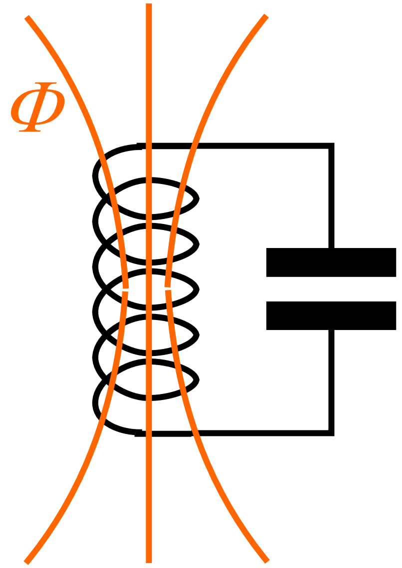
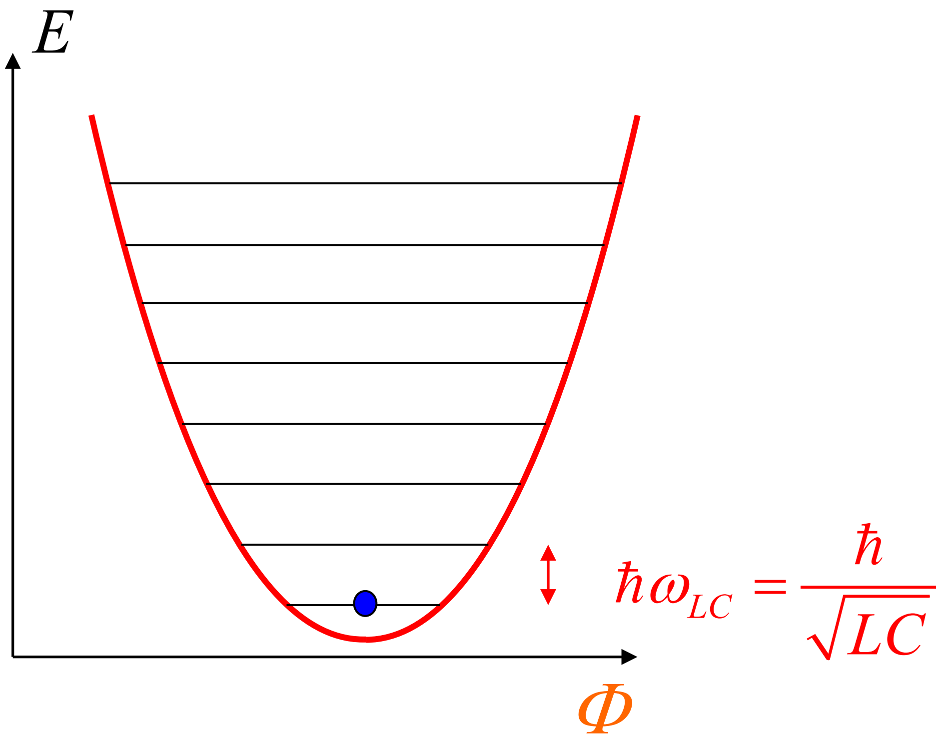
CAPRI SPRING SCHOOL 2024

Michel Devoret

LECTURE 2

RESET: PLACE CIRCUIT IN ITS GROUND STATE





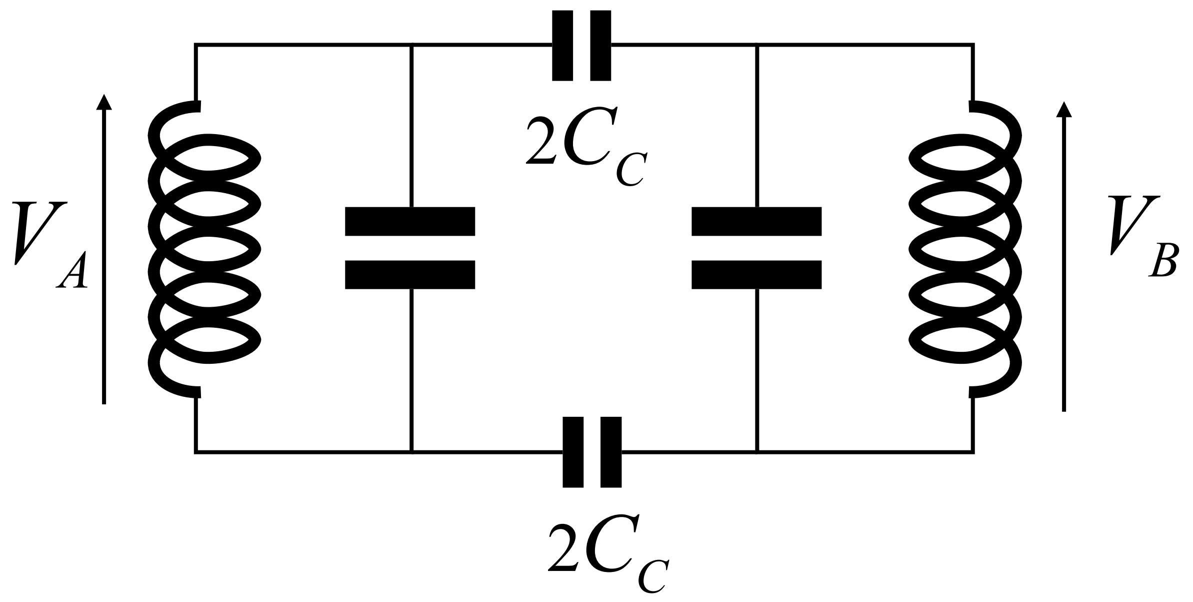
some cold dissipation is actually needed: provides reset of circuit!

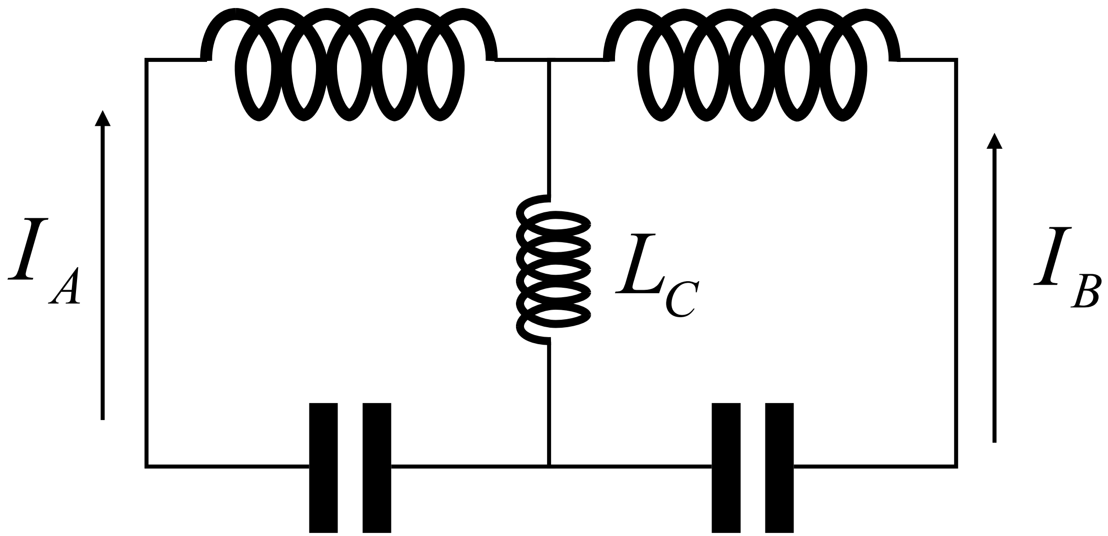
$$\hbar\omega_{LC} \gg k_B T$$

10-5 GHz ($\hbar\omega_{LC}$) 10mK (T)

UNLIKE ATOMS IN VACUUM, TWO CIRCUITS EASILY COUPLE:

CAPACITIVE vs INDUCTIVE COUPLING

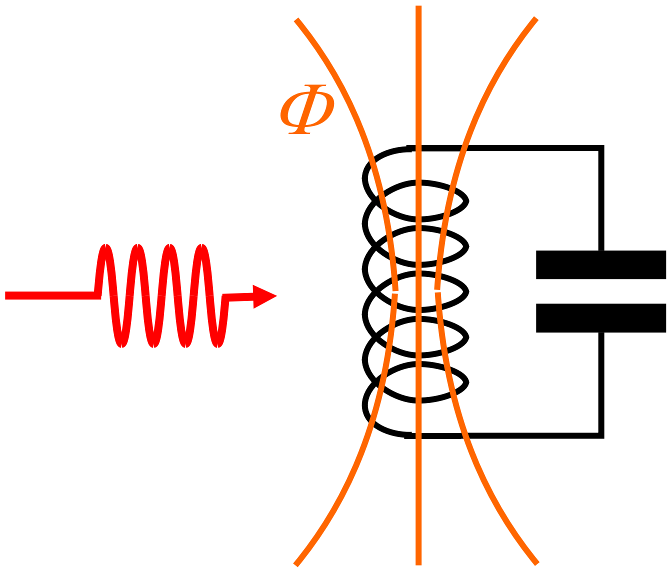


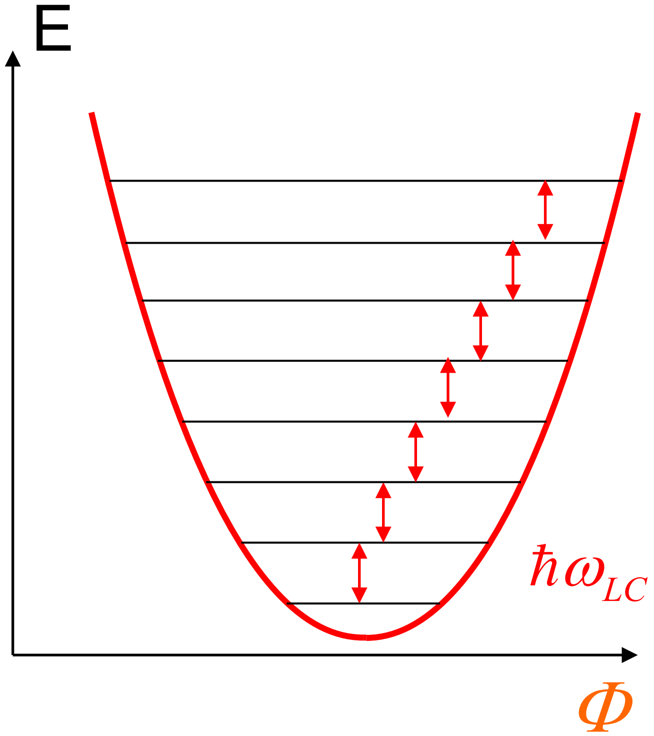


$$\hat{H}_{\text{coupling}} = -C_C \hat{V}_A \hat{V}_B = \frac{\hbar}{2}\sqrt{\omega_A \omega_B}\,\frac{C_C}{\sqrt{C_A C_B}}\left(\hat{a}-\hat{a}^\dagger\right)\left(\hat{b}-\hat{b}^\dagger\right)$$

$$\hat{H}_{\text{coupling}} = L_C \hat{I}_A \hat{I}_B = \frac{\hbar}{2}\sqrt{\omega_A \omega_B}\,\frac{L_C}{\sqrt{L_A L_B}}\left(\hat{a}+\hat{a}^\dagger\right)\left(\hat{b}+\hat{b}^\dagger\right)$$

