Metastable states in an RF driven Josephson oscillator

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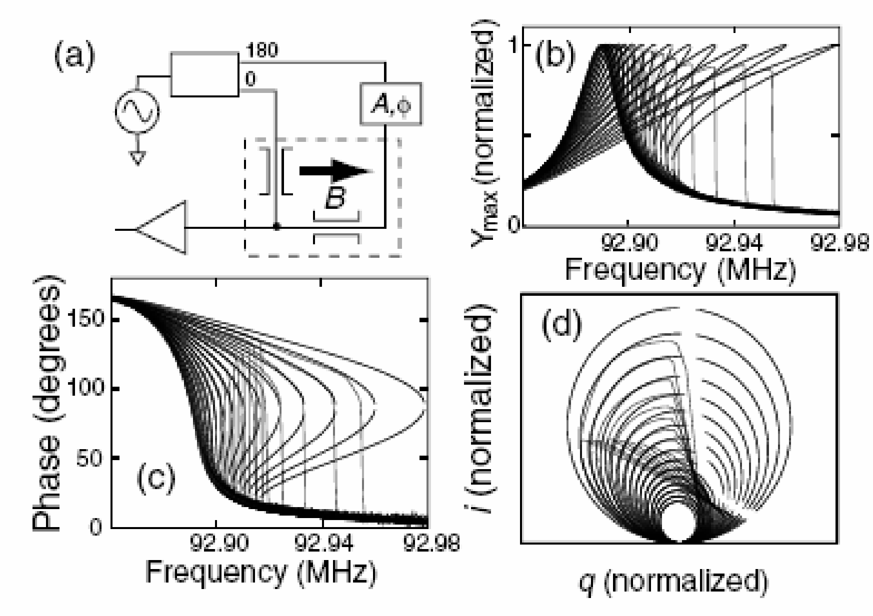
ARDA

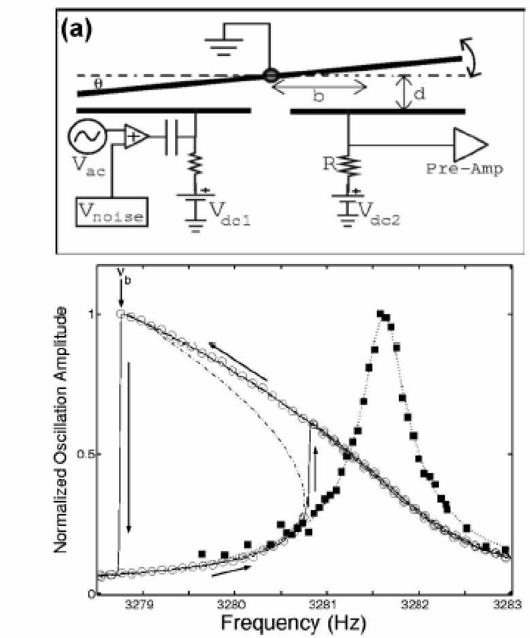
W. M. KECK FOUNDATION

INTRODUCTION

DOUBLY CLAMPED MECHANICAL RESONATORS



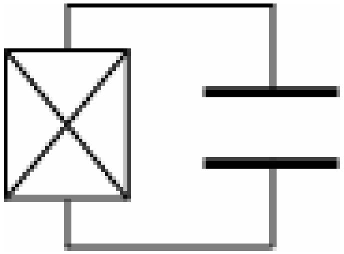
MICROMECHANICAL TORSIONAL OSCILLATOR



RESONANT FREQ.	~ 90 MHz	~3 KHz
QUALITY FACTOR	~7000	~2000 - 8000
TEMPERATURE	4K	4K - 77K
TRANSITIONS	ADDED NOISE	ADDED NOISE

INTRODUCTION

ELECTRICAL OSCILLATOR



RESONANT FREQUENCY ~ 1.5 GHz

QUALITY FACTOR ~ 20

FAST DYNAMICS
~ nanoseconds

THERMALLY INDUCED TRANSITIONS

TEMPERATURE: 10 - 200 mK

CLASSICAL
TO
QUANTUM
DYNAMICS

OUTLINE

Josephson Junction

– Non-dissipative , non-linear circuit element

RF biased Josephson Junction

– Driven, non-linear oscillator

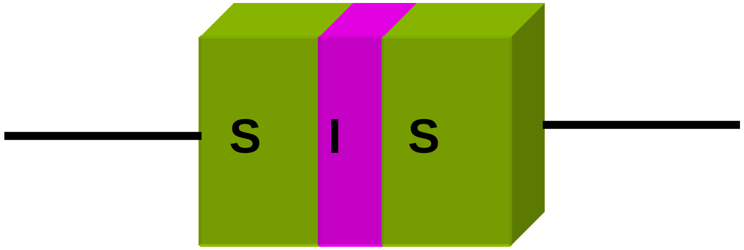
– Metastable states; transitions

– Quantum regime

Applications

JOSEPHSON TUNNEL JUNCTION

$I_0\ , C_J$



δ

Superconducting phase

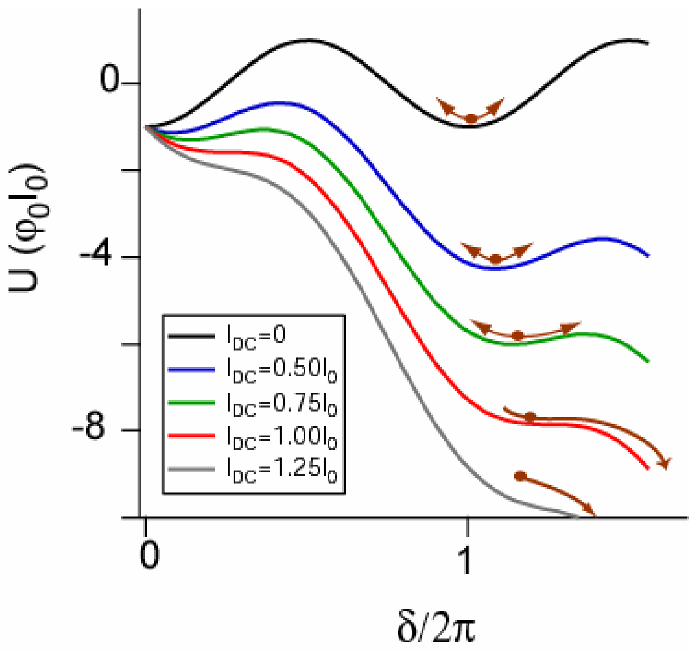
Josephson relations

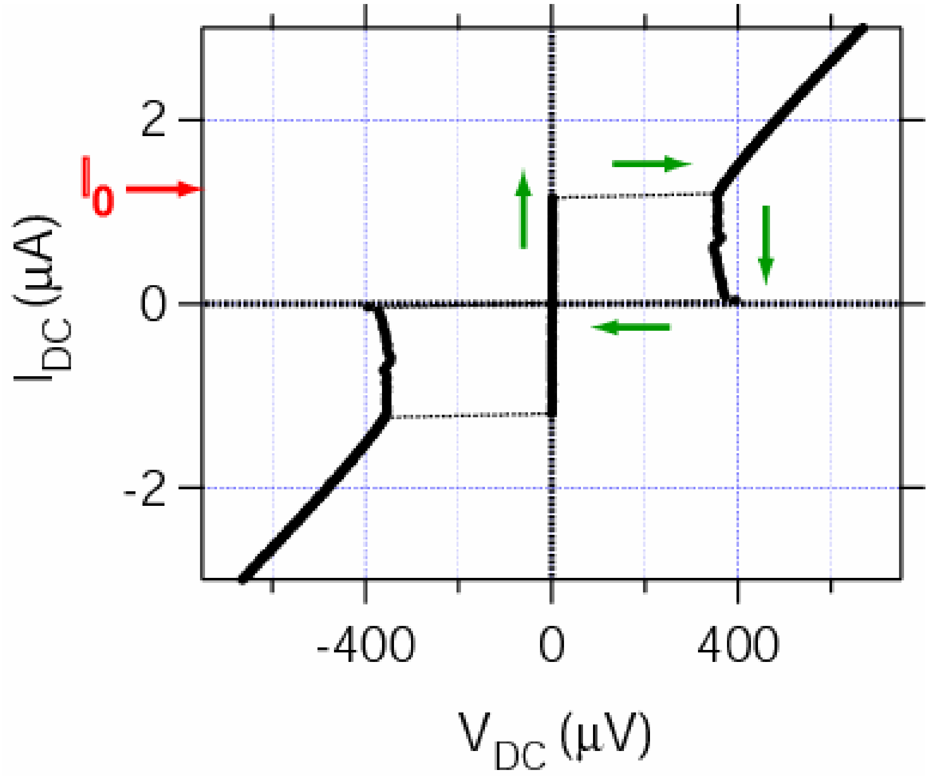
$$I = I_0 \sin(\delta)$$

I_0 – critical current

$$V = \frac{\hbar}{2e}\frac{d\delta}{dt} = \varphi_0 \frac{d\delta}{dt}$$

DC CURRENT BIAS

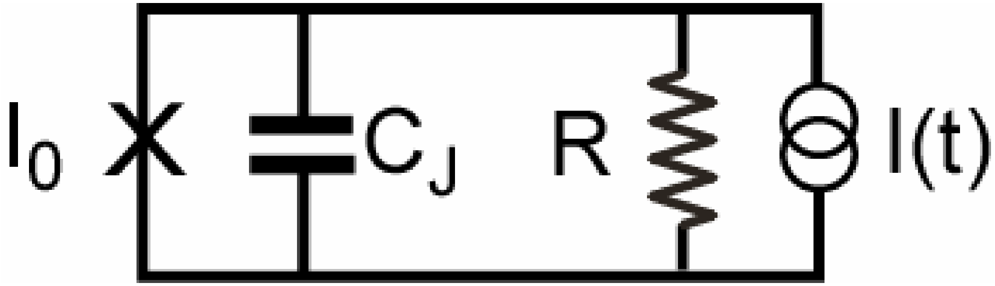




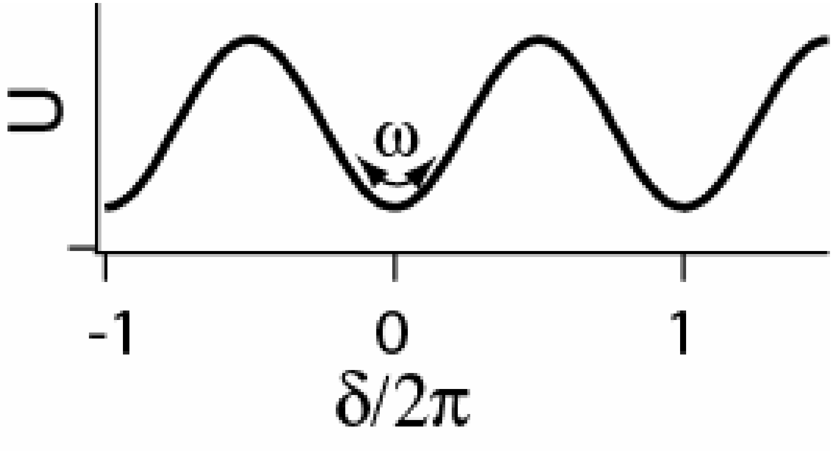
$I_{DC} < I_0 : \langle V \rangle = 0$ ⇨ SUPERCONDUCTING

