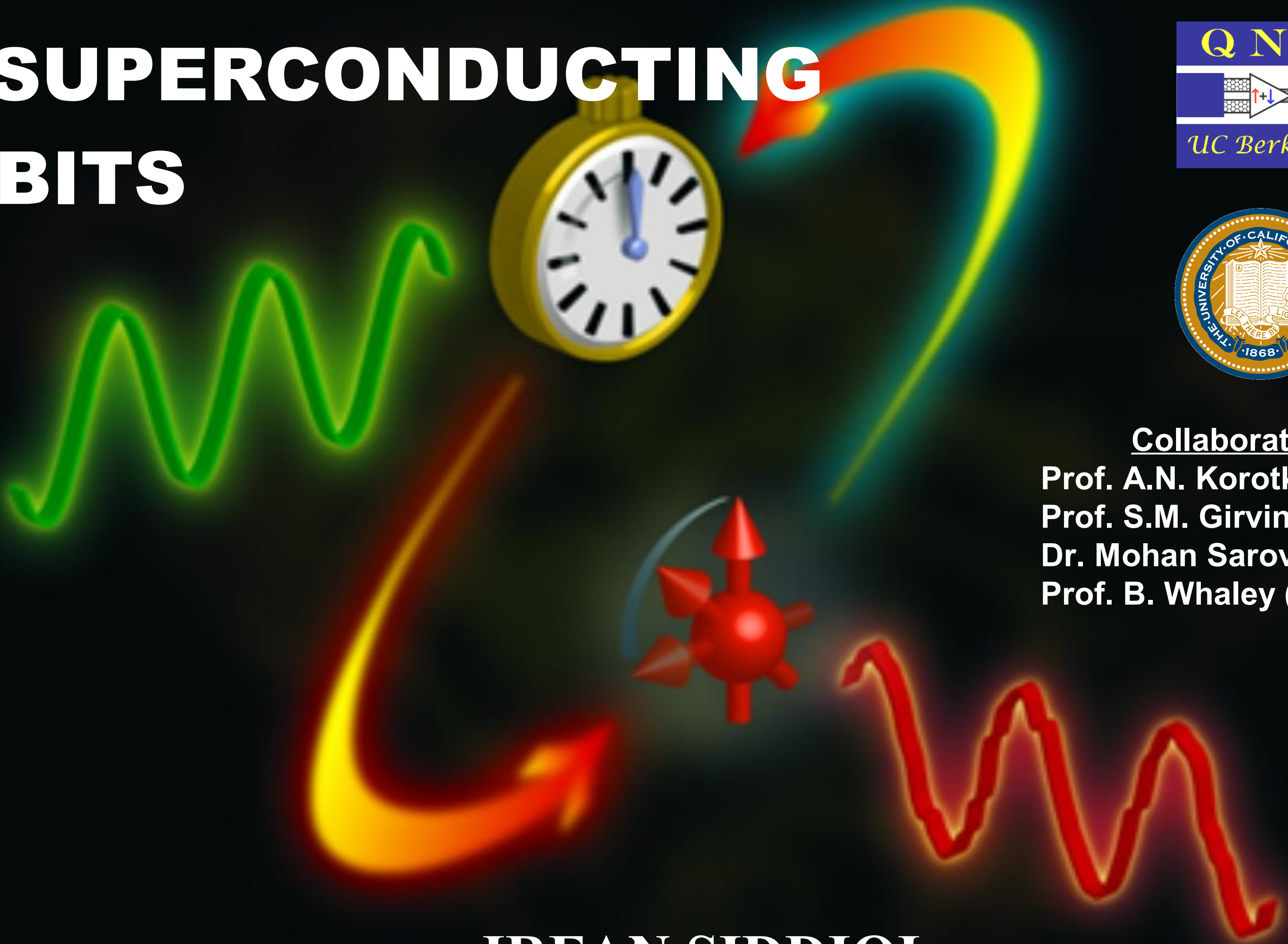
DISSIPATION ENHANCED COHERENCE IN SUPERCONDUCTING QUBITS



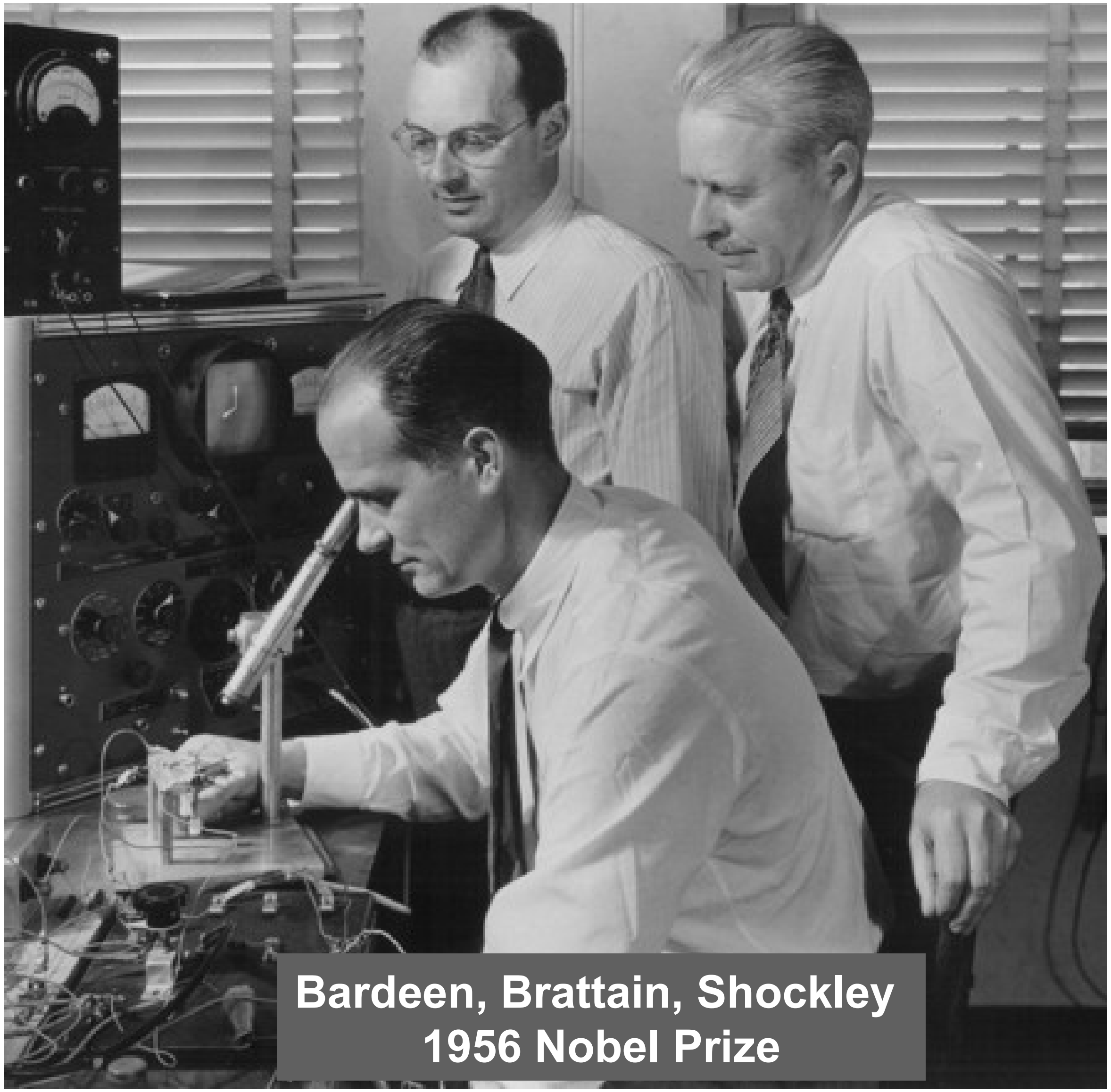
Collaborators
Prof. A.N. Korotkov (UCR)
Prof. S.M. Girvin (Yale)
Dr. Mohan Sarovar (Sandia)
Prof. B. Whaley (UCB)

CQIQC Seminar
March 22, 2013
U. Toronto

IRFAN SIDDIQI

Quantum Nanoelectronics Laboratory
Department of Physics, UC Berkeley

AN INDUSTRY BUILT ON SAND…

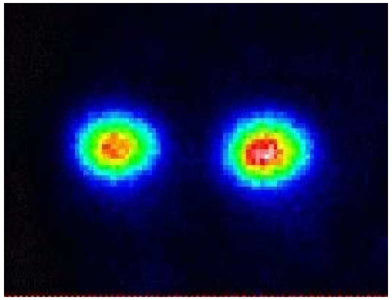


Bardeen, Brattain, Shockley
1956 Nobel Prize

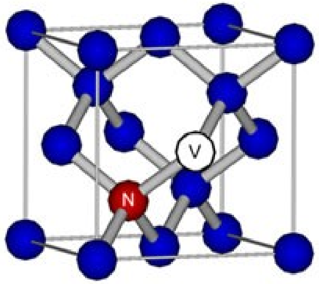
1947

QUANTUM BITS

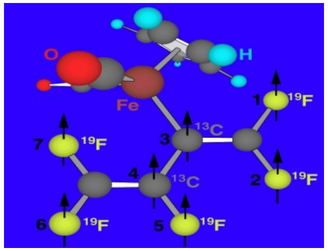
Trapped ions



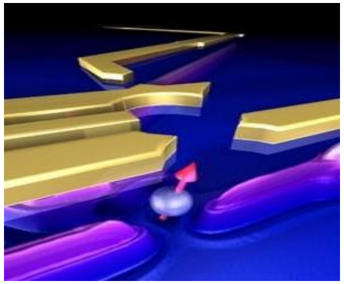
NV Centers



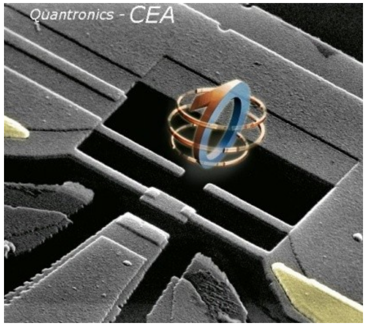
Molecules



Quantum Dot

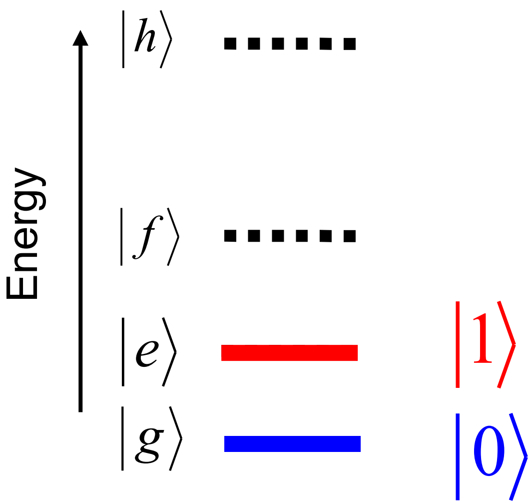


Superconducting Circuit



- standard nanofabrication
- engineered parameters
- decoherence (T_1, T_2)

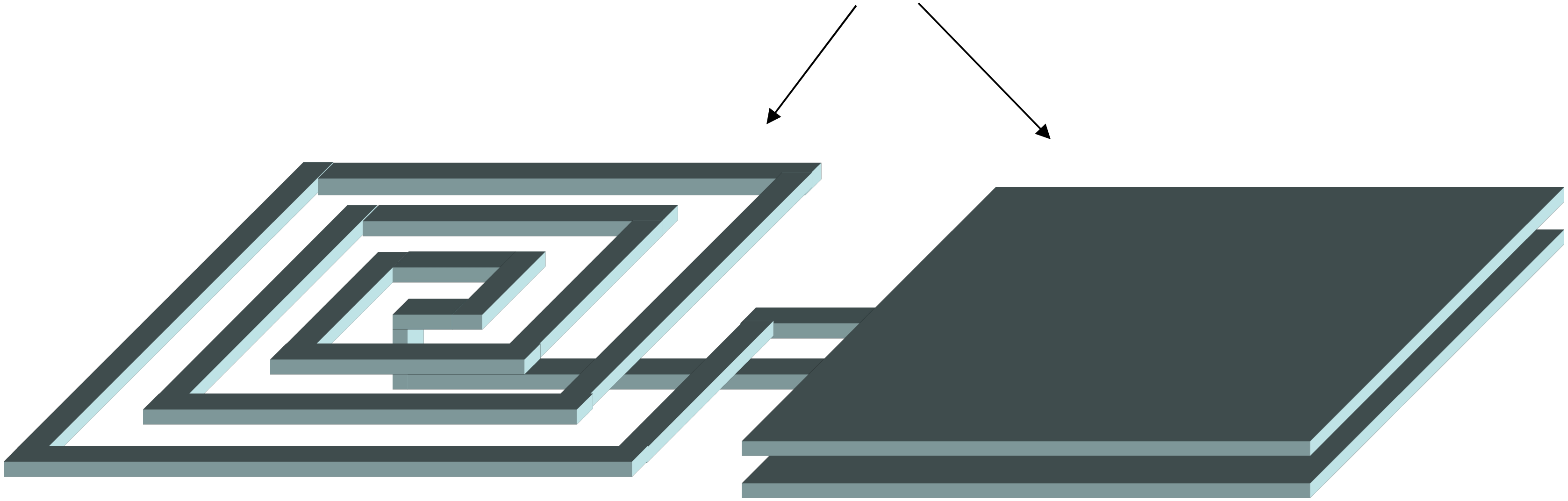
quantum energy levels



THE
QUBIT

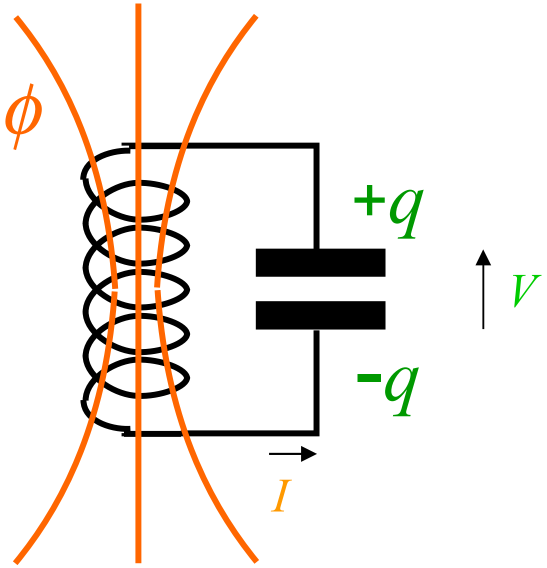
HOW CAN A SUPERCONDUCTING CIRCUIT BECOME QUANTUM-MECHANICAL AT THE LEVEL OF CURRENTS AND VOLTAGES?

SIMPLEST EXAMPLE: SUPERCONDUCTING **LC** OSCILLATOR CIRCUIT



MICROFABRICATION → $L \sim 3\text{nH}$, $C \sim 10\text{pF}$, $\omega_r / 2\pi \sim 1\text{GHz}$, $Q \sim 10$

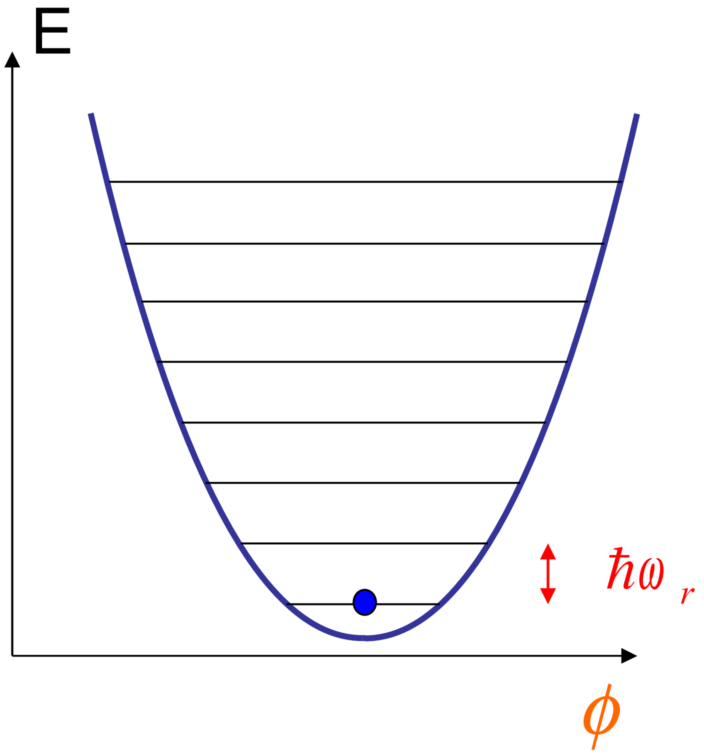
LC OSCILLATOR AS A QUANTUM CIRCUIT



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

$$\phi = LI$$

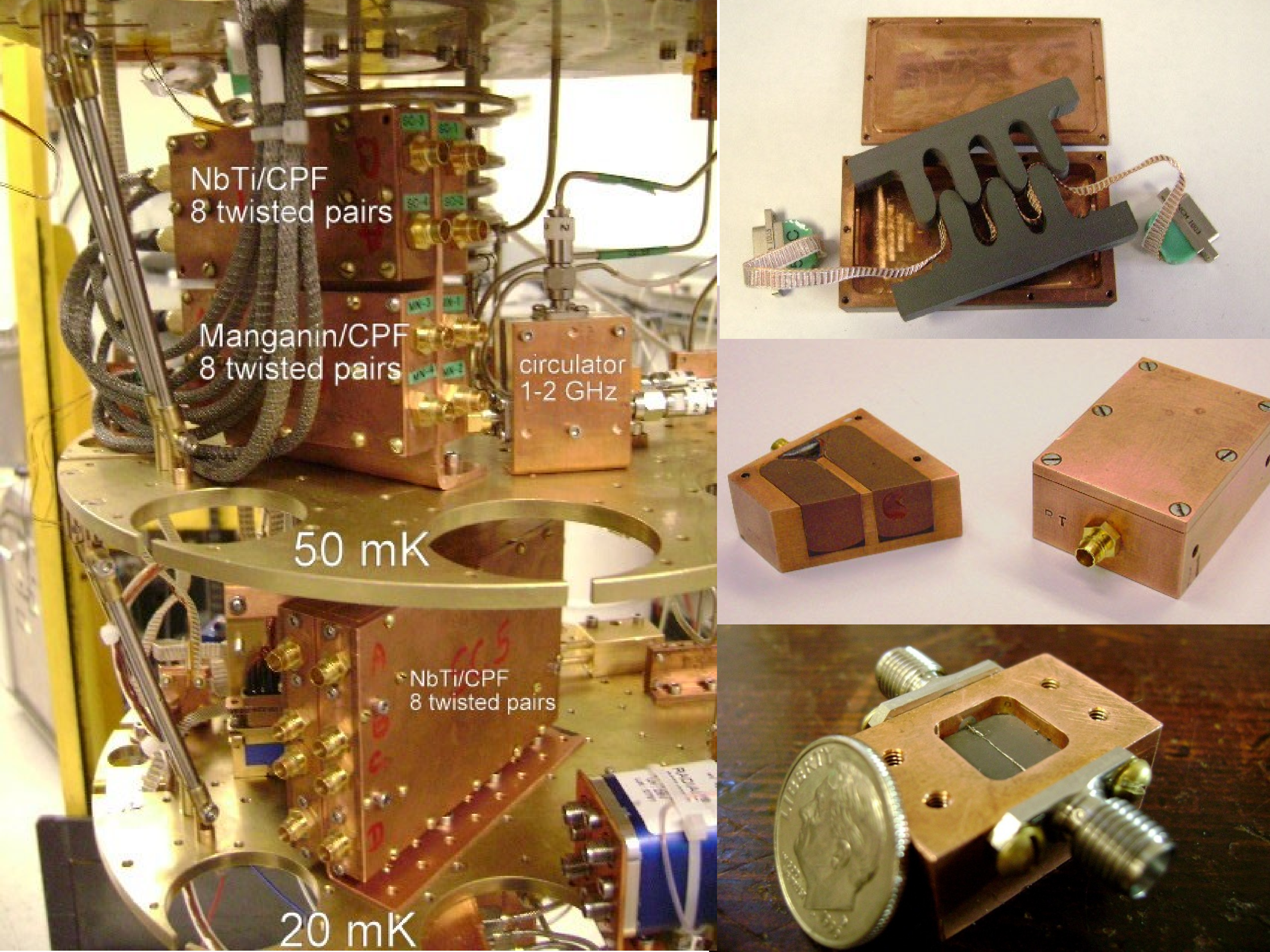
$$q = CV$$



$$\hbar\omega_r > k_B T$$

1GHz
(~ 50mK)

10mK

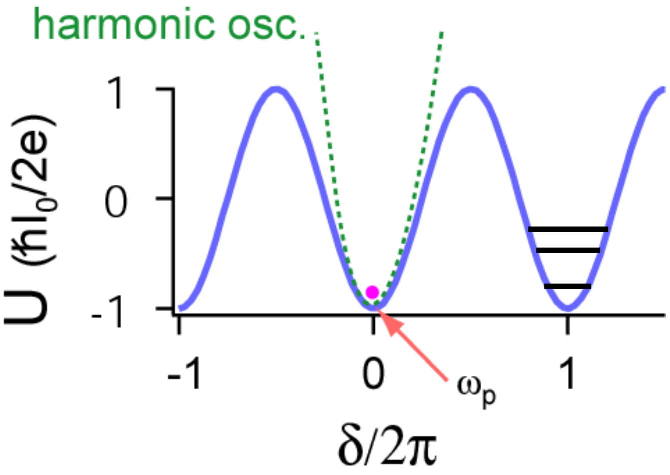

NbTi/CPF
8 twisted pairs
Manganin/CPF
8 twisted pairs
circulator
1-2 GHz
50 mK
NbTi/CPF
8 twisted pairs
20 mK
SC-3
SC-1
SC-4
SC-2
MN-3
MN-1
MN-4
MN-2
P T

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

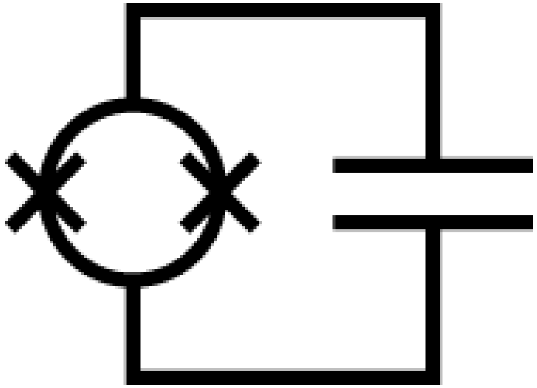
$$I(\delta) = I_0 \sin(\delta)$$

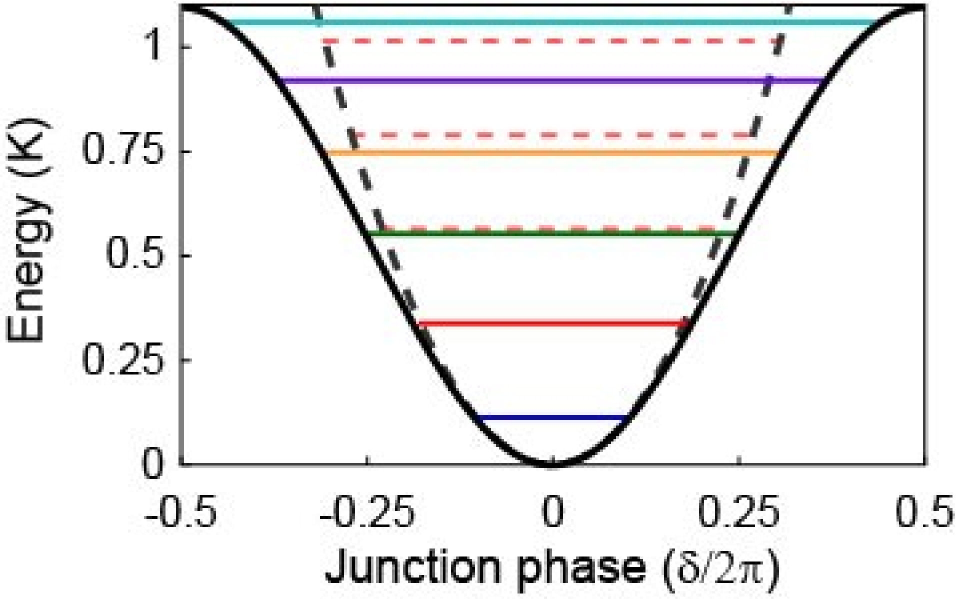
(NON-LINEAR INDUCTOR)

