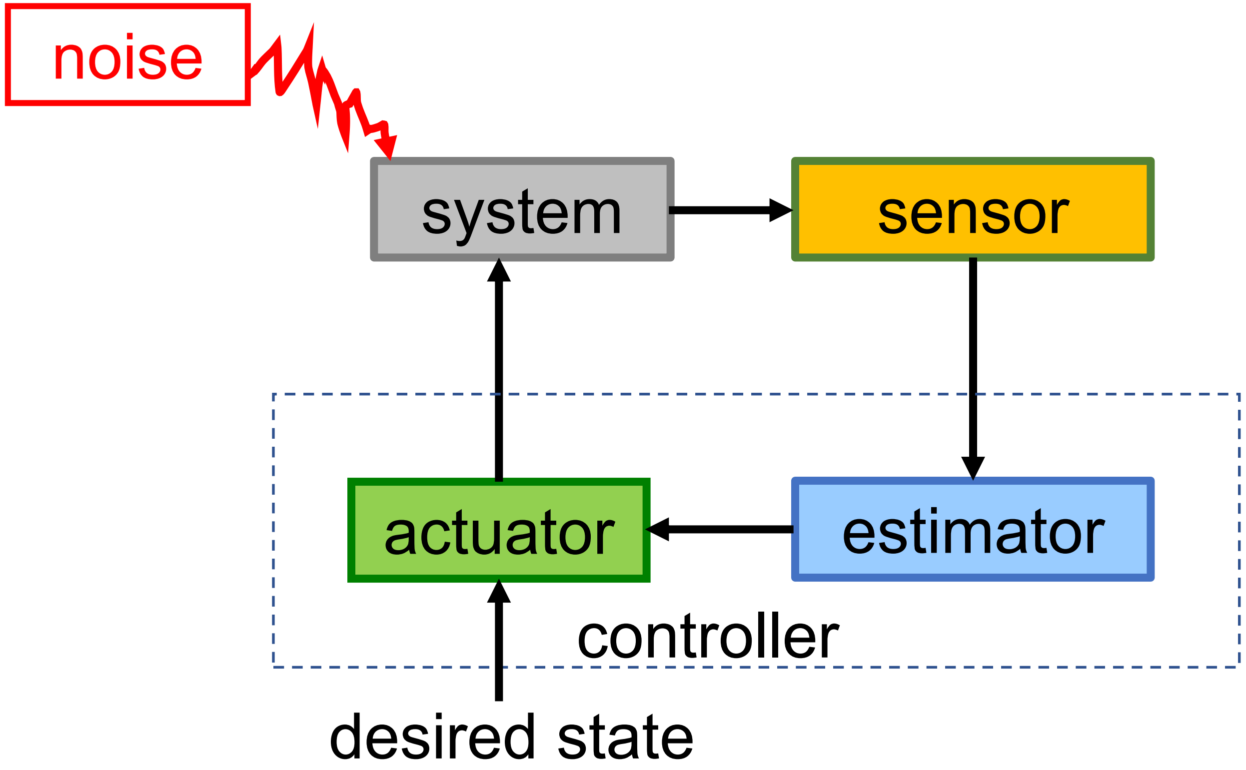
Dynamics and control of classical and quantum systems
Workshop at Ecole des Mines, Paris June 2-5

INTRODUCTION TO THE CONTROL OF QUANTUM SUPERCONDUCTING CIRCUITS

Michel Devoret
Yale (emeritus), UC Santa Barbara, Google Quantum AI

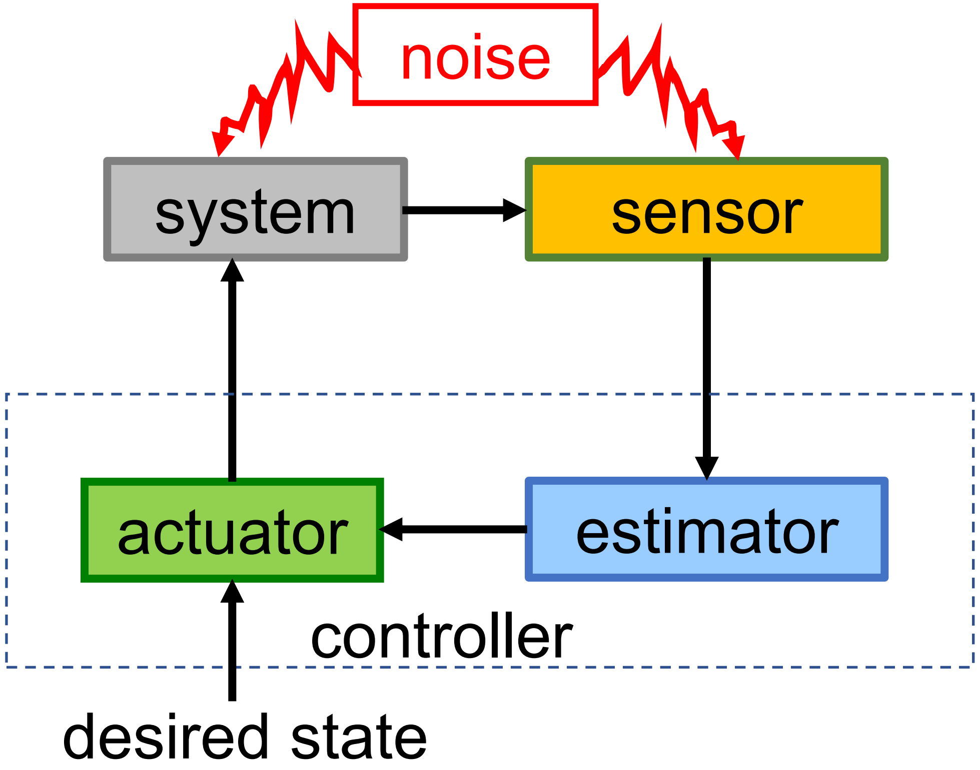
WHAT WE LEARNED FROM PIERRE, MAZYAR AND ZAKI

CLASSICAL REALM



WHAT WE LEARNED FROM PIERRE, MAZYAR AND ZAKI

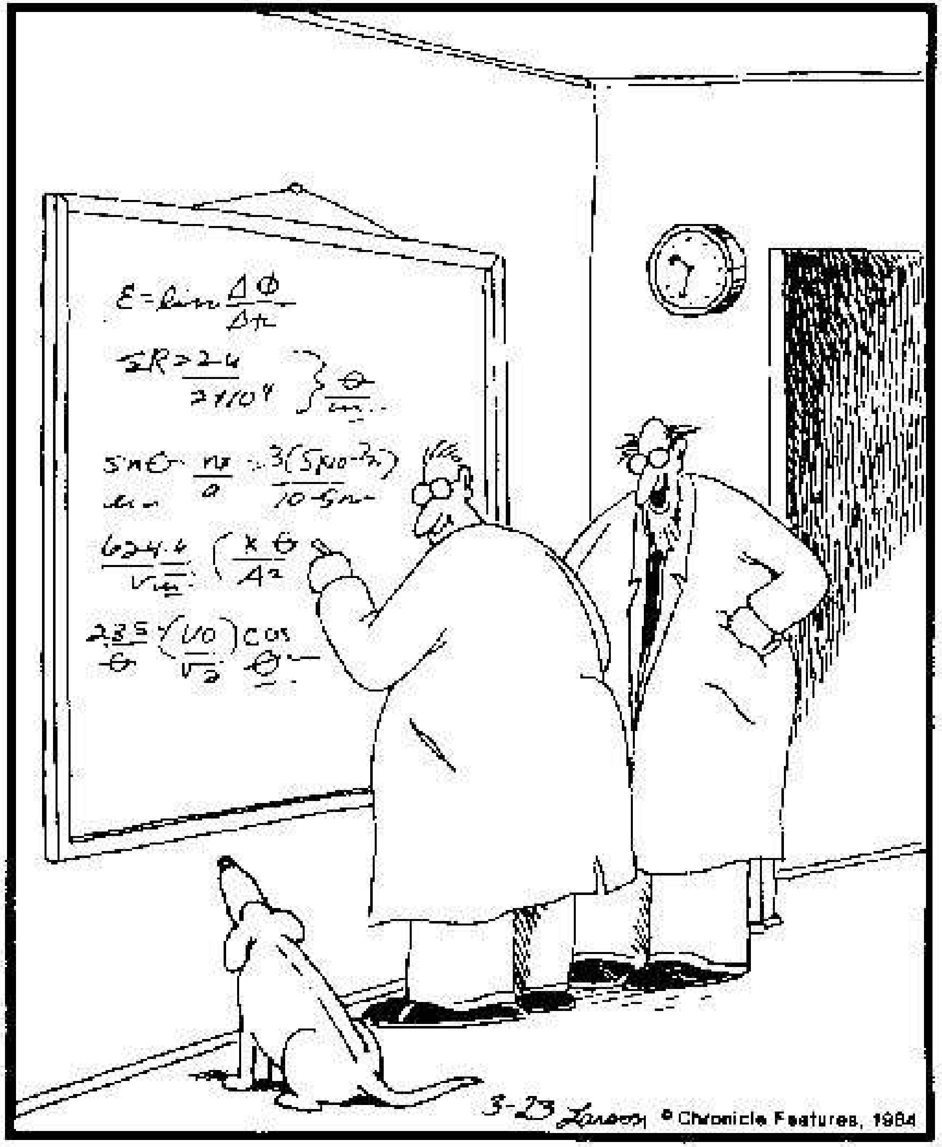
QUANTUM
REALM



SEE TALKS BY PHILIPPE, MAZYAR, ZAKI, PATRICE

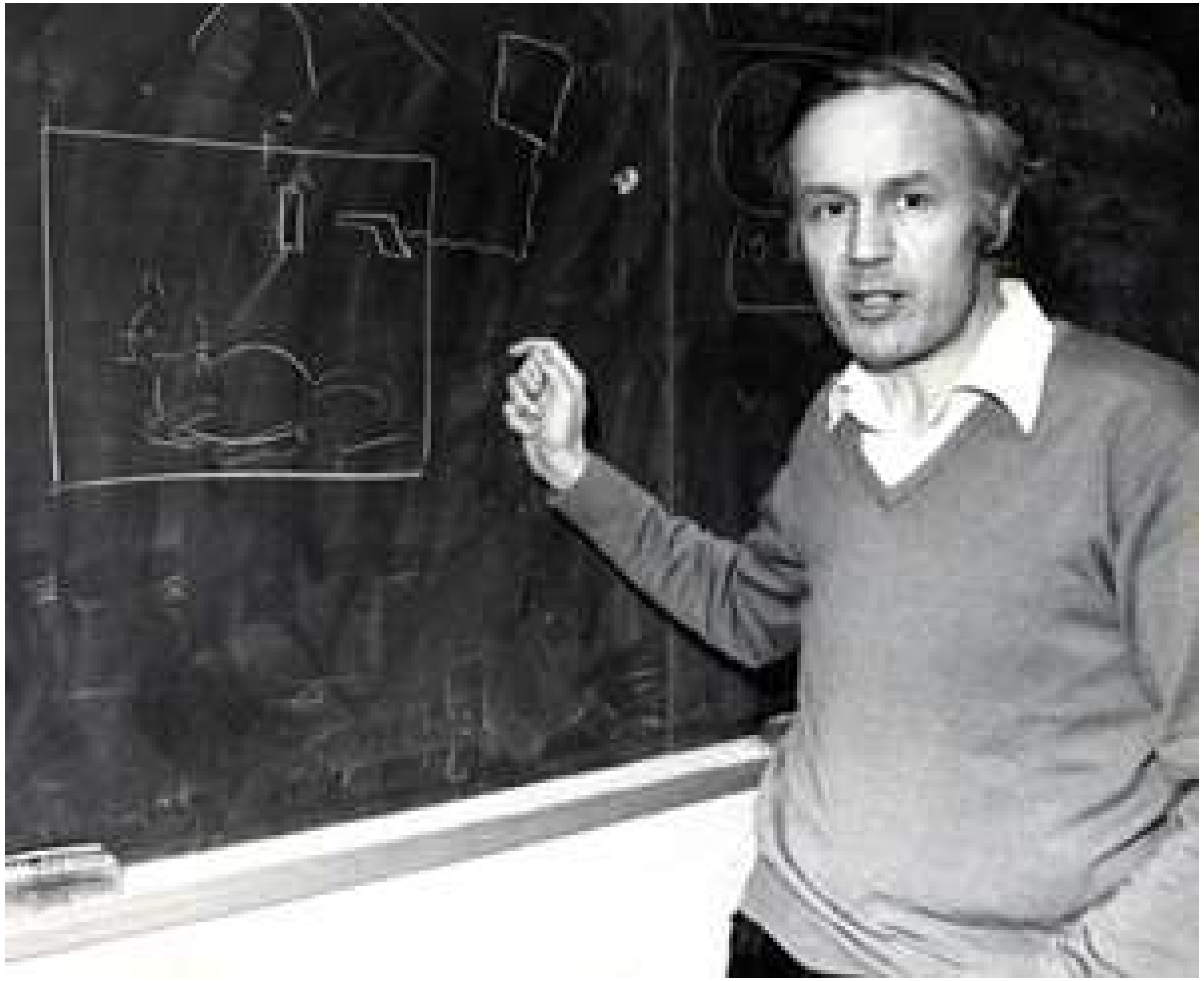
"ACTUALLY I STARTED OUT IN QUANTUM MECHANICS, BUT SOMEWHERE ALONG THE WAY I TOOK A WRONG TURN."

THE FAR SIDE By GARY LARSON



"Ohhhhhhh . . . Look at that, Schuster . . . Dogs are so cute when they try to comprehend quantum mechanics."

HOW OUR WORK BEGAN: A PROPOSAL FOR AN EXPERIMENT TESTING THE FOUNDATIONS OF QUANTUM MECHANICS



The late Sir Anthony Leggett, with permission of the University of Illinois (Laureate of the 2003 Physics Nobel Prize for theory of He3 superfluidity).

DO MACRO-VARIABLES OBEY QUANTUM MECHANICS?

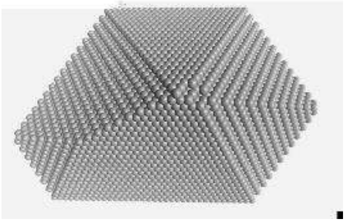
MACROSCOPIC MANIFESTATIONS OF QUANTUM MECHANICS CAN OCCUR AT TWO LEVELS

Level 1

microscopic dynamical variables

"Pyrite 60608" by Vassil

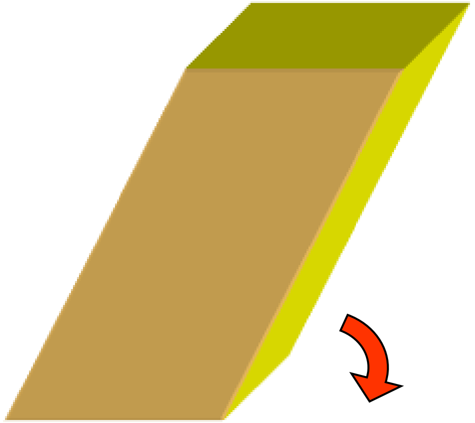
quantum atom bonds emerge in crystal facets



Arizona State University

Level 2

MACROscopic dynamical variables



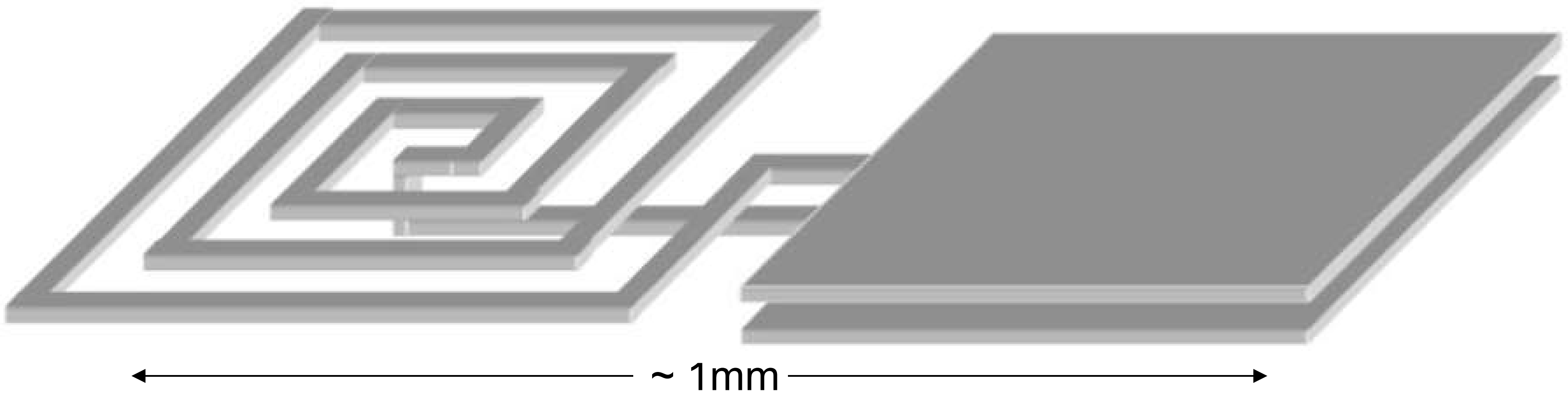
hypothetical spontaneous fall of crystal due to quantum zero-point motion of center-of-mass

A MACROSCOPIC DEGREE OF FREEDOM THAT IS QUANTUM?

Leggett, 1980;
Caldeira and Leggett, 1982

T = 20mK

SIMPLEST EXAMPLE: **LC** OSCILLATOR CIRCUIT



MICROFABRICATION ⇒ $L \sim 3\text{nH}$, $C \sim 1\text{pF}$, $\omega_r/2\pi \sim 6\text{GHz}$

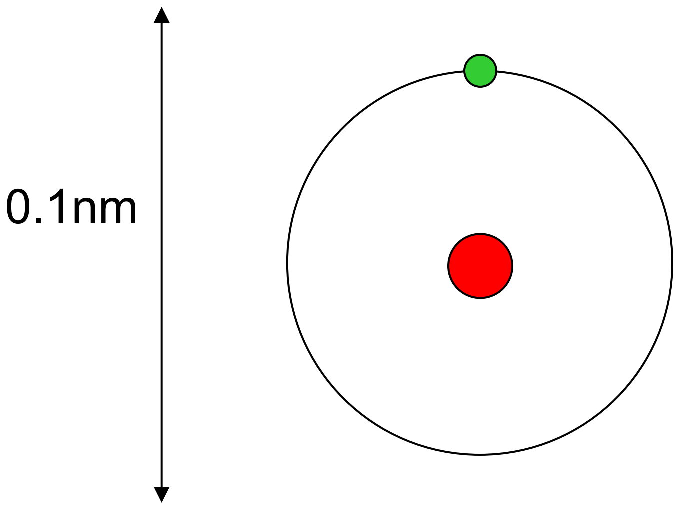
CELL PHONE FREQUENCY, OPTIMAL ELECTRONICS CONTROL

CHARGE MOVES BACK AND FORTH BETWEEN THE TWO PLATES

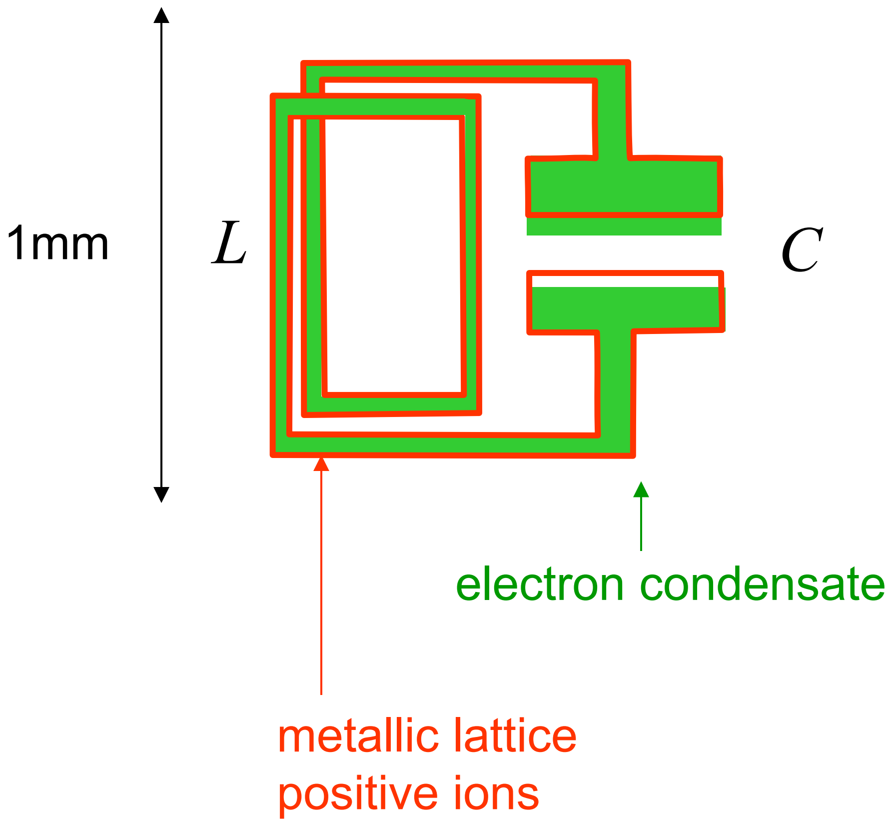
ALL THE ELECTRONS BEHAVE AS A SINGLE CHARGE CARRIER!

