REALIZING QUANTUM MEASUREMENTS WITH SUPERCONDUCTING NANOCIRCUITS

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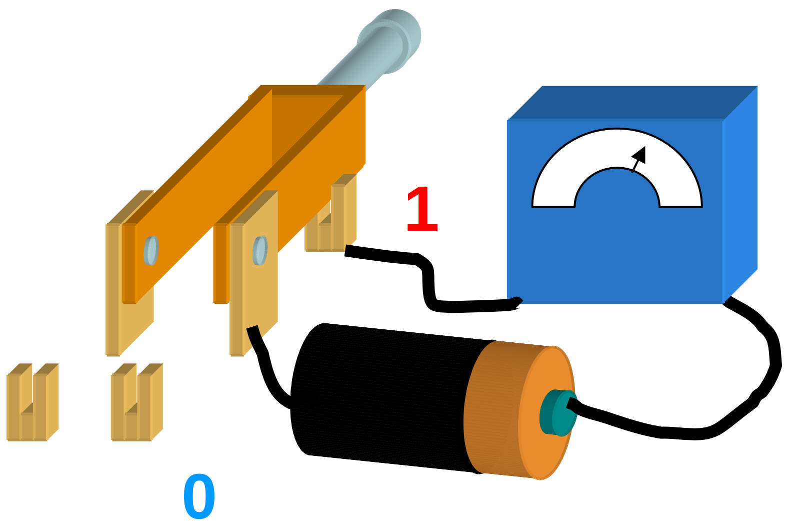
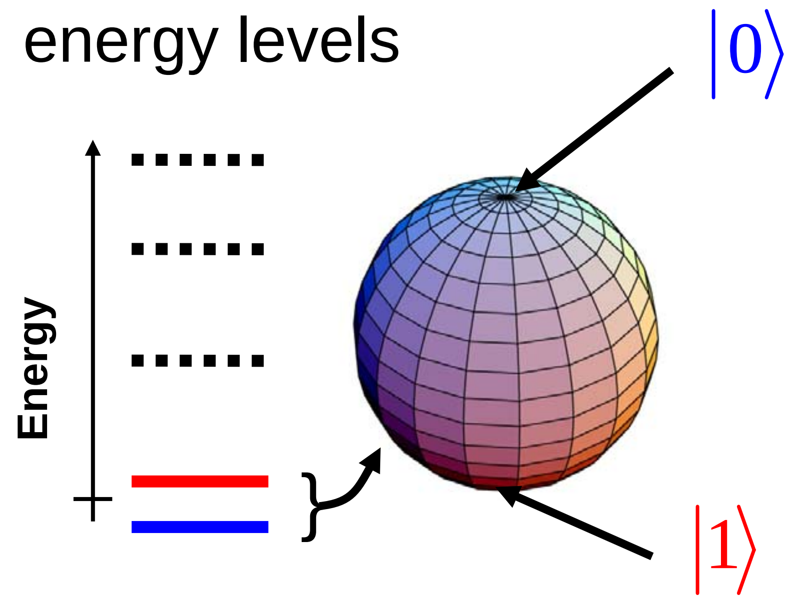
ISCP – Islamabad March 26-30 2007

CLASSICAL vs. QUANTUM INFORMATION

classical
equilibrium states



quantum
energy levels



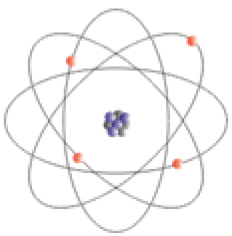
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

0 <u>OR</u> 1

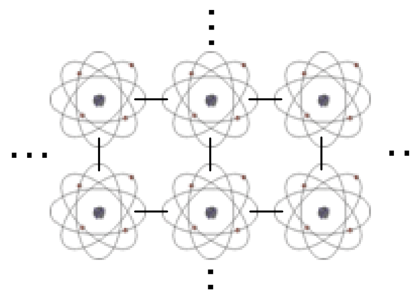
|0> <u>AND</u> |1>

QUANTUM COHERENT MACHINES: MIRACLE or MIRAGE ?

N = 1
ATOM



N = 10^5
QUANTUM COMPUTER



N > 10^{24}
OSCILLOSCOPE

QUANTUM

COMPLEXITY

“CLASSICAL”

ENTANGLE 10^5 QUANTUM OBJECTS → TECHNOLOGICALLY FEASIBLE ?
FUNDAMENTALLY ALLOWED ?

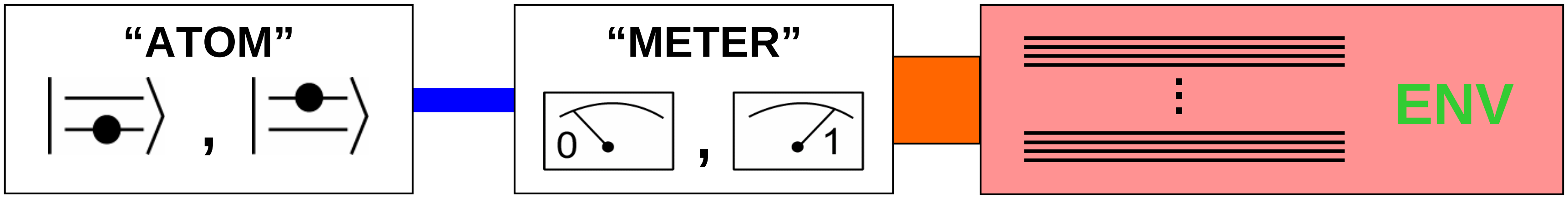
QUANTUM REALITY ?

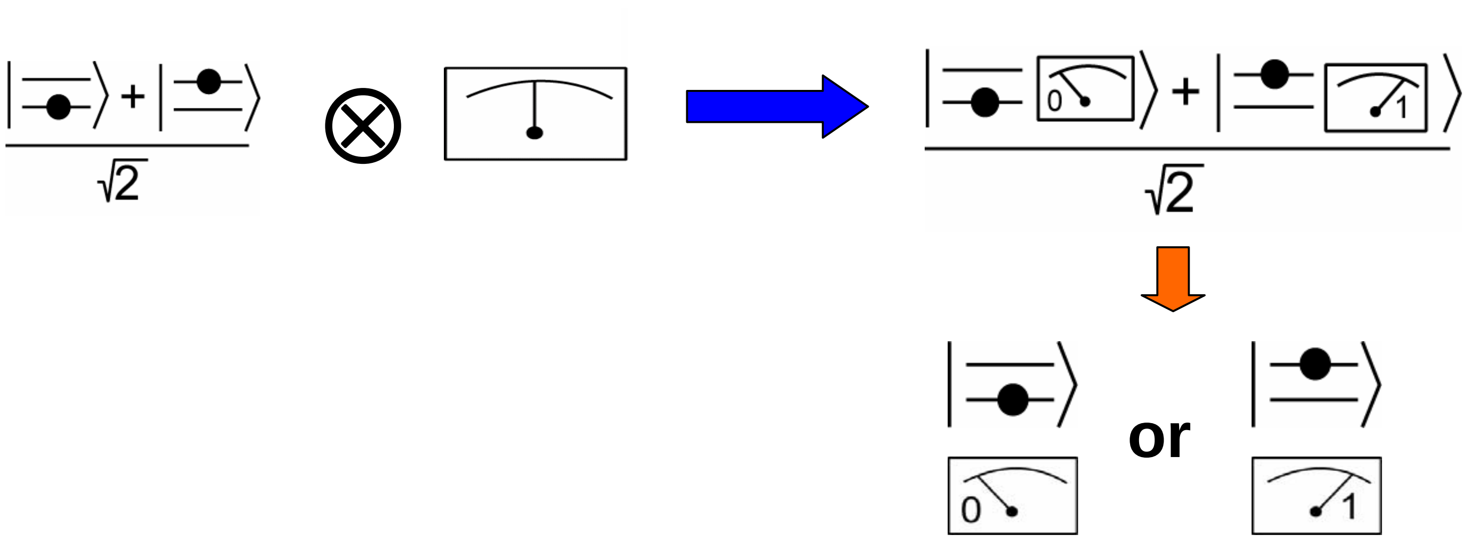
“There is no quantum world. There is only an abstract physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.”

- N. Bohr

Niels Bohr in the early 1920s. (Niels Bohr Archive.)

QUANTUM MEASUREMENT PARADOX



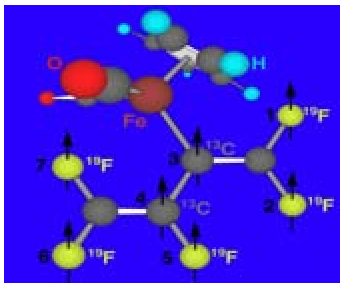


Can we fully control the measurement process?

… if yes, how “macroscopic” can we make the meter ?

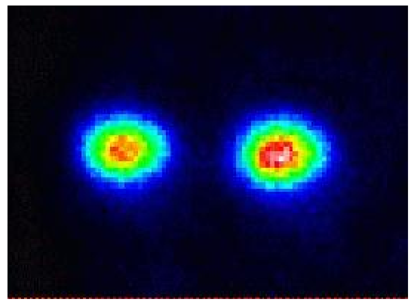
CHOSING AN "ATOM": QUANTUM BITS

Nuclear Magnetic Resonance



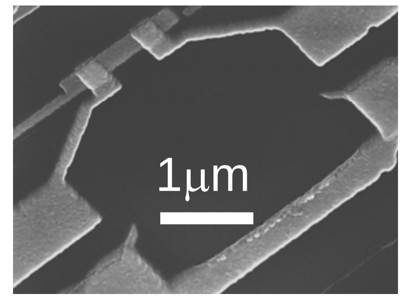
(IBM/MIT)

Trapped Ions



(NIST)

Superconducting Circuits



(YALE)

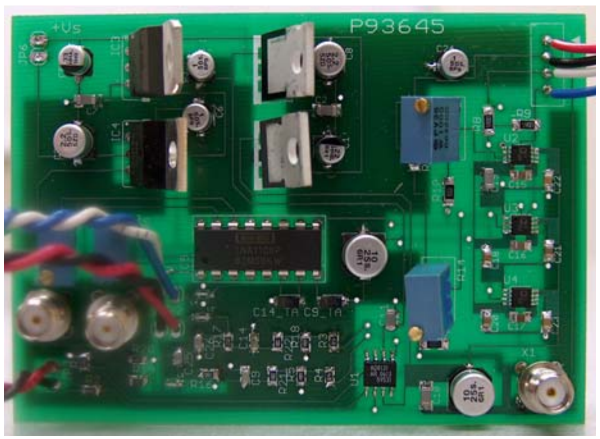
Advantages

- strong atom/meter coupling
- engineered "atoms"
- quantum electrical circuits

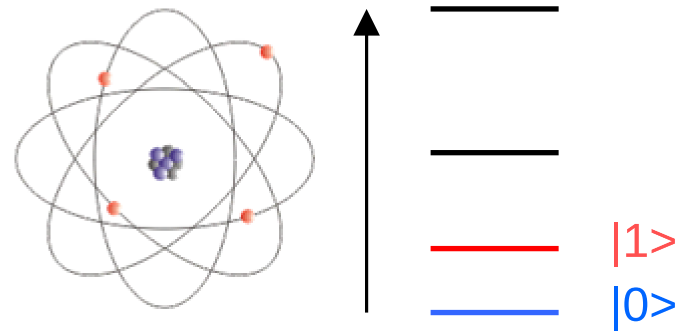
Challenges

- decoherence
- **readout**

HOW CAN WE MAKE A CIRCUIT ATOM-LIKE?



?



Electrical Circuit

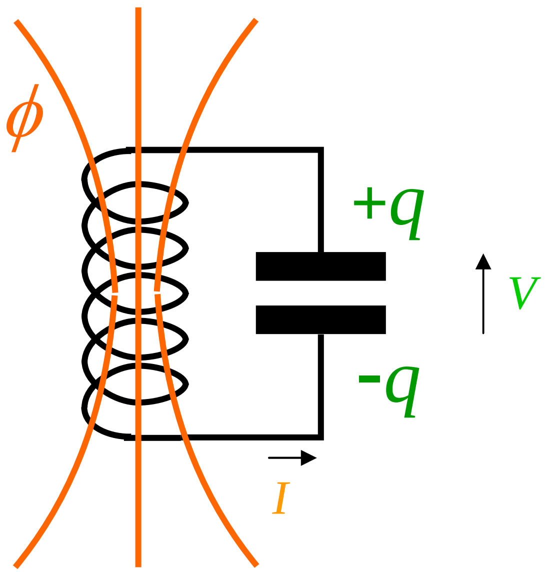
“Artificial Atom”

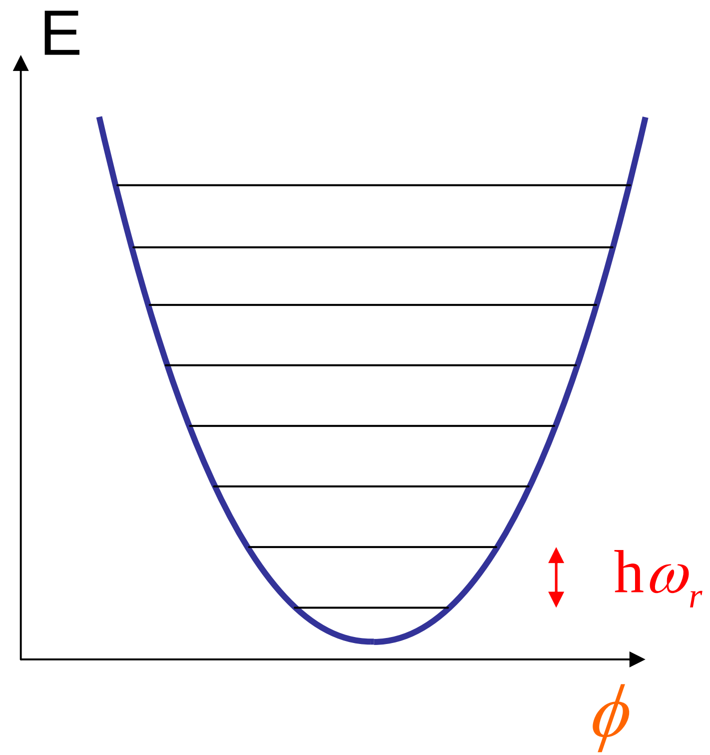
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT

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

LC OSCILLATOR AS A QUANTUM CIRCUIT





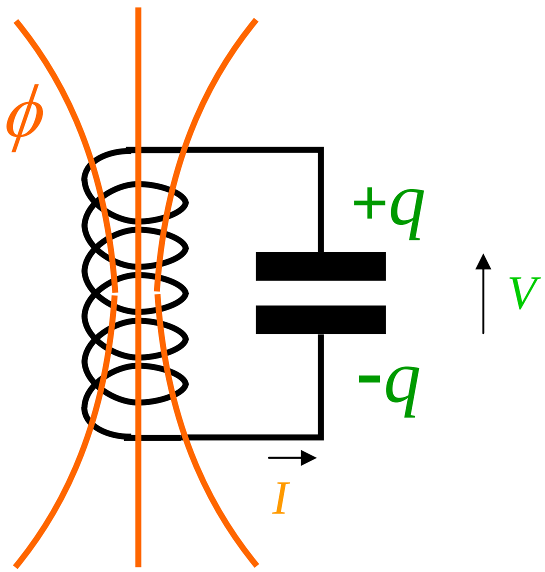
$$[\phi, q] = i\hbar$$

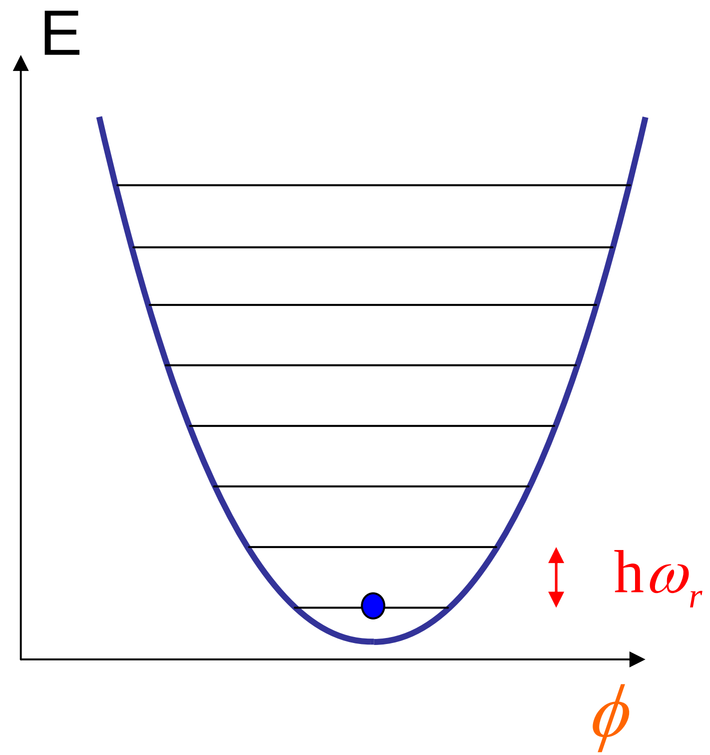
$$\phi = LI$$

$$q = CV$$

SUPERCONDUCTING → "ELIMINATE" DISSIPATIVE ENVIRONMENT

LC OSCILLATOR AS A QUANTUM CIRCUIT





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

$$\phi = LI$$

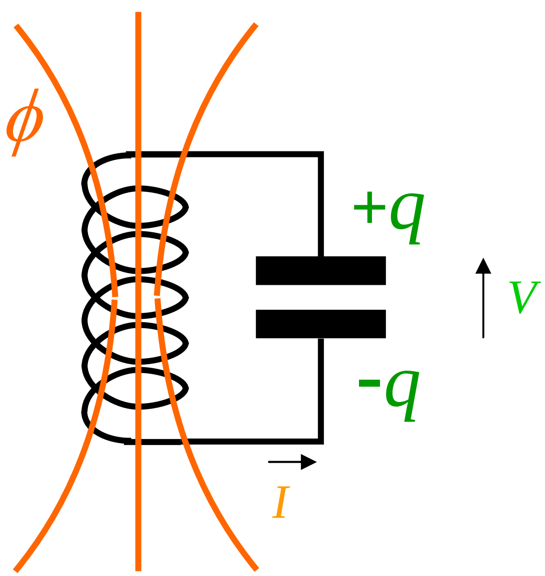
$$q = CV$$

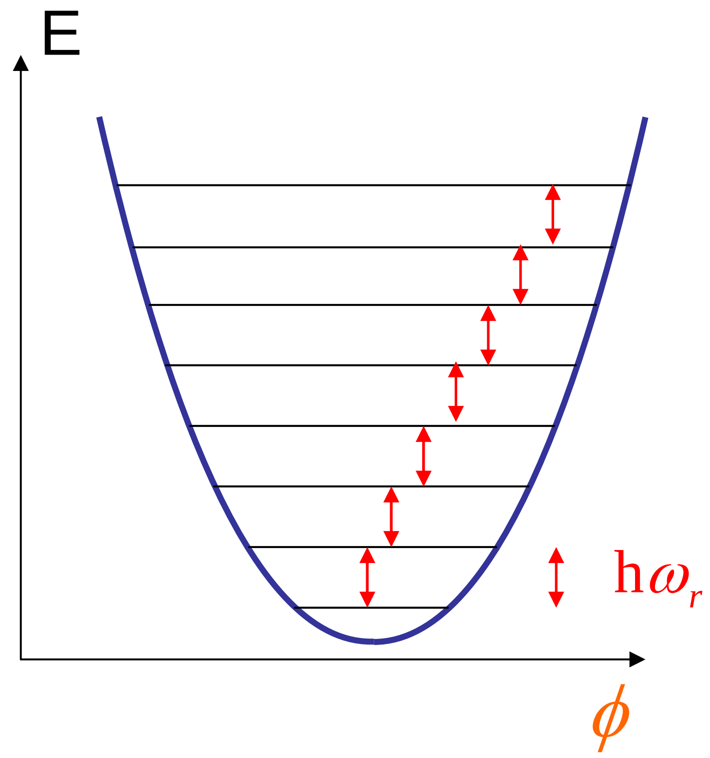
$$\hbar\omega_r > k_B T$$

1GHz

10mK

LC OSCILLATOR AS A QUANTUM CIRCUIT





$$[\phi, q] = i\mathrm{h}$$

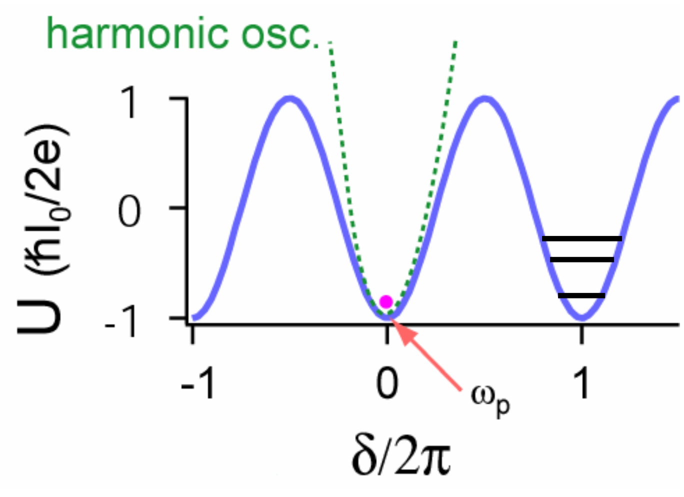
CANNOT STEER THE SYSTEM TO AN ARBITRARY STATE

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

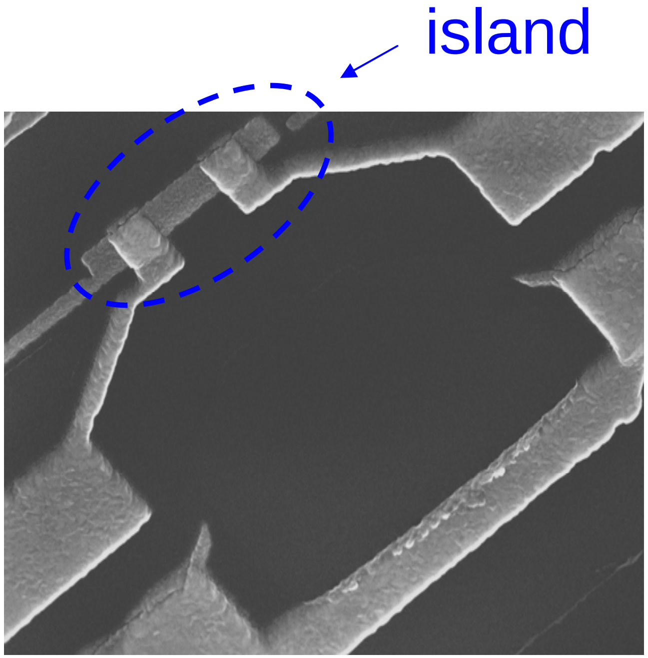
$$I(\delta) = I_0 \sin(\delta)$$

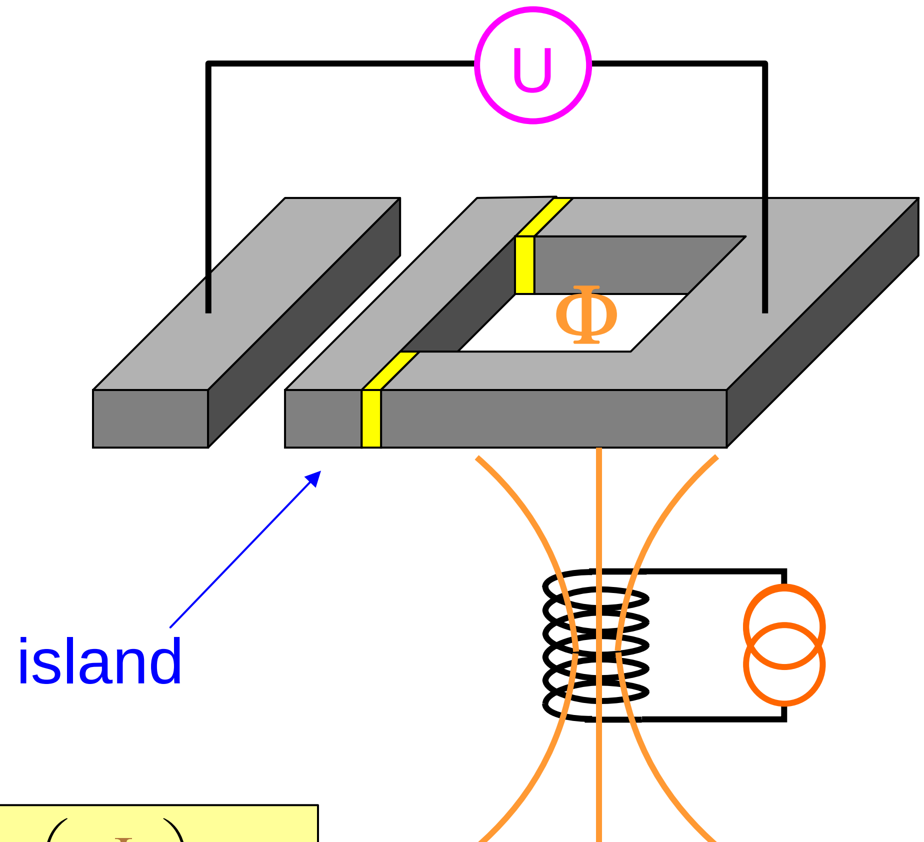
(NON-LINEAR INDUCTOR)

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



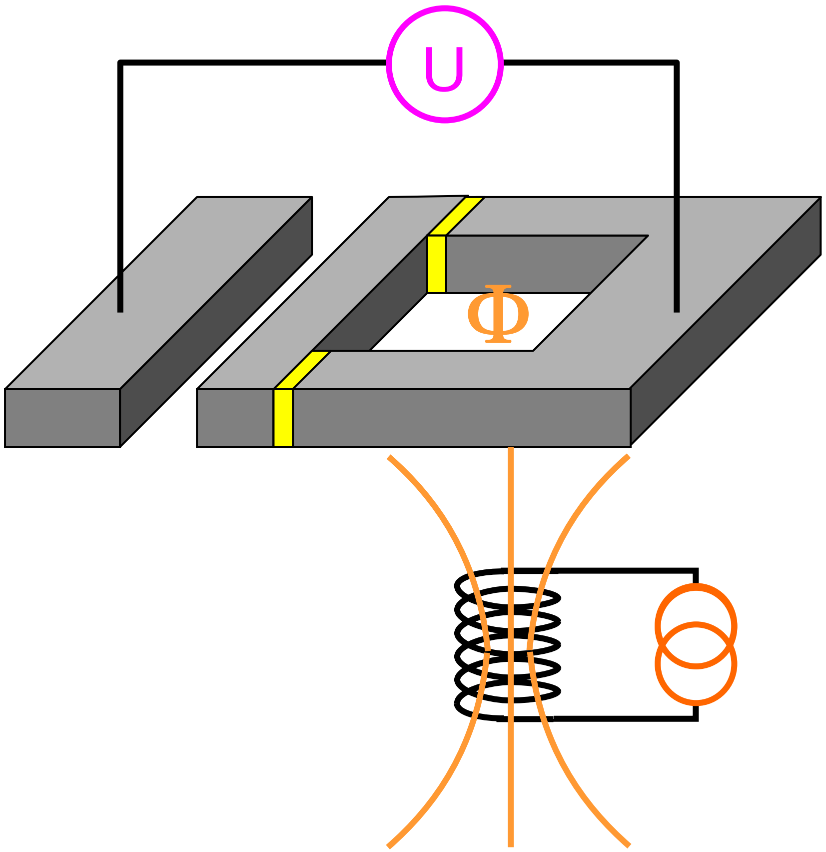
VARY LEVEL SPACING USING CHARGE & FLUX

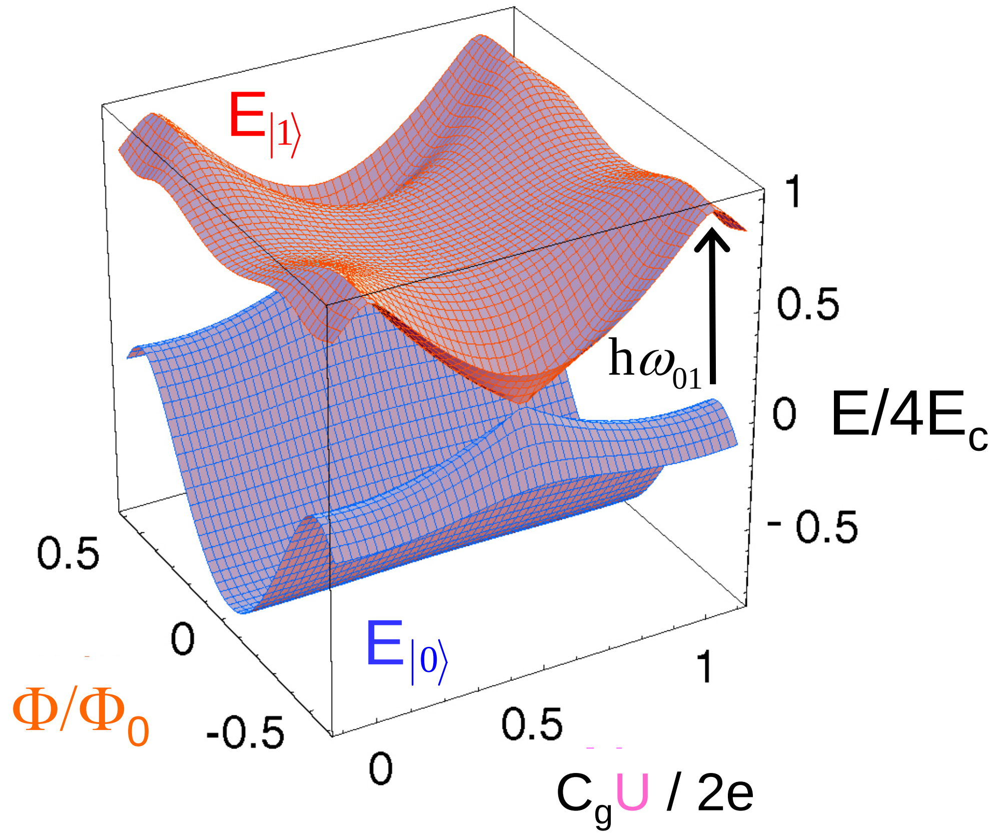




$$\hat{H} = 4E_c(\hat{n} - C_g/2e)^2 \quad - \quad 2E_j \cos\left(\frac{\Phi}{2\varphi_0}\right)\cos\hat{\delta}$$

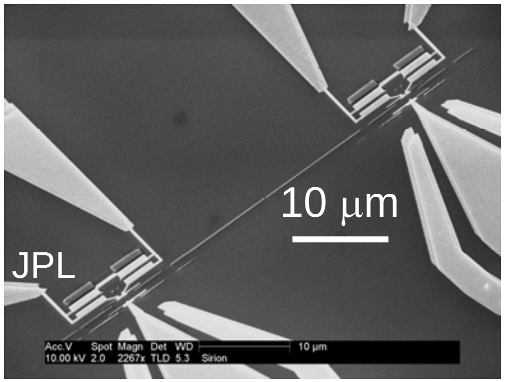
SPLIT COOPER-PAIR BOX: TUNABLE ‘ATOM’





