Clarke, Michel H. Devoret and John M. Martinis "for the discovery of macroscopic quantum mechanical tunnelling and energy quantisation in an electric circuit"

[<https://www.nobelprize.org/prizes/physics/2025/summary/>]

The Laureates...



John M. Martinis

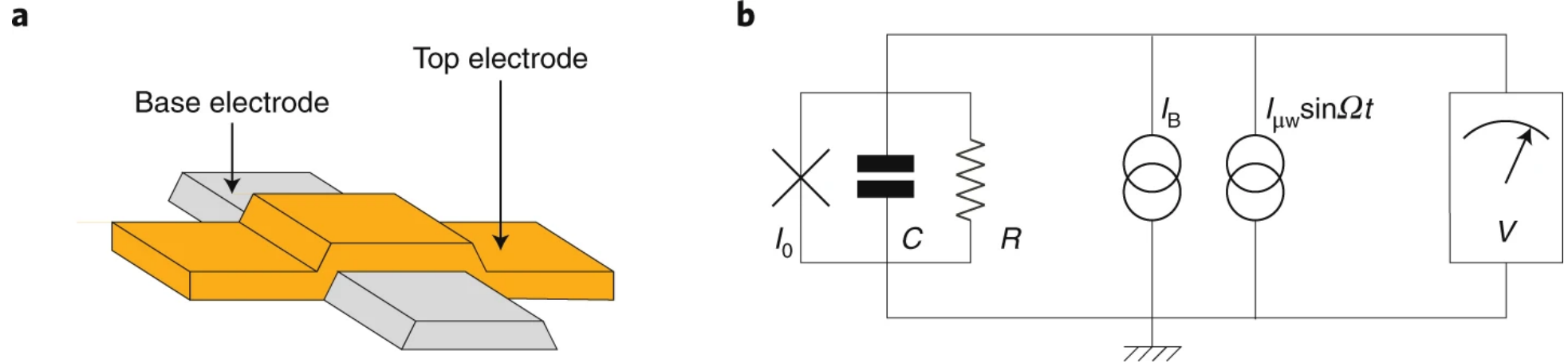


Michel Devoret



John Clarke

... and *The Device* they build

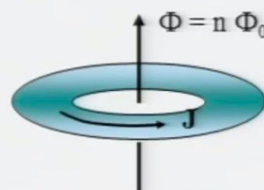


a, Schematic of a cross-strip Josephson superconducting tunnel junction. Our devices consist of a Nb base electrode and a top PbIn alloy electrode separated by a ~1-nm thick Nb-oxide layer formed by plasma-oxidation of the base electrode. **b**, Circuit schematic of a Josephson element (cross) shunted by a capacitance C and resistance R , and connected to both static bias (I_B) and microwave ($I_{\mu w}$) current sources. The voltage V across the junction is measured by a low-noise audio-frequency amplifier chain represented symbolically. Panel **b** adapted with permission from ref. [2](#), APS.

[from: [Martinis, Devoret, Clarke, Nature Physics 16, 234–237 \(2020\)](#)]

Birth of Superconducting Electronics: 1961 - 1964

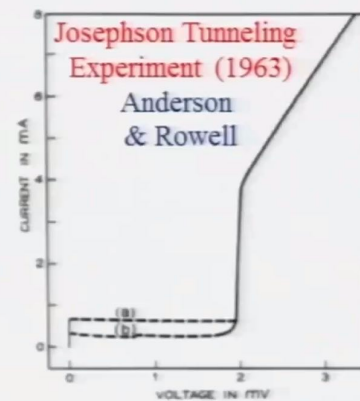
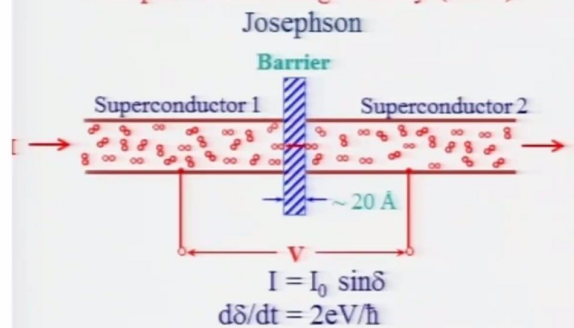
Flux Quantization (1961)



Flux $\Phi = n\Phi_0$ ($n = 0, \pm 1, \pm 2, \dots$), where $\Phi_0 \equiv h/2e \approx 2 \times 10^{-15} \text{ Tm}^2$ is the **flux quantum**

Deaver and Fairbank, Doll and Nábauer

Josephson Tunneling Theory (1962)



[Applied Superconductivity Conference, Charlotte, August 2014]

John Clarke (b.1942)

— leading expert on SQUIDs
(= **S**uperconducting **Q**uantum **I**nterference **D**evice)

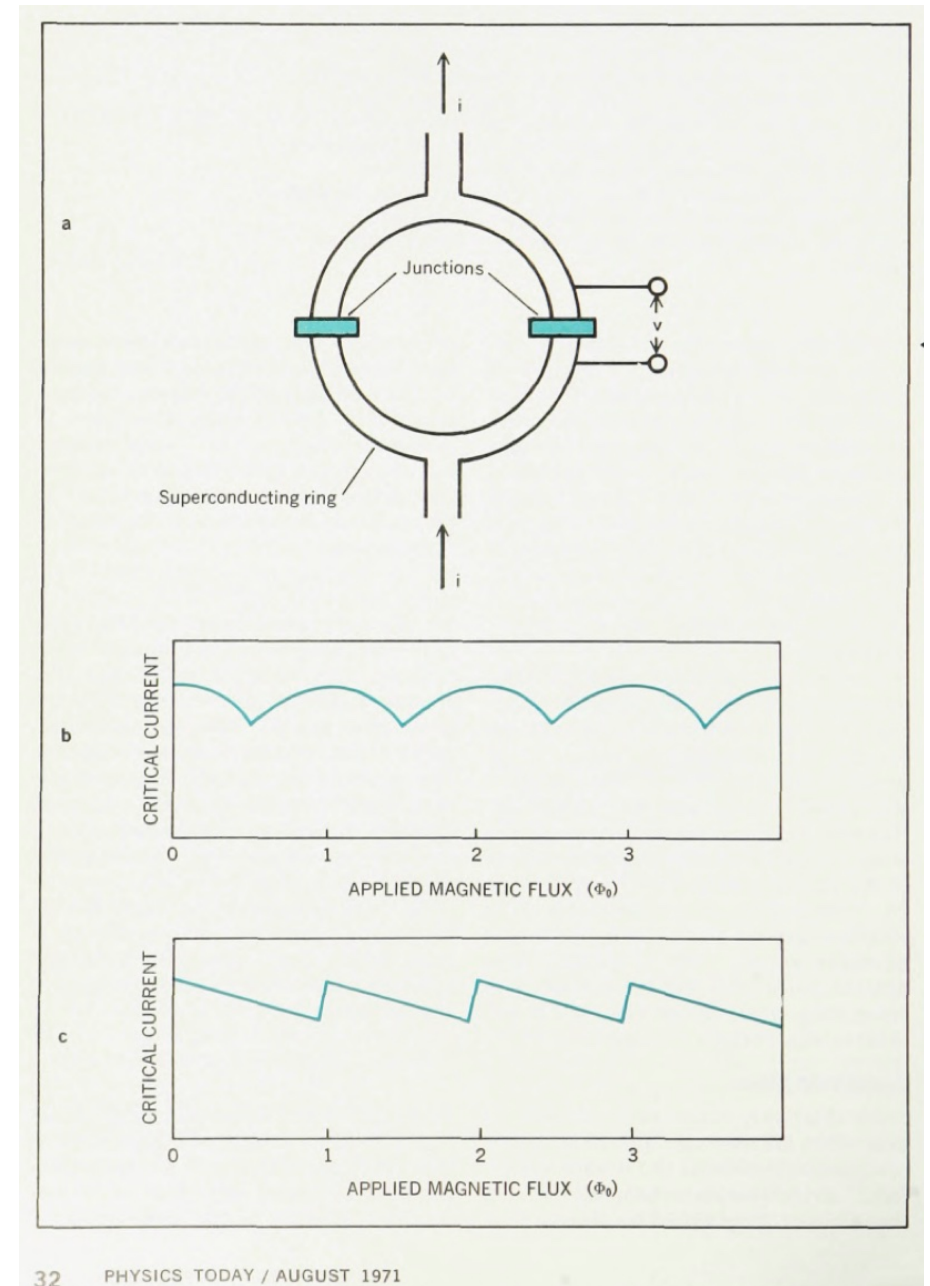
[Clarke, *Physics Today* **24**, 30 (1971)]

— In 1975, wrote a visionary paper:
*Application of Josephson junctions to
computer storage and logic elements
and to magnetic measurements*

[*AIP Conf. Proc.*, 1975, (29), 17]

— In 1970s studied the flicker $1/f$ noise
(aka *the pink noise*)

[' **$1/f$ noise**' in music and speech,
Voss & Clarke, *Nature* **258**, 317 (1975)]



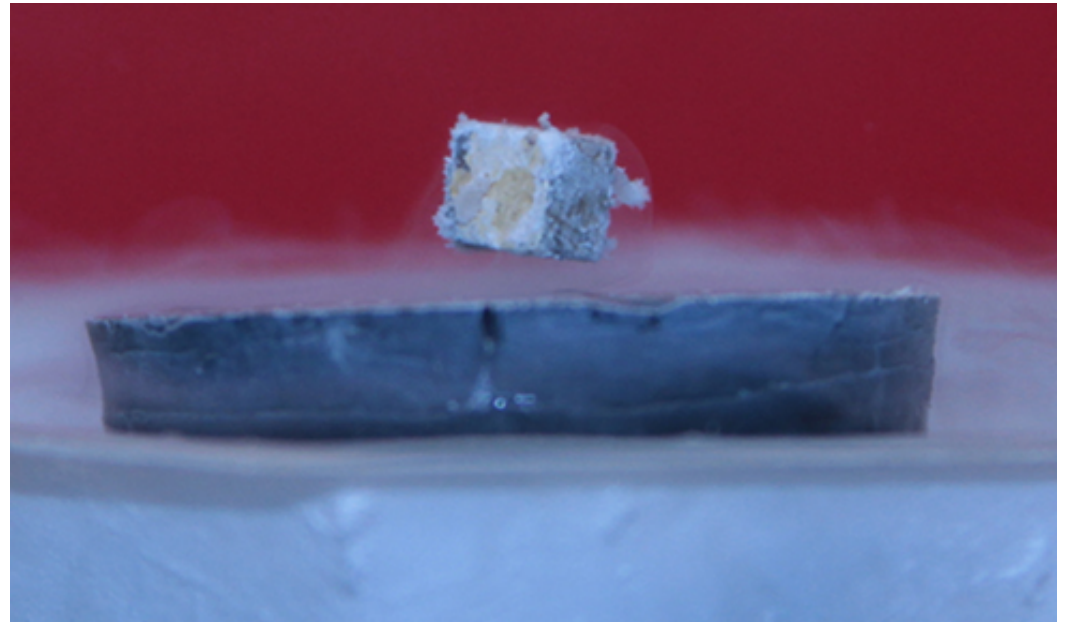
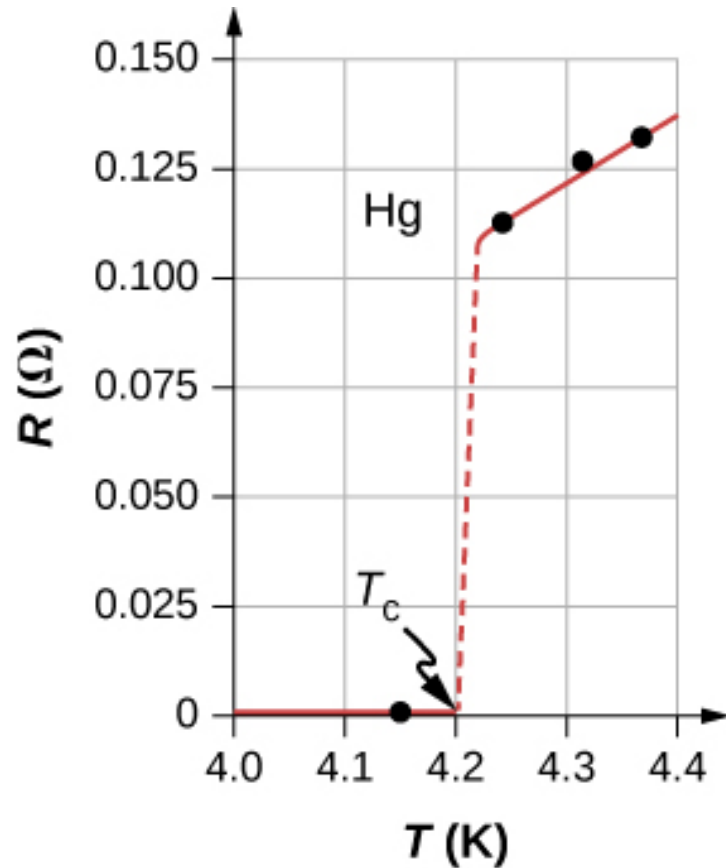
Superconductivity–related Noble prizes