MICROSCOPIC ATOM vs MACROSCOPIC CIRCUIT

Hydrogen atom

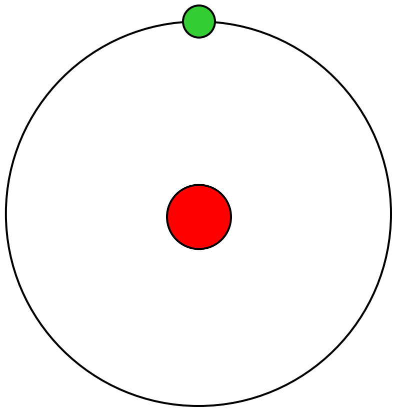


Superconducting
LC oscillator

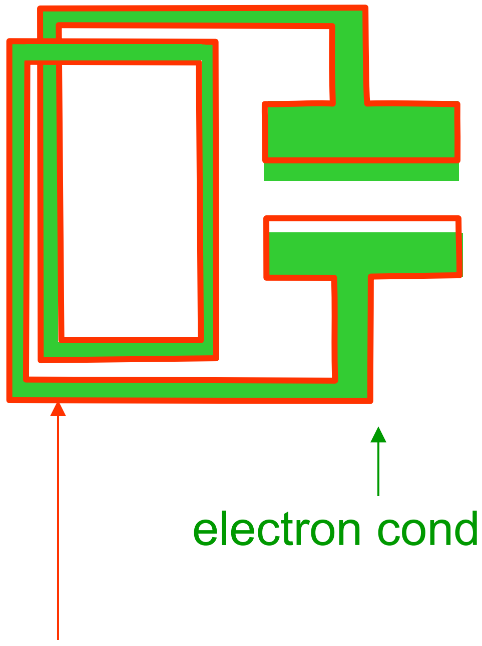


MICROSCOPIC ATOM vs MACROSCOPIC CIRCUIT

Hydrogen atom

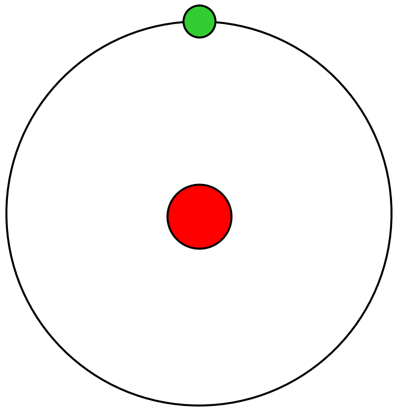


Superconducting
LC oscillator

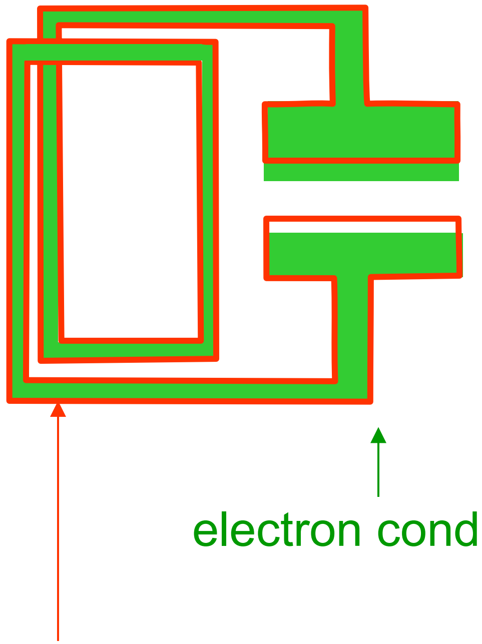


MICROSCOPIC ATOM vs MACROSCOPIC CIRCUIT

Hydrogen atom

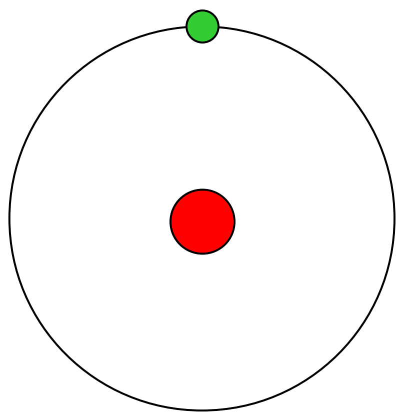


Superconducting
LC oscillator

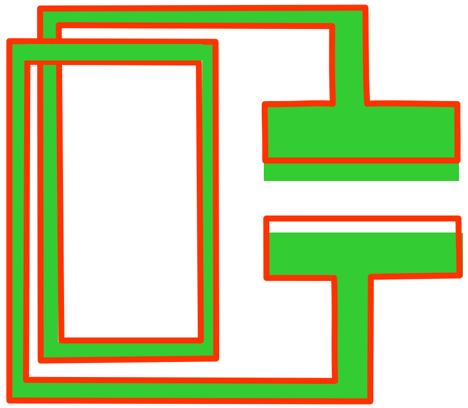


MICROSCOPIC ATOM vs MACROSCOPIC CIRCUIT

Hydrogen atom



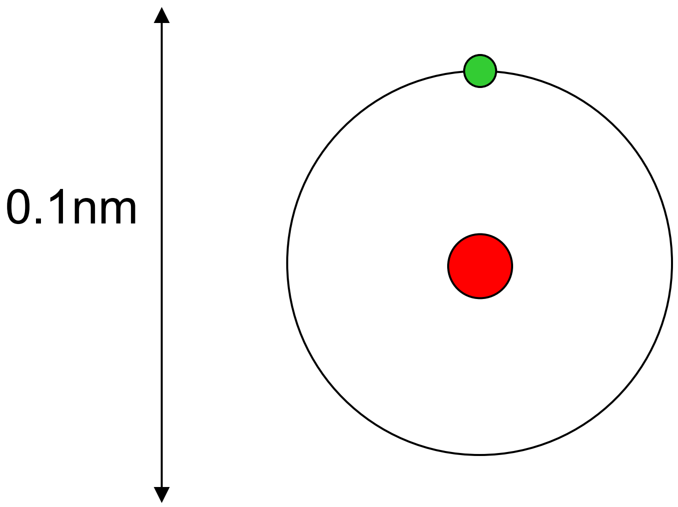
Superconducting
LC oscillator



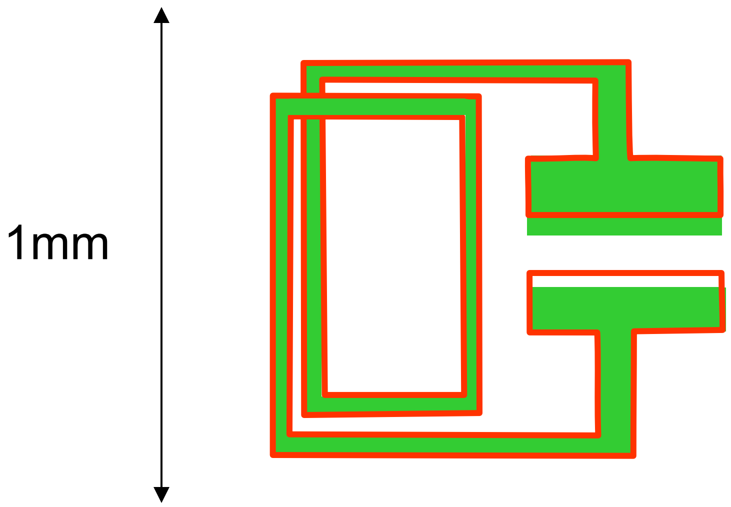
unique electron → whole superconducting condensate
velocity of electron → **current through inductor**
force on electron → **voltage across capacitor**

MICROSCOPIC ATOM vs MACROSCOPIC CIRCUIT

Hydrogen atom



Superconducting
LC oscillator



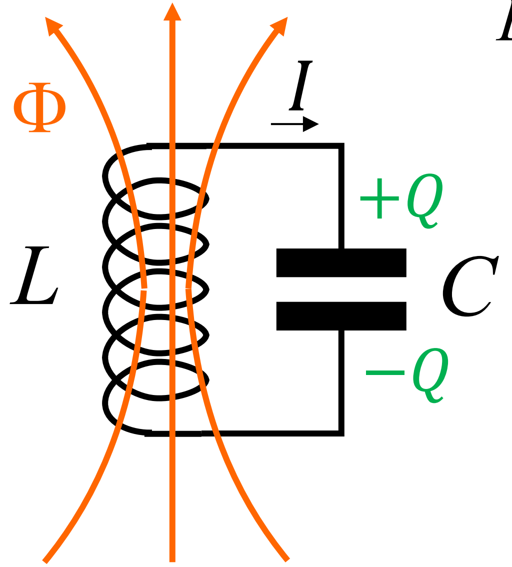
CAN ATTACH WIRES!

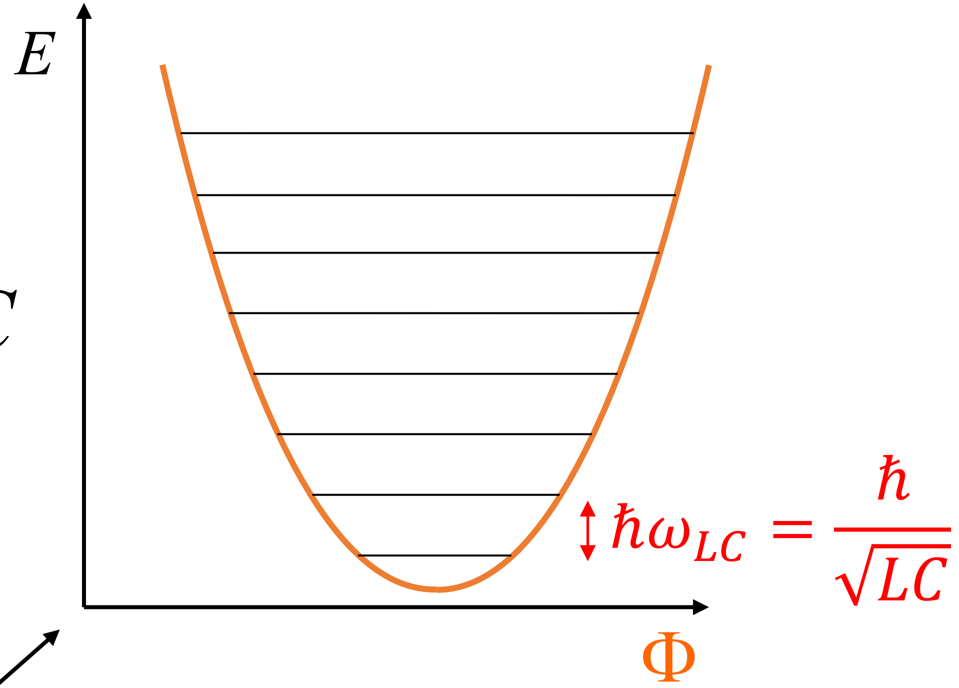
unique electron → whole superconducting condensate

velocity of electron → **current through inductor**

force on electron → **voltage across capacitor**

SUPERCONDUCTING LC CIRCUIT AS A QUANTUM HARMONIC OSCILLATOR





$\Phi = LI$

$Q = CV$

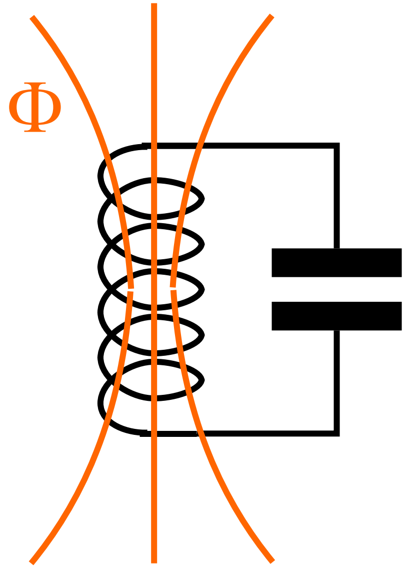
Leggett's hypothesis: $[\hat{\Phi}, \hat{Q}] = i\hbar\hat{1}$

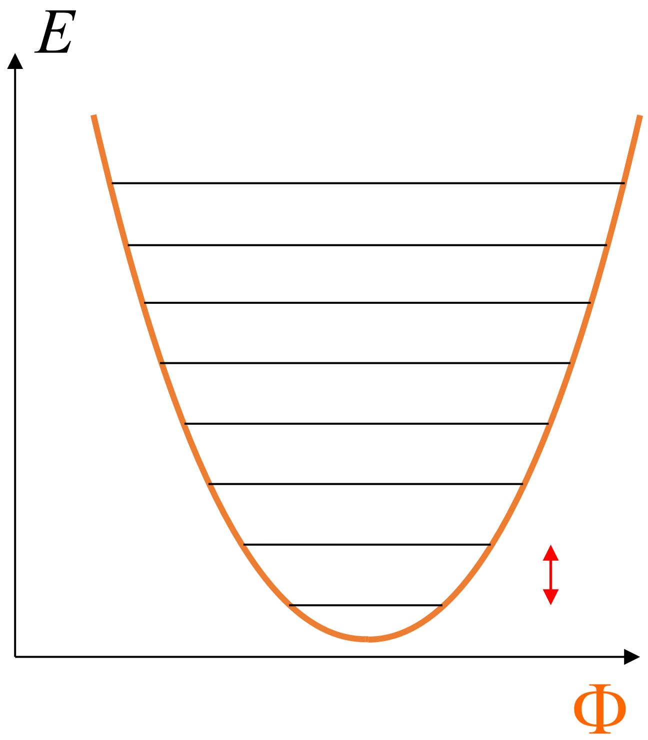
COMMUTATOR OF ELECTROMAGNETIC FIELDS OPERATORS

$$\left[\hat{B}_z\left(x_1,y_1,z_1\right),\hat{E}_y\left(x_2,y_2,z_2\right)\right]=\frac{i\hbar}{\varepsilon_0}\frac{\partial}{\partial x_1}\delta\left(x_1-x_2\right)\delta\left(y_1-y_2\right)\delta\left(z_1-z_2\right)$$

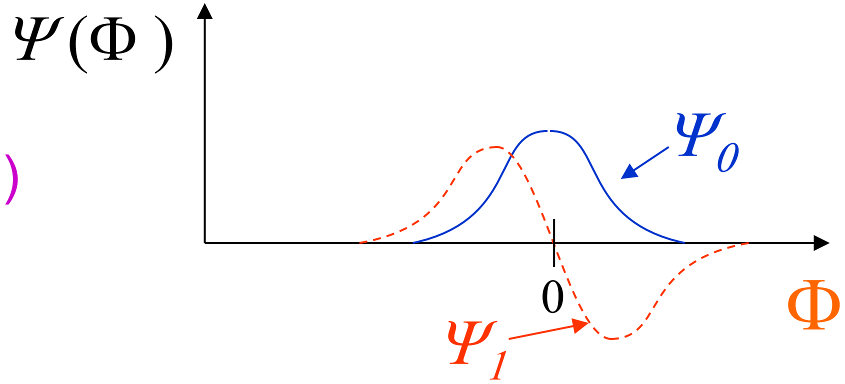
and similar relations for other field components
obtained by permutation of x, y and z.

WAVEFUNCTIONS OF LC CIRCUIT



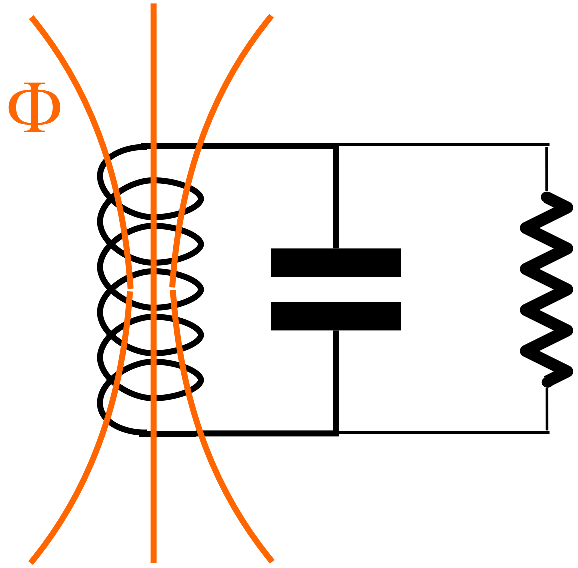


$$\hbar\omega_{LC} = \frac{\hbar}{\sqrt{LC}}$$

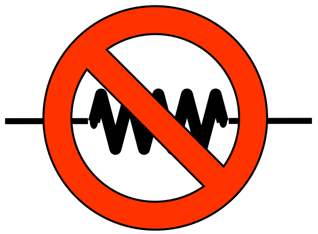


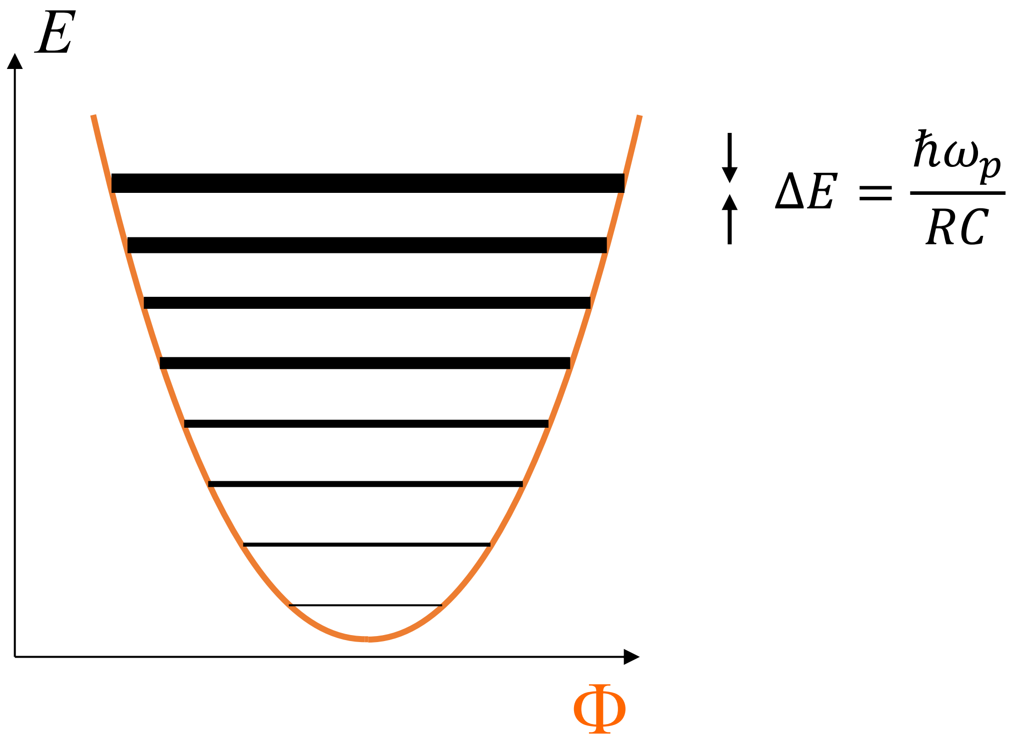
In every energy eigenstate,
(standing photon number state)
current flows in opposite
directions simultaneously!