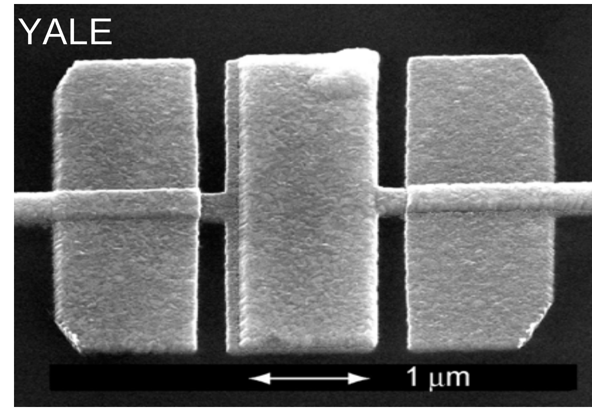
DISPERSIVE QUANTUM MEASUREMENT

SPIN 1/2



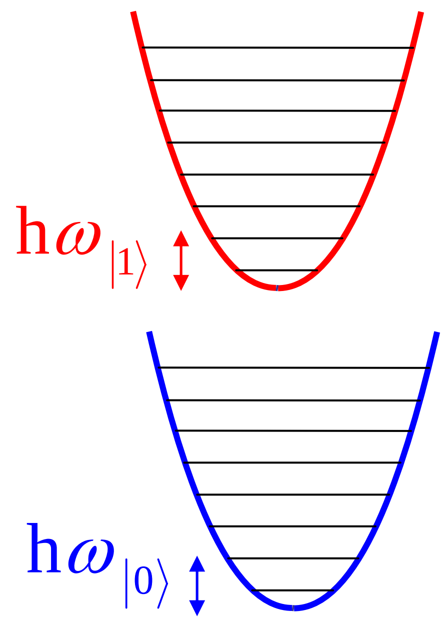
couple

OSCILLATOR

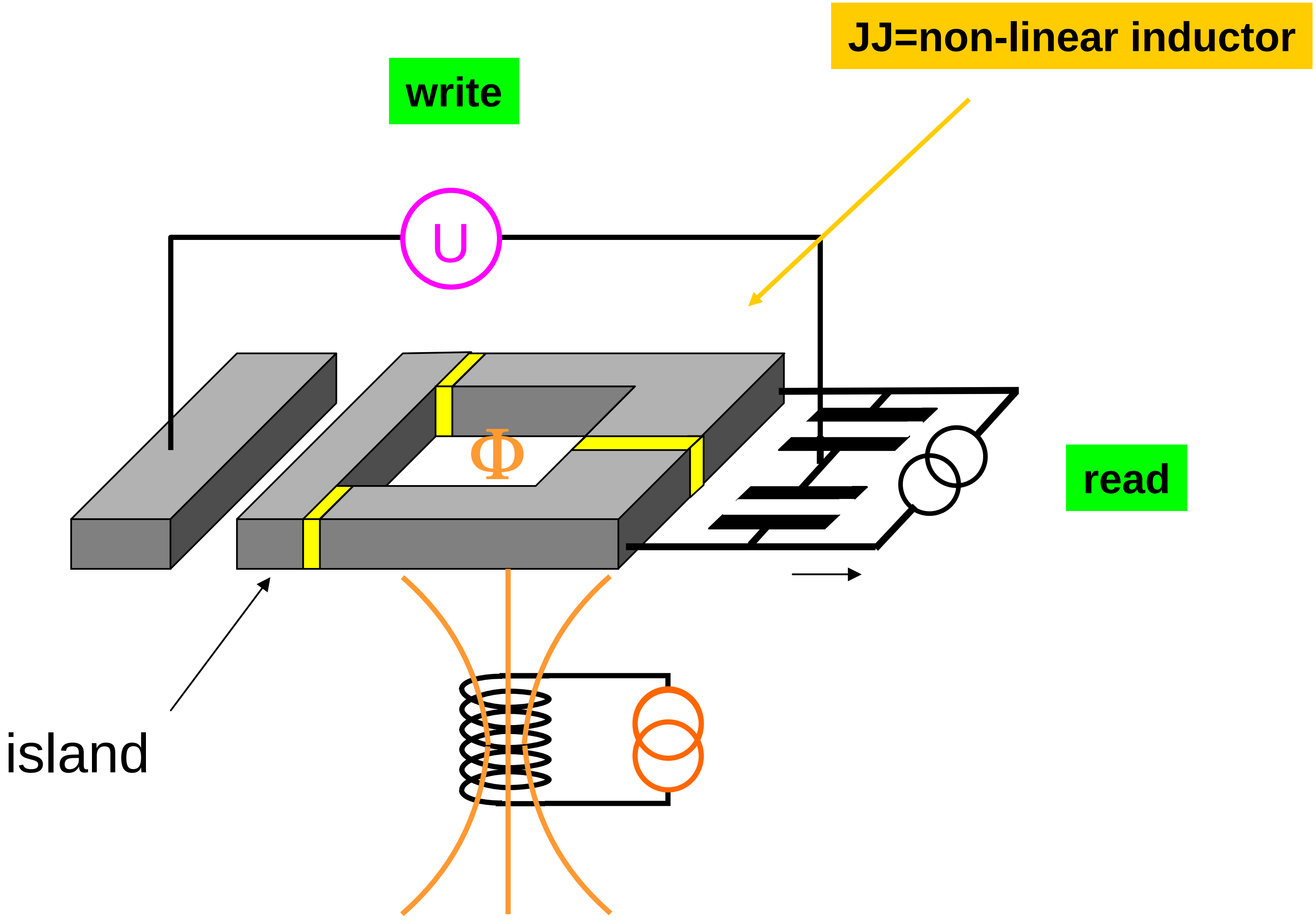


$|1\rangle$

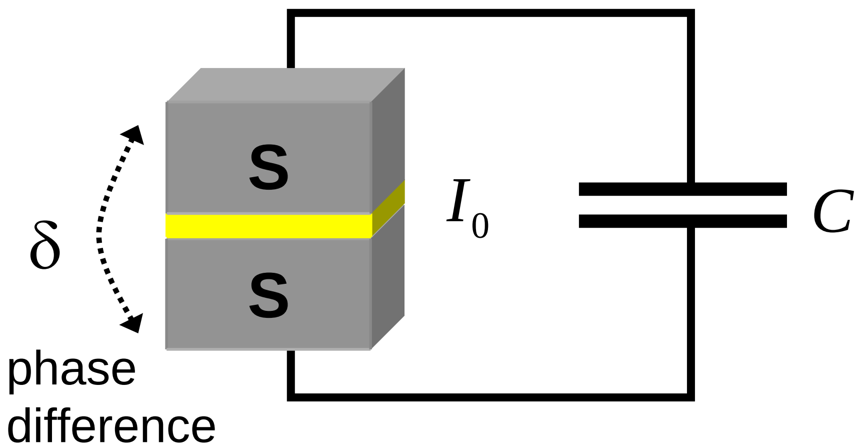
$|0\rangle$

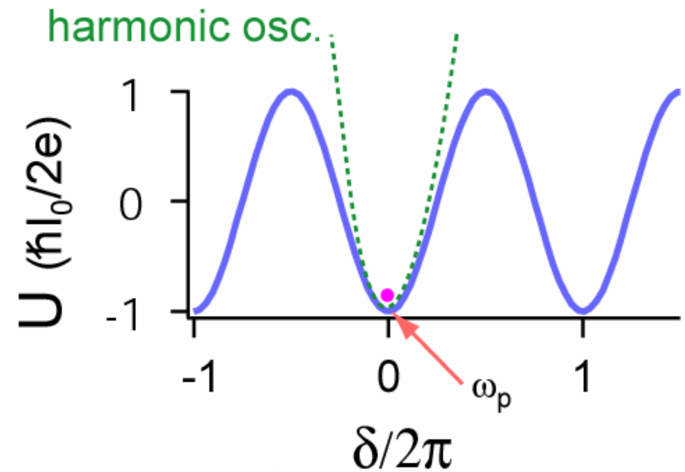


NON-LINEAR INDUCTIVE READOUT: QUANTRONIUM



THE NON-LINEAR JOSEPHSON OSCILLATOR





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

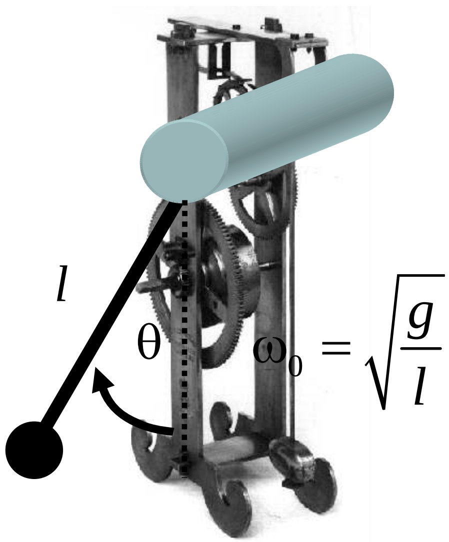
$$U(\delta) = -\frac{\hbar}{2e} I_0 \cos(\delta)$$

<u>Nonlinear Oscillator</u>

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

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

THE JOSEPHSON ELECTRICAL PENDULUM: Non-linearity with minimal friction



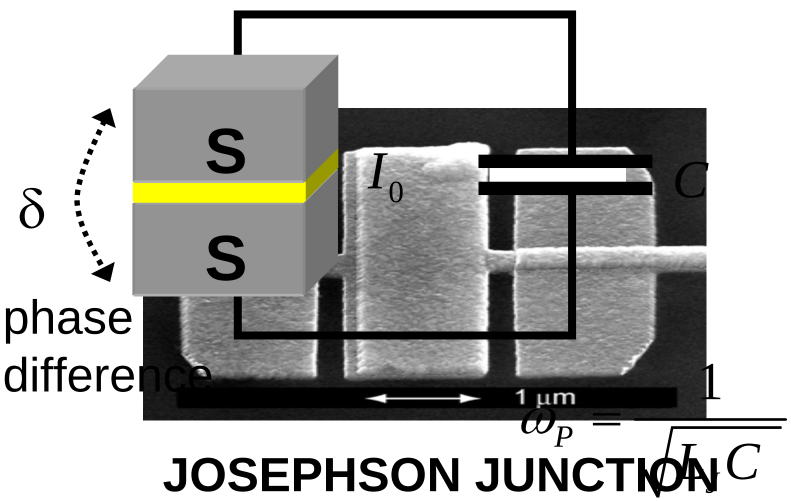
PENDULUM CLOCK (Galileo, ca. 1600)

$$L_J \propto I_0^{-1} \leftrightarrow l$$

$$C \leftrightarrow g^{-1}$$

$$\omega_p \leftrightarrow \omega_0$$

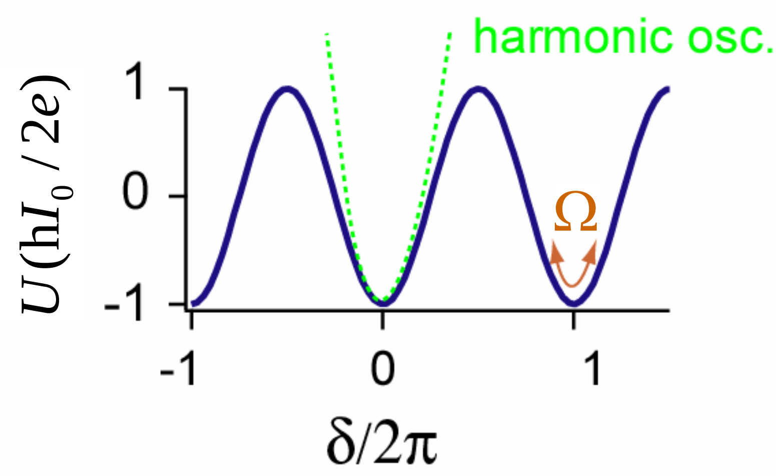
$$\delta \leftrightarrow \theta$$

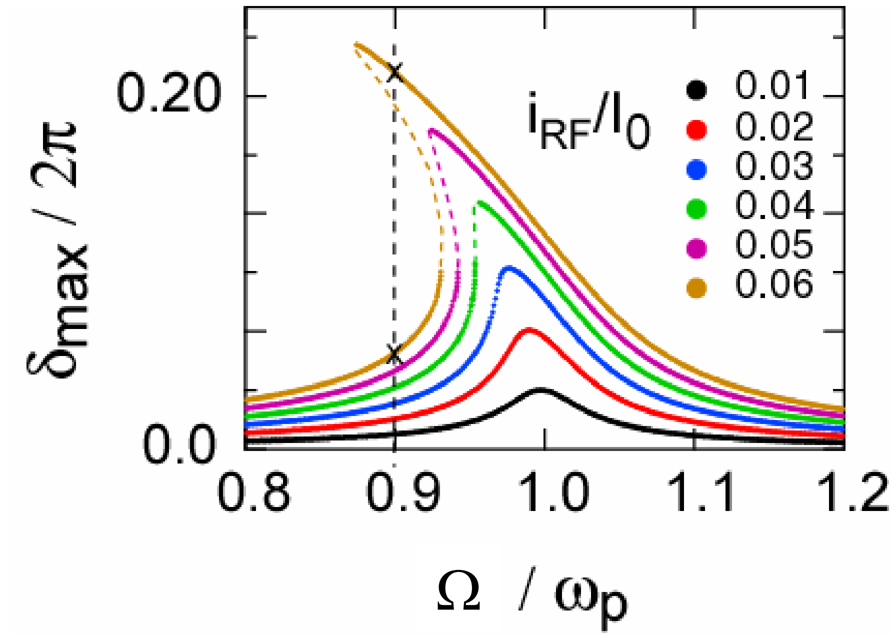


JOSEPHSON JUNCTION

- **$\omega_p/2\pi$ ~ 1-10 GHz**
- **Non-linear & Non-dissipative**
- **Quantum Regime**
  $(\hbar\omega_P >> k_B T)$

PERIODIC DRIVE





$$I(t) = i_{RF}\sin(\Omega t)$$

$$U(\delta) = -\frac{\hbar}{2e} I_0 \left(1 - \frac{\delta^2}{2} + \underbrace{\frac{\delta^4}{12} - \ldots}_{\text{non-linear inductance}}\right)$$

