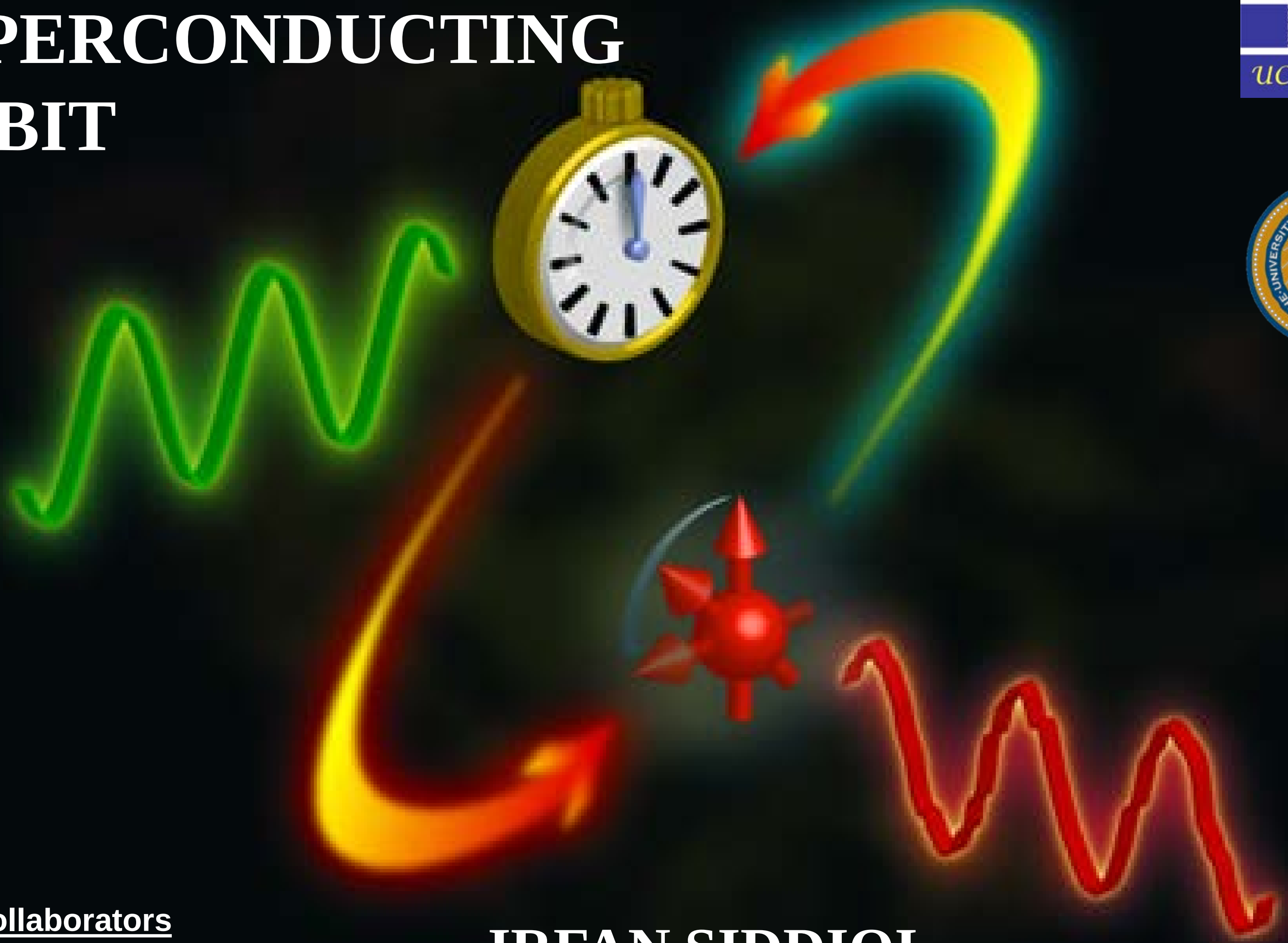
QUANTUM FEEDBACK IN A SUPERCONDUCTING QUBIT



IRFAN SIDDIQI

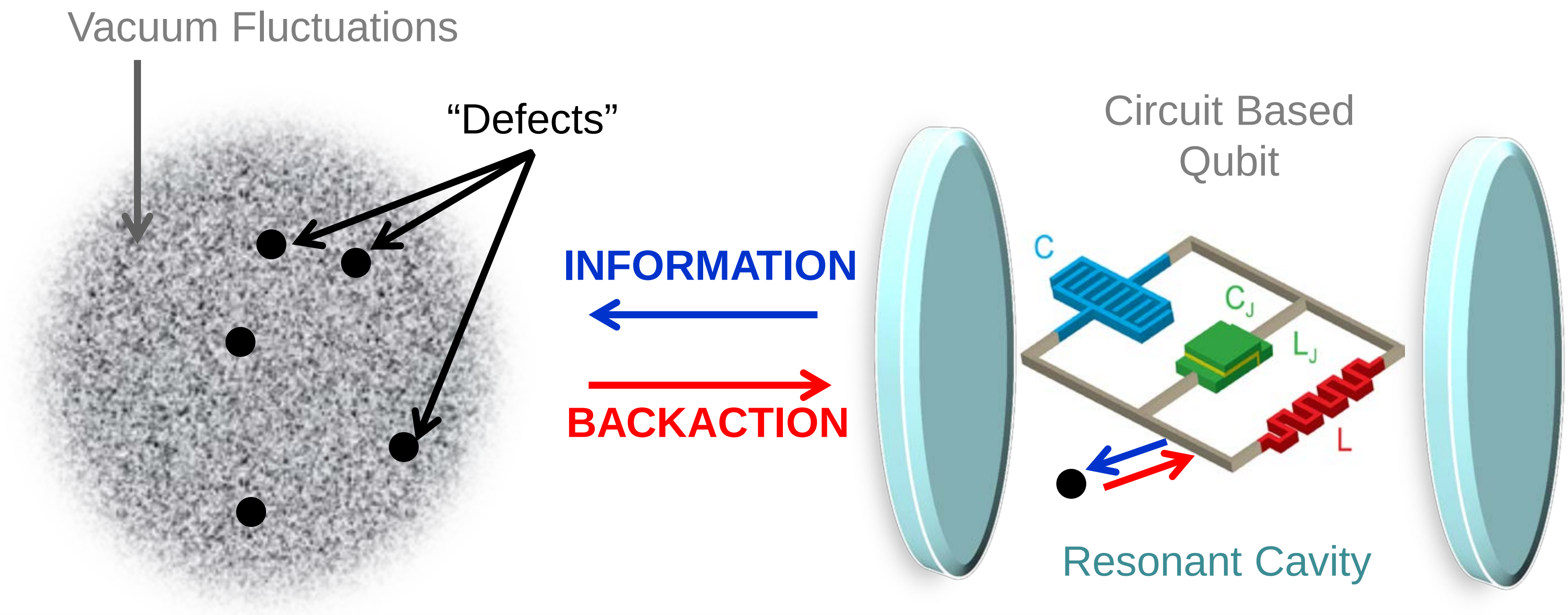
Quantum Nanoelectronics Laboratory

Department of Physics, UC Berkeley

Collaborators

Prof. A.N. Korotkov (UCR)
Prof. S.M. Girvin (Yale)
Dr. Mohan Sarovar (Sandia)
Prof. B. Whaley (UCB)

THE CHALLENGE OF GREGARIOUS QUBITS…



Vacuum Fluctuations

“Defects”

INFORMATION

BACKACTION

Circuit Based Qubit

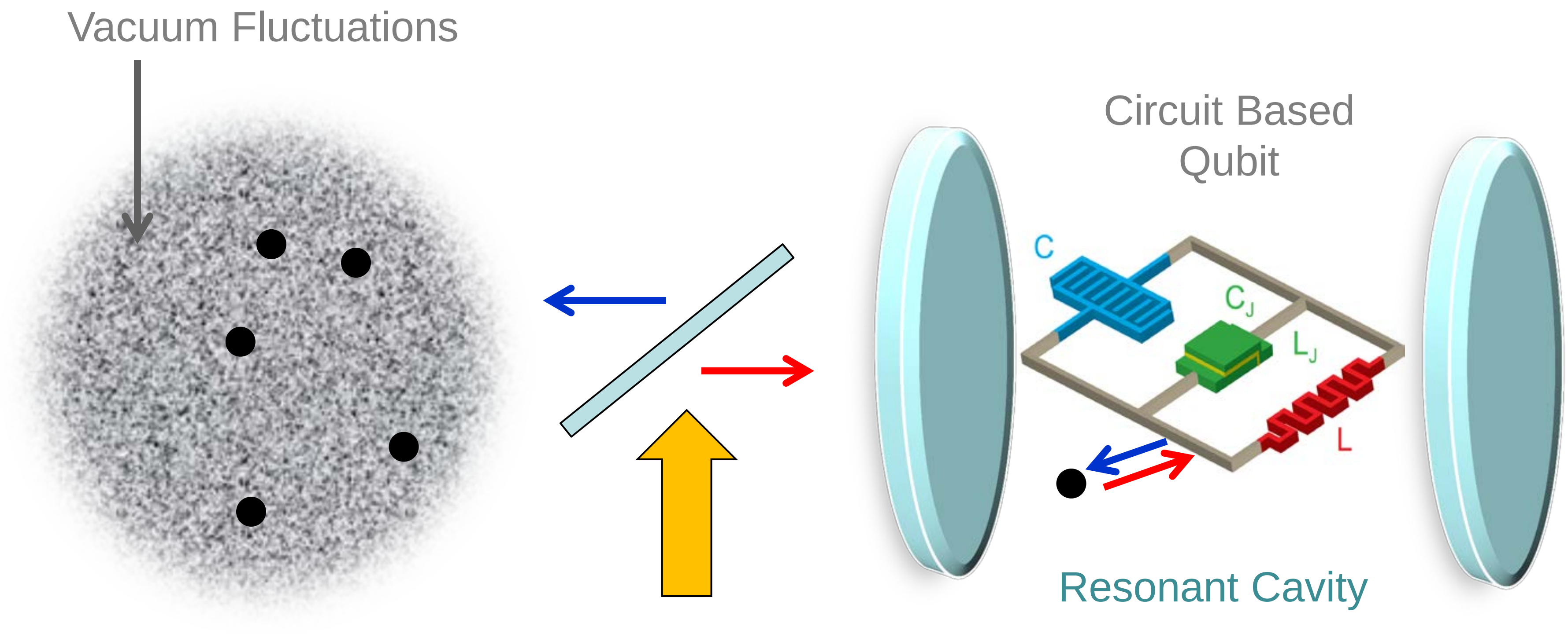
Resonant Cavity

- Current state of the art (no control): T_1, T_2 ~ 10-100 μs
- **Active control via engineered dissipation**
  - quantum bath engineering
  - squeeze vacuum fluctuations
  - measurement based feedback

JOSEPHSON PARAMETRIC AMPLIFIERS

→ Remote Entanglement / Stabilization of Qubits

QUANTUM BATH ENGINEERING: COOLING



Vacuum Fluctuations

Circuit Based
Qubit

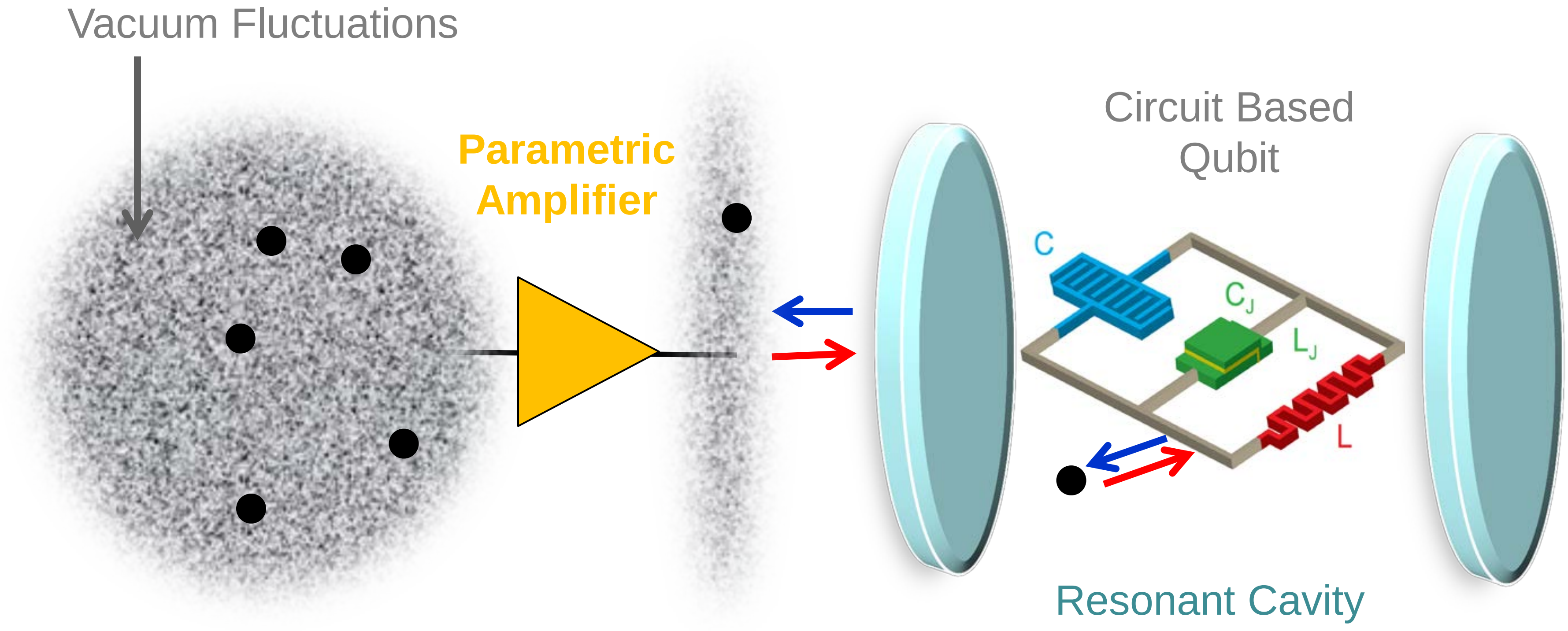
Resonant Cavity

MICROWAVE
PULSES

AUTONOMOUSLY COOL TO ANY ARBITRARY STATE ON THE BLOCH SPHERE

Poyatos, Zoller (1996)
Lutkenhaus (1998)
Wiseman (1994)
Kraus (2008)
Diehl (2008,2010)
Schirmer (2010)
Wang (2001,2005)
Carvalho (2007, 2008)
Marcos (2012)