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



SUPERCONDUCTING TRANSMON QUBIT





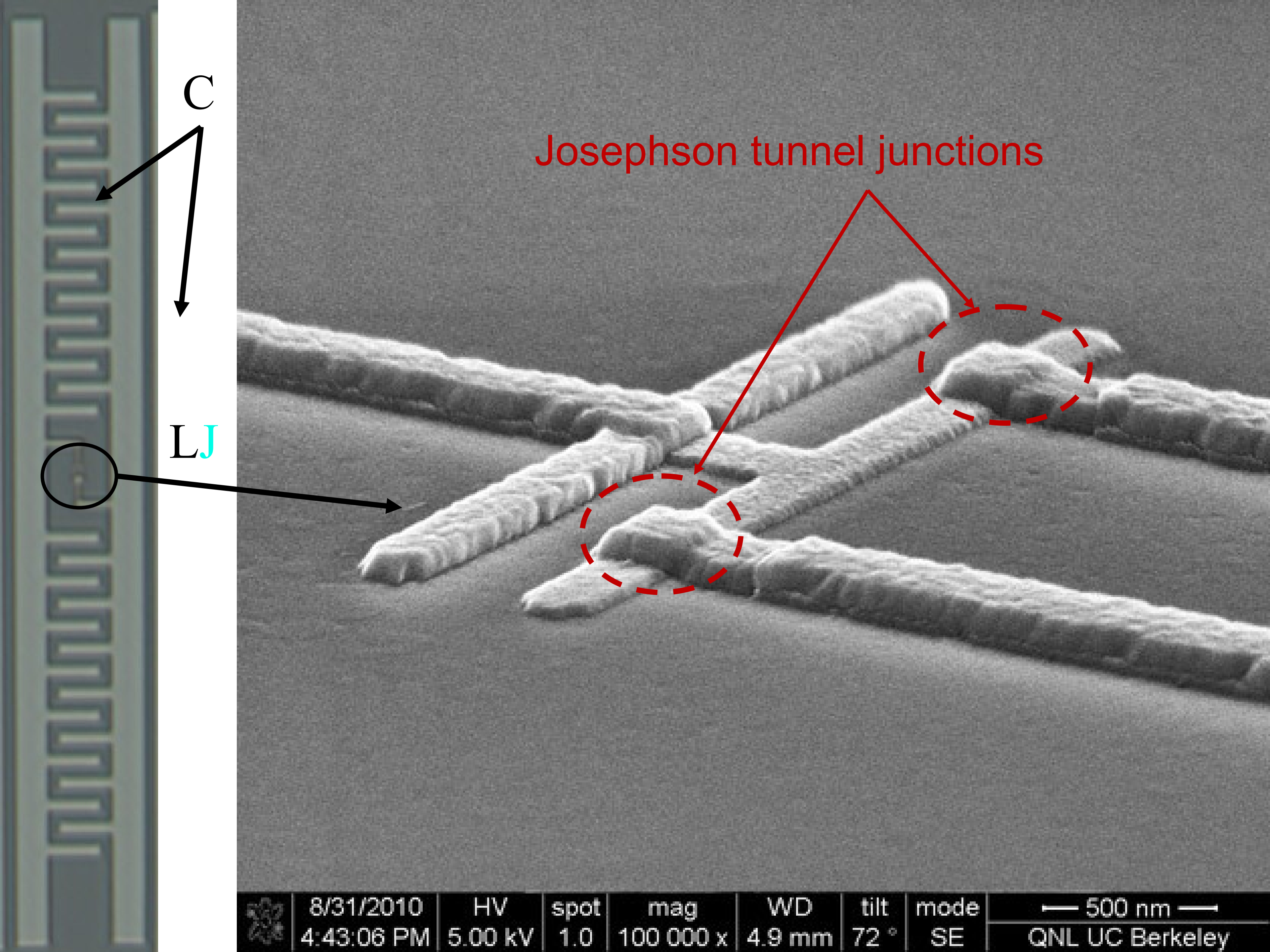
LJ ~ 13 nH C ~ 70 fF

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

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

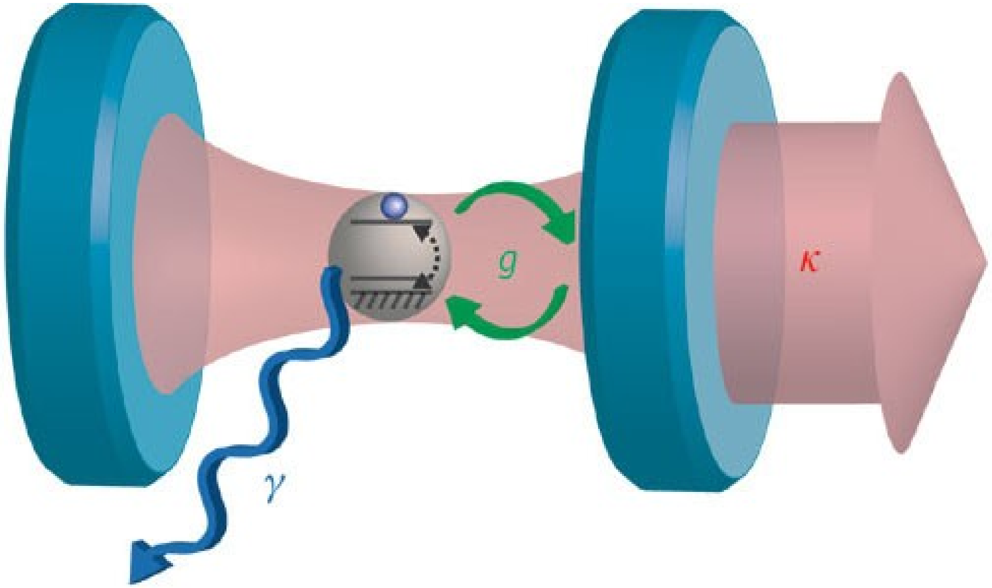
- Tunable qubit frequency
- ω01 ~ 5-8 GHz

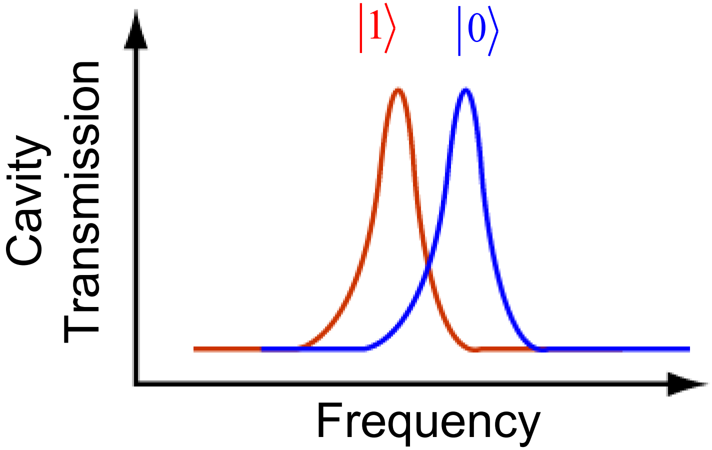
J. Koch et al., *Physical Review A* ***76,*** 042319 (2007)


C
LJ
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

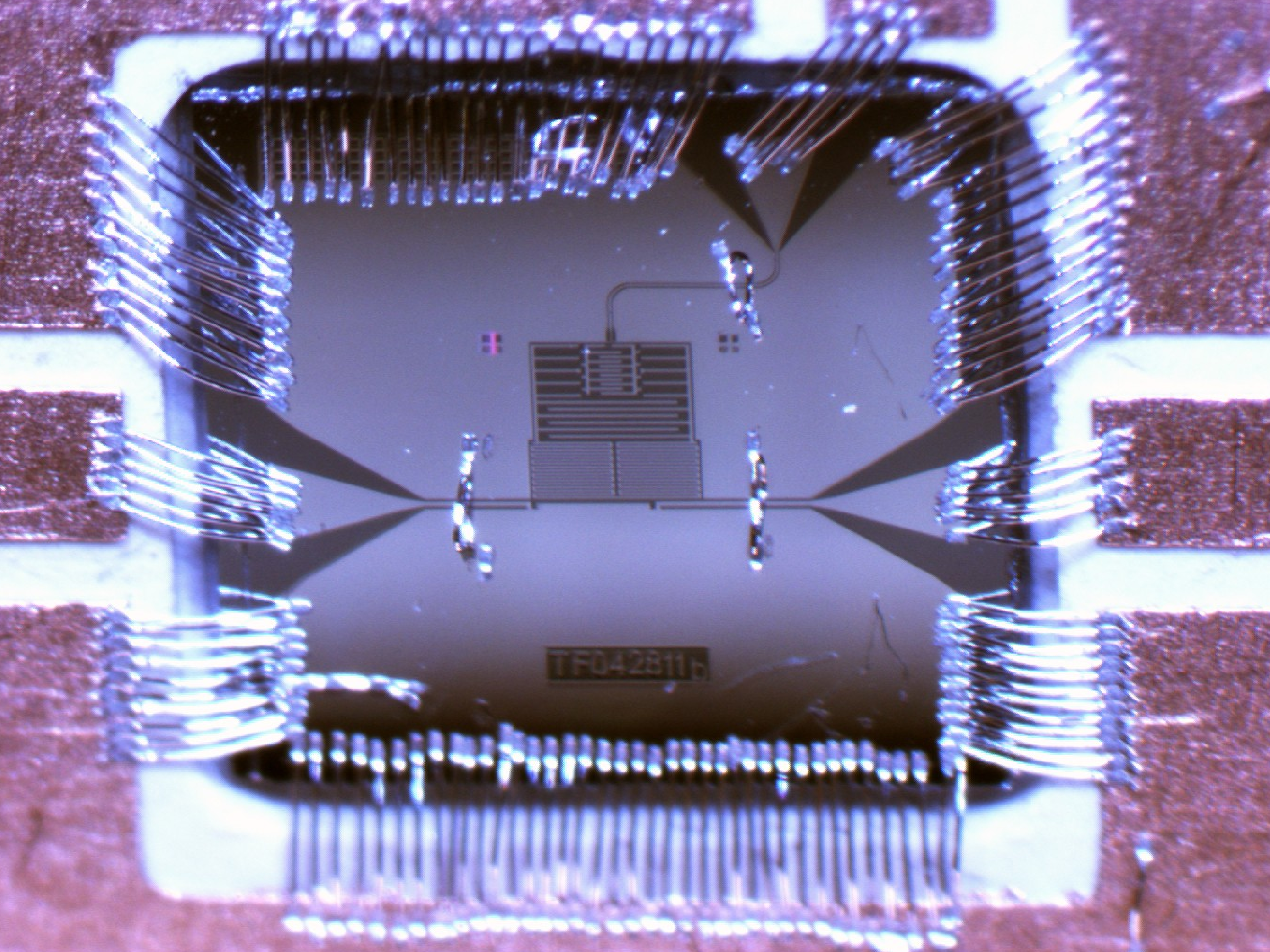
MEASUREMENT : COUPLE TO E-M FIELD OF CAVITY (Jaynes-Cummings)

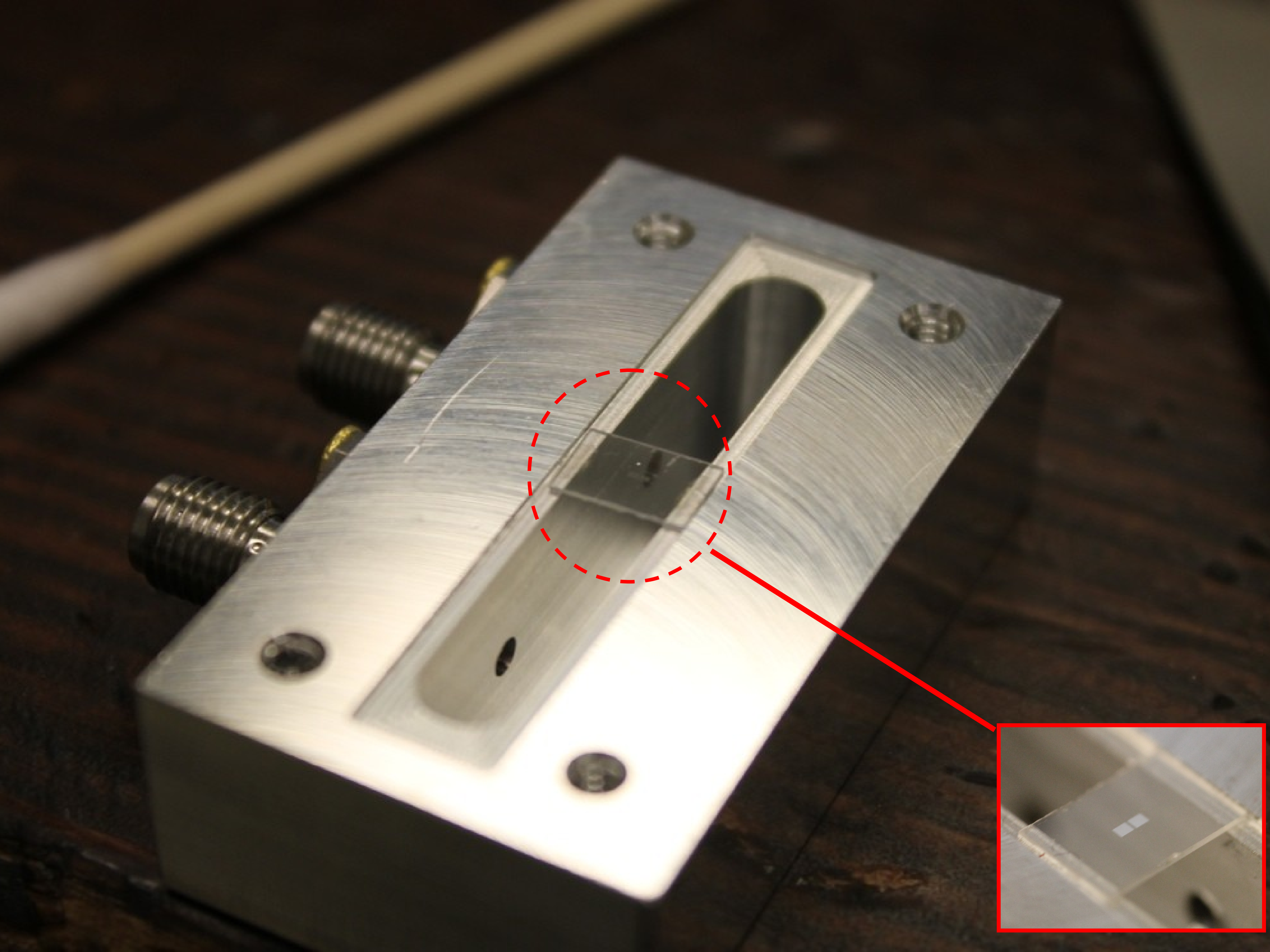




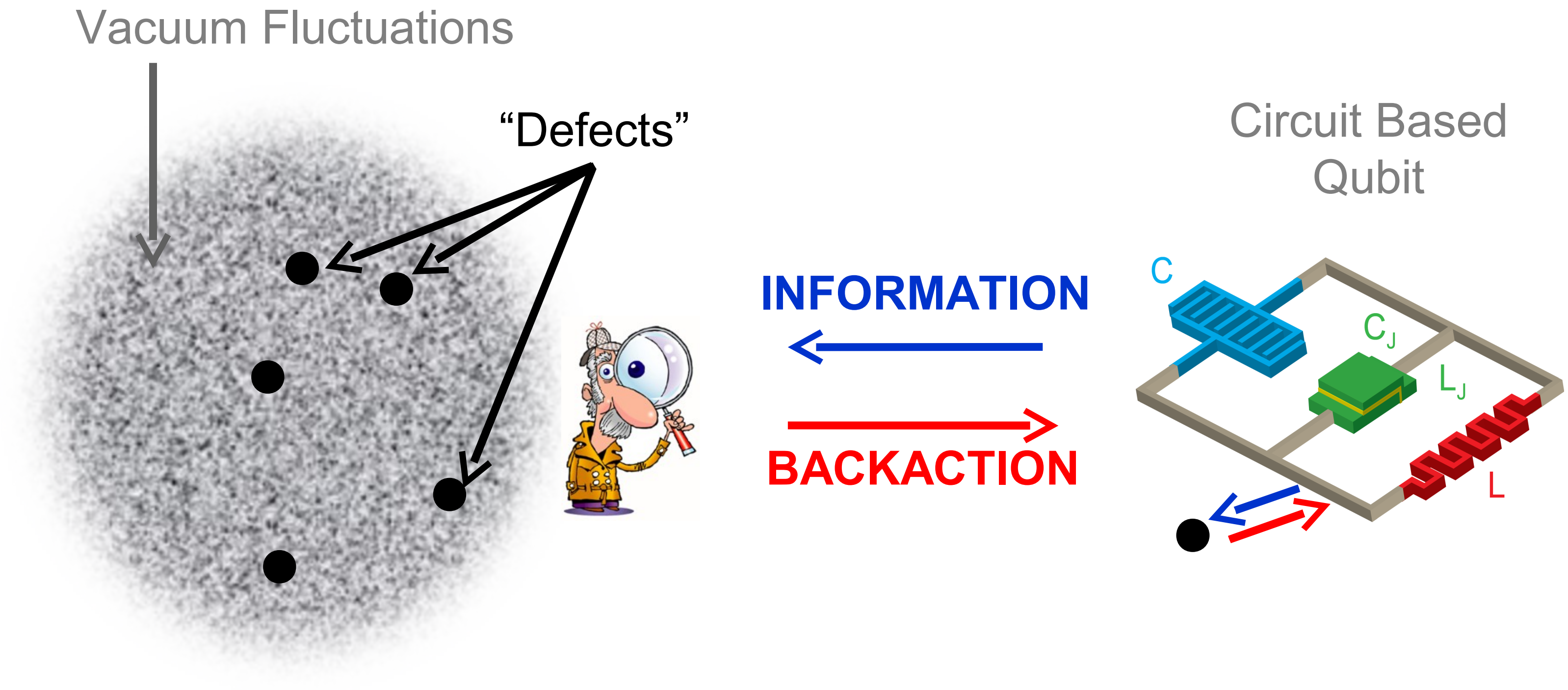
$$H = \frac{1}{2}\hbar\omega_q\sigma_z + \hbar\omega_r(a^\dagger a + \frac{1}{2}) + \hbar g(a^\dagger\sigma_- + a\sigma_+)$$

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


TF042B11b



THE CHALLENGE OF GREGARIOUS QUBITS…



Vacuum Fluctuations

“Defects”

INFORMATION

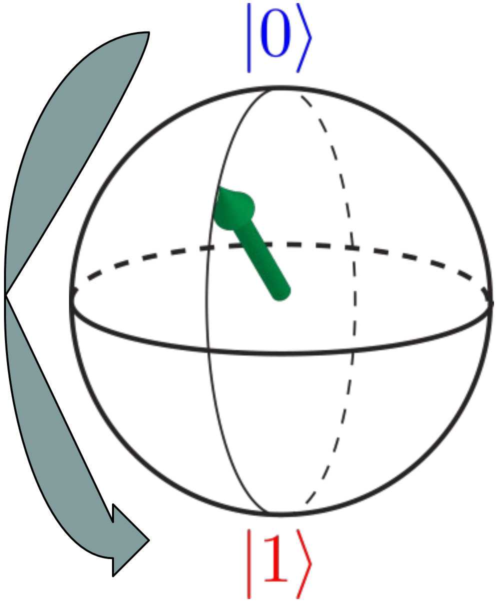
BACKACTION

Circuit Based Qubit

- Current state of the art (no control): T1, T2 ~ 10-100’s μs

- **Active control via engineered dissipation**
  - measurement based feedback (PART I)
  - quantum bath engineering (PART II)

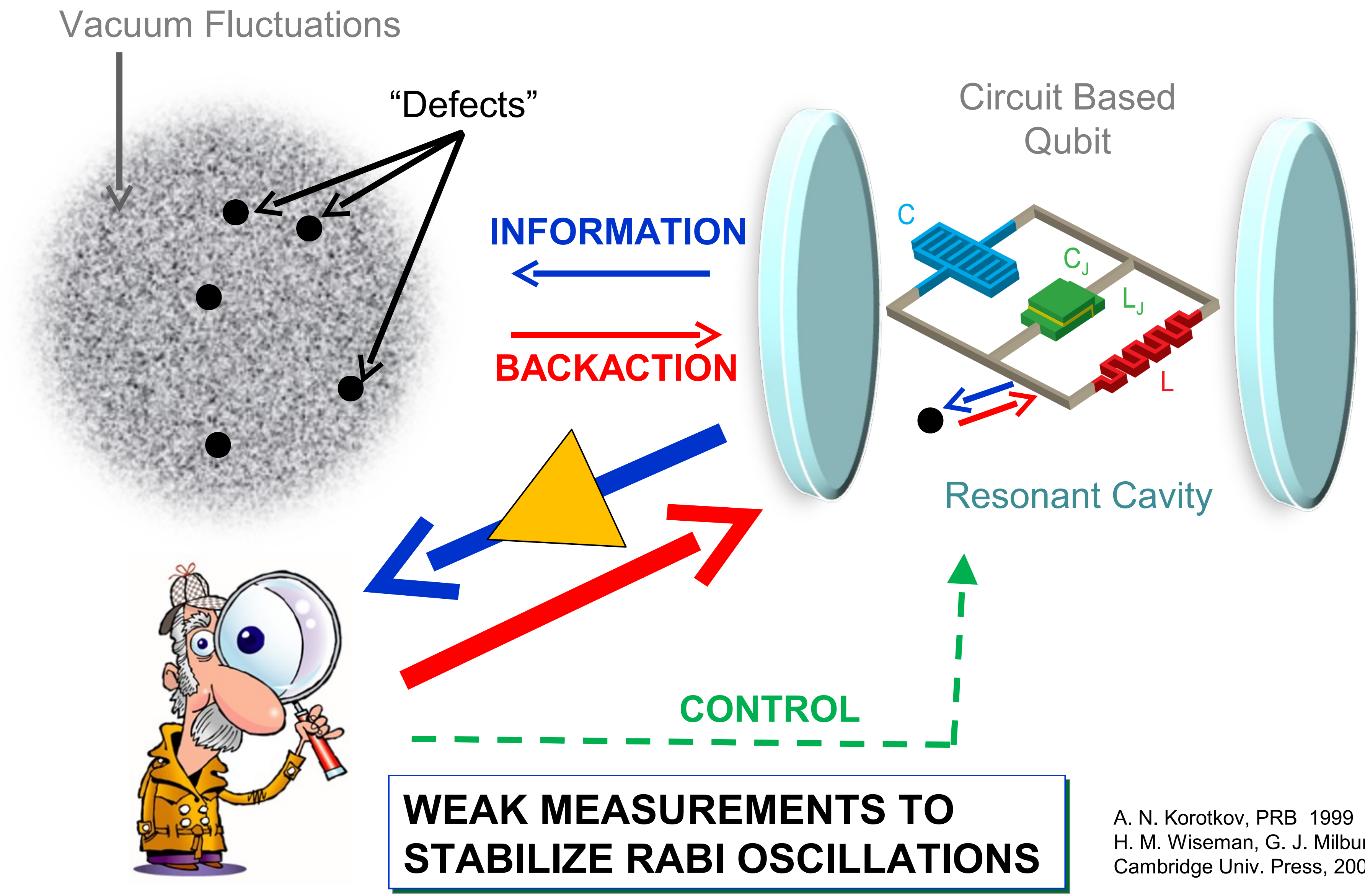
HOW DO WE STABILIZE AN OSCILLATION?