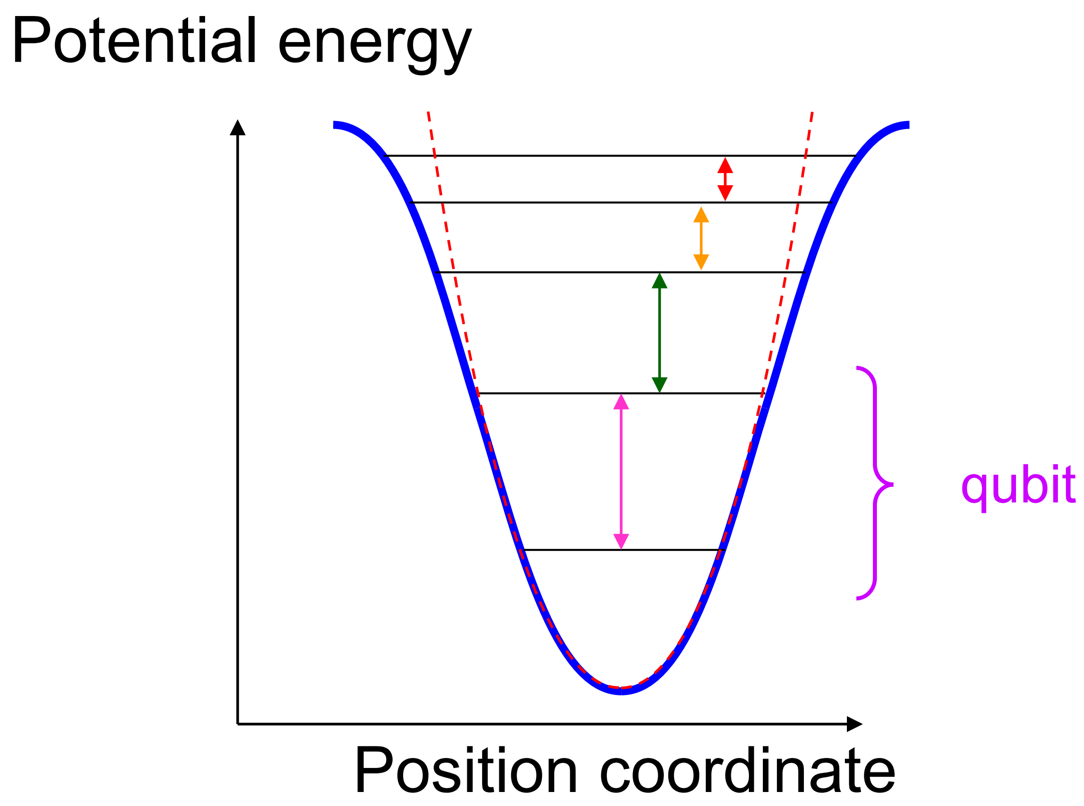
CAVEAT: THE QUANTUM STATES OF A PURELY LINEAR CIRCUIT CANNOT BE FULLY CONTROLLED!



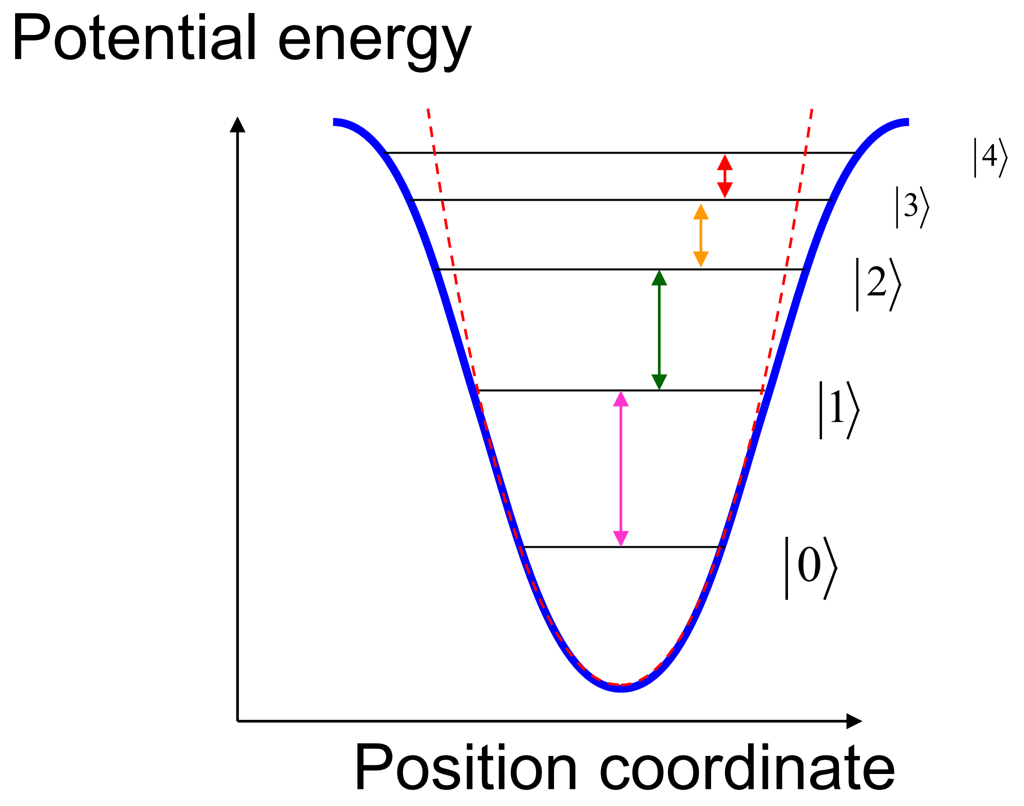


NO STEERING TO AN ARBITRARY STATE
IF SYSTEM PERFECTLY LINEAR

NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

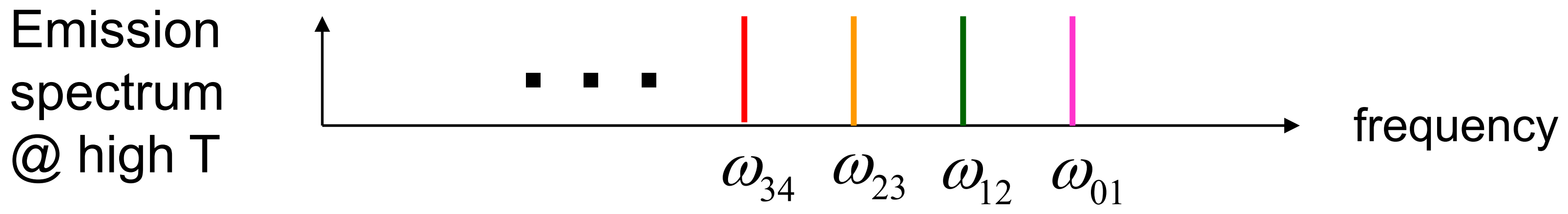


NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

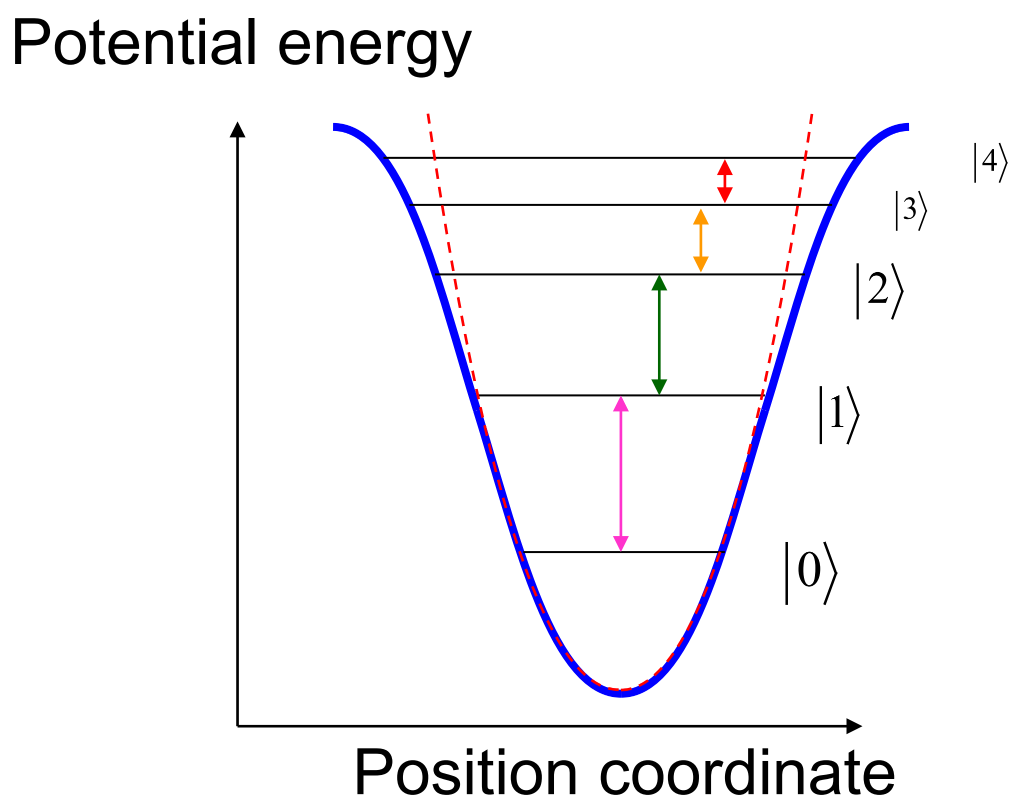


non-linearity ratio:

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

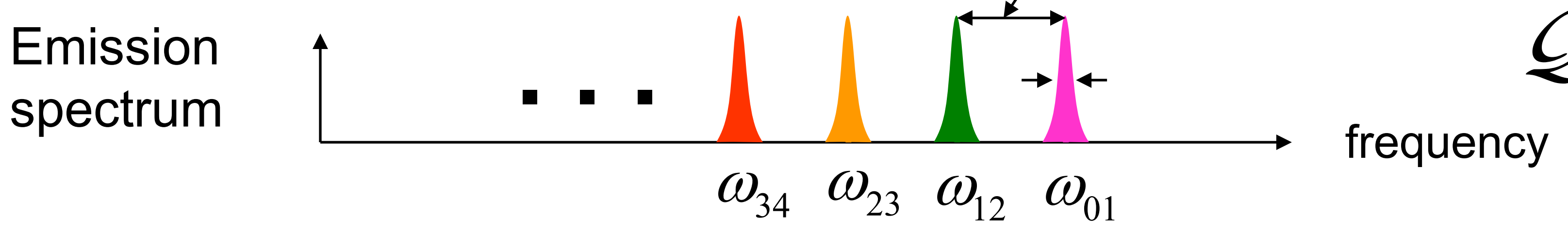


NEED NON-LINEARITY TO FULLY REVEAL QUANTUM-MECHANICAL BEHAVIOR

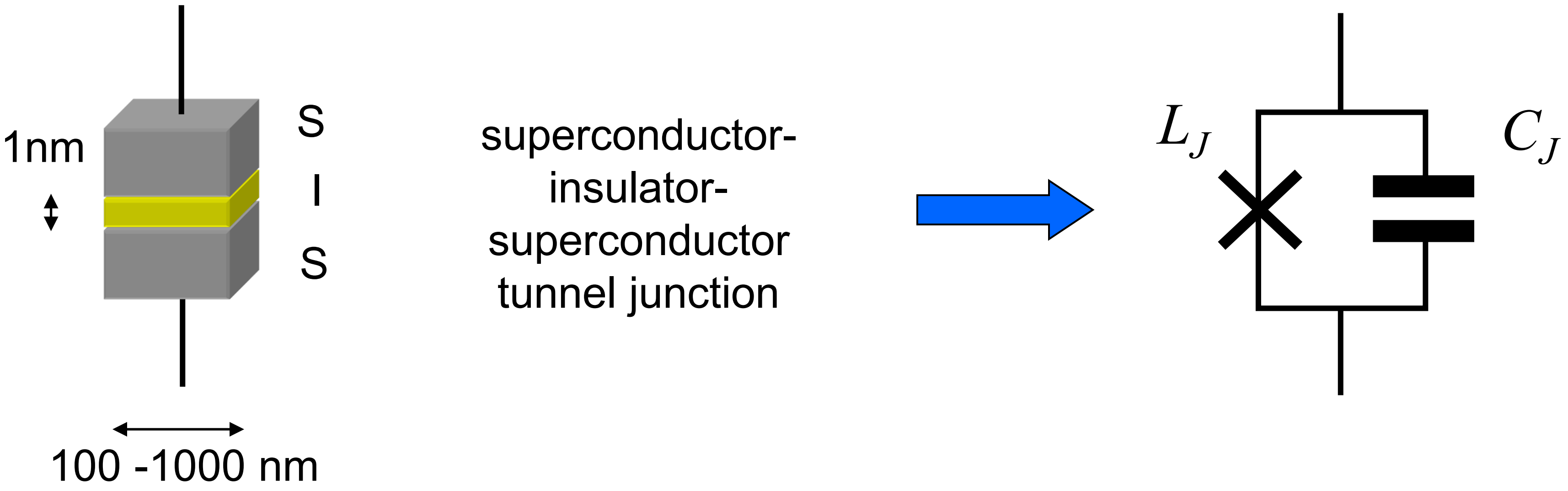


effective relative non-linearity: ratio of peak distance to peak width

$\mathcal{Q} \times NLR$

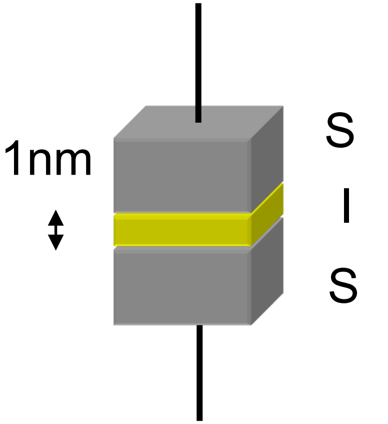


JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO FUNDAMENTAL DISSIPATION

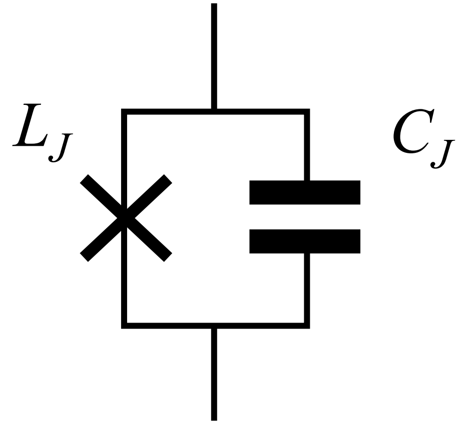


MIGHT BE SUPERSEDED SOME DAY BY ANOTHER DEVICE,
BUT Al-AlOx-Al TUNNEL JUNCTIONS STILL REIGN...

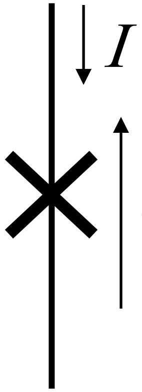
JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO FUNDAMENTAL DISSIPATION



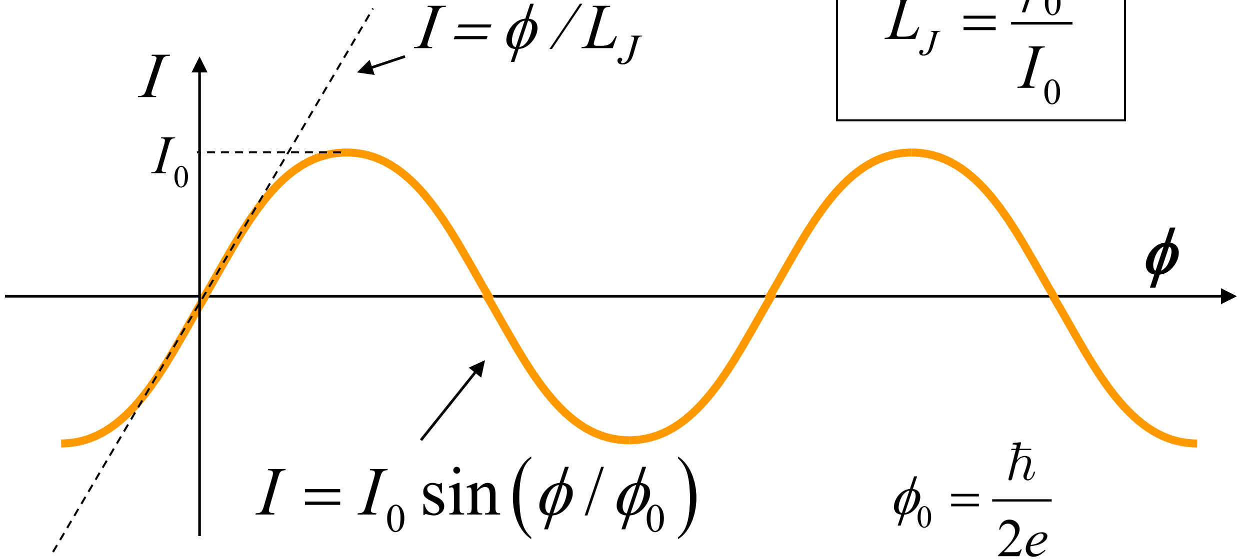
superconductor-
insulator-
superconductor
tunnel junction



$$L_J = \frac{\phi_0}{I_0}$$



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

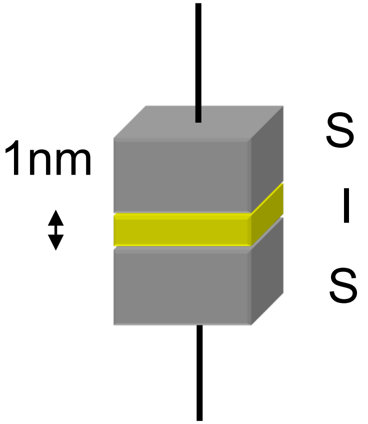


$$I = \phi / L_J$$

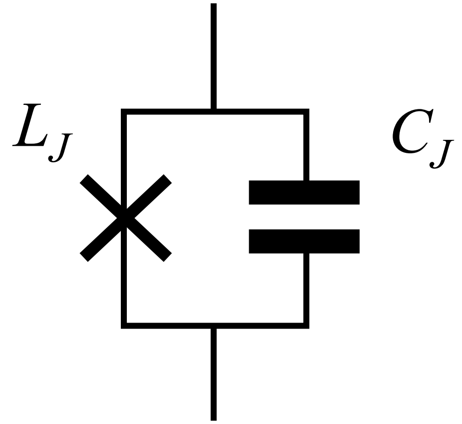
$$I = I_0 \sin(\phi / \phi_0)$$

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

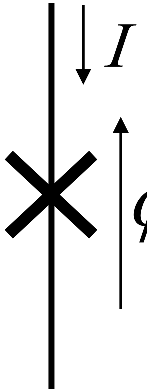
JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO FUNDAMENTAL DISSIPATION