EFFECT OF DAMPING



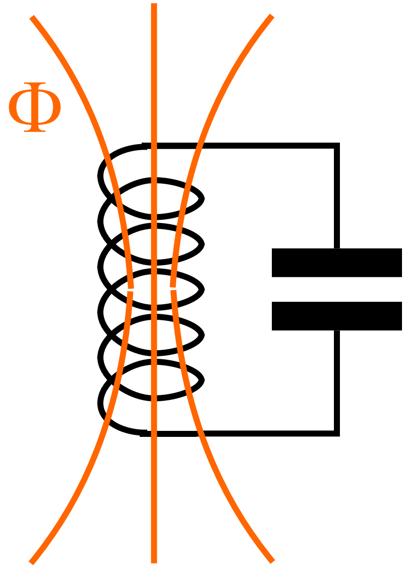
important: as little dissipation as possible

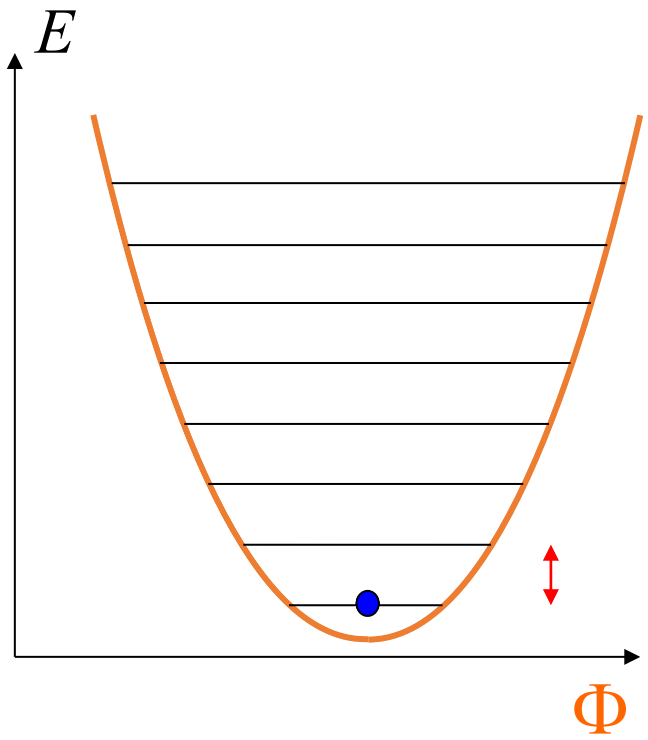




dissipation broadens energy levels

RESET: PLACE CIRCUIT IN ITS GROUND STATE





$$\hbar\omega_{LC} = \frac{\hbar}{\sqrt{LC}}$$

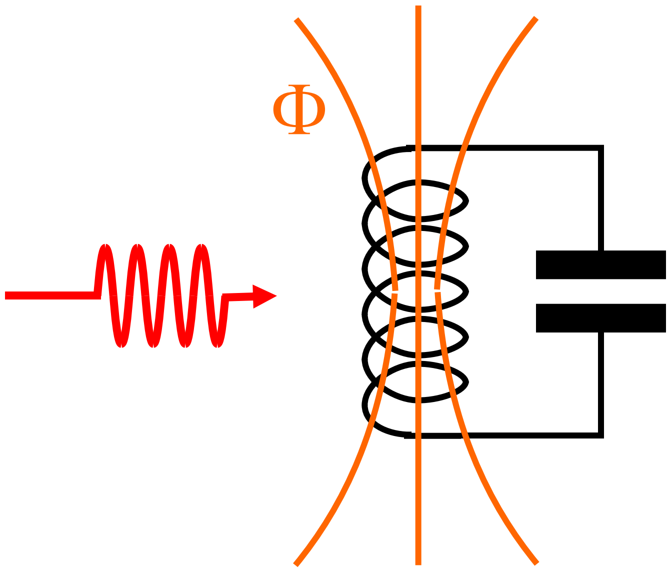
some cold dissipation is actually needed!

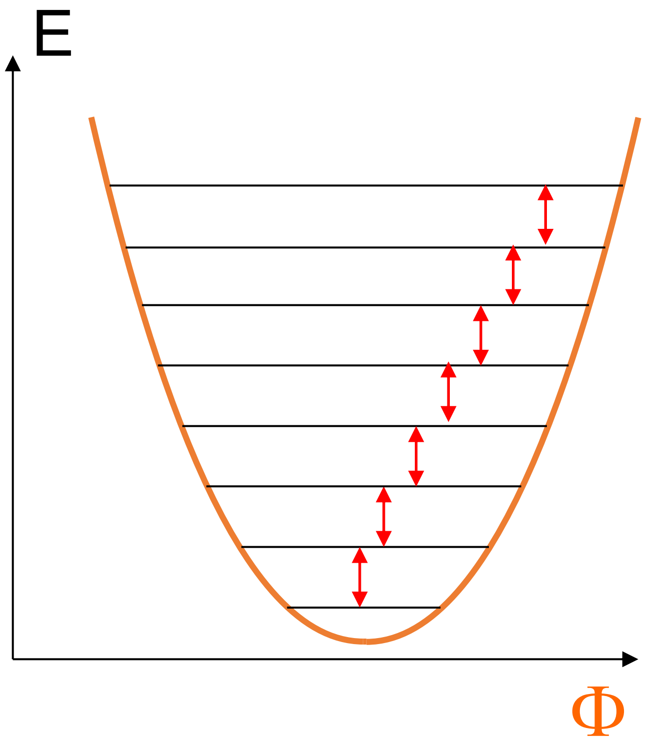
$$\hbar\omega_{LC} \gg k_B T$$

5-10 GHz → $\hbar\omega_{LC}$; 10mK → T

$\hbar$ is not small for microwave circuits at dilution refrigerator temperature!

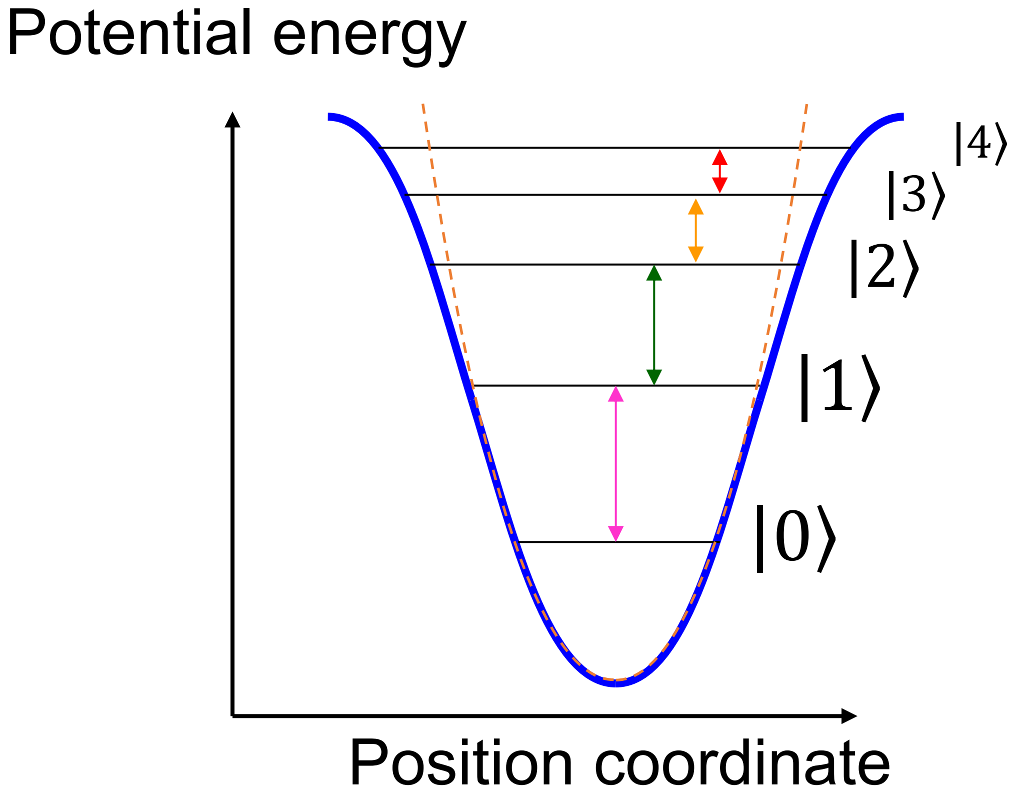
CAVEAT: THE QUANTUM STATES OF A PURELY LINEAR CIRCUIT CANNOT BE FULLY CONTROLLED!





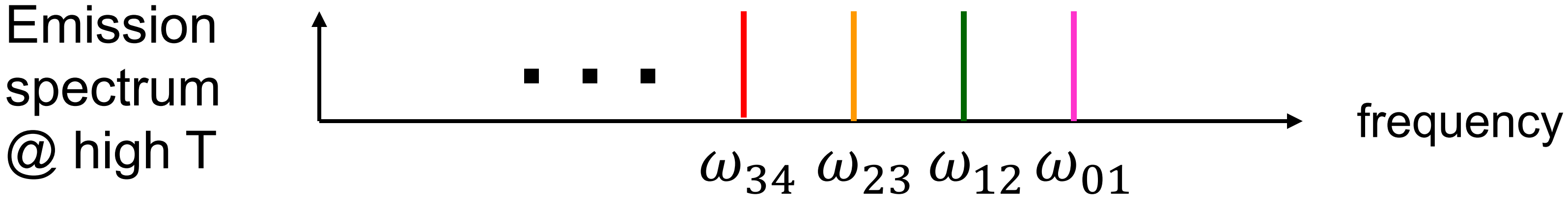
NO STEERING TO AN ARBITRARY STATE
IF SYSTEM PERFECTLY LINEAR

NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

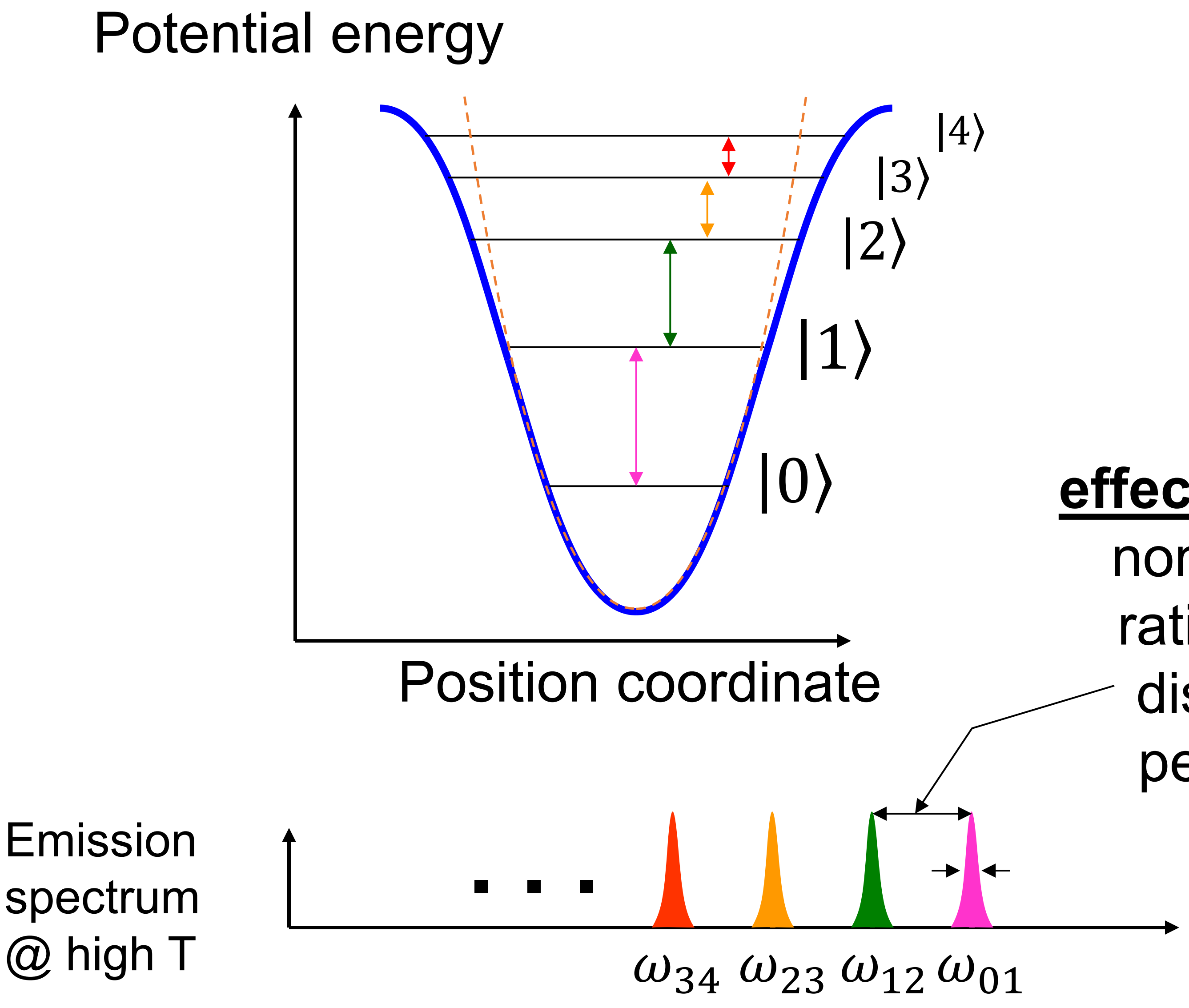


non-linearity ratio:

$$NLR = \frac{\omega_{01} - \omega_{12}}{\omega_{01}}$$



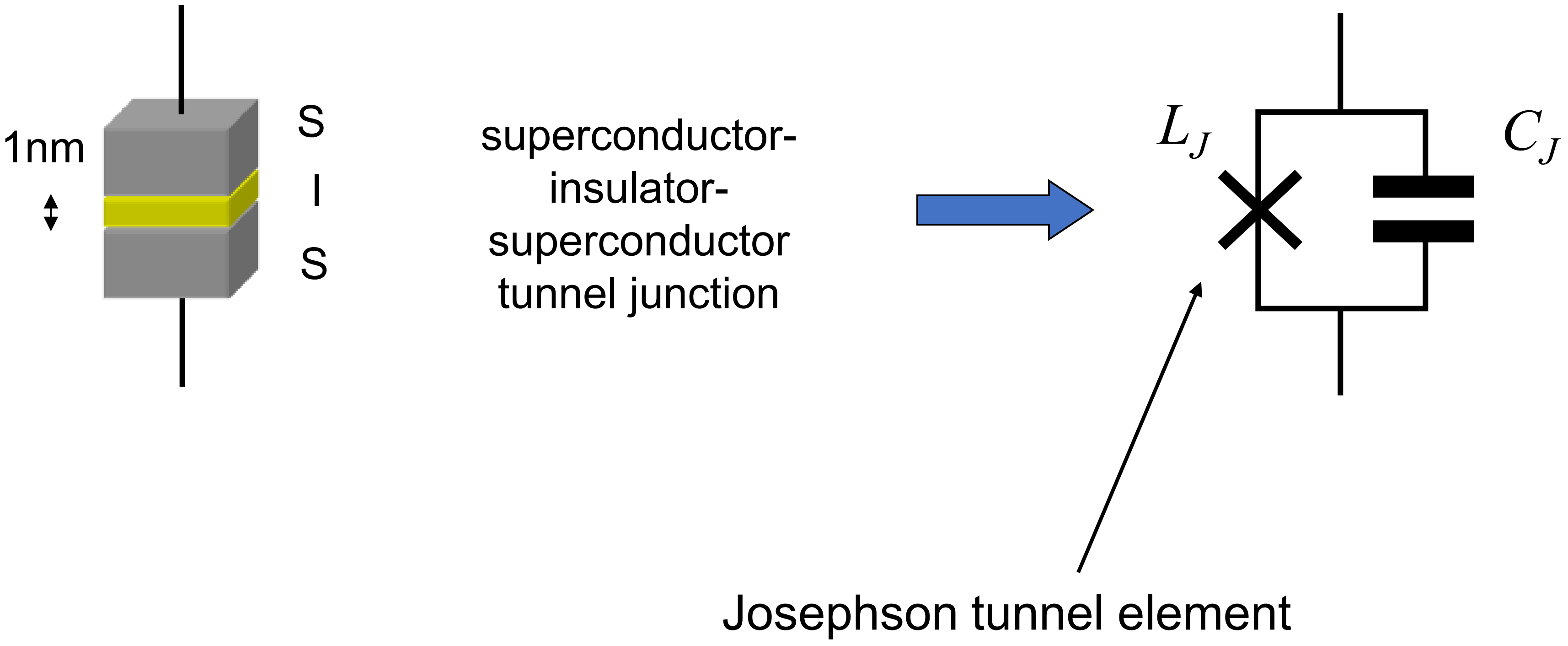
NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