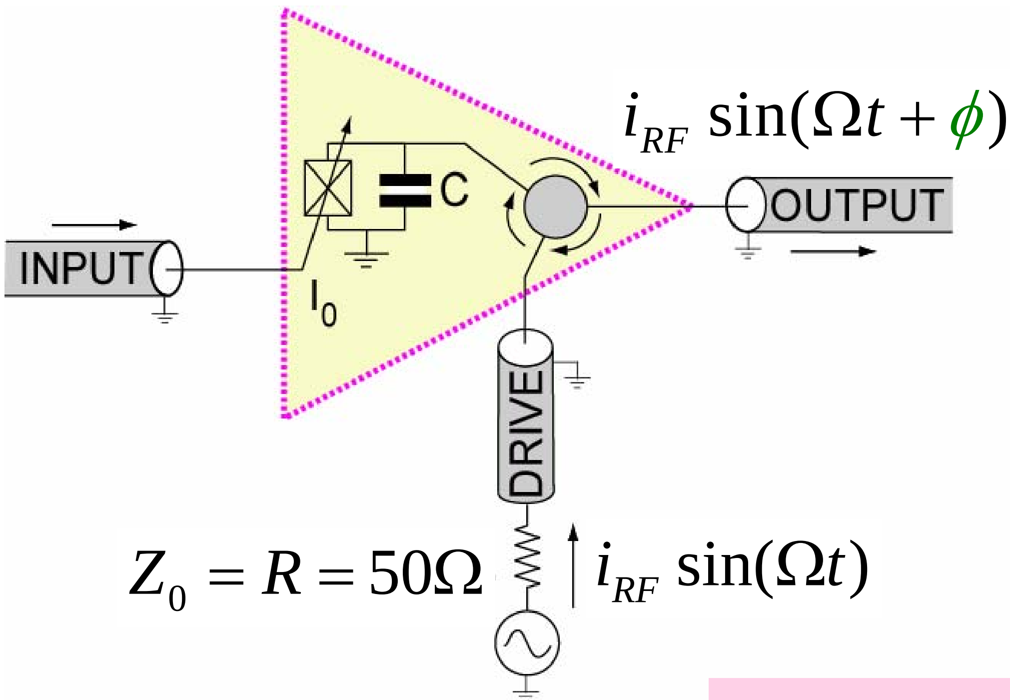
linear inductance

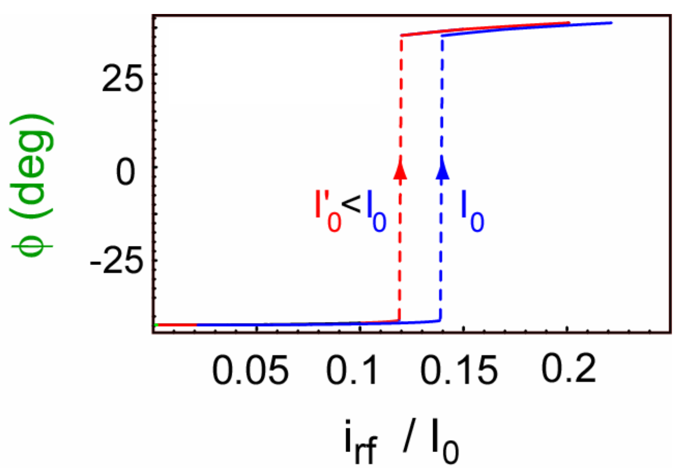
non-linear inductance

- two dynamical (Floquet) states
- $\delta_{max} \le 0.25$

IS *et al*., PRL **94** 027005 (2005)

JOSEPHSON BIFURCATION AMPLIFIER





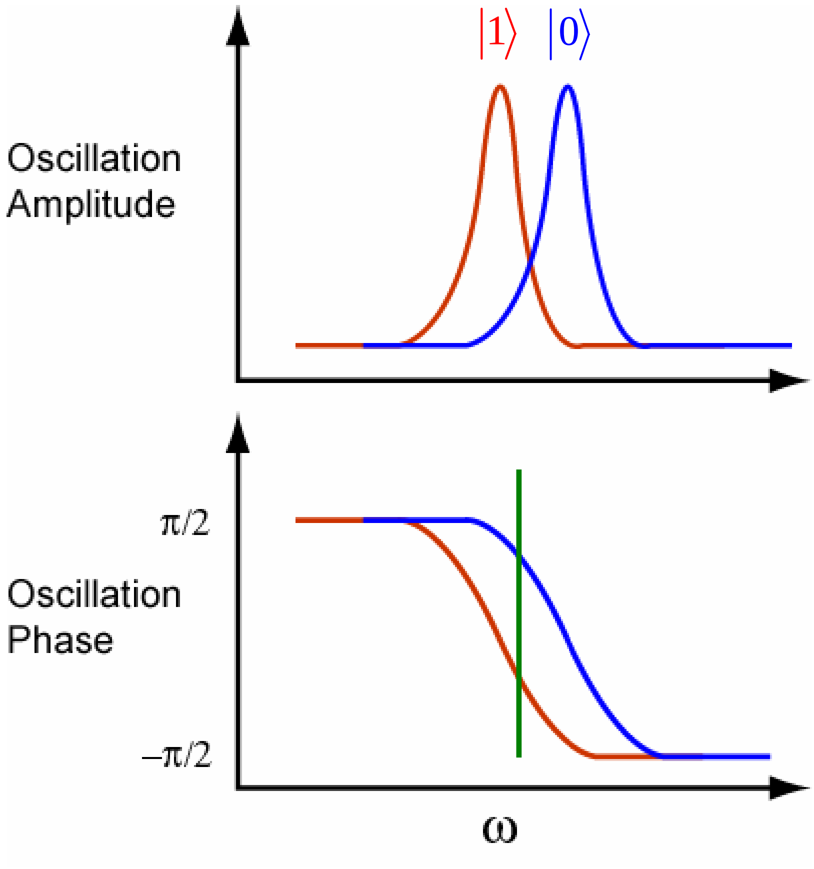
JBA: INPUT COUPLES TO I_0

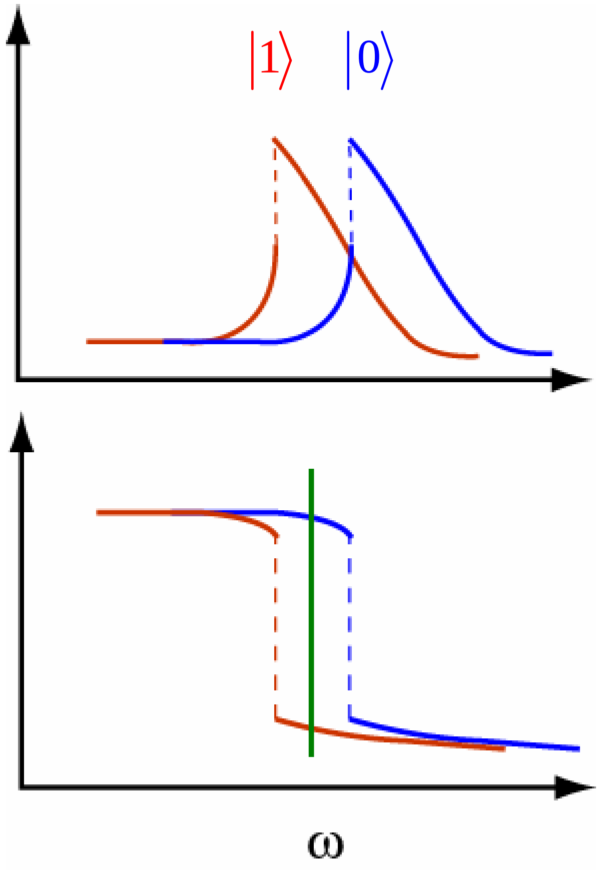
- $\phi\ (i_{rf}, I_0)$

- no on-chip dissipation
- only fluctuations from R (minimal backaction)

IS *et al.*, PRL **93** 207002 (2004)

COMBINING HIGH SENSITIVITY & SPEED





LINEAR OSCILLATOR

Q sets sensitivity

NON-LINEAR OSCILLATOR

kT sets sensitivity !

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

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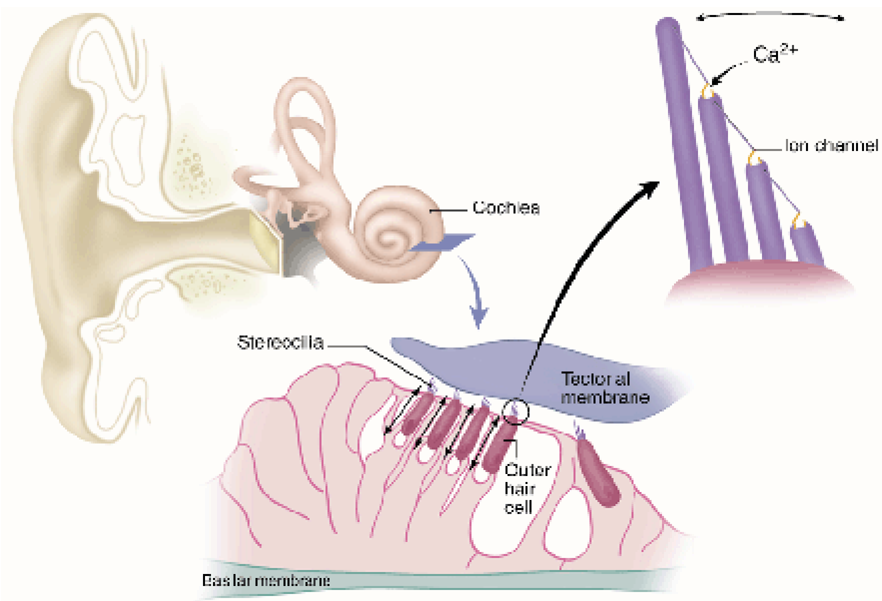
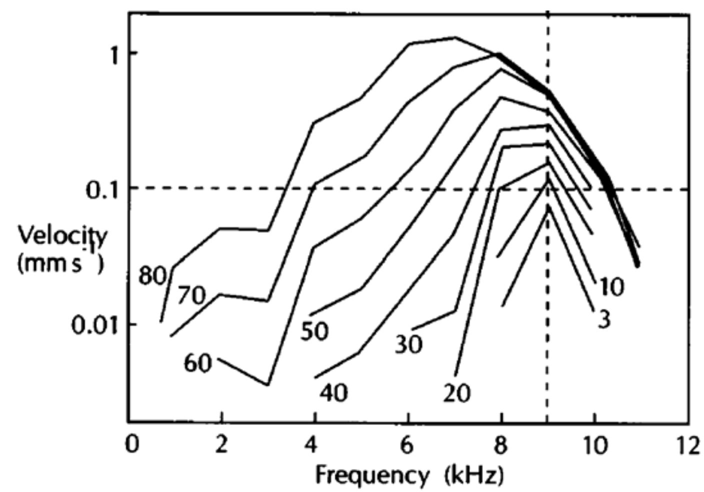
Laboratory of Mathematical Physics, The Rockefeller University, 1230 York Avenue, New York, New York 10021
Laboratory of Sensory Neuroscience, The Rockefeller University, 1230 York Avenue, New York, New York 10021
Howard Hughes Medical Institute, The Rockefeller University, 1230 York Avenue, New York, New York 10021

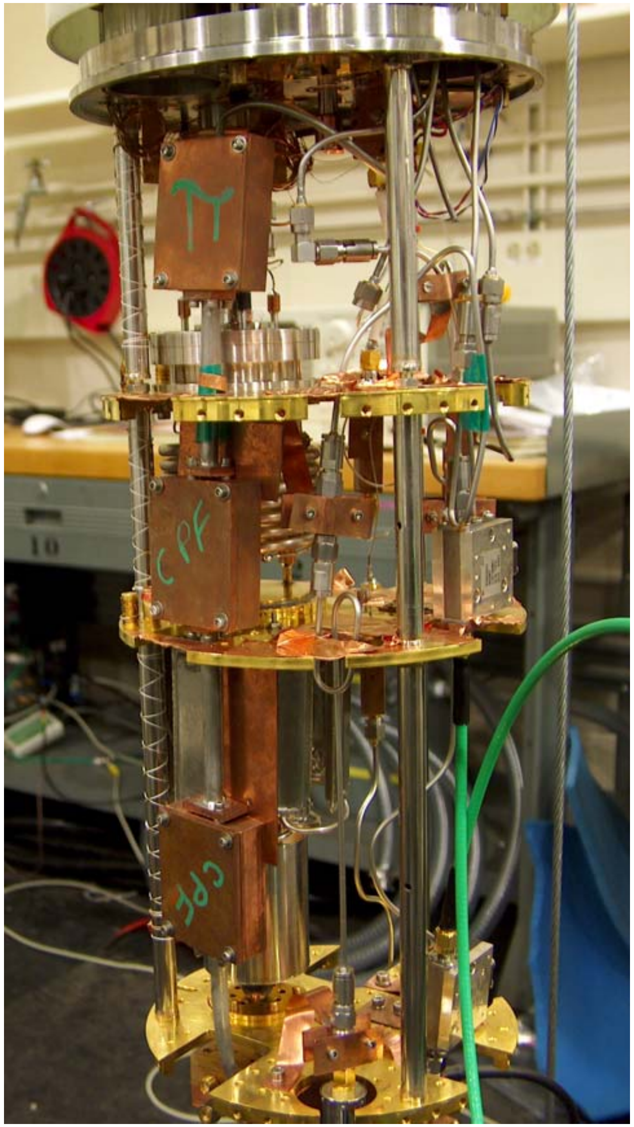
(Received 23 September 1999)





