Amplifying Quantum Signals with the Josephson Bifurcation Amplifier (JBA)

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LUX ET VERITAS

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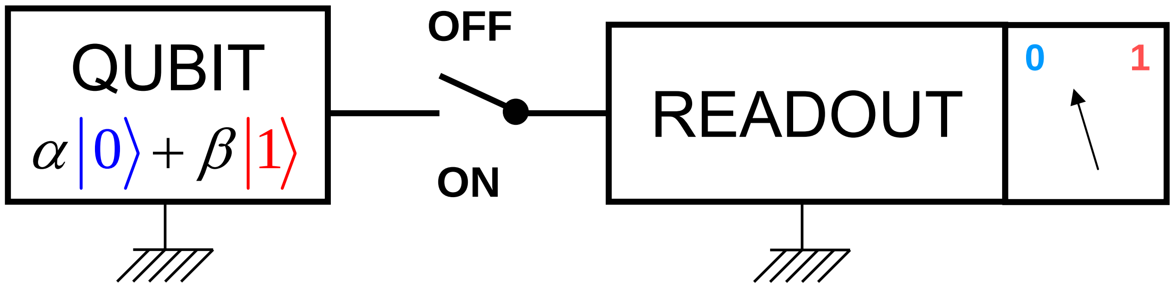
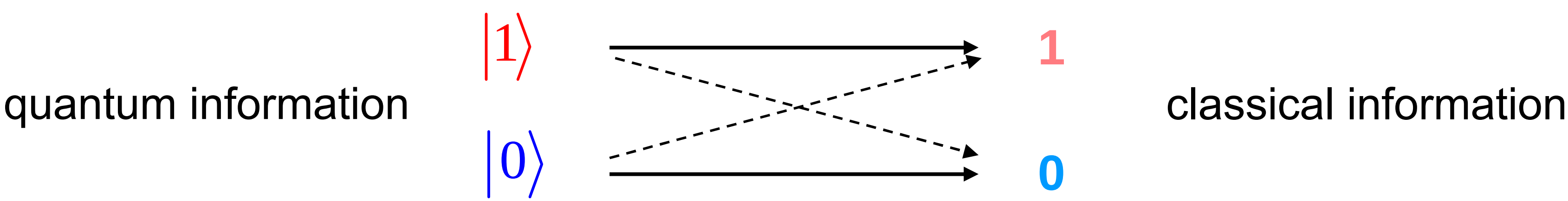
THE READOUT PROBLEM FOR SQUBITS

Devoret & Schoelkopf (2000)

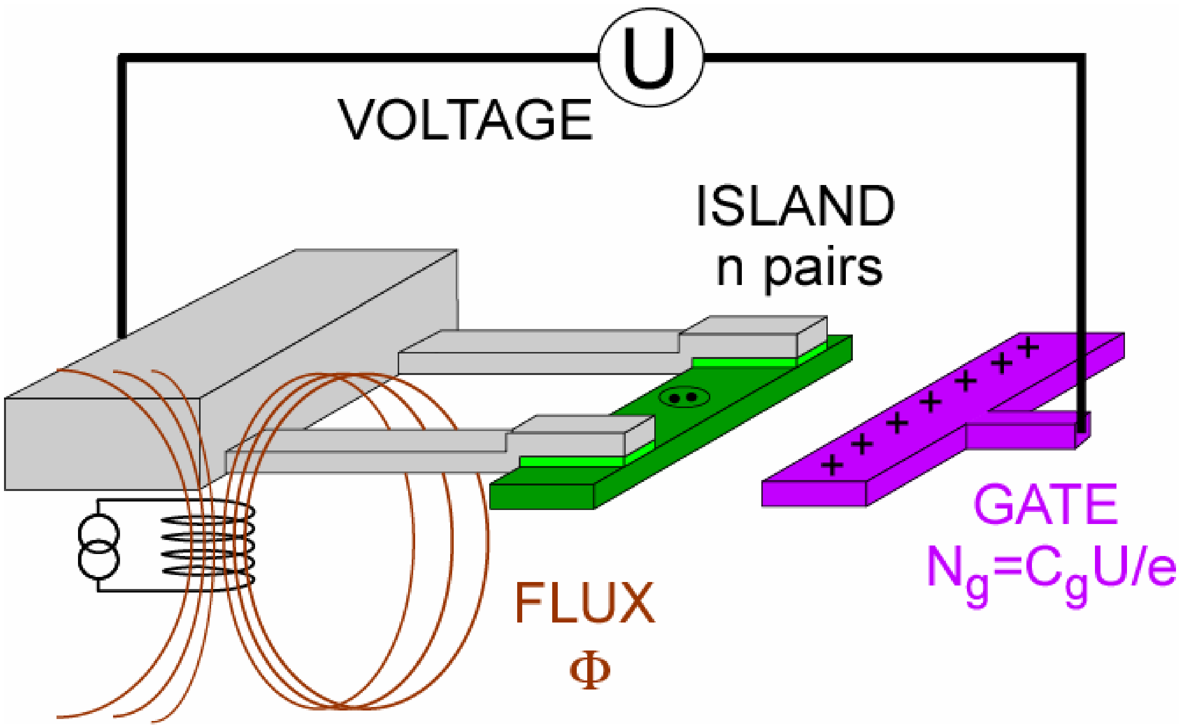




WANT:

- Readout ON: $T_1 / \tau_{meas} >> 1$ (sensitivity, low backaction)
- Readout OFF: T_1, T_φ not reduced (good switch, low backaction)
- Short duty cycle (speed to fight drifts)
- No energy dissipated on chip (no noise to junction)

ARTIFICIAL ATOM : SPLIT COOPER PAIR BOX



$$\hat{H} = \sum_n \left[E_C (n - N_g)^2 |n\rangle\langle n| \quad - \quad \tfrac{1}{2} E_j \cos\left(\frac{\Phi/\Phi_0}{2}\right)\left(|n\rangle\langle n+1| - |n+1\rangle\langle n|\right) \right]$$