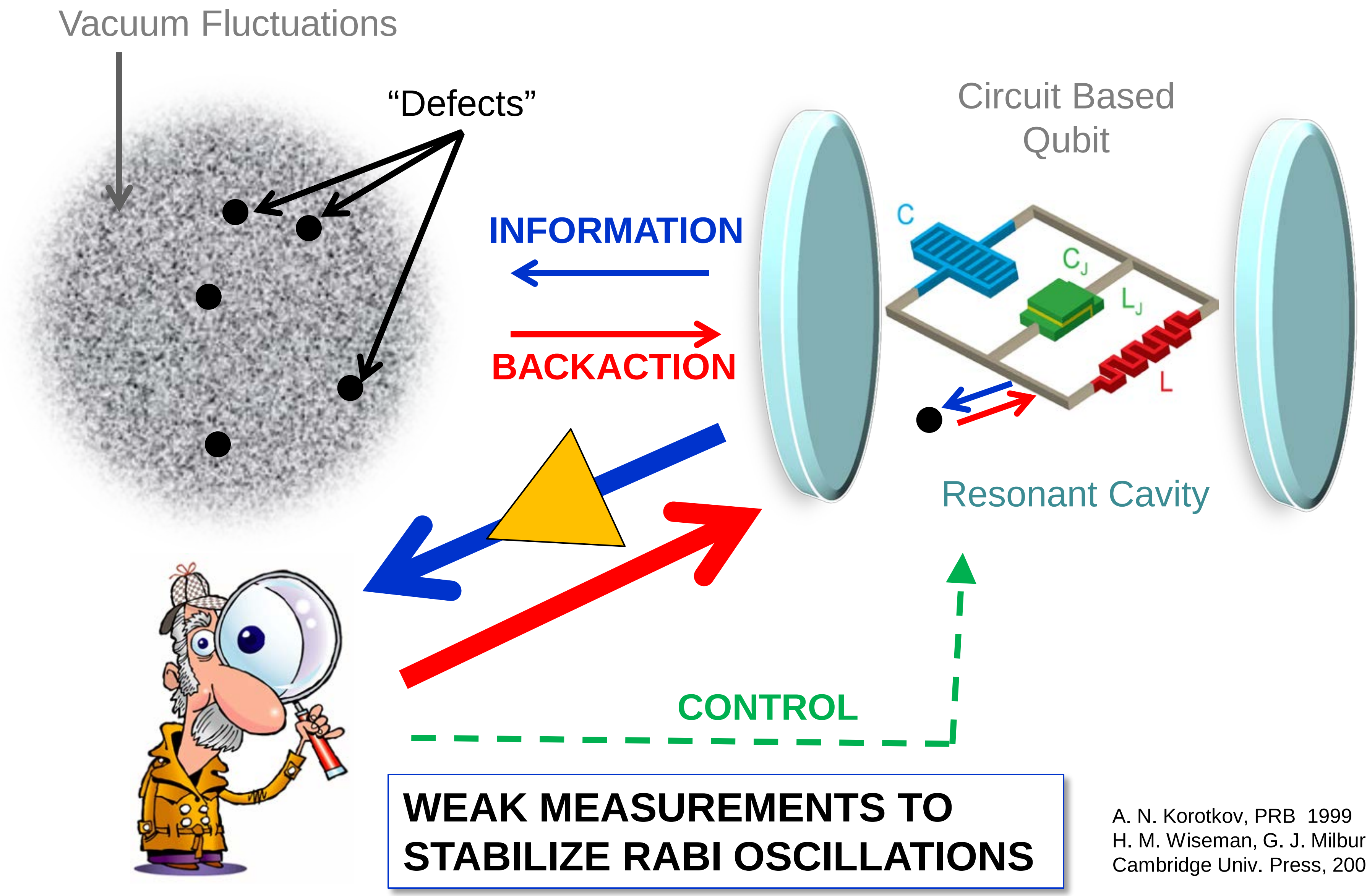
QUANTUM BATH ENGINEERING: SQUEEZING



SQUEEZED LIGHT / MATTER INTERACTION MODIFIES TRANSVERSE/LONGITUDINAL DECAY

Slusher et al, PRL 1985
Treps et al, PRL 2002
Gardiner, PRL 1986

MEASUREMENT BASED FEEDBACK



Vacuum Fluctuations

“Defects”

INFORMATION

BACKACTION

Circuit Based Qubit

C

C_J

L_J

L

Resonant Cavity

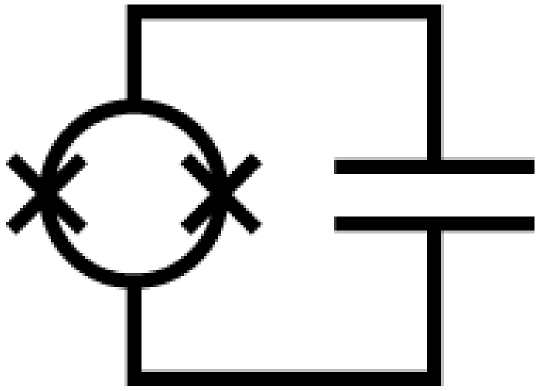
CONTROL

WEAK MEASUREMENTS TO STABILIZE RABI OSCILLATIONS

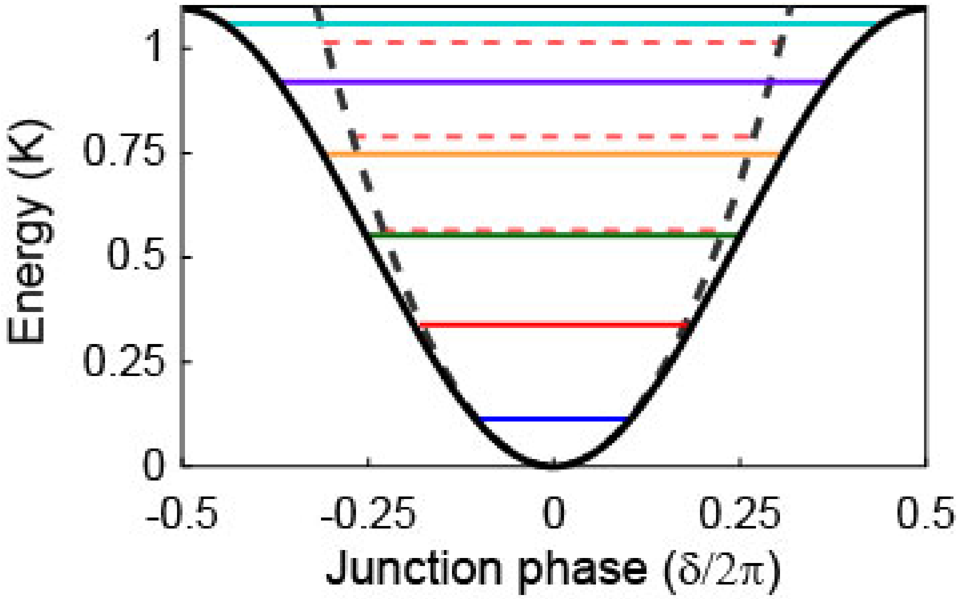
A. N. Korotkov, PRB 1999
H. M. Wiseman, G. J. Milburn, Cambridge Univ. Press, 2009

THE QUBIT

SUPERCONDUCTING TRANSMON QUBIT



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

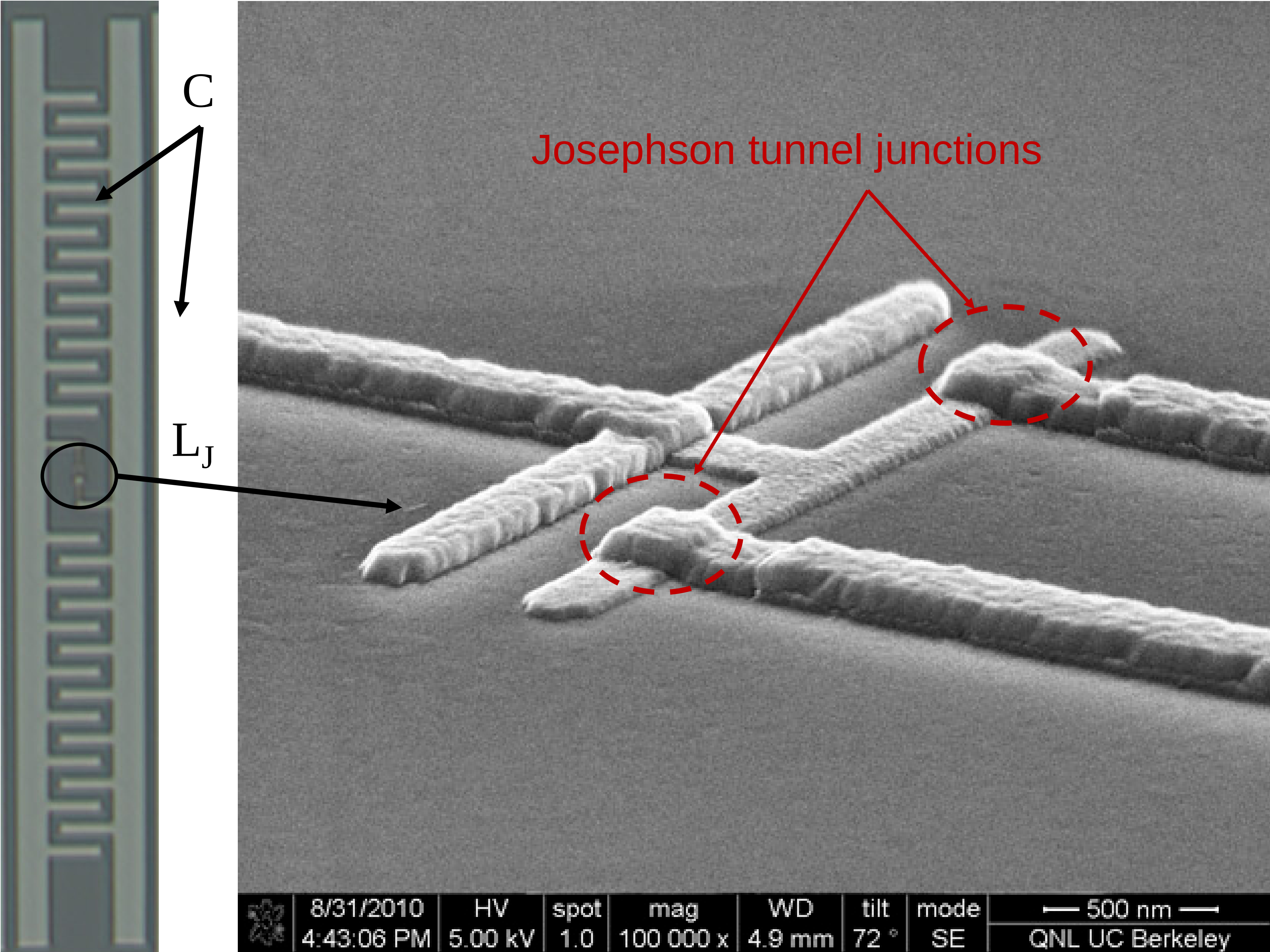


$$\omega_{01} \simeq \frac{1}{\sqrt{L_J C}}$$

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

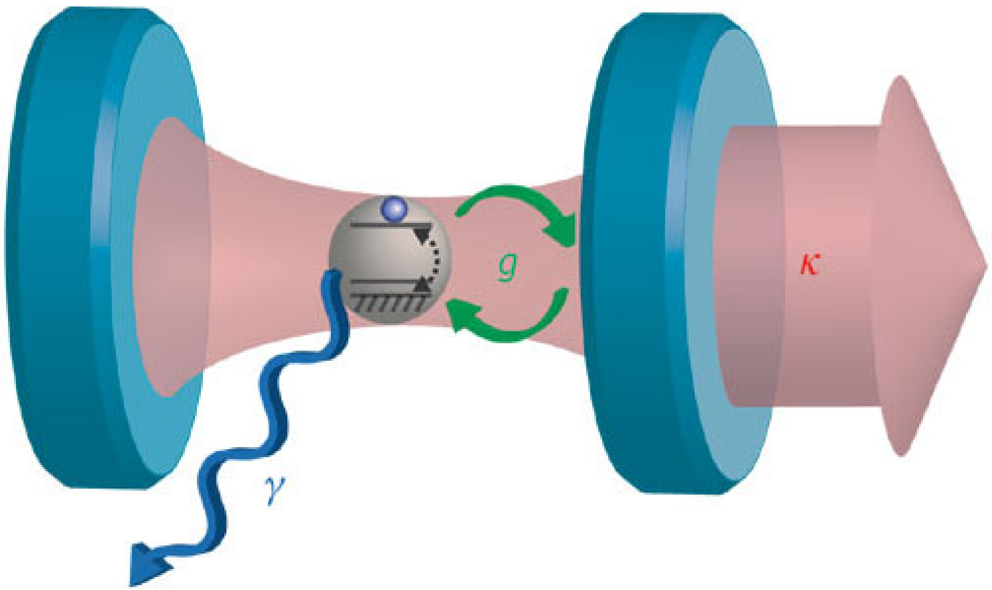
- Tunable qubit frequency
- $\omega_{01} \sim$ 5-8 GHz

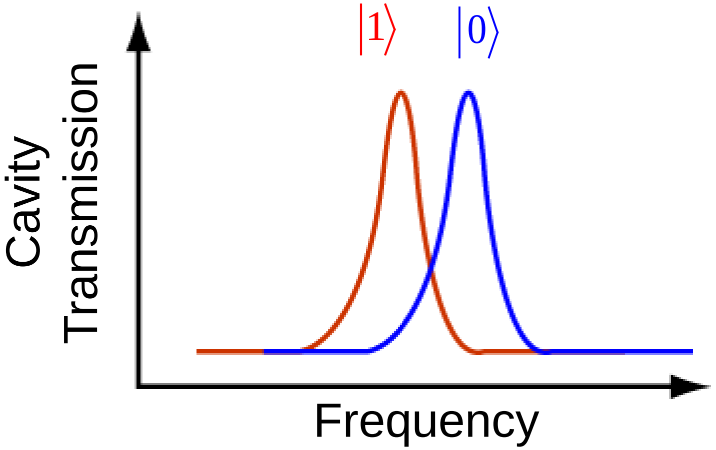
J. Koch et al., *Physical Review A* ***76,*** 042319 (2007)


C
L_J
Josephson tunnel junctions
8/31/2010
4:43:06 PM
HV
5.00 kV
spot
1.0
mag
100 000 x
WD
4.9 mm
tilt
72 °
mode
SE
500 nm
QNL UC Berkeley

