SUPERCONDUCTING QUANTUM BITS

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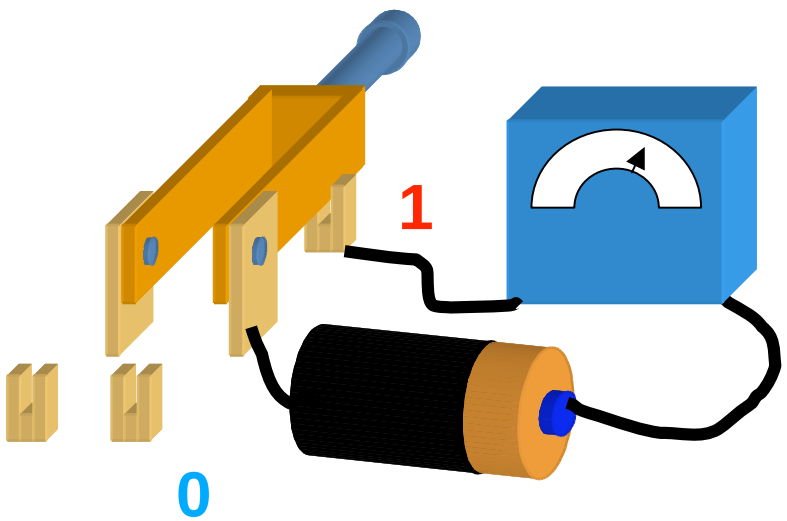
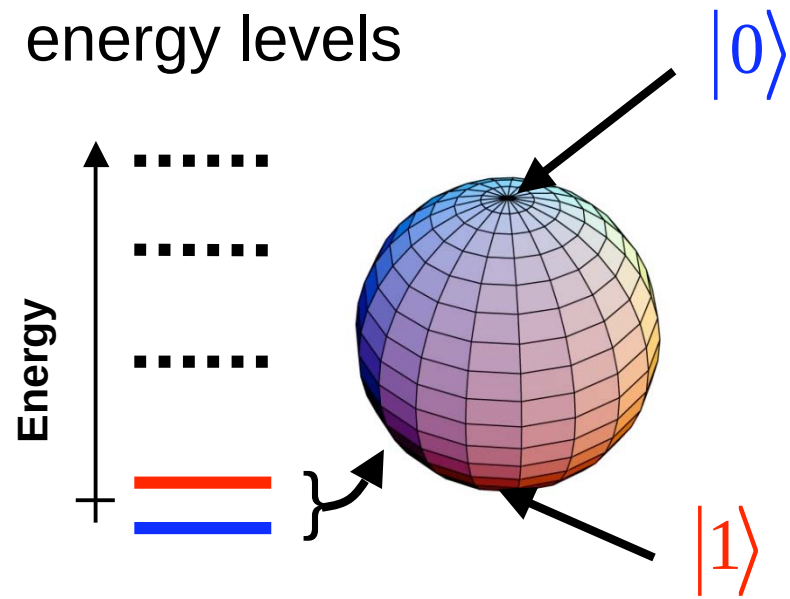
C191 Seminar – 11/27/2007

CLASSICAL vs. QUANTUM INFORMATION

classical
equilibrium states



quantum
energy levels



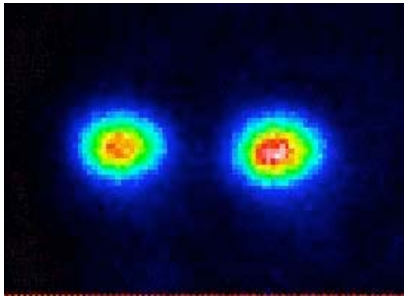
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

write: 0 <u>OR</u> 1
read: 0 <u>OR</u> 1

write: |0> <u>AND</u> |1>
read: |0> <u>OR</u> |1>

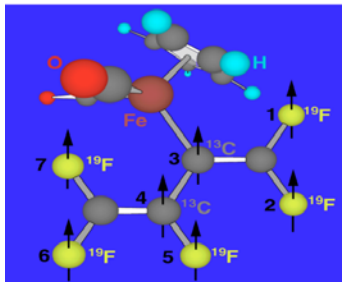
CHOSING A QUANTUM TWO-LEVEL SYSTEM

Trapped Ions



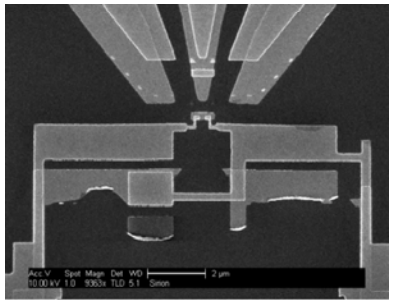
(NIST)

Nuclear Magnetic Resonance



(IBM/MIT)

Superconducting Circuits



(SACLAY/YALE)

& Spins in Semiconductors, NV Centers in Diamond, e^{-1} on LHe, Graphitic Circuits, Magnetic Molecules, etc……..

CAN ALL BE DESCRIBED (APPROXIMATELY) BY A TWO LEVEL HAMILTONIAN

QUANTUM INFORMATION SYSTEMS

micro

MACRO

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

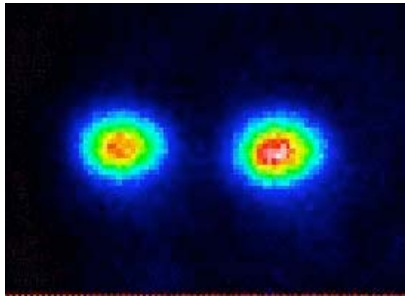
coupling with env^t.

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

A.J. Leggett, 1982

HMMM…THE ENVIRONMENT!

Trapped Ions

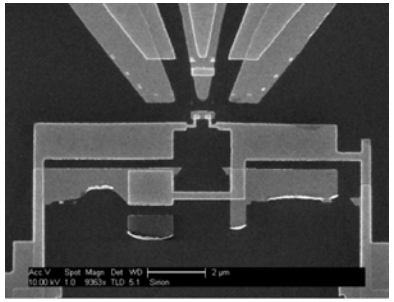


weak coupling to environment →

Long coherence times

Weak qubit-qubit coupling (slow gates)

Superconducting Circuits

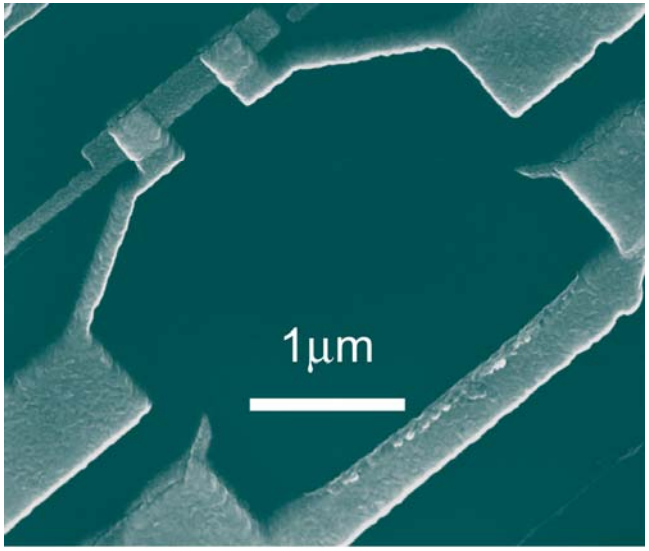


strong coupling to environment →

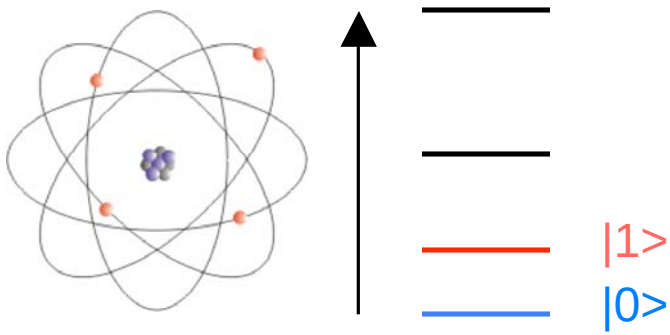
Short coherence times

Strong qubit-qubit coupling (fast gates)

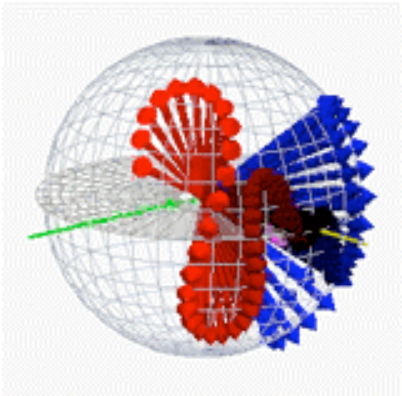
SUPERCONDUCTING QUBITS



Electrical Circuit

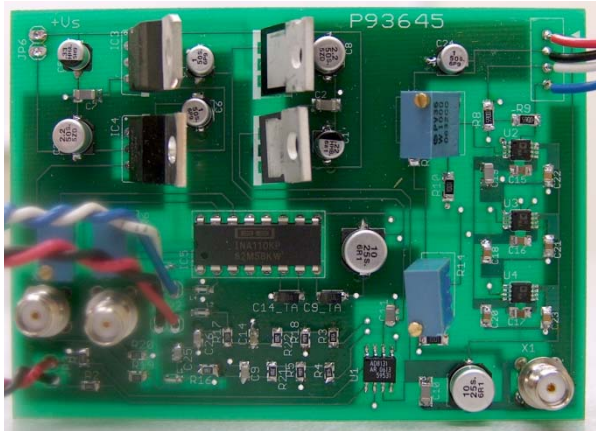


"Artificial Atom"

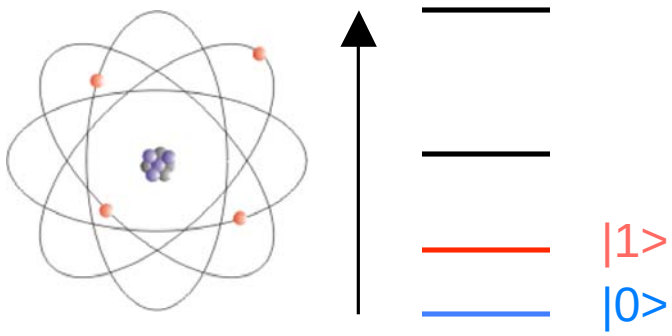


Single Spin ½ NMR

HOW CAN WE MAKE A CIRCUIT ATOM-LIKE?



?



Electrical Circuit

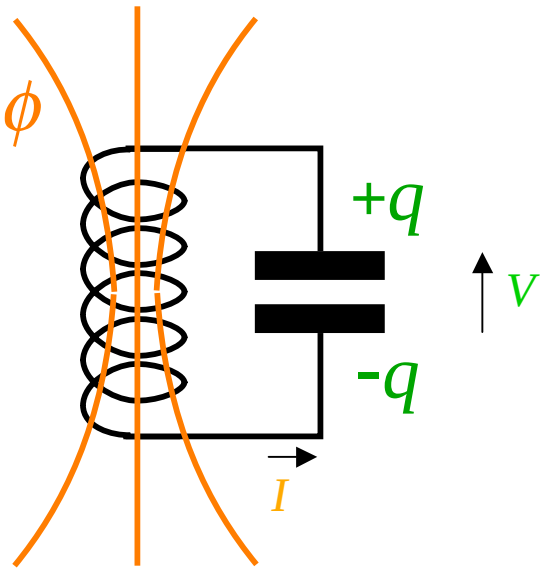
“Artificial Atom”

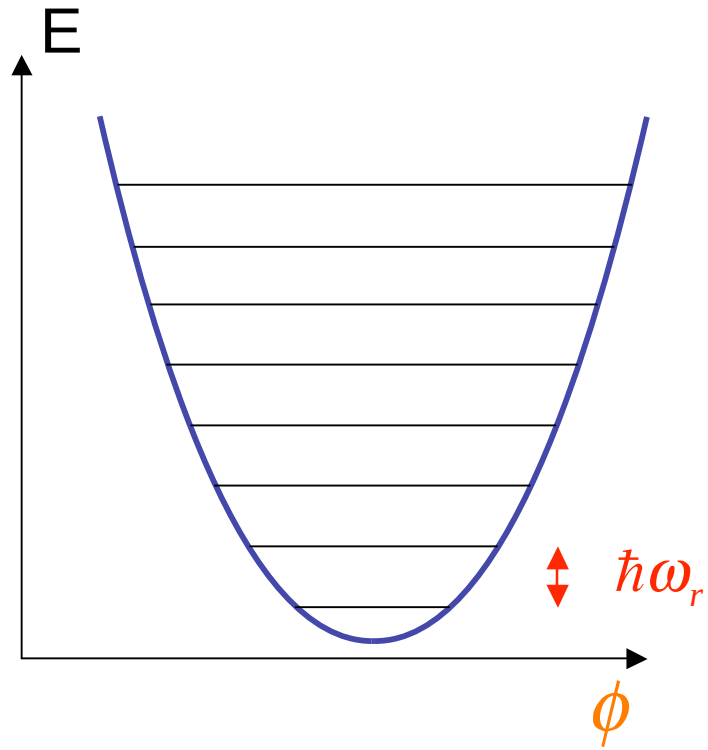
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

