Macroscopic quantum phenomena in superconducting junctions

Ph.D.
|Qu>ANTUM
|T>ECHNOLOGIES

U. NAPOLI FEDERICO II, U. CAMERINO & CNR

PHILOSOPHIÆ
DOCTOR
IN QUANTUM
TECHNOLOGIES

UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II - DIPARTIMENTO DI
FISICA "ETTORE PANCINI"

DIETI

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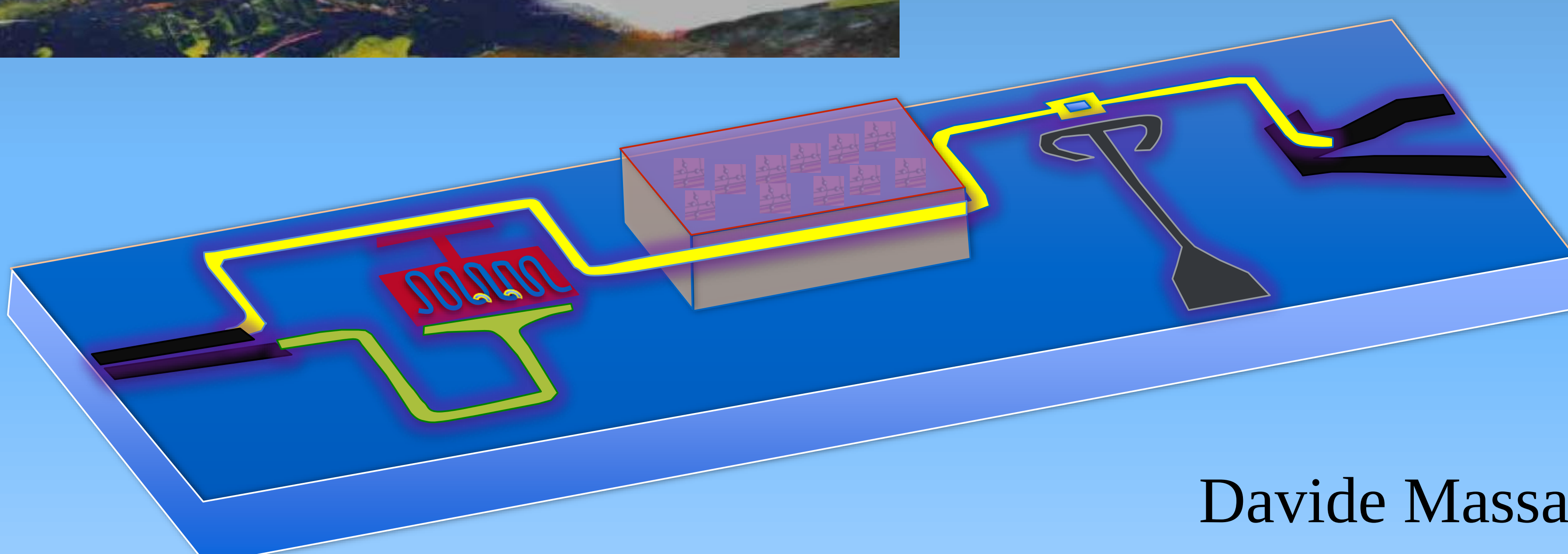


Davide Massarotti, February 8, 2019

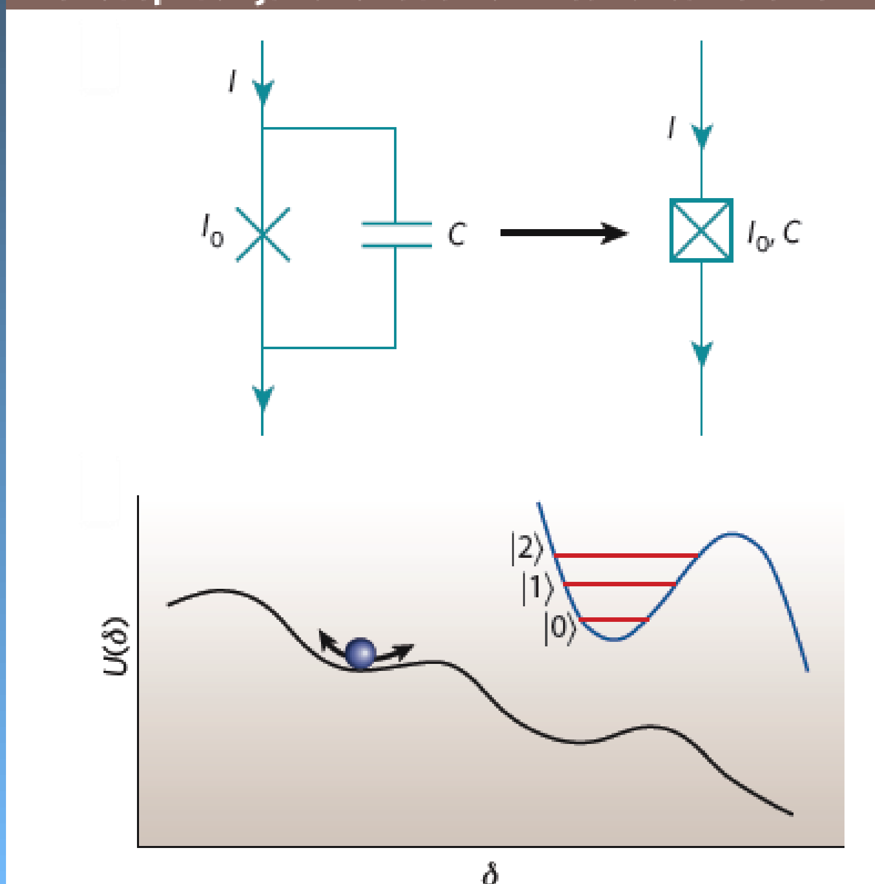
The Josephson junction is a nonlinear dissipationless device. These unique features make the junction the primitive building block of all superconducting qubits. The quantum nature of the macroscopic degree of freedom- the phase difference φ– can be measured

NATURE|Vol 453|19 June 2008|doi:10.1038/nature07128

Superconducting quantum bits

John Clarke[1,2] & Frank K. Wilhelm[3]

The Josephson junction as a nonlinear circuit element



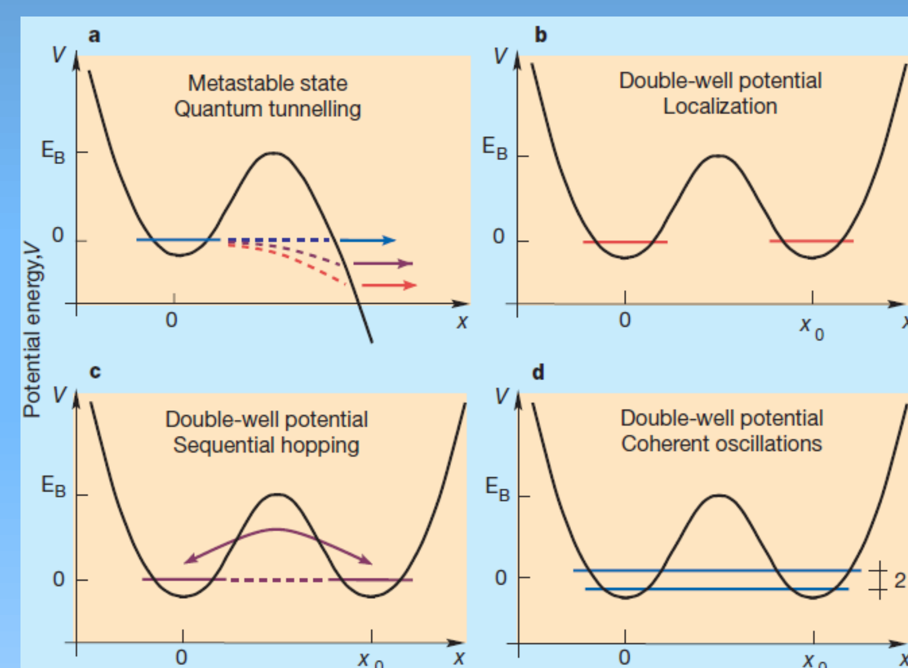
$$I = I_c \sin\varphi \qquad \frac{\partial\varphi}{\partial t} = \frac{2eV}{\hbar}$$

Volume 46 26 JANUARY 1981 Number 4

PHYSICAL REVIEW LETTERS

Influence of Dissipation on Quantum Tunneling in Macroscopic Systems

A. O. Caldeira and A. J. Leggett



news and views NATURE | VOL 406 | 6 JULY 2000 | www.nature.com

Schrödinger's cat is now fat

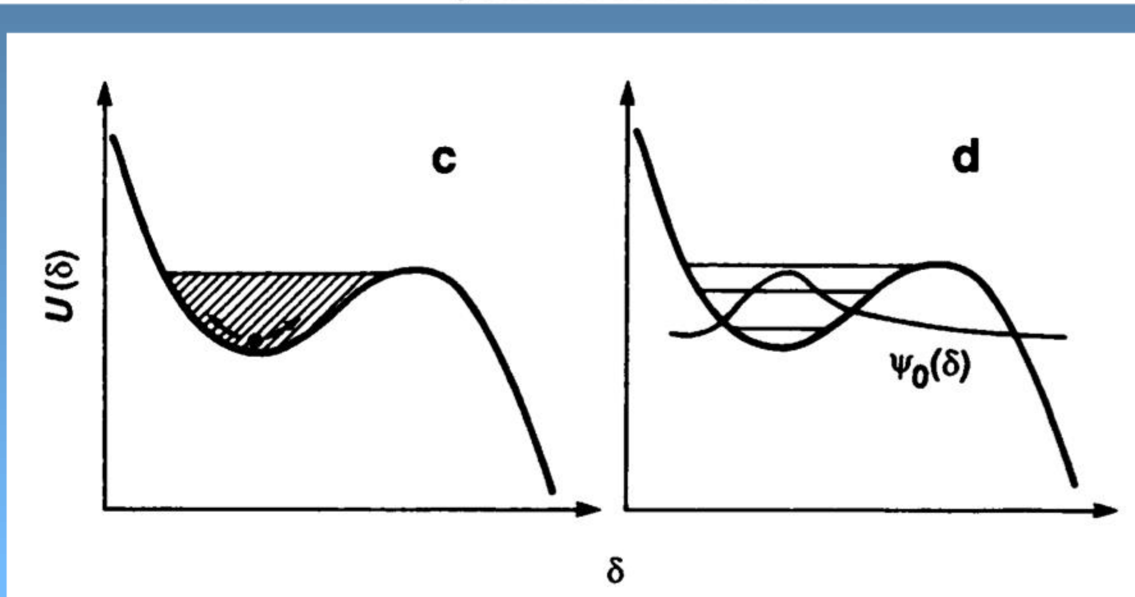
Gianni Blatter

Macroscopic quantum phenomena

SCIENCE, VOL. 239 26 FEBRUARY 1988

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

JOHN CLARKE, ANDREW N. CLELAND, MICHEL H. DEVORET, DANIEL ESTEVE, JOHN M. MARTINIS



Macroscopic atom

ARE MACROSCOPIC DEGREES OF FREEDOM GOVERNED BY quantum mechanics? Our everyday experience tells us that a classical description appears to be entirely adequate. The trajectory of the center of mass of a billiard ball is predicted wonderfully well by classical mechanics. Even the Brownian motion of a tiny speck of dust in a drop of water is a purely classical phenomenon. Until recently, quantum mechanics manifested itself at the macroscopic level only through such collective phenomena as superconductivity, flux quantization, or the Josephson effect. However, these "macroscopic" effects actually arise from the coherent superposition of a large number of microscopic variables each governed by quantum mechanics. Thus, for example, the current through a Josephson tunnel junction and the phase difference across it are normally treated as classical variables. As Leggett (*1*) has

emphasized, one must distinguish carefully between macroscopic quantum phenomena originating in the superposition of a large number of microscopic variables and those displayed by a single macroscopic degree of freedom. It is the latter that we discuss in this article.

Our usual observations on a billiard ball or Brownian particle reveal classical behavior because Planck's constant $\hbar$ is so tiny. However, at least in principle there is nothing to prevent us from designing an experiment in which these objects are quantum mechanical. To do so we have to satisfy two criteria: (i) the thermal energy must be small compared with the separation of the quantized energy levels, and (ii) the macroscopic degree of freedom must be sufficiently decoupled from all other degrees of freedom if the lifetime of the quantum states is to be longer than the characteristic time scale of the system (*1*). To illustrate the application of these

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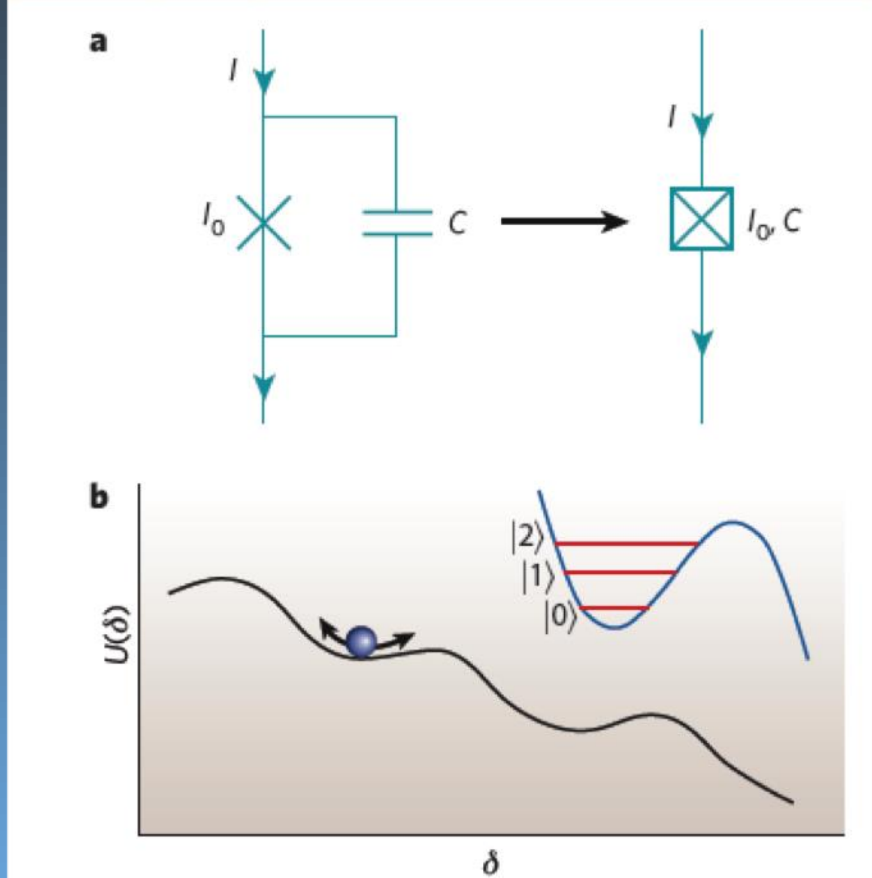
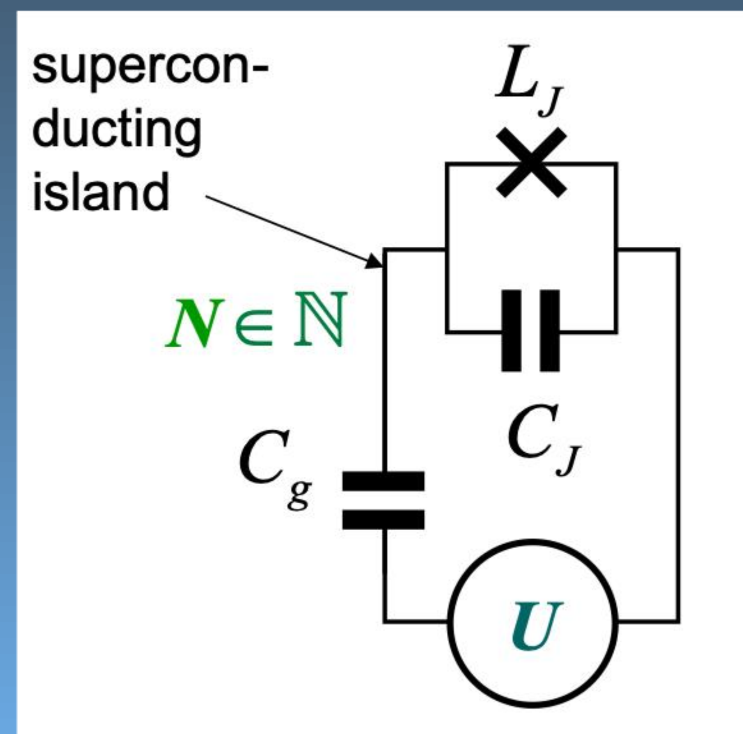
The Josephson junction as a nonlinear circuit element



