COLLÈGE DE FRANCE 1530

Chaire de Physique Mésoscopique
Michel Devoret
Année 2009, 12 mai - 23 juin

CIRCUITS ET SIGNAUX QUANTIQUES (II)

QUANTUM SIGNALS AND CIRCUITS (II)

Sixième Leçon / *Sixth Lecture*

VISIT THE WEBSITE OF THE CHAIR OF MESOSCOPIC PHYSICS

http://www.college-de-france.fr

then follow
Enseignement > Sciences Physiques > Physique Mésoscopique > Site web

or

http://www.physinfo.fr/lectures.html

PDF FILES OF ALL LECTURES ARE POSTED ON THESE WEBSITES

Questions, comments and corrections are welcome!

write to "phymeso@gmail.com"

CALENDAR OF SEMINARS

May 12: Daniel Esteve, (Quantronics group, SPEC-CEA Saclay)
Faithful readout of a superconducting qubit

May 19: Christian Glattli (LPA/ENS)
Statistique de Fermi dans les conducteurs balistiques : conséquences expéri-mentales et exploitation pour l'information quantique

June 2: Steve Girvin (Yale)
Quantum Electrodynamics of Superconducting Circuits and Qubits

June 9: Charlie Marcus (Harvard)
Electron Spin as a Holder of Quantum Information: Prospects and Challenges

June 16: Frédéric Pierre (LPN/CNRS)
Energy exchange in quantum Hall edge channels

June 23: Lev Ioffe (Rutgers)
Implementation of protected qubits in Josephson junction arrays

09-VI-3

CONTENT OF THIS YEAR'S LECTURES

OUT-OF-EQUILIBRIUM NON-LINEAR QUANTUM CIRCUITS

1. Introduction and review of last year's course
2. Non-linearity of Josephson tunnel junctions
3. Readout of qubits
4. Amplification of quantum signals: detecting RF photons
5. Dynamical cooling and quantum error correction
6. Defying the fine structure constant: the prospect of the observation of Bloch oscillations.

09-VI-4

LECTURE VI : THE FLUXONIUM AND PERSPECTIVES FOR OBSERVING BLOCH OSCILLATIONS IN A JOSEPHSON CIRCUIT

1. Quantum error correction and quantum feedback
2. The quantum metrology triangle and Bloch oscillations
3. Defying the fine structure constant
4. Fluxonium sample
5. Single Cooper pair effects without charge offsets

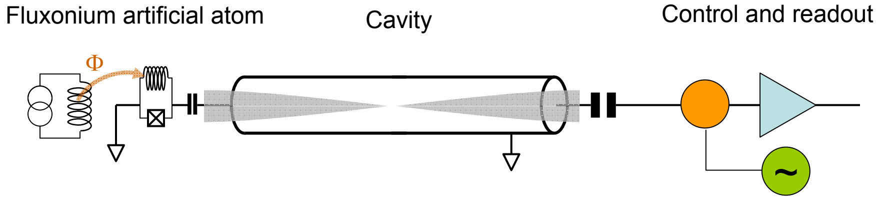
09-VI-5

OUTLINE

1. Quantum error correction and quantum feedback
2. The quantum metrology triangle and Bloch oscillations
3. Defying the fine structure constant
4. Fluxonium sample
5. Single Cooper pair effects without charge offsets

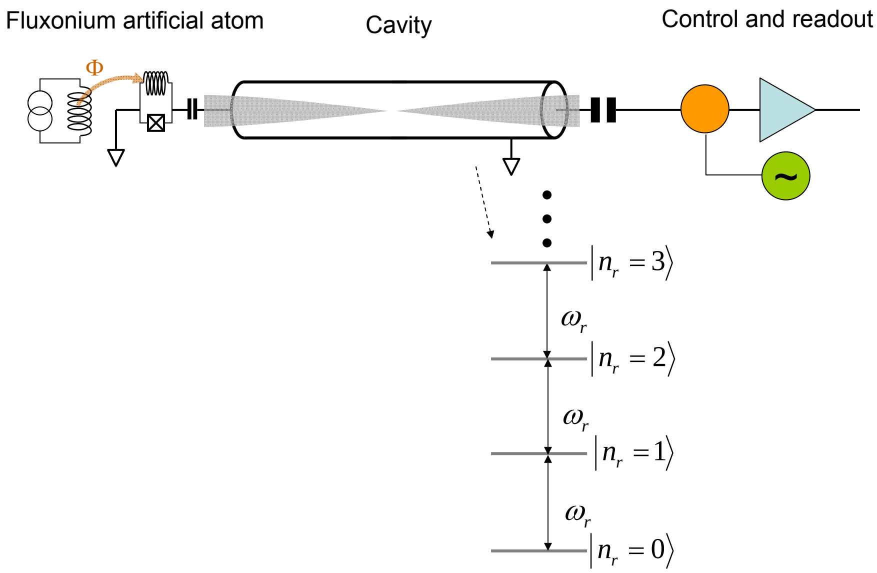
09-VI-5a

CIRCUIT QED: STANDING ATOMS (II)



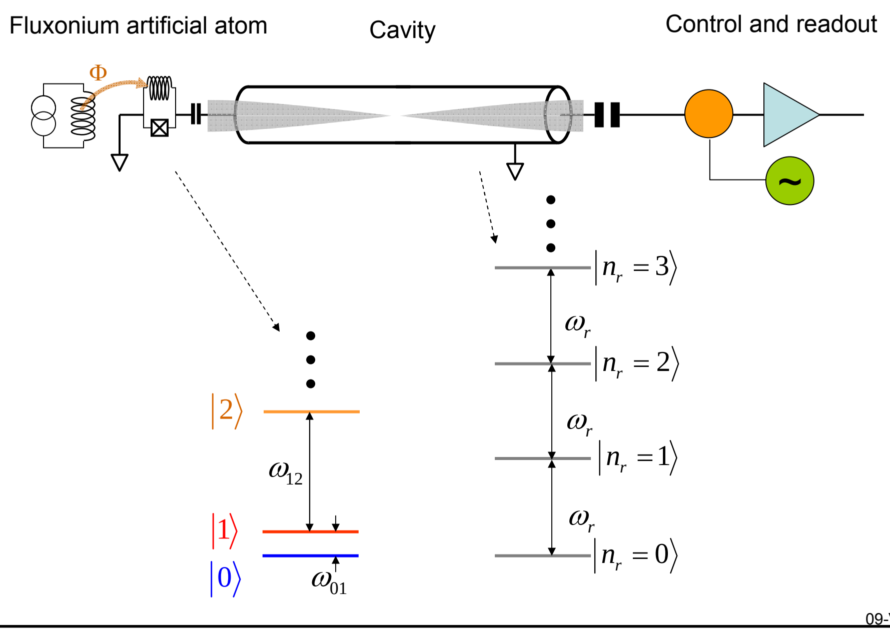
09-VI-6

CIRCUIT QED: STANDING ATOMS (II)

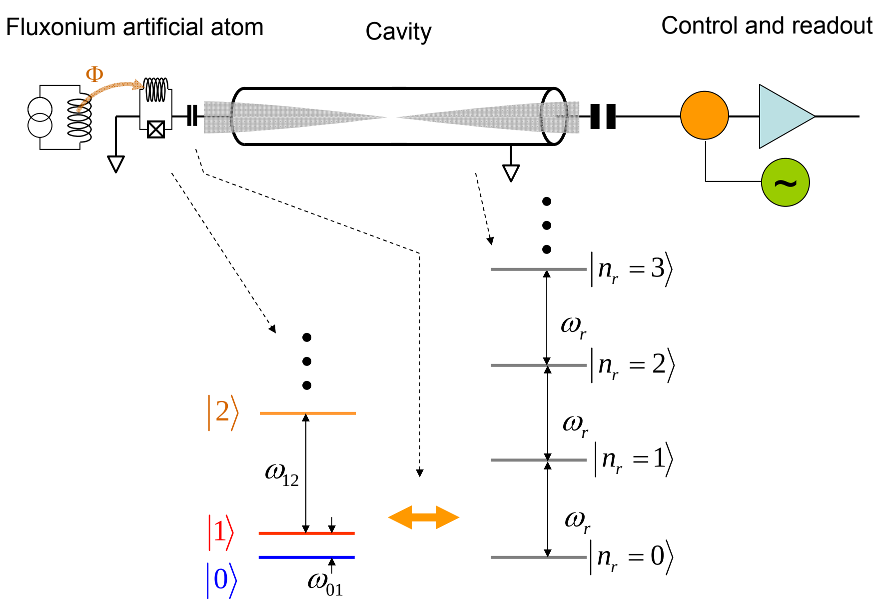


09-VI-6a

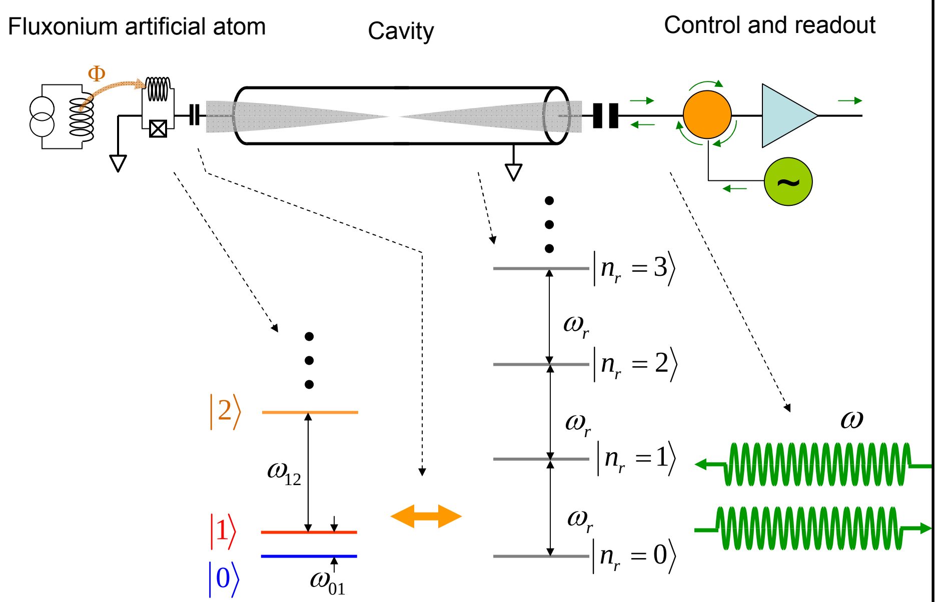
CIRCUIT QED: STANDING ATOMS (II)



