QUANTUM-MECHANICAL ELECTRICAL CIRCUITS

YALE, USA

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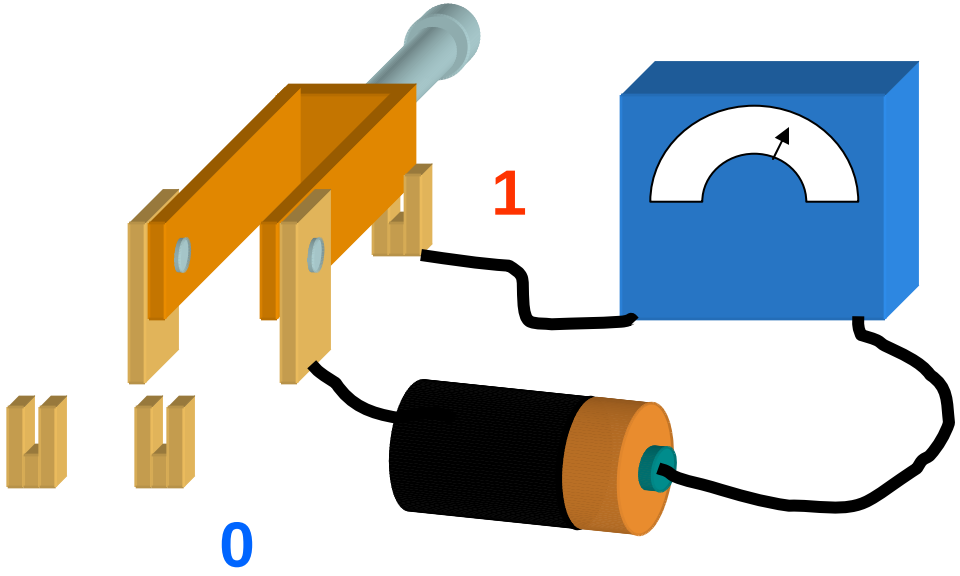
Acknowl[ts]: R. Schoelkopf, D. Prober, A. Blais & S. Girvin (Yale), A. Clerk (Mc Gill)

W.M. KECK

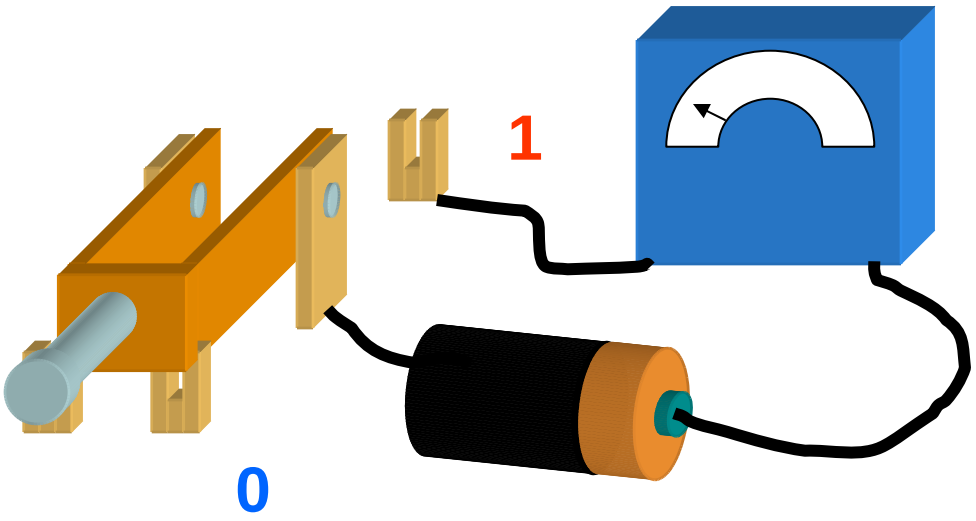
UBC, Feb. 2006

CLASSICAL INFORMATION



FLIPPING THE SWITCH WRITES ONE BIT OF INFORMATION

CLASSICAL INFORMATION



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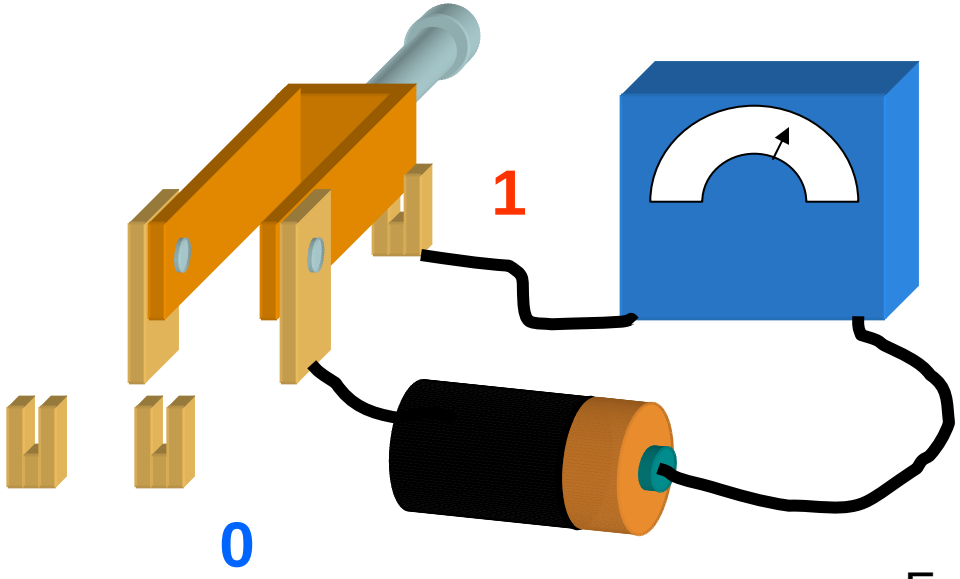
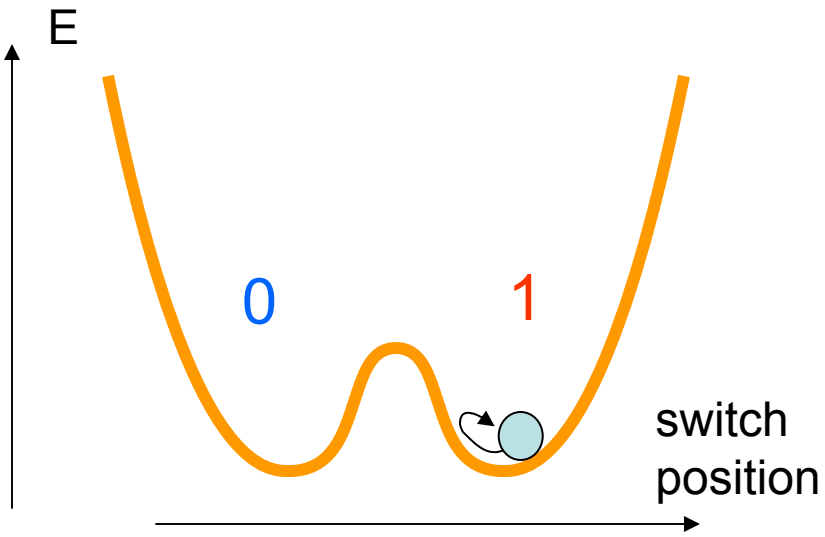
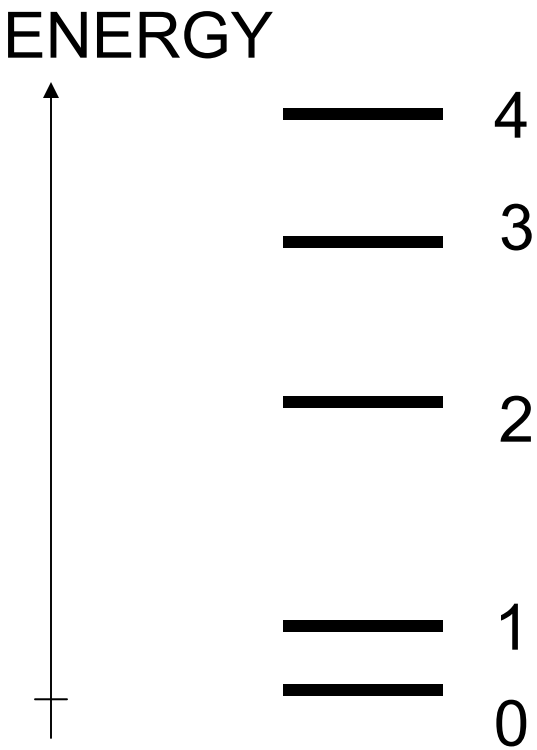


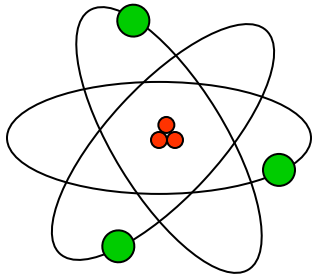
FLIPPING THE SWITCH WRITES ONE BIT OF INFORMATION

STATES ARE ROBUST, READOUT CAN BE MADE FAITHFUL



ELEMENTARY QUANTUM INFORMATION UNIT: QUBIT





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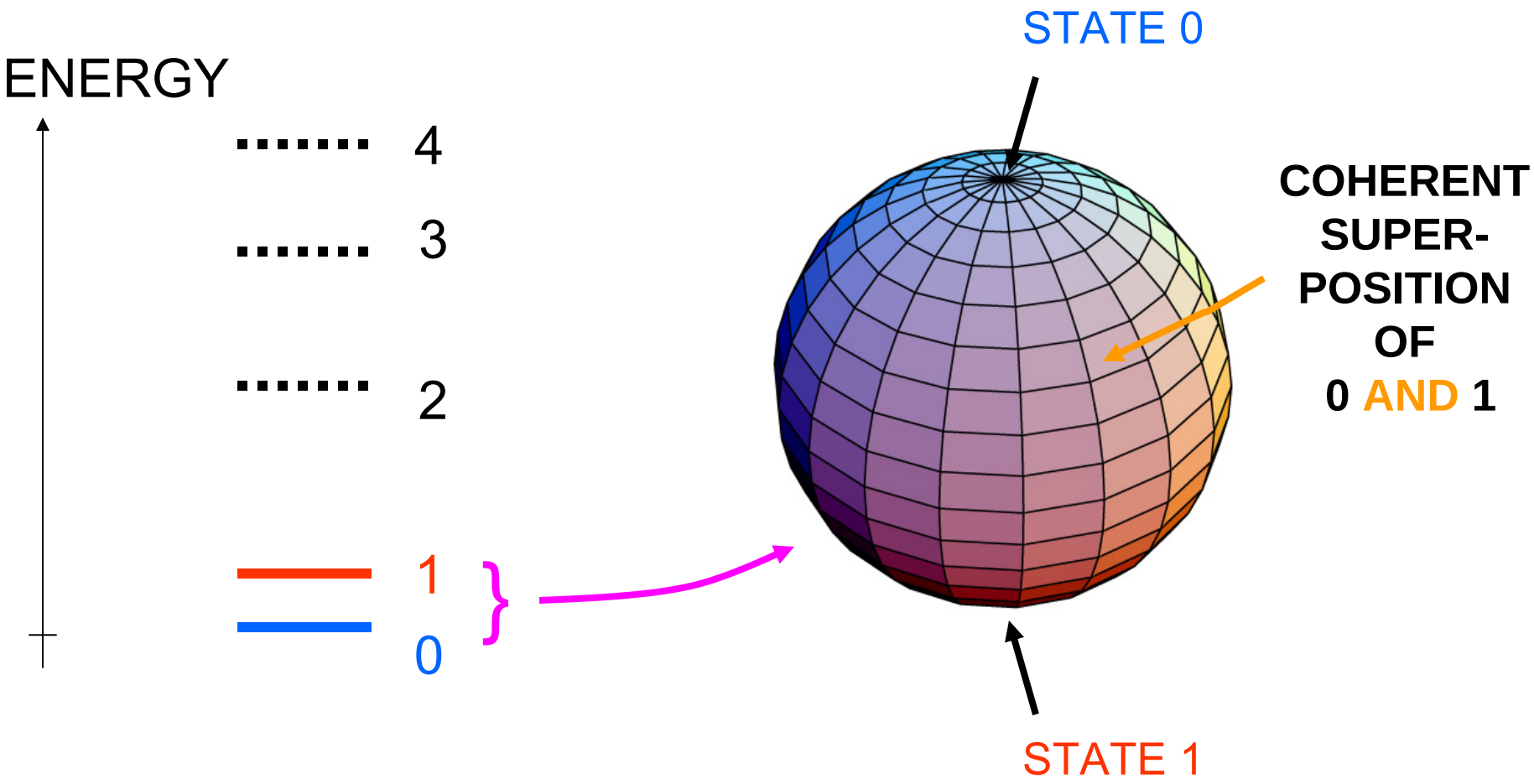
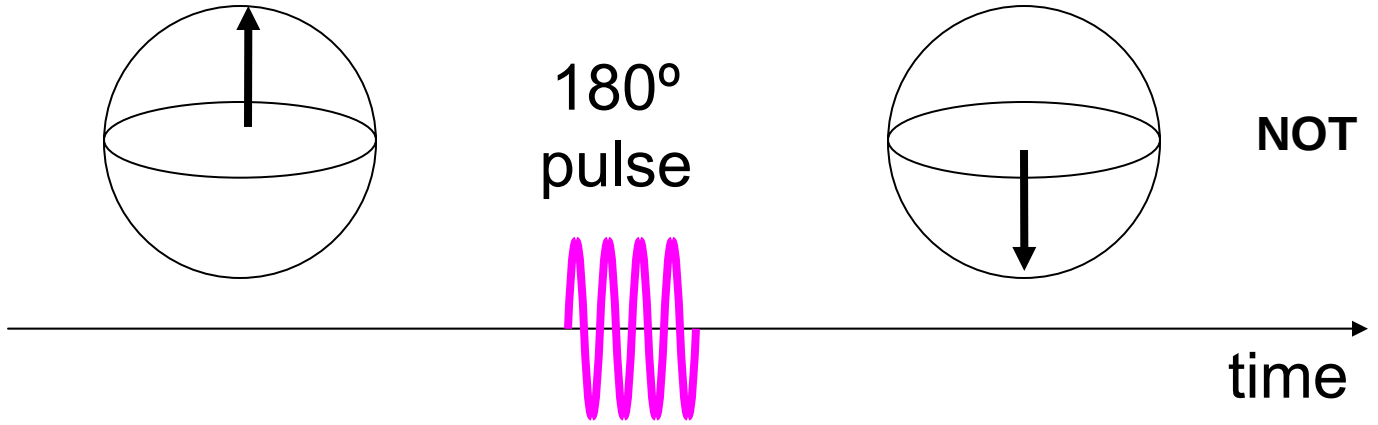


WRITING A SUPER-POSITION



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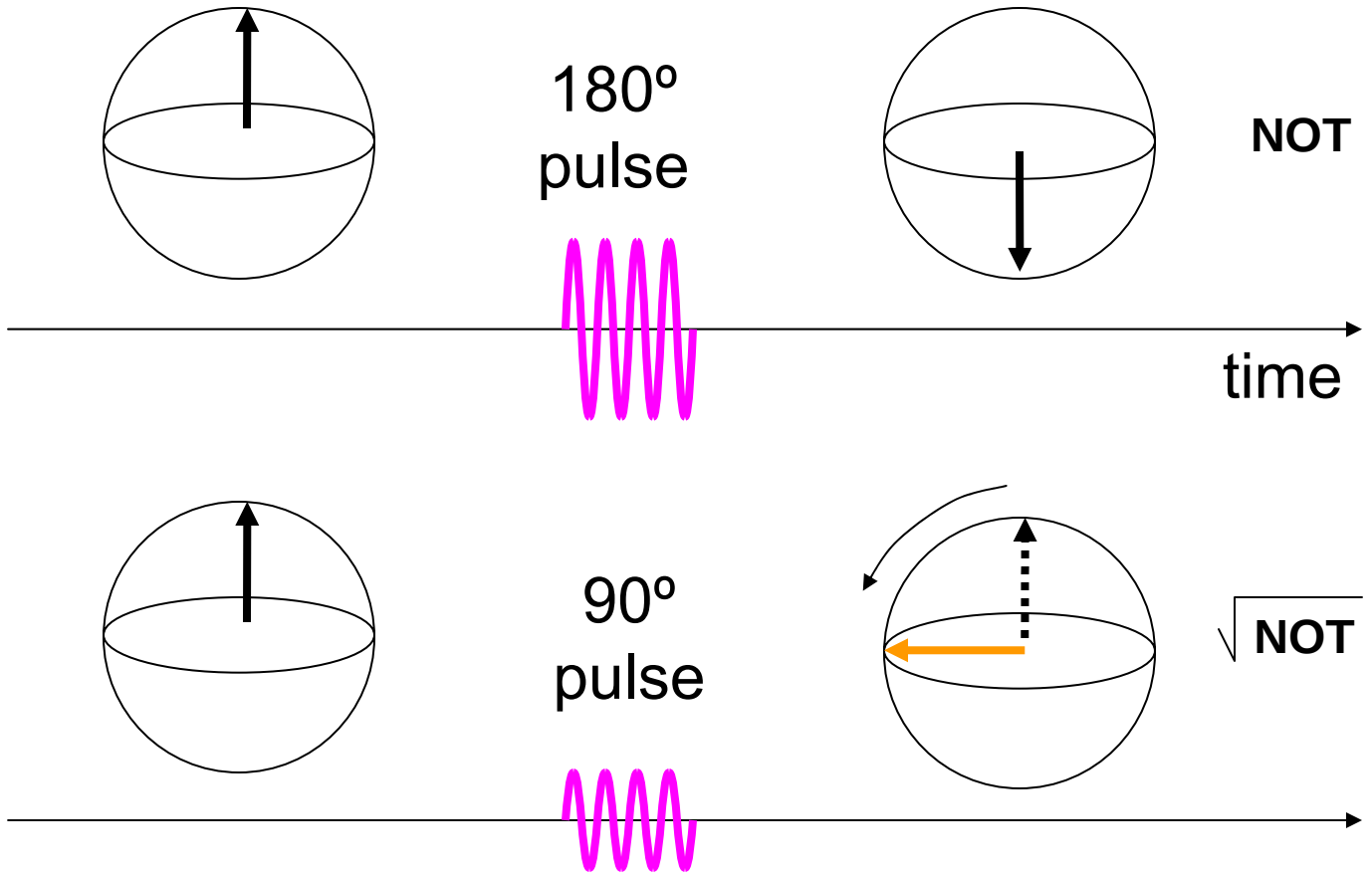