- 1913 — *Heike Kamerlingh Onnes*, for investigations on the properties of matter at low temperatures
- 1972 — *John Bardeen, Leon Cooper, Robert Schrieffer* the BCS theory of superconductivity
- 1973 — *Leo Esaki, Ivar Giaever, Brian Josephson* (33yo!) tunneling phenomena in semiconductors and superconductors; predictions for a supercurrent through a tunnel barrier
- 1987 — *Georg Bednorz and K. Alex Müller* the discovery of high-temperature superconductivity
- 2003 — *Alexei Abrikosov, Vitaly Ginzburg, and Anthony Leggett* theories on superconductors

[2016 — *David J. Thouless, Duncan Haldane, John M. Kosterlitz*
theoretical discoveries of topological phase transitions
⇒ later link to superconductivity]

**2025 — *John Clarke, Michel Devoret, and John Martinis*
demonstrating macroscopic quantum phenomena
in superconducting circuits**

Superconductivity = Zero resistance + Meissner effect

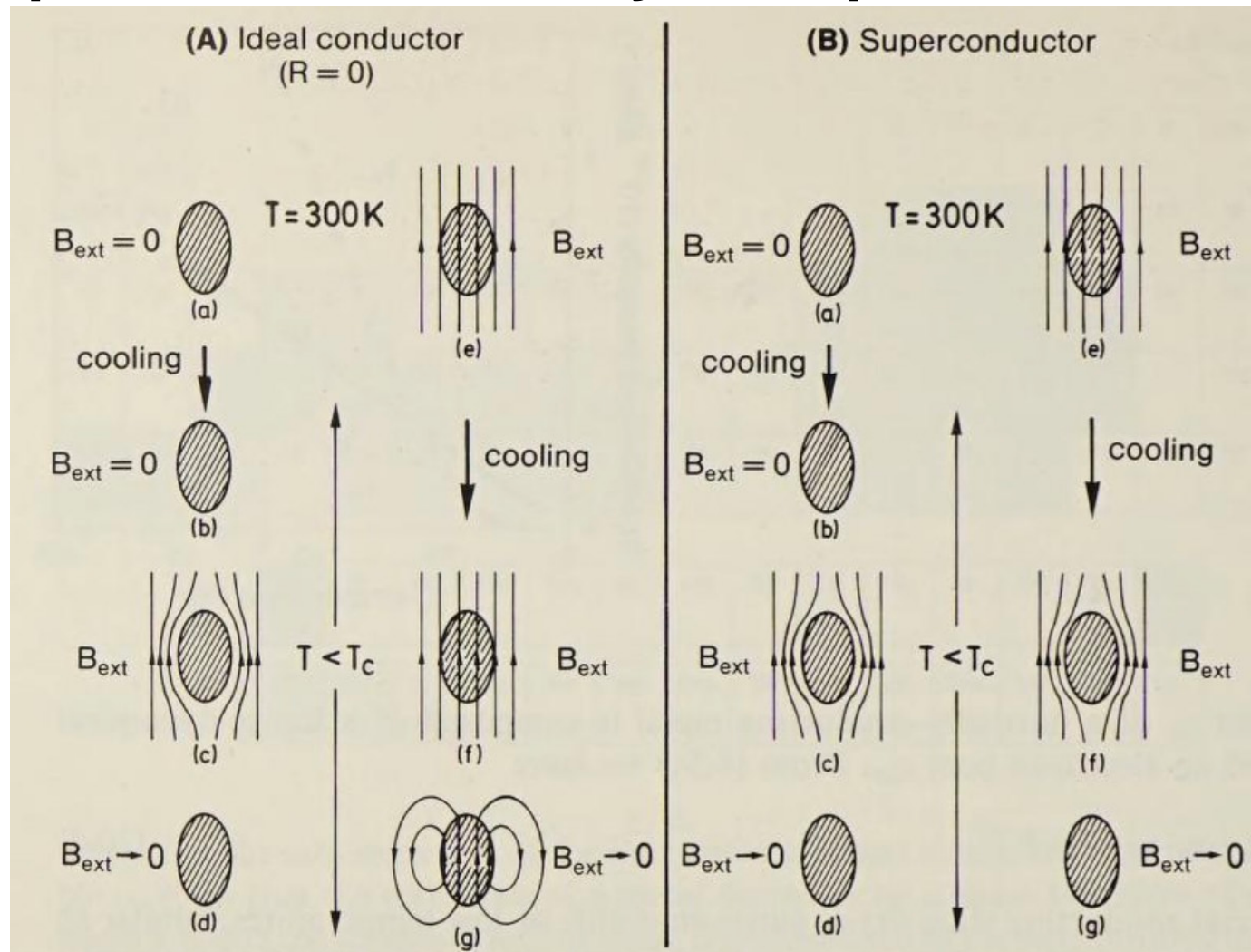


Left: Resistance of mercury — *H. K. Onnes* (1911). **Right:** Small magnet levitates over a superconductor [from phys.libretext.org]

H	ambient pressure superconductor																high pressure superconductor																He						
Li 0.0004 14 30	Be 0.026	T _c (K) T _c ^{max} (K) P(GPa)																T _c ^{max} (K) P(GPa)																B 11 250	C	N	O 0.6 100	F	Ne
Na	Mg																																	Al 1.14	Si 8.2 15.2	P 13 30	S 17.3 190	Cl	Ar
K	Ca 29 217	Sc 19.6 106	Ti 0.39 3.35 56.0	V 5.38 16.5 120	Cr	Mn	Fe 2.1 21	Co	Ni	Cu	Zn 0.875	Ga 1.091 7 1.4	Ge 5.35 11.5	As 2.4 32	Se 8 150	Br 1.4 100	Kr																						
Rb	Sr 7 50	Y 19.5 115	Zr 0.546 11 30	Nb 9.50 9.9 10	Mo 0.92	Tc 7.77	Ru 0.51	Rh .00033	Pd	Ag	Cd 0.56	In 3.404	Sn 3.722 5.3 11.3	Sb 3.9 25	Te 7.5 35	I 1.2 25	Xe																						
Cs	Ba 5 18	insert La-Lu	Hf 0.12 8.6 62	Ta 4.483 4.5 43	W 0.012	Re 1.4	Os 0.655	Ir 0.14	Pt	Au	Hg-α 4.153	Tl 2.39	Pb 7.193	Bi .00053 8.5 9.1	Po	At	Rn																						
Fr	Ra	insert Ac-Lr	Rf	Ha																																			
			La-fcc 6.00 13 15	Ce 1.7 5	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb 4.8 180	Lu 12.4 174																						
			Ac	Th 1.368	Pa 1.4	U 0.8(β) 2.4(α) 1.2	Np	Pu	Am 0.79 2.2 6	Cm	Bk	Cf	Es	Fm	Md	No	Lr																						

[From: web.physics.wustl.edu, ca. 2017]

⇒ A superconductor is not just “a perfect conductor”...



[From: Ibach, Lüth, *Solid-state physics*, Springer-Verlag, NY 1991]

Type I– vs type II– (*aka* high- T_c) superconductor

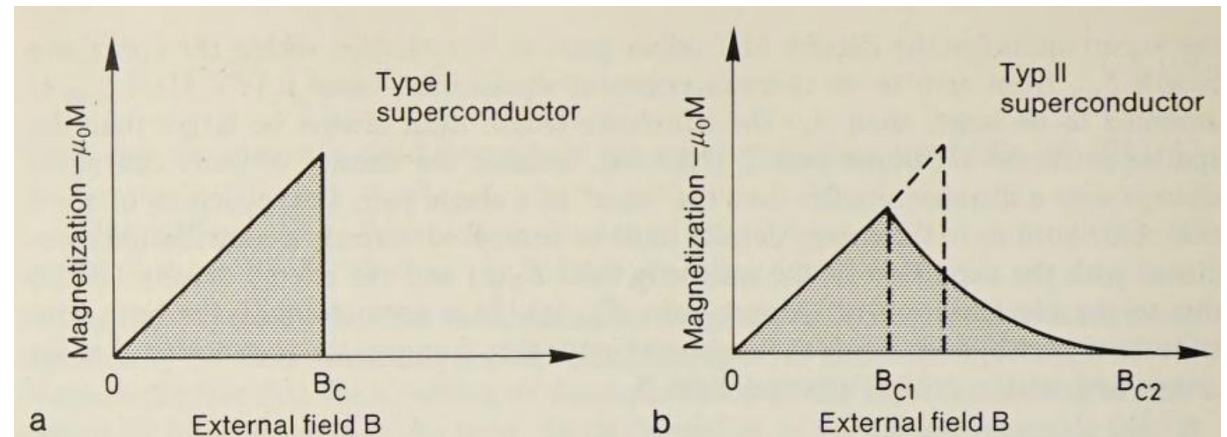


Fig. 10.21. Magnetization curve for a type I superconductor (a) and a type II superconductor (b). In a type I superconductor there is a single critical field B_c , whereas a type II superconductor has lower and upper critical fields, B_{c1} and B_{c2}