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

LC OSCILLATOR AS A QUANTUM CIRCUIT



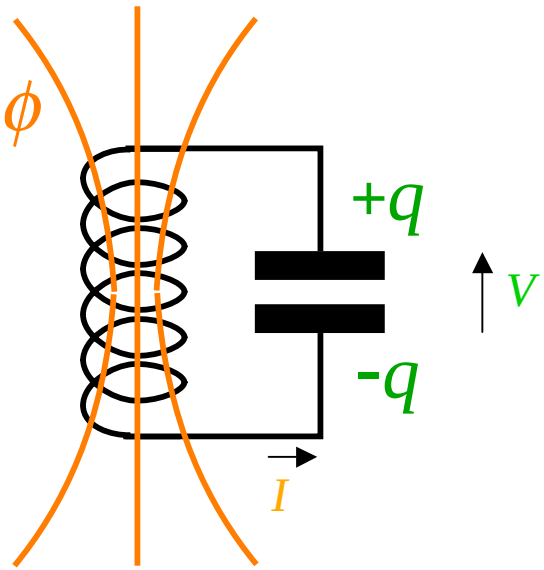


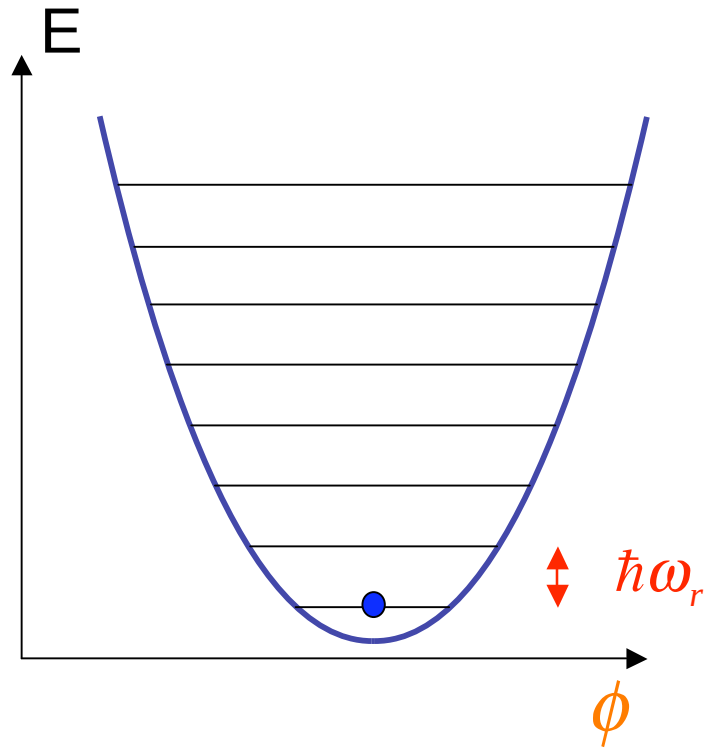
$$[\phi, q] = i\hbar$$

$$\phi = LI$$

$$q = CV$$

LC OSCILLATOR AS A QUANTUM CIRCUIT





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

$$\phi = LI$$

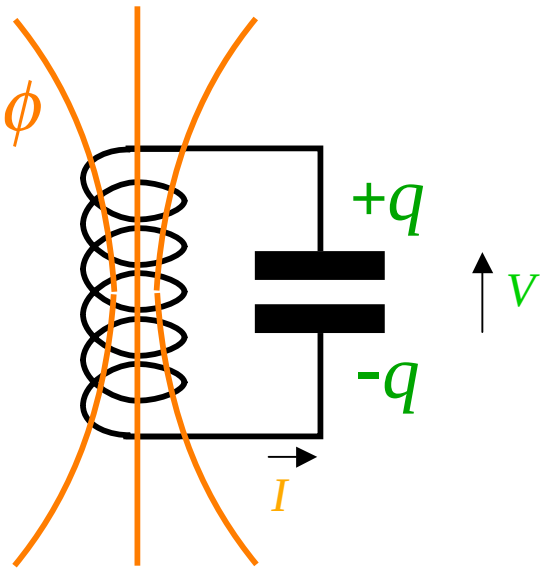
$$q = CV$$

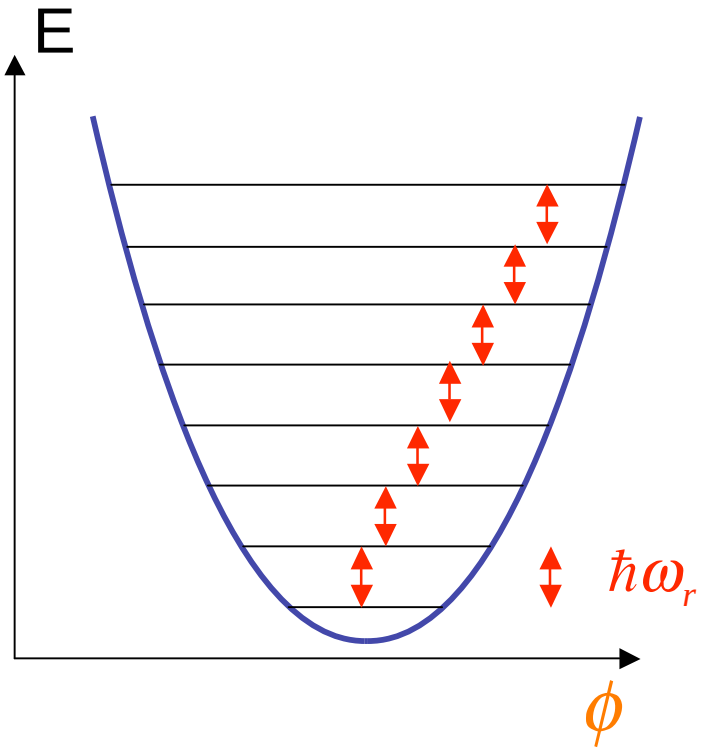
$$\hbar\omega_r > k_B T$$

1GHz

10mK

LC OSCILLATOR AS A QUANTUM CIRCUIT

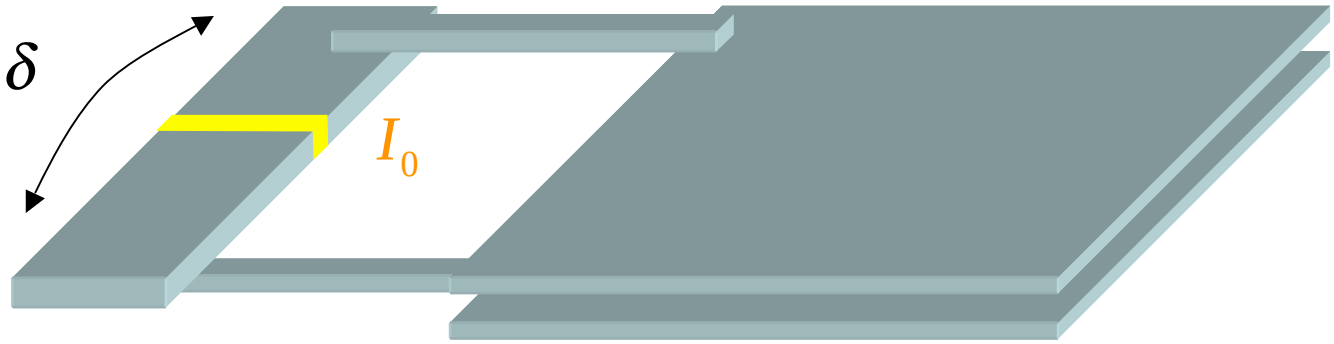




$$[\phi, q] = i\hbar$$

CANNOT STEER THE SYSTEM TO AN ARBITRARY STATE

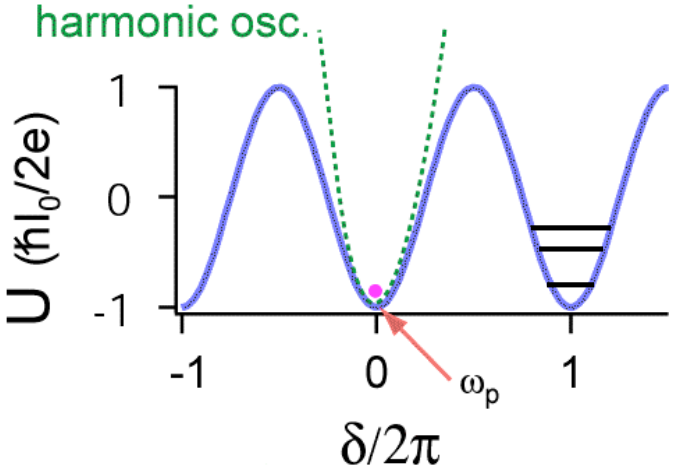
THE JOSEPHSON TUNNEL JUNCTION: NON-LINEARITY AT ITS FINEST!



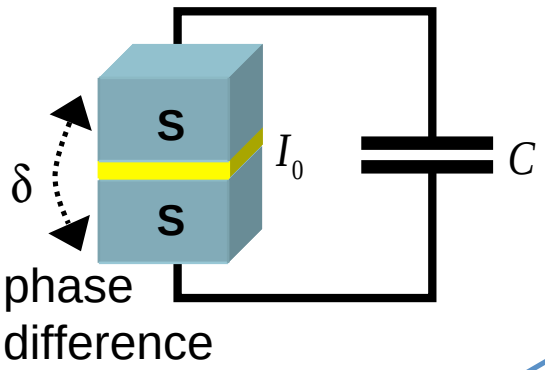
$$I(\delta) = I_0 \sin(\delta)$$

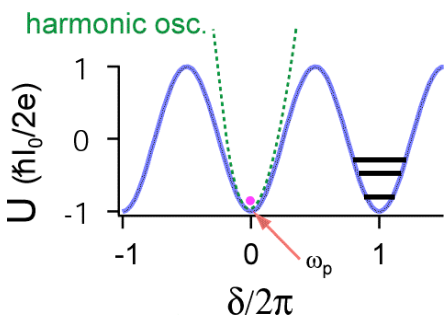
(NON-LINEAR INDUCTOR)

$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$



JOSEPHSON JUNCTION QUBITS



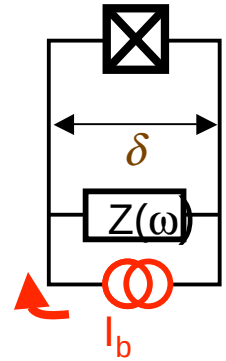


CURRENT

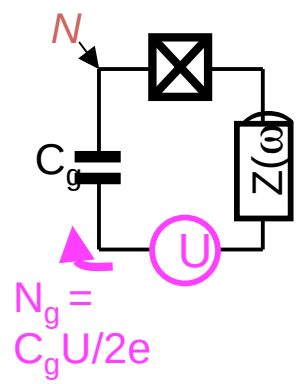
CAPACITOR

INDUCTOR

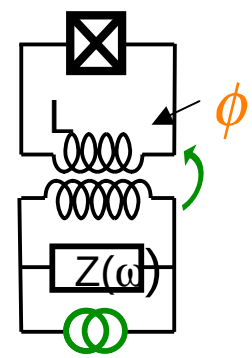
PHASE QUBIT



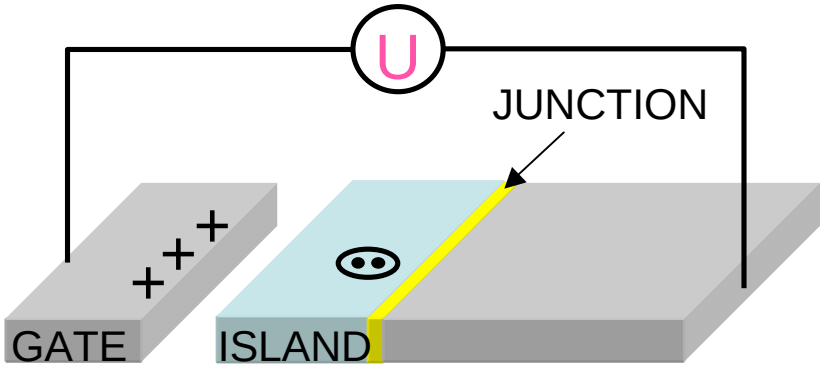
CHARGE QUBIT

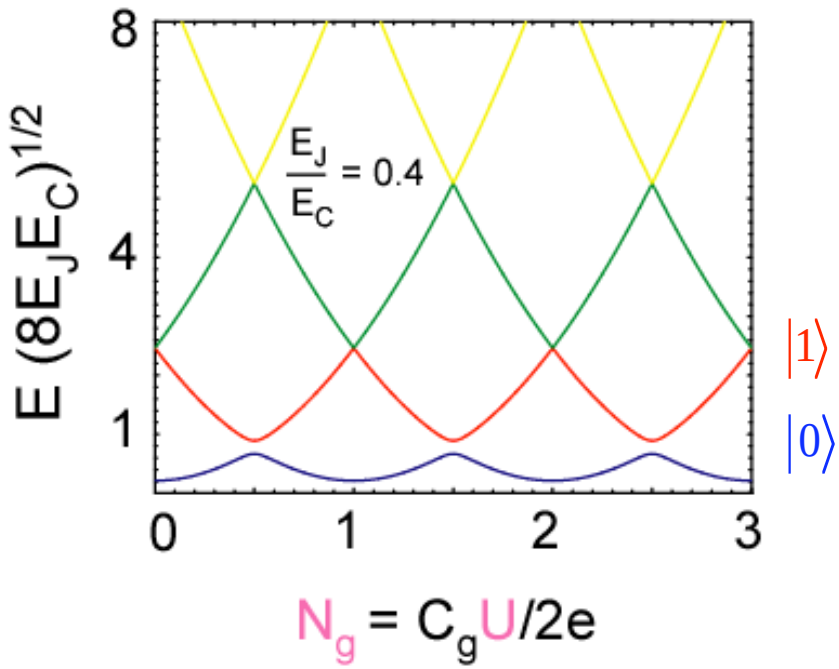


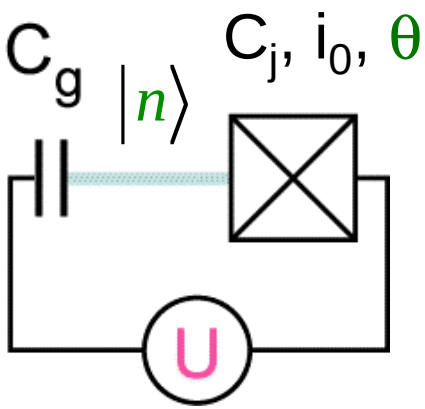
FLUX QUBIT



CHARGE QUBIT: COOPER PAIR BOX





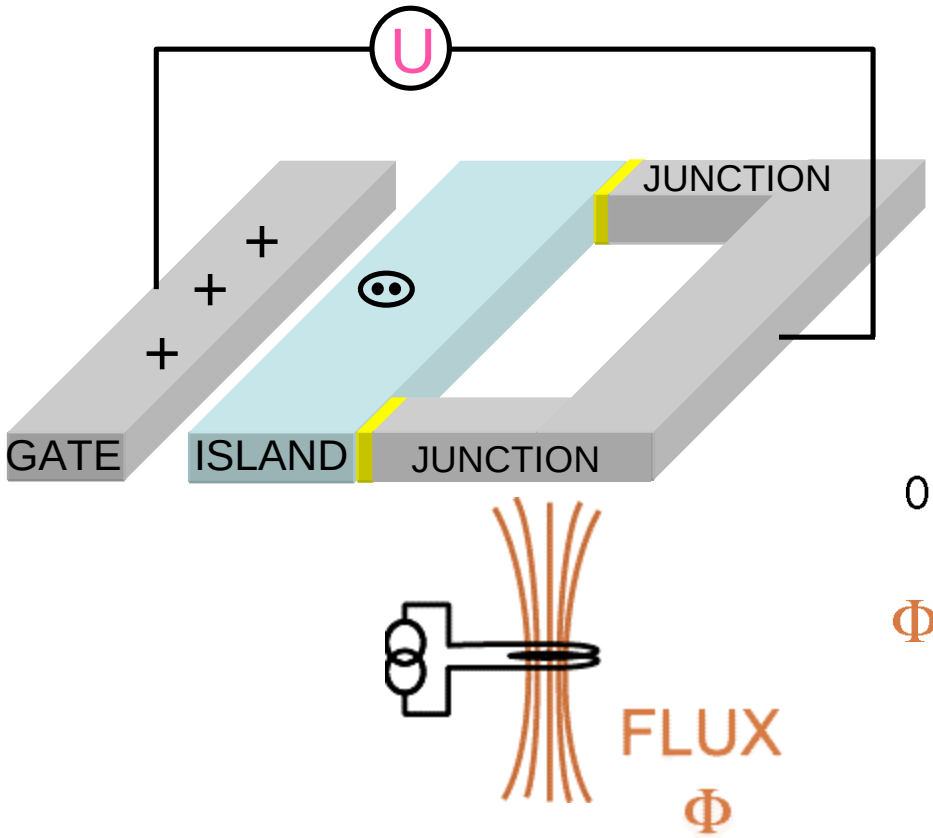


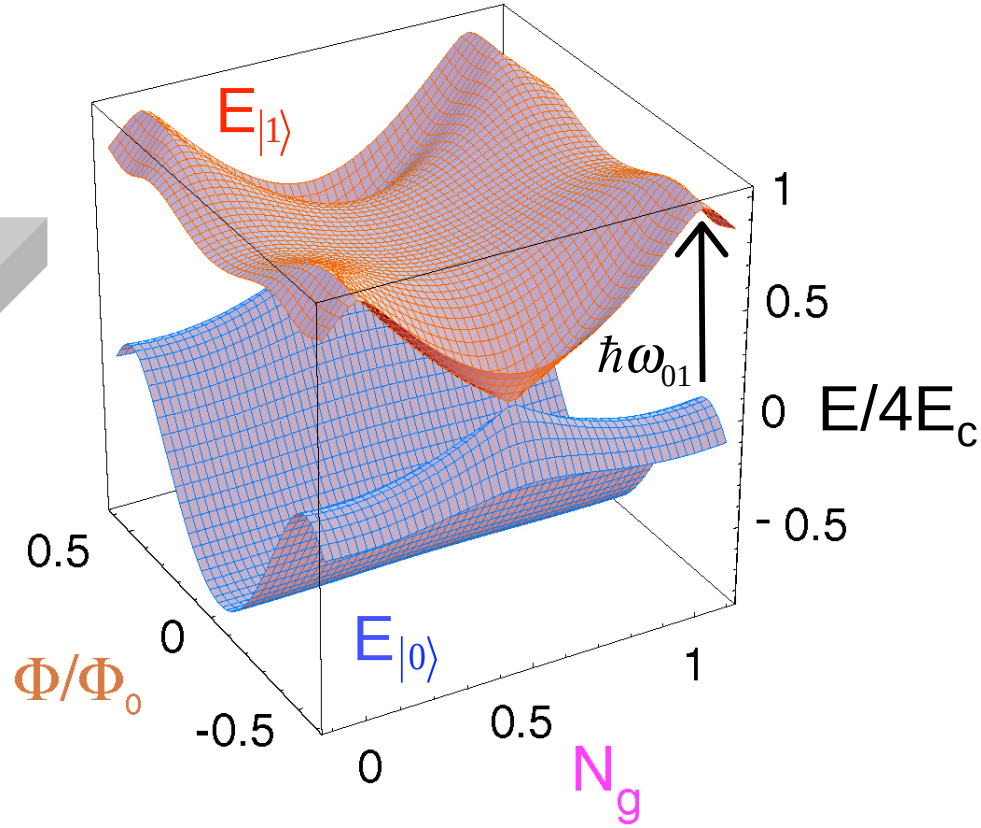
$$\hat{H}_{el} = 4E_c\left(\hat{n} - \frac{C_g U}{2e}\right)^2 ; \quad E_c = \frac{e^2}{2(C_g + C_j)}$$

$$\hat{H} = \frac{E_{el}}{2}\hat{\sigma}_x - \frac{E_j}{2}\hat{\sigma}_z$$

$$\hat{H}_j = -E_j \cos\hat{\theta} \;\; ; \;\; E_j = \varphi_0 i_0$$

SPLIT COOPER PAIR BOX





$$\hat{H} = 4E_c(\hat{n} - N_g)^2 \quad - \quad 2E_j \cos\left(\frac{\Phi}{2\varphi_0}\right)\cos\hat{\theta}$$