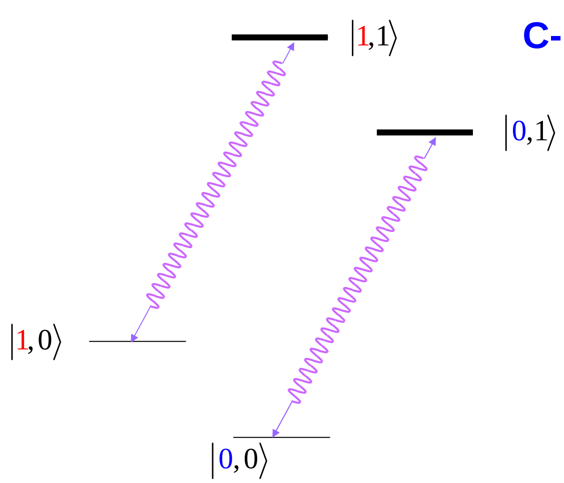
CIRCUIT QED: STANDING ATOMS (II)

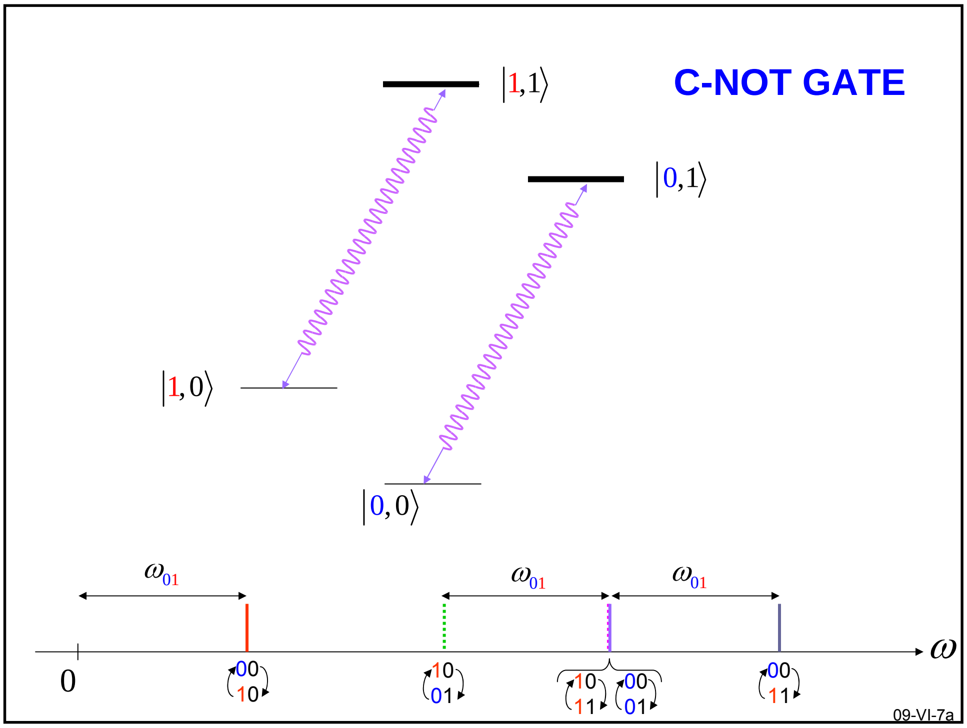


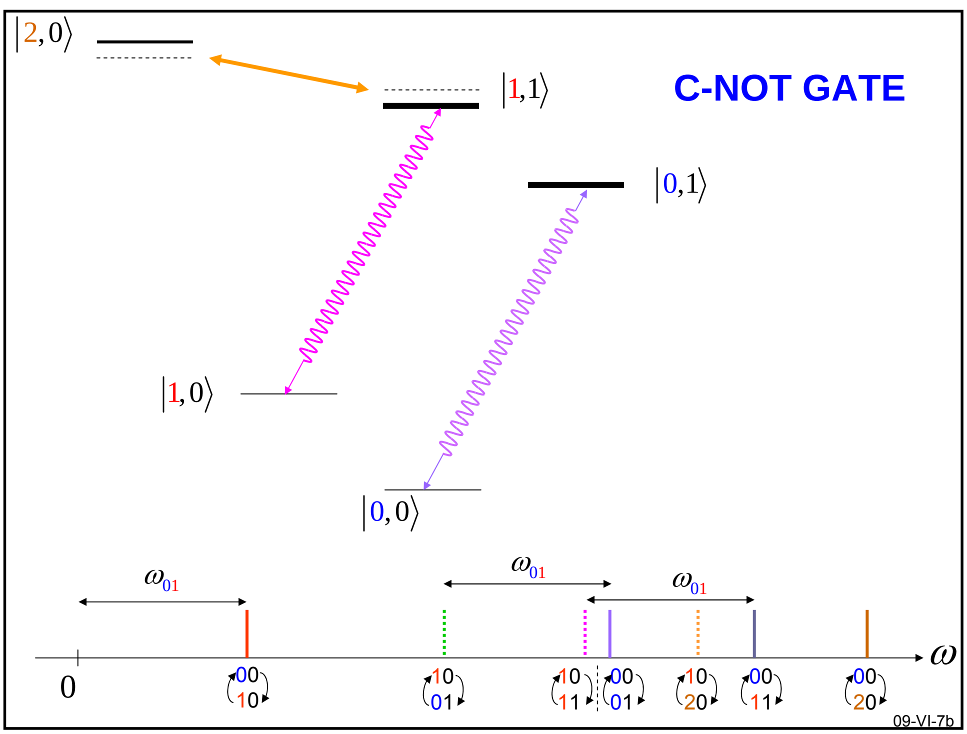
CIRCUIT QED: STANDING ATOMS (II)



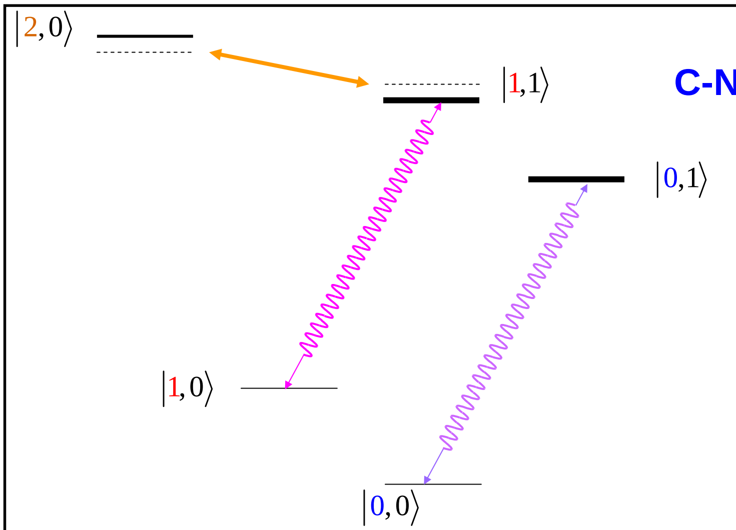
C-NOT GATE




C-NOT GATE
|1,1⟩
|0,1⟩
|1,0⟩
|0,0⟩
ω01
ω01
ω01
0
ω
09-VI-7a

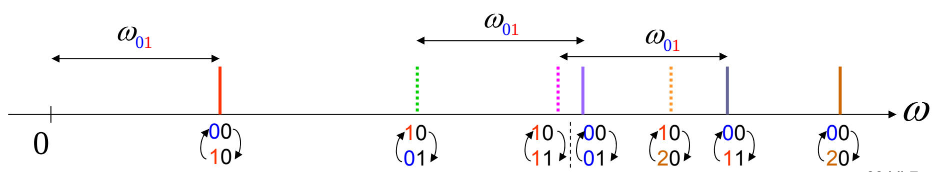

|2,0⟩
|1,1⟩
C-NOT GATE
|0,1⟩
|1,0⟩
|0,0⟩
ω01
ω01
ω01
0
ω
09-VI-7b

C-NOT GATE



c: control
t: target

before		after	
c	t	c'	t'
0	0	0	0
0	1	0	1
1	0	1	1
1	1	1	0



09-VI-7c

WE HAVE LEARNED HOW WE CAN READ, RESET, WRITE A SQUBIT AND COMPUTE WITH IT.

CAN WE ALSO CORRECT ERRORS AFFECTING SUPERPOSITIONS OF STATE?

