John Stewart Bell Prize

Part 1: Michel Devoret, Yale University

SUPERCONDUCTING ARTIFICIAL ATOMS: FROM TESTS OF QUANTUM MECHANICS TO QUANTUM COMPUTERS

Part 2: Robert Schoelkopf, Yale University

CIRCUIT QED, SCHRODINGER CATS AND QUANTUM JUMPS OF PARITY

CQIQC, University of Toronto, Aug. 15, 2013

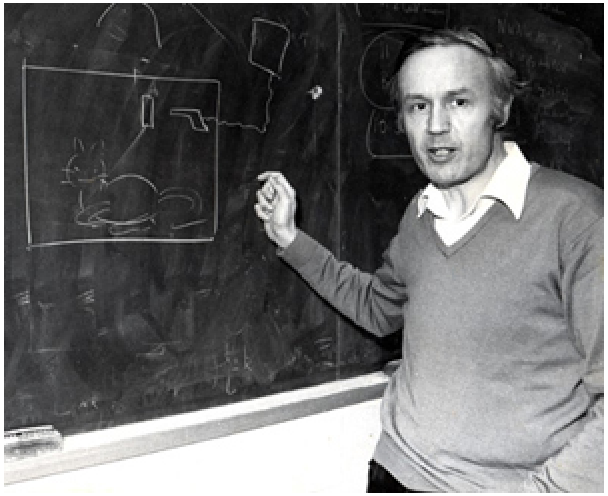
RESISTING THE TEMPTATION OF SUAC*

courtesy University of St Andrews

John Bell (1965)
Test local realism

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

Tony Leggett (1980)
Test macroscopic realism



courtesy University of Illinois, Urbana-Champaign

* Shut Up And Calculate !

A MACROSCOPIC, YET <u>QUANTUM</u>, DEGREE OF FREEDOM?

SIMPLEST EXAMPLE: **LC** OSCILLATOR CIRCUIT

~ 1mm

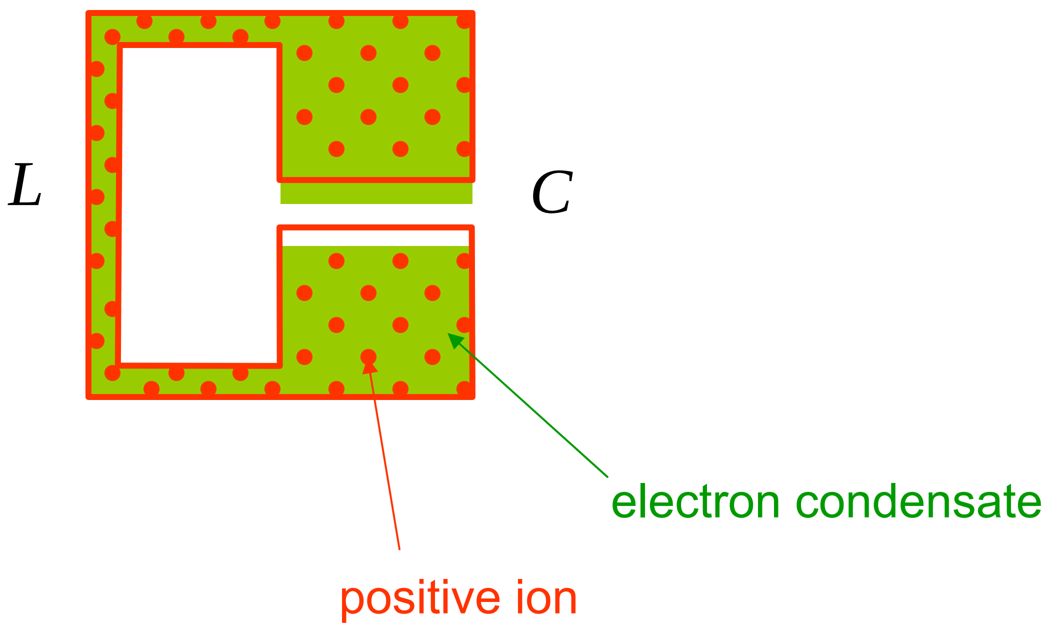
MICROFABRICATION → L ~ 3nH, C ~ 10pF, $\omega_r/2\pi$ ~ 2GHz

CELL PHONE FREQUENCY, ELECTRONICS CONTROL

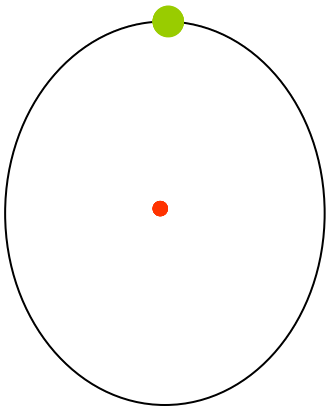
CHARGE ON PLATES SLOSHES BACK AND FORTH,
INTERNAL MODES ARE FROZEN.
ALL THE ELECTRONS BEHAVE AS A SINGLE CHARGE CARRIER