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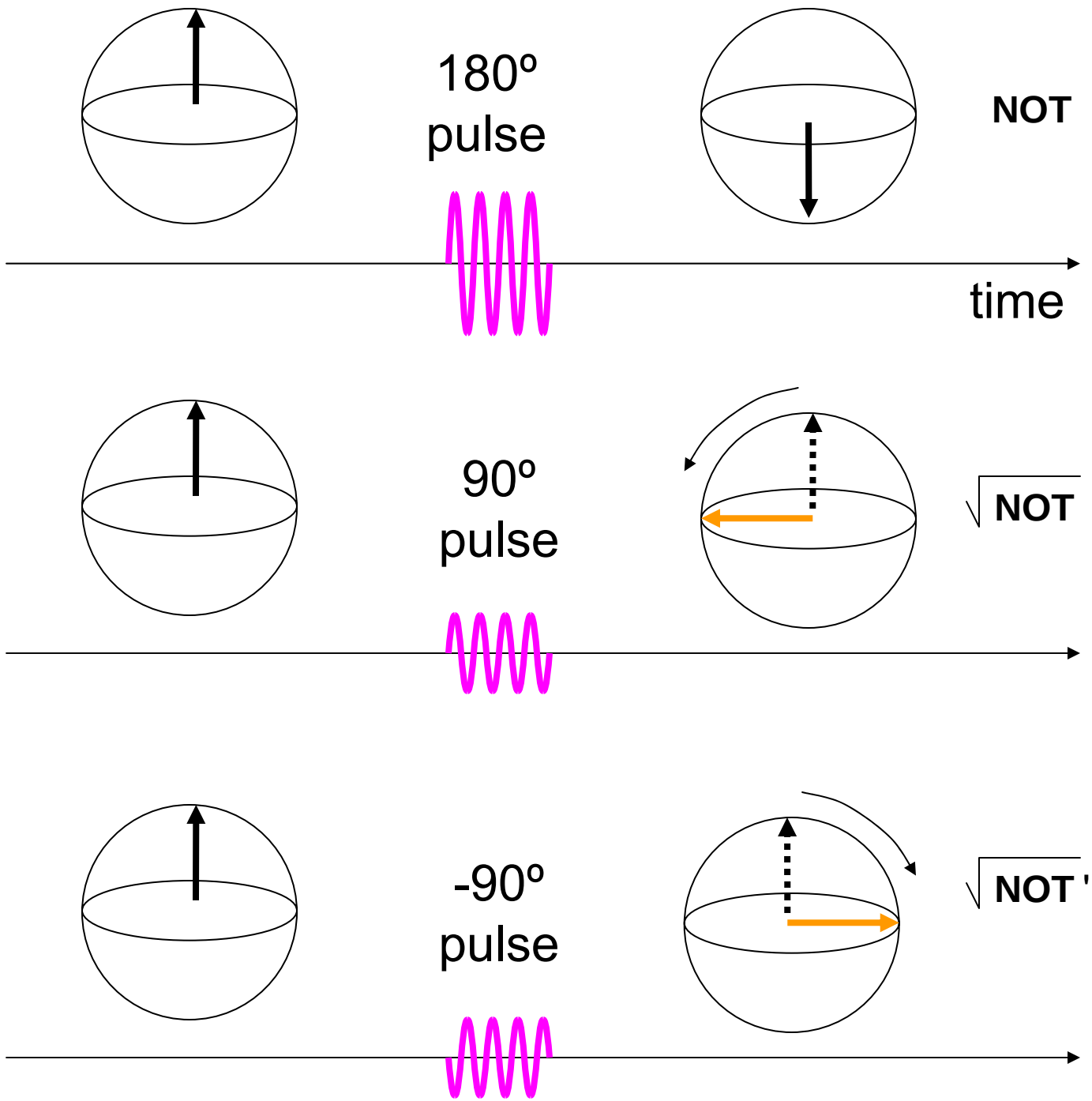
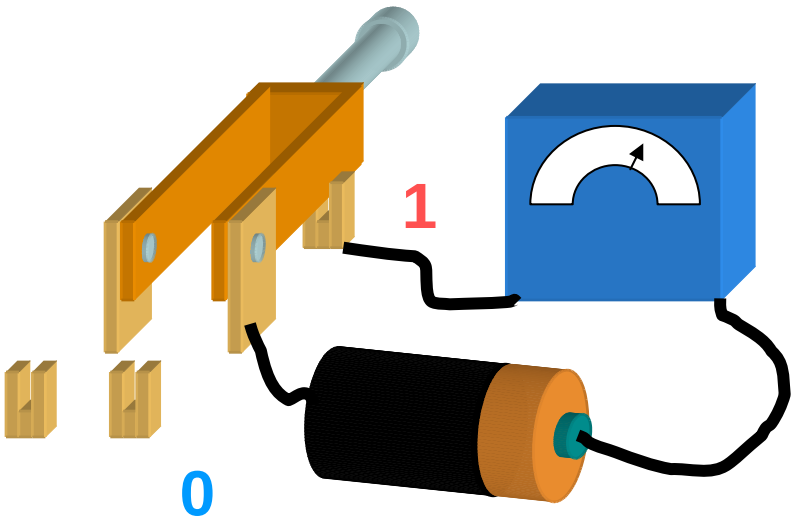
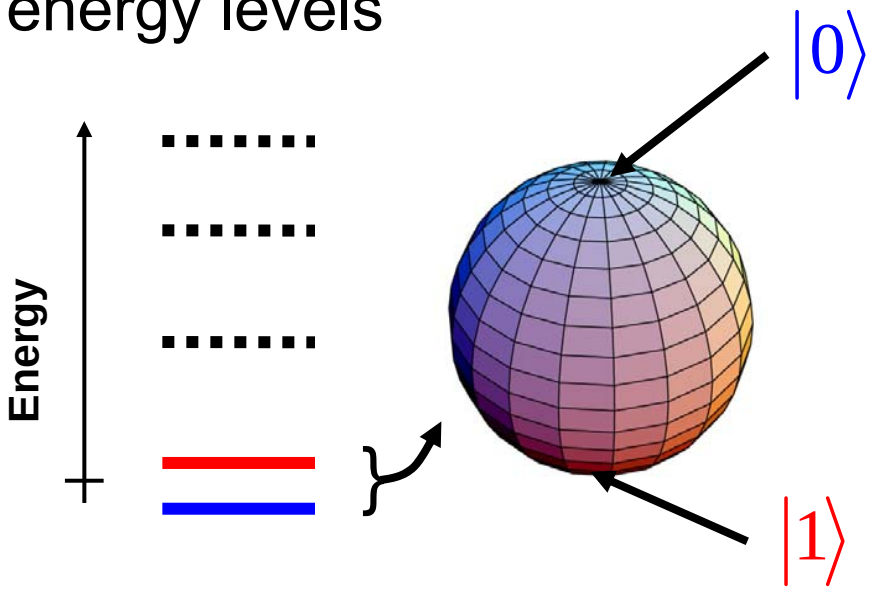


CLASSICAL vs. QUANTUM INFORMATION SUMMARY

classical
equilibrium states



quantum
energy levels

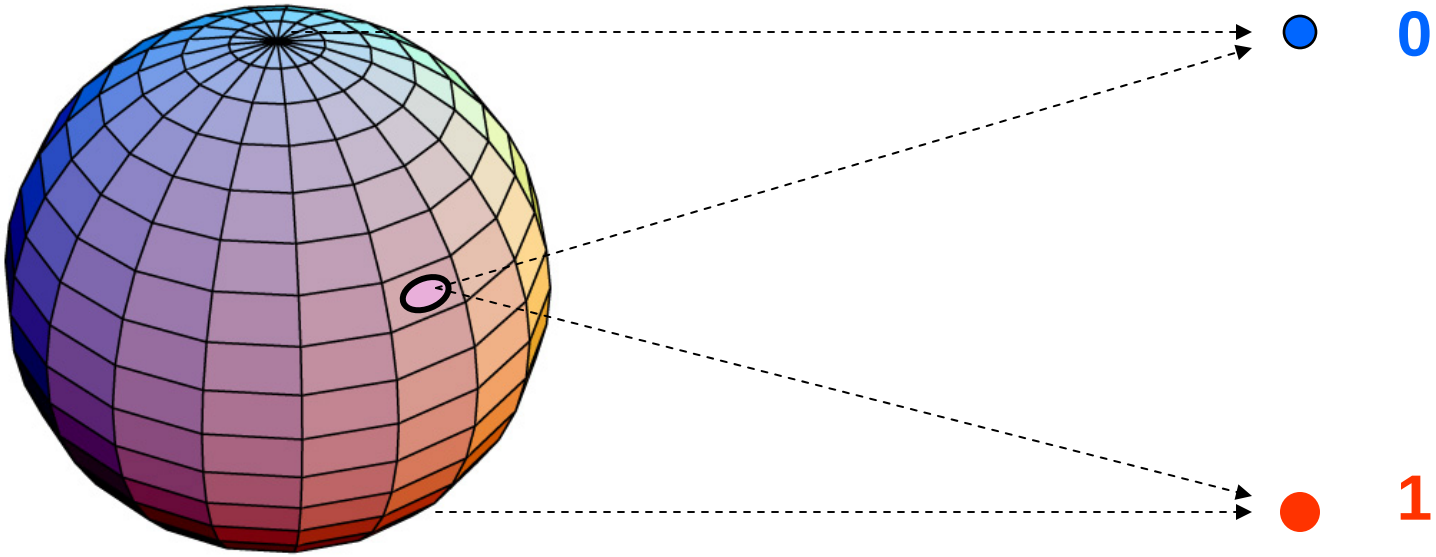


$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

write: 0 OR 1
read: 0 OR 1

write: |0> AND |1>
read: |0> OR |1>

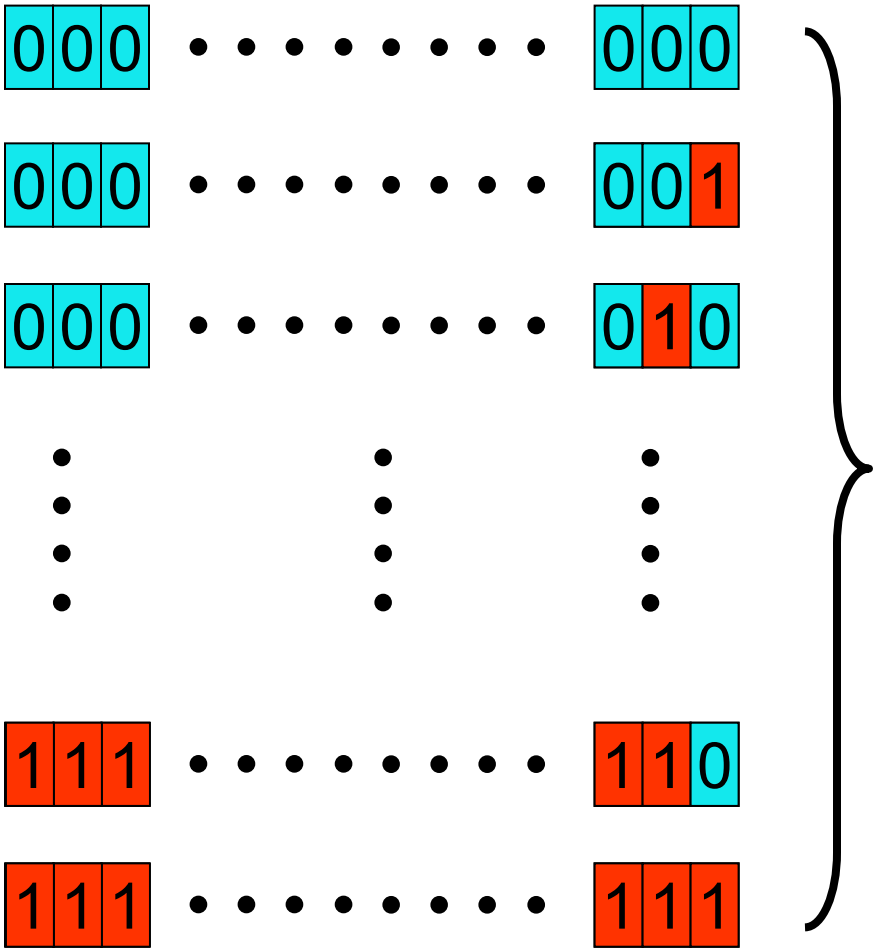
THE DISTURBING PROPERTY OF QUANTUM INFORMATION



DURING READOUT,
QUANTUM INFORMATION
COLLAPSES
INTO 0 OR 1

THE POWER OF QUANTUM INFORMATION

REGISTER WITH N BITS:

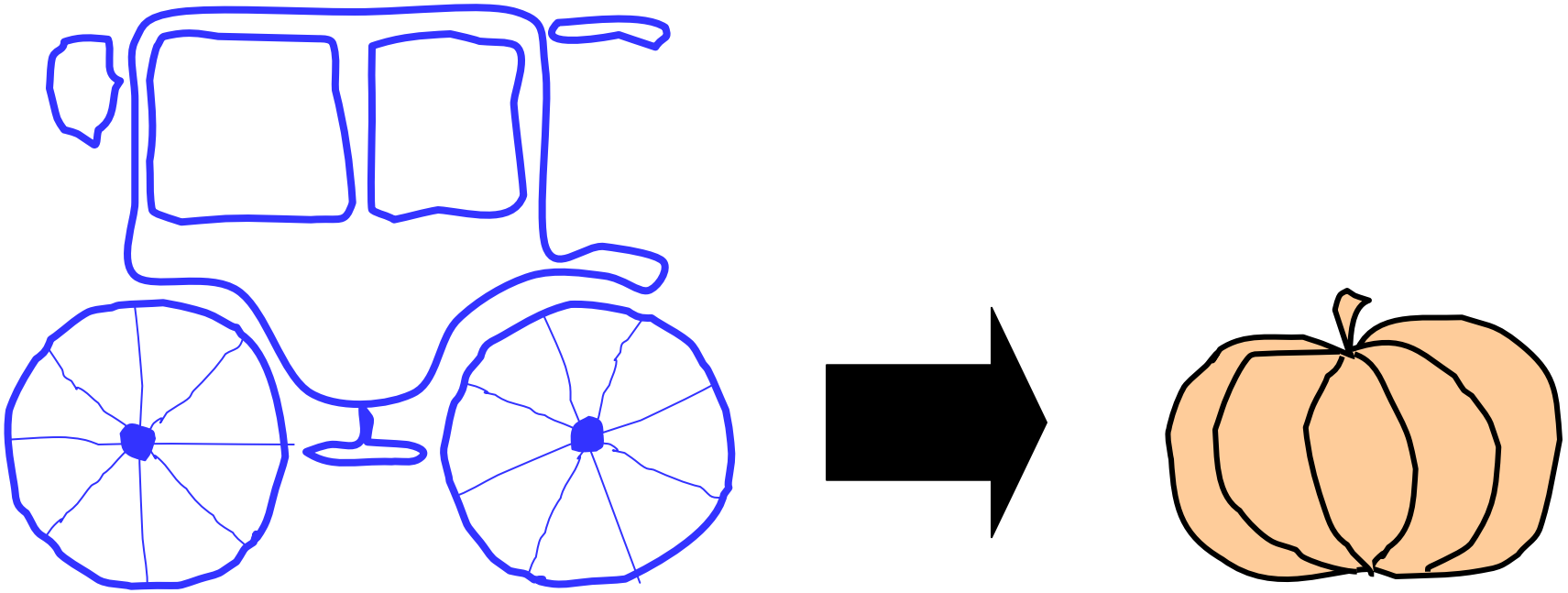


REPRESENTS NUMBERS BETWEEN 0 AND 2^N - 1

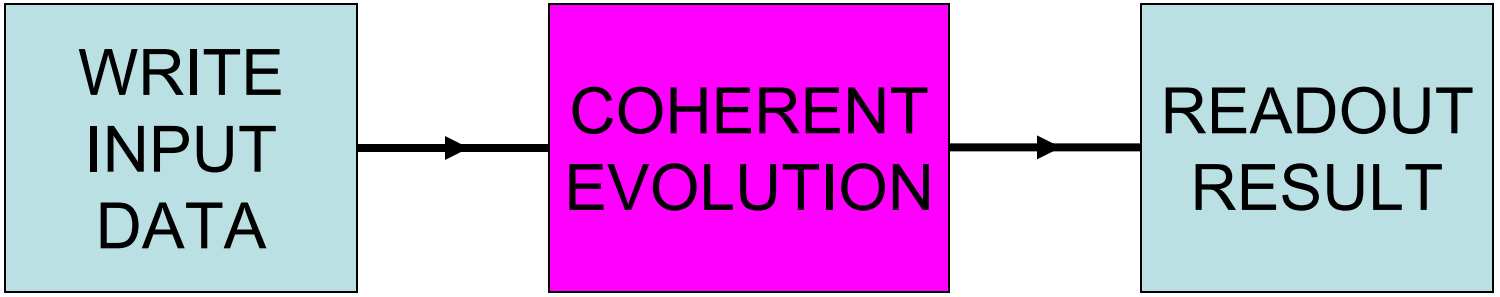
classically, can store or retrieve only 1 number

"quantally", can loop over of all numbers in only 1 operation!

READING THE RESULT OF A QUANTUM ALGORITHM



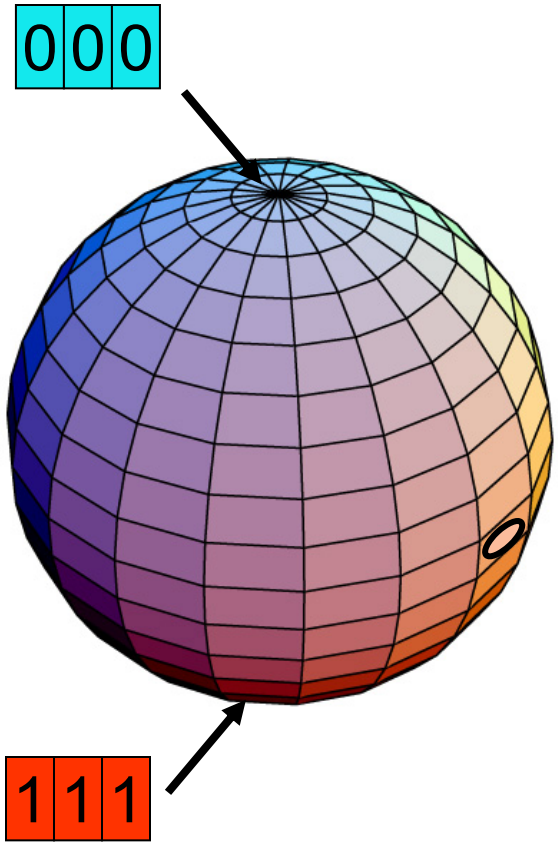
QUANTUM COMPUTATION REQUIRES LOTS OF COHERENCE



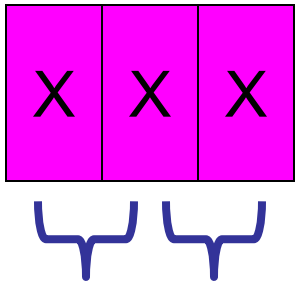
$$N_{op} = \frac{\text{COHERENCE TIME}}{\text{ELEM. OP. TIME}}$$

$N_{op} > 10^4$ for 1-qubit and 2-qubit operations?