09-VI-8

QUANTUM ERROR CORRECTION

$|\Psi\rangle =$

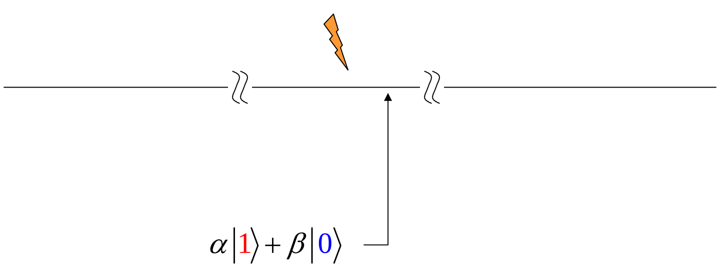
$\alpha|0\rangle + \beta|1\rangle$

09-VI-9

QUANTUM ERROR CORRECTION

$|\Psi\rangle =$

$\alpha|0\rangle + \beta|1\rangle$

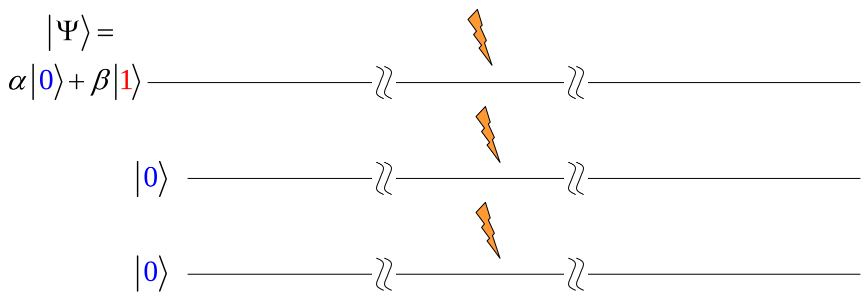


$\alpha|1\rangle + \beta|0\rangle$

"BIT FLIP" ERROR

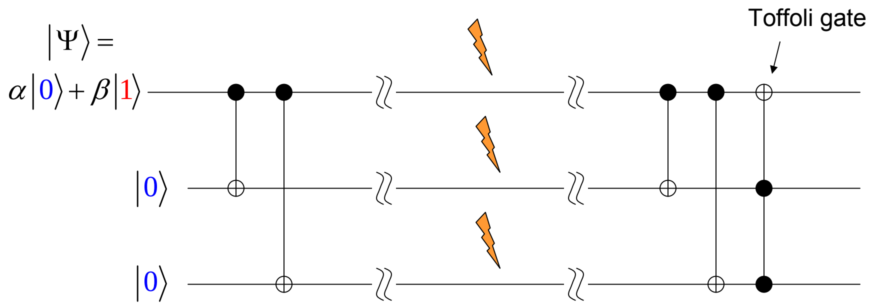
09-VI-9a

QUANTUM ERROR CORRECTION



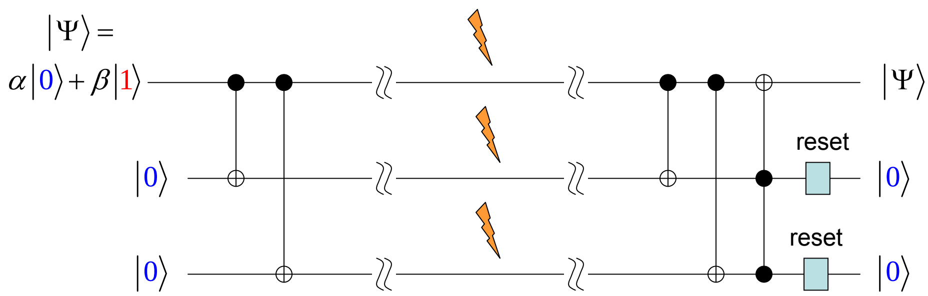
09-VI-9b

QUANTUM ERROR CORRECTION



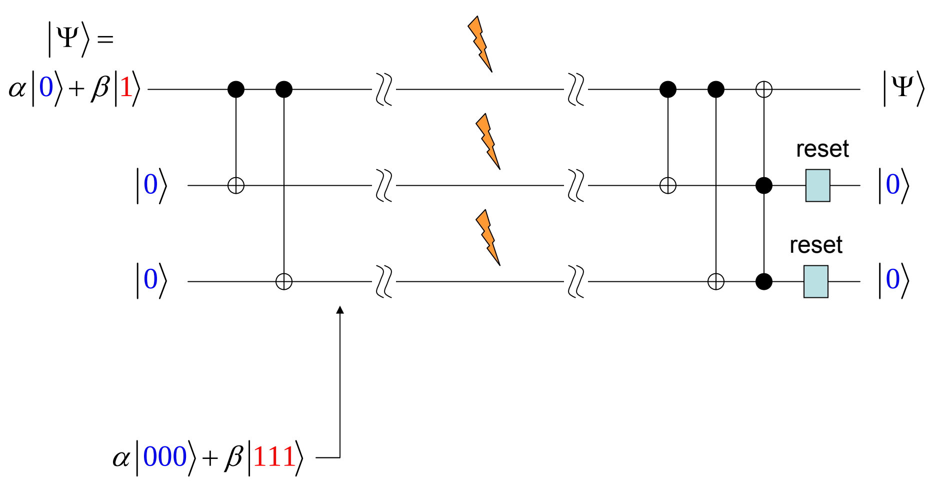
09-VI-9c

QUANTUM ERROR CORRECTION



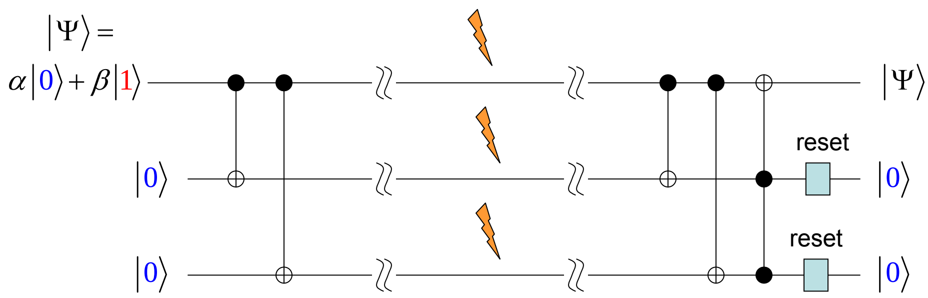
09-VI-9d

QUANTUM ERROR CORRECTION



09-VI-9e

QUANTUM ERROR CORRECTION

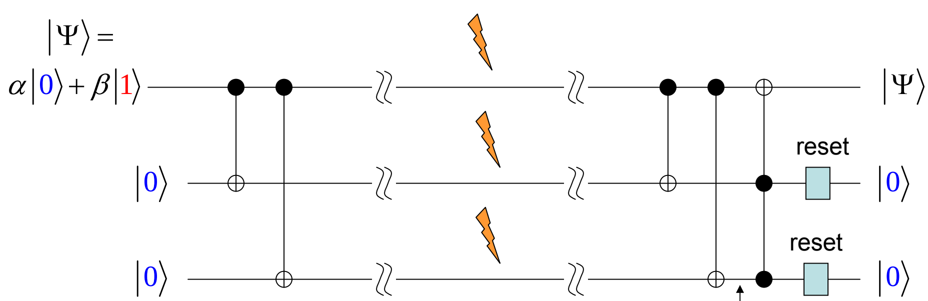


$\alpha|000\rangle+\beta|111\rangle$ →

$\alpha|000\rangle+\beta|111\rangle$
or
$\alpha|100\rangle+\beta|011\rangle$
or
$\alpha|010\rangle+\beta|101\rangle$
or
$\alpha|001\rangle+\beta|110\rangle$

09-VI-9f

QUANTUM ERROR CORRECTION

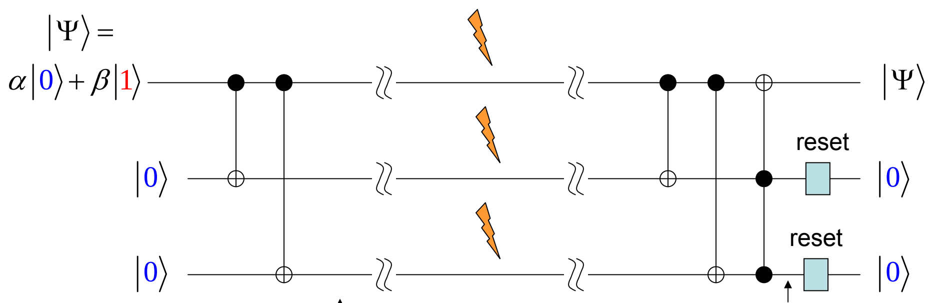


$\alpha|000\rangle+\beta|111\rangle$ →

$\alpha|000\rangle+\beta|111\rangle \to (\alpha|0\rangle+\beta|1\rangle)|00\rangle$
or
$\alpha|100\rangle+\beta|011\rangle \to (\alpha|1\rangle+\beta|0\rangle)|11\rangle$
or
$\alpha|010\rangle+\beta|101\rangle \to (\alpha|0\rangle+\beta|1\rangle)|10\rangle$
or
$\alpha|001\rangle+\beta|110\rangle \to (\alpha|0\rangle+\beta|1\rangle)|01\rangle$

09-VI-9g

QUANTUM ERROR CORRECTION



$\alpha|000\rangle + \beta|111\rangle$

$\alpha|000\rangle + \beta|111\rangle$
or
$\alpha|100\rangle + \beta|011\rangle$
or
$\alpha|010\rangle + \beta|101\rangle$
or
$\alpha|001\rangle + \beta|110\rangle$

$(\alpha|0\rangle + \beta|1\rangle)|00\rangle$
or
$(\alpha|0\rangle + \beta|1\rangle)|11\rangle$!
or
$(\alpha|0\rangle + \beta|1\rangle)|10\rangle$
or
$(\alpha|0\rangle + \beta|1\rangle)|01\rangle$

SEE NEXT YEAR'S COURSE ON QUANTUM COMPUTATION

09-VI-9h

CAN NON-EQUILIBRIUM QUANTUM EFFECTS
IN SUPERCONDUCTING CIRCUITS
BE USED
FOR PRECISION MEASUREMENTS?

