CONTINUOUS MONITORING OF A SUPERCONDUCTING QUBIT

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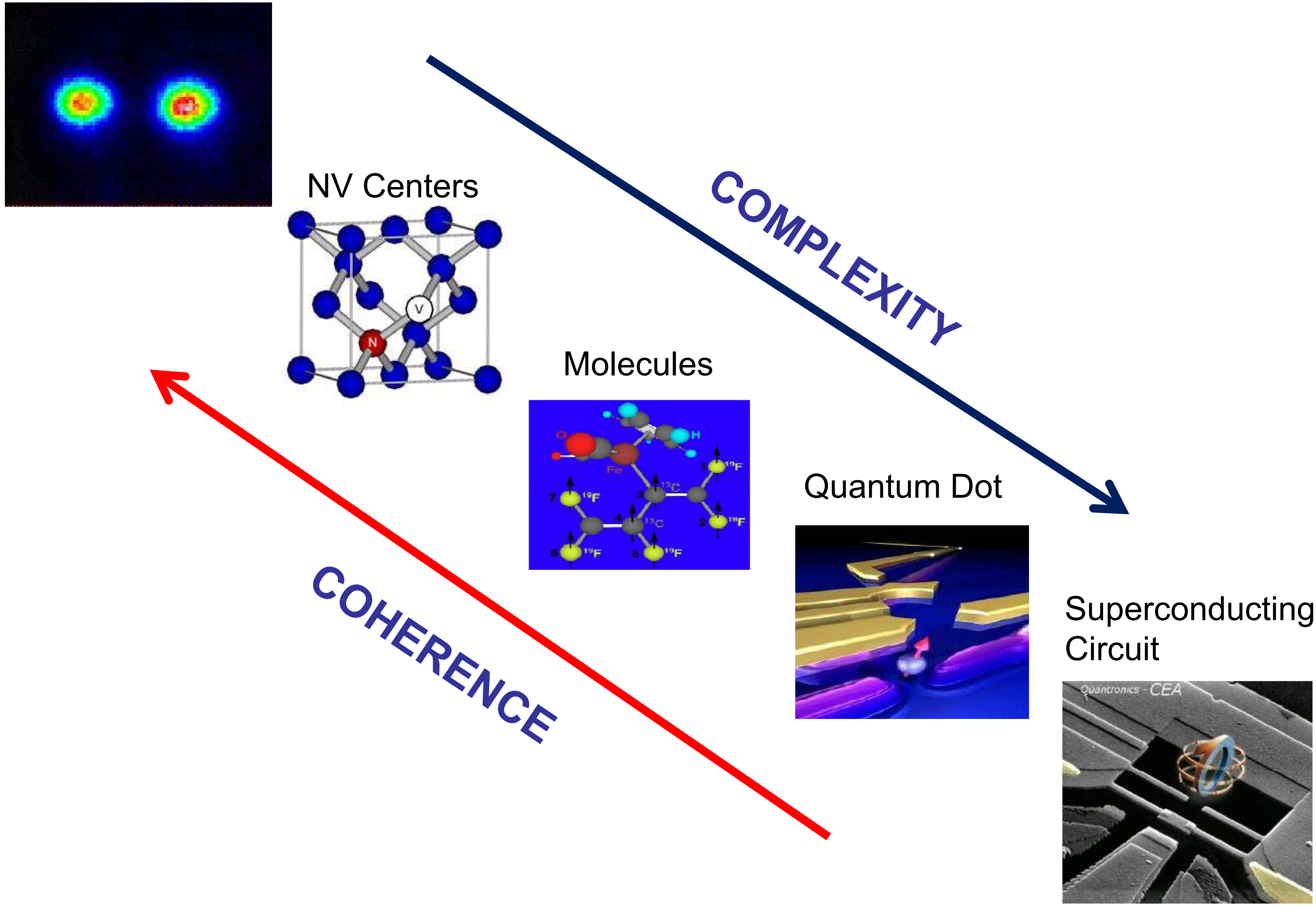
Materials Sciences Division, LBNL

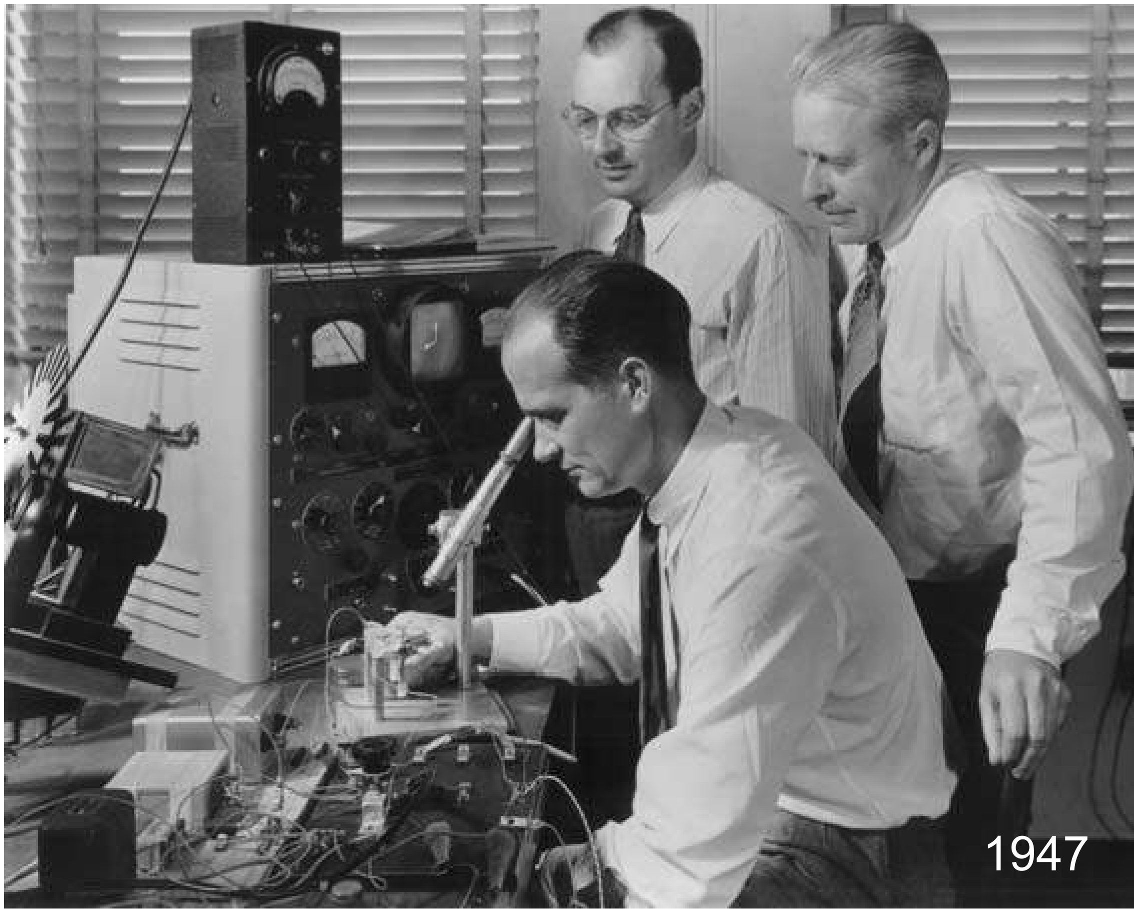
Collège de France Seminar
May 31, 2011

United by our desire to implement quantum machines…

QUANTUM COHERENCE



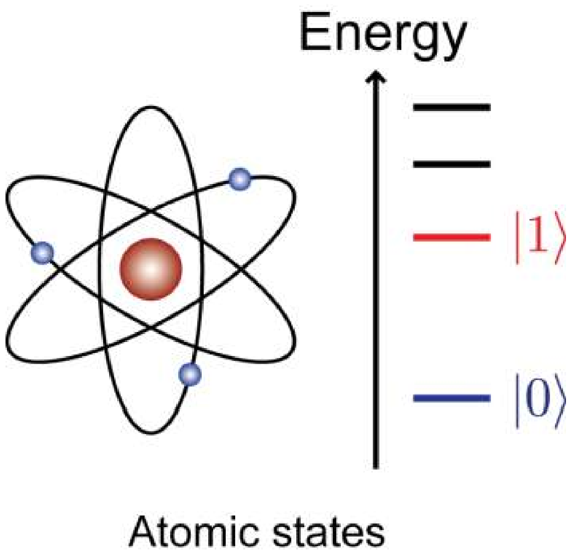
AN INDUSTRY BUILT ON SAND…



Bardeen, Brattain, Shockley

1956 Nobel Prize

HOW TO MAKE A CIRCUIT QUANTUM?