$$E_C = \frac{(2e)^2}{2(C_g + C_{j1} + C_{j2})}$$

$$E_j = \frac{\hbar}{2e} i_0 = \varphi_0 i_0$$

BOX ENERGY SPECTRUM

charge

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

capacitance

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

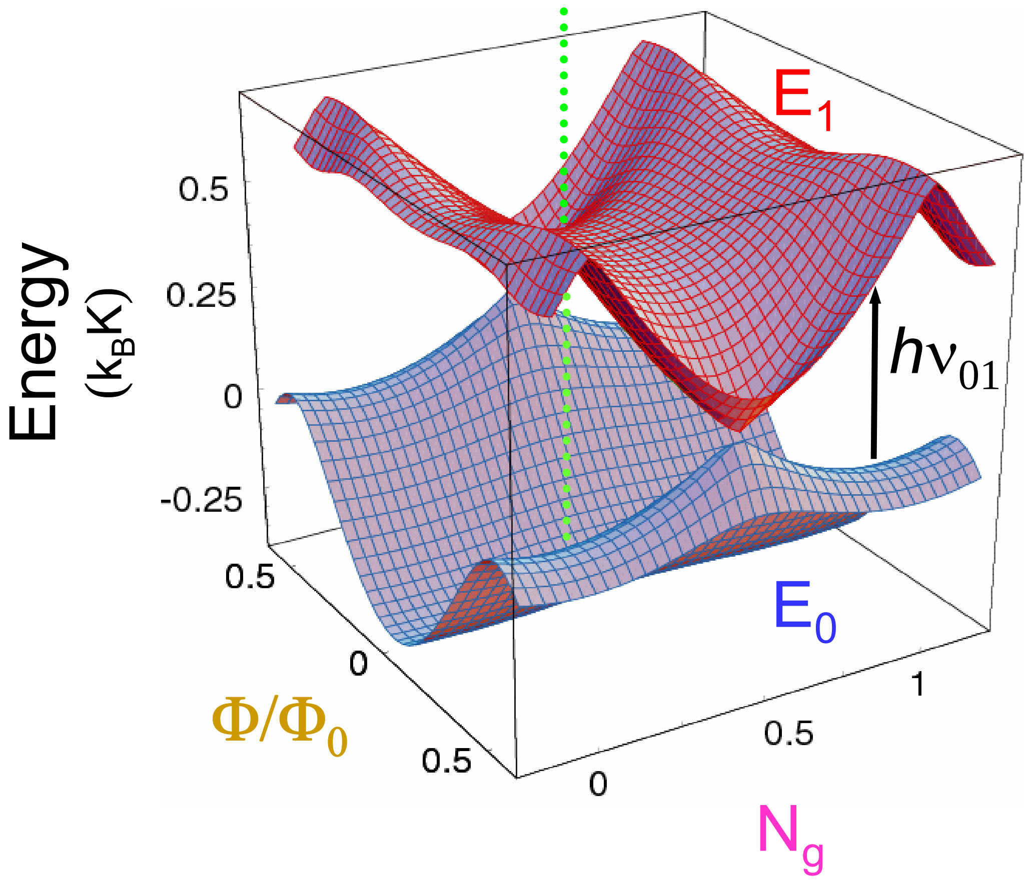
current

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

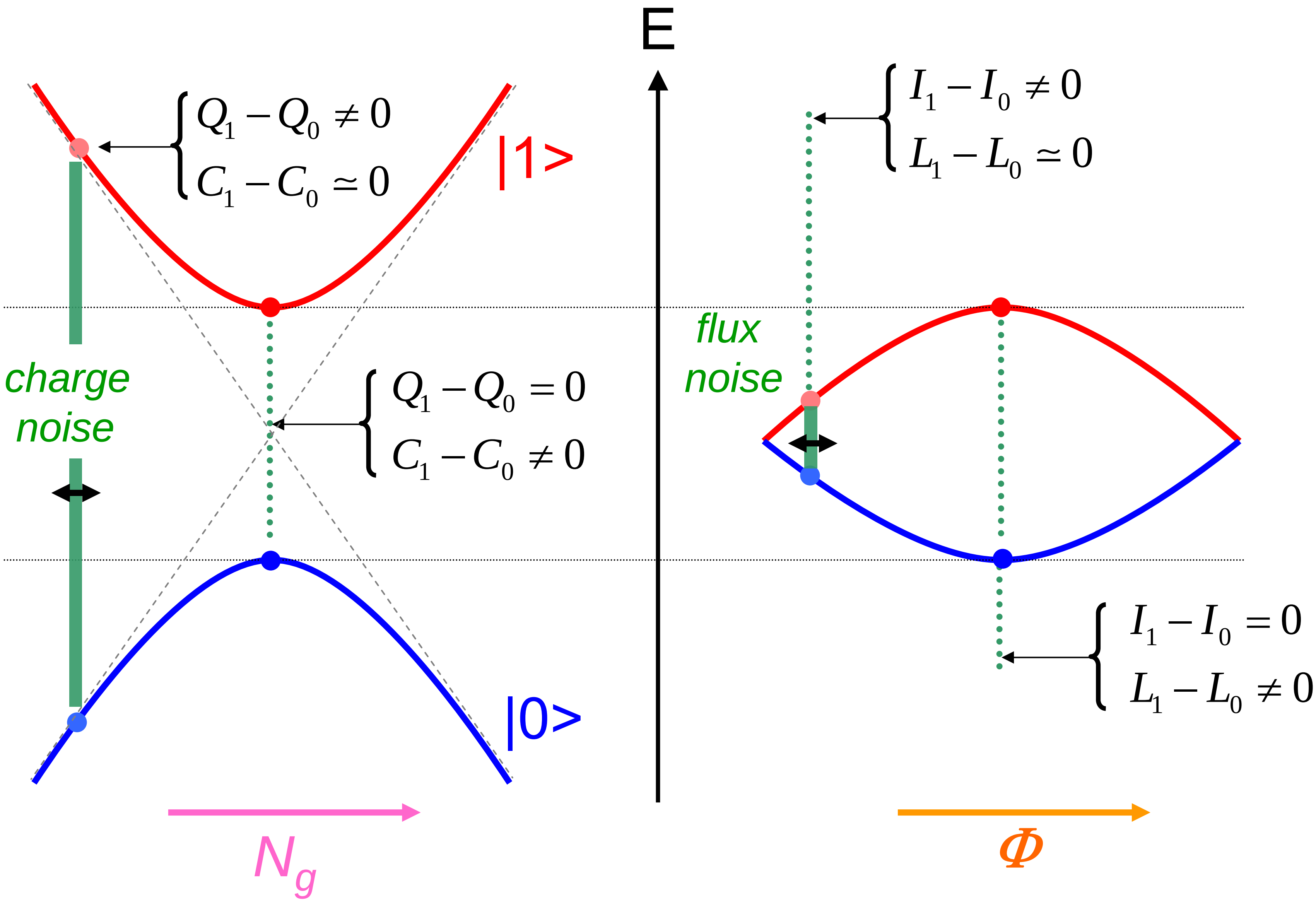
inductance

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

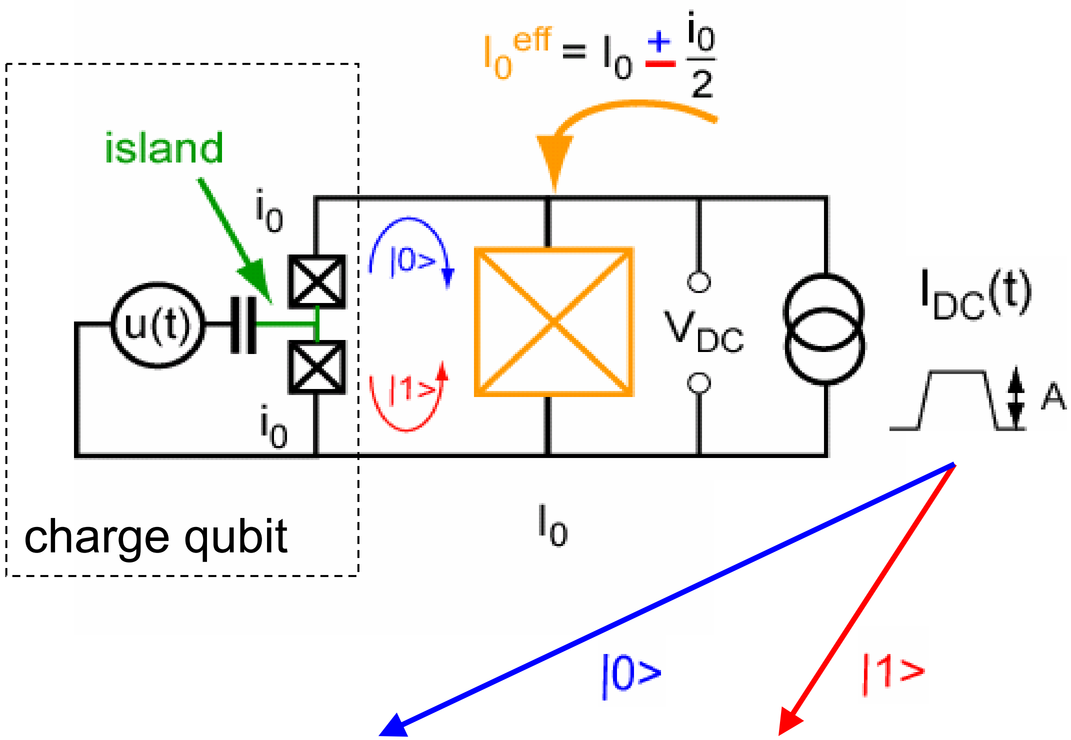
Optimum Working Point



CAN'T READ CHARGE OR CURRENT!



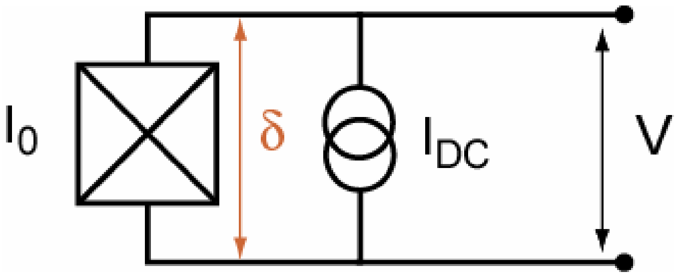
QUANTRONIUM (a.k.a. Charge-Phase Qubit)



$A < I_0^{eff}$	$A > I_0^{eff}$
Superconducting	Dissipative
$V_{DC}=0$	$V_{DC}=2\Delta/e$
(DC Readout 0)	(DC Readout 1)

- $I_{DC}=0 \rightarrow$ Readout off
- 1/f charge & flux noise immunity
- T_1 = 1.8 μs
  T_ϕ = 500 ns ~10^3 ops!
  (D. Vion et al., Science 2002)
- **Quasiparticles**
  -slow reset (>10μs)
- **Reduced Visibility**

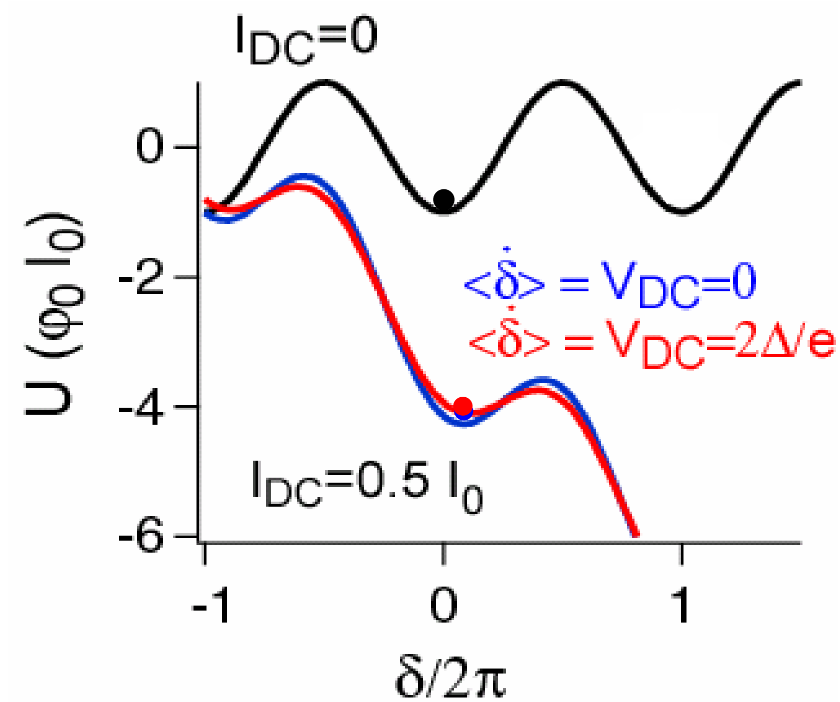
DC DRIVE



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

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

Josephson



$$L_J = \frac{\varphi_0}{I_0}\frac{1}{\cos(\delta)}$$

$$U = -\frac{\hbar}{2e} I_0 \cos(\delta) \; - \; \frac{\overbrace{\hbar}^{\varphi_0}}{2e} I_{DC}\delta$$

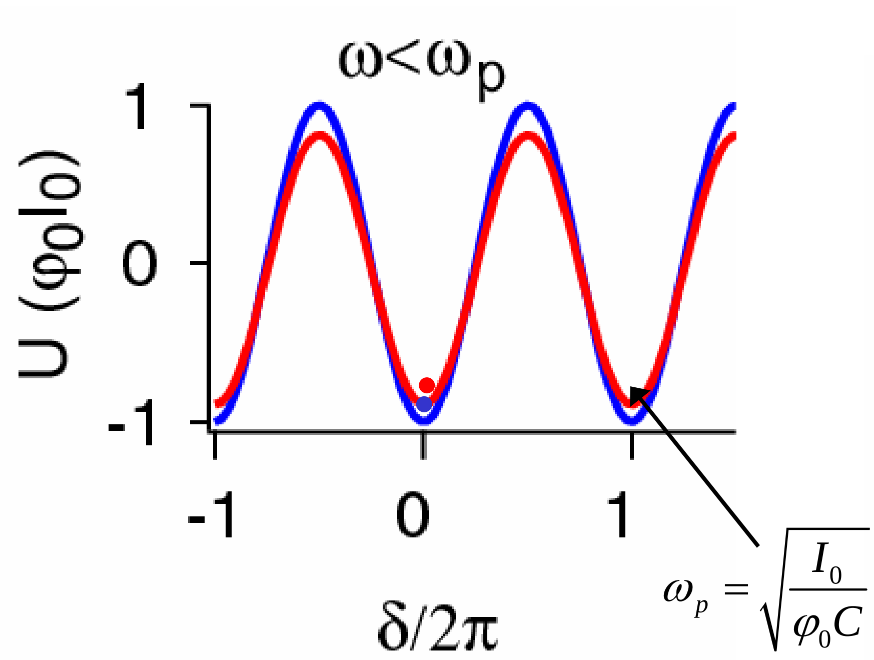
|qubit=0> → ($I_{DC} < I_0$) zero-voltage state

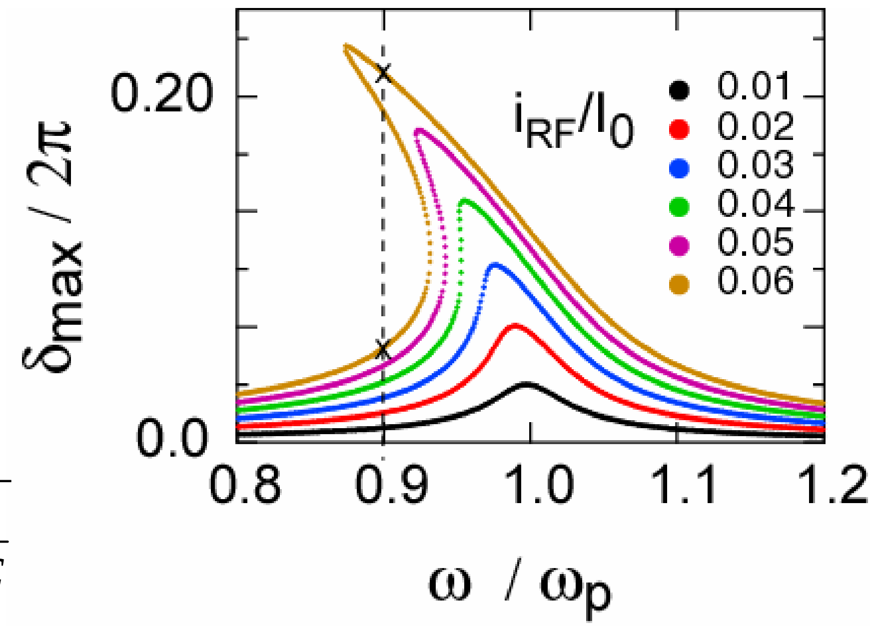
|qubit=1> → ($I_{DC} > I_0$) voltage state

READOUT: WHY NOT USE PHOTONS?

