CONTINUOUS MONITORING OF A SUPERCONDUCTING QUBIT: From Quantum Jumps to Feedback

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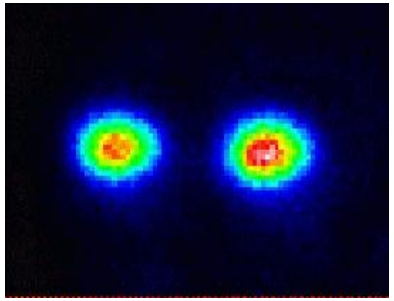
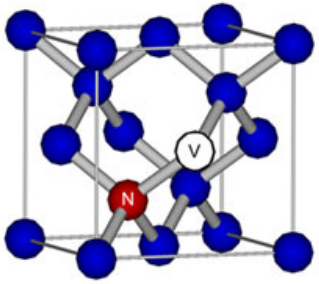
NASA QFT 1.0, January 20, 2011

THE MANY FACES OF QUANTUM MECHANICS

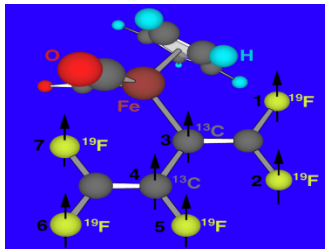
Trapped ions



NV Centers



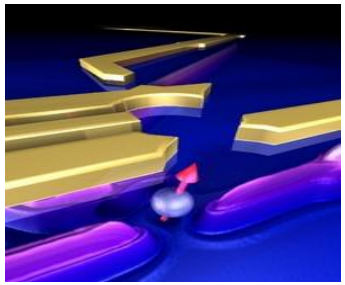
Molecules



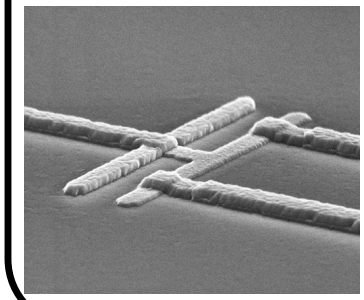
- Highly tunable
- Strong coupling
- Scalable…

- Decoherence
- Efficient measurement

Quantum Dot



Superconducting Circuit

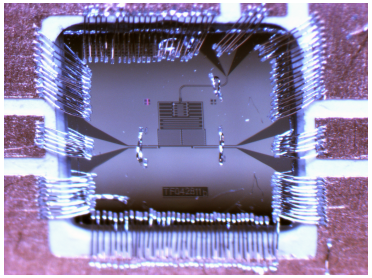


High Fidelity, Continuous Measurement

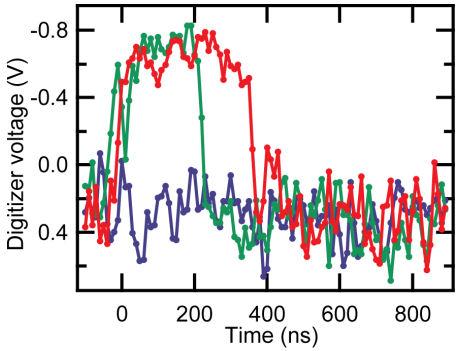
- strong measurement
  (single shot qubit readout)
- weak measurement
  (measurement based feedback)

OUTLINE

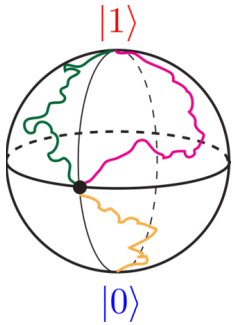
BRIEF INTRODUCTION TO SUPERCONDUCTING QUBITS



HIGH FIDELITY SINGLE SHOT MEASUREMENT: QUANTUM JUMPS
(STRONG MEASUREMENT)



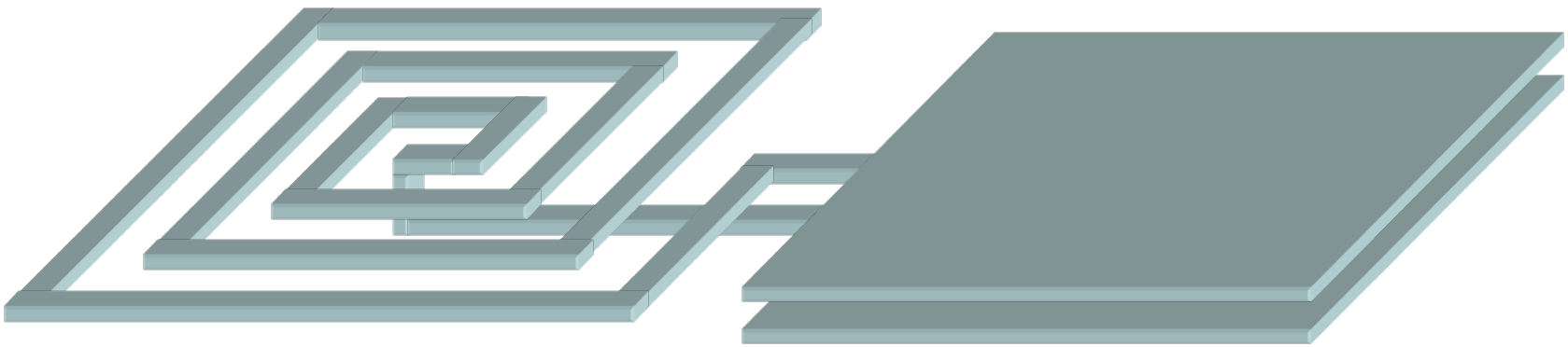
STABILIZATION OF COHERENT OSCILLATIONS: QUANTUM FEEDBACK
(WEAK MEASUREMENT)



THE QUBIT

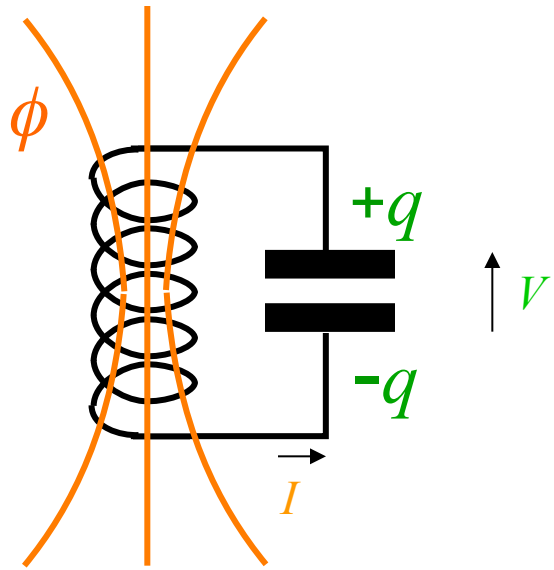
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES?

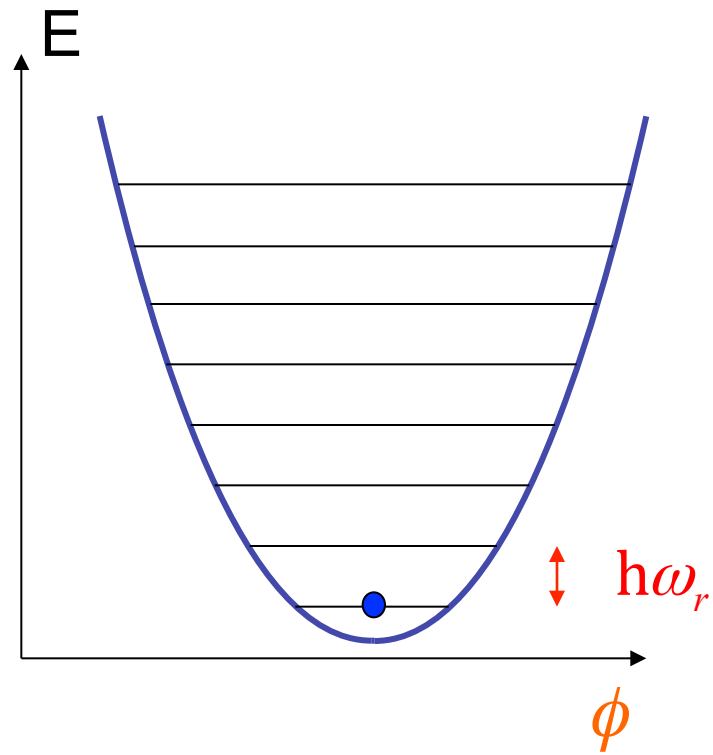
SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT



MICROFABRICATION → L ~ 3nH, C ~ 10pF, $\omega_r/2\pi$ ~ 1GHz, Q ~ 10^6

LC OSCILLATOR AS A QUANTUM CIRCUIT





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

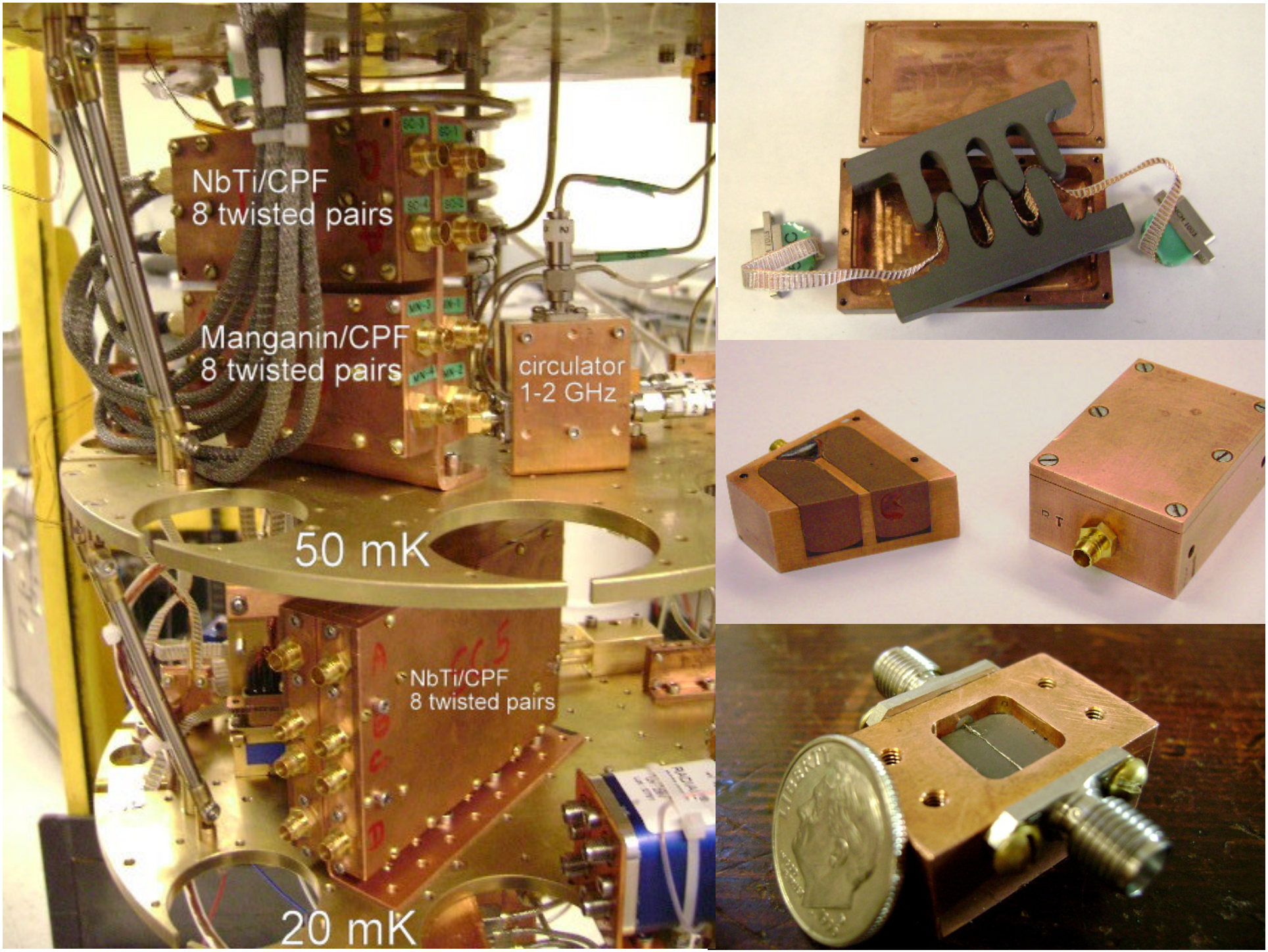
$$\phi = LI$$

$$q = CV$$

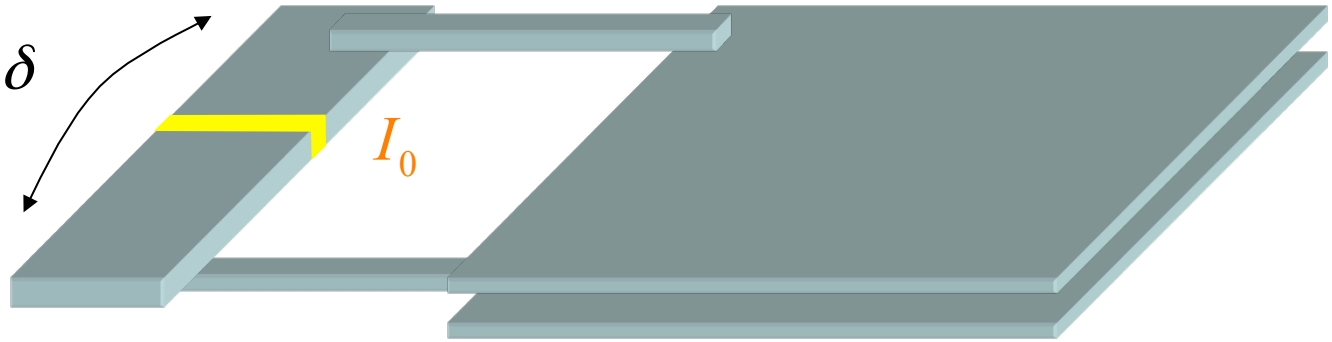
$$h\omega_r > k_B T$$

1GHz
(~ 50mK)

10mK


NbTi/CPF
8 twisted pairs
Manganin/CPF
8 twisted pairs
circulator
1-2 GHz
50 mK
NbTi/CPF
8 twisted pairs
20 mK

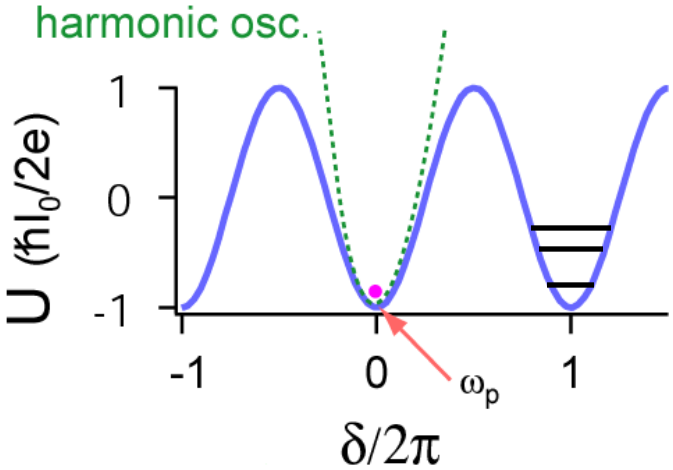
THE JOSEPHSON TUNNEL JUNCTION: NON-LINEARITY AT ITS FINEST!