QUANTUM FEEDBACK
via
WEAK CONTINUOUS MEASUREMENT

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

MEASUREMENT BASED FEEDBACK



Vacuum Fluctuations

"Defects"

INFORMATION

BACKACTION

Circuit Based Qubit

C

C_J

L_J

L

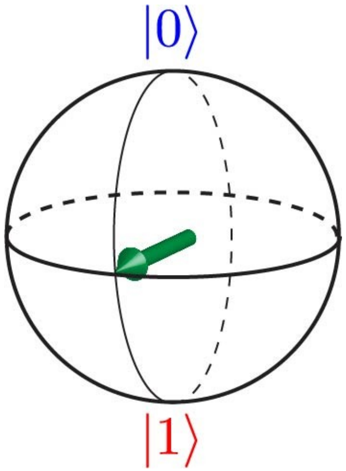
Resonant Cavity

CONTROL

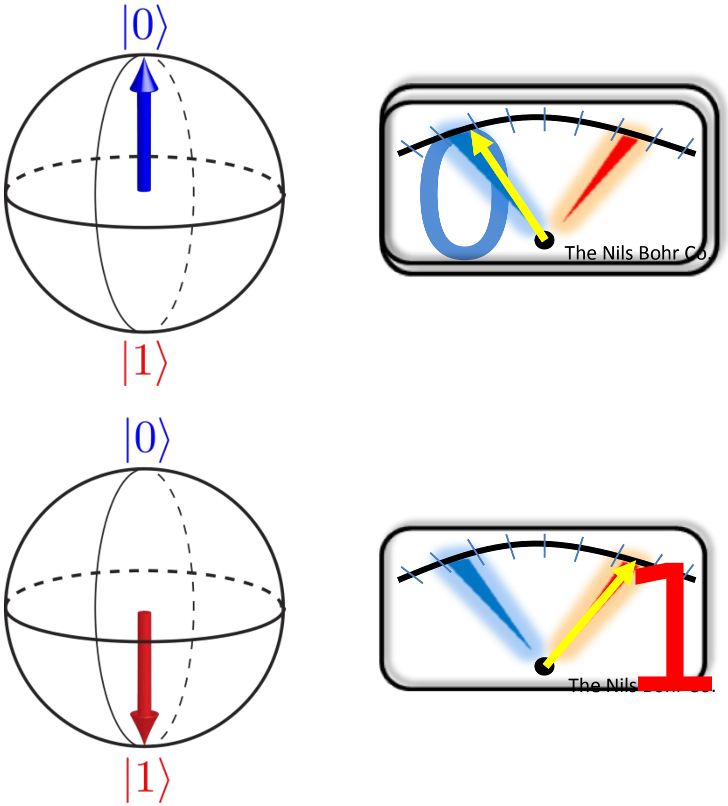
WEAK MEASUREMENTS TO STABILIZE RABI OSCILLATIONS

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

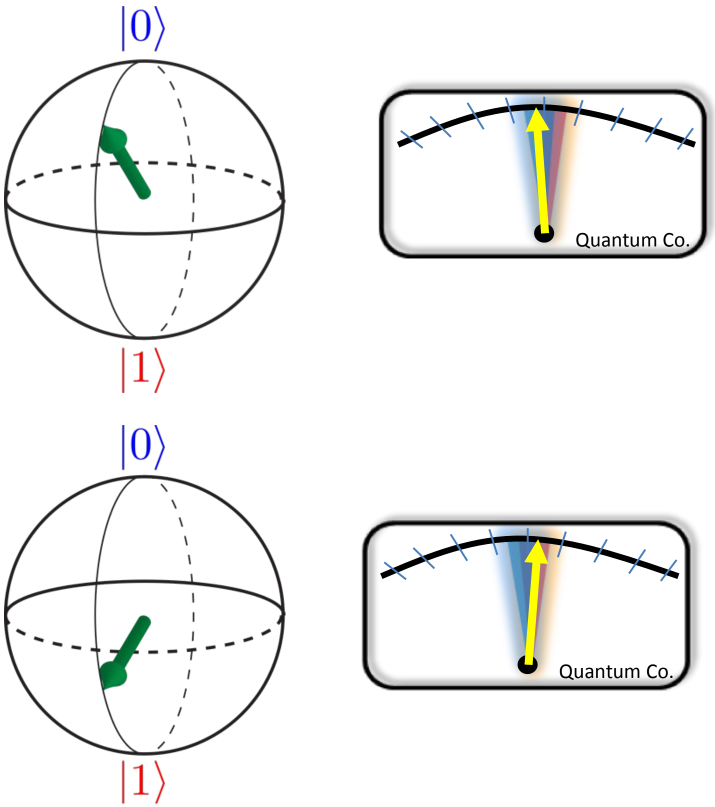
INITIAL STATE:
$|\psi\rangle = |0\rangle + |1\rangle$



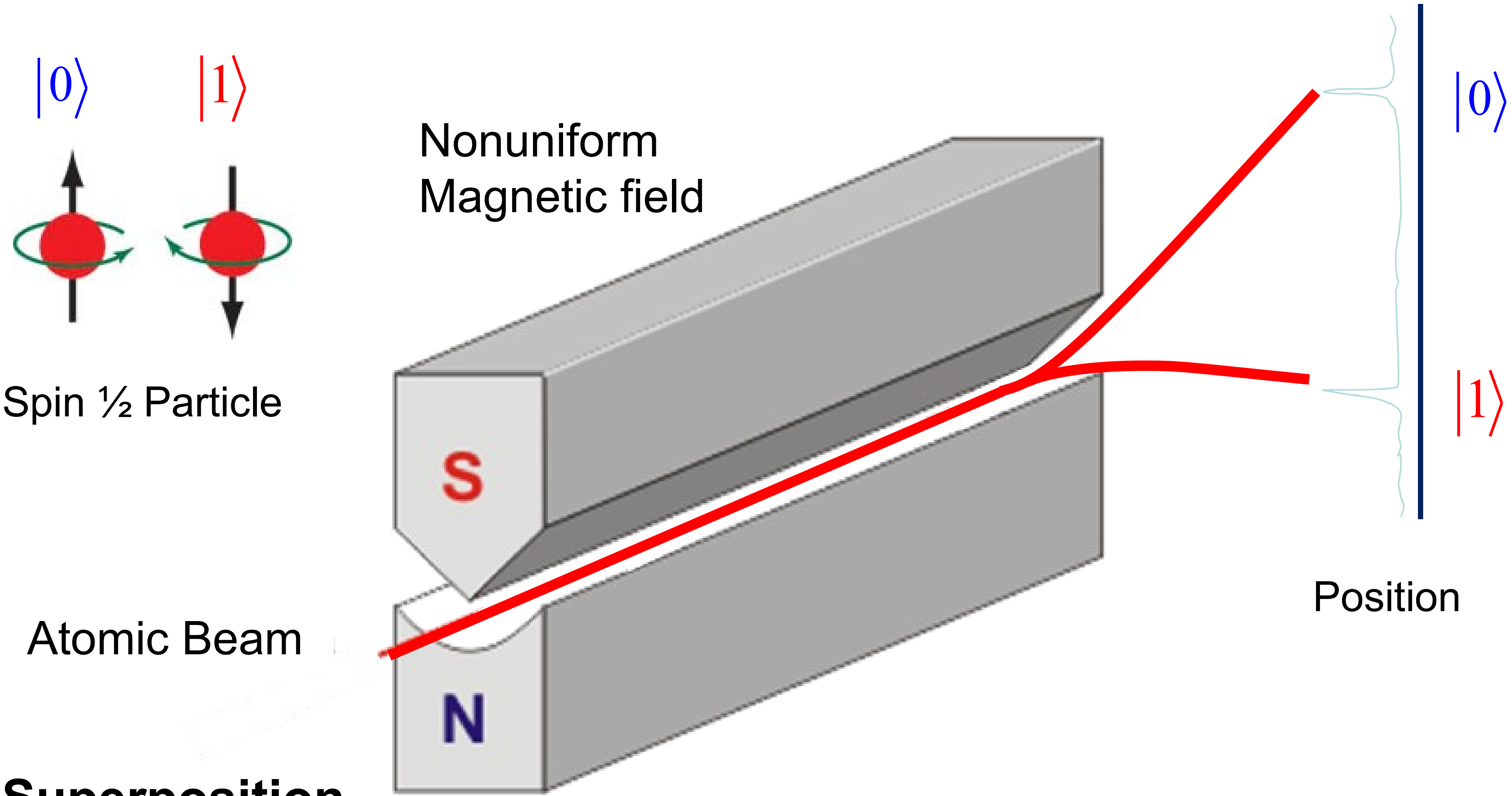
Strong QND Measurement



Weak QND Measurement



STRONG MEASUREMENT



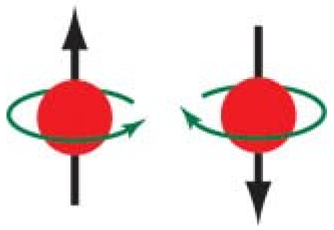
Superposition State

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

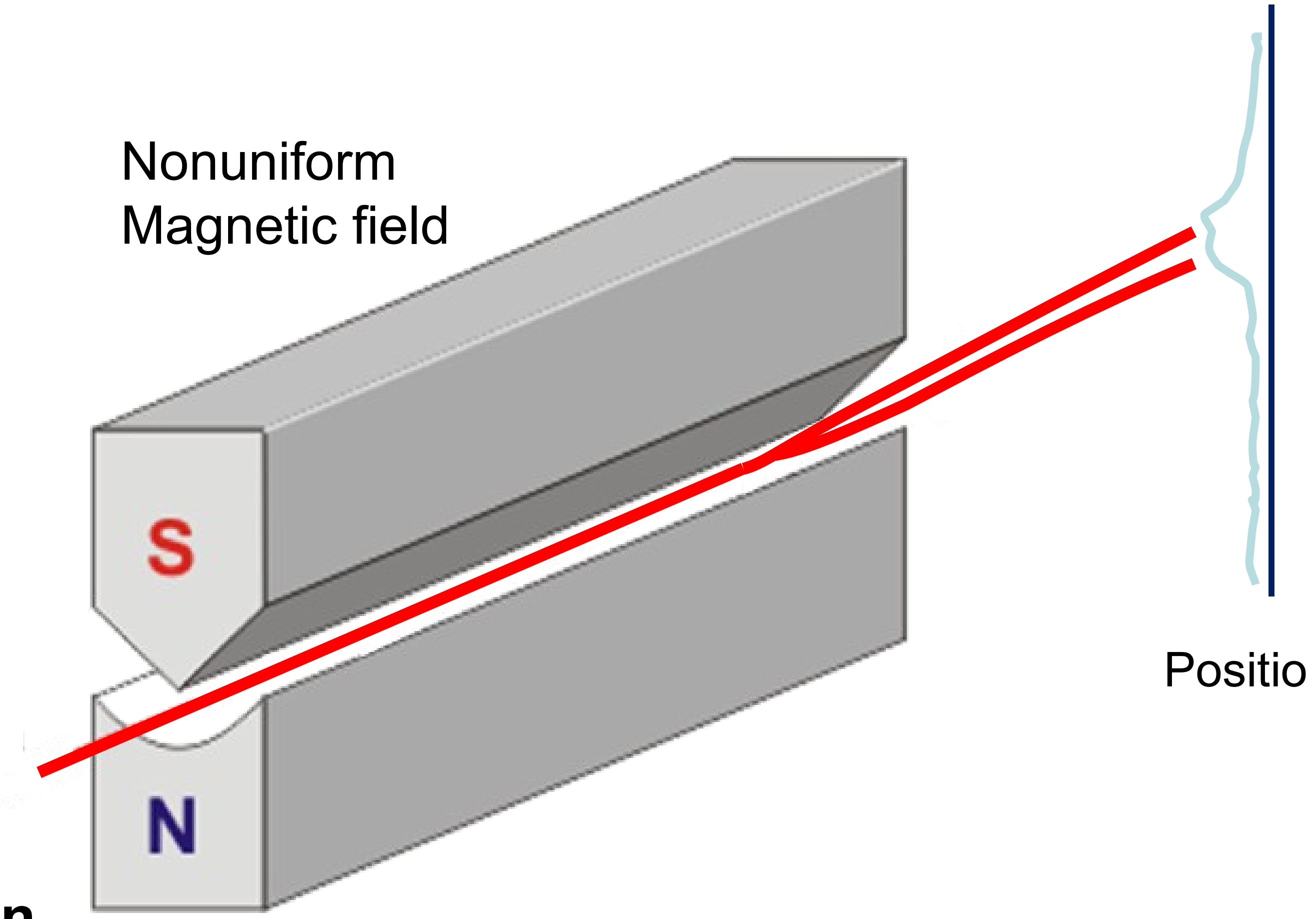
PROJECTIVE MEASUREMENT:
ABLE TO RESOLVE STATES

WEAK MEASUREMENT

$|0\rangle$ $|1\rangle$



Spin ½ Particle



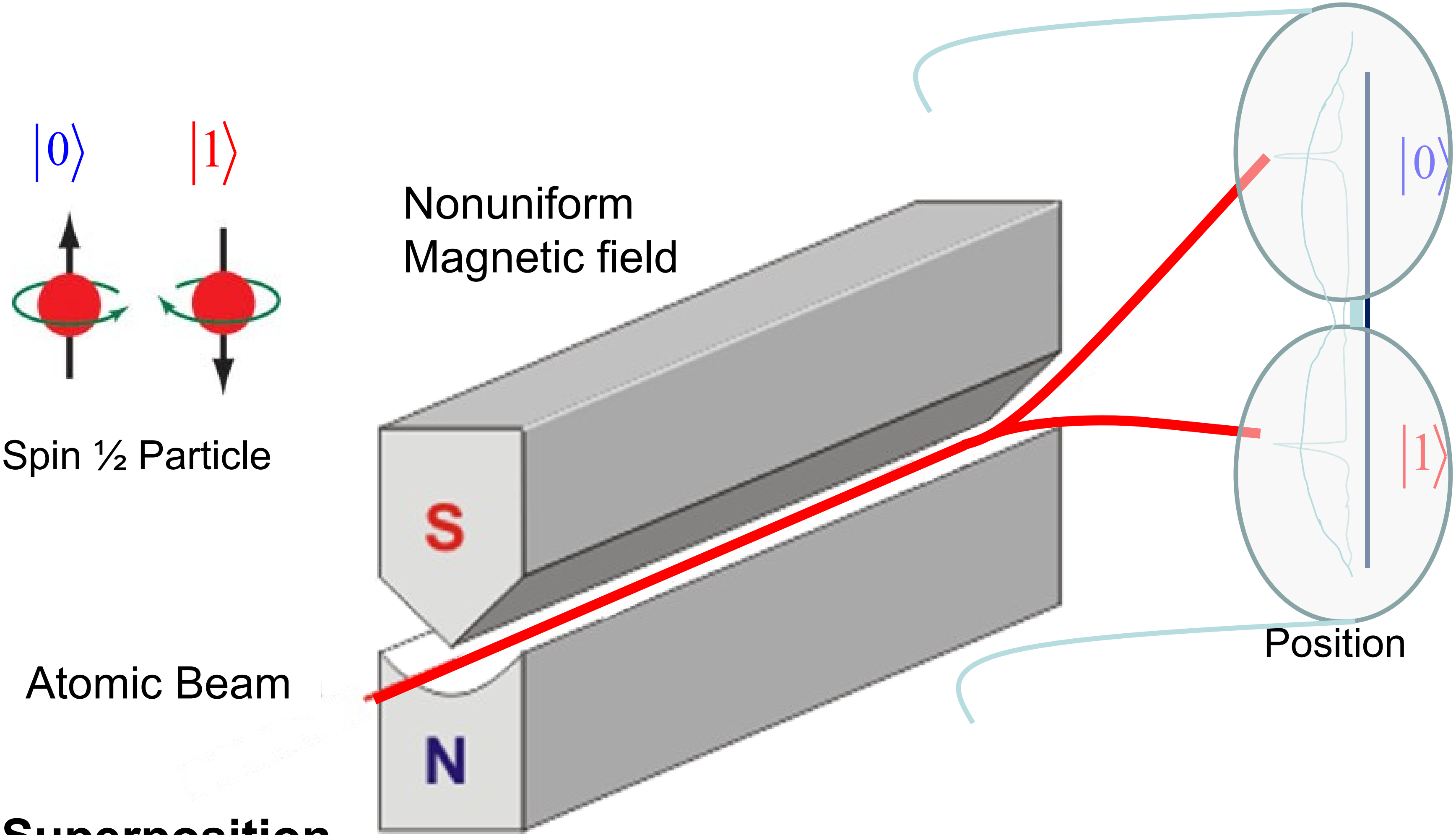
Atomic Beam

Superposition State

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

EXTRACT SOME INFORMATION,
BUT NOT ENOUGH TO DETERMINE STATE

“BAD” MEASUREMENT

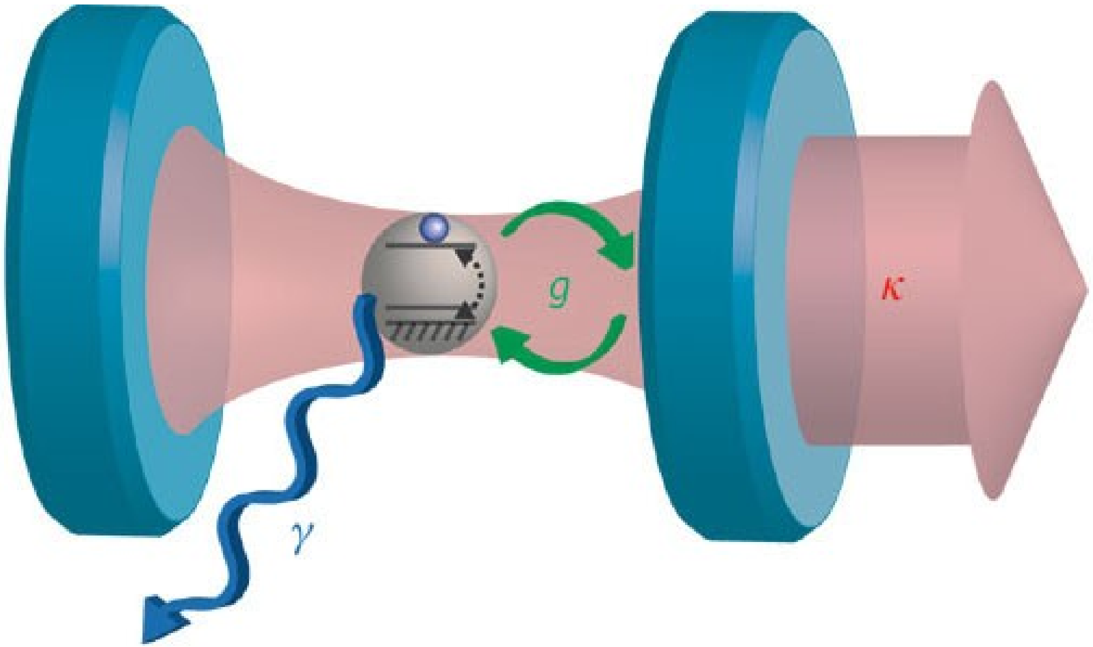


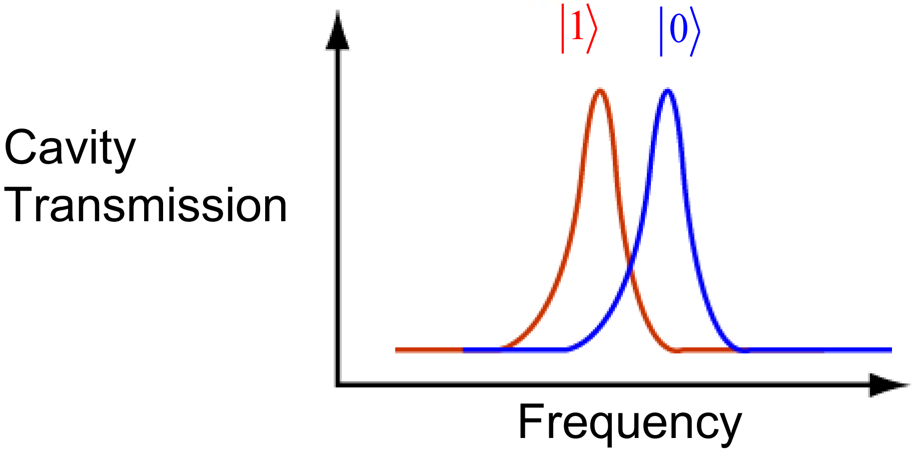
Superposition State

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

PROJECTIVE MEASUREMENT BUT CAN’T RESOLVE POINTER STATES

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



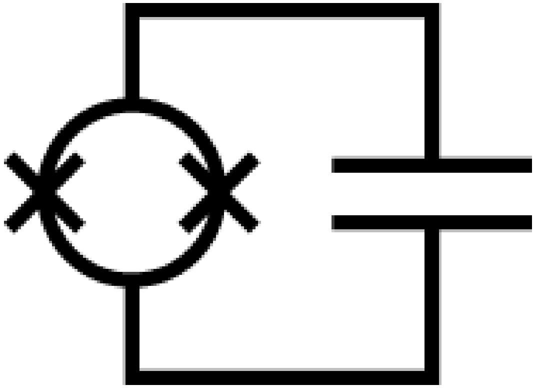


VARY MEASUREMENT STRENGTH USING DISPERSIVE SHIFT & PHOTON NUMBER

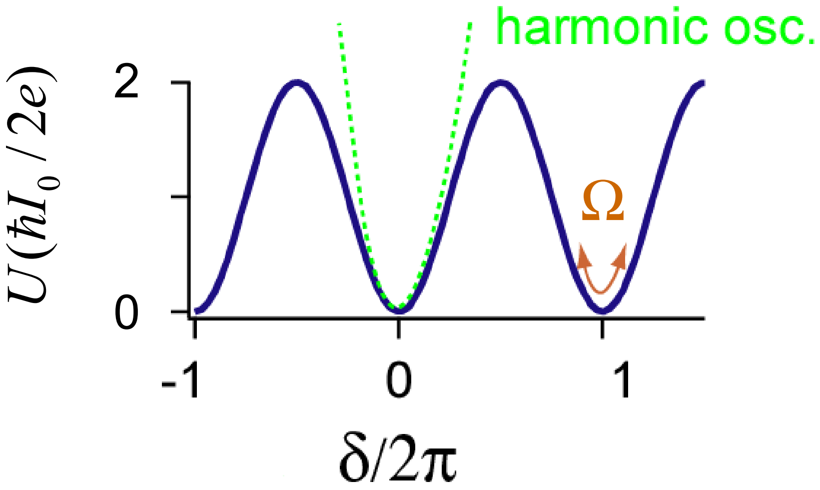
NEED TO DETECT ~ SINGLE MICROWAVE PHOTONS in T_1 ~ μs