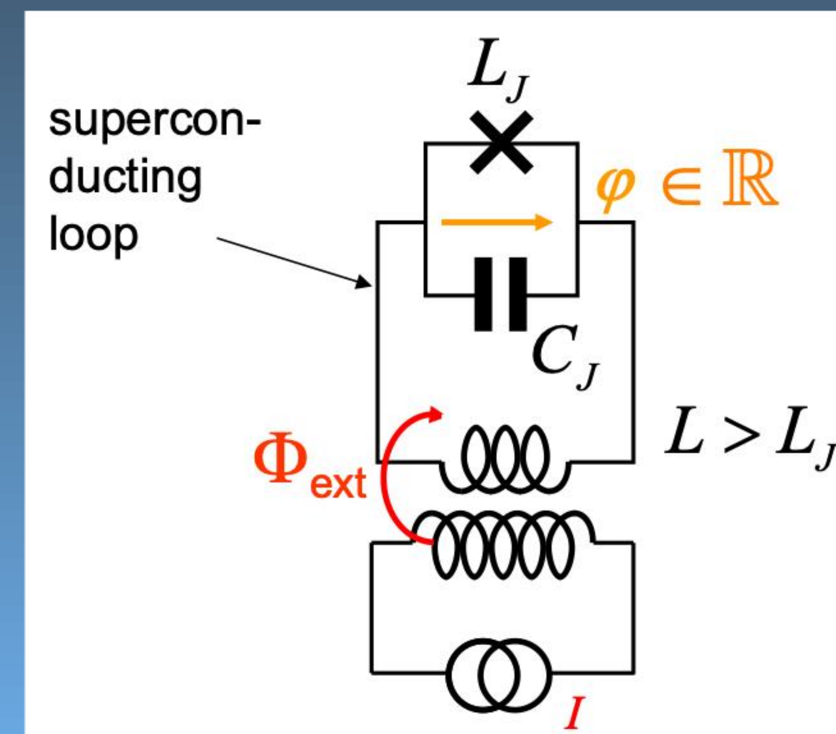
$$H = \frac{Q^2}{2C} + \frac{(\phi - \phi_0)^2}{2L}$$

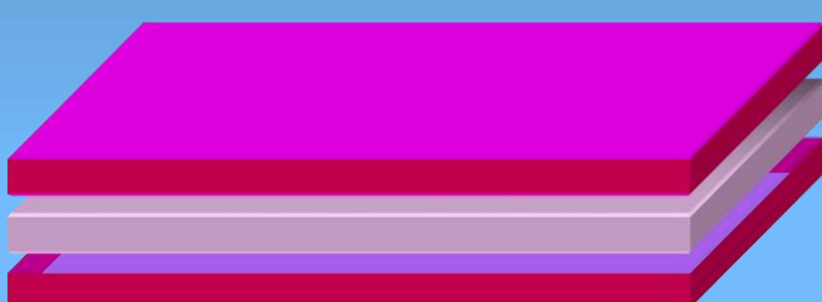
Charging energy   Josephson energy

Charge-Transmon

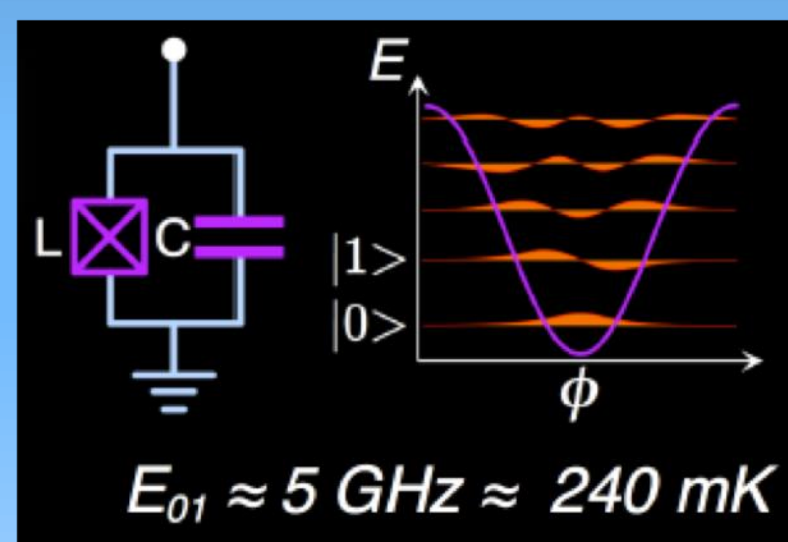


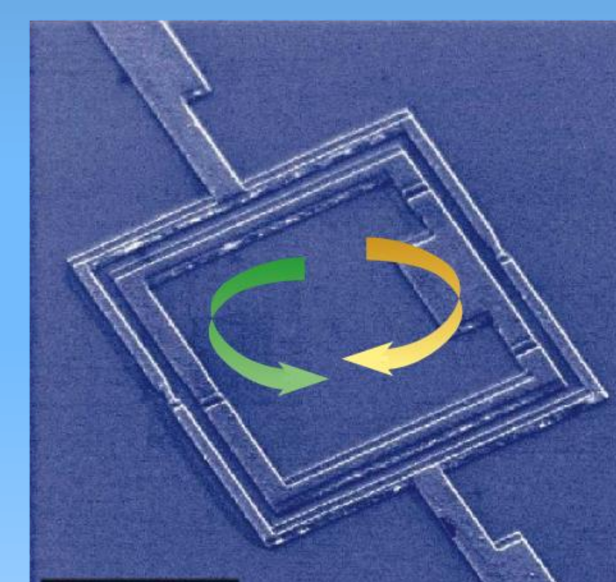
Flux-Phase



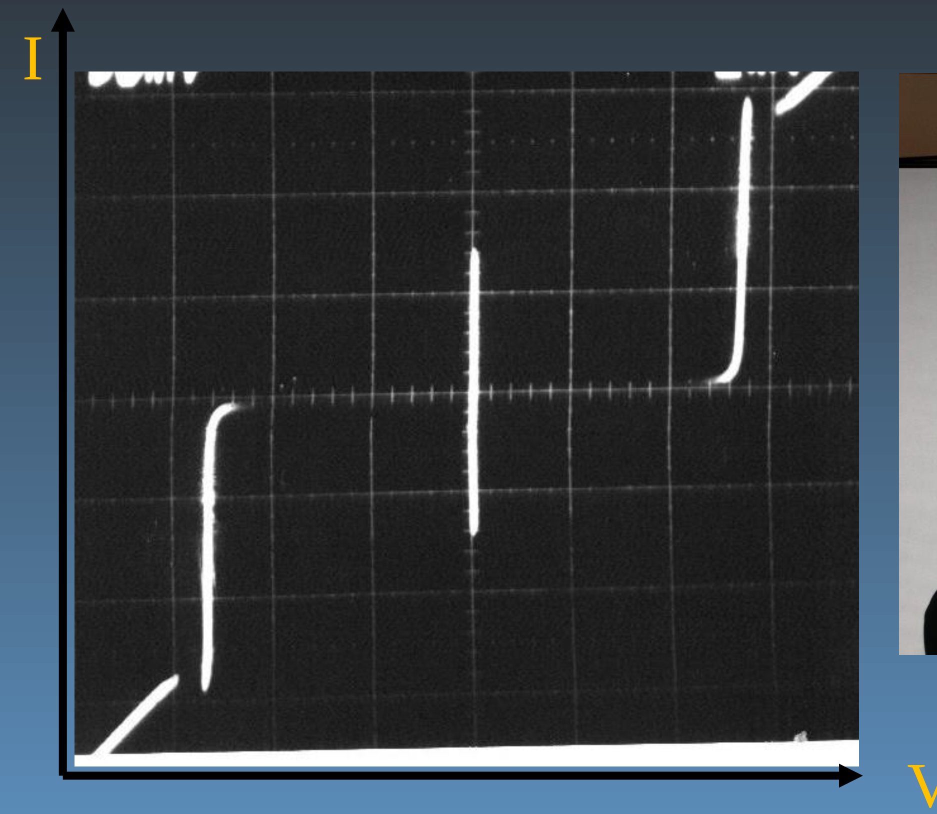


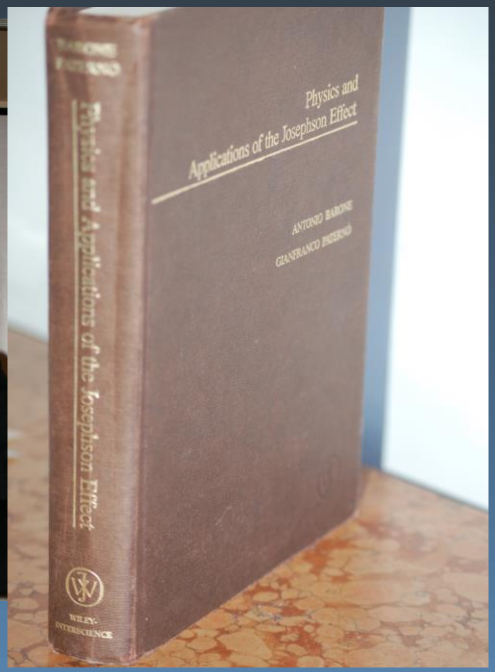
Al/AlOx/Al
Josephson junction
T_1, T_2 ~ 100 μs