superconductor-insulator-superconductor tunnel junction

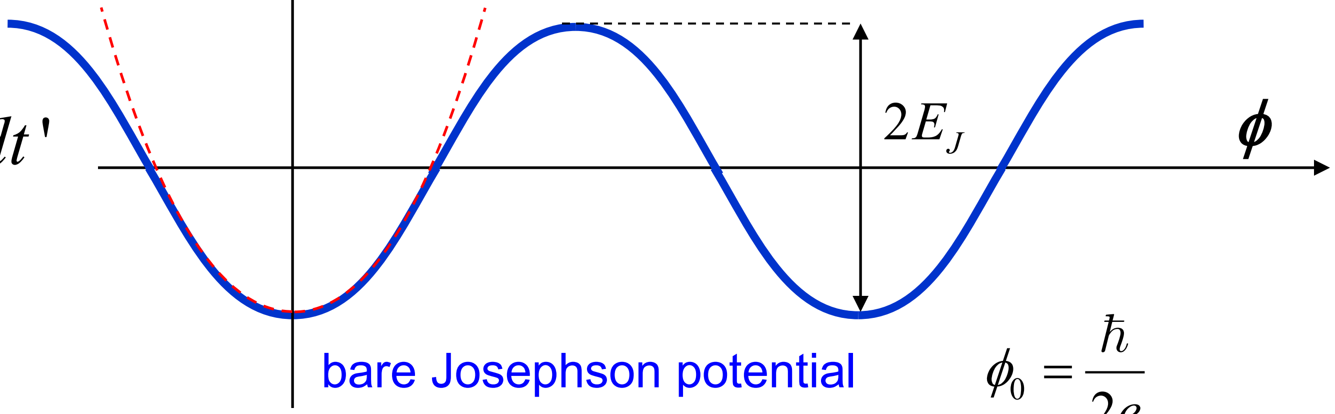


$$L_J = \frac{\phi_0^2}{E_J}$$



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

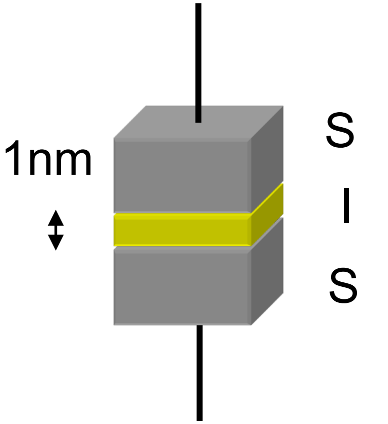
$$U = -E_J \cos\left(\phi / \phi_0\right)$$



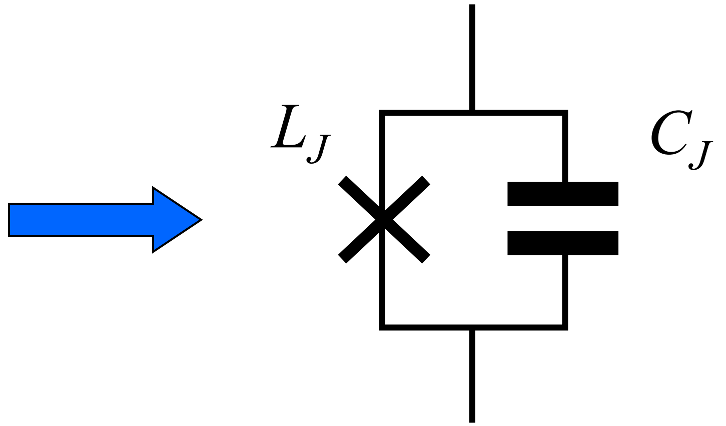
bare Josephson potential

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

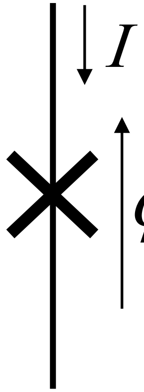
A NON-LINEAR INDUCTANCE WITH NO FUNDAMENTAL DISSIPATION: THE JOSEPHSON TUNNEL ELEMENT



superconductor-
insulator-
superconductor
tunnel junction



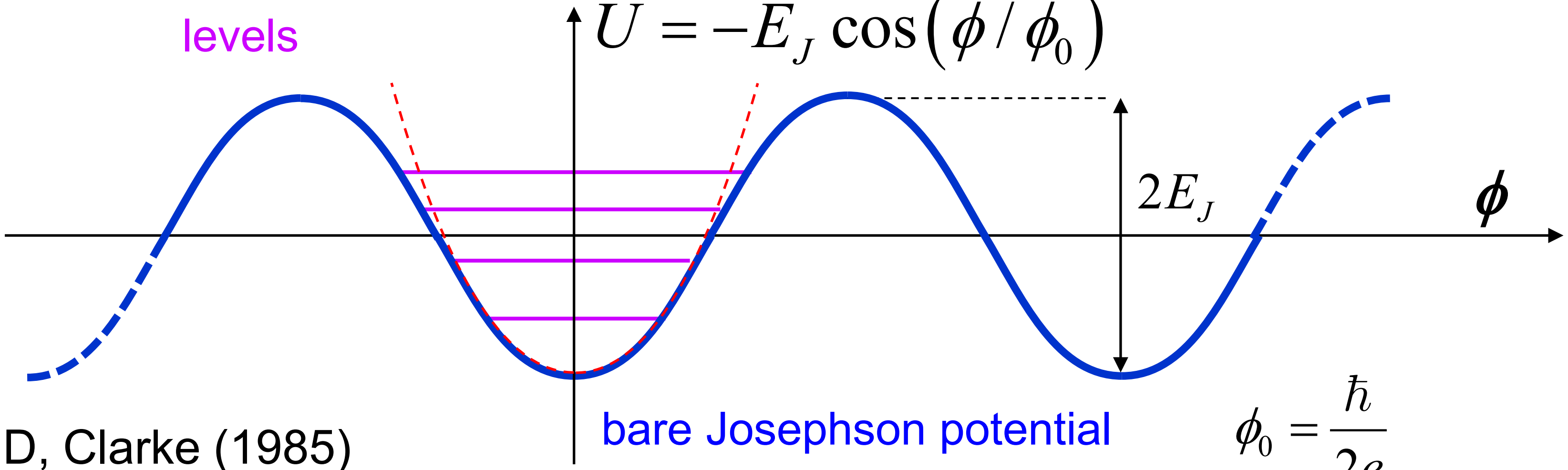
$$L_J = \frac{\phi_0^2}{E_J}$$



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

synthetic
atom
levels

$$U = -E_J \cos(\phi / \phi_0)$$

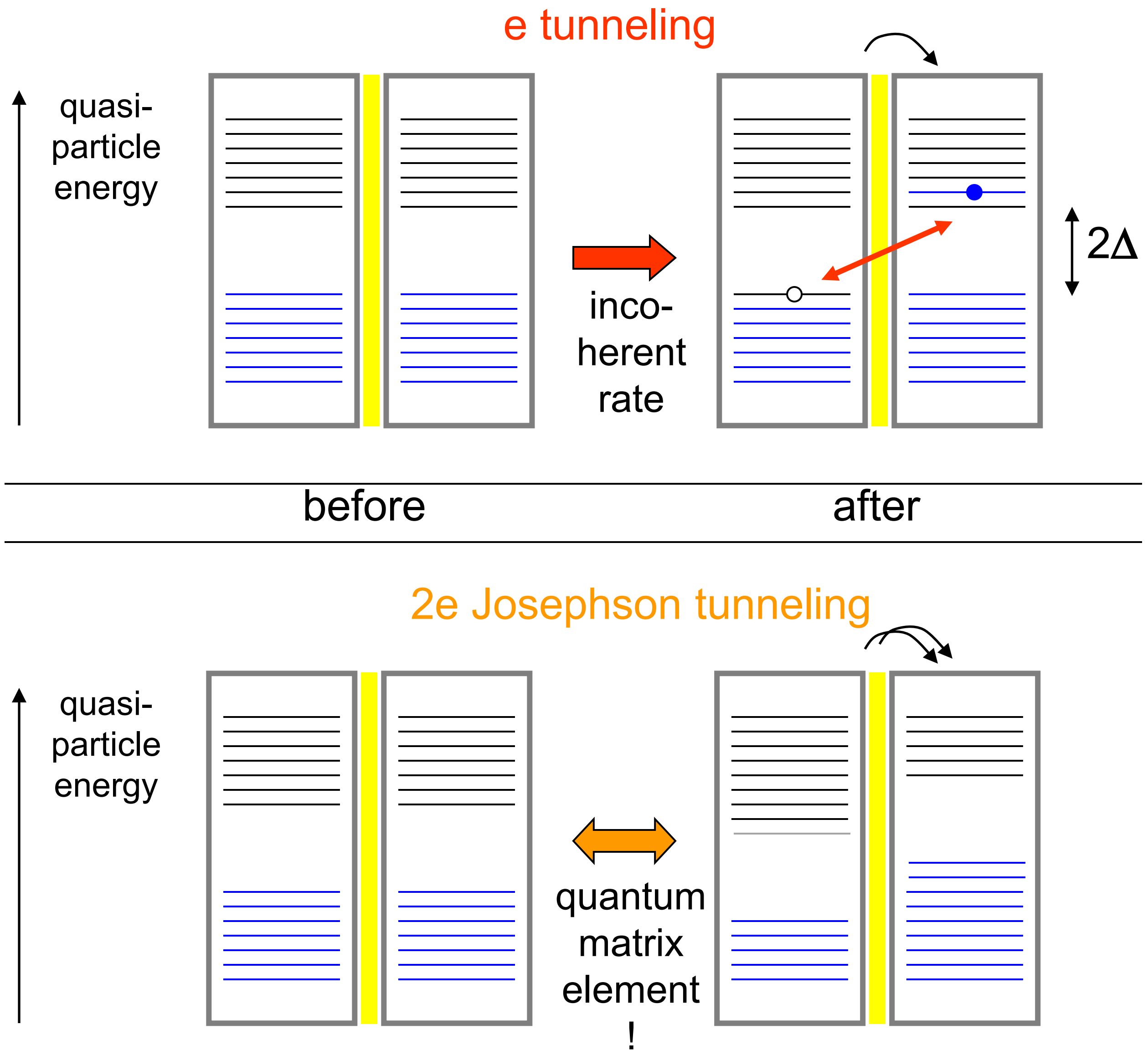


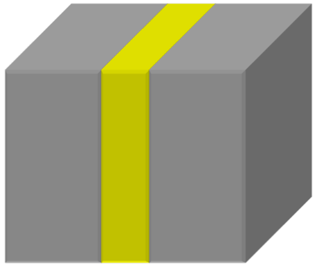
bare Josephson potential

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

Martinis, MD, Clarke (1985)

TWO TYPES OF TUNNELING





Josephson tunneling hamiltonian in charge basis:

$$\hat{H}_J = -\frac{E_J}{2}\sum_N \left(|N\rangle\langle N+1| + |N+1\rangle\langle N| \right)$$