QUANTUM ERROR CORRECTION CODES

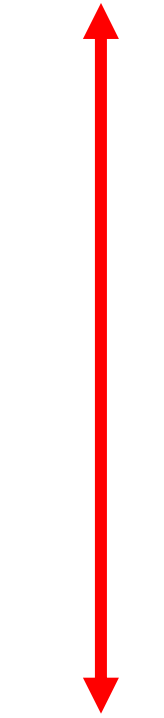


1) code 1 qubit information using a 3 qubit register

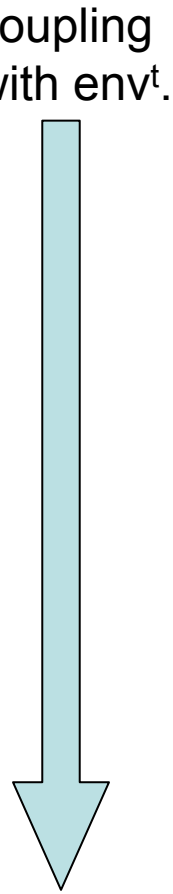


2) check if these couples are identical or not

QUANTUM INFORMATION SYSTEMS



- PHOTONS
- NUCLEAR SPINS
- IONS
- ATOMS
- ELECTRONS ON HELIUM
- QUANTUM DOTS
- SUPERCONDUCTING CIRCUITS



- electrical access
- readily integrable
- engineered hamiltonian with "LEGO" blocks:
  capacitors, inductors and Josephson junctions

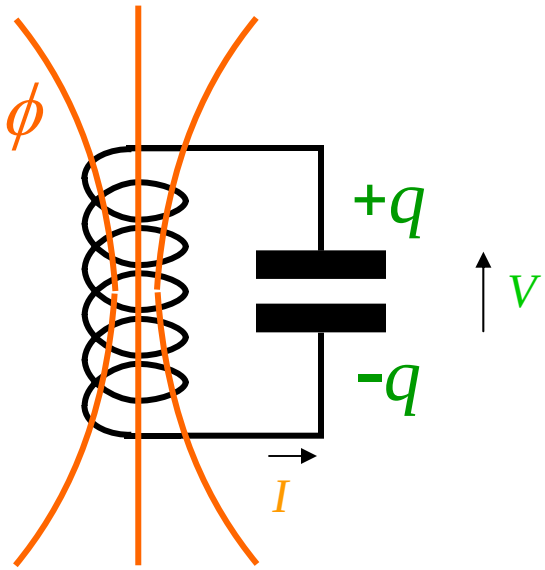
A.J. Leggett, 1982

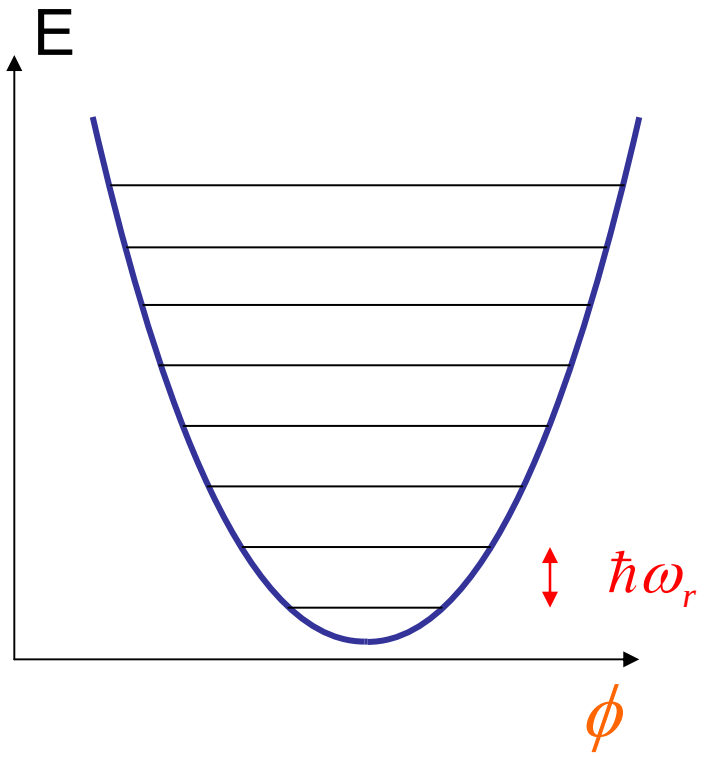
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES ?

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

MICROFABRICATION ➡ L ~ 3nH, C ~ 10pF, $\omega_r/2\pi$ ~ 1GHz

LC OSCILLATOR AS A QUANTUM CIRCUIT



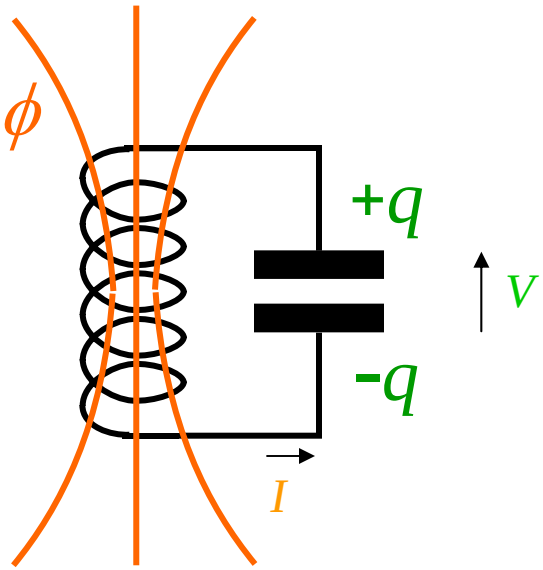


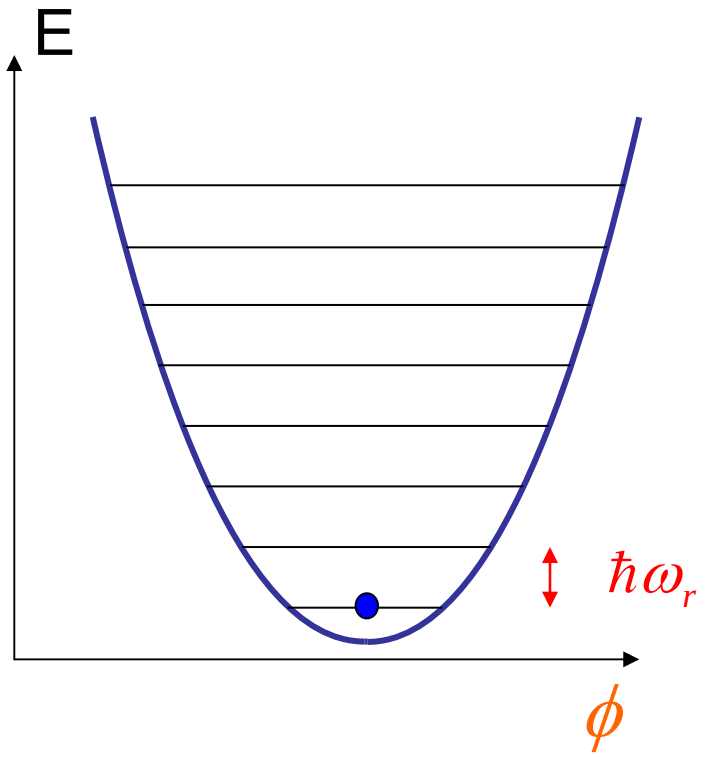
$$[\phi, q] = i\hbar$$

$$\phi = LI$$

$$q = CV$$

LC OSCILLATOR AS A QUANTUM CIRCUIT





$$[\phi, q] = i\hbar$$

$$\phi = LI$$

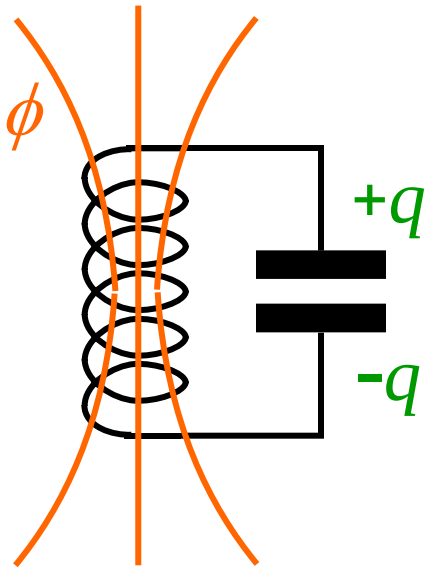
$$q = CV$$

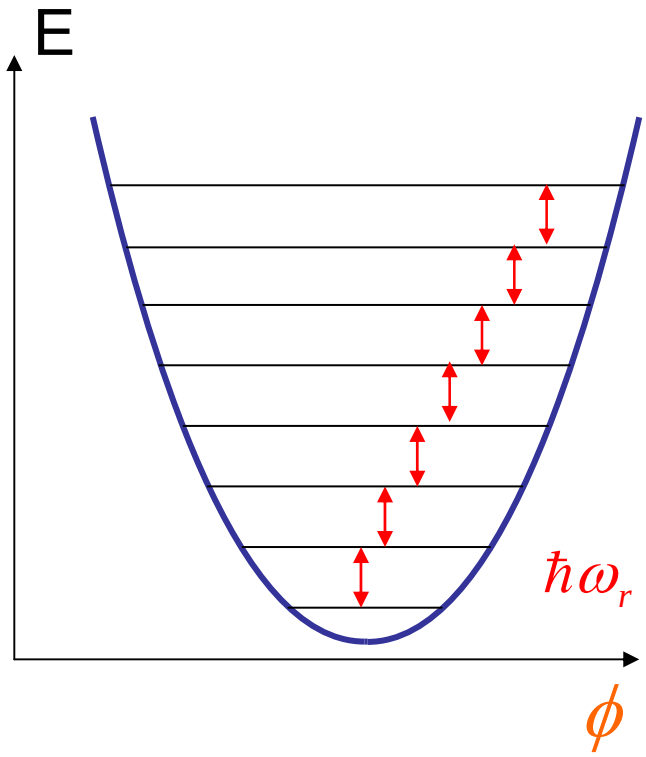
$$\hbar\omega_r \gg k_B T$$

1GHz

10mK

LC OSCILLATOR AS A QUANTUM CIRCUIT

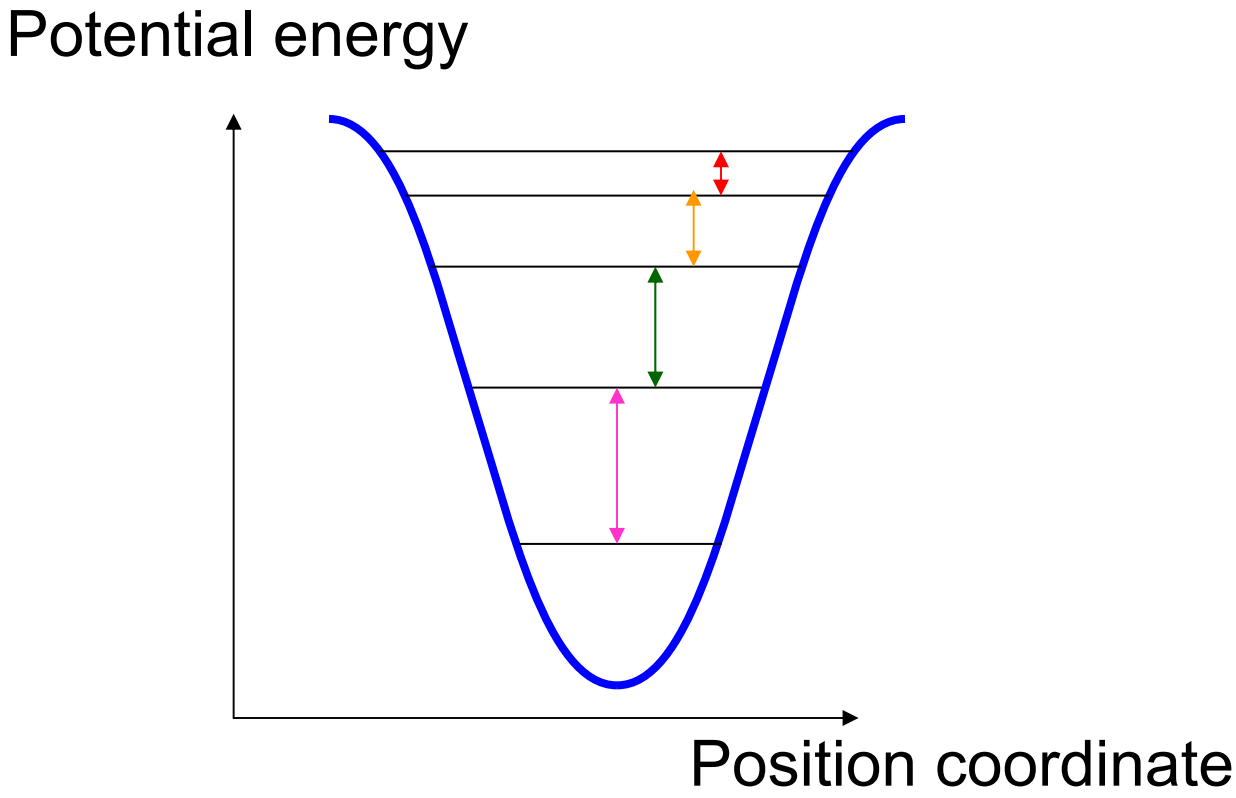




$$[\phi, q] = i\hbar$$

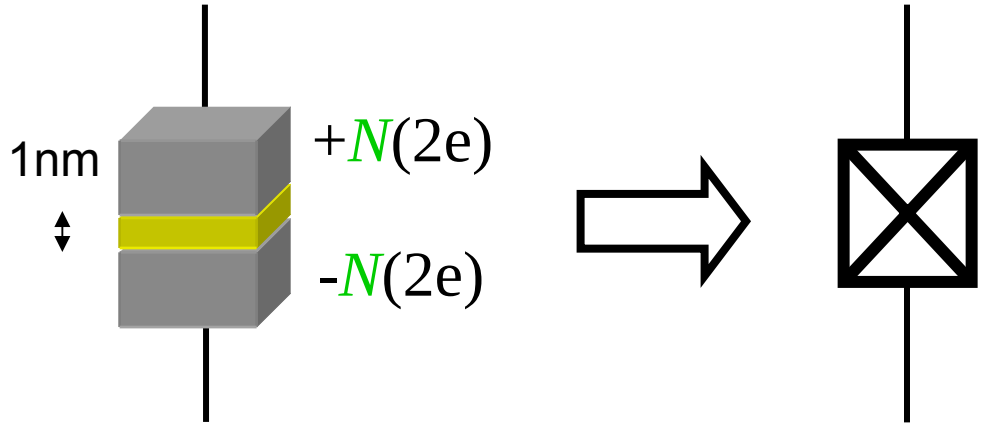
CANNOT STEER THE SYSTEM TO AN ARBITRARY STATE

NEED NON-LINEARITY



CAN NOW STEER THE SYSTEM TO AN ARBITRARY STATE

THE JOSEPHSON TUNNEL JUNCTION: THE ONLY NON-LINEAR LC RESONATOR....

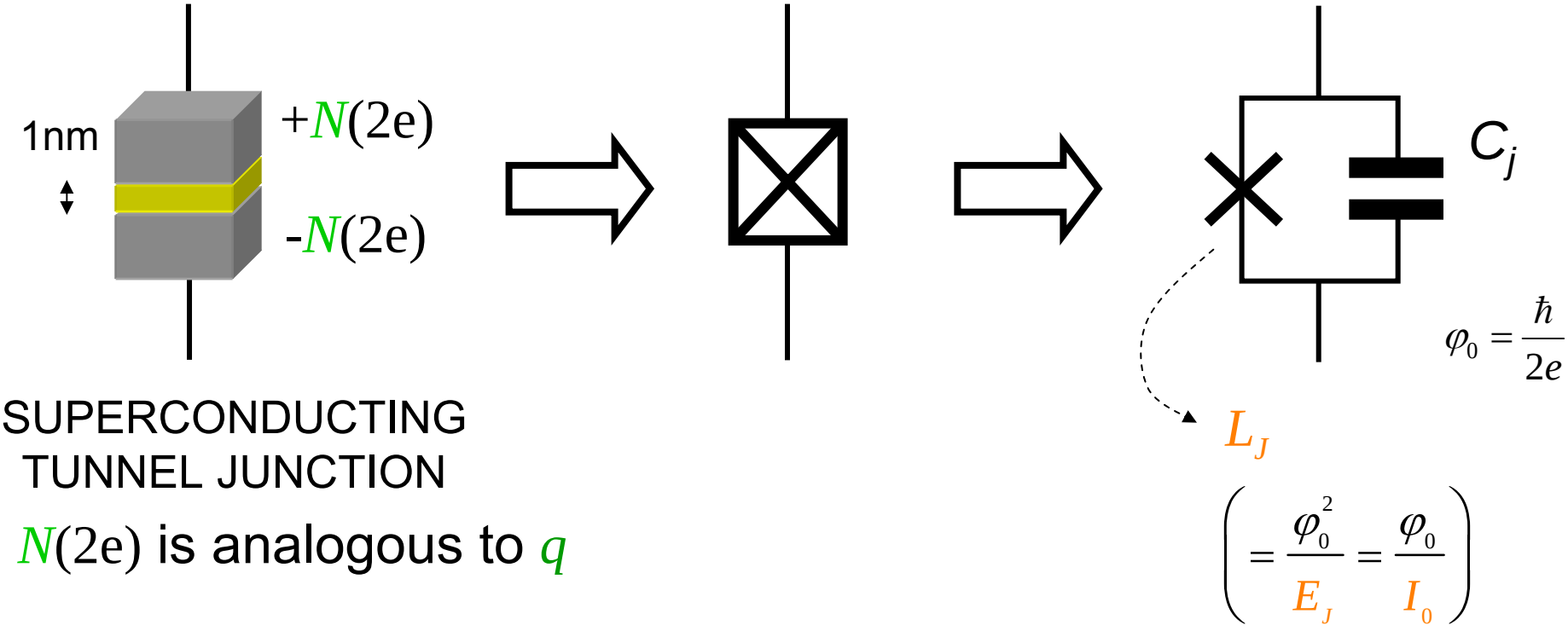


SUPERCONDUCTING
TUNNEL JUNCTION

$N(2e)$ is analogous to q

.... WITH NO DISSIPATION (BCS, kT<<Δ)

THE JOSEPHSON TUNNEL JUNCTION: THE ONLY NON-LINEAR LC RESONATOR....



