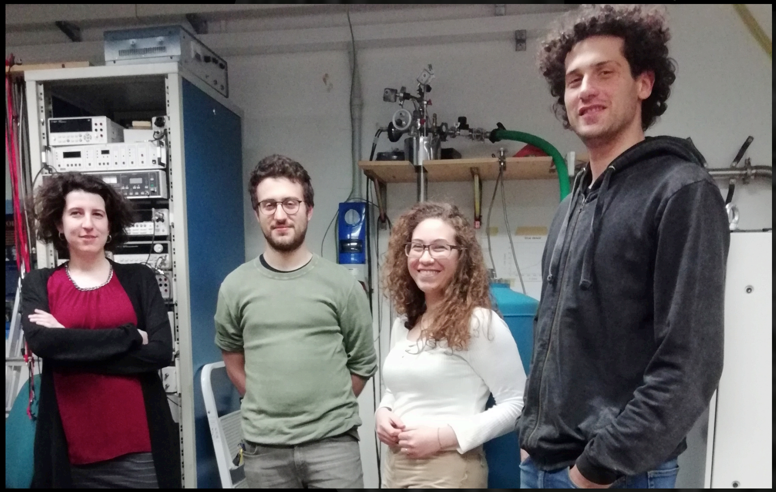
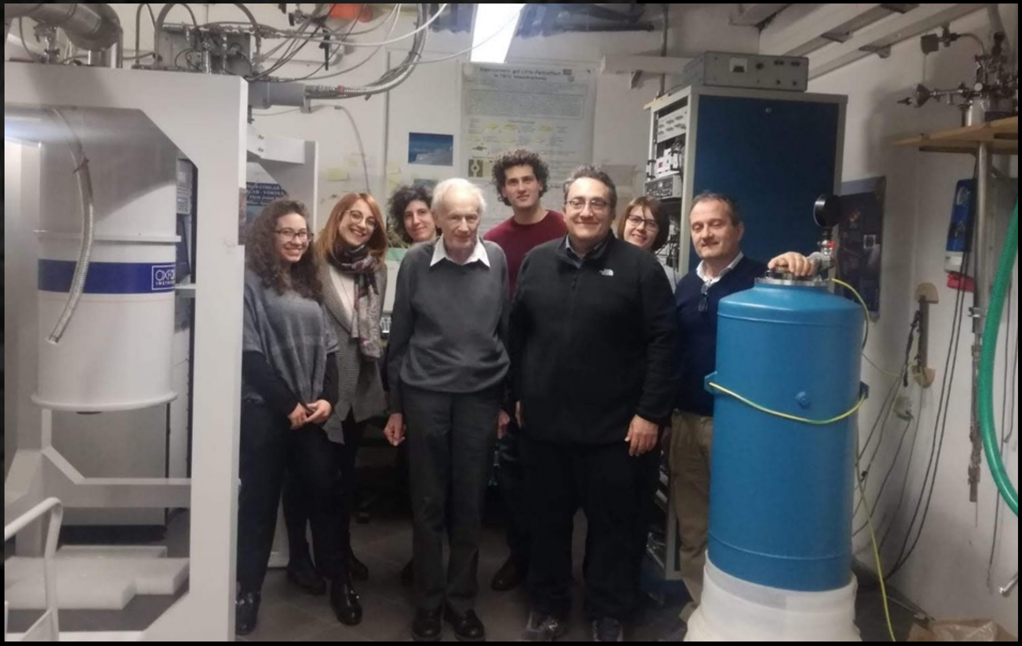
The Josephson effect for (superconducting) hybrids solutions for quantum technologies

Halima Ahmad, Roberta Caruso, Davide Massarotti, Alessandro Miano, Domenico Montemurro, Loredana Parlato, Giampiero Pepe, Roberta Satariano, Daniela Stornaiuolo & Francesco Tafuri

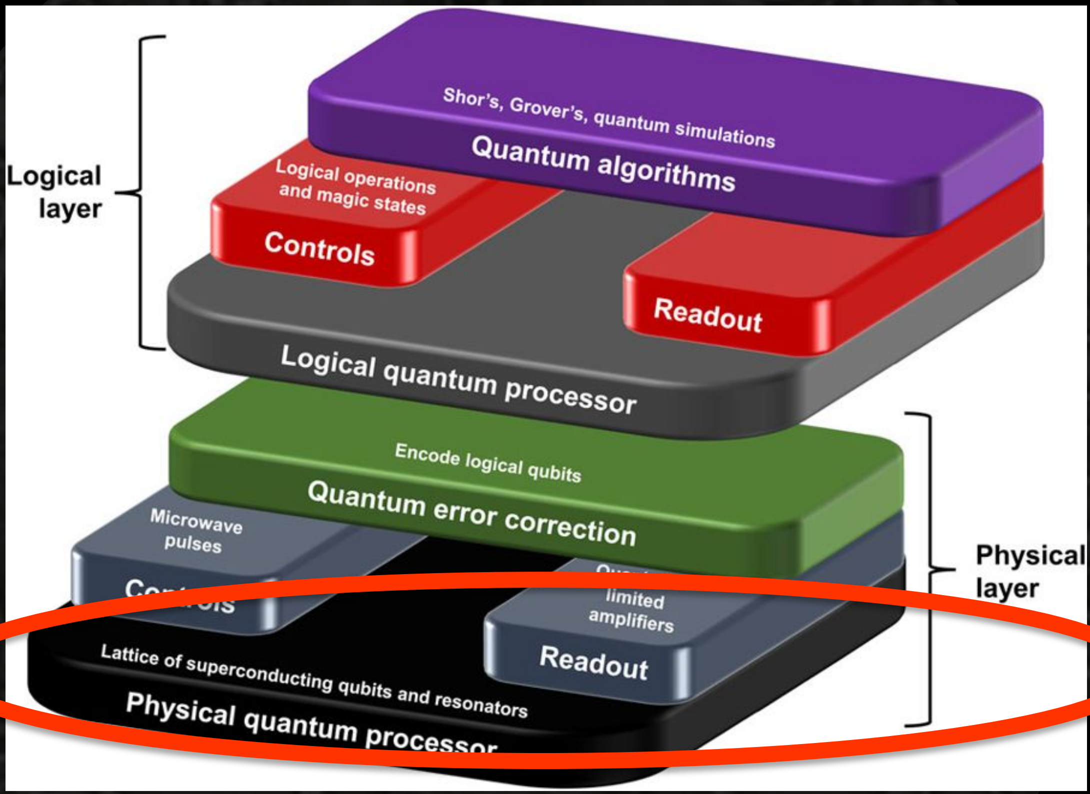
Università di Napoli "Federico II" Italy