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

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

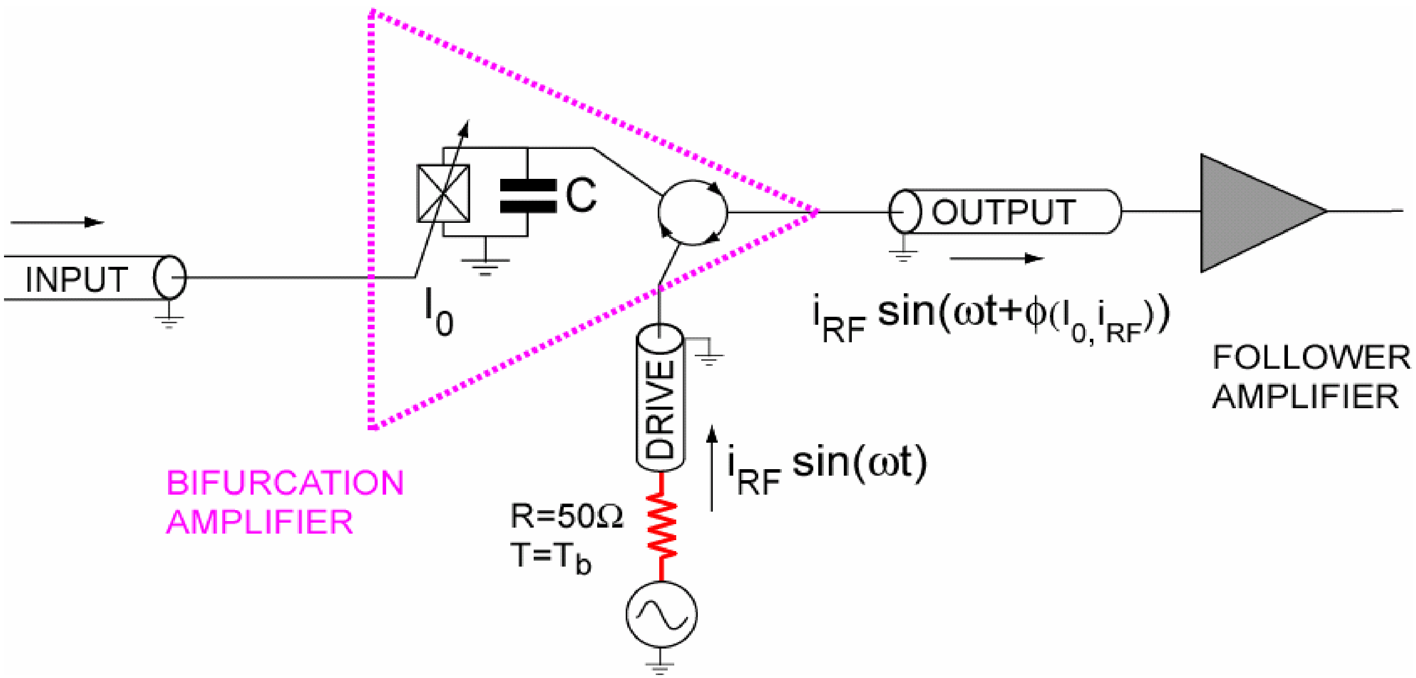




$i_{RF} < i_B\,(I_0,\Delta\omega)$ → low-amp. & phase lagging (RF readout 0)

$i_{RF} > i_B\,(I_0,\Delta\omega)$ → high-amp. & phase leading (RF readout 1)