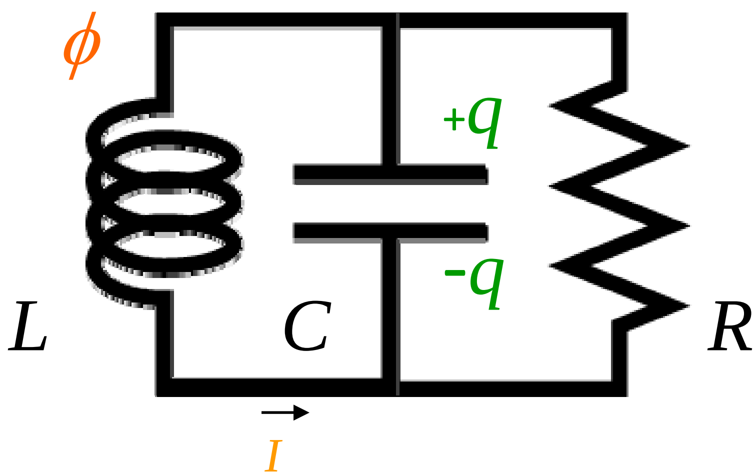


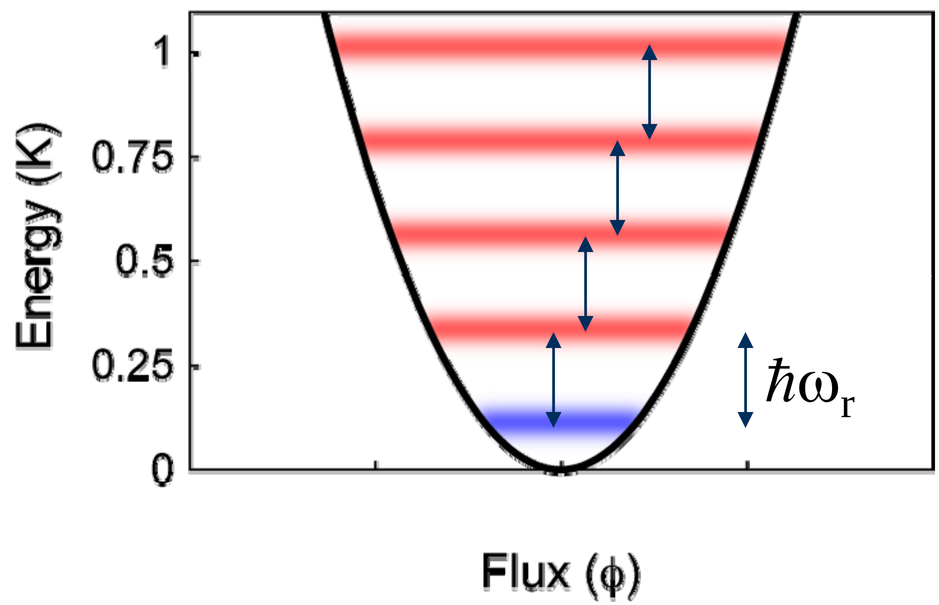
Atom

Electrical Circuit

QUANTUM LC OSCILLATOR

$$\omega_r = \frac{1}{\sqrt{LC}}$$





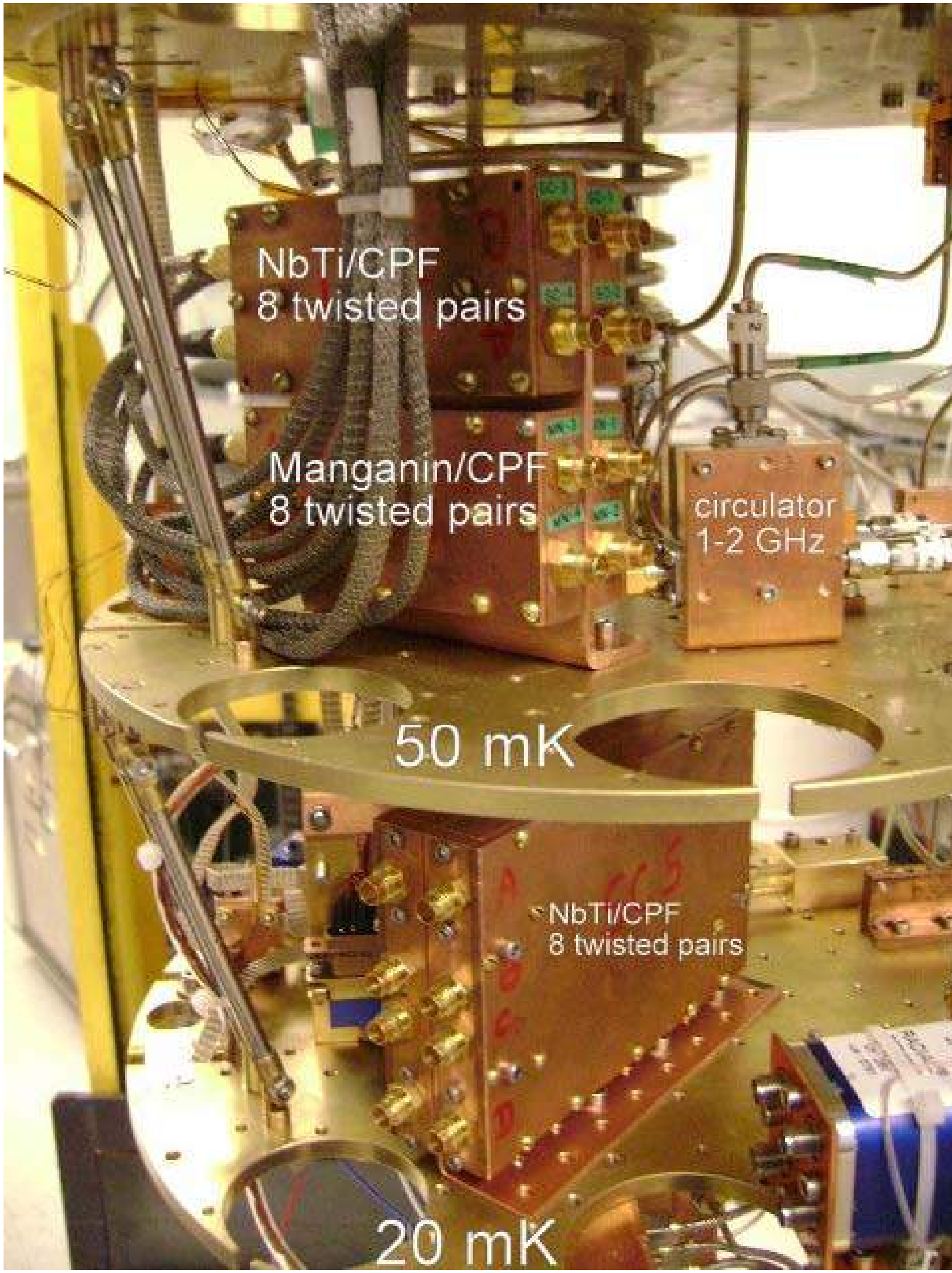
$$[\phi, q] = i\hbar$$

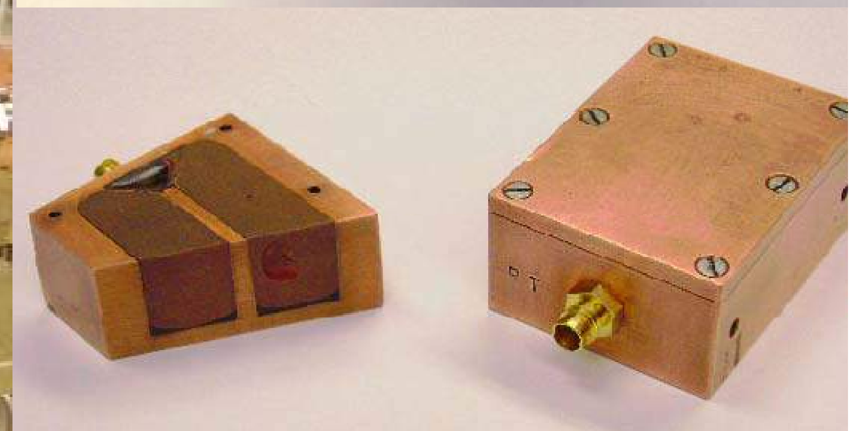
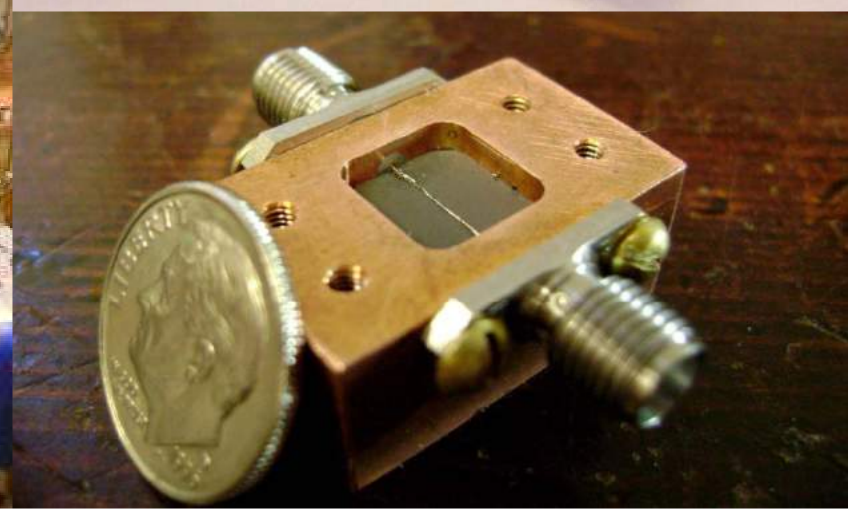
$$\phi = LI$$