Oleg Mukanhov, Marco Arzeo, Matthew Hutchings



Rewinding the tape
to touch the macroscopic quantum world

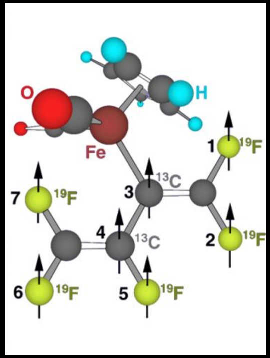


Jay M. Gambetta , Jerry M. Chow & Matthias Steffen

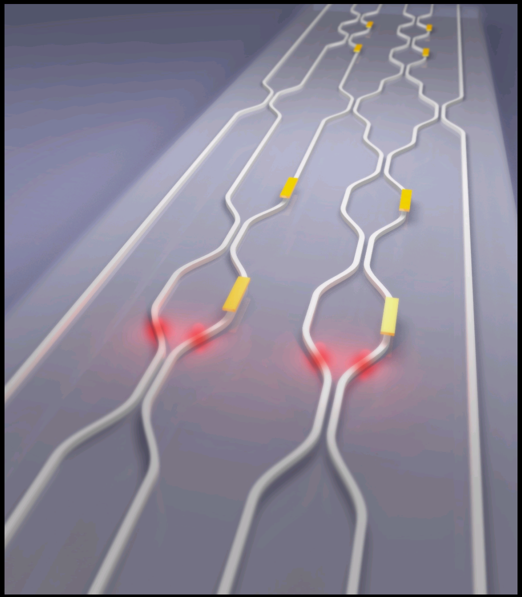
npj Quantum Information **3**, Article number: 2 (2017)

Physical implementations ?

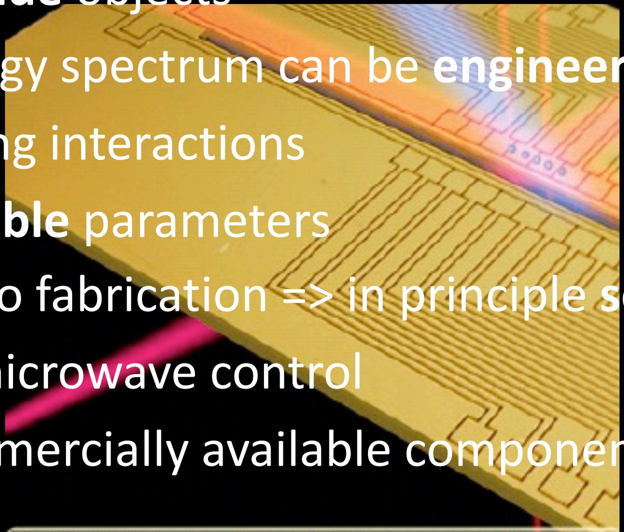
NMR



Photons



Trapped ions (or atoms)



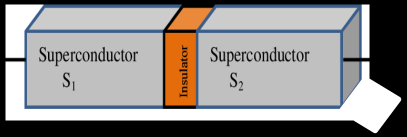
manmade objects

- energy spectrum can be **engineered**
- strong interactions
- **tunable** parameters
- micro fabrication => in principle **scalable**
- all microwave control
- commercially available components

Electrical circuits ?

usually not quantum !

A quantum component
The Josephson junction



Quantum Mechanics of a Macroscopic Variable:
The Phase Difference of a **Josephson Junction**