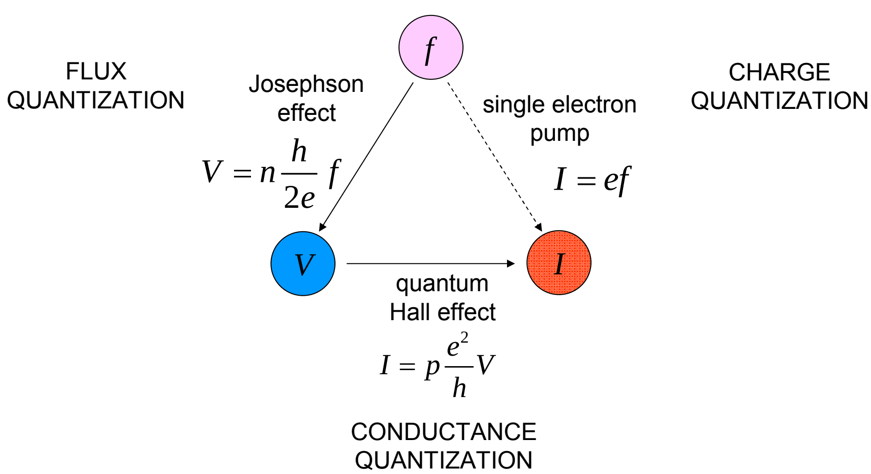
09-VI-10

OUTLINE

1. Quantum error correction and quantum feedback
2. The quantum metrology triangle and Bloch oscillations
3. Defying the fine structure constant
4. Fluxonium sample
5. Single Cooper pair effects without charge offsets

09-VI-5b

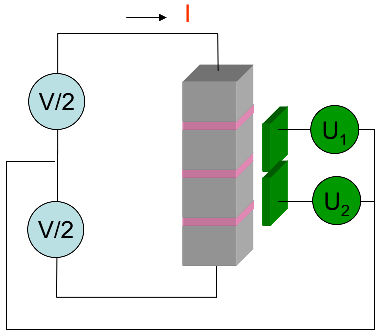
TRIANGLE OF METROLOGICAL MESOSCOPIC EFFECTS

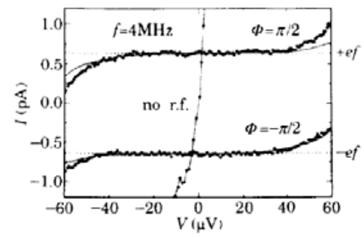


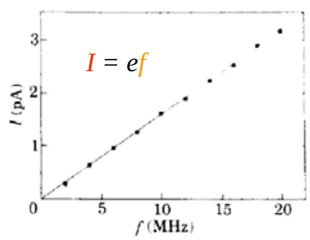
09-VI-11

SINGLE ELECTRON PUMP

Pothier et al., 1992
Keller, Martinis and Kautz, 1998







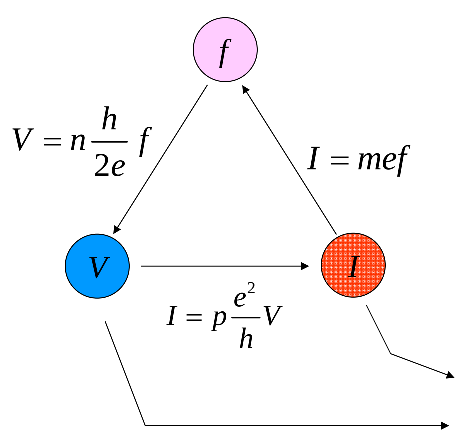
$$U_1(t) = U_0 \cos(2\pi f t)$$
$$U_2(t) = U_0 \cos(2\pi f t \pm \pi/2)$$

Problem: precision can reach 10^{-8} but current cannot exceed a few pA

09-VI-12

TRIANGLE OF METROLOGICAL MESOSCOPIC EFFECTS

ATOMIC CLOCK

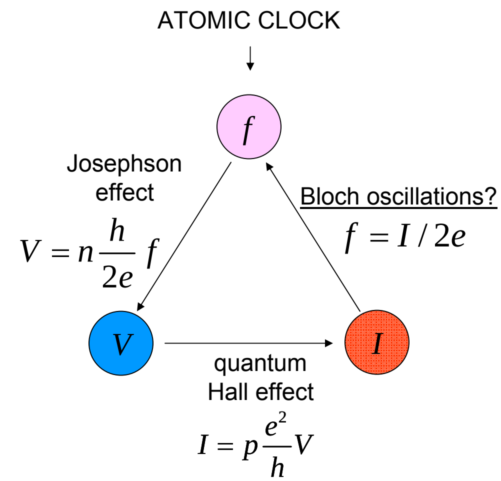


if nA currents possible

revision of SI system

09-VI-13

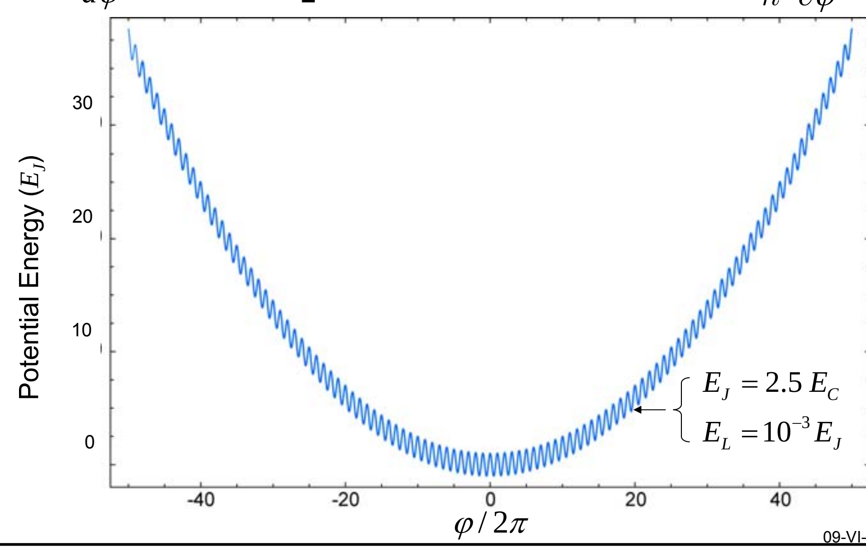
TRIANGLE OF METROLOGICAL MESOSCOPIC EFFECTS



09-VI-13b

BLOCH OSCILLATIONS OF VOLTAGE ACROSS JOSEPHSON JUNCTION TRAVERSED BY CURRENT

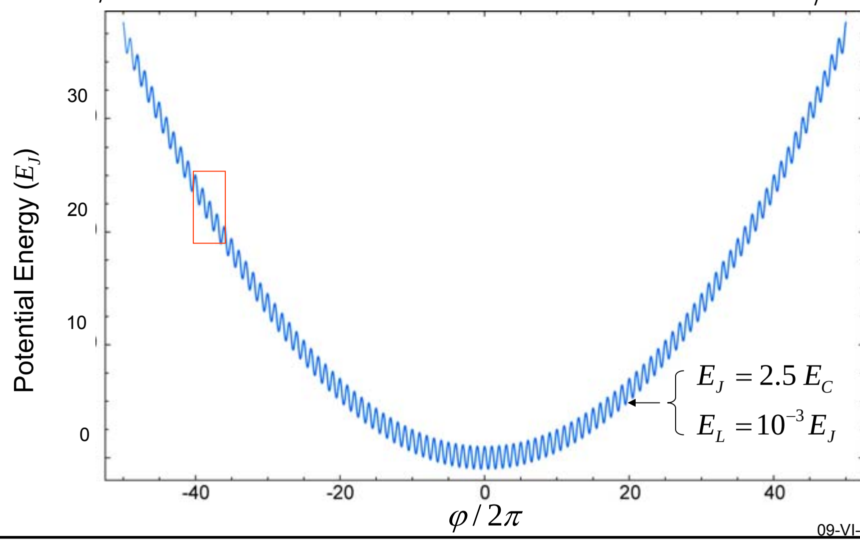
$$H = -4E_C\frac{d^2}{d\varphi^2} - E_J\cos\varphi + \frac{1}{2}E_L\left(\varphi - \Phi_b\right)^2 \qquad \hat{I} = \frac{2e}{\hbar}\frac{\partial\hat{H}}{\partial\hat{\varphi}}$$



09-VI-14

BLOCH OSCILLATIONS OF VOLTAGE ACROSS JOSEPHSON JUNCTION TRAVERSED BY CURRENT

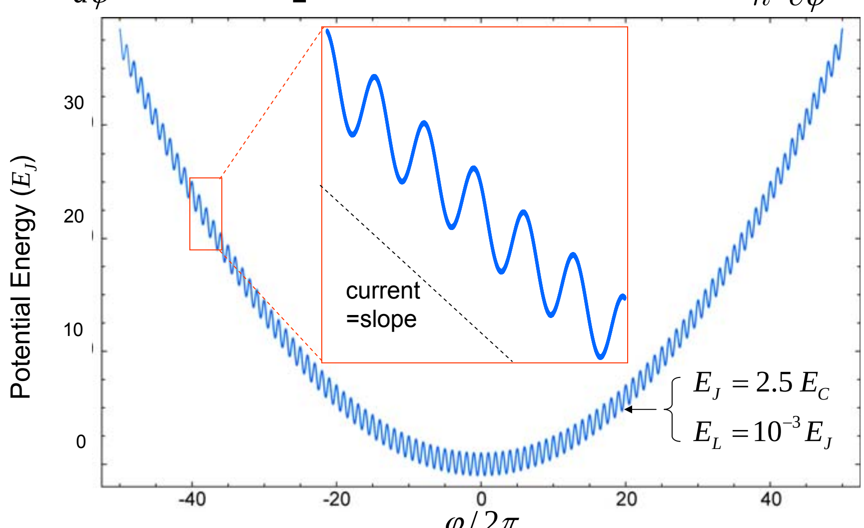
$$H = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos\varphi + \frac{1}{2} E_L \left(\varphi - \Phi_b\right)^2 \qquad \hat{I} = \frac{2e}{\hbar} \frac{\partial \hat{H}}{\partial \hat{\varphi}}$$