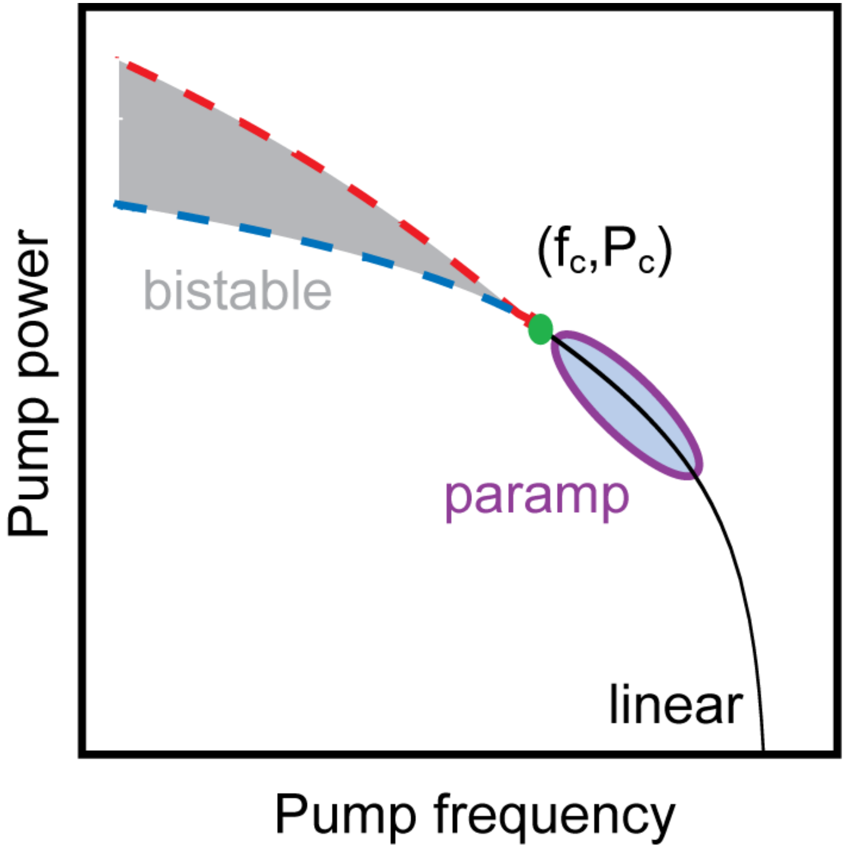
THE
AMPLIFIER

PARAMETRIC AMPLIFICATION



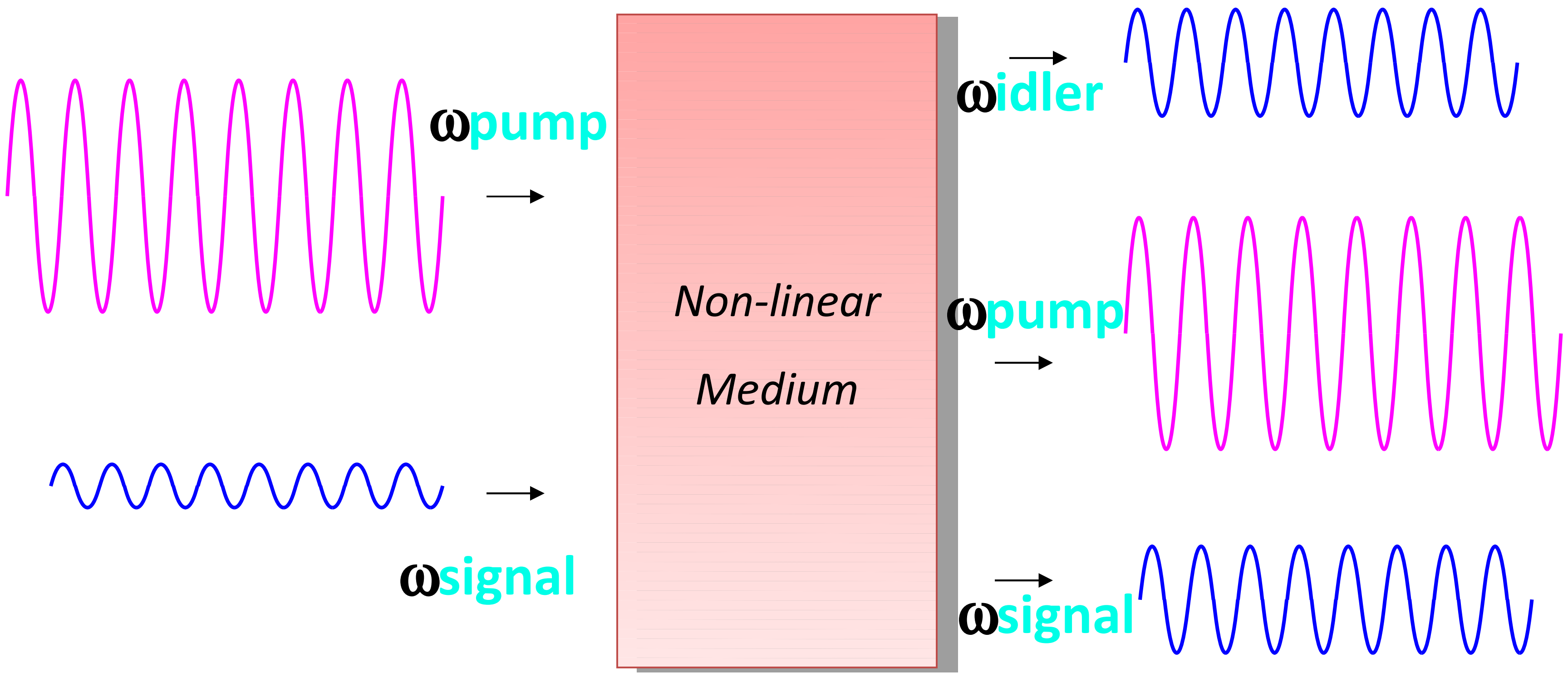
LJ ~ 0.1 nH C ~ 10000 fF





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

PARAMETRIC AMPLIFICATION



ωpump

ωsignal

Non-linear

Medium

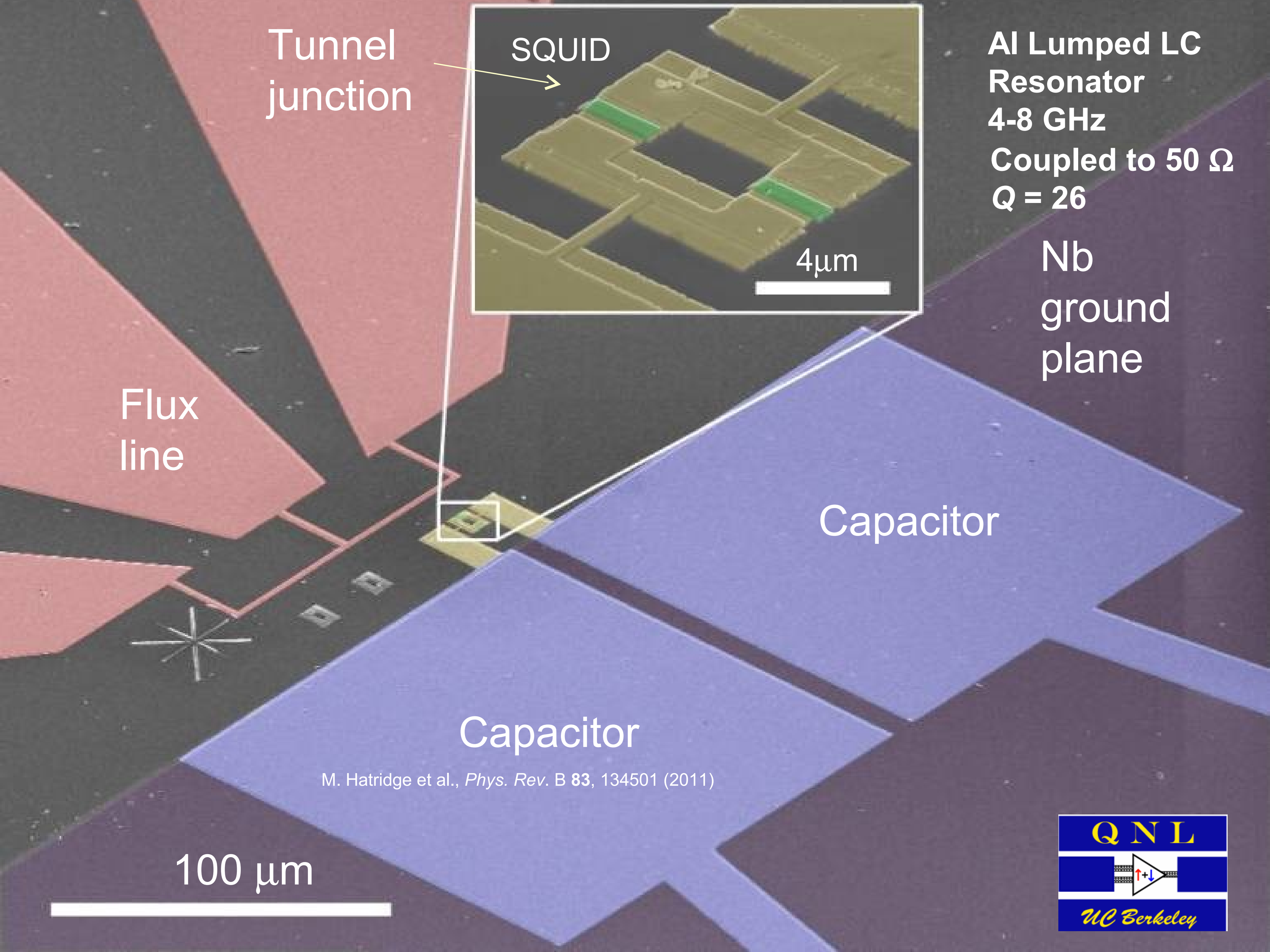
ωidler

ωpump

ωsignal

$$\omega\text{pump} = \omega\text{signal} + \omega\text{idler}$$

$$2\omega\text{pump} = \omega\text{signal} + \omega\text{idler}$$

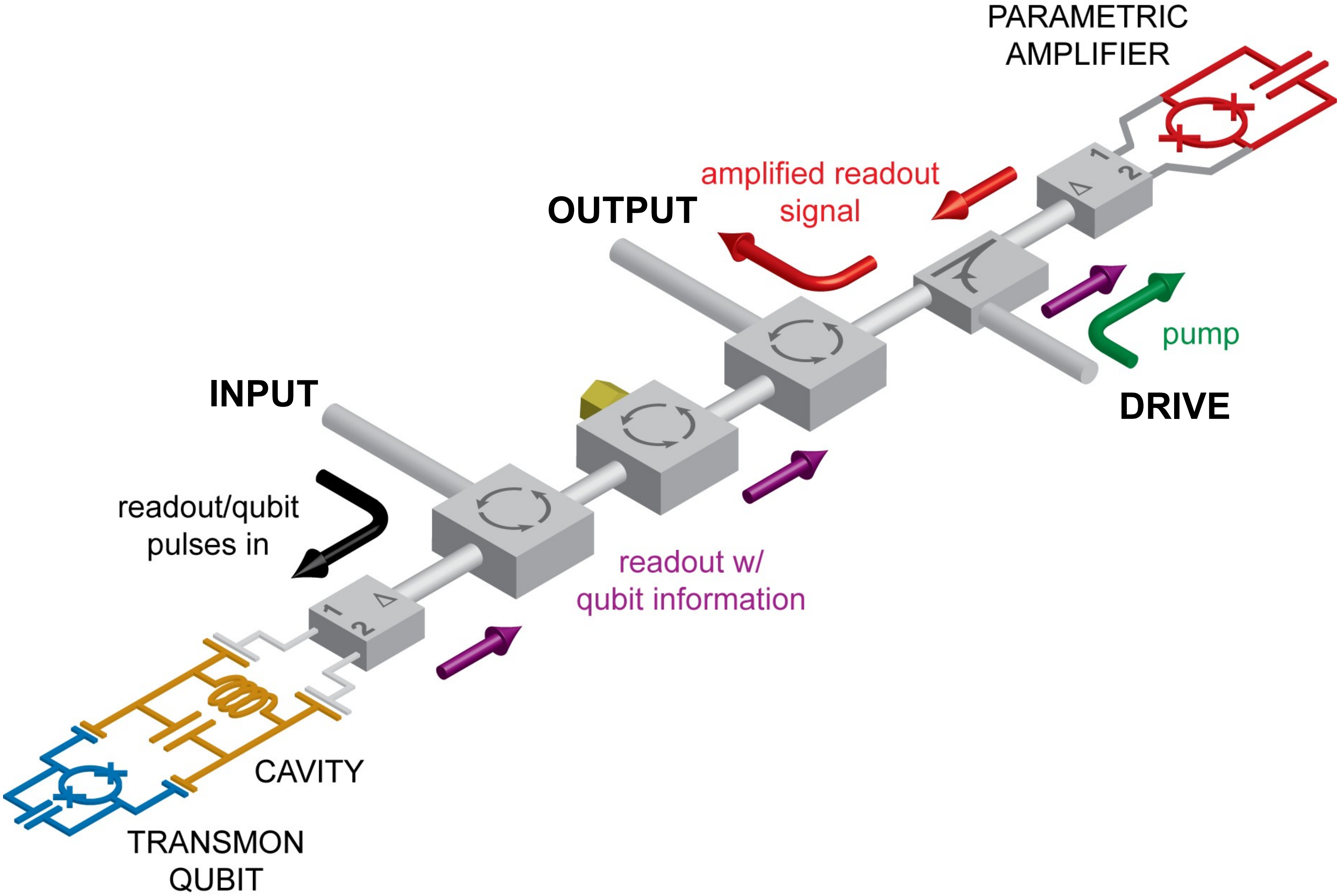


Al Lumped LC
Resonator
4-8 GHz
Coupled to 50 Ω
Q = 26

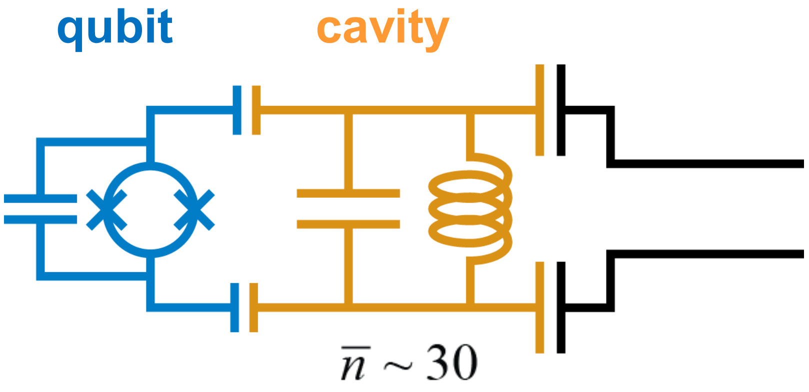
M. Hatridge et al., *Phys. Rev.* B **83**, 134501 (2011)

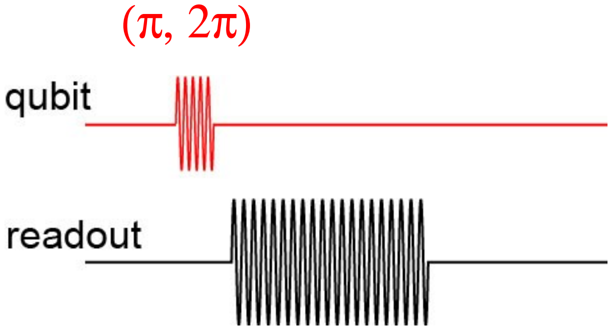
QNL
UC Berkeley

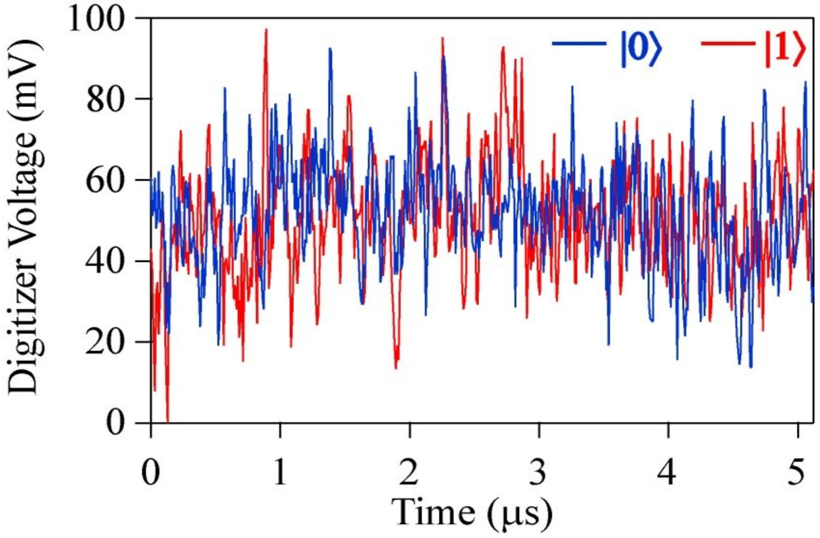
EXPERIMENTAL SETUP

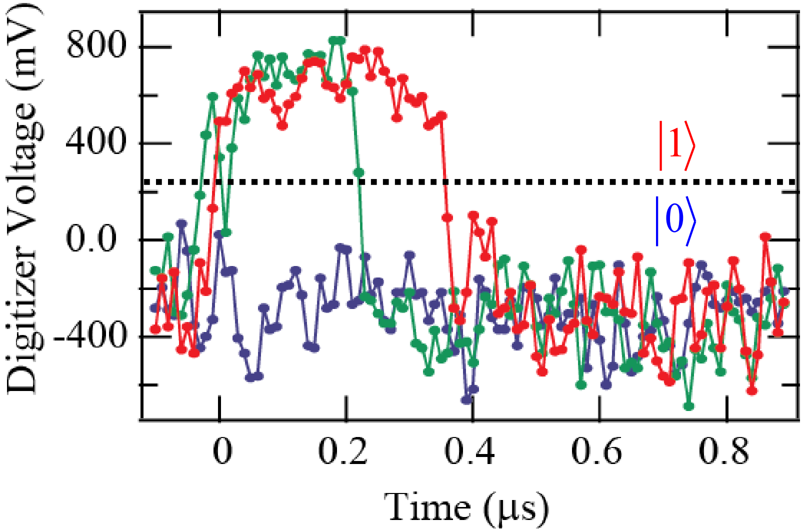


SINGLE SHOT MEASUREMENT TRACES







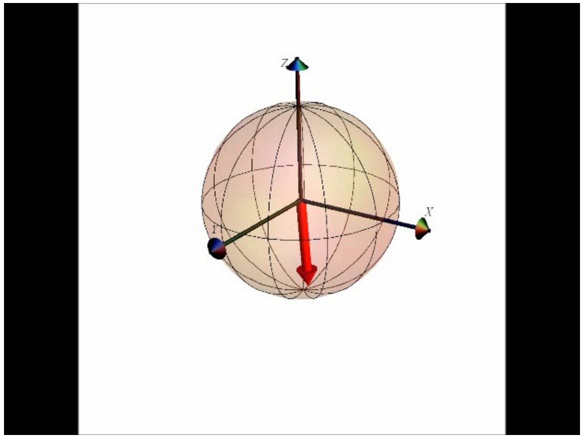


SEMICONDUCTOR HEMT AMPLIFIER

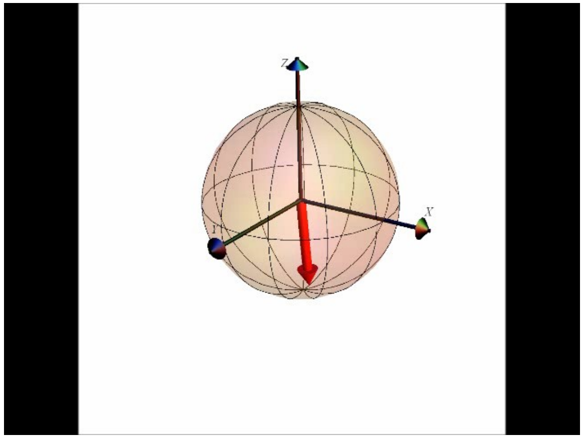
JOSEPHSON PARAMETRIC AMPLIFIER

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

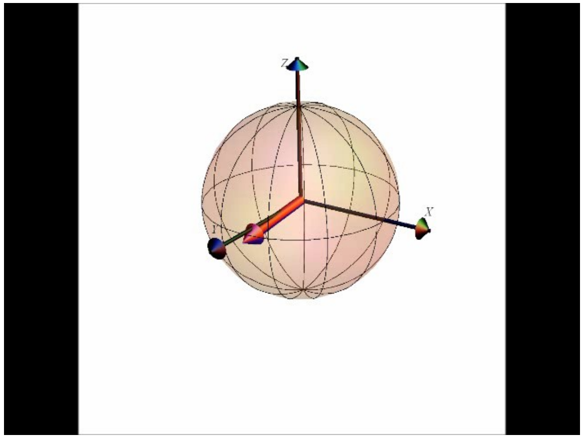
RABI OSCILLATIONS



No Measurement



Strong Measurement



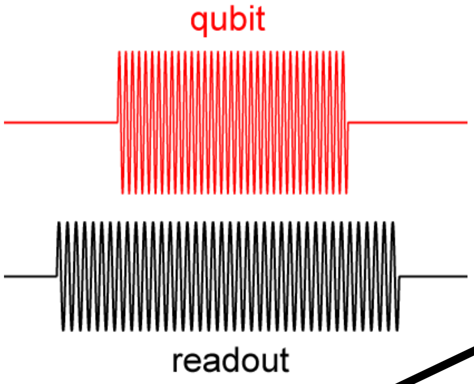
Weak Measurement

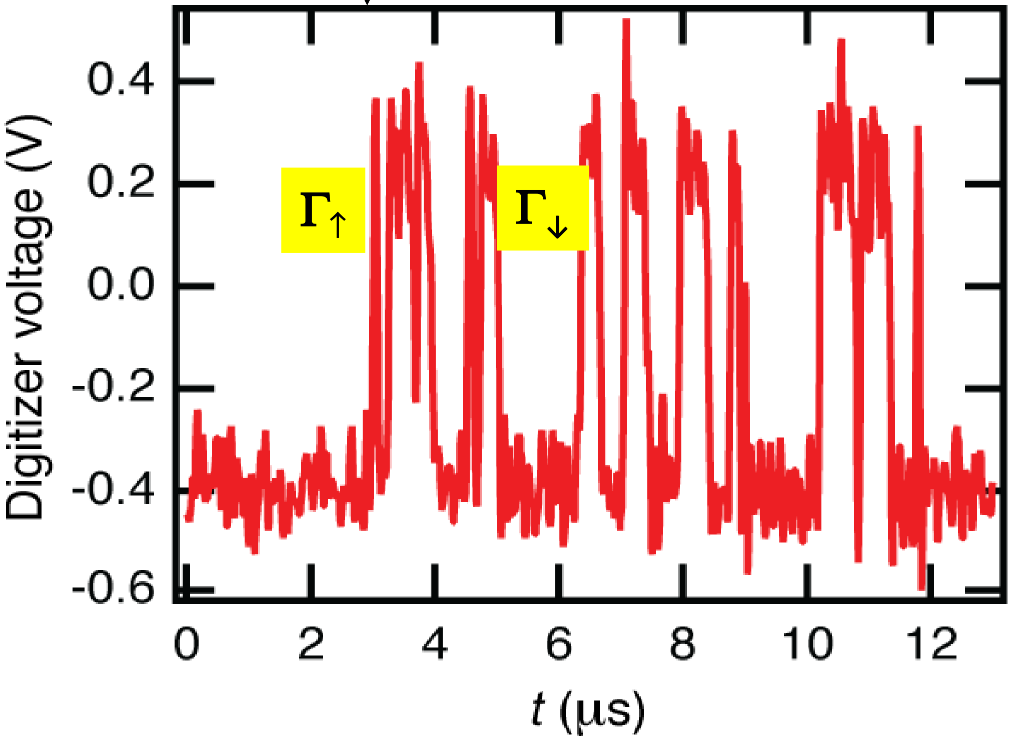
- *Noisy* detector output <-> Random evolution of qubit

- **Stabilize oscillatory motion (eg. Rabi Oscillations) by locking to a classical clock**

A. N. Korotkov, *Phys. Rev.* B **60,** 5737 (1999)
A. Frisk Kockum, L. Tornberg, and G. Johansson, arXiv:1202.2386v2
C. Sayrin et al., *Nature* **477**, 73 (2011)
A. Palacios-Laloy et al., *Nature Phys.* **6**, 442 (2010)
H. M. Wiseman, G. J. Milburn, *Quantum Measurement and Control,* (Cambridge Univ. Press, 2009)