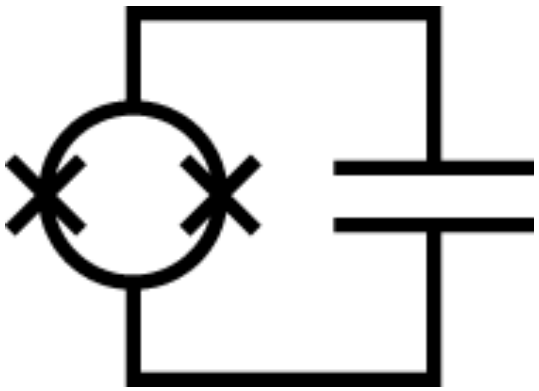
$$I(\delta) = I_0 \sin(\delta)$$

(NON-LINEAR INDUCTOR)

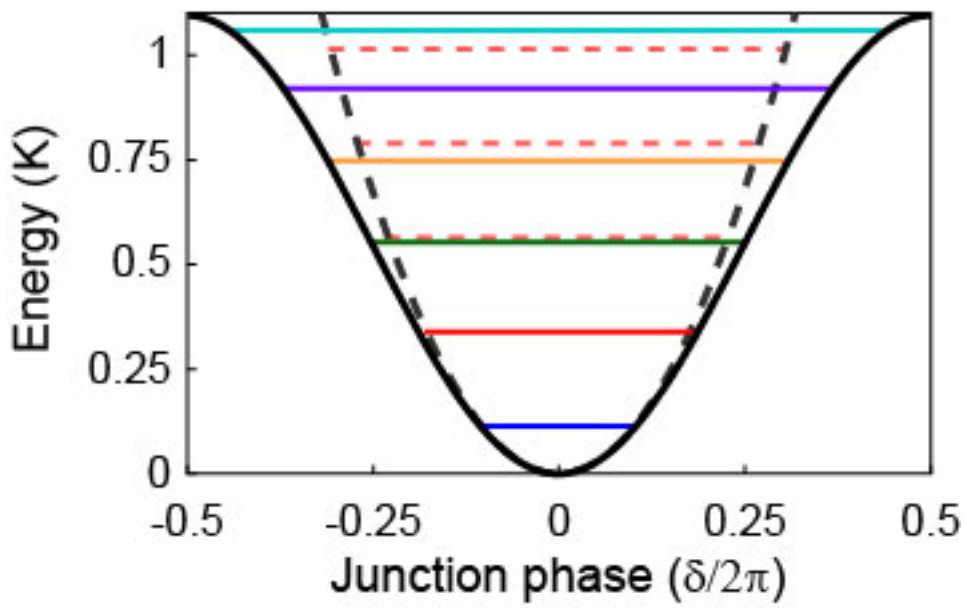
$$U(\delta) = -\frac{\mathrm{h}}{2e} I_0 \cos(\delta)$$



SUPERCONDUCTING TRANSMON QUBIT



$L_J \sim 13$ nH $\qquad$ $C \sim 70$ fF



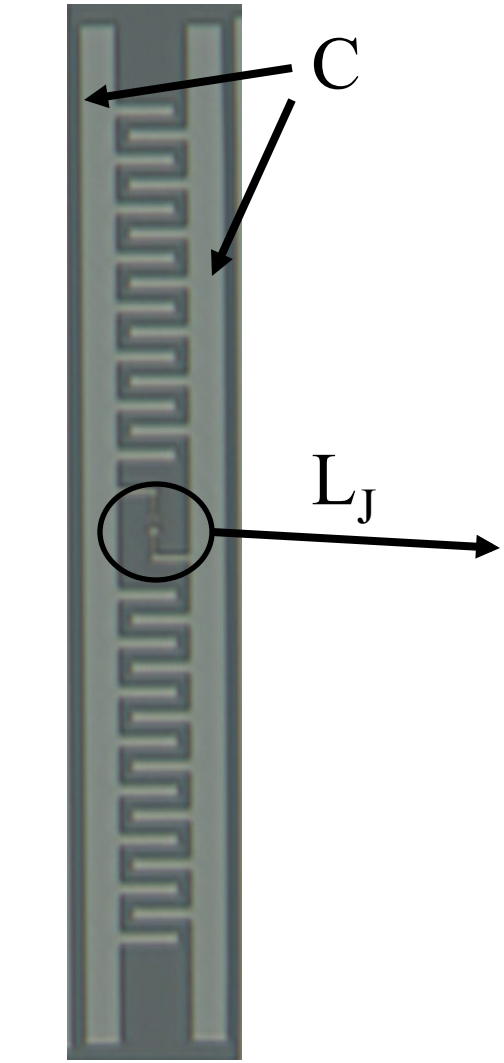
$$\omega_{01} \simeq \frac{1}{\sqrt{L_J C}}$$

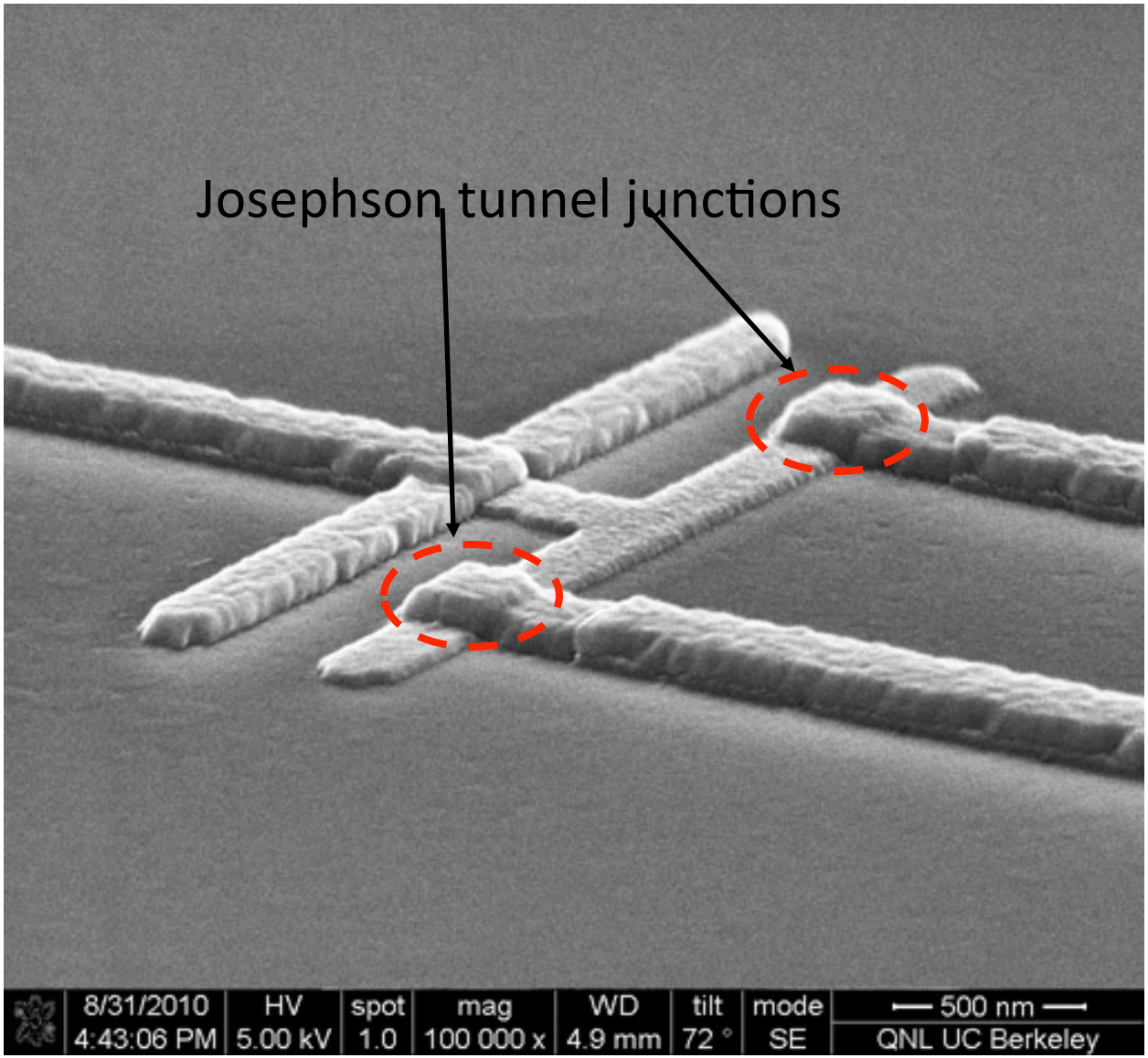
$$\omega_{01} \neq \omega_{12}$$

J. Koch et al., *Physical Review A* ***76,*** 042319 (2007)

- Tunable qubit frequency
- $\omega_{01} \sim$ 5-8 GHz
- T_1 , $T_2 \sim$ 0.3 - 50 μs

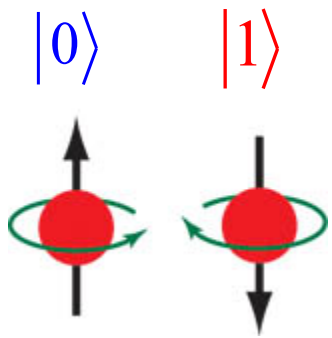
TRANSMON QUBIT





THE MEASUREMENT APPARATUS

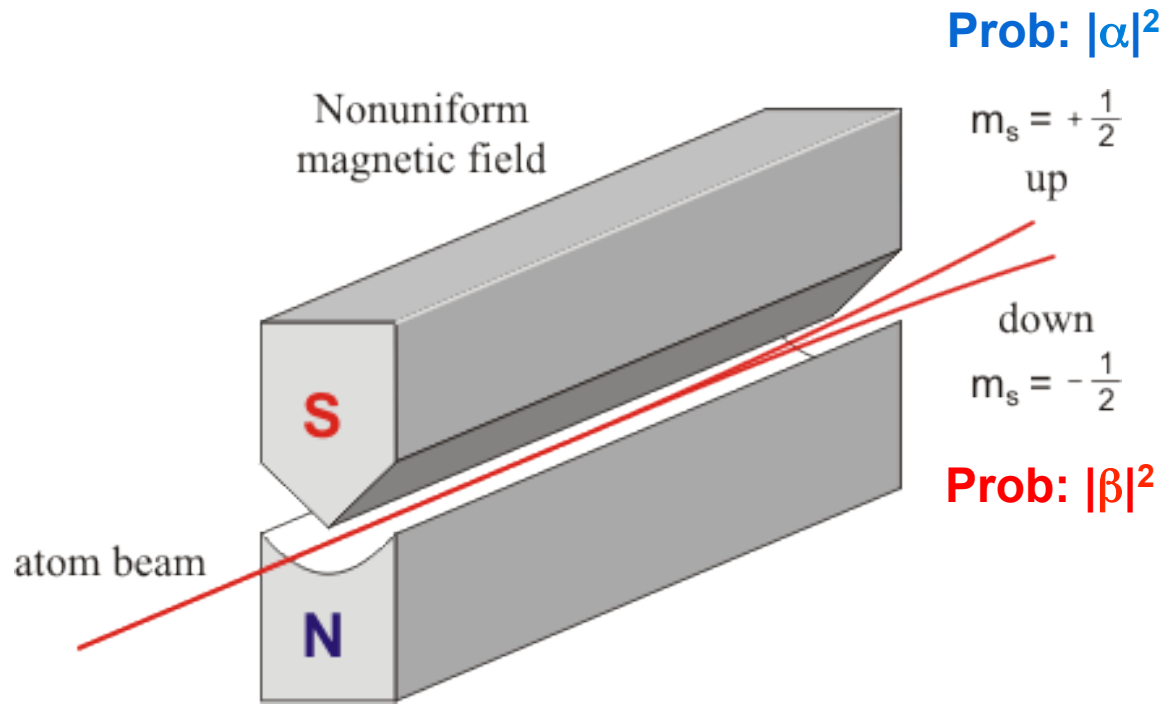
MEASUREMENT: STERN-GERLACH EXPERIMENT WITH VARIABLE MAGNET



Spin ½ Particle

Superposition State

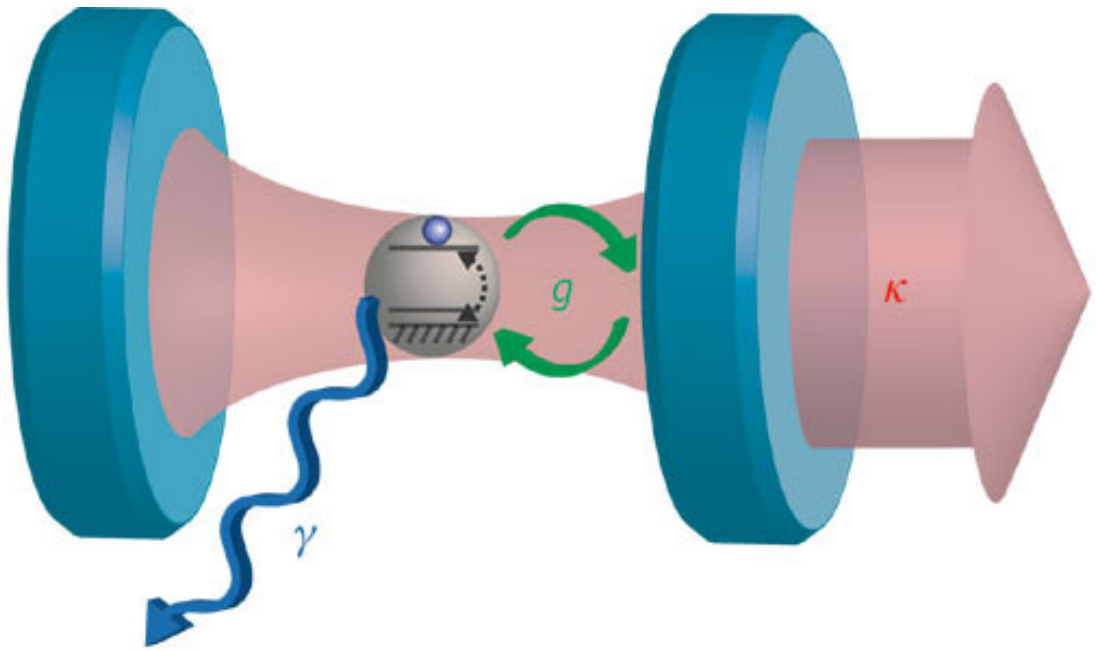
$$|\Psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