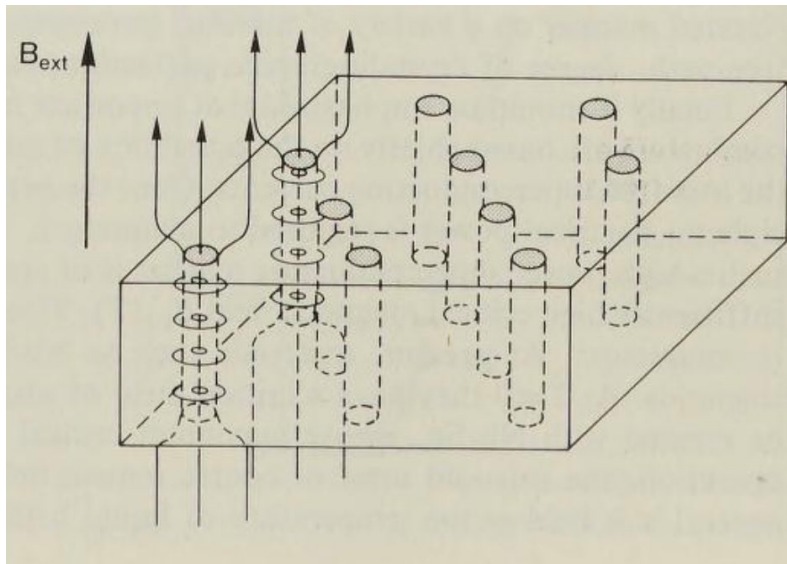
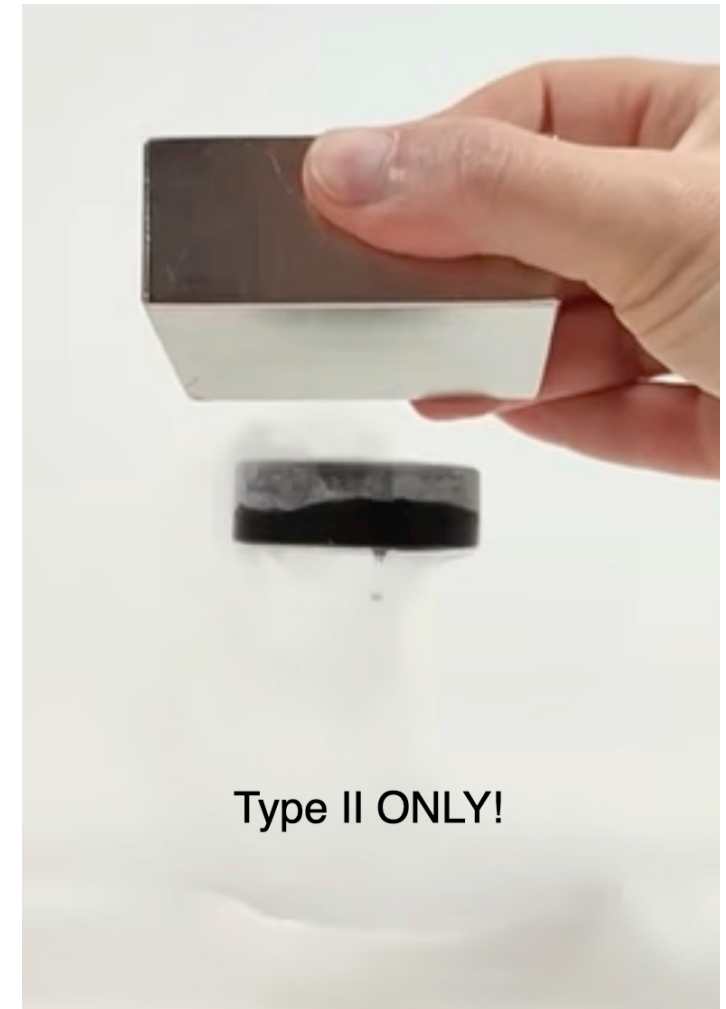


Fig. 10.23. Schematic representation of the Shubnikov phase of a type II superconductor. So-called flux tubes, arranged on a two-dimensional translational lattice, allow the magnetic field to “penetrate”. Each flux tube is surrounded by superconducting ring currents and encloses one magnetic flux quantum

[From: Ibach, Lüth, *Solid-state physics*, Springer-Verlag, NY 1991]

Type I– vs type II– (*aka* high- T_c) superconductor



[From: www.magneticgames.eu/; $\Rightarrow$ <https://tinyurl.com/mputcf5t> $\Leftarrow$]

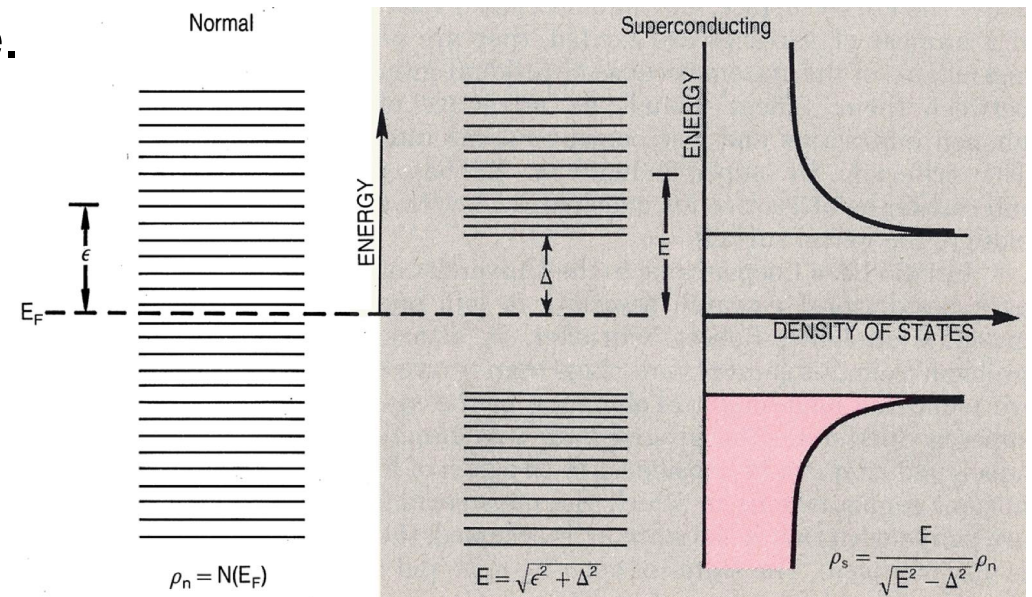
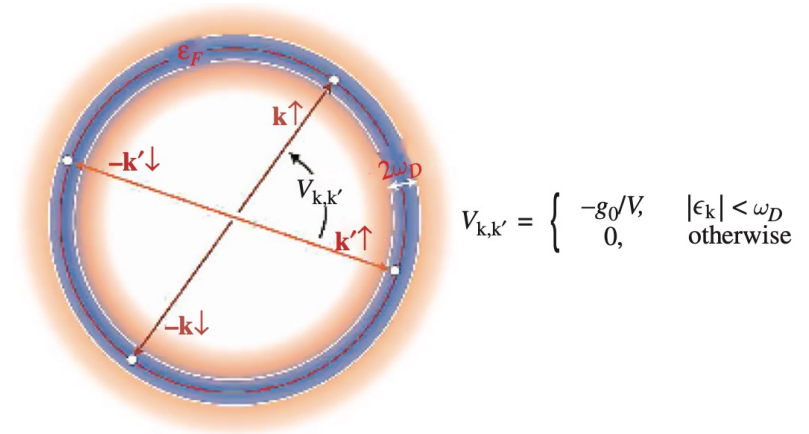
The BCS theory

Electron-lattice coupling generates weak, attractive interaction between electrons with opposite momenta, if they're close to the Fermi surface.

At low temperatures ($T < T_c$) the gap (2Δ) opens in the excitation spectrum. For weak interaction, $V_0\rho(E_F) \ll 1$, and $T \rightarrow 0$, $\Delta_0 \approx 2\hbar\omega_D e^{-1/V_0\rho(E_F)}$. For $T \rightarrow T_c$,

$$\frac{1}{V_0\rho(E_F)} = \int_0^{\hbar\omega_D} \frac{d\epsilon}{\epsilon} \tanh \frac{\epsilon}{2k_B T_c}$$

$$\approx \ln(\hbar\omega_D/k_B T_c) + 0.1256. \text{ In turn, } \Rightarrow \Delta_0/k_B T_c \approx 2e^{-0.1256} = 1.7639 \Leftarrow .$$



[Bardeen, [Physics Today 43, 25 \(1990\)](#)]

Flux quantization

Macroscopic wavefunction for s.c.

$$\Psi = \sqrt{\rho(\mathbf{r})} e^{i\theta(\mathbf{r})};$$

the current density:

$$\mathbf{J} = \frac{\hbar}{m_{\star}} \left(\nabla \theta - \frac{q_{\star}}{\hbar} \mathbf{A} \right) \rho.$$

Inside s.c. $\mathbf{J} = 0$, so

$$\hbar \nabla \theta = q_{\star} \mathbf{A}.$$

[Note: $\mathbf{B} = \text{rot } \mathbf{A}$]

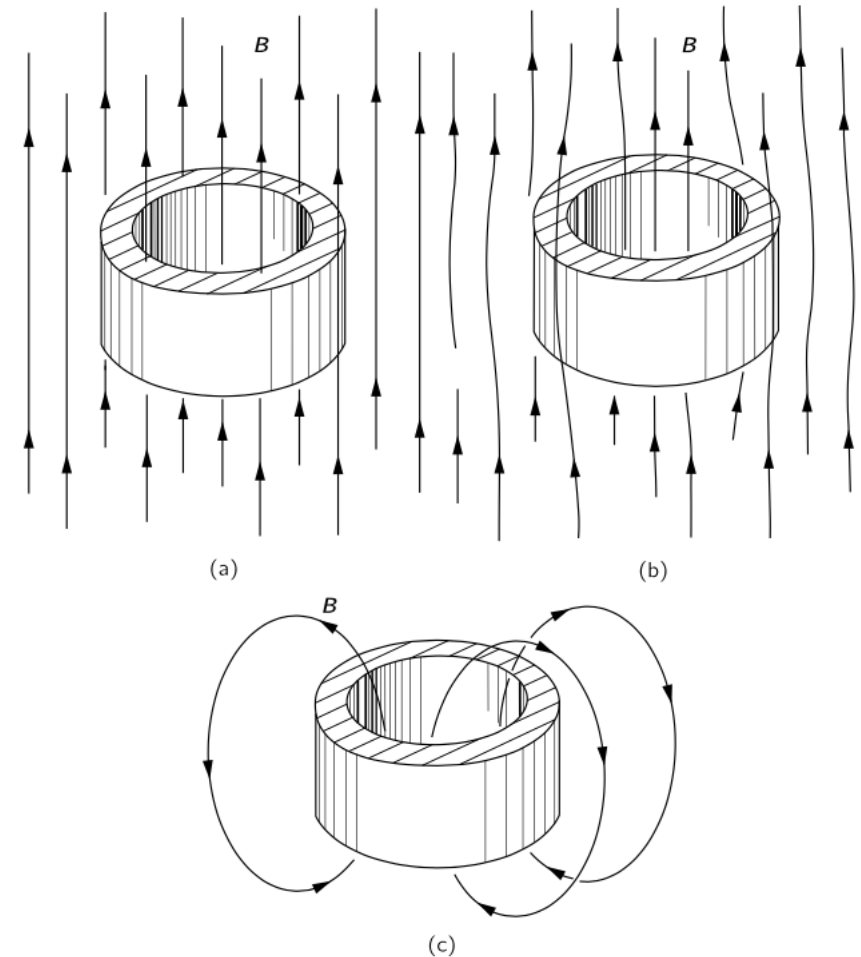


Fig. 21-4. A ring in a magnetic field: (a) in the normal state; (b) in the superconducting state; (c) after the external field is removed.

[From: [feynmanlectures.caltech.edu](https://www.feynmanlectures.caltech.edu)]

Flux quantization

Since $\oint \nabla \theta \cdot d\mathbf{l} = 2\pi n$ (with n -integer), $\oint \mathbf{A} \cdot d\mathbf{l} = \iint \mathbf{B} \cdot d\hat{\mathbf{s}} = \Phi$,

we finally get: $\Phi = n \frac{h}{q_{\star}} = n\Phi_0$.

Deaver & Fairbank proven in 1961 that $q_{\star} = 2e$
($\Leftrightarrow \Phi_0 = h/2e = 2.0679 \times 10^{-15} \text{ T m}^2$) in accordance with the BCS theory. For a ring with a diameter of 1 cm, Φ_0 correspond to the field strength of about 10^{-6} of the Earth's magnetic field.