READOUT STRATEGIES

charge

$$Q_k \propto \frac{\partial E_k}{\partial N_g}$$

CPB + SET

capacitance

$$C_k \propto \frac{\partial^2 E_k}{\partial N_g{}^2}$$

cQED Qubit

current

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

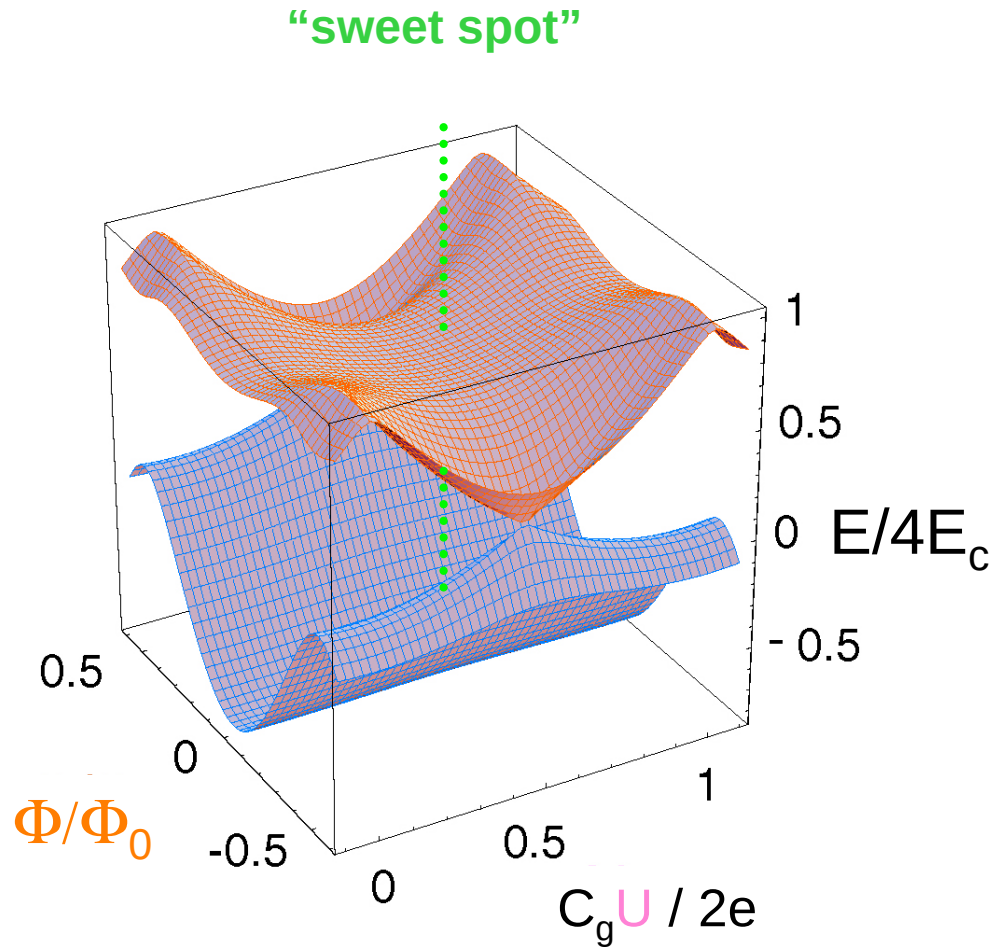
Quantronium

inductance

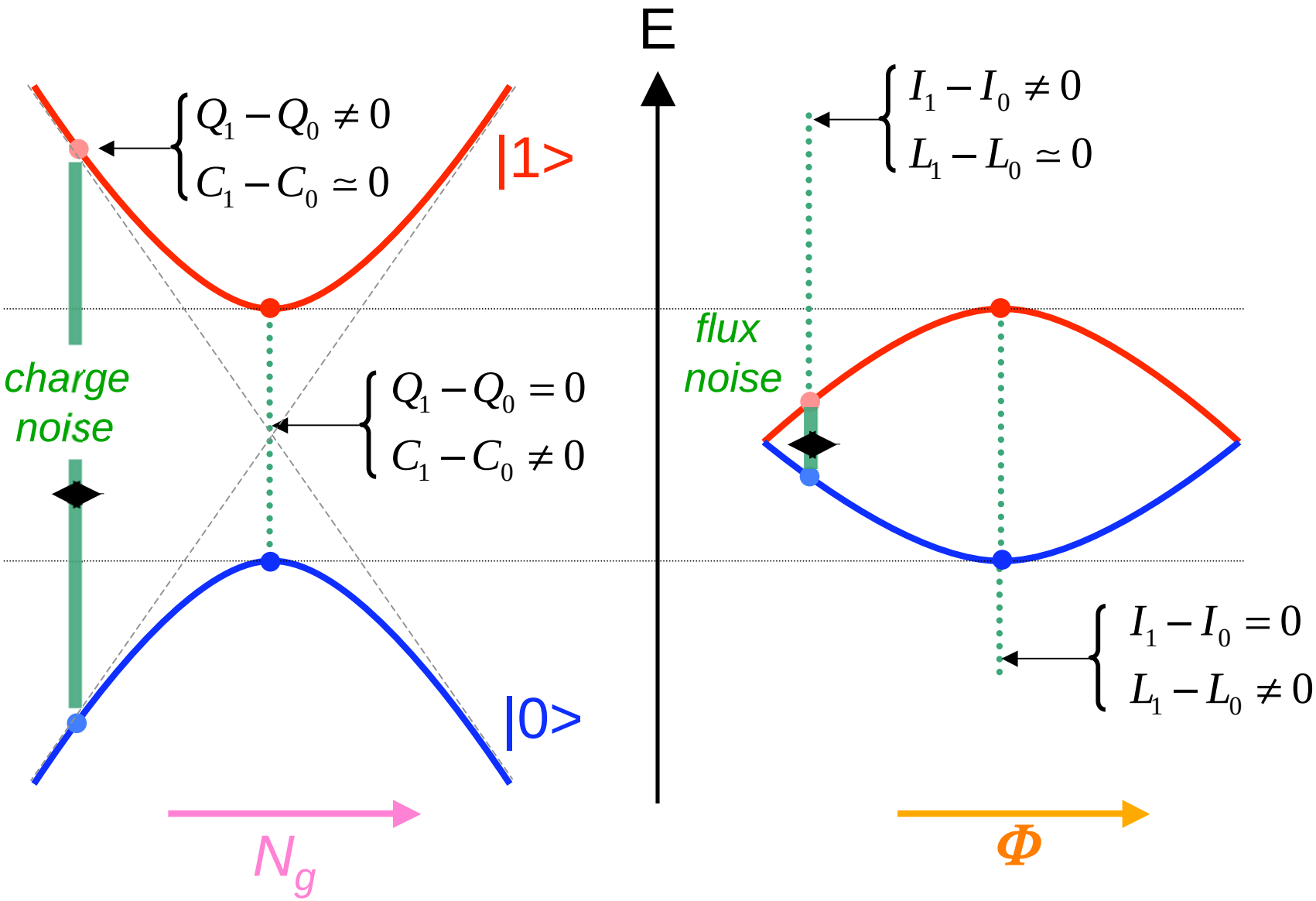
$$L_k \propto \left(\frac{\partial^2 E_k}{\partial \Phi^2} \right)^{-1}$$

Quantronium + JBA

- work @ sweet spot
- readout @ sweet spot

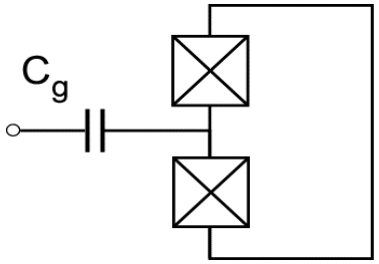


CAN'T READ CHARGE OR CURRENT!



DISPERSIVE READOUT

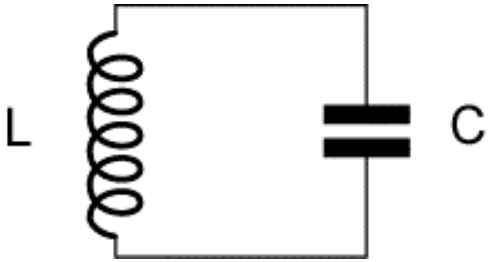
Cooper Pair Box

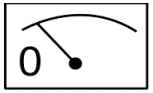


$|0\rangle$

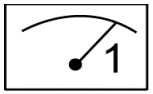
$|1\rangle$

LC Oscillator





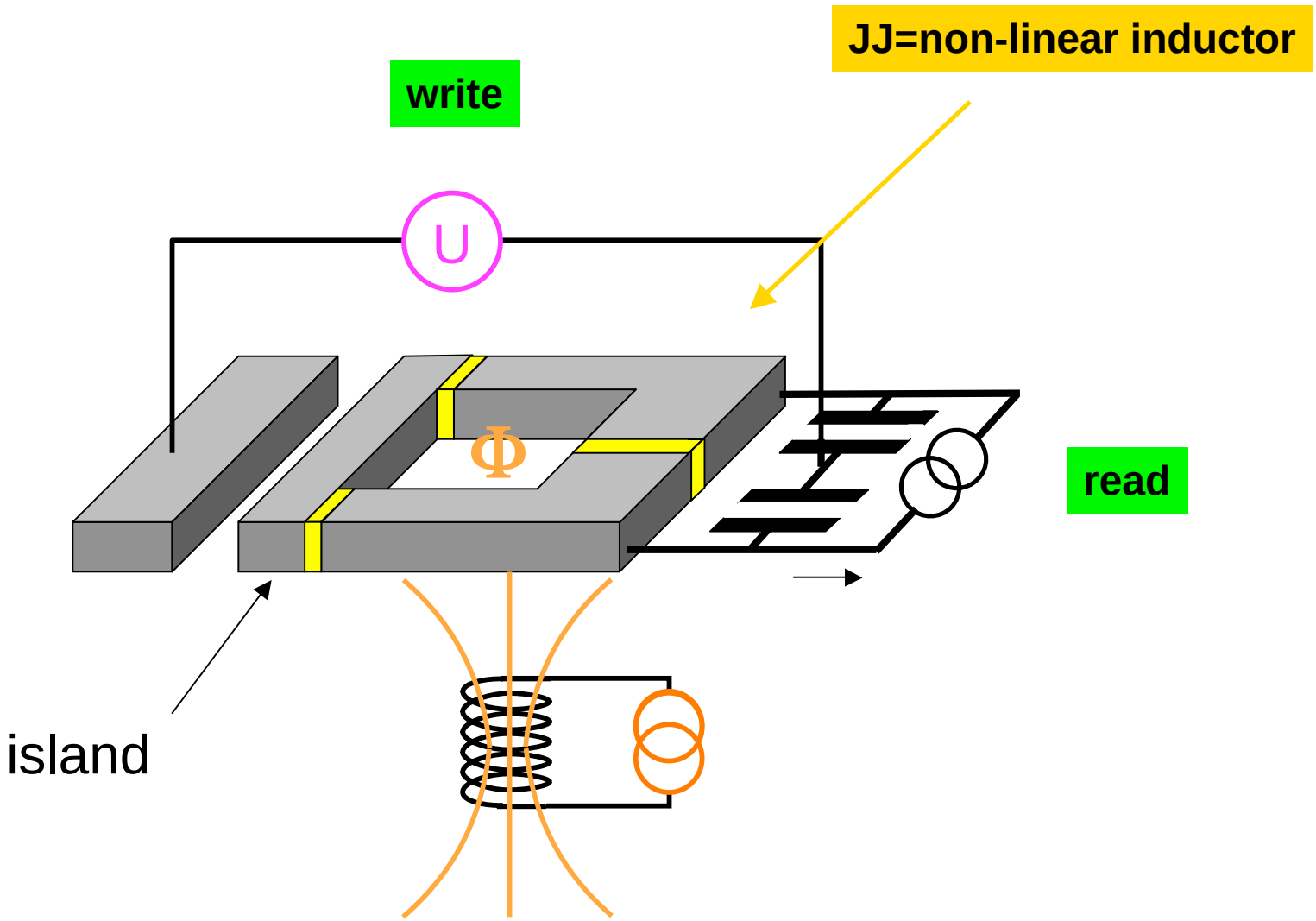
$= \omega_{|0\rangle}$



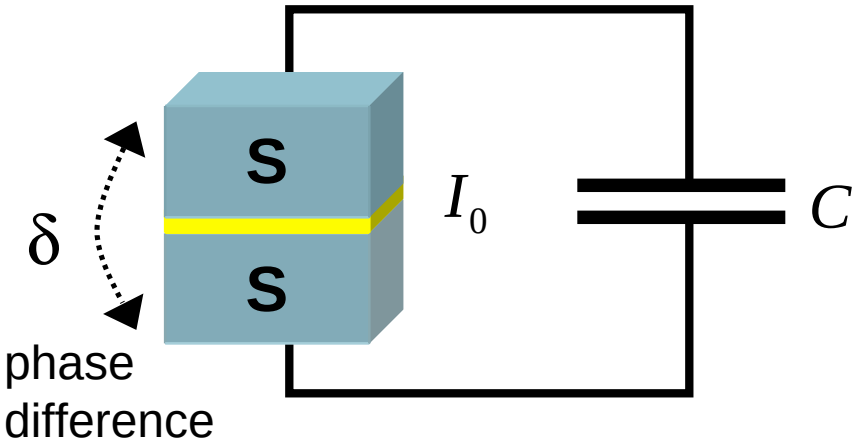
$= \omega_{|1\rangle}$

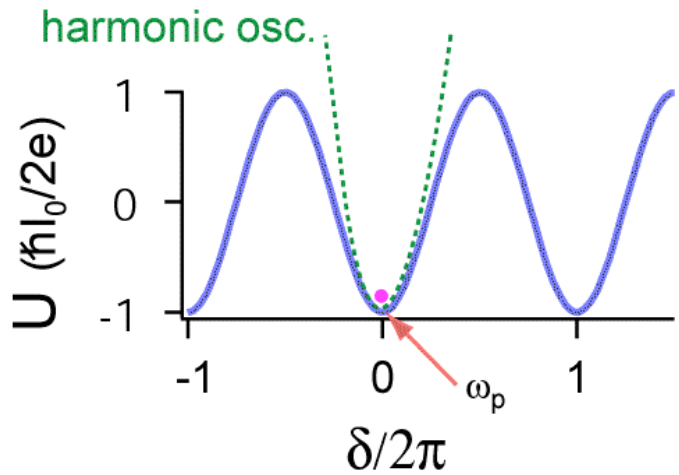
- qubit state modifies oscillator frequency
- measure susceptibility, not loss