SUPERCONDUCTING TUNNEL JUNCTION

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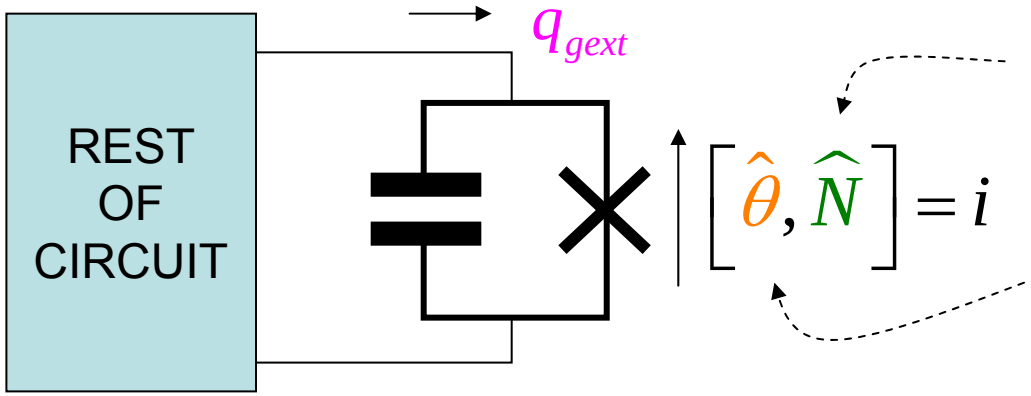
DEGREES OF FREEDOM AND PARAMETERS OF THE JOSEPHSON JUNCTION "ATOM"



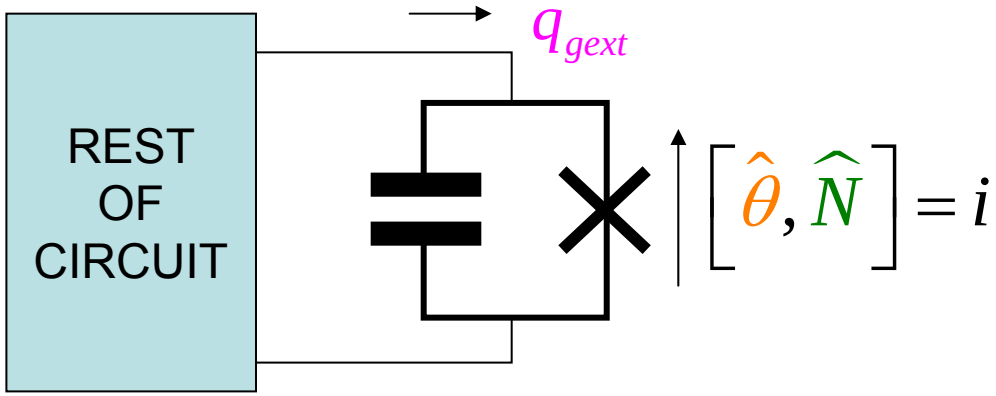
number of Cooper pairs thru junction, (angular momentum)

phase difference across junction, (position on a circle)

THE hamiltonian:
(we mean it!)

$$\hat{H}_j = E_C \left(\hat{N} - \frac{q_{ext}}{2e} \right)^2 - E_J \cos\hat{\theta}$$

DEGREES OF FREEDOM AND PARAMETERS OF THE JOSEPHSON JUNCTION "ATOM"



THE hamiltonian:
(we mean it!)

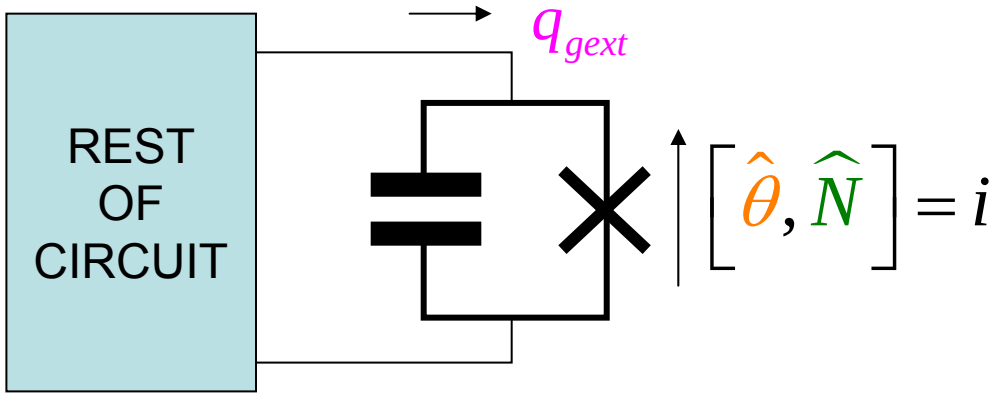
$$\hat{H}_j = E_C \left(\hat{N} - \frac{q_{ext}}{2e} \right)^2 - E_J \cos\hat{\theta}$$

$E_C = \dfrac{(2e)^2}{2C_\Sigma}$ charging energy
= kinetic energy

E_J Josephson energy
= potential energy

q_{gext} ext. bias charge

DEGREES OF FREEDOM AND PARAMETERS OF THE JOSEPHSON JUNCTION "ATOM"



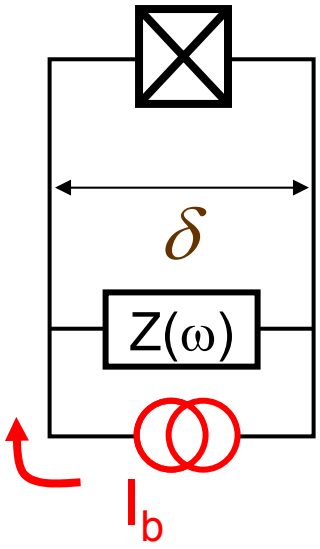
THE hamiltonian:
(we mean it!)

$$\hat{H}_j = E_C \left(\hat{N} - \frac{q_{ext}}{2e} \right)^2 - E_J \cos\hat{\theta}$$

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

3 DIFFERENT BIAS MODES FOR q_{ext}

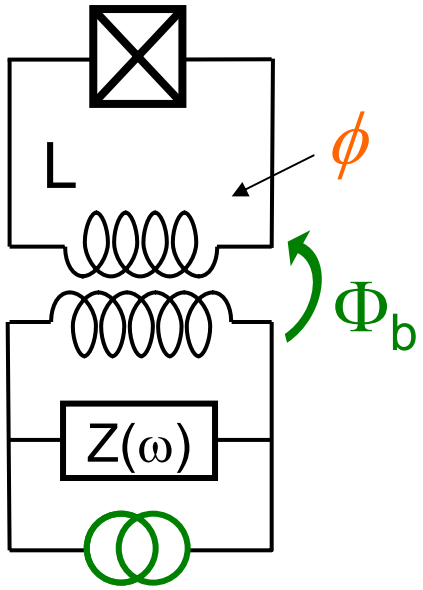
"CURRENT-BIASED JUNCTION"



phase across junction

UC Berkeley
U. Maryland
NIST, UCSB
.....

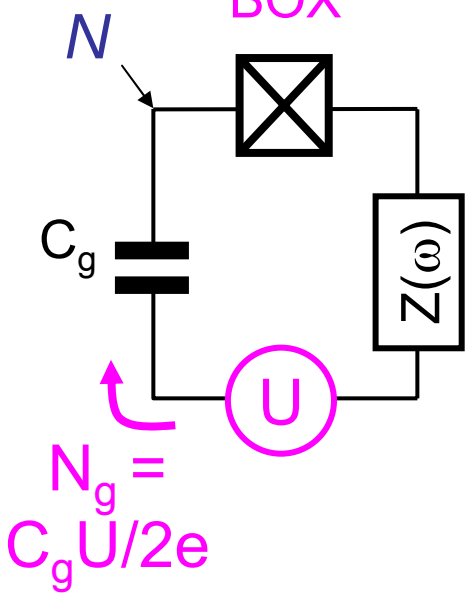
"RF-SQUID"



flux thru loop

TU Delft, NEC
UC Berkeley
NTT
IPHT Jena
.....

"COOPER-PAIR BOX"



island charge

CEA Saclay, Yale
NEC
Chalmers, JPL

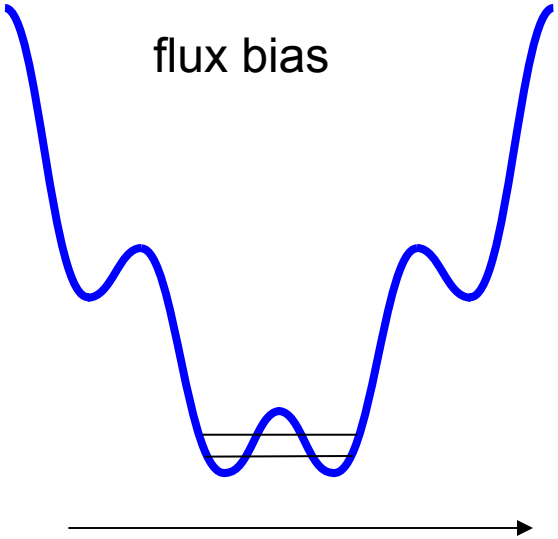
$$Z(\omega) \sim Z_{\text{vac}} = 377\Omega$$

STATIC POTENTIAL REPRESENTATIONS OF 3 BIAS SCHEMES

phase bias

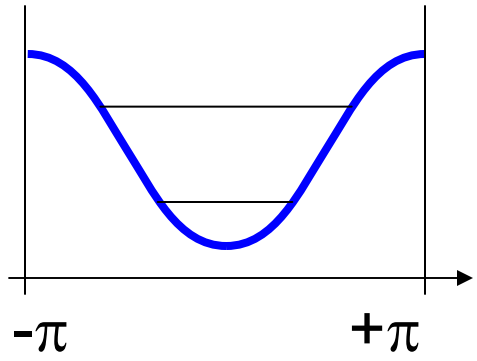
$$\delta = \frac{2e}{\hbar}\int_{-\infty}^{t} dt \int_{1}^{2} E(x,t)dx$$

flux bias



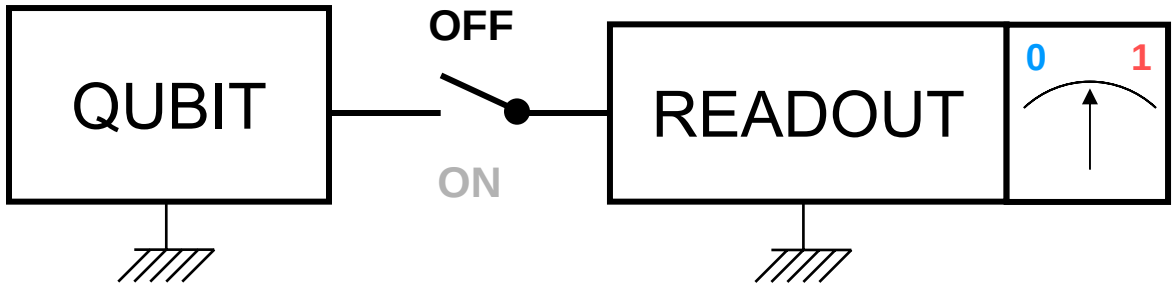
$$\phi = \iint_{loop} Bda$$

charge bias



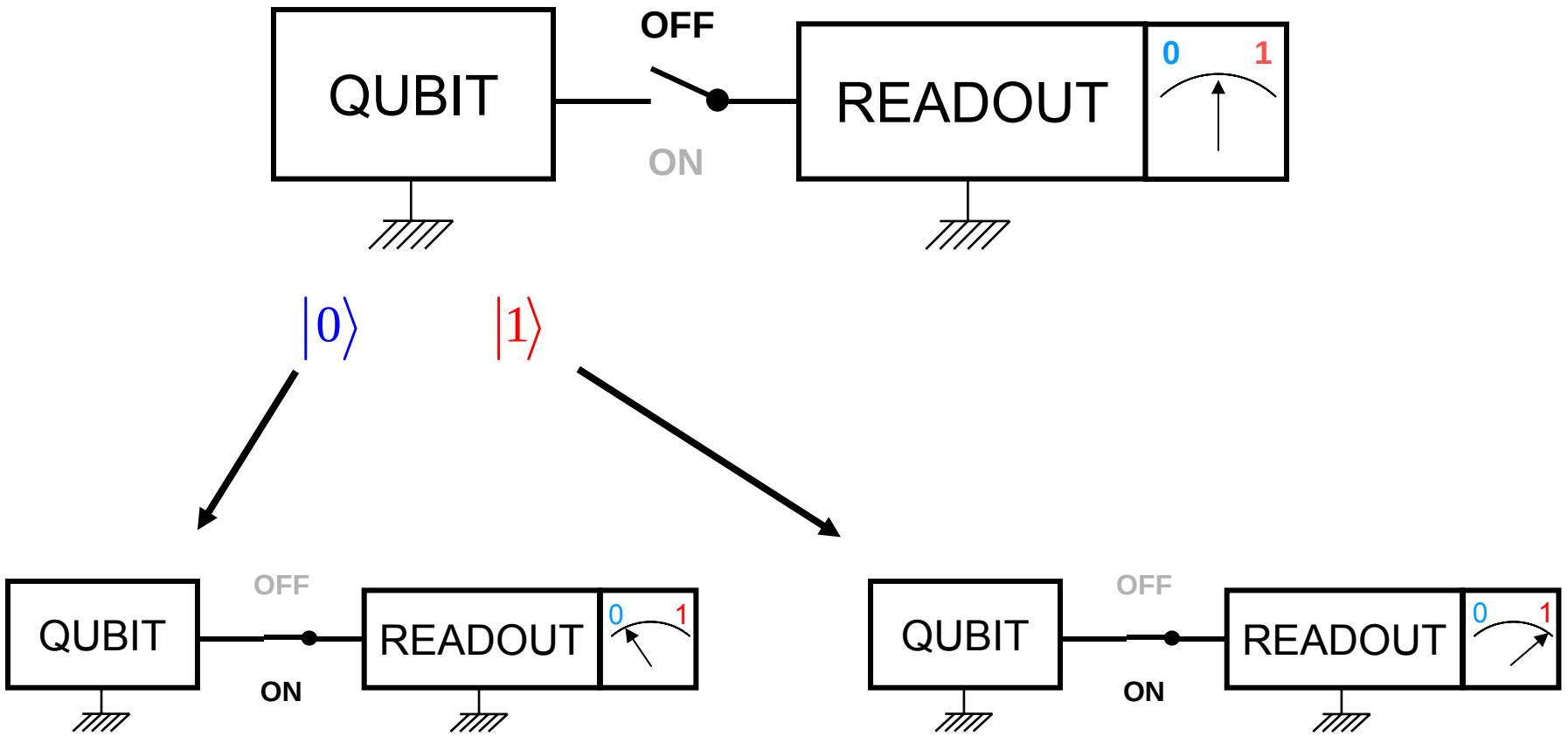
$$\theta = \theta_1 - \theta_2$$

THE READOUT PROBLEM



$|0\rangle$ or $|1\rangle$

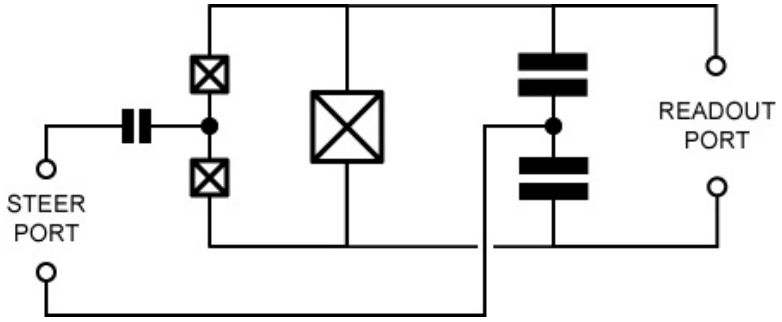
THE READOUT PROBLEM



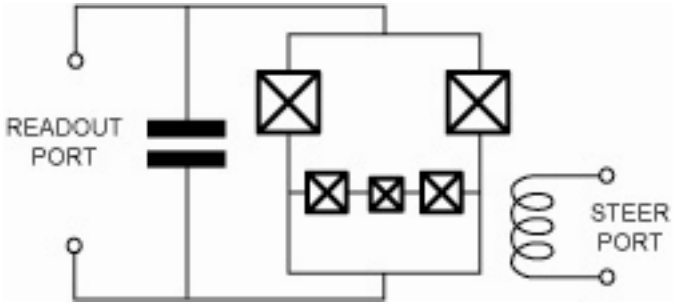
WANT:

1) GOOD SWITCH
2) FAITHFUL READOUT

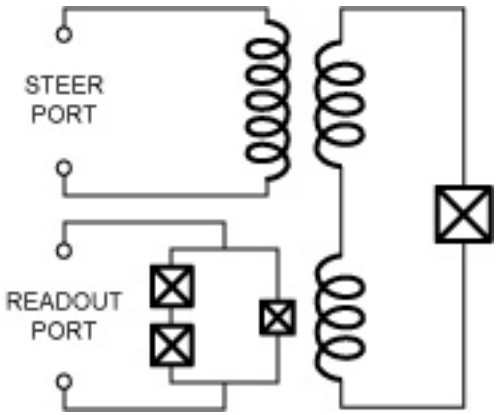
DIVERSITY OF CIRCUIT STRATEGIES



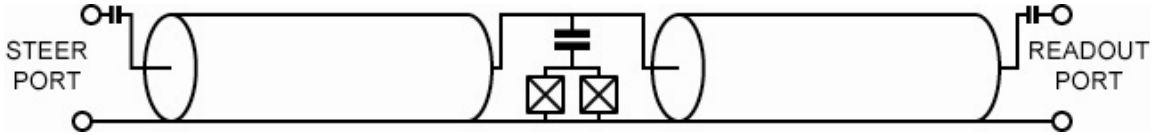
SACLAY, YALE (Quantronium)



TU DELFT, NEC



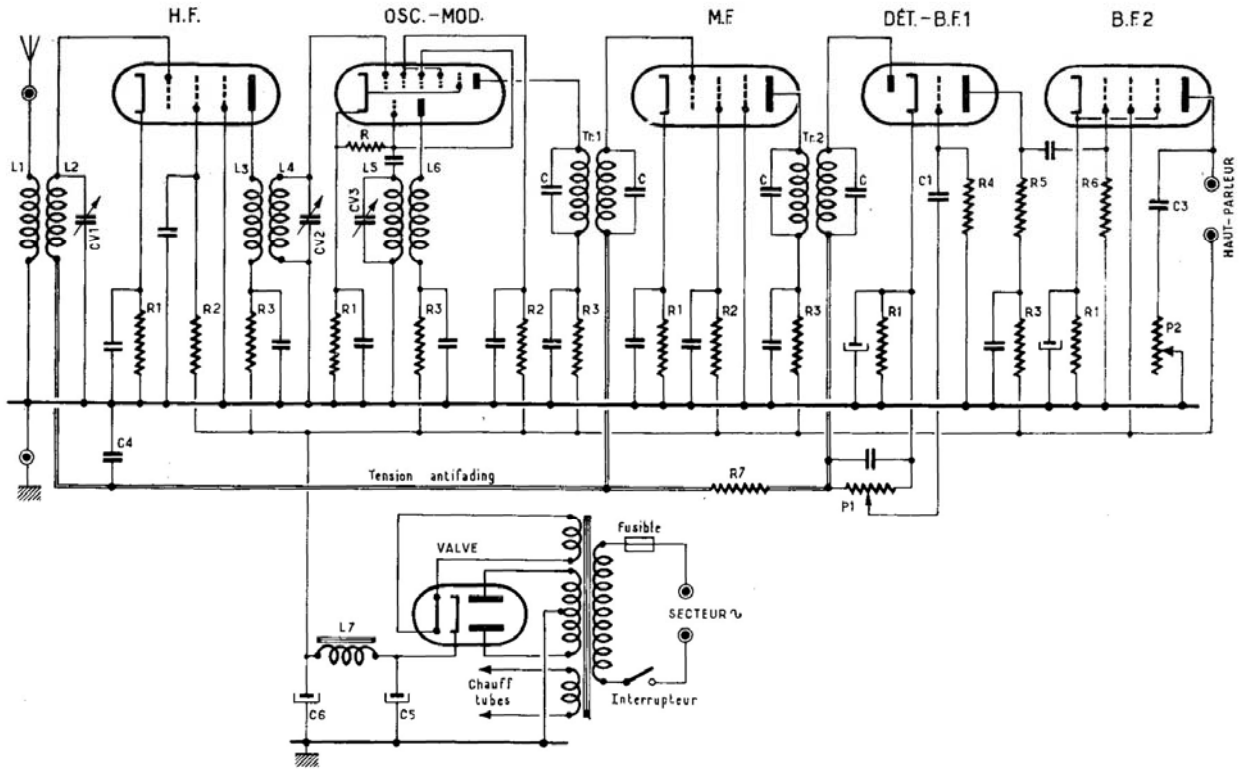
NIST, UCSB



YALE (cQED)

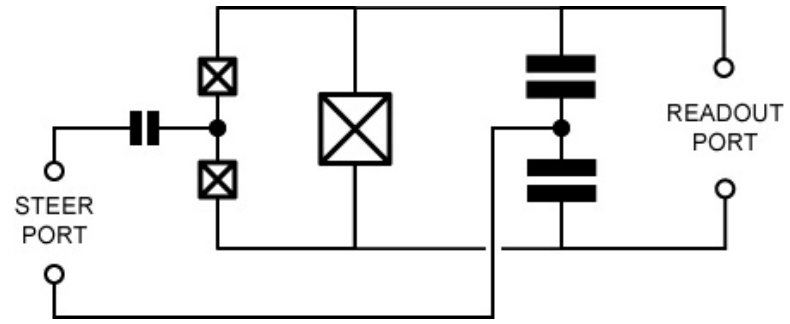
see also "Tetrahedral"
qubit of Ioffe et al.