QT activities in Napoli

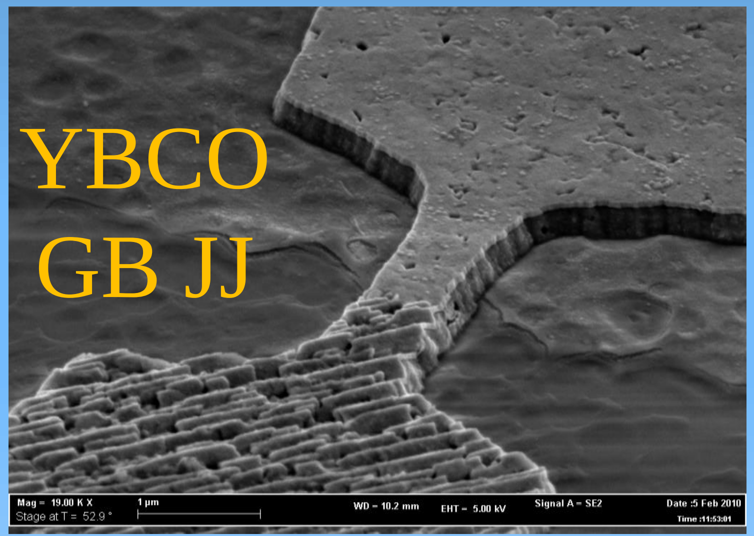


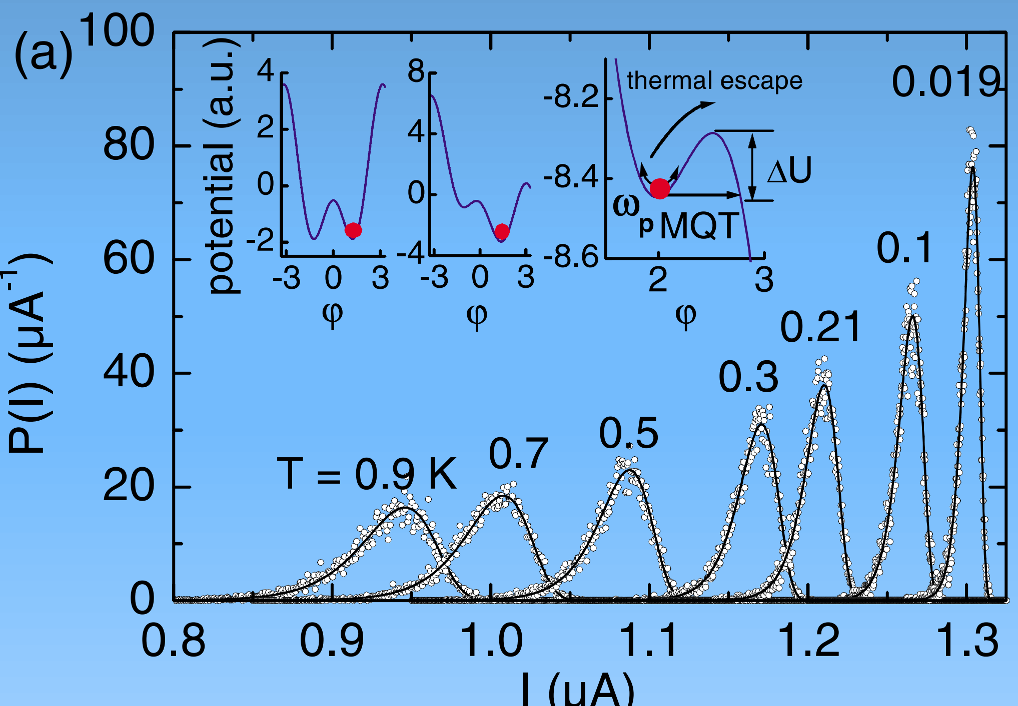


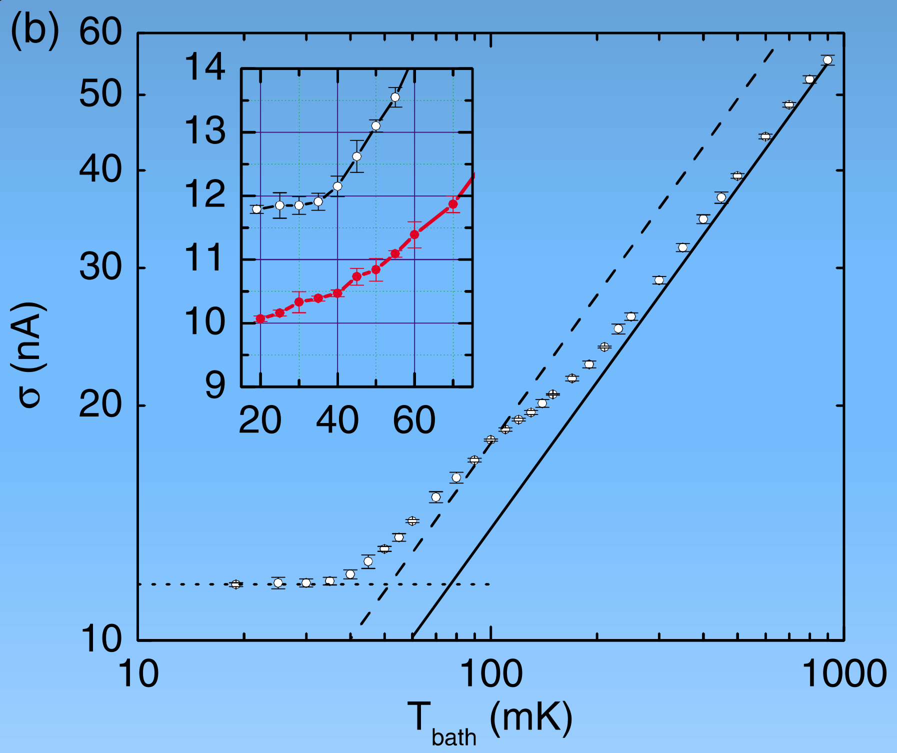
PRL **94**, 087003 (2005) PHYSICAL REVIEW LETTERS week ending 4 MARCH 2005

Macroscopic Quantum Tunneling in *d*-Wave $YBa_2Cu_3O_{7-\delta}$ Josephson Junctions

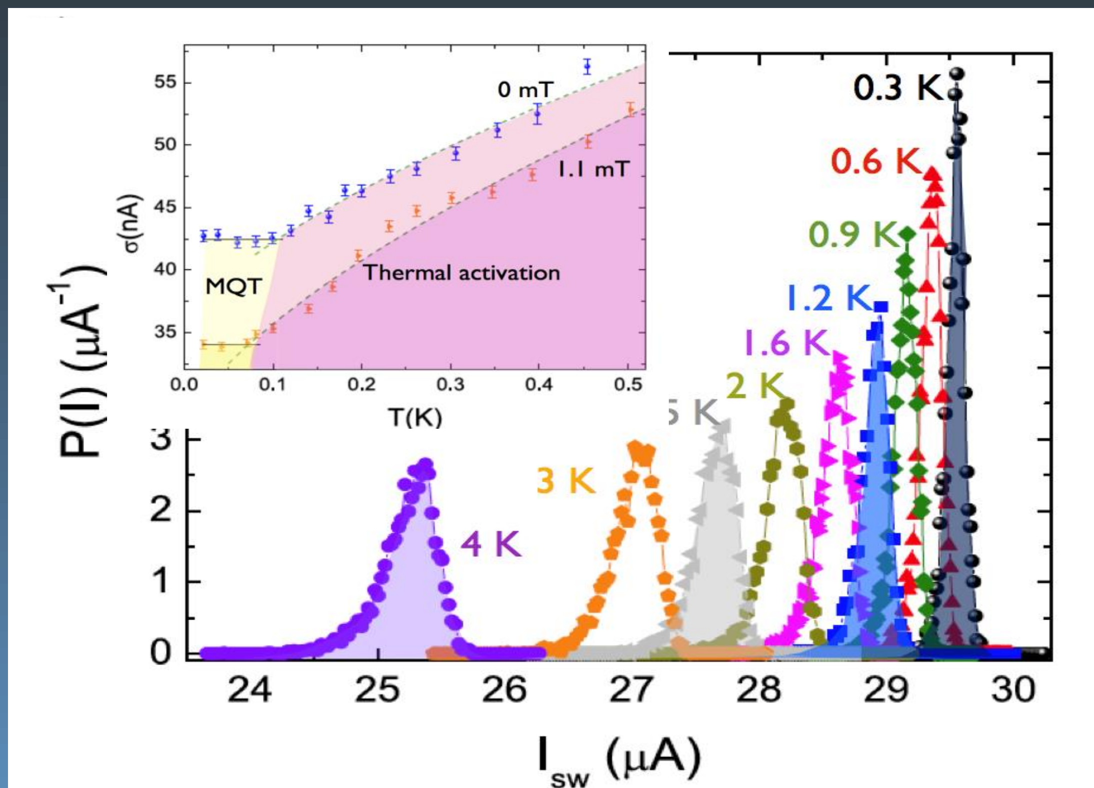
T. Bauch,[1] F. Lombardi,[1] F. Tafuri,[2] A. Barone,[3] G. Rotoli,[4] P. Delsing,[1] and T. Claeson[1]

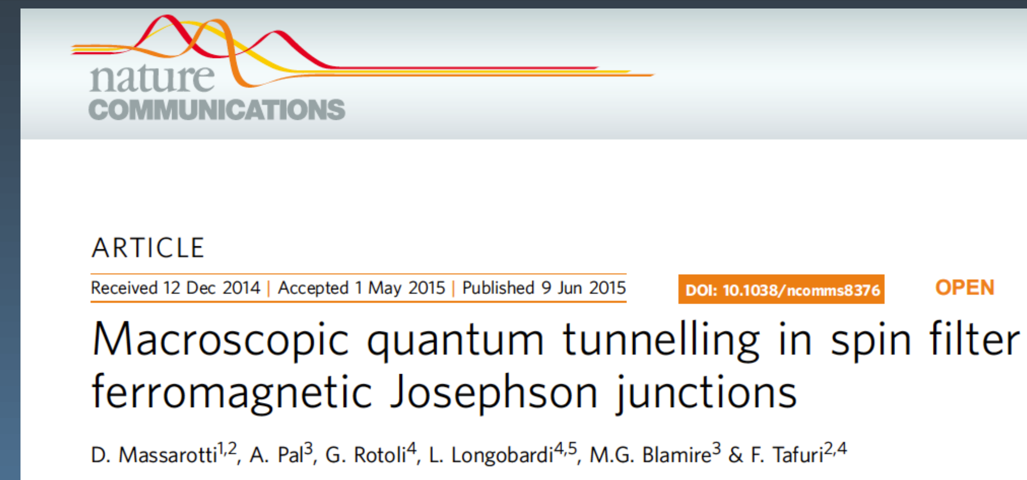






Hybrid ferromagnetic Josephson junctions

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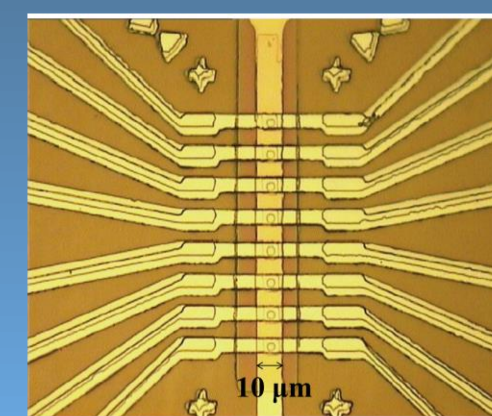
Received 12 Dec 2014 | Accepted 1 May 2015 | Published 9 Jun 2015 DOI: 10.1038/ncomms8376 OPEN

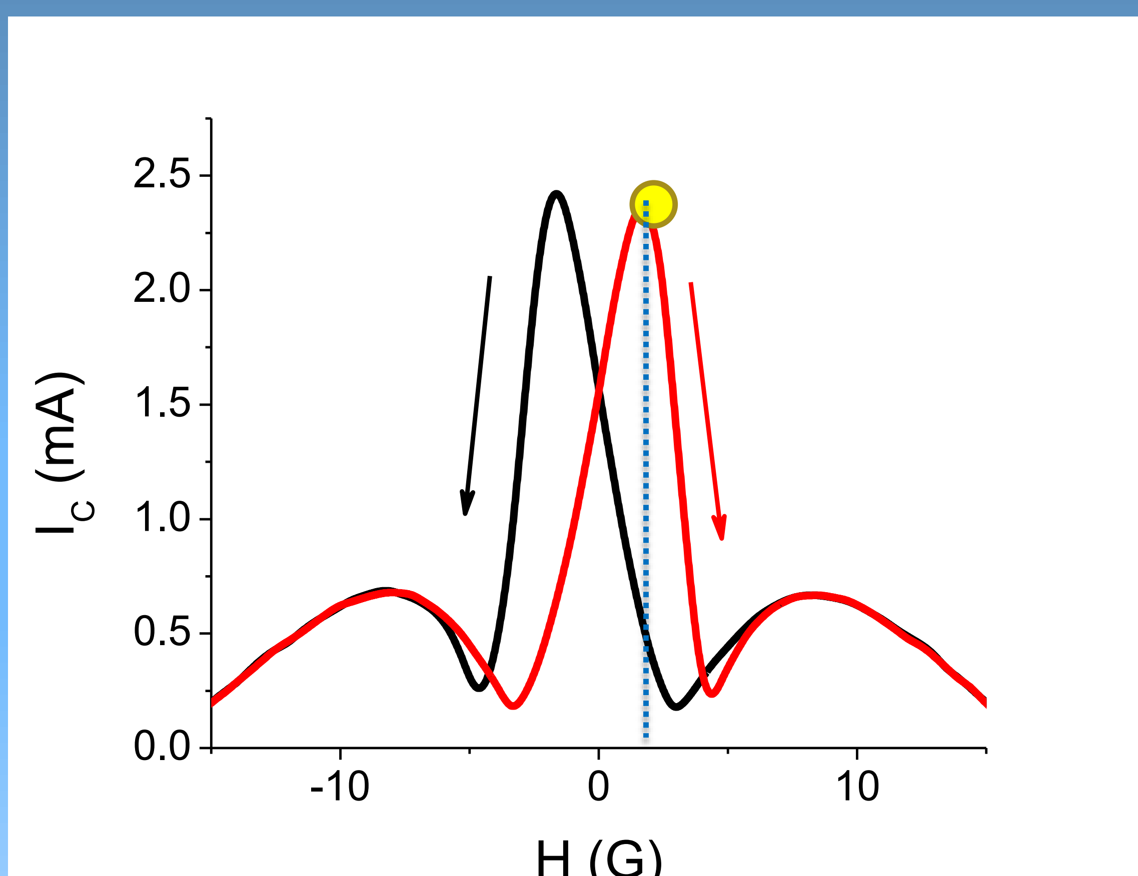
Macroscopic quantum tunnelling in spin filter ferromagnetic Josephson junctions

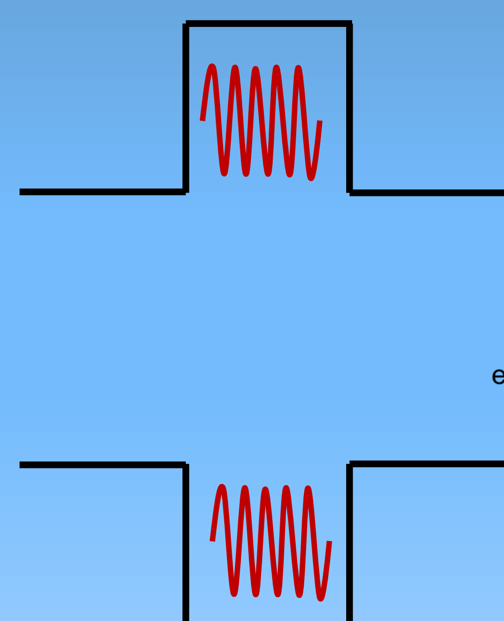
D. Massarotti[1,2], A. Pal[3], G. Rotoli[4], L. Longobardi[4,5], M.G. Blamire[3] & F. Tafuri[2,4]