BIFURCATION AMPLIFICATION

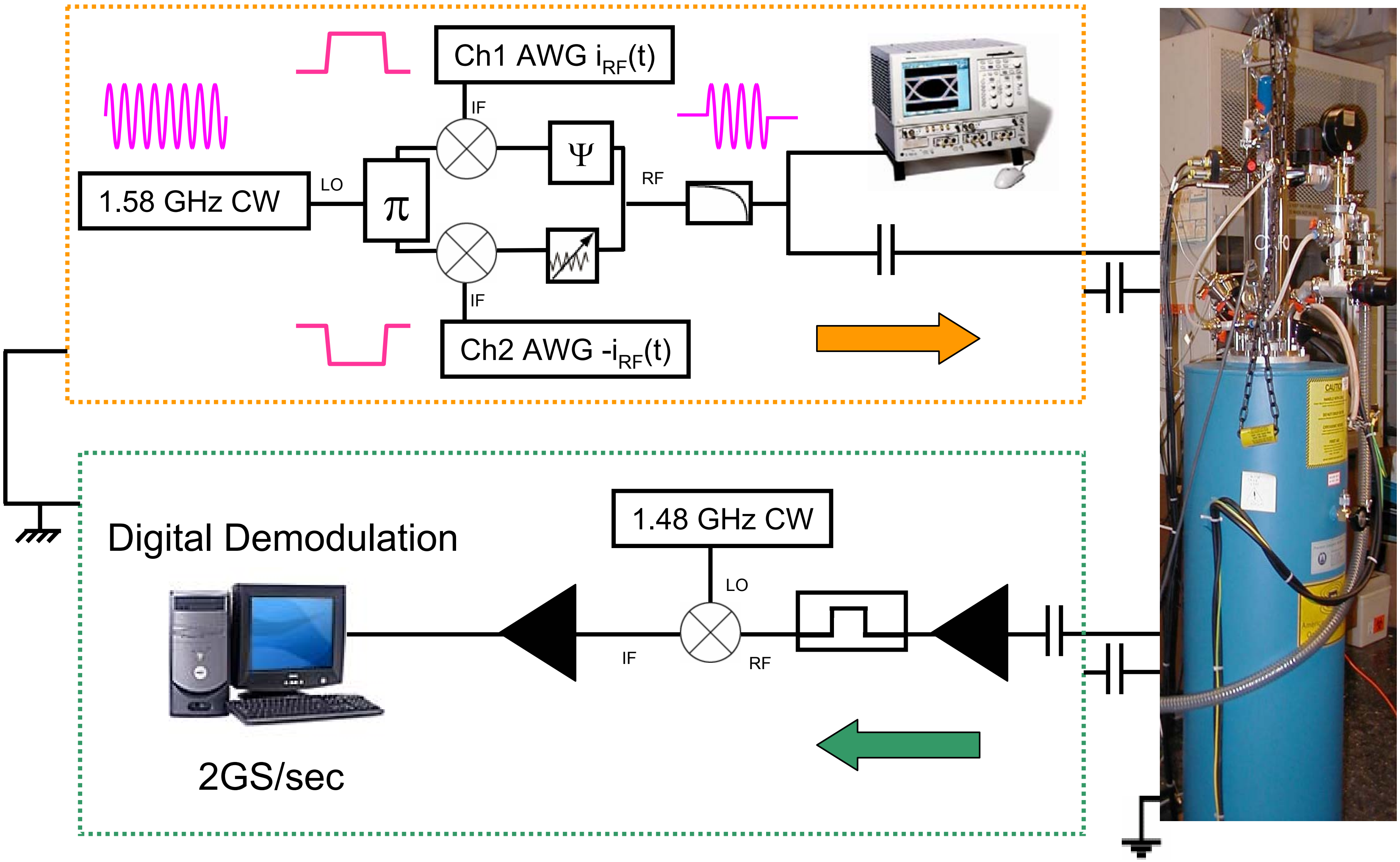


• Bifurcation amplifier: sensitive to any input variable coupled to I_0

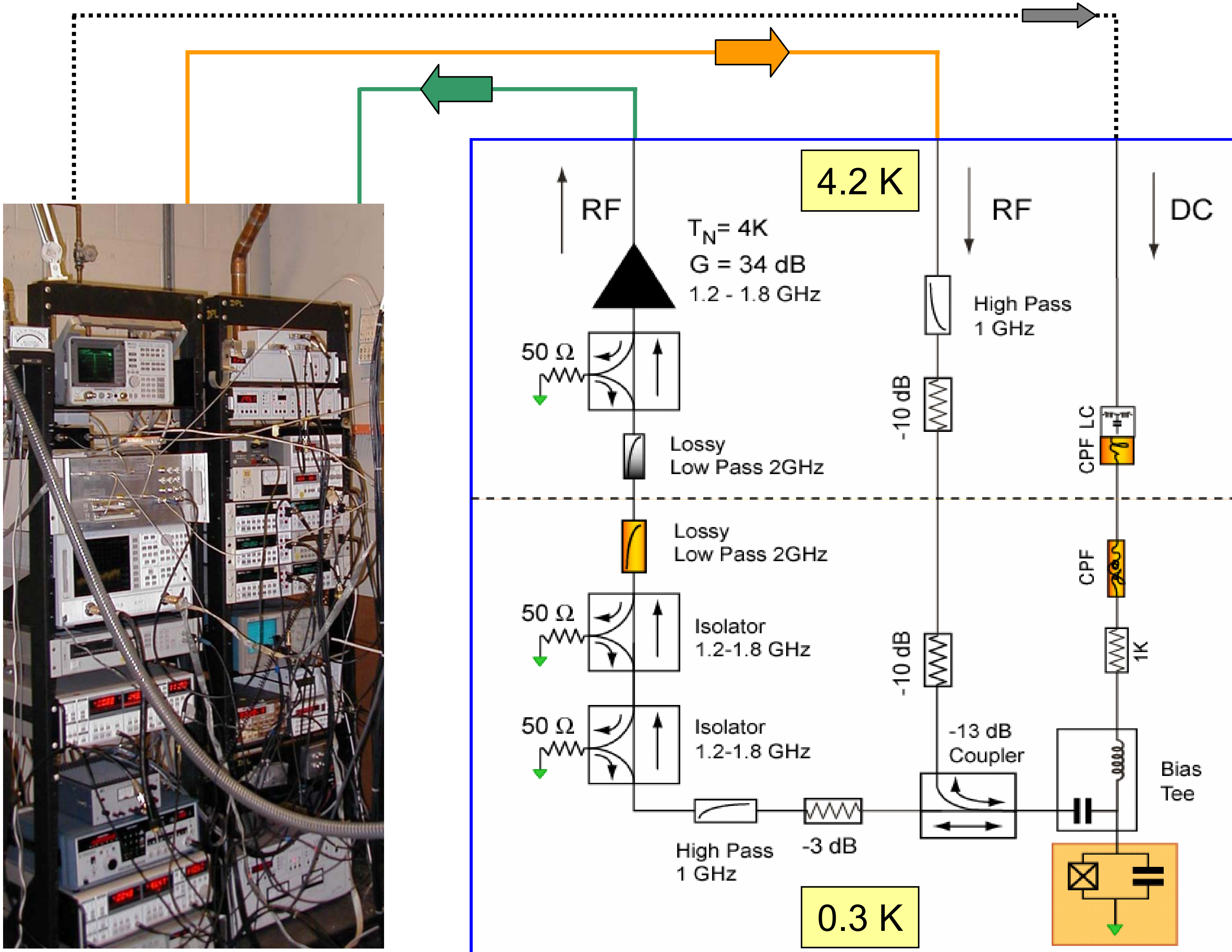
minimal back-action

- no on-chip dissipation
- efficiently thermalize load
- back-action narrow band

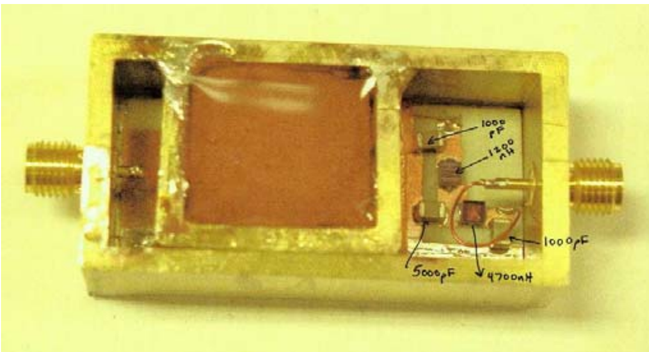
SCHEMATIC RF SETUP T = 300K

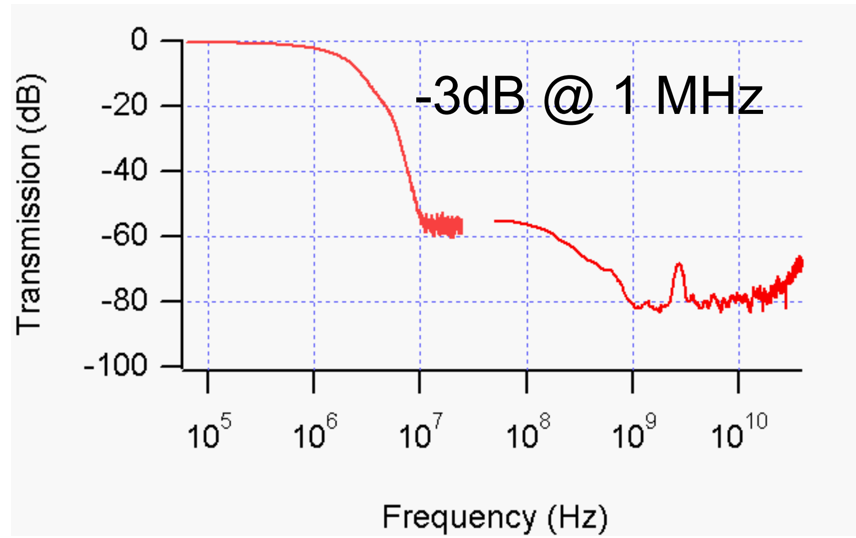


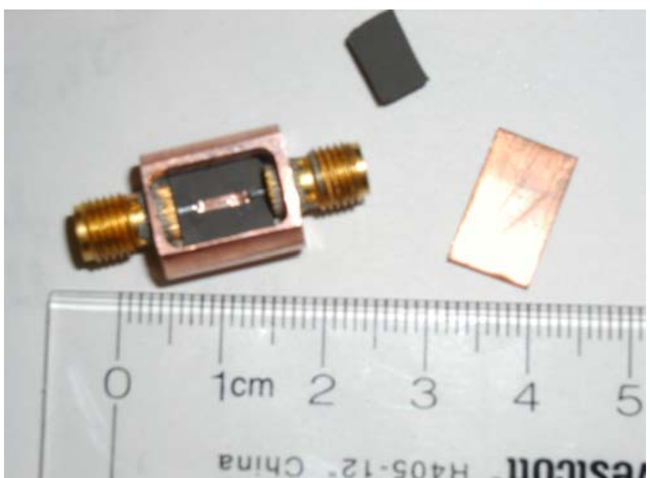
SCHEMATIC CRYOGENIC SETUP

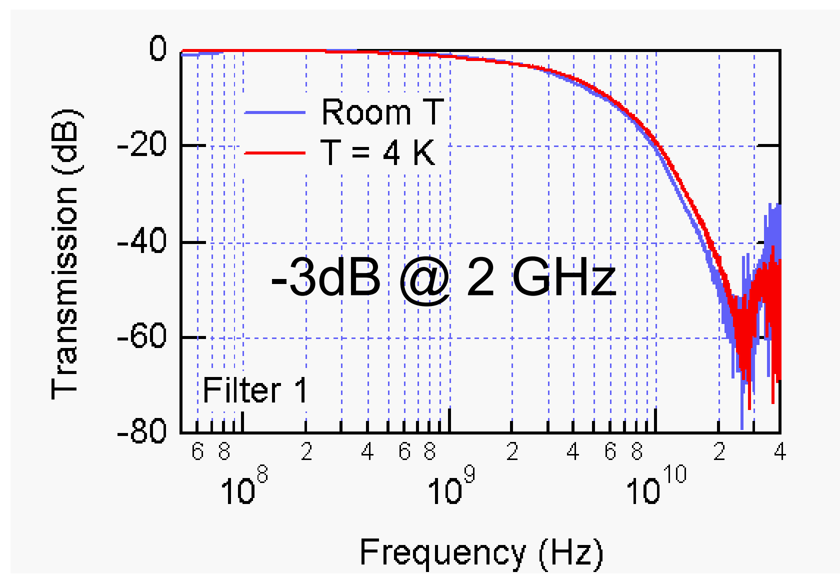


NEW ERA OF FILTERS !