A VACUUM TUBE RADIO SCHEMATIC (around 1955)



LINEAR ELEMENTS ARE CHEAP, NON-LINEAR ELEMENTS ARE EXPENSIVE

DIVERSITY OF CIRCUIT STRATEGIES



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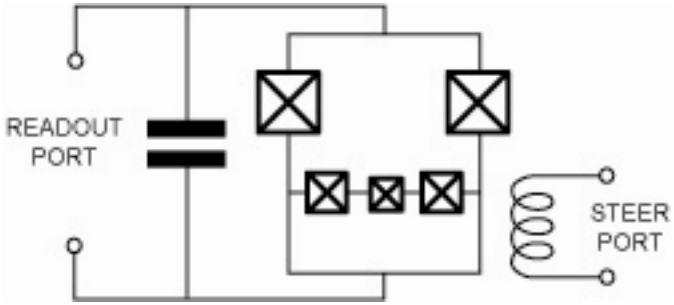

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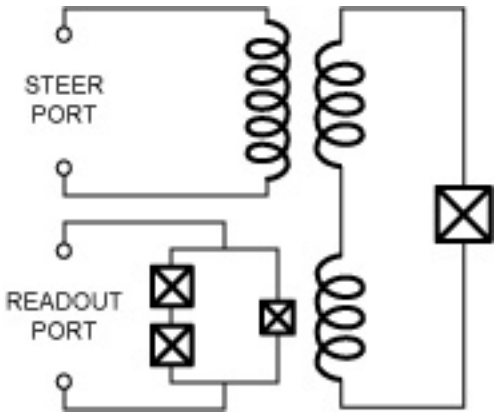
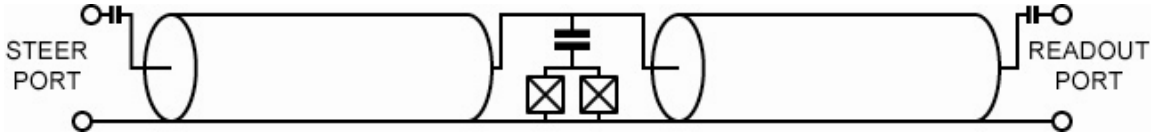


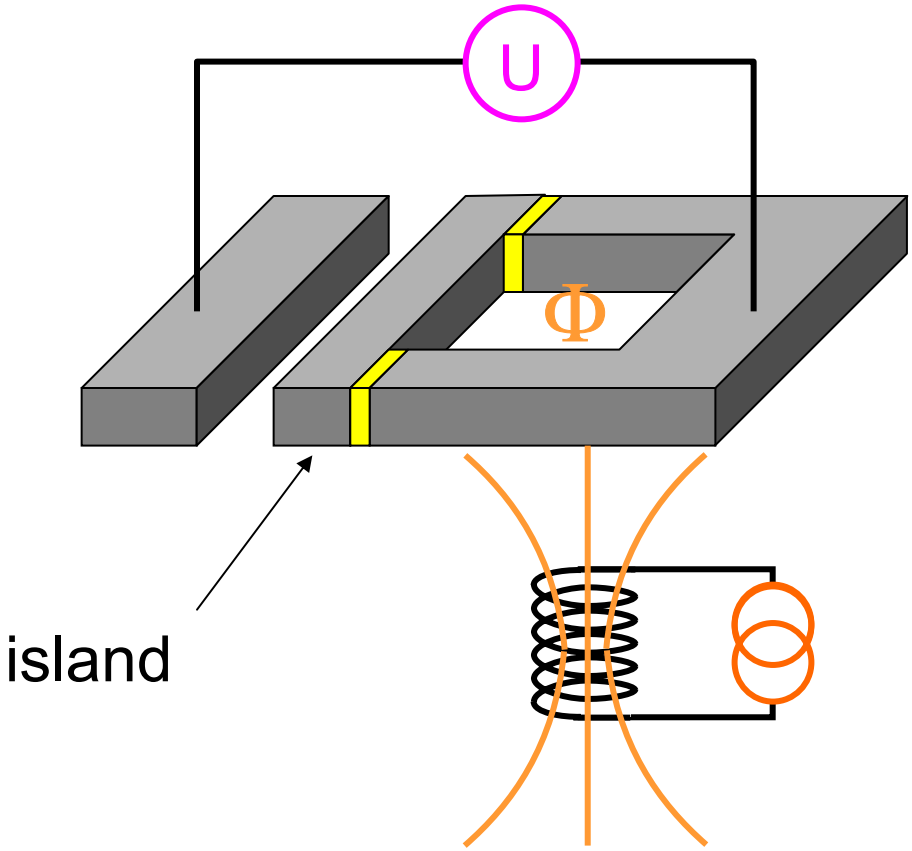
NIST, UCSB

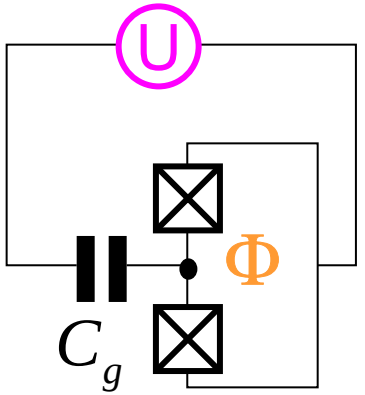


YALE (cQED)

see also "Tetrahedral"
qubit of Ioffe et al.

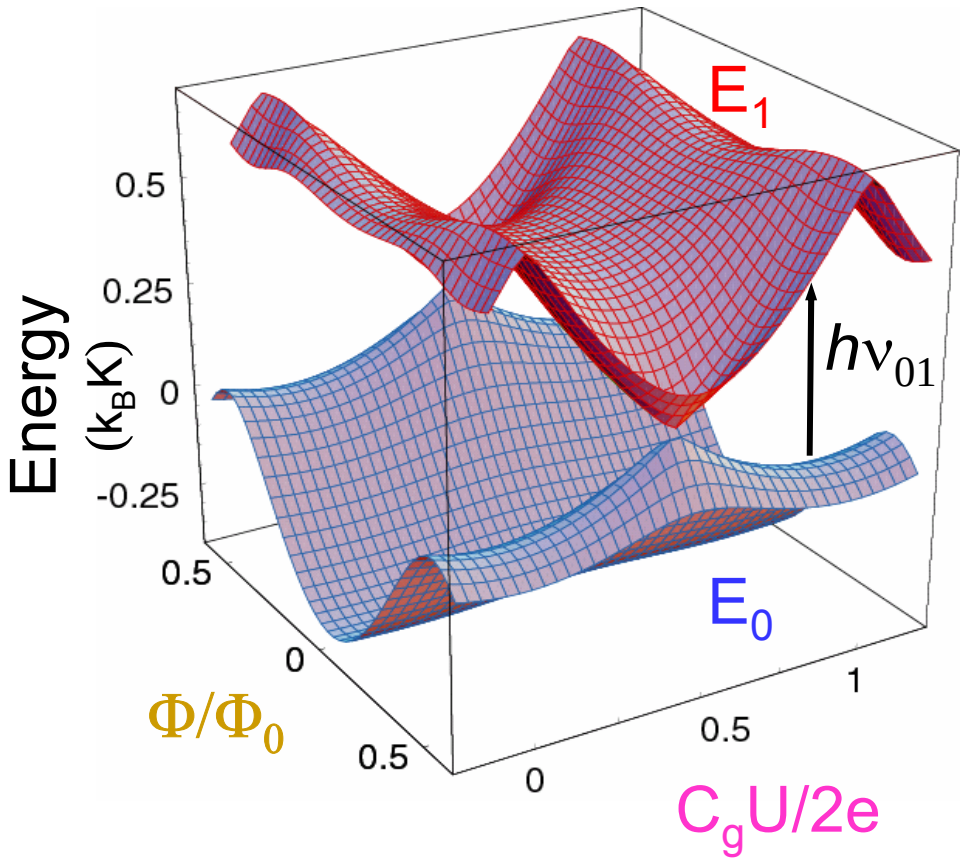
THE SPLIT COOPER-PAIR BOX





Bouchiat et al. 97
Nakamura, Pashkin & Tsai 99

BOX QUANTUM LEVELS AND MEASUREABLE QUANTITIES



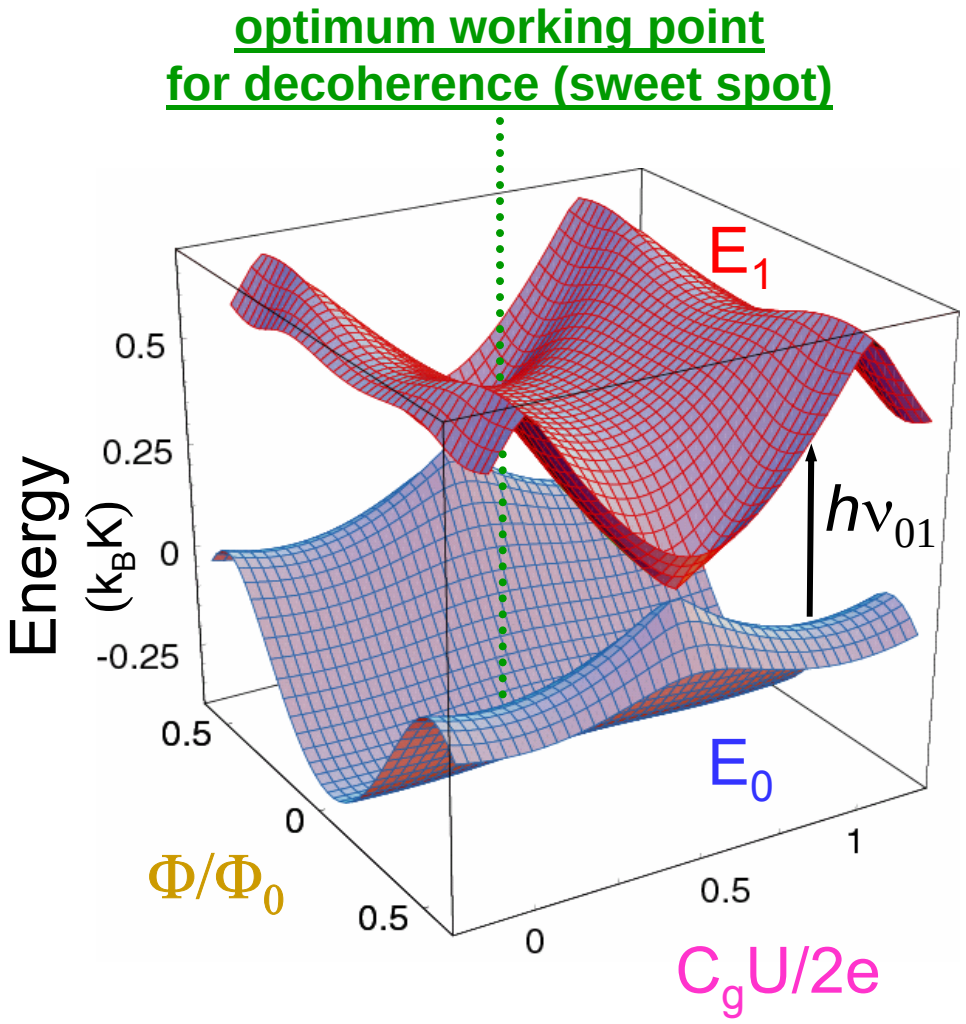
charge

$$Q_k = \frac{\partial E_k}{\partial U}$$

current

$$I_k = \frac{\partial E_k}{\partial \Phi}$$

BOX QUANTUM LEVELS AND MEASUREABLE QUANTITIES



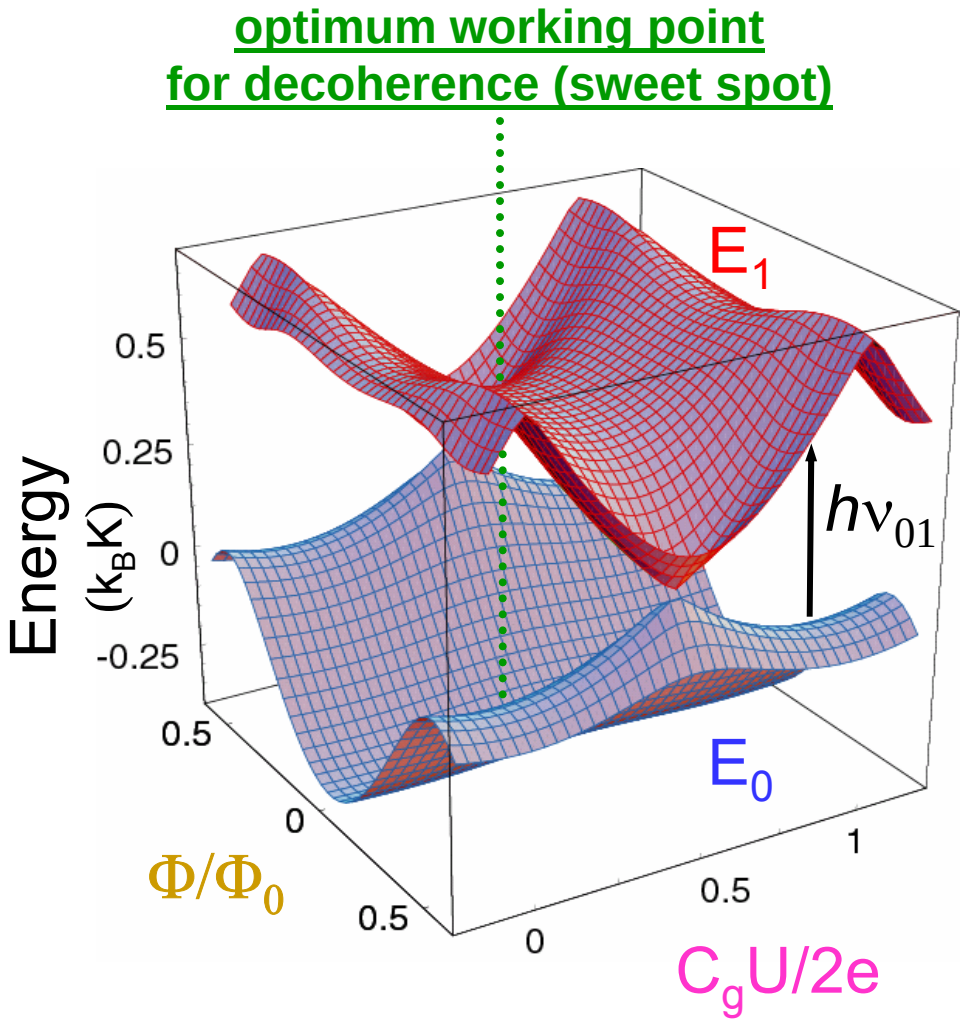
charge

$$Q_k = \frac{\partial E_k}{\partial U} = 0$$

current

$$I_k = \frac{\partial E_k}{\partial \Phi} = 0$$

BOX QUANTUM LEVELS AND MEASUREABLE QUANTITIES



Walraff et al.
Wilson et al.