Quantum Inf Process (2009) 8:81–103
DOI 10.1007/s11128-009-0105-1

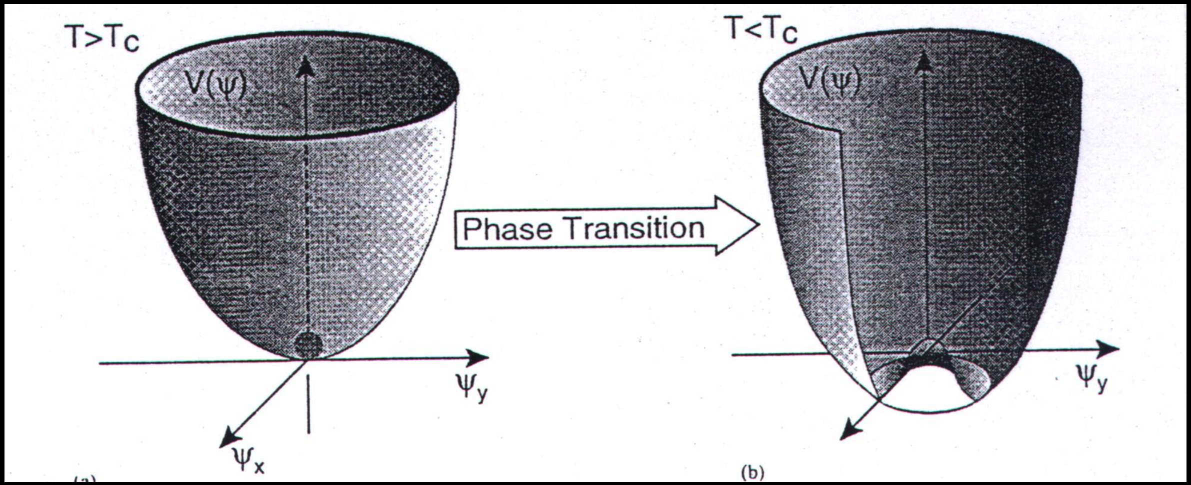
Superconducting phase qubits

John M. Martinis

Google

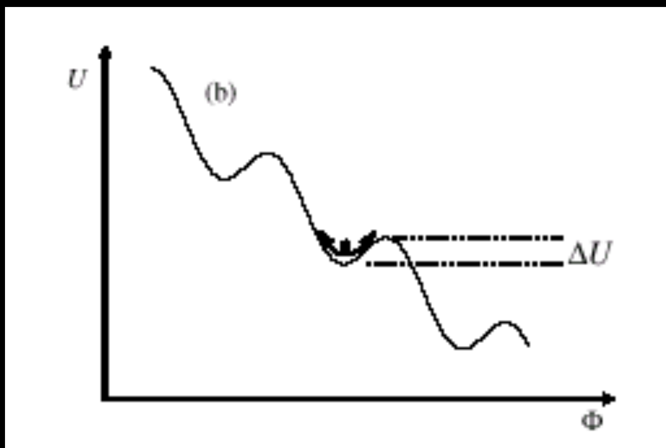
Superconducting qubit research began in the 1980s motivated by the question, posed by Anthony Leggett, whether macroscopic variables would behave in a quantum mechanical fashion [23]. Initial experiments verified quantum behavior via the phenomenon of tunneling out of the zero-voltage state of a current-biased Josephson junction [7]. At UC Berkeley, quantum mechanical behavior was also demonstrated by the existence of quantized energy levels [28]. This observation provided stronger proof of quantum behavior, and established at an early stage (before the ideas of qubits were even widely established) that superconducting circuits could be used as general quantum systems [3].

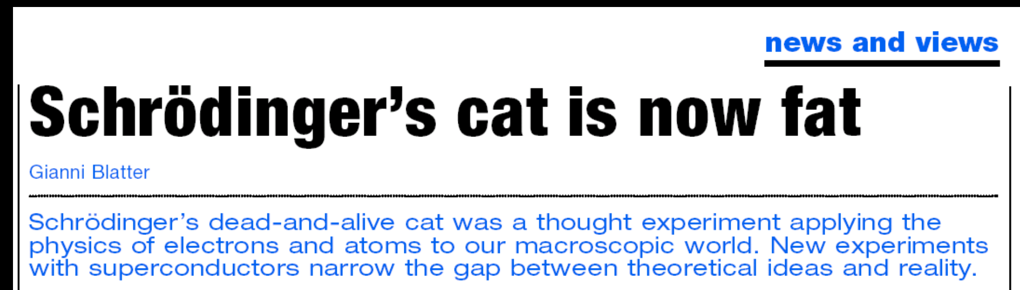
Superconductivity as a Macroscopic Quantum Phenomenon



$$\psi = n_S e^{i\Phi}$$

Quantum behavior displayed by a single macroscopic degree of freedom (the phase difference across a current-biased Josephson tunnel junctions): whether or not macroscopic systems like this exhibit quantum mechanical behavior, for example zero point motion, macroscopic quantum tunneling, or quantization of energy.

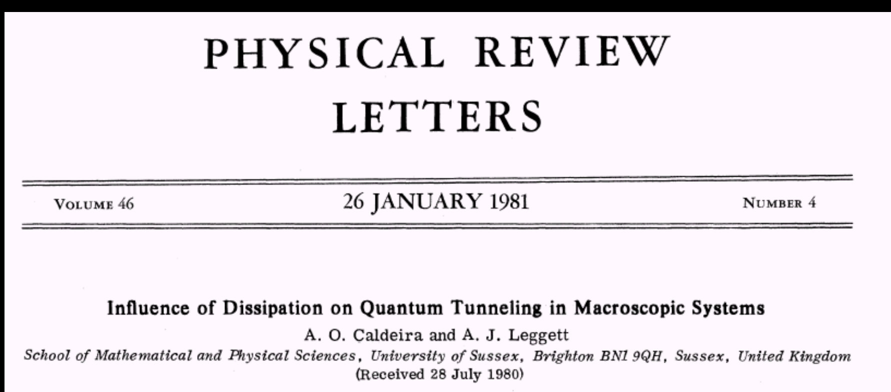



news and views

Schrödinger's cat is now fat

Gianni Blatter

Schrödinger's dead-and-alive cat was a thought experiment applying the physics of electrons and atoms to our macroscopic world. New experiments with superconductors narrow the gap between theoretical ideas and reality.



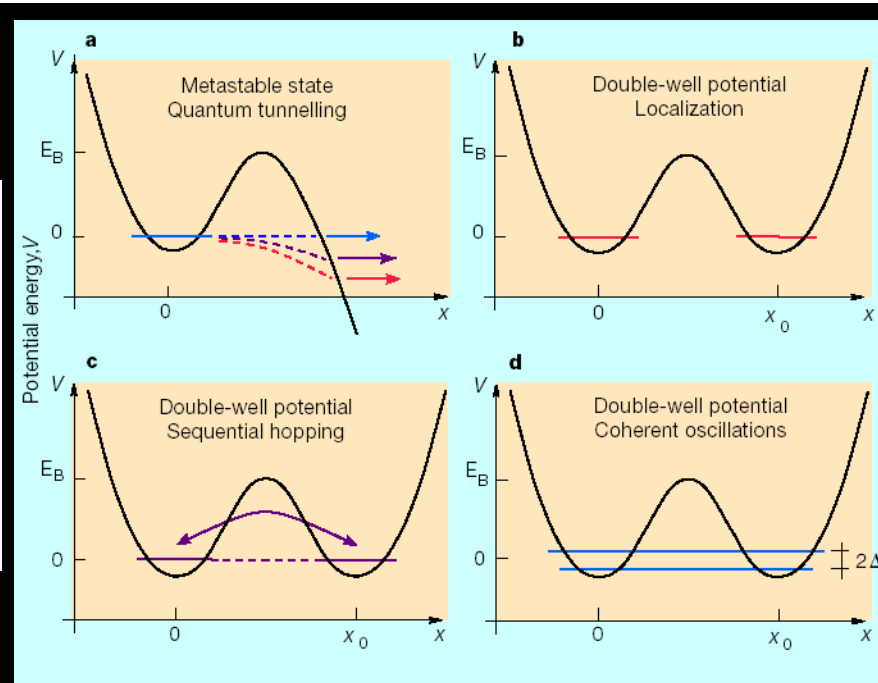
PHYSICAL REVIEW LETTERS

VOLUME 46 | 26 JANUARY 1981 | NUMBER 4

Influence of Dissipation on 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