$$q = CV$$

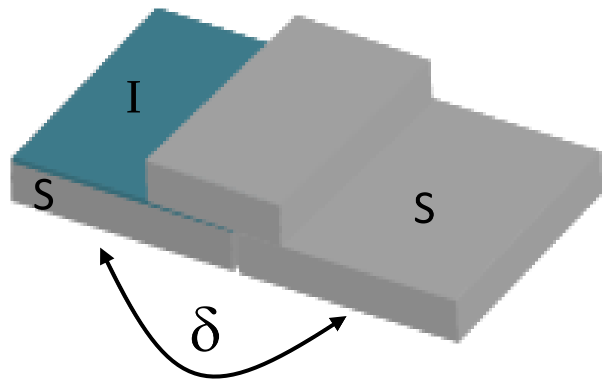
$$k_B T \ll \hbar\omega_r$$

25 mK 5 GHz ~ 250 mK


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

JOSEPHSON JUNCTION:
"LOSS-LESS" NONLINEAR INDUCTOR



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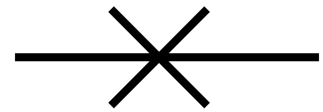
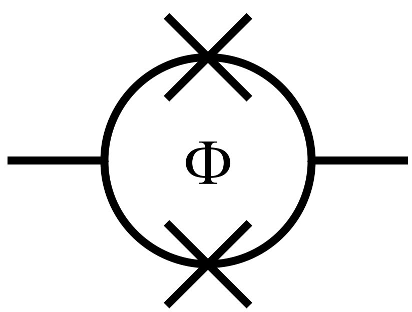


$$L_J = \frac{\hbar}{2eI_0 \cos\delta} \equiv \frac{L_{J0}}{\cos\delta}$$

$$I = I_0 \sin\delta$$

$$V = \frac{\hbar}{2e}\frac{\partial\delta}{\partial t}$$

SQUID:



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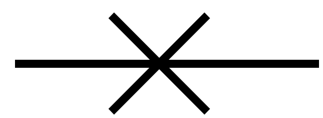
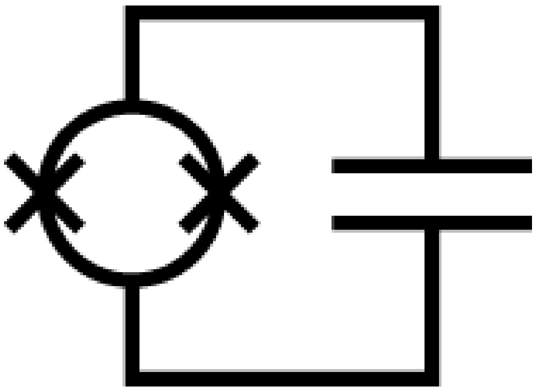