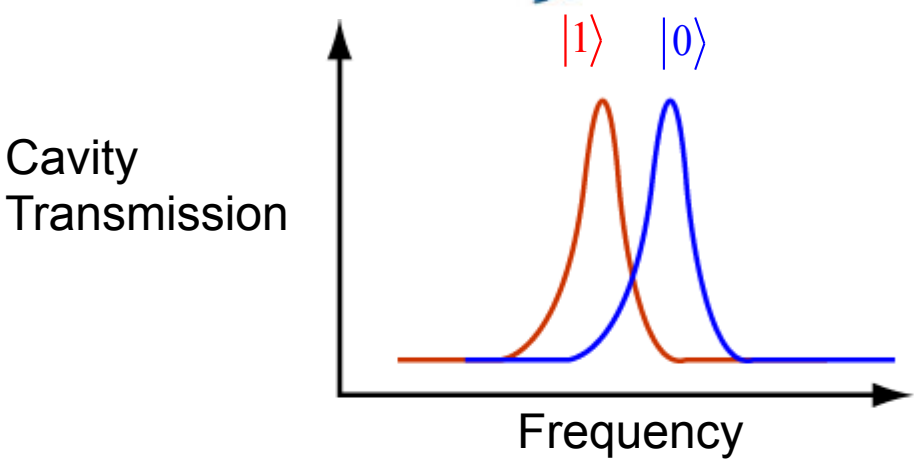


STUDY BY CONTINUOUSLY VARYING MEASUREMENT STRENGTH

H. M. Wiseman, G. J. Milburn, *Quantum Measurement and Control* (Cambridge Univ. Press, 2009).

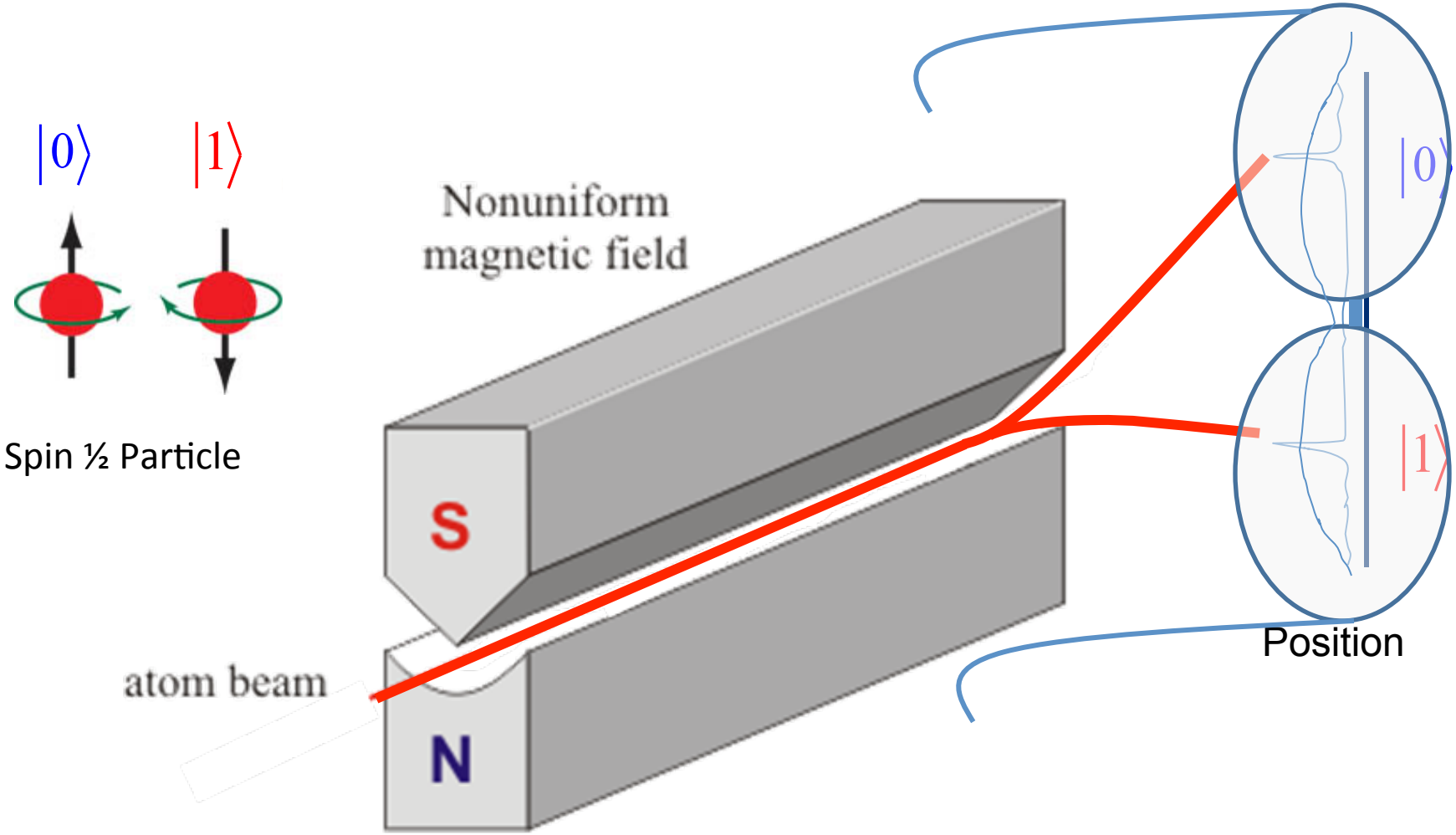
MEASUREMENT: COUPLE TO E-M FIELD OF CAVITY (Jaynes-Cummings)