$I_{DC} > I_0 : \langle V \rangle \neq 0$ ⇨ DISSIPATIVE

RF DRIVEN NON-LINEAR OSCILLATOR



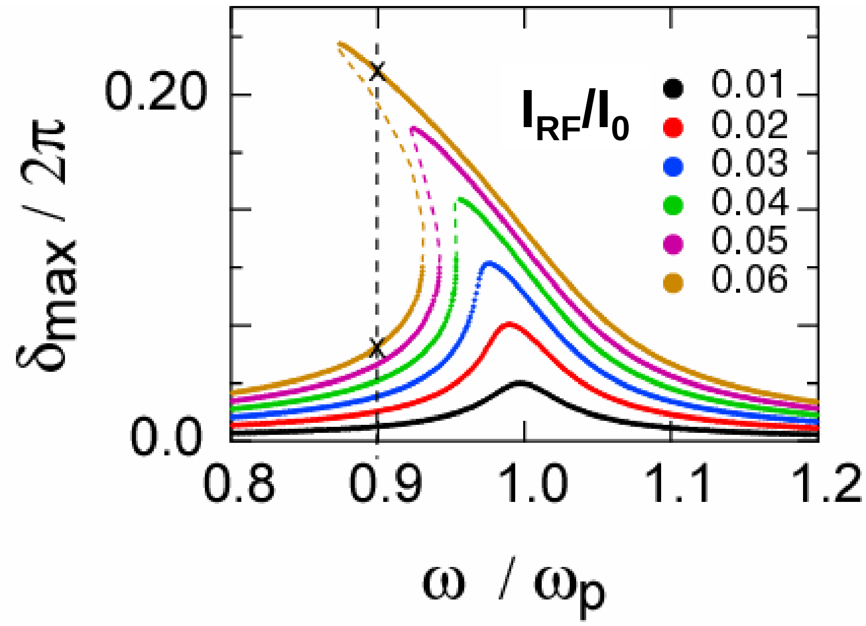
$$\underbrace{\varphi_0^2 C_J}_{mass} \frac{d^2\delta}{dt^2} + \frac{\varphi_0^2}{\underbrace{R}_{drag}} \frac{d\delta}{dt} + \underbrace{\varphi_0 I_0 \sin\delta}_{force} = \underbrace{\varphi_0 I_{RF} \sin\omega t}_{drive}$$



DRIVEN STATES IN THE SAME WELL

NO TRANSITIONS OUT OF THE WELL

TWO DYNAMICAL STATES



$$\delta(t) = \delta_{\max} \sin(\omega t + \gamma)$$

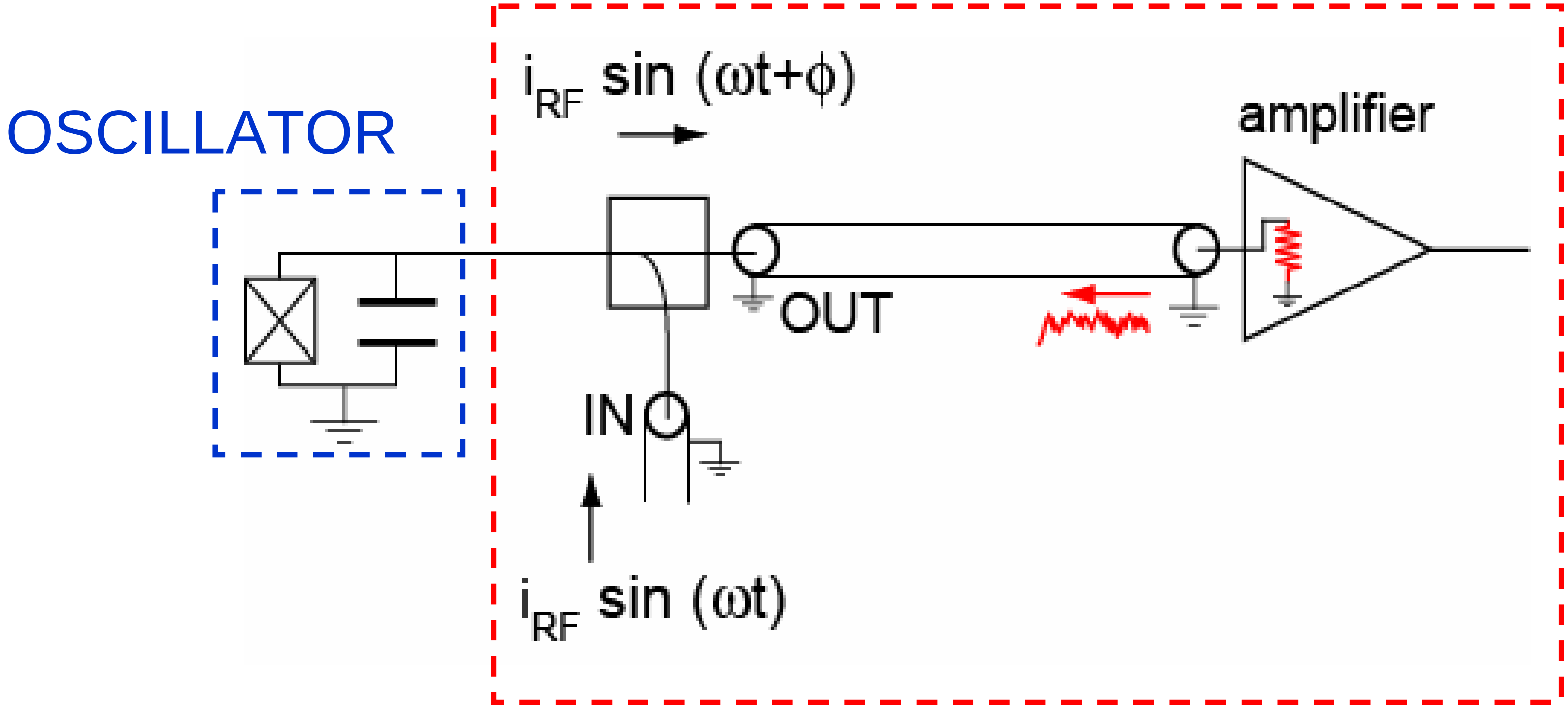
$$\omega_p = \sqrt{\frac{I_0}{\varphi_0 C_J}}$$ PLASMA FREQUENCY

$$Q = \omega_p R C_J$$ QUALITY FACTOR

If $\omega_p - \omega > \frac{\omega_p}{Q}\frac{\sqrt{3}}{2}$ $\rightarrow$ bistability