RABI OSCILLATIONS with CONTINUOUS STRONG MEASUREMENT



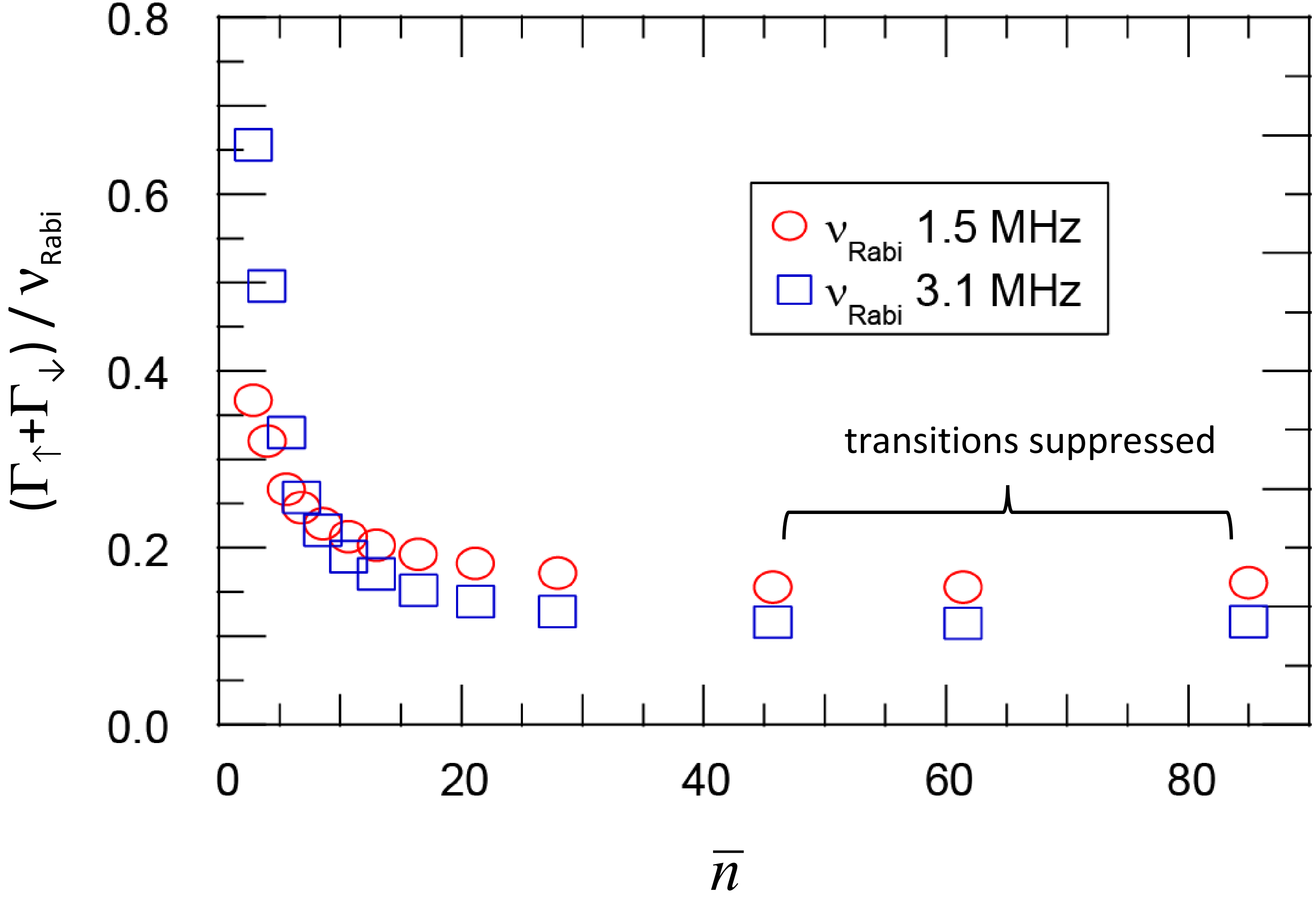


turn on Rabi drive

- Continuously drive qubit
- Continuously measure
- Display single measurement

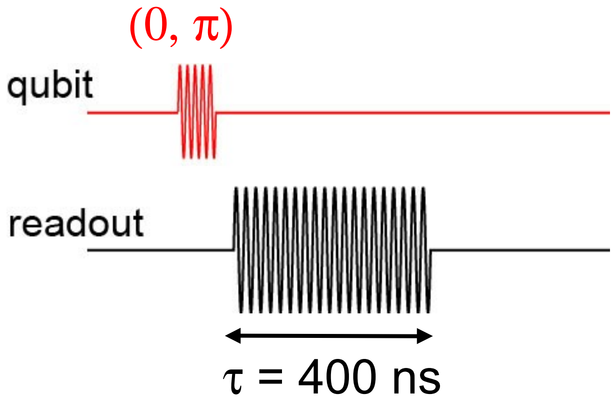
Strong Measurement Pins Qubit

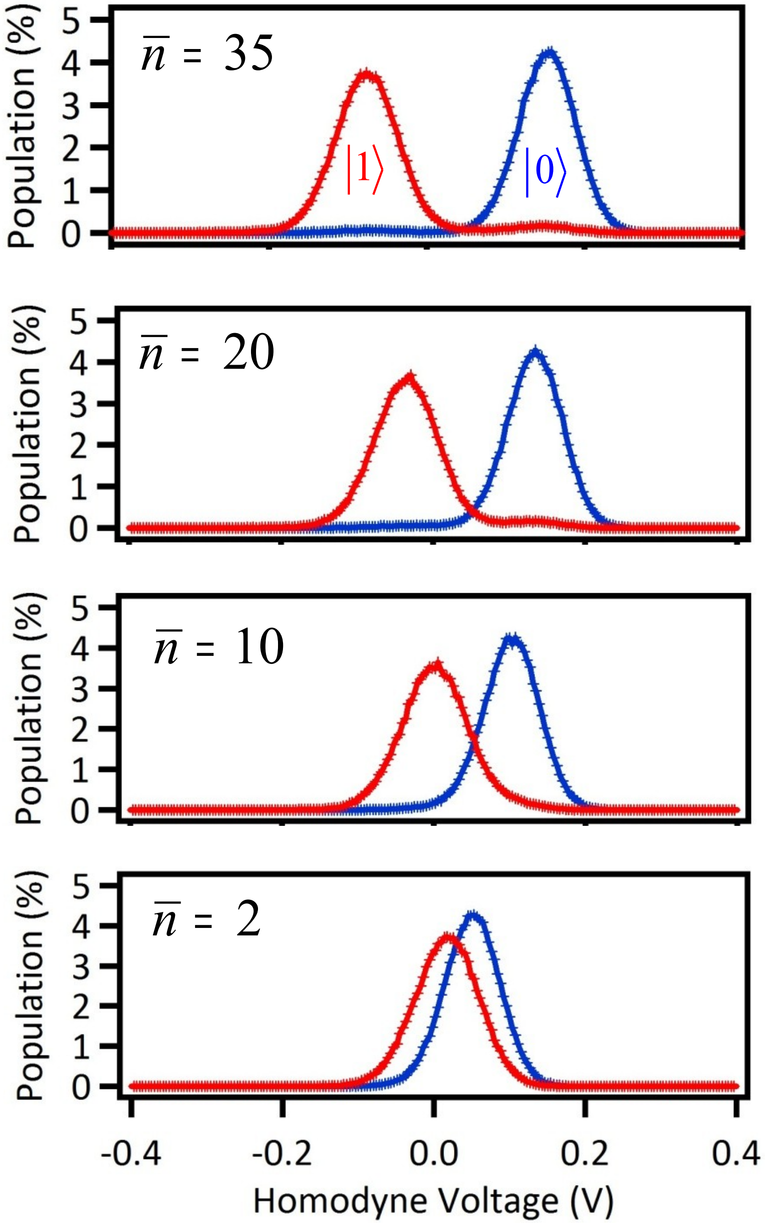
QUANTUM ZENO EFFECT



W. M. Itano et al., *Phys. Rev*. A **41**, 2295 (1990)
J. Gambetta et al., *Phys. Rev*. A **77**, 012112 (2008)

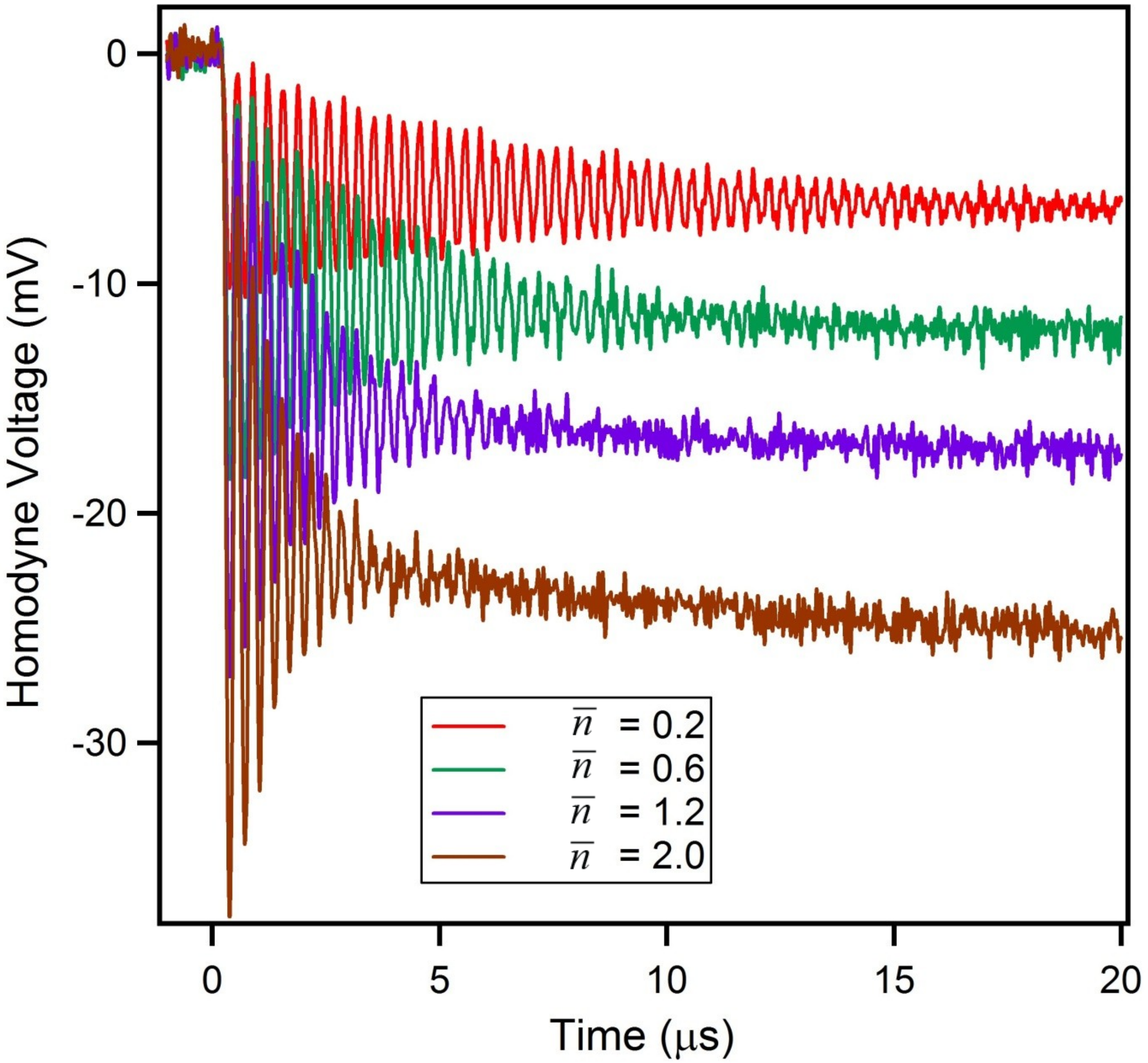
VARYING MEASUREMENT STRENGTH

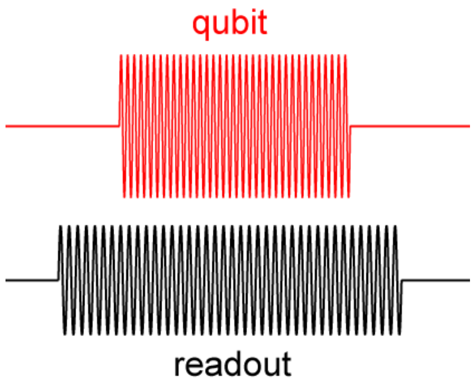




- Integrate measurement trace for 400 ns
- Repeat and histogram
- ~ 2x quantum noise floor

RABI OSCILLATIONS with CONTINUOUS WEAK MEASUREMENT: ENSEMBLE AVERAGE

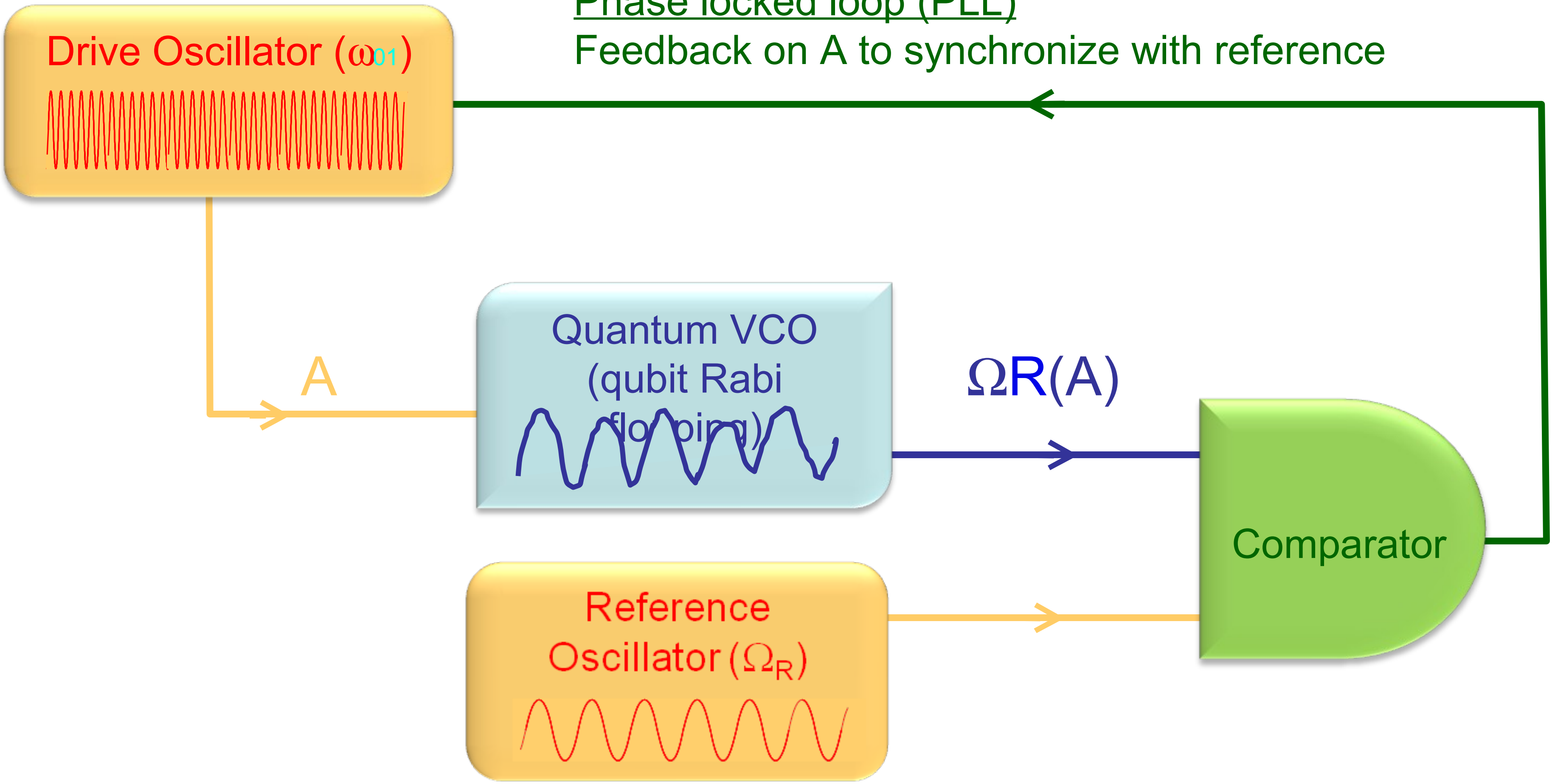




- Continuously drive qubit
- Continuously measure (weakly)
- Repeat
- Display average

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

Drive Oscillator (ω_{01})

A

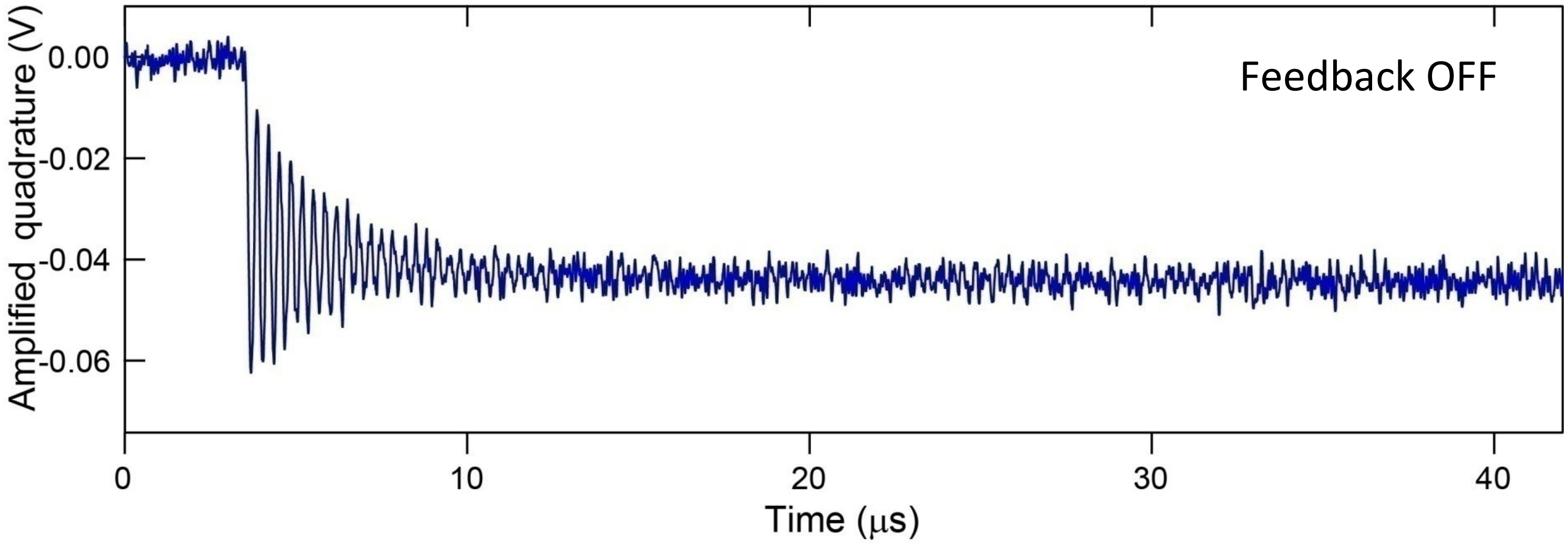
Quantum VCO (qubit Rabi flopping)

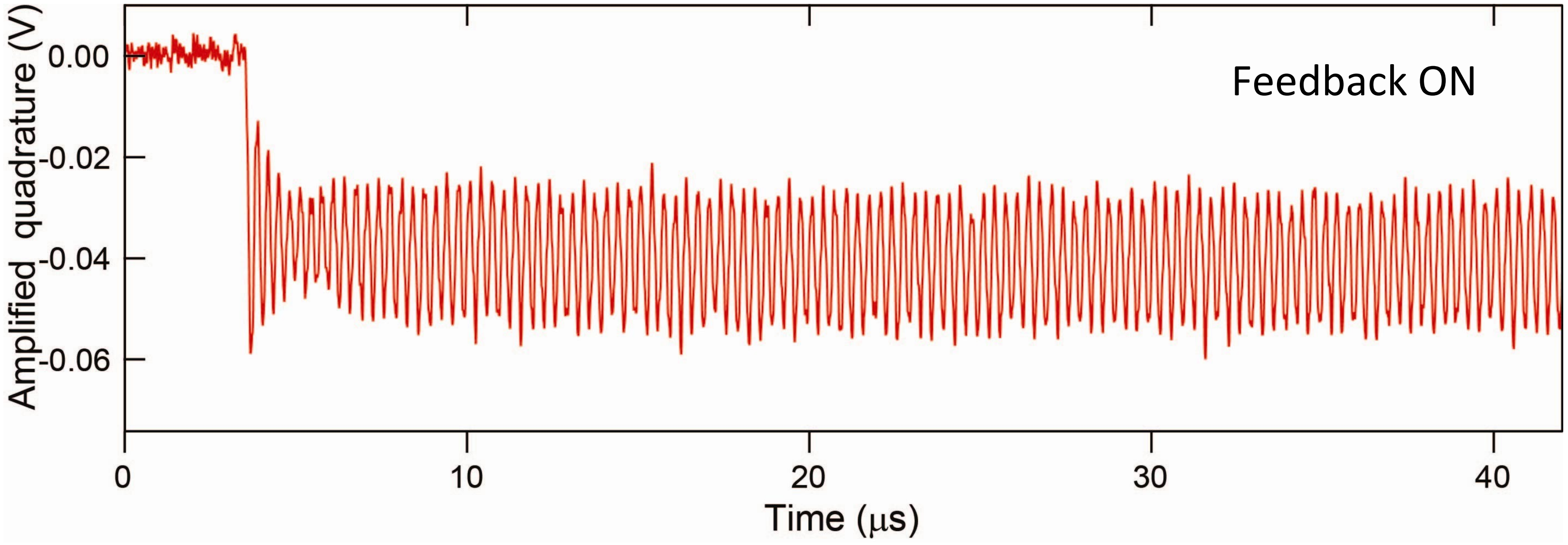
$\Omega R(A)$

Comparator

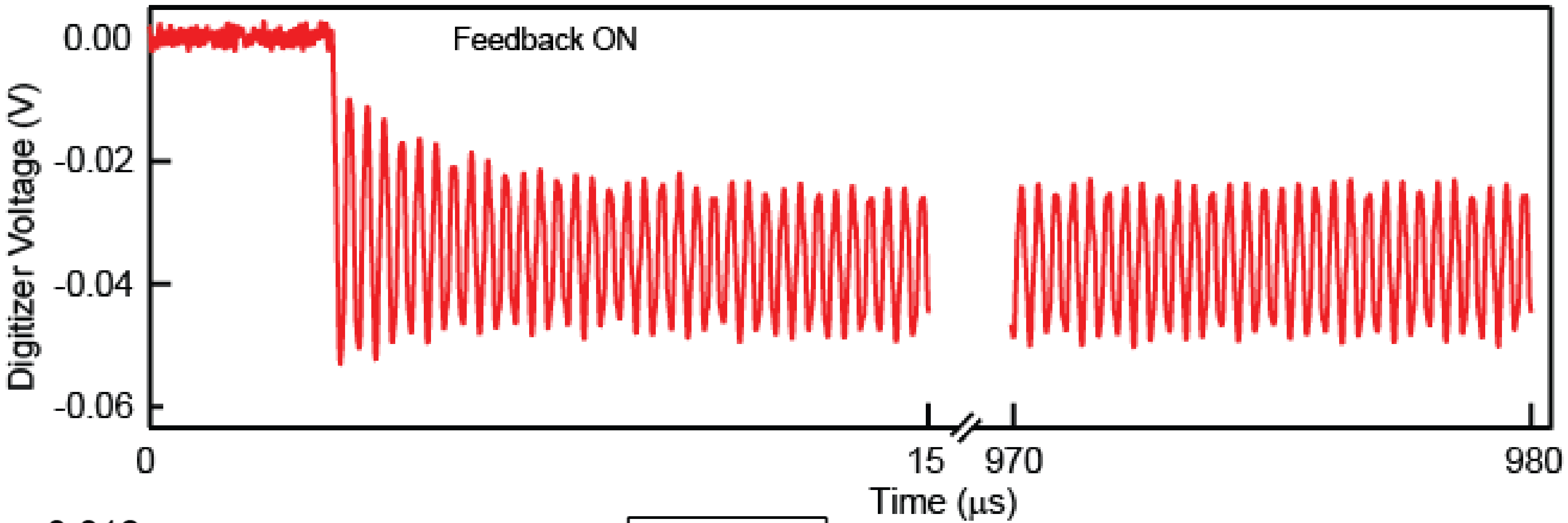
Reference Oscillator (Ω_R)

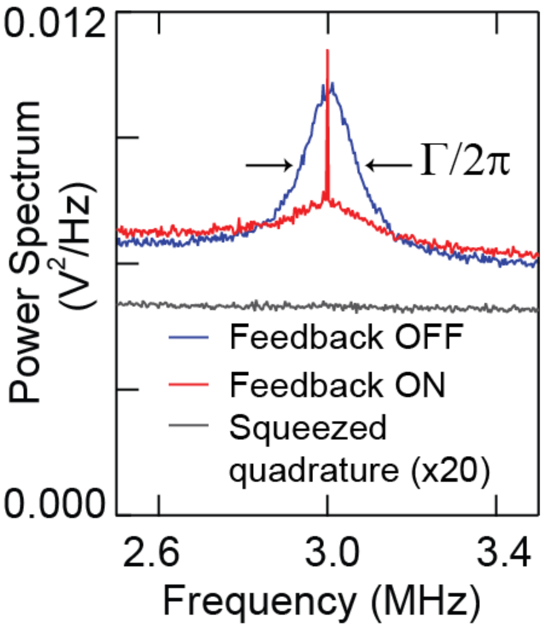
STABILIZED RABI OSCILLATIONS

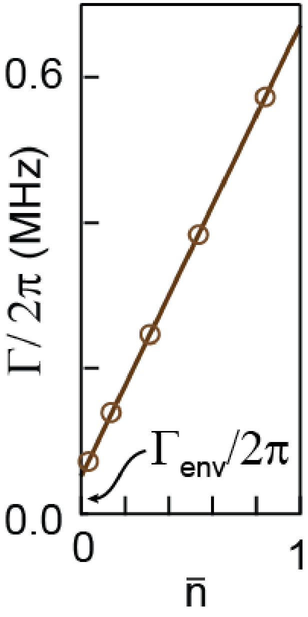




STILL GOING…

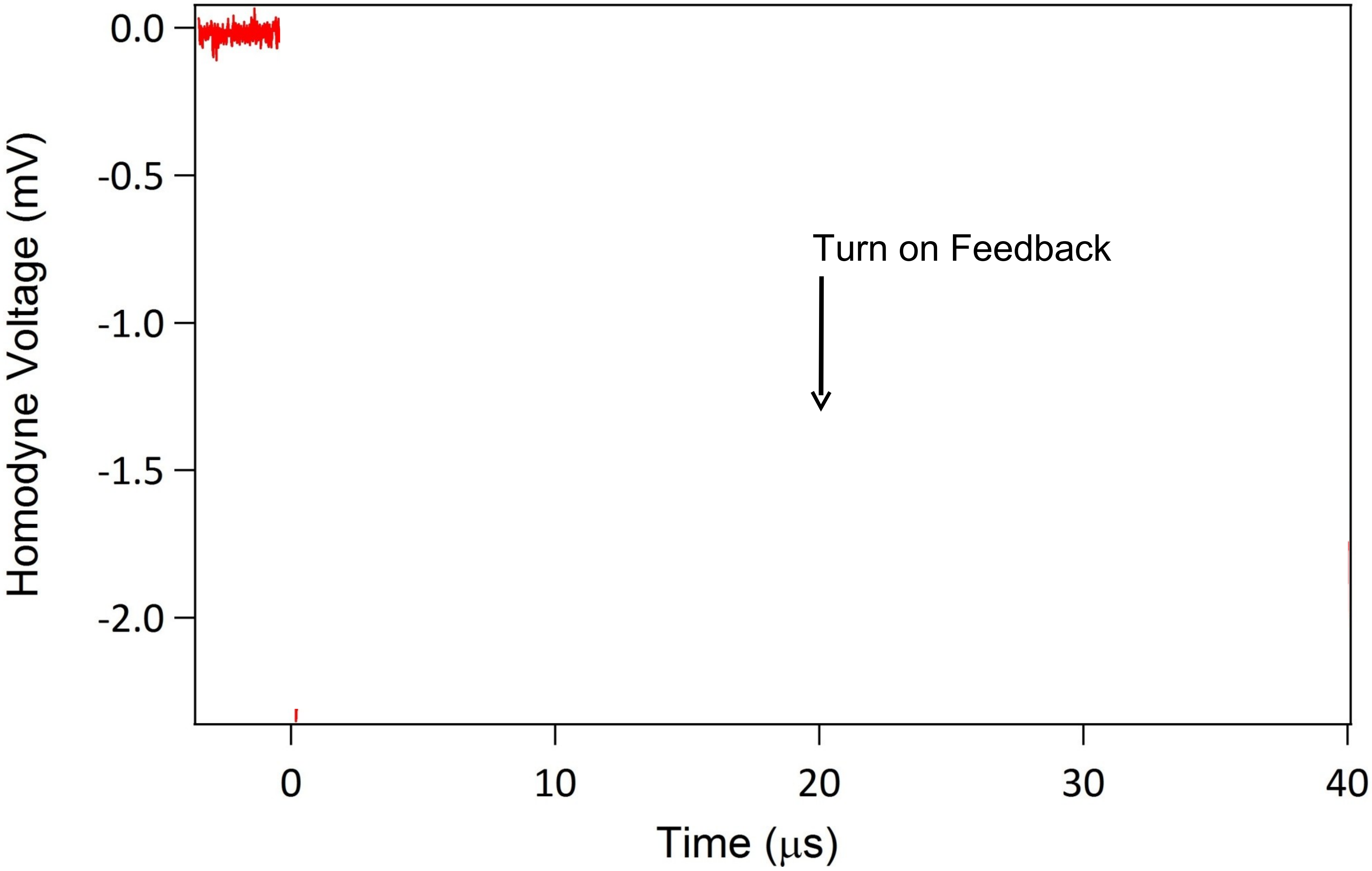




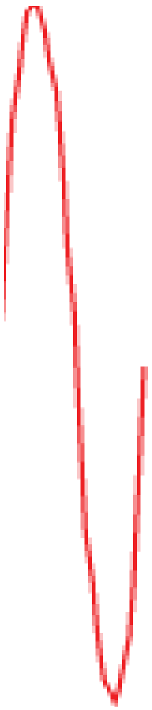


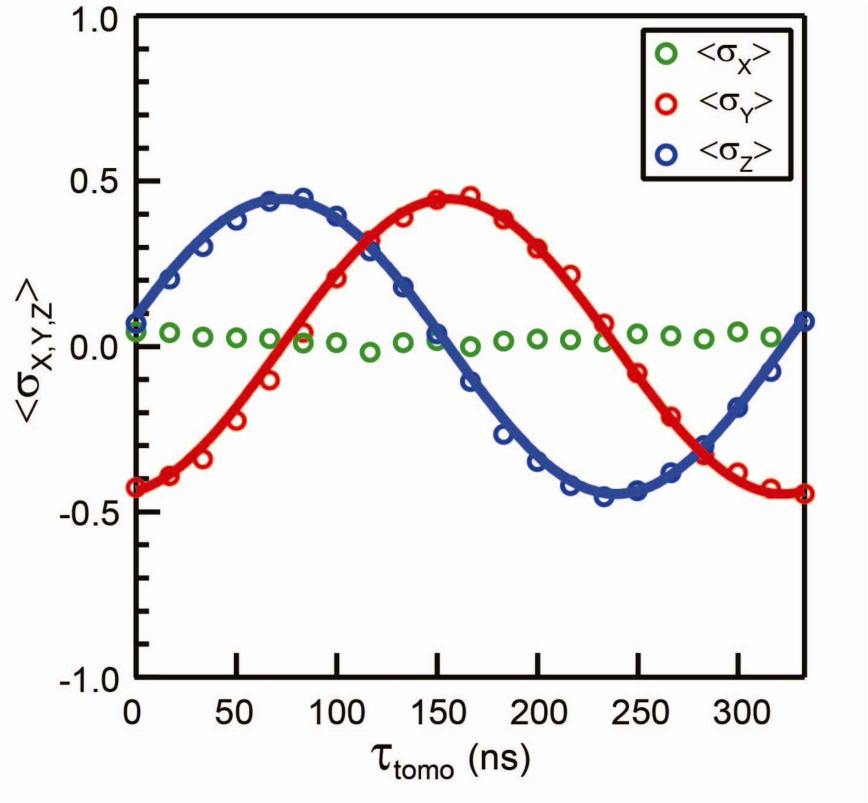
- Single quadrature measurement
- Operate with measurement dephasing dominant
- Appearance of narrow peak when PLL operational