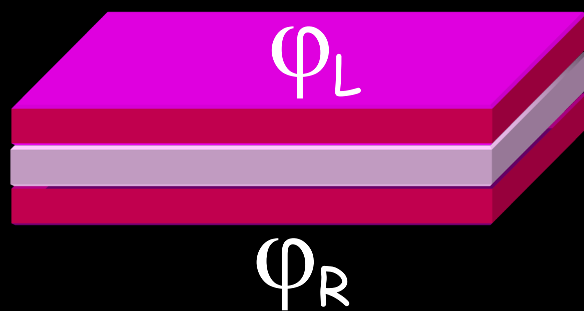
(Received 28 July 1980)

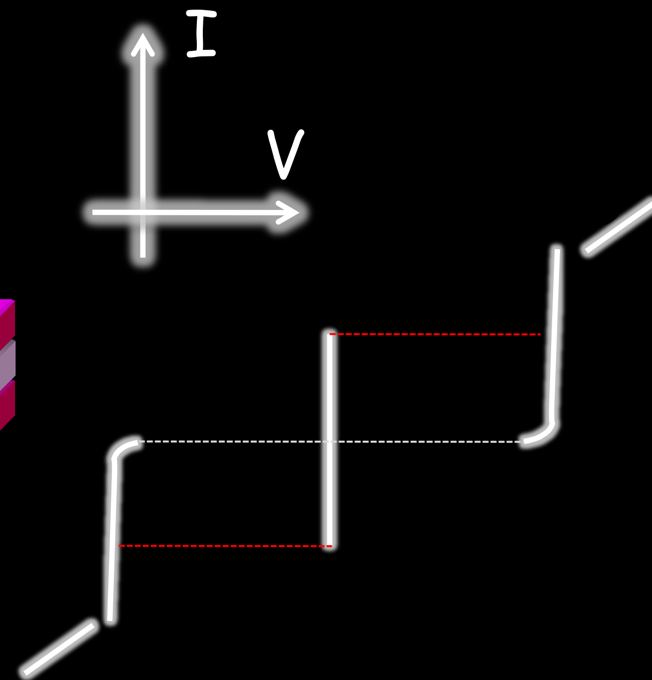


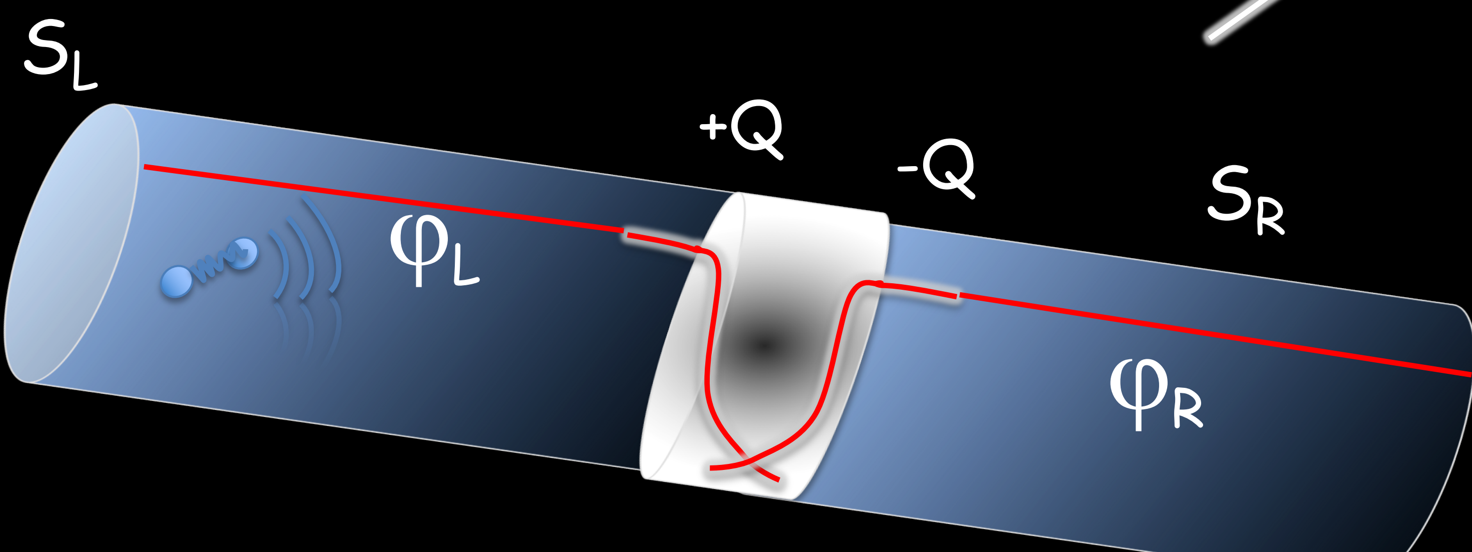
The Josephson effect

$$\begin{cases} I_S(\varphi) = I_C \sin\varphi \\ \dfrac{\partial\varphi}{\partial t} = \dfrac{2eV}{\hbar} \end{cases}$$