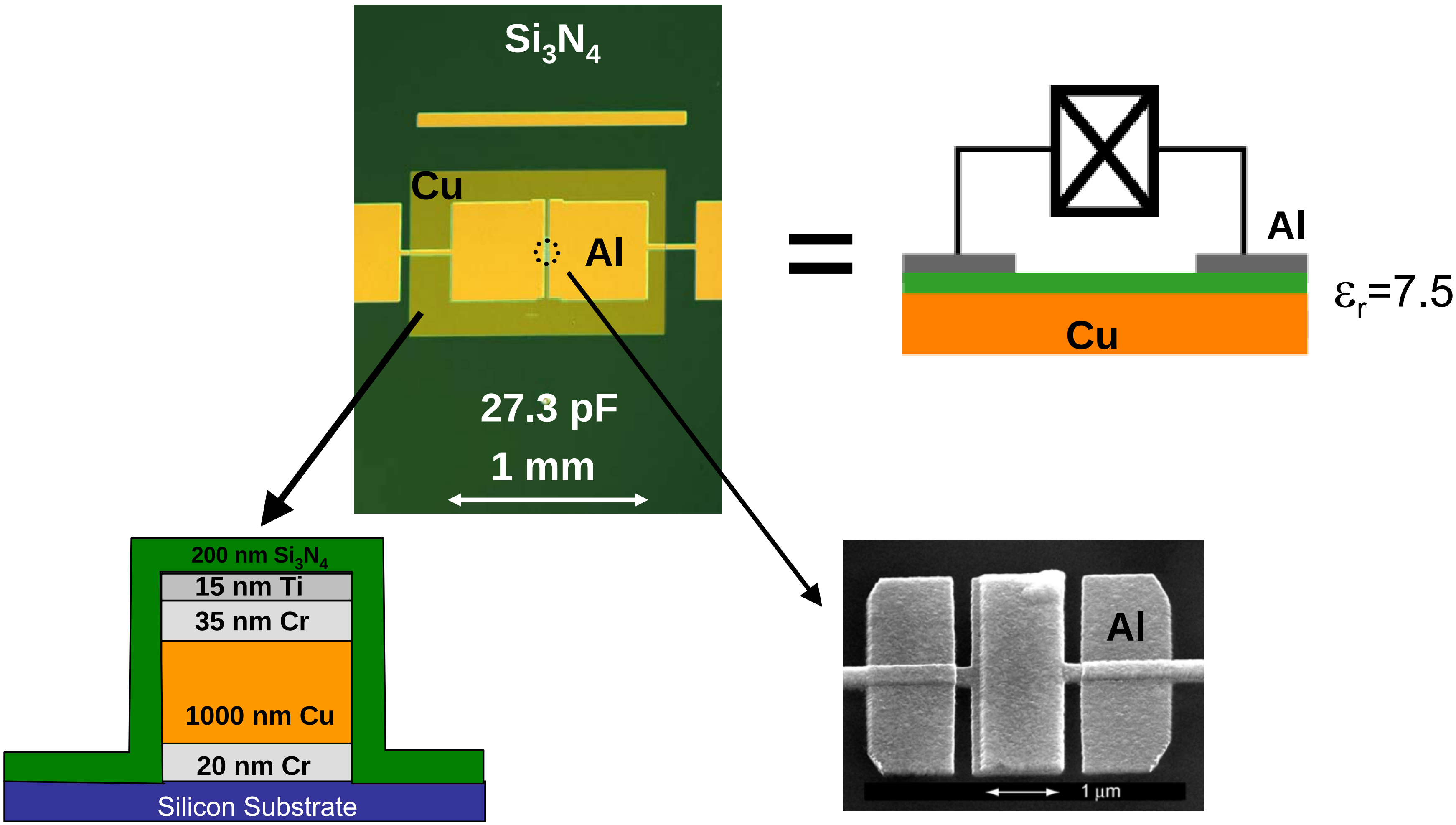








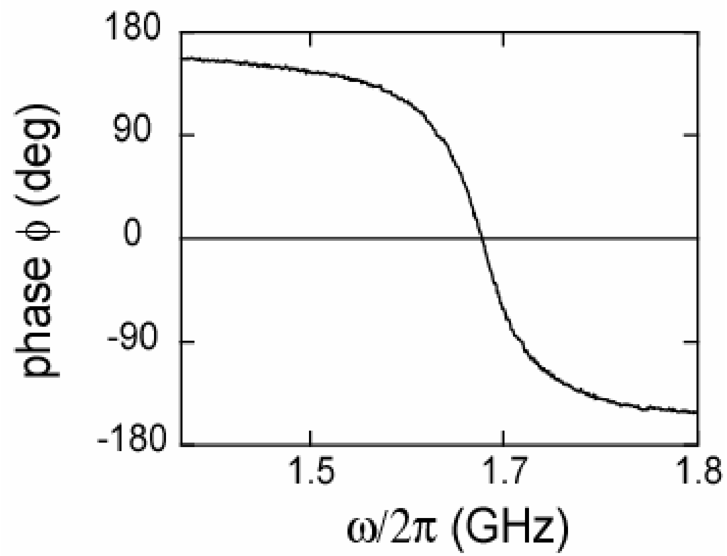
JUNCTION + MICROWAVE CAPACITOR

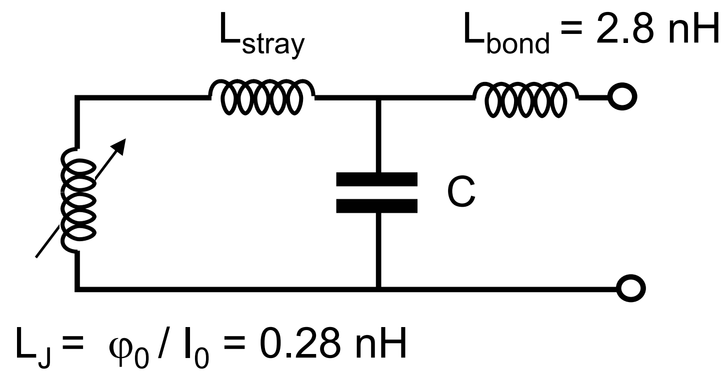


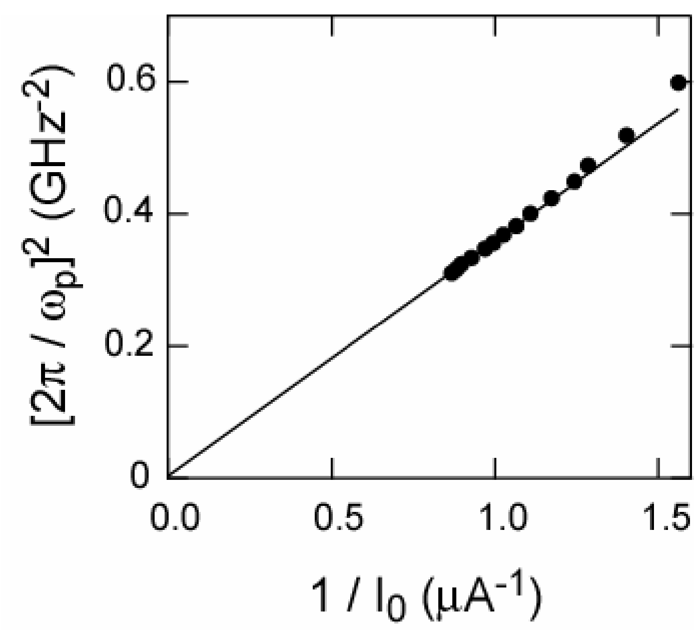
METALLIC UNDERLAYER

$Al/Al_2O_3/Al$ Junction (1.17 µA)

MINIMAL STRAY INDUCTANCE





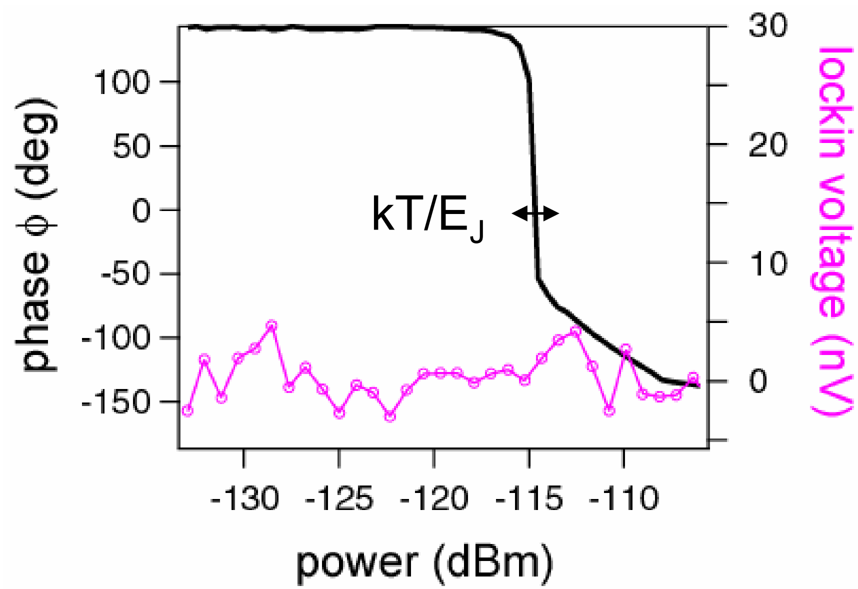


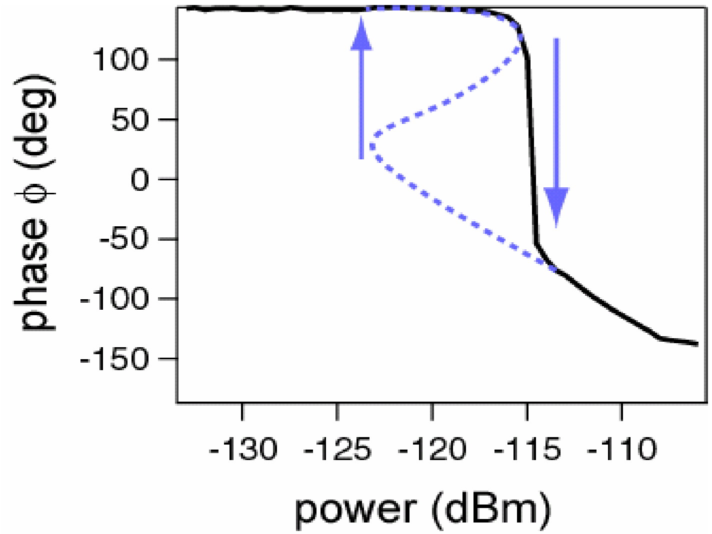
$$\frac{1}{\omega_p^2} = \frac{\hbar}{2e} C \frac{1}{I_0} + C\, L_{stray}$$

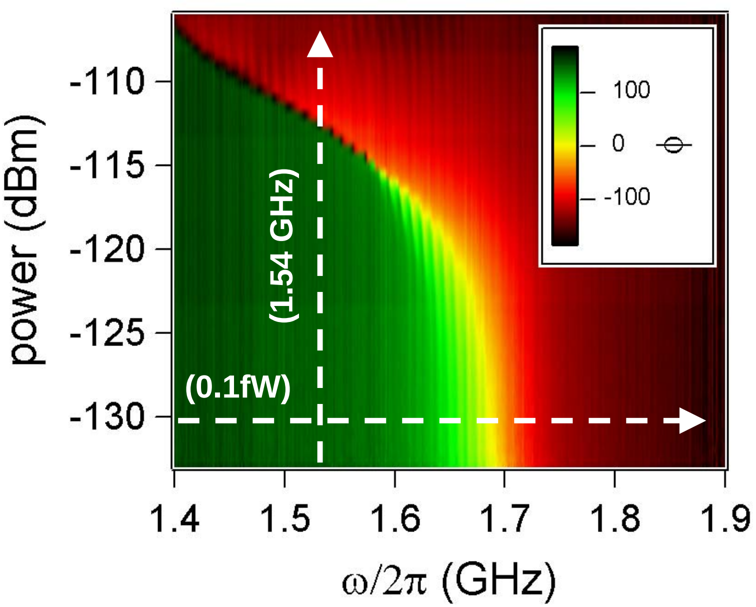
L_{stray} = 0.003 nH

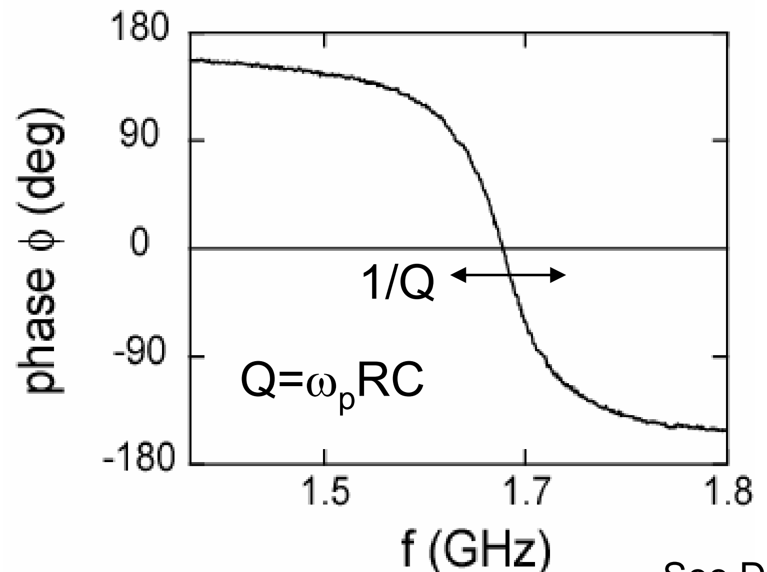
C = 27.3 pF

RF-DRIVEN JUNCTION: PHASE DIAGRAM







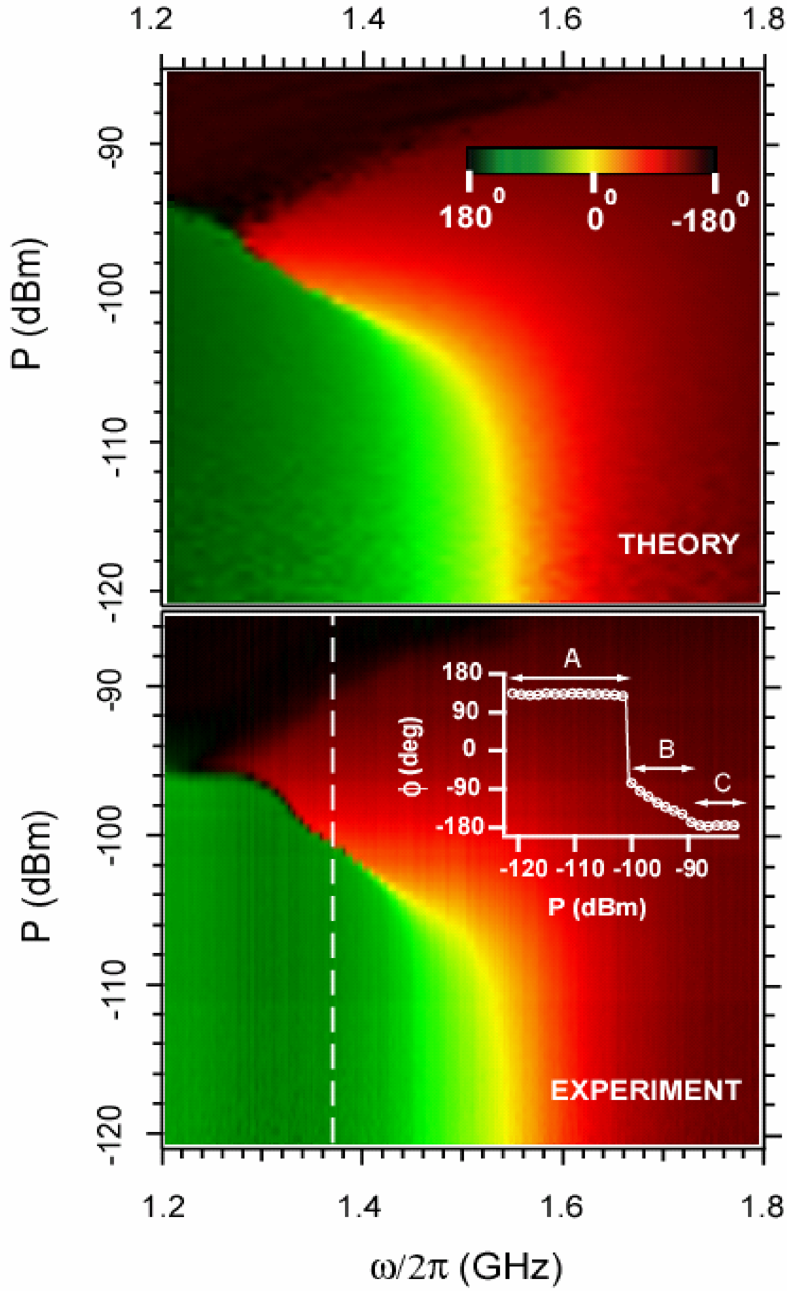


See Delft

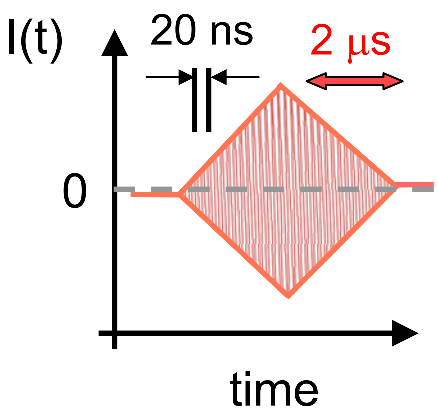
PHASE DIAGRAM: EXP & THY IN GOOD AGEEMENT