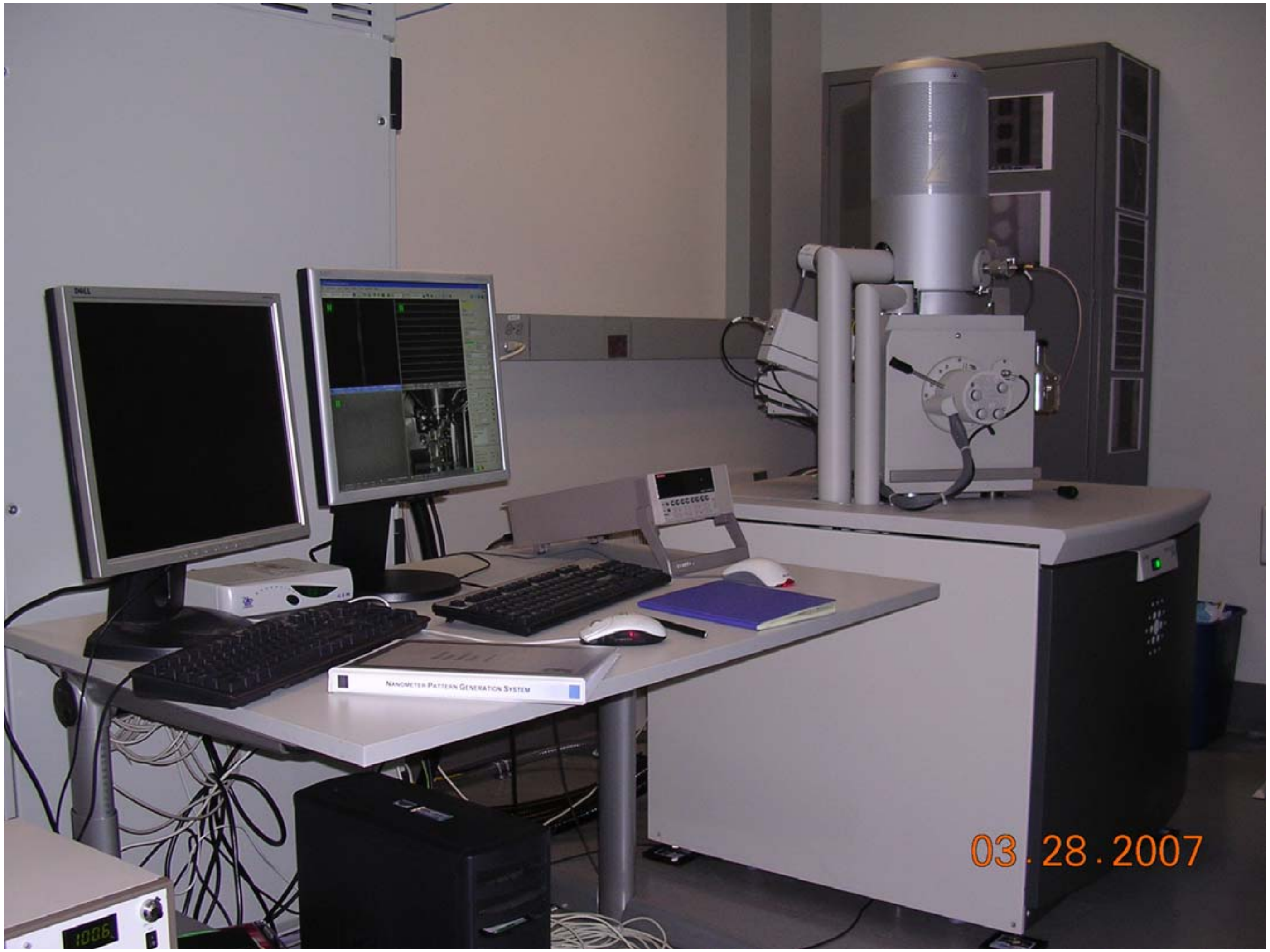
Science

MICROWAVE QUANTUM EAR



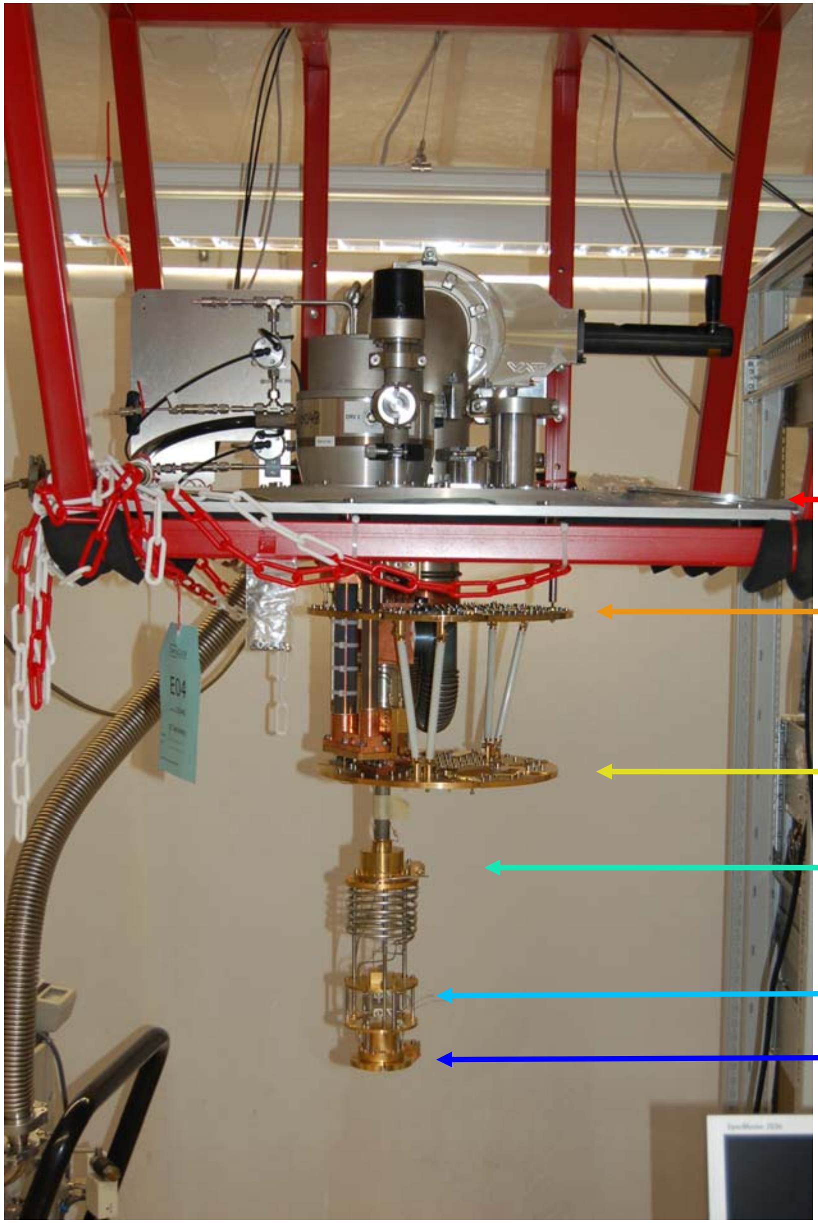
- **nm**
- **mK**
- **GHz**

ELECTRON BEAM LITHOGRAPHY



IMAGING: < 1 nm WRITING: ~ 10 nm – 10 cm

LIQUID HELIUM FREE COOLING in 24 hrs!