charge

$$Q_k = \frac{\partial E_k}{\partial U}$$

capacitance

$$C_k = \frac{\partial^2 E_k}{\partial U^2}$$

current

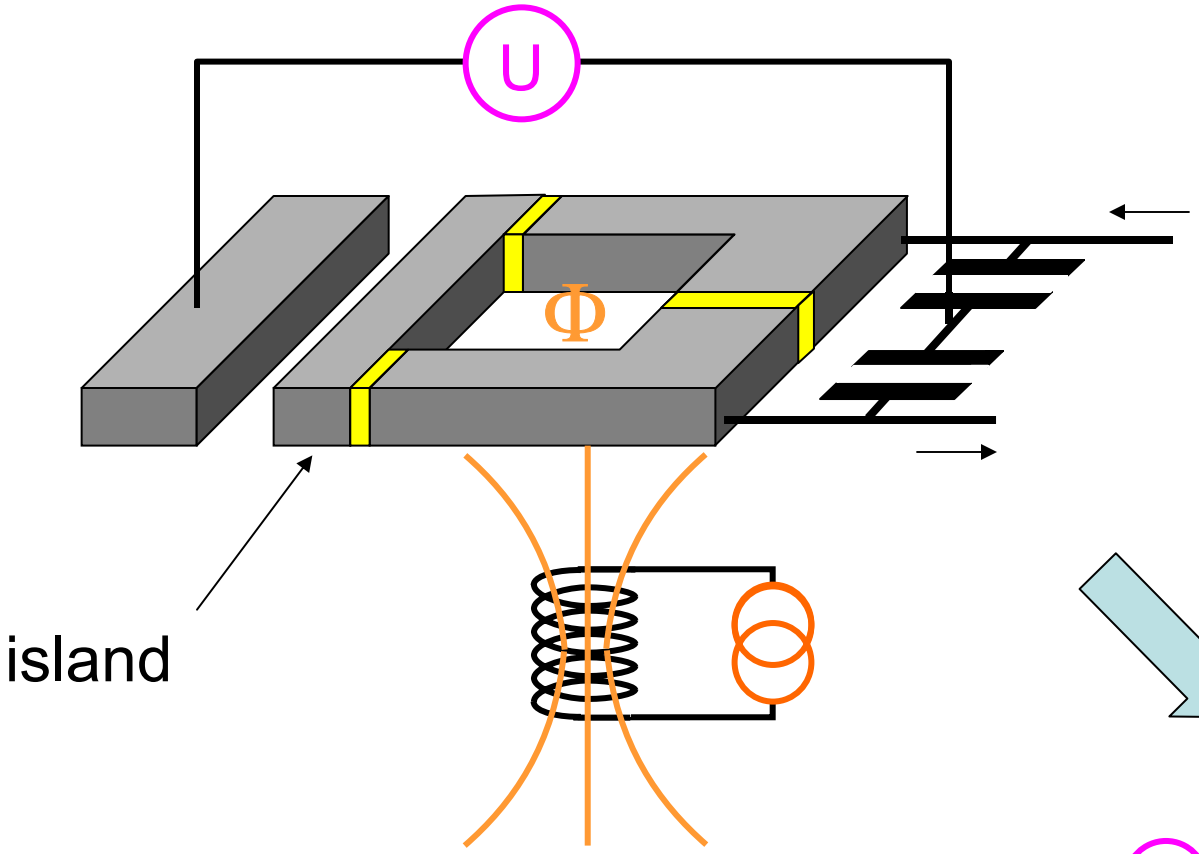
$$I_k = \frac{\partial E_k}{\partial \Phi}$$

inductance

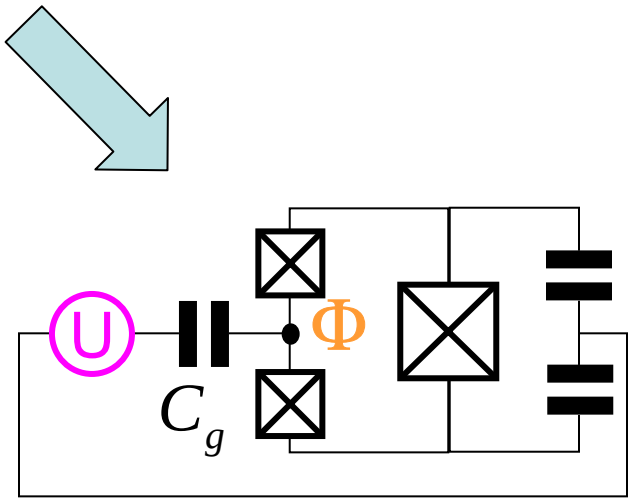
$$L_k = \left(\frac{\partial^2 E_k}{\partial \Phi^2} \right)^{-1}$$

Siddiqi et al.