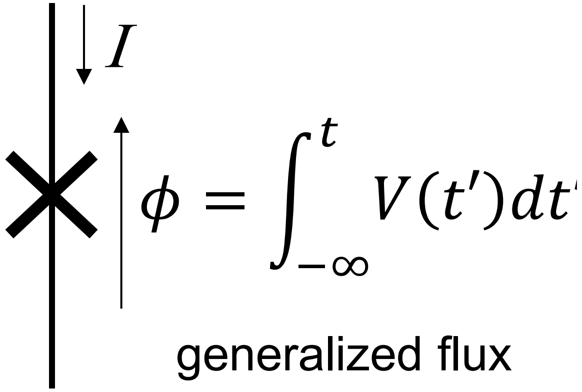


effective relative non-linearity: ratio of peak distance to peak width

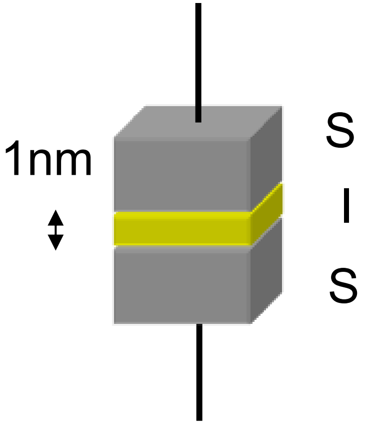
$NLR \times Q$

A NON-LINEAR INDUCTANCE WITH NO FUNDAMENTAL DISSIPATION: THE JOSEPHSON TUNNEL ELEMENT

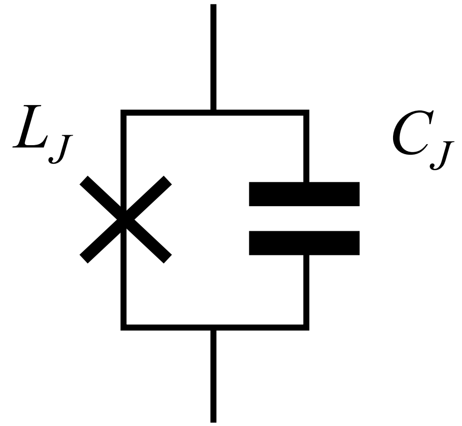




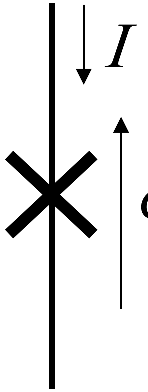
A NON-LINEAR INDUCTANCE WITH <u>NO FUNDAMENTAL DISSIPATION:</u> THE JOSEPHSON TUNNEL ELEMENT



superconductor-insulator-superconductor tunnel junction

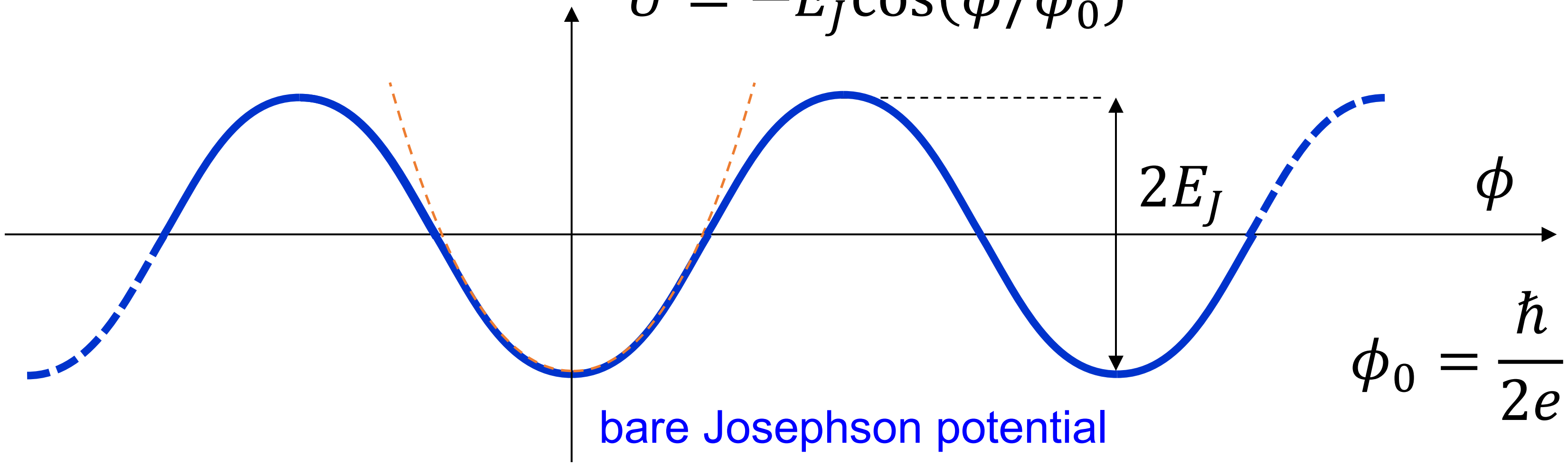


$$L_J = \frac{{\phi_0}^2}{E_J}$$



$$\phi = \int_{-\infty}^{t} V(t')dt'$$

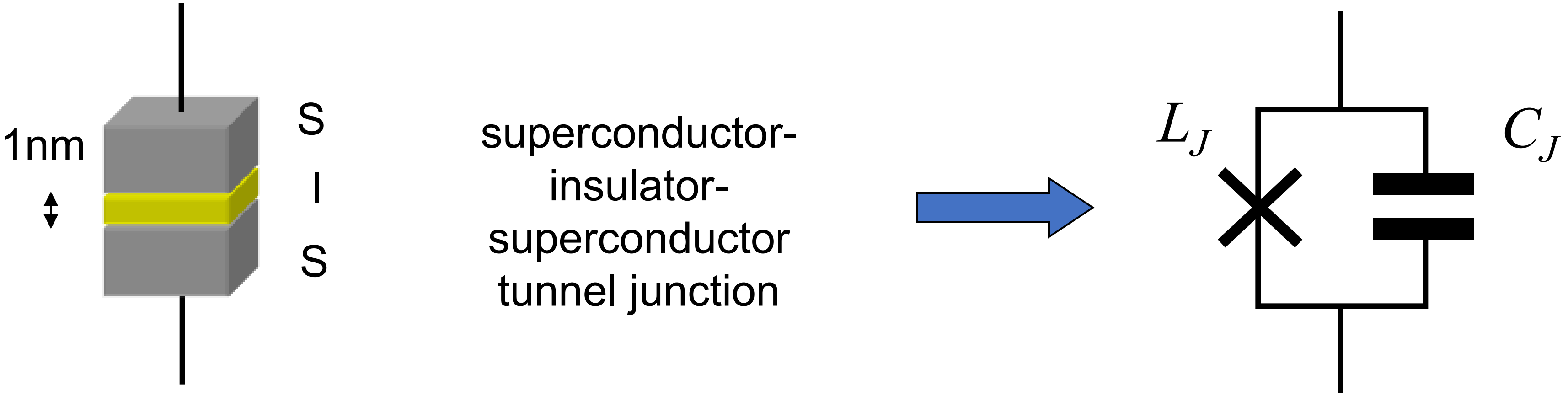
generalized flux



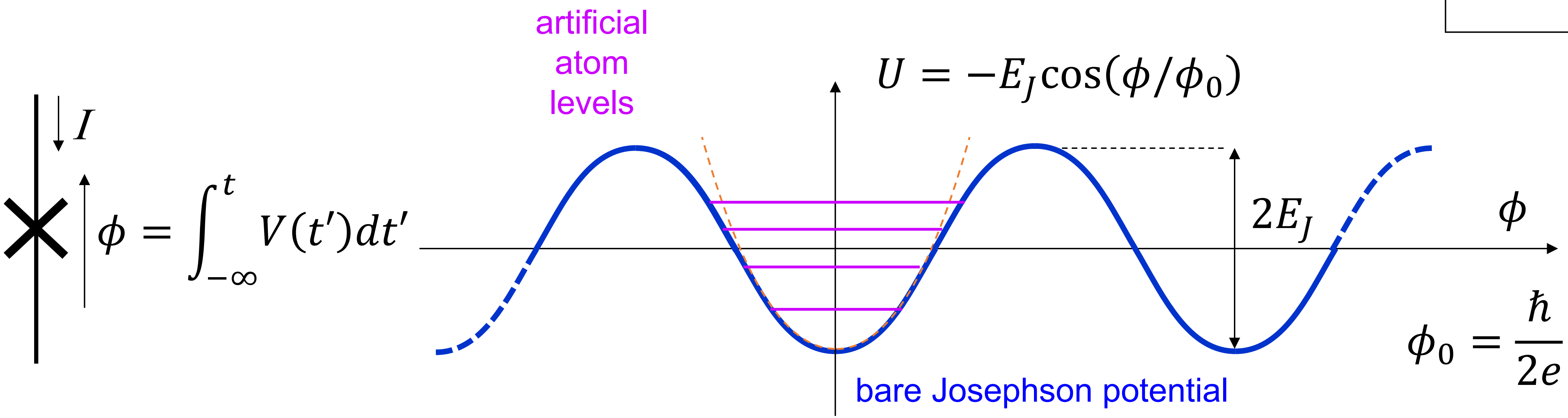
$$\phi_0 = \frac{\hbar}{2e}$$

bare Josephson potential

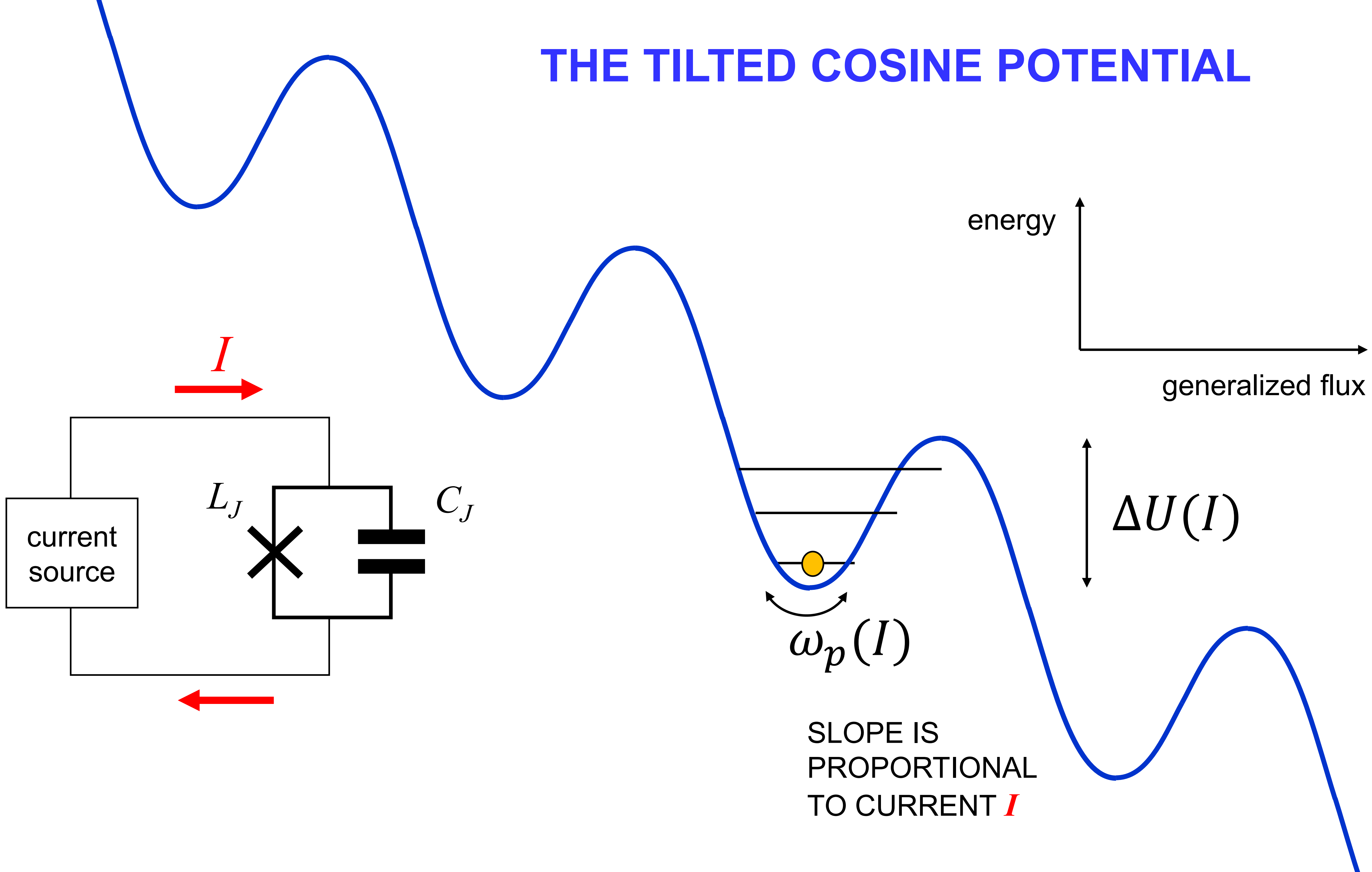
A NON-LINEAR INDUCTANCE WITH NO FUNDAMENTAL DISSIPATION: THE JOSEPHSON TUNNEL ELEMENT