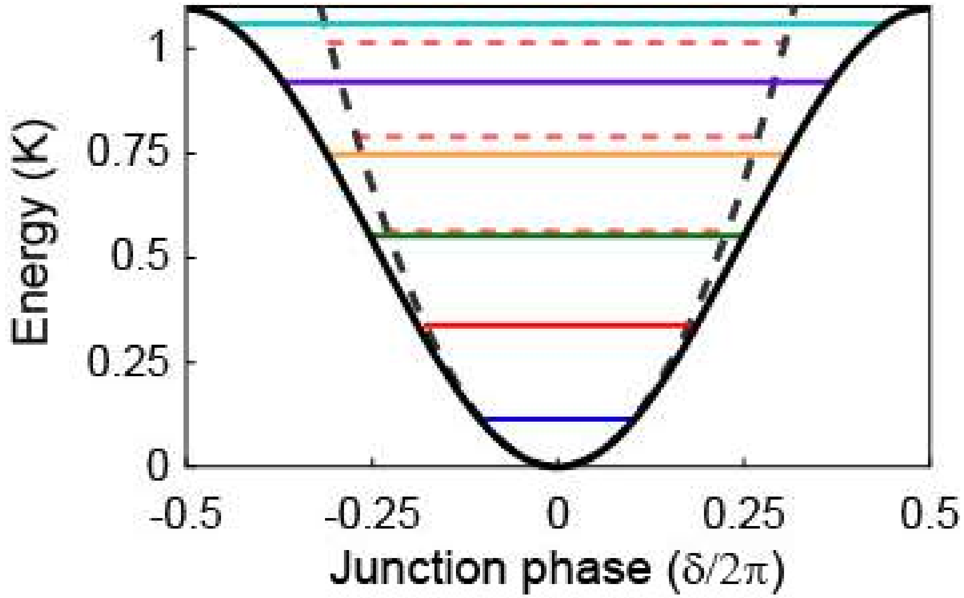
$L_J(\Phi)$

Flux tunable
Nonlinear
Inductor

SUPERCONDUCTING TRANSMON QUBIT



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

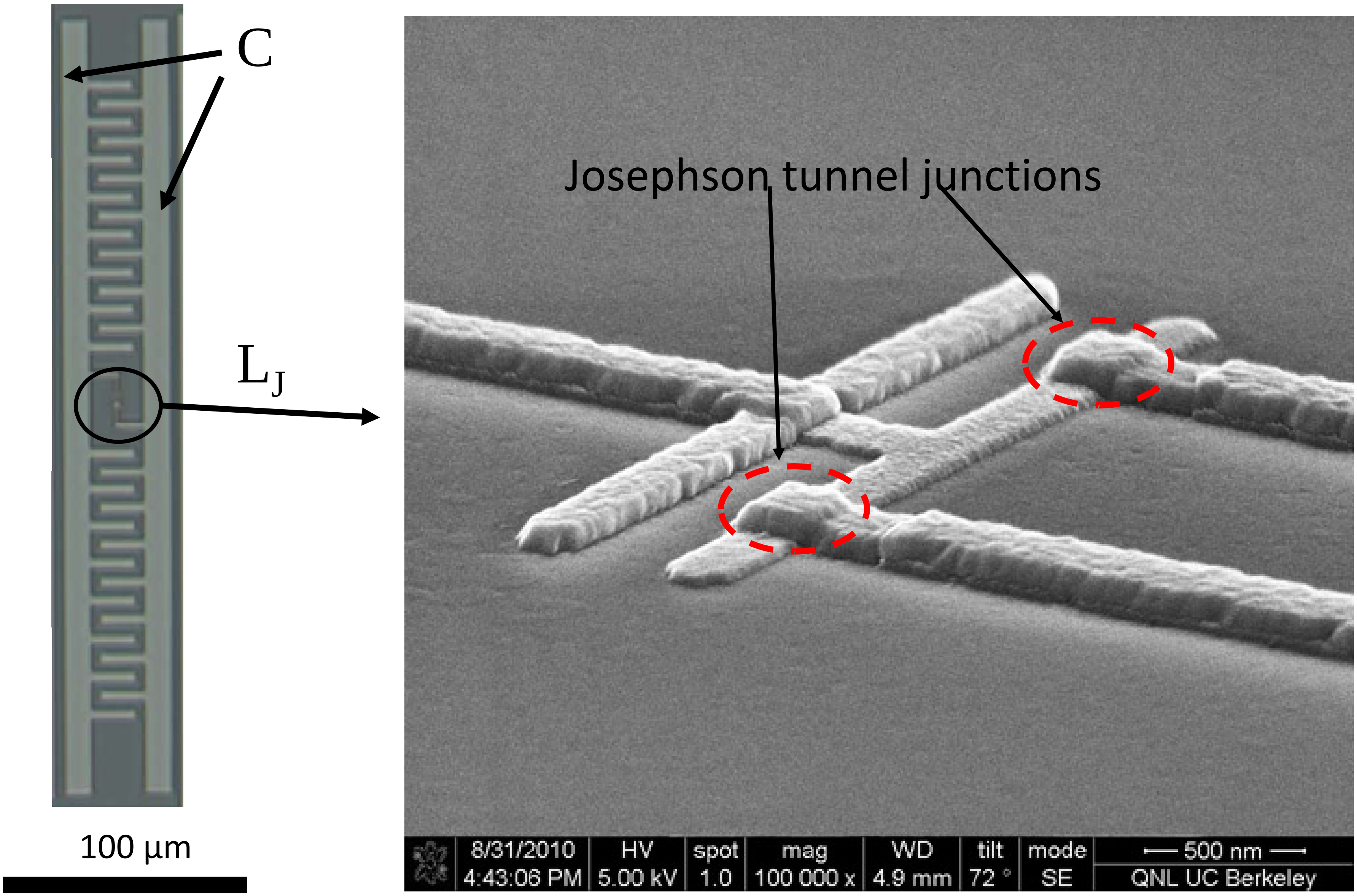


$$\omega_{01} \simeq \frac{1}{\sqrt{L_J C}}$$

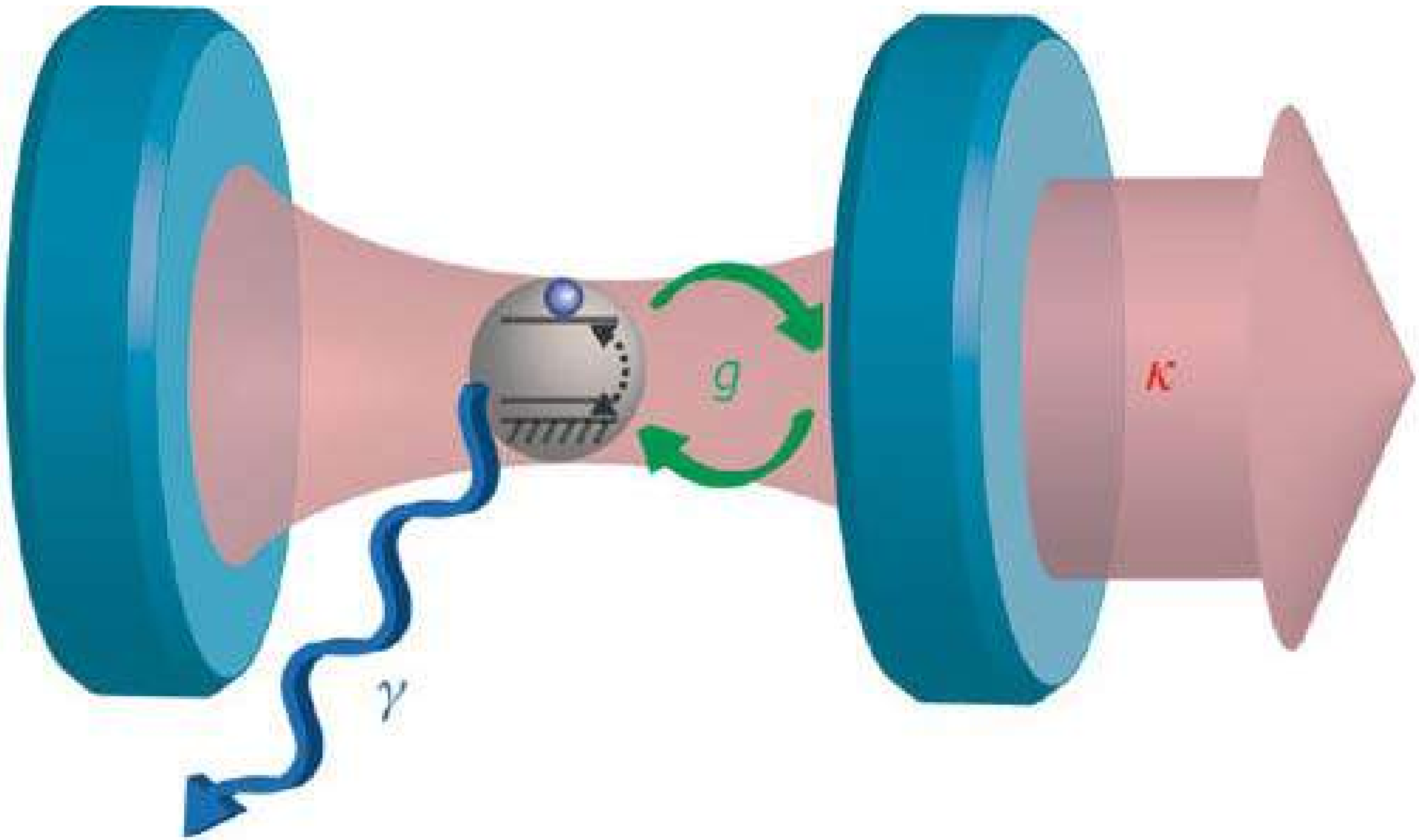
$$\omega_{01} \neq \omega_{12}$$

- Tunable qubit frequency
- Sufficient anharmonicity

TRANSMON QUBIT

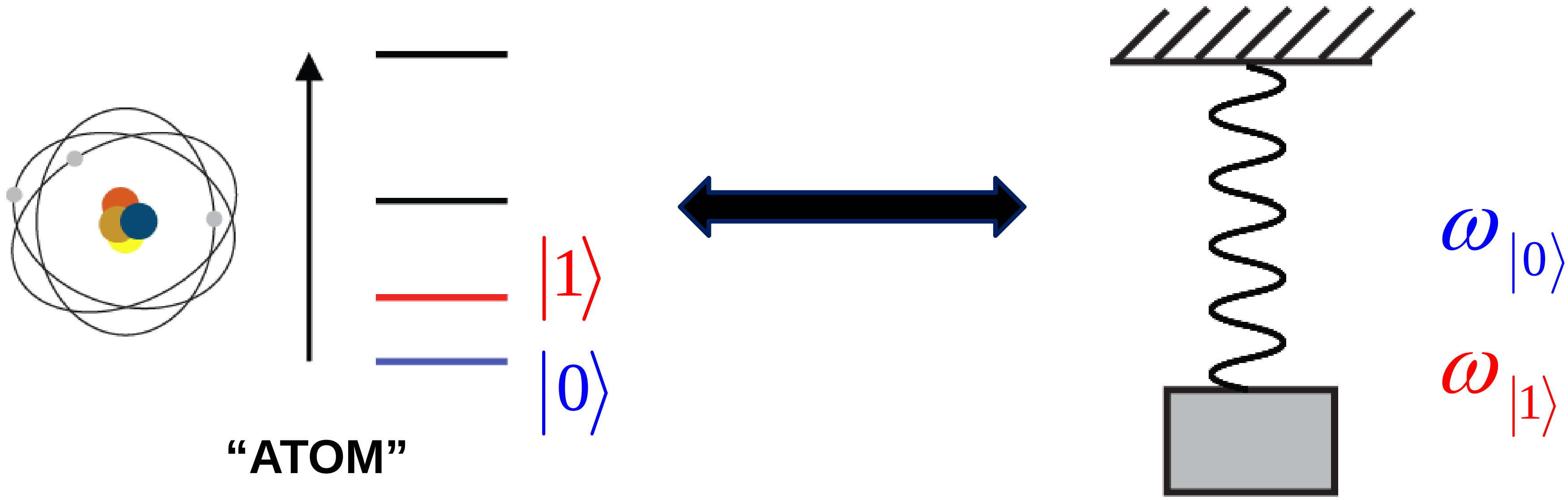


HOW TO MEASURE
THIS ARTIFICIAL ATOM?