09-VI-14a

BLOCH OSCILLATIONS OF VOLTAGE ACROSS JOSEPHSON JUNCTION TRAVERSED BY CURRENT

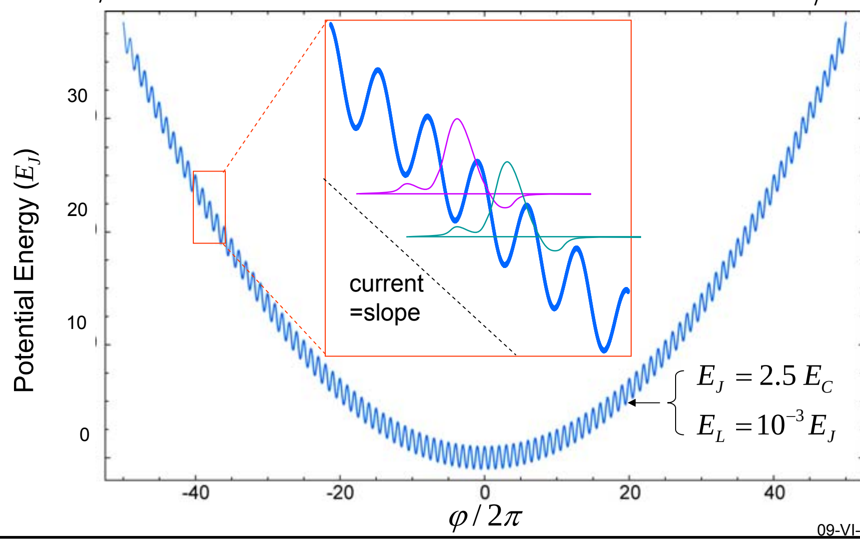
$$H = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos\varphi + \frac{1}{2} E_L \left(\varphi - \Phi_b\right)^2 \qquad \hat{I} = \frac{2e}{\hbar} \frac{\partial \hat{H}}{\partial \hat{\varphi}}$$



09-VI-14b

BLOCH OSCILLATIONS OF VOLTAGE ACROSS JOSEPHSON JUNCTION TRAVERSED BY CURRENT

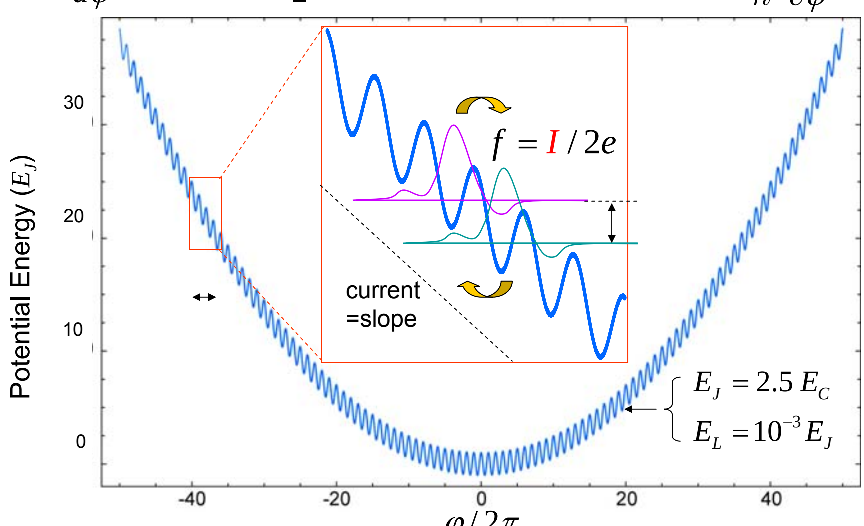
$$H = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos\varphi + \frac{1}{2} E_L (\varphi - \Phi_b)^2 \qquad \hat{I} = \frac{2e}{\hbar} \frac{\partial \hat{H}}{\partial \hat{\varphi}}$$



09-VI-14c

BLOCH OSCILLATIONS OF VOLTAGE ACROSS JOSEPHSON JUNCTION TRAVERSED BY CURRENT

$$H = -4E_C \frac{d^2}{d\varphi^2} - E_J \cos\varphi + \frac{1}{2} E_L (\varphi - \Phi_b)^2 \qquad \hat{I} = \frac{2e}{\hbar} \frac{\partial \hat{H}}{\partial \hat{\varphi}}$$



09-VI-14d

SELECTED BIBLIOGRAPHY

Electrons in a lattice

Bloch, Phys. 52, 555 (1928), Zener, Proc. R. Soc. London Ser. (1934)
Waschke et al., Phys. Rev. Lett. 70, 3319 (1993)

original theory

Phase of Josephson junction

Likharev and Zorin, J. Low. Temp. Phys. 59, 347 (1985)
Kuzmin and Haviland, Phys. Rev. Lett., 67, 2890 (1991)
Bylander, Duty and Delsing, Nature 434, 361 (2005)
Nguyen et al., Phys. Rev. Lett. 99, 187005 (2007)

Atoms in optical lattice

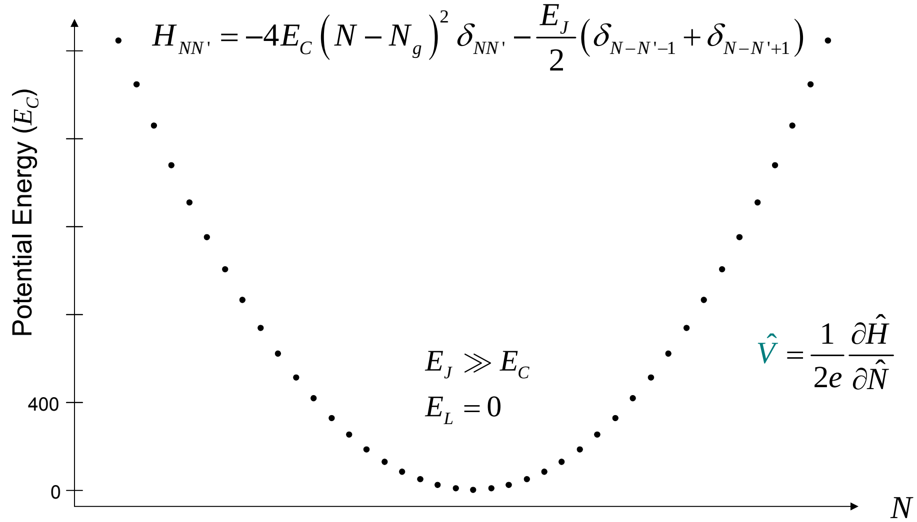
Ben Dahan et al., Phys. Rev. Lett. 76, 4508 (1996)
Clade et al., Phys. Rev. A 74, 052109 (2006)

Measurement of α with metrological precision

09-VI-15

AC JOSEPHSON EFFECT CAN BE SEEN AS A TYPE OF BLOCH OSCILLATION

$$H_{NN'} = -4E_C\left(N - N_g\right)^2 \delta_{NN'} - \frac{E_J}{2}\left(\delta_{N-N'-1} + \delta_{N-N'+1}\right)$$

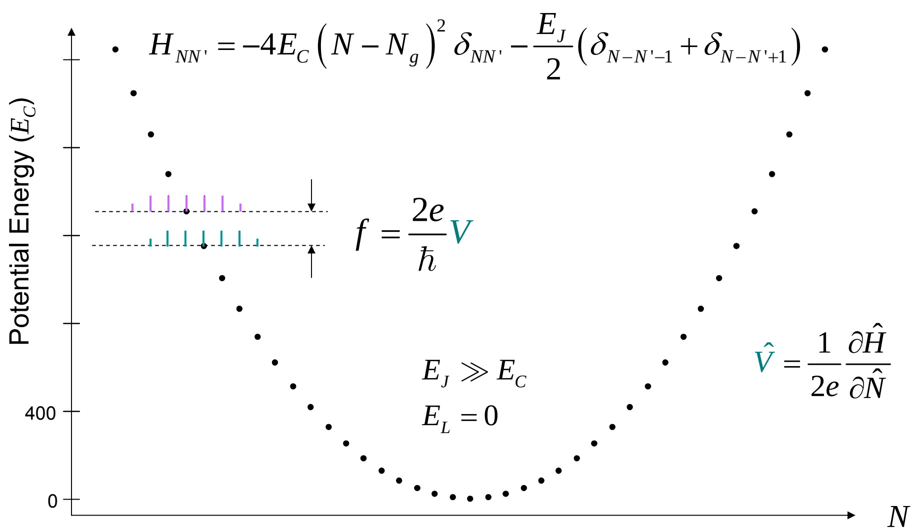


$$E_J \gg E_C$$
$$E_L = 0$$

$$\hat{V} = \frac{1}{2e}\frac{\partial \hat{H}}{\partial \hat{N}}$$

09-VI-16

AC JOSEPHSON EFFECT CAN BE SEEN AS A TYPE OF BLOCH OSCILLATION



09-VI-16a

OUTLINE

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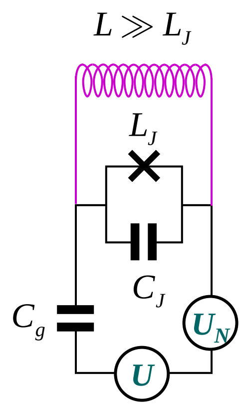
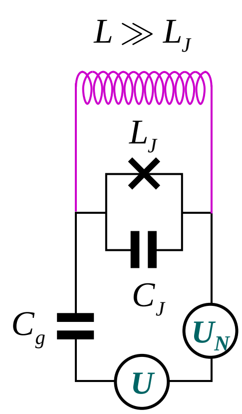
09-VI-5c

IDEA: SHUNT A COOPER PAIR BOX AT DC, LEAVE IT UNSHUNTED AT RF



09-VI-17

IDEA: SHUNT A COOPER PAIR BOX AT DC, LEAVE IT UNSHUNTED AT RF



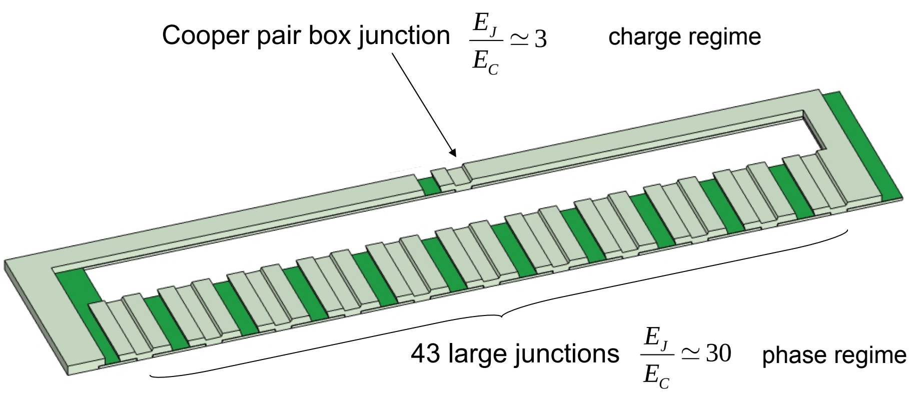
WIRE INDUCTANCE?