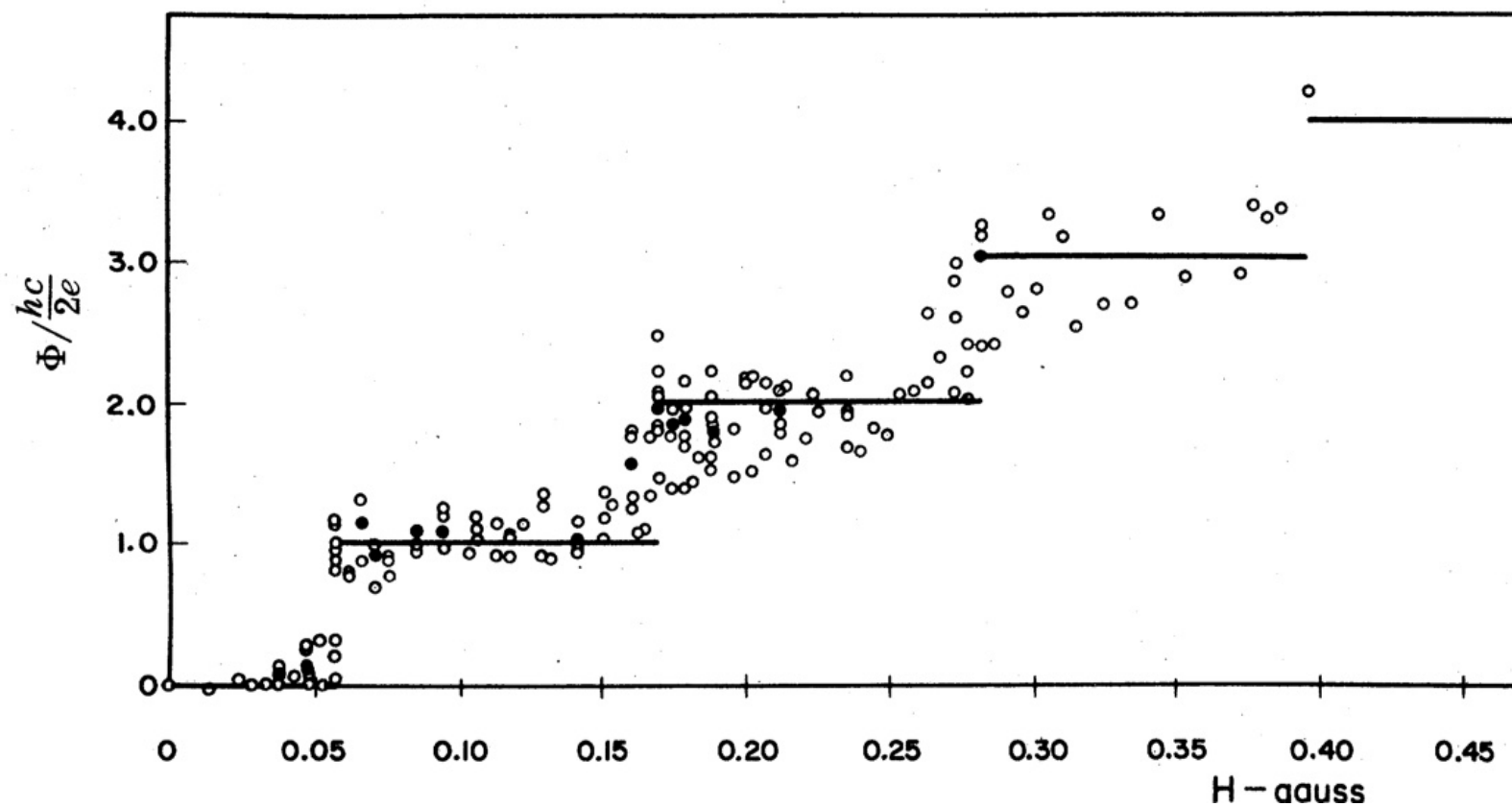
[***A ring with 2 Josephson junctions = d.c. SQUID, nowadays allowing to measure magnetic fields $< 10^{-17} \text{ T}$.***]

EXPERIMENTAL EVIDENCE FOR QUANTIZED FLUX IN SUPERCONDUCTING CYLINDERS*

Bascom S. Deaver, Jr., and William M. Fairbank

Department of Physics, Stanford University, Stanford, California

(Received June 16, 1961)



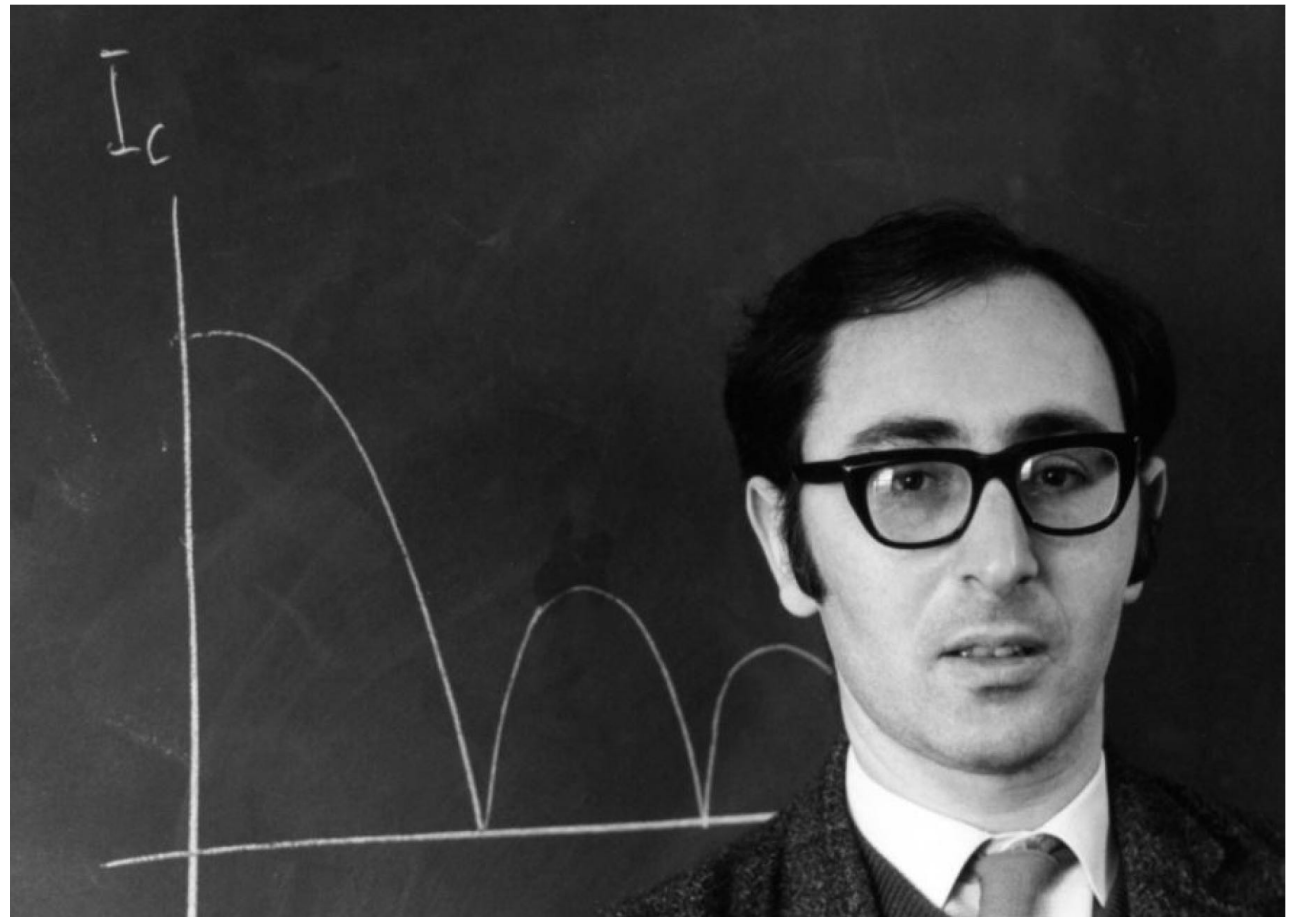
The Josephson effect

— The effect predicted by 22yo student at Cambridge, England.

[*B.D. Josephson, Physics Letters 1, 251 (1962).*]

Sketch on the blackboard show the critical current versus the flux piercing the junction cross-section, i.e.,

$$I_c \propto \frac{\sin \pi \Phi / \Phi_0}{\pi \Phi / \Phi_0}.$$



The Josephson effect

— Experimental confirmation came shortly afterwards.

[*P.W. Anderson, J.M. Rowell, Phys. Rev. Lett. **10**, 230 (1963).*]

— Josephson has share 1/2 of The Nobel Prize in Physics 1973, with Leo Esaki (1/4) and Ivar Giaever (1/4), just one year after Nobel Prize for Bardeen, Cooper and Schrieffer for their theory (!)

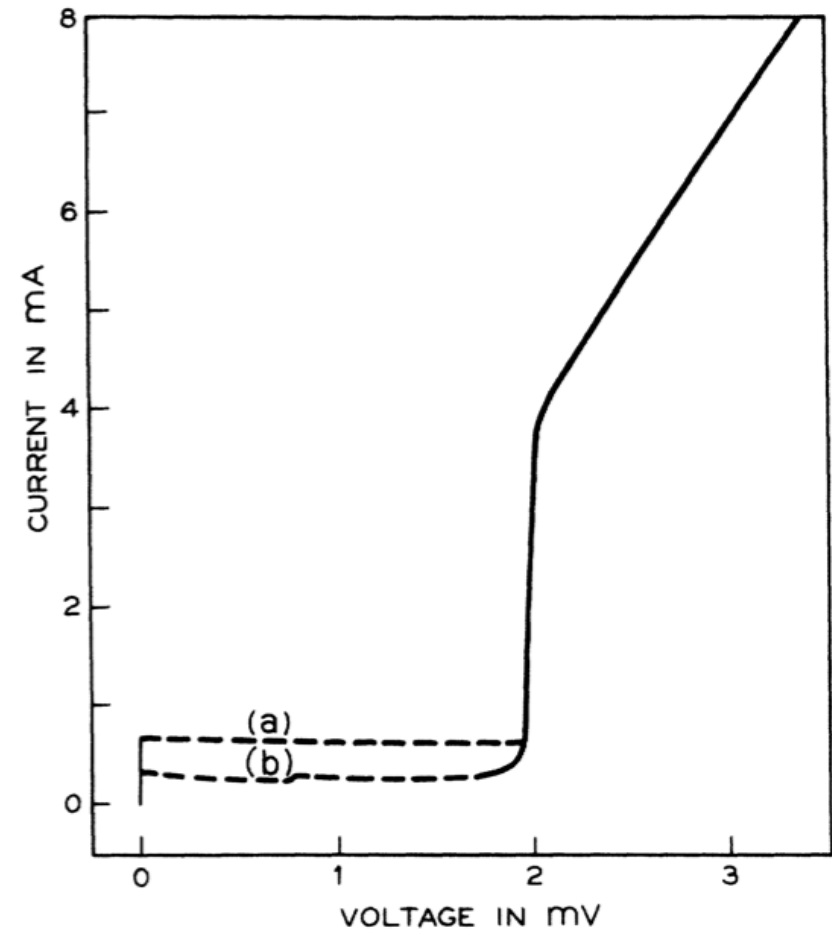


FIG. 1. Current-voltage characteristic for a tin-lead tunnel structure at $\sim 1.5^\circ\text{K}$, (a) for a field of 6×10^{-3} gauss and (b) for a field 0.4 gauss.