$$\varphi = \varphi_L - \varphi_R$$

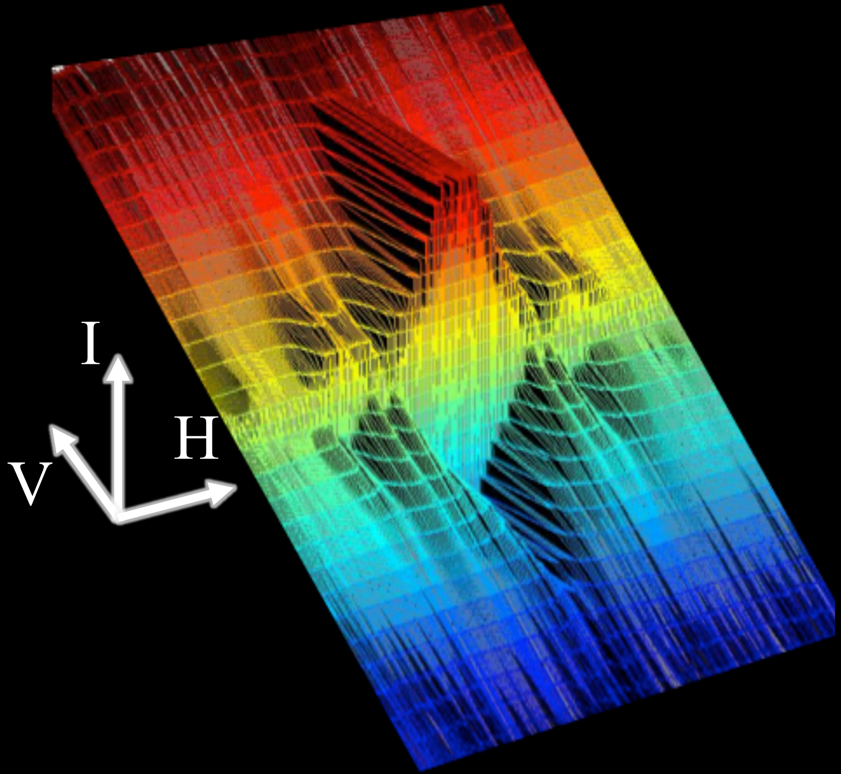






A. Barone and G. Paternò, Physics and Applications of the Josephson effect, Wiley 1982

The Josephson effect



$$H = Q^2/(2C) - E_J \cos\varphi$$

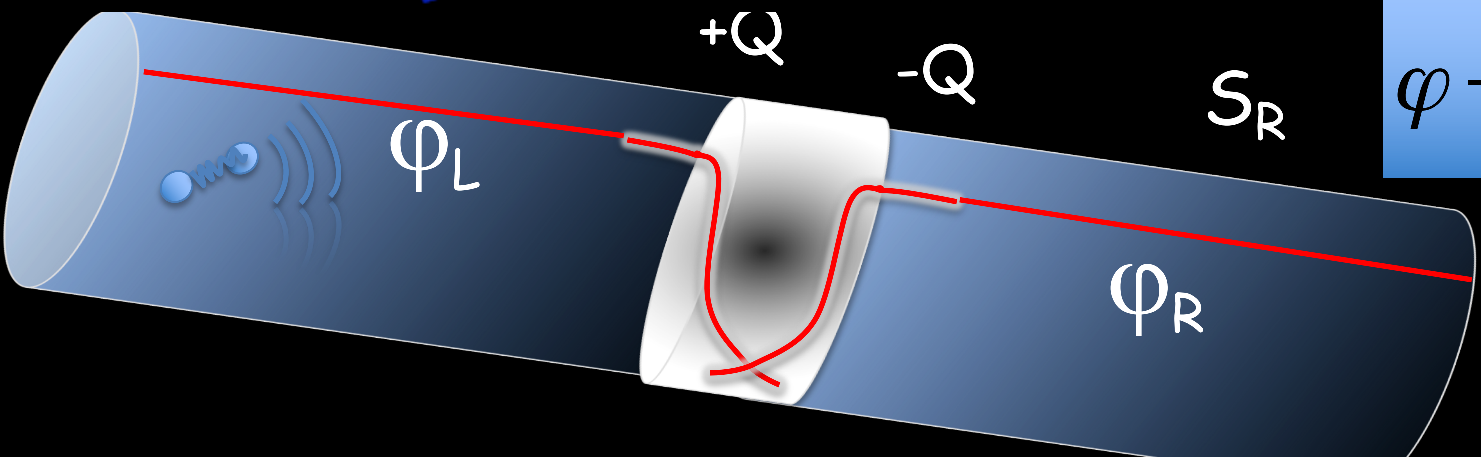
$$[\varphi, Q] = 2i\hbar \qquad E_J << E_C$$

$$2eN = Q = CV$$

$$N \rightarrow E_C = \frac{(2eN)^2}{2C}$$

$$\varphi \rightarrow E_J = \frac{I_c \phi_o}{2\pi}$$

$$E_J >> E_C$$



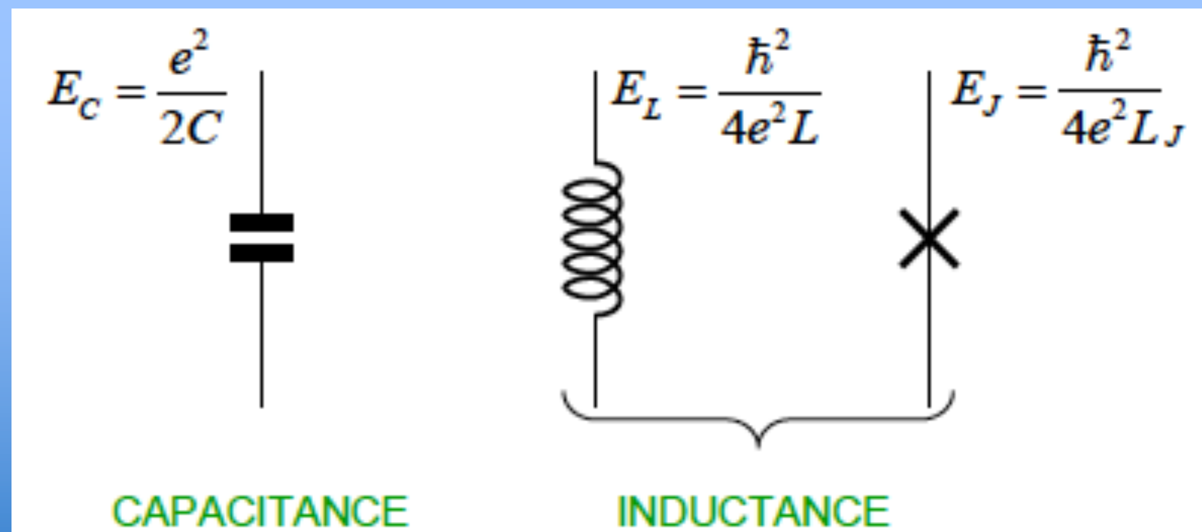
A. Barone and G. Paternò, Physics and Applications of the Josephson effect, Wiley 1982