NON-LINEAR INDUCTIVE READOUT: QUANTRONIUM



THE JOSEPHSON OSCILLATOR





$$\begin{cases} I(\delta) = I_0 \sin(\delta) \\ V(t) = \dfrac{\hbar}{2e}\dfrac{d}{dt}(\delta) \end{cases}$$

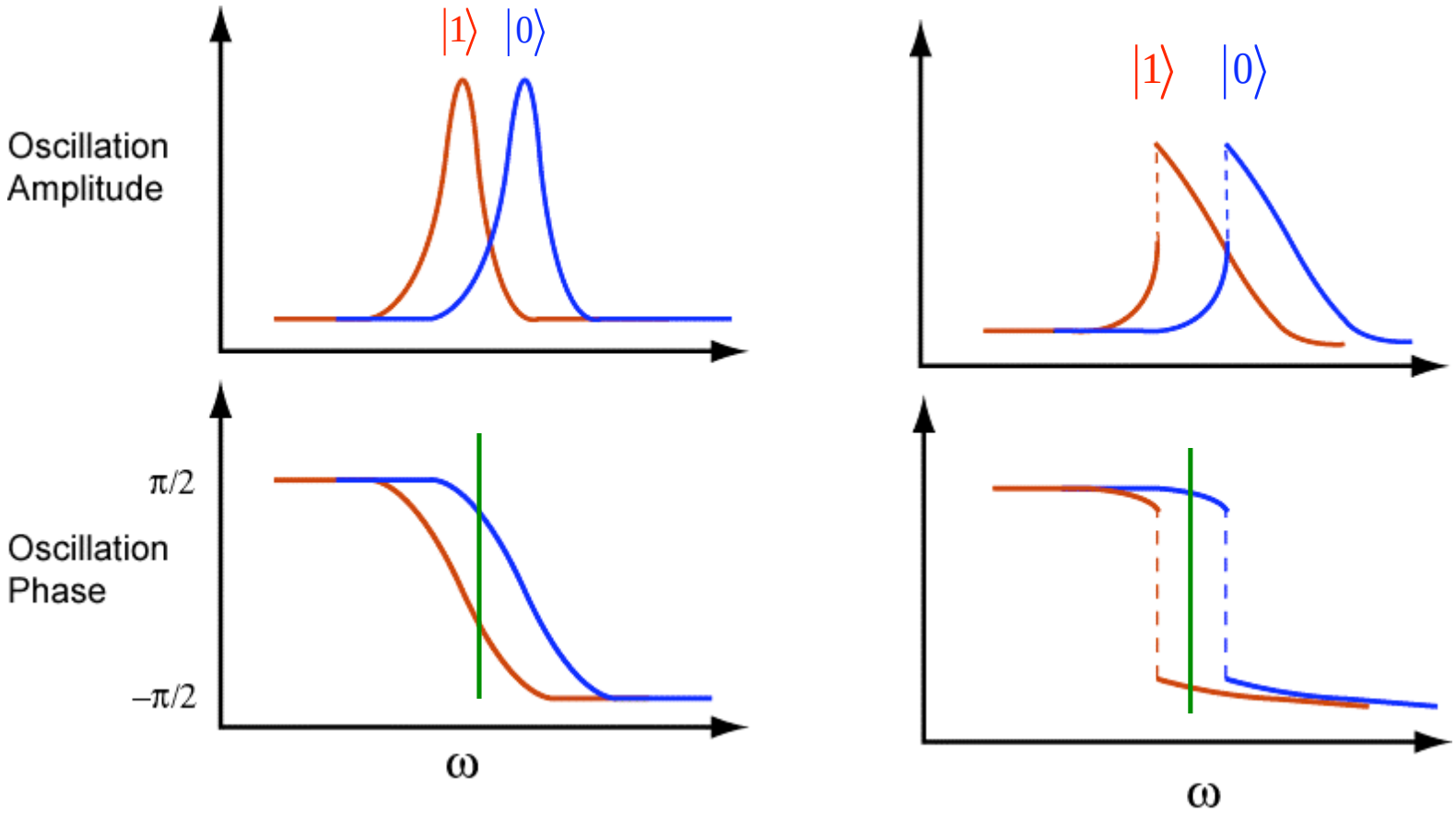
$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$

<u>Nonlinear Oscillator</u>

$$L_J = \frac{V(t)}{dI/dt} = \frac{\hbar}{2e}\frac{1}{I_0}\frac{1}{\cos(\delta)}$$

$$\omega_P = \frac{1}{\sqrt{L_J C}}$$

COMBINING HIGH SENSITIVITY & SPEED



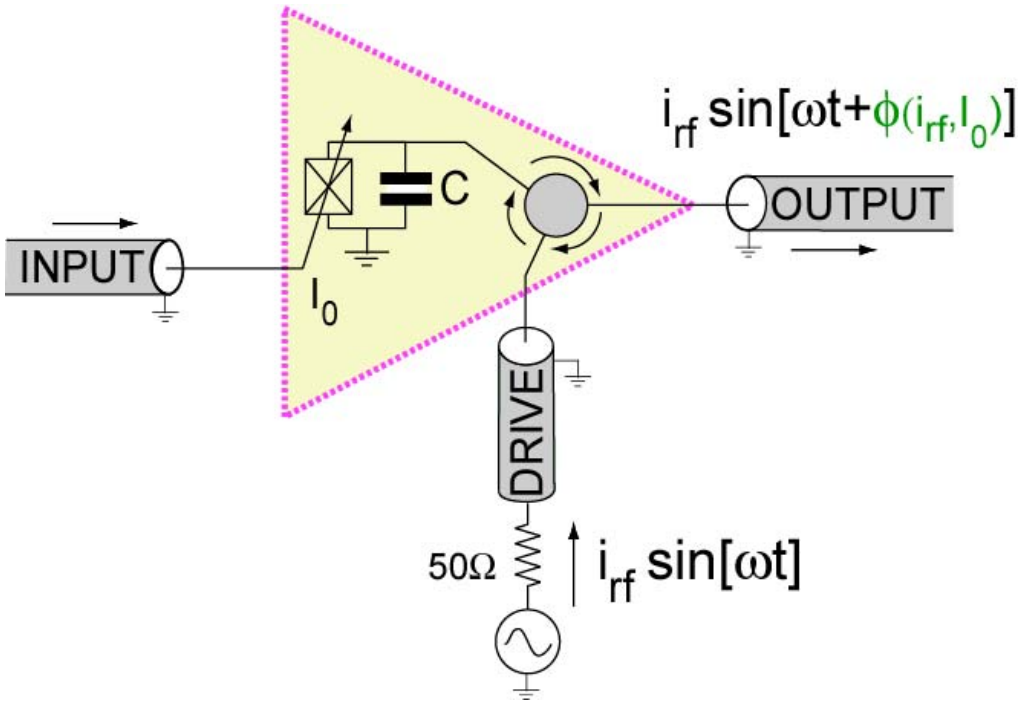
LINEAR OSCILLATOR (review)

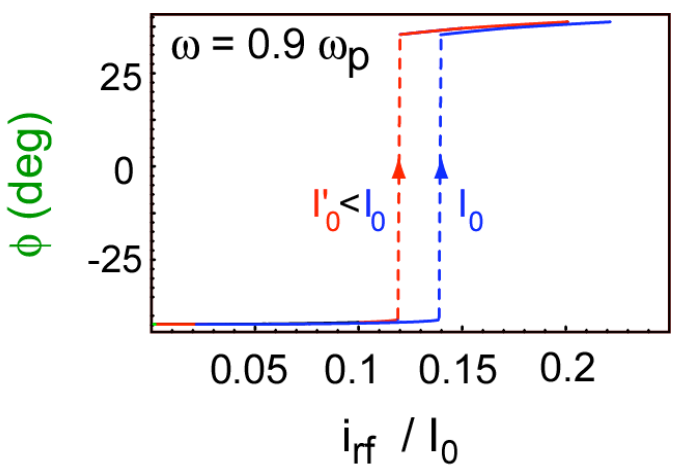
Q sets sensitivity

NON-LINEAR OSCILLATOR

kT sets sensitivity !

JOSEPHSON BIFURCATION AMPLIFIER





JBA: INPUT COUPLES TO I_0

- $\phi(i_{rf},I_0)$
- $P_{switch}(i_{rf},I_0)$

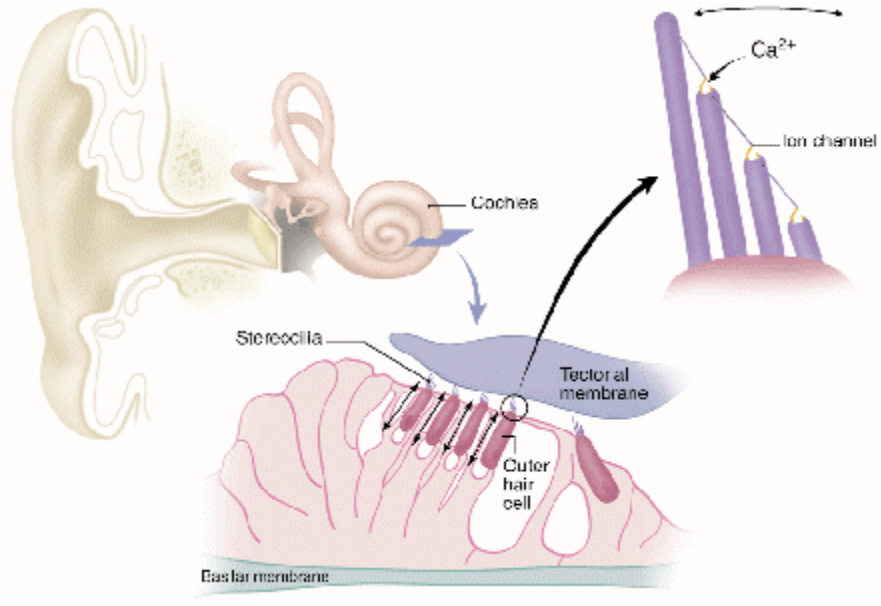
- minimal backaction
- no on-chip dissipation

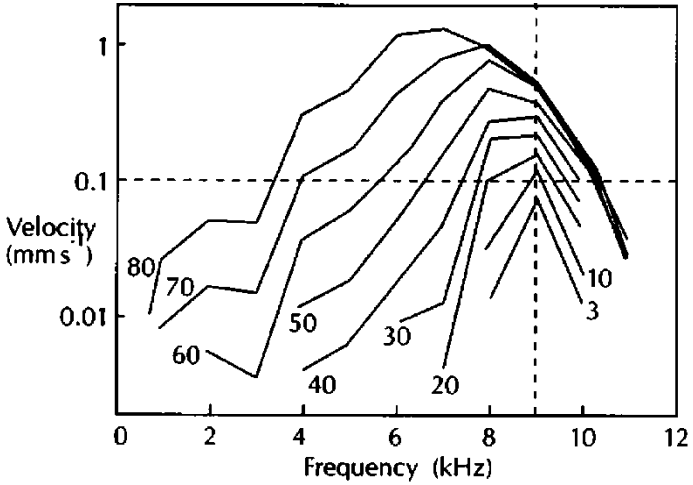
NATURE'S BIFURCATION AMPLIFIER

VOLUME 84, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY 2000

Essential Nonlinearities in Hearing

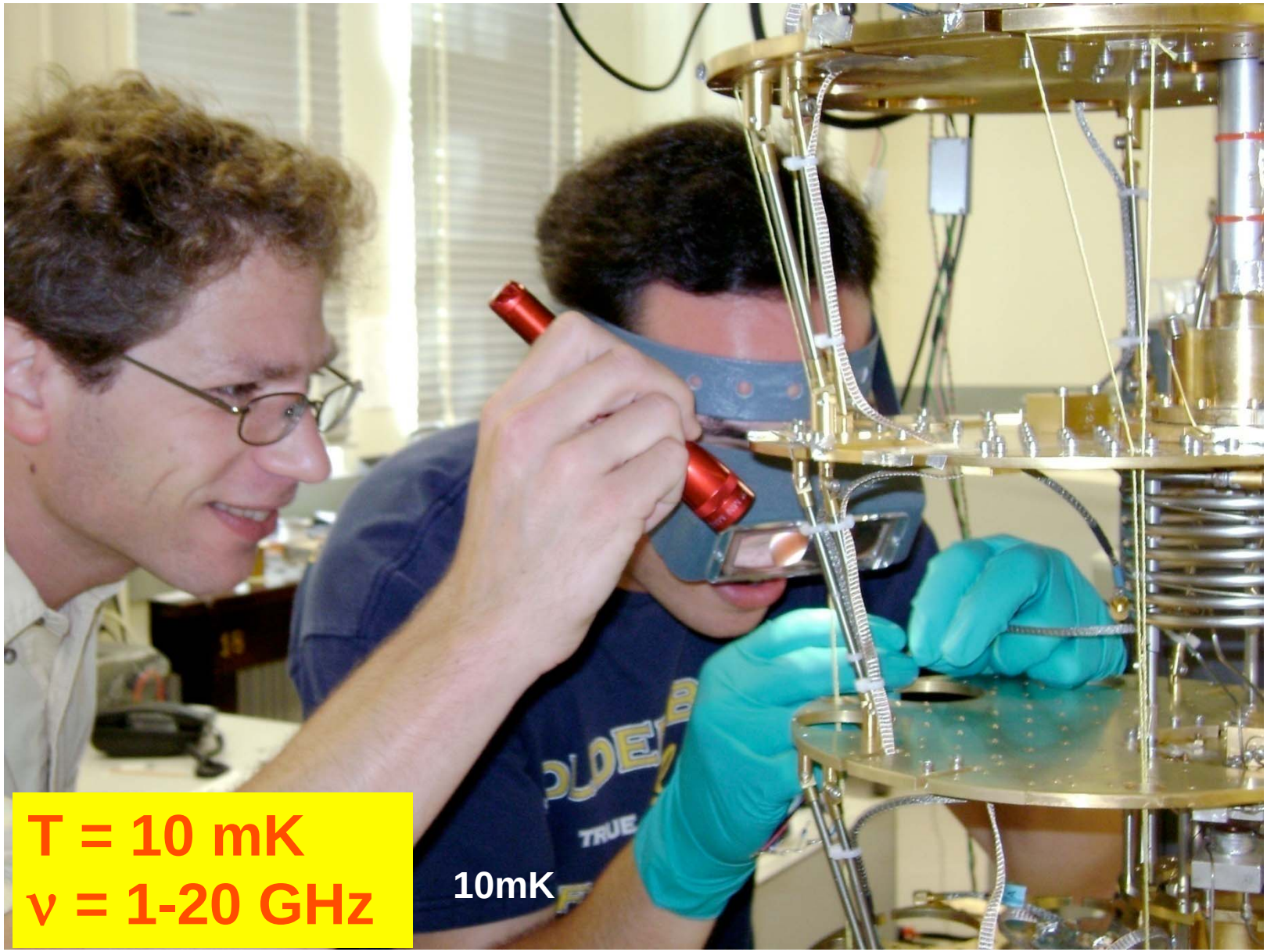
V. M. Eguíluz, M. Ospeck, Y. Choe, A. J. Hudspeth, and M. O. Magnasco
Instituto Mediterráneo de Estudios Avanzados IMEDEA (CSIC-UIB), E-07071 Palma de Mallorca, Spain
Laboratory of Mathematical Physics, The Rockefeller University, 1230 York Avenue, New York, New York 10021
Laboratory of Sensory Neuroscience, The Rockefeller University, 1230 York Avenue, New York, New York 10021
Howard Hughes Medical Institute, The Rockefeller University, 1230 York Avenue, New York, New York 10021
(Received 23 September 1999)