$$L_J = \frac{{\phi_0}^2}{E_J}$$

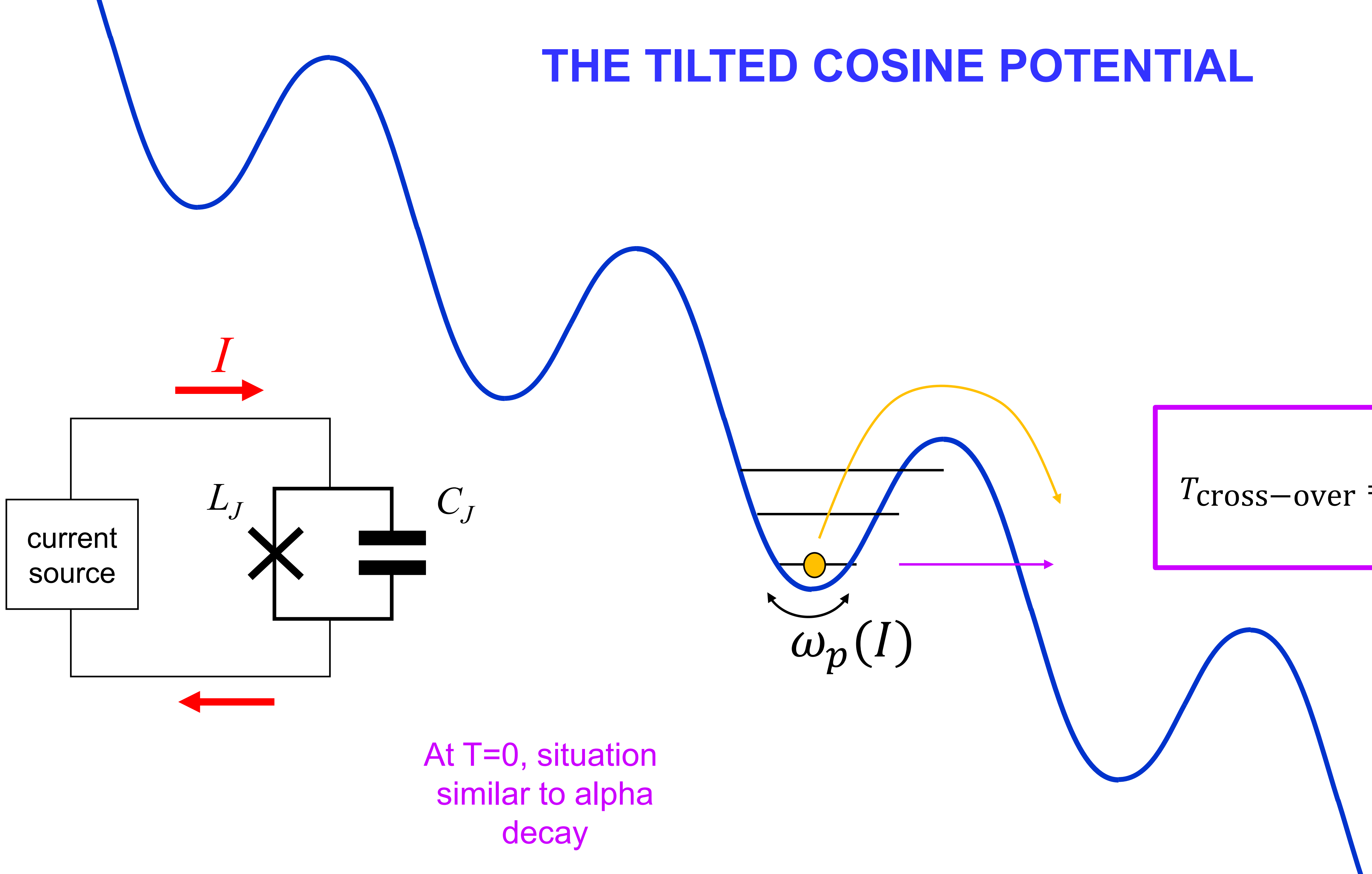


THE TILTED COSINE POTENTIAL



SLOPE IS PROPORTIONAL TO CURRENT I

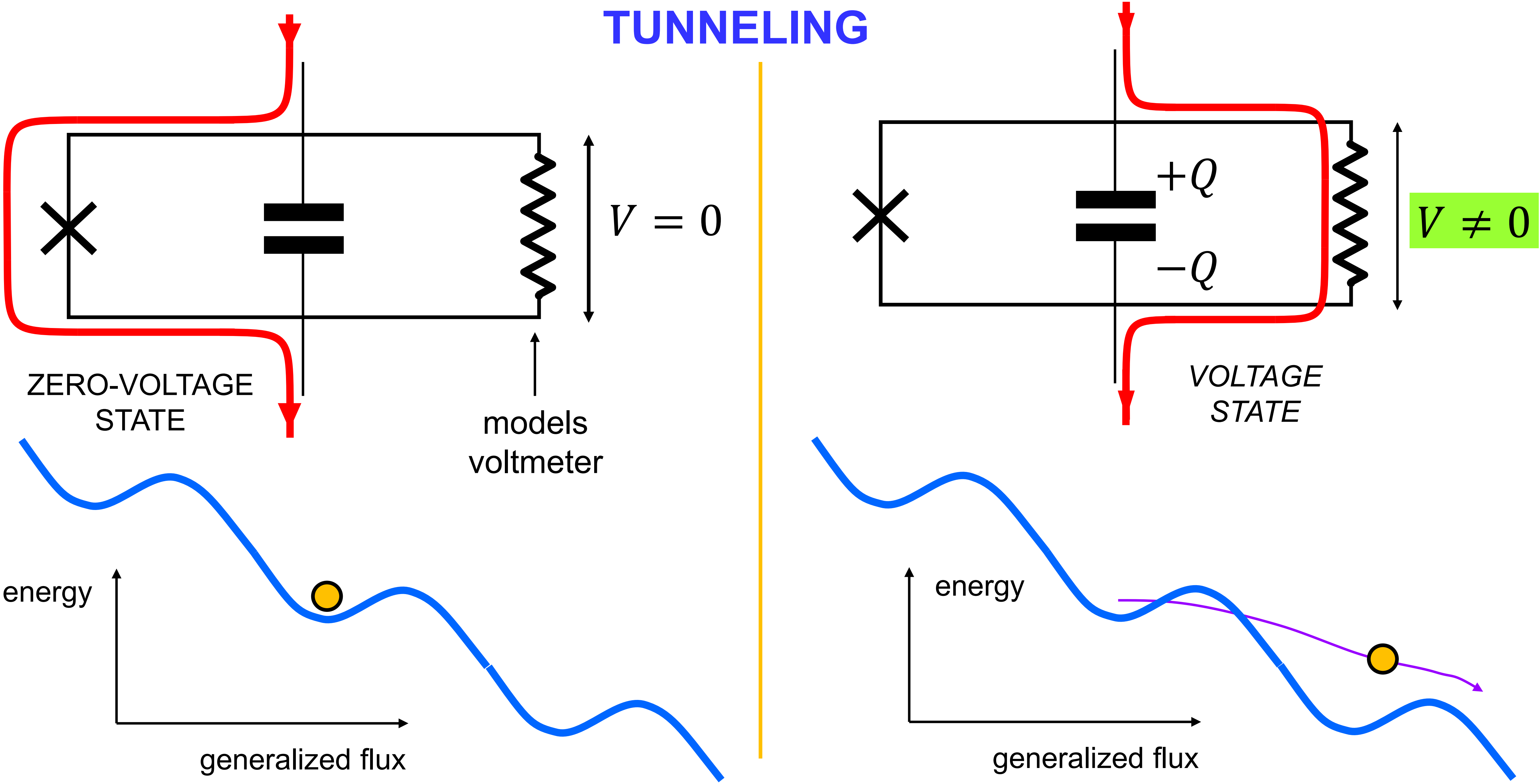
THE TILTED COSINE POTENTIAL



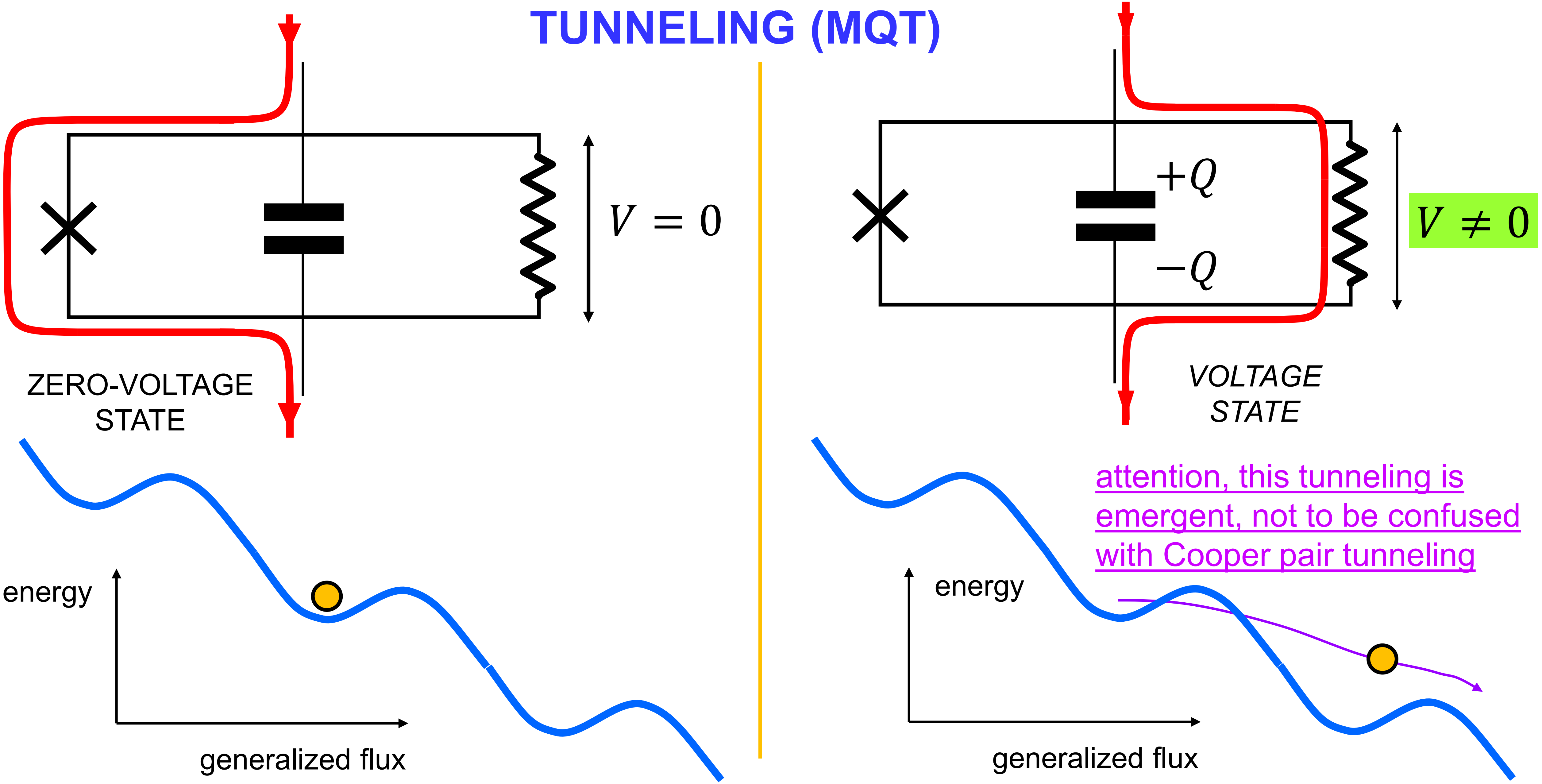
$$T_{\text{cross-over}} = \frac{\hbar\omega_p}{k_B}$$

At T=0, situation similar to alpha decay

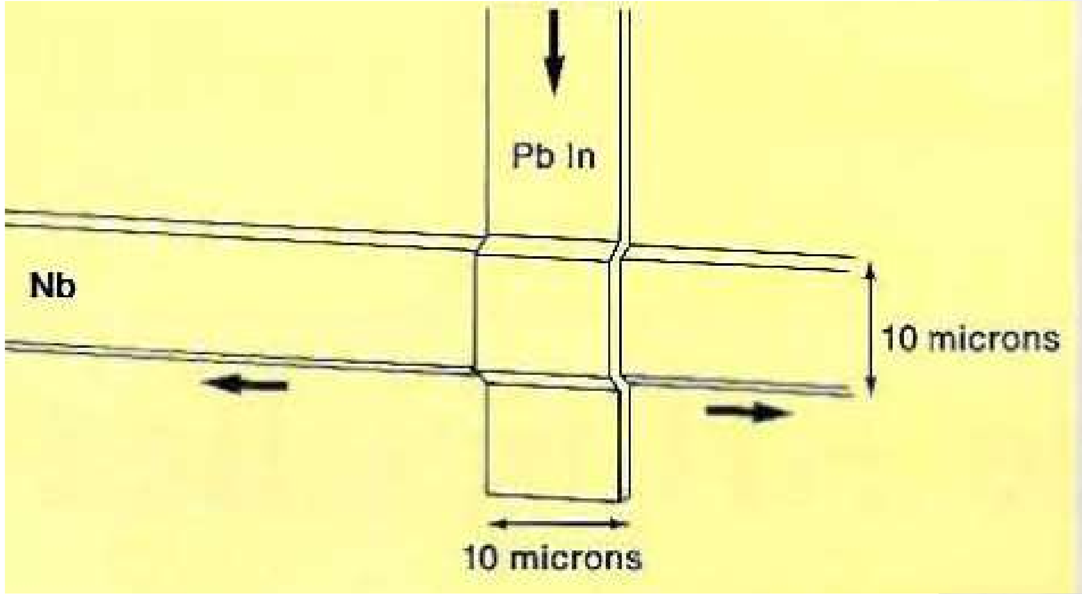
MACROSCOPIC QUANTUM TUNNELING



MACROSCOPIC QUANTUM TUNNELING (MQT)

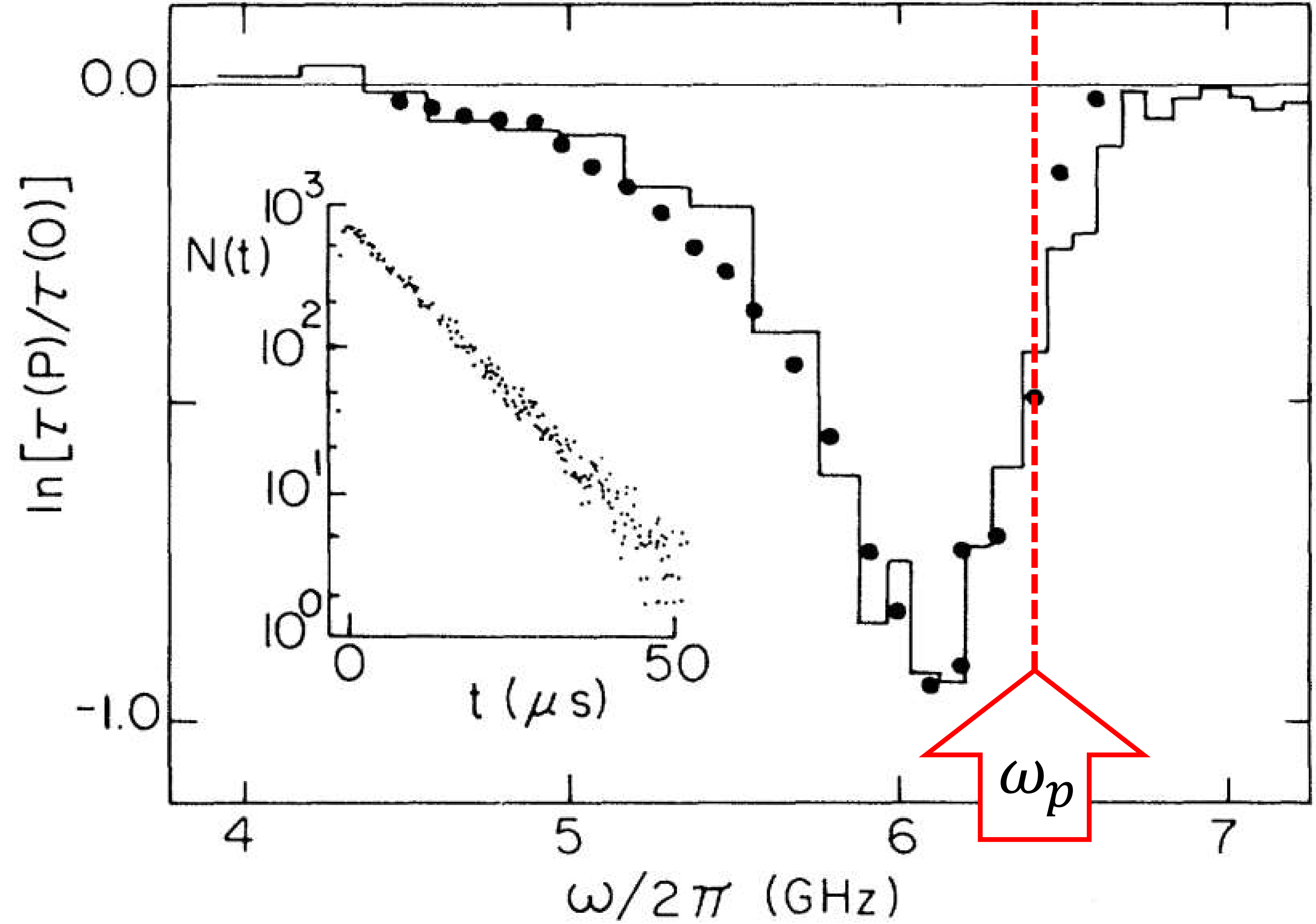


EXPERIMENTAL SETUP OF THE 1985 BERKELEY EXPERIMENT



Devoret, Esteve,
Martinis and Clarke
PRL 1984

RESONANT ACTIVATION IN THE CLASSICAL REGIME

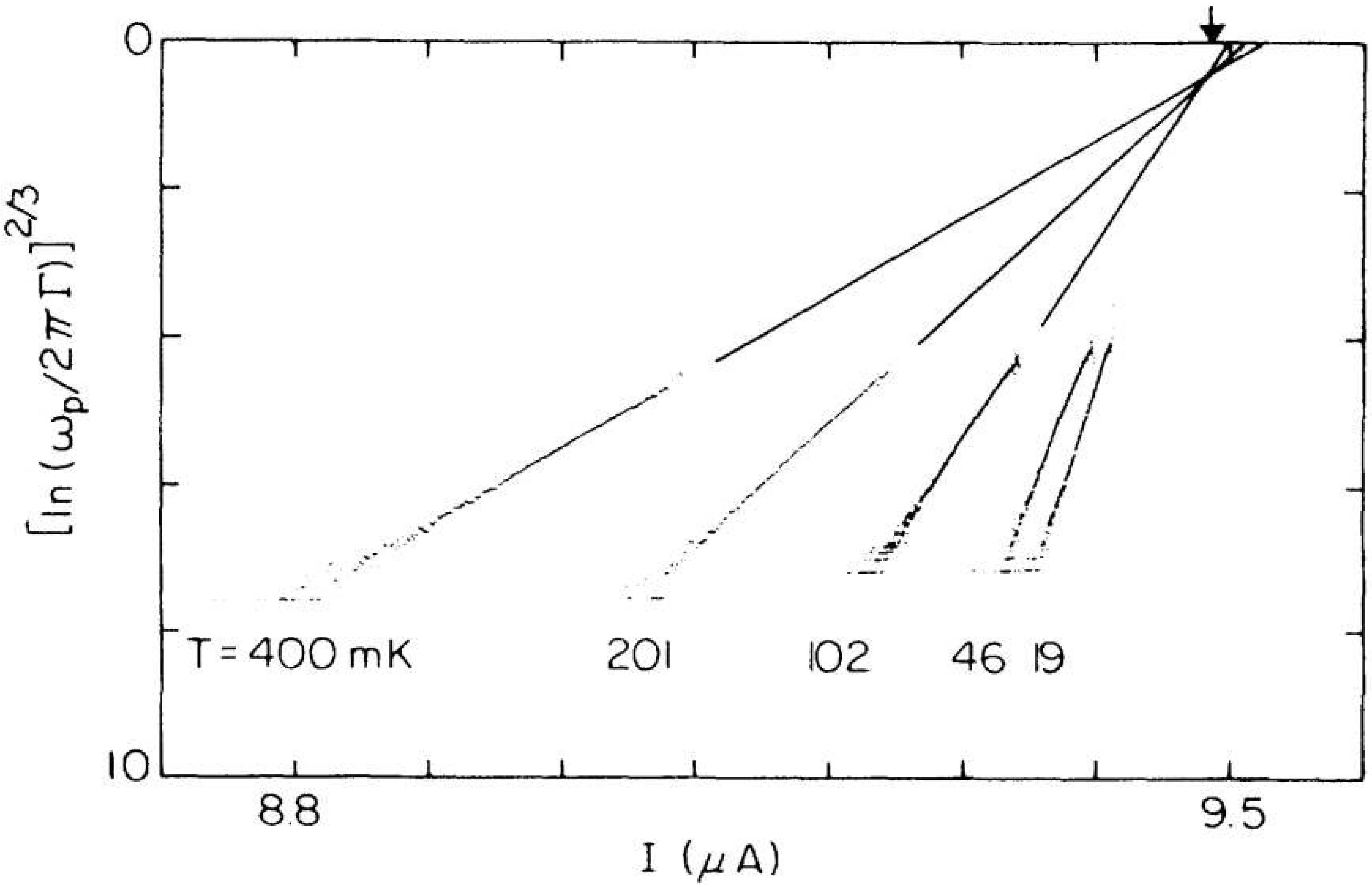


● : experiment

— : simulation

$$\frac{\Delta U}{\hbar\omega_P} \gg 1$$

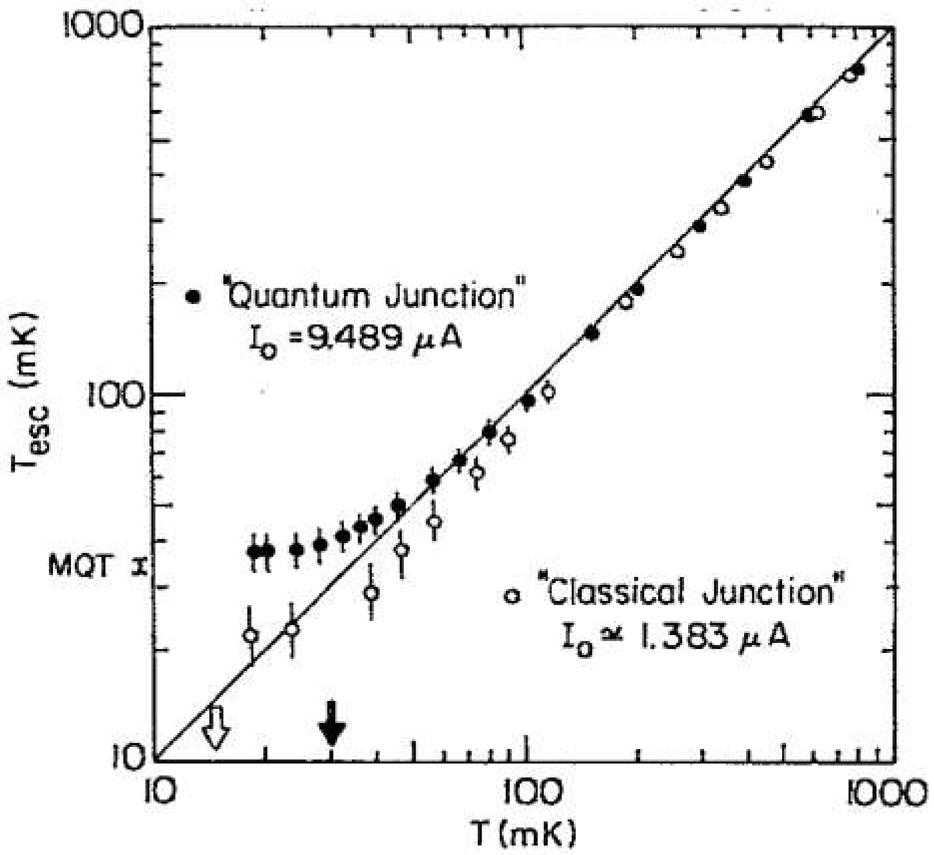
DETERMINATION OF CRITICAL CURRENT AND ENERGY BARRIER



QUANTUM REGIME: MEASUREMENTS OF SUPERCONDUCTING ARTIFICIAL ATOM 'SELF-IONIZATION' (MQT) AND ENERGY LEVELS

VOLUME 55, NUMBER 18 PHYSICAL REVIEW LETTERS 28 OCTOBER 1985

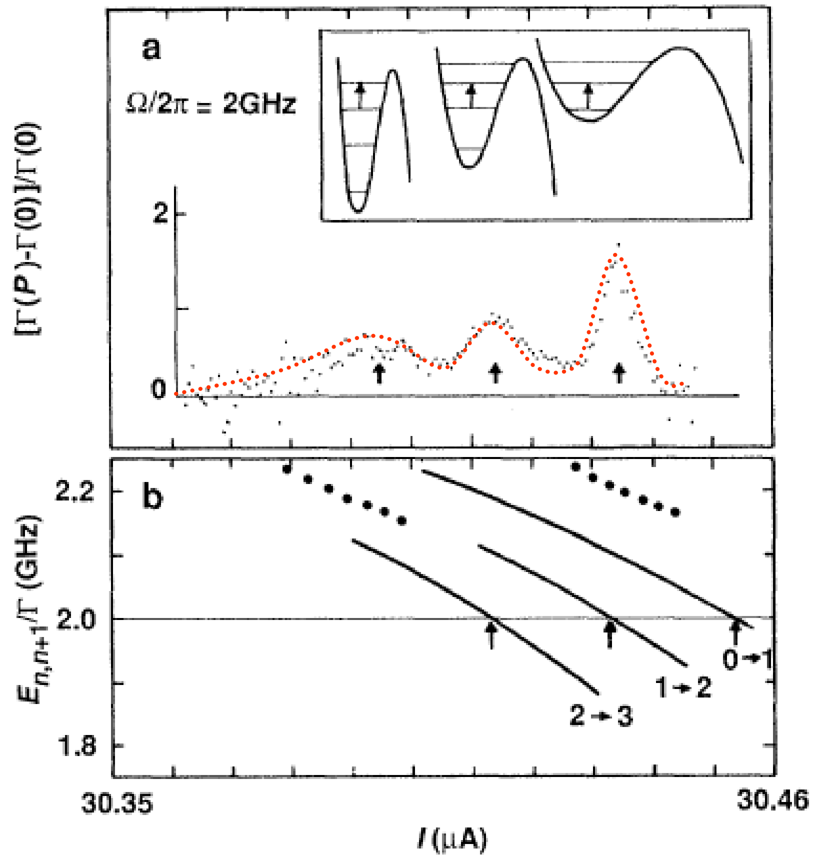
Measurements of Macroscopic Quantum Tunneling out of the Zero-Voltage State of a Current-Biased Josephson Junction