THE MEASUREMENT APPARATUS

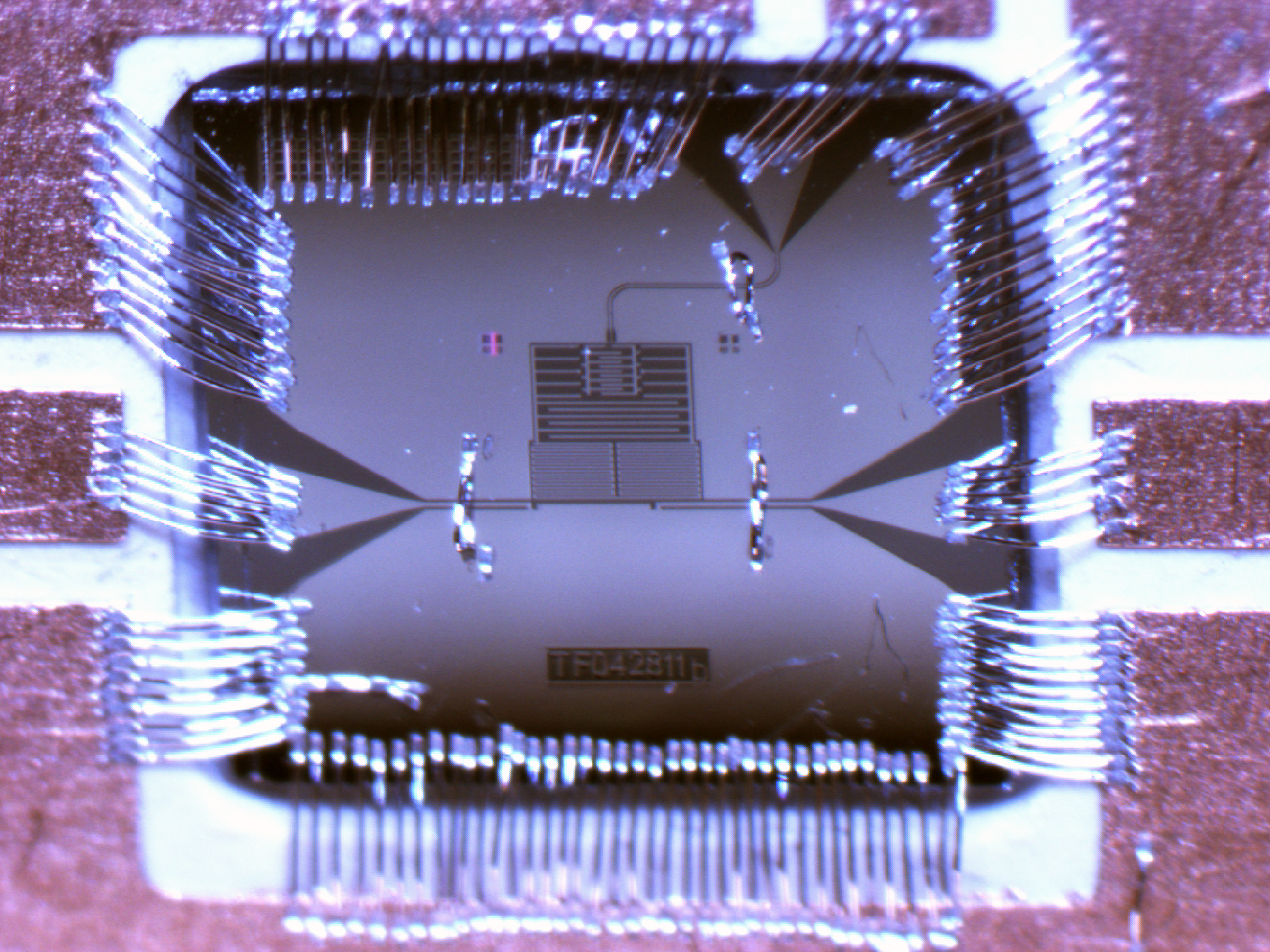
MEASUREMENT : COUPLE TO E-M FIELD OF CAVITY (Jaynes-Cummings)

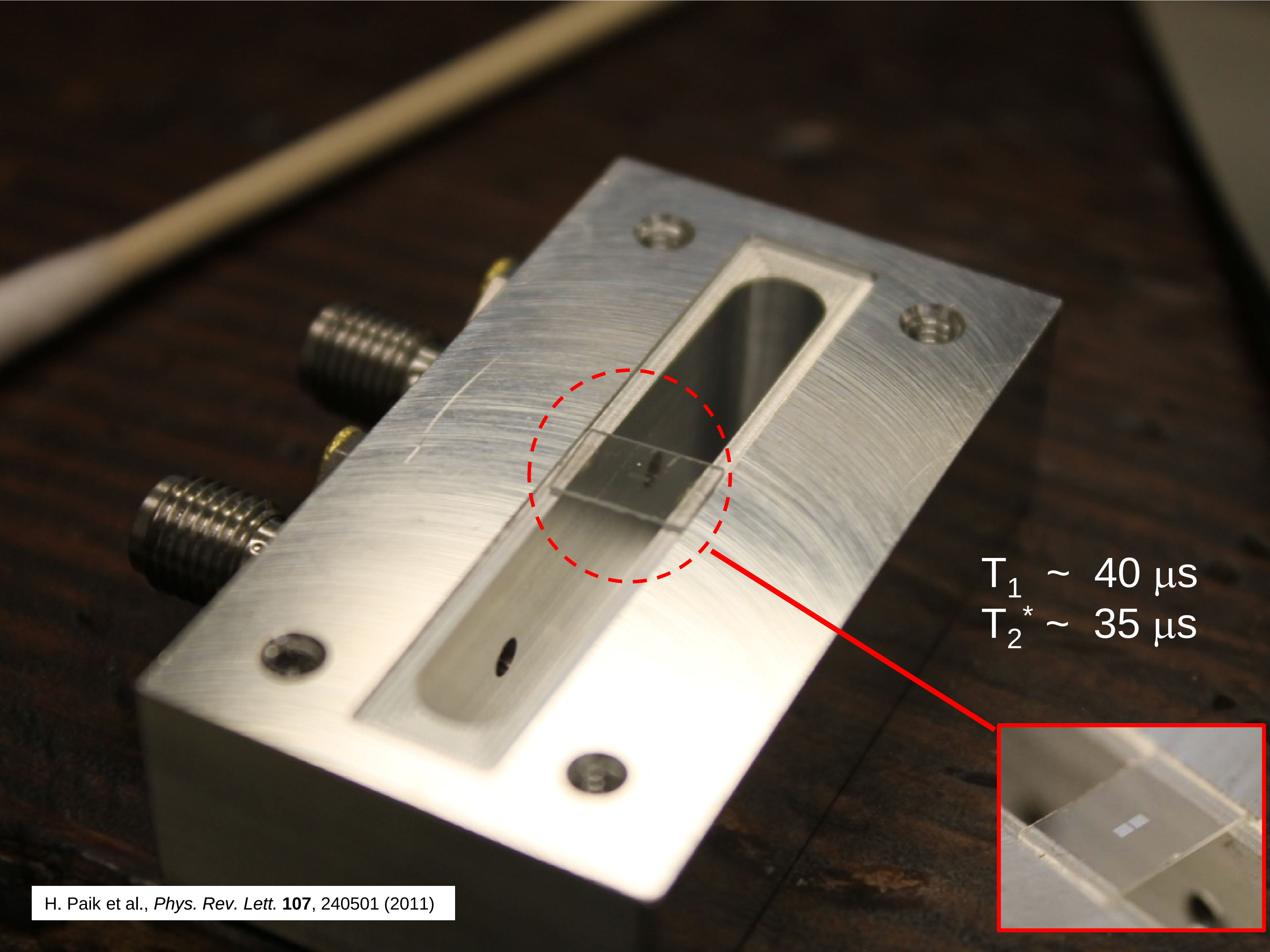




$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\omega_r(a^\dagger a + \frac{1}{2}) + \hbar g(a^\dagger\sigma_- + a\sigma_+)$$

$$H_{disp} = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\left(\omega_r + \boxed{\chi\sigma_z}\right)(a^\dagger a + \frac{1}{2})$$


TF042811b

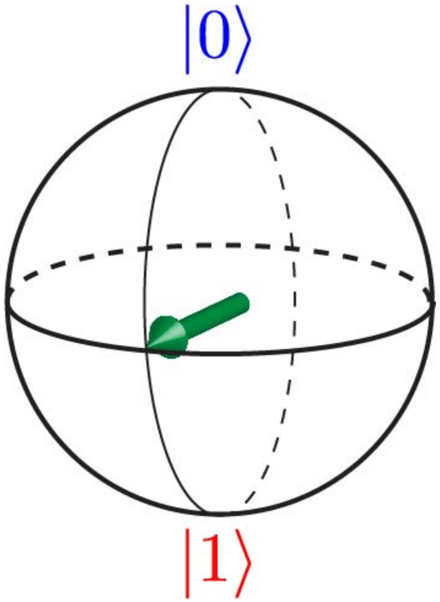


$T_1 \sim 40\ \mu s$

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

H. Paik et al., *Phys. Rev. Lett.* **107**, 240501 (2011)

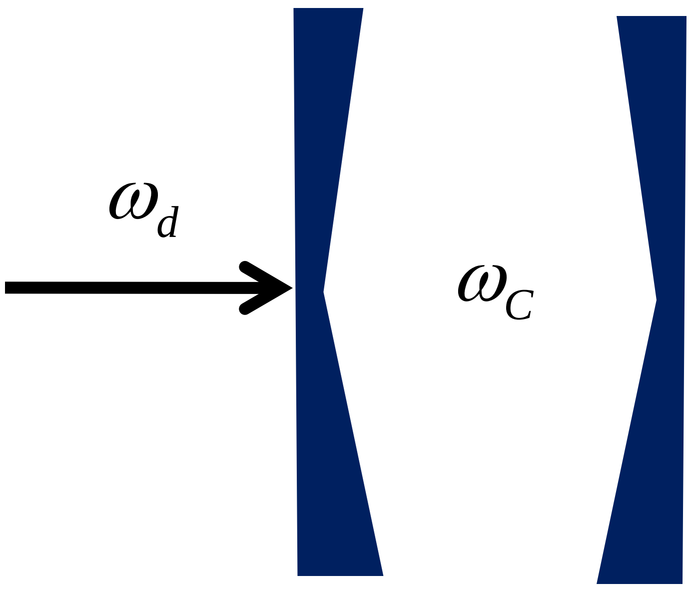
HOW DO WE STABILIZE A SUPERPOSITION ?

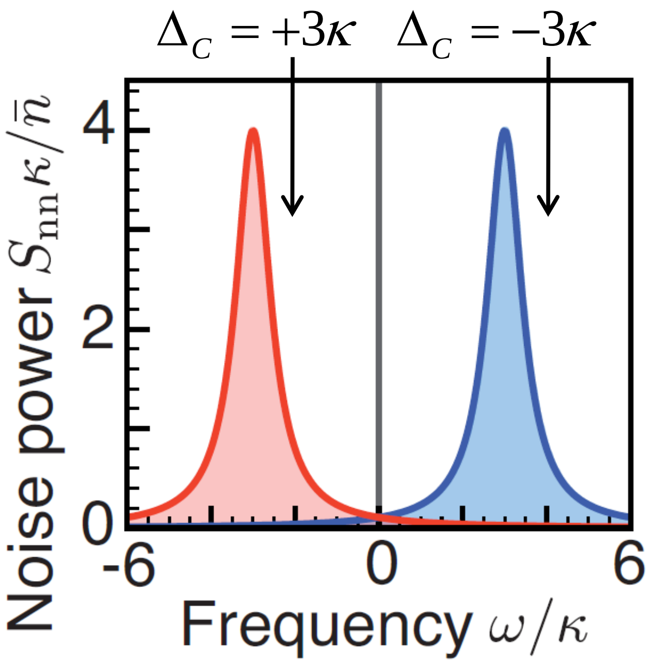


CAVITY ASSISTED QUANTUM BATH ENGINEERING

K. Murch et al., *Phys. Rev. Lett.* **109**, 183602 (2012)

QUANTUM RESERVOIR:
SHOT NOISE IN DRIVEN CAVITY





$$\Delta_C = \omega_d - \omega_C$$

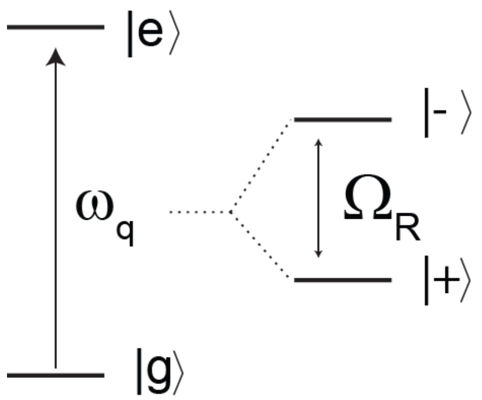
$$S_{nn}[\omega] = \frac{\bar{n}\cdot\kappa}{(\kappa/2)^2 + (\omega + \Delta_c)^2}$$

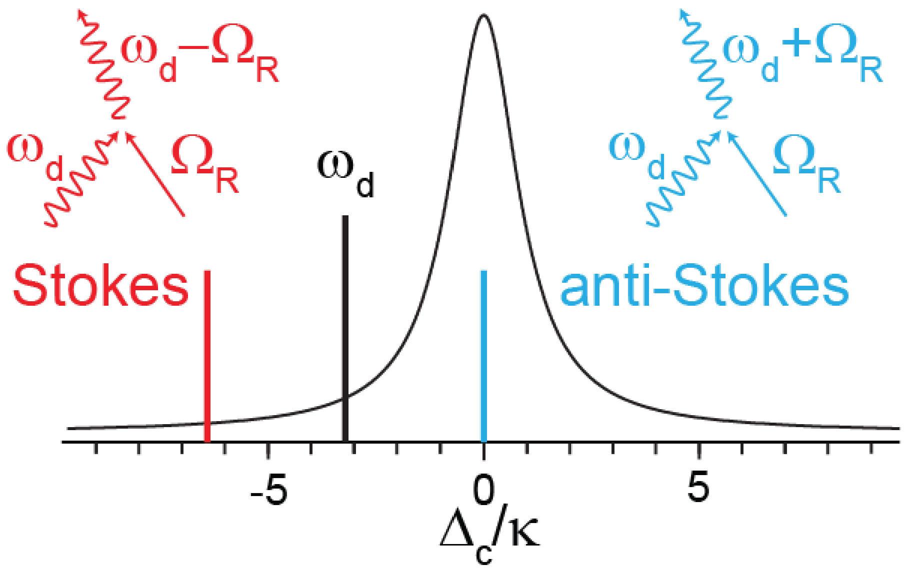
$\Delta_C > 0:$ Noise peaks at ω < 0
Cavity emits → heating

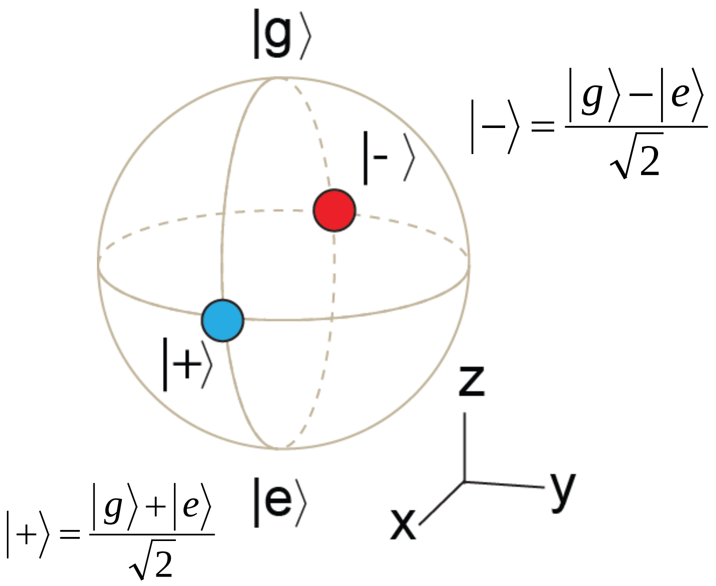
$\Delta_C < 0:$ Noise peaks at ω > 0
Cavity absorbs → cooling

A.A. Clerk et al., *Rev. Mod. Phys* ***82,*** 1155 (2010)