The Josephson effect — *key features*

— The supercurrent may pass thin (~ 1 nm) insulator layer separating two s.c.-s [no voltage across for $|I| \leq I_c$], the phase difference θ between superconductors follows

$$I = I_c \sin \theta, \text{ with the critical current } I_c \approx \frac{\pi \Delta_0}{2eR_N} \quad (T \rightarrow 0),$$

where Δ_0 is the superconducting gap and R_N is the resistivity in the normal state. [$\Rightarrow$ *d.c. Josephson effect*]

— When constant voltage (V) is applied, the alternating current appears, with the frequency $(2e/\hbar) V$. [$\Rightarrow$ *a.c. Josephson effect*]

A simple reasoning build on *Ginzburg-Landau* theory

The current along x-axis: $J_x = \frac{2e}{2m} \left[\Psi^* \left(-i\hbar \frac{\partial}{\partial x} - 2eA_x \right) \Psi + \text{c.c.} \right].$

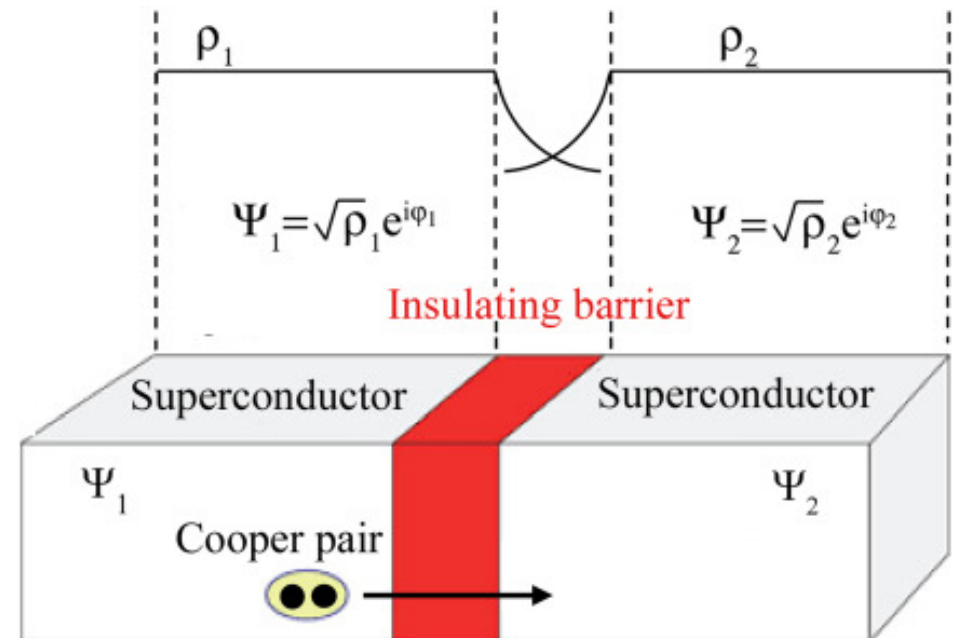
For a thick barrier, we have: $-i\hbar \frac{\partial \Psi_{1,2}}{\partial x} - 2eA_x \Psi_{1,2} = 0.$

Otherwise, one can suppose that

$$\left(-i\hbar \frac{\partial}{\partial x} - 2eA_x \right) \Psi_{1,2} = -\frac{i\hbar}{b} \Psi_{2,1}.$$

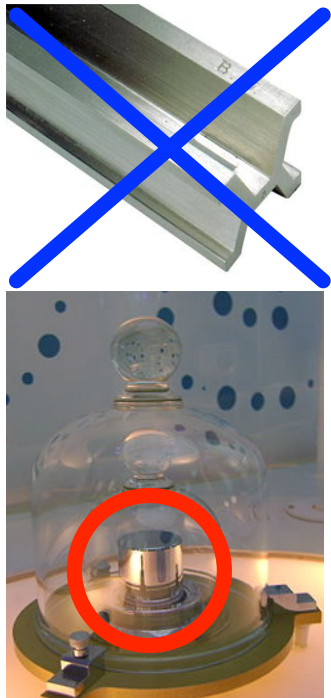
Substituting into the eq. for J_x :

$$\Rightarrow J_x = \frac{2e\hbar}{mb} |\Psi_1| |\Psi_2| \sin(\varphi_2 - \varphi_1).$$



[See: [Cyrot, Pavuna, Introduction to Superconductivity and High Tc Materials, World Scientific, Singapore, 1992](#); figure from: sciencedirect.com]

The quantum metrological triangle



Efekt Josephsona:

$$I \propto \sin\left(\frac{4\pi eV}{h}\right)t$$

$$\Rightarrow f_J = 2eV/h,$$

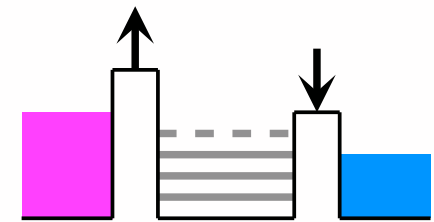
$$K_J = 2e/h = 483597.853(3) \text{ GHz/V}$$

The NIST Reference on
Constants, Units, and Uncertainty

f [Hz]

Pompa kwantowa (?)

$$I = \text{const} \times e f$$



(m, kg, s)



(V, A, Hz)

U [V]

I [A]

QHE: $R_H = h/(\nu e^2)$, $\nu = 1, 2, \dots$
 $R_K = h/e^2 = 25812.807456(6) \Omega$

The RCSJ model

The total current:

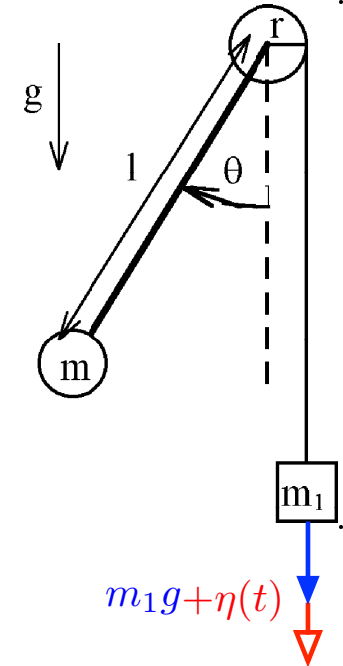
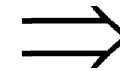
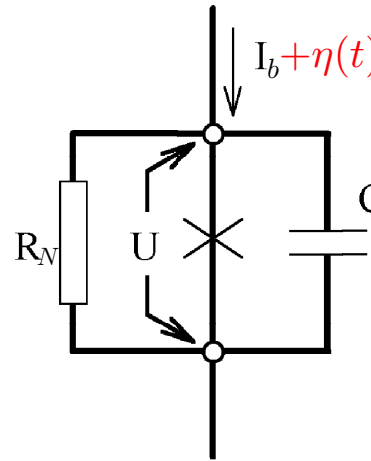
$$C\dot{U} + \frac{U}{R_N} + I_c \sin \theta - I_b = \eta(t).$$

Since $U = \frac{\hbar}{2e}\dot{\theta} = \frac{\Phi_0}{2\pi}\dot{\theta}$, and

$\dot{U} = \frac{\Phi_0}{2\pi}\ddot{\theta}$, one can rewrite

$$C \frac{\Phi_0}{2\pi} \ddot{\theta} + R_N^{-1} \frac{\Phi_0}{2\pi} \dot{\theta} + I_c \sin \theta - I_b = \eta(t),$$

being equivalent to the **equation of motion for a pendulum**,
 subjected to a constant torque ($\propto I_b$) and a perturbation ($\propto \eta(t)$)
 [*thermal AND/OR harmonic*].



The RCSJ model

The total energy:

$$H = E_{\text{kin}} + E_{\text{pot}},$$

$$E_{\text{kin}} = \frac{Q^2}{2C}, \quad (Q = CU)$$

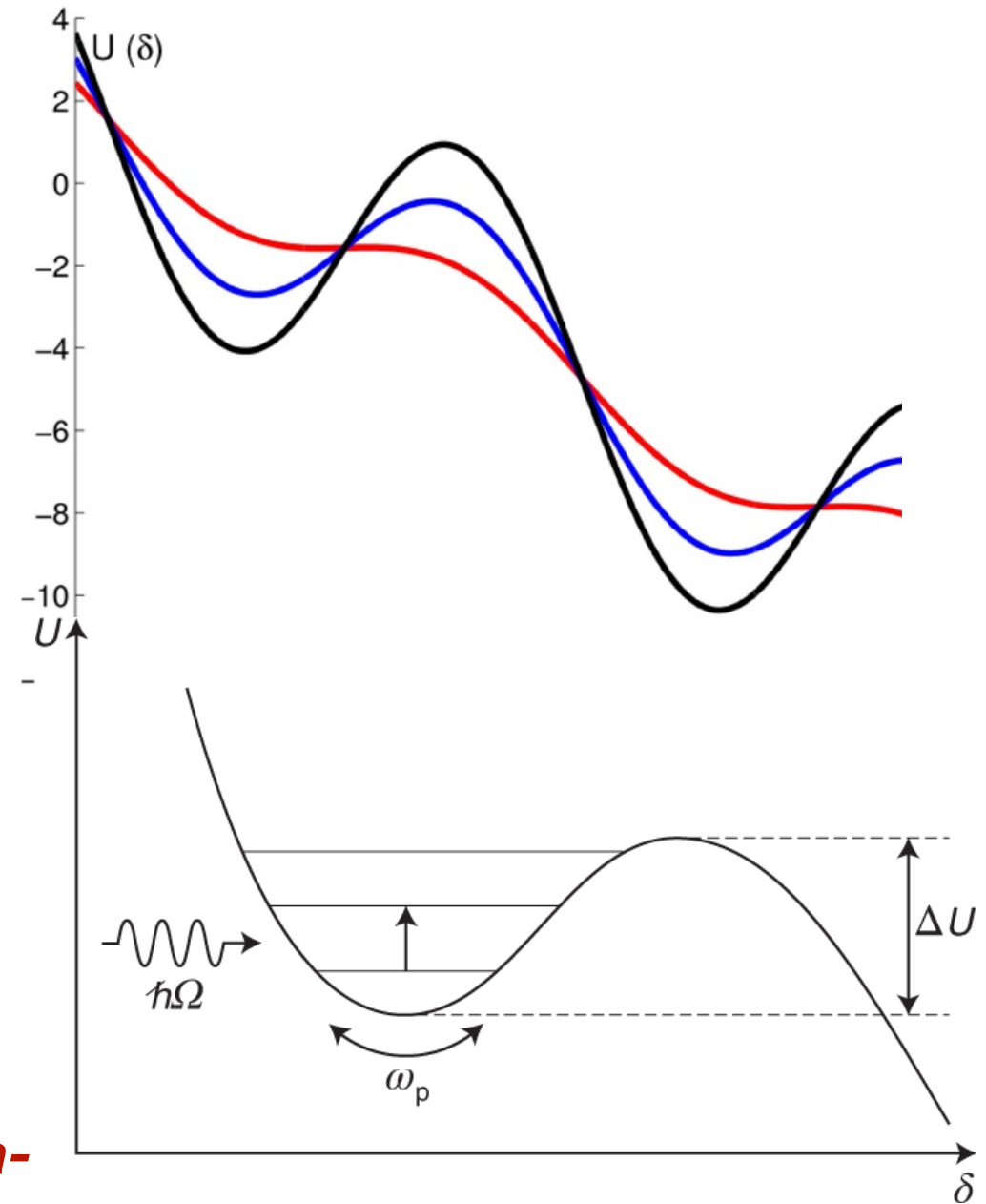
$$E_{\text{pot}} = -I_b \frac{\Phi_0}{2\pi} \theta - E_J \cos \theta,$$

where $E_J = I_c \Phi_0 / 2\pi$.

($\Rightarrow$ *Tilted washboard potential*)

Next step: $[\hat{Q}, \hat{\theta}] \propto -2e i,$

$\Delta Q \delta \theta \geq e$ ($\Rightarrow$ **quantum-mechanical operators, uncertainty principle, etc.**)



Footnote: The above is no a guess but follows from the BSC theory. Up to the normalization, the BCS wavefunction can be

written as $|BSC\rangle = \prod_k \left(1 + \phi_k c_{k\uparrow}^\dagger c_{-k\downarrow} \right) |0\rangle = \sum_n \frac{1}{\sqrt{n!}} |n\rangle,$

where $|n\rangle = \frac{1}{\sqrt{n!}} (\Lambda^\dagger)^n |0\rangle$, with $\Lambda^\dagger = \sum_k \phi_k c_{k\uparrow}^\dagger c_{-k\downarrow}$, is a state

containing n pairs. The gauge transformation $|BSC\rangle \rightarrow |\alpha\rangle$, defined via the substitution $c_{k\sigma}^\dagger \rightarrow e^{i\alpha} c_{k\sigma}^\dagger$, immediately leads to the

number operator $\hat{N} |\alpha\rangle = \sum_n \frac{1}{\sqrt{n!}} 2ne^{2in\alpha} |n\rangle = -i \frac{d}{d\alpha} |\alpha\rangle$, and

to $[\alpha, N] = i$.