Nb-NbOx-Pb junction, current-bias configuration

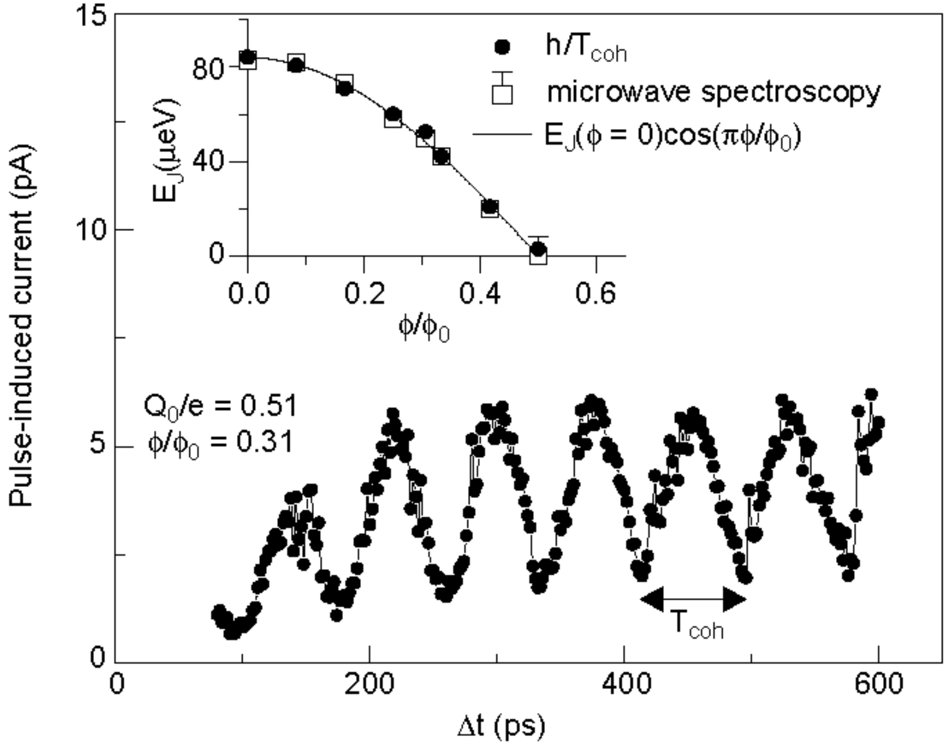
VOLUME 55, NUMBER 15 PHYSICAL REVIEW LETTERS 7 OCTOBER 1985

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



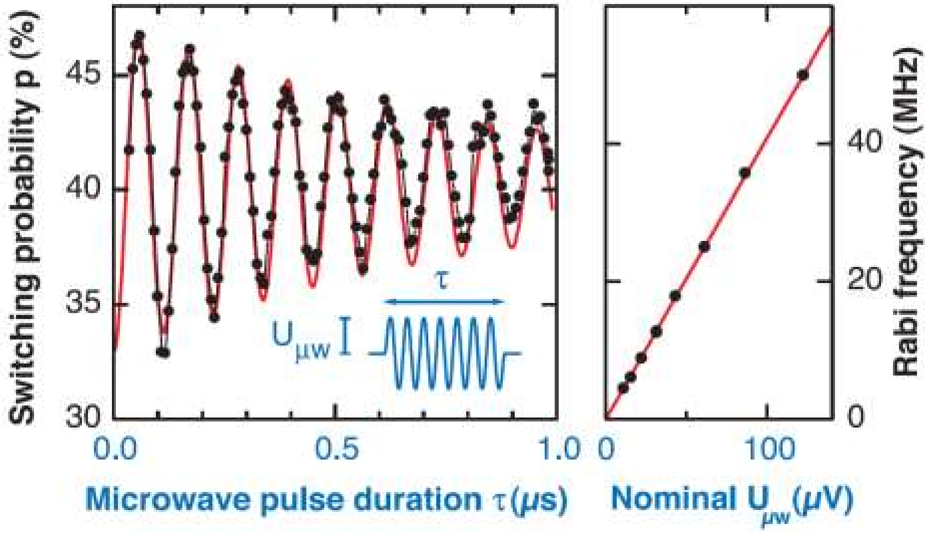
MACROSCOPIC QUANTUM RABI OSCILLATIONS AND RAMSEY FRINGES

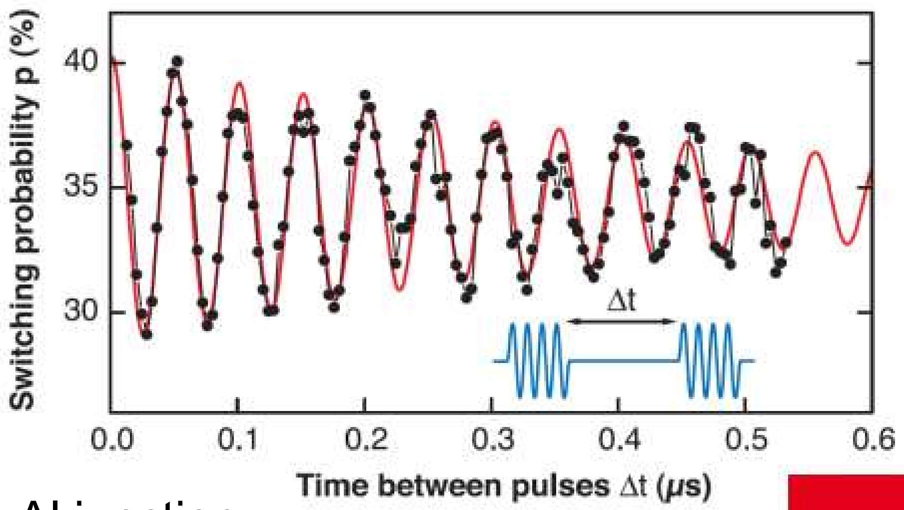
Nakamura, Pashkin and Tsai, Nature (1999)



Al-AlOx-Al junction
Cooper pair box qubit
Rabi oscillations

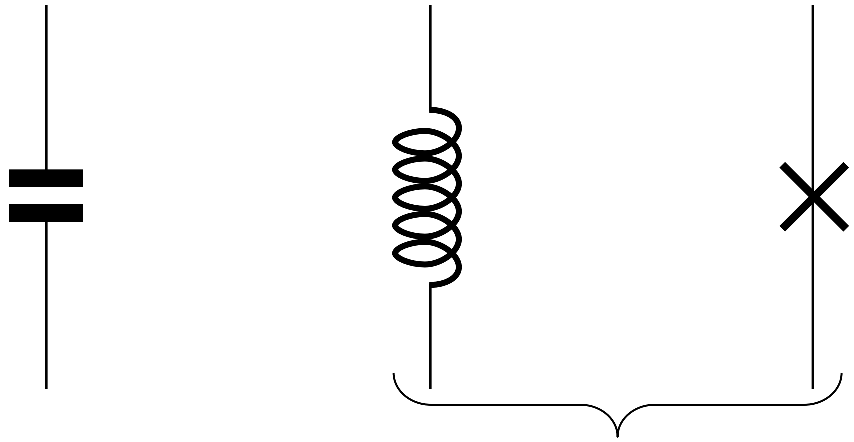
Vion *et al*.
Science (2002)





Al-AlOx-Al junction
Quantronium qubit
Rabi oscillations and Ramsey fringes

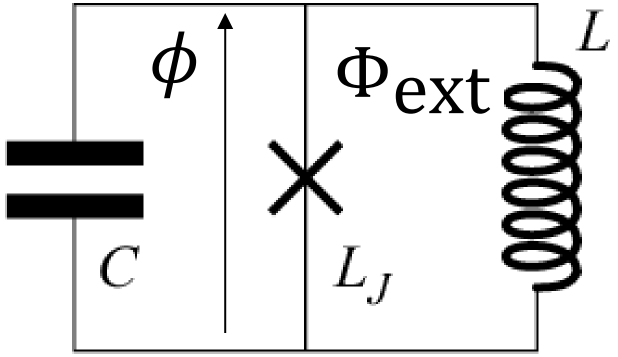
BASIC ELEMENTS OF QUANTUM SUPERCONDUCTING CIRCUITS

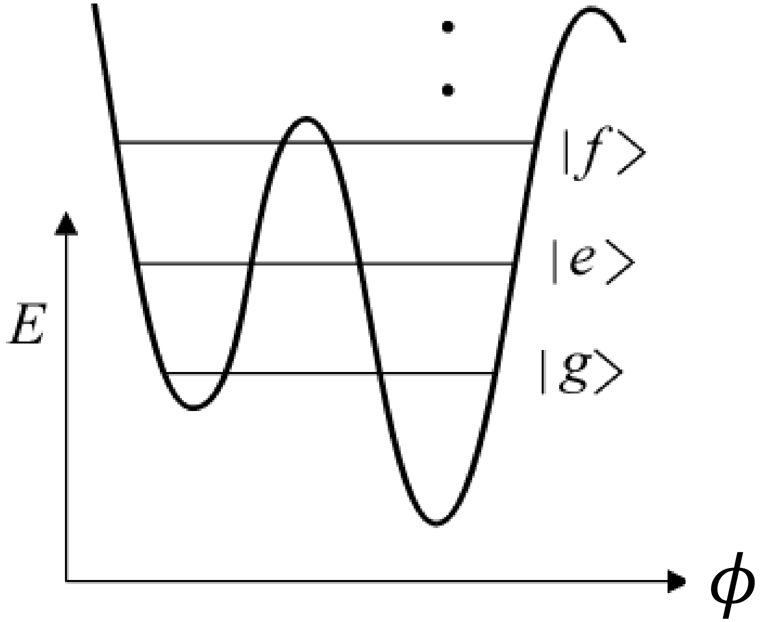


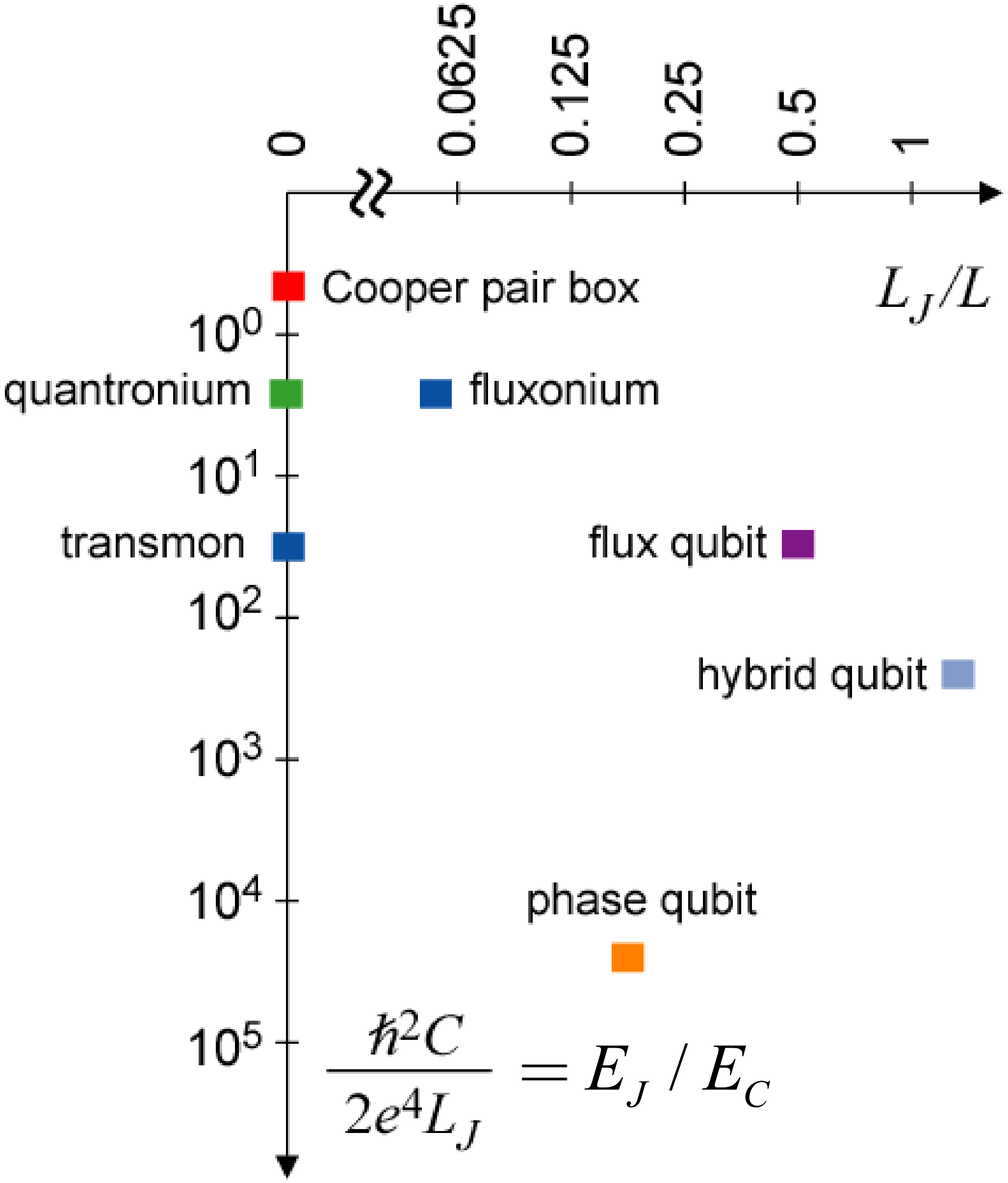
A VERY SIMPLE LEGO-LIKE SET!

WITH IT, WE CAN CONSTRUCT COMPLEX ARTIFICIAL QUANTUM SYSTEMS.

MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS





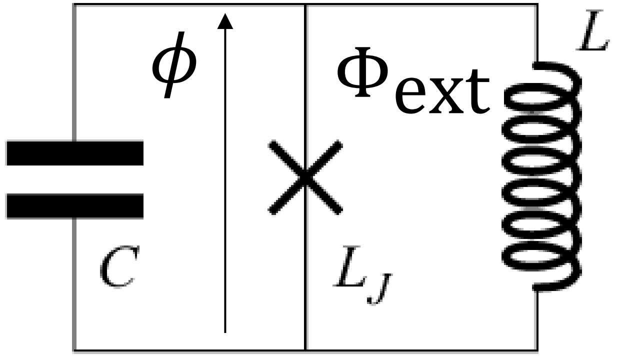


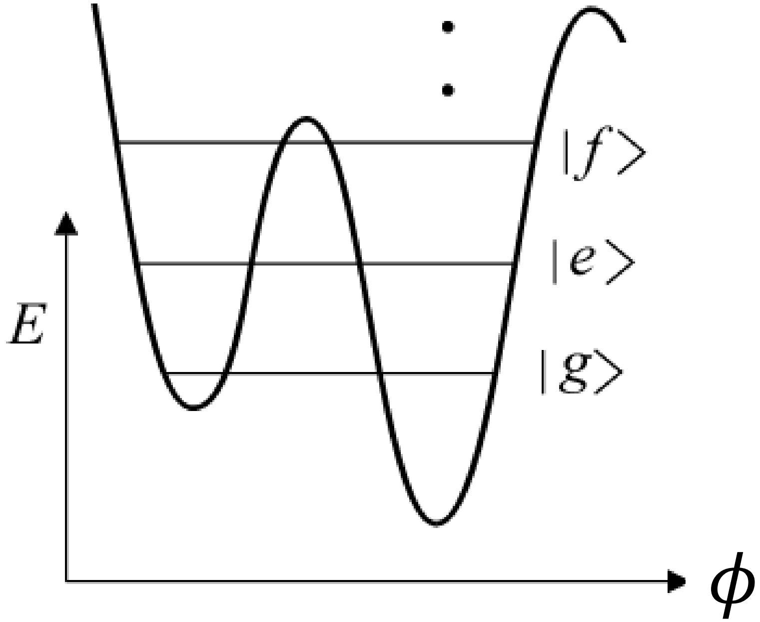
Circuit parameters from:

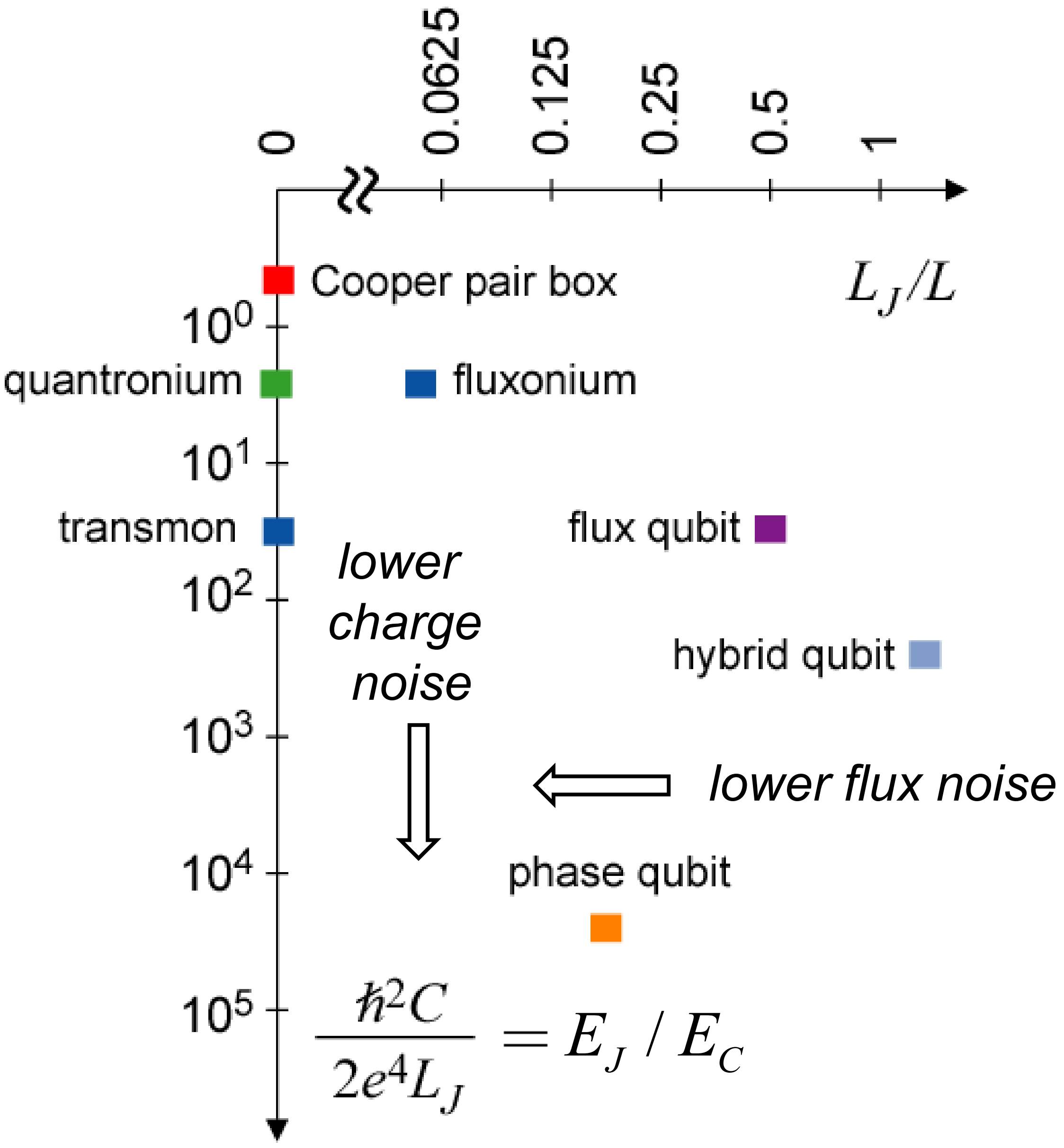
Delft, NEC, MIT
IBM
NEC
Saclay
UCSB
Yale

MHD & R. Schoelkopf, Science (2013)

MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS





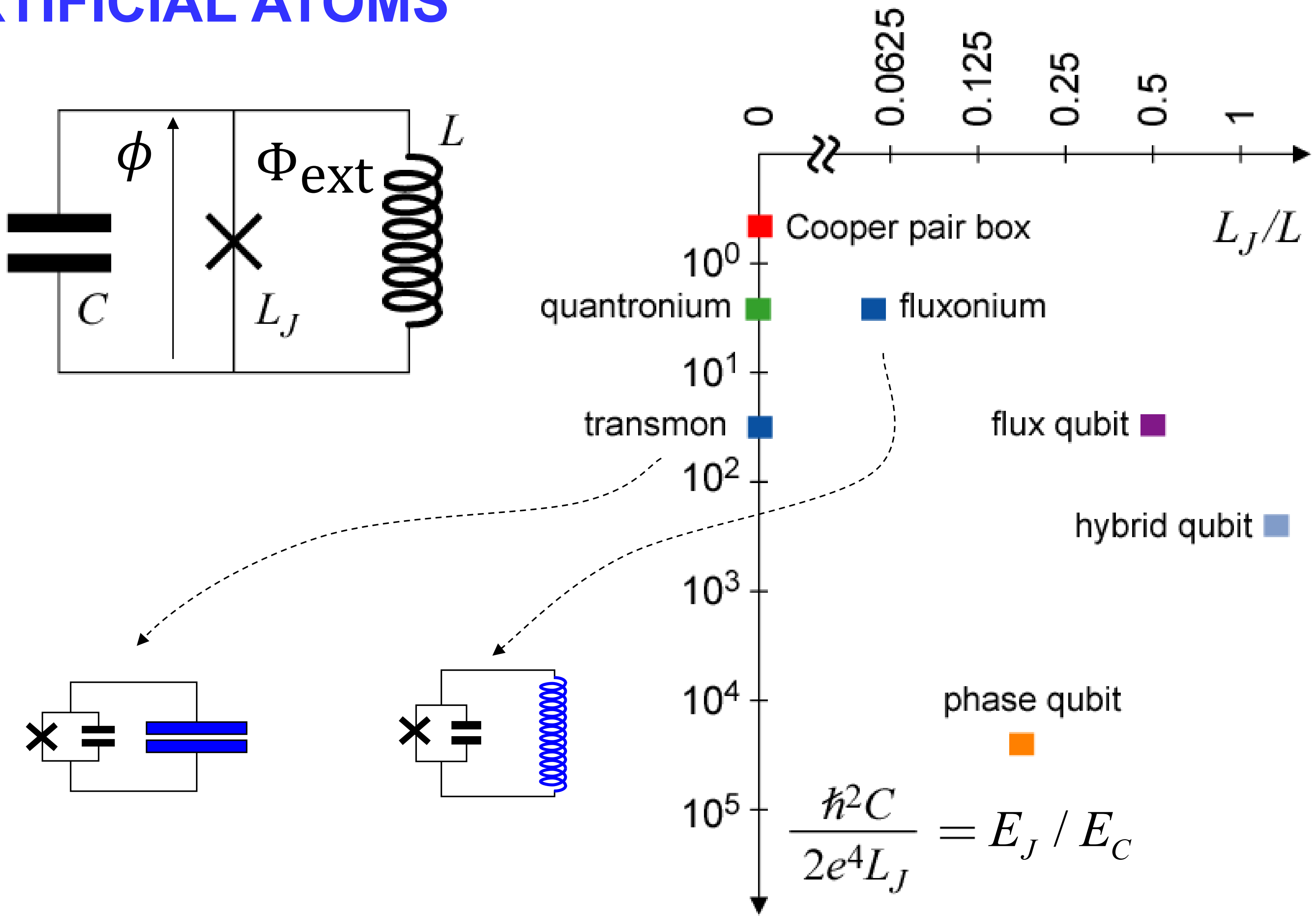


Circuit parameters from:

Delft, NEC, MIT
IBM
NEC
Saclay
UCSB
Yale

MHD & R. Schoelkopf, Science (2013)

MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS



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Delft, NEC, MIT
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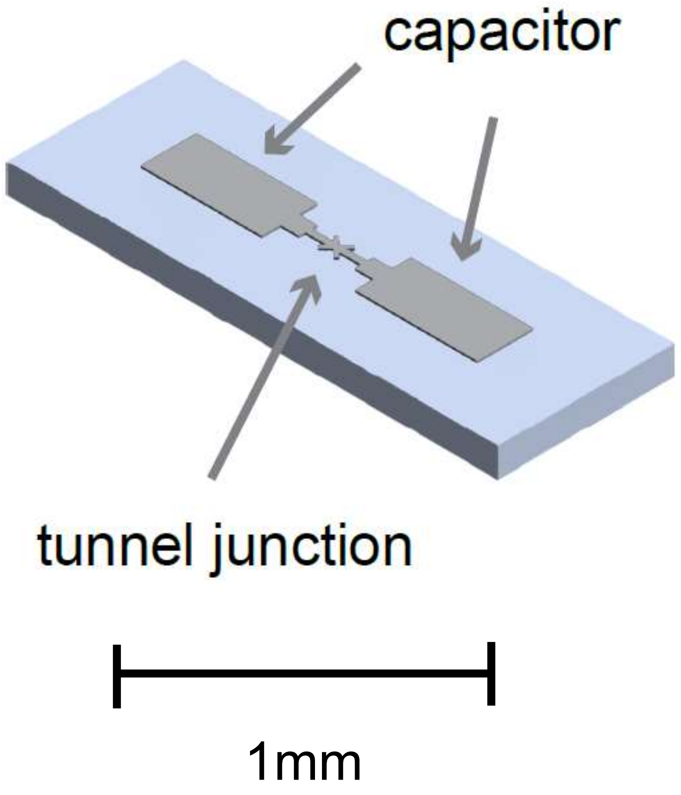
MHD & R. Schoelkopf, Science (2013)

THE TRANSMON ARTIFICIAL ATOM

Koch *et al.* PRA 2007
Schreier *et al*. PRB 2008
Paik *et al*. PRL 2011



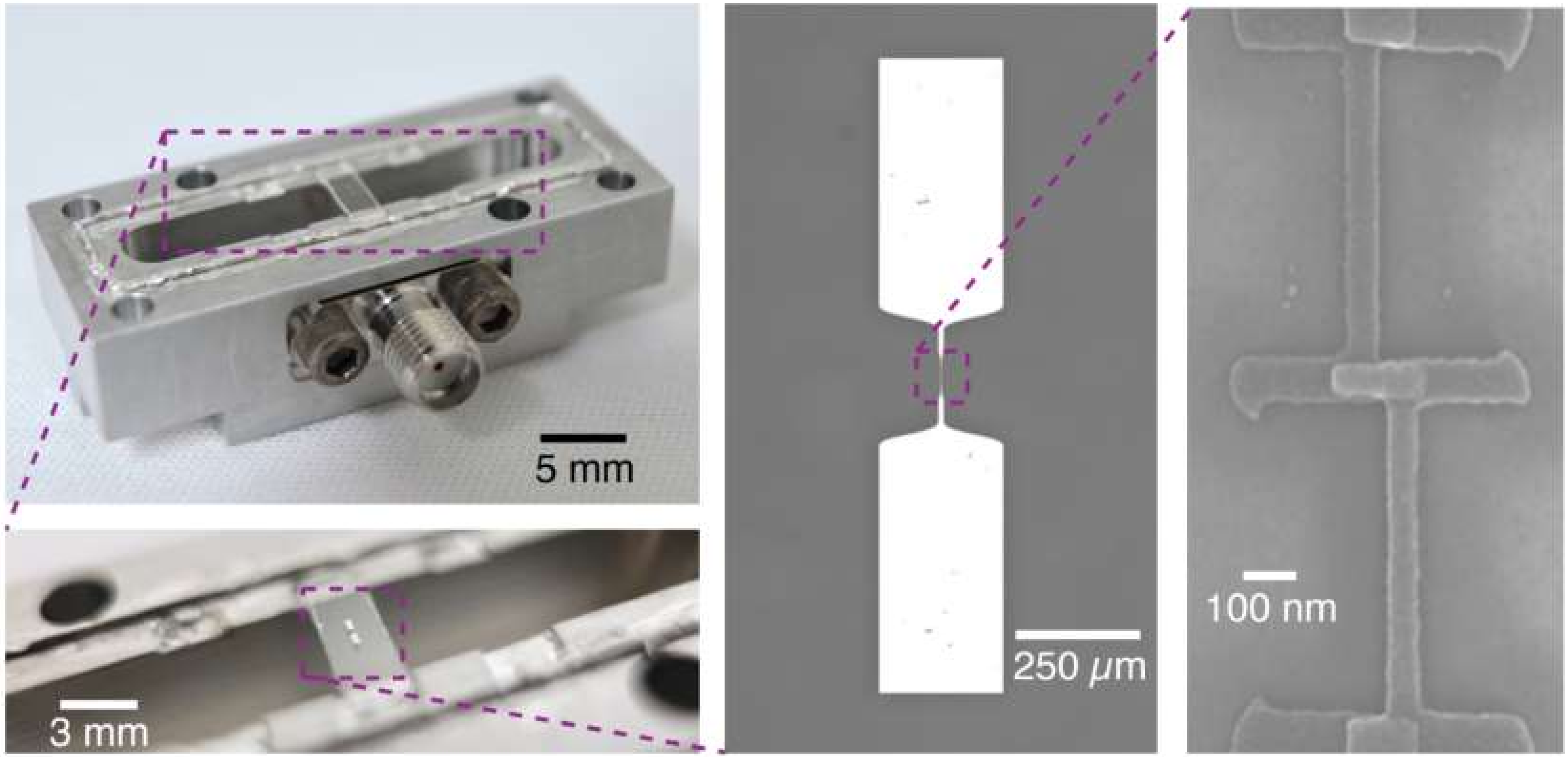
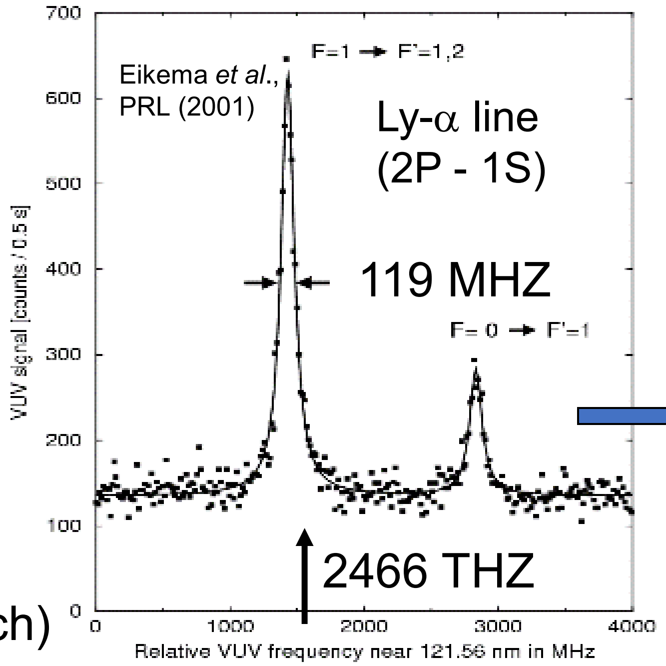


image credit: Kyle Serniak

COHERENCE OF ARTIFICIAL ATOMS NOW COMPETES WITH SIMPLEST NATURAL ATOM

Hydrogen atom



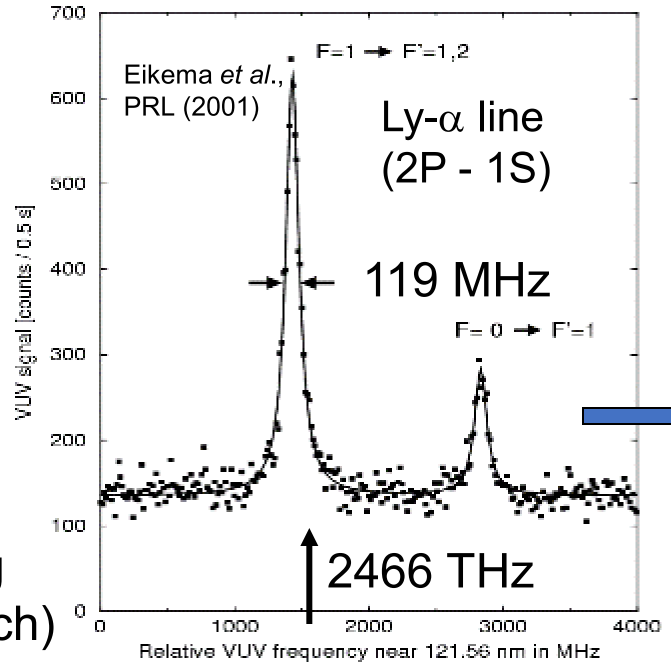
MPI Garching (T. Hänsch)

$Q_{Hydrogen}$ ~ 20,000,000

photon energy ~ 10eV

COHERENCE OF ARTIFICIAL ATOMS NOW COMPETES WITH SIMPLEST NATURAL ATOM

Hydrogen atom



MPI Garching (T. Hänsch)

$Q_{Hydrogen}$ ~ 20,000,000

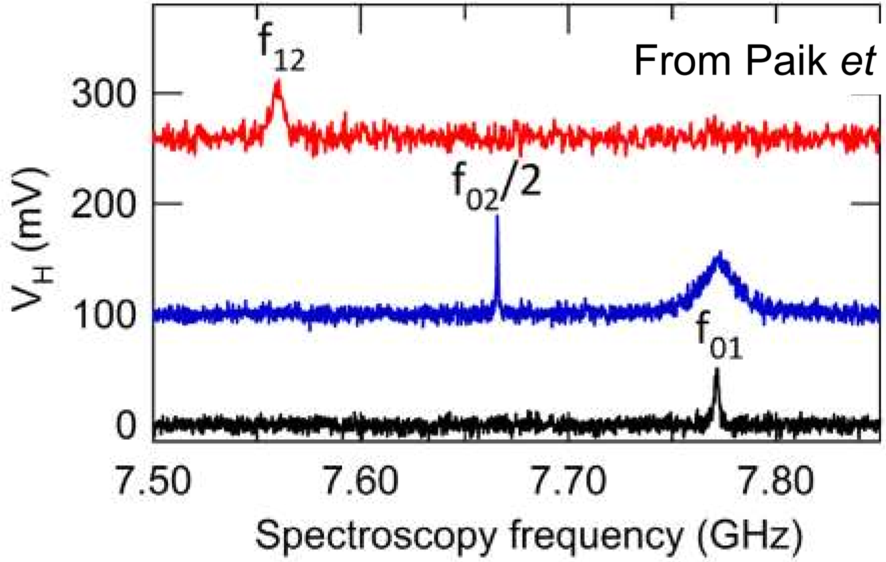
photon energy ~ 10eV

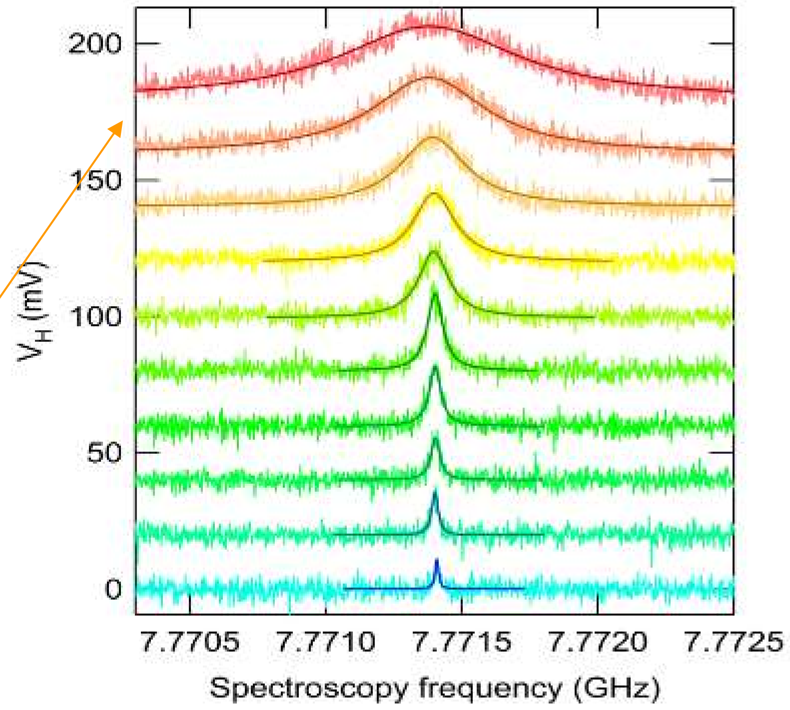
$Q_{Transmon}$ ~ 8,000,000

photon energy ~ 30μeV

Transmon

From Paik *et al.*, PRL (2012)

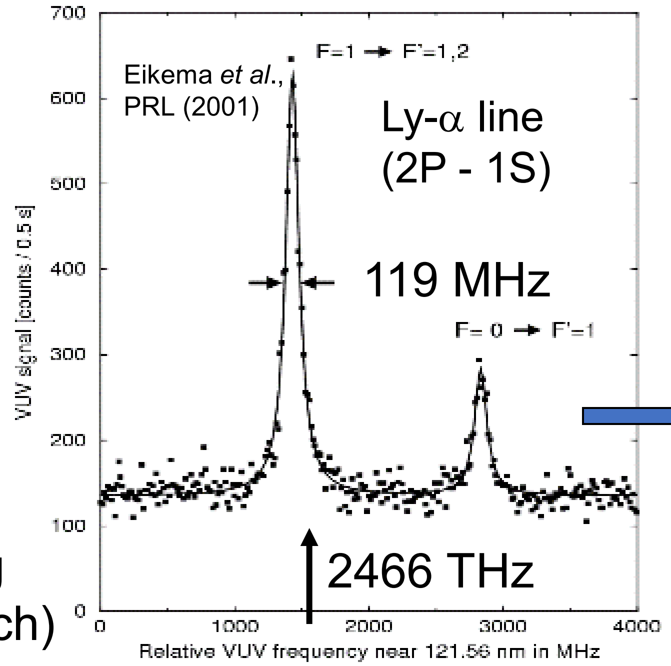




Ultimate linewidth from T2 echo: ~1kHz

COHERENCE OF ARTIFICIAL ATOMS NOW COMPETES WITH SIMPLEST NATURAL ATOM

Hydrogen atom



MPI Garching (T. Hänsch)