CAVITY ASSISTED COOLING

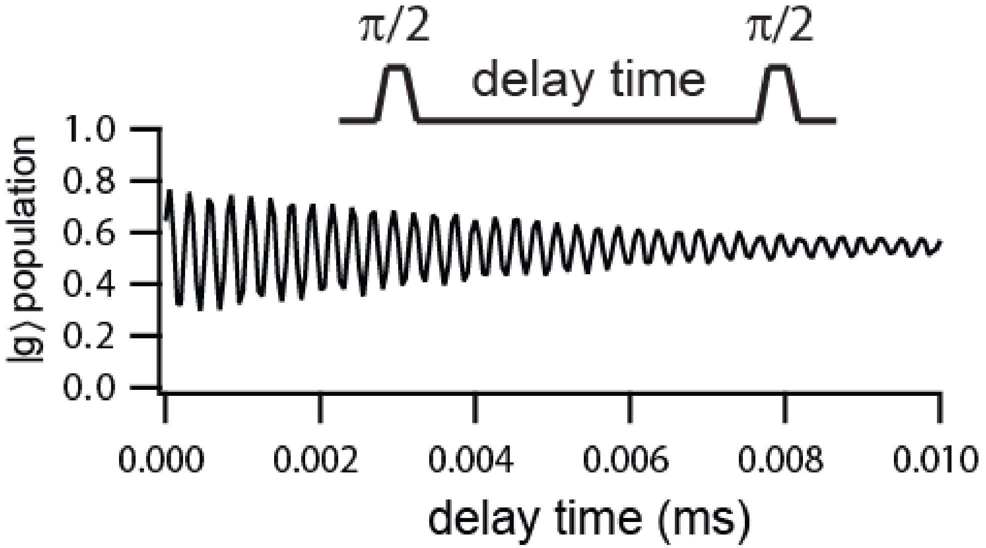




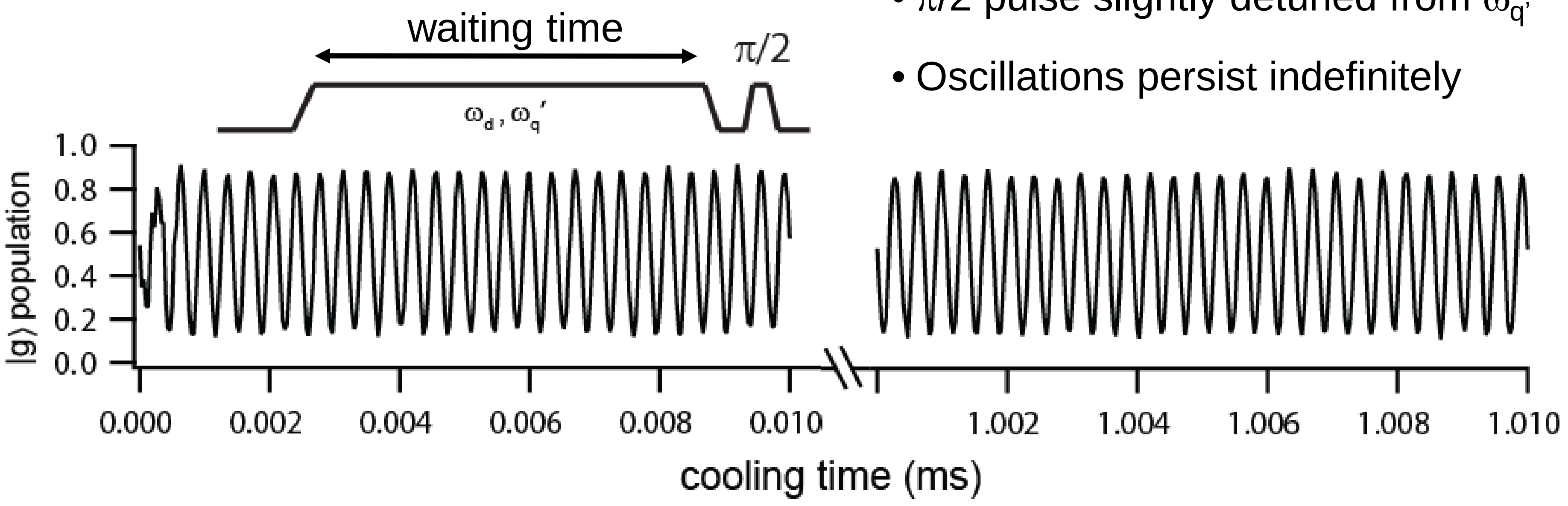


- Drive qubit at ω_q (on resonance)
- $\Omega_R / 2\pi$ ~ 10 MHz → thermal state
- Apply additional tone at ω_d (red detuned)
- Cavity enhances anti-Stokes response
  → cool thermal state to |+>

BUILDING UP COHERENCE



- Conventional Ramsey experiment
  - $T_2^* = 4.9\ \mu s$; 40% contrast
- Apply tone at Stark shifted qubit frequency $\omega_{q'}$ & ω_d ($\Delta_C = -\Omega_R$)
- Cool for a variable cooling time
- $\pi/2$ pulse slightly detuned from $\omega_{q'}$
- Oscillations persist indefinitely



RATES

The effective qubit Hamiltonian (dispersive, rotating)

$$H = -\frac{\Omega_{\rm R}}{2}\sigma_x - \chi a^\dagger a \sigma_z$$

The rates between the two states + and - are:

$$\Gamma_\pm = \frac{1}{4}\left\{\tilde{S}_{zz}(\mp\Omega_{\rm R}) + \tilde{S}_{yy}(\mp\Omega_{\rm R})\right\}$$

$$= \frac{1}{4}\left\{4\chi^2 S_{nn}(\mp\Omega_{\rm R}) + \tilde{S}'_{zz}(\mp\Omega_{\rm R}) + \tilde{S}_{yy}(\mp\Omega_{\rm R})\right\}$$

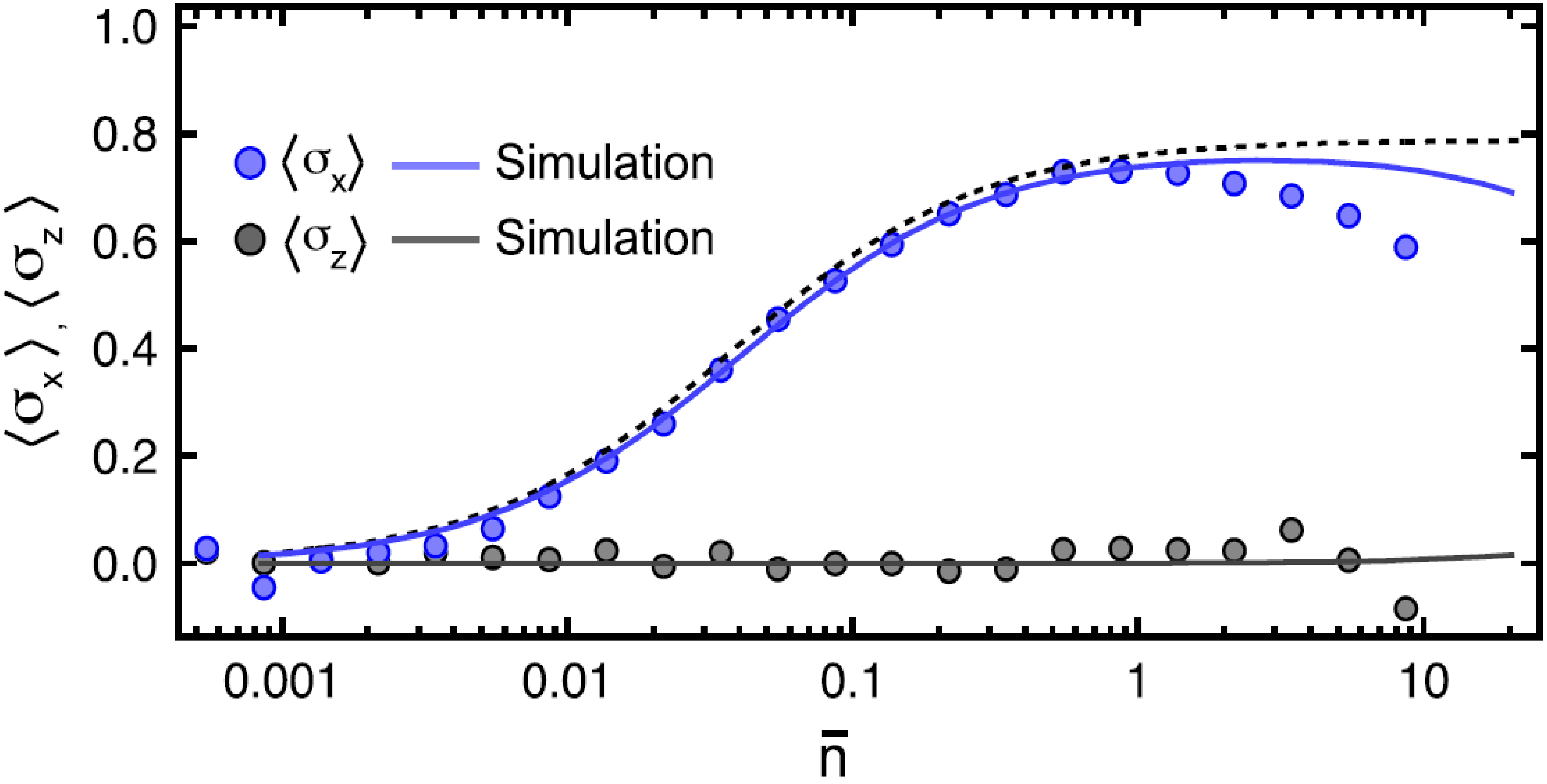
but, now we choose $\Delta_c = -\Omega_r$. The transition rates are now asymmetric.

$$\Gamma_- = \frac{4\chi^2\bar{n}}{\kappa} + \frac{1}{2T_2}, \quad \Gamma_+ = \frac{\kappa\chi^2\bar{n}}{(2\Omega_R)^2 + (\kappa/2)^2} + \frac{1}{2T_2};$$

If we choose $\bar{n}$, such that $\Gamma_- \gg \Gamma_+$, the |+> state is preferred.

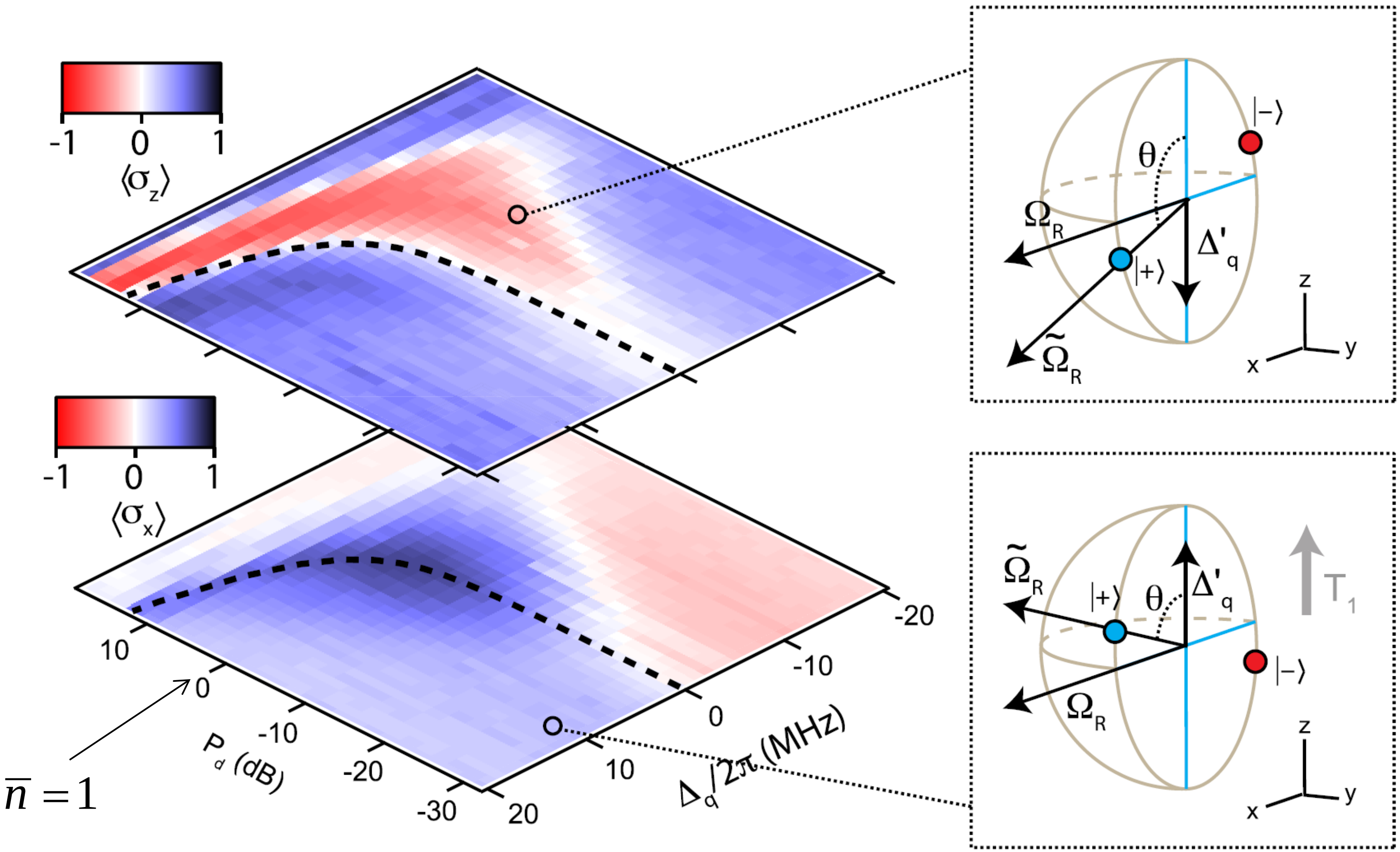
final state purity = $\frac{\Gamma_-}{\Gamma_- + \Gamma_+}$

TOMOGRAPHY: RESONANT RABI DRIVE



- Indeed cool to |+>
- Maximum contrast ~ 70%
- Readout fidelity ~ 90%, Population in excited states ~ 20%
- Cool dressed state to a chilly 150 μK