REPHASING THE QUBIT



STATE TOMOGRAPHY





- Observe expected rotation in the X,Z plane
- Observe Bloch vector reduced to 50% of maximum

FEEDBACK EFFICIENCY

$$D = \frac{2}{\frac{1}{\eta}\frac{F}{\Gamma/\Omega_R} + \frac{\Gamma/\Omega_R}{F}}$$

D: "feedback efficiency"

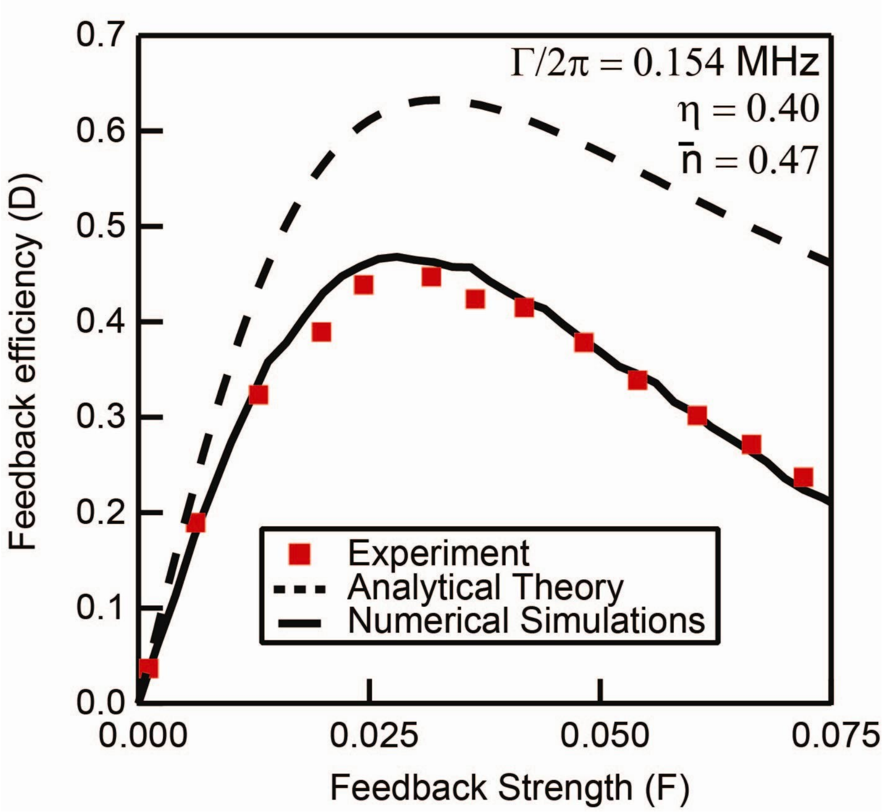
F: feedback strength

η: detector efficiency (0-1)

Γ: dephasing rate

Ω_R: Rabi frequency

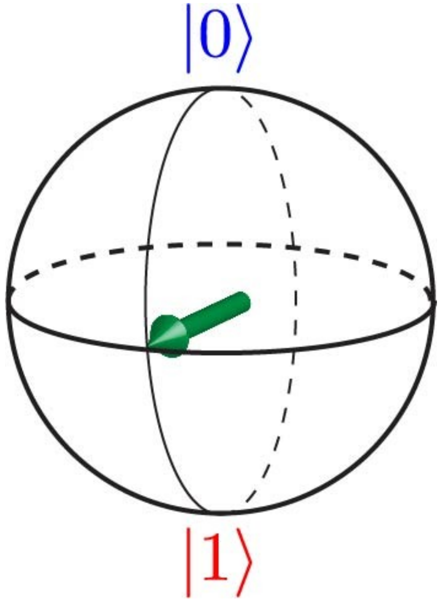
(A.N. Korotkov)



- Analytics do not include delay time, finite bandwidth, T_1

- Numerics include delay and bandwidth → good agreement

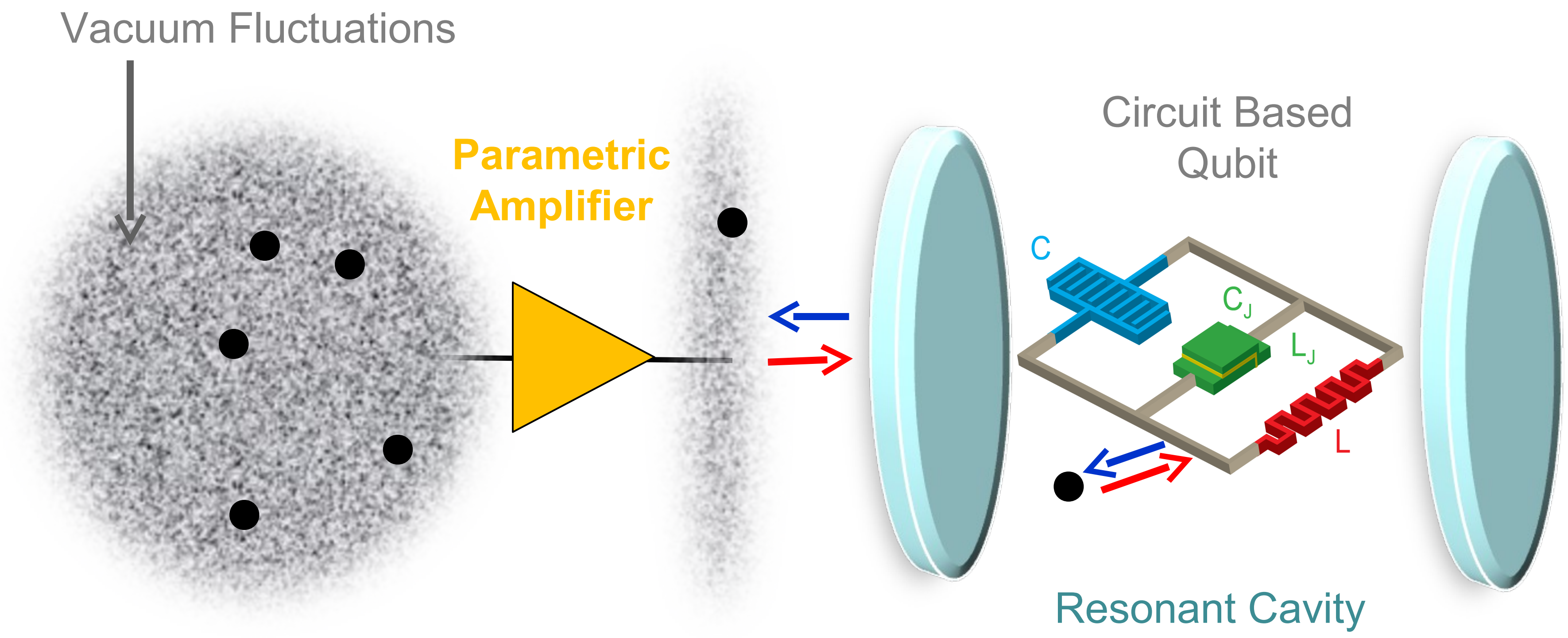
CAN WE OBSERVE THE "PHYSICAL" EFFECTS OF SQUEEZED VACUUM?



SUPPRESSION OF THE RADIATIVE DECAY OF ATOMIC COHERENCE IN SQUEEZED VACUUM

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

QUANTUM BATH ENGINEERING: SQUEEZING

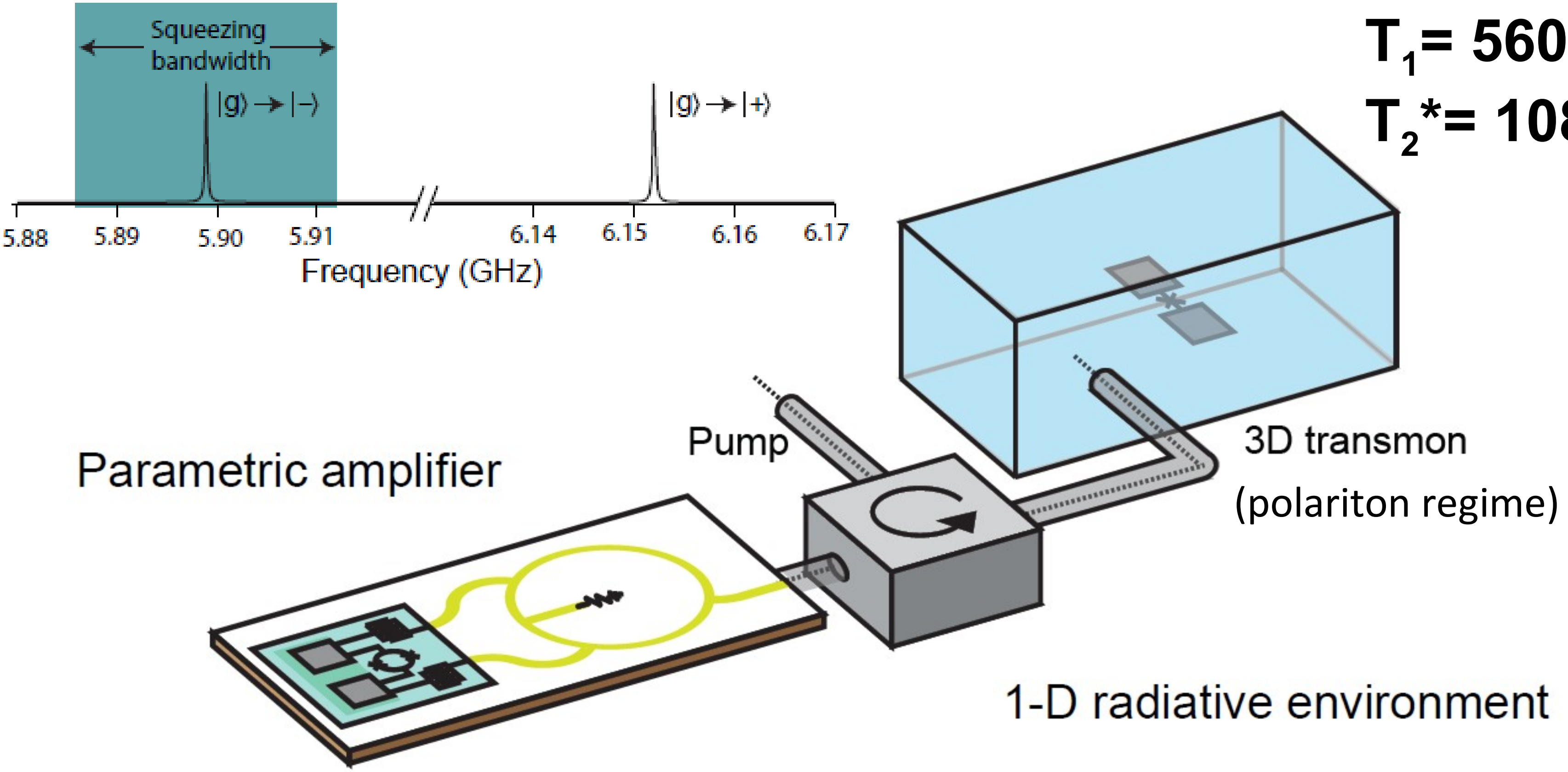


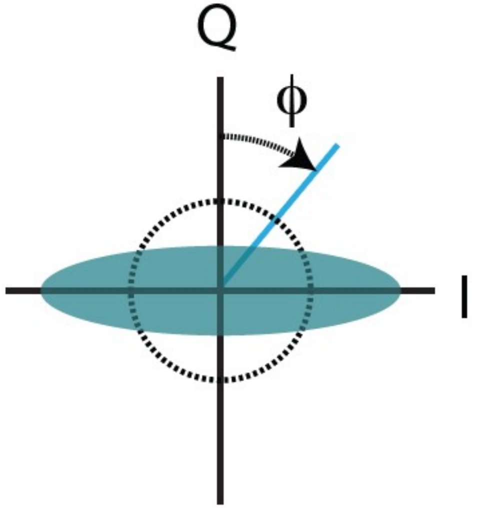
SQUEEZED LIGHT / MATTER INTERACTION MODIFIES TRANSVERSE/LONGITUDINAL DECAY

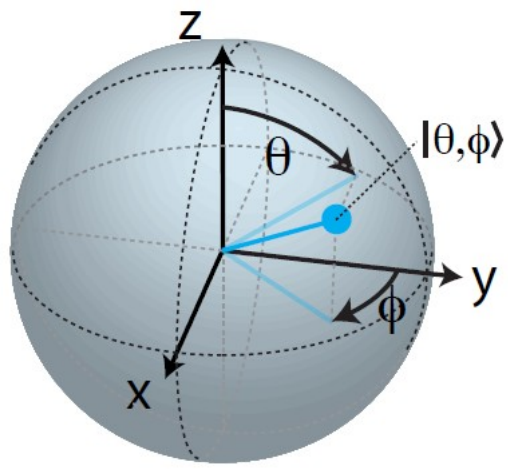
Slusher et al, PRL 1985
Treps et al, PRL 2002
Gardiner, PRL 1986

T_1= 560 ns

T_2*= 1080 ns







Squeezing with Josephson parametric amplifiers:

Castellanos-Beltran et al,
Nature Physics 2008

Beregeal et al, Nature 2010

Eichler et al, PRL 2011

SQUEEZING MOMENTS

N, M values:

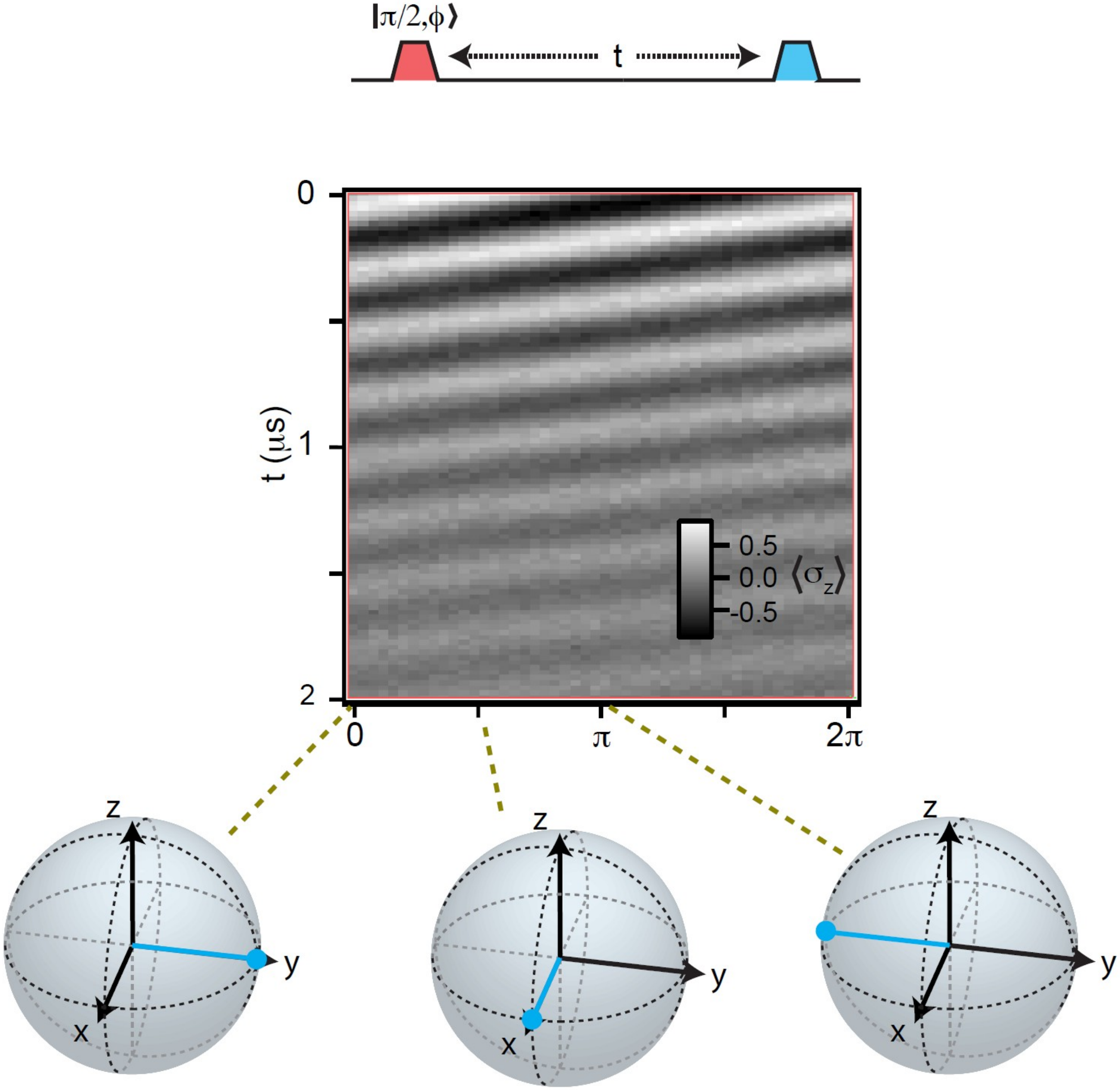
$$\langle a^\dagger(t+\tau)a(t)\rangle = N\delta(\tau)$$ → fluctuation ‘amplitude’

N, M values:

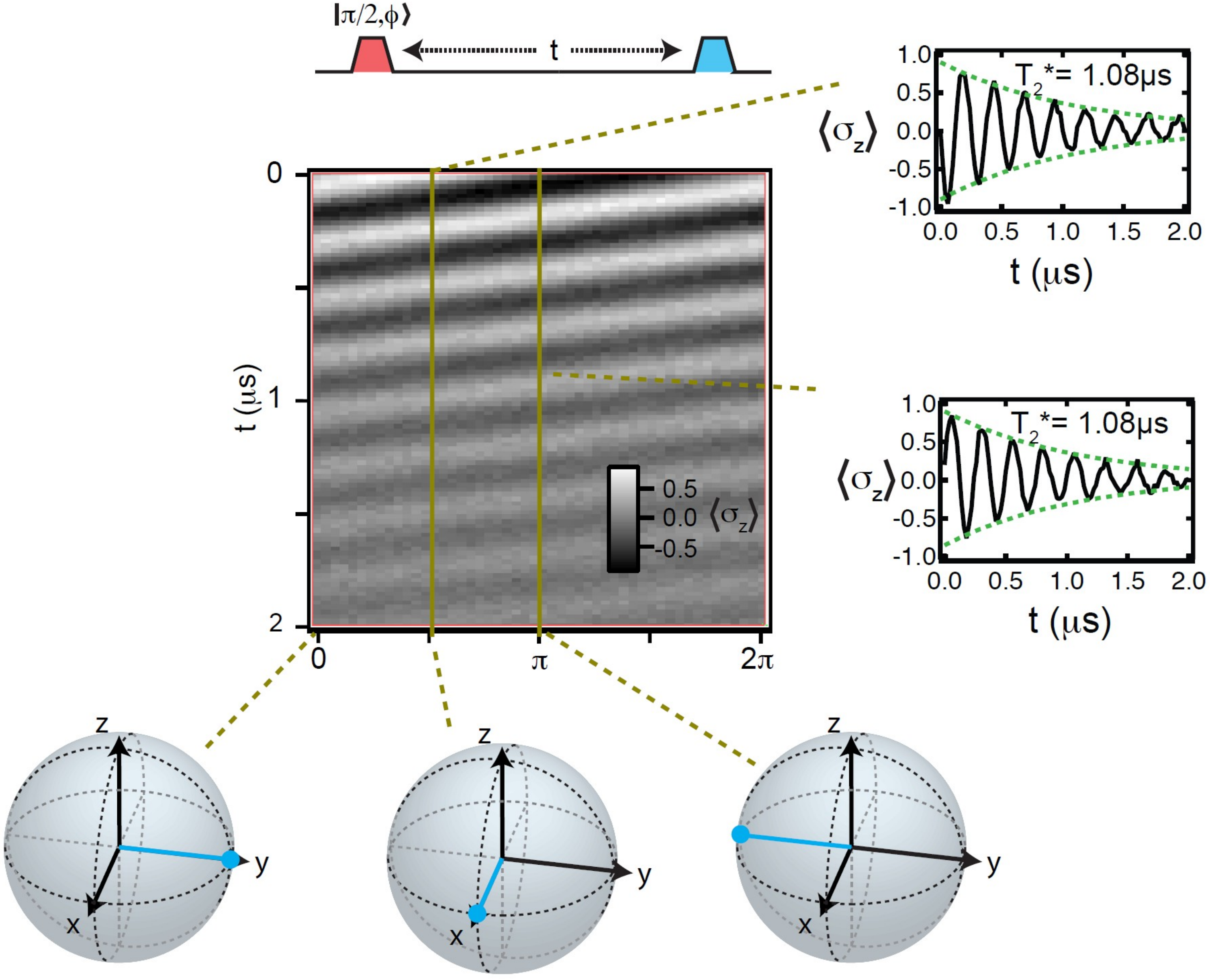
$$\langle a^\dagger(t+\tau)a(t)\rangle = N\delta(\tau)$$