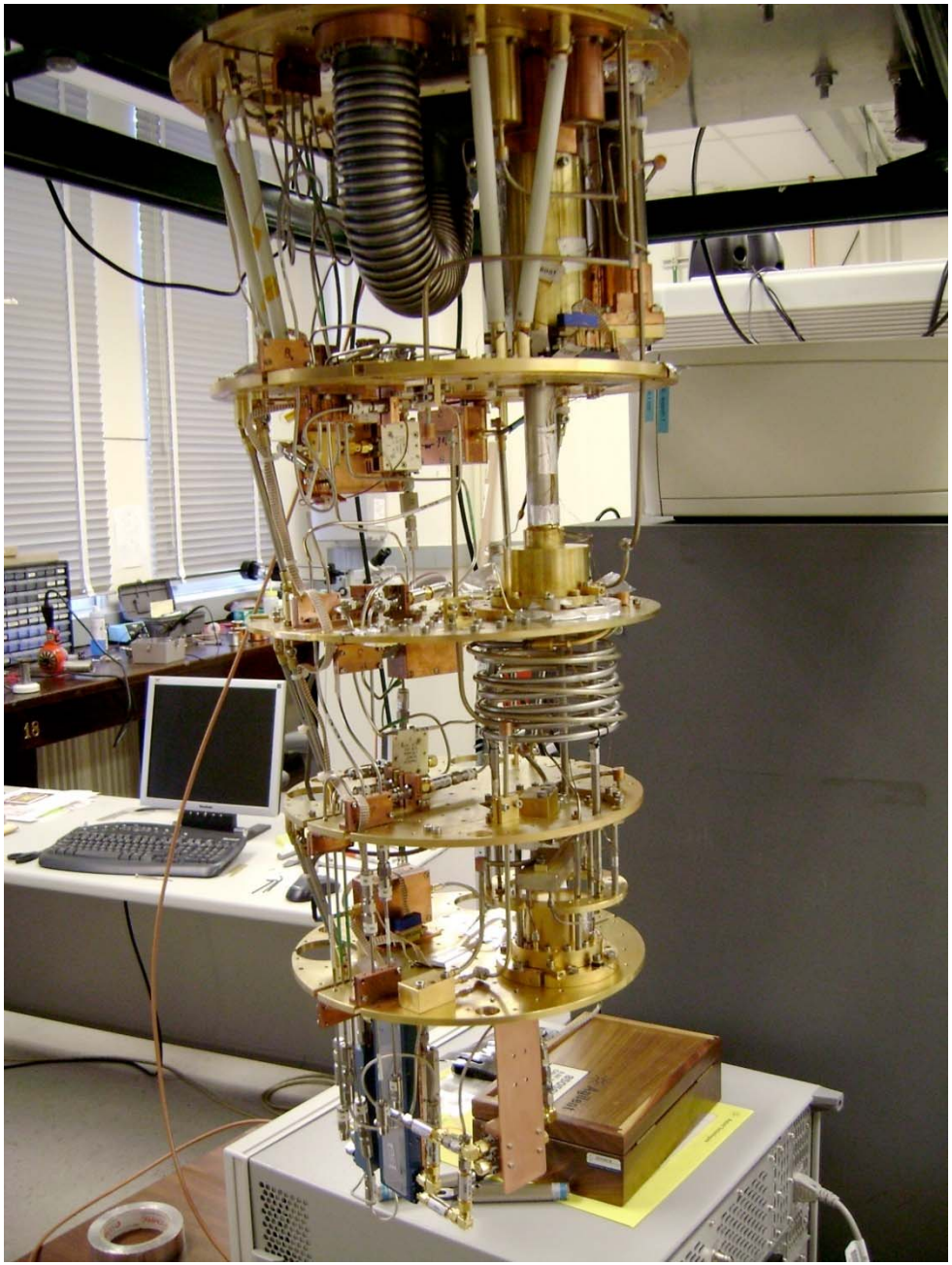


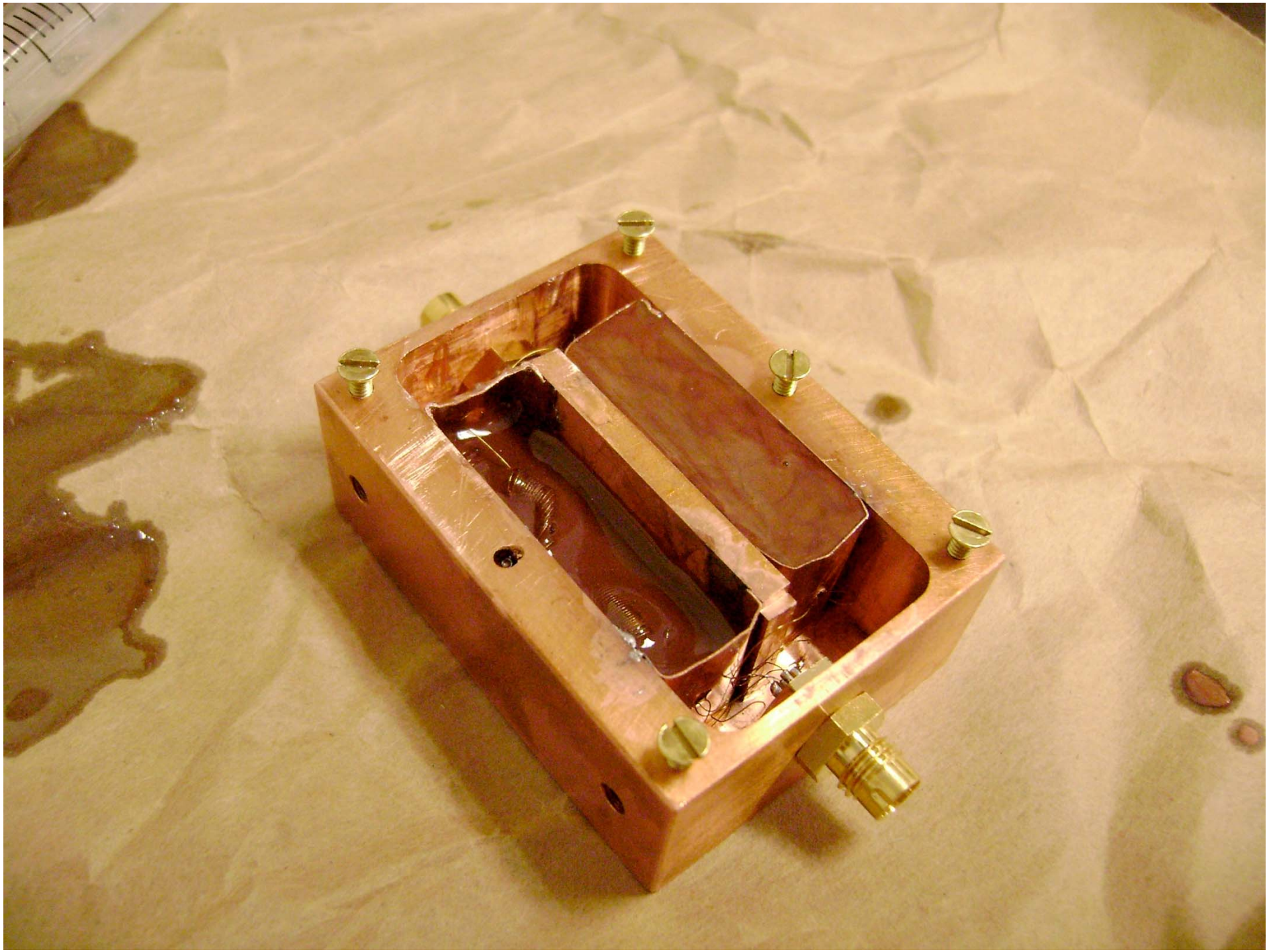
Science

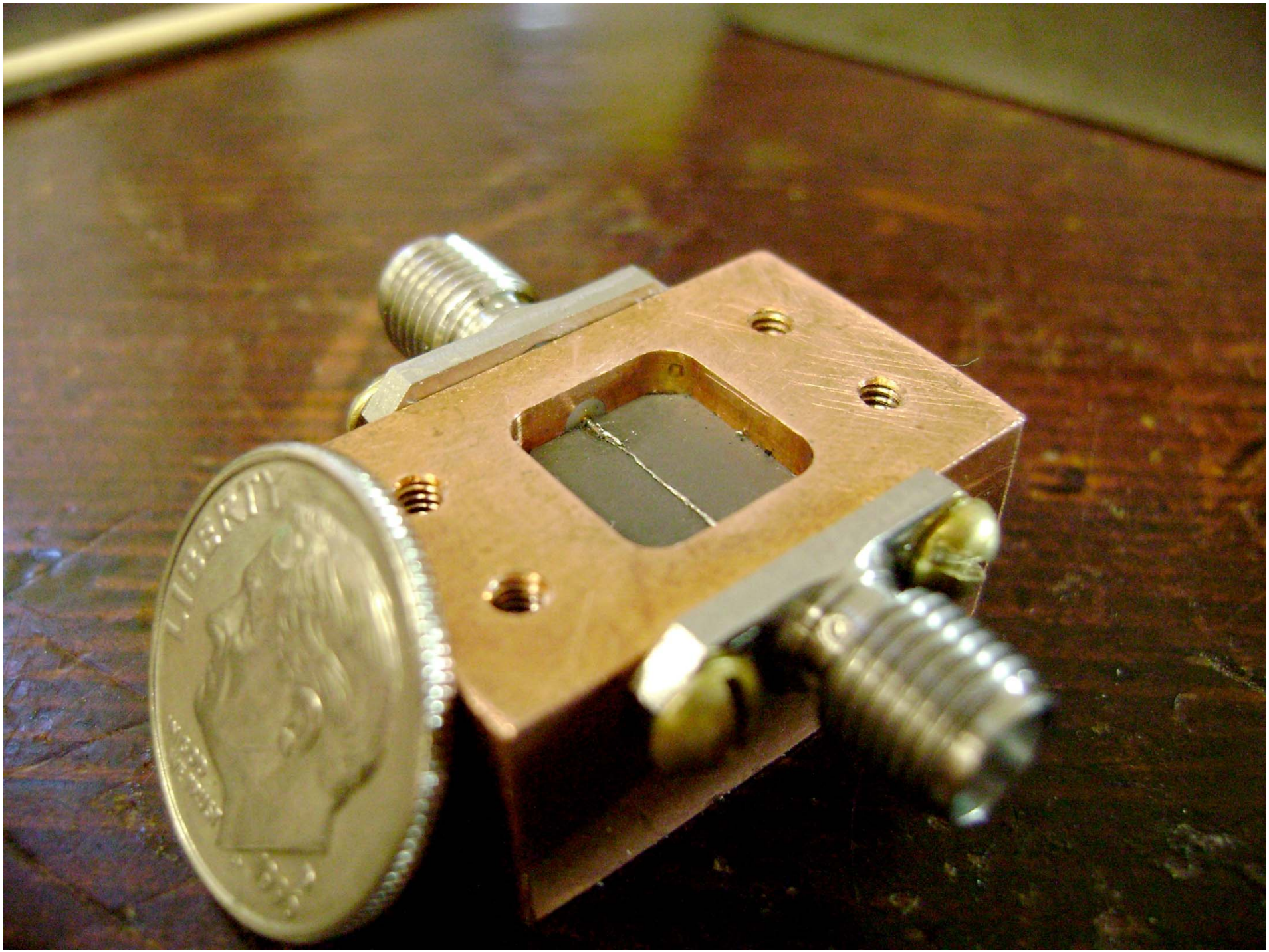
THE CHALLENGE OF THE MICROWAVE EAR



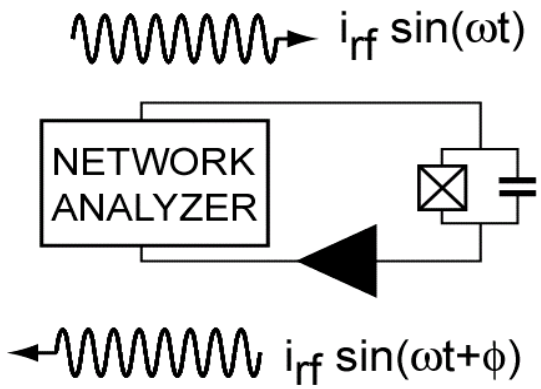
T = 10 mK
ν = 1-20 GHz

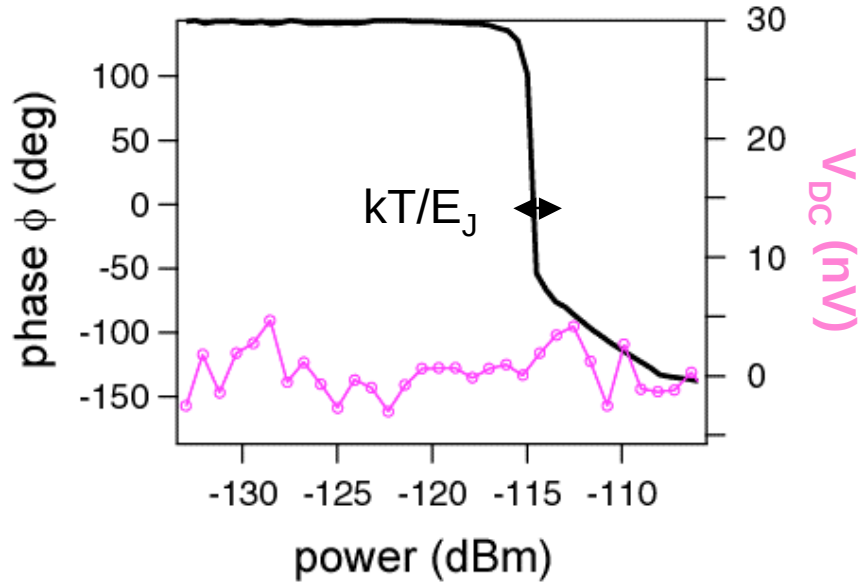


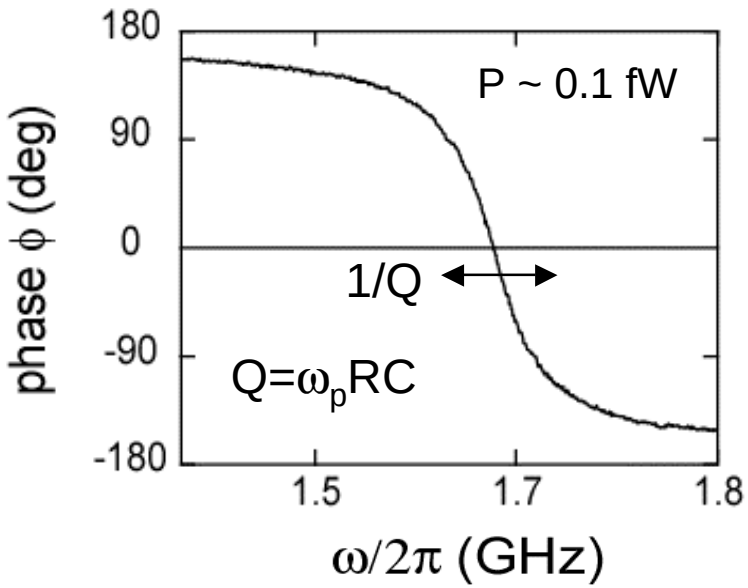


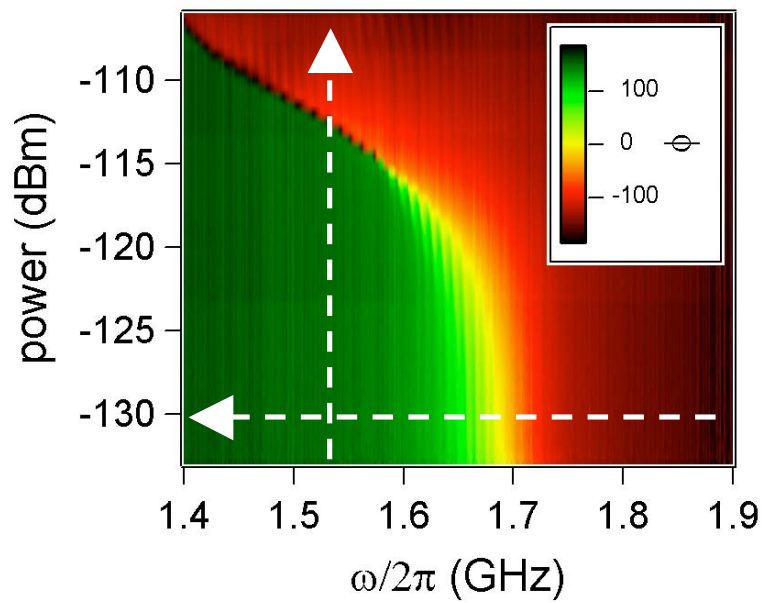

LIBERTY

RF BIASED JUNCTION: PHASE DIAGRAM

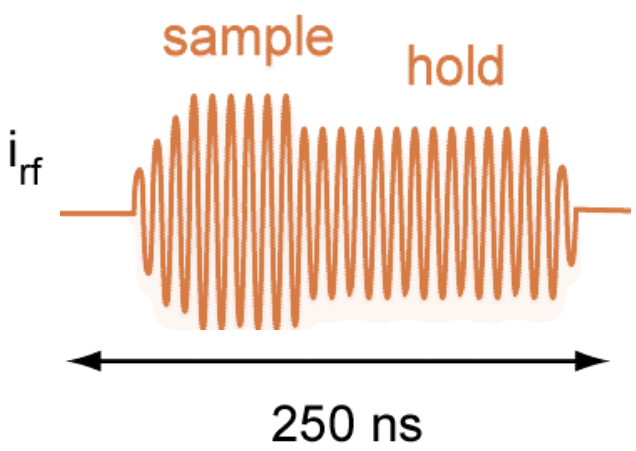


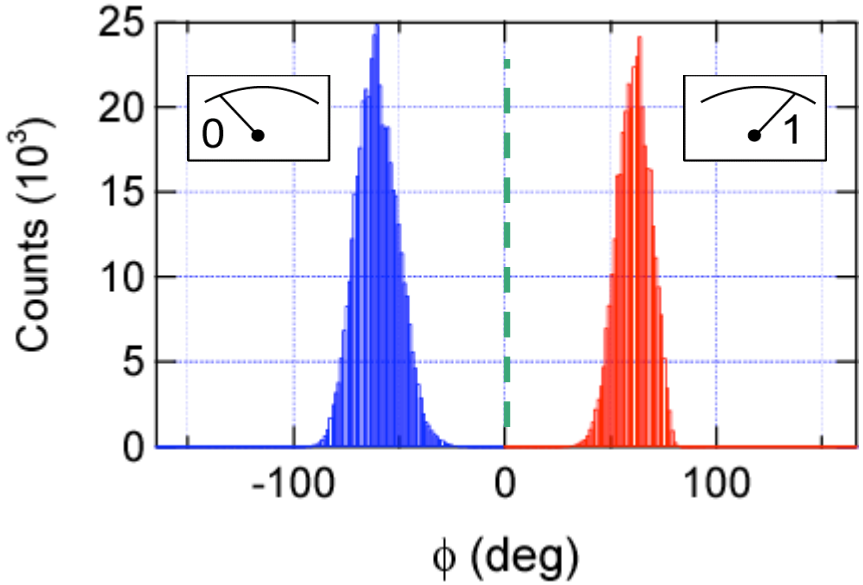




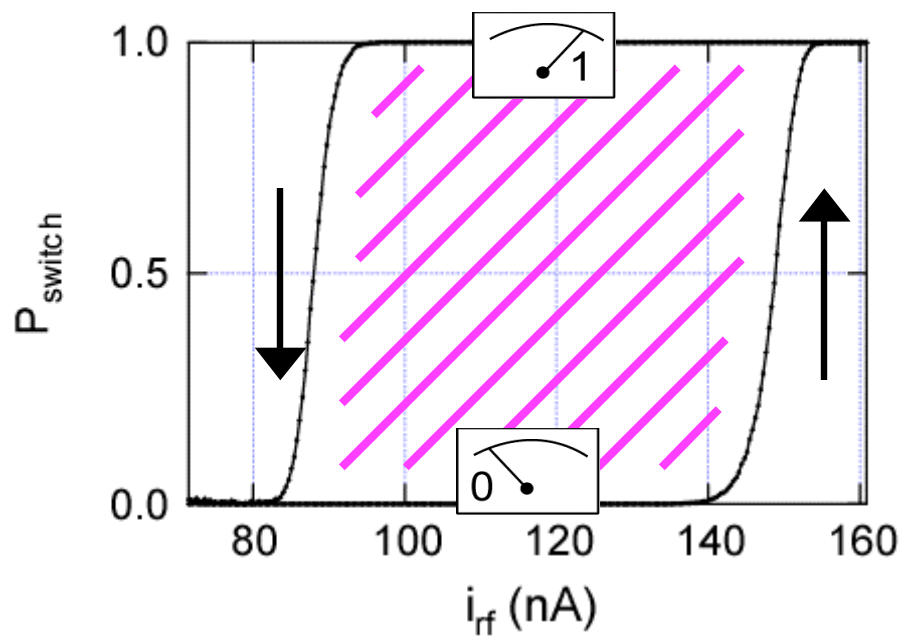