300 K

77 K

4.2 K

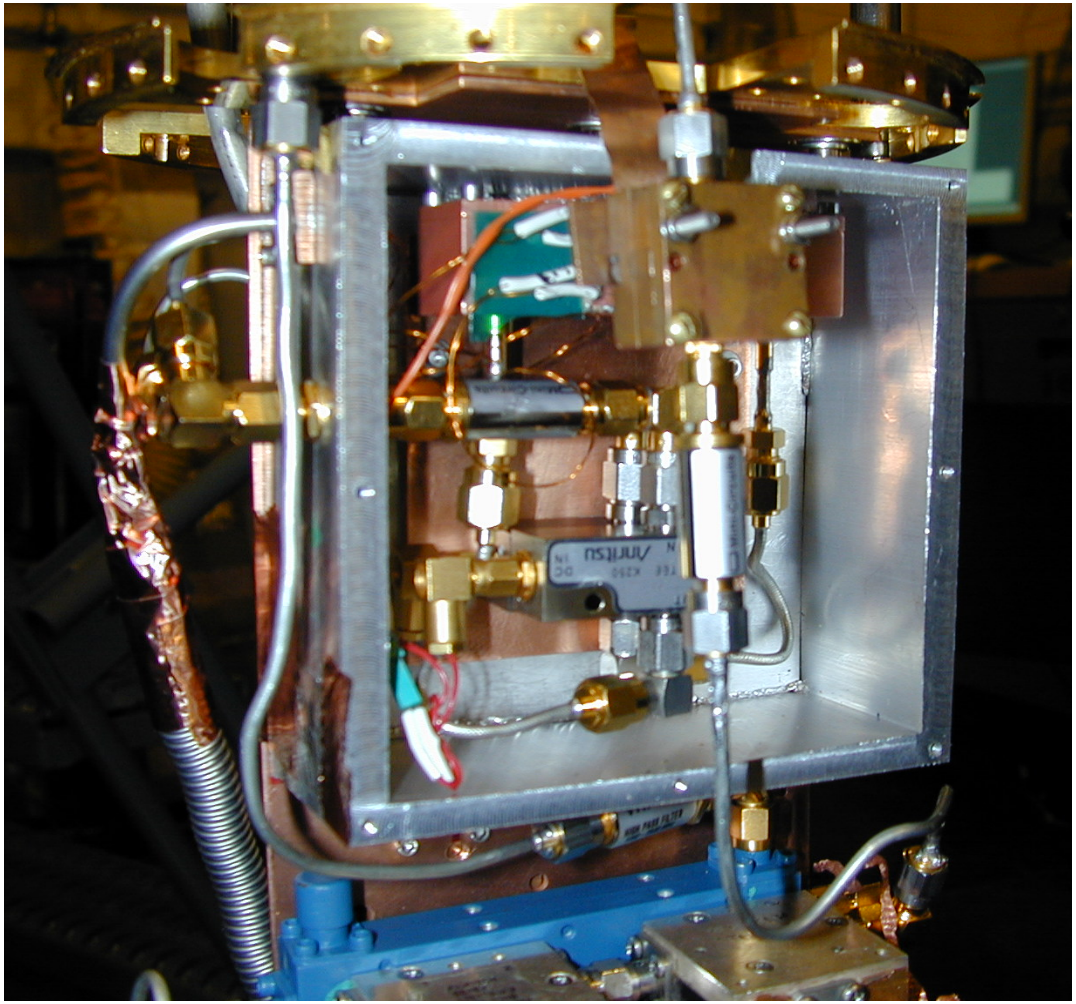
800 mK

100 mK

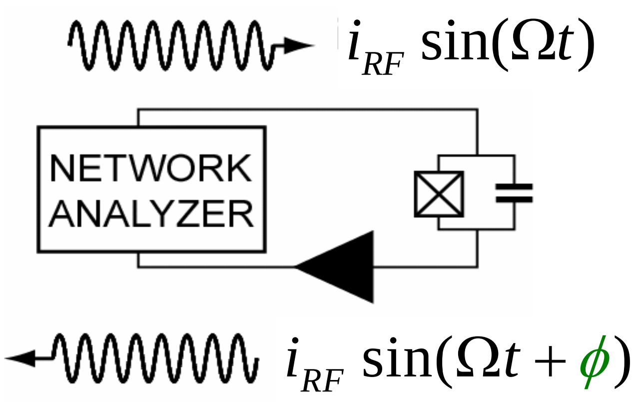
7 mK

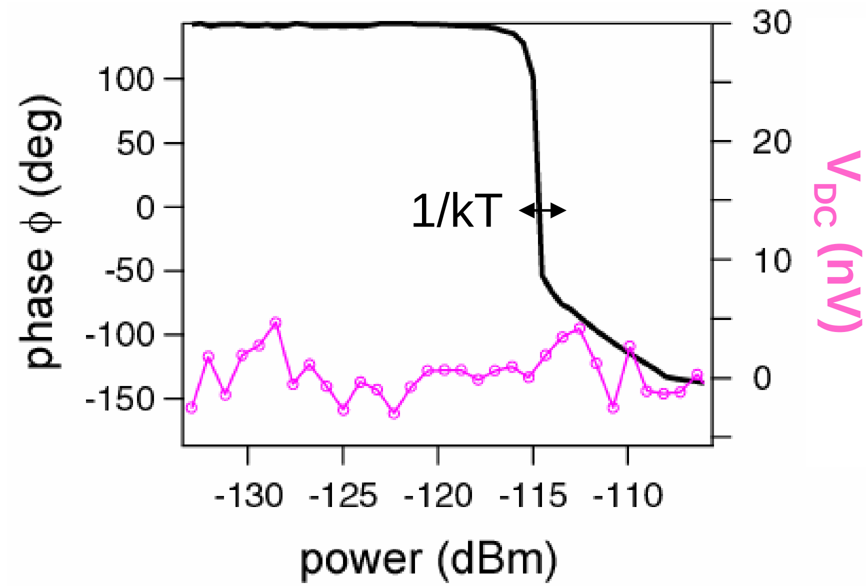
ISOLATED POWER, ETC…

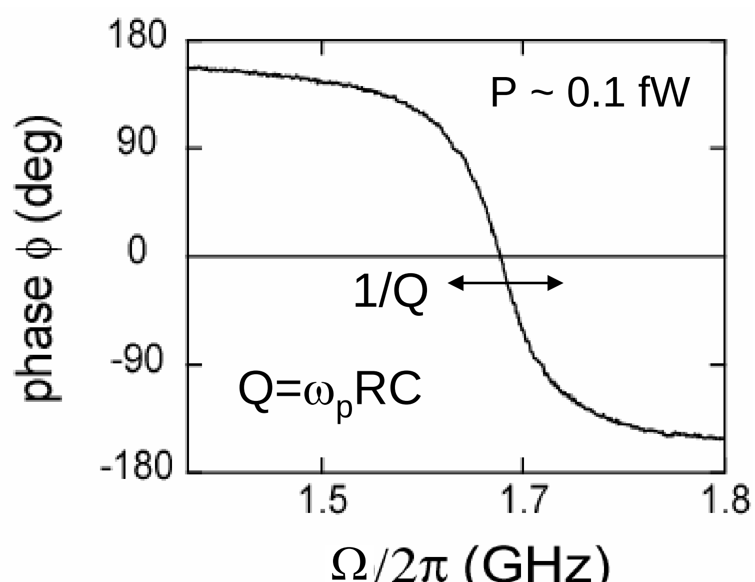
Filters, Filters, and more Filters…

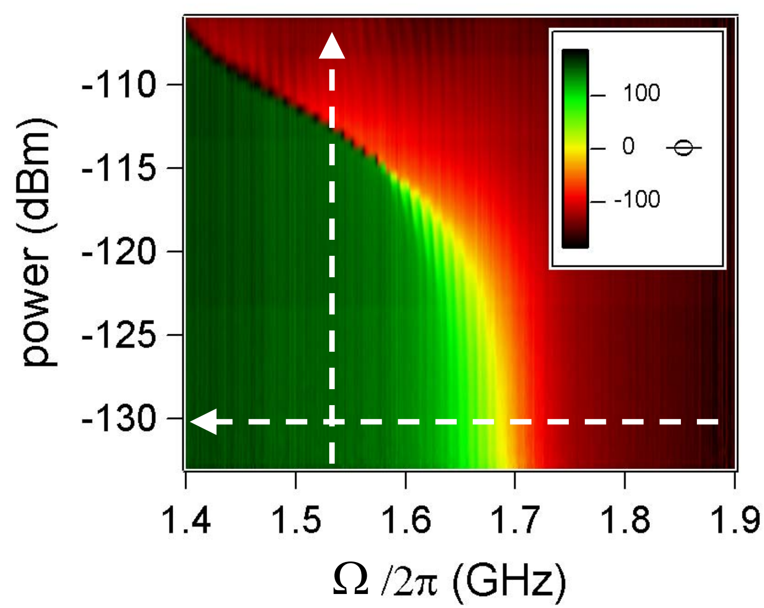


RF BIASED JUNCTION: PHASE DIAGRAM

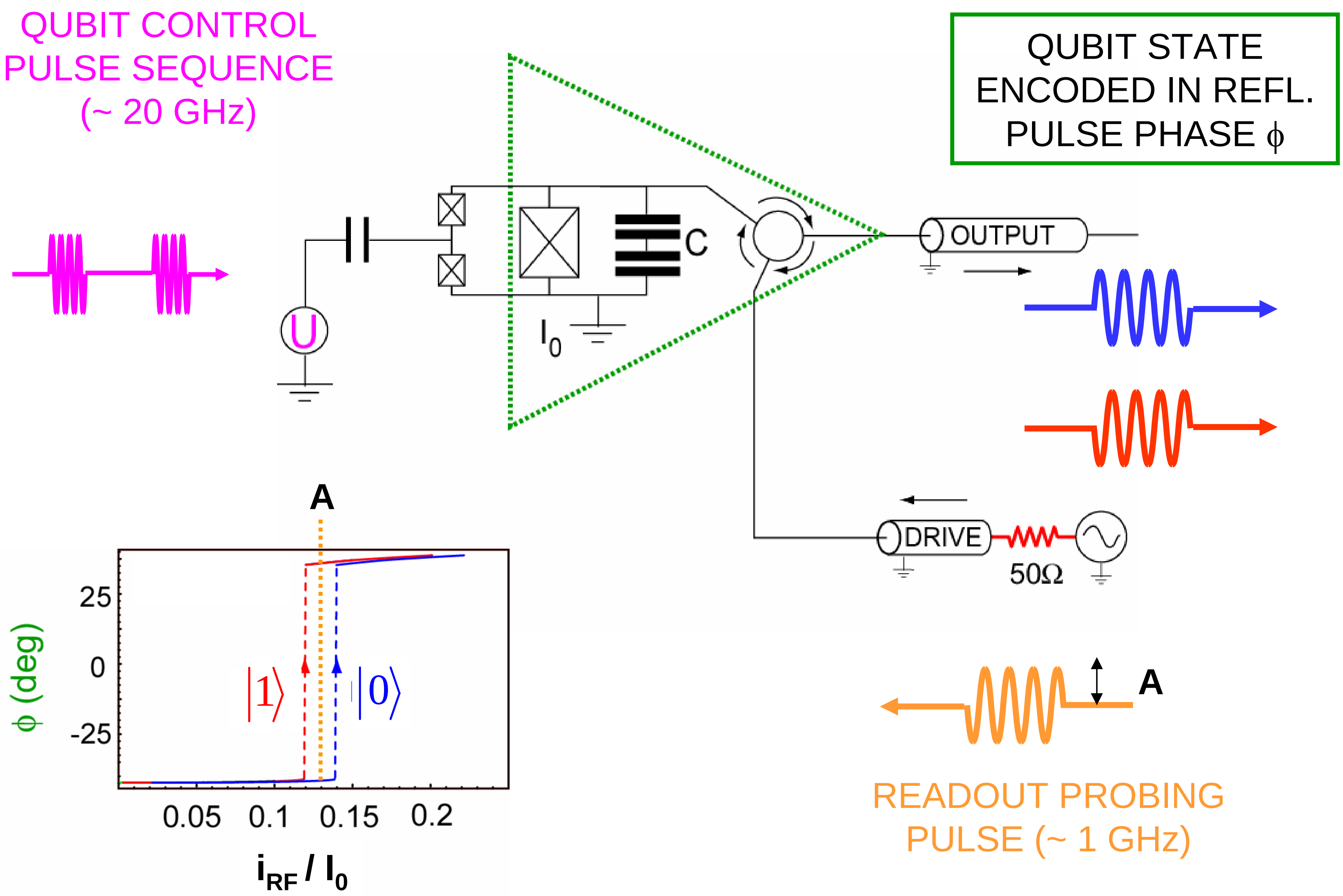


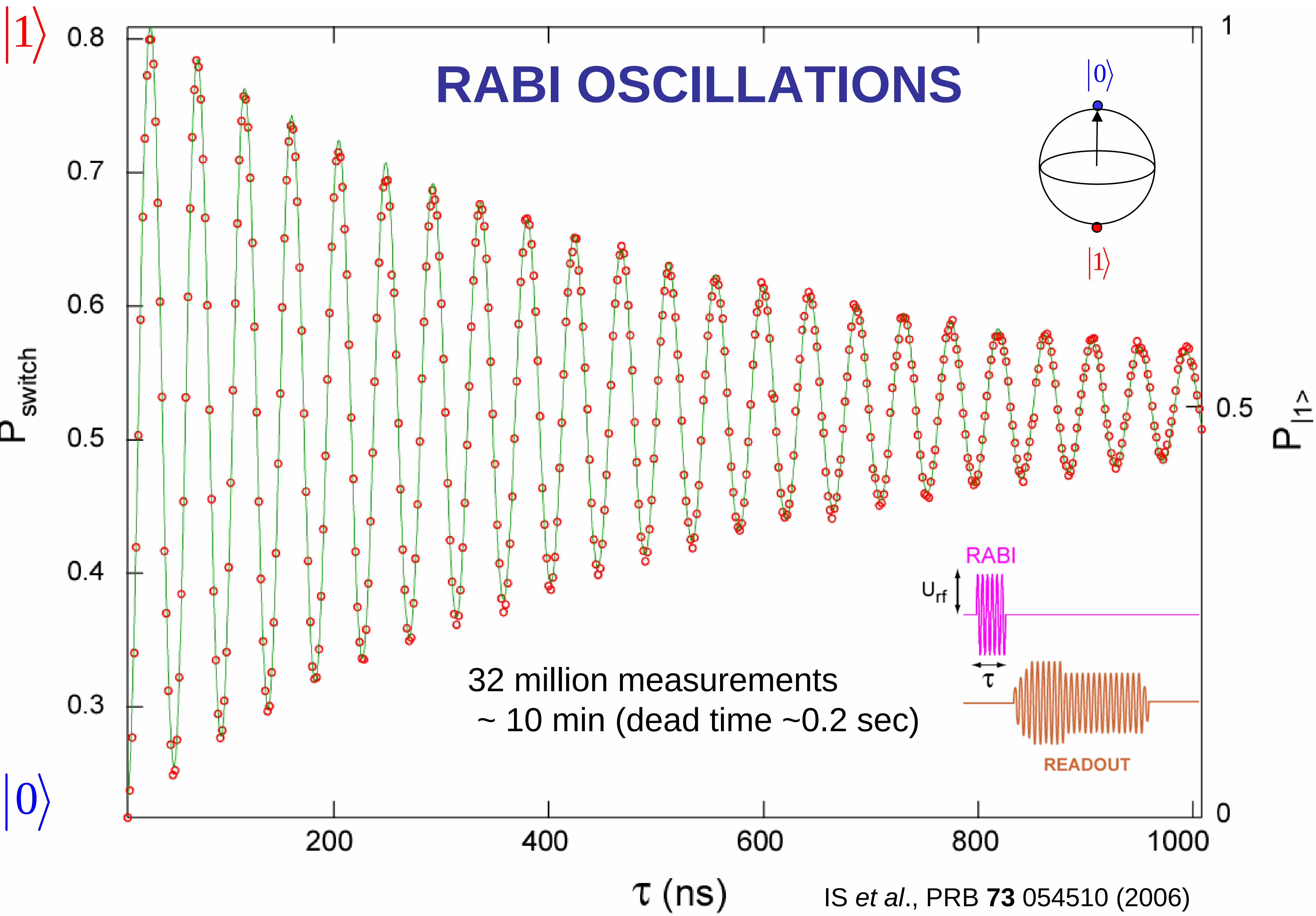




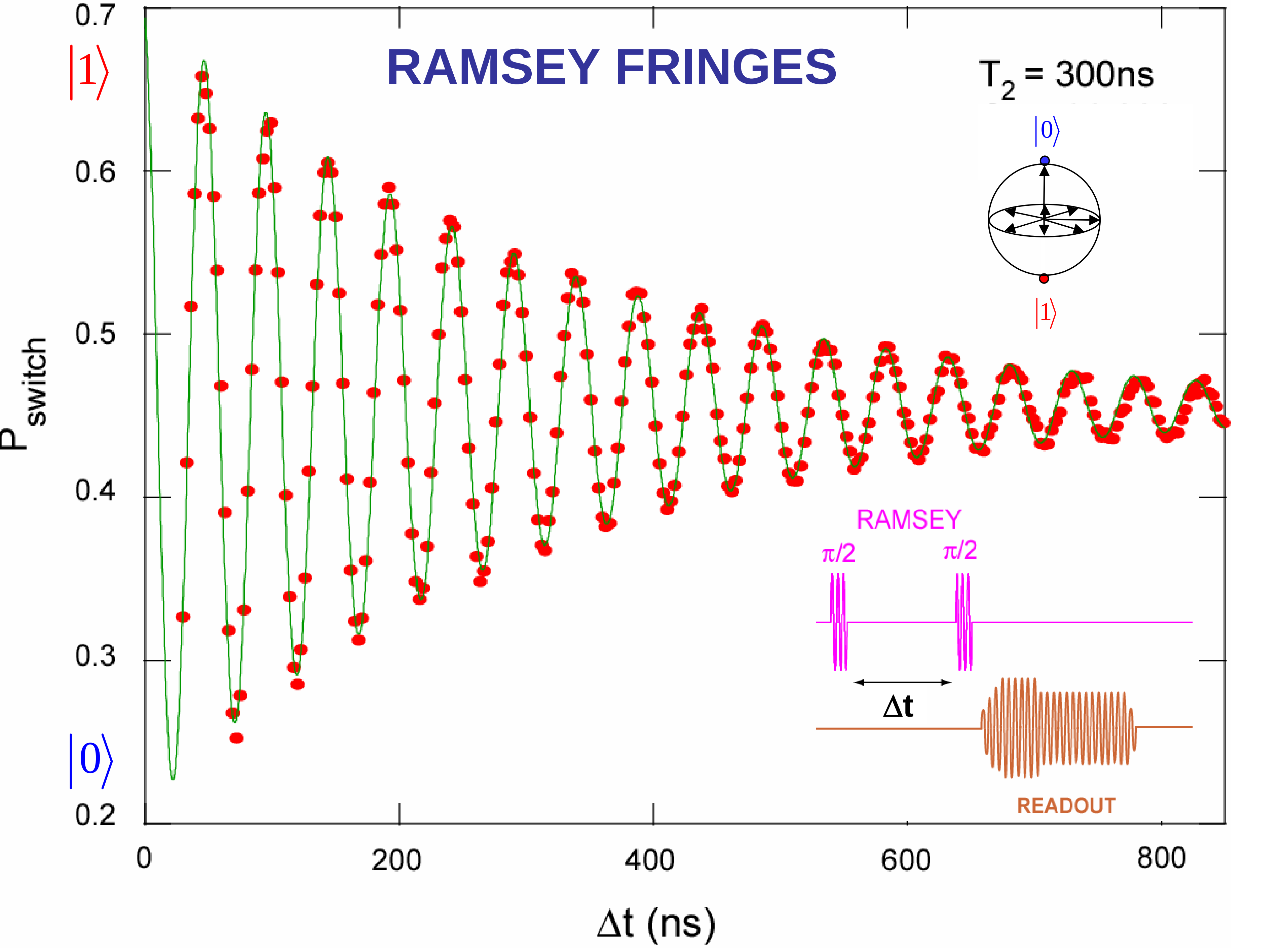


QUANTRONIUM with BIFURCATION READOUT

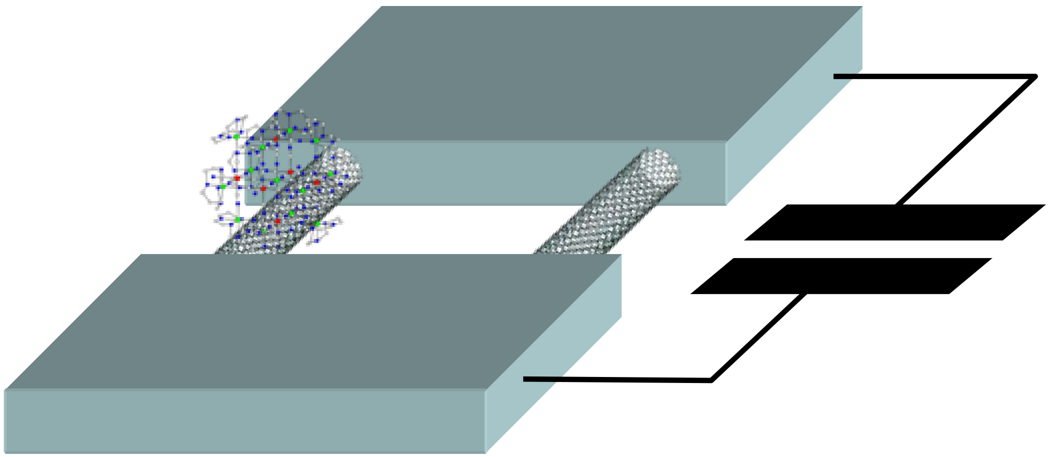


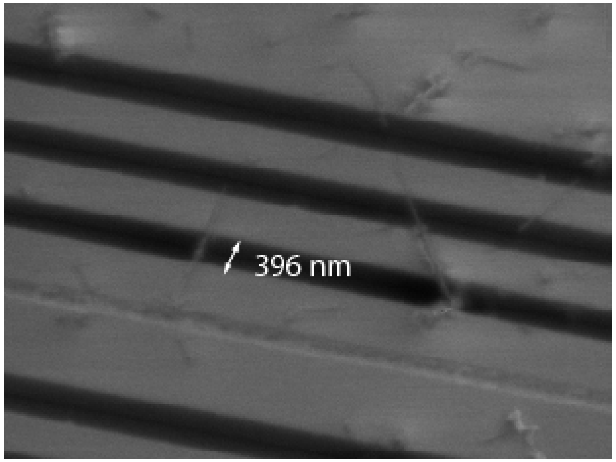


IS *et al.*, PRB **73** 054510 (2006)


RAMSEY FRINGES
T2 = 300ns
|0⟩
|1⟩
|1⟩
|0⟩
0.7
0.6
0.5
0.4
0.3
0.2
Pswitch
0
200
400
600
800
Δt (ns)
RAMSEY
π/2
π/2
Δt
READOUT

SINGLE MOLECULE MAGNET QUBIT



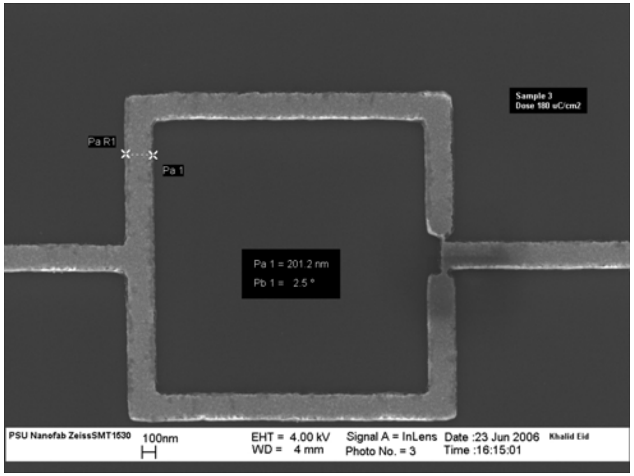


CNT Weak Links (K. Ray)

- Cr_7Ni (S=1/2)
  $[(cyclen)_{12}Ni_{13}Cr_6(CN)_{36}]^{8+}$ (S = 22)
  $[Mn_{19}O_8(N_3)_8(HL)_{12}(MeCN)_6]^{2+}$ (S=83/2)