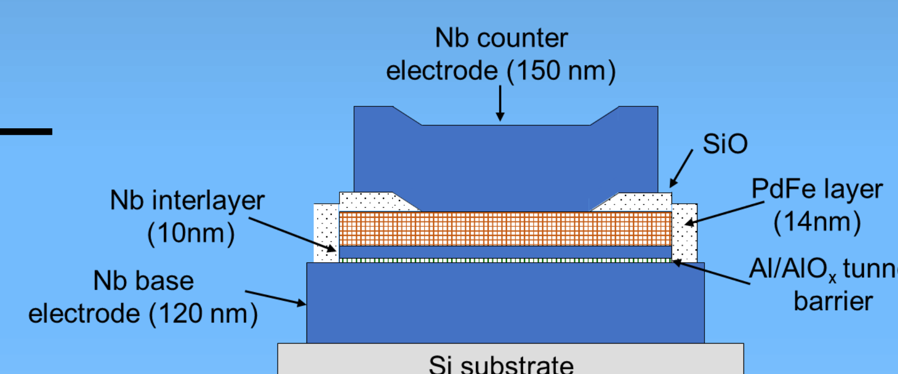
R. Caruso et al. PRL 2019

External magnetic field pulse
+
MW train



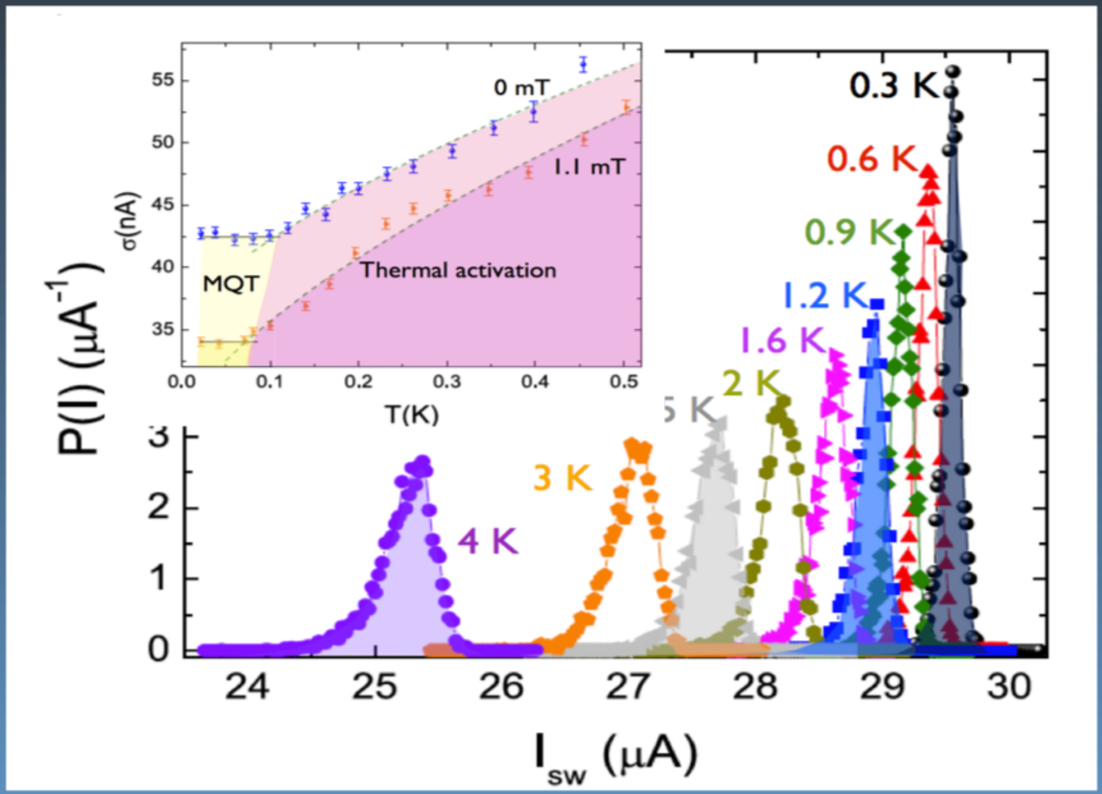


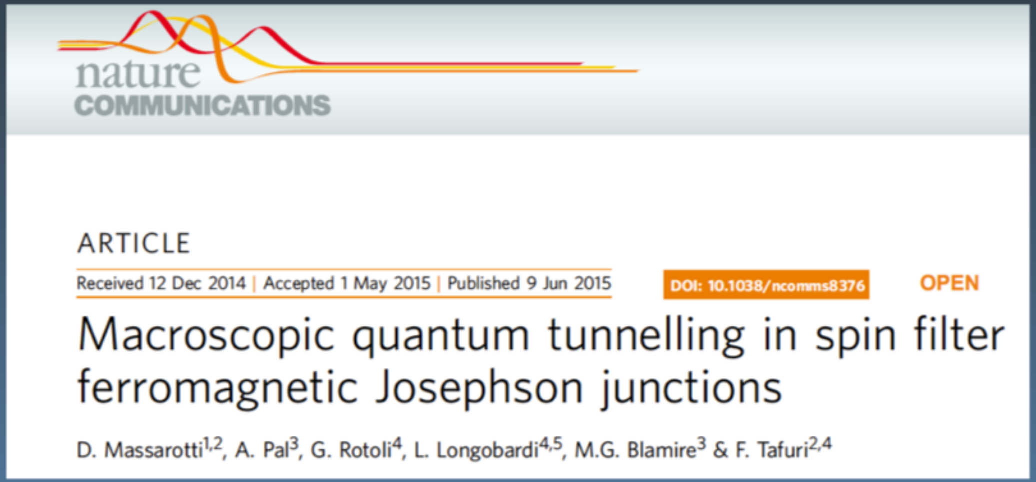




R. Caruso et al. JAP 2018
H. Ahmad et al. in preparation

Hybrid ferromagnetic Josephson junctions

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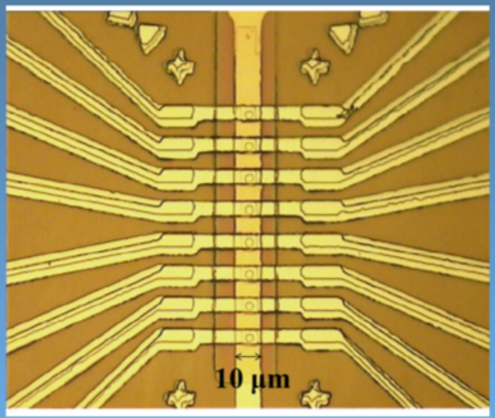

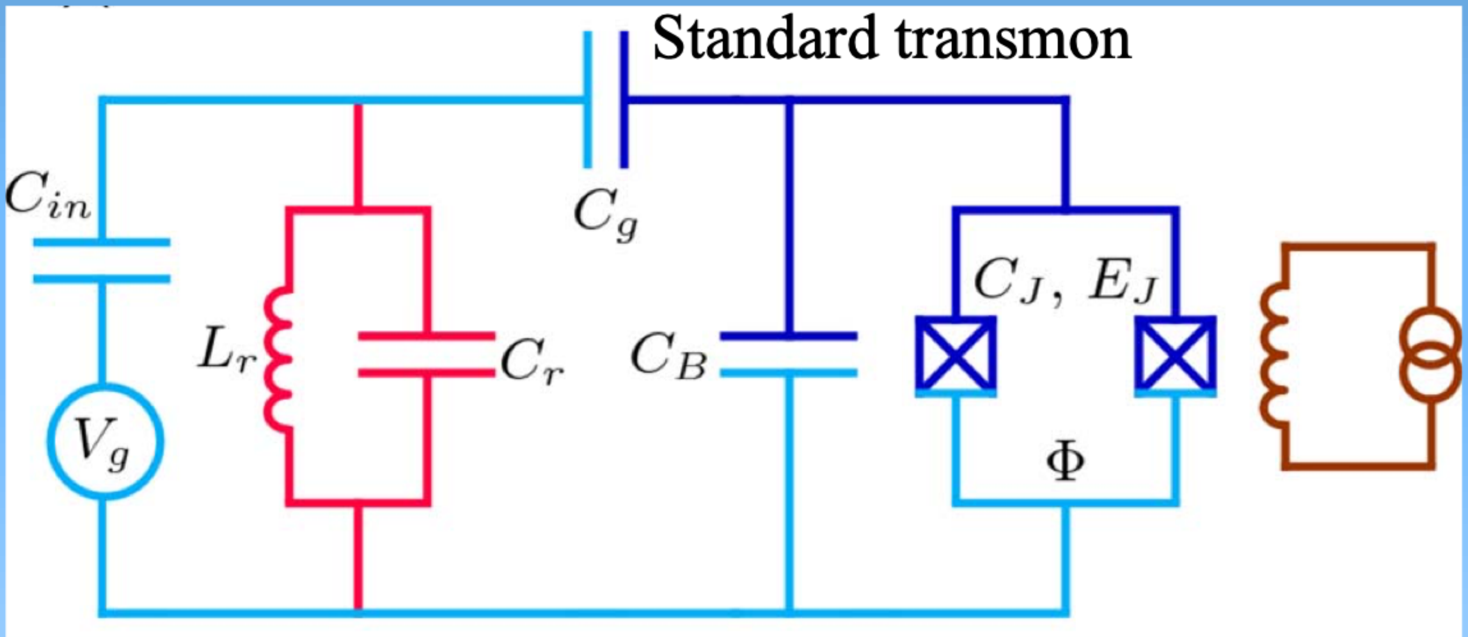

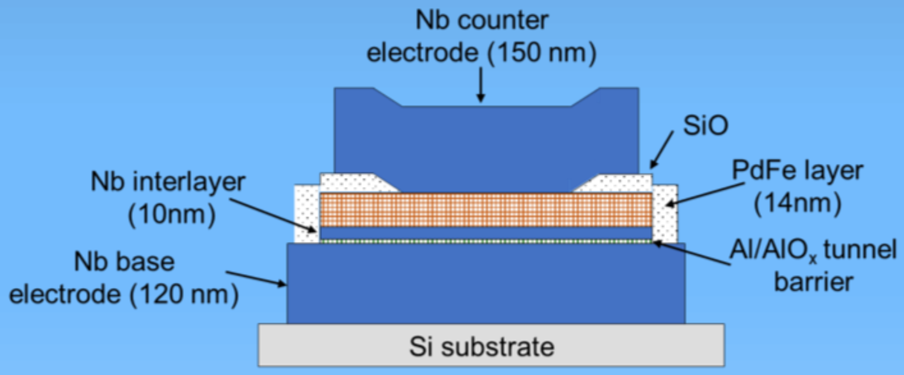

R. Caruso et al. JAP 2018

H. Ahmad et al. in preparation

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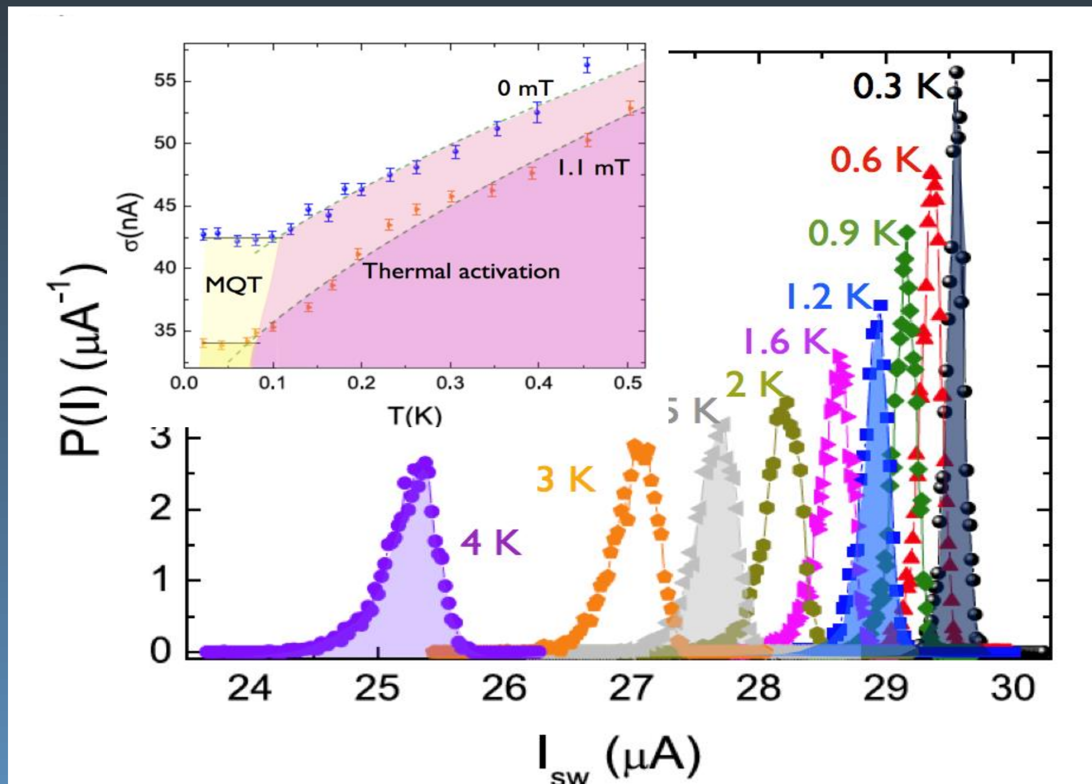