$Q_{Hydrogen}$ ~ 20,000,000

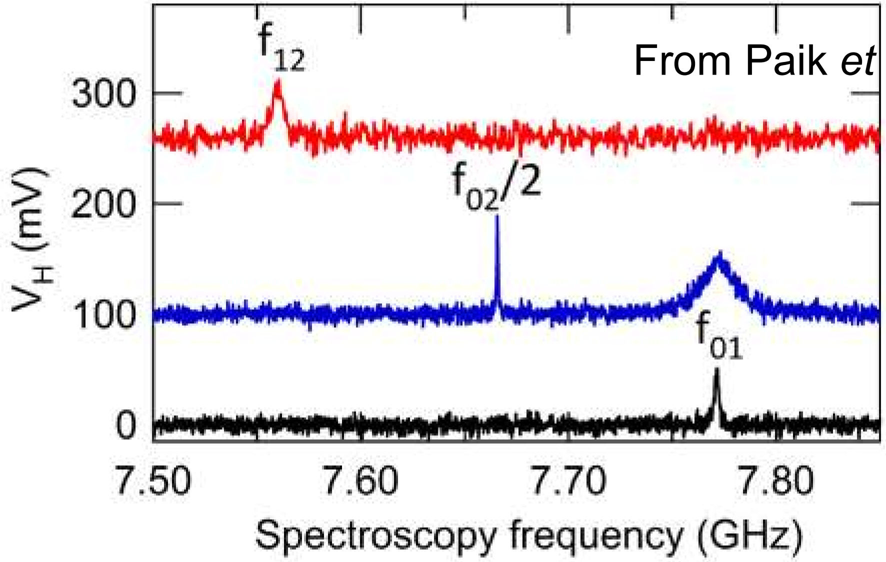
photon energy ~ 10eV

Q ~20 million!
Nathalie de Leon
& Andrew Houck
Princeton, 2025

$Q_{Transmon}$ ~ 8,000,000

photon energy ~ 30μeV

Transmon



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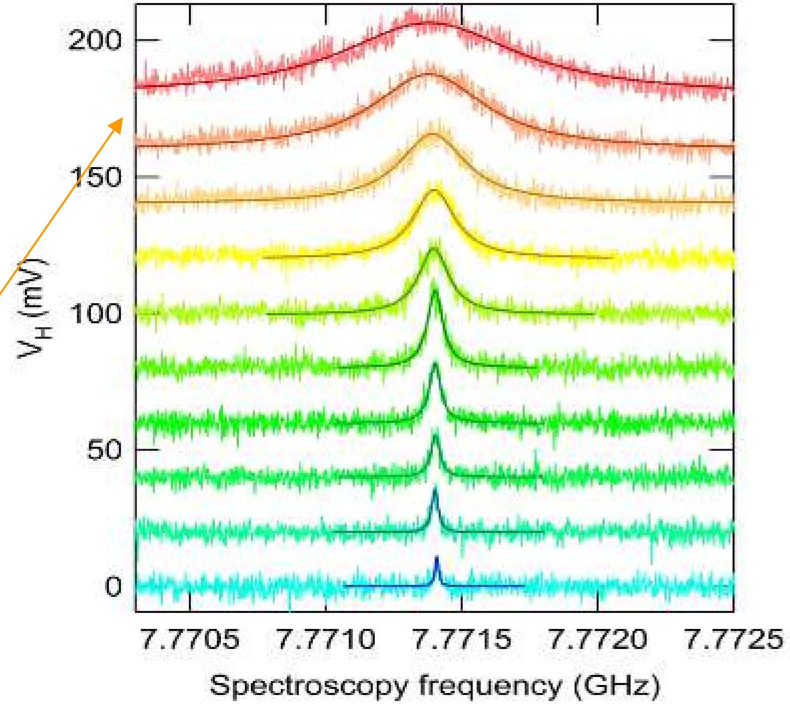
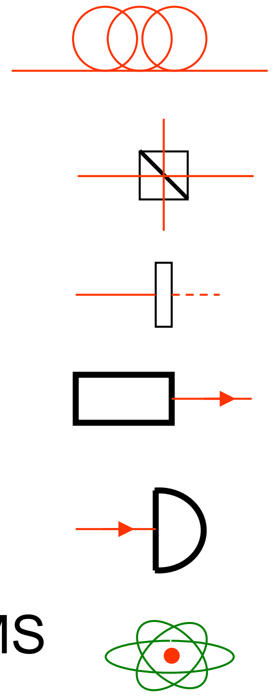
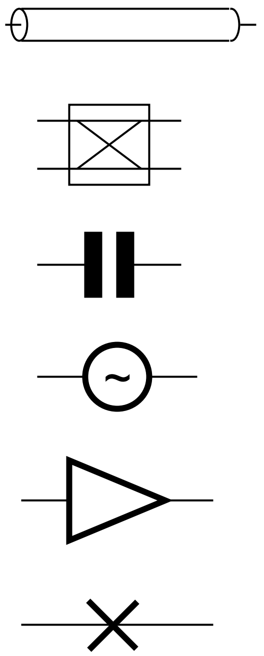


Ultimate linewidth from T2 echo: ~1kHz

QUANTUM OPTICS	↔	QUANTUM MICROWAVE OPTICS
FIBERS, BEAMS		TRANSM. LINES, WIRES
BEAM-SPLITTERS		DIR. COUPLERS
MIRRORS		CAPACITORS
LASERS		GENERATORS
PHOTODETECTORS		QUANTUM LIMITED AMPLIFIERS
ELECTRONS IN ATOMS		JOSEPHSON ELEMENT

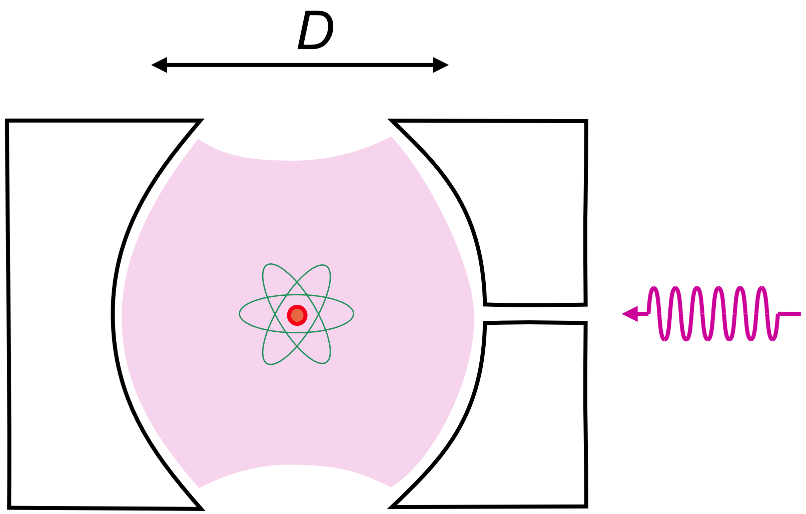


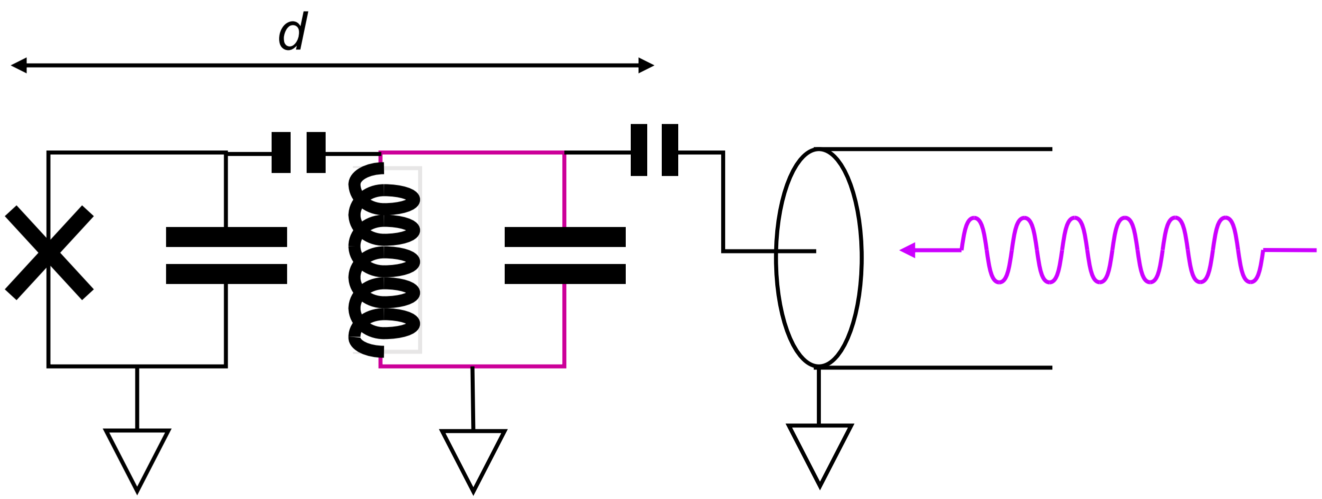


See review by Blais, Grimsmo, Girvin and Wallraff, Rev. Mod. Phys. **93**, 025005, 2021

READOUT: CAVITY QED vs CIRCUIT QED

QED =
Quantum ElectroDynamics





Cavity resonantly **enhances** coupling between natural atom and readout electromagnetic field

$$\omega_{\text{atom}} = \omega_{\text{cavity}}$$

$$\lambda / 2 \ll D$$

Resonator acts as bandpass filter and **diminishes** coupling between synthetic atom and electromagnetic field

$$\omega_{\text{atom}} < \omega_{\text{cavity}}$$

$$\lambda / 2 \gg d$$

lumped element,
near-field regime

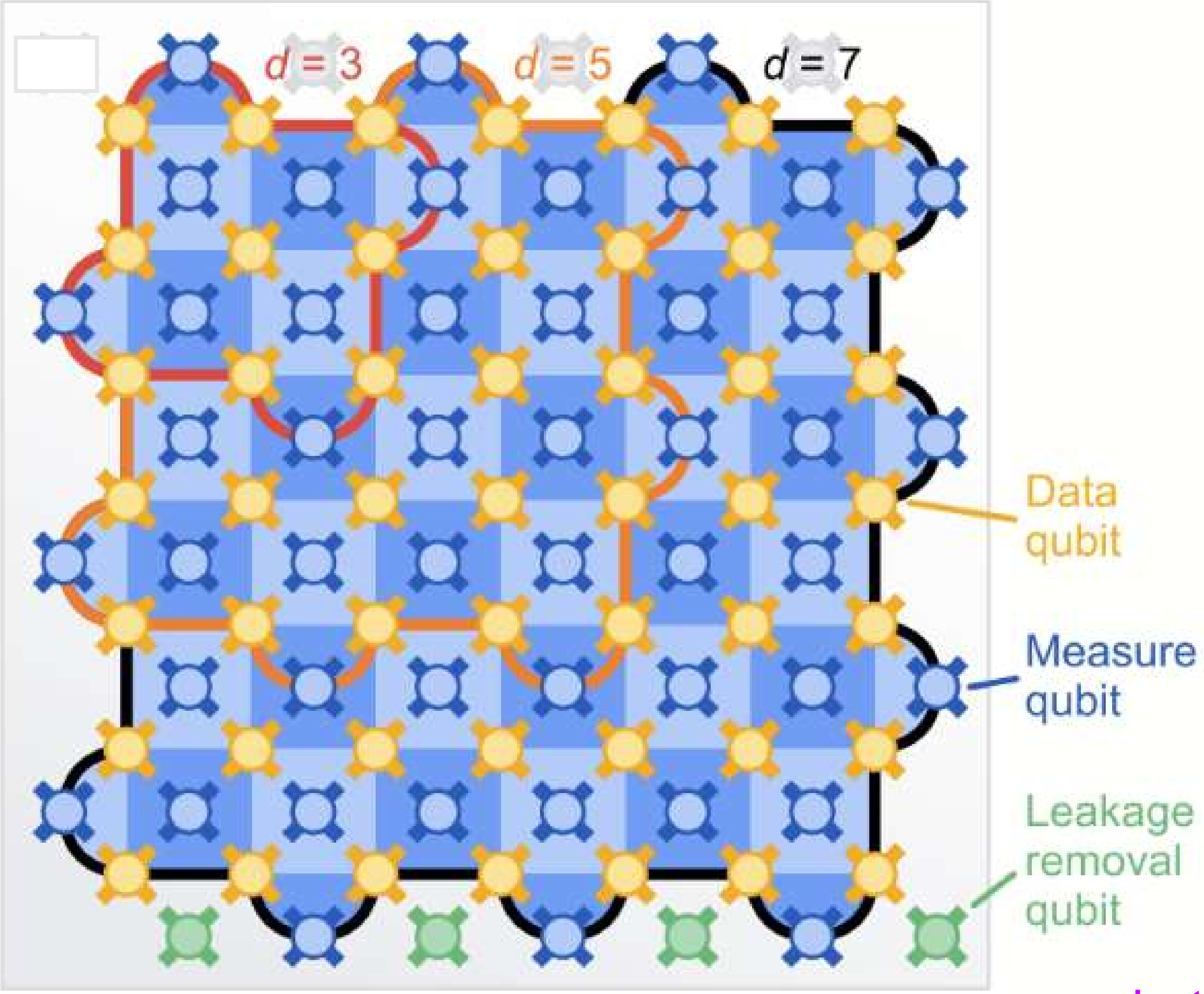
Blais, Grimsmo, Girvin and Wallraff, Rev. Mod. Phys. **93**, 025005, 2021

WHAT CAN YOU DO WITH ARTIFICIAL ATOMS THAT YOU CANNOT DO WITH NATURAL ATOMS (YET)?

- measure the traversal time of tunneling (Saclay, 1988)
- prepare a Schroedinger Cat state living in two boxes (Yale, 2016)
- observe the finite duration of quantum jumps and reverse them (Yale, 2018)
- perform random circuit sampling beyond classical regime (Google, 2019)
- **do quantum error correction beyond break-even (Yale, 2023; Google, 2025)**
- employ as detectors to perform NMR experiments on single nuclei (Saclay, 2025)
- run verifiable quantum echoes algorithm with practical advantage (Google, 2025)

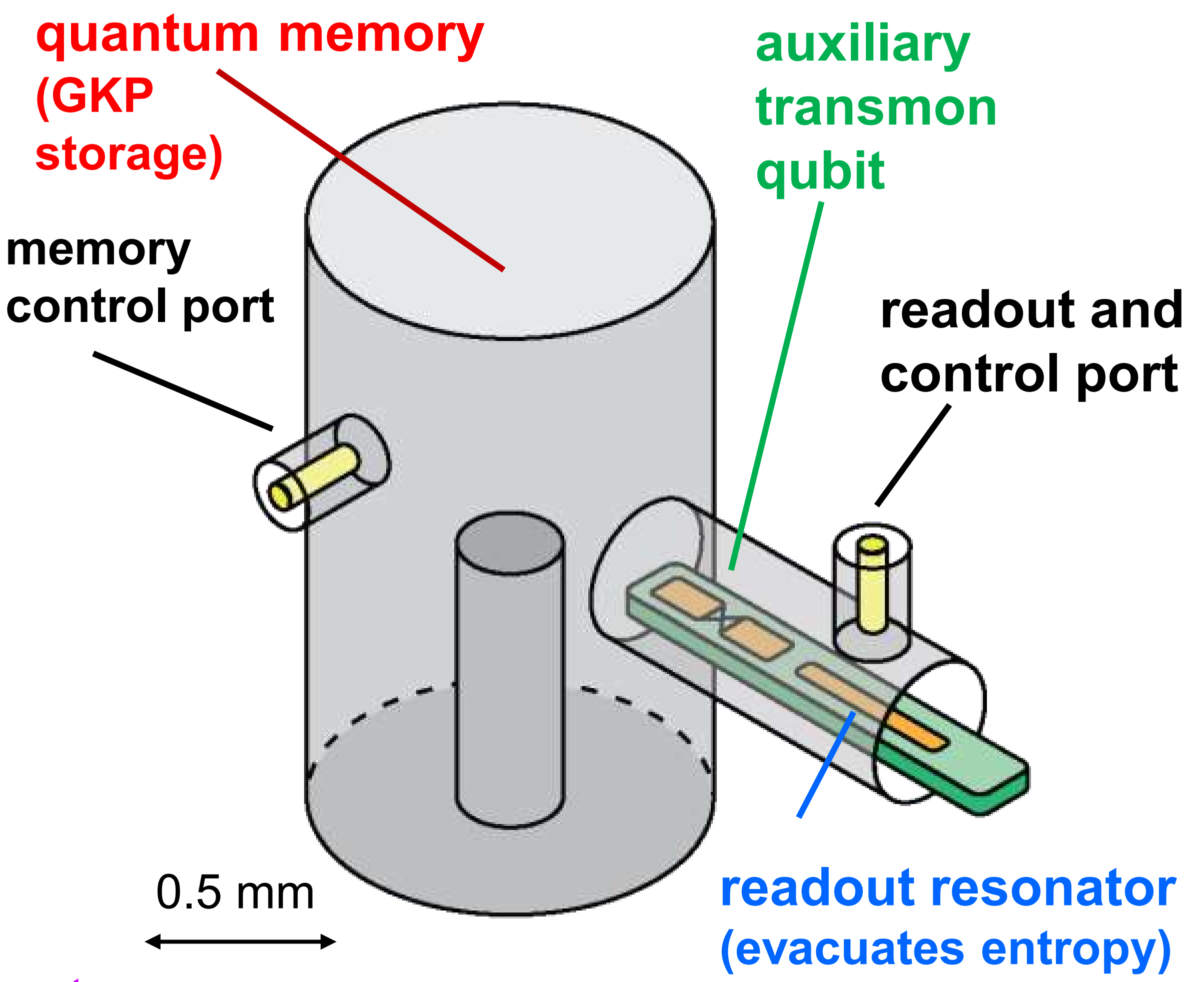
READOUT OF QUBITS: CRUCIAL FOR QUANTUM ERROR CORRECTION

SURFACE CODE (KITAEV 1997)



Google QAI, Nature **638**, 920 (2025)

GOTTESMANN-KITAEV-PRESKILL CODE (2001)



Sivak *et al.*, Nature **616**, 50 (2023)

both expts achieve beyond break-even QEC!

PROBLEM:
TOO MANY WIRES!

credit: Google Quantum AI, Santa-Barbara

CONCLUSIONS AND PERSPECTIVES

EMERGENT COLLECTIVE VARIABLES LIKE ELECTRICAL CURRENTS AND VOLTAGES CAN BE CONTROLLED THROUGH THE TRANSITION FROM THE CLASSICAL TO THE QUANTUM REGIME

FRICTION AFFECTING THESE VARIABLES CAN BE MANIPULATED TO THE POINT AT WHICH ENTROPY IS REMOVED FASTER THAN THE ERROR-CORRECTION THRESHOLD

THE NEW FIELD OF ARTIFICIAL ATOMIC PHYSICS AND MICROWAVE QUANTUM OPTICS IS BEING APPLIED TO QUANTUM INFORMATION PROCESSING AND QUANTUM SENSING

HOW FAR IN SCALE CAN WE EXTEND THE SUCCESS OF STANDARD QUANTUM MECHANICS?

ACKNOWLEDGEMENTS

Principal investigators

N.O. Birge, John Clarke, Daniel Esteve, Luigi Frunzio, Steve Girvin, Leonid Glazman, Hermann Grabert, Benjamin Huard, Liang Jiang, Mazyar Mirrahimi, Hans Mooij, Pief Orfila, Shruti Puri, Jan van Ruitenbeek, Rob Schoelkopf, Doug Stone, Hong Tang, Cristian Urbina.

Students at Saclay:

Vincent Bouchiat, Audrey Cottet, Ronald Cron, Sophie Guéron, Philippe Joyez, Philippe Lafarge, Frédéric Pierre, Hugues Pothier, Emmanuel Turlot.

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Abdelhanin Aassime, Andrew Cleland, Thorsten Holst, John Martinis, Elke Scheer, Andy Steinbach, Denis Vion.

Students at Yale

Luke Bell, Tom Connolly, Wei Dai, Spencer Diamond, Andy Ding, Alec Eickbusch, Simon Fissette, Nicholas Frattini, Kurtis Geerlings, Sofia Gonzalez (UCSB), Thomas Max Hays, Vidul Joshi, Archana Kamal, Akshay Koottandavida, Pavel Kurilovich, Yehan Liu, Vladimir Manucharyan, Nicholas Masluk, Zlatko Minev, Michael Metcalfe, Shantanu Mundhada, Anirudh Narla, Heekun Nho, Chad Rigetti, Ananda Roy, Flavius Schackert, Max Schaefer, Kyle Serniak, Volodymyr Sivak, Katrina Sliwa, Cassidy Smith, William Clarke Smith, Steven Touzard, Gautham Umasankar, Jaya Venkat, Rajamani Vijay, Uri Vool, Xu Xiao, Evan Zalys- Geller, Zhixin Wang. UCSB: Vivek Dhande.

Postdocs at Yale

Baleegh Abdo, Nicolas Bergeal, Etienne Boaknin, Charlotte Boettcher, Markus Brink, Benjamin Brock Philippe Campagne-Ibarcq, Aash Clerk, Liam Cohen (UCSB), Rodrigo Cortinas, Alexander Grimm, Gijs de Lange, Valla Fatemi, Michael Hatridge, Philippe Hyafill, Ioannis Tsioutsios, Sumeru Hazra, Angela Kou, Zaki Leghtas, Gangqiang Liu, Sandro Miano, Frederic Pierre, Ioan Pop, Shyam Shankar, Irfan Siddiqi, Chris Wilson.

Funding: CEA, Yale, Keck, College de France, ANR, NSF, BSF, ARO, AFOSR, ONR, DOE, DARPA, Google

THE END