SWITCHING DYNAMICS: TESTING THE “METER”





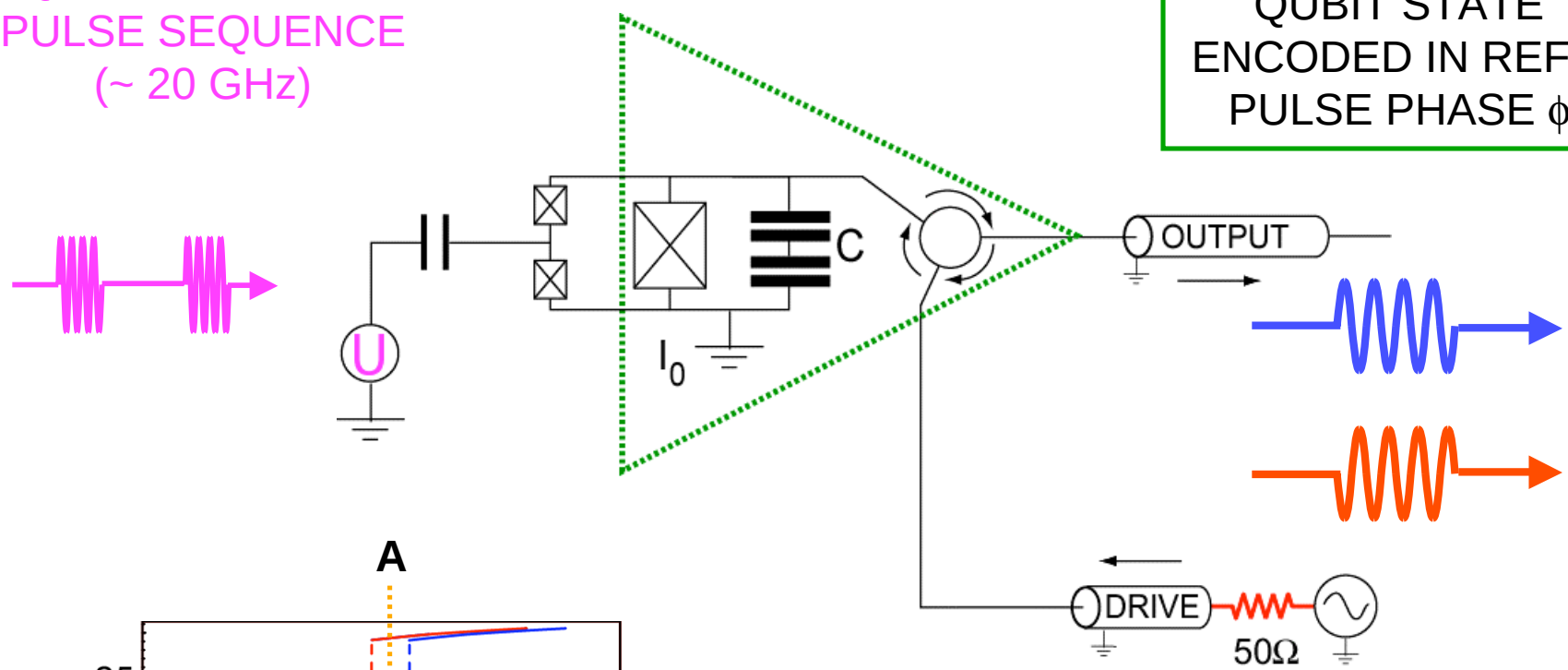
- histogram reflected phase ϕ
  - record in 30ns
  - repeat at 4 MHz
- identify “meter” states
- hysteresis: sample & hold !

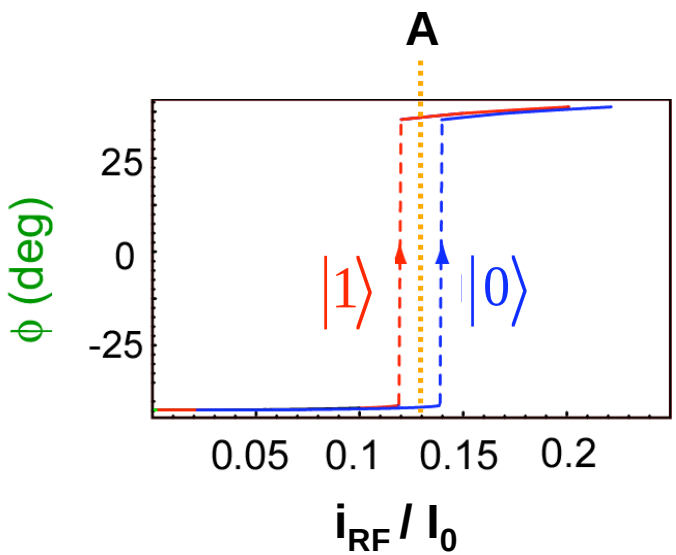


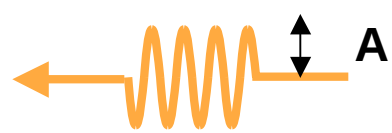
QUANTRONIUM with BIFURCATION READOUT

QUBIT CONTROL
PULSE SEQUENCE
(~ 20 GHz)

QUBIT STATE
ENCODED IN REFL.
PULSE PHASE ϕ

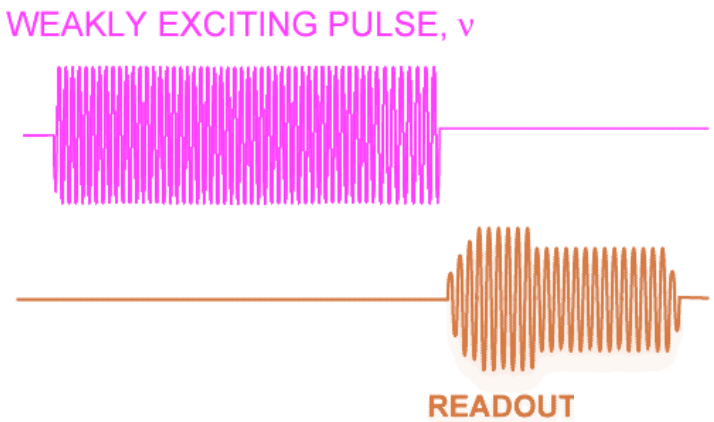


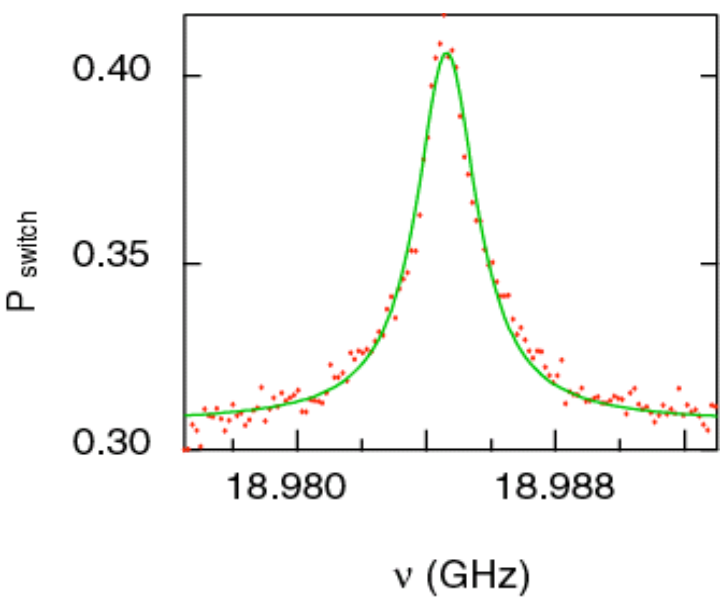


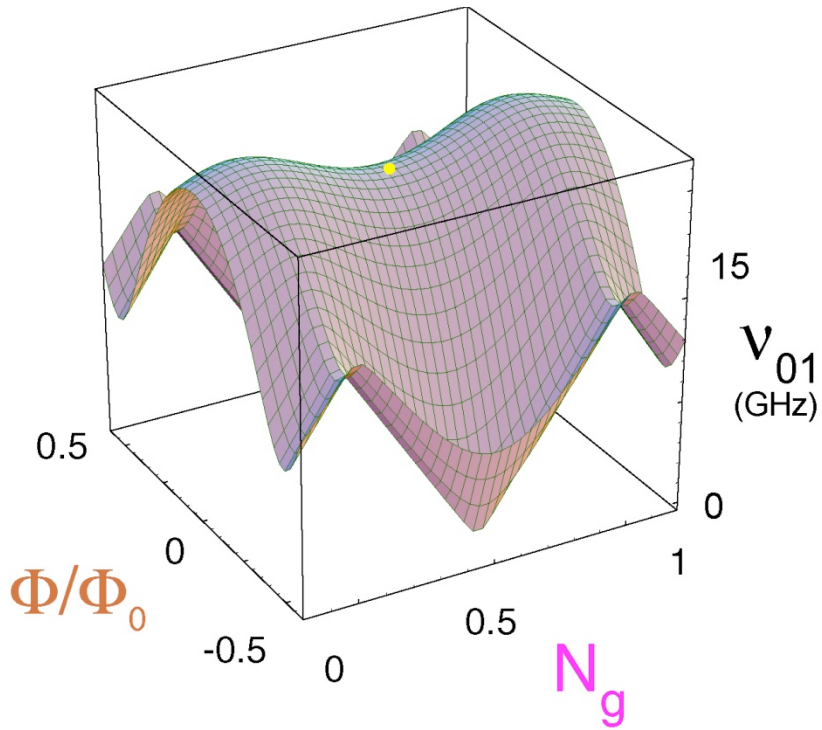


READOUT PROBING
PULSE (~ 1 GHz)