CIRCUIT vs ATOM

Superconducting
LC oscillator

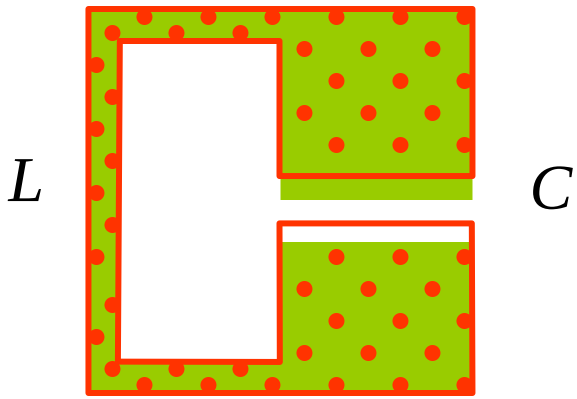


Hydrogen atom

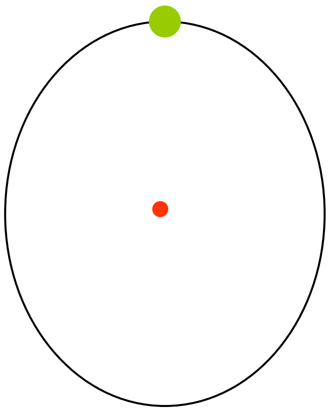


CIRCUIT vs ATOM

Superconducting
LC oscillator

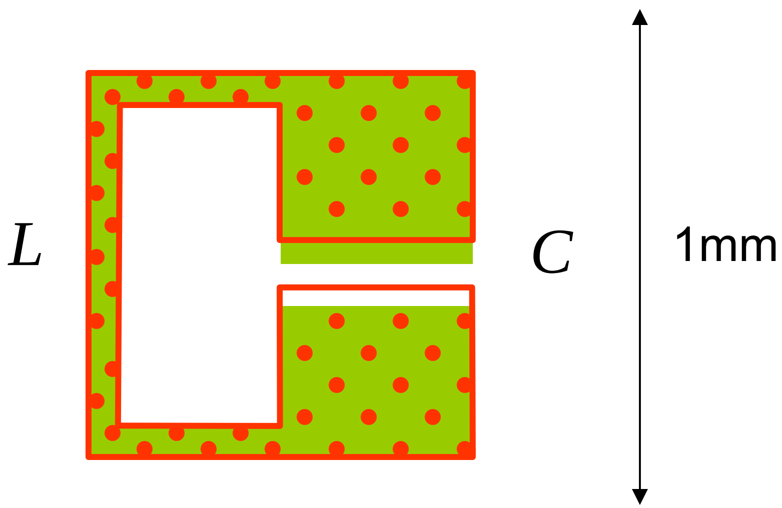


Hydrogen atom

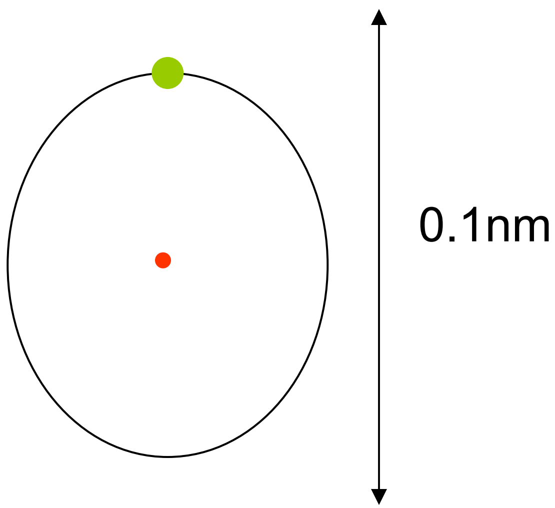


CIRCUIT vs ATOM

Superconducting
LC oscillator



Hydrogen atom

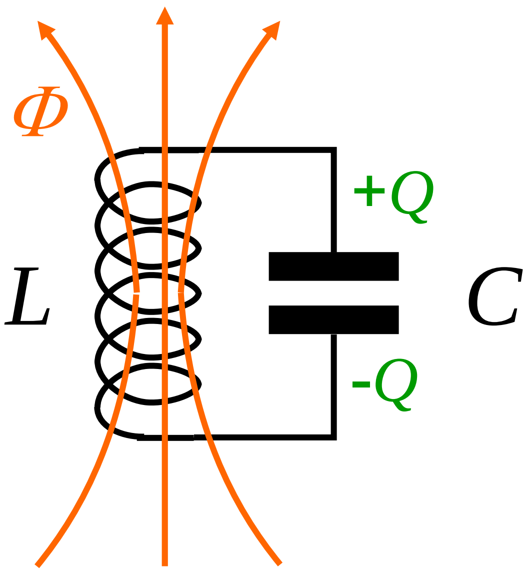


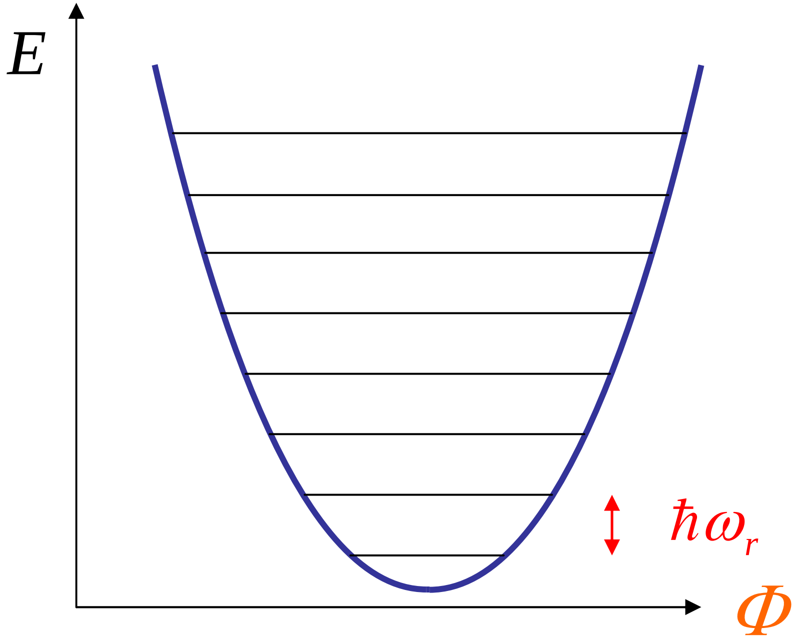
superconducting condensate → unique electron
current through inductor → velocity of electron
voltage across capacitor → force on electron

Can a collective variable
involving billions and
billions of atoms
be as perfectly quantum
as a single atom?

Question is both fundamental and applied

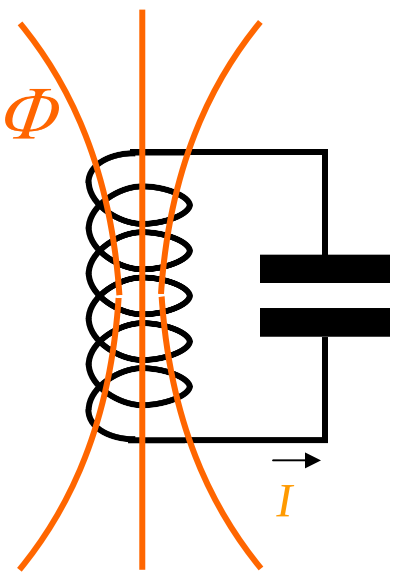
LC CIRCUIT AS A QUANTUM HARMONIC OSCILLATOR

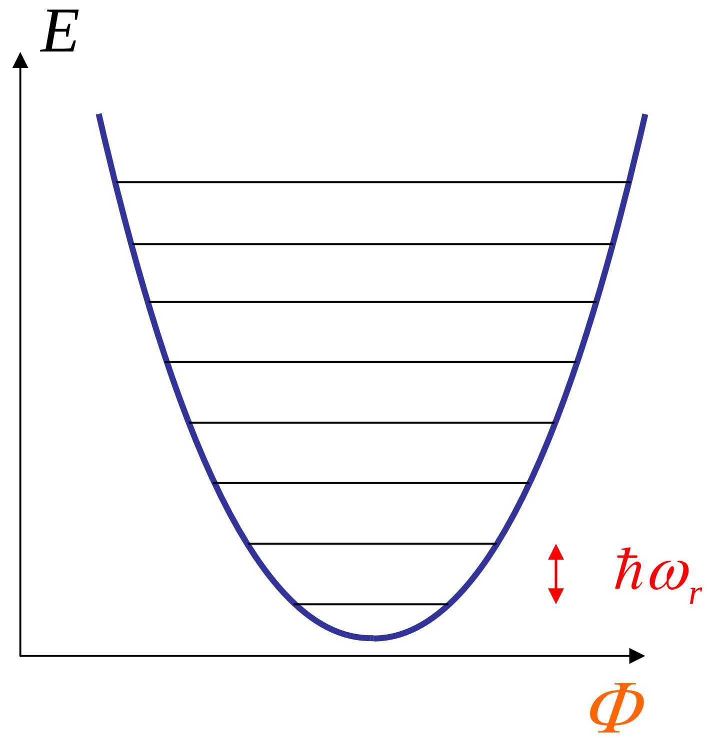


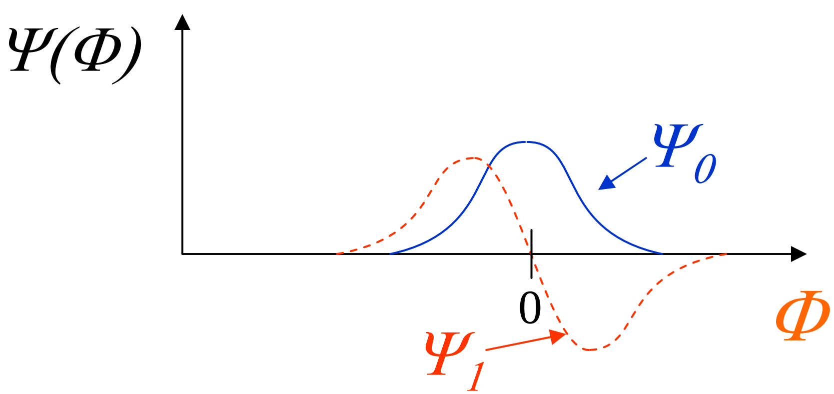


$$\left[\hat{\Phi},\hat{Q}\right]=i\hbar$$

WAVEFUNCTIONS OF LC CIRCUIT

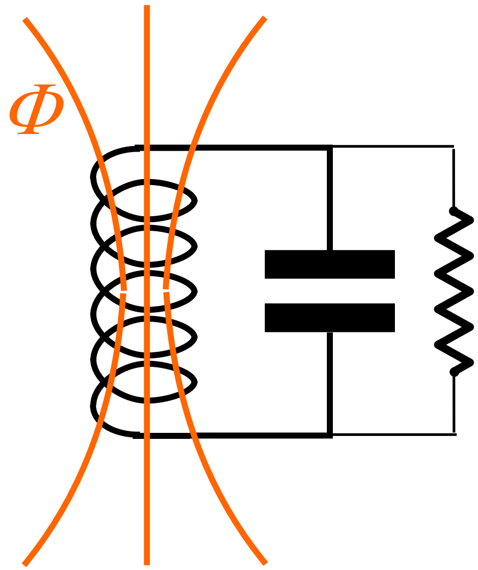


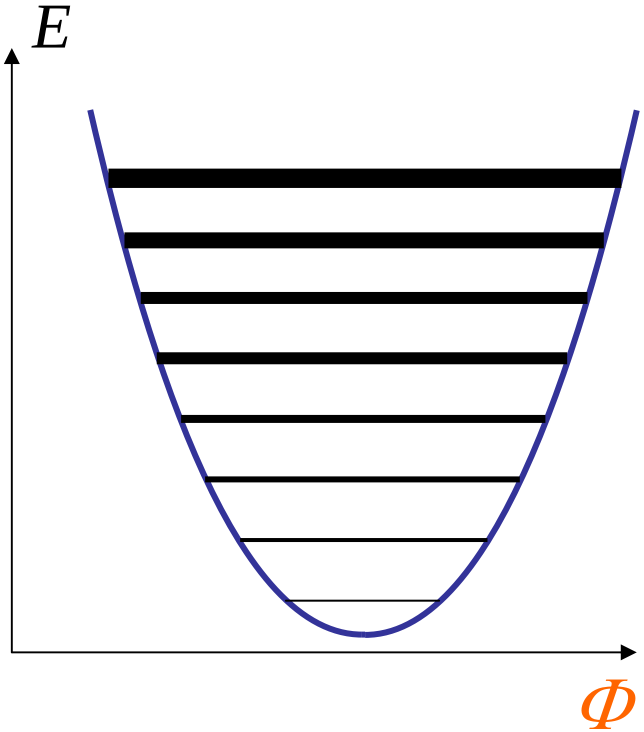




In every energy eigenstate, (microwave photon state) current flows in opposite directions simultaneously!