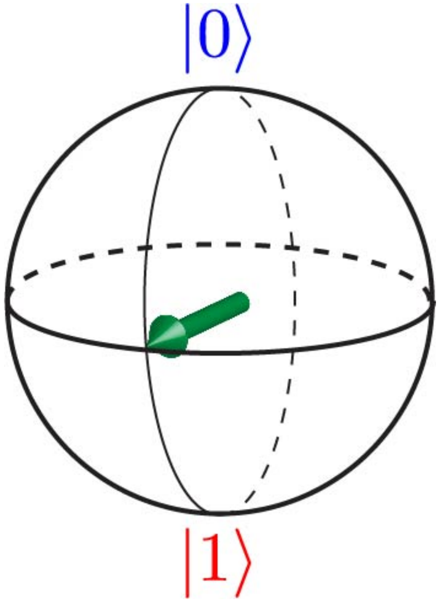
TOMOGRAPHY: OFF RESONANT RABI



Drive qubit off resonance: $\Delta'_q = \omega'_q - \omega_r$

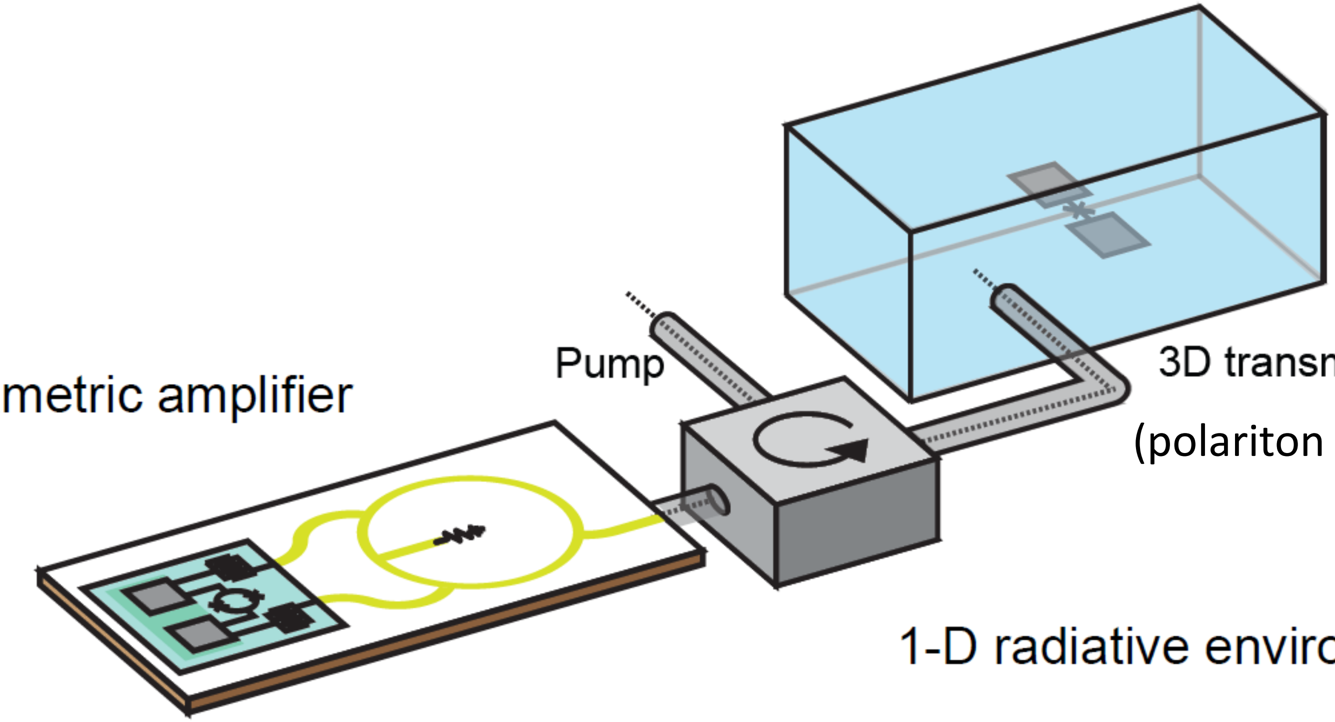
Drive cavity at effective Rabi frequency: $\Delta_C = -\tilde{\Omega}_R$

CAN WE OBSERVE THE “PHYSICAL” EFFECTS OF SQUEEZED VACUUM?



SUPPRESSION OF THE RADIATIVE DECAY OF ATOMIC COHERENCE IN SQUEEZED VACUUM

K. Murch et al., *arXiv:* 1301.6276



Parametric amplifier

Pump

3D transmon

(polariton regime)

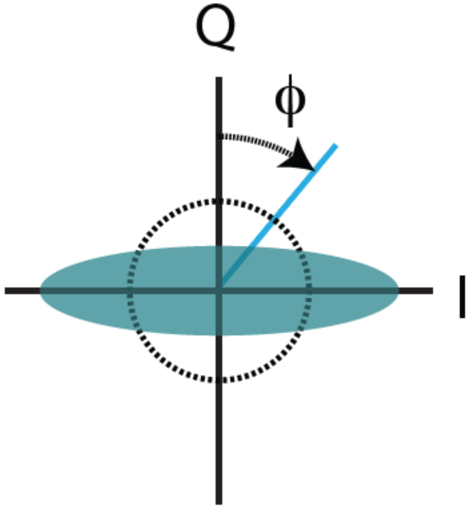
1-D radiative environment

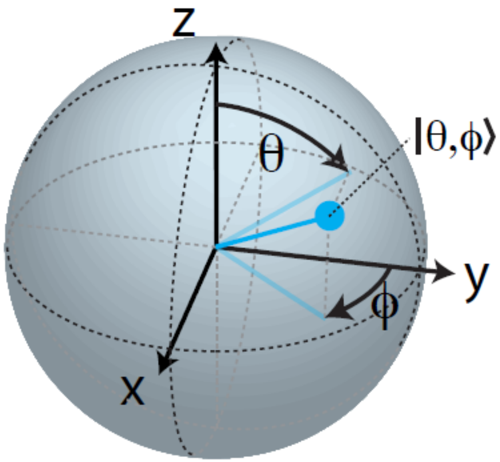
Squeezing with Josephson parametric amplifiers:

Castellanos-Beltran et al,
Nature Physics 2008

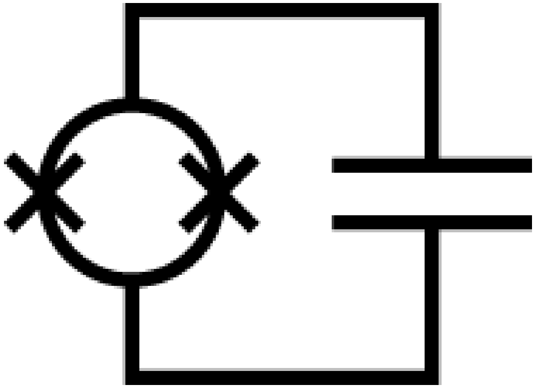
Beregeal et al, Nature 2010

Eichler et al, PRL 2011

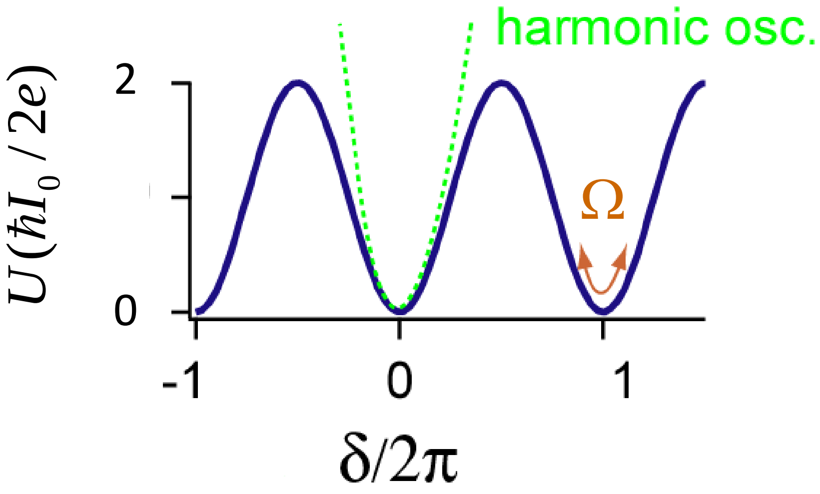


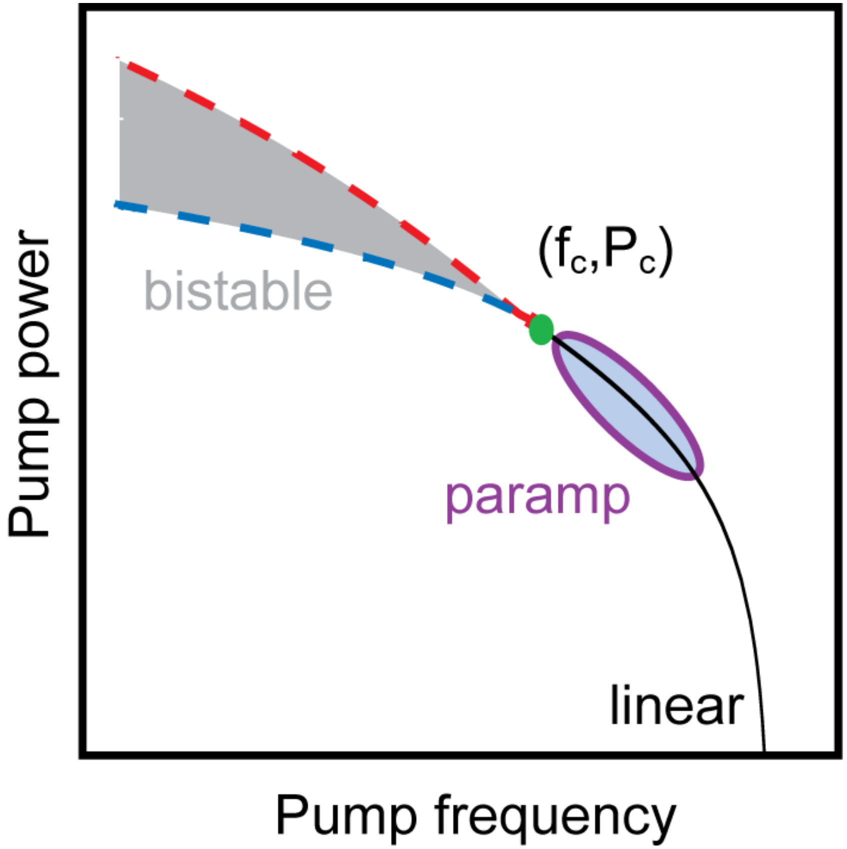


PARAMETRIC AMPLIFICATION

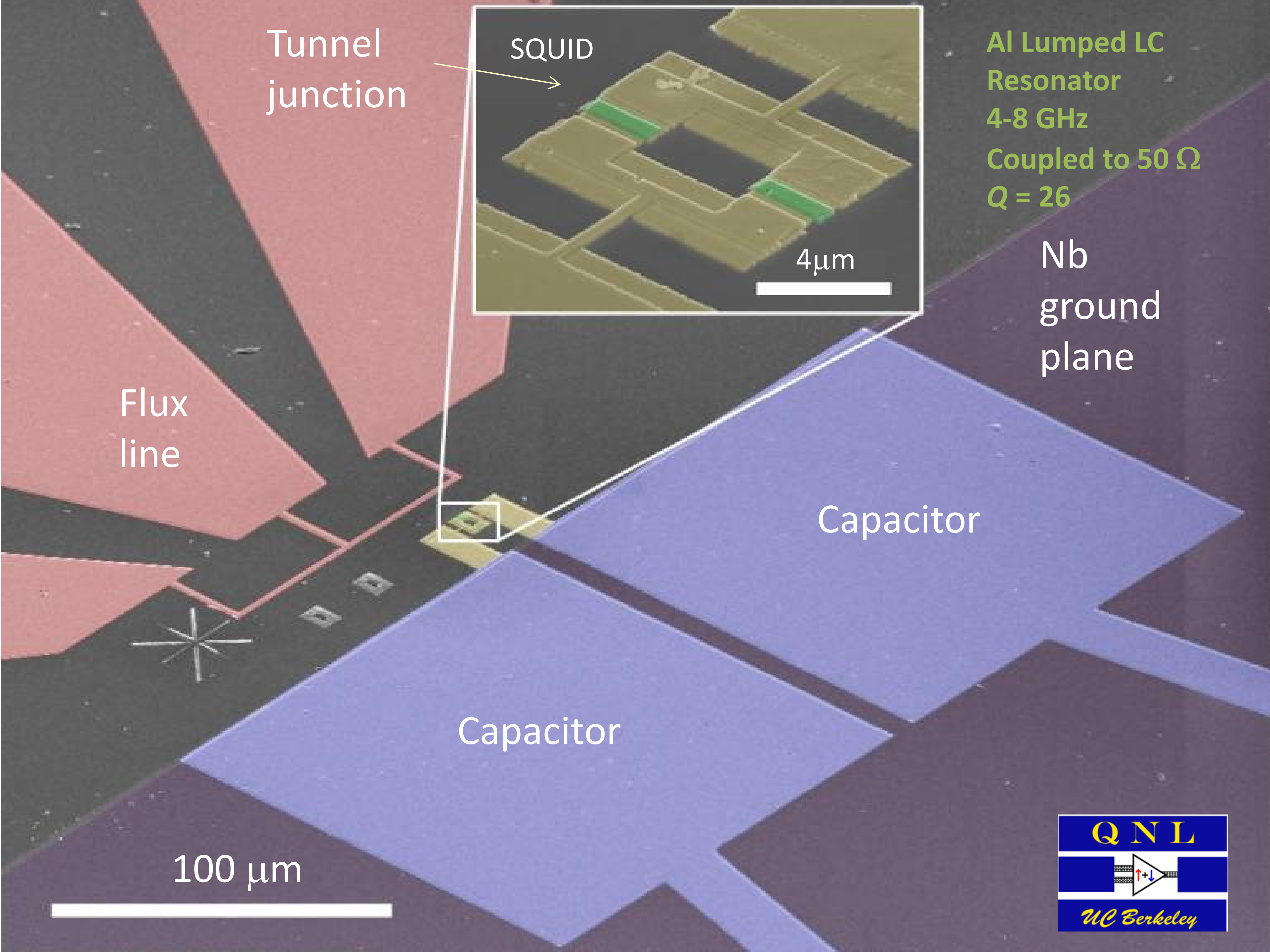


$L_J \sim 0.1$ nH $\qquad$ $C \sim 10000$ fF





M. J. Hatridge et al., *Phys. Rev*. B **83**, 134501 (2011)



Al Lumped LC Resonator
4-8 GHz
Coupled to 50 Ω
$Q = 26$

SQUEEZING MOMENTS

N, M values:

$$\langle a^\dagger(t+\tau)a(t)\rangle = N\delta(\tau)$$

$$\langle a(t+\tau)a(t)\rangle = M\delta(\tau)$$

Squeezed states: $N < M \leq \sqrt{N(N+1)}$

classical states: $N > M$

vacuum: $N = M = 0$

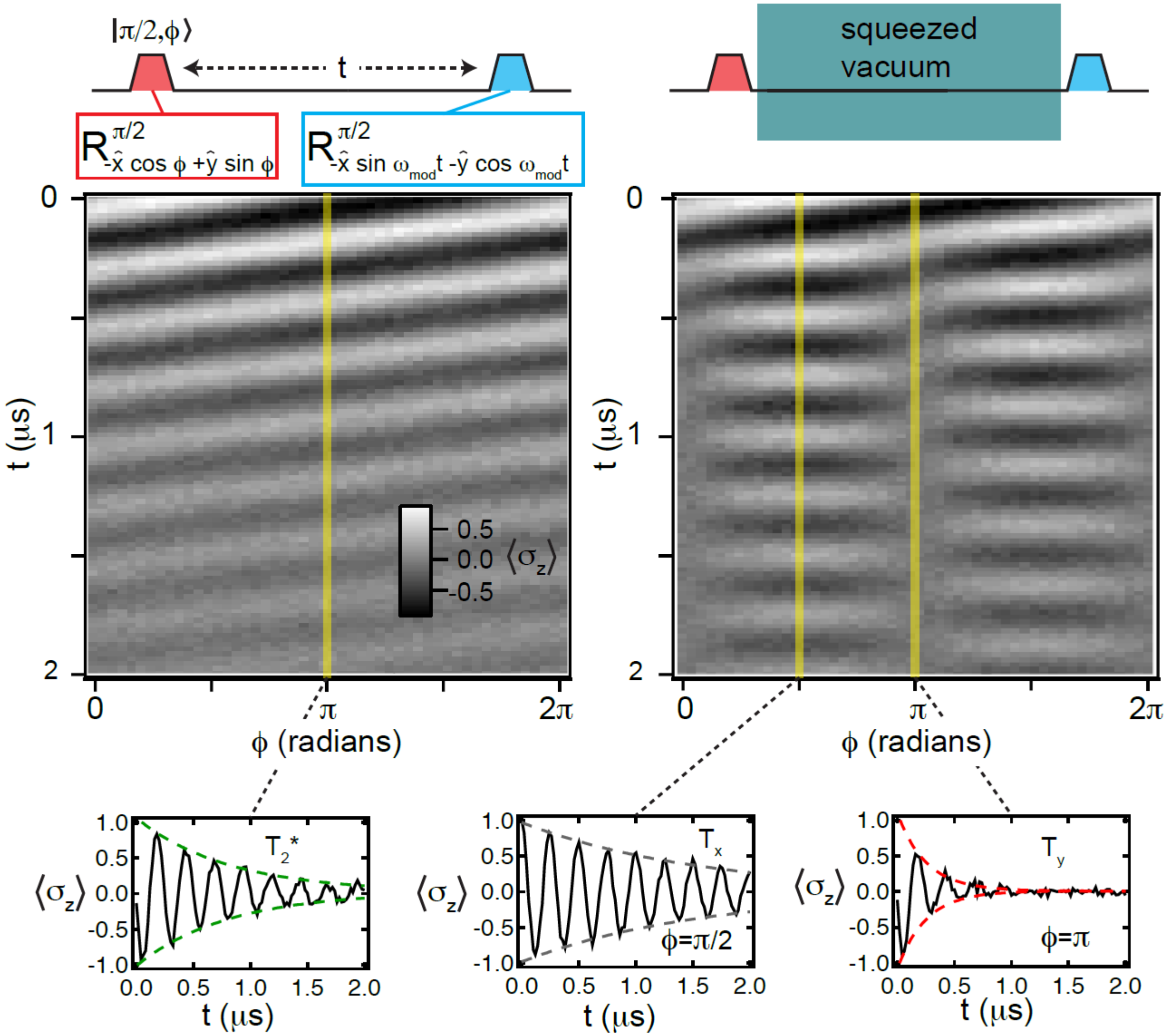
atom decay:

$$\langle \dot{\sigma}_z\rangle = -\gamma(2N+1)\langle\sigma_z\rangle - \gamma$$

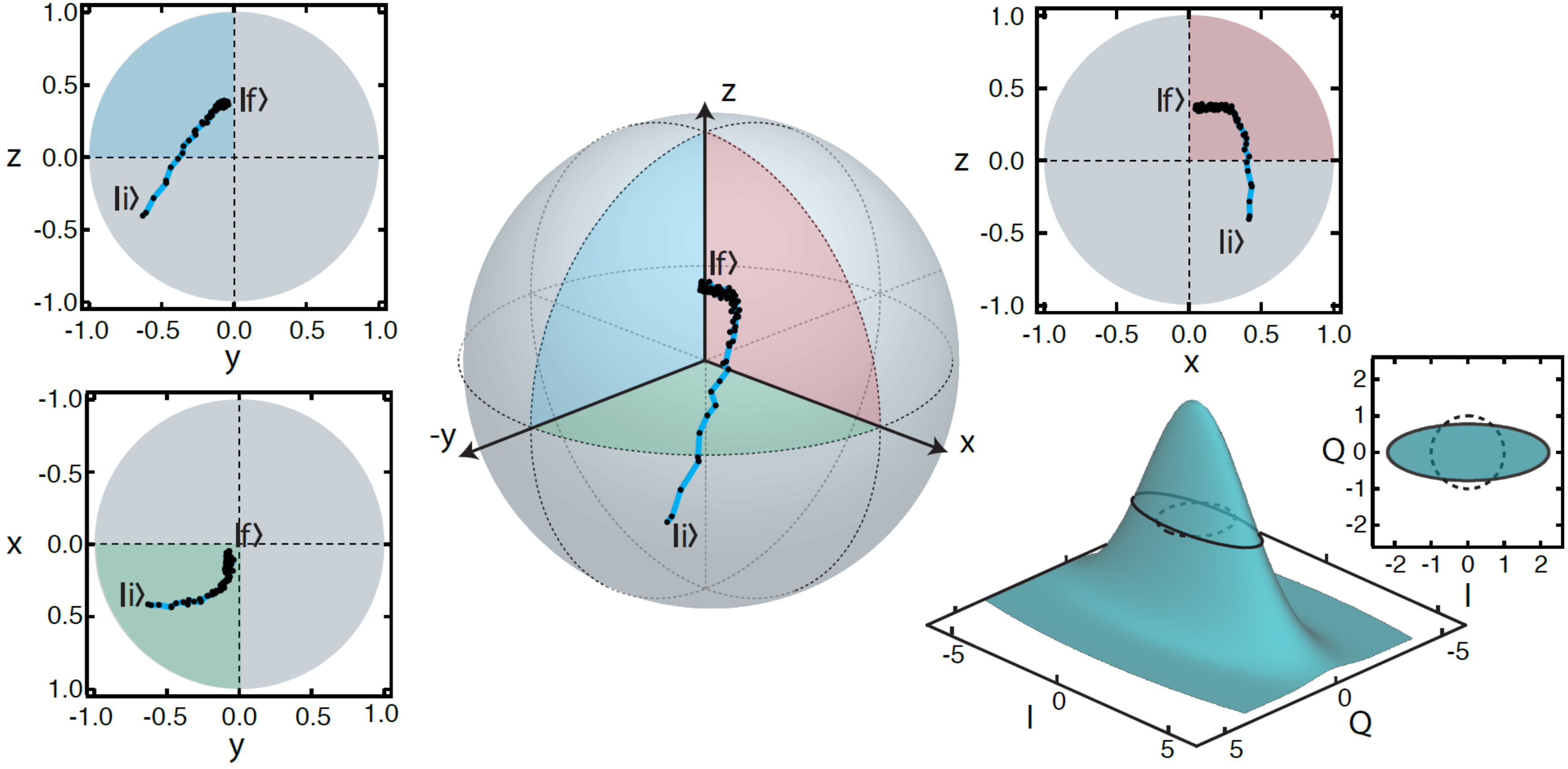
$$\langle \dot{\sigma}_y\rangle = -\gamma(N+M+1/2)\langle\sigma_y\rangle$$

$$\langle \dot{\sigma}_x\rangle = -\gamma(N-M+1/2)\langle\sigma_x\rangle$$

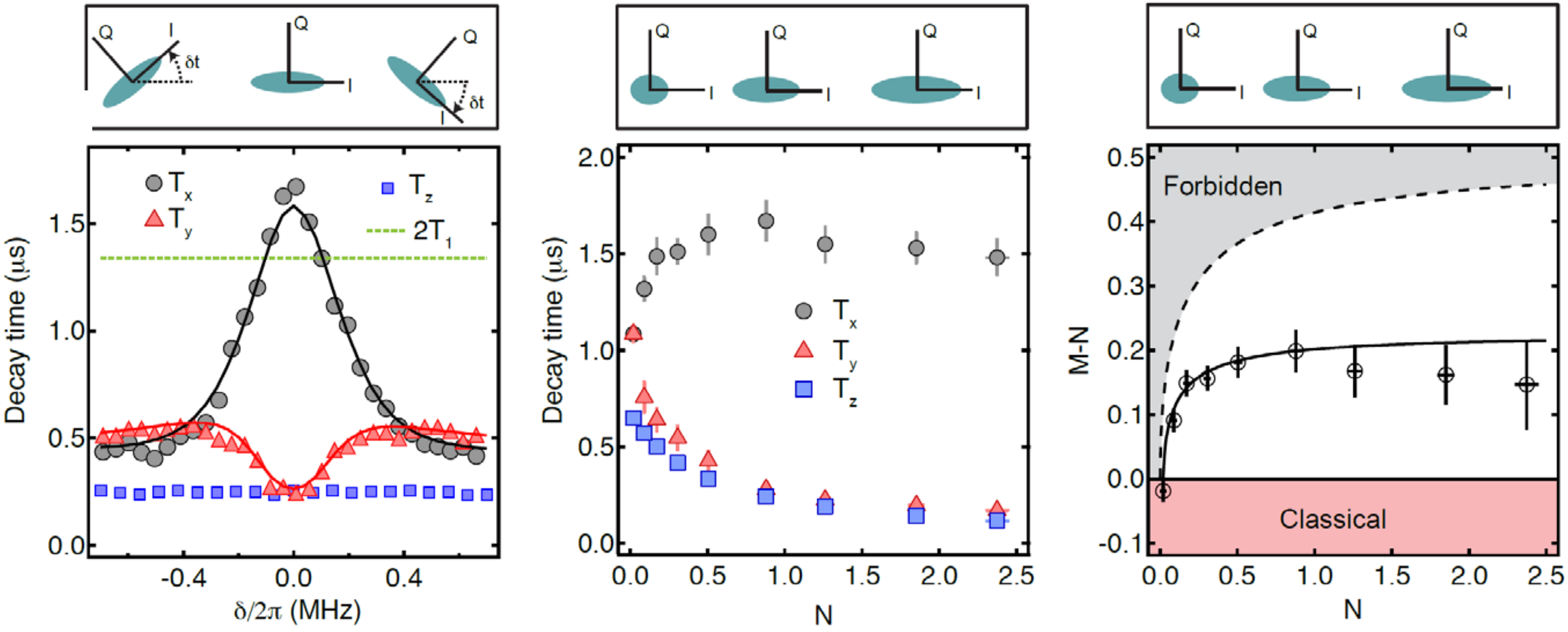
PHASE DEPENDENT DECAY!



QUBIT ENABLED RECONSTRUCTION OF AN ITINERANT SQUEEZED STATE

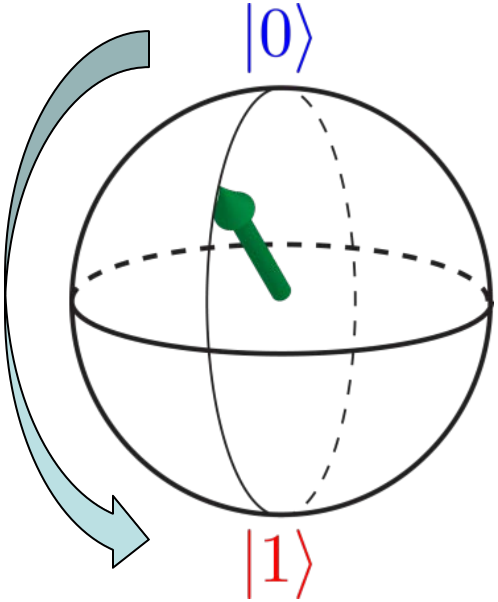


$T_2 > 2T_1$!



Q
I
δt
T_x
T_y
T_z
$2T_1$
Decay time (μs)
0.0
0.5
1.0
1.5
-0.4
0.0
0.4
δ/2π (MHz)
2.0
N
0.0
0.5
1.0
1.5
2.0
2.5
M-N
-0.1
0.1
0.2
0.3
0.4
0.5
Forbidden
Classical

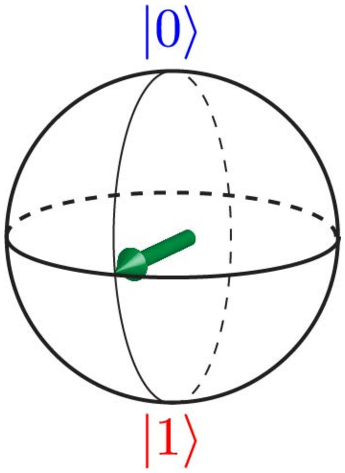
HOW DO WE STABILIZE AN OSCILLATION?



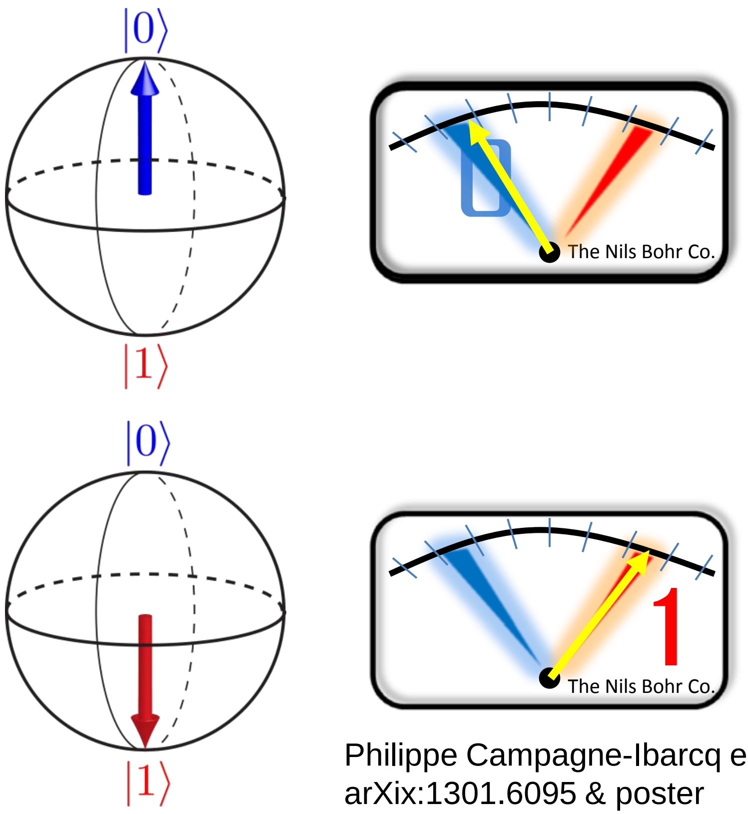
QUANTUM FEEDBACK
via
WEAK CONTINUOUS MEASUREMENT