VARY MEASUREMENT STRENGTH USING DISPERSIVE SHIFT & PHOTON NUMBER

STRONG MEASUREMENT

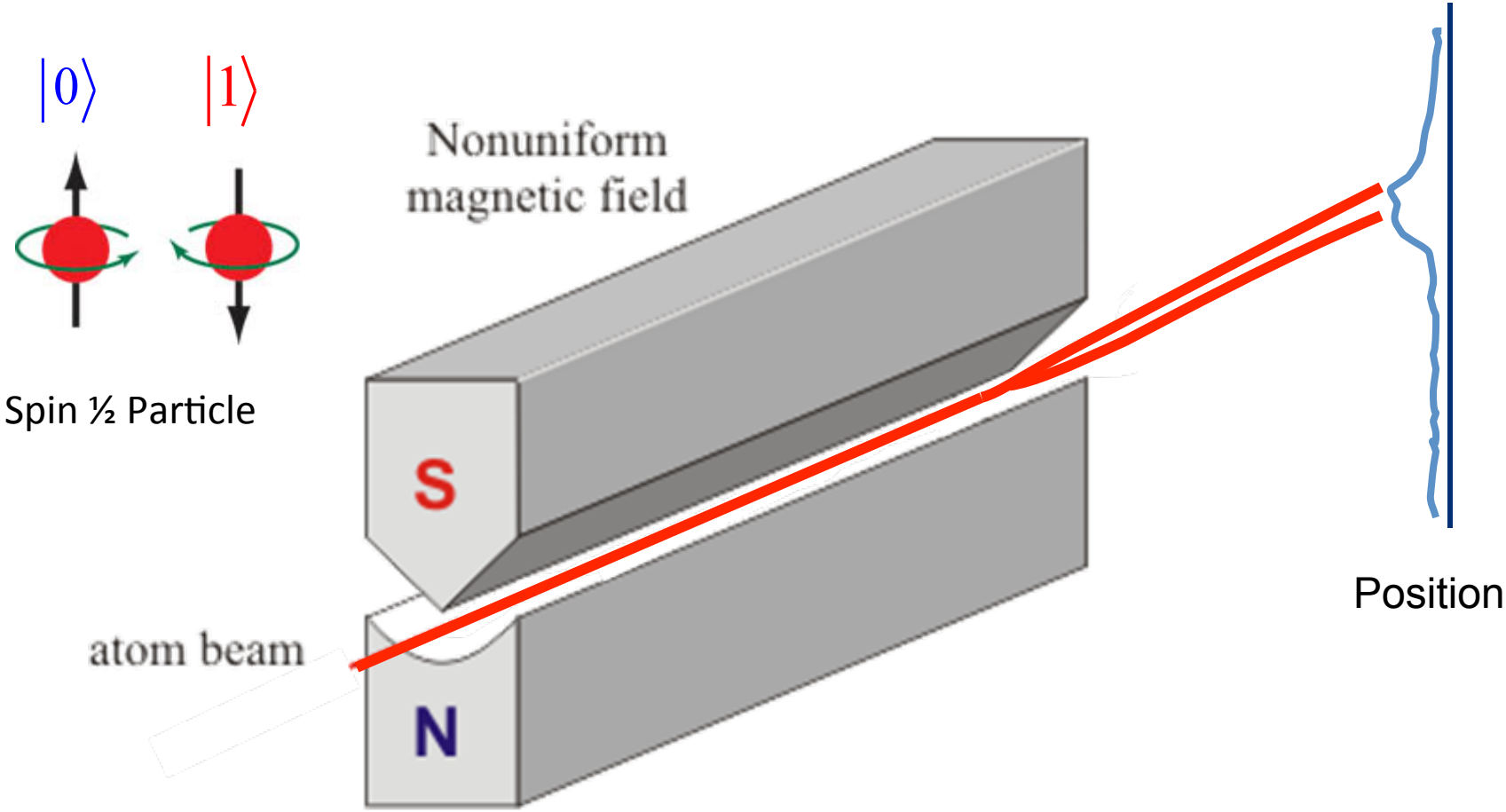


Superposition State

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

PROJECTIVE MEASUREMENT: ABLE TO RESOLVE STATES

WEAK MEASUREMENT

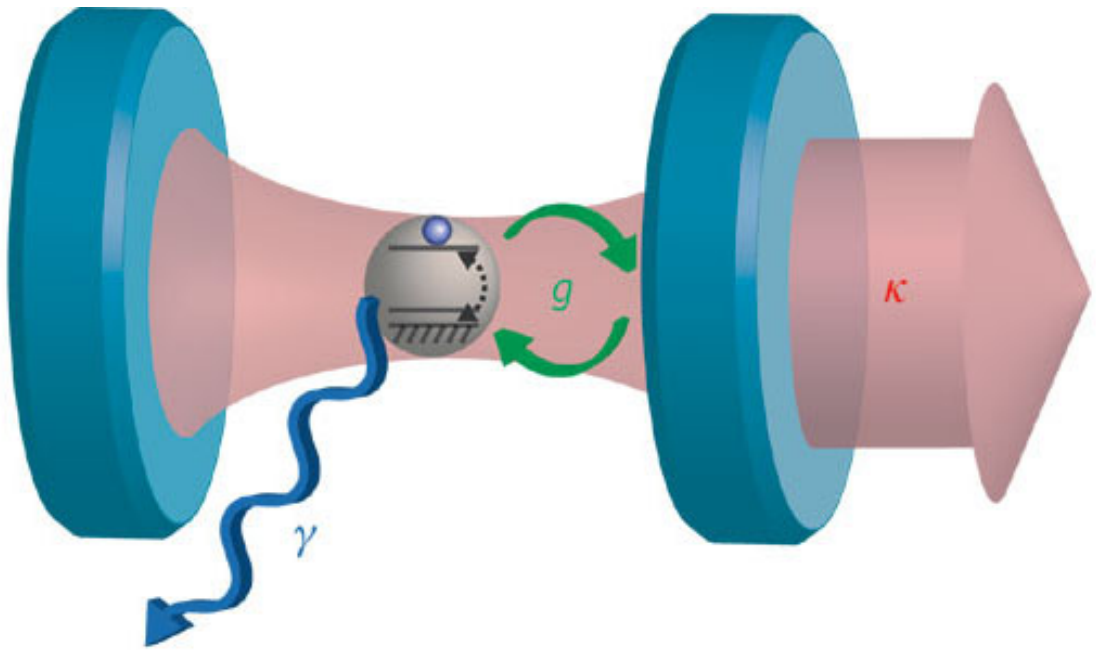


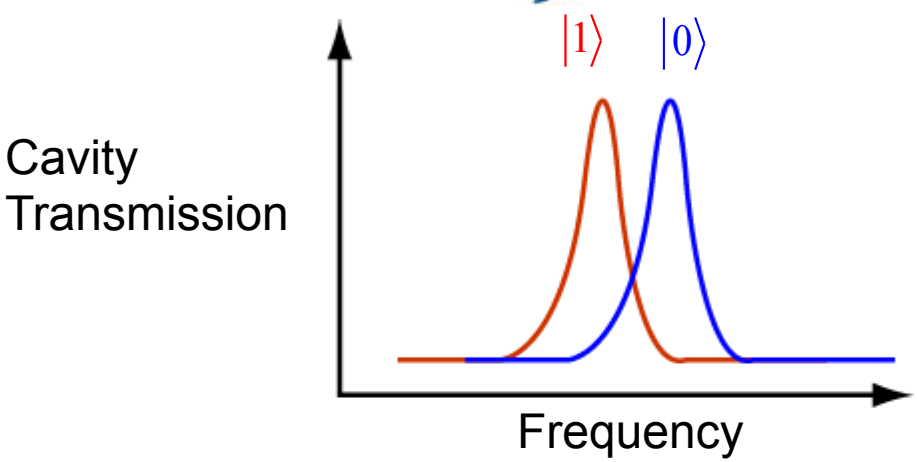
Superposition State

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

EXTRACT SOME INFORMATION,
BUT NOT ENOUGH TO DETERMINE STATE

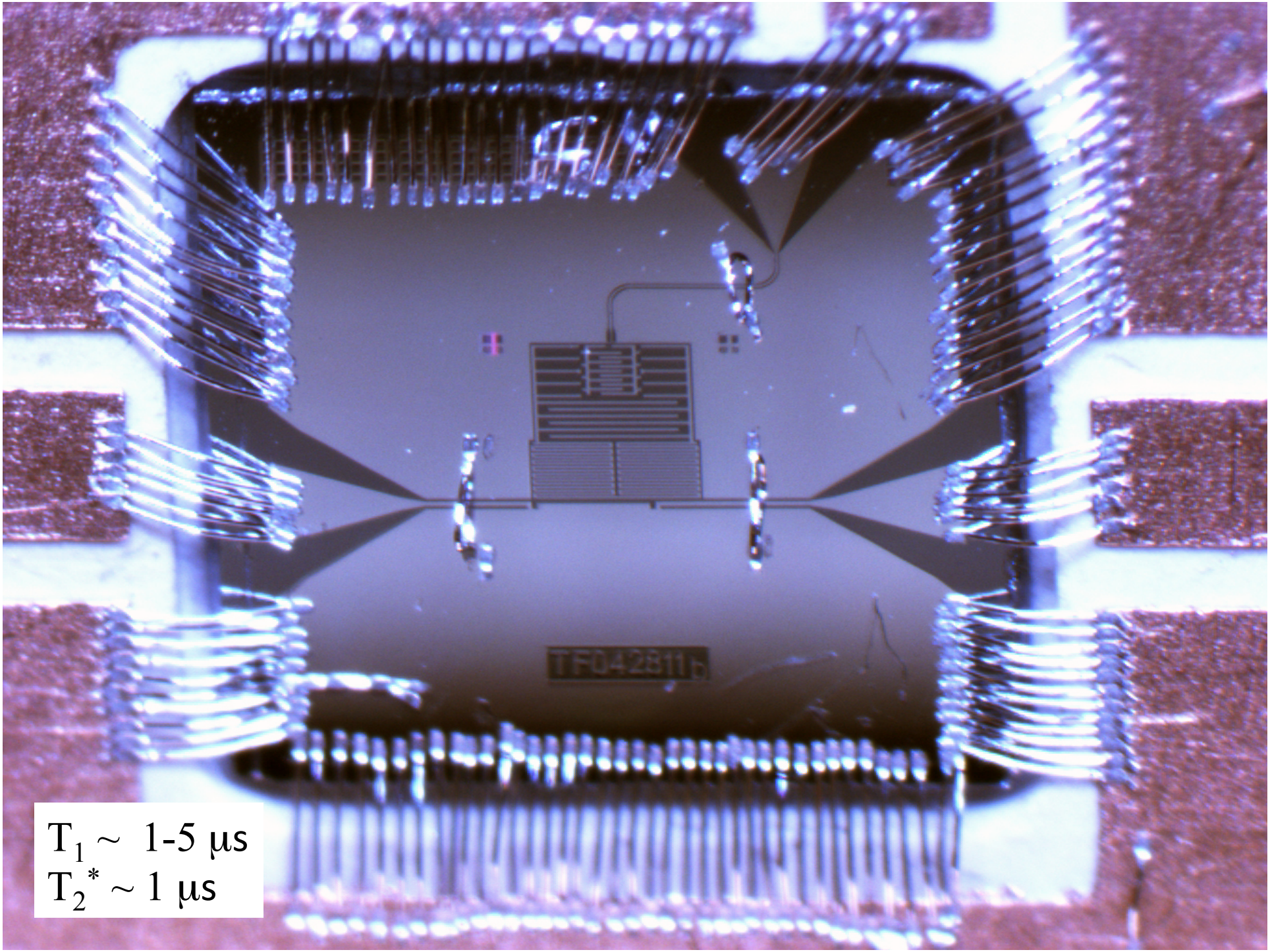
MEASUREMENT: COUPLE TO E-M FIELD OF CAVITY (Jaynes-Cummings)

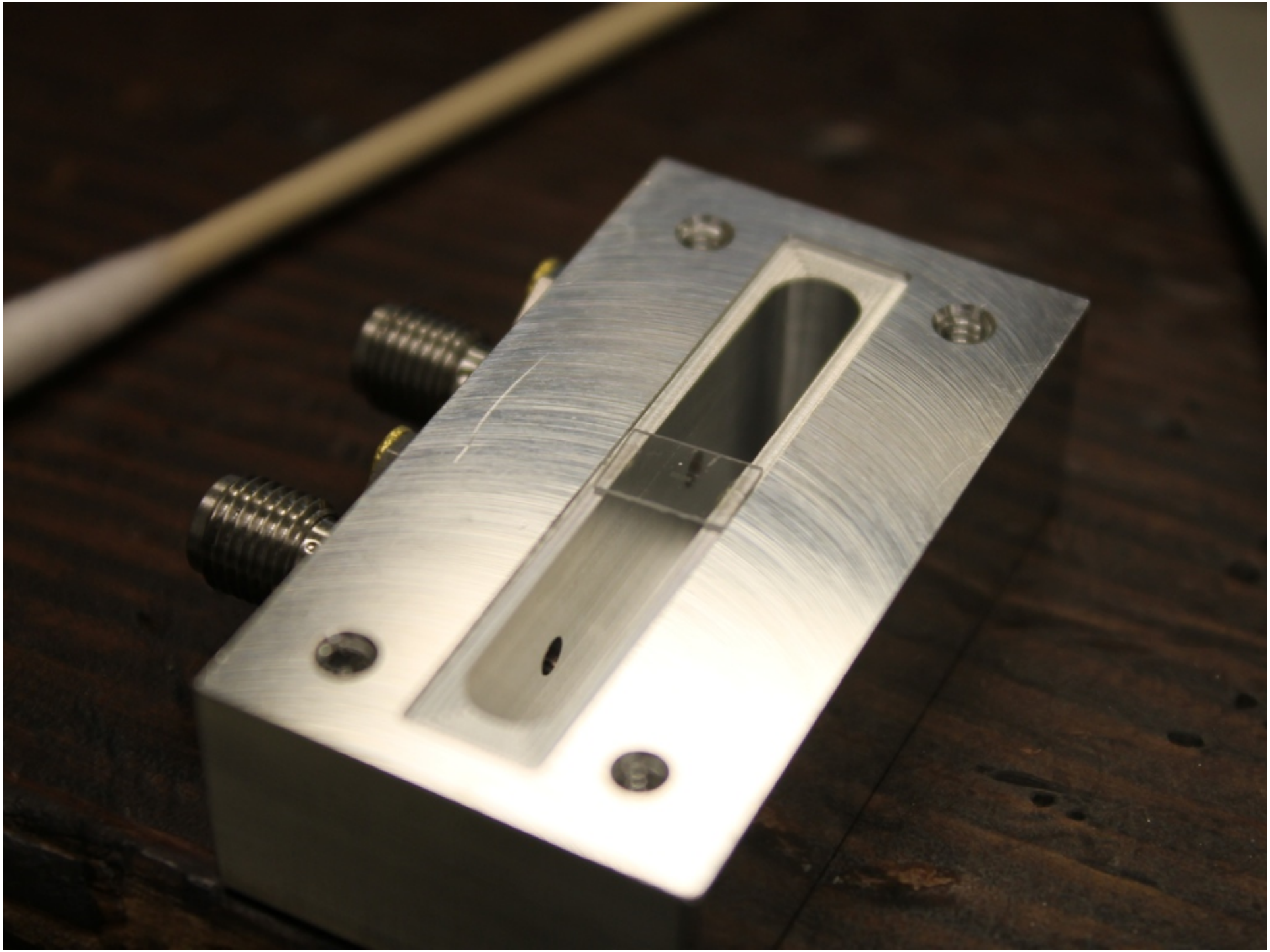


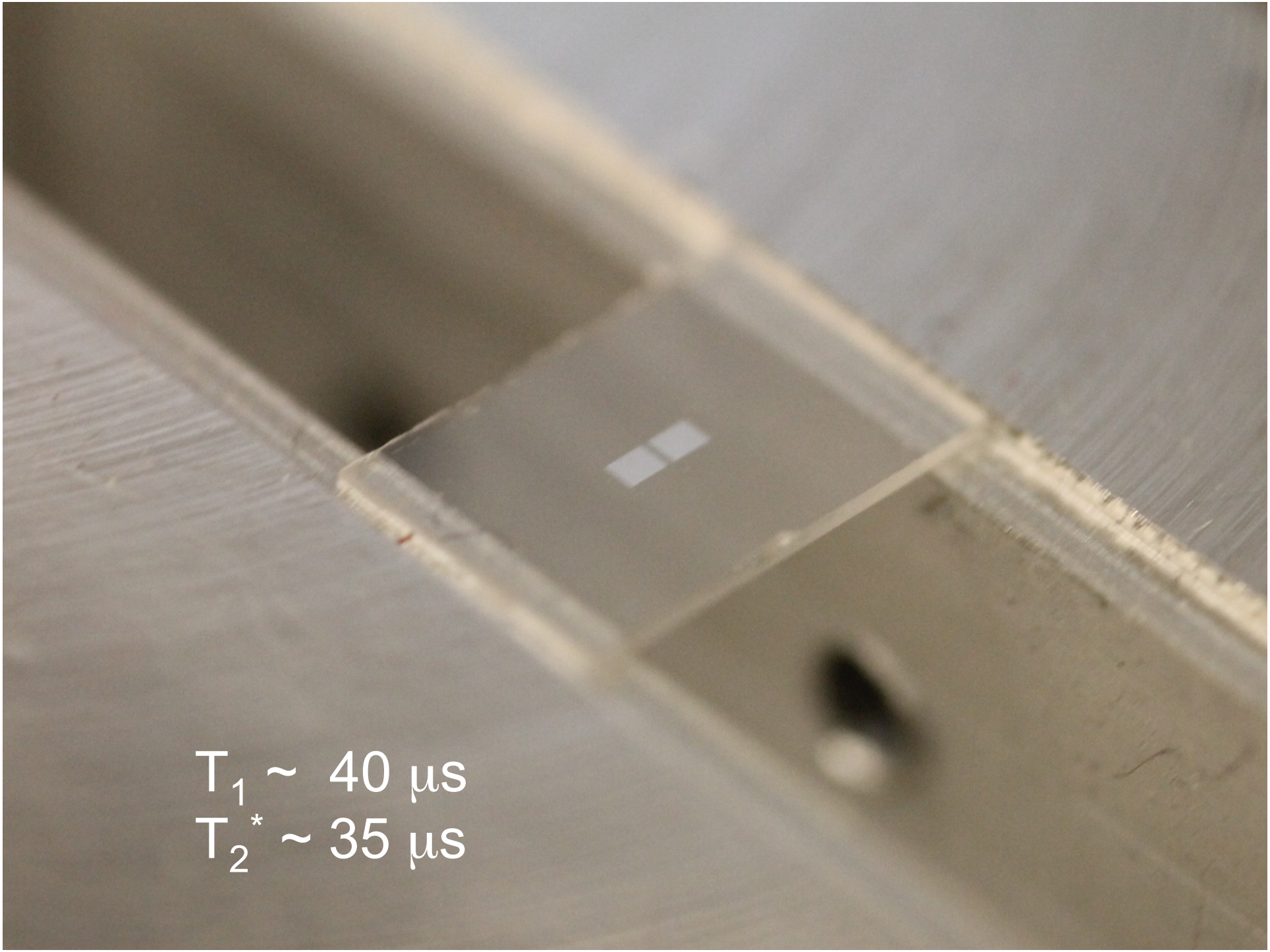


VARY MEASUREMENT STRENGTH USING DISPERSIVE SHIFT & PHOTON NUMBER

NEED TO DETECT ~ SINGLE MICROWAVE PHOTONS in T_1 ~ μs

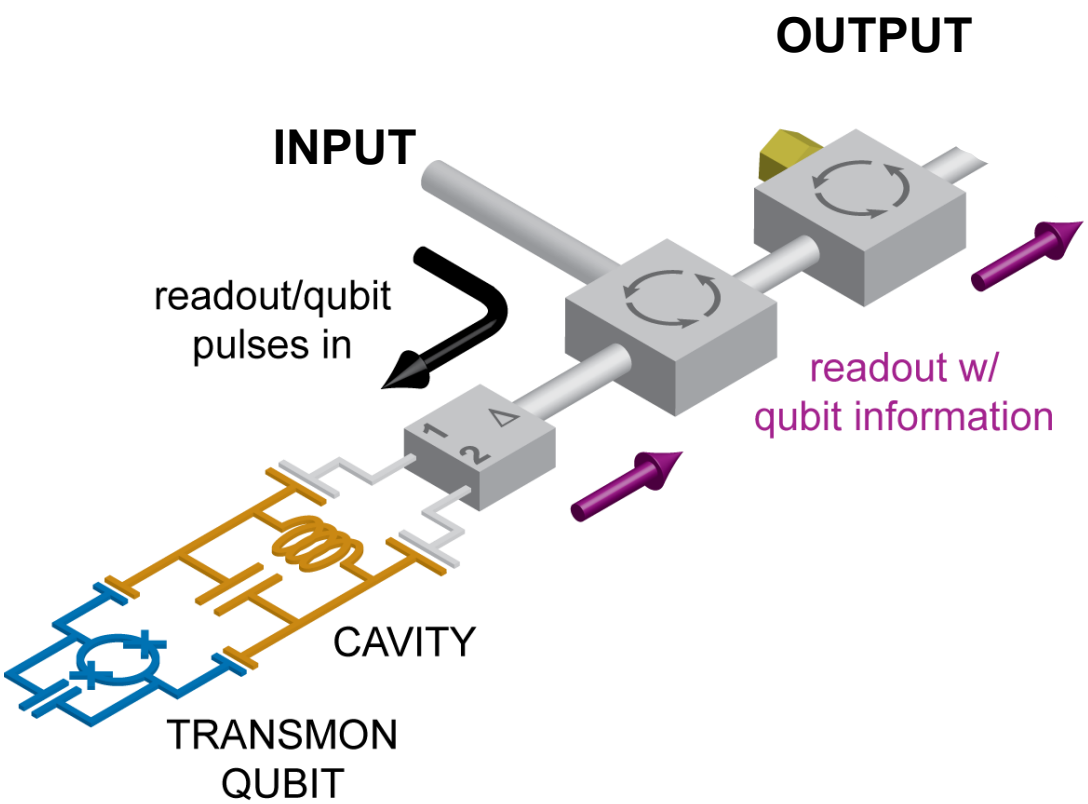

$T_1 \sim$ 1-5 μs
$T_2^* \sim 1$ μs




$T_1 \sim 40\ \mu s$
$T_2^* \sim 35\ \mu s$

HIGH-FIDELITY STRONG MEASUREMENT: QUANTUM JUMPS

CONVENTIONAL EXPERIMENTAL SETUP



- Prepare qubit

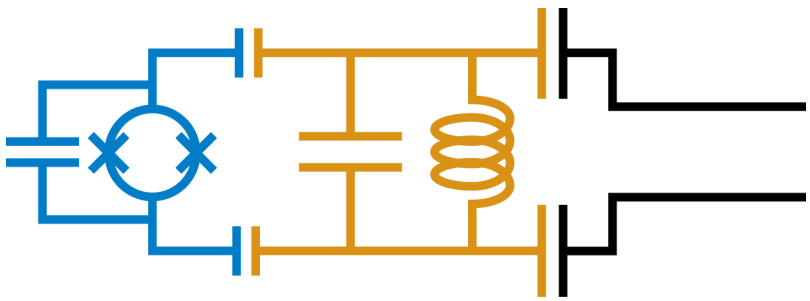
- Excite cavity with photons

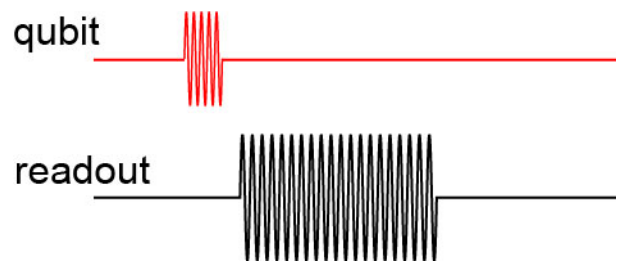
- Amplify with cryogenic semiconductor amplifier (25-40 added photons)