Charge states: $\hat{N}|N\rangle = N|N\rangle$

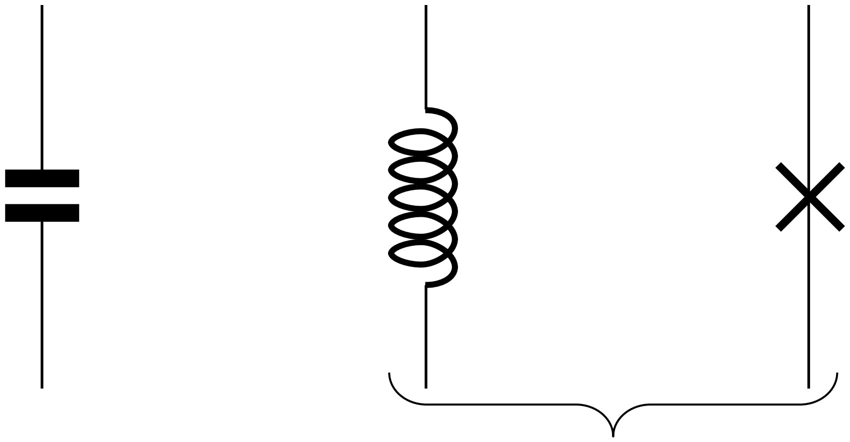
$$\hat{H}_J = -\frac{E_J}{2}\left(e^{i\hat{\varphi}} + e^{-i\hat{\varphi}}\right)$$

$$= E_J \cos\left(\hat{\phi}/\phi_0\right) \qquad \phi_0 = \frac{\hbar}{2e}$$

since: $e^{i\hat{\varphi}}\hat{N}e^{-i\hat{\varphi}} = \hat{N} - 1$

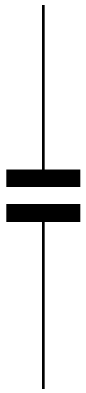
$$\hat{I}_J = \frac{E_J}{\phi_0}\sin\hat{\varphi}$$

SUPERCONDUCTING CIRCUIT ELEMENTS

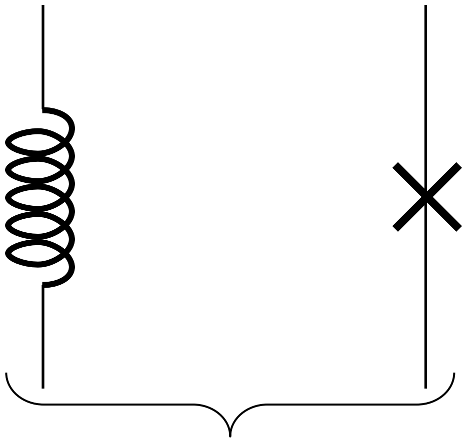


VERY SIMPLE LEGO-LIKE SET!

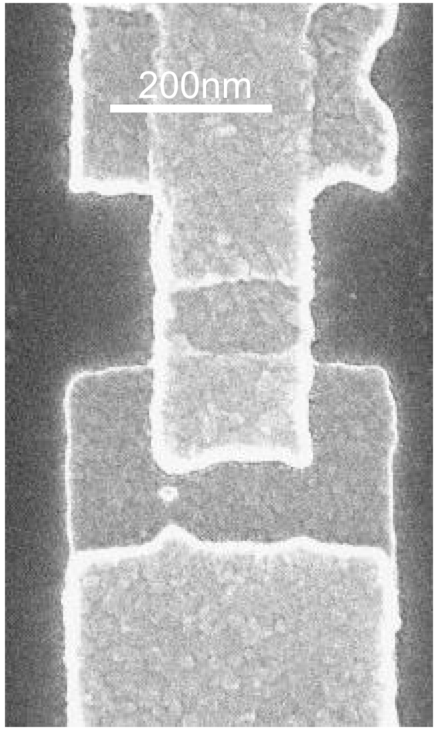
SUPERCONDUCTING CIRCUIT ELEMENTS



CAPACITANCE

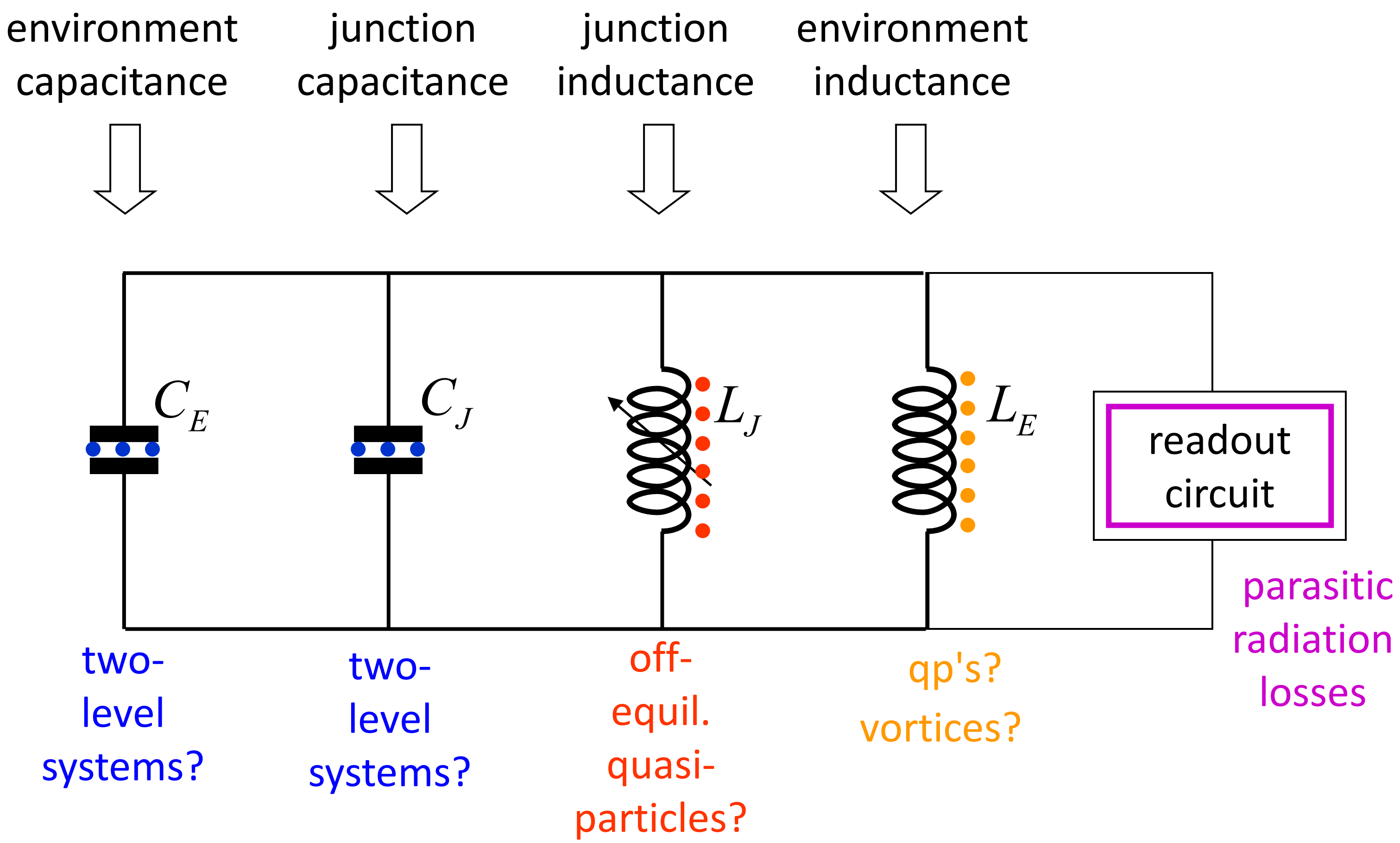


INDUCTANCE



Should we worry?

5 CONTRIBUTIONS TO DISSIPATION & NOISE



WHAT WE HAVE LEARNED ABOUT DISSIPATION IN SUPERCONDUCTING CIRCUITS

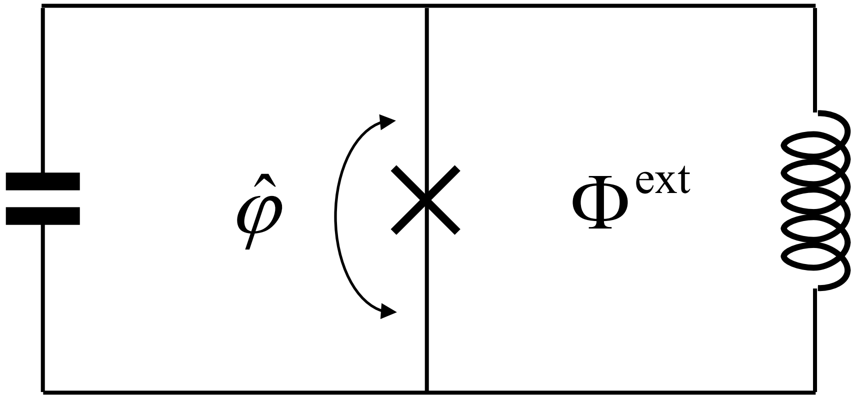
$$Q_J^{cap} > 20,000,000$$ Kim et al. (2011)

$$Q_J^{ind} > 100,000,000$$ Serniak et al. (2018)

$$Q_E^{cap} > 10,000,000$$ Place et al. (2020)

GIVEN BASIC CIRCUIT ELEMENTS, HOW SHOULD WE ENGINEER OUR ATOMS ?