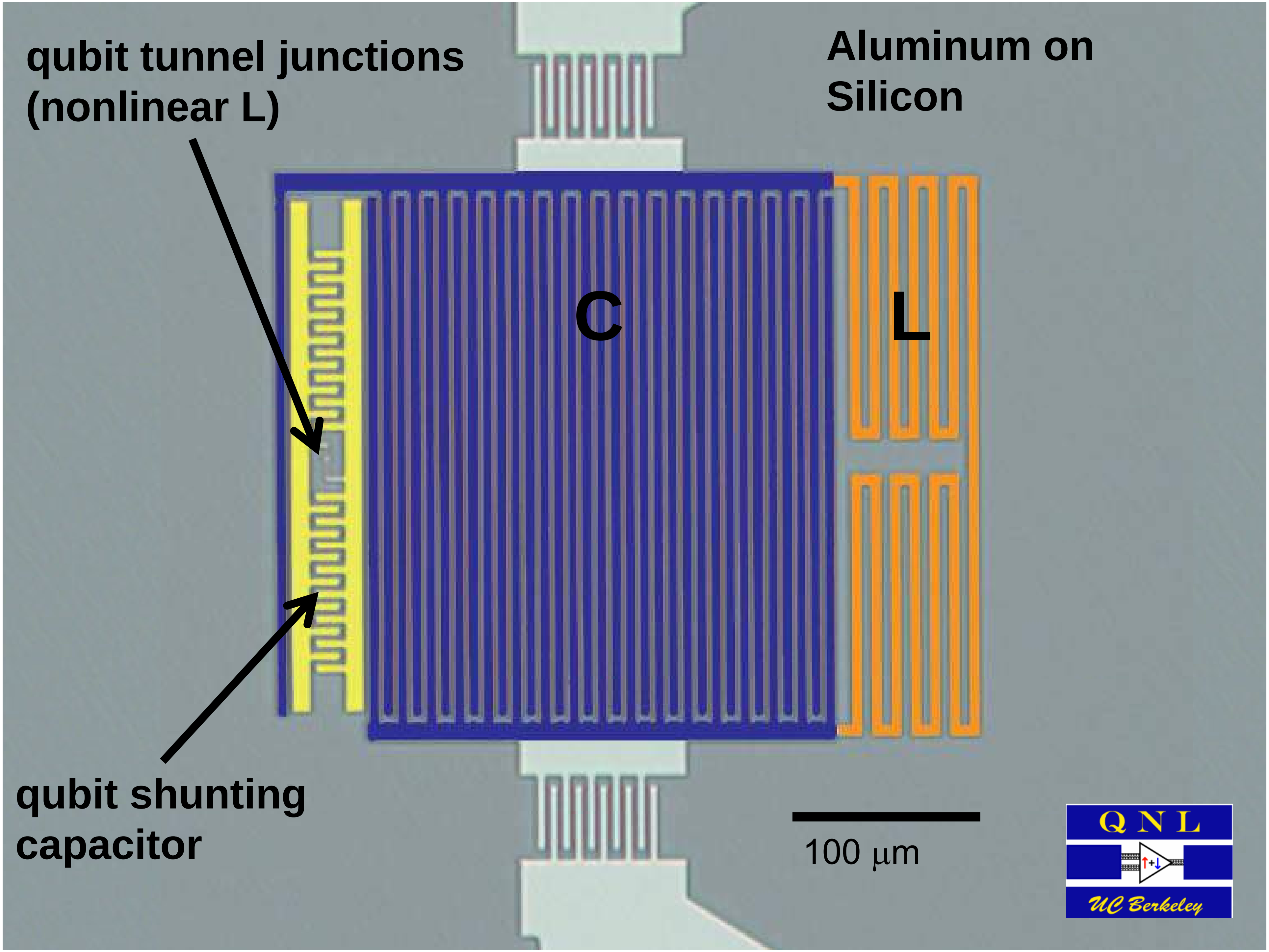


g
κ
γ

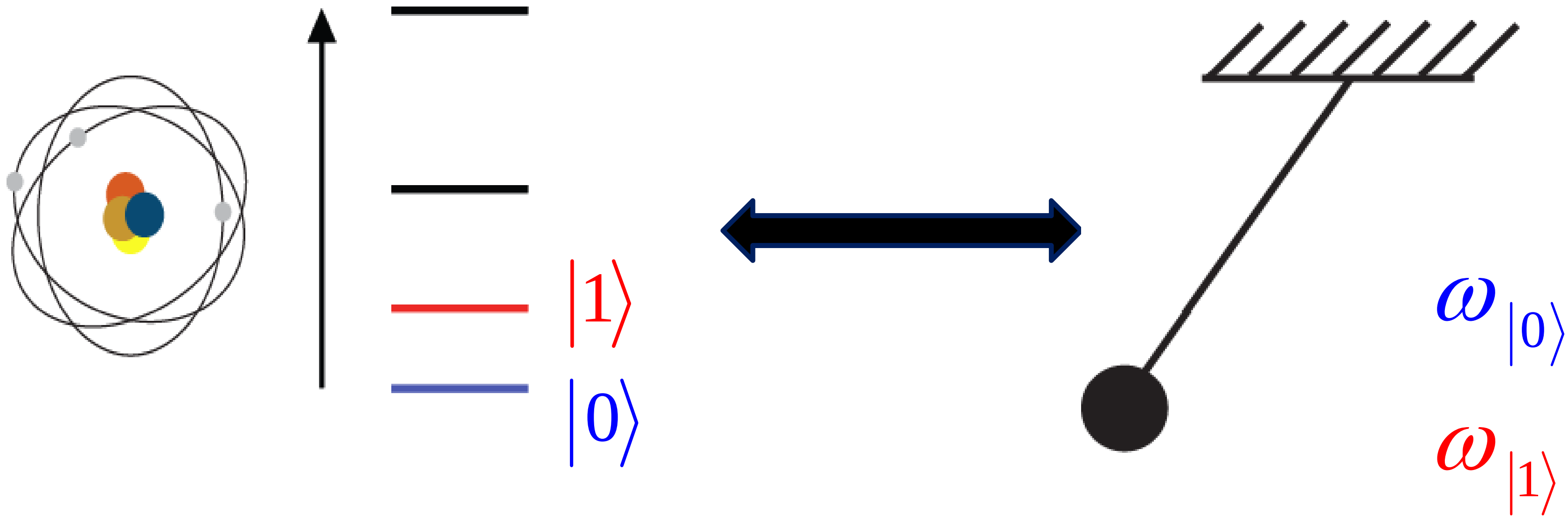
DISPERSIVE MEASUREMENT:
ATOM ON A LOADED SPRING



MEASUREMENT OSCILLATOR: SPRING (no amplitude dispersion)


qubit tunnel junctions
(nonlinear L)
Aluminum on
Silicon
C
L
qubit shunting
capacitor
100 μm
Q N L
UC Berkeley

NONLINEAR DISPERSIVE MEASUREMENT: ATOM ON A PENDULUM

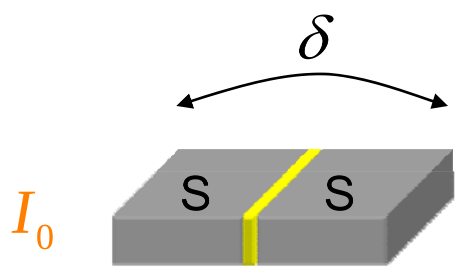


ATOM LIKE SYSTEM

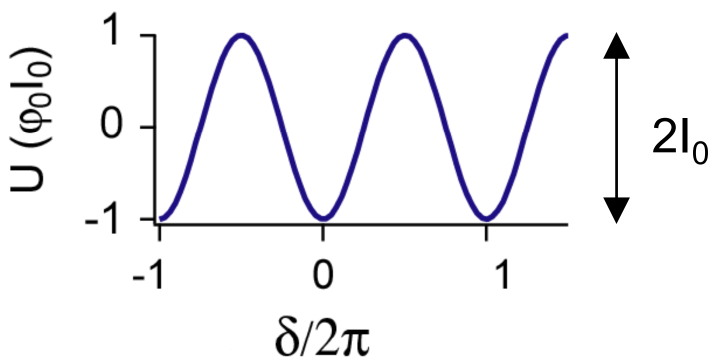
MEASUREMENT OSCILLATOR
(with amplitude dispersion)

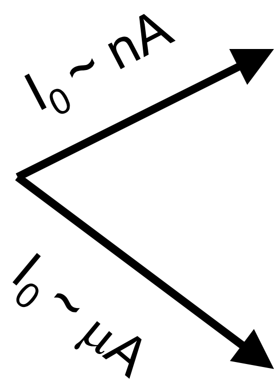
Frequency changes with quantum state **and** the oscillation amplitude!

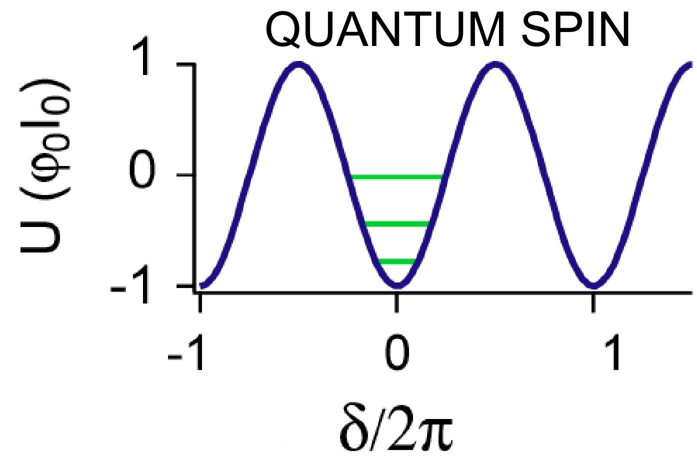
CLASSICAL & QUANTUM JOSEPHSON OSCILLATORS