The Noble-prize papers

[0]

VOLUME 53, NUMBER 13

PHYSICAL REVIEW LETTERS

24 SEPTEMBER 1984

Resonant Activation from the Zero-Voltage State of a Current-Biased Josephson Junction

Michel H. Devoret,^(a) John M. Martinis, Daniel Esteve,^(a) 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 1984)

[1]

VOLUME 55, NUMBER 15

PHYSICAL REVIEW LETTERS

7 OCTOBER 1985

Energy-Level Quantization in the Zero-Voltage State of a Current-Biased Josephson Junction

John M. Martinis, Michel H. Devoret,^(a) 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 14 June 1985)

[2]

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)

[1] Martinis et al., *PRL* 1985

The escape time (τ_{esc}) is the average time, after which voltage appears

- A cubic potential is a sufficient approx. of the washboard potential
- Thermal escape rate ($k_B T \gg \hbar \omega_p$):

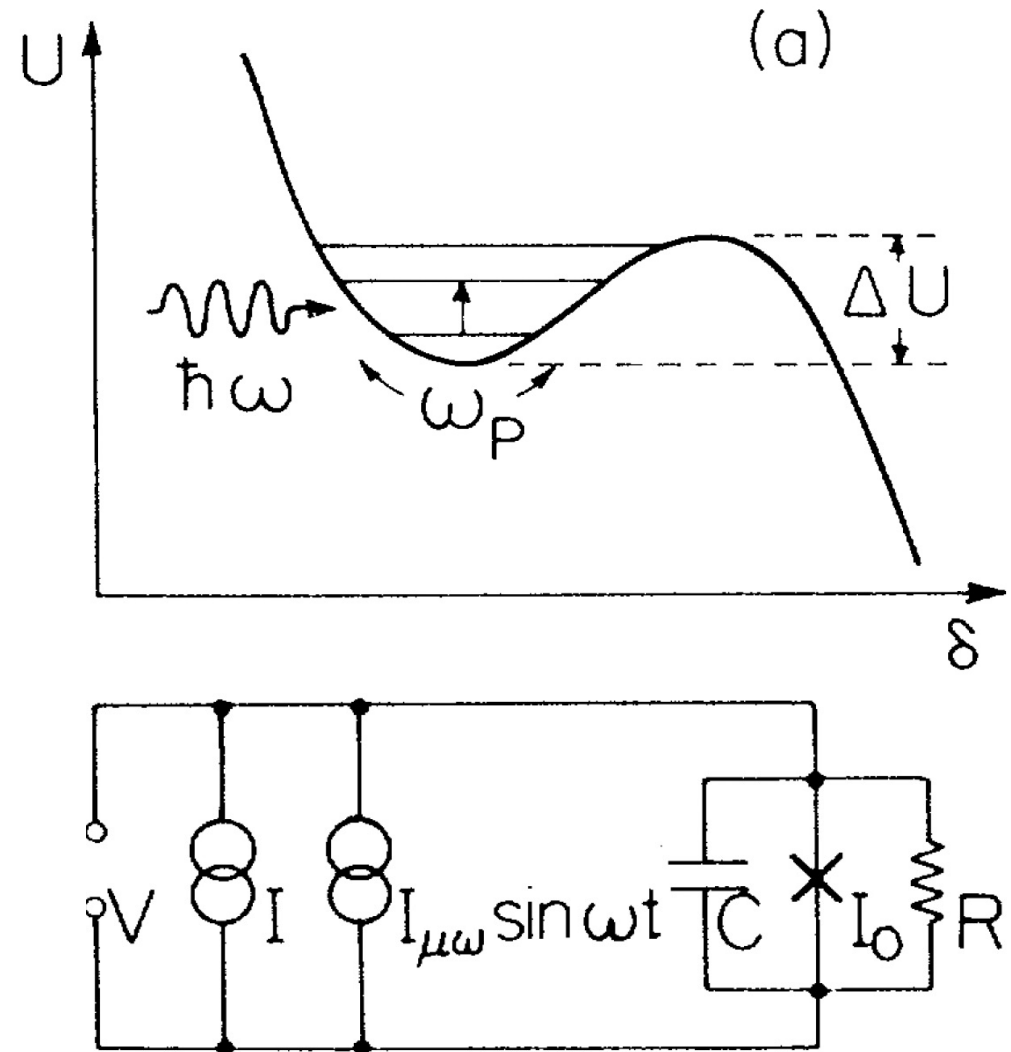
$$\Gamma_t = \tau_{\text{esc}}^{-1} = a_t (\omega_p / 2\pi) \exp(-\Delta U / k_B T),$$

where

$$a_t = 4 / [\sqrt{1 + Q k_B T / 1.8 \Delta U} + 1]^2,$$

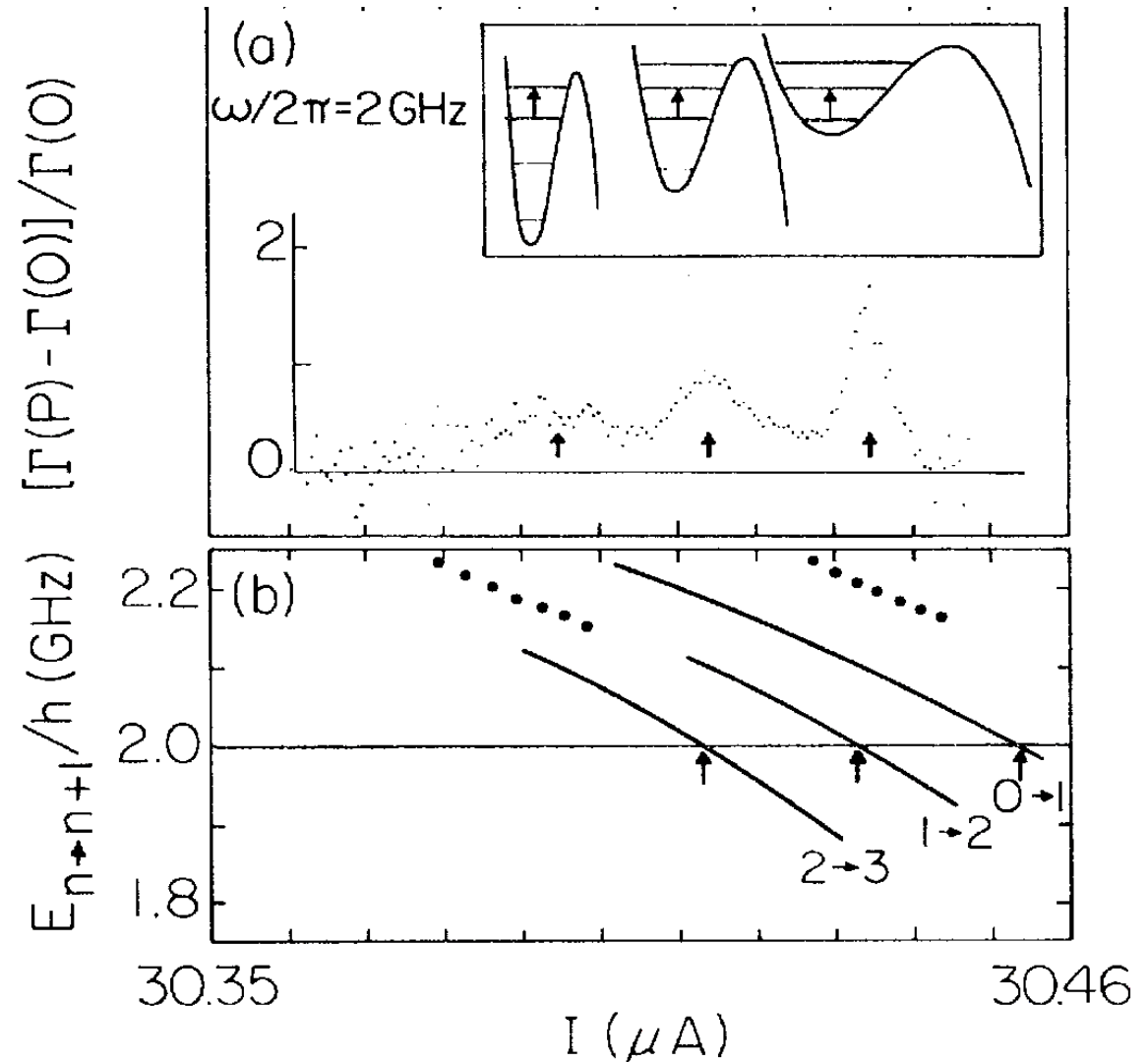
$$Q = \omega_p R C, \quad \text{and}$$

$$\omega_p = (2\pi I_c / C \Phi_0)^{1/2} [1 - (I/I_c)^2]^{1/4}.$$



[1] Martinis *et al.*, *PRL* '85

The ratio $[\Gamma(P) - \Gamma(0)]/\Gamma(0)$, with the microwave power P on/off, displayed as a function of a bias current for a fixed frequency, shows resonances corresponding to transitions between subsequent quantum levels [*which are NOT equally-spaced due to anharmonicity!*].



Is it really a quantum phenomenon or just perturbation-assisted thermal escape near the resonance ?!

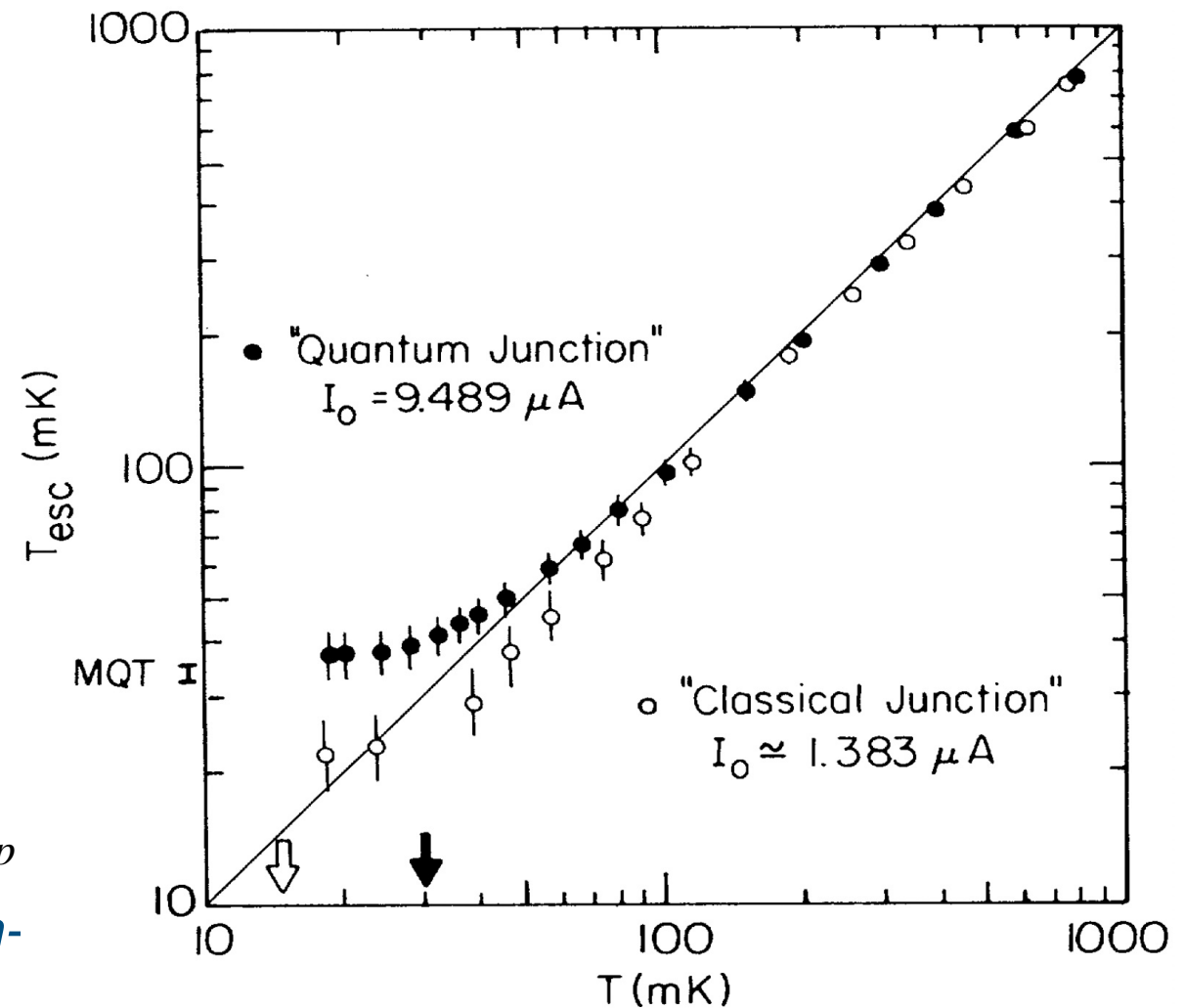
[2] Devoret *et al.*, *PRL* 1985

Let's define the effective
“escape temperature” via

$$\Gamma = (\omega_p/2\pi)\exp(-\Delta U/k_B T_{\text{esc}}).$$

As long as $T_{\text{esc}} \approx T$ (the actual temperature), the behavior is *classical*.