BASIC
"ATOM"

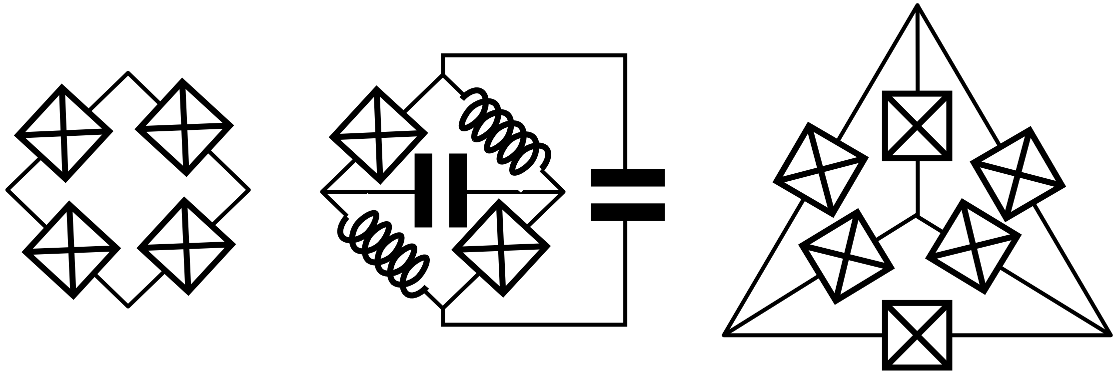


characteristic energies: $E_C = \dfrac{e^2}{2C}$ $\quad E_J = \dfrac{\hbar^2}{4e^2 L_J}$ $\quad E_L = \dfrac{\hbar^2}{4e^2 L}$

constraints: $E_C, \sqrt{8E_C E_J} \ll \Delta \leftarrow$ superconducting gap

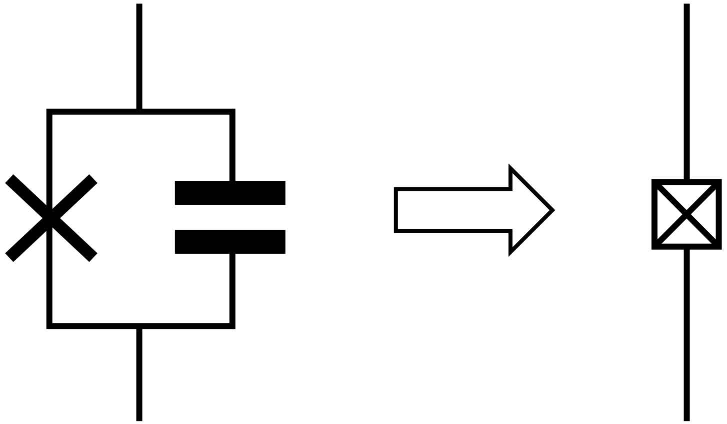
MULTI-JUNCTION CIRCUITS

"MOLECULES":



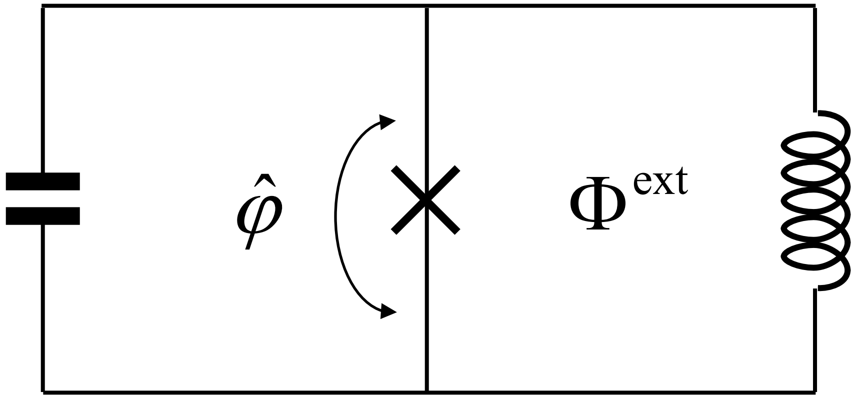
ETC....

idea:
protect quantum info from
decoherence through
circuit topology



Saclay, Yale, Rutgers, Grenoble, Paris, Mumbai, etc...

CIRCUIT HAMILTONIAN



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

$$\varphi = \frac{\phi}{\phi_0}$$

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

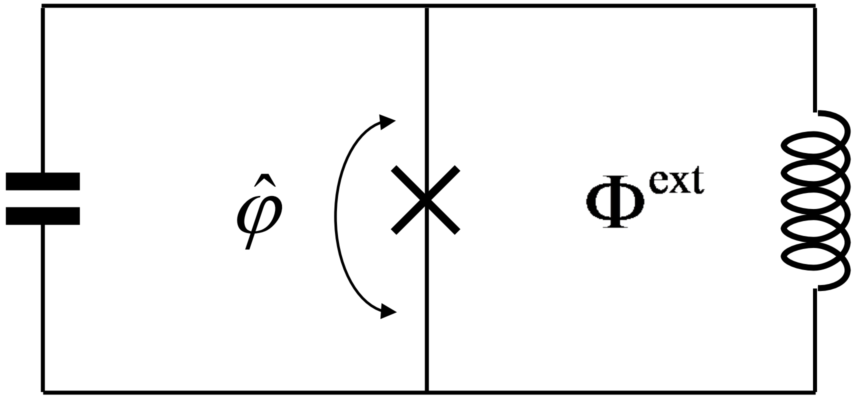
$$E_C = \frac{e^2}{2C} \qquad E_J = \frac{\hbar^2}{4e^2 L_J} \qquad E_L = \frac{\hbar^2}{4e^2 L}$$

$$\hat{H} = 4E_C\left(\hat{N} - N_t^{\text{ext}}\right)^2 - E_J \cos\left(\hat{\varphi}\right) + \frac{1}{2}E_L\left(\hat{\varphi} - \varphi_t^{\text{ext}}\right)^2$$

Compare with Hydrogen atom:

$$H = \frac{1}{2m_e}\left(\hat{p} - eA\right)^2 - \frac{e^2}{4\pi\varepsilon_0}\frac{1}{\hat{r}}$$

RELEVANT CIRCUIT PARAMETERS

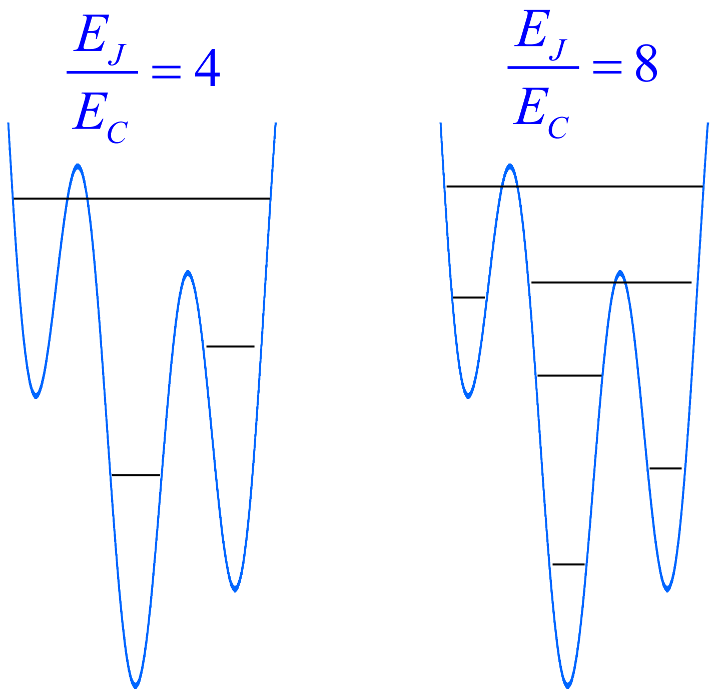


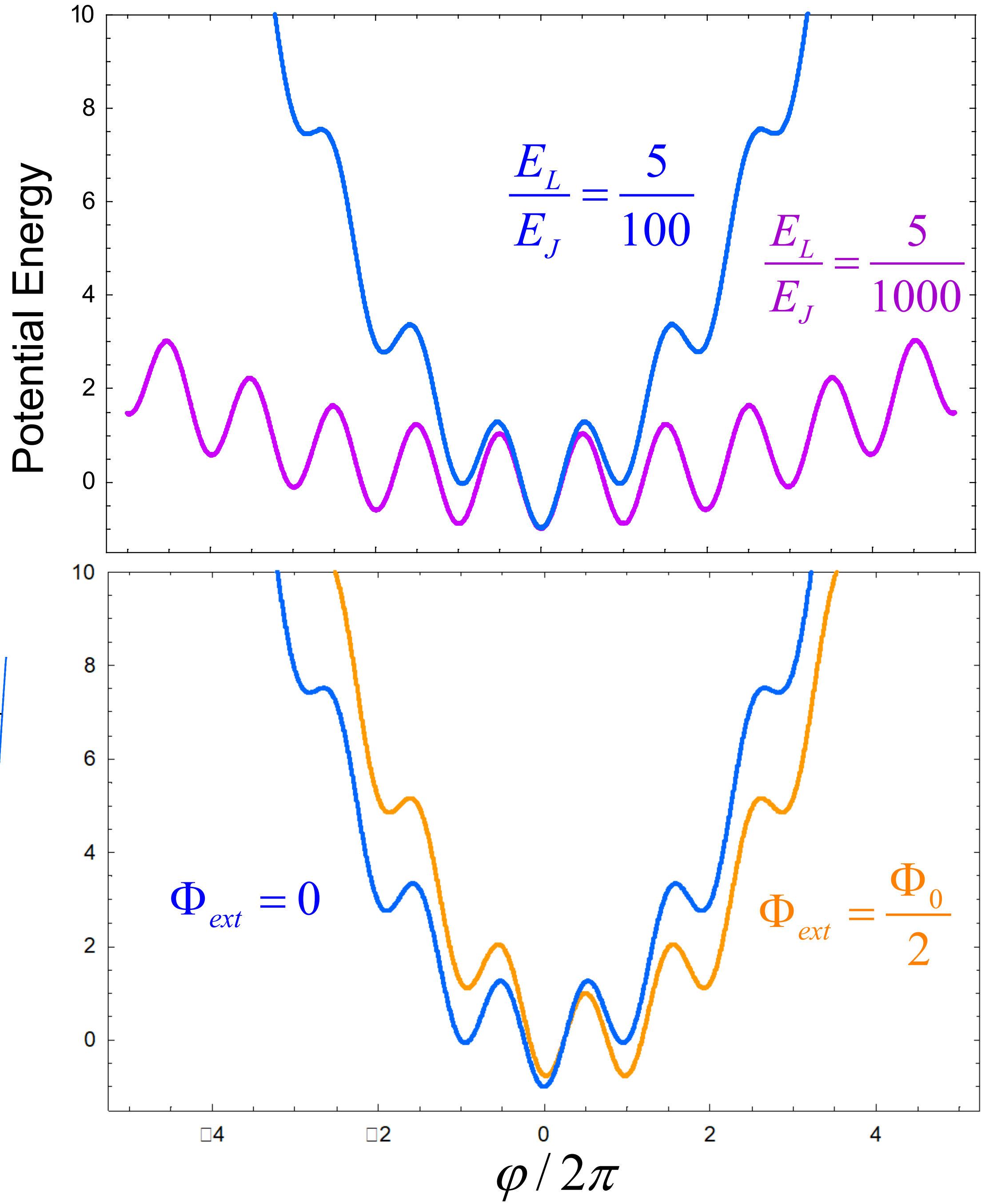
$$E_C = \frac{e^2}{2C} \qquad E_J = \frac{\hbar^2}{4e^2 L_J} \qquad E_L = \frac{\hbar^2}{4e^2 L}$$