R. Vijay et al., *Nature* **490**, 77 (2012).

INITIAL STATE:
$|\psi\rangle = |0\rangle + |1\rangle$

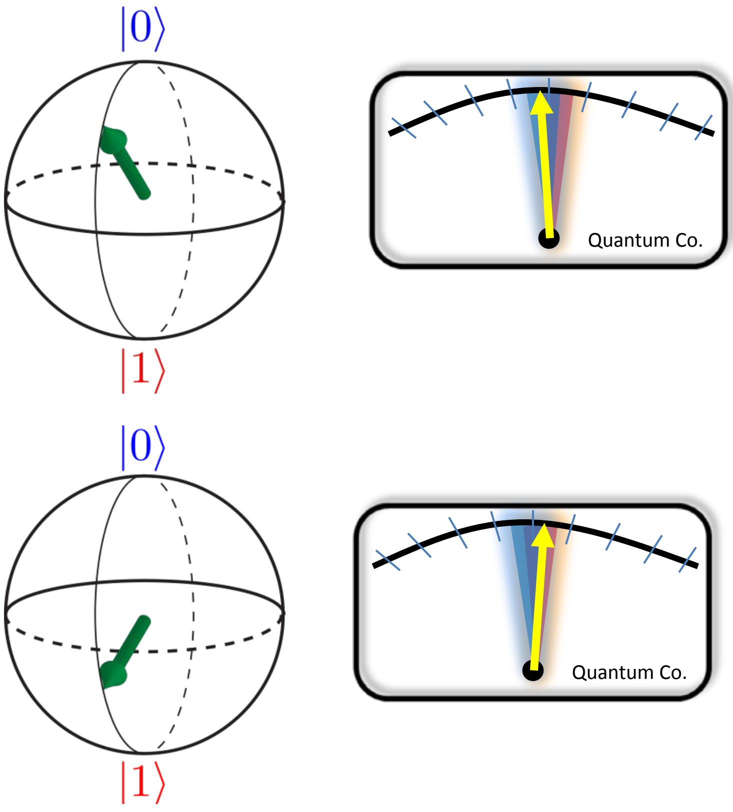


Strong QND Measurement

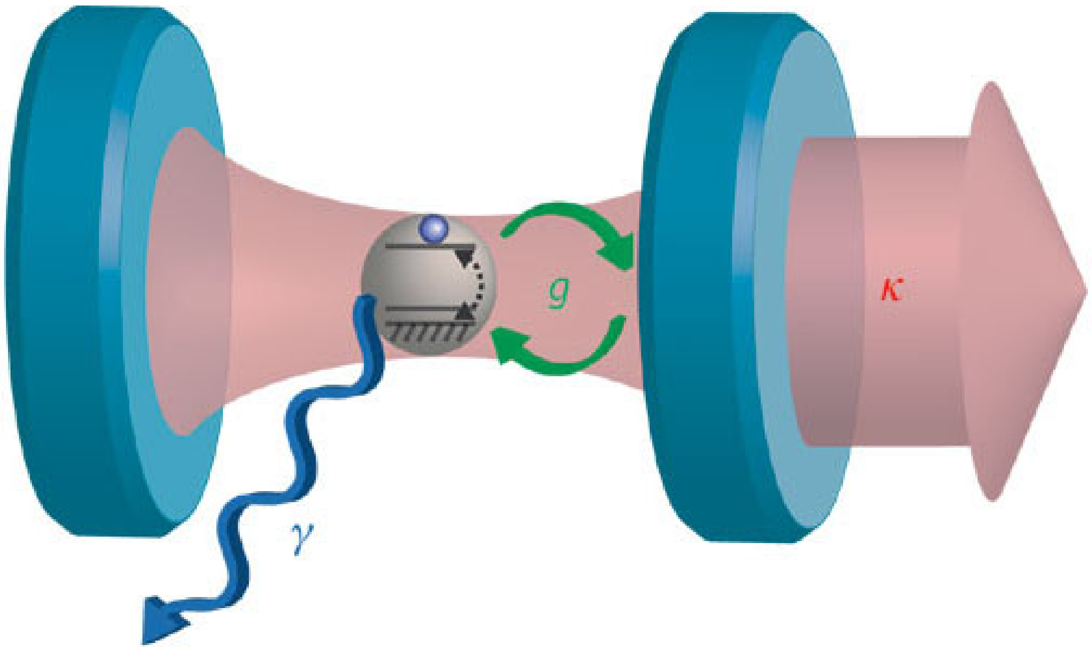


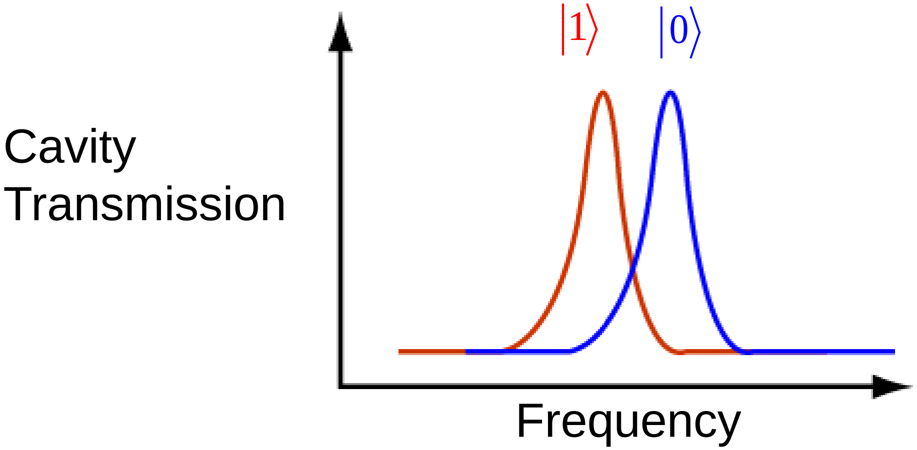
Philippe Campagne-Ibarcq et al,
arXix:1301.6095 & poster

Weak QND Measurement



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

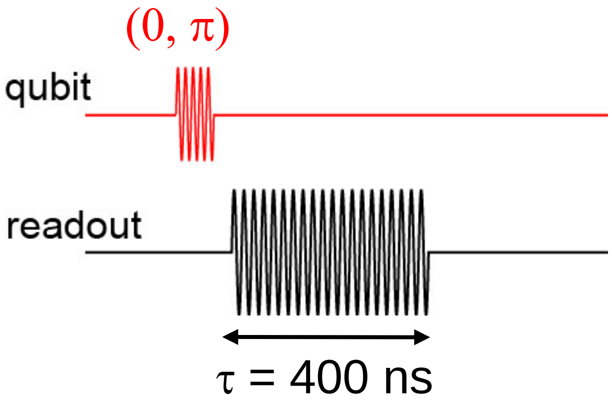




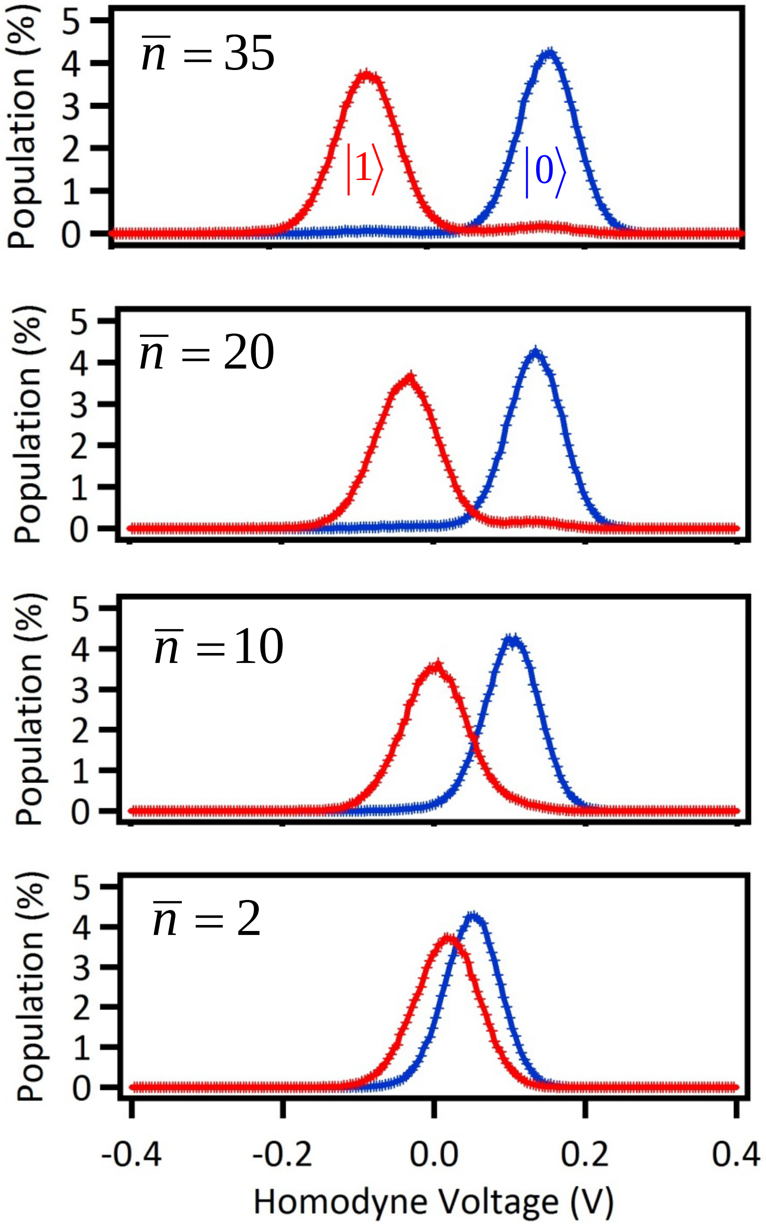
VARY MEASUREMENT STRENGTH USING DISPERSIVE SHIFT & PHOTON NUMBER

NEED TO DETECT ~ SINGLE MICROWAVE PHOTONS in T_1 ~ μs

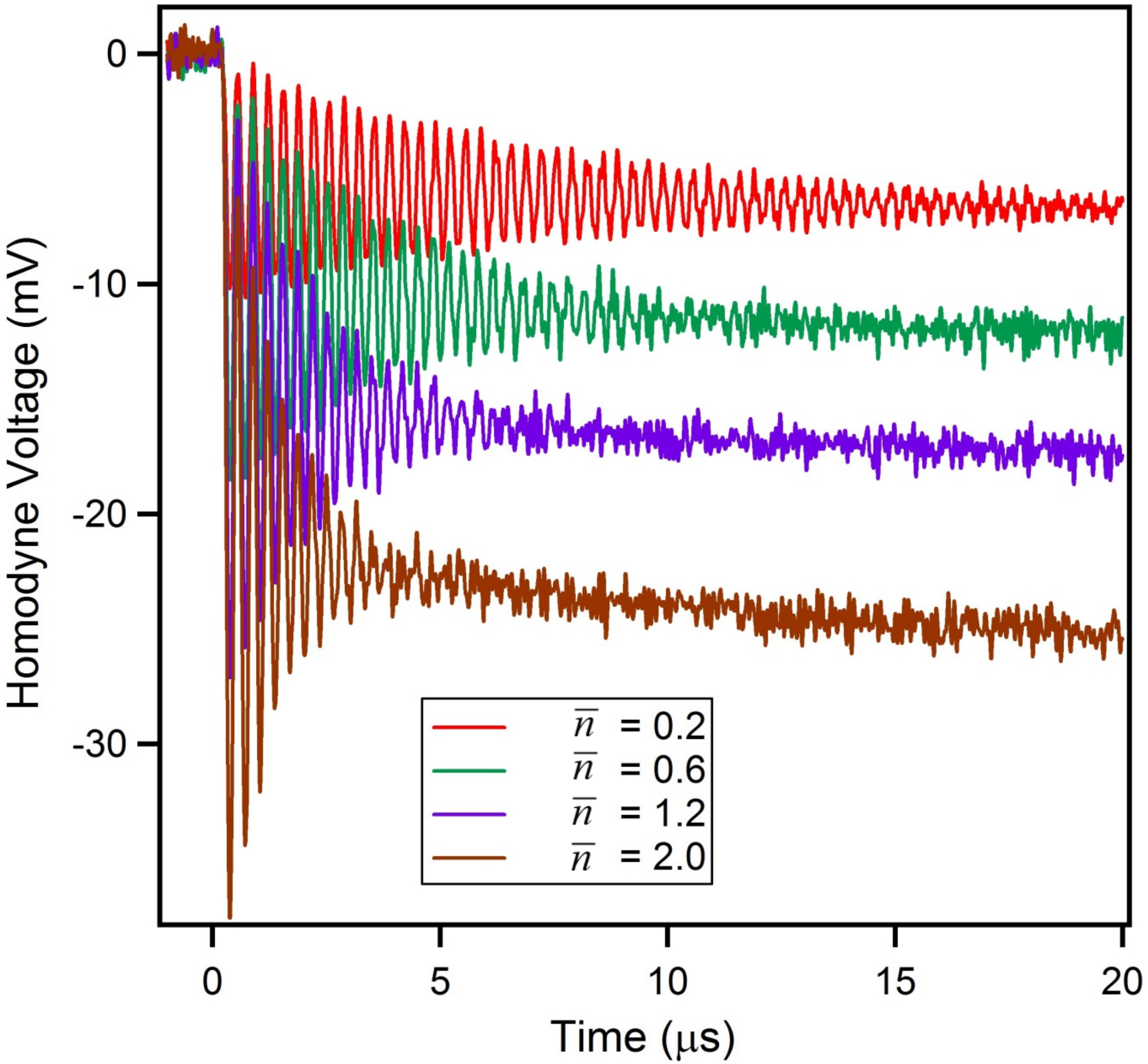
VARYING MEASUREMENT STRENGTH

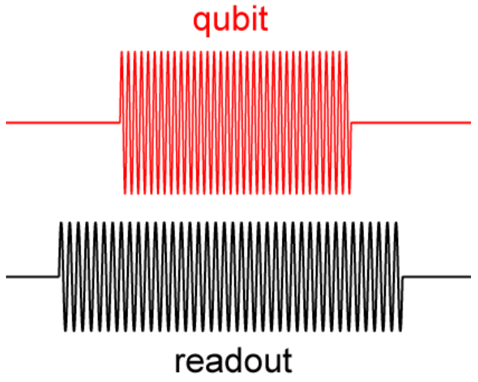


- Integrate measurement trace for 400 ns
- Repeat and histogram
- ~ 2x quantum noise floor



RABI OSCILLATIONS with CONTINUOUS WEAK MEASUREMENT: ENSEMBLE AVERAGE

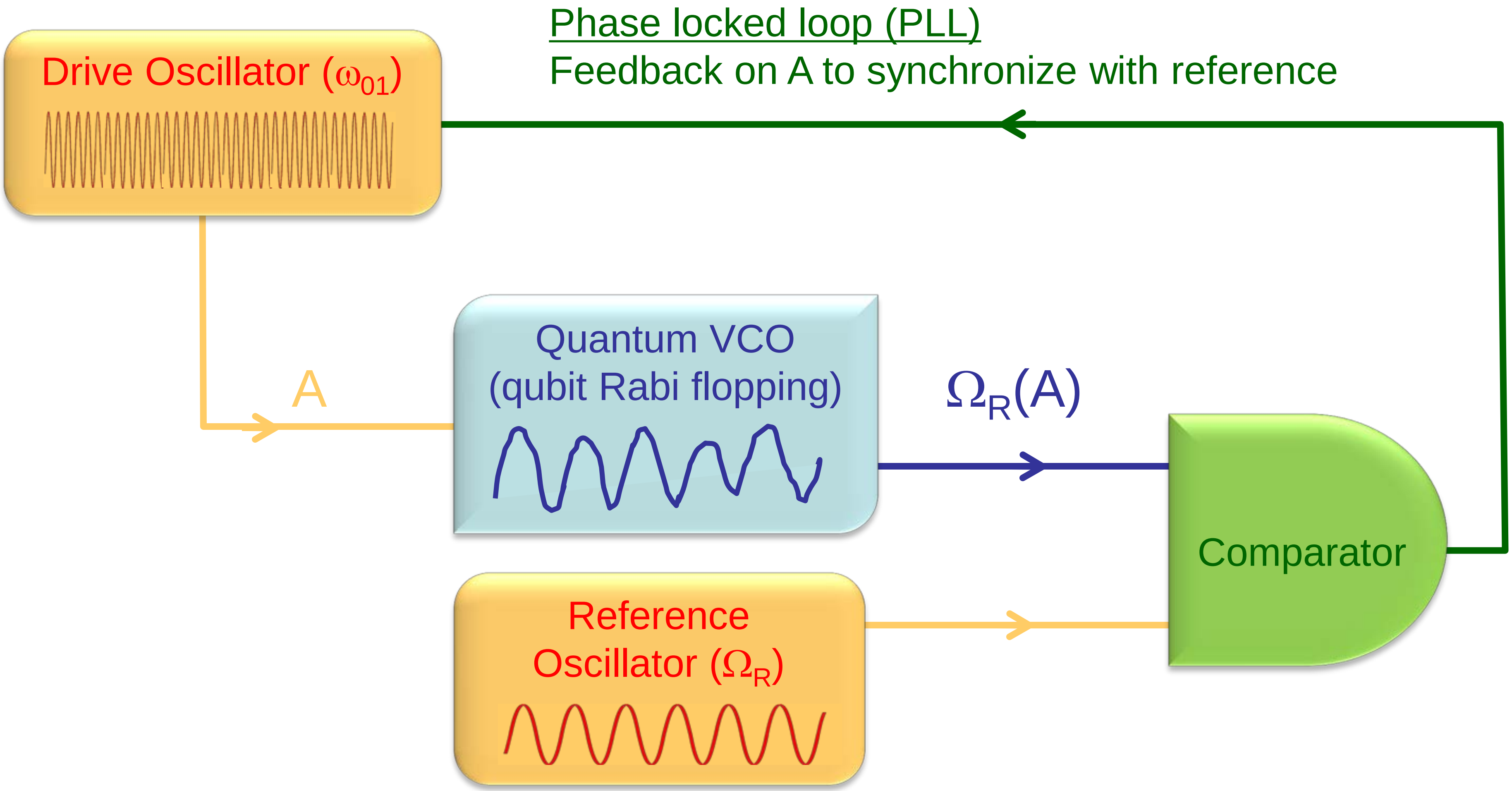




- Continuously drive qubit
- Continuously measure (weakly)
- Repeat
- Display average