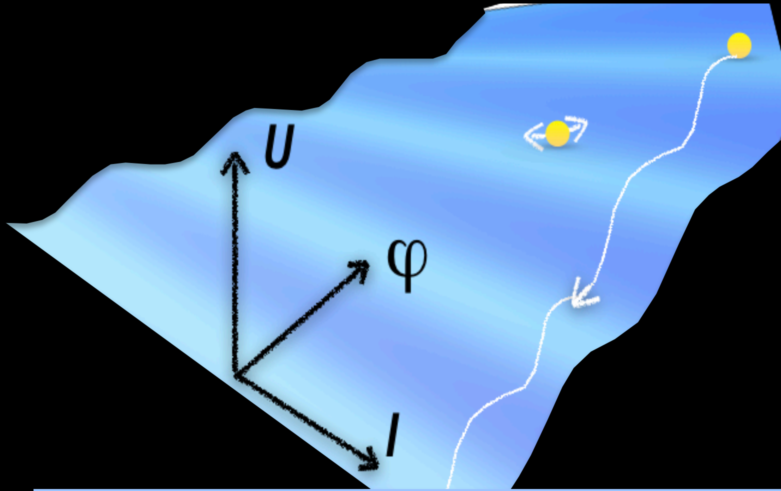
Josephson junction: the only non-linear and non-dissipative component

$$I_S(\varphi) = I_C \sin\varphi$$

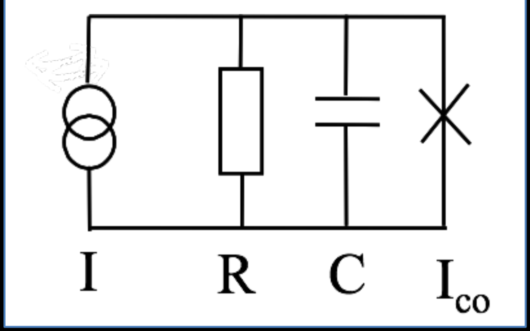
$$L_{J0} = \frac{\Phi_0}{2\pi I_c}$$

$$L_J\left(\Phi_J\right) = \frac{L_{J0}}{\cos\varphi}$$





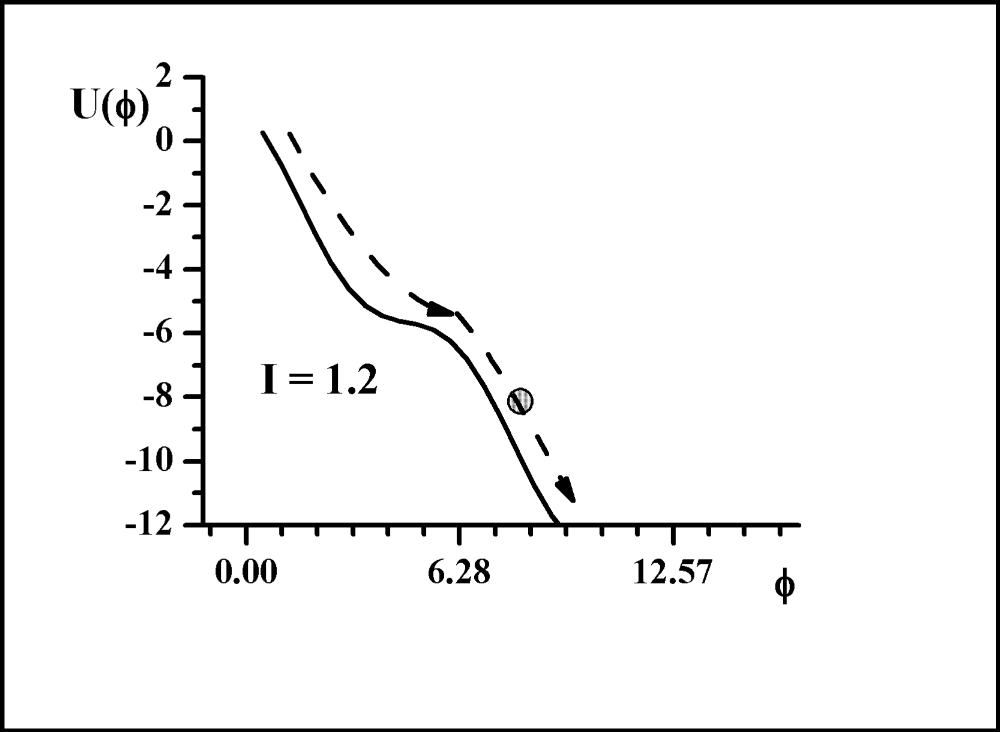
Phase dynamics

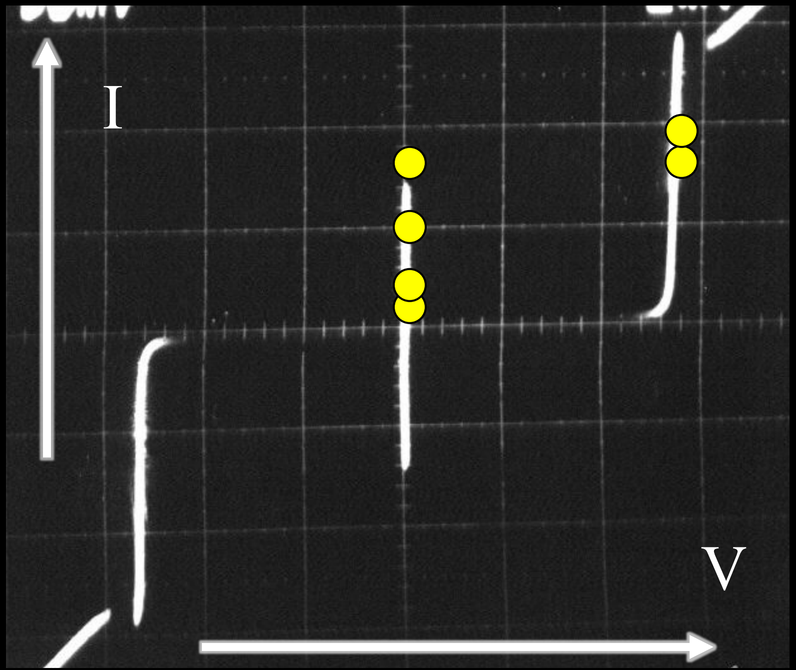


$$I = C\frac{dV(t)}{dt} + GV(t) + I_c \sin\varphi(t)$$

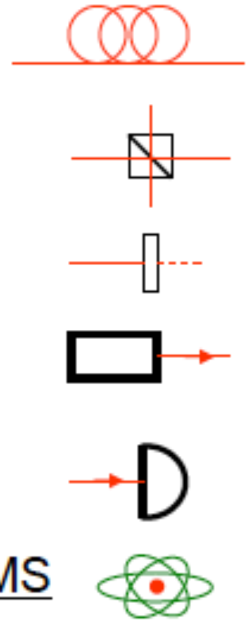
$$\left(\frac{\phi_o}{2\pi}\right)^2 C\frac{\partial^2\varphi}{\partial t^2} + \left(\frac{\phi_o}{2\pi}\right)^2 \frac{1}{R}\frac{\partial\varphi}{\partial t} + \frac{\partial U(\varphi,I)}{\partial\varphi} = 0$$