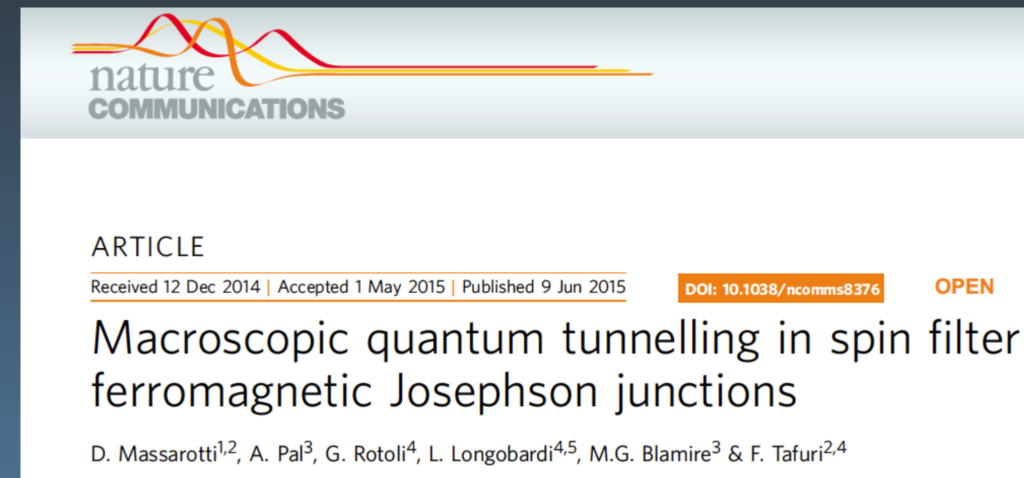

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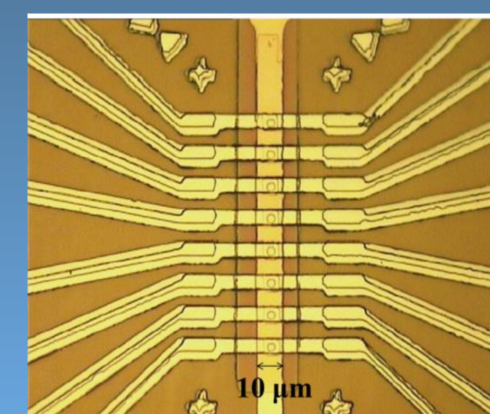
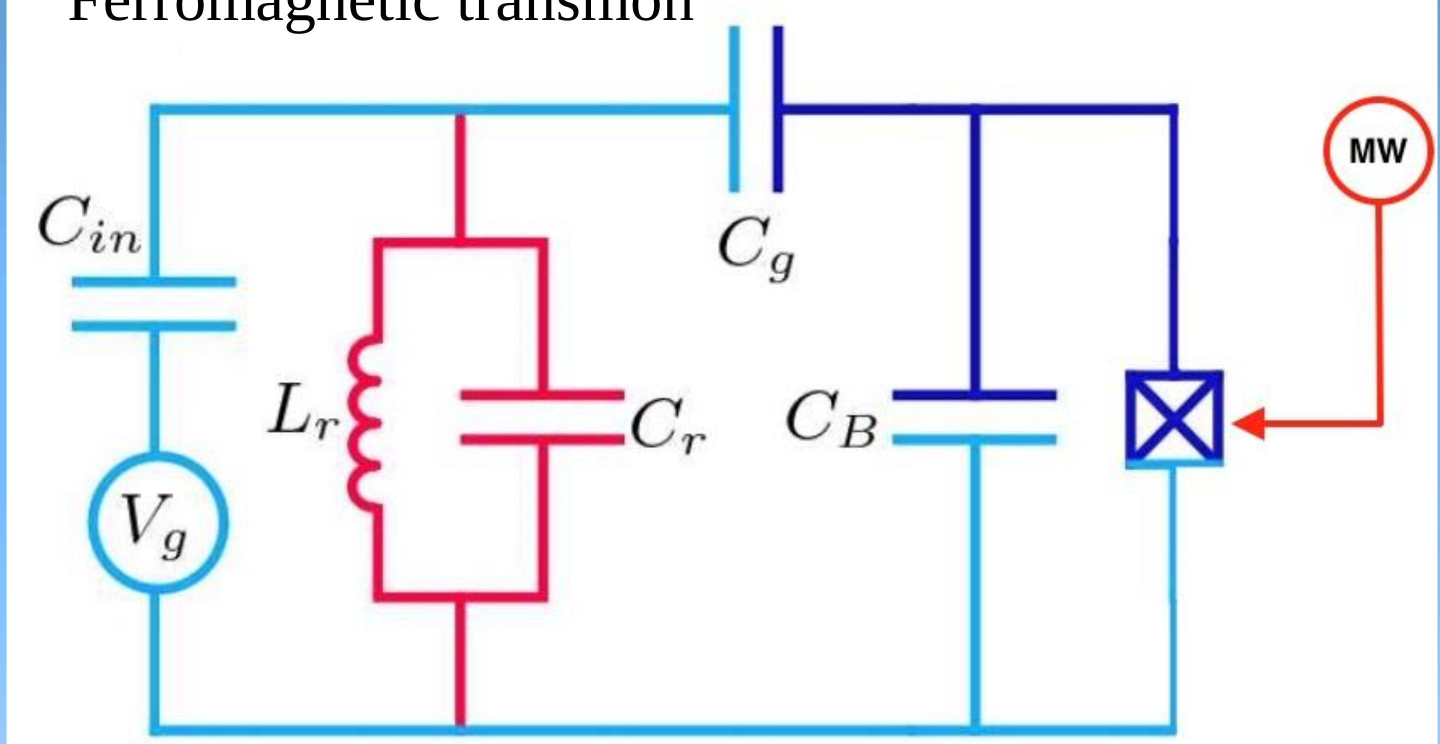
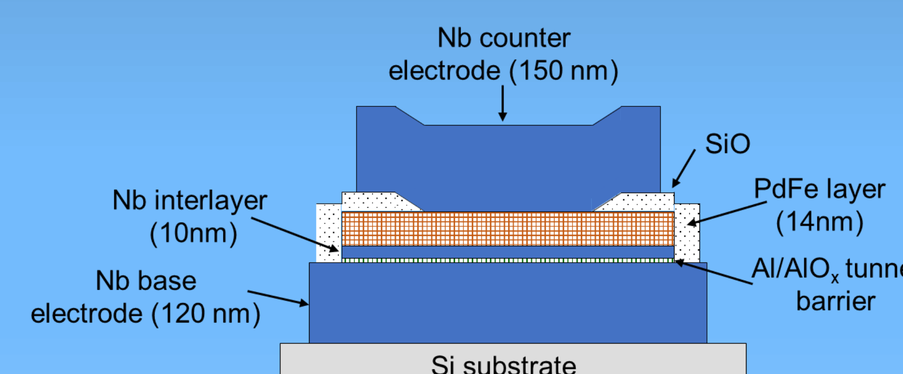


Ferromagnetic transmon



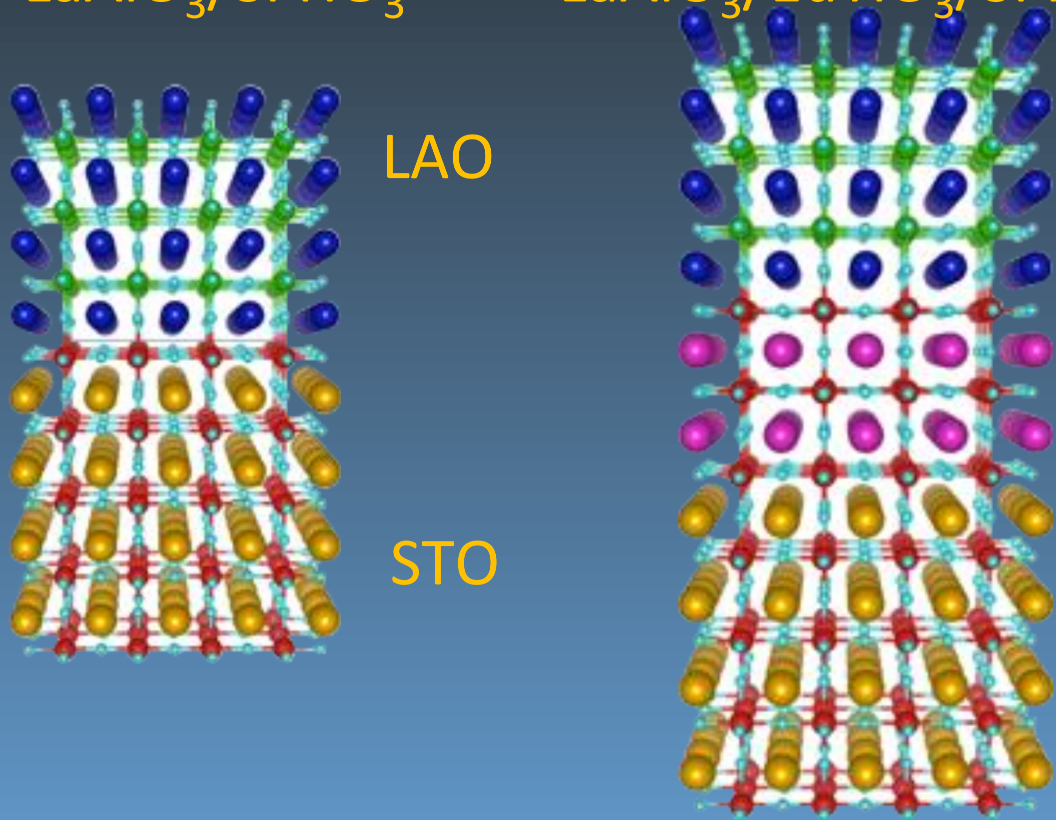


R. Caruso et al. JAP 2018

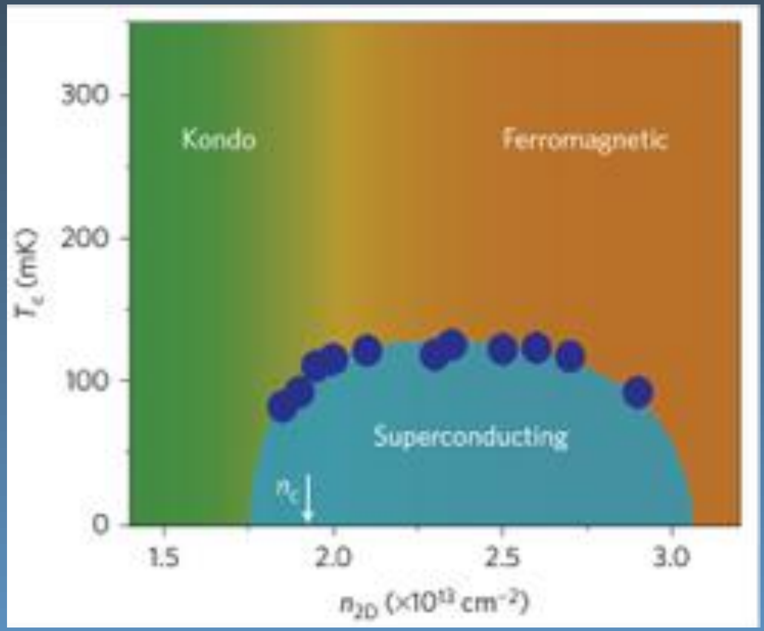
H. Ahmad et al. in preparation

Engineering oxide 2DES

$LaAlO_3/SrTiO_3$ $\quad$ $LaAlO_3/EuTiO_3/SrTiO_3$



Doping of an oxide 2DES with $EuTiO_3$

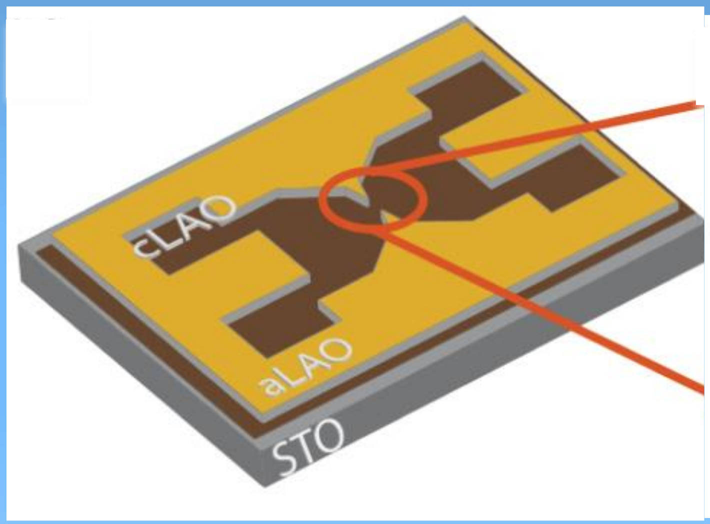


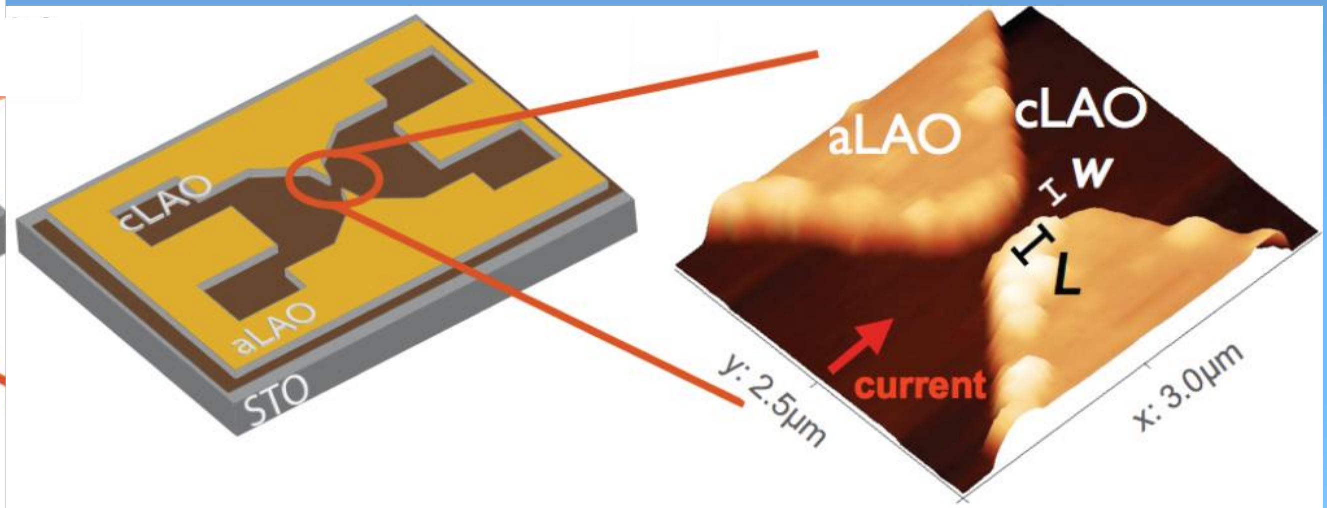
D. Stornaiuolo et al. Nature Materials 2016

Tunable Josephson effect

2DES based nano junctions

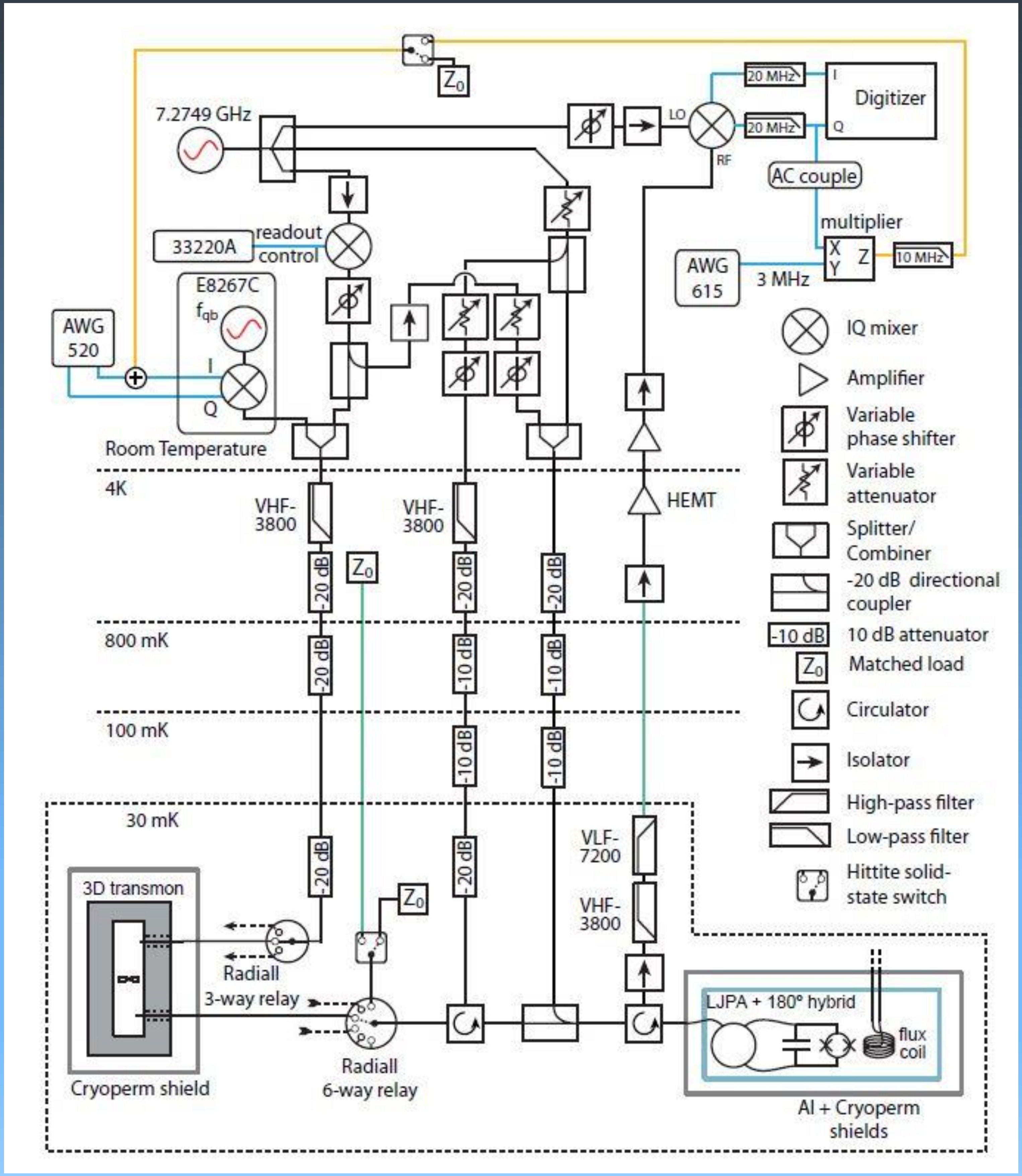
Tunable superconductivity: unconventional superconducting ground state, possible topological states