- Convert microwave signal to DC voltage (homodyne) to detect variation of microwave amplitude/phase

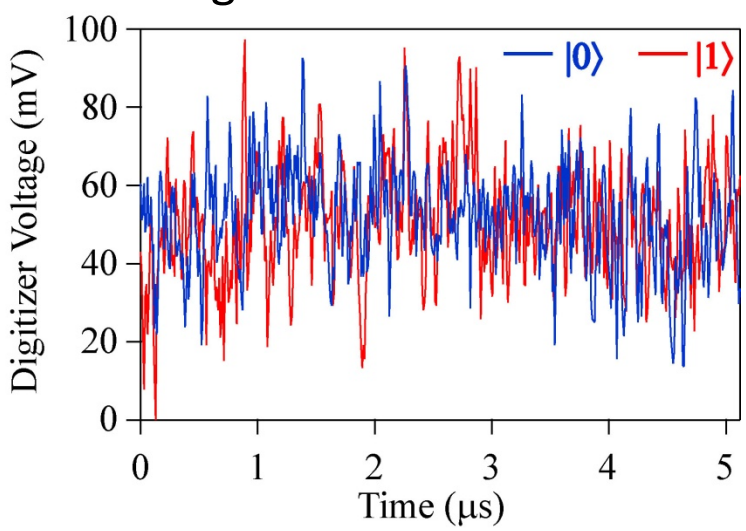
- **Repeat and average**

SINGLE SHOT MEASUREMENTS



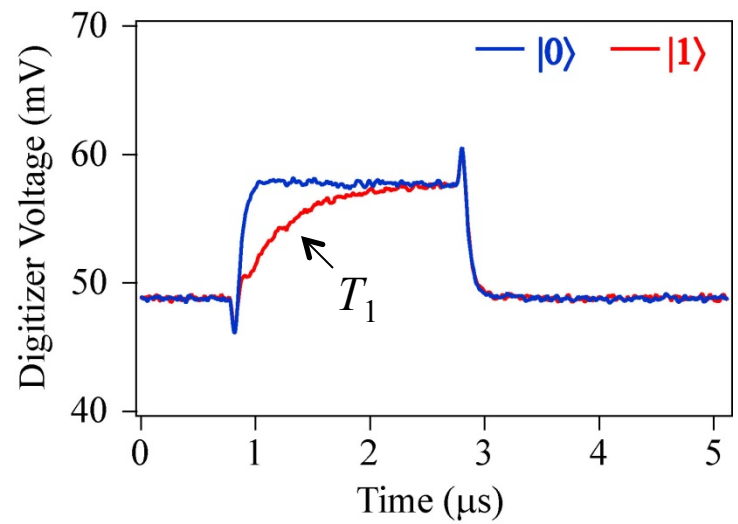


Single measurement trace



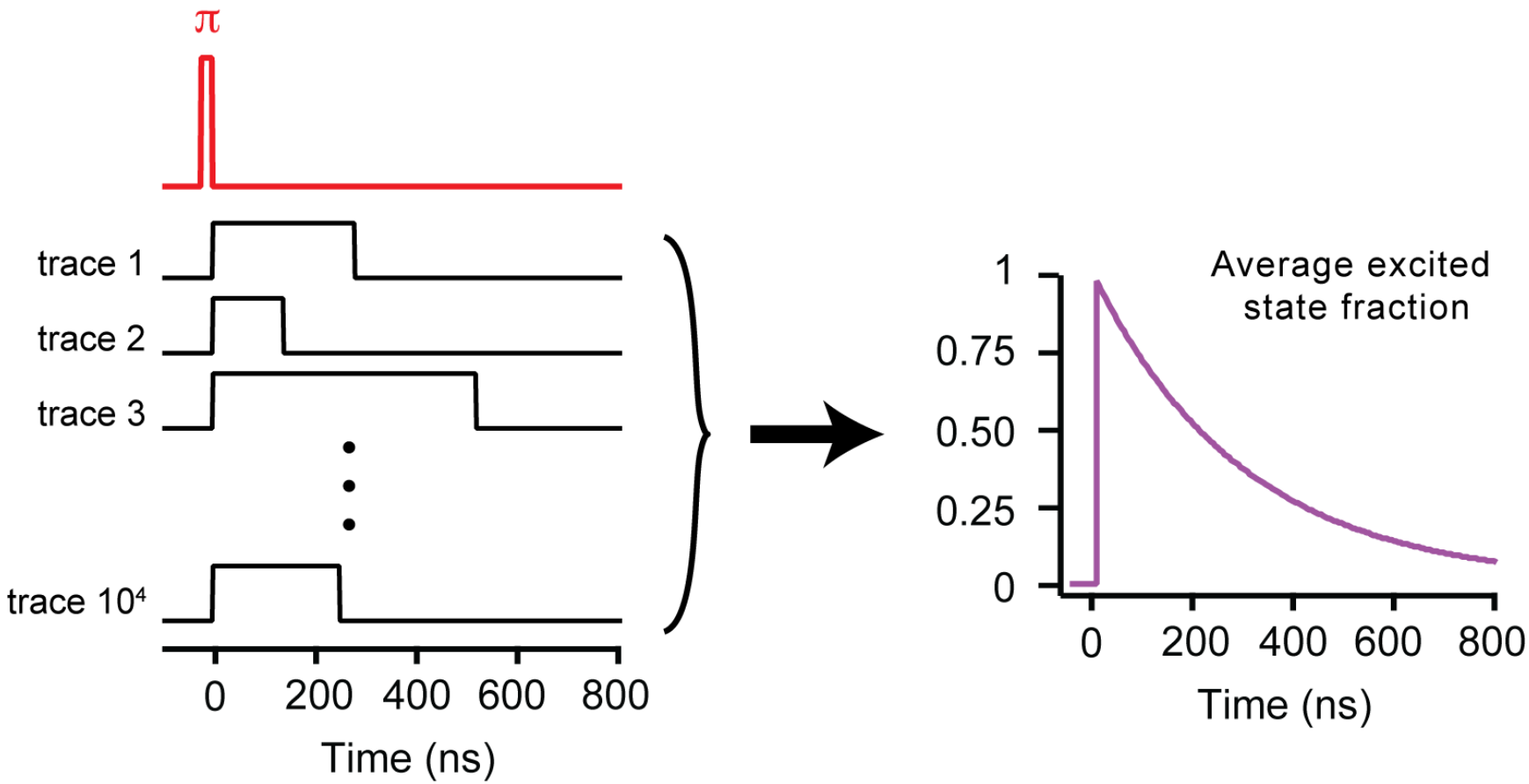
10^4 Averages

Averaged measurement trace

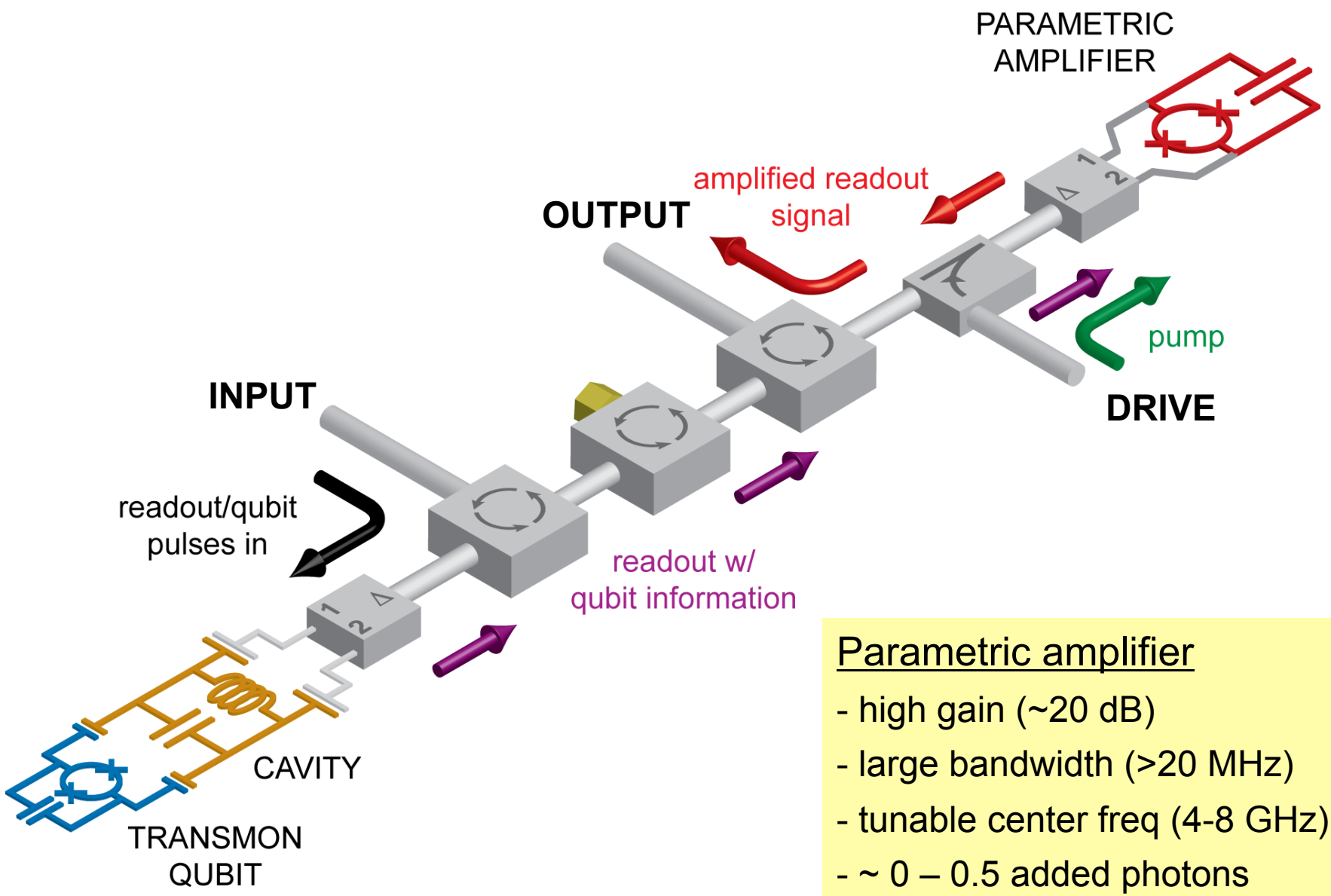


Amplifier (T_{SYS} = 7K) noise masks qubit state information

STOCHASTIC QUANTUM JUMPS

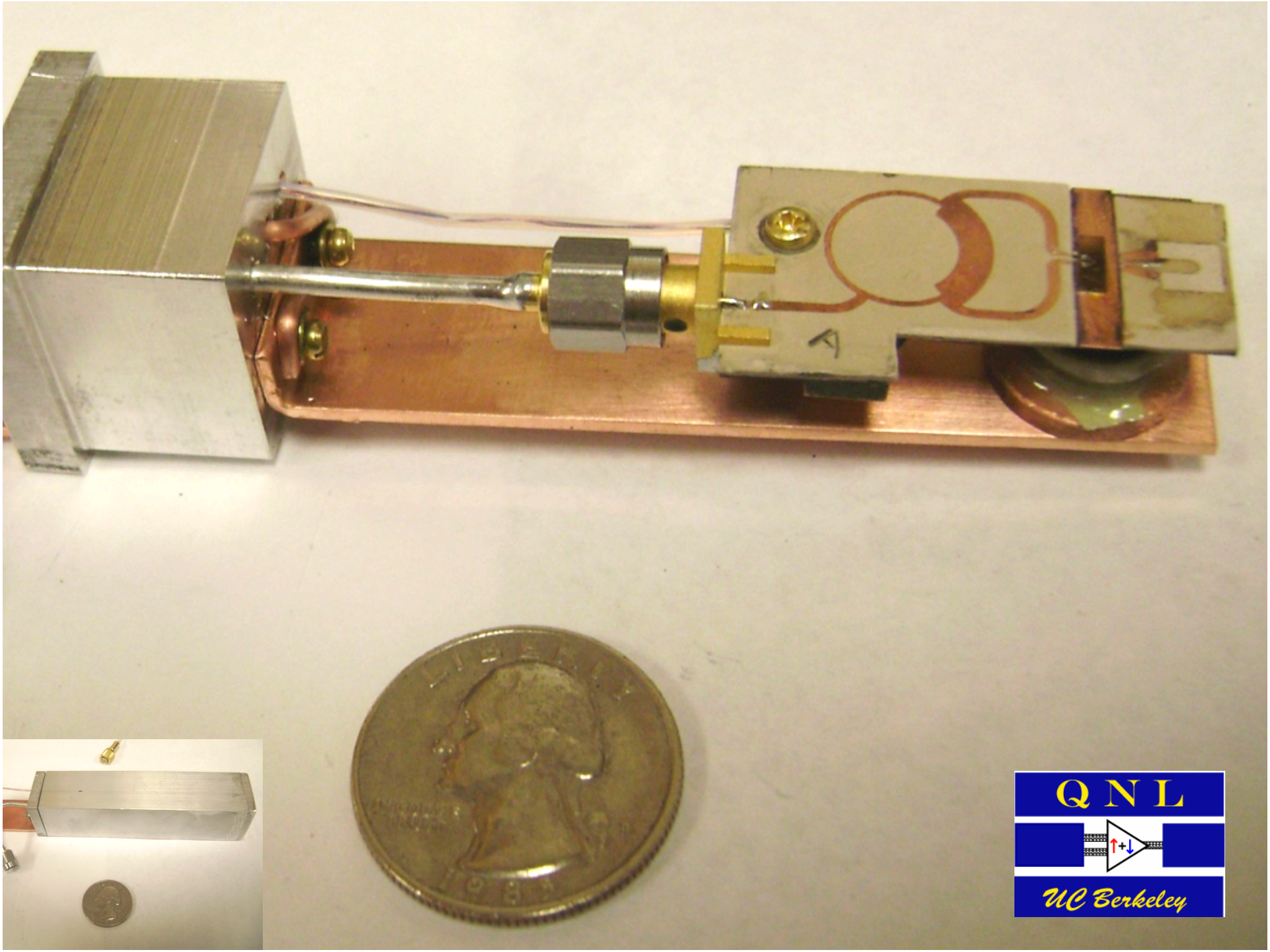


EXPERIMENTAL SETUP

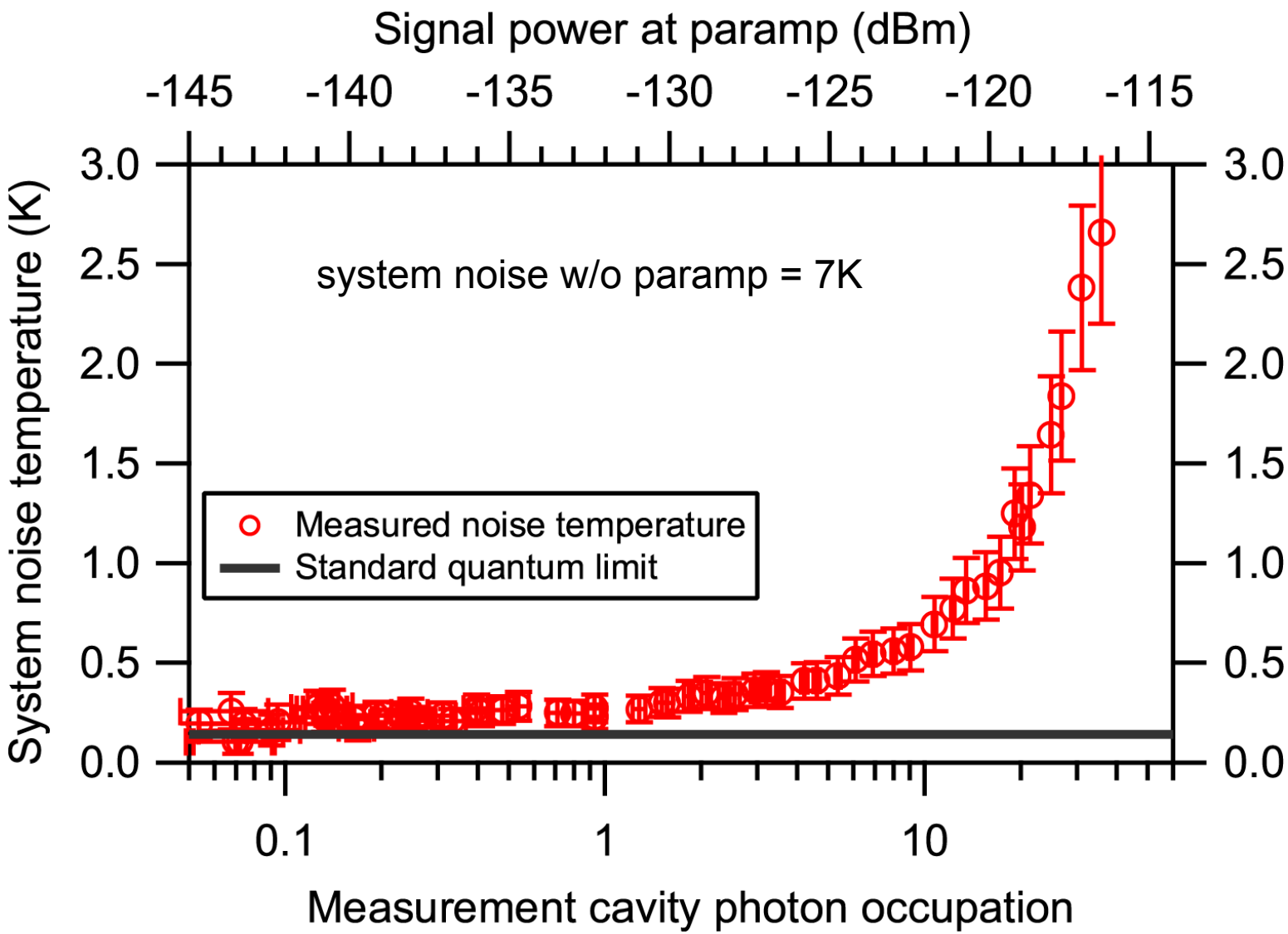


<u>Parametric amplifier</u>

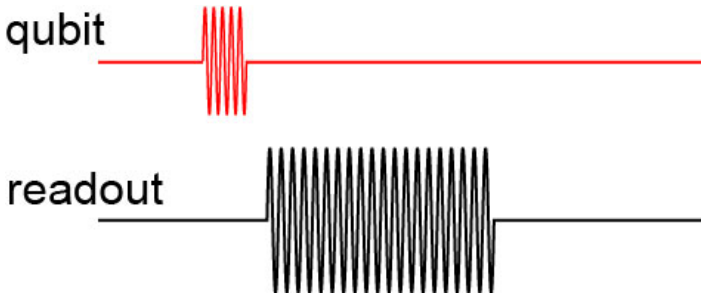
- high gain (~20 dB)
- large bandwidth (>20 MHz)
- tunable center freq (4-8 GHz)
- ~ 0 – 0.5 added photons

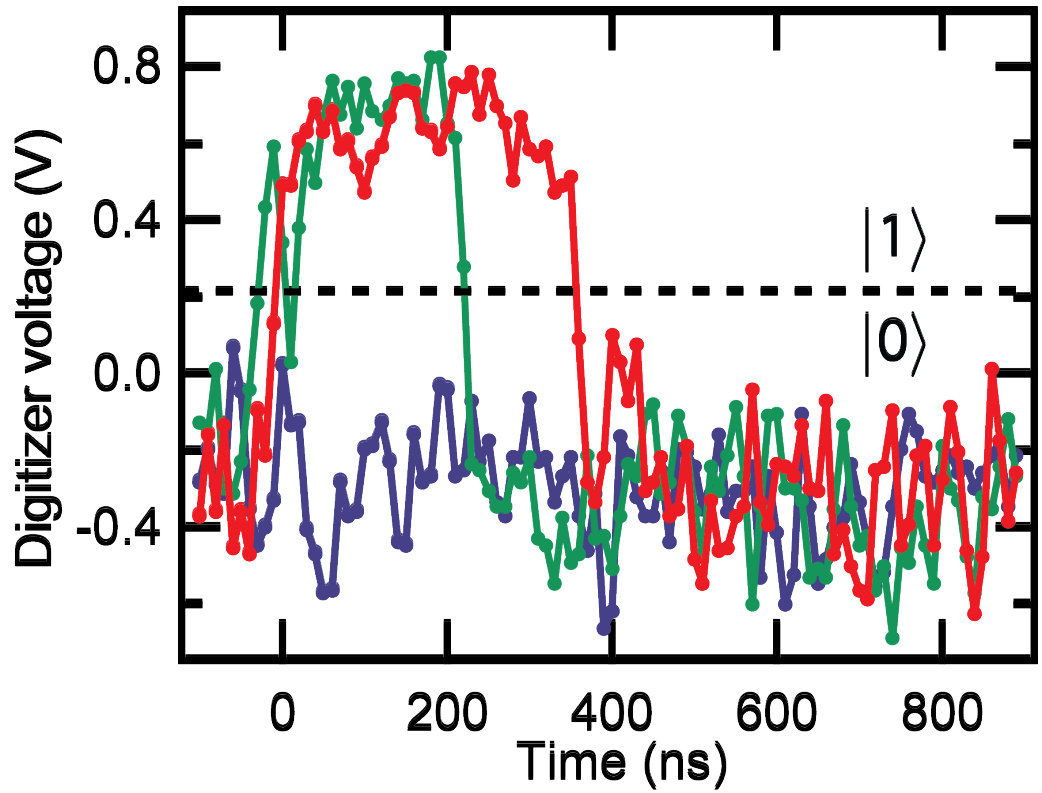

A
LIBERTY