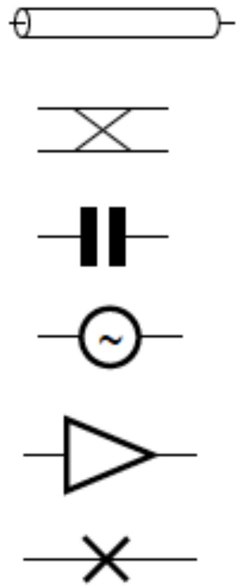
$$U(\varphi,I) = E_J\left(-\frac{I}{I_c}\varphi - \cos(\varphi)\right)$$





QUANTUM OPTICS ⟷ QUANTUM CIRCUITS





QUANTUM OPTICS	QUANTUM CIRCUITS
FIBERS, BEAMS	TRANSM. LINES, WIRES
BEAM-SPLITTERS	COUPLERS
MIRRORS	CAPACITORS
LASERS	GENERATORS
PHOTODETECTORS	AMPLIFIERS
<u>ELECTRONS IN ATOMS</u>	<u>JOSEPHSON JUNCTIONS</u>

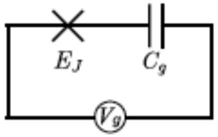
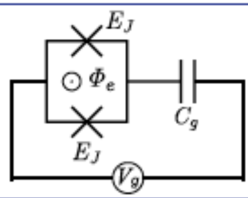
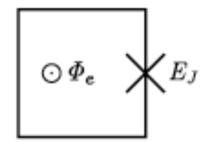
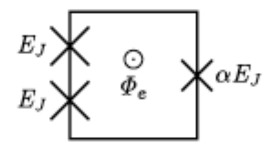
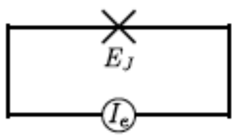
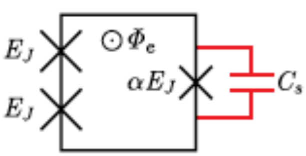
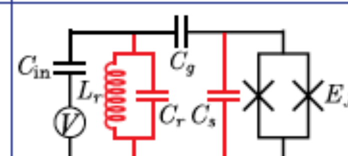
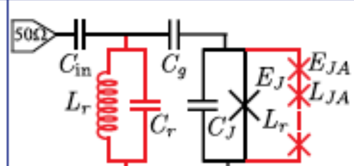
ADVANTAGES OF CIRCUITS:
- PARALLEL FABRICATION METHODS
- MECHANICAL STABILITY
- <u>LEGO BLOCK CONSTRUCTION OF HAMILTONIAN</u>
- <u>ARBITRARILY LARGE ATOM-FIELD COUPLING</u>

DRAWBACKS OF CIRCUITS: ARTIFICIAL ATOMS PRONE TO VARIATIONS

REVIEWS OF MODERN PHYSICS, VOLUME 85, APRIL–JUNE 2013

Hybrid quantum circuits: Superconducting circuits interacting with other quantum systems

Ze-Liang Xiang* Sahel Ashhab† J.Q. You‡
Franco Nori§

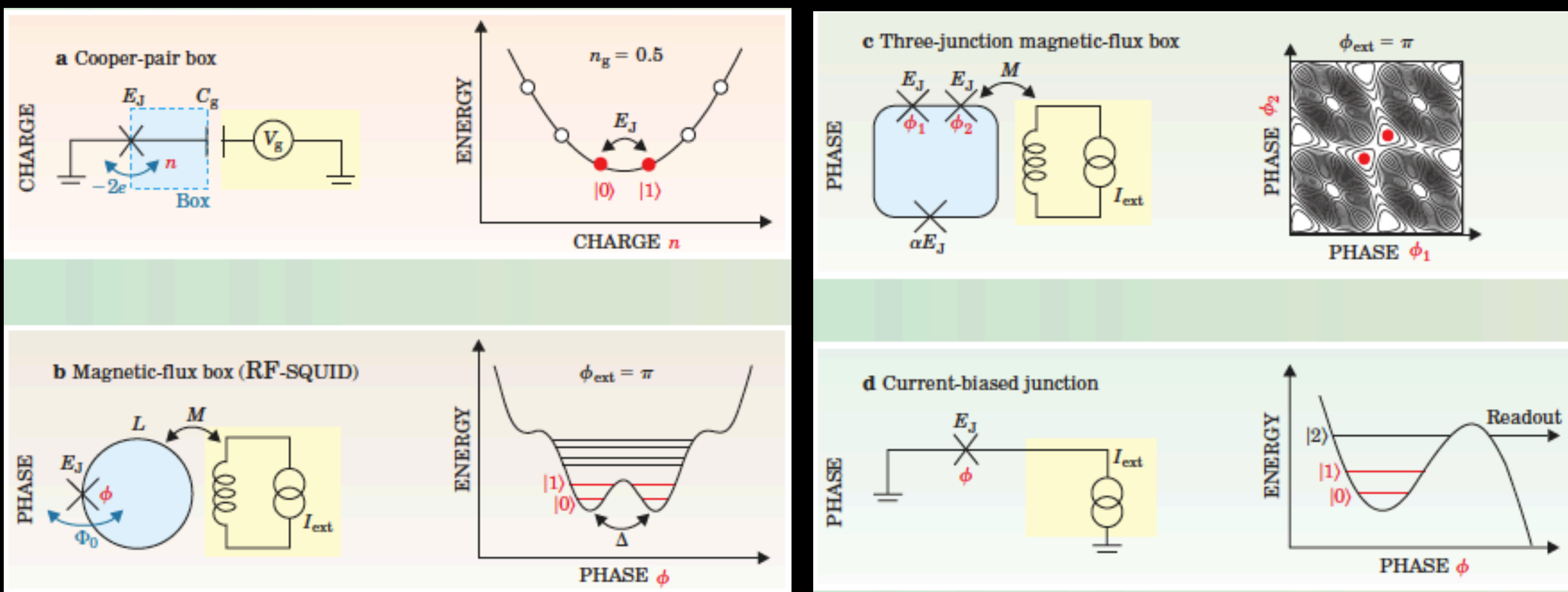
	Circuit	Properties	Dominant noise
Charge qubit		$E_J/E_C < 1$ Controlled by V_g.	Charge fluctuations; mainly 1/f noise.
		$E_J/E_C < 1$ Controlled by both V_g and Φ_e.	
Flux qubit		$E_J/E_C > 1$ Controlled by Φ_e.	Flux fluctuations; mainly 1/f noise.
		$E_J/E_C > 1$ $0.5 < \alpha < 1$ Controlled by Φ_e.	
Phase qubit		$E_J/E_C \gg 1$ Controlled by I_e.	Flux fluctuations; mainly 1/f noise.
Low-decoherence qubit		Shunt capacitance C_s. $E_J/E_C > 1$ Controlled by Φ_e flux qubit: $0.5 < \alpha < 1$ phase qubit: $\alpha < 0.5$	Both charge noise and flux noise can be suppressed.
Transmon		Shunt capacitance C_s. $E_J/E_C > 1$ Behaves like a phase qubit	Charge noise can be suppressed.
Fluxonium		Needs an array of larger-area tunnel junctions. $E_J/E_C > 1$ Behaves like a phase qubit	Charge noise can be suppressed with appropriate parameters.