D. Stornaiuolo et al. PRB 2017

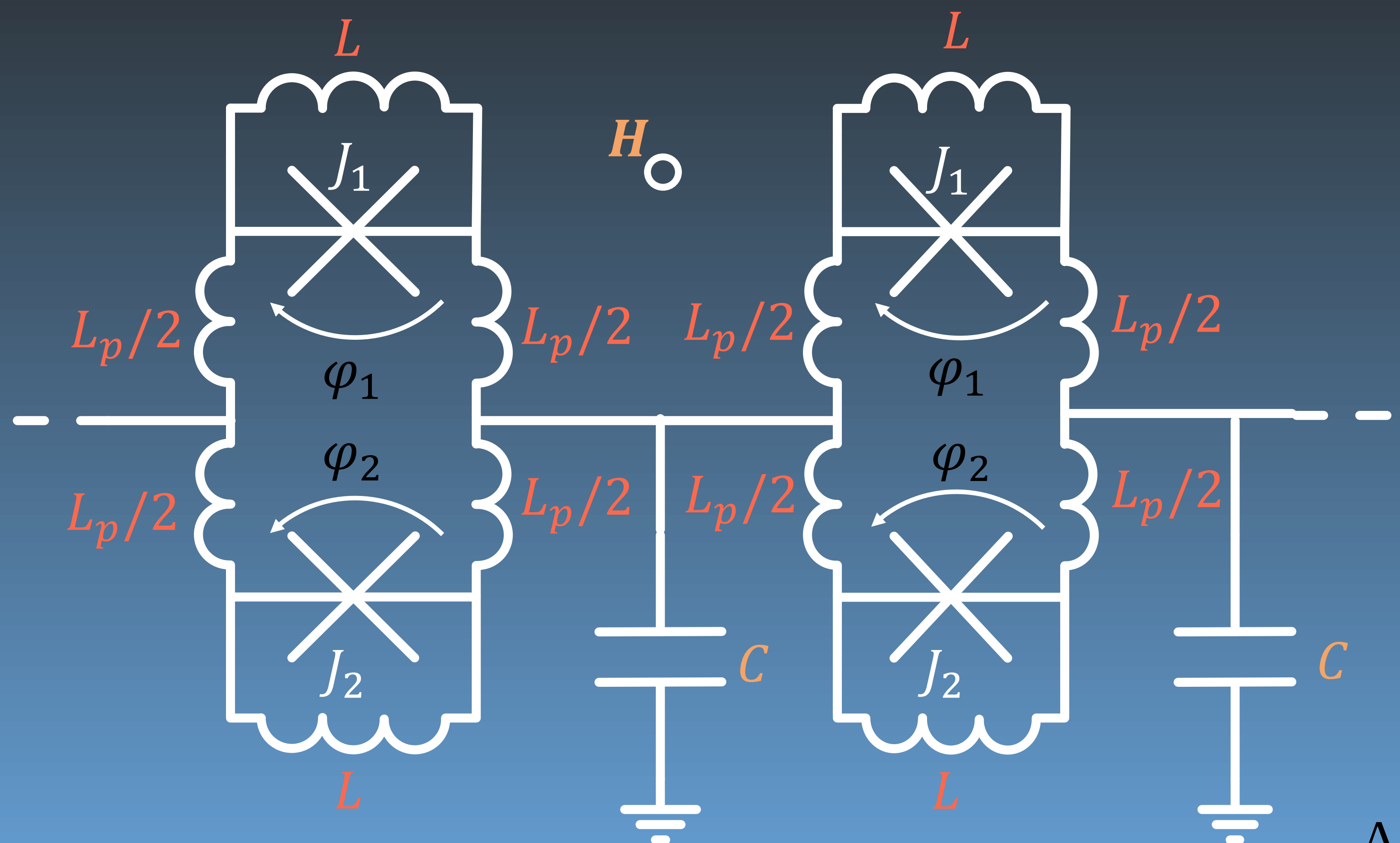
Electronic setup



SeeQC

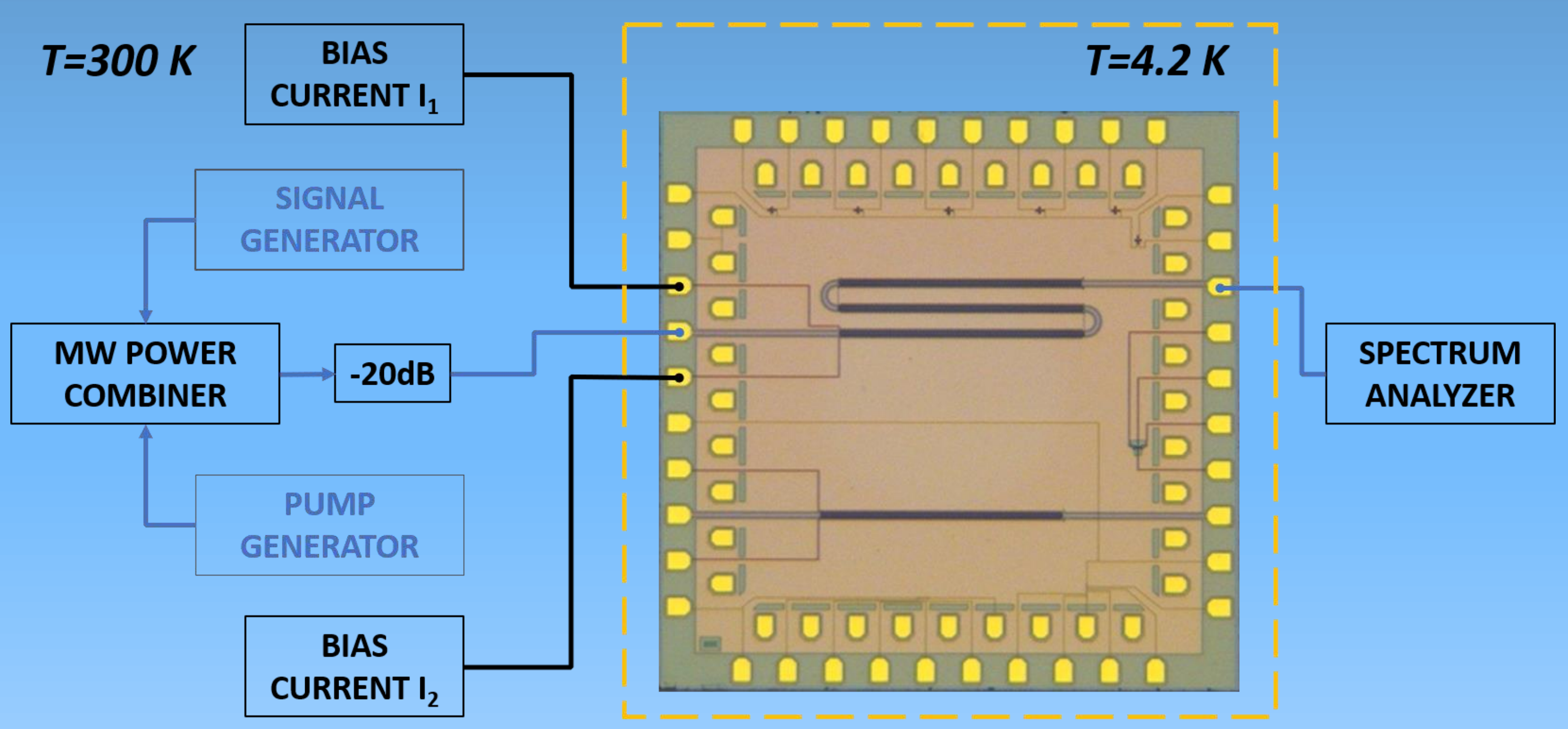
HYPRES

Electronic setup



Traveling wave
parametric amplifiers

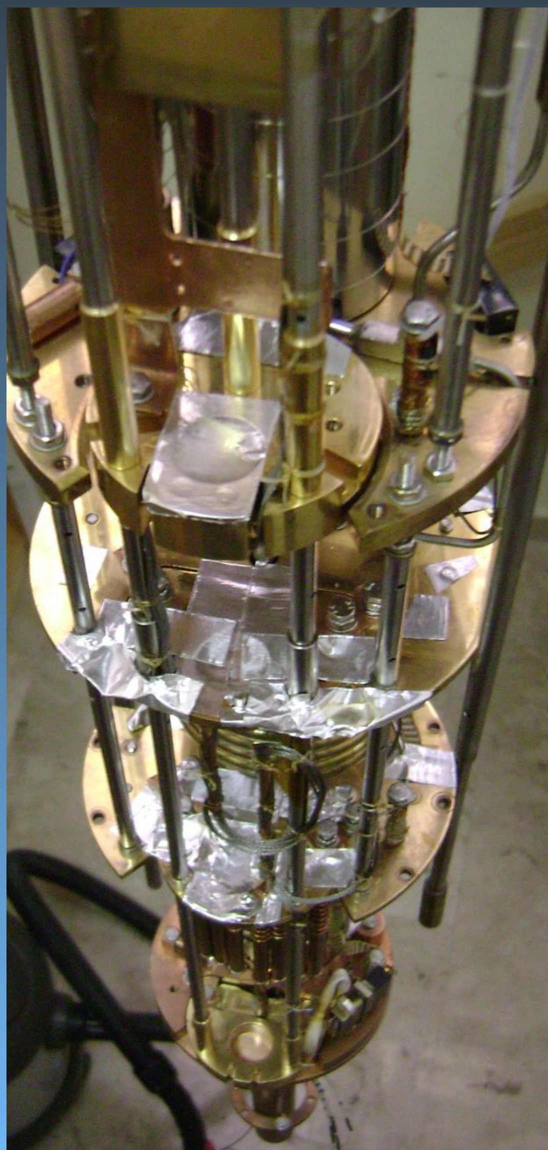
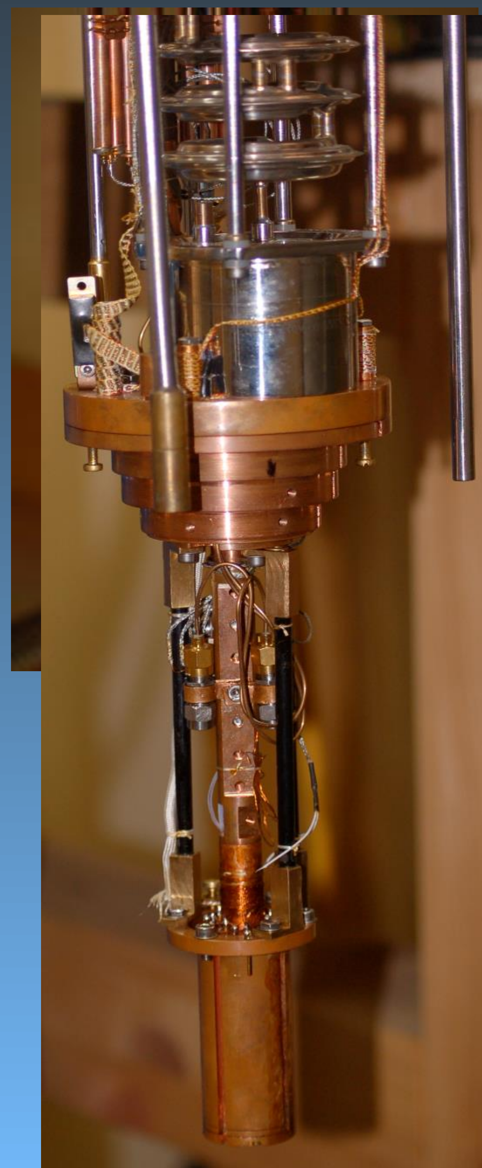
A. Miano and O. Mukhanov, IEEE 2019