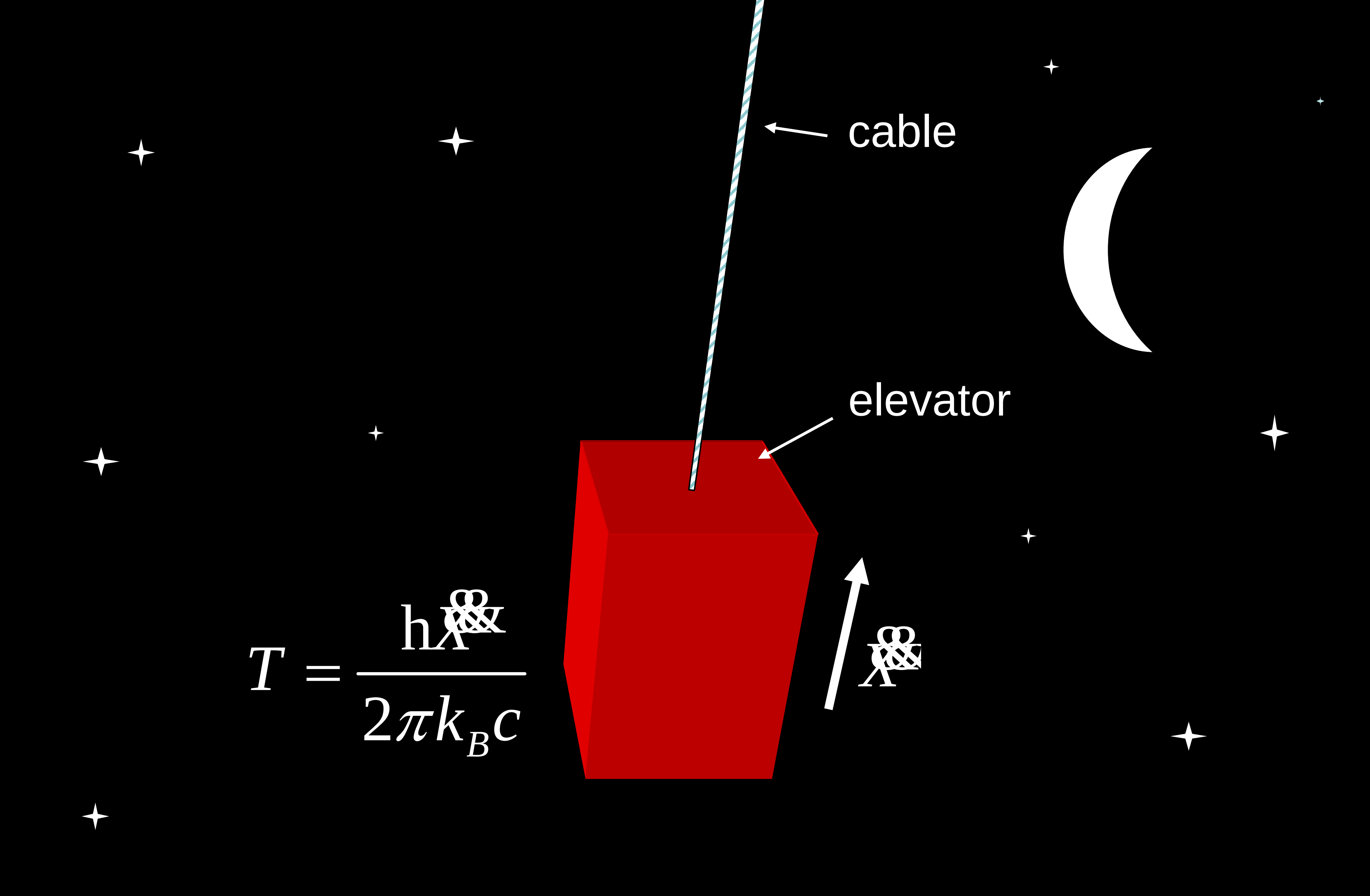
- measure spin state in 10-100 ns

- strong magnetic coupling



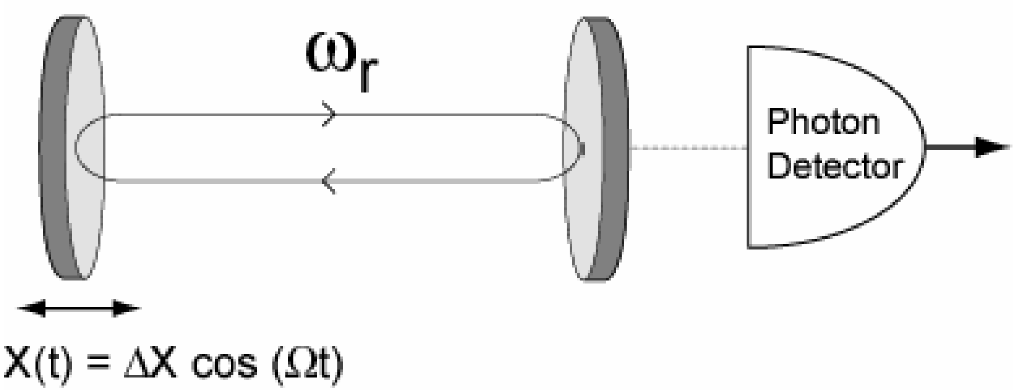
Metal Weak Links (K. Eid)

DRIVEN PENDULUM IN THE QUANTUM REGIME



THE UNRUH EFFECT

HEAT WITHOUT FRICTION:
THE DYNAMIC CASIMIR EFFECT

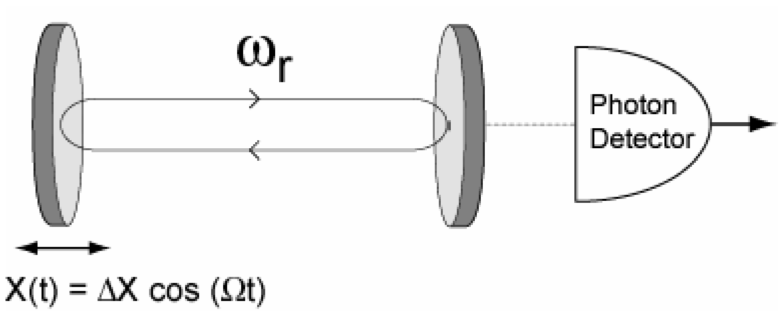


“Shaking Light from the Void”

Paul Davies

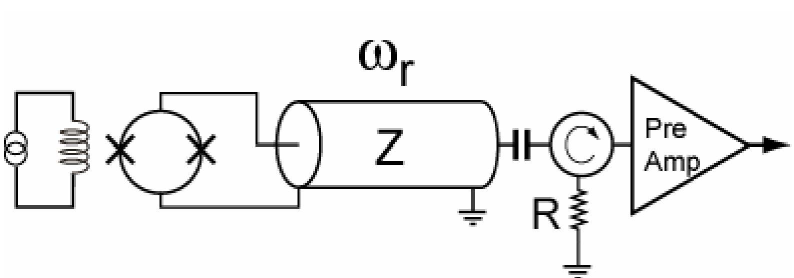
Nature, News & Views, **382** 761, 1996

HEAT WITHOUT FRICTION:
THE DYNAMIC CASIMIR EFFECT

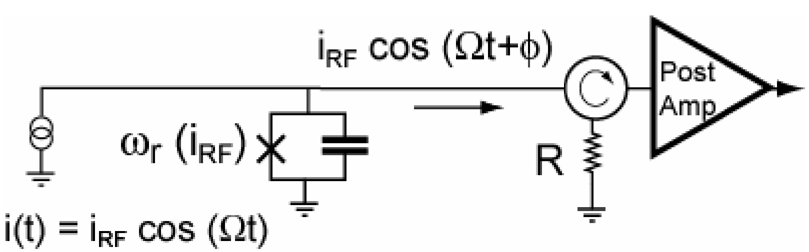


$$T = \frac{h\Omega^2 \Delta X}{k_B c} \frac{\Delta X\, \omega_r}{c} F$$

Lambrecht, Jaekel, and Reynaud
PRL **77**, 615 (1996)



$$\Delta X \rightarrow \Delta L_{eff}$$

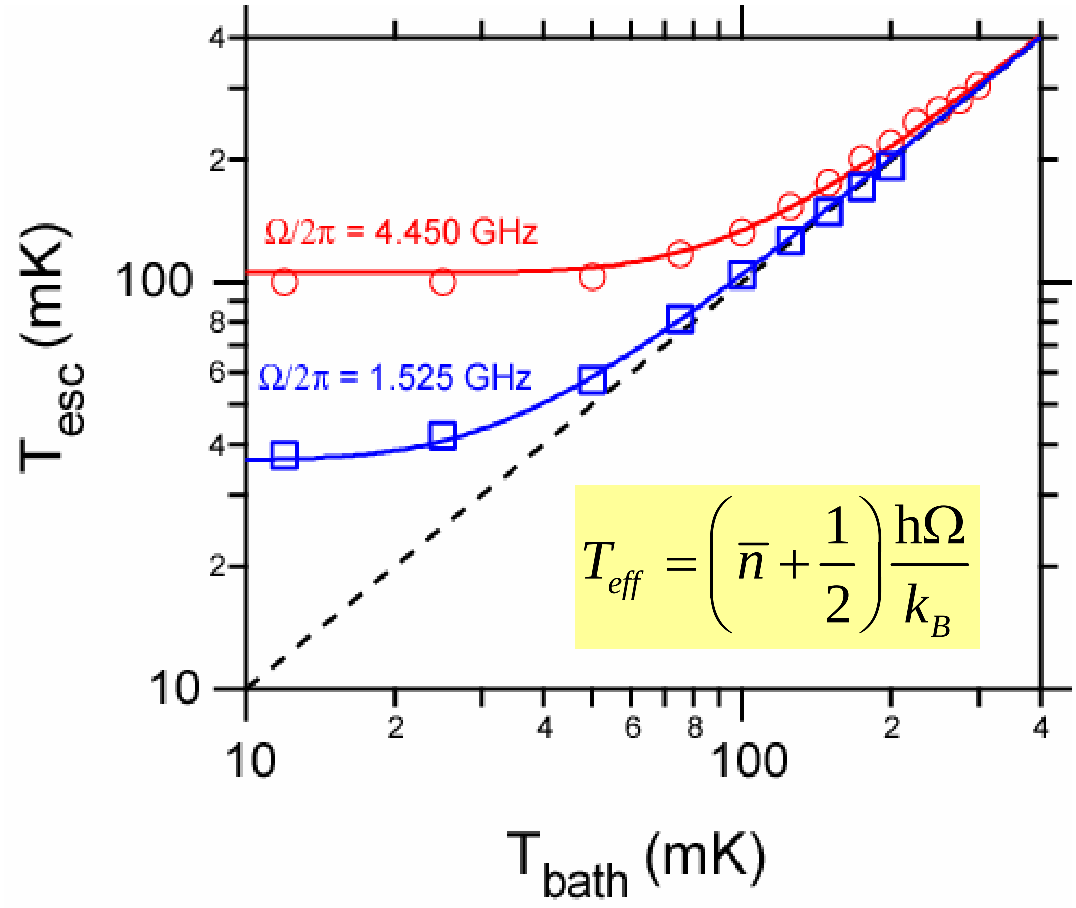


$$F, \frac{\Omega}{\omega_r} \sim 1$$

$$\boxed{T \sim \frac{h\omega_r}{k_B} \sim 100mK}$$

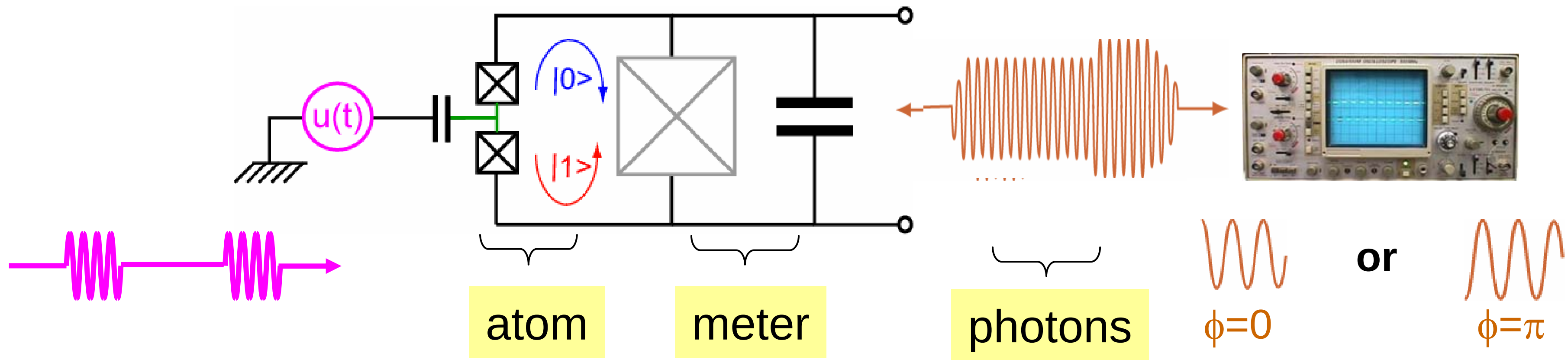
QUANTUM ACTIVATION

- measure Γ
- $\Gamma \rightarrow T_{esc}$

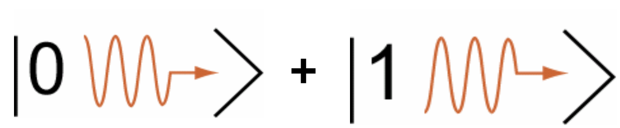


SCHRÖDINGER'S CATS and KITTENS

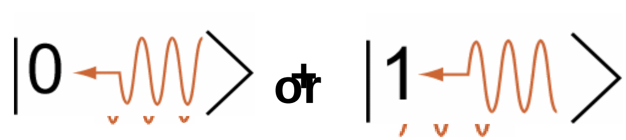
MACROSCOPIC QUANTUM ERASURE



- prepare atom in superposition $|0\rangle + |1\rangle$
- send photons, entangle meter with atom $|0\ \phi=0\rangle + |1\ \phi=\pi\rangle$
- photons arrive at classical readout



- send pulse back to atom/meter
- detect pulse (actual qubit readout)



- photons arrive at meter $|0\ \phi=0\rangle + |1\ \phi=\pi\rangle$
- atom recovers original superposition $|0\rangle + |1\rangle$

LIMITS OF SUPERPOSITION ?

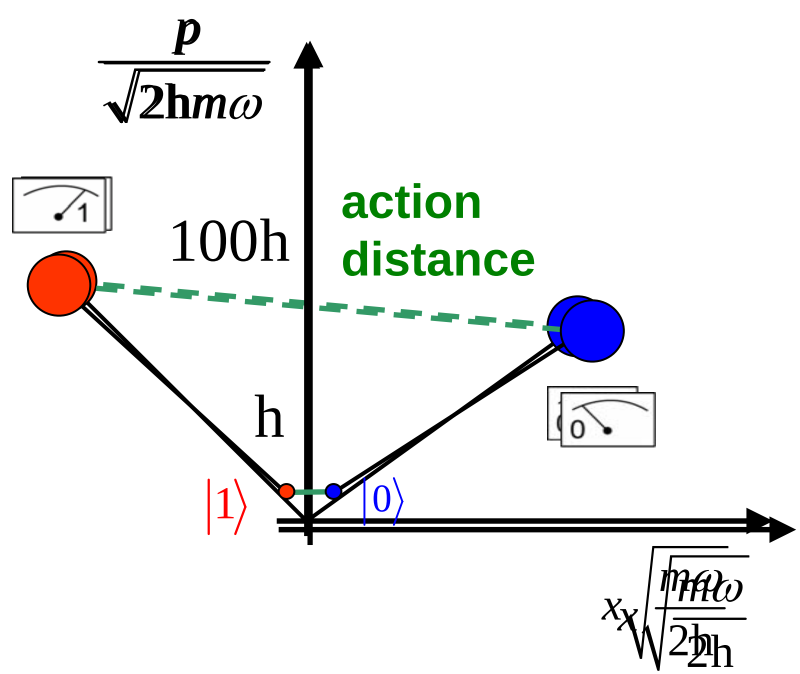
MACROSCOPIC

size | engineered | action-distance >> h

Macroscopic Quantum Coherence

Giant Macroscopic Quantum Coherence

Does it exist ?



- MQC ~ 1 h
- quantum optics
  Schrödinger "lean" cat states ~ 10 h
- JBA states ~ 100 h ("fat" cat)

CONCLUSIONS

SUPERCONDUCTING QUBIT READOUT

DISPERSIVE: NO ENERGY LEFT BEHIND

FAST: MEASURE 30ns, RECORD 100ns

MINIMAL DEAD TIME: REPETITION RATE SET BY T_1

NON-INVASIVE: CAN TURN READOUT OFF

PHYSICS QUESTIONS

DECOHERENCE IN MANY-BODY QUANTUM SYSTEMS

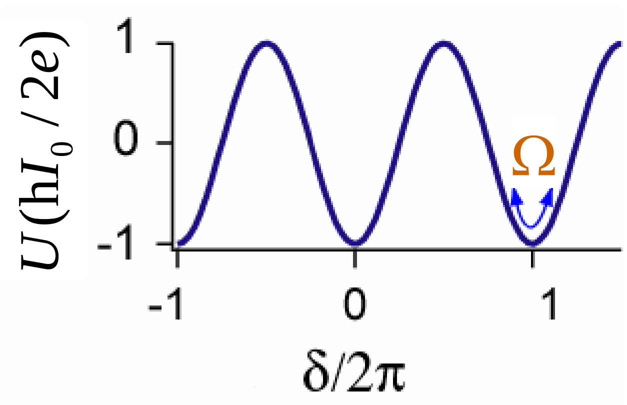
COHERENCE TIMES IN SINGLE MOLECULES/NANOTUBES

AMPLIFY QUANTUM INFORMATION?