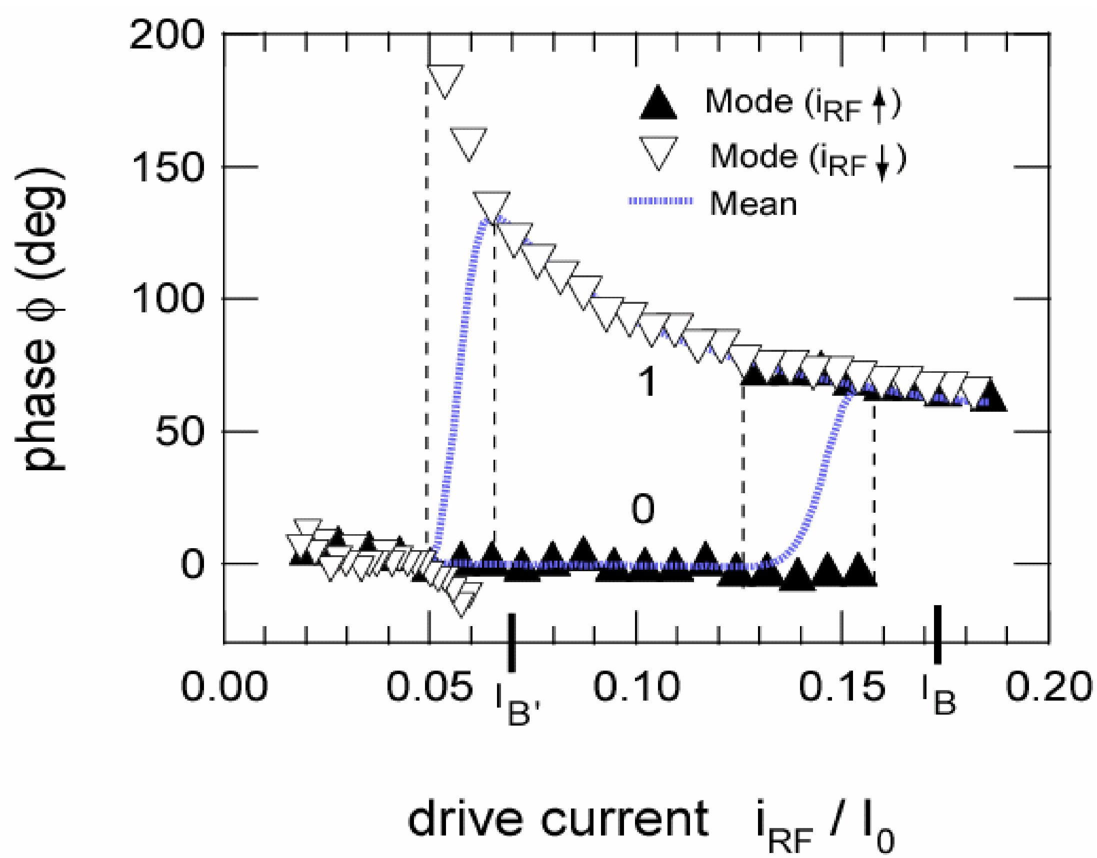
- Dark region corresponds to well-jumping
- All parameters in prediction measured experimentally!

I.S. *et al*, cond-mat/0312553



DYNAMICS OF DYNAMICAL SWITCHING

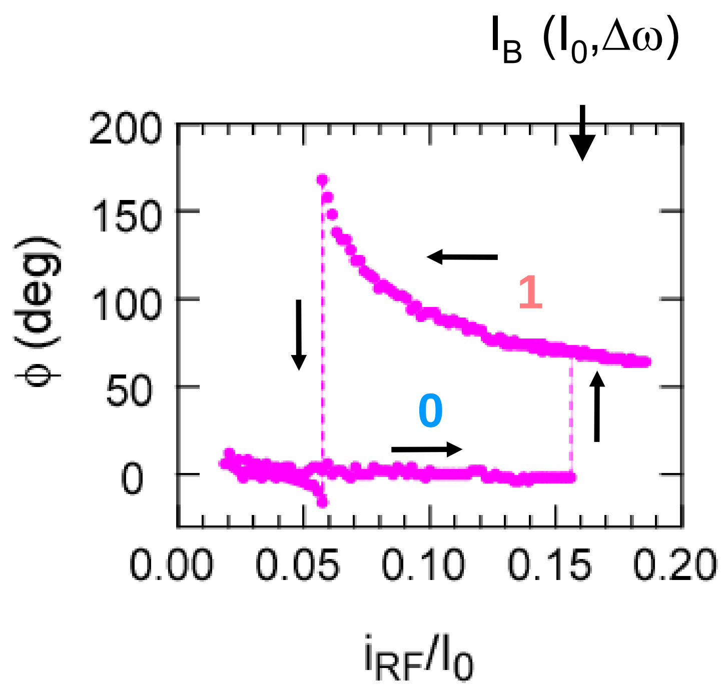


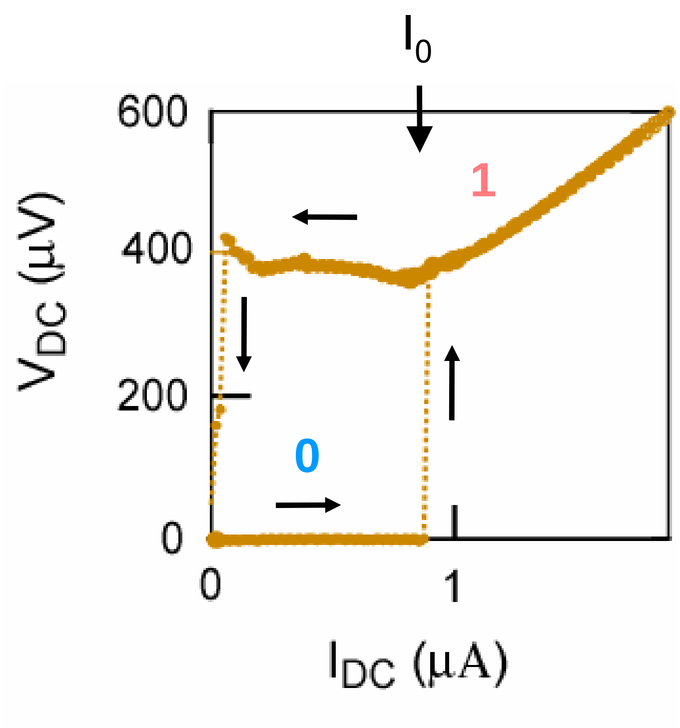


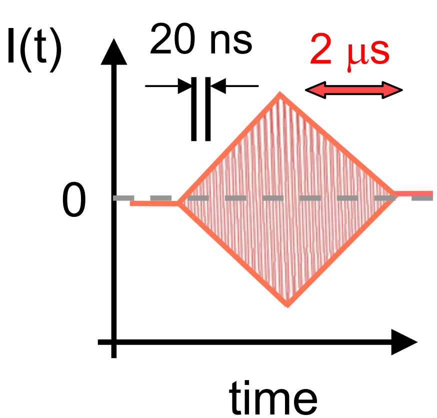
- N = 600,000
- $\Delta\phi$ = 74 deg
- Hysteresis
  I_B and $I_{B'}$ correct !

$$I_B = \left[\frac{16}{3\sqrt{3}} \alpha^{3/2} (1-\alpha)^{3/2} \right] I_0 \qquad \alpha = \left(1 - \frac{\omega}{\omega_p} \right) = 0.122$$