However, at low temperatures, and high I_c , such that $k_B T \ll \hbar\omega_p$ T_{esc} saturates [*i.e., becomes temperature-independent*].



⇒ **The “quantum junction” was build!**

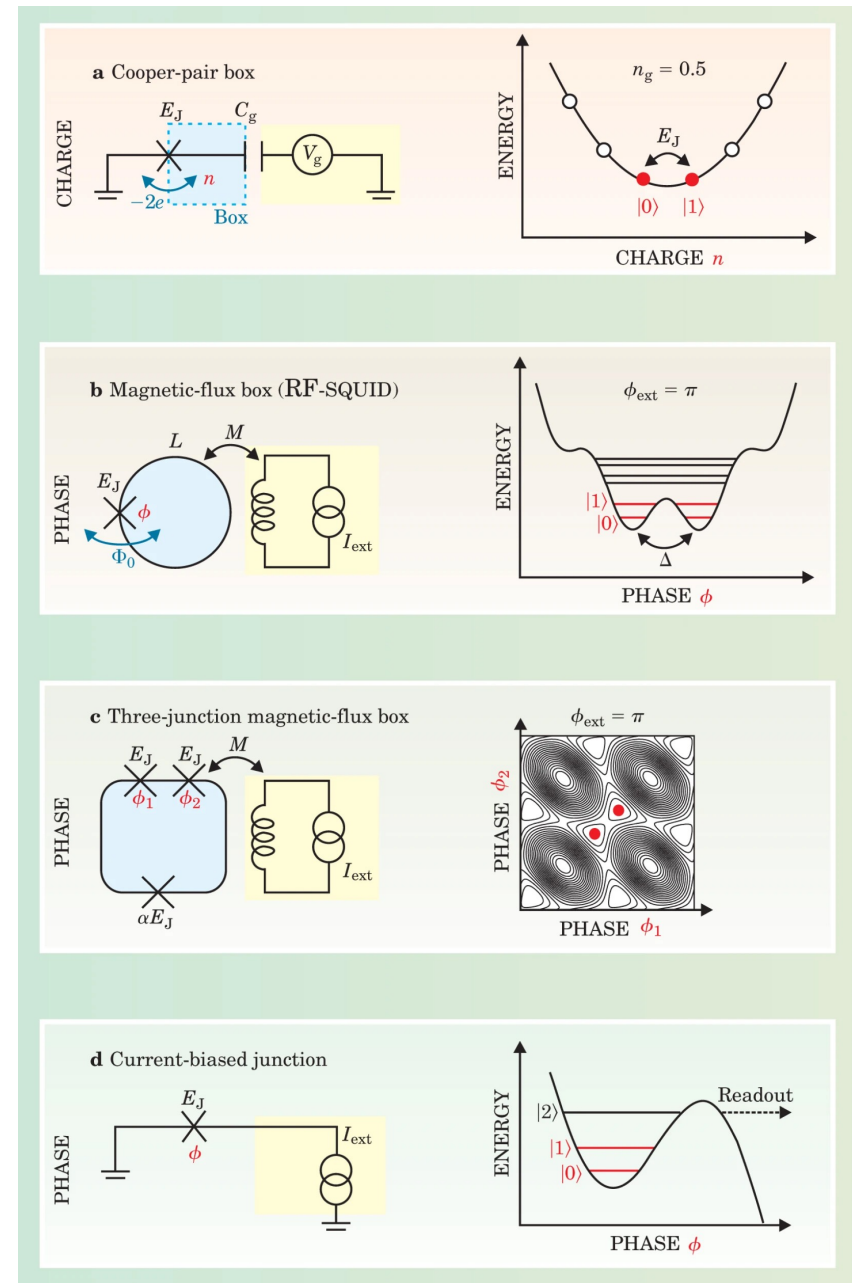
Consequences

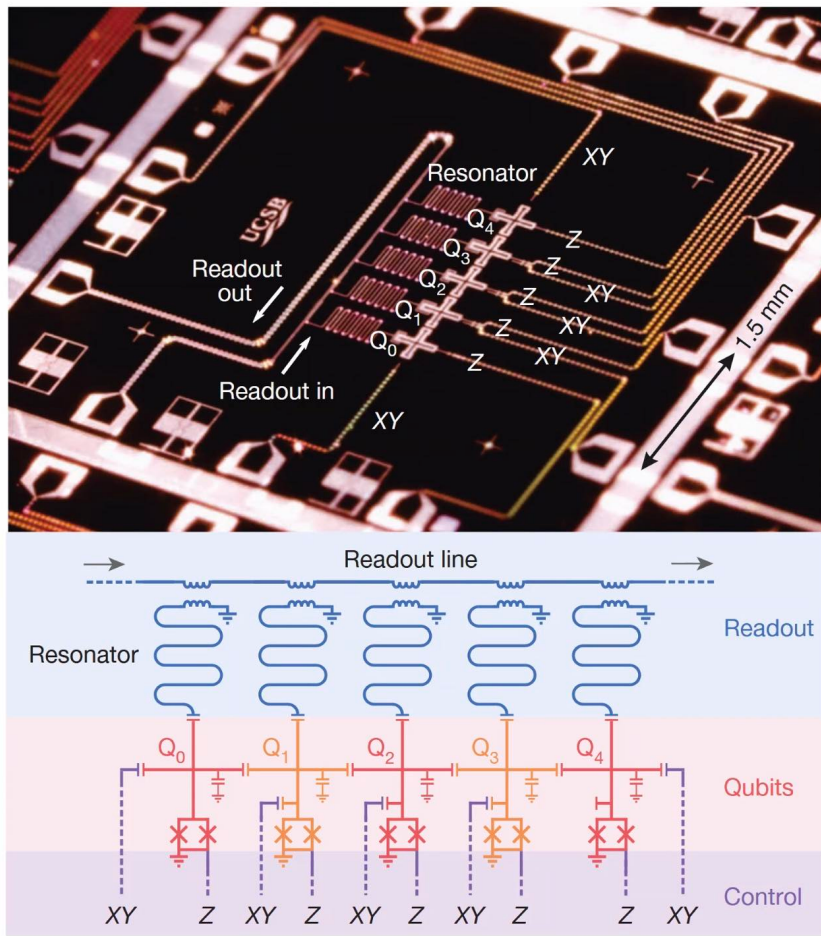
The experimental setup by Clarke, Devoret, and Martinis, properly improved, constitutes a platform for several types of **superconducting qubits**.

Josephson-based technology seems close to become practical (?)

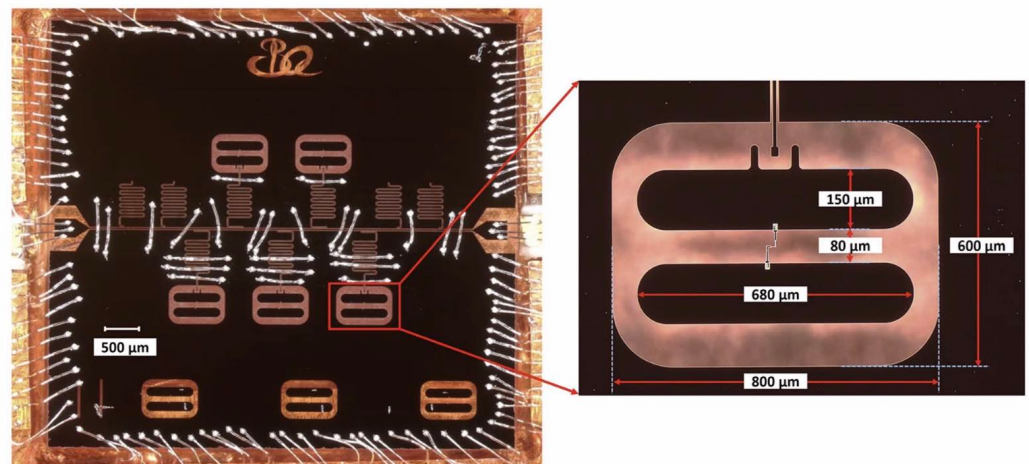
[*fault tolerance, quantum advantage...*]

[*You & Nori, Phys. Today 58, 42 (2005)*]





[R. Barends et al. *Nature*, 2014, 508(7497), 500]



[C. Wang et al. *Npj Quantum Information*, 8(1), 3, 2022]

Michael H. Devoret (b. 1953)

PhD in 1982, Paris Saclay (atomic optics). Postdoc at UC Berkeley, then Saclay, then Yale University.

Since 2023 — *Google Quantum AI* (hardware scientist) & professor at Santa Barbara.

Research: 1990s— quantum sensors, quantum dots, single-electron transistor.

Letter | Published: 03 April 1997

Individual single-wall carbon nanotubes as quantum wires

[Sander J. Tans](#), [Michel H. Devoret](#), [Hongjie Dai](#), [Andreas Thess](#), [Richard E. Smalley](#), [L. J. Geerligs](#)
& [Cees Dekker](#)

[Nature](#) **386**, 474–477 (1997) | [Cite this article](#)

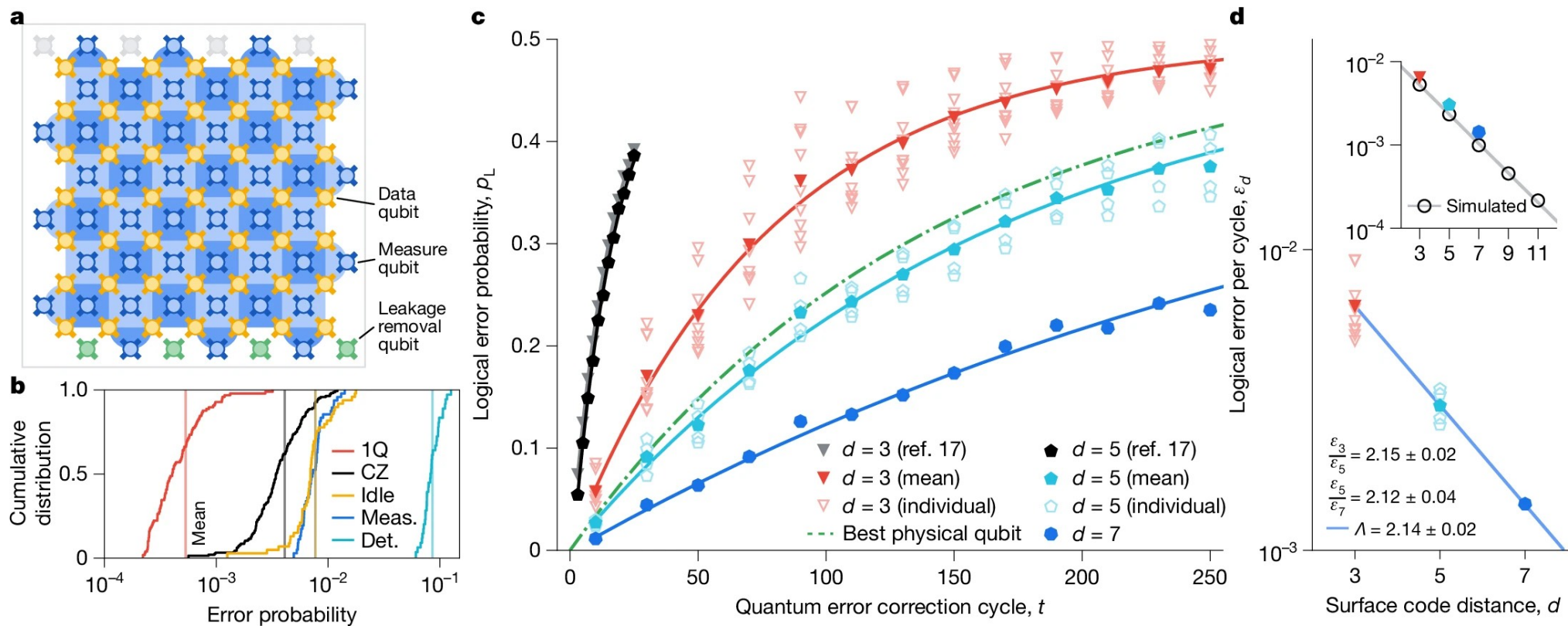
8183 Accesses | **2738** Citations | **16** Altmetric | [Metrics](#)

Michael H. Devoret — *research*

2010: “*Introduction to Quantum Noise, Measurement and Amplification*” [[Reviews of Modern Physics](#) **82**, 1155 (2010).]