SPECTROSCOPIC FINGERPRINT





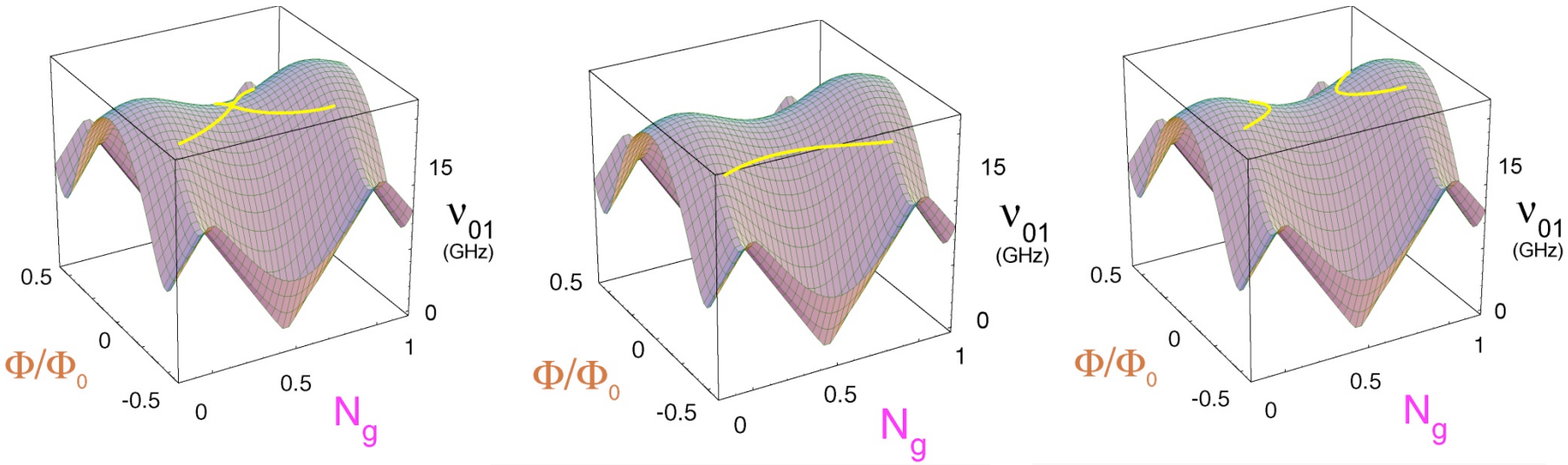


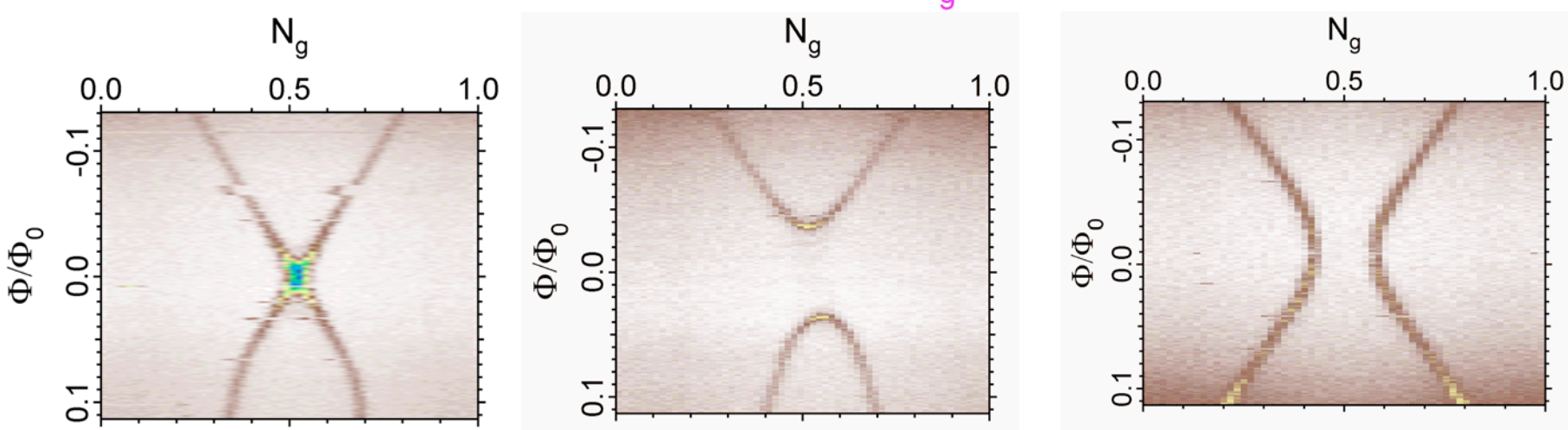
$\nu_{\text{sweet spot}} = 18.984$ GHz

$\nu = \nu_{\text{sweet spot}}$

$\Delta\nu = -100\text{MHz}$

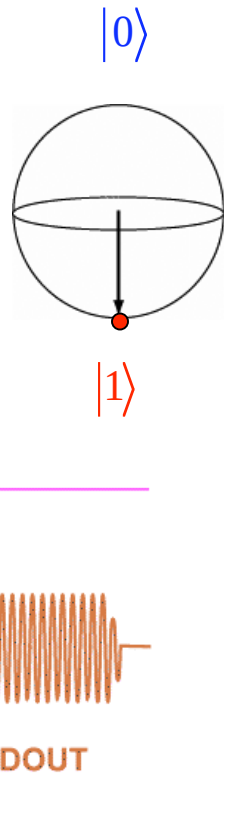
$\Delta\nu = +100\text{MHz}$

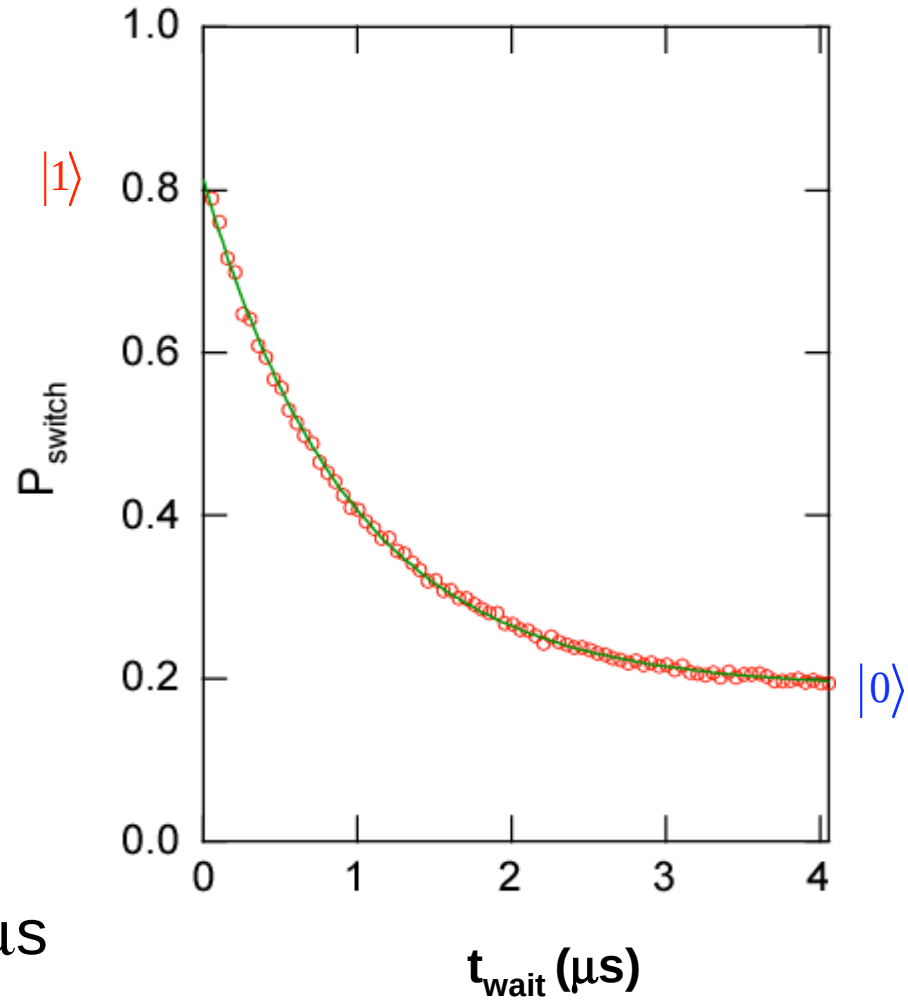




EXCITED STATE LIFETIME – T_1

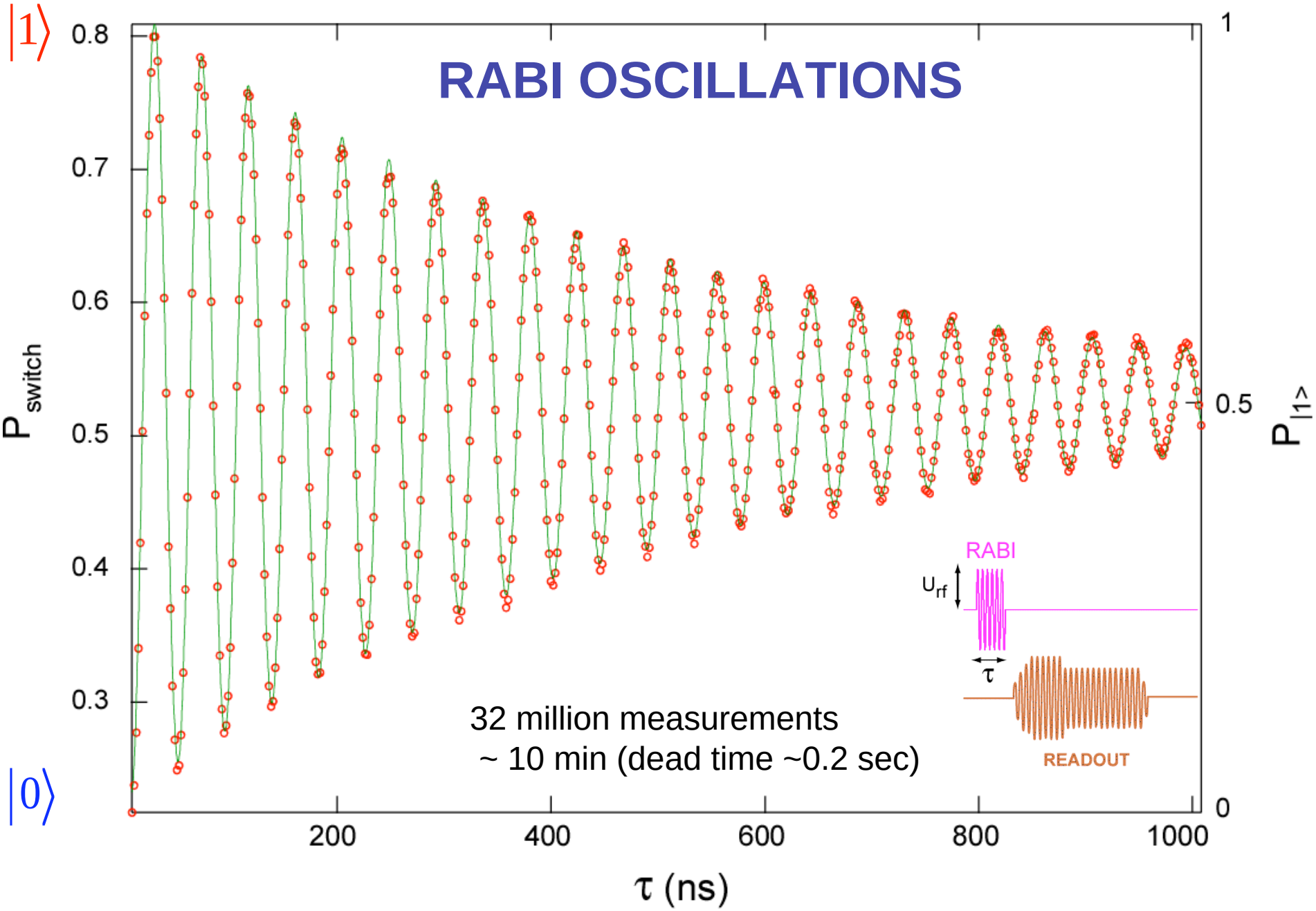
Prepare qubit in |1 state

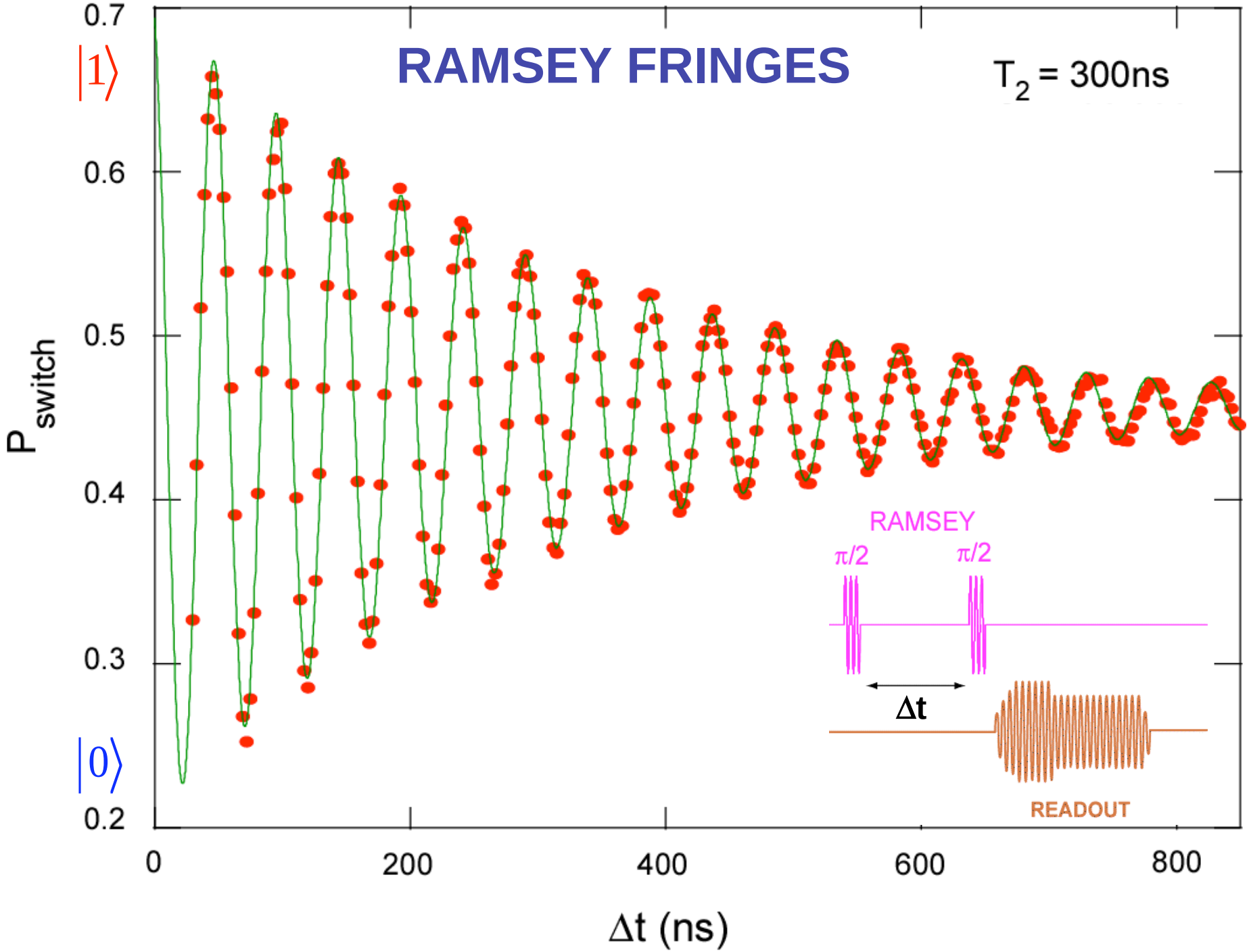




Exponential decay, T_1 = 1-5 μs

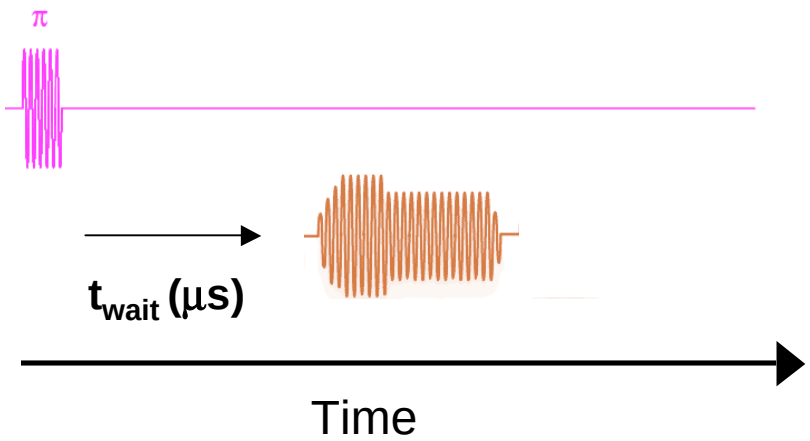
T_1 >> readout time


|1⟩
|0⟩
RABI OSCILLATIONS
0.8
0.7
0.6
0.5
0.4
0.3
P switch
1
0.5
0
P |1>
200
400
600
800
1000
τ (ns)
RABI
U rf
τ
READOUT
32 million measurements
~ 10 min (dead time ~0.2 sec)