QUANTRONIUM

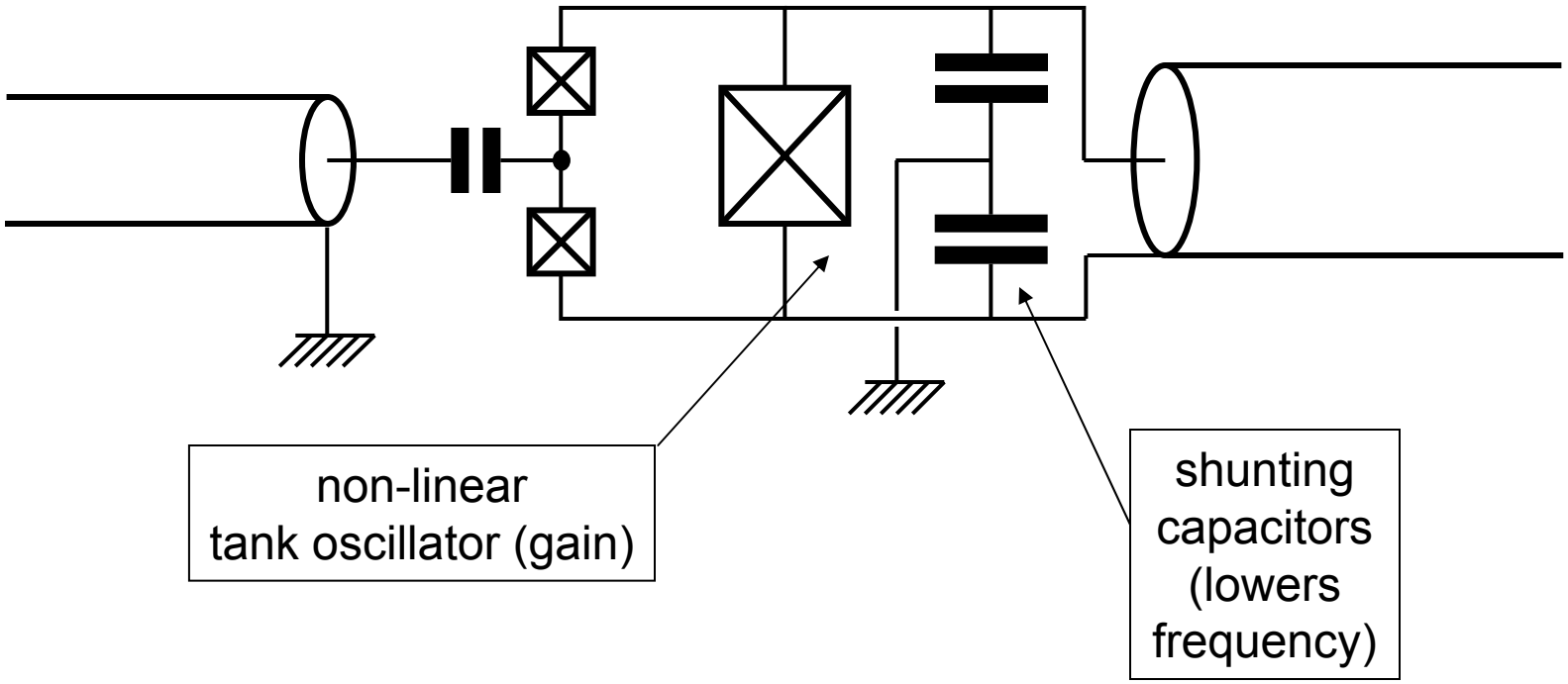


orthogonality
of steer and
read modes



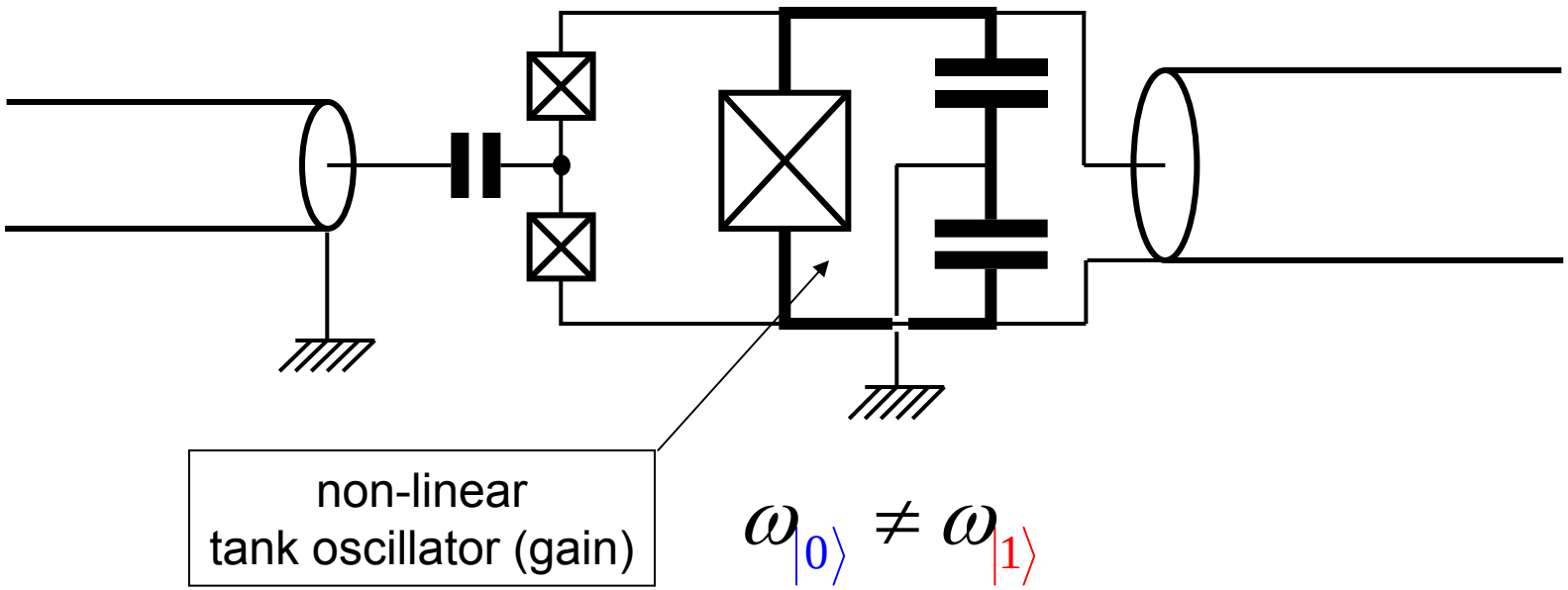
Vion et al. 2002

"QUANTRONIUM" WITH RF READOUT



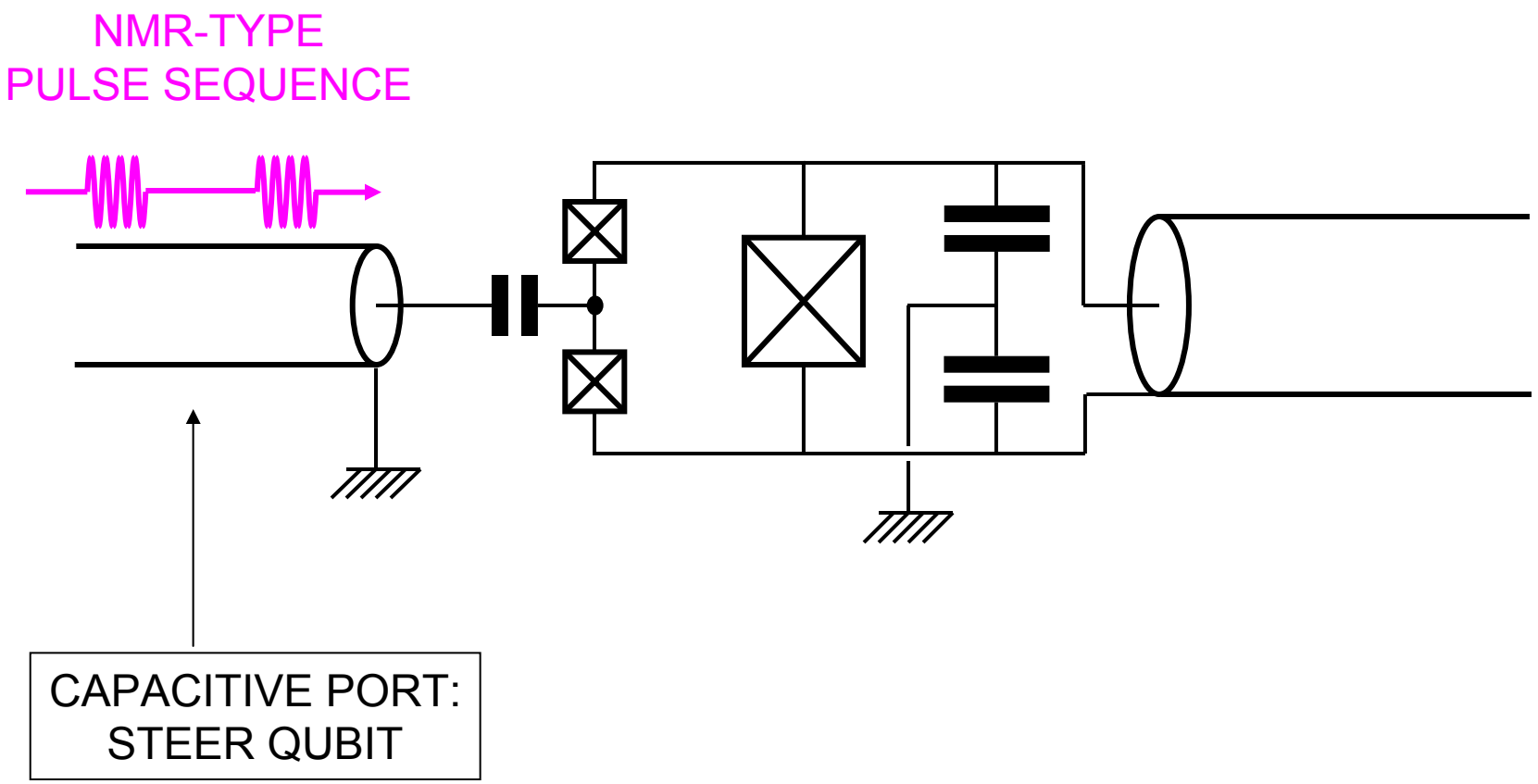
WHEATSTONE BRIDGE CIRCUIT SYMMETRY

"QUANTRONIUM" WITH RF READOUT

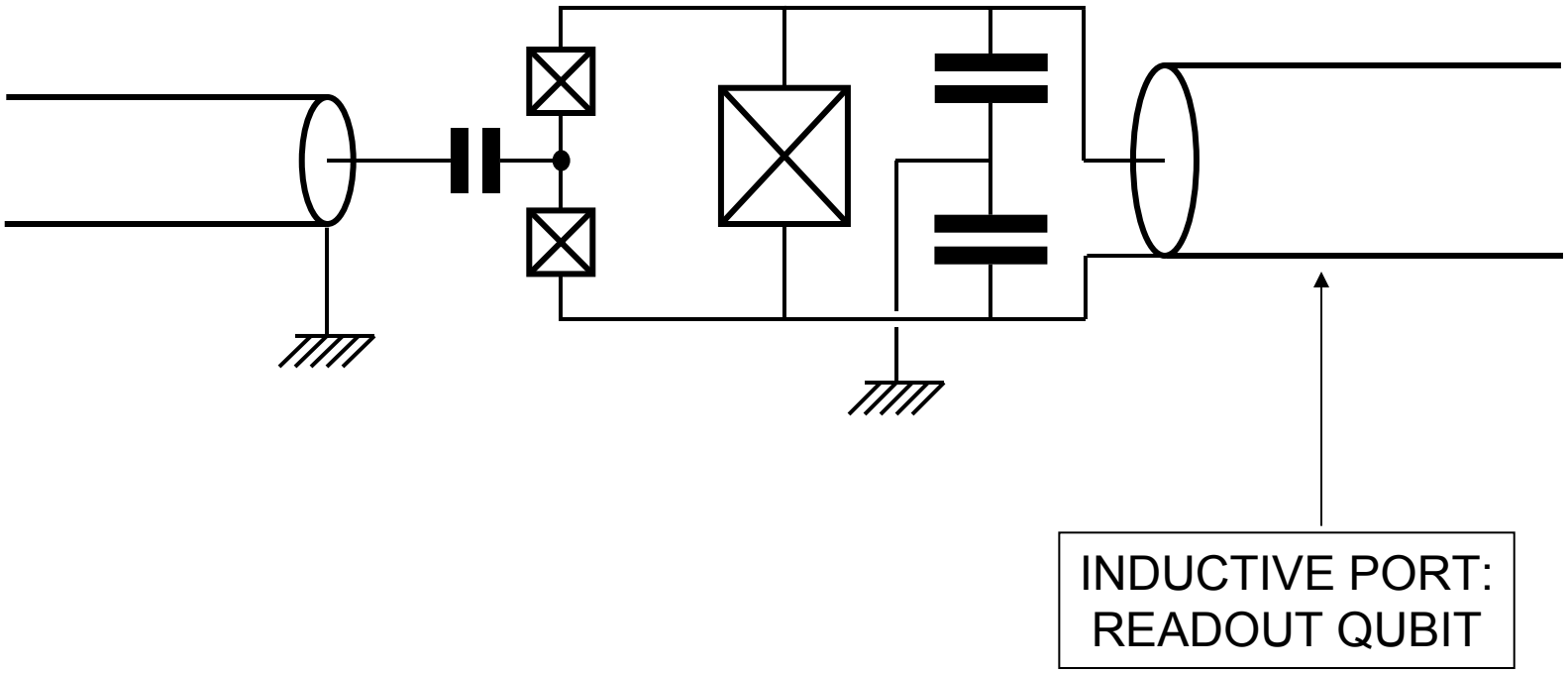


WHEATSTONE BRIDGE CIRCUIT SYMMETRY

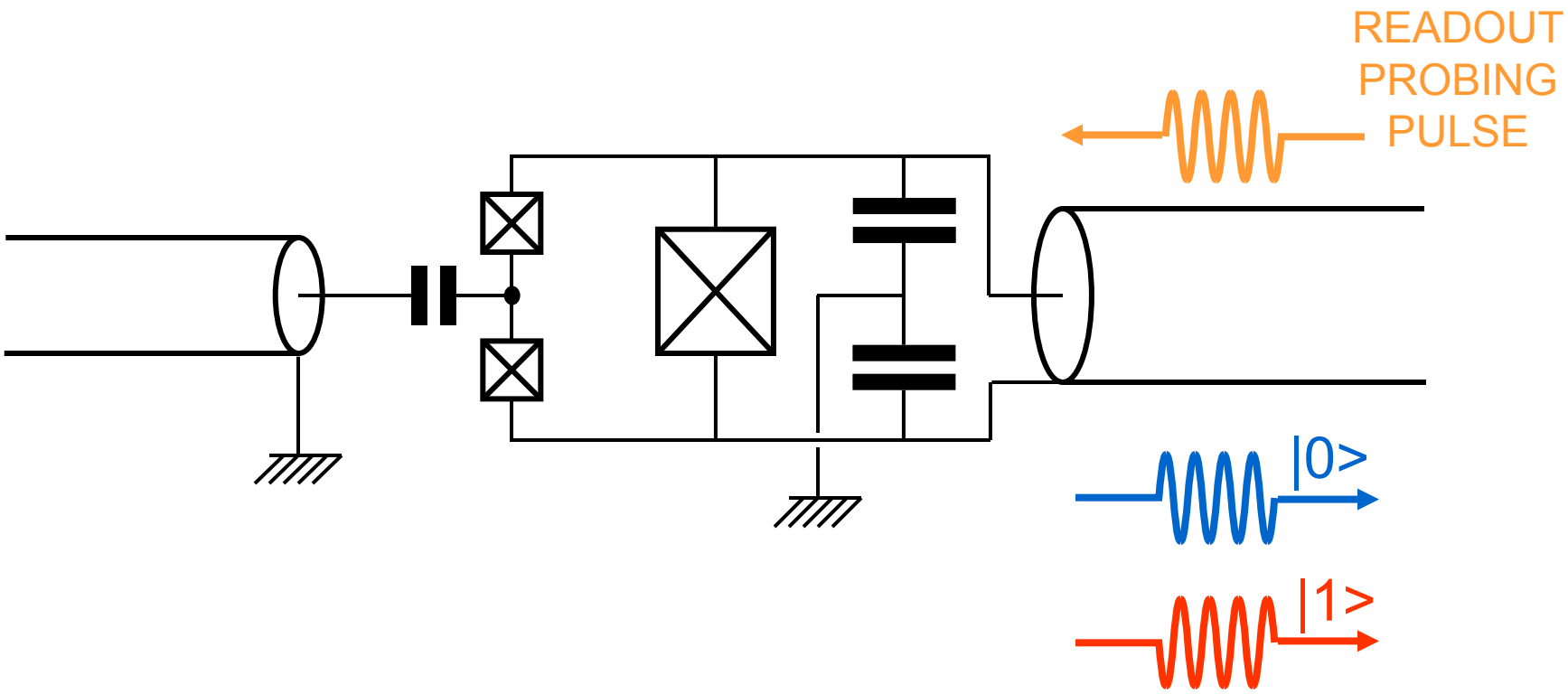
"QUANTRONIUM" WITH RF READOUT



"QUANTRONIUM" WITH RF STEER AND READOUT

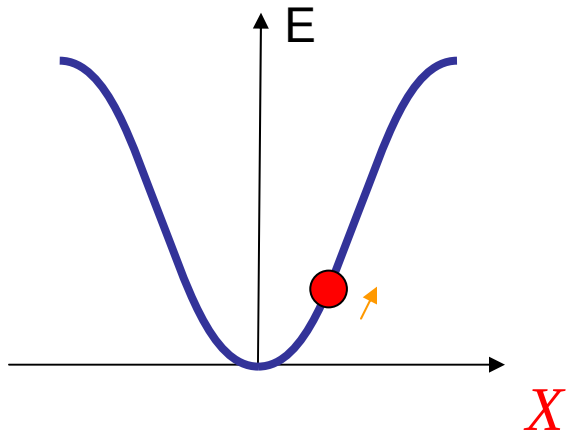


"QUANTRONIUM" WITH RF READOUT



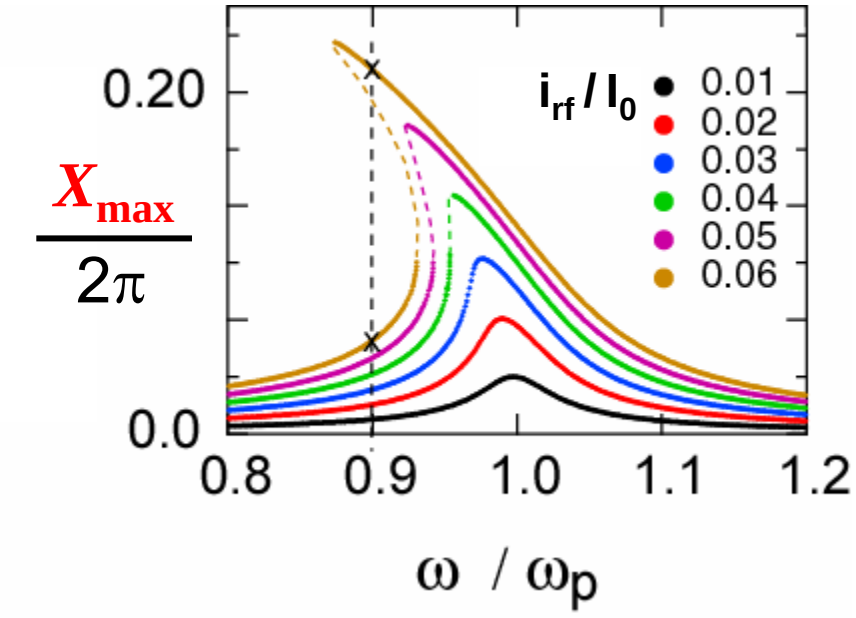
QUBIT STATE
ENCODED IN PHASE
OF REFLECTED PULSE

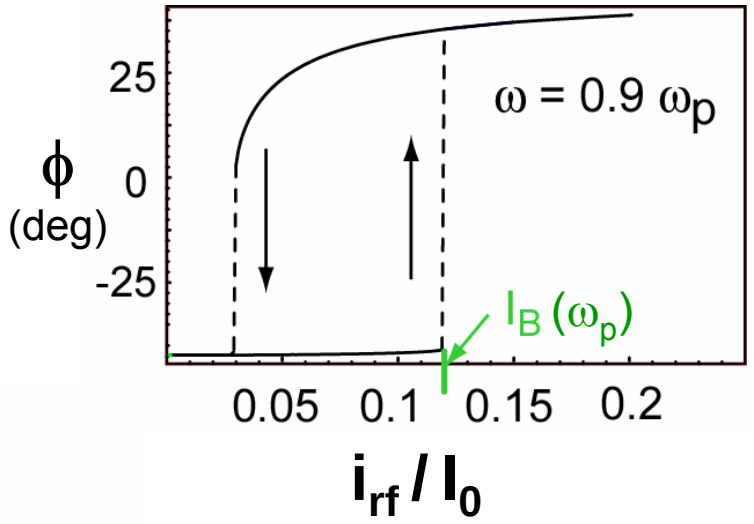
AMPLIFYING WITH NON-LINEARITY



AC Drive: $i_{rf}\sin(\omega t)$

$$X = X_{max}\sin(\omega t+\phi)$$

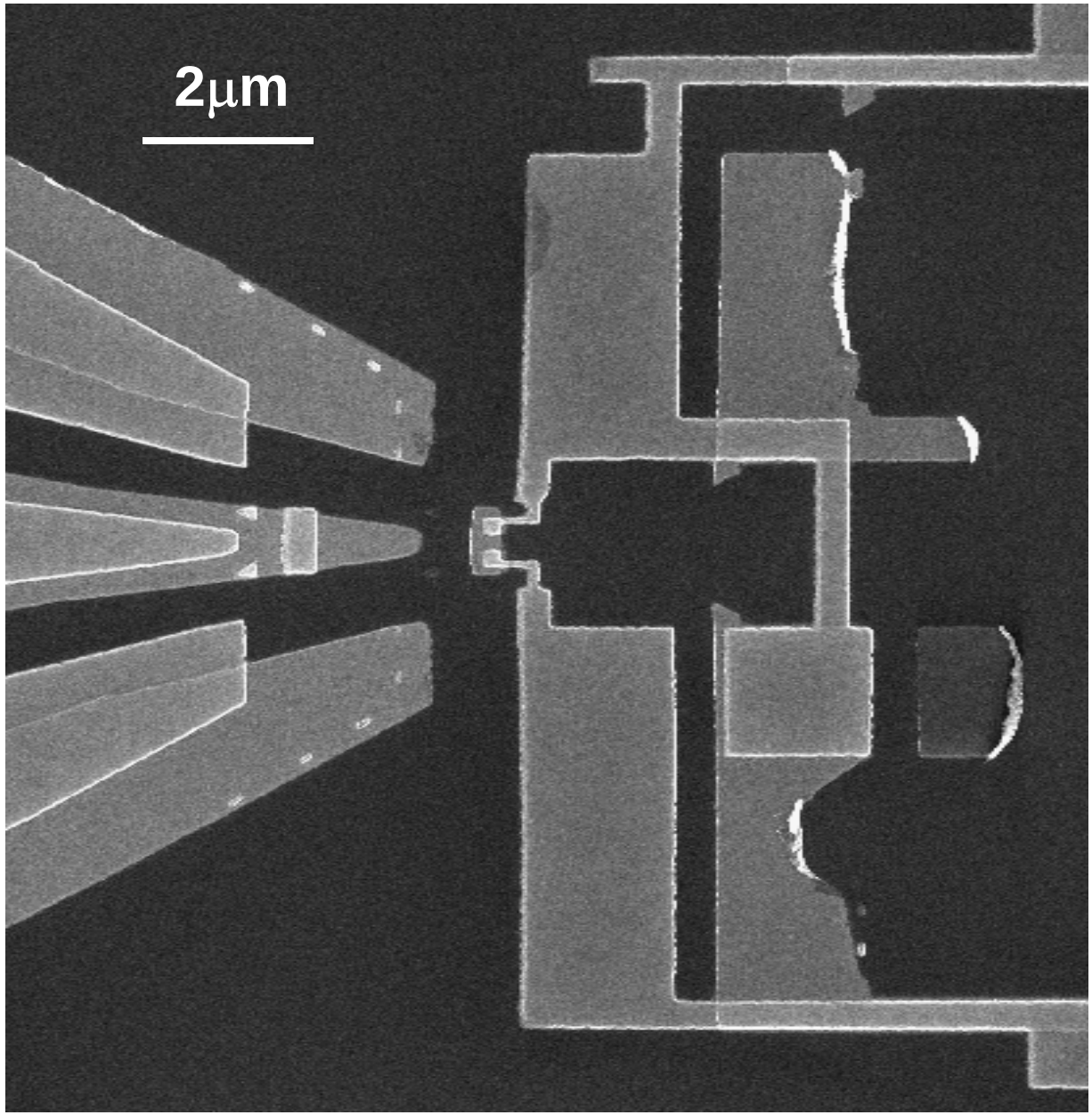




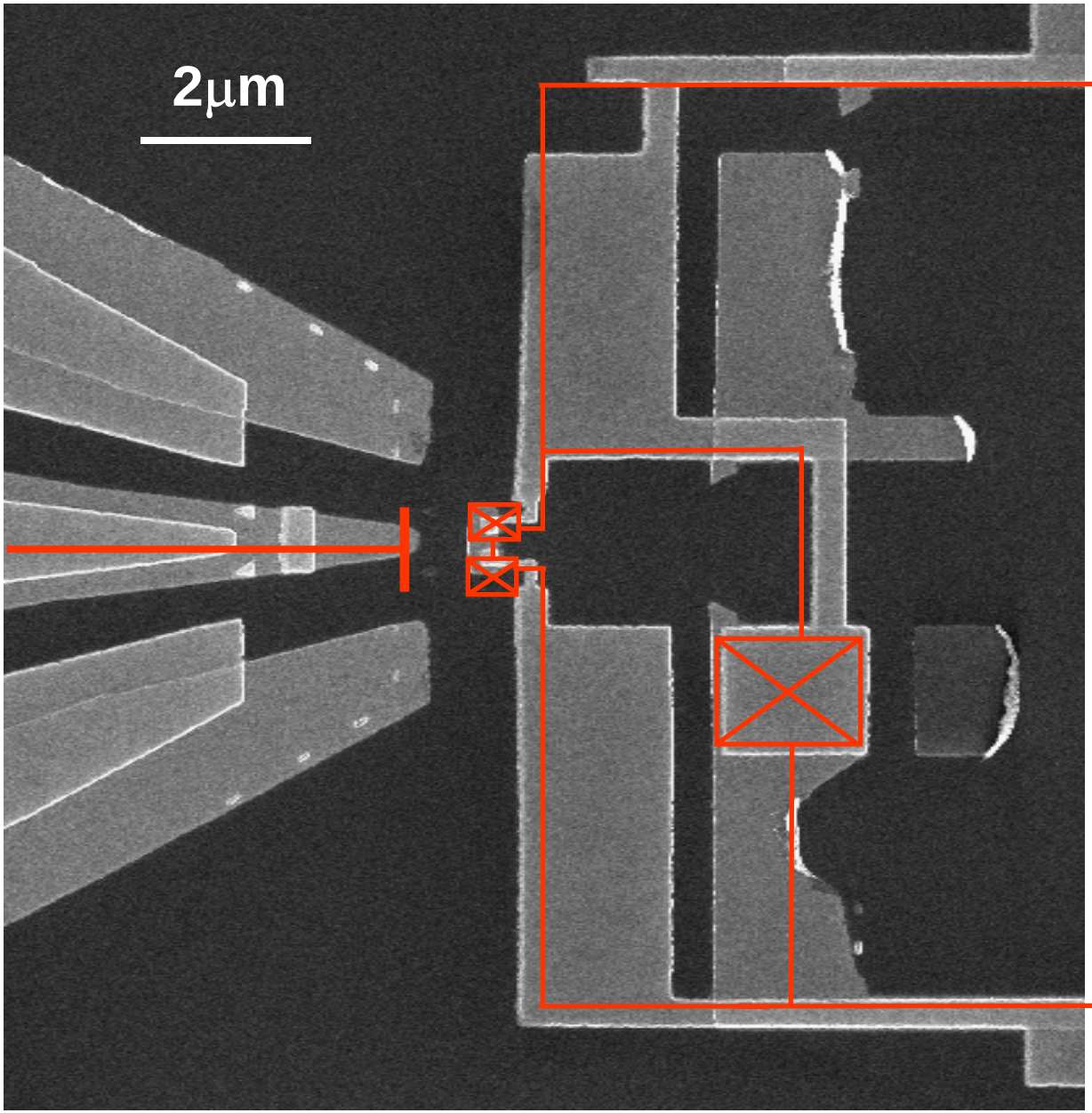
EXPERIMENTAL APPARATUS

mK

GHz

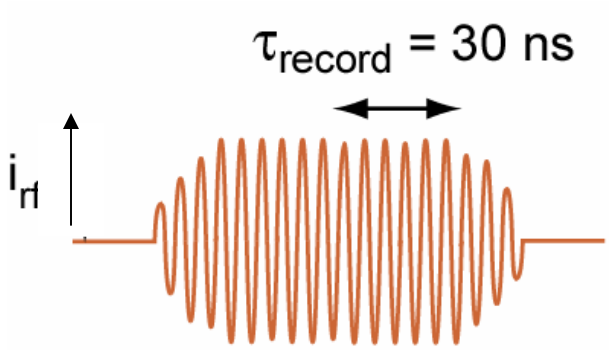


Double-angle
shadow-mask
Al/AlOx/Al
(Yale nanofab)

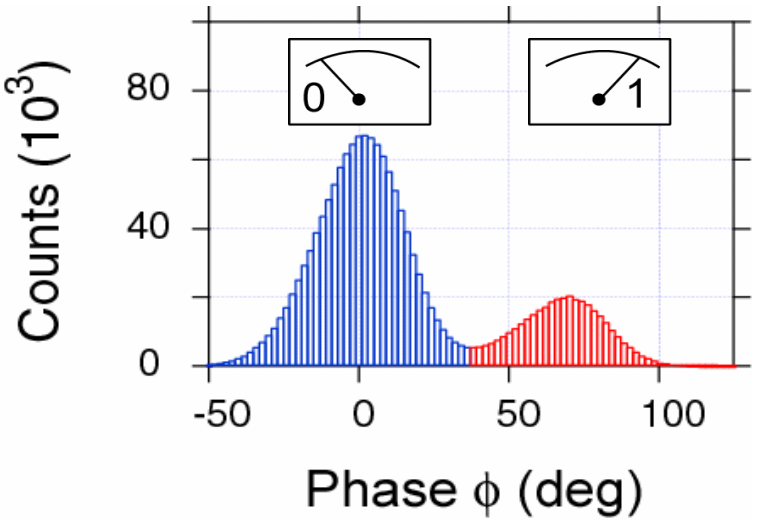


Double-angle
shadow-mask
Al/AlOx/Al
(Yale nanofab)