Dynamical states differ in oscillation amplitude & phase

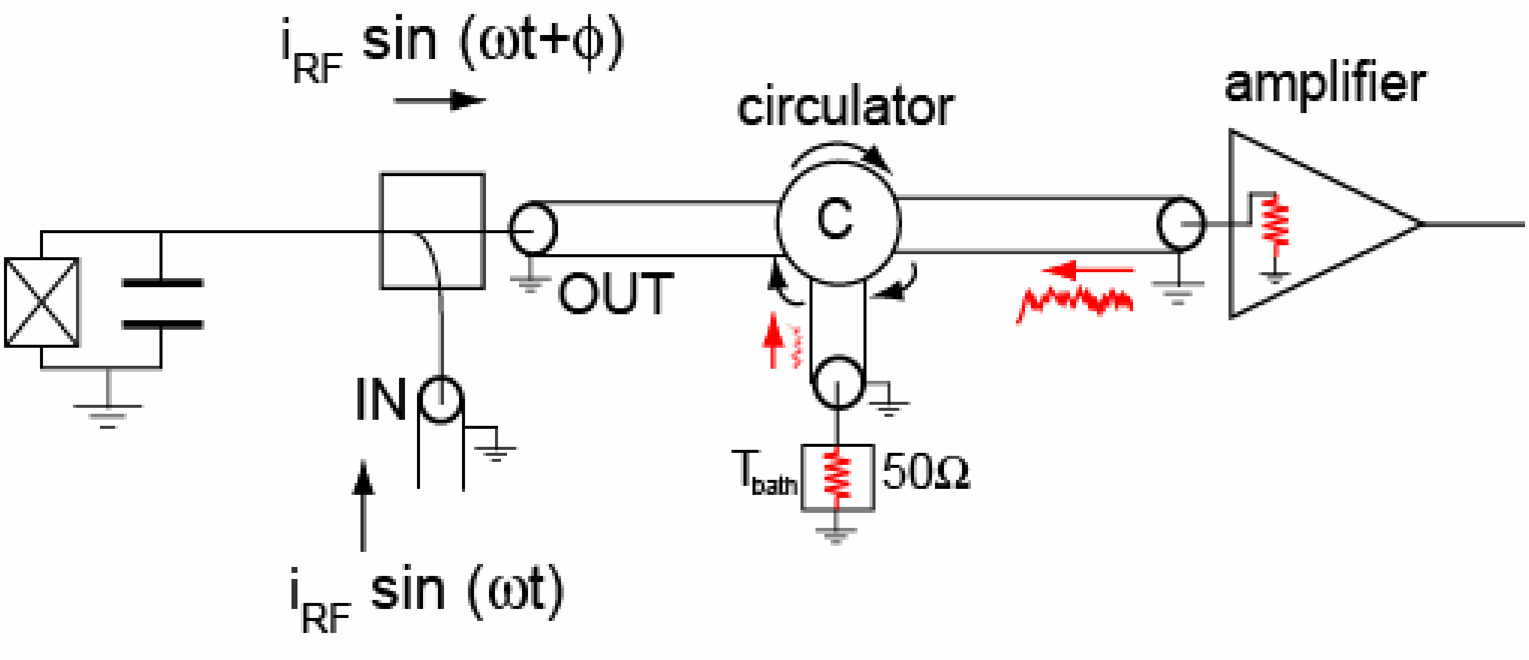
THE REFLECTION EXPERIMENT



ENVIRONMENT

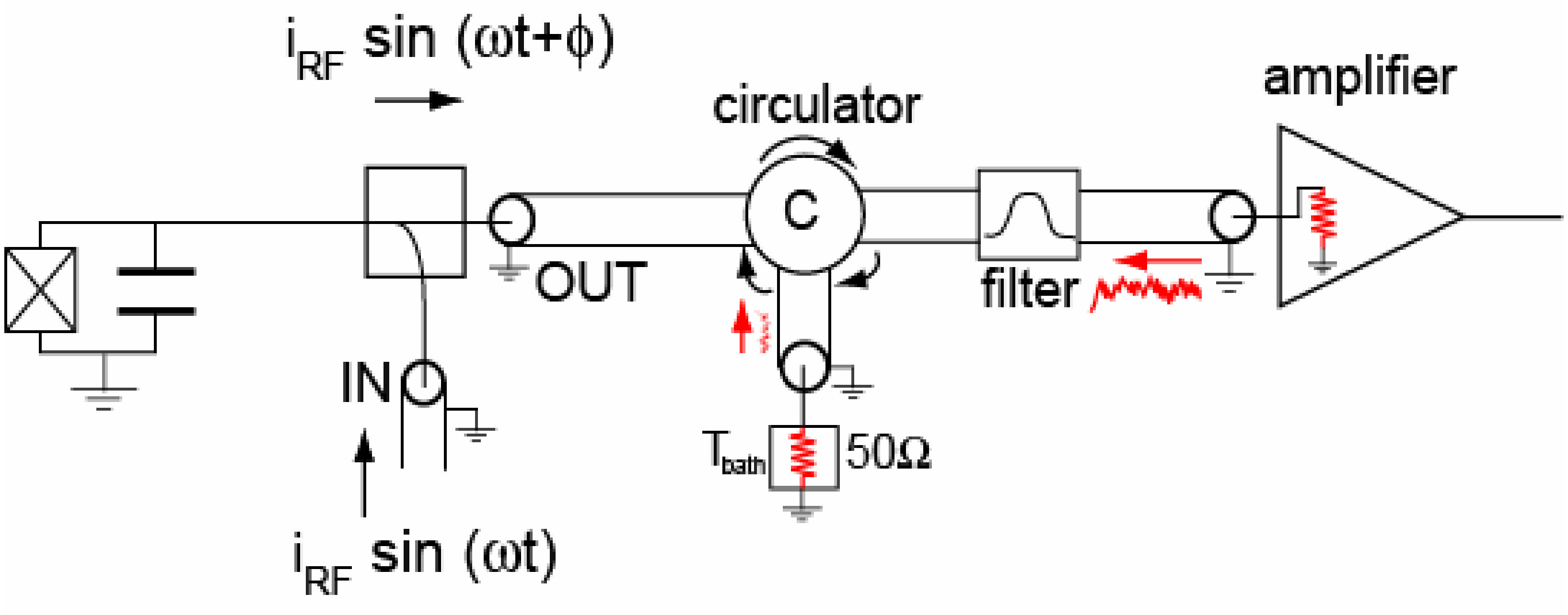
50 OHM CHARACTERISTIC IMPEDANCE

MINIMIZING NOISE



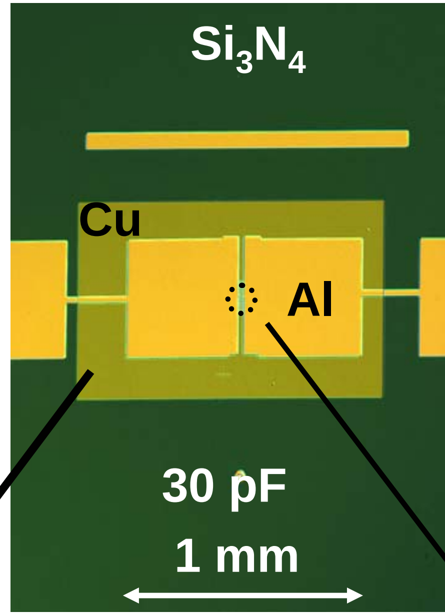
USE CIRCULATOR TO PROTECT SAMPLE FROM IN-BAND NOISE

MINIMIZING NOISE



USE FILTERS TO PROTECT SAMPLE FROM OUT OF BAND NOISE

JUNCTION + MICROWAVE CAPACITOR



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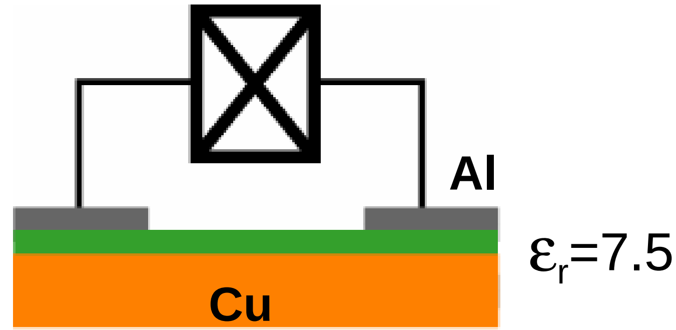
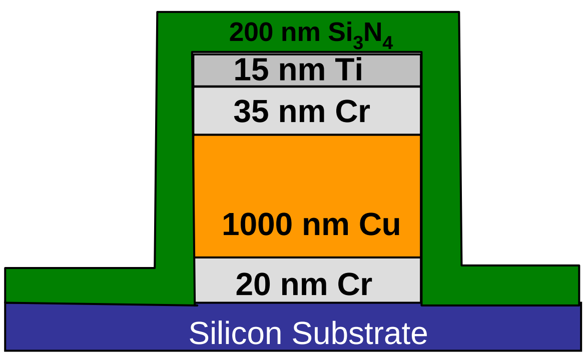
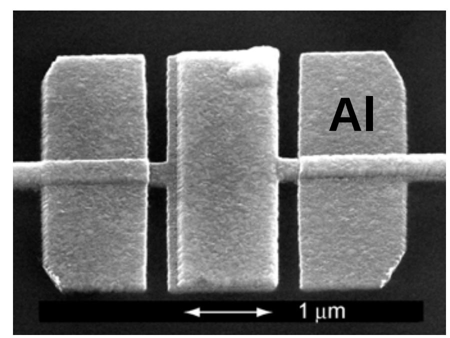


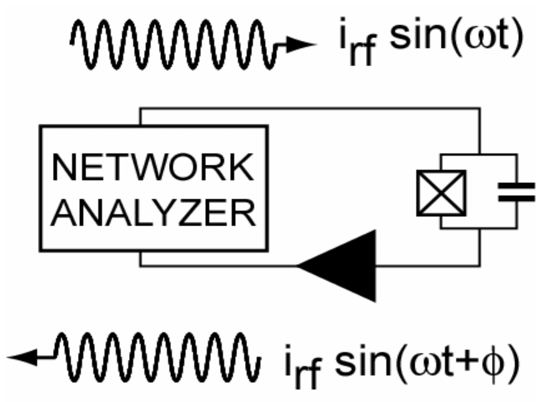


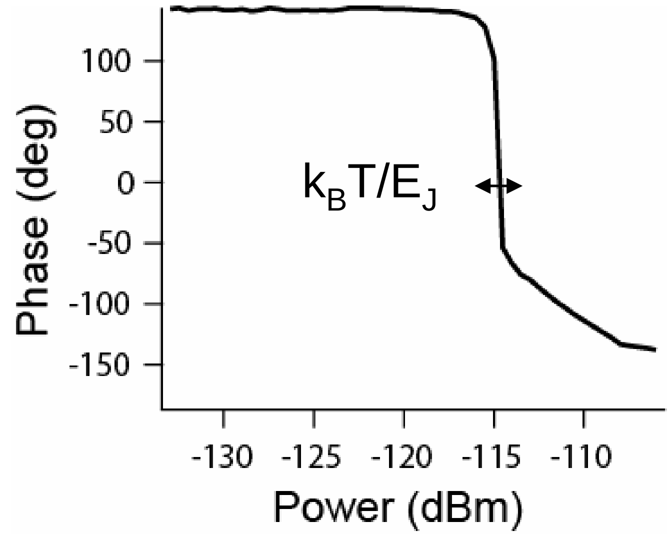
METALLIC UNDERLAYER

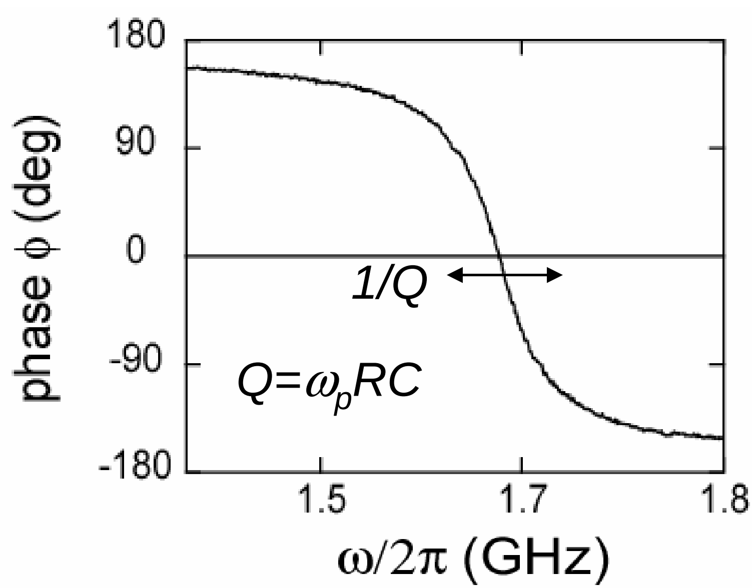


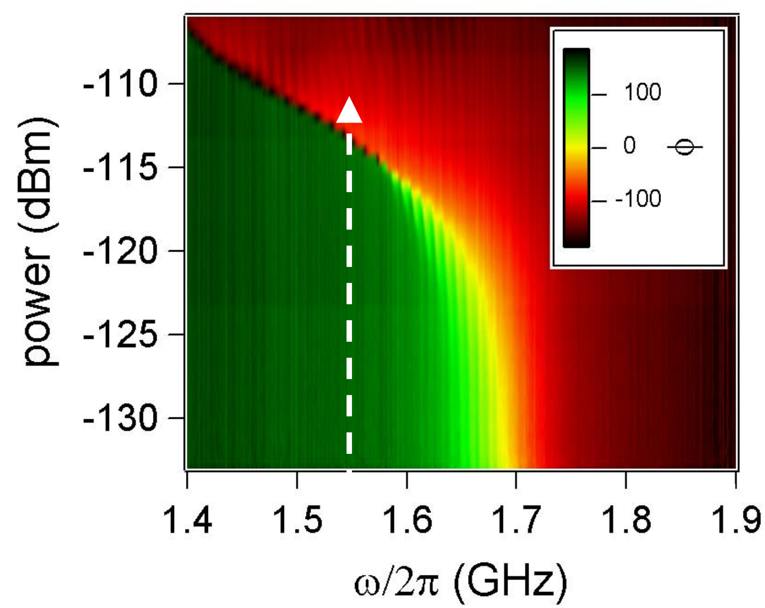
$Al/Al_2O_3/Al$ Junction (1 µA , 0.330 nH)