EFFECT OF DAMPING



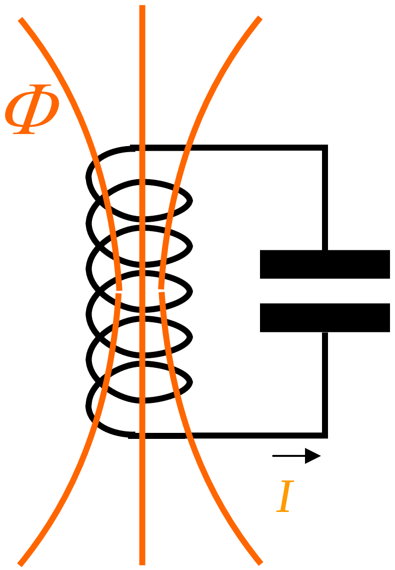


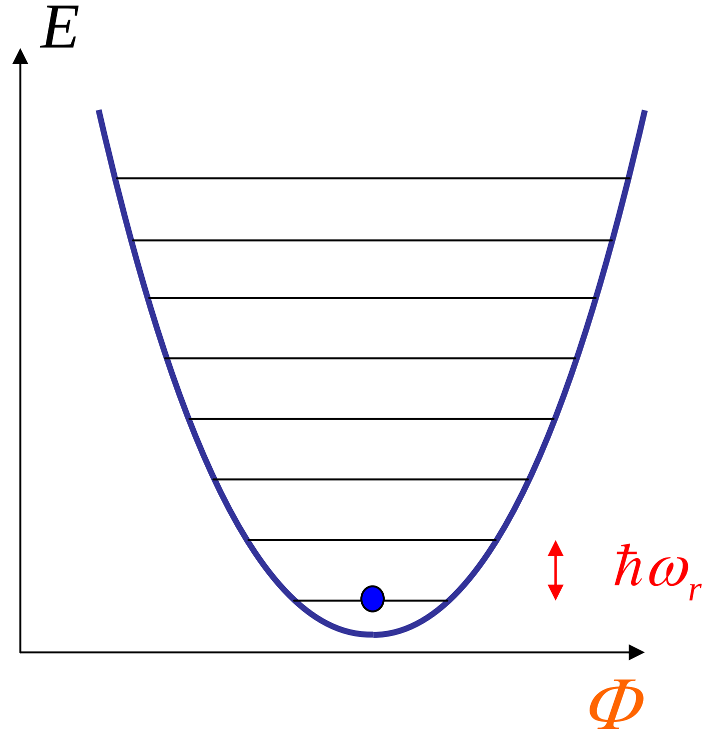
important: as little dissipation as possible

dissipation broadens energy levels

$$\left.\begin{aligned} E_n &= \hbar\omega_r\left[n\left(1+\frac{i}{2\mathcal{Q}}\right)+\frac{1}{2}\right] \\ \mathcal{Q} &= RC\omega_r \end{aligned}\right\}$$

CAN PLACE CIRCUIT IN ITS GROUND STATE





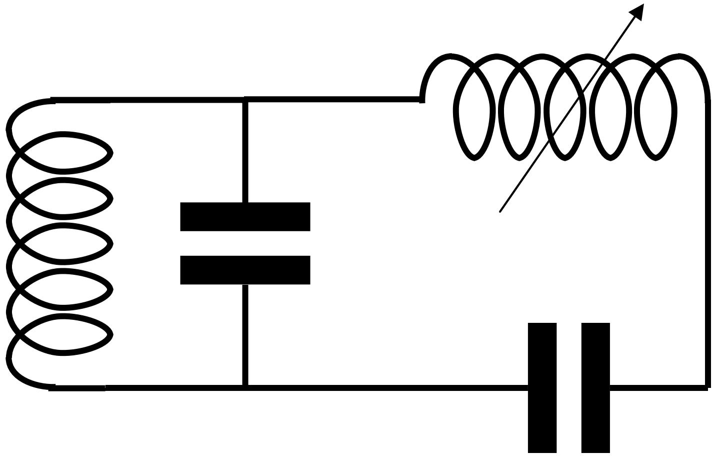
residual dissipation provides
reset of circuit

$$\hbar\omega_r \gg k_B T$$

10-5 GHz

10mK

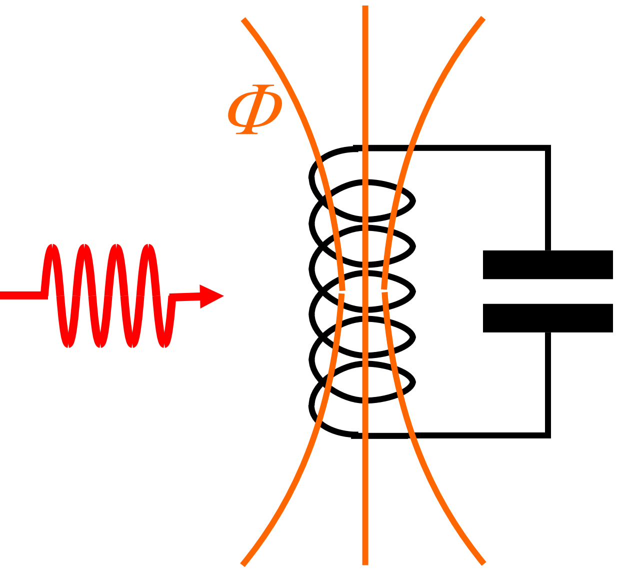
UNLIKE ATOMS IN VACUUM, TWO CIRCUITS EASILY COUPLE THROUGH THEIR WIRES:

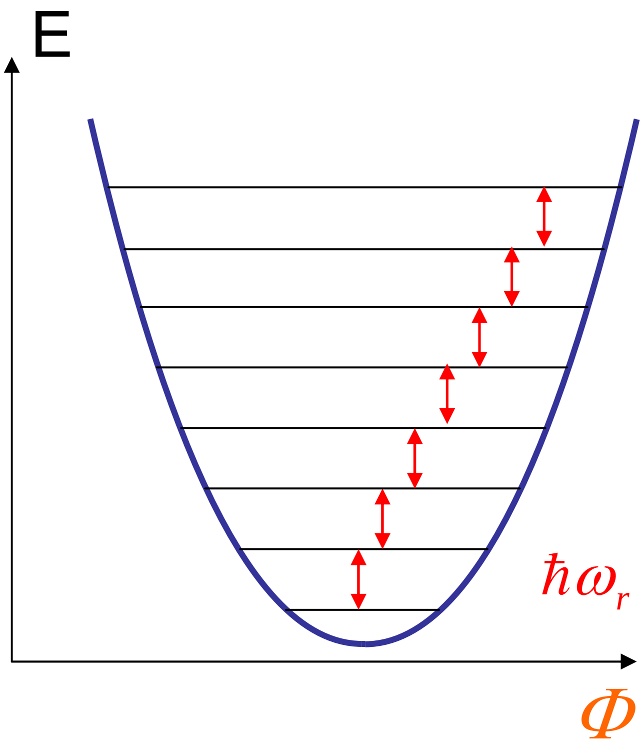


COUPLING CAN BE ARBITRARILY STRONG! HAMILTONIAN BY DESIGN!