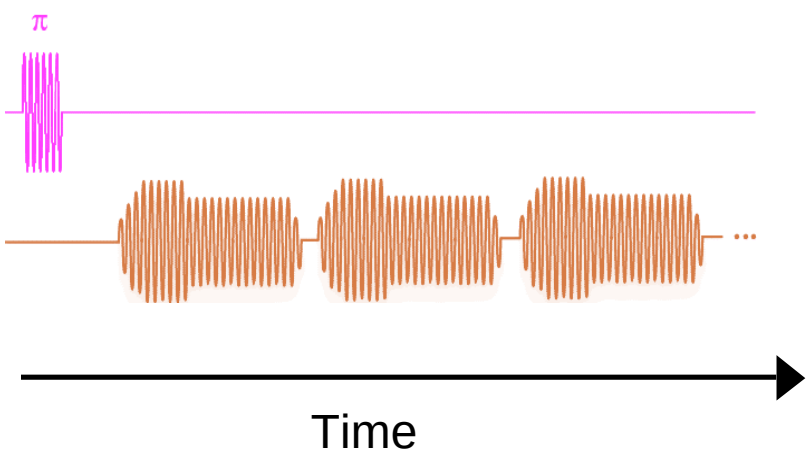

RAMSEY FRINGES
T_2 = 300ns
$|1\rangle$
$|0\rangle$
P_{switch}
0.7
0.6
0.5
0.4
0.3
0.2
0
200
400
600
800
Δt (ns)
RAMSEY
π/2
π/2
Δt
READOUT

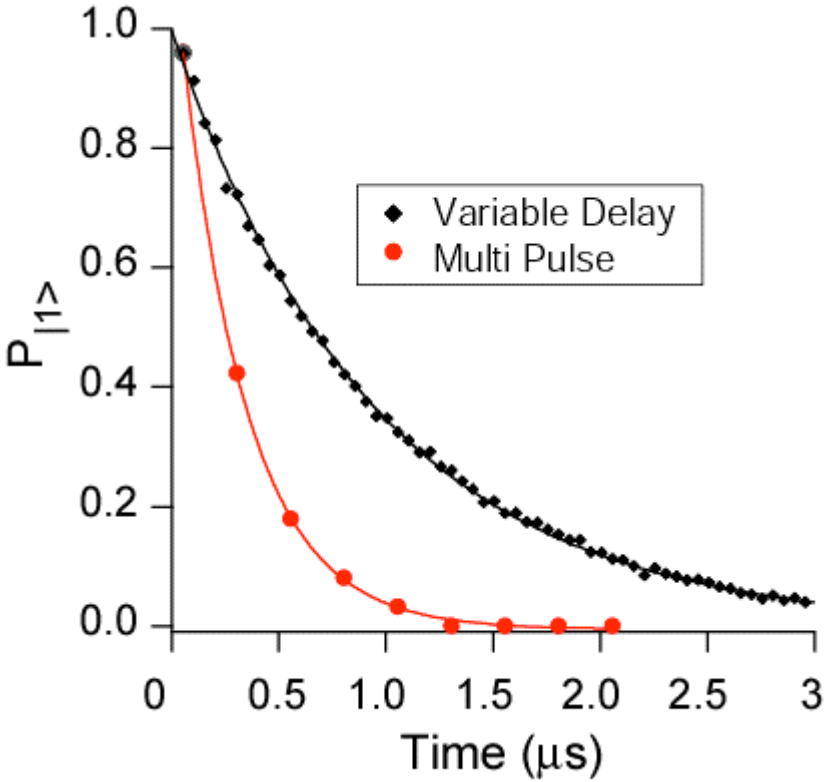
QUANTUM NON-DEMOLITION READOUT ?

Measure once, vary time delay

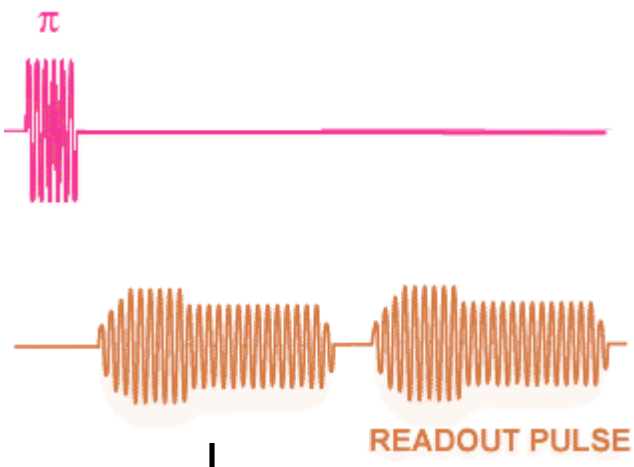


Measure multiple times

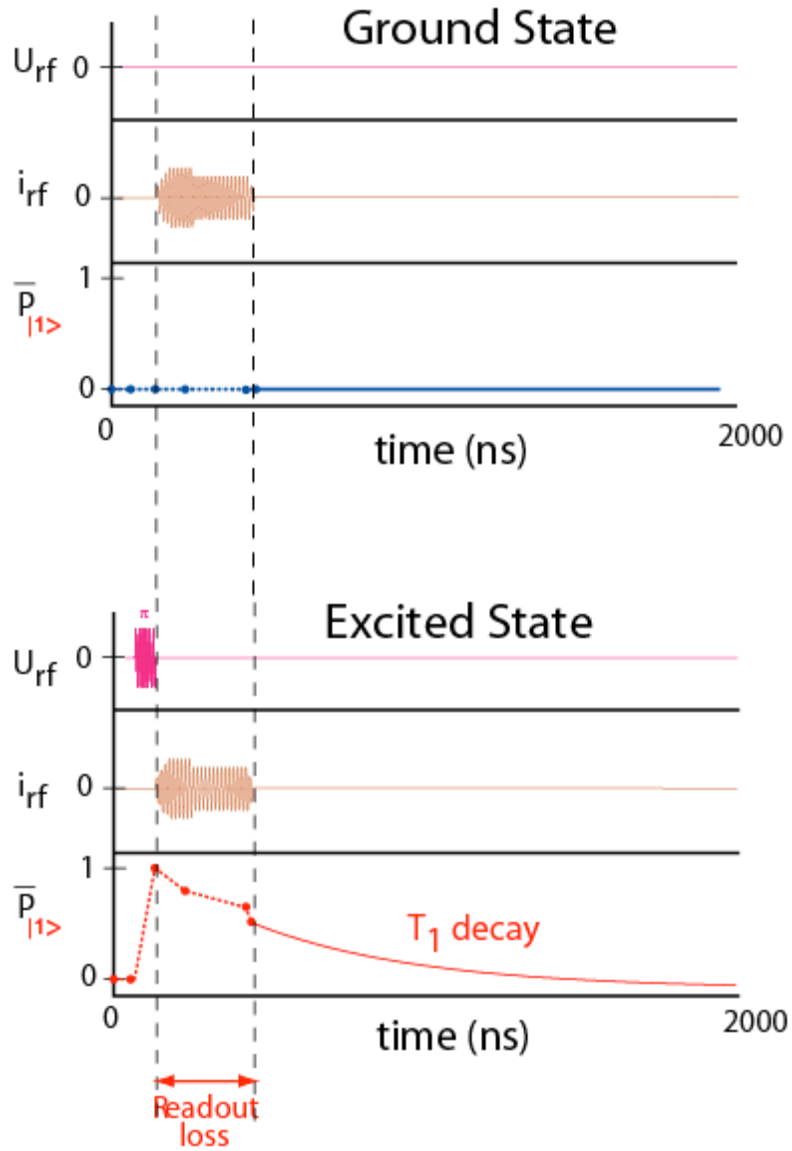




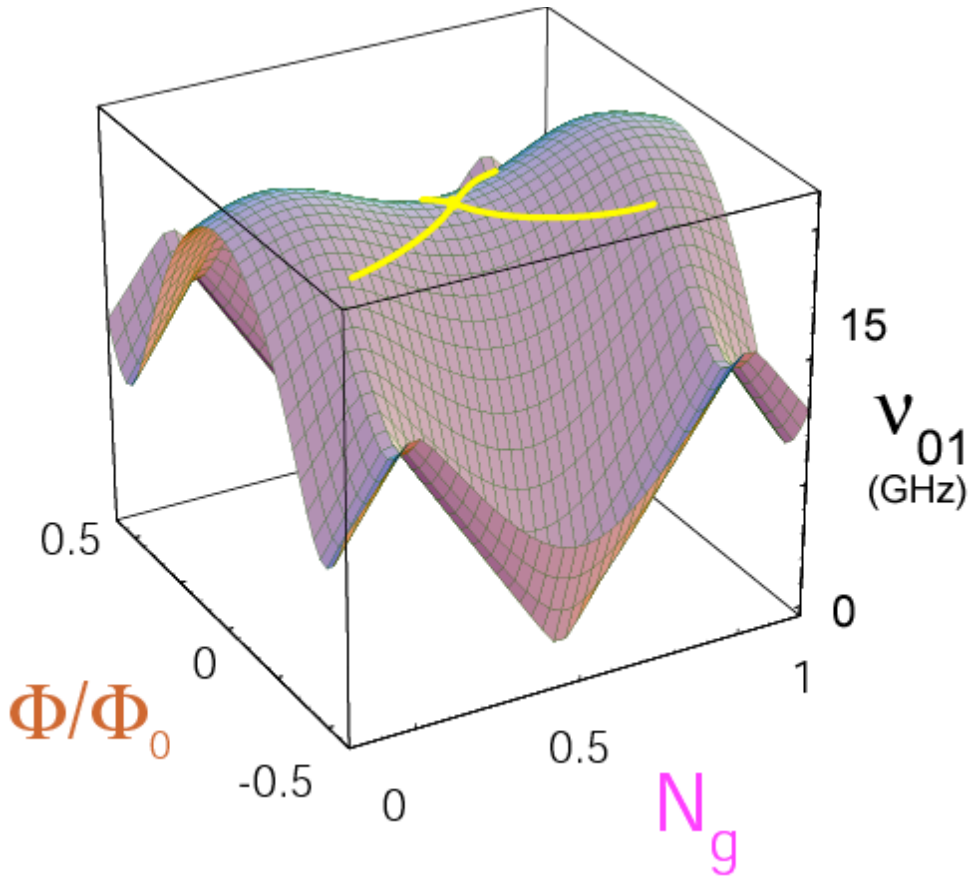
READOUT INDUCES LOSSES

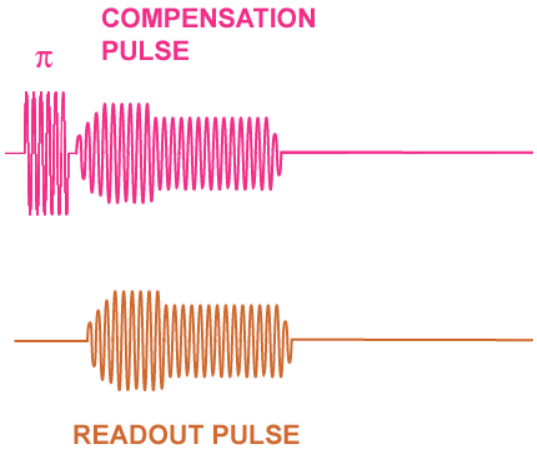


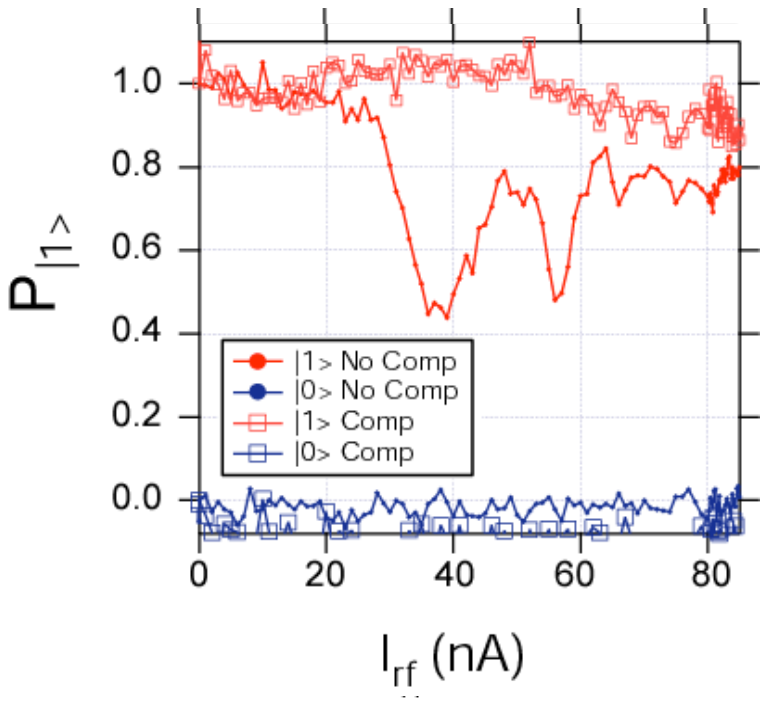
VARY TEST PULSE



BALANCING ZEEMAN & STARK SHIFTS







CONCLUSIONS

SUPERCONDUCTING QUANTRONIUM QUBIT

T_1 ~ 1-5 μs , T_2 ~ 0.5 μs, T_π ~ 1ns

DISPERSIVE MEASUREMENT: NO ENERGY LEFT BEHIND

FAST MEASUREMNT: MEASURE 30ns, RECORD 100ns

MINIMAL DEAD TIME: REPETITION RATE SET BY T_1

NON-INVASIVE: CAN TURN READOUT OFF

SINGLE SHOT: FIDELITY 67%
VISIBILITY 87%

→ TAILOR MEASUREMENT TO MINIMIZE LOSSES