2016+: Several results on **quantum error corrections**
[[Ofek et al., Nature](#) **536**, 441 (2016); [Sivak et al., Nature](#) **616**, 50 (2023).]

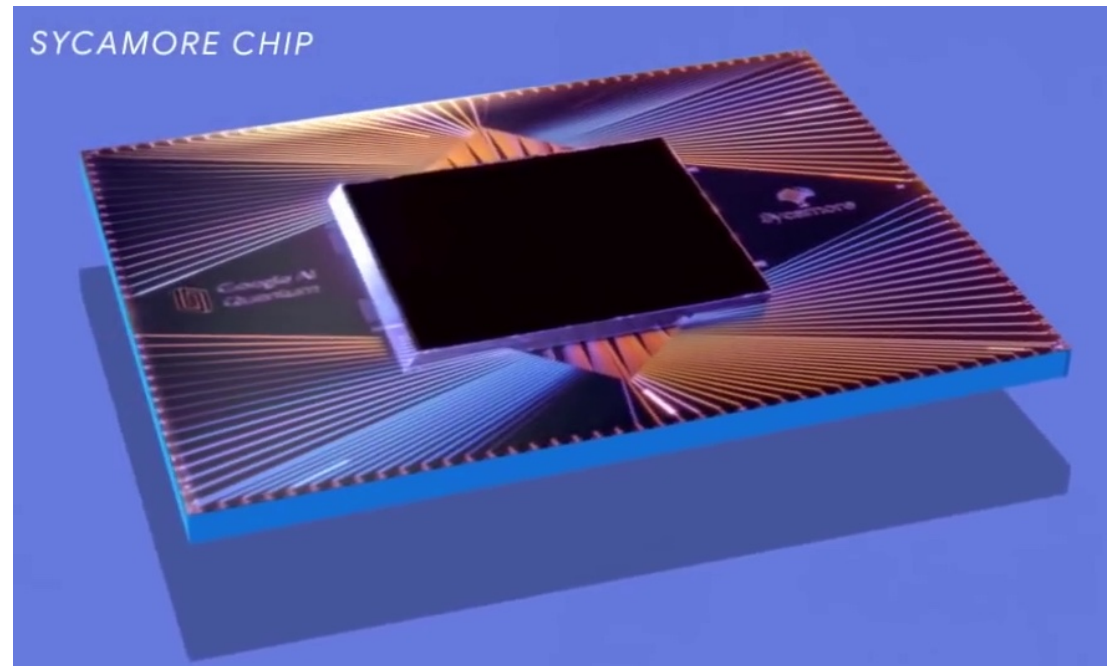
2025: Google Quantum AI paper on ***the Willow chip***: “Quantum error correction below the surface code threshold”
[[Nature](#) **638**, 920–926 (2025)]



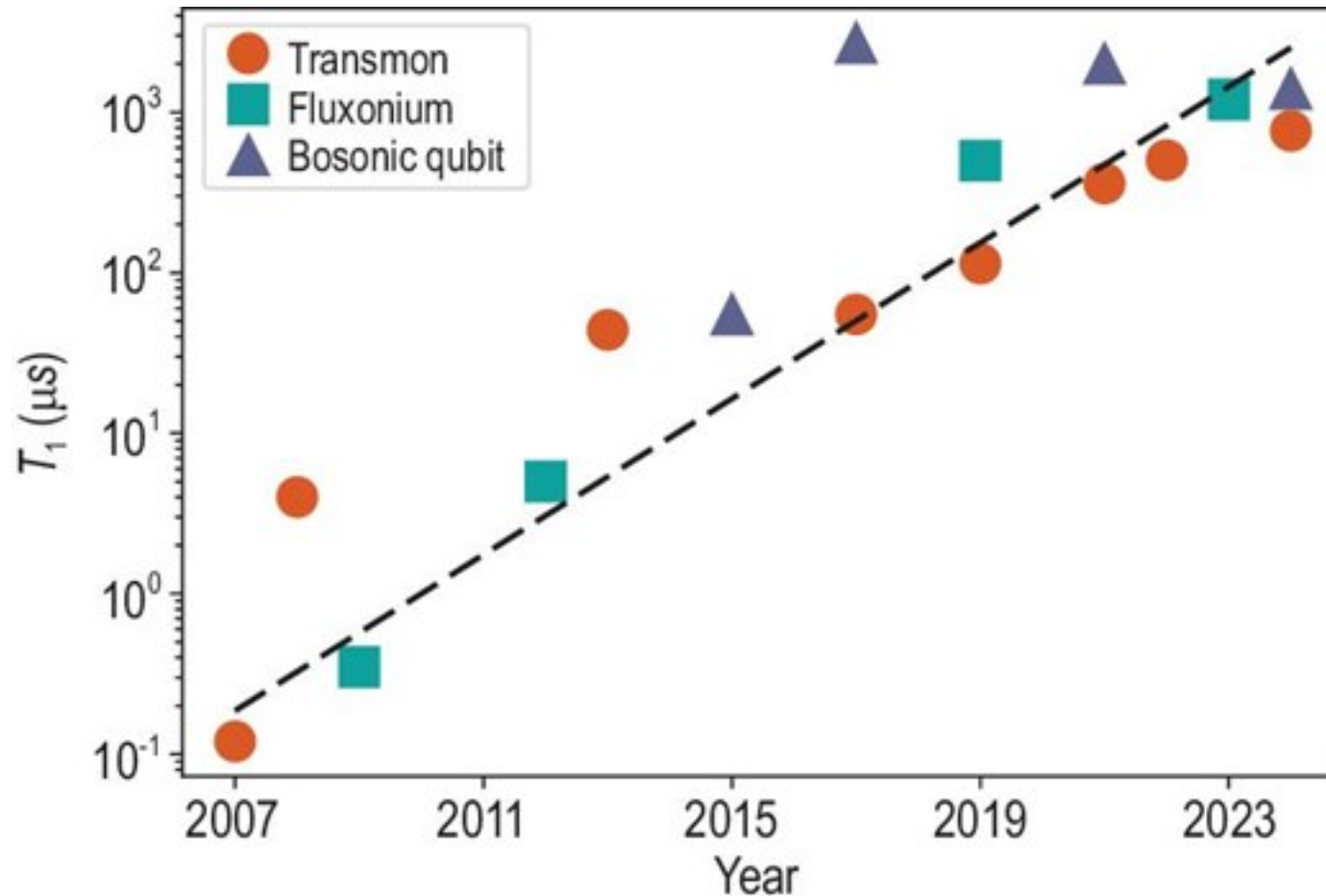
[From: *Nature* **638**, 920–926 (2025)]

John M. Martinis (b. 1958)

- PhD 1987, UC Berkeley (*with John Clarke*)
- 1990s: quantum sensors
- 2000s: qubits, decoherence, quantum computing
[See: “*Violation of Bell's inequality in Josephson phase qubits*”,
Nature **461**, 504 (2009)]
- Since 2014: lead Google Quantum AI Lab.
- The **Sycamore chip**:
“*Quantum supremacy using a programmable superconducting procesor*”
[*Nature* **574**, 505 (2019).]

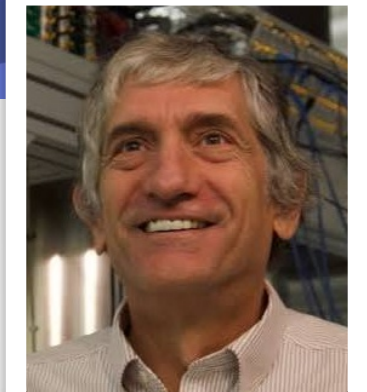
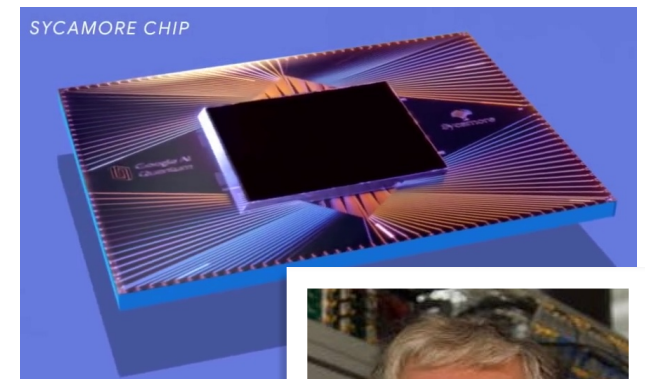
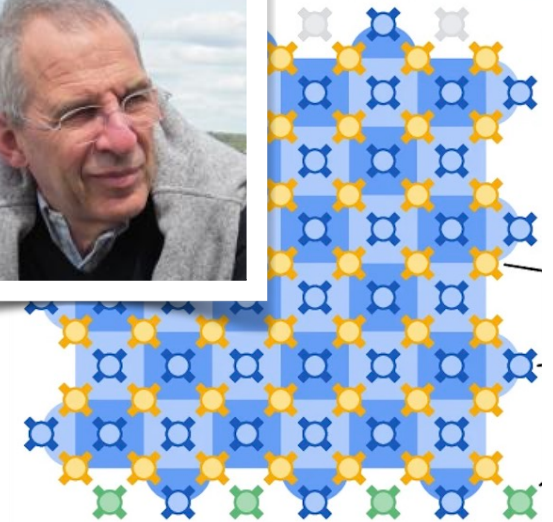
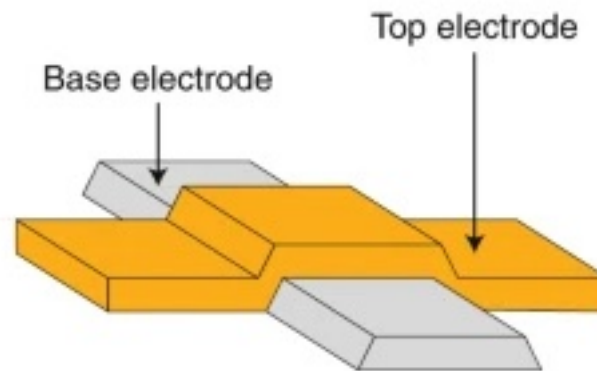
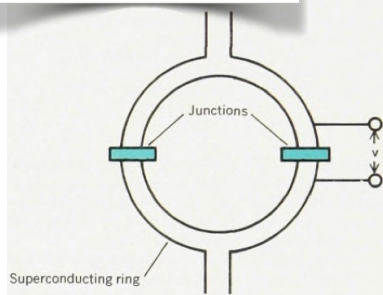


Progress in quantum coherence



[Yao-Yao Jiang et al., “Advancements in superconducting quantum computing”, *Nat. Sci. Rev.* 12, nfaw246 (2025)]

Overview



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