(more on this later)

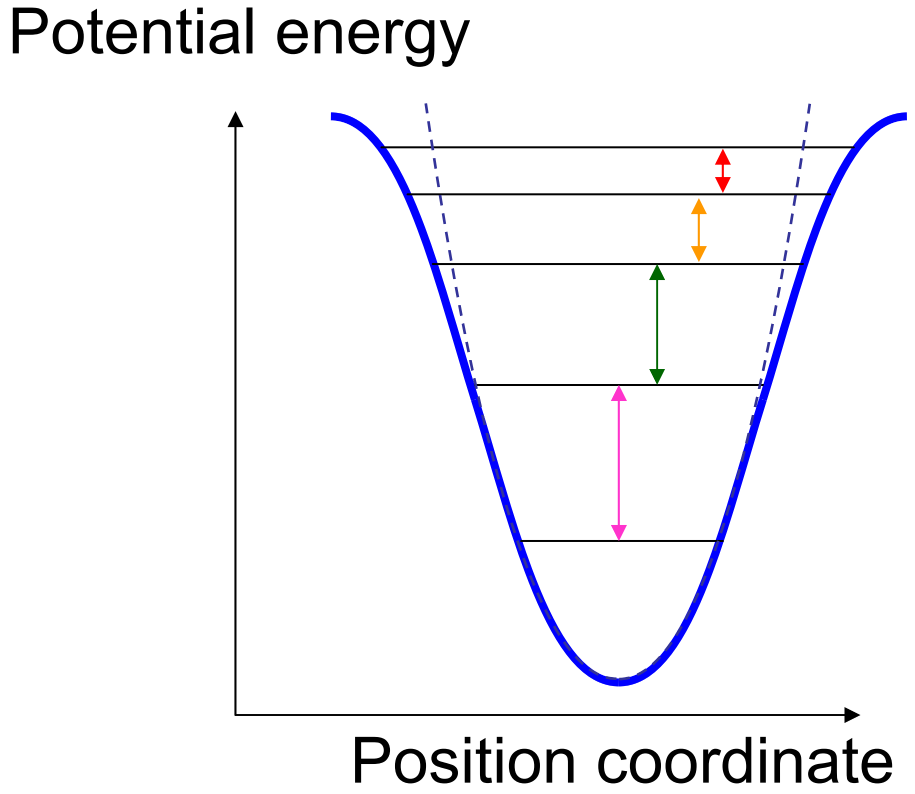
CAVEAT: THE QUANTUM STATES OF A PURELY LINEAR CIRCUIT CANNOT BE FULLY CONTROLLED!