NON-LINEAR RESONANCE



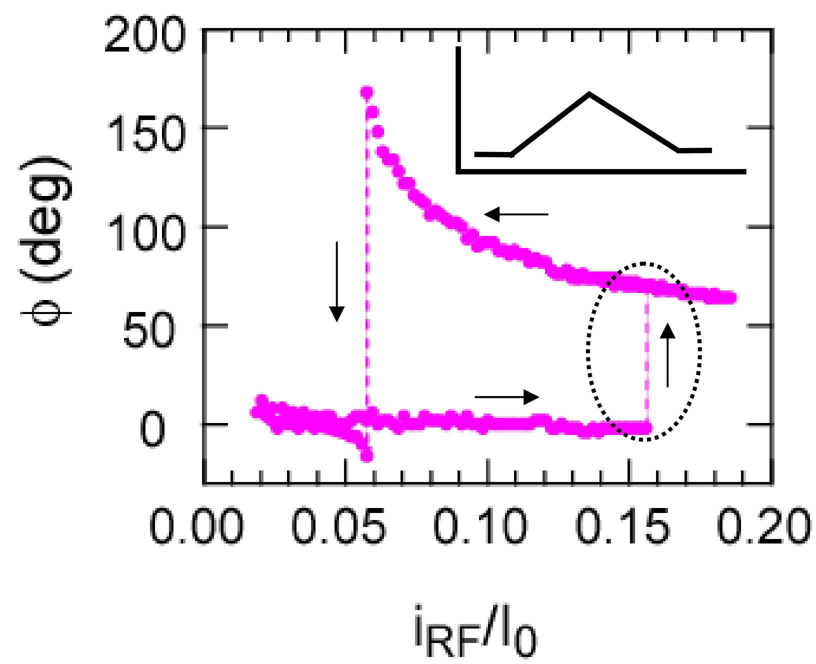


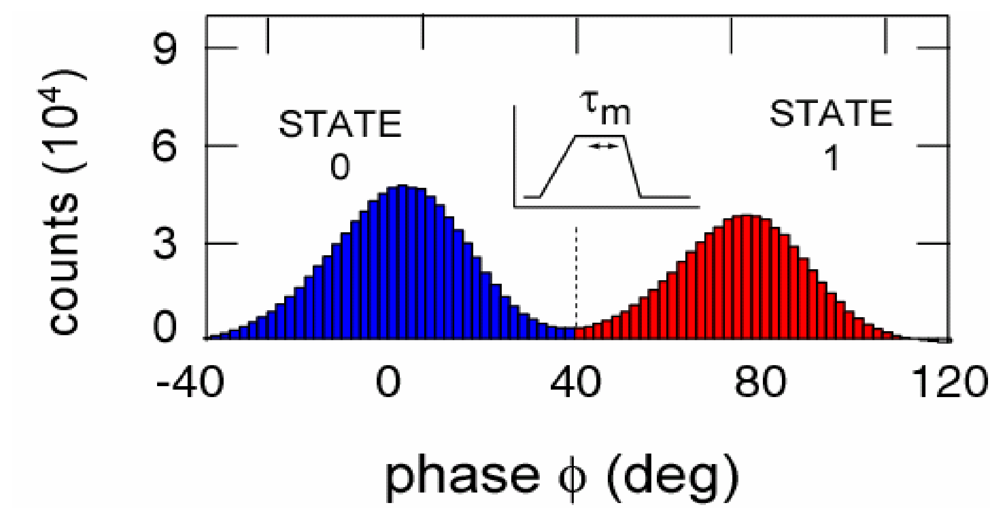




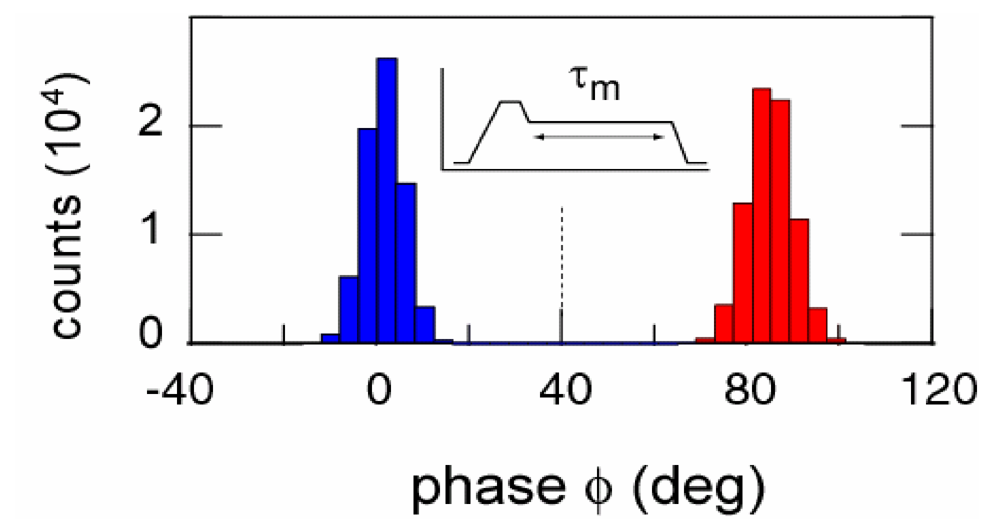
Siddiqi. *et al*, PRL. 94, 027005 (2005)

HYSTERESIS AND BISTABILITY



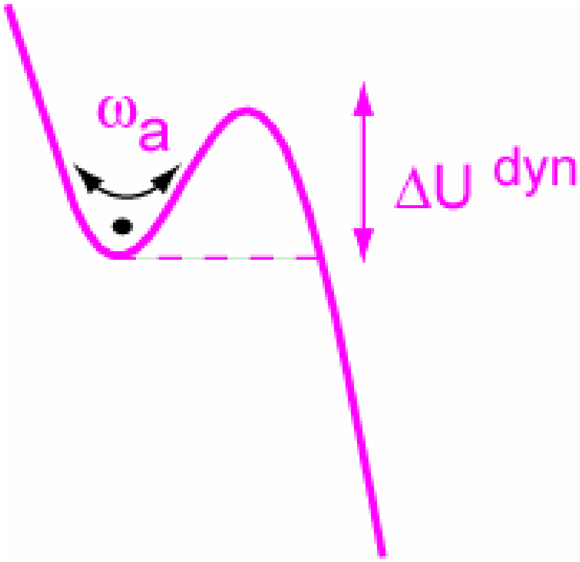


EXPLOIT HYSTERESIS TO IMPROVE SIGNAL TO NOISE RATIO



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

TRANSITION RATES

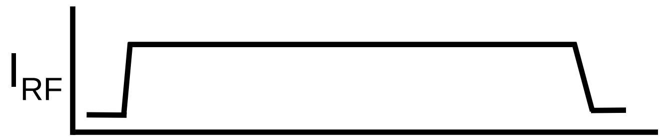


$$\Gamma = \frac{\omega_a}{2\pi} \exp\left(-\frac{\Delta U}{k_B T} \right) \qquad (kT >> \hbar\omega)$$

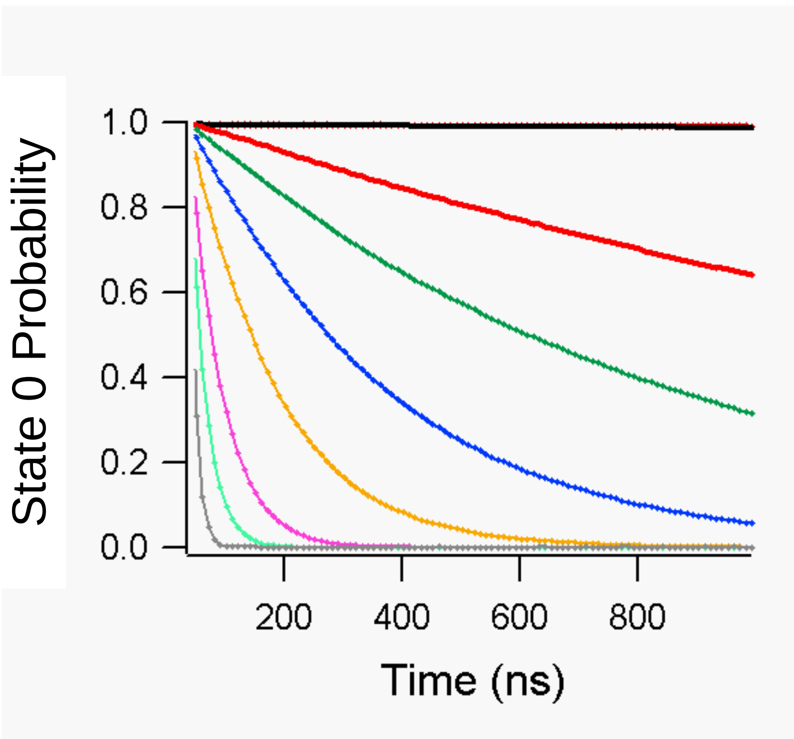
$$\Delta U^{dyn} = U_0 \left(1 - \left(\frac{I_{RF}}{I_B} \right)^2 \right)^{3/2}$$

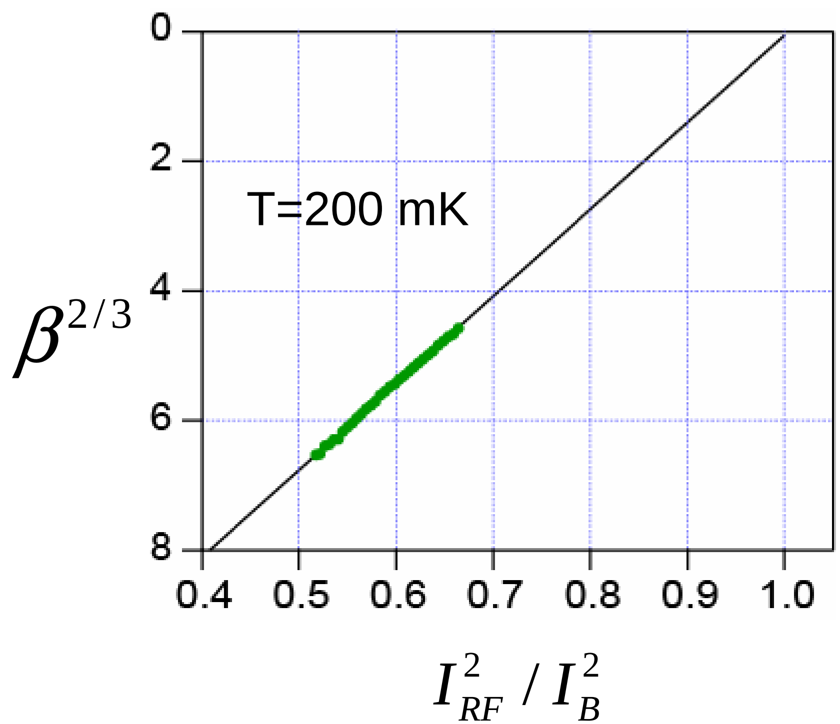
Dykman et. al. Physica 104 A, pp. 480-94 (1980).