Each individual trace has random, measurement induced phase jitter

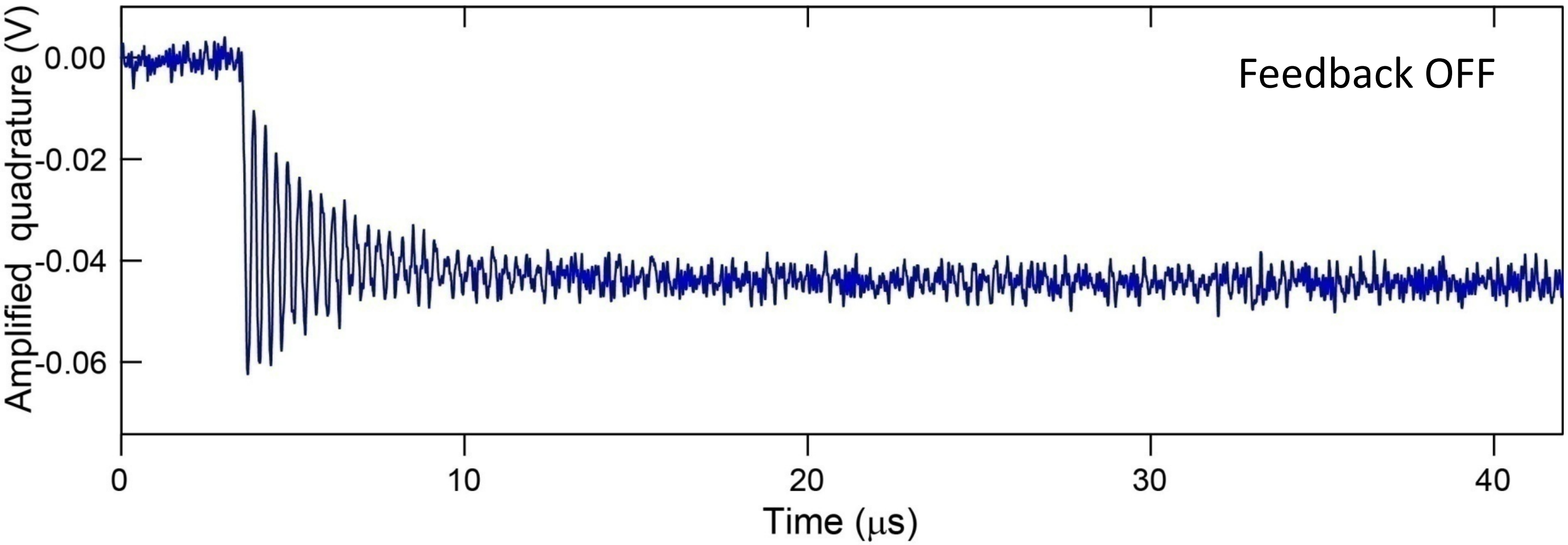
STABILIZING A QUANTUM "VOLTAGE CONTROLLED OSCILLATOR"

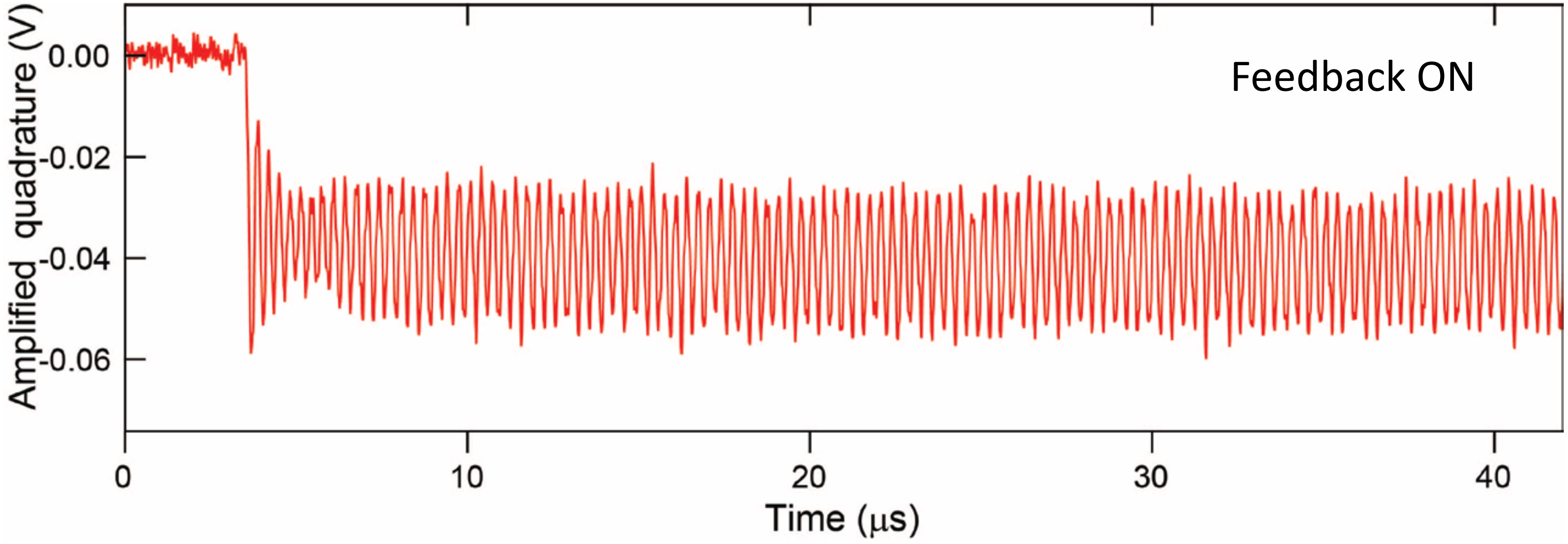


Phase locked loop (PLL)

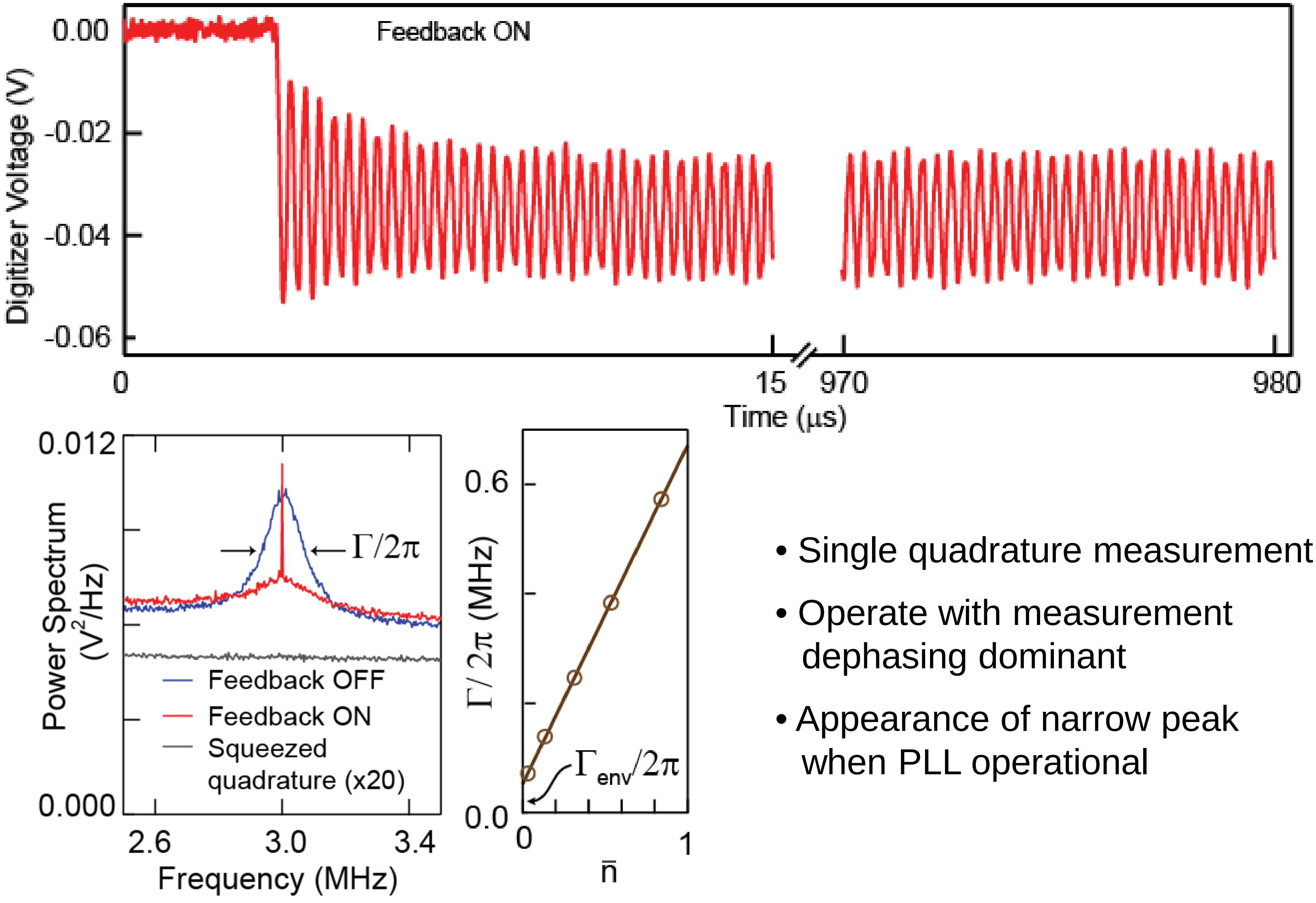
Feedback on A to synchronize with reference

STABILIZED RABI OSCILLATIONS



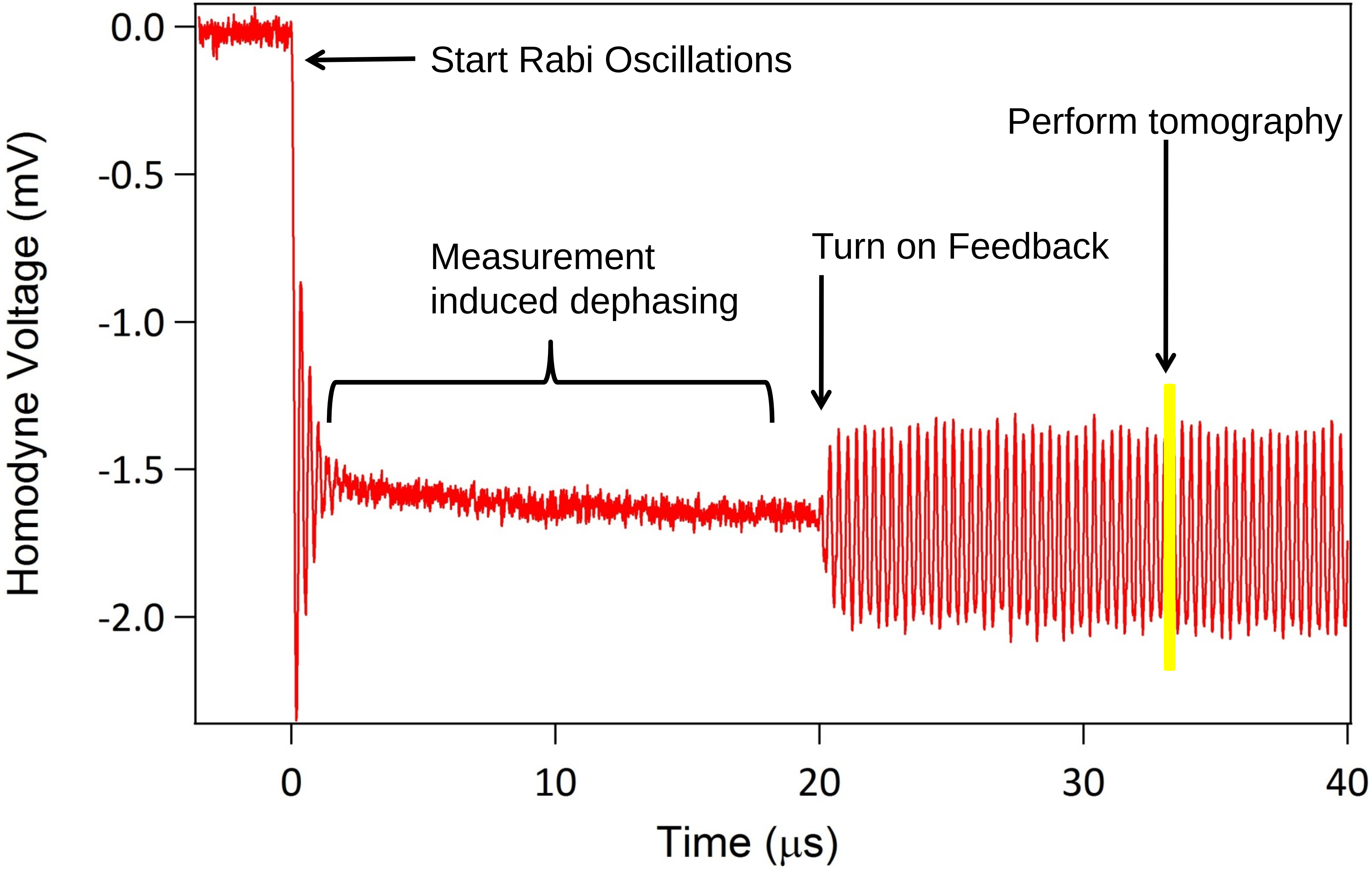


STILL GOING…



- Single quadrature measurement
- Operate with measurement dephasing dominant
- Appearance of narrow peak when PLL operational

REPHASING THE QUBIT



FUTURE DIRECTIONS

- QUANTUM FEEDBACK/CONTROL
  - OPTIMIZE EFFICIENCY
  - FULL BAYESIAN FEEDBACK
  - GENERATION/STABILIZATION OF ENTANGLED STATES
- MULTIPLEXED QUBIT READOUT
- ON-CHIP PARAMPS
  - BACKACTION OF NONLINEAR TANK CIRCUIT
  - TRANSMISSION LINE AMPLIFIERS

DEPARTMENT OF DEFENSE UNITED STATES OF AMERICA

the Hertz FOUNDATION
freedom to innovate

QUEST

YFA DARPA

DARPA

IARPA

NSF

SCIENCE TO SHAPE THE FUTURE OF THE ARMY
ARMY RESEARCH OFFICE
1951