RF vs. DC



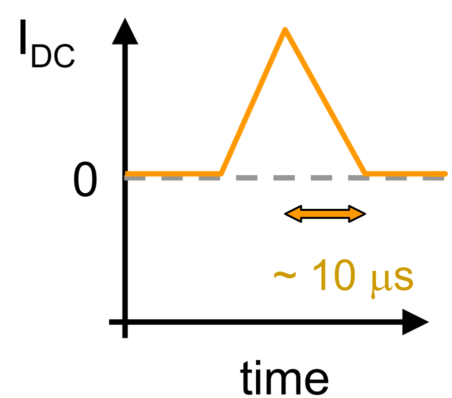




i_{RF} $\leftrightarrow$ I_{DC}

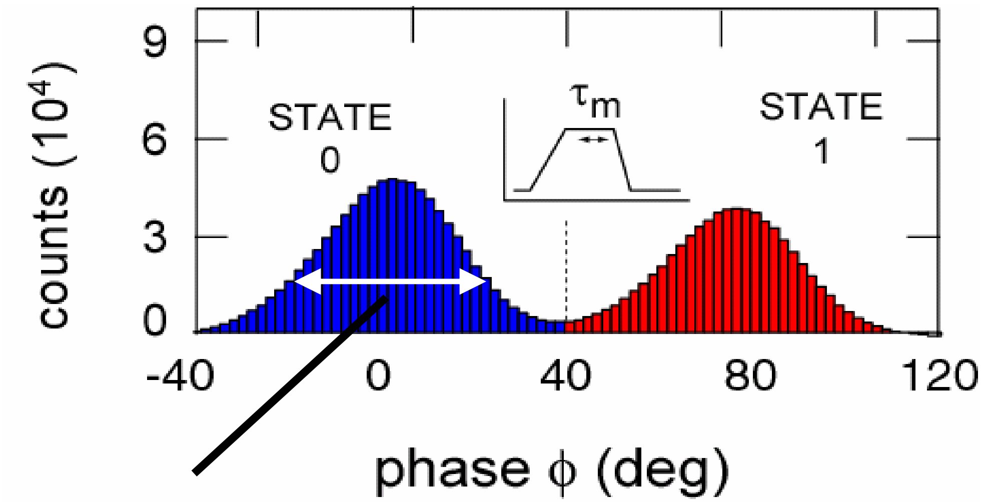
ϕ $\leftrightarrow$ V_{DC}

$\Delta\omega$ $\leftrightarrow$ R_s



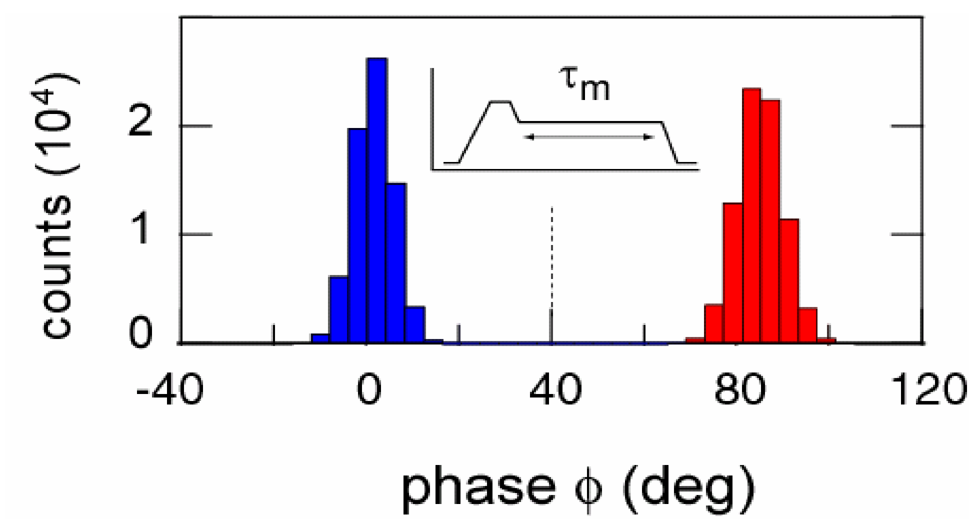
SWITCHING HISTOGRAMS

- No latching
- 40 ns rise + 20 ns settle
- τ_m = 20 ns
- N = 1.6 x 10^6
- Overlap = 10^{-2}



Set by SNR

- Latching
- 40 ns rise + 20 ns settle
- τ_m = 300 ns
- N = 1.5 x 10^5
- Overlap = 6 x 10^{-5}



SWITCHING PROBABILITY

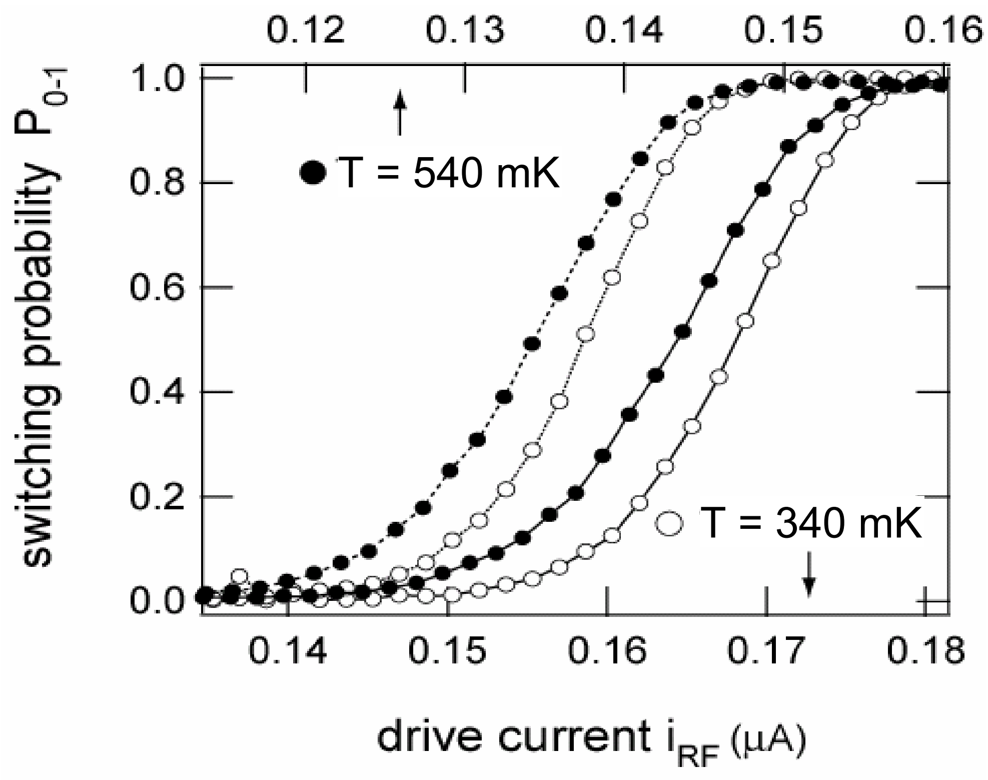
- $\Delta I_0/I_0 = 1\%$

- d = 80% @ 250mK
  d = 57% @ 340mK
  d = 49% @ 540mK

- Predict d > 95% @ 60mK

- $\Delta I_B/I_B = 6\%$

$$\frac{\Delta I_B / I_B}{\Delta I_0 / I_0} = \frac{3}{4\alpha} - \frac{1}{2} = 5.6$$

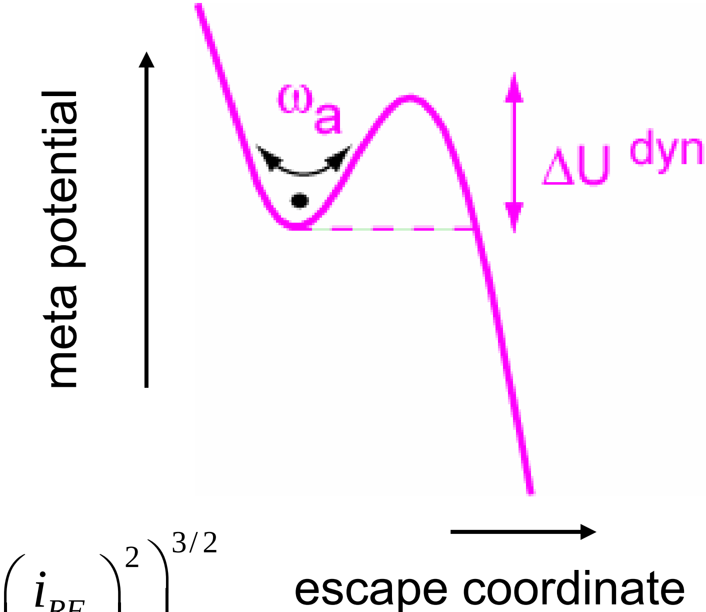


Single Shot, Latching Qubit Readout
>95% Fidelity
10-20 MHz Rep. Rate !

I.S. *et al*, cond-mat/0312623

1D METAPOTENTIAL

- Expand system near bifurcation
- Reduce to cubic metapotential



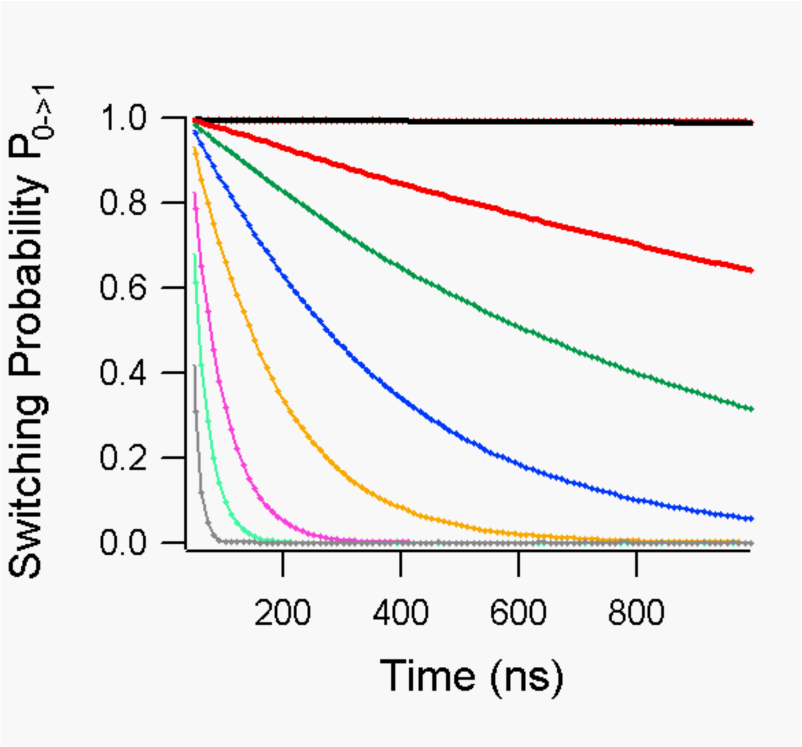
$$\Gamma^{dyn}_{0\to 1} = \frac{\omega_a}{2\pi} \exp\left(-\frac{\Delta U^{dyn}}{kT} \right)$$

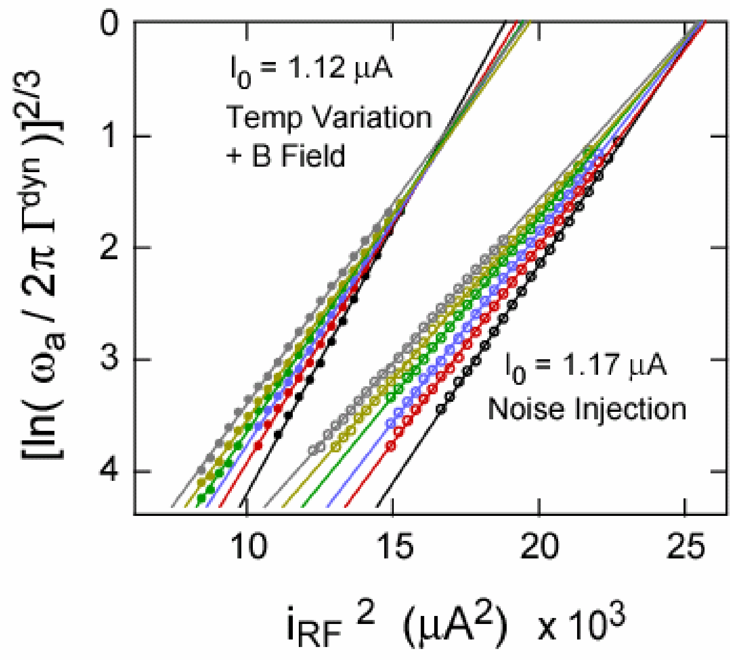
$$\Delta U^{dyn}(I_0, i_{RF}, \alpha) = \underbrace{\left[\frac{64\hbar}{18e\sqrt{3}} I_0\, \alpha (1-\alpha)^3 \right]}_{u_0^{dyn} \approx 10\,\mathrm{K}} \left(1 - \left(\frac{i_{RF}}{I_B} \right)^2 \right)^{3/2}$$

$$\omega_a = \underbrace{\left[\frac{4}{3\sqrt{3}} RC (\alpha\omega_p)^2 \right]}_{\omega_{a0} \approx (2\pi) \bullet 350\mathrm{MHz}} \left(1 - \left(\frac{i_{RF}}{I_B} \right)^2 \right)^{1/2}$$

(M. Dykman)