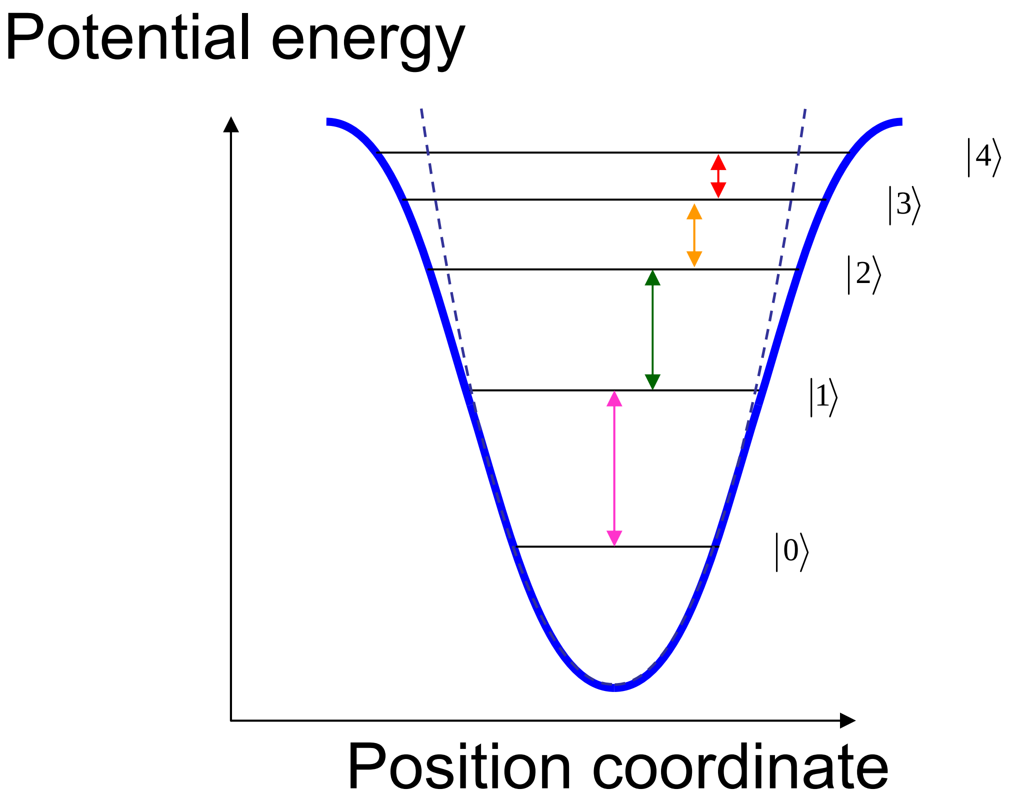


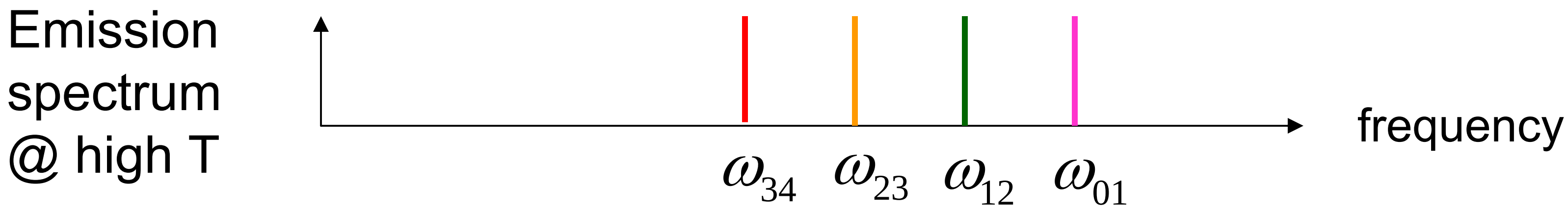
NO STEERING TO AN ARBITRARY STATE IF SYSTEM PERFECTLY LINEAR

NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

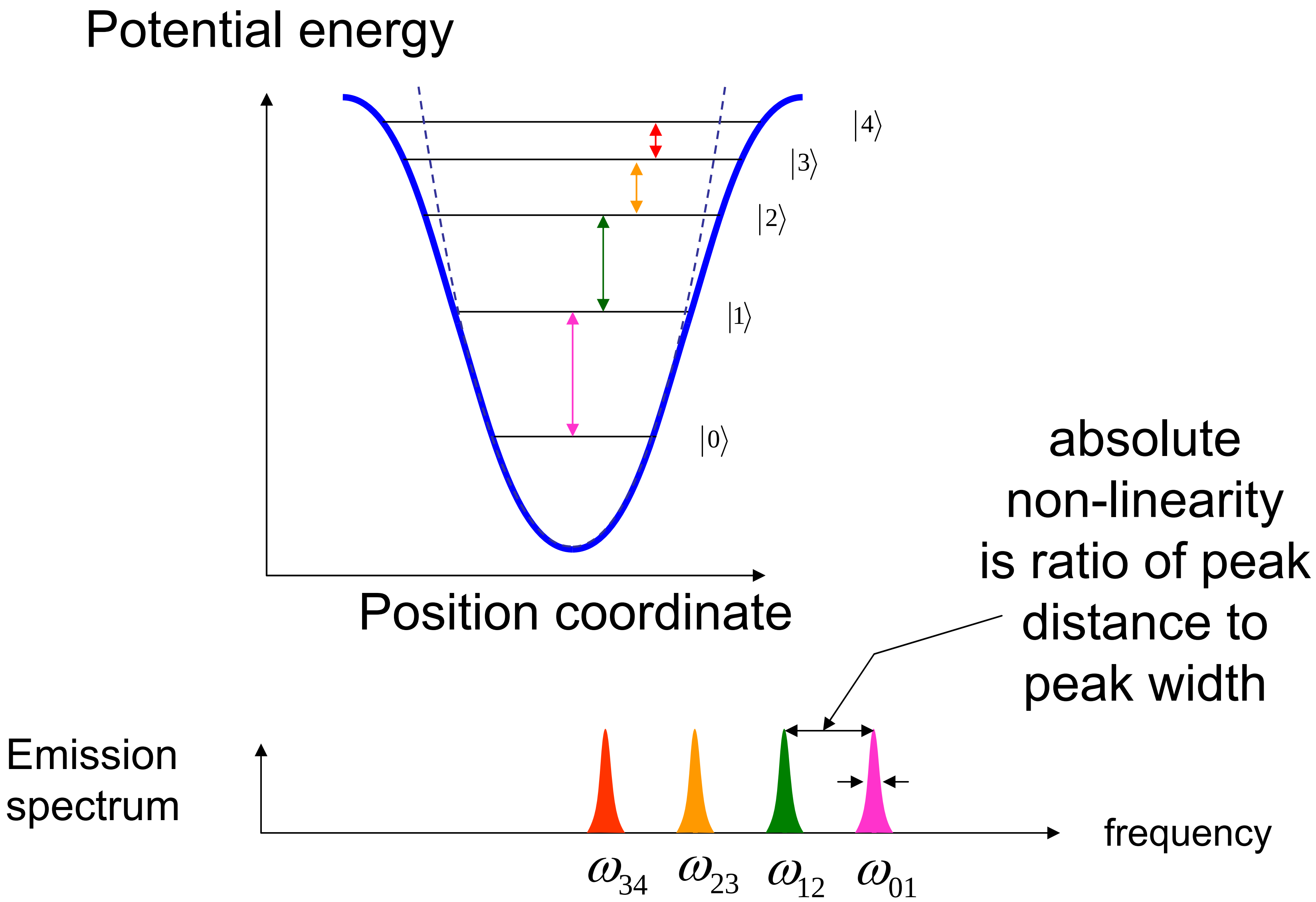


NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS

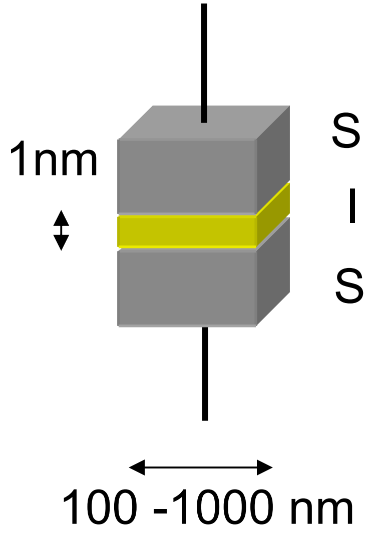




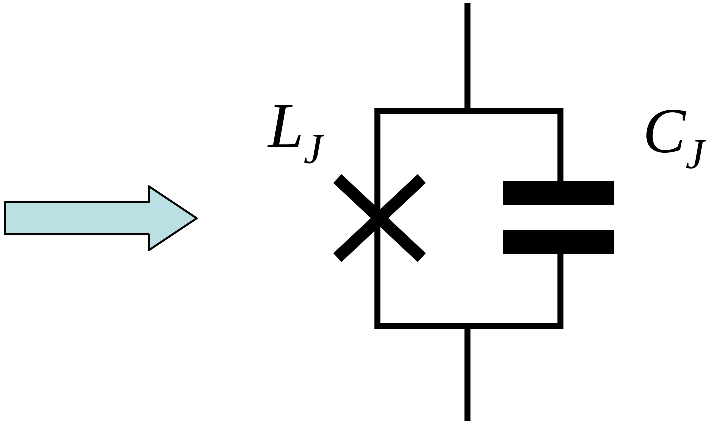
NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS



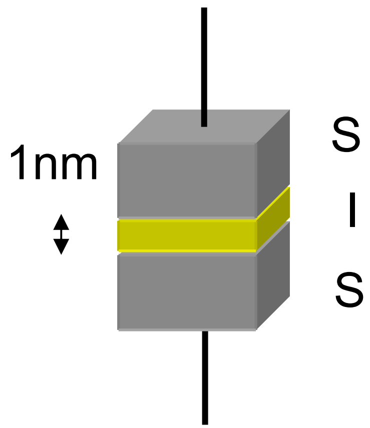
JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO DISSIPATION



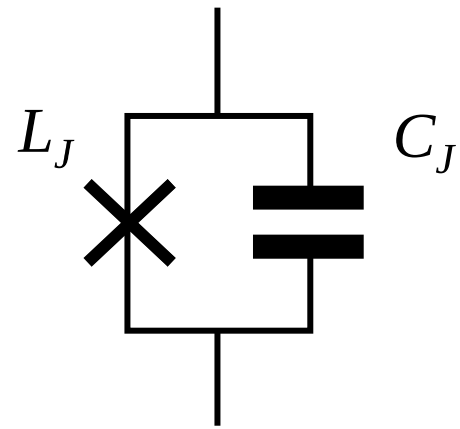
superconductor-
insulator-
superconductor
tunnel junction



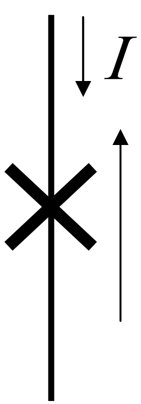
JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO DISSIPATION



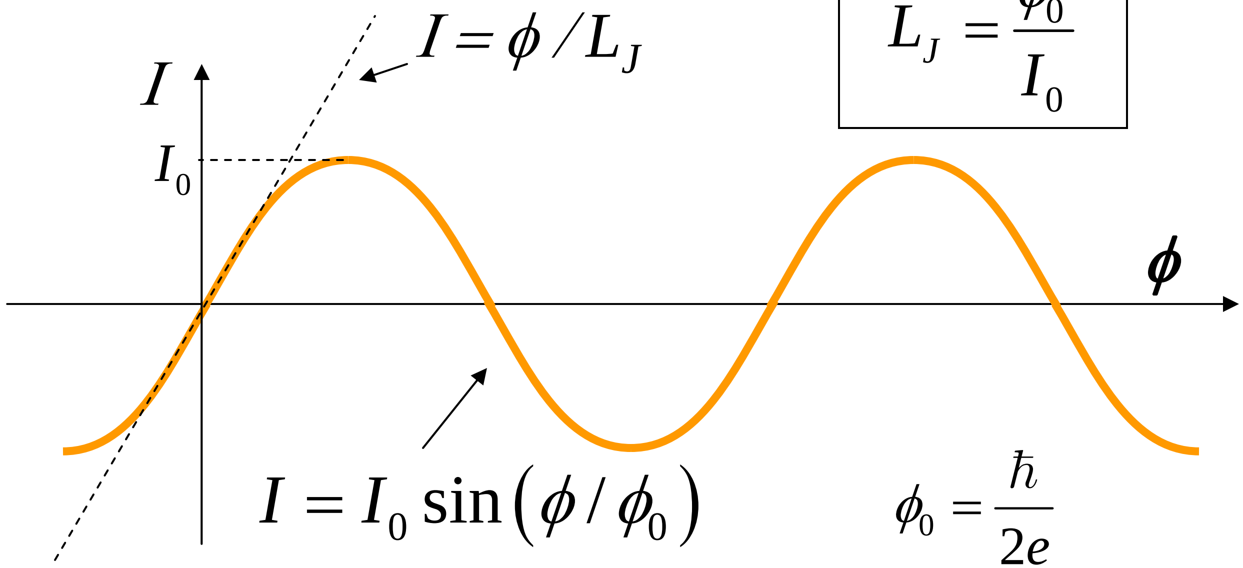
superconductor-
insulator-
superconductor
tunnel junction