MEASURING ESCAPE TEMPERATURE



$$\beta^{2/3} = \left[\frac{U_0}{k_B T_{esc}}\right]^{2/3}\left(1 - \frac{I_{RF}^2}{I_B^2}\right)$$

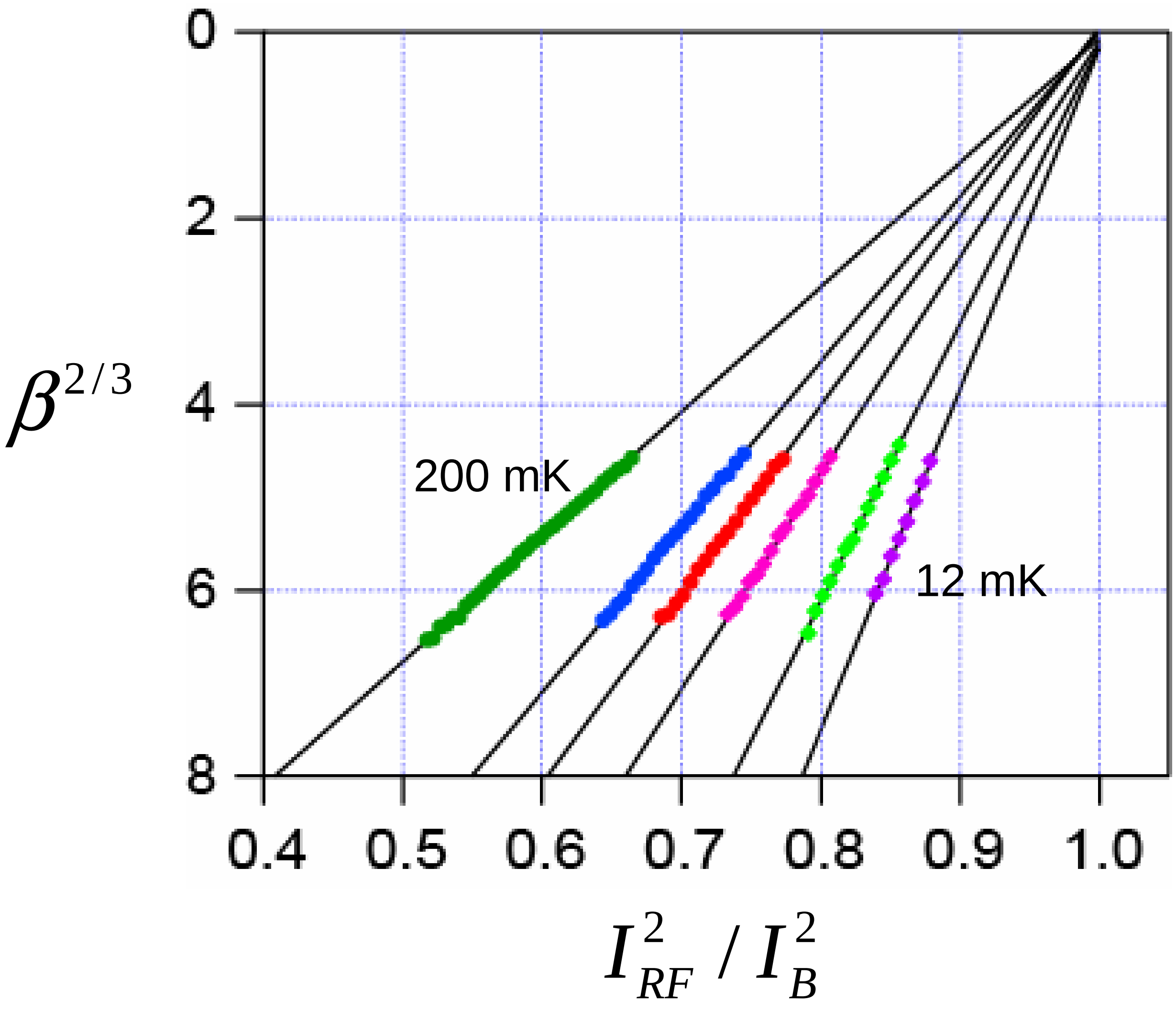




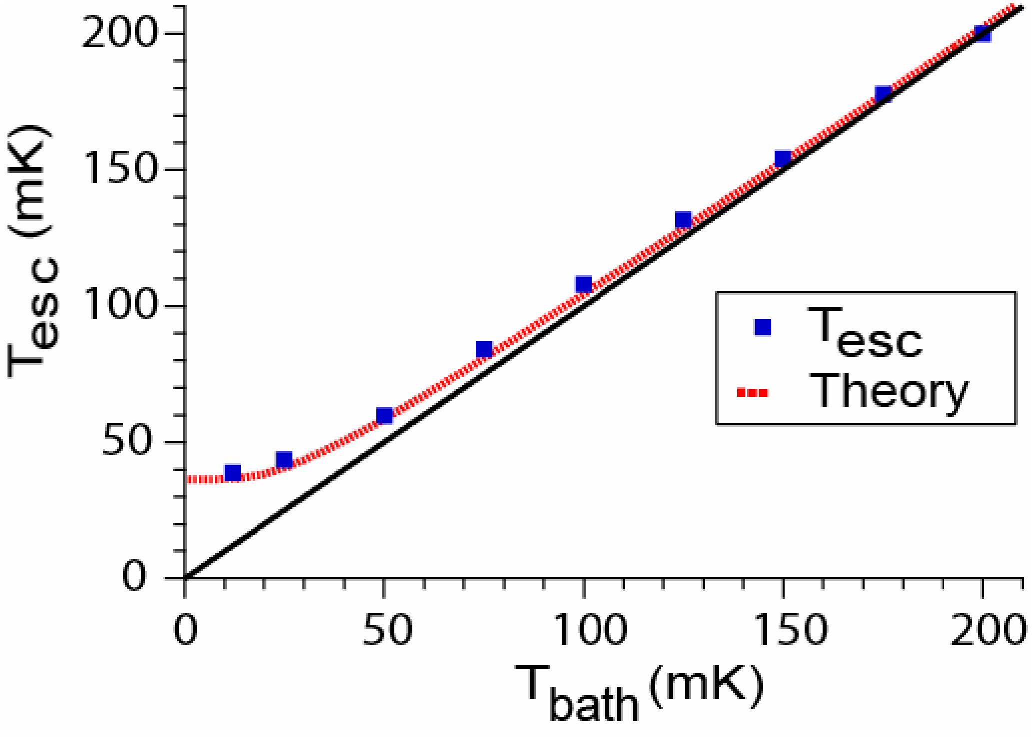
Exponential decay of population

Escape rate vs drive amplitude

MEASURING ESCAPE TEMPERATURE



QUANTUM REGIME



$$k_B T_{esc}^{Q} = \hbar\omega\left(\bar{n} + \frac{1}{2}\right)$$

$$\bar{n} = \frac{1}{exp\left(\hbar\omega / k_B T\right) - 1}$$

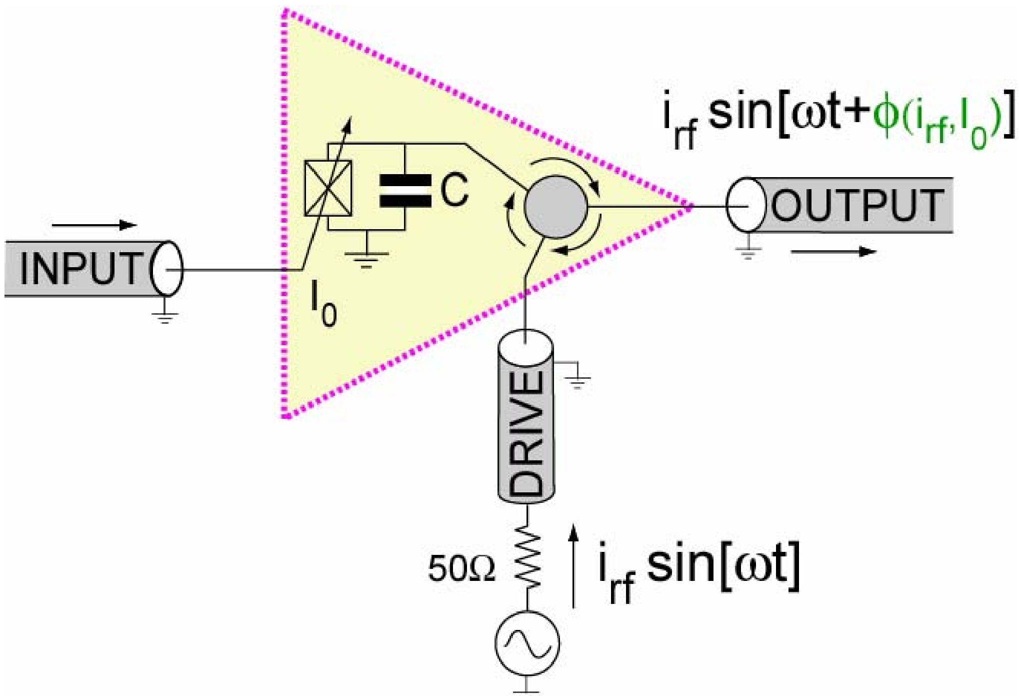
$$\frac{\omega}{2\pi} = 1.525\,GHz$$

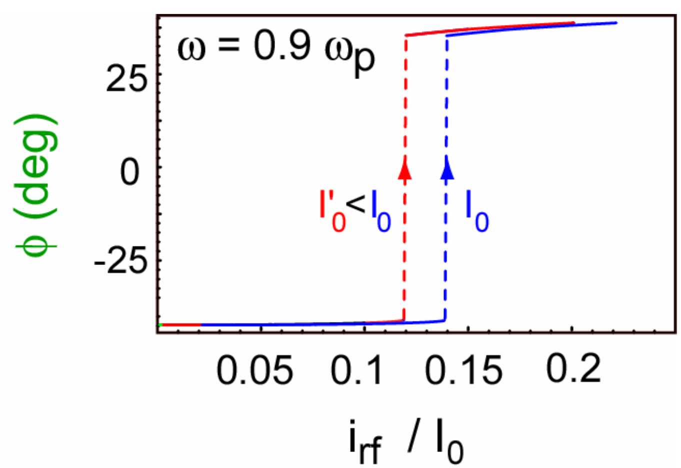
Good agreement with quantum activation theory