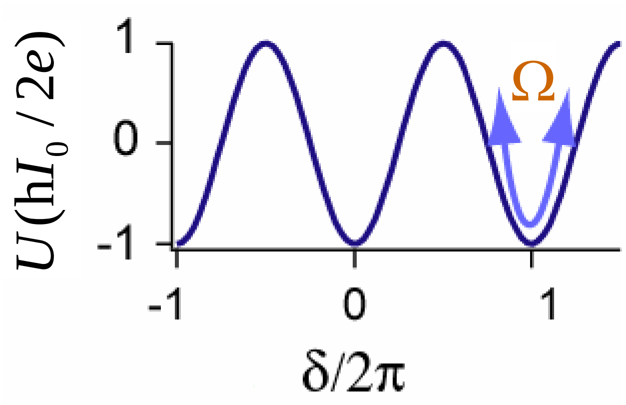
FUNDAMENTAL LIMITS TO QUANTUM COMPLEXITY?

THE QUANTUM PENDULUM → DYNAMICAL CASIMIR EFFECT

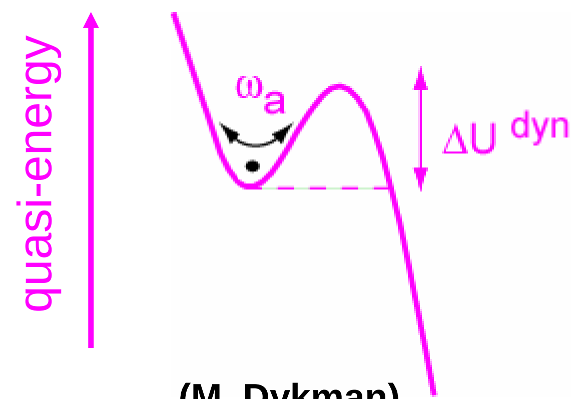
DRIVEN PENDULUM: ACTIVATION @ ALL T!



low amplitude state



high amplitude state

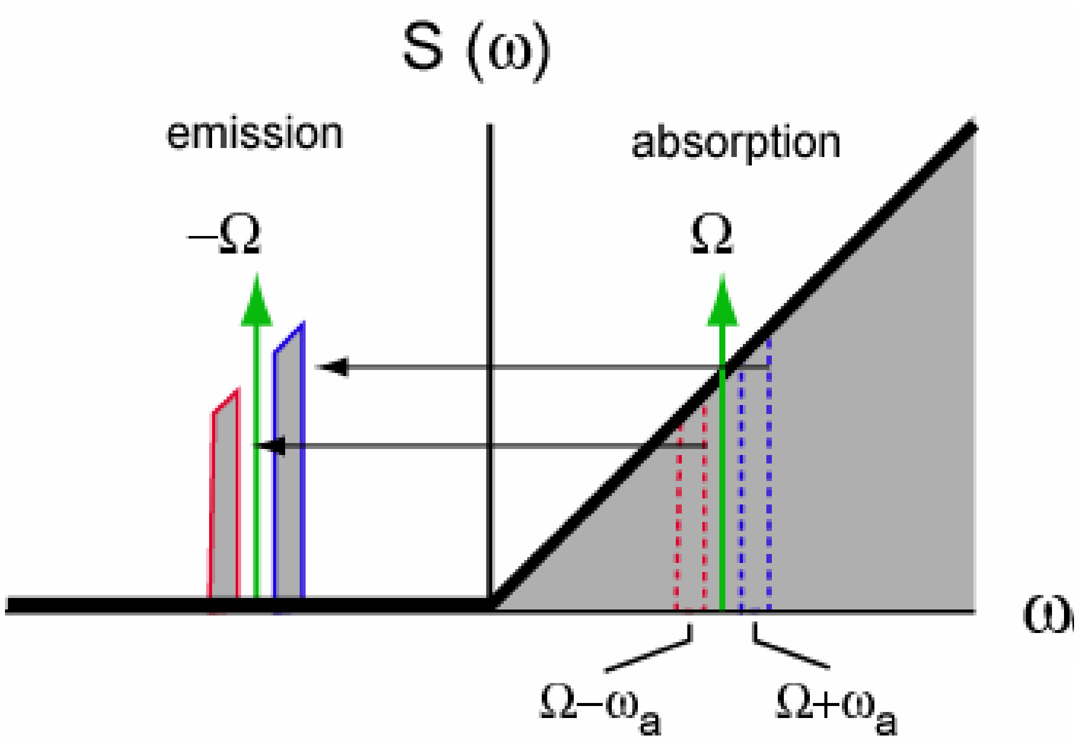


(M. Dykman)

$$\Gamma^{dyn}_{0\rightarrow1} = \frac{\omega_a}{2\pi} \exp\left(-\frac{\Delta U^{dyn}}{kT} \right)$$

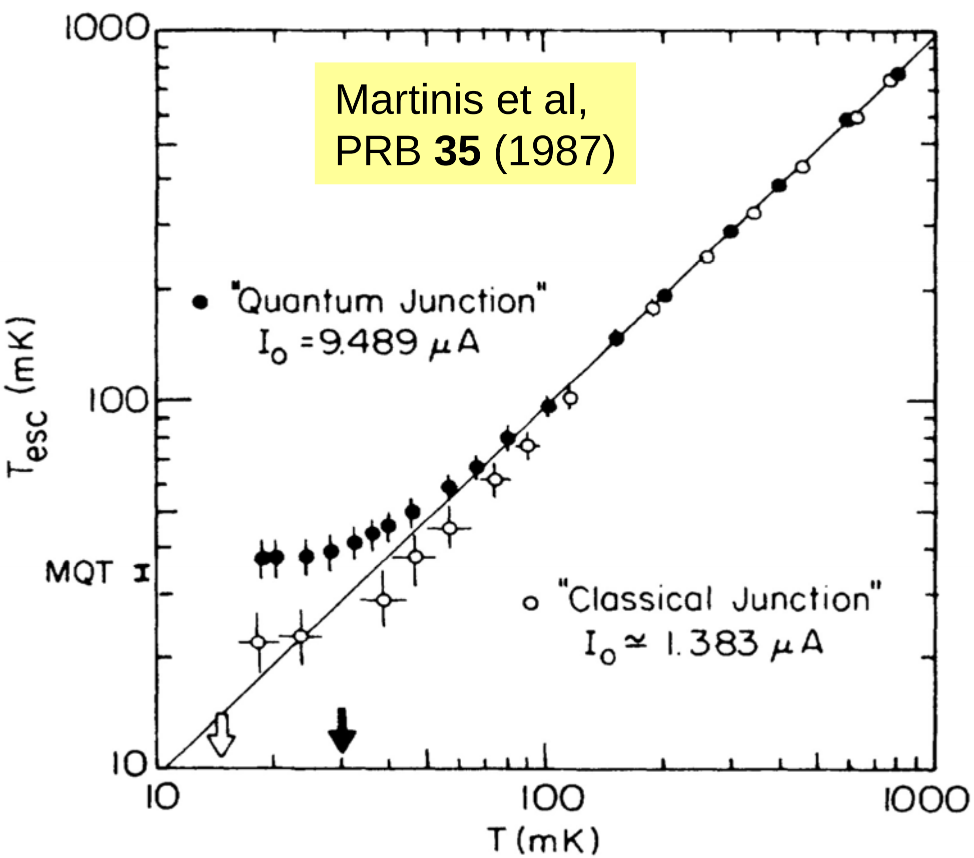
- Non-equilibrium quantum system
- Drive: Virtual vacuum fluctuations
  → real photons → switching

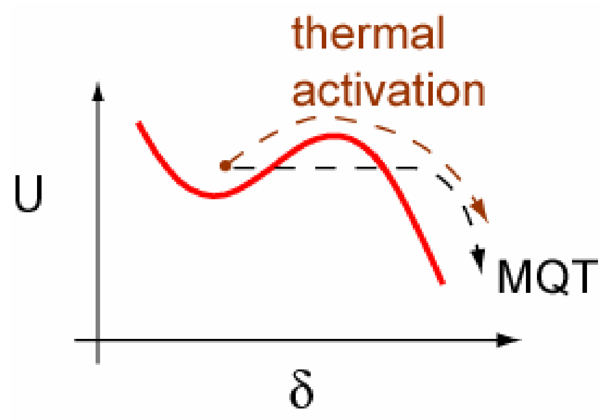
$k_BT \ll \hbar\omega$: QUANTUM ACTIVATION



• equilibrium case → only relaxation

DC CURRENT BIAS:
Macroscopic Quantum Tunneling (MQT)





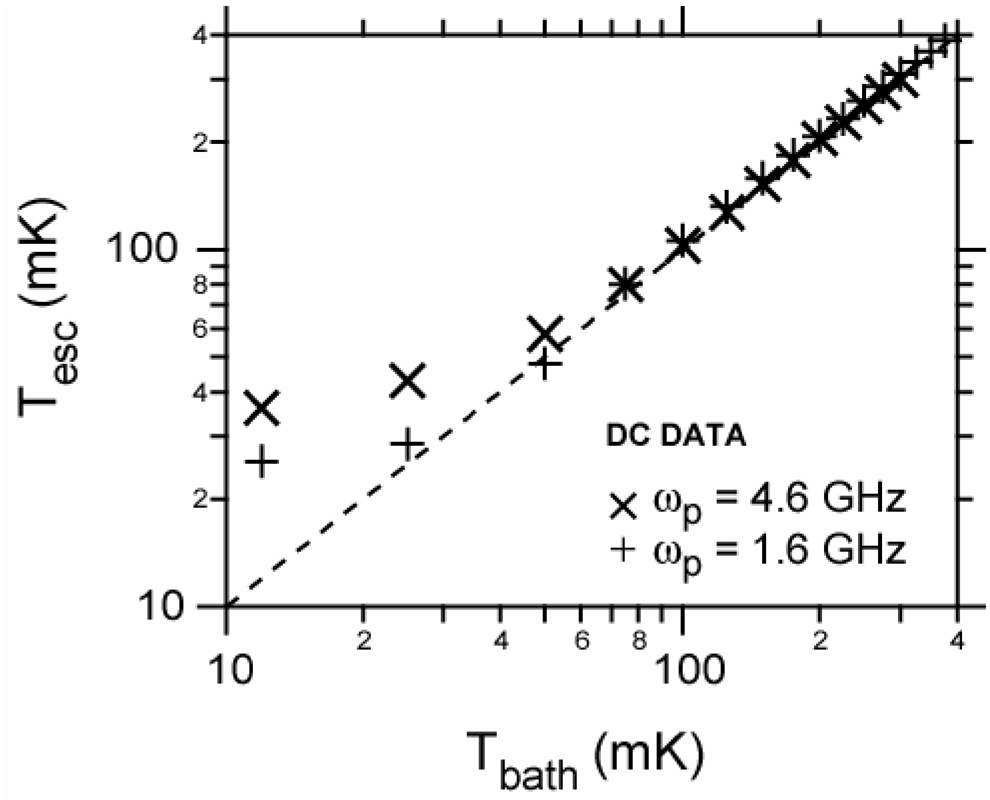
thermal activation

$$T > T^* = \frac{\hbar\omega_p}{7.2k} \quad : \; \Gamma \propto e^{\frac{-\Delta U}{kT}}$$

MQT

$$T < T^* = \frac{\hbar\omega_p}{7.2k} \quad : \; \Gamma = \text{constant}$$

CAN COOL JUNCTION & ENVIRONMENT



cool R to 25-35 mK;   >1 GHz RF bandwidth

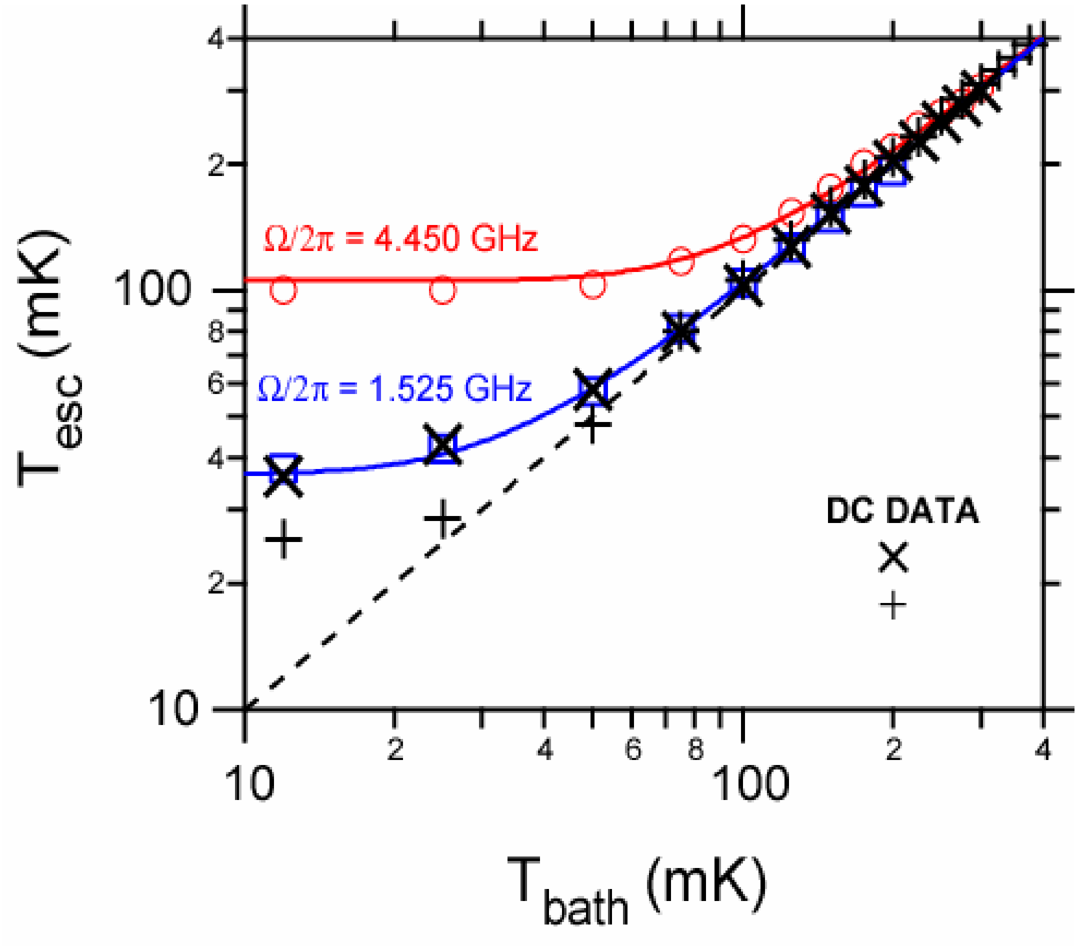
$$T^* = \frac{h\omega_p}{7.2k} \ = \ 5-15mK$$

QUANTUM ACTIVATION VS. MQT

SATURATION
<u>TEMPERATURE</u>

$$T_{MQT} = \frac{\hbar\omega_p}{7.2k_B}$$

$$T_{QA} = \frac{\hbar\Omega}{2k_B}$$



CONCLUSIONS

QUANTUM STATE READOUT

- DISPERSIVE: NO ENERGY LEFT BEHIND
- FAST: MEASURE 30ns, RECORD 100ns, NO DEAD TIME
- NON-INVASIVE: CAN TURN READOUT OFF

OBSERVATION OF THE DYNAMIC CASIMIR EFFECT

PERSPECTIVES

- COHERENCE TIMES IN SINGLE MOLECULES/NANOTUBES
- DECOHERENCE IN MANY-BODY QUANTUM SYSTEMS
- FUNDAMENTAL LIMITS TO QUANTUM COMPLEXITY?