SeeQC

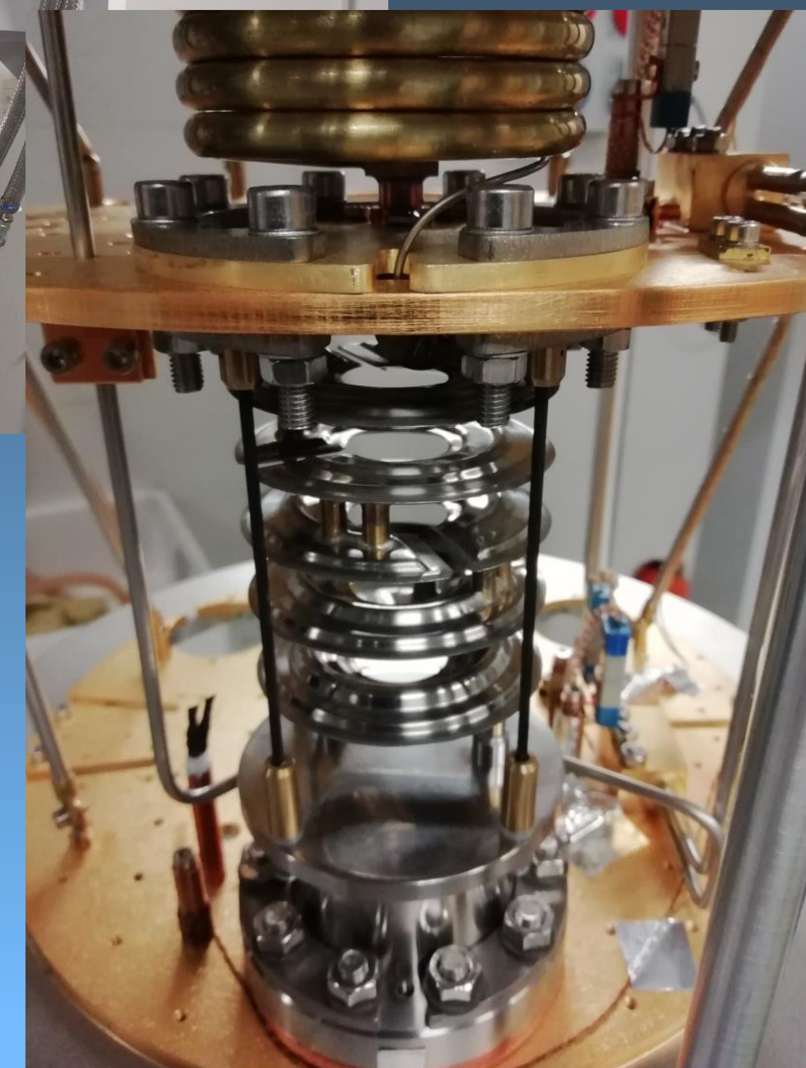
HYPRES

Low temperature setup

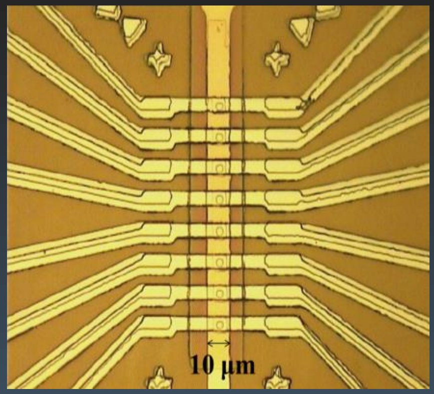



Dilution fridge
Kelvinox MX 400

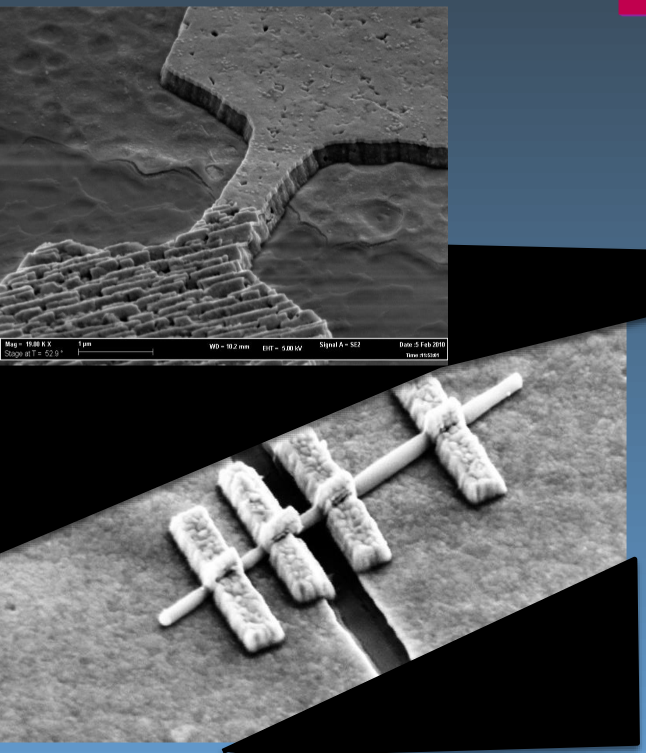


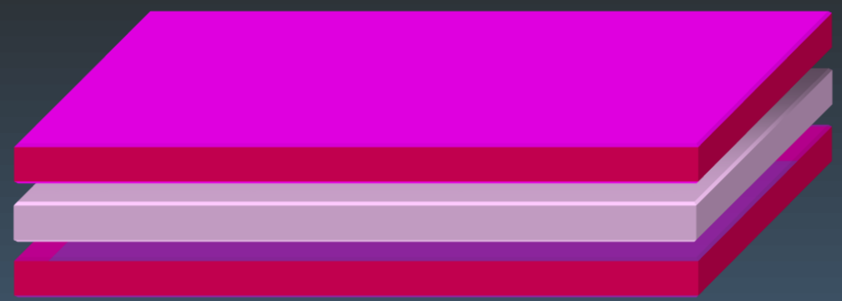


Triton 400: base temperature
10 mK and cryogen-free

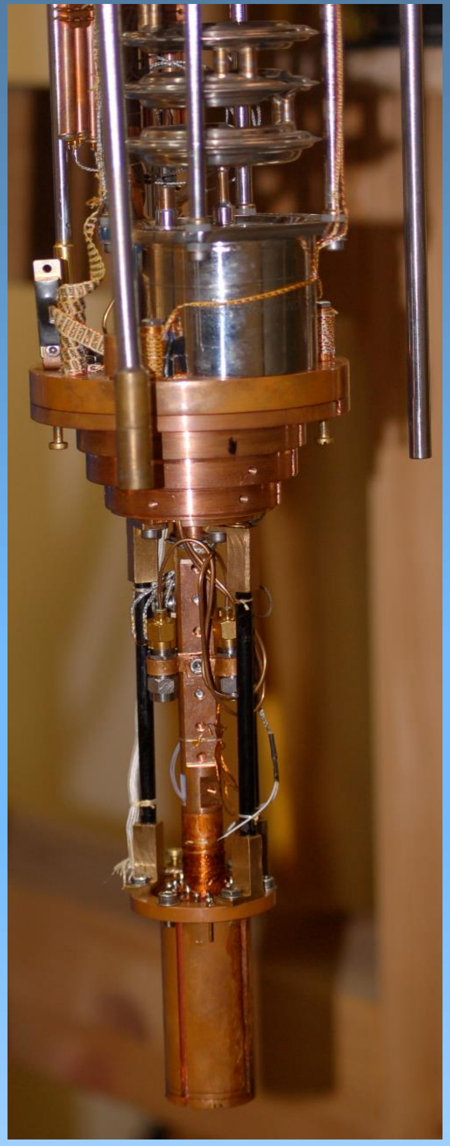


Josephson effect





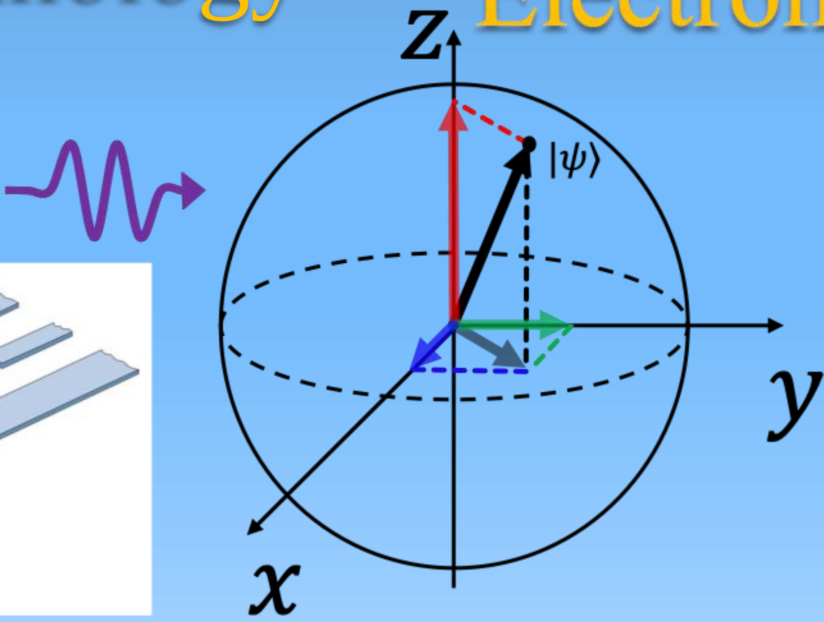
Measurement & operation

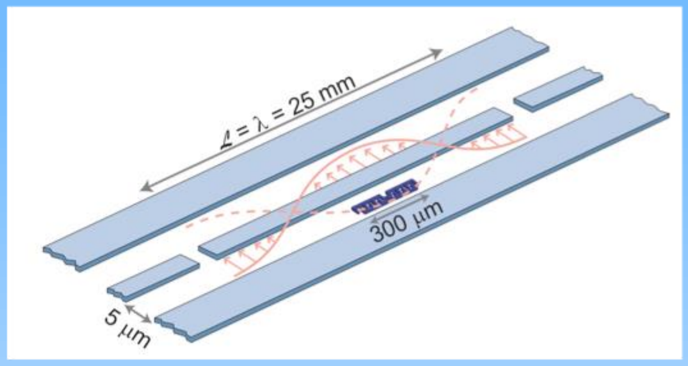


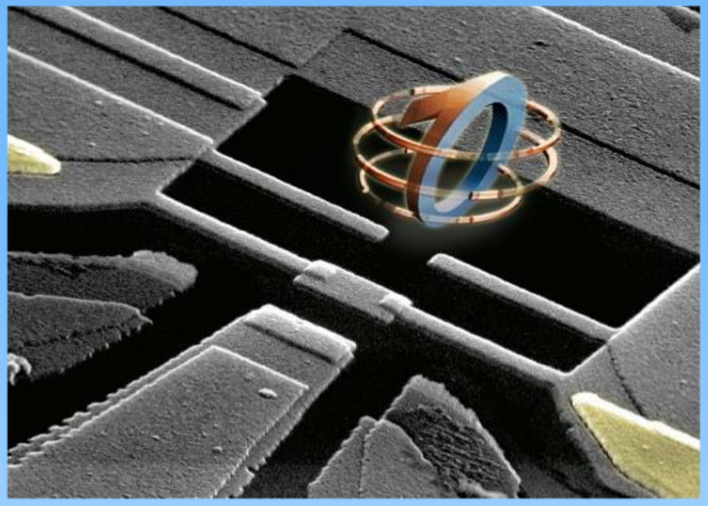
Quantum Physics
Quantum Engineering

Material science & nanotechnology

Electromagnetic control

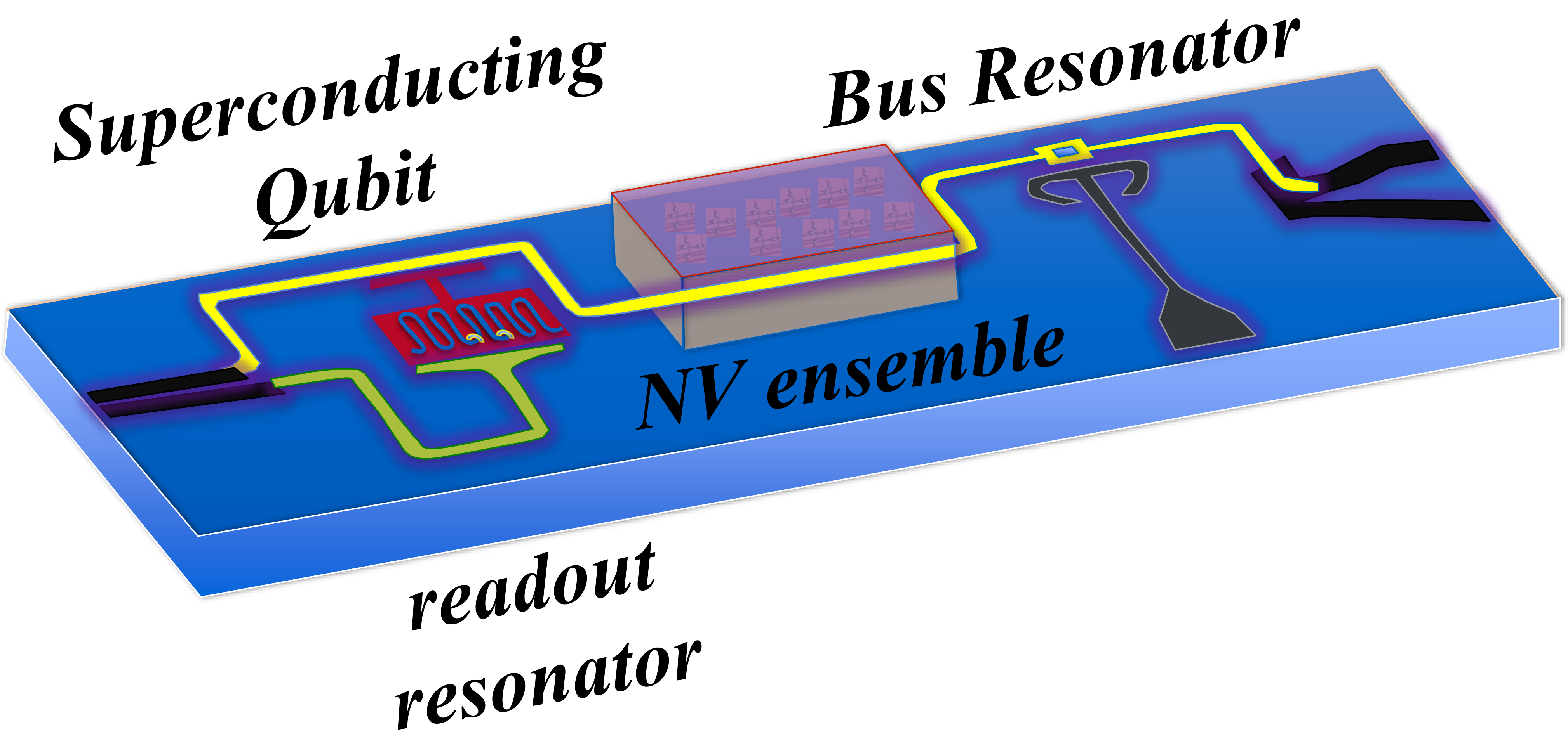






Hybrid Quantum Information Processing

Quantum Information **is well transmitted by photons, better processed by superconducting circuits and efficiently stored with cold atoms**