Need higher oscillator frequencies

Marthaler et. al. arXiv:cond-mat/0602288

JOSEPHSON BIFURCATION AMPLIFIER

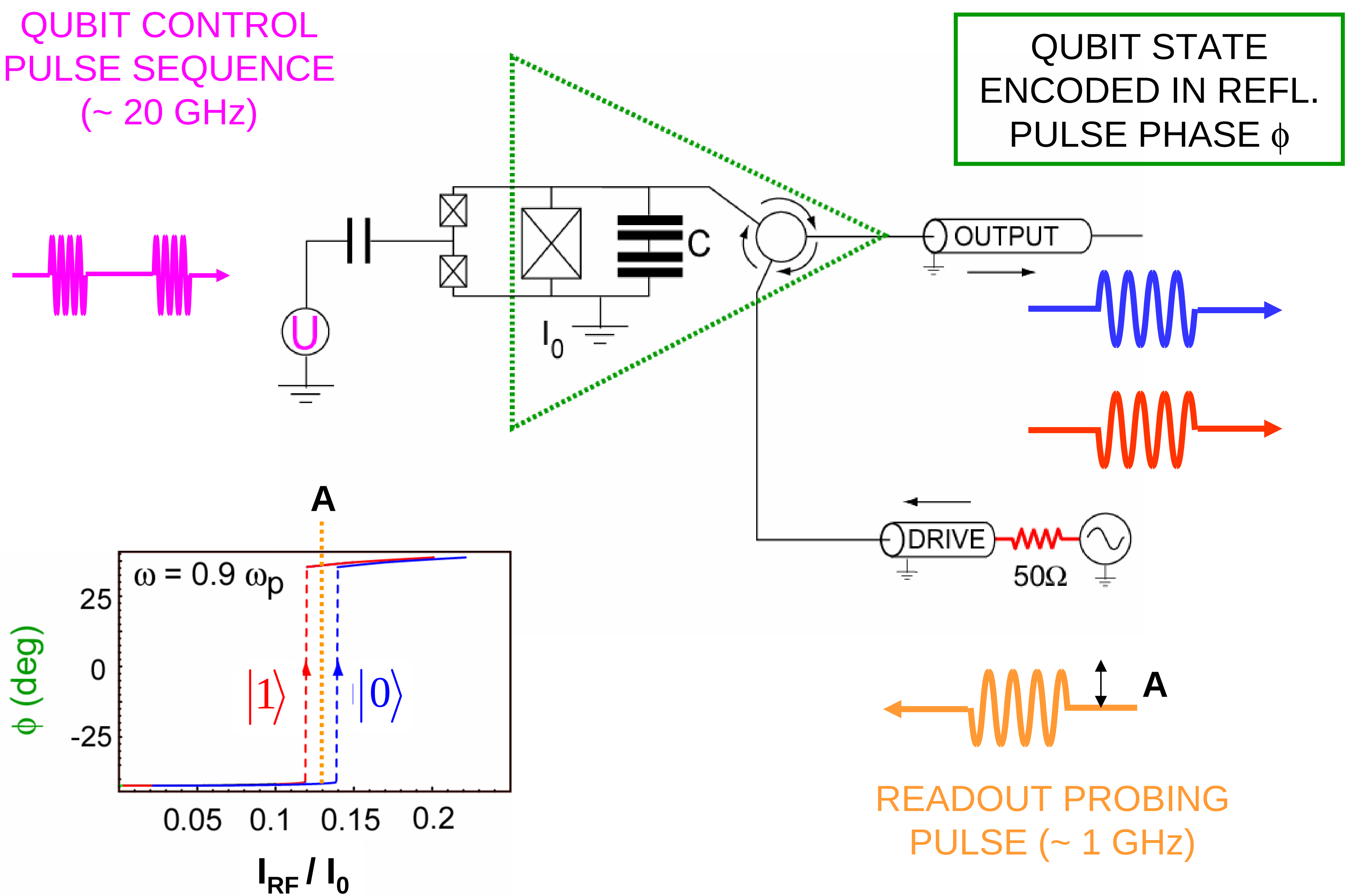


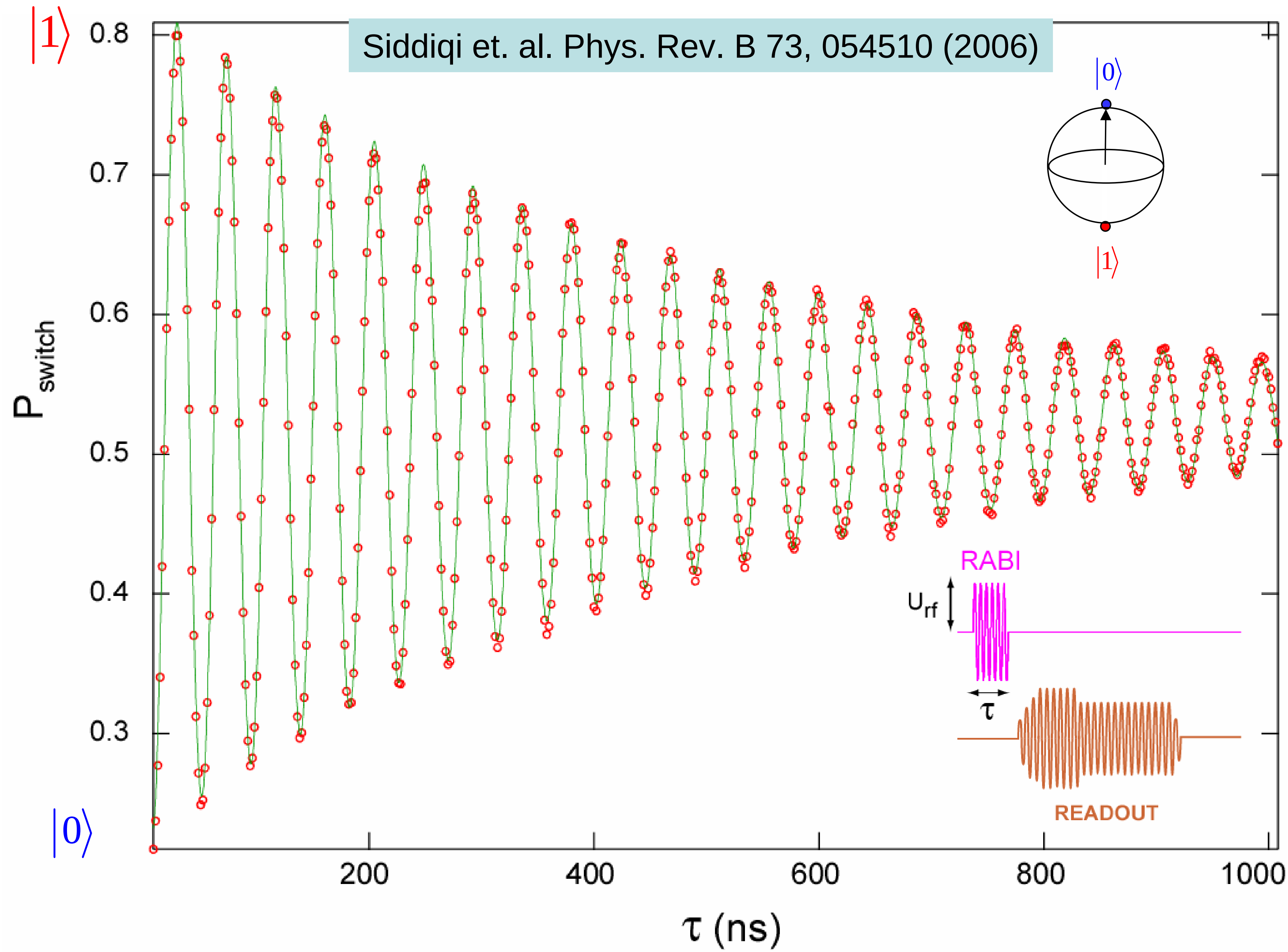


JBA: INPUT COUPLES TO I_0

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

QUBIT READOUT

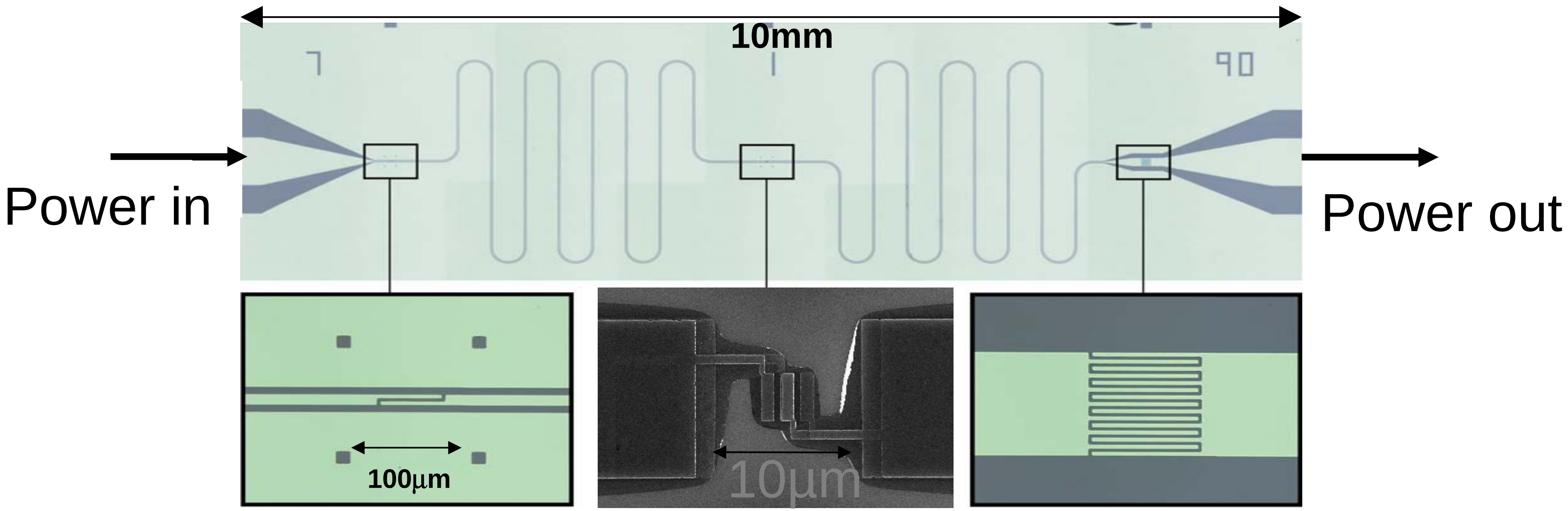




Siddiqi et. al. Phys. Rev. B 73, 054510 (2006)
|1⟩
|0⟩
P_{switch}
0.8
0.7
0.6
0.5
0.4
0.3
200
400
600
800
1000
τ (ns)
|0⟩
|1⟩
RABI
U_{rf}
τ
READOUT

NON-LINEAR CAVITY RESONATORS

Superconducting Nb 1D cavity (1-10GHz)
Al-AlO-Al junction (I_0~0.5-5 μA)

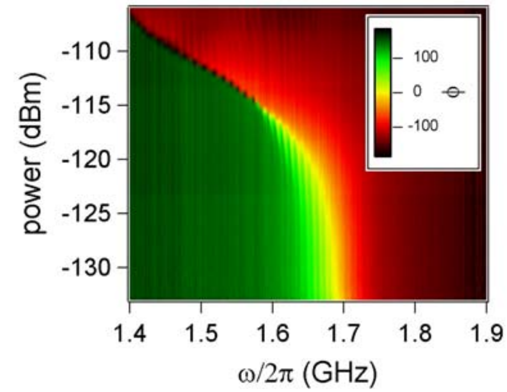


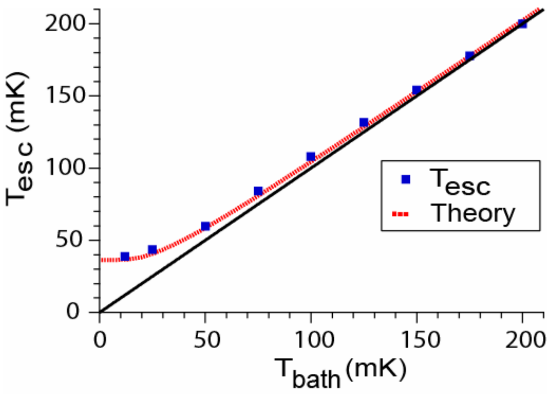
See the following talks later today for more details:

W39.0002 (Vladimir Manucharyan , 2.42 pm , Room 342)
W39.0003 (Etienne Boaknin, 2.54 pm , Room 342)
W39.0004 (Michael Metcalfe, 5.06 pm , Room 342)

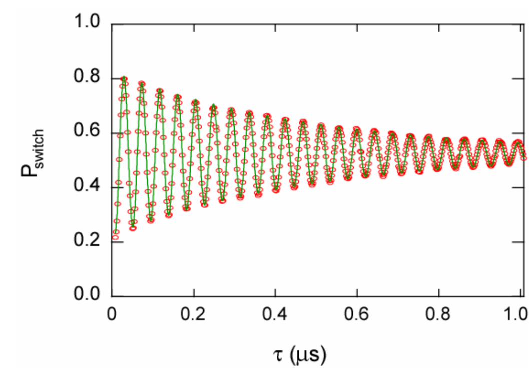
CONCLUSIONS

WELL CONTROLLED NON-LINEAR OSCILLATOR AT GHz FREQUENCIES

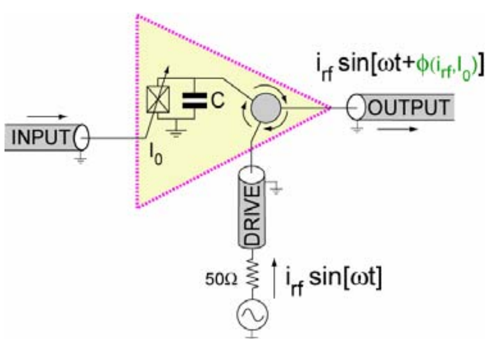




INTERESTING ESCAPE PHYSICS IN THE QUANTUM REGIME



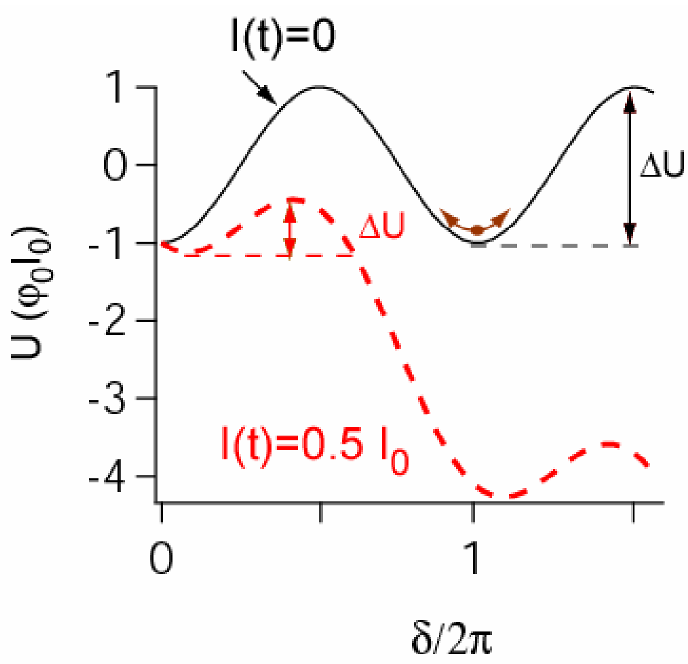
HIGH FIDELITY QUBIT READOUT



TOOLBOX FOR SENSITIVE DETECTORS AND AMPLIFIERS

SLIDES AFTER THIS ARE ADDITIONAL

DC CURRENT BIAS II: Metastability & Switching



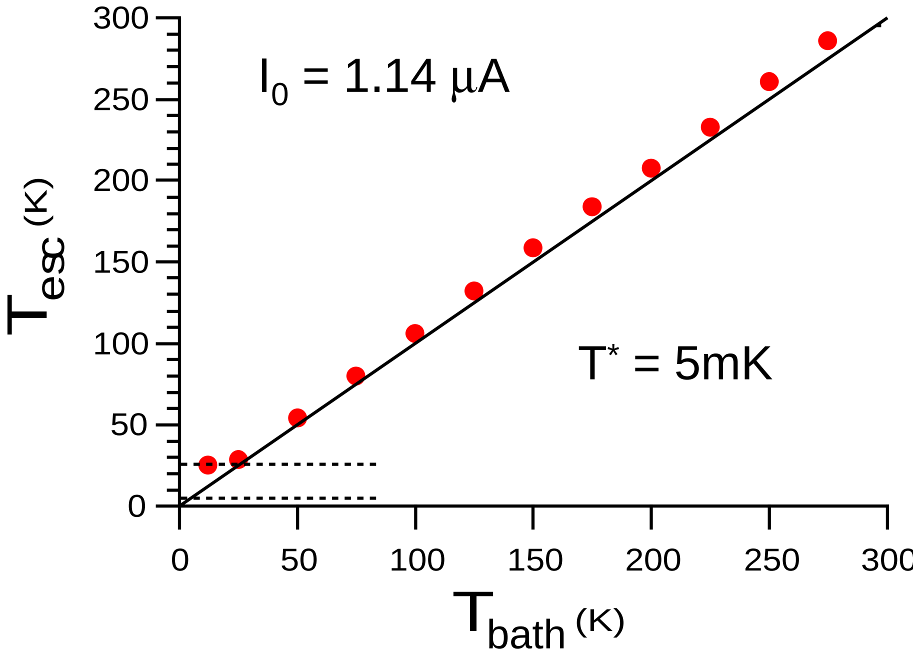
$$\Gamma_{0\to1}\left(I_0, I_{DC}, T\right) = \frac{\omega_p}{2\pi}\exp\left(-\frac{\Delta U}{kT}\right)$$

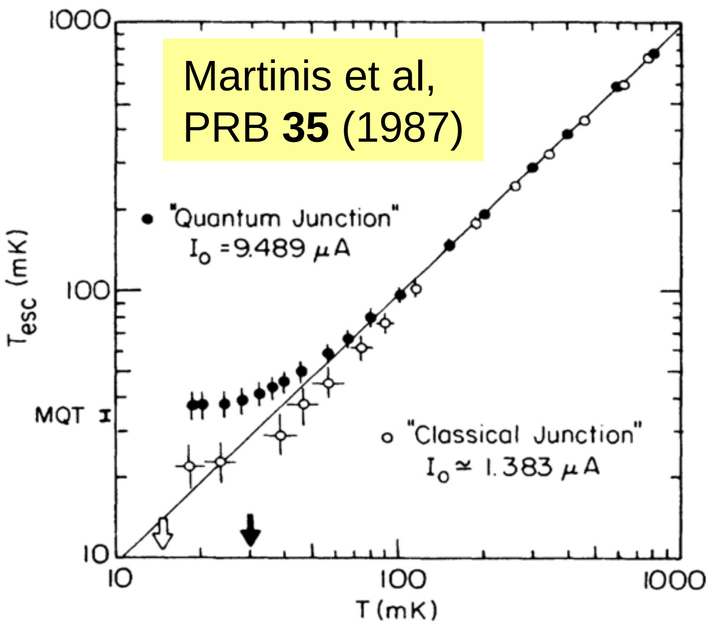
$$\Delta U\left(I_0, I_{DC}\right) = \left[\frac{2\sqrt{2}}{3}\frac{\hbar}{e}I_0\right]\cdot\left(1-\frac{I_{DC}}{I_0}\right)^{3/2}$$

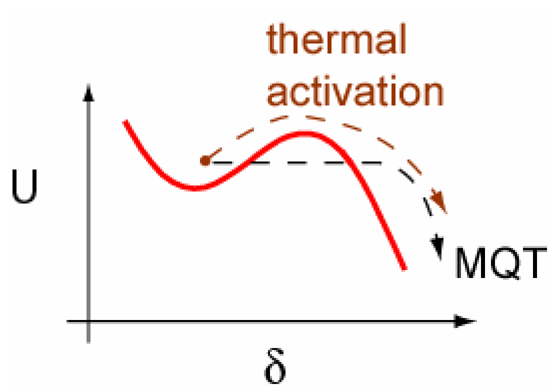
$$\left[\ln\left(\frac{\omega_p}{2\pi\,\Gamma\left(I_{DC}\right)}\right)\right]^{2/3} = \left[\frac{2\sqrt{2}}{3}\frac{\hbar}{e}\frac{I_0}{k_B T}\right]^{2/3}\left(1-\frac{I_{DC}}{I_0}\right)$$

Extract I_0 and escape temperature T_{esc}

DC CURRENT BIAS III: Macroscopic Quantum Tunneling (MQT)







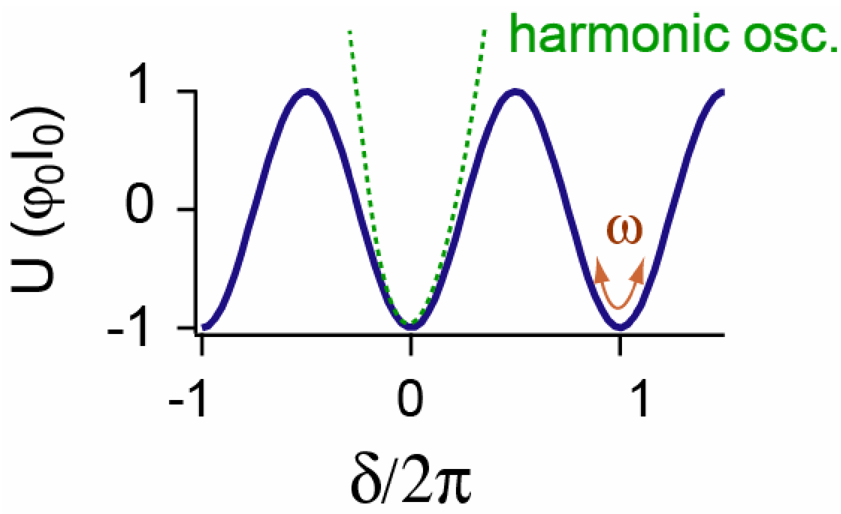
$$T > T^* = \frac{\hbar\omega_p}{7.2k} \quad : \ \Gamma \propto e^{\frac{-\Delta U}{kT}}$$