Two aspect ratios fixed by fabrication: $\frac{E_L}{E_J}, \frac{E_C}{E_J}$

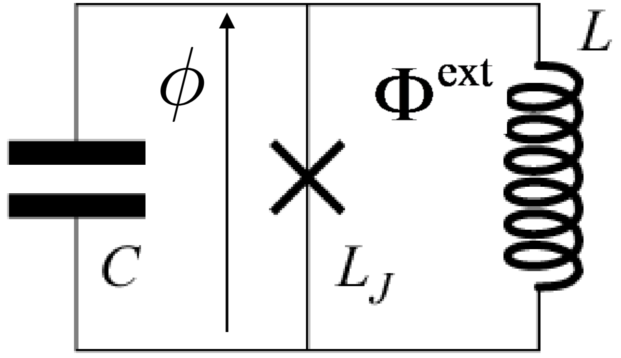
One in-situ knob: Φ^{ext}

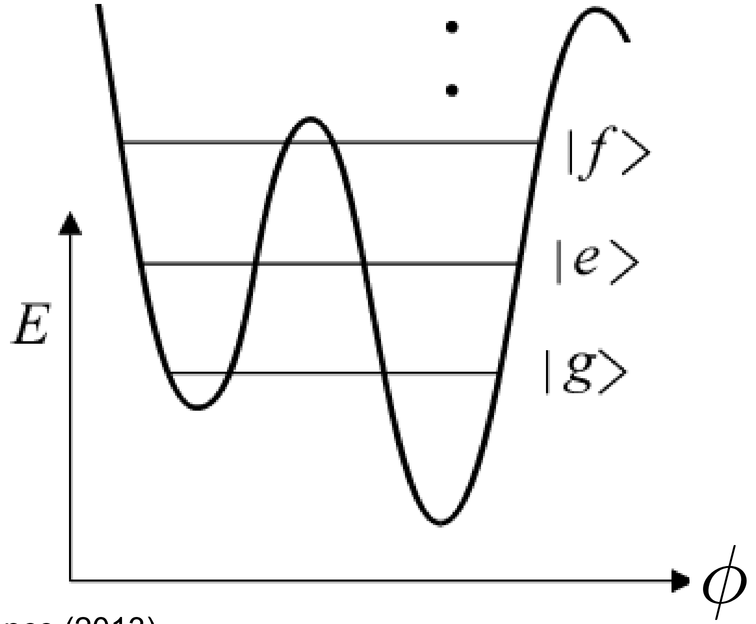
CHANGING POTENTIAL LANDSCAPE WITH CIRCUIT PARAMETERS

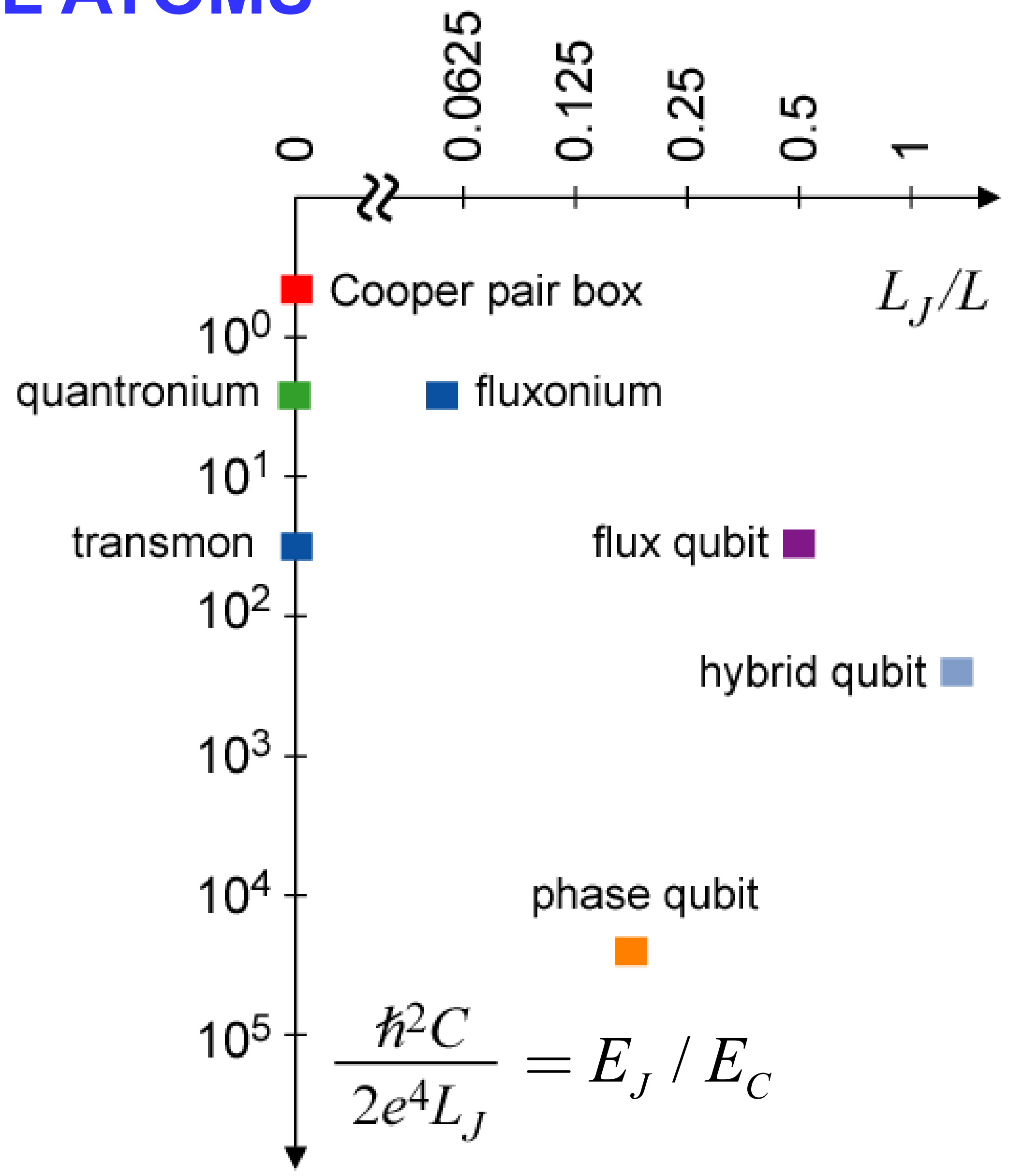




MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS

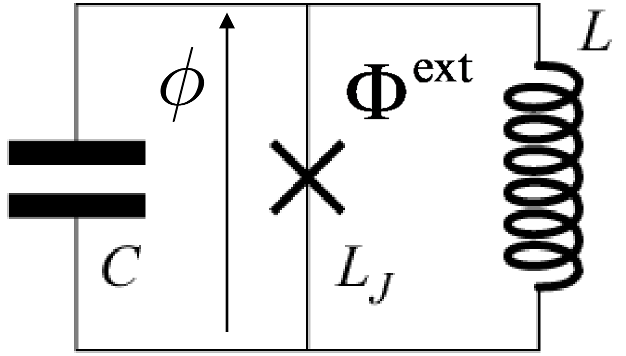


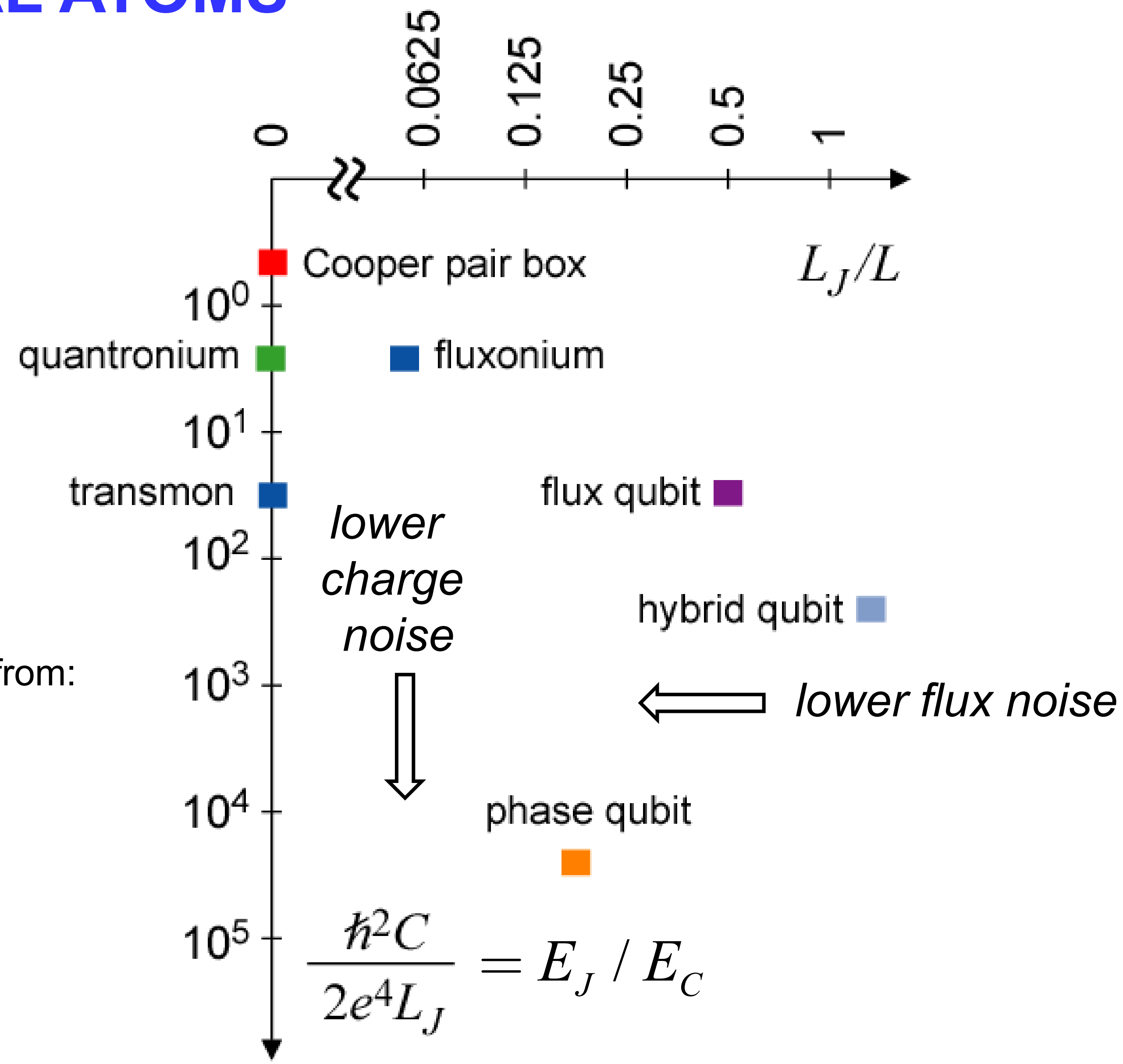




MD & R. Schoelkopf, Science (2013)

MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS

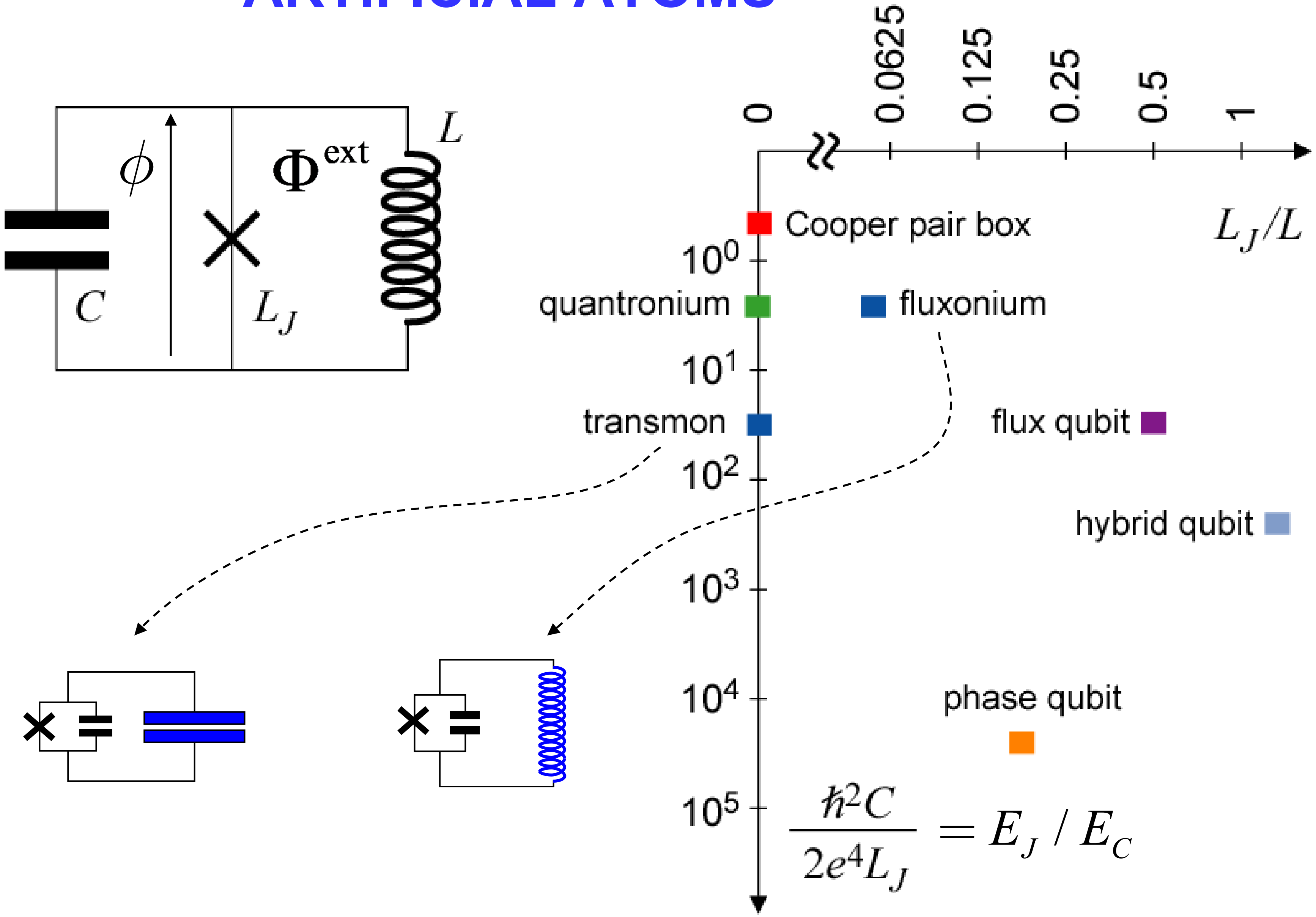




Original circuit parameters from:
Delft, NEC, MIT
IBM
NEC
Saclay
UCSB
Yale

MD & R. Schoelkopf, Science (2013)

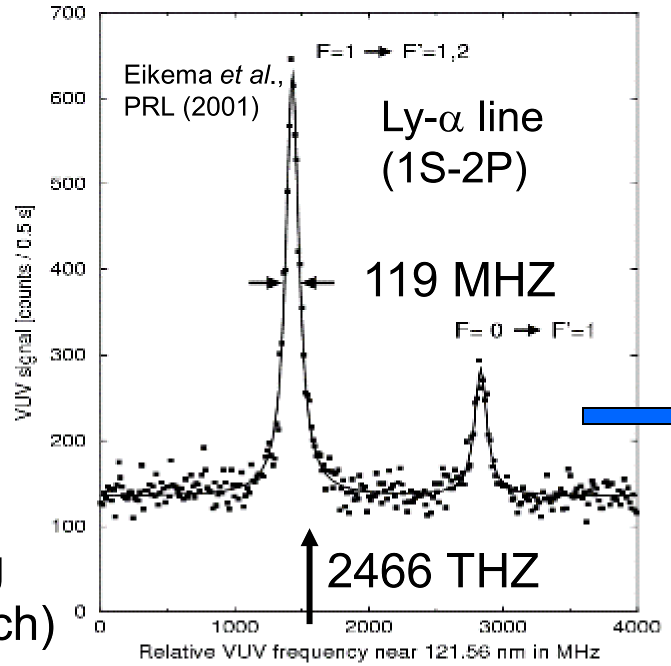
MENDELEEV-LIKE CLASSIFICATION OF SUPERCONDUCTING ARTIFICIAL ATOMS



MD & R. Schoelkopf, Science (2013)

COHERENCE OF ARTIFICIAL ATOMS NOW COMPETES WITH SIMPLEST NATURAL ATOM

Hydrogen atom



MPI Garching (T. Hänsch)

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

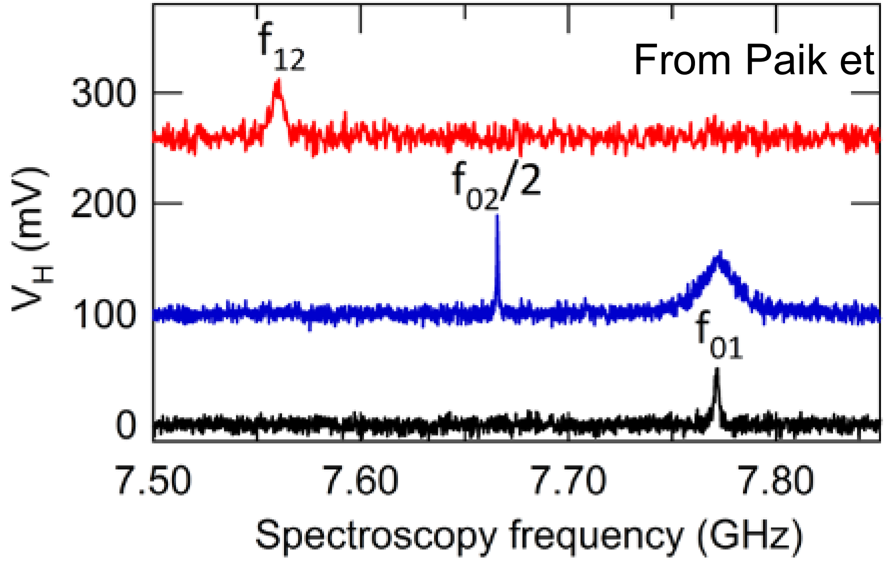
photon energy ~ 10eV

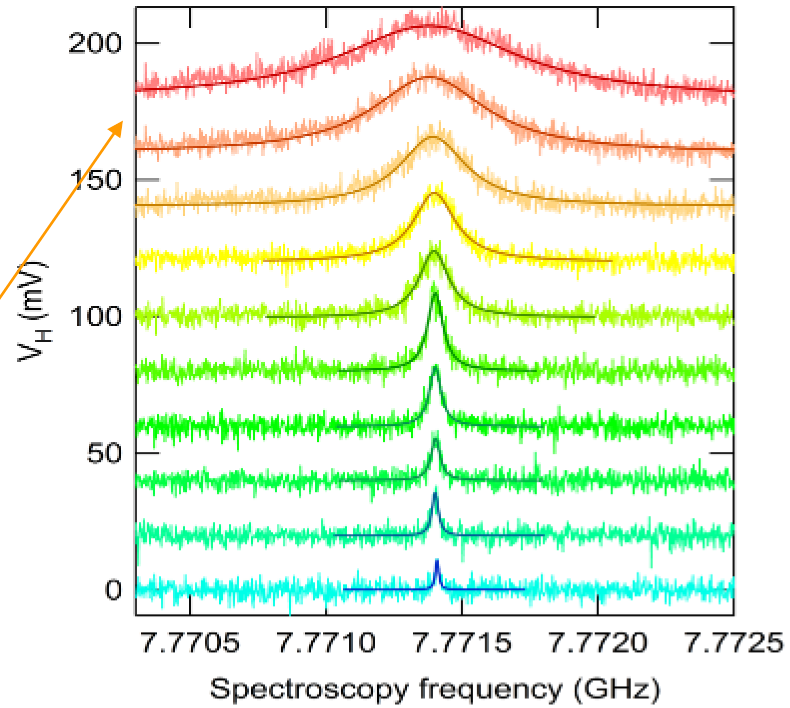
$Q_{Transmon}$ ~ 10,000,000

photon energy ~ 30μeV

Transmon

From Paik et al., PRL (2012)





Ultimate linewidth from T2 echo: ~1kHz