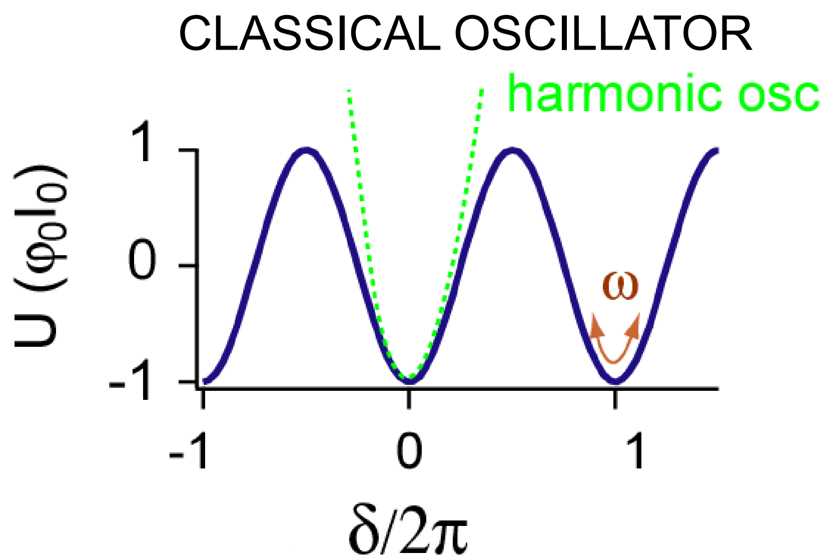


$I = I_0 \sin \delta$

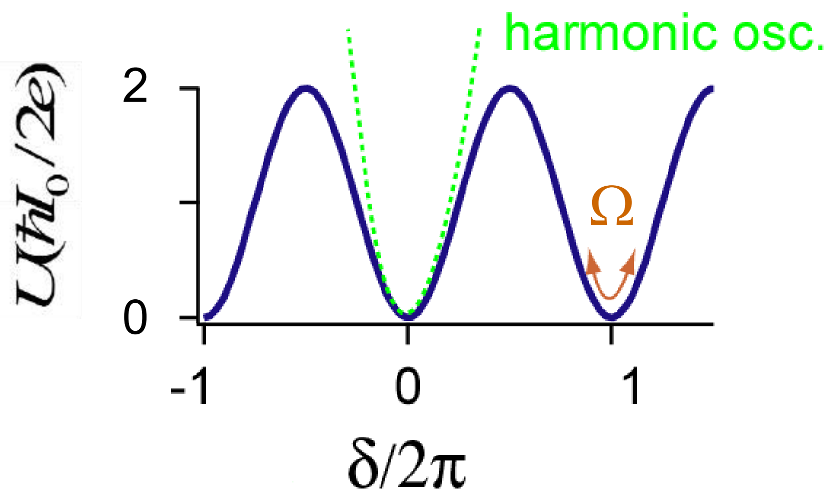


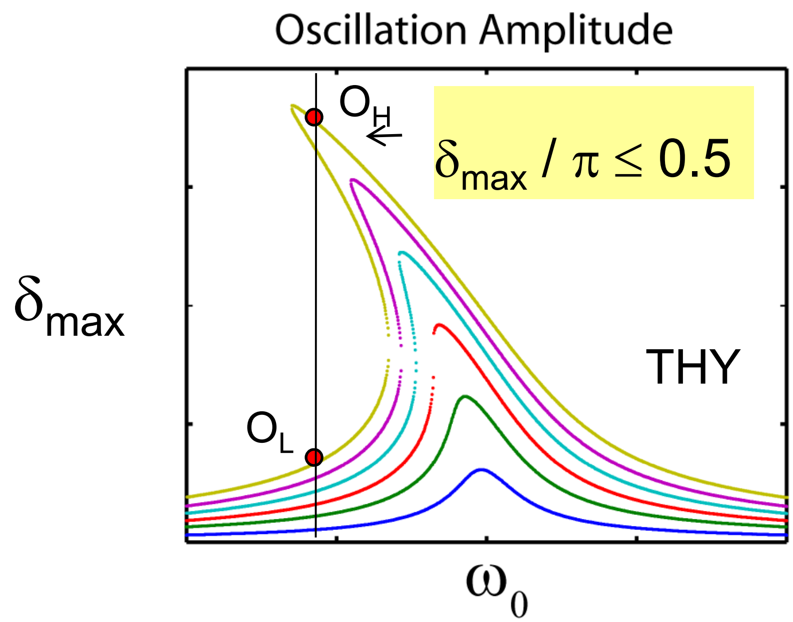






PERIODIC DRIVE: DYNAMICAL BIFURCATION



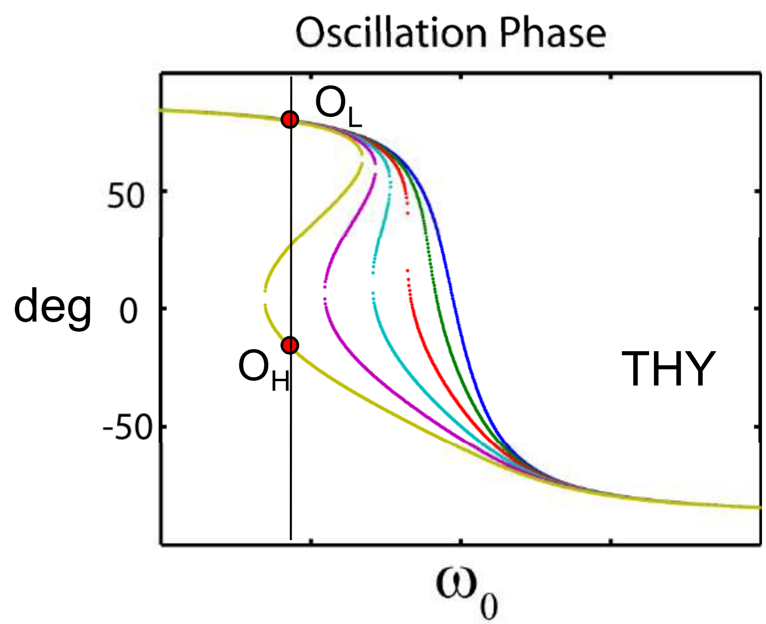


$$I(t) = i_{RF}\sin(\Omega t)$$

$$U(\delta) = -\frac{\hbar}{2e} I_0 \left(-\frac{\delta^2}{2} + \frac{\delta^4}{12} - \ldots \right)$$