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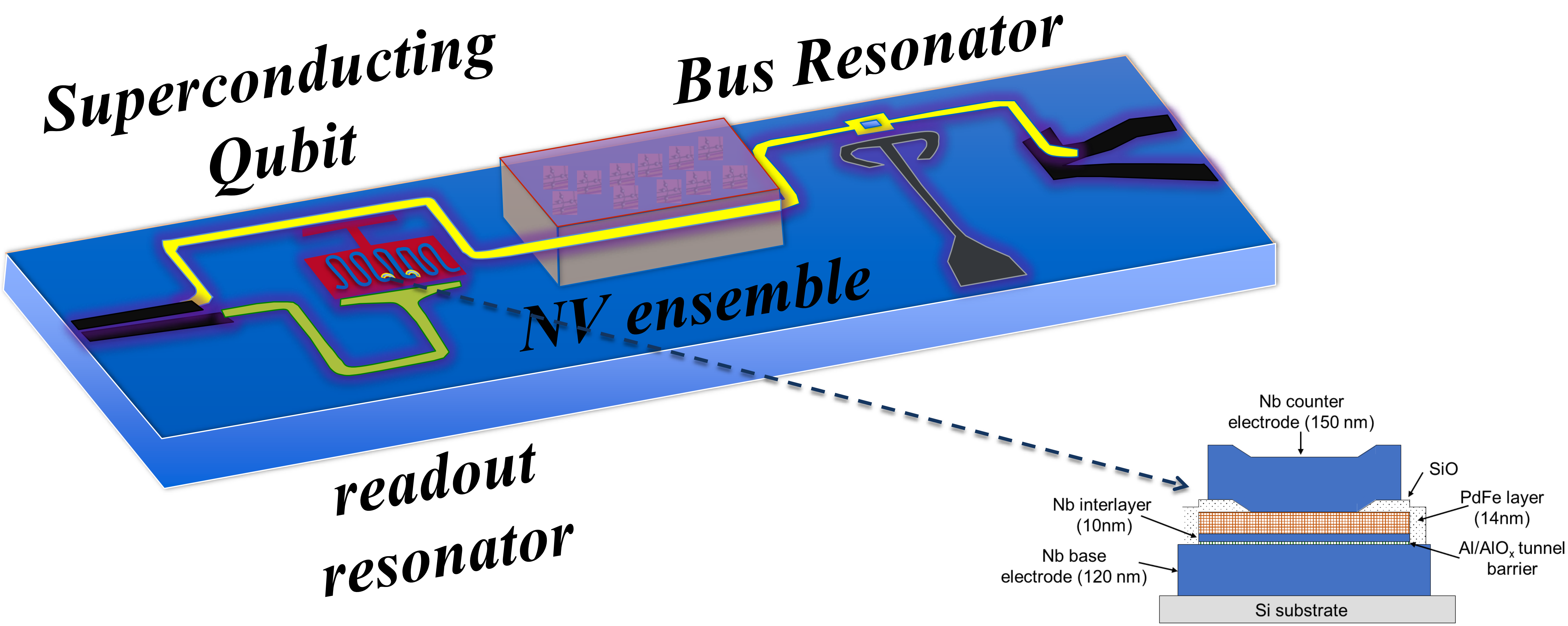
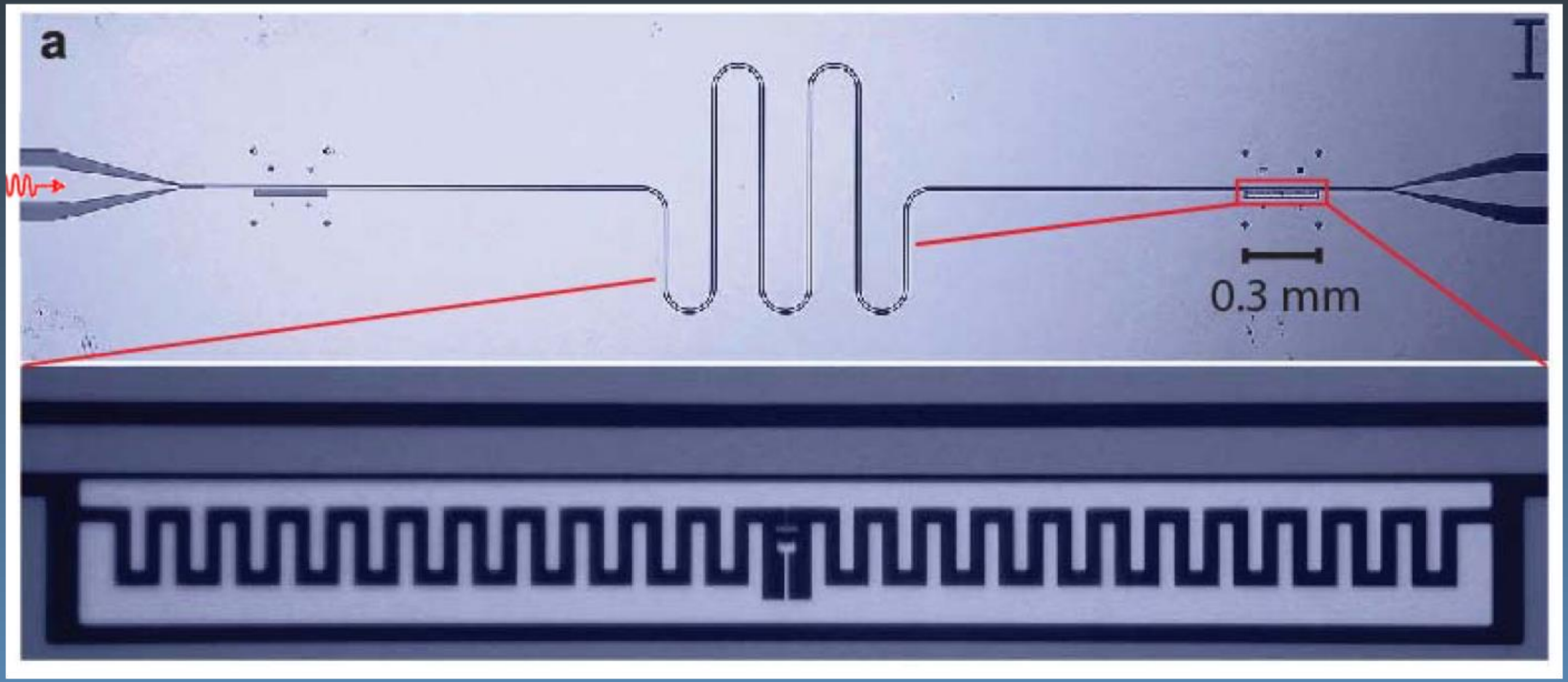
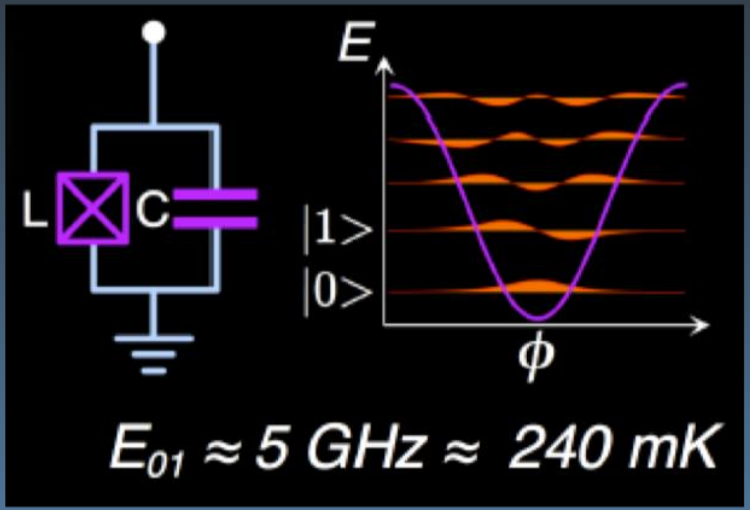


Unconventional Josephson junctions give more possibilities to quantum processors

Superconducting qubit processor



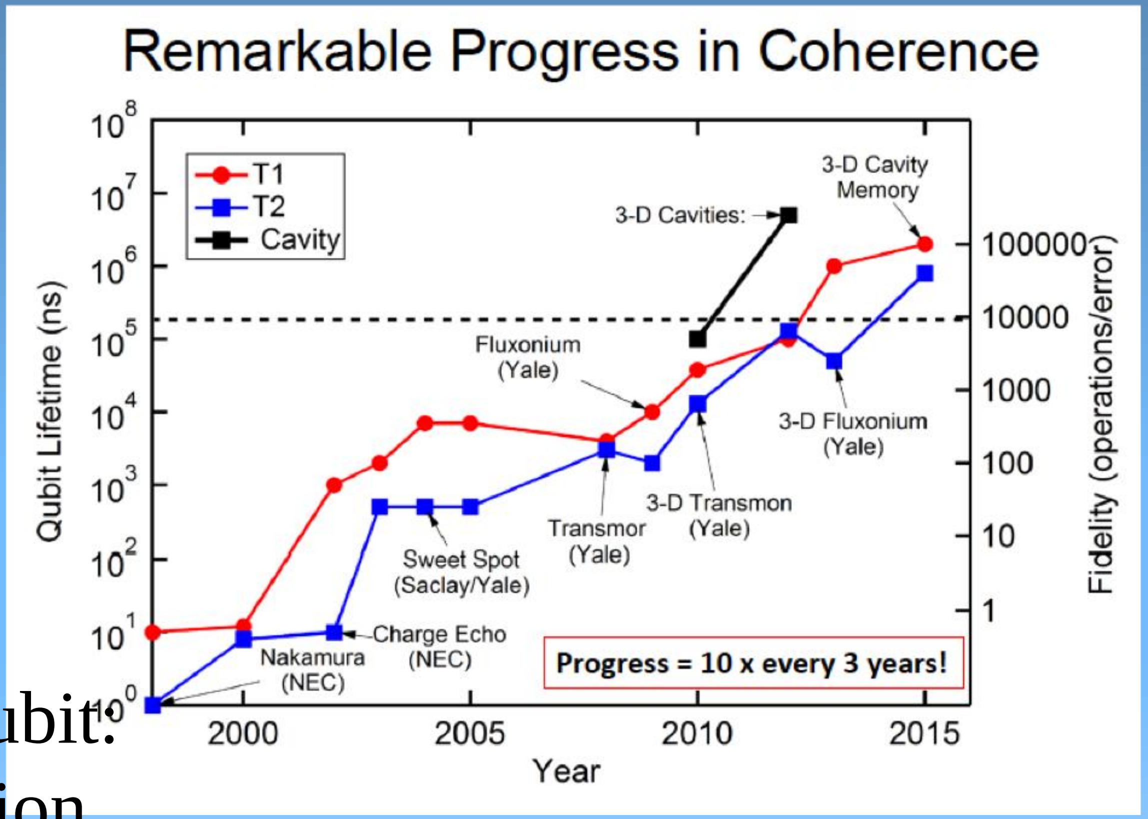


www.sciencemag.org SCIENCE VOL 339 8 MARCH 2013

REVIEW

Superconducting Circuits for Quantum Information: An Outlook

M. H. Devoret[1,2] and R. J. Schoelkopf[1]*

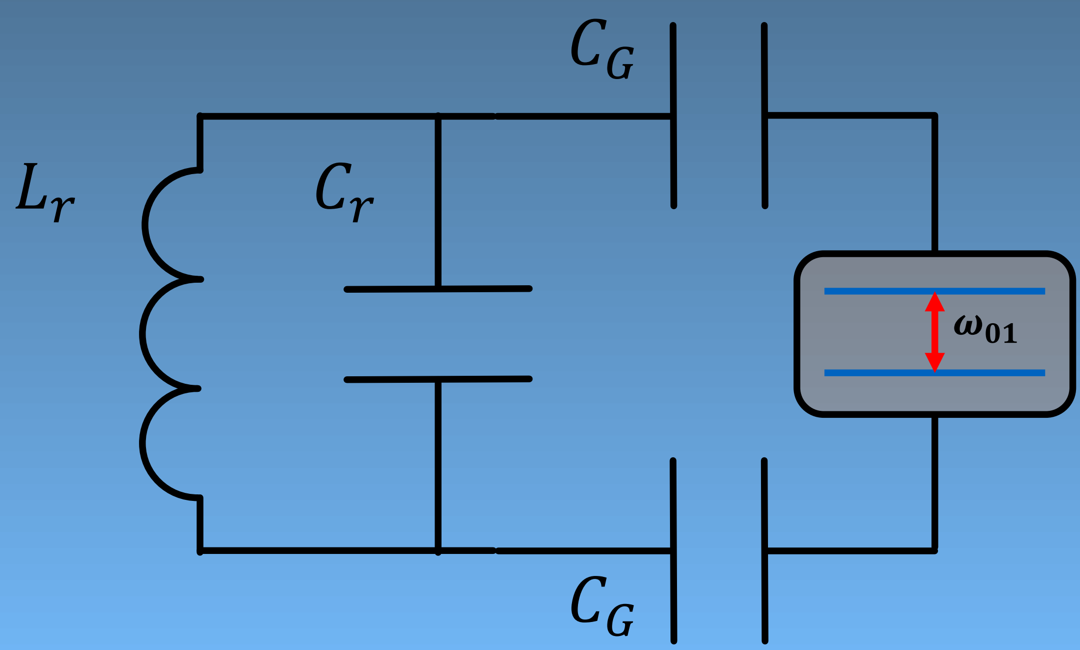


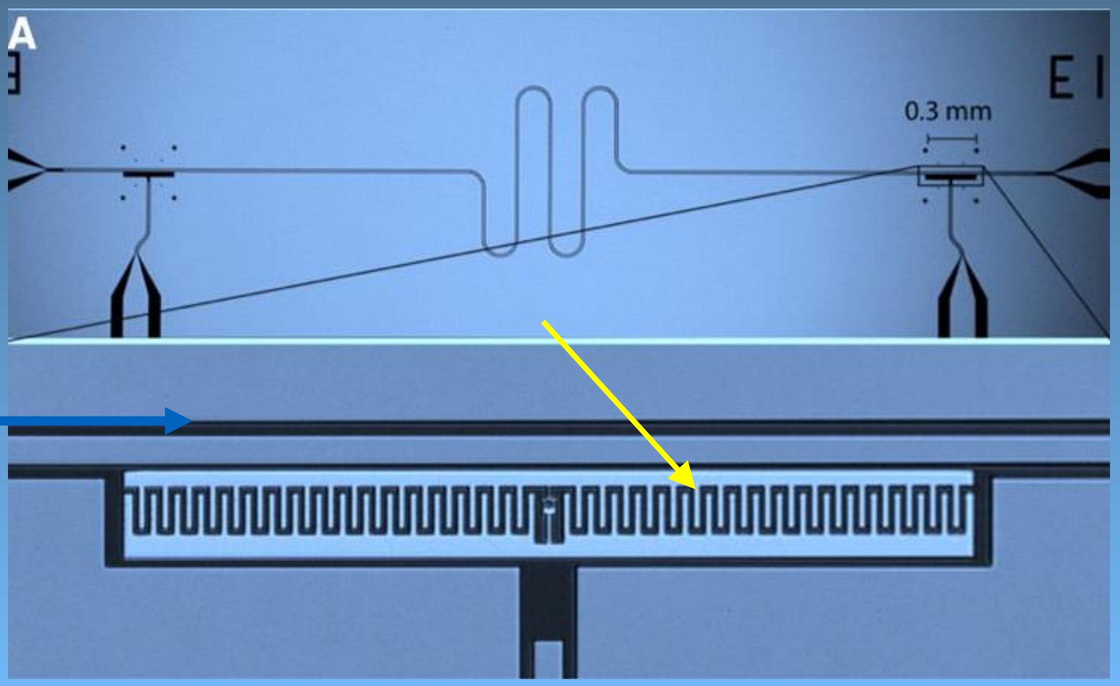
Microwave resonator:
- Read-out of qubit states
- Multi-qubit quantum bus

Superconducting qubit:
- Josephson junction
- Nearly dissipationless → T_1, T_2 ~ 100 μs

Circuit Quantum electrodynamics (CQED)

The idea is to weakly connect the two level system to a superconducting RF resonant cavity, expecting the qubit state to slightly perturb the overall resonating properties (being the qubit a resonator itself)





Voltage Antinode

If the cavity frequency $\omega_r = \sqrt{1/L_R C_R}$ is tuned far from energy transitions, an $\omega = \omega_r$ photon **will not cause transitions** between states!

Koch et. al "Charge-insensitive qubit design derived from the Cooper pair box"