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



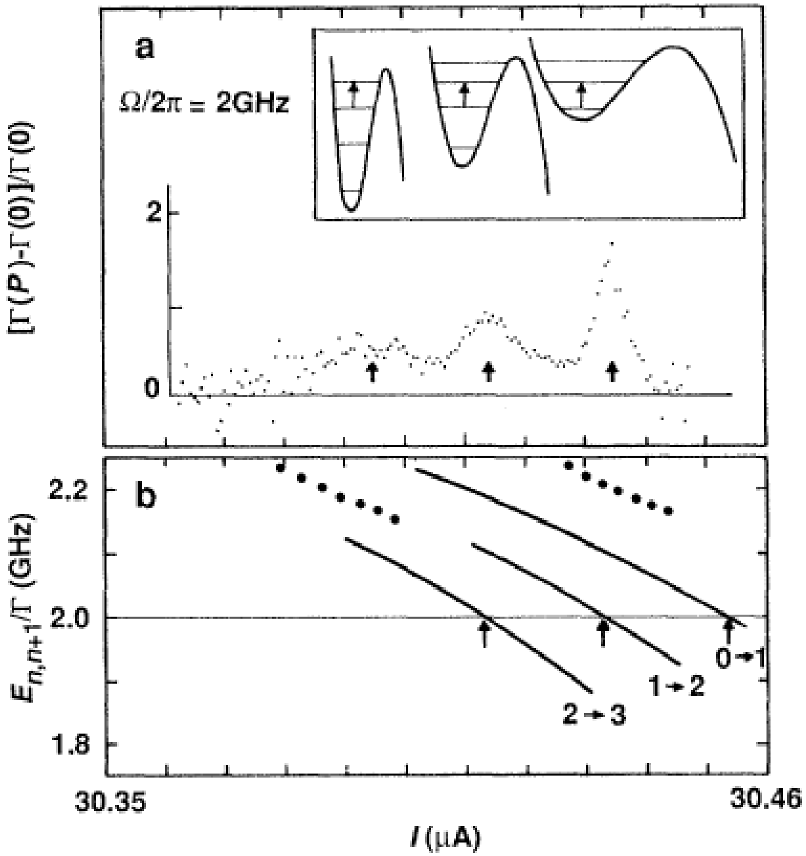
$$\phi = \int_{-\infty}^{t} V(t')dt'$$



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

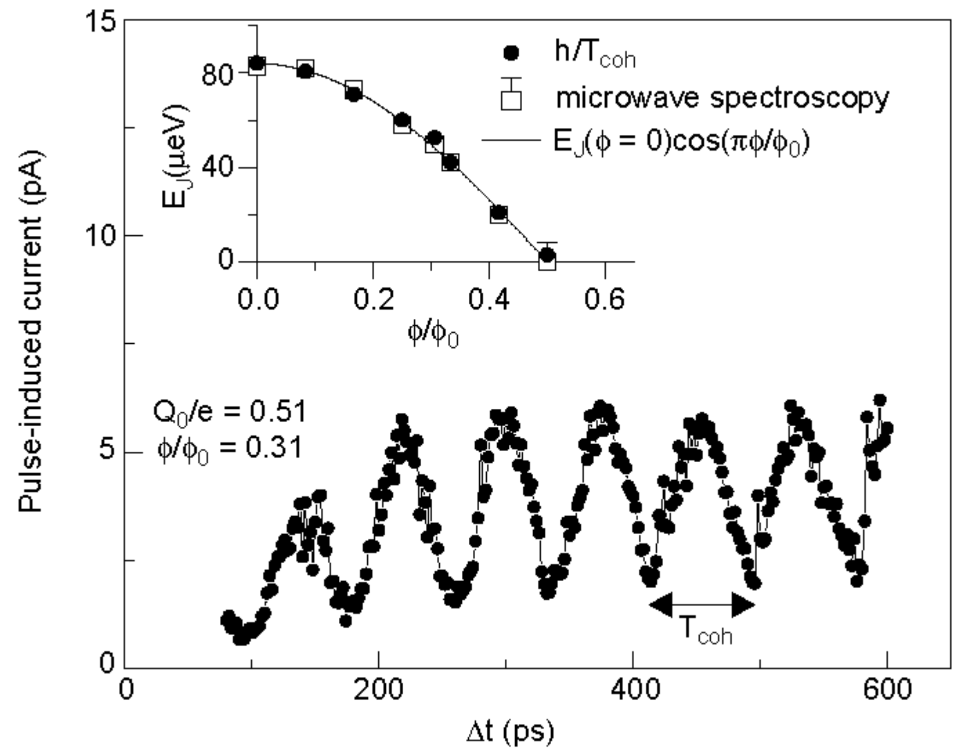
FIRST ATTEMPTS AT MEASURING ARTIFICIAL ATOM "NATURAL" LINEWIDTH

Martinis, Devoret and Clarke, PRL (1985)



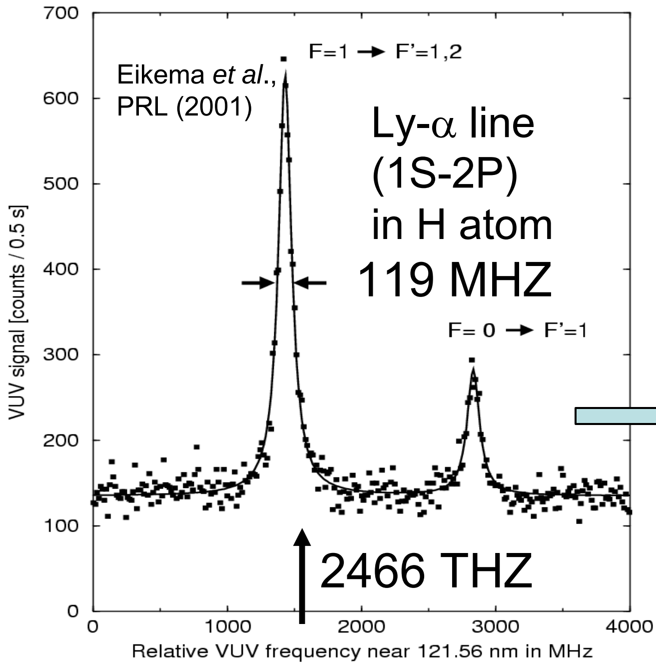
Nb-NbOx-Pb junction
Current-bias configuration
MQT experiments

Nakamura, Pashkin and Tsai, Nature (1999)