linear inductance

non-linear inductance



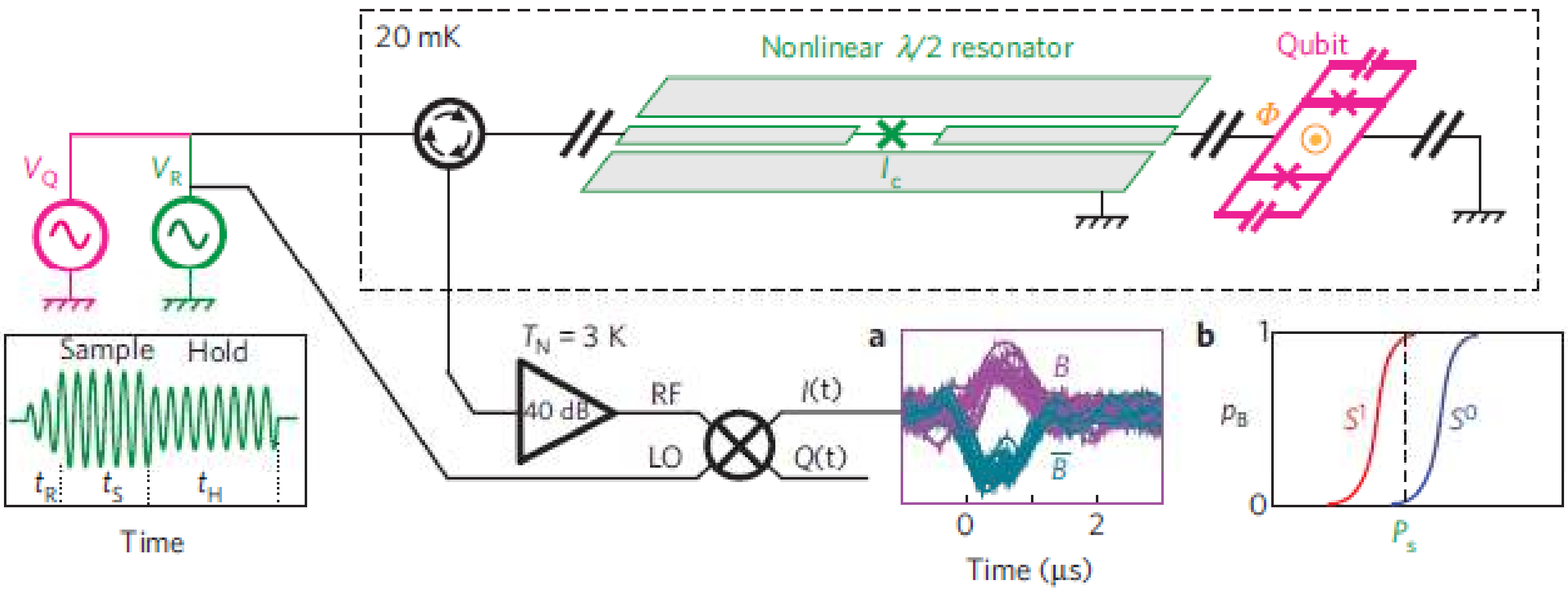
nature physics

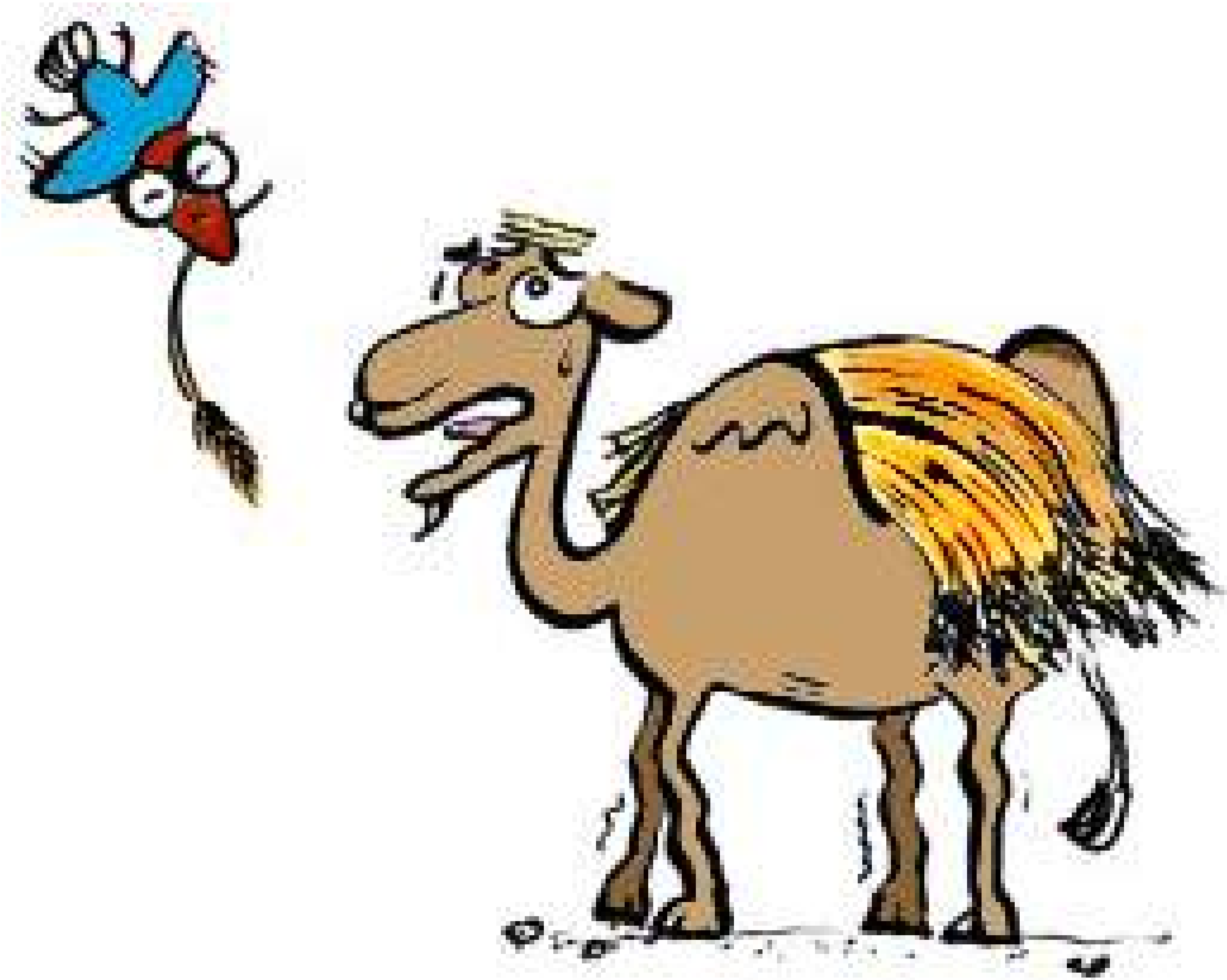
LETTERS

PUBLISHED ONLINE: 27 SEPTEMBER 2009 | DOI: 10.1038/NPHYS1400

Single-shot qubit readout in circuit quantum electrodynamics

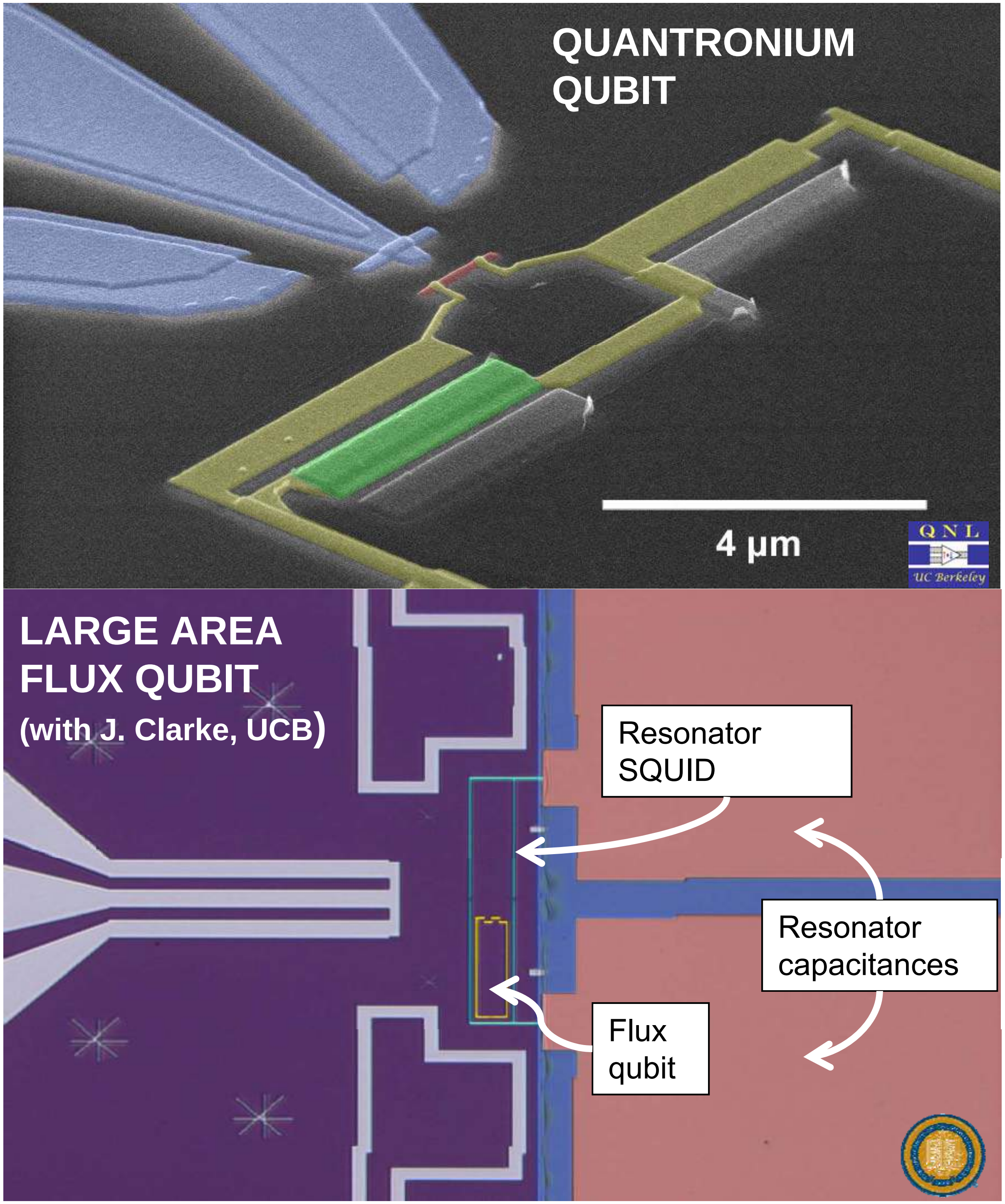
François Mallet, Florian R. Ong, Agustin Palacios-Laloy, François Nguyen, Patrice Bertet, Denis Vion* and Daniel Esteve