DEFIES $\alpha = \frac{1}{137.0}$

$$= \frac{Z_{\text{vac}}}{2R_K}$$

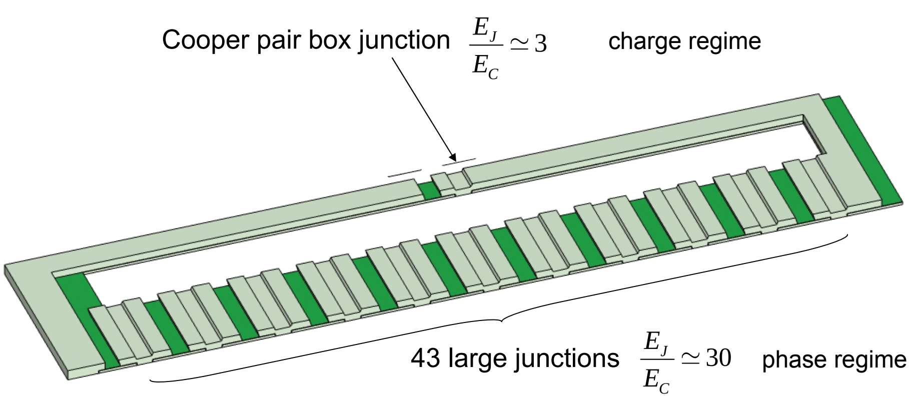
09-VI-17a

"FLUXONIUM" QUBIT USES ***KINETIC*** INDUCTANCE OF JOSEPHSON ARRAY



09-VI-18

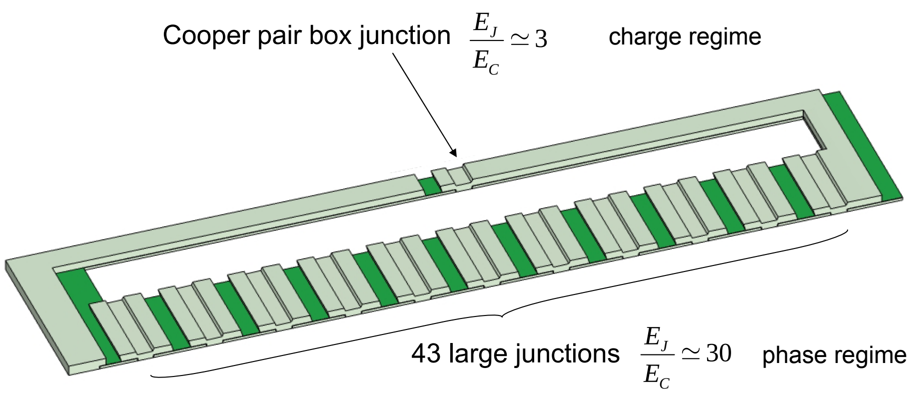
"FLUXONIUM" QUBIT USES ***KINETIC*** INDUCTANCE OF JOSEPHSON ARRAY



<u>design minimizes island self-capacitance</u>

09-VI-18a

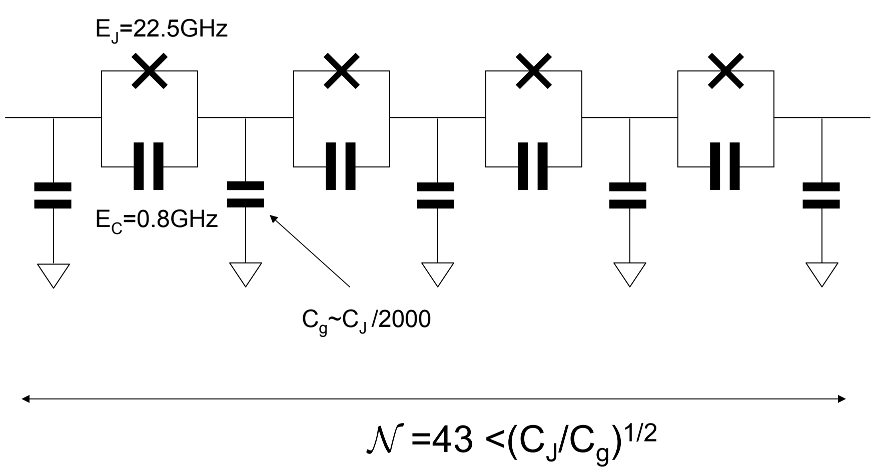
"FLUXONIUM" QUBIT USES *KINETIC* INDUCTANCE OF JOSEPHSON ARRAY



IMPORTANT PROPERTY: ANY TWO ISLANDS ARE CONNECTED BY AT LEAST ONE PATH INVOLVING LARGE JUNCTIONS

09-VI-18b

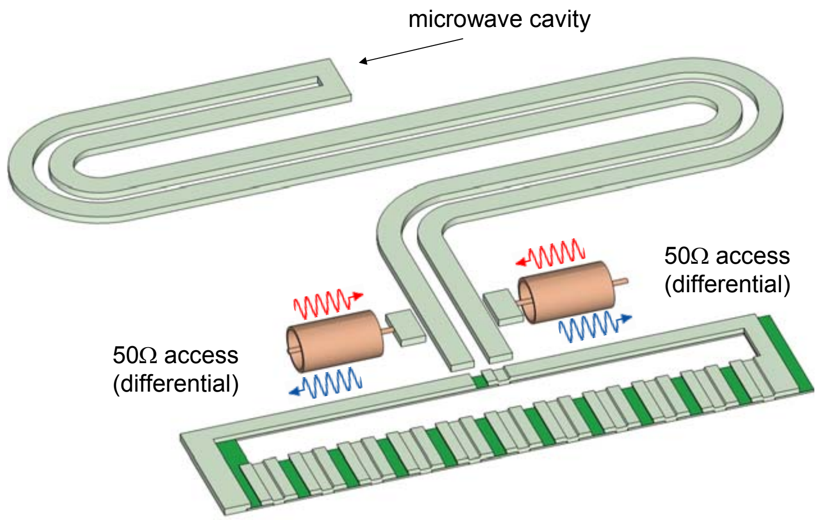
PARAMETERS OF THE ARRAY



$\mathcal{N}$ =43 <$(C_J/C_g)^{1/2}$

09-VI-19

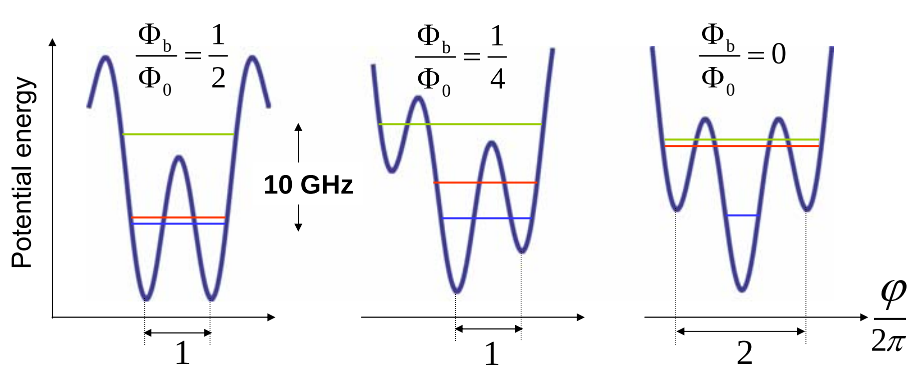
μWAVE READOUT OF FLUXONIUM QUBIT



cQED: Wallraff et al (2004), Schuster et. al (2005)

09-VI-20

SPECTRUM CHARACTER^ISTICS ARE VERY DIFFERENT FROM RF-SQUID-LIKE QUBITS



J.Koch, V.Manucharyan, L.Glazman, M.Devoret, arXiv:0902.2980 (2009)