1984
Q N L
UC Berkeley

SYSTEM NOISE TEMPERATURE



SINGLE SHOT MEASUREMENTS

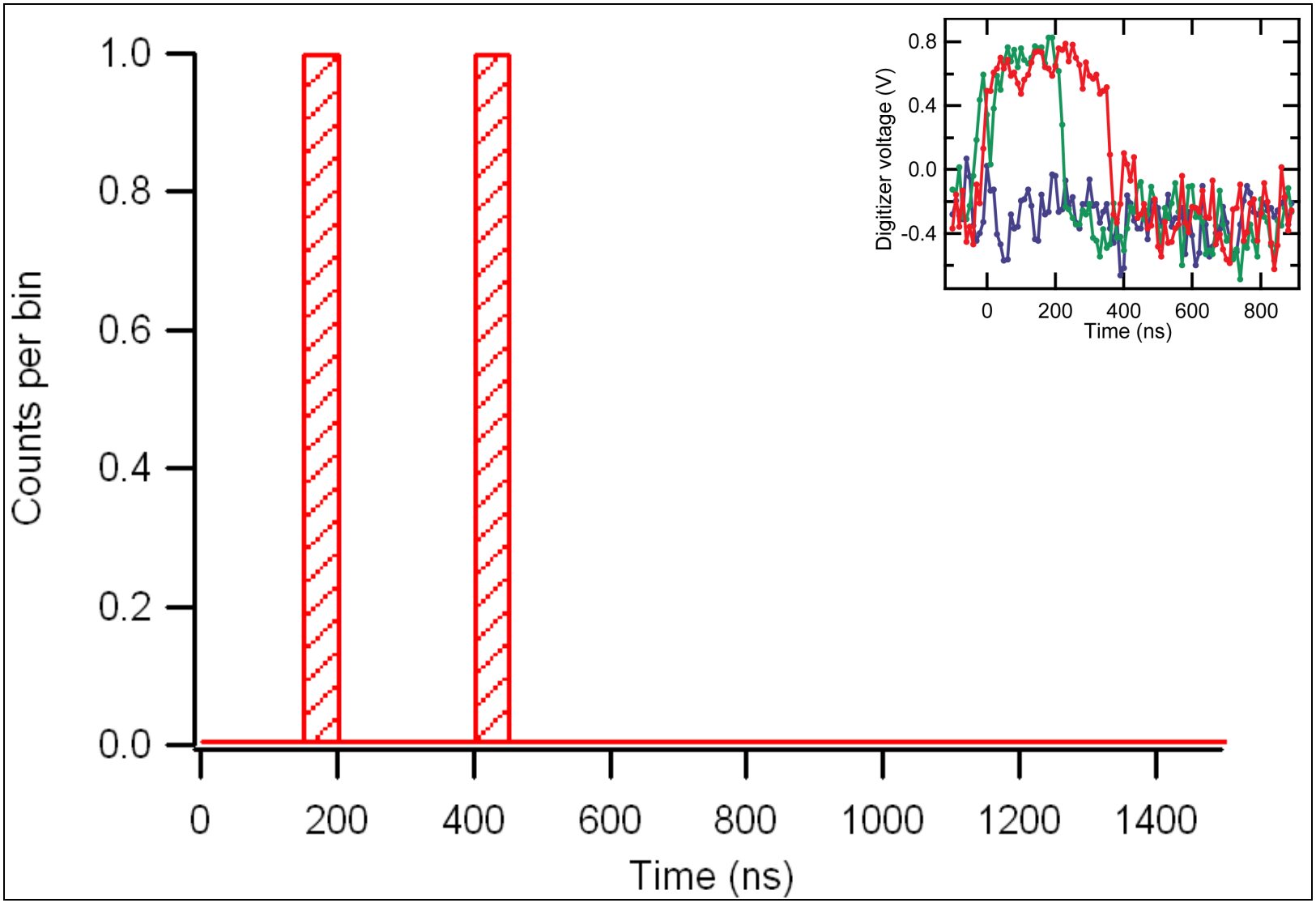




Real time observation of quantum jumps due to spontaneous decay

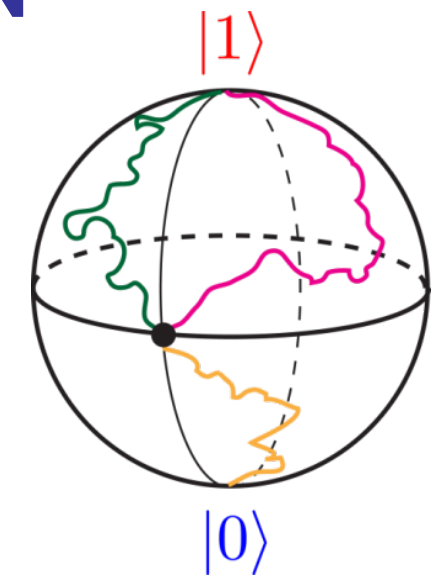
R. Vijay et al., *Phys. Rev. Lett.* **106**, 110502 (2011)

JUMP STATISTICS



WEAK MEASUREMENT: QUANTUM FEEDBACK

SINGLE QUBIT EVOLUTION



- Weak continuous measurement
  -> CONTINUOUS COLLAPSE

- *Noisy* detector output <-> Random evolution of qubit

- Ideal detector: No decoherence in a <u>single</u> qubit

- Bayesian evolution:

$$\dot{\rho}_{11} = -2H\,\mathrm{Im}\,\rho_{12} + 2\rho_{11}\rho_{22}[I(t) - I_0]\Delta I/S_I,$$

$$\dot{\rho}_{12} = i\varepsilon\rho_{12} + iH(\rho_{11} - \rho_{22}) - \gamma\rho_{12} - (\rho_{11} - \rho_{22})\rho_{12}[I(t) - I_0]\Delta I/S_I,$$