Al-AlOx-Al junction
Cooper pair box configuration
Rabi oscillations msmts

PURITY OF ARTIFICIAL ATOMS NOW RIVAL WITH NATURAL ATOMS

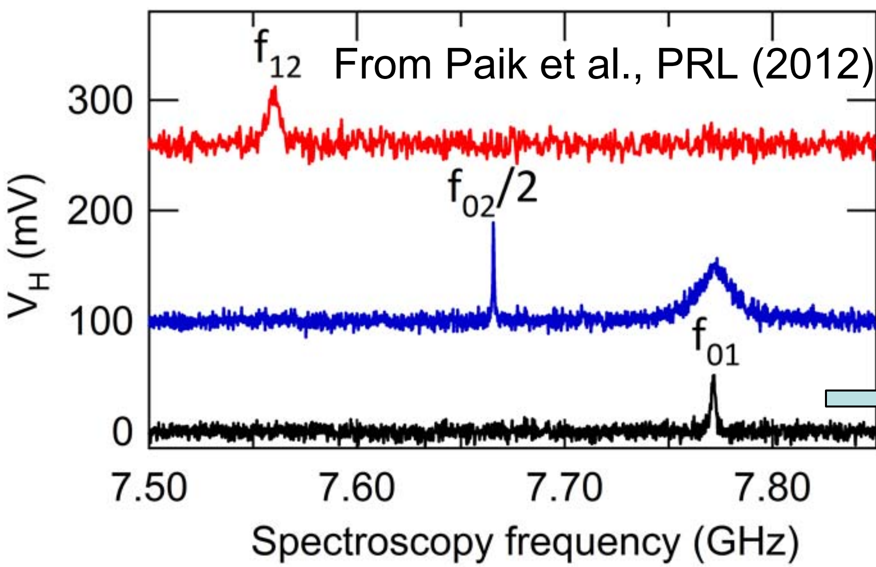


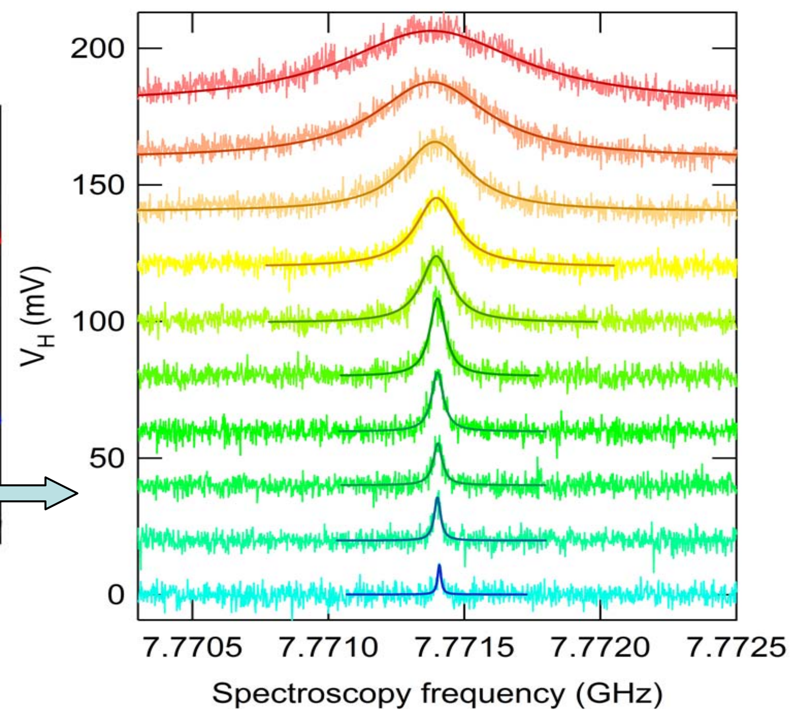
$Q_{Hydrogen}$ ~ 10,000,000

photon energy ~ 10eV

$Q_{Transmon}$ ~ 7,000,000

photon energy ~ 30μeV

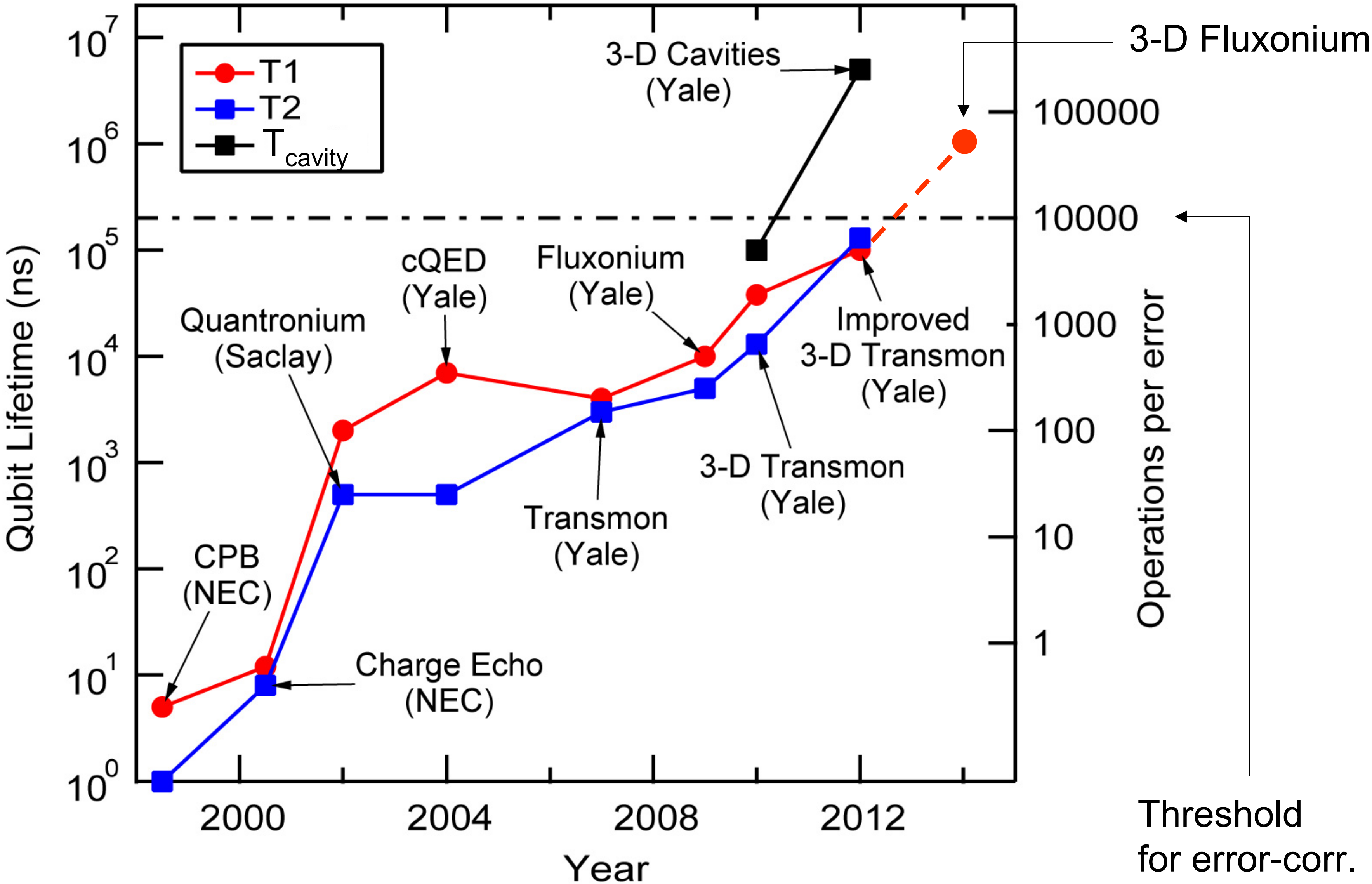




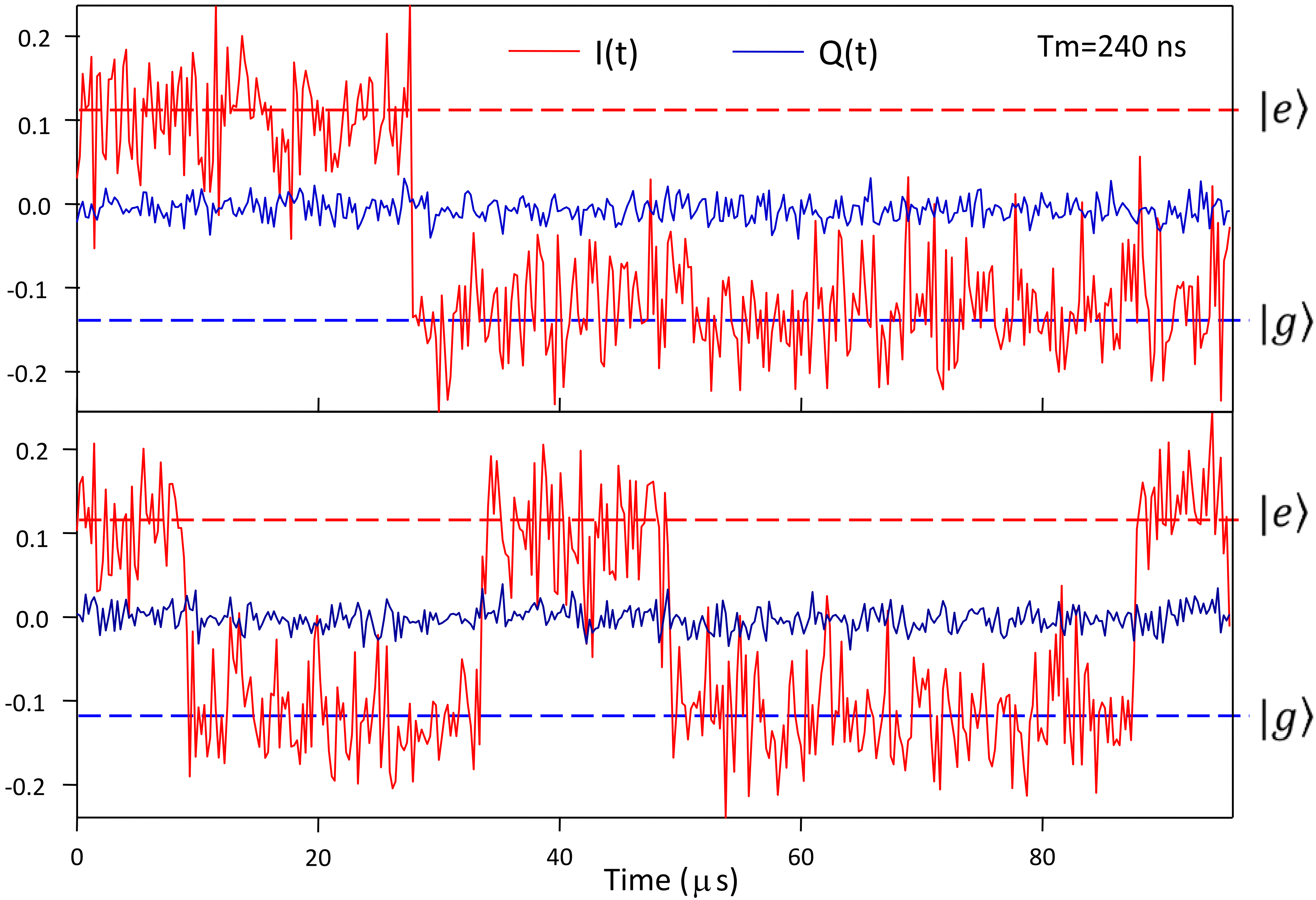
Ultimate linewidth from T2 echo: ~1kHz

SCHOELKOPF'S LAW

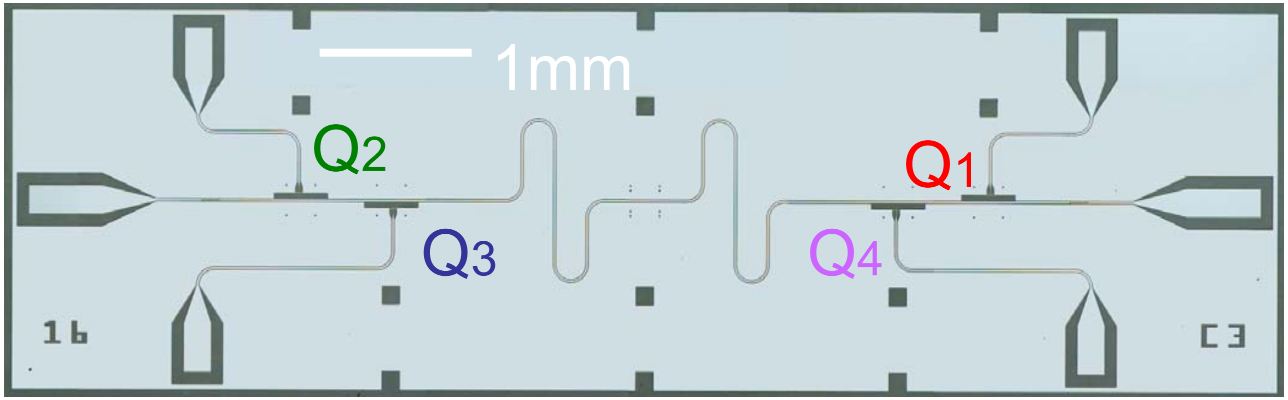
Devoret & Schoelkopf, Science (2013)