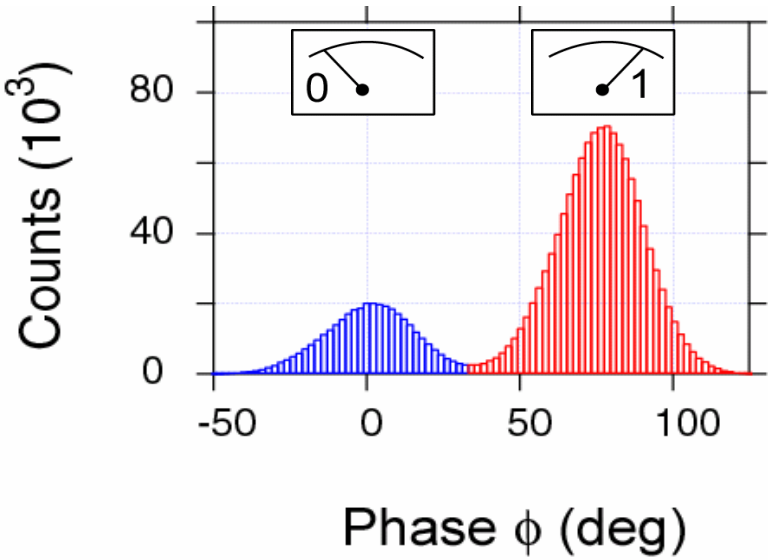
BIFURCATION READOUT



$|0\rangle$

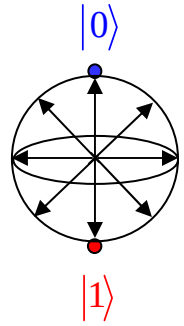


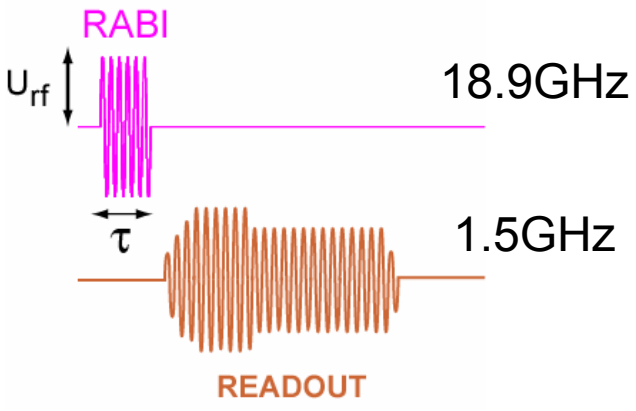
$|1\rangle$

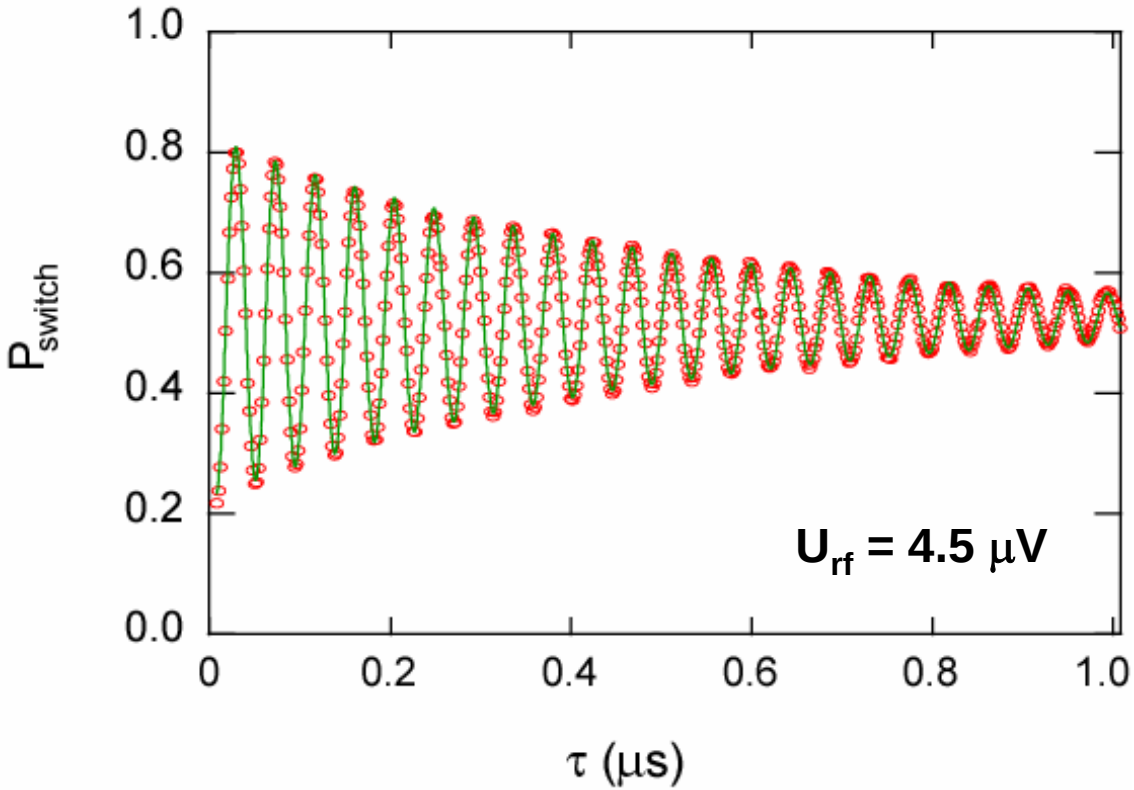


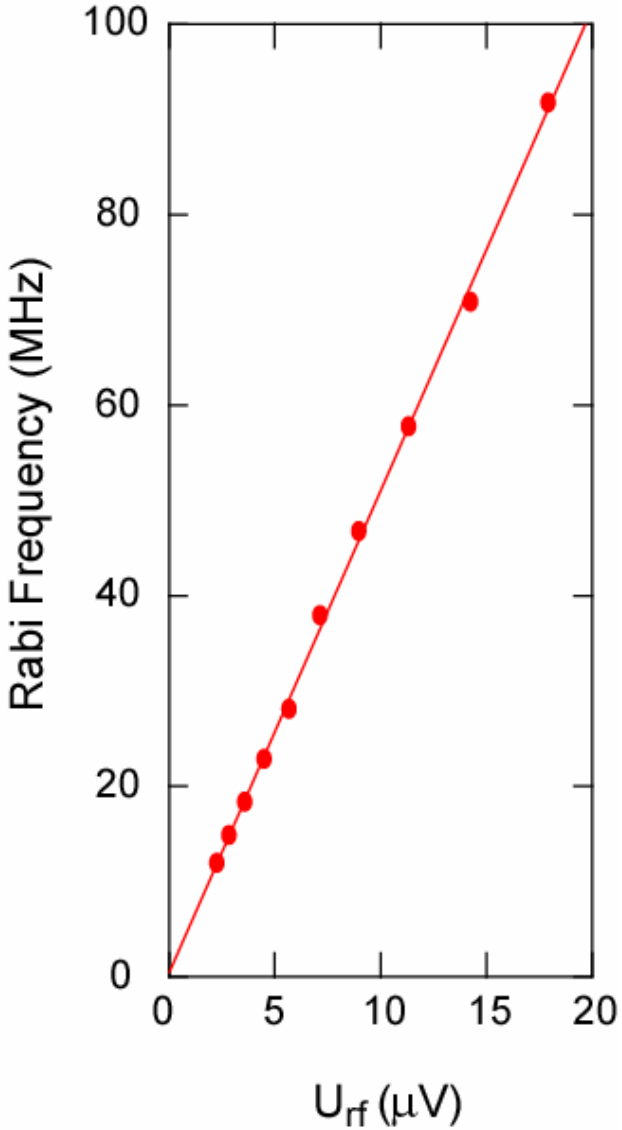
Repetition rate 4 MHz

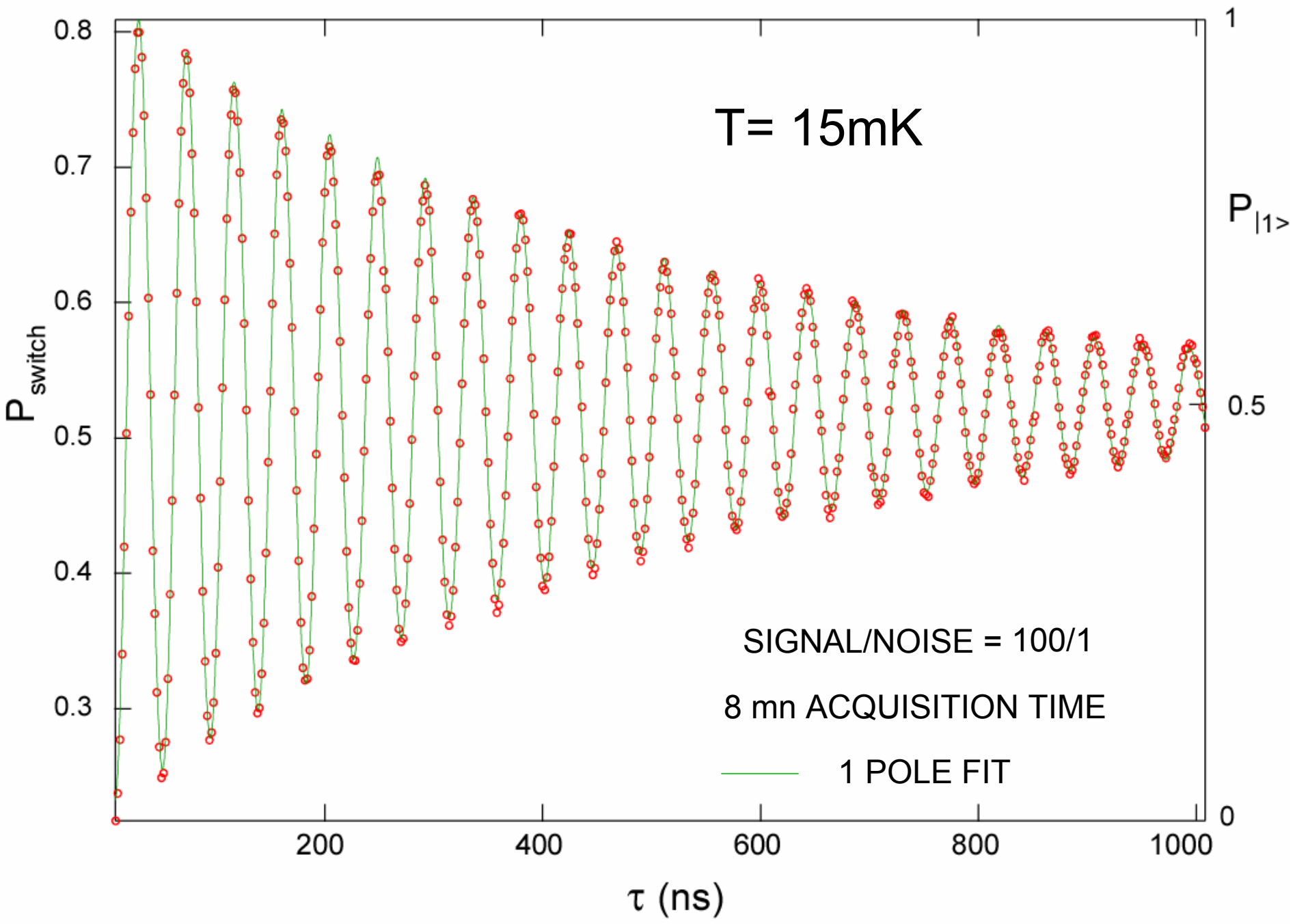
RABI OSCILLATIONS



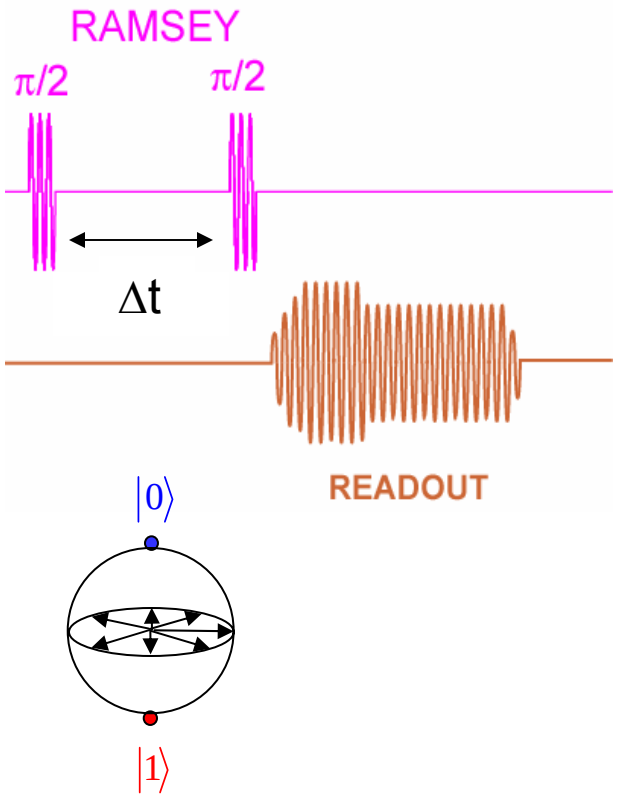


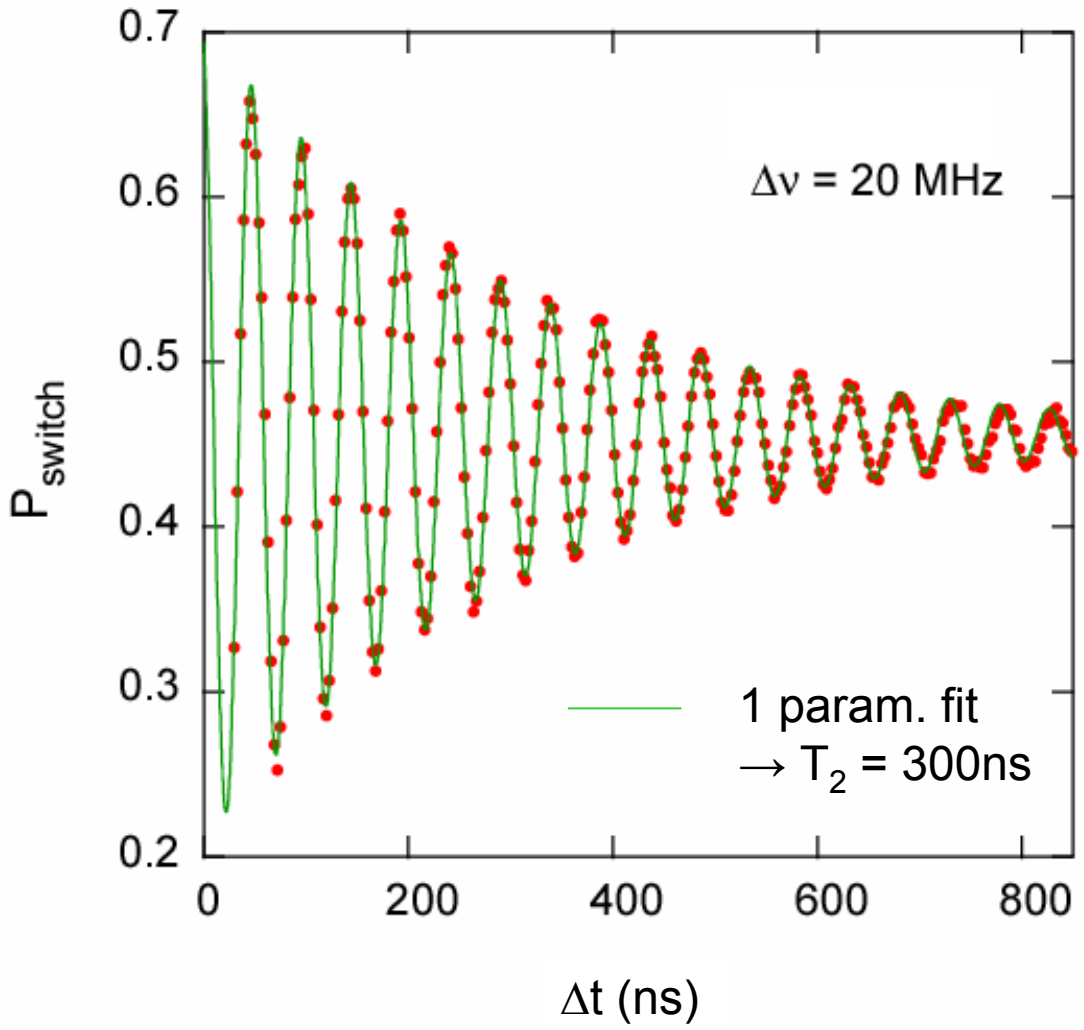





T= 15mK
SIGNAL/NOISE = 100/1
8 mn ACQUISITION TIME
1 POLE FIT
P switch
P |1>
τ (ns)
0.8
0.7
0.6
0.5
0.4
0.3
1
0.5
0
200
400
600
800
1000

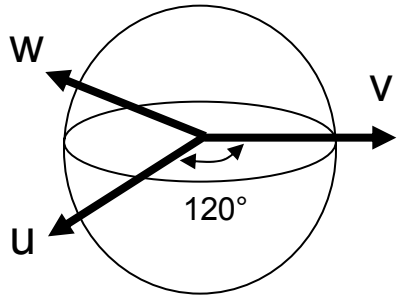
DECOHERENCE TIME (T_2)





$Q_\phi = \omega_{Larmor} T_2$	
Vion et al.	50,000
Siddiqi et al.	36,000
Wallraff et al.	19,000

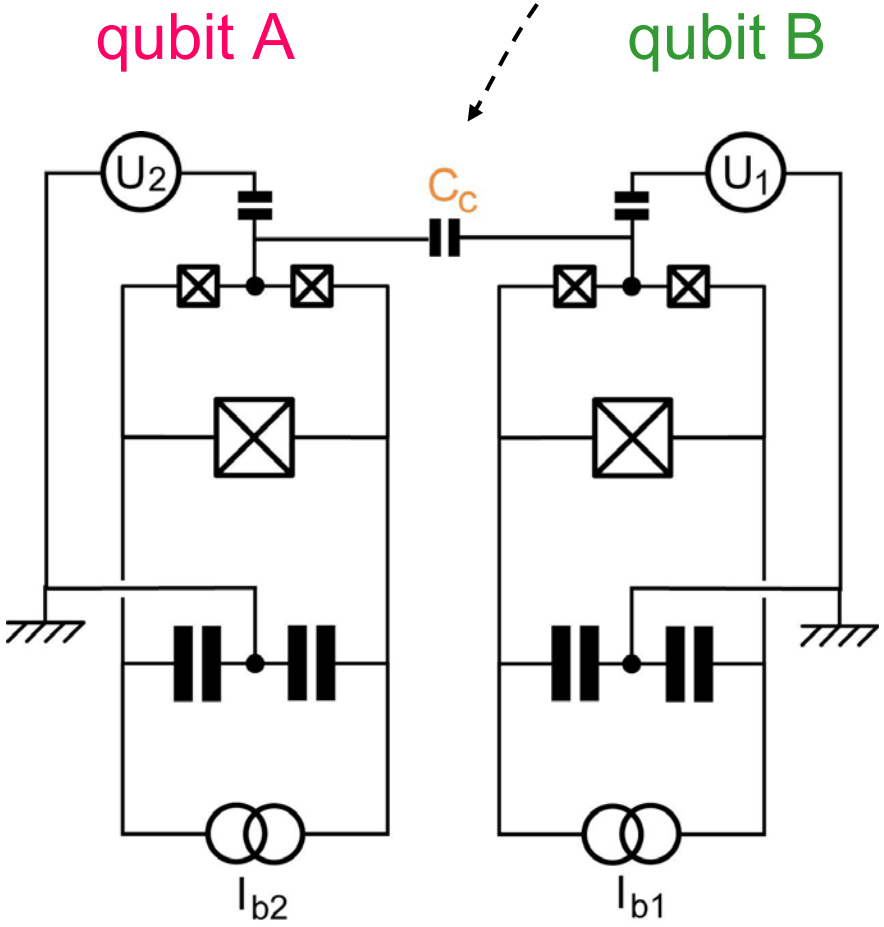
QUANTUM vs CLASSICAL CORRELATIONS FOR 2 QUBITS



(Bell's inequalities, Mermin's version)

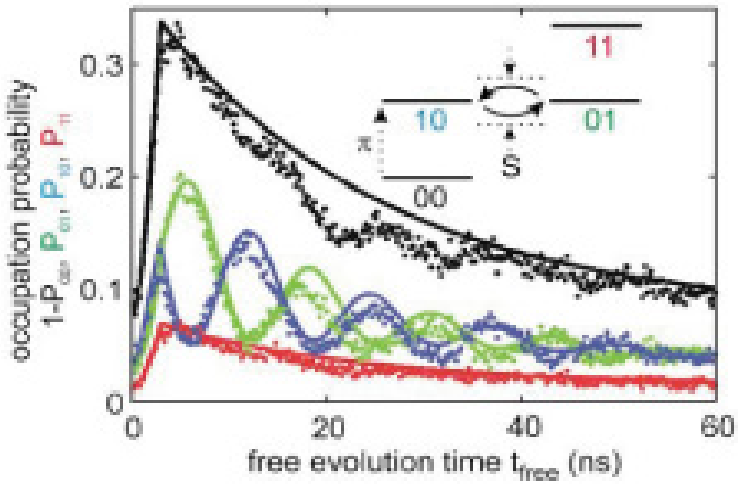
Qubit A \ Qubit B	u	v	w
u	-1	0.5 (<0.33)	0.5 (<0.33)
v	0.5 (<0.33)	-1	0.5 (<0.33)
w	0.5 (<0.33)	0.5 (<0.33)	-1

2-QUBIT GATE



linear coupling element suffices to prepare entangled states like

$$\frac{|01\rangle \pm |10\rangle}{\sqrt{2}}$$



UCSB/NIST recent results
for phase qubits
(McDermott et al., Science, 2005)

CONCLUSIONS AND PERSPECTIVES

- COHERENCE QUALITY FACTORS Q_φ IN EXCESS OF 10^4 FOR SUPERCONDUCTING QUANTUM CIRCUITS.
- PROTECTION FROM NOISE CAN BE IMPROVED FURTHER USING CIRCUIT SYMMETRIES.
- RF READOUT SCHEMES IMPROVES GAIN, SPEED AND REPETITION RATE. IMPORTANT FOR NOISE DIAGNOSTIC.
- GATES CAN BE BASED ON SIMPLE LINEAR ELEMENTS.
- $Q_\varphi \sim 10^6$ NEEDED FOR QUANTUM ERROR CORRECTION.