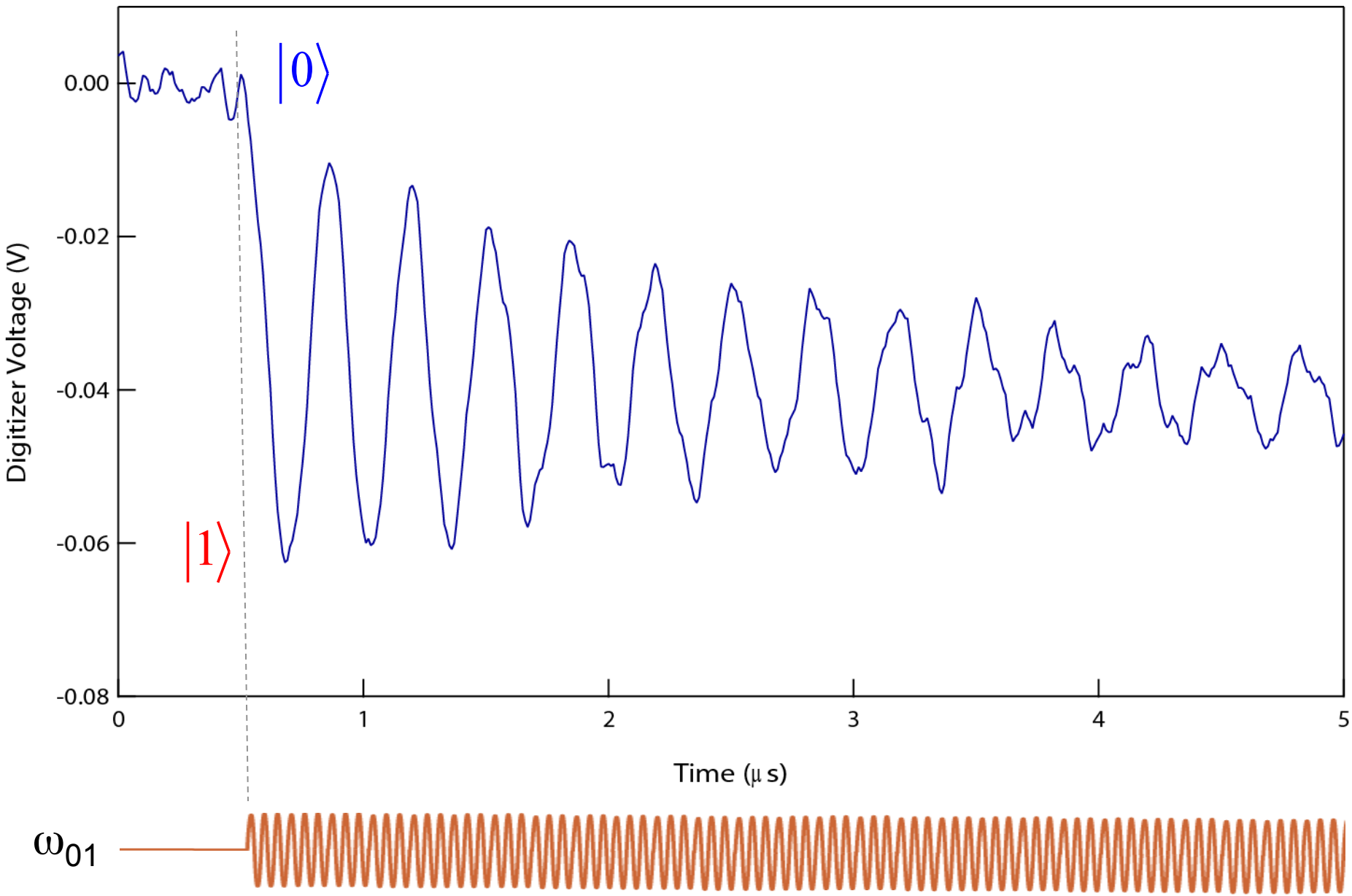
I: Detector output
S_I: Output noise on detector
γ: Decoherence rate
(measurement & environment)

A. N. Korotkov, *Phys. Rev.* B **60,** 5737 (1999)

Calculate ρ_m (t) from I(t) and apply real time correction to steer toward desired ρ(t)

In general, requires significant calculation & wide bandwidth

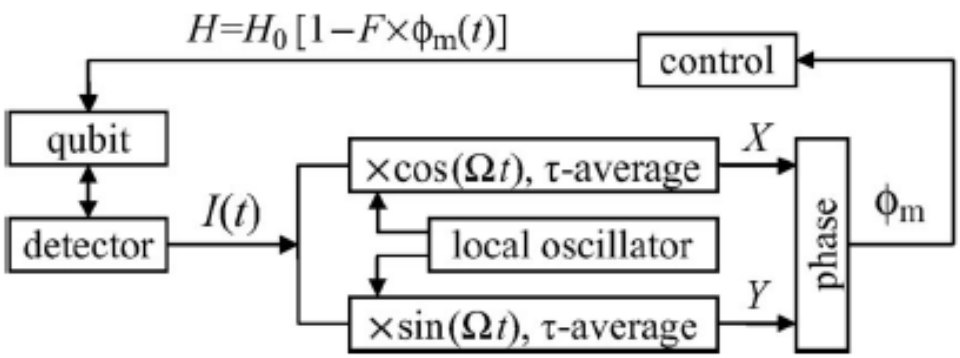
RABI OSCILLATIONS (ENSEMBLE MEASUREMENT)



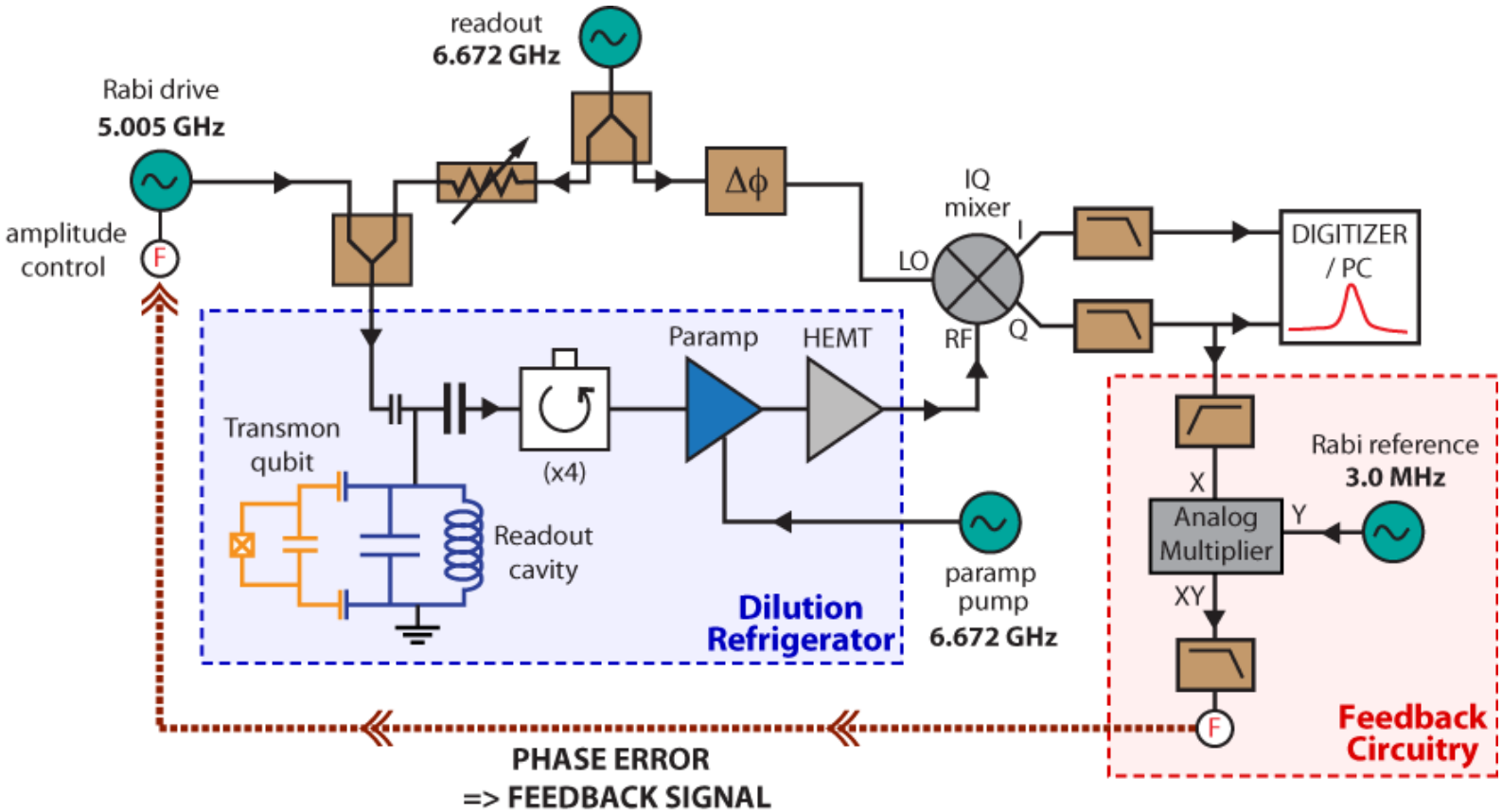
PHASE LOCKED RABI OSCILLATIONS

- Experiment is to maintain coherent oscillations
- Use oscillatory component of measurement signal rather than noise

  A. N. Korotkov, *Phys. Rev.* B **71** 201305 (2005)
- Phase-lock to a classical reference oscillator



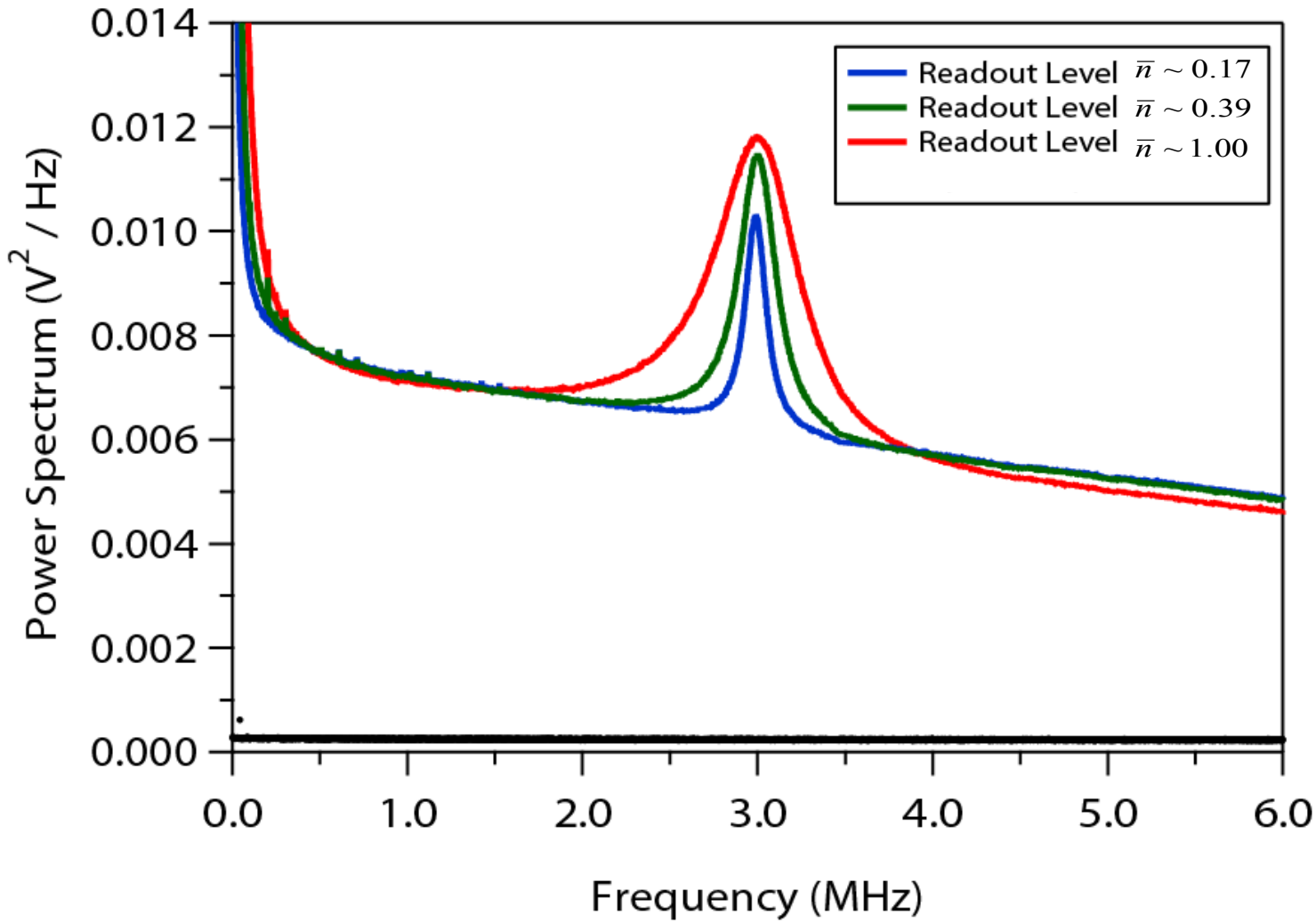
EXPERIMENTAL SETUP & PARAMETERS



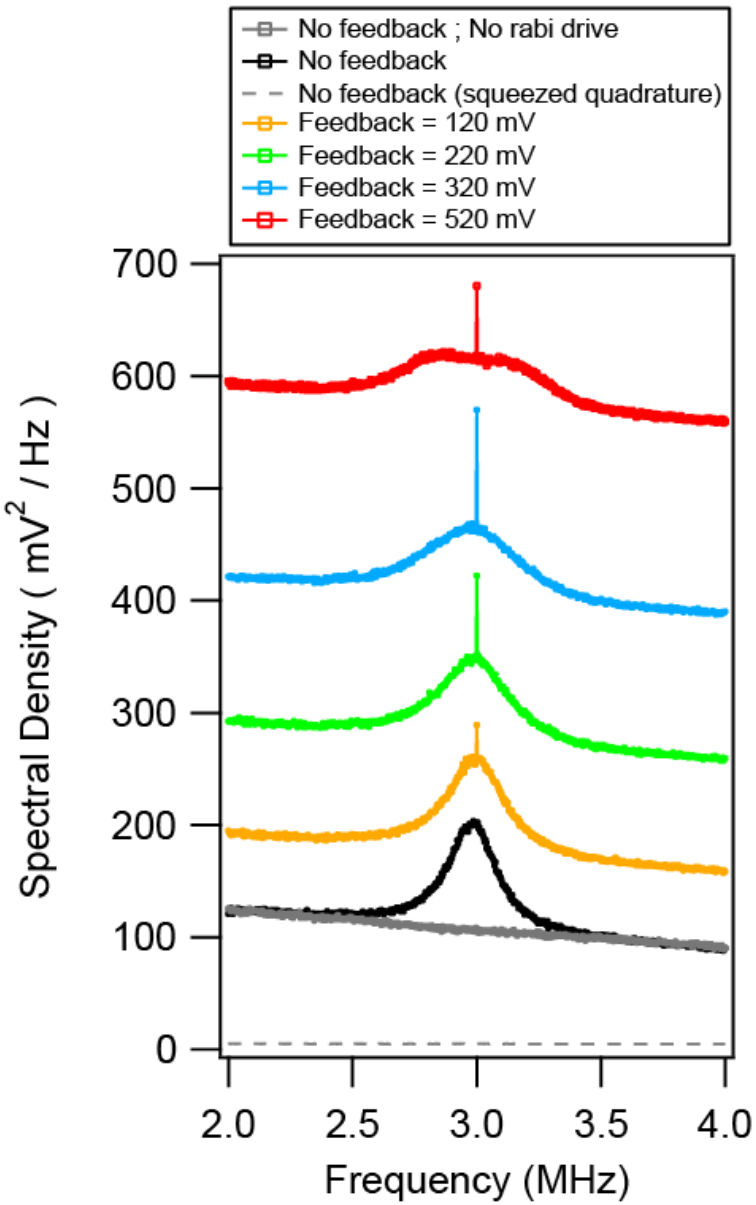
Requirements:

BW	~	$\kappa/2$	>	Ω_R	>	Γ_f	>	Γ_m	>	Γ_d
6 MHz	~	7 MHz	>	3 MHz	>	1 MHz	>	0.25 MHz	>	0.05 MHz
Paramp Bandwidth		Cavity linewidth		Rabi frequency		Feedback rate		Measurement dephasing		Environment dephasing

RABI OSCILLATIONS w. MEASUREMENT

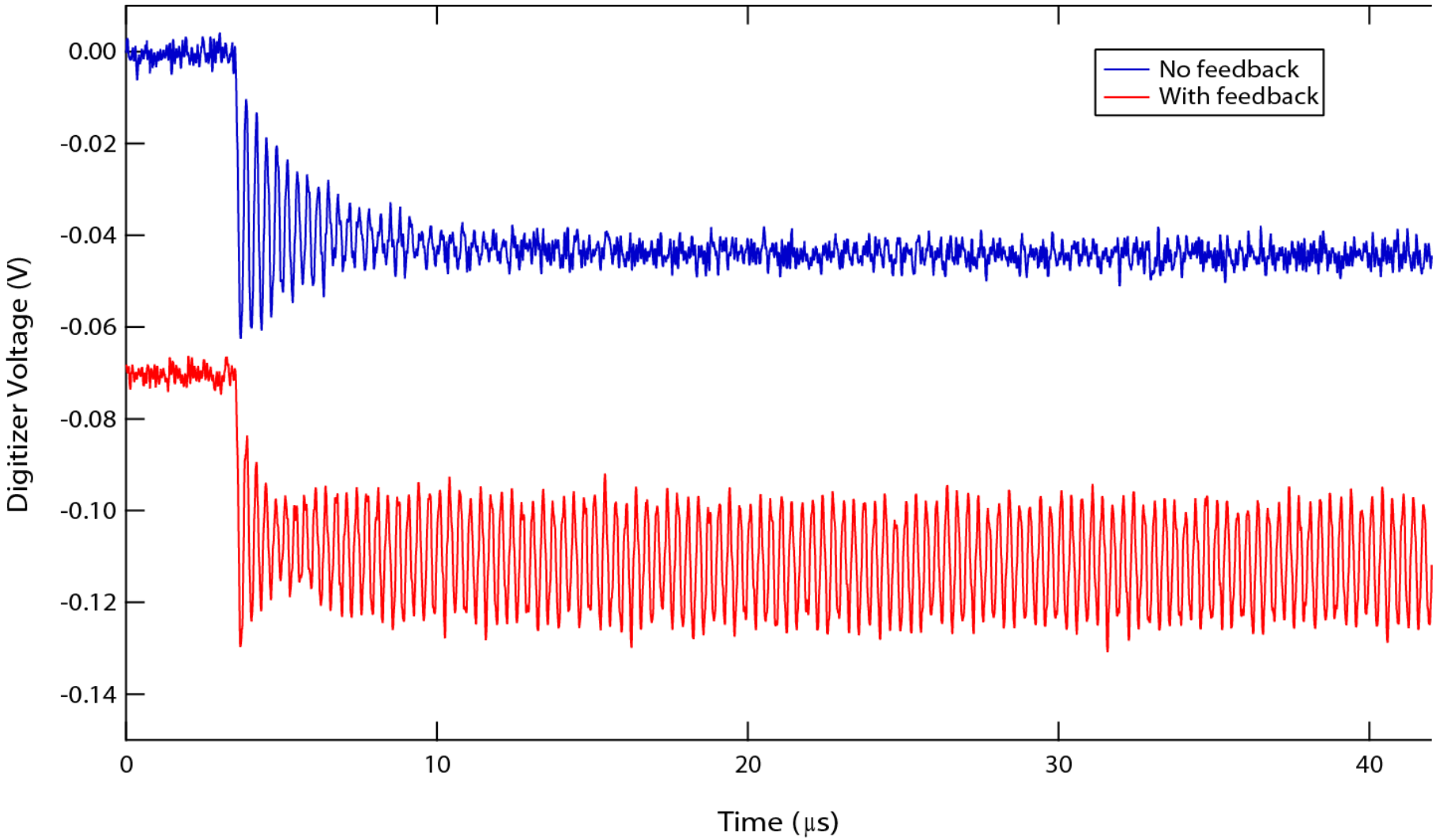


STABILIZED RABI OSCILLLATIONS

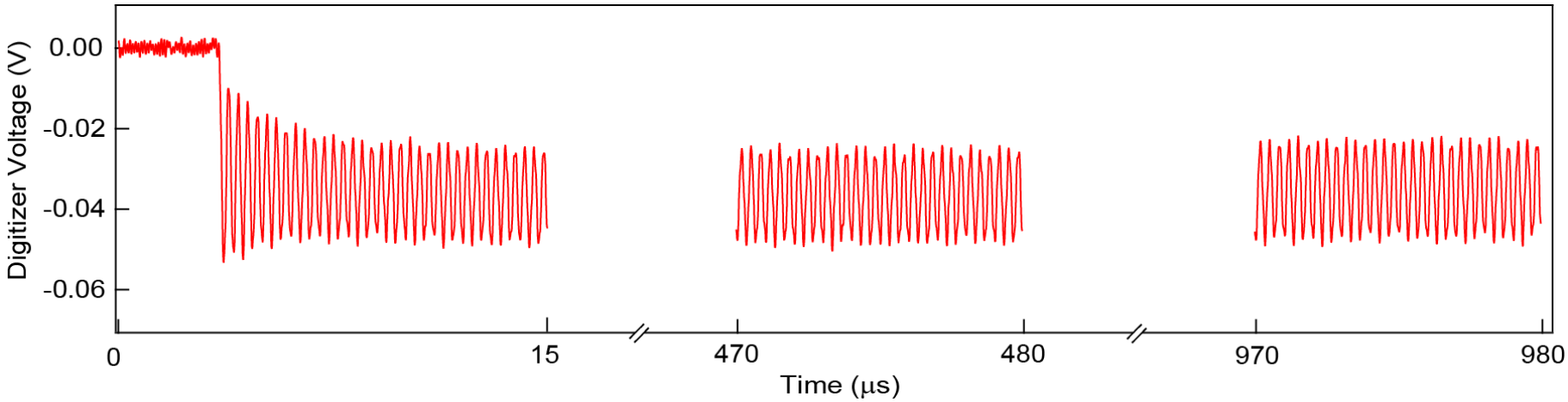


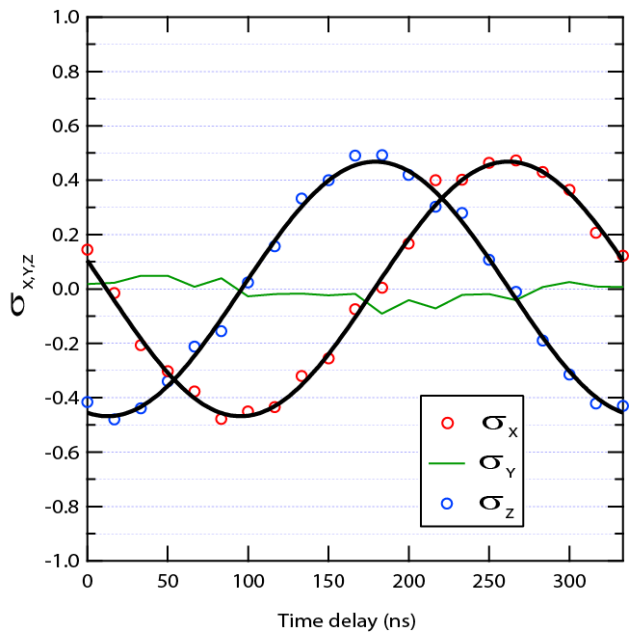
- Single quadrature measurement
- Spectral signature of Rabi oscillations
  - first observed with HEMT amplifier
    A. Palacios-Laloy *et al.*,
    Nature Phys. **6**, 442 (2010)

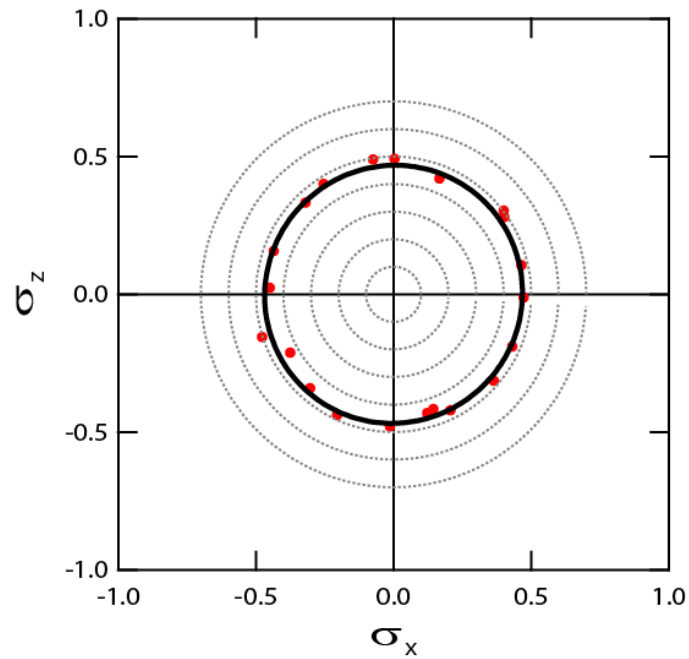
STABILIZED RABI OSCILLLATIONS



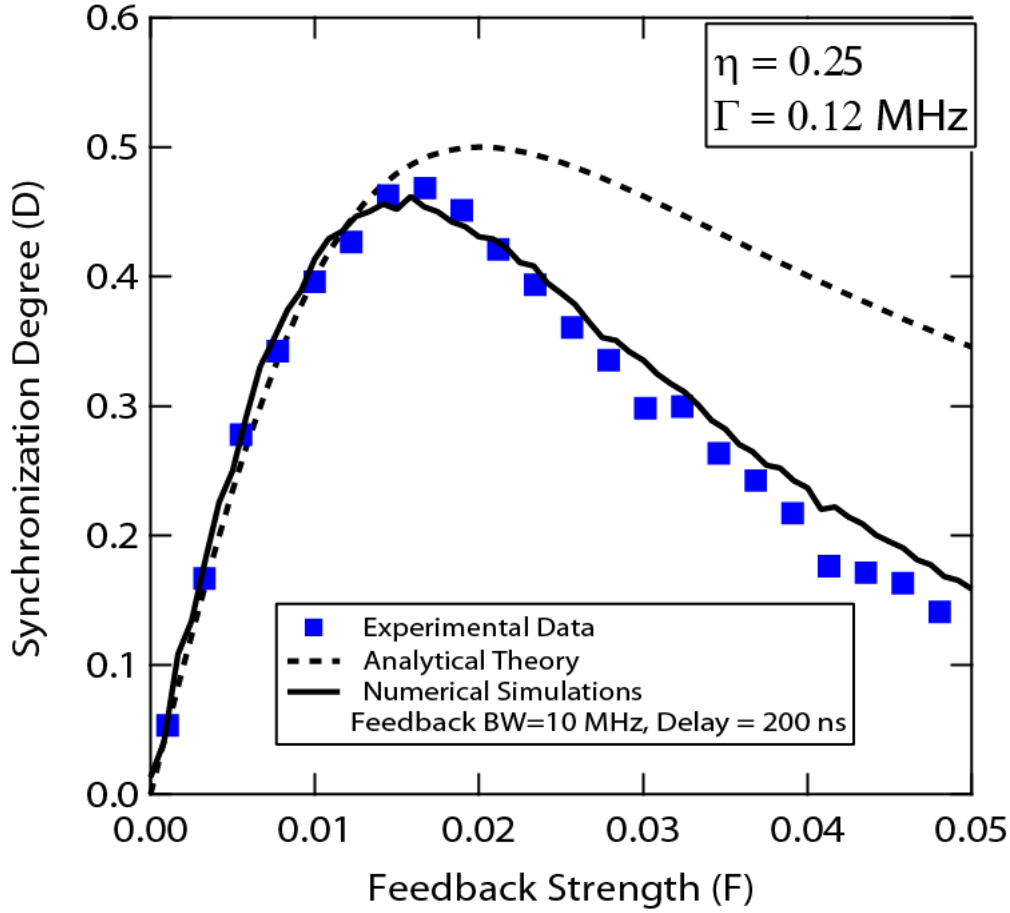
TOMOGRAPHY


Digitizer Voltage (V)
0.00
-0.02
-0.04
-0.06
0
15
470
480
970
980
Time (μs)


σ x,Y,Z
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
0
50
100
150
200
250
300
Time delay (ns)
σ X
σ Y
σ Z


σ Z
1.0
0.5
0.0
-0.5
-1.0
-1.0
-0.5
0.0
0.5
1.0
σ X

FEEDBACK EFFICIENCY



- Highest efficiency achieved ~ 50%
- In principle, can achieve 99% with full Bayesian feedback
- Measurement based quantum error correction
- **Feedback efficiency limited by delay time & connector loss**

ACKNOWLEDGEMENTS

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FUTURE DIRECTIONS

- QUANTUM FEEDBACK/CONTROL
  - OPTIMIZE EFFICIENCY
  - BAYESIAN FEEDBACK
  - MEASUREMENT BASED ERROR CORRECTION
- MULTIPLEXED QUBIT READOUT
- ON-CHIP PARAMP
  - BACKACTION OF NONLINEAR TANK CIRCUIT