09-VI-21

OUTLINE

1. Quantum error correction and quantum feedback
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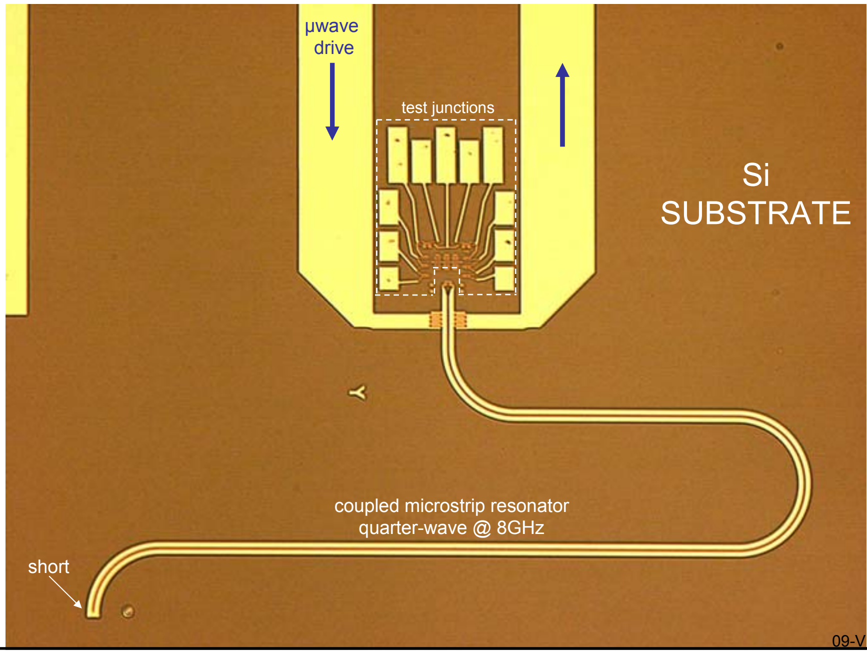
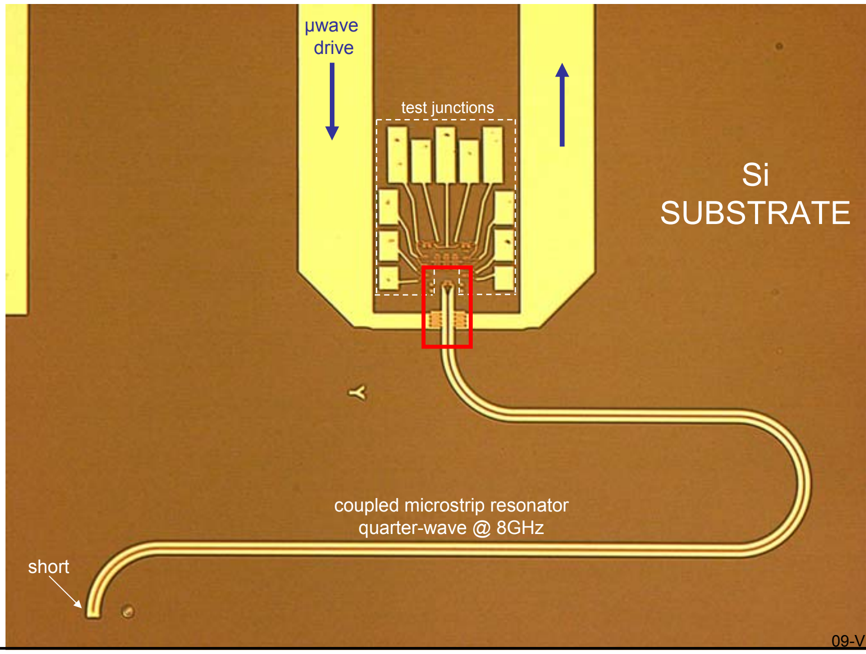
09-VI-5d

SAMPLE: COUPLE MINIMALLY TO FLUX



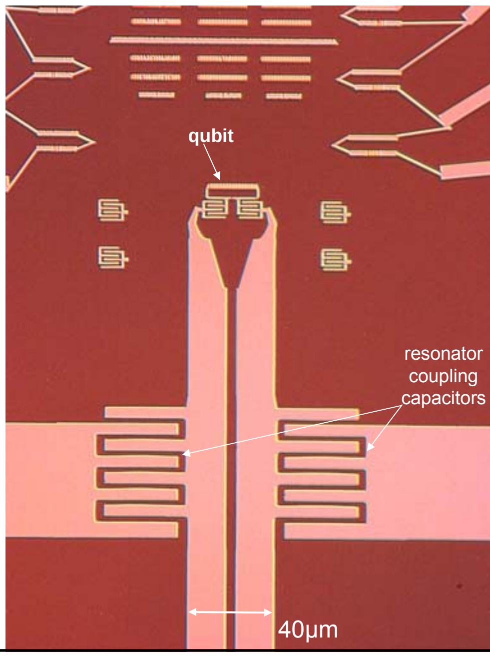
09-VI-22

SAMPLE: COUPLE MINIMALLY TO FLUX



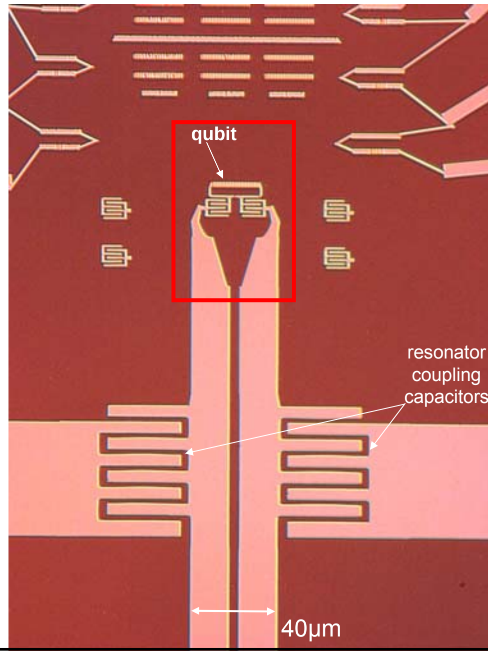
09-VI-22a

SAMPLE: COUPLE MINIMALLY TO FLUX



09-VI-23

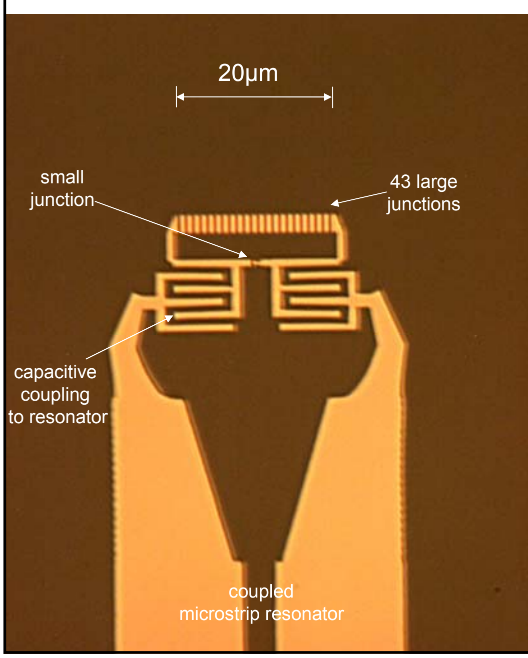
SAMPLE: COUPLE MINIMALLY TO FLUX



09-VI-23a

09-VI-24

SAMPLE: COUPLE MINIMALLY TO FLUX



small junction

$E_J/h = 8.9\,\mathrm{GHz}$ $\quad \frac{E_J}{E_C} = 3.5$

$E_C/h = 2.5\,\mathrm{GHz}$

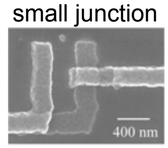
array of large junctions

43 junctions, each with:

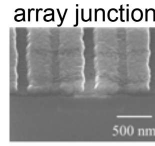
$E_J/h = 22.5\,\mathrm{GHz}$ $\quad \frac{E_J}{E_C} = 28$

$E_C/h = 0.8\,\mathrm{GHz}$

small junction



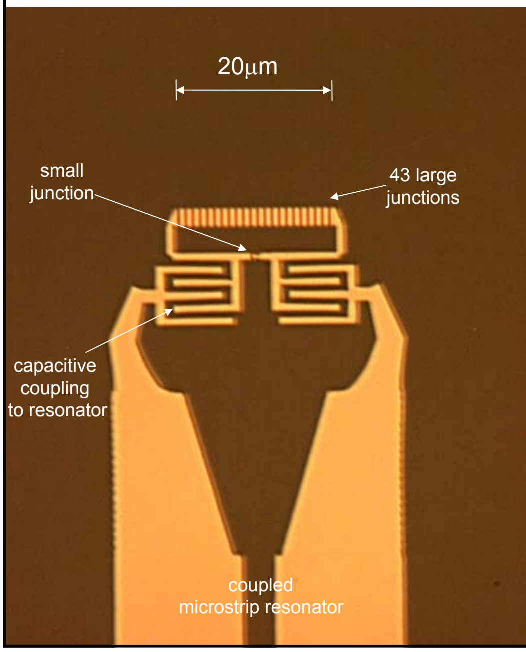
array junctions



Single step e-beam; Al/**AlOx**/Al

09-VI-24a

SAMPLE: COUPLE MINIMALLY TO FLUX



small junction

$E_J/h = 8.9\,\mathrm{GHz}$ $\quad \frac{E_J}{E_C} = 3.5$

$E_C/h = 2.5\,\mathrm{GHz}$

array of large junctions

43 junctions, each with:

$E_J/h = 22.5\,\mathrm{GHz}$ $\quad \frac{E_J}{E_C} = 28$

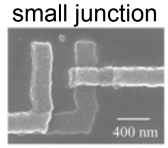
$E_C/h = 0.8\,\mathrm{GHz}$

array behaves as a large inductance:

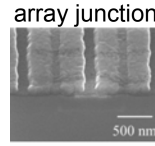
$L = 310\,\mathrm{nH}$ $\quad E_L/h = 0.52\,\mathrm{GHz}$

negligible quantum phase slips
and parasitic capacitances

small junction



array junctions



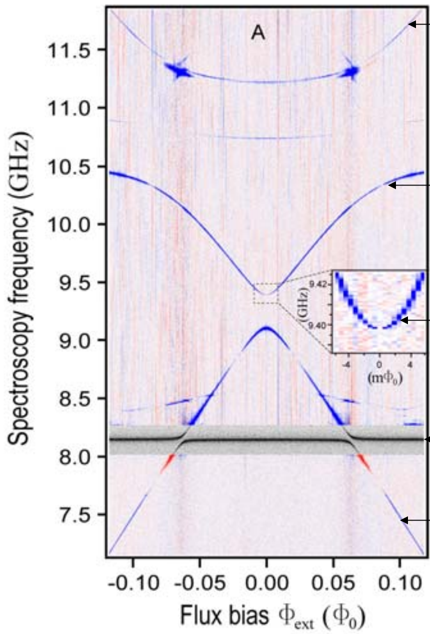
Single step e-beam; Al/**AlOx**/Al

OUTLINE

1. Quantum error correction and quantum feedback
2. The quantum metrology triangle and Bloch oscillations
3. Defying the fine structure constant
4. Fluxonium sample
5. Single Cooper pair effects without charge offsets