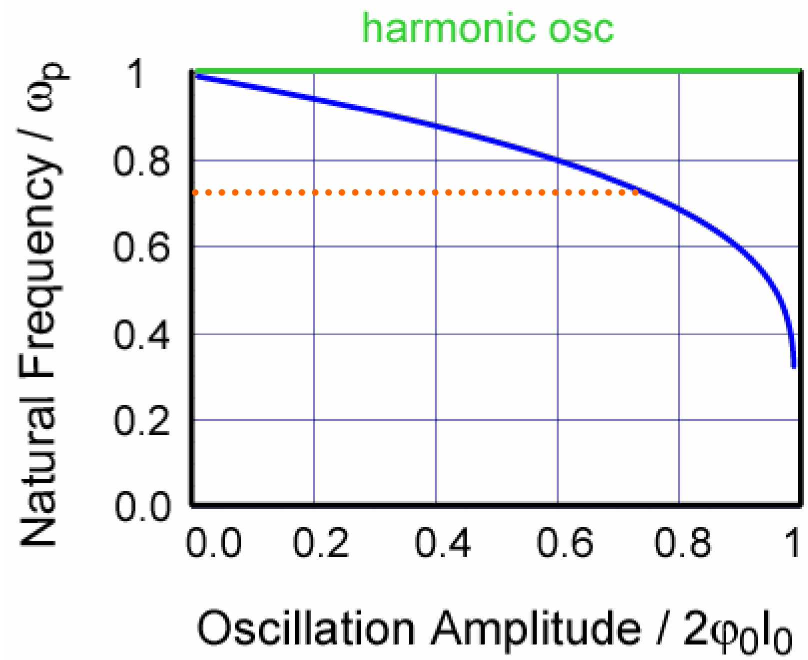
thermal activation

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

MQT

“SOFTENING” POTENTIAL



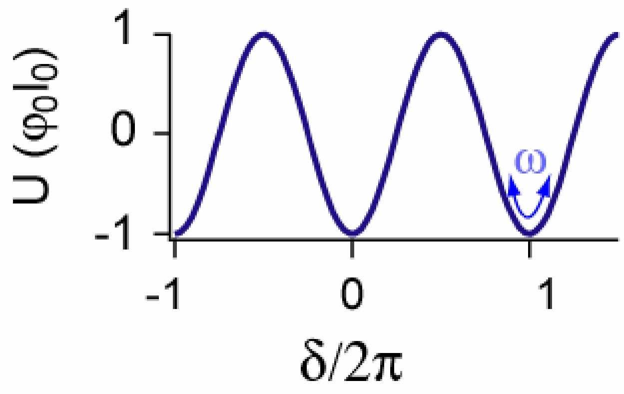


- Frequency decreases with drive amplitude

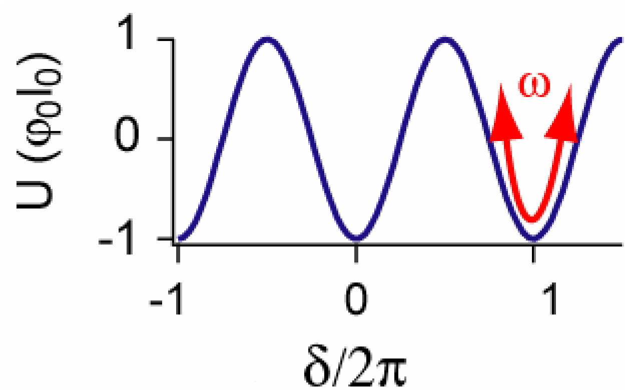
- For $\omega<\omega_p$, weak drive → off resonance
  strong drive → on resonance

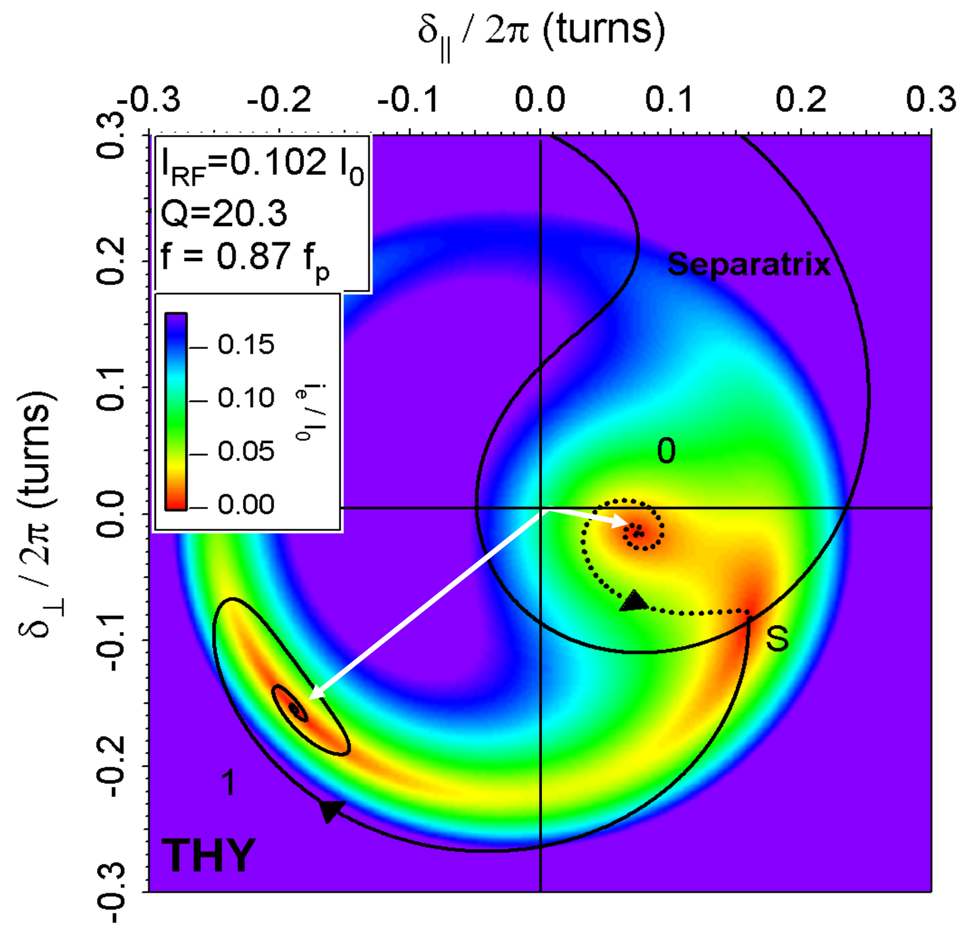
ATTRACTORS

0



1



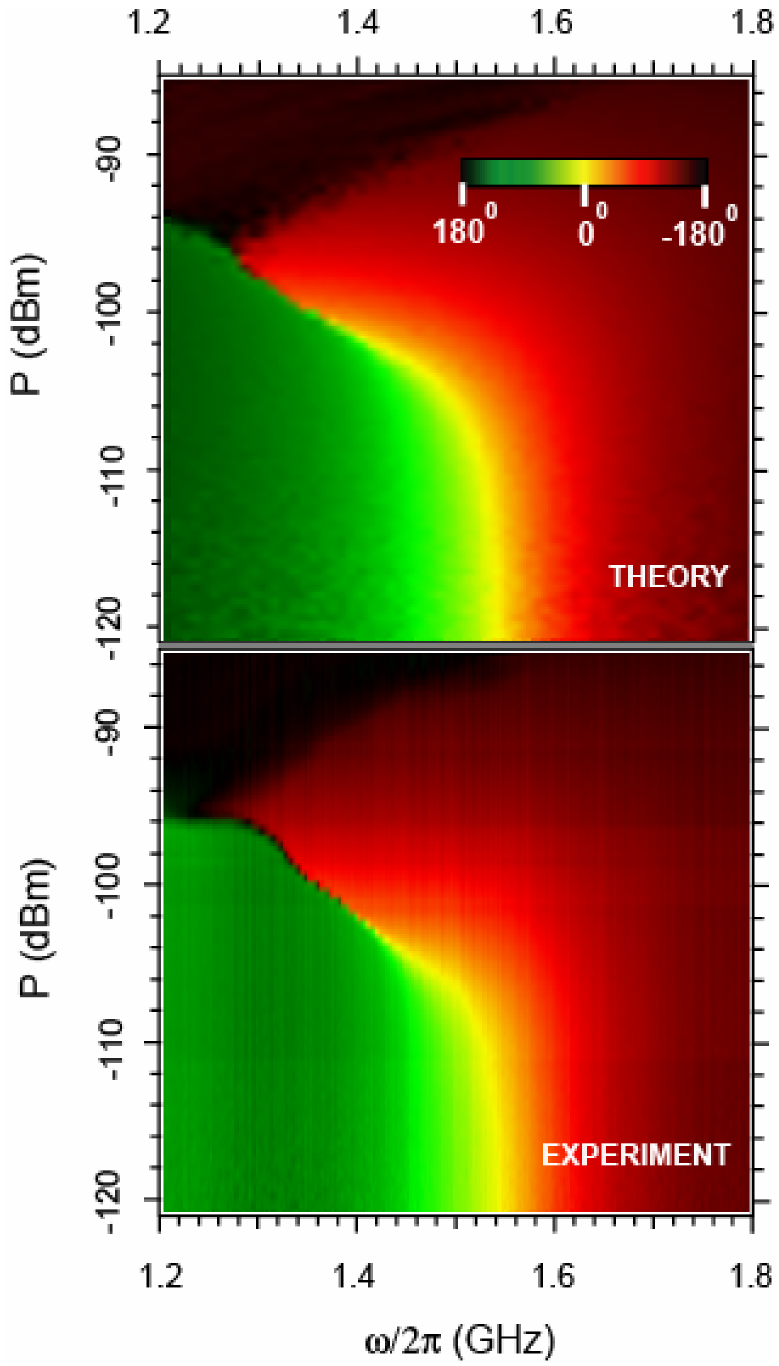


$$\delta(t) = \delta_{\parallel} \sin(\omega t) + \delta_{\perp} \cos(\omega t)$$

PHASE DIAGRAM: EXP & THY IN GOOD AGREEMENT

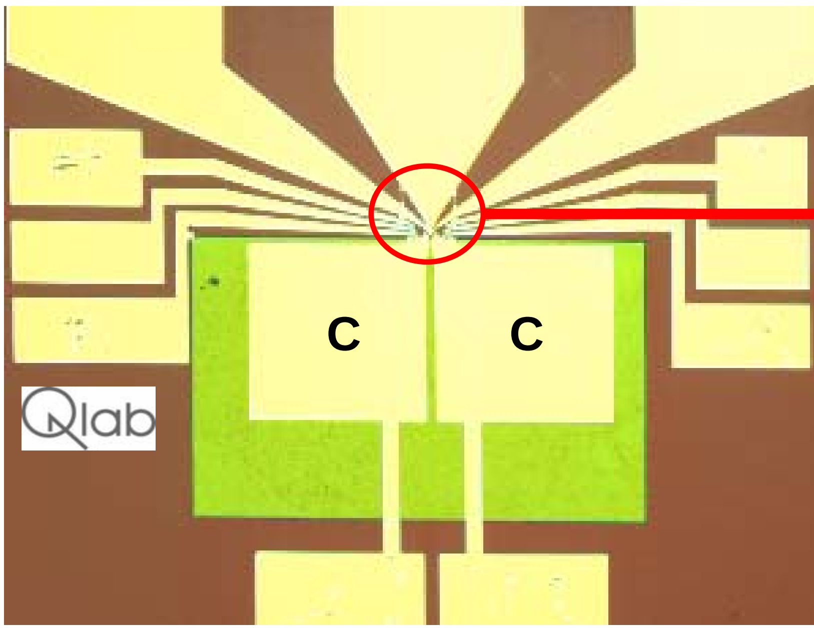
All parameters in prediction measured experimentally!

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



QUBIT + JBA CHIP

WRITE PORT



READ PORT