Superconducting Circuits and Quantum Information

Superconducting circuits can behave like atoms making transitions between two levels. Such circuits can test quantum mechanics at macroscopic scales and be used to conduct atomic-physics experiments on a silicon chip.

J. Q. You and Franco Nori

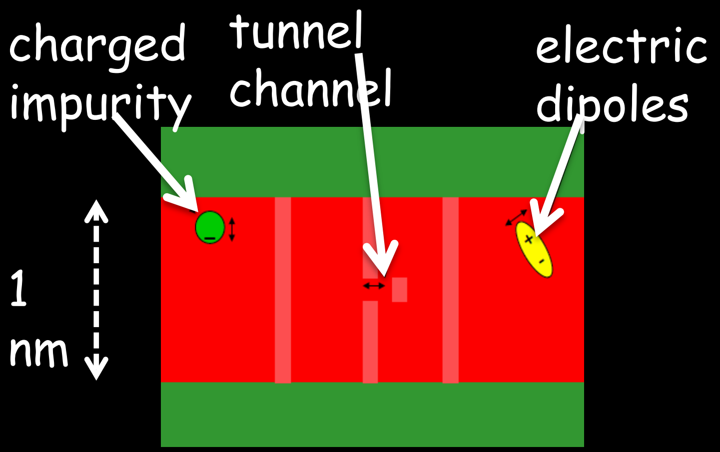
2005 Physics Today



Junction parameter fluctuations

Q_r, E_J, E_C

get rid of randomness of static offset charge



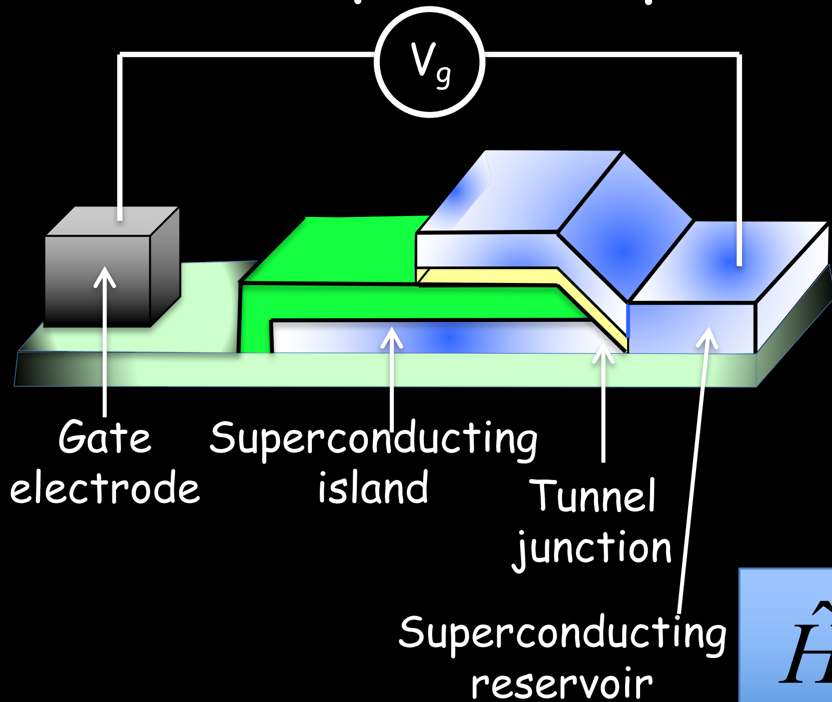
possible solutions

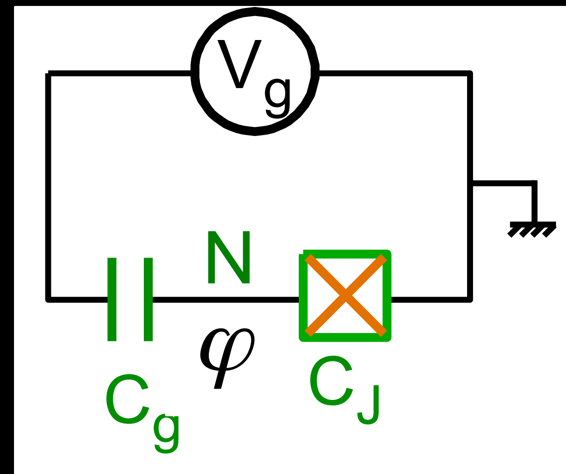
possible solutions

1-Control offset charge with a gate → Cooper pair box (charge qubit)

2-make E_J/E_C very large → RF SQUID (flux qubit)
Current biased Junction (phase qubit)

The quantum path, the single Cooper pair box





$$\left[\hat{\varphi}, \hat{N}\right] = i$$

Hamiltonian

$$\hat{H} = E_c(\hat{N} - N_g)^2 - E_J \cos(\hat{\varphi})$$

Strategy: compensate static offset charge with gate

$$N_g = \frac{C_g V_g}{2e}$$

$$E_J = \frac{h\Delta}{8e^2 R_t}$$

$$E_c = \frac{(2e)^2}{2(C_g + C_J)}$$

Two limit regimes :