09-VI-5e

TWO-TONE SPECTROSCOPY vs EXTERNAL FLUX



0-3 transition

0-2 transition

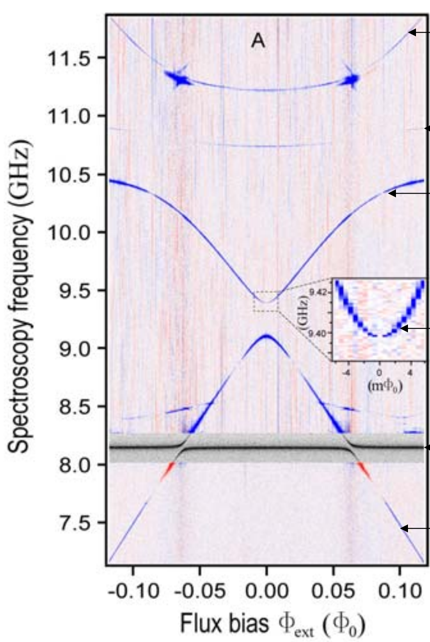
Inset:
0-2 transition symmetry-forbidden
at zero flux

resonator & vacuum Rabi

0-1 transition

09-VI-25

TWO-TONE SPECTROSCOPY vs EXTERNAL FLUX



0-3 transition

Parasitic resonance in the array
(accounted by a minor model correction)

0-2 transition

Inset:
0-2 transition symmetry-forbidden
at zero flux

resonator & vacuum Rabi

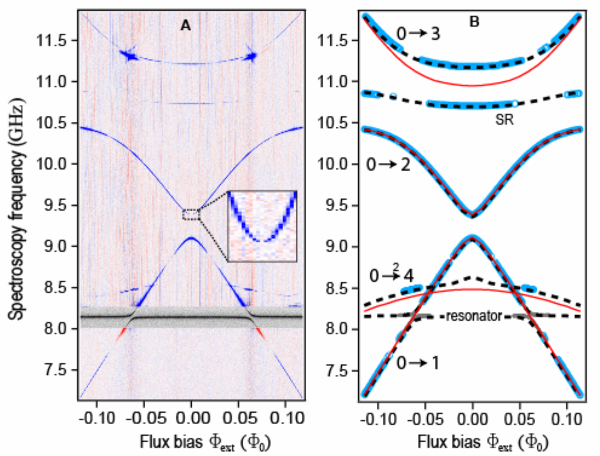
0-1 transition

More than 10^6 points,
taken over >72 hours
w/o jumps or drifts!

NO OFFSET CHARGE

09-VI-25a

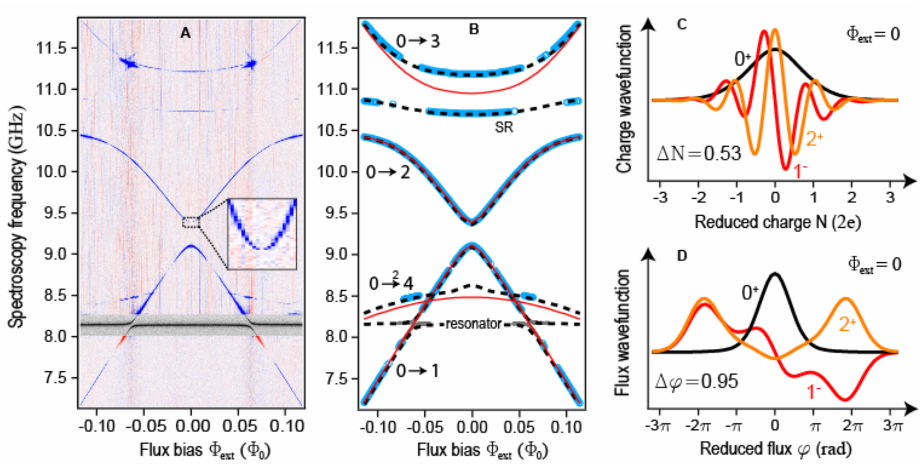
THY vs EXP CONFIRMS SINGLE COOPER PAIR REGIME



V.Manucharyan, J.Koch, L.Glazman, M.Devoret, arXiv:0906.0831 (2009)

09-VI-26

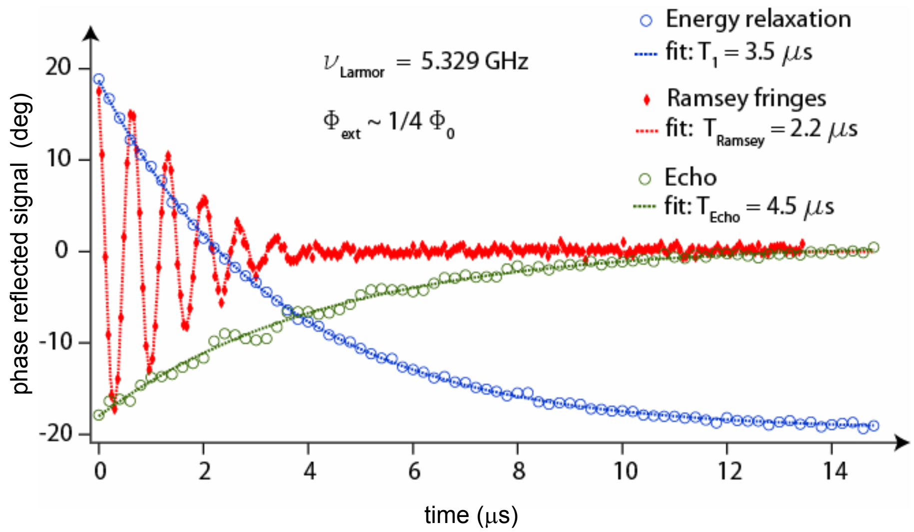
THY vs EXP CONFIRMS SINGLE COOPER PAIR REGIME



V.Manucharyan, J.Koch, L.Glazman, M.Devoret, arXiv:0906.0831 (2009)

09-VI-26a

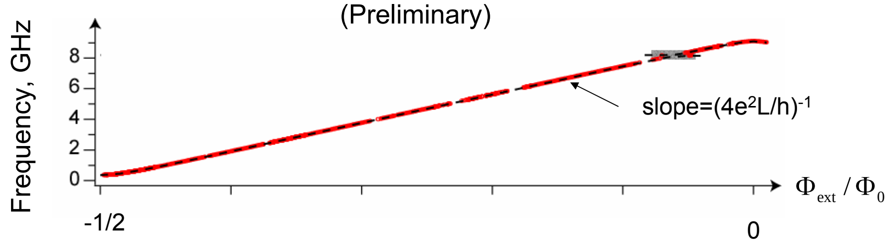
COHERENCE IN TIME DOMAIN



09-VI-27

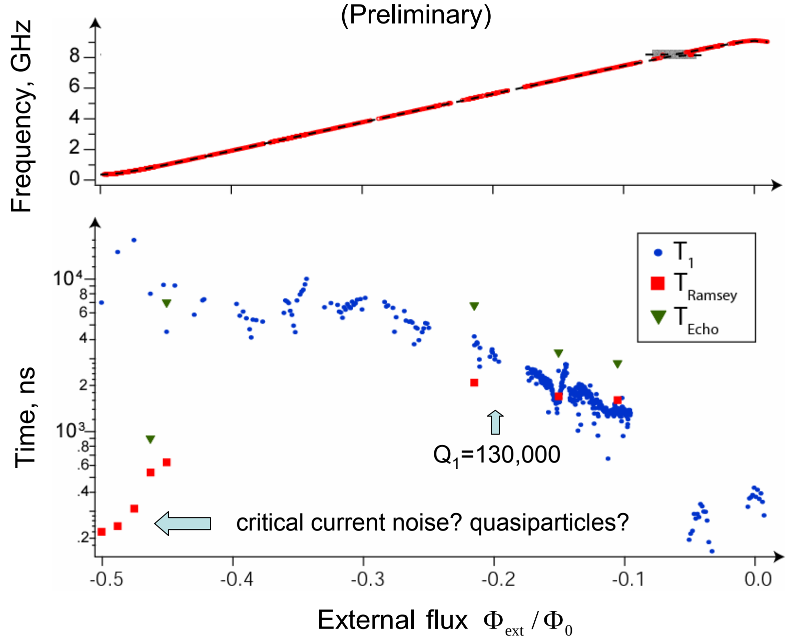
COHERENCE AS A FUNCTION OF FLUX BIAS

(Preliminary)



09-VI-28

COHERENCE AS A FUNCTION OF FLUX BIAS

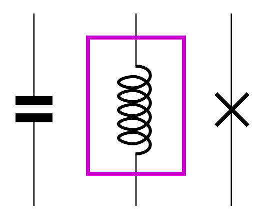


09-VI-29

PERSPECTIVES: ROLE OF INDUCTANCE

ARRAY WORKS AS SHUNTING INDUCTANCE >> L_J IN CHARGE REGIME

DESPITE LARGE NUMBER OF JUNCTIONS, FLUXONIUM IS AMONG BEST COHERENT SQUBITS



STRONG ANHARMONICITY PROVIDE EFFICIENT READOUT AND RESET

FLUXONIUM WOULD WORK AS COUPLING ELEMENT

OBSERVATION OF BLOCH OSCILLATIONS WILL REQUIRE LARGER INDUCTANCE AND APPLICATION OF COOLING

09-VI-30

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W.M. KECK

09-VI-31

END OF COURSE