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

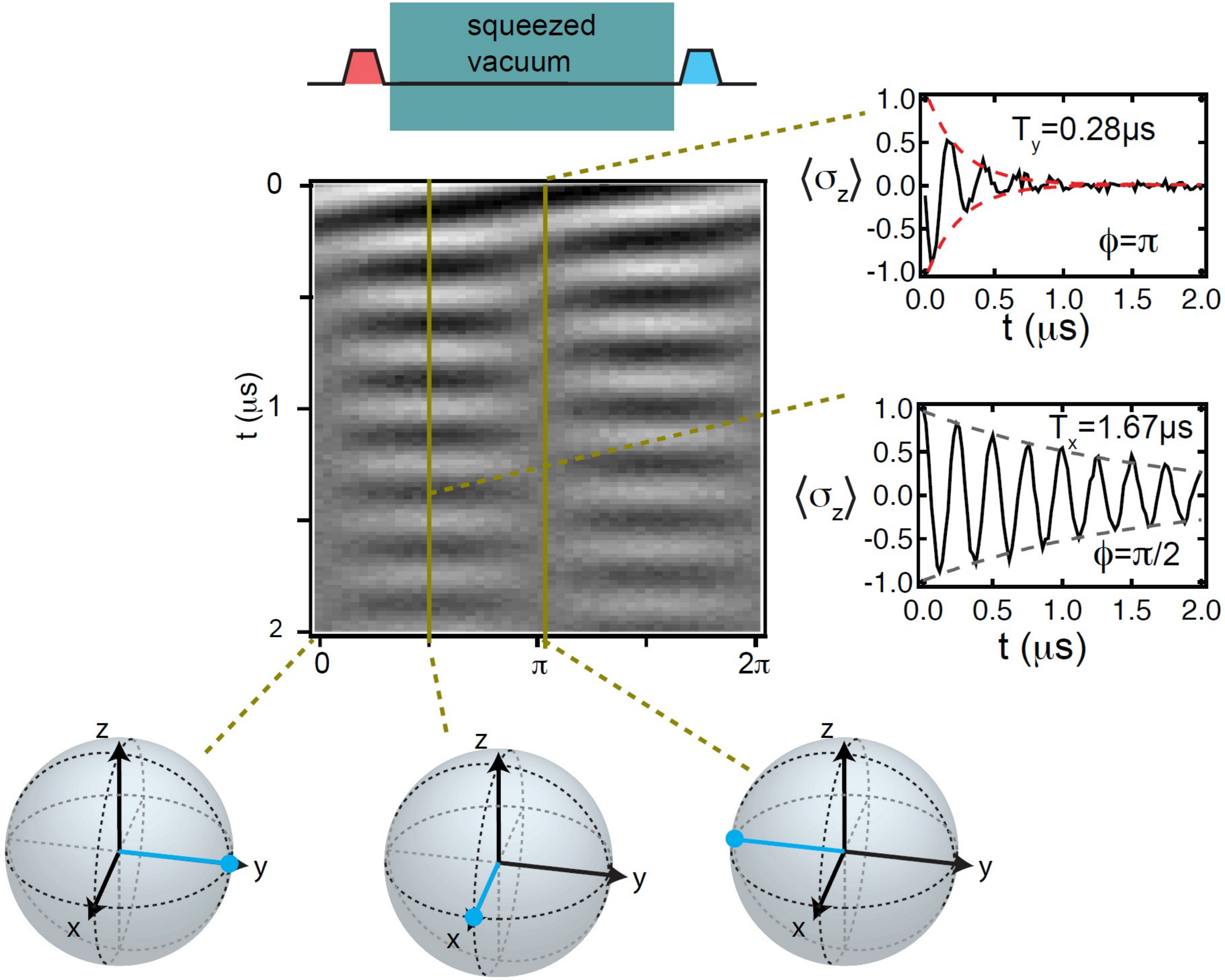
RAMSEY WITH GAUSSIAN FLUCTUATIONS



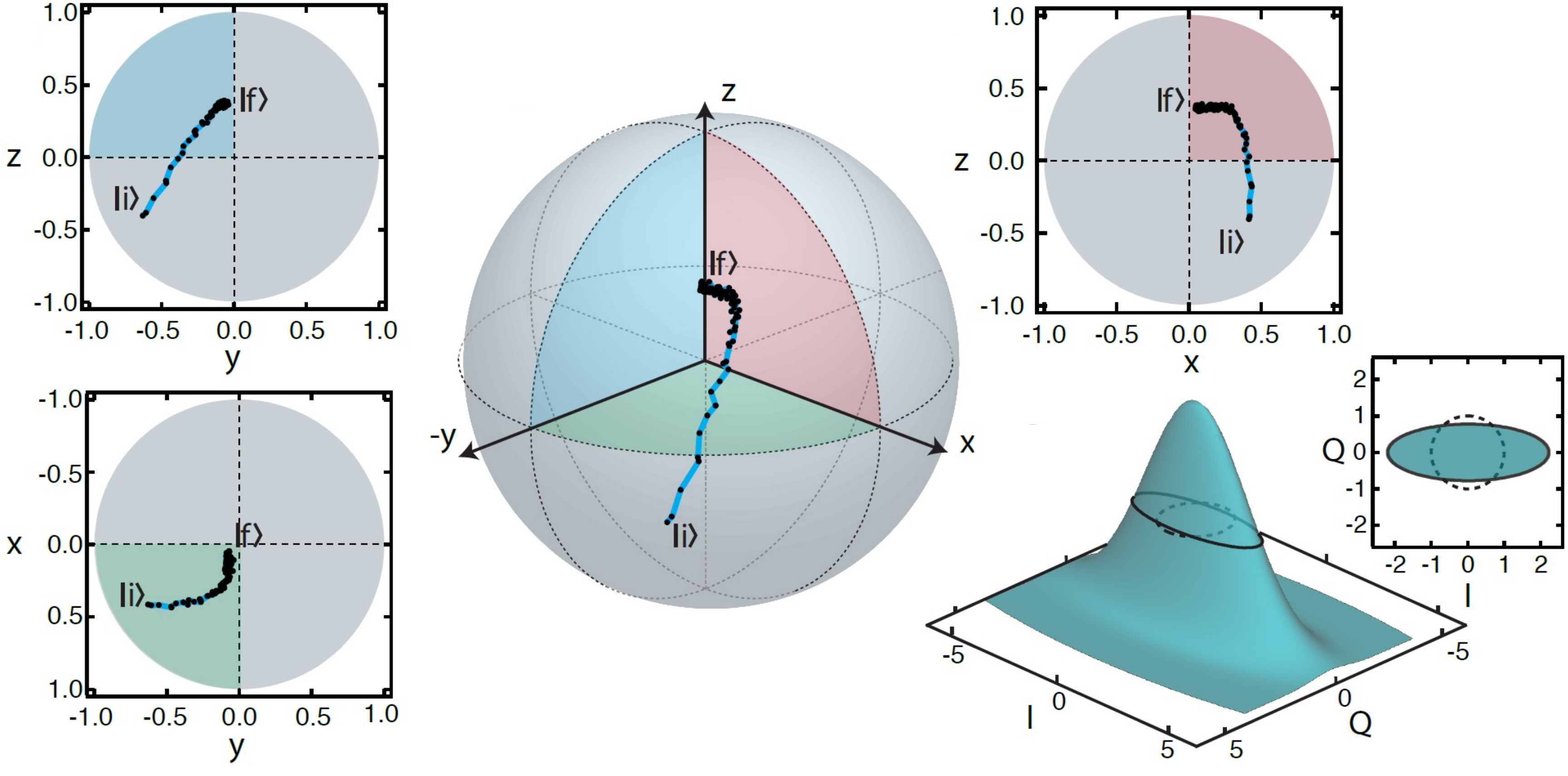
RAMSEY WITH GAUSSIAN FLUCTUATIONS



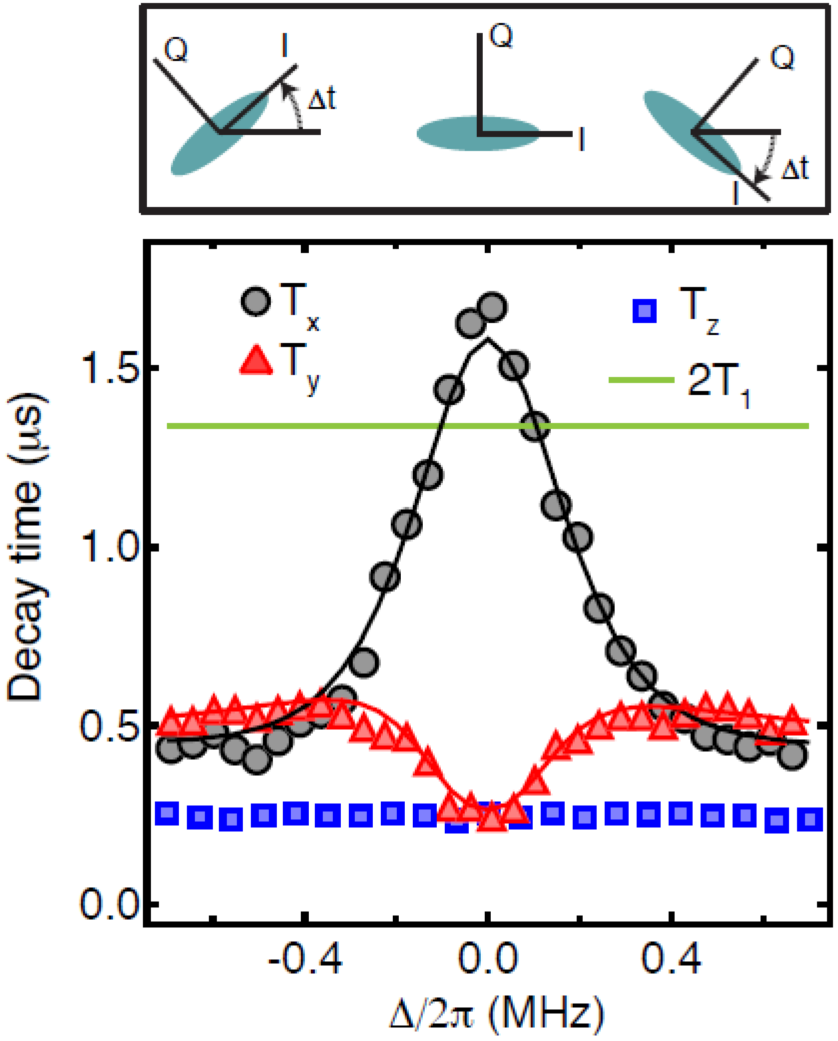
RAMSEY WITH SQUEEZED FLUCTUATIONS

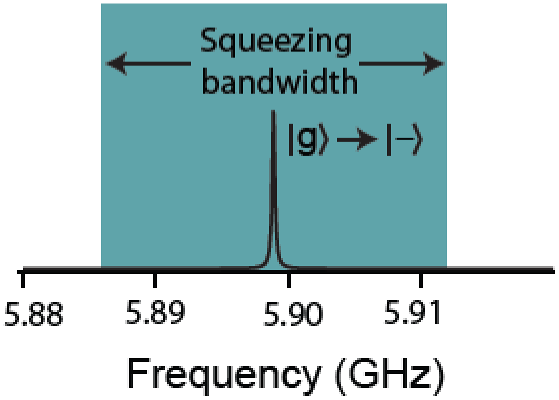


QUBIT ENABLED RECONSTRUCTION OF AN ITINERANT SQUEEZED STATE



ROTATING THE SQUEEZER

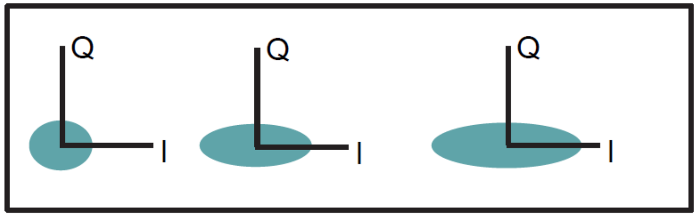


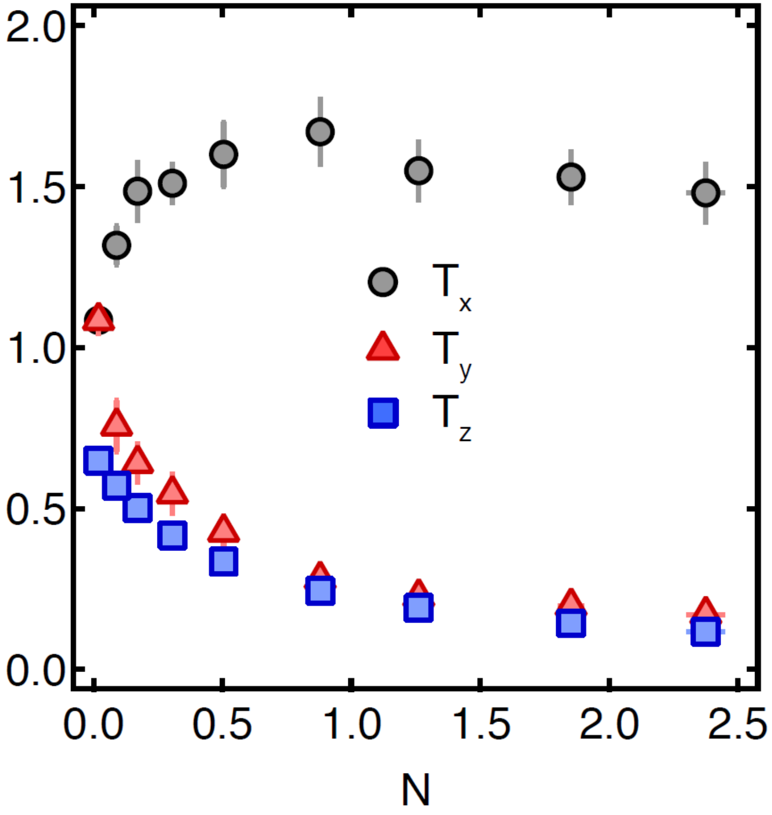


$T_2 > 2T_1$!

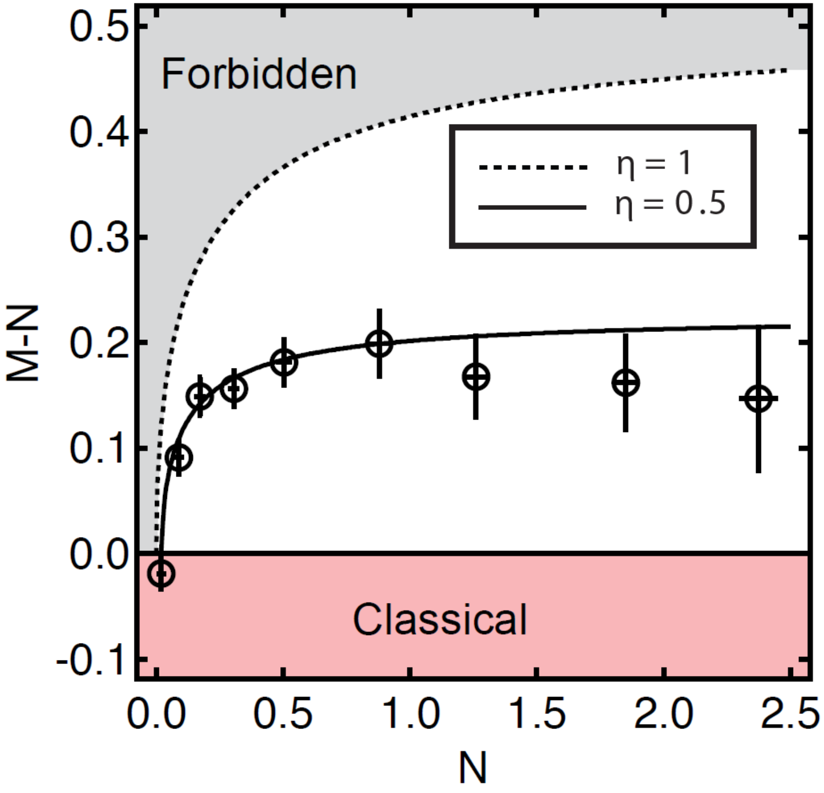
nonclassical light -
matter interaction

HOW EFFICIENT IS THE SQUEEZING?



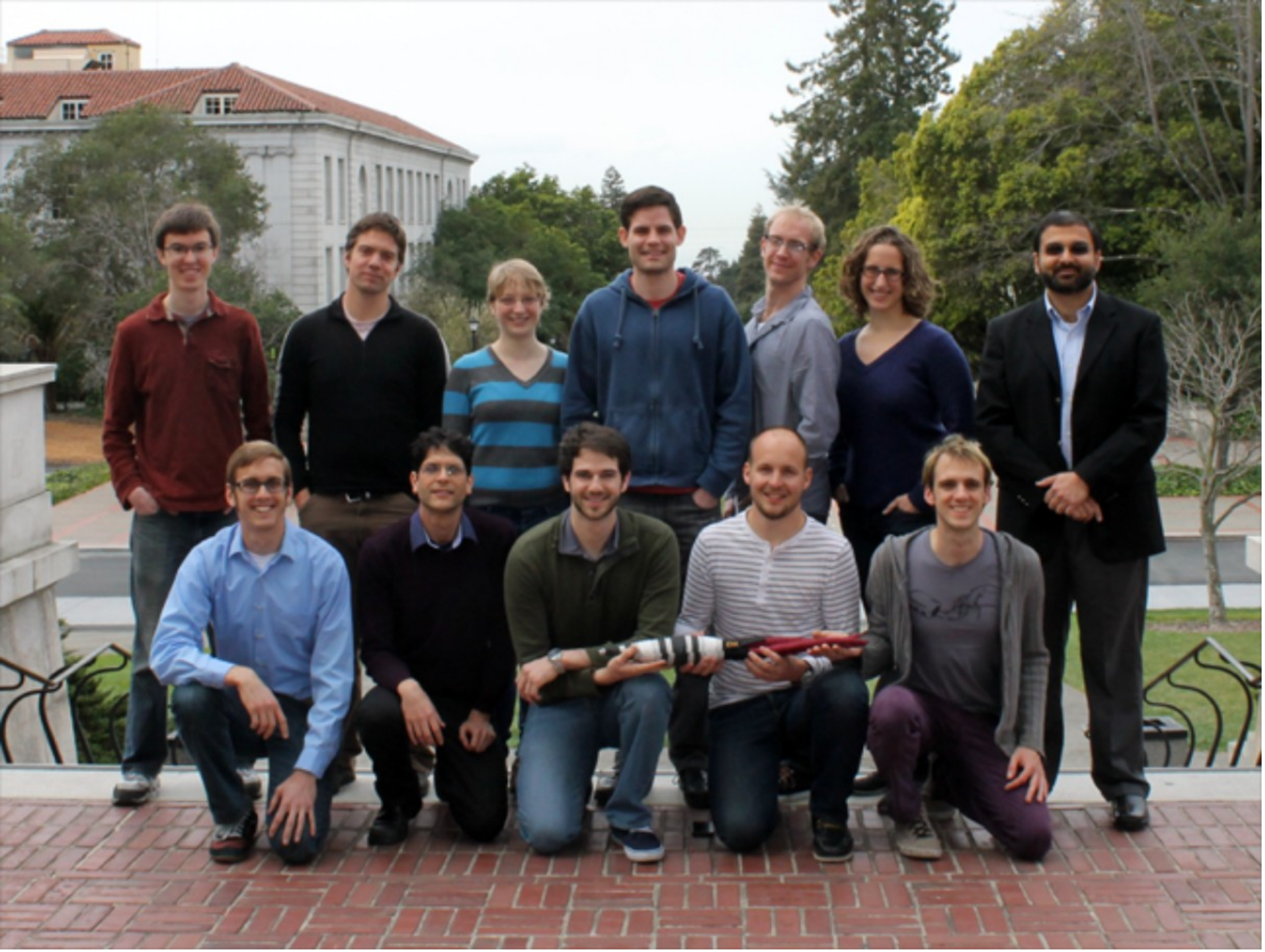


$$N \rightarrow \eta N$$
$$M \rightarrow \eta M$$



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



QNL

Dr. Kater Murch
Dr. Andrew Schmidt
Dr. Shay Hacohen-Gourgy
Dr. Nico Roch
Eli Levenson-Falk
Edward Henry
Chris Macklin
Natania Antler
Steven Weber
Andrew Eddins
Mollie Schwartz

Daniel Slichter (NIST)
Michael Hatridge (Yale)
Anirudh Narla (Yale)
Zlatko Minev (Yale)
Yu-Dong Sun
Ravi Naik (U. Chicago)
Dr. R. Vijay (TIFR)
Seita Onishi (UC Berkeley)
Dr. Ofer Naaman (Grumann)

the Hertz FOUNDATION
freedom to innovate

QUEST

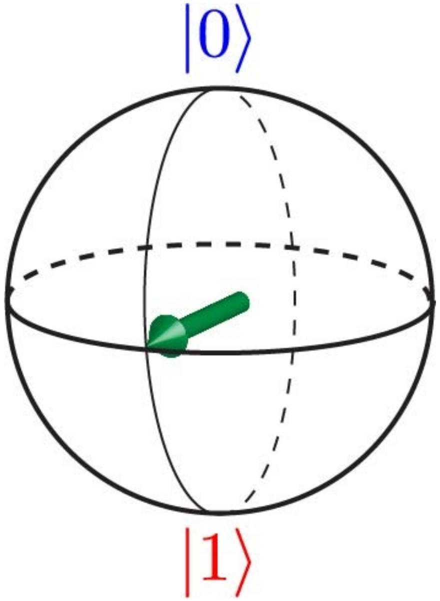
YFA

DARPA

IARPA

NSF

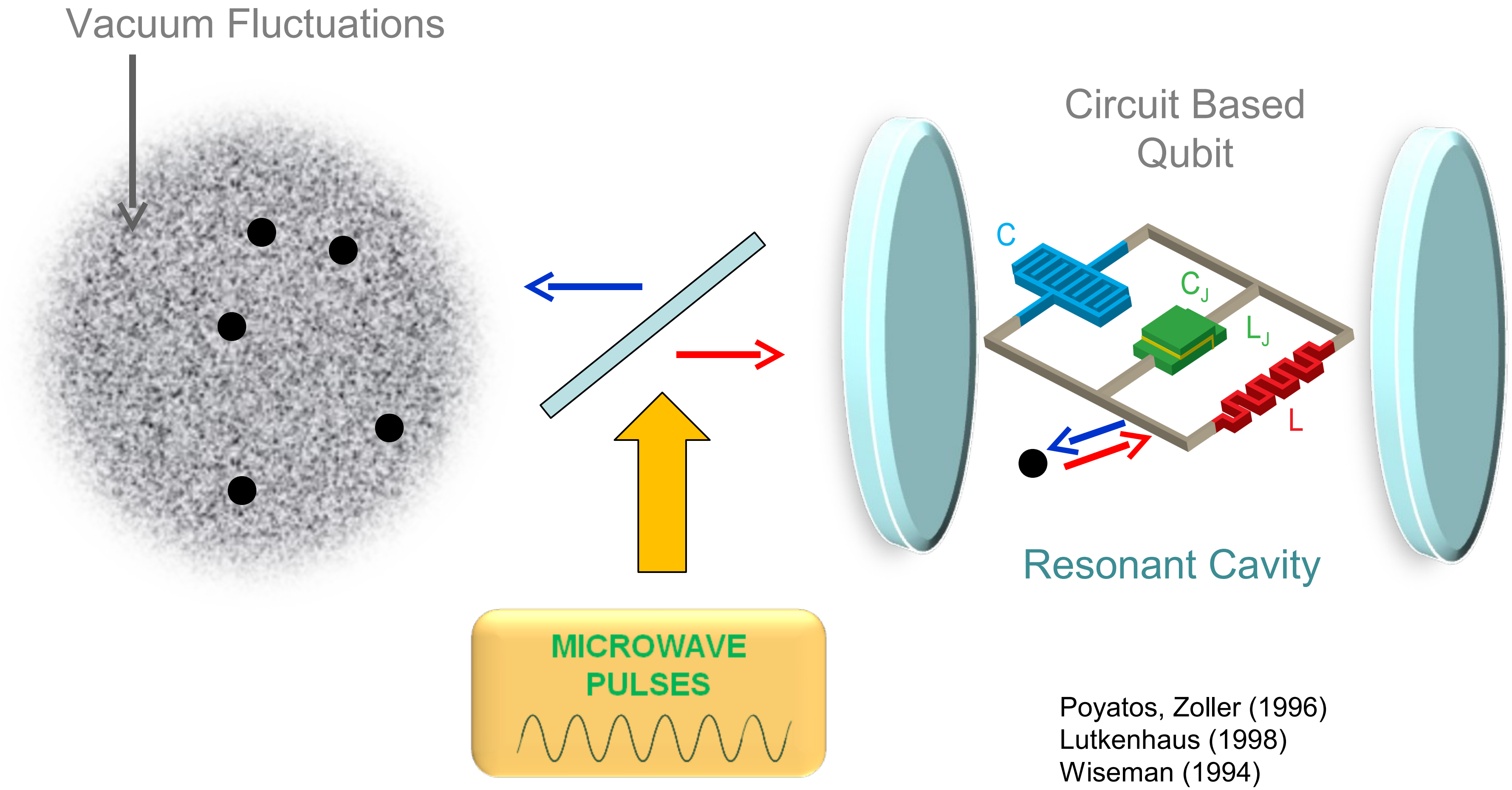
HOW DO WE STABILIZE A SUPERPOSITION ?