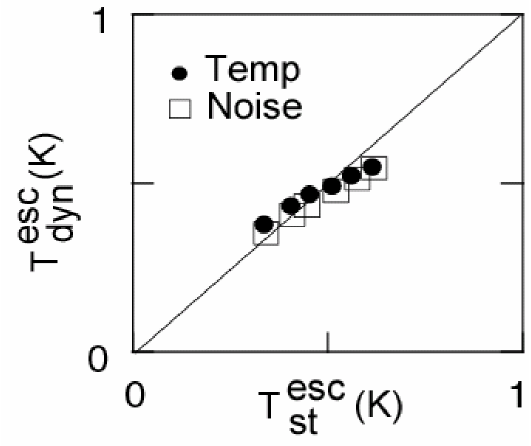
ESCAPE RATES FOR DYN. SWITCHING



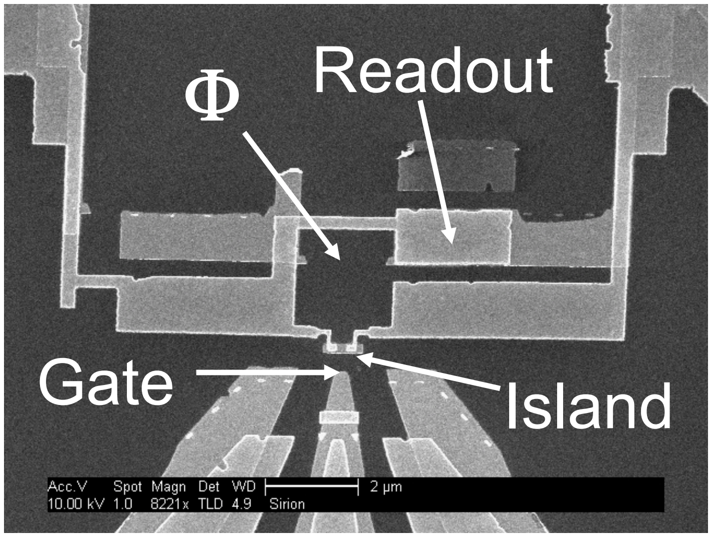


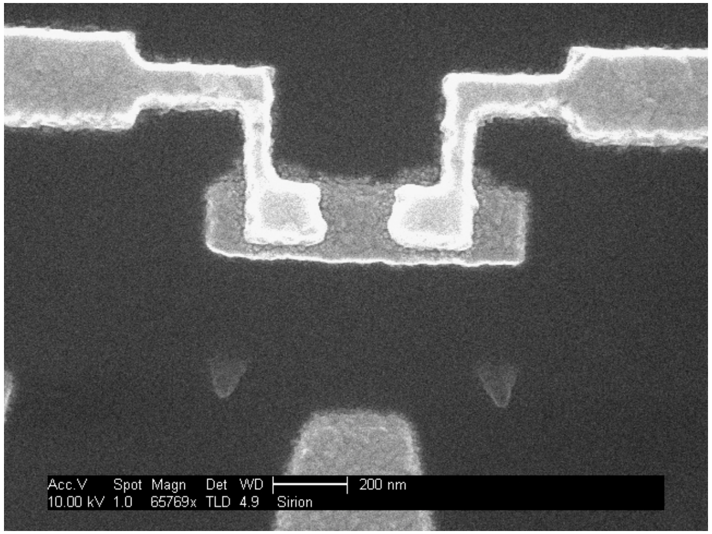
$$u_0^{dyn} = 9.1\,\mathrm{K} \text{ for } I_0 = 1.12\,\mu A,\ T_{st}^{esc} = 340\,\mathrm{mK}$$
$$(THY = 10.0\,\mathrm{K})$$

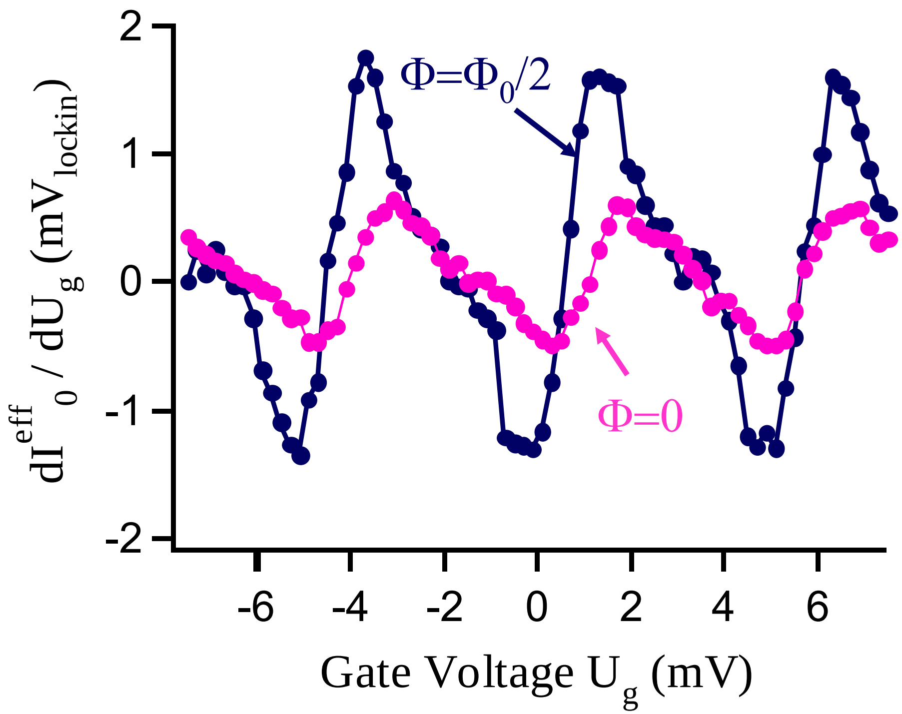
$$u_0^{dyn} = 10.7\,\mathrm{K} \text{ for } I_0 = 1.17\,\mu A,\ T_{st}^{esc} = 340\,\mathrm{mK}$$
$$(THY = 11.0\,\mathrm{K})$$



YALE QUANTRONIUM

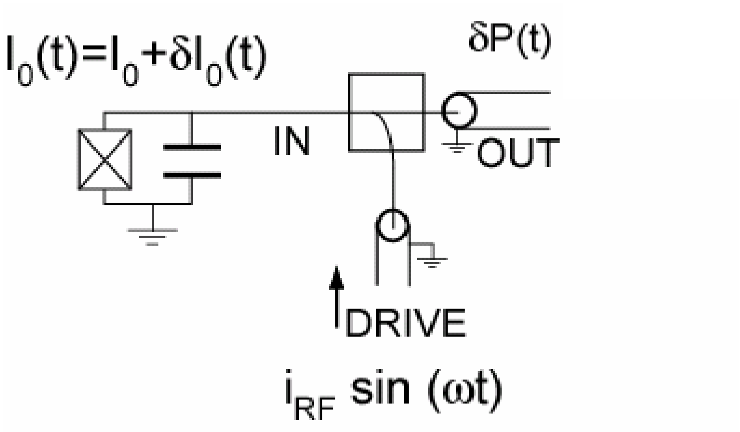






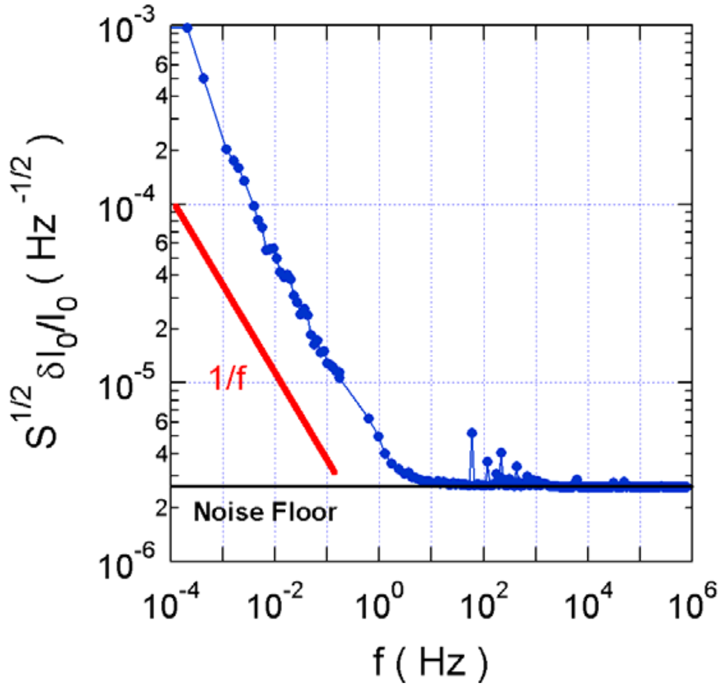
- Observe I_0 modulation with gate volage
- Spectroscopy in progress
- T=400mK!

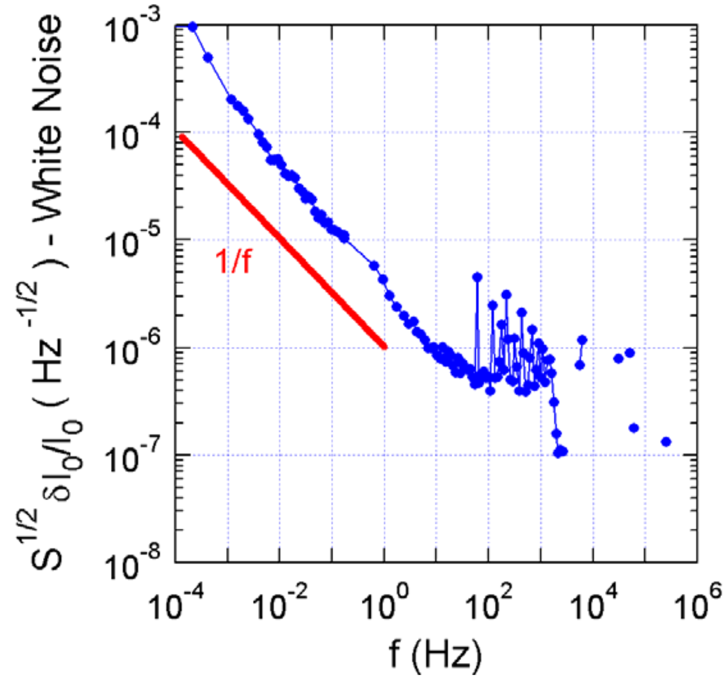
CRITICAL CURRENT FLUCTUATIONS



- Apply fixed i_{RF} and observe variation in switching probability P(t) caused by $I_0(t)$

- $S^{1/2}_{\delta I_0/I_0}$ (1Hz, 0.3K) = 3.5×10^{-6}





SUMMARY & PERSPECTIVES

• BIFURCATION AMPLIFICATION OBSERVED AS PREDICTED

- GAIN
- SPEED
- ESCAPE RATES
- ABSENCE OF EXCESS DISSIPATION

• **QUBIT MEASUREMENTS:** Bell Inequalities, Error Correction

• **QUANTUM LIMIT:** Quantum Diffusion vs MQT, Ultimate T_N

• **NOISE:** Temperature dependence of 1/f

• **APPLICATIONS:** Current Standard, Single Photon Detectors