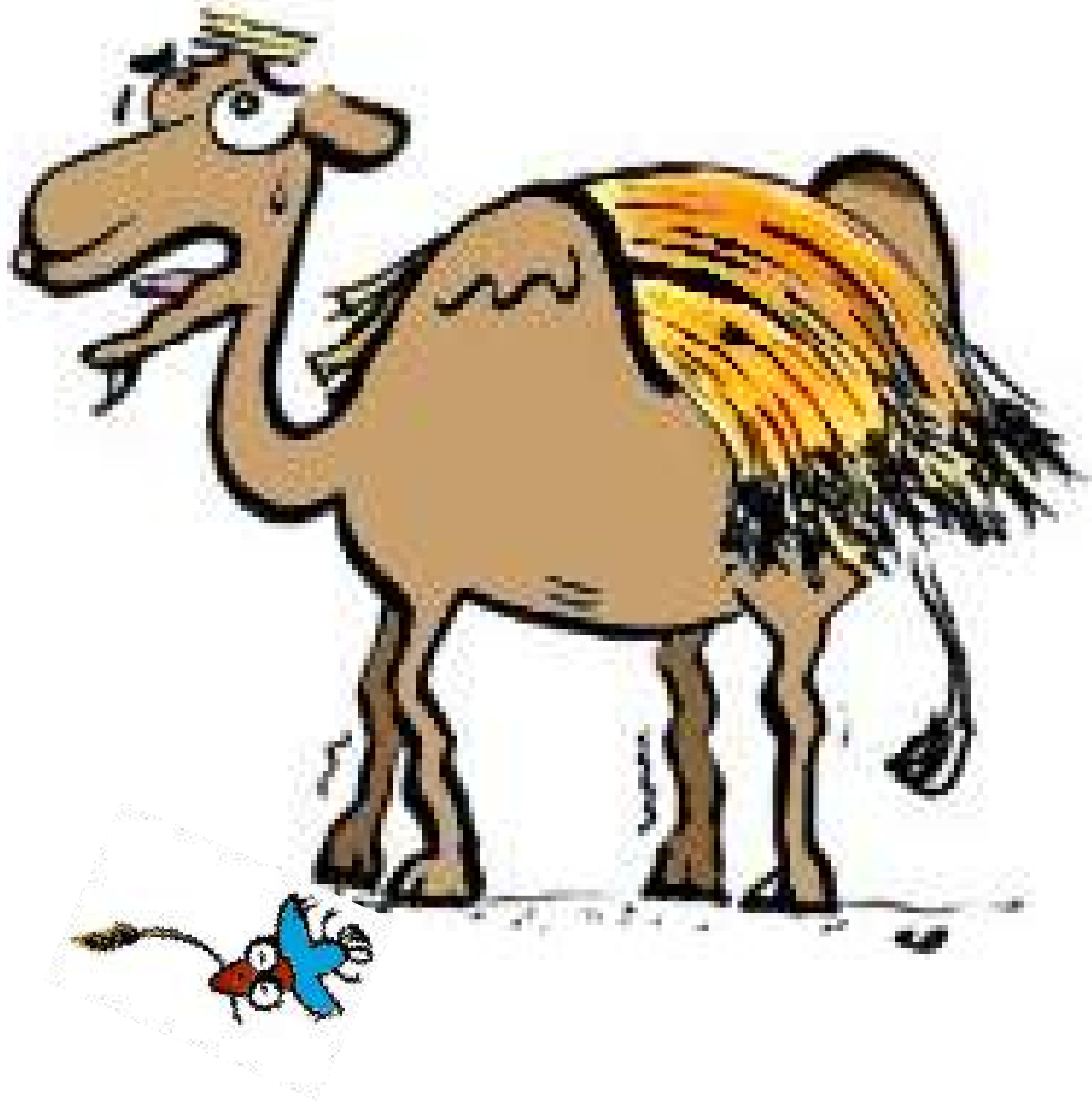
BUT…

GAIN ISN’T EVERYTHING IN QUANTUM MECHANICS



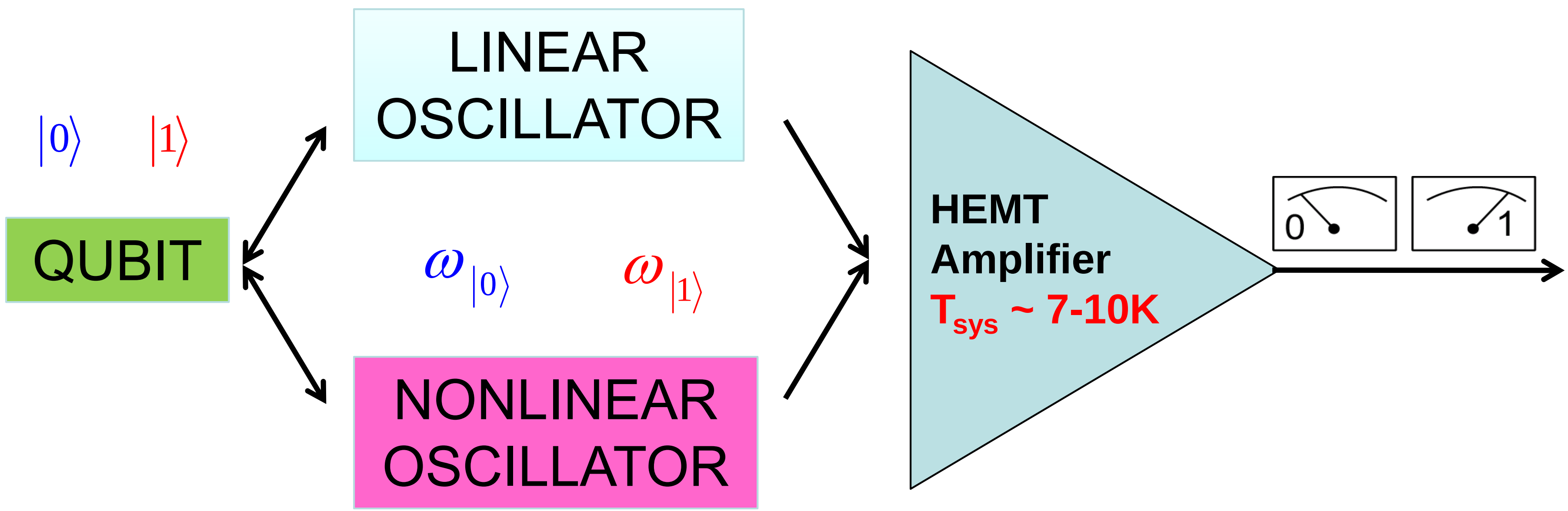
DIFFERENT QUBITS READOUT WITH A NONLINEAR OSCILLATOR

→ DIFFERENT LEVELS OF FIDELITY



SINGLE STAGE READOUT: COMBINED MEASURE AND RECORD FUNCTIONS

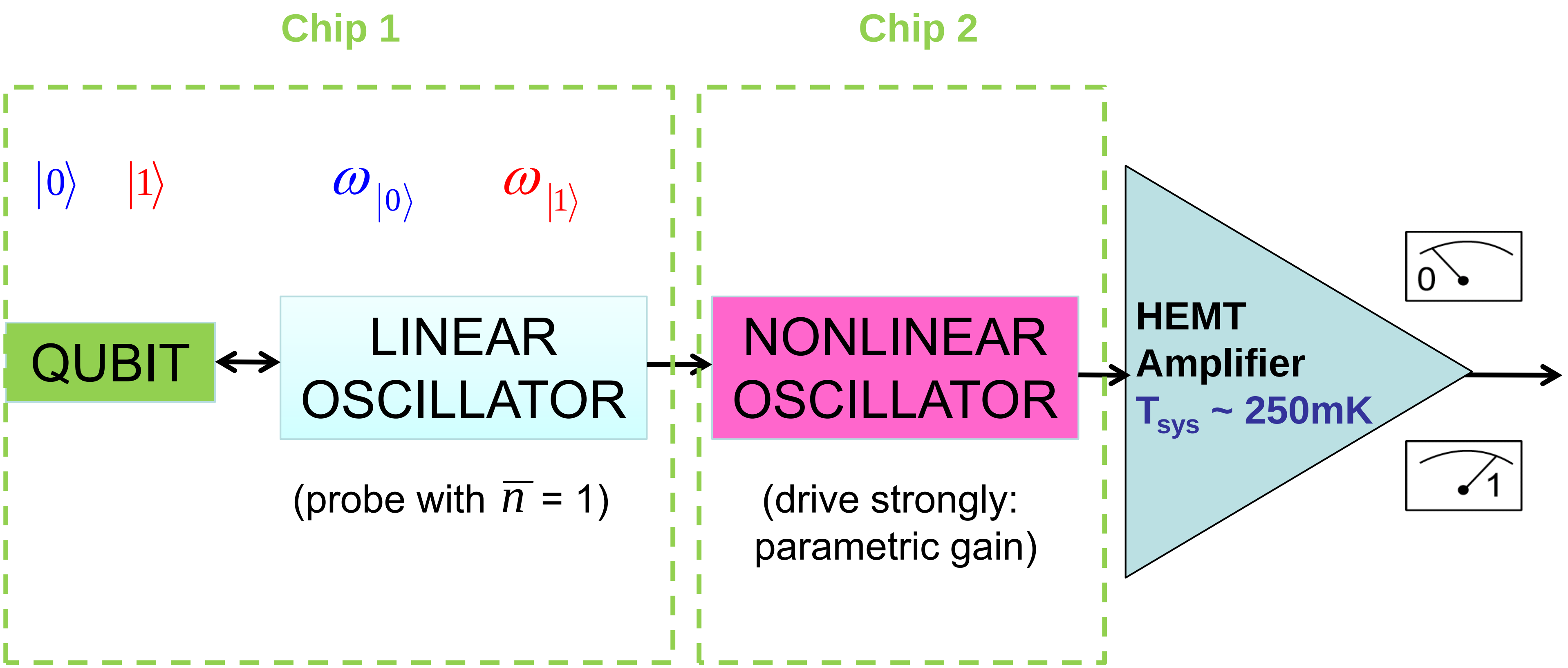
(probe with large photon number $\bar{n}$ to overcome system noise)



(probe with large photon number $\bar{n}$ to access nonlinearity in low Q system)

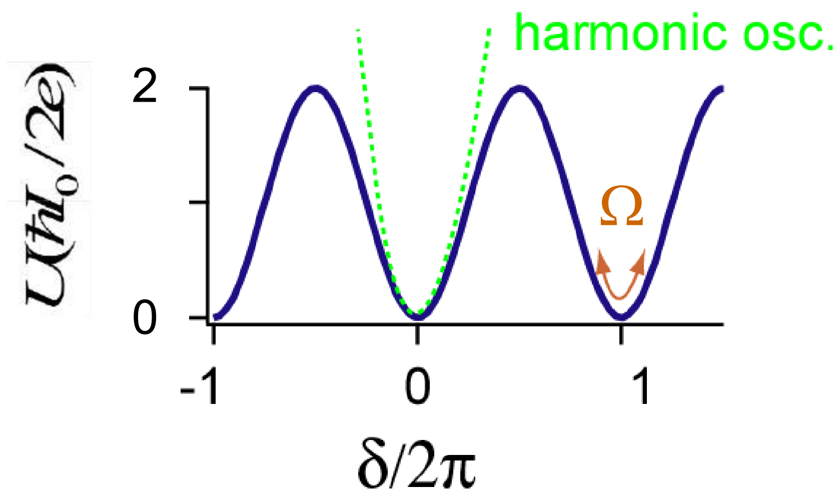
HIGHLY EXCITED OSCILLATOR COUPLED TO QUBIT → RELAXATION (DEGREE VARIES WITH QUBIT TYPE)