CAVITY ASSISTED QUANTUM BATH ENGINEERING

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

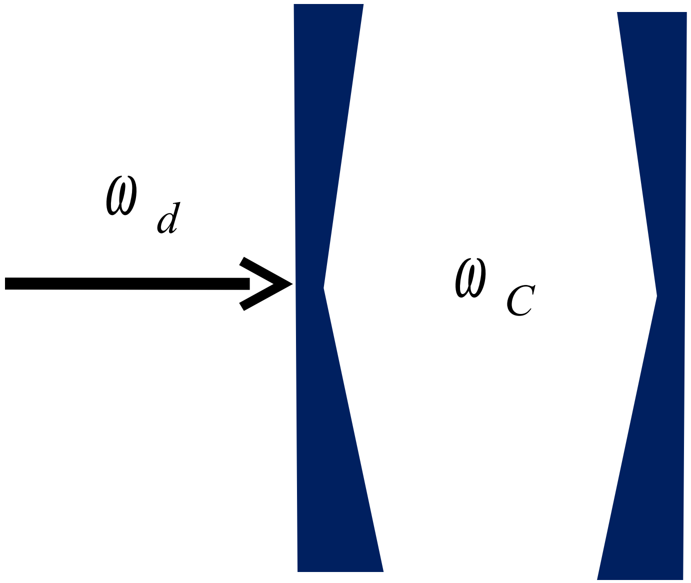
QUANTUM BATH ENGINEERING: COOLING

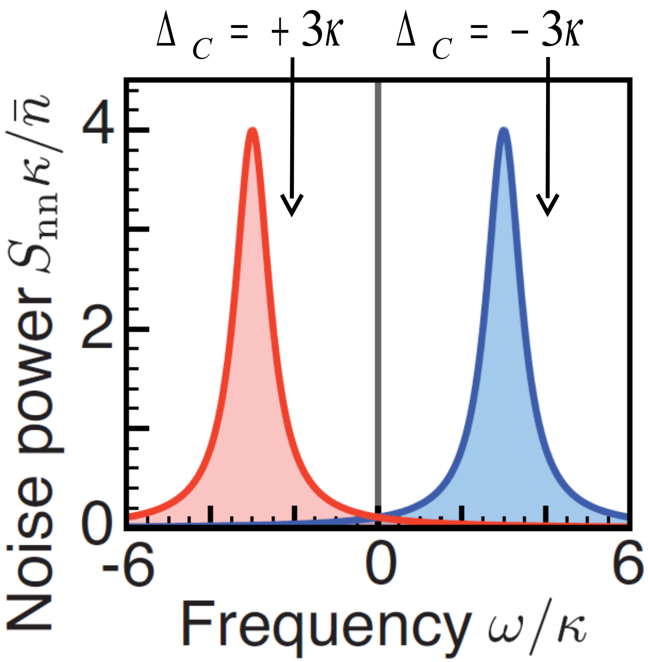


AUTONOMOUSLY COOL TO ANY ARBITRARY STATE ON THE BLOCH SPHERE

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

QUANTUM RESERVOIR:
SHOT NOISE IN DRIVEN CAVITY





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

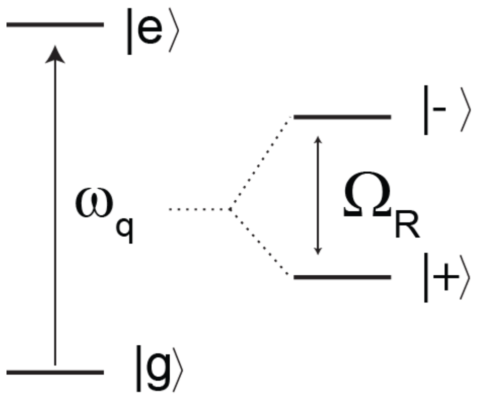
$$S_{nn}[\omega] = \frac{\bar{n}\cdot\kappa}{(\kappa/2)^2+(\omega+\Delta_c)^2}$$

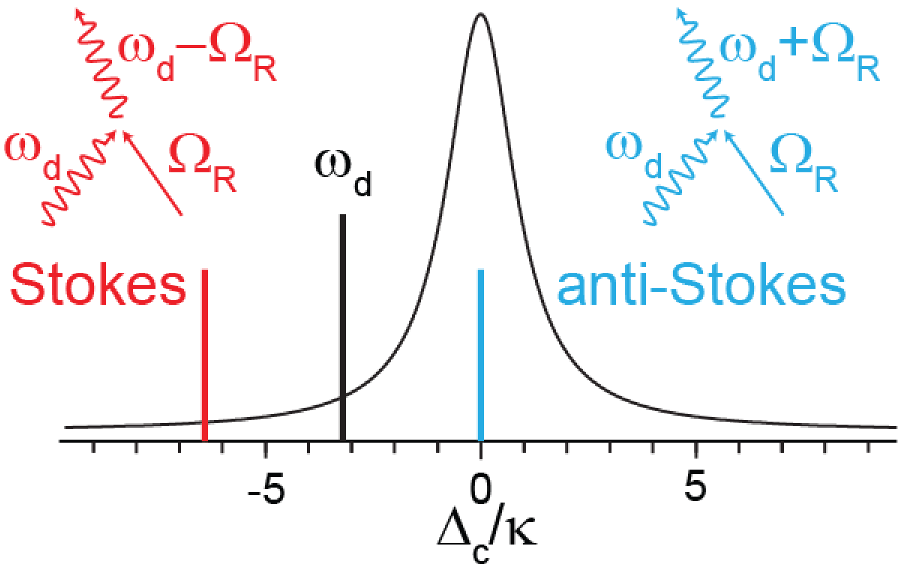
$\Delta_C > 0$: Noise peaks at $\omega < 0$
Cavity emits → heating

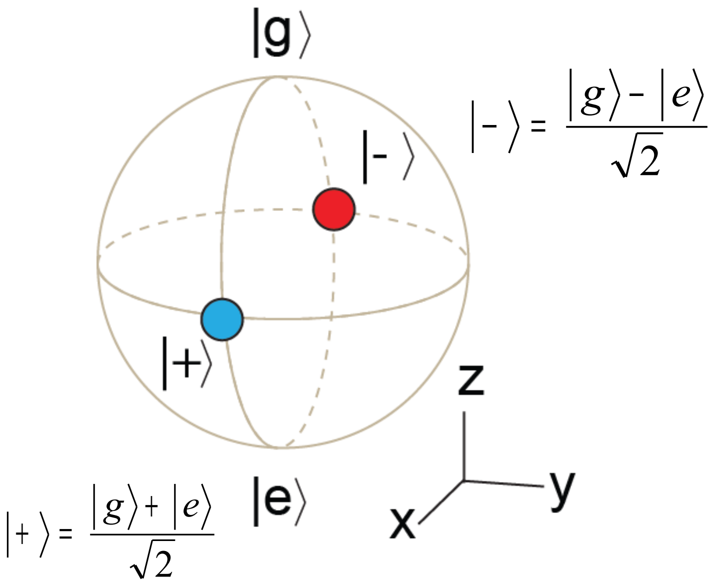
$\Delta_C < 0$: Noise peaks at $\omega > 0$
Cavity absorbs → cooling

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

CAVITY ASSISTED COOLING





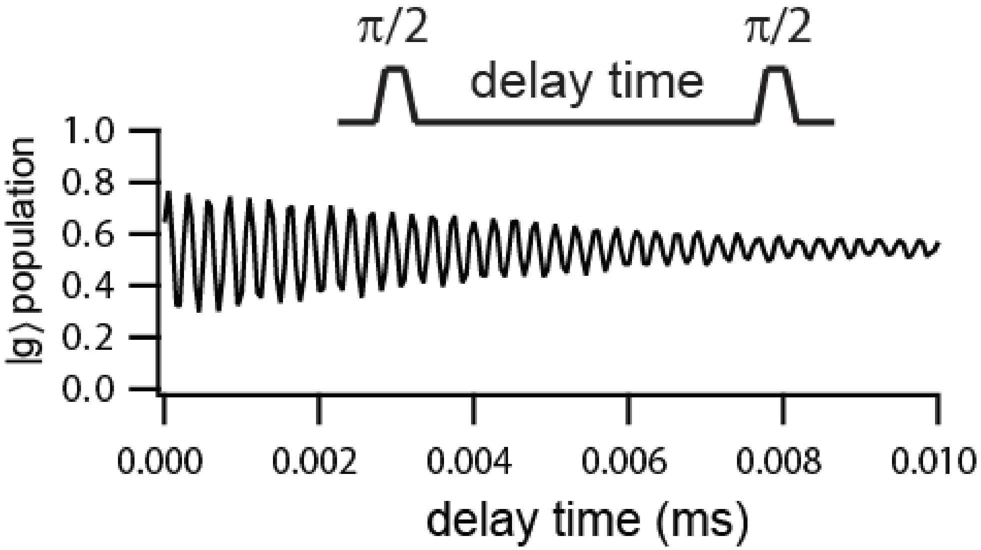


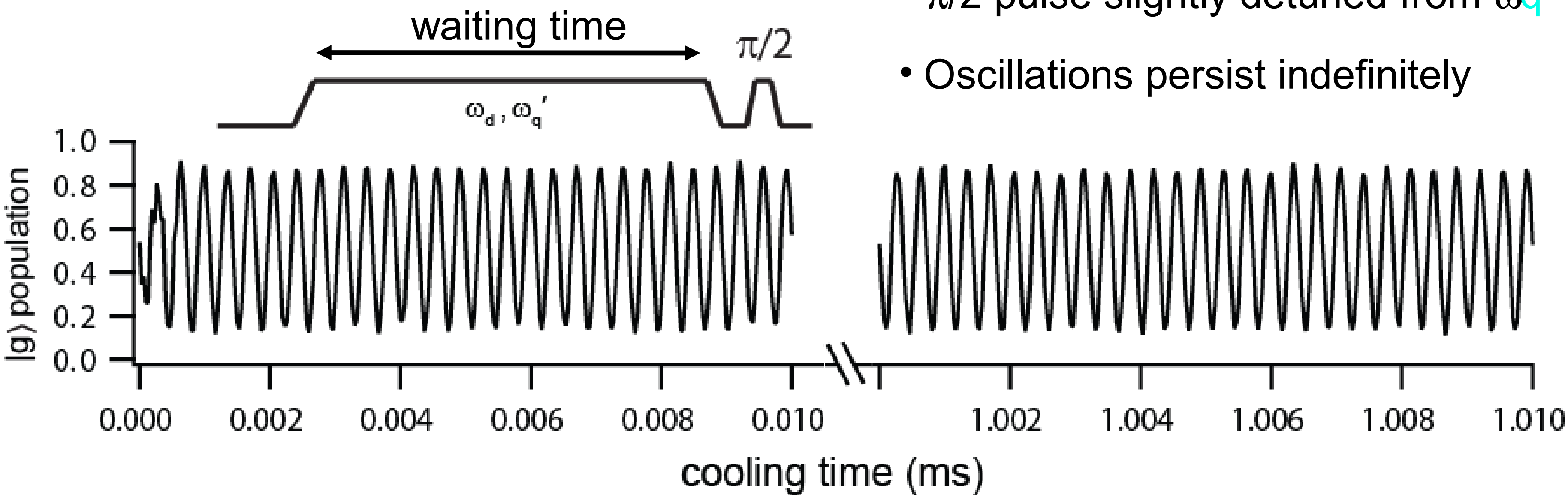
$$|-\rangle = \frac{|g\rangle - |e\rangle}{\sqrt{2}}$$

$$|+\rangle = \frac{|g\rangle + |e\rangle}{\sqrt{2}}$$

- 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 |+>

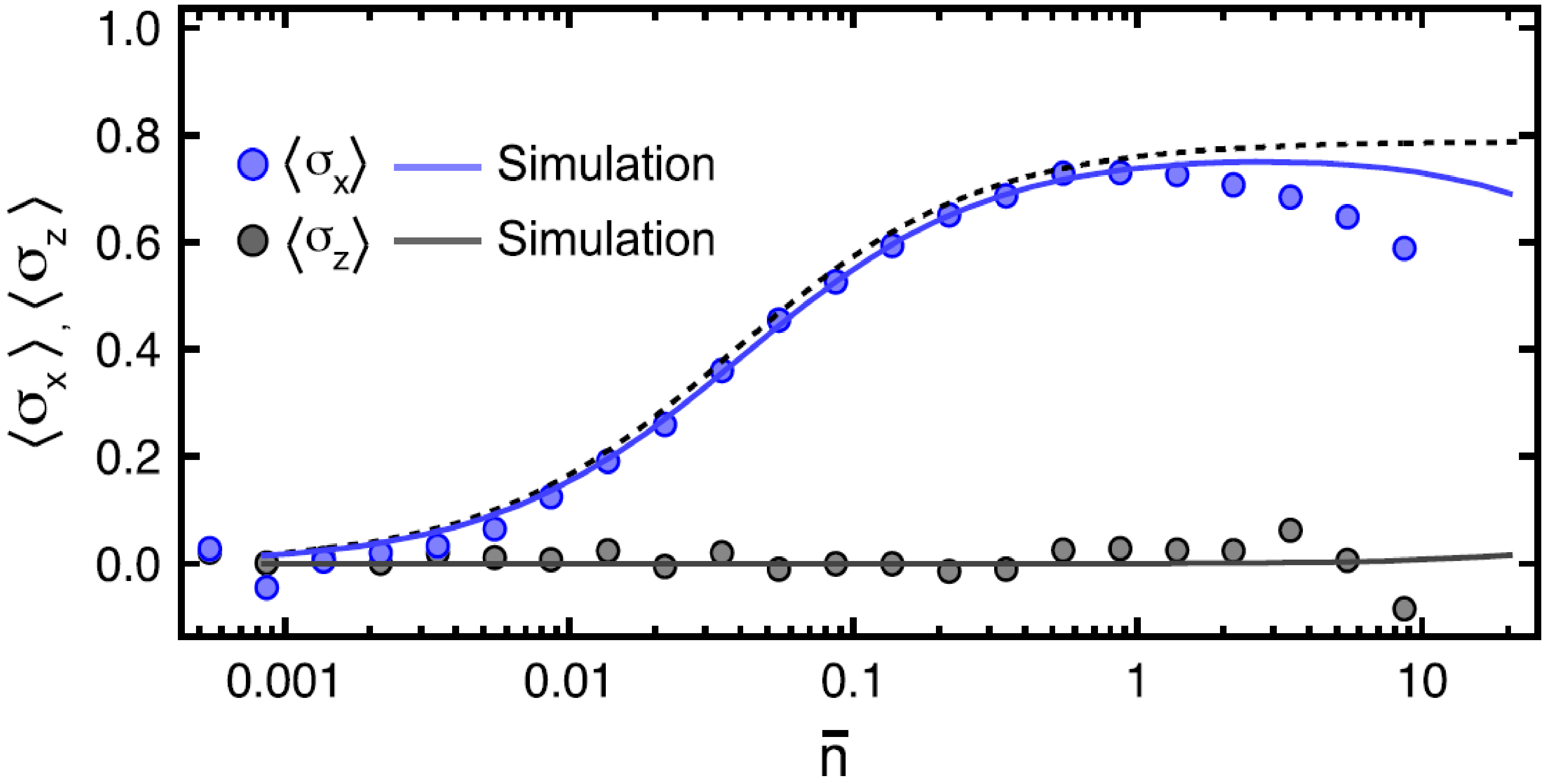
BUILDING UP COHERENCE





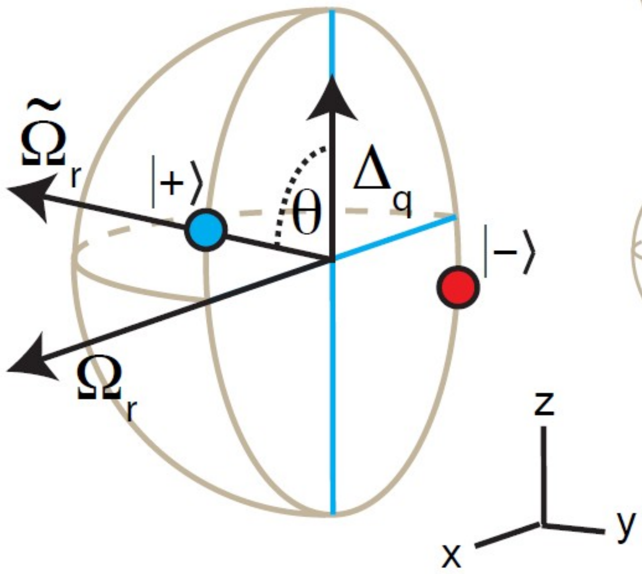
- Conventional Ramsey experiment
  - T_2 = 4.9 μs ; 40% contrast
- Apply tone at qubit frequency ω_q' & ω_d ($\Delta_C = -\Omega_R$)
- Cool for a variable cooling time
- π/2 pulse slightly detuned from ω_q'
- Oscillations persist indefinitely

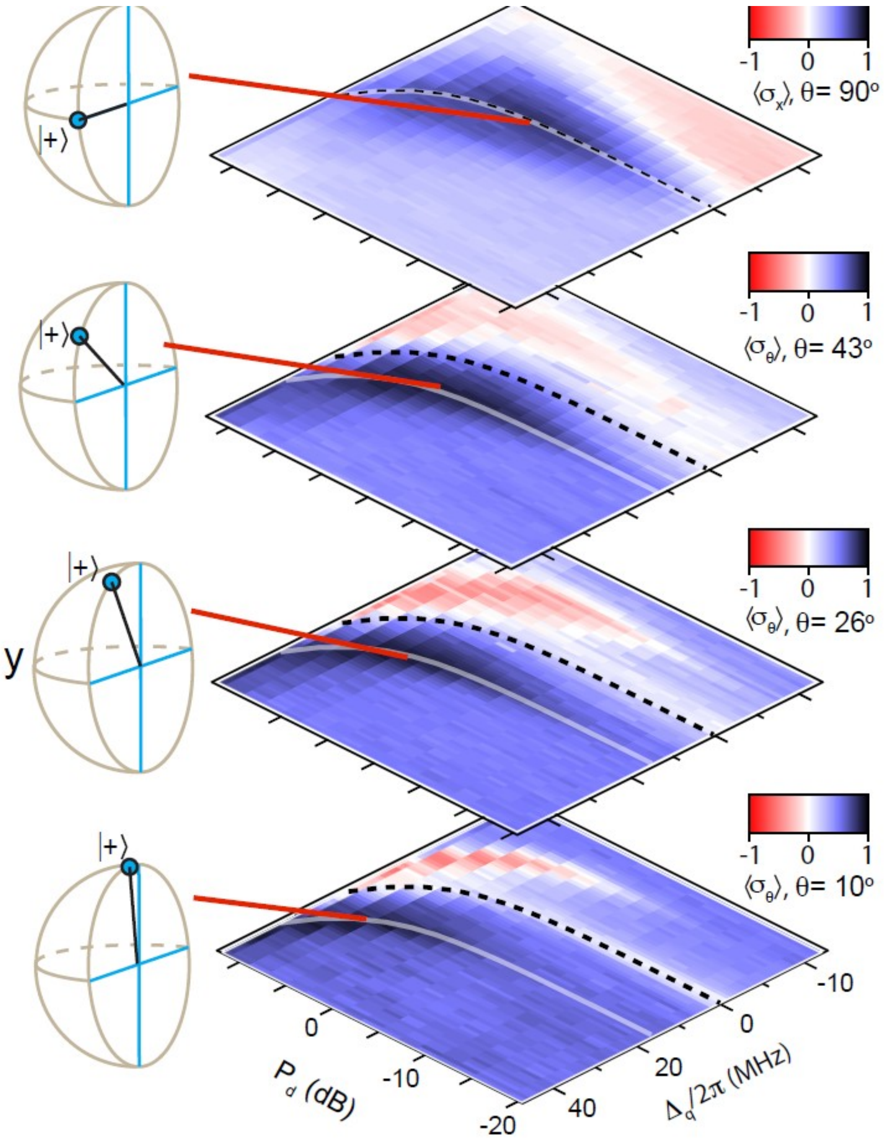
TOMOGRAPHY: RESONANT RABI DRIVE



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

COOLING TO ARBITRARY LATITUDES





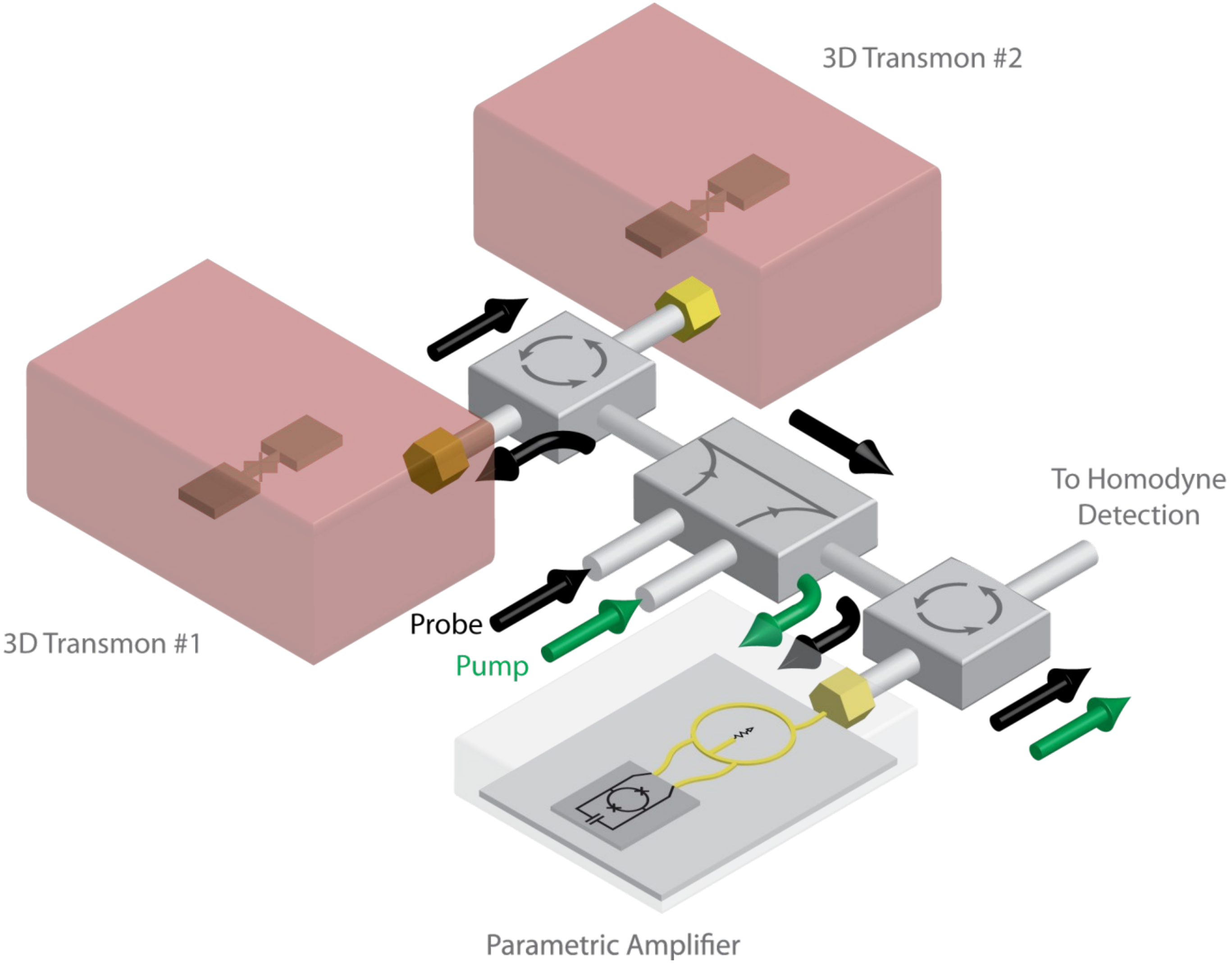
Optimal cooling is now for

$$-\Delta_c = \tilde{\Omega}_R = \sqrt{\Omega_R^2 + \Delta_q'^2}$$

REMOTE ENTANGLEMENT BY MEASUREMENT

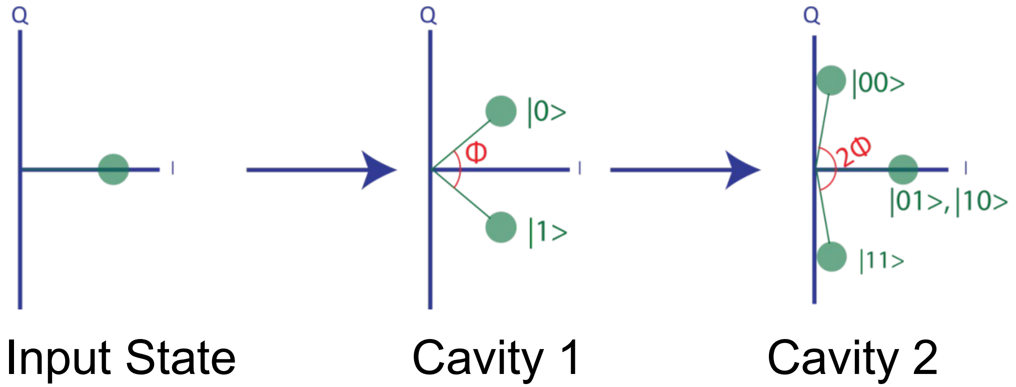
(first steps)

“BOUNCE-BOUNCE” SETUP

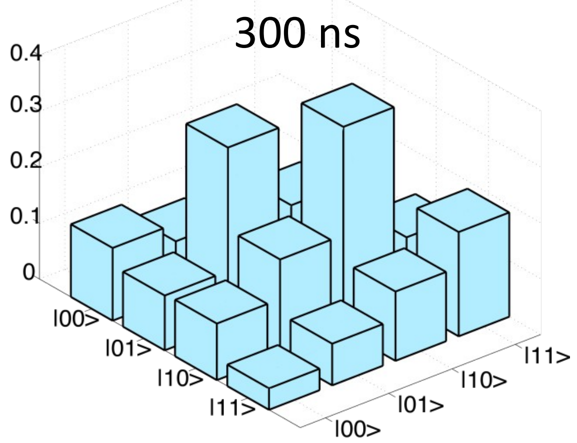


Kerkhoff, Bouten, Silberfarb and Mabuchi, *PRA* **79**, 024305

2 QUBIT ENTANGLEMENT VIA MEASUREMENT



$\overline{n}$ ~ 0.6



Width sets p_{ent}