QUANTUM JUMPS OF TRANSMON (Φ-SENSITIVE)



ENTANGLEMENT OF ARTIFICIAL ATOMS



$$\left|GHZ_{\phi}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|000\right\rangle - ie^{i\phi}\left|111\right\rangle\right)$$

Bell violation: 75% of max

(not loophole-free)

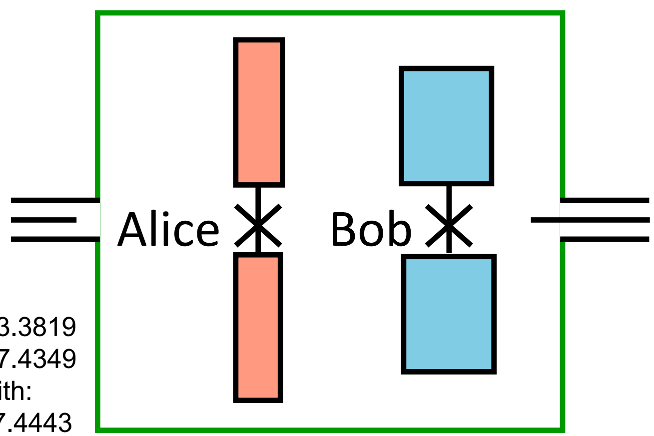
DiCarlo et al., Nature 574, 467 (2010)

see also:

Neeley et al., Nature 467, 570 (2010)

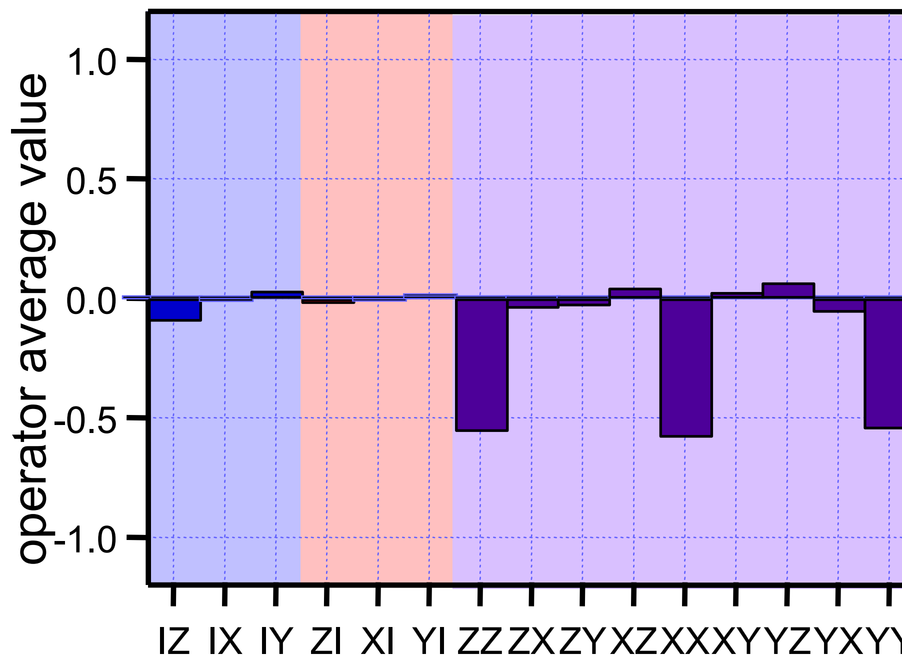
Autonomous stabilization of Bell state:

CW drives



Leghtas et al., arXiv:1303.3819
Shankar et al., arxiv:1307.4349
jointly with:
Gaebler at al., arxiv:1307.4443

Entangled state $\frac{\left|ge\right\rangle - \left|eg\right\rangle}{\sqrt{2}}$ lives forever!



Fidelity 67%

see also measurement-feedback stabilization by E. Polzik group (2011)

CONCLUDING SUMMARY

ELECTRICAL CIRCUITS CAN BE MADE QUANTUM AT LEVEL OF SIGNAL CURRENTS AND VOLTAGES!

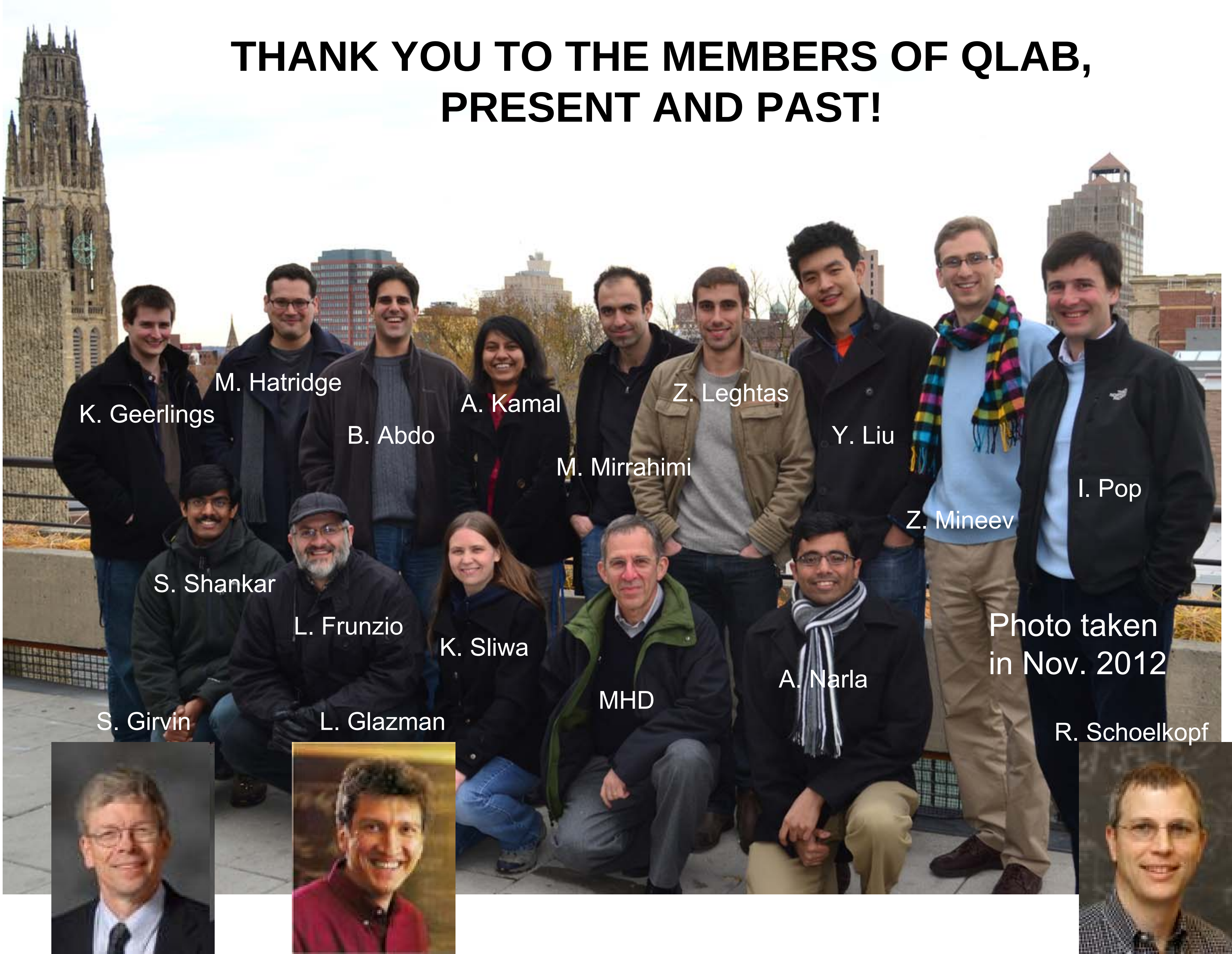
COHERENCE OF SUPERCONDUCTING ARTIFICIAL ATOMS SOON TO REACH ~1ms

READOUT AND GATES TAKE ~100ns

READOUT FIDELITY > 99%, 2-GATE FIDELITY > 90%

NEW "ATOMS" MEDIATE A STRONG AND CONTROLLABLE INTERACTION BETWEEN PHOTONS (SEE ROB'S TALK)

THANK YOU TO THE MEMBERS OF QLAB, PRESENT AND PAST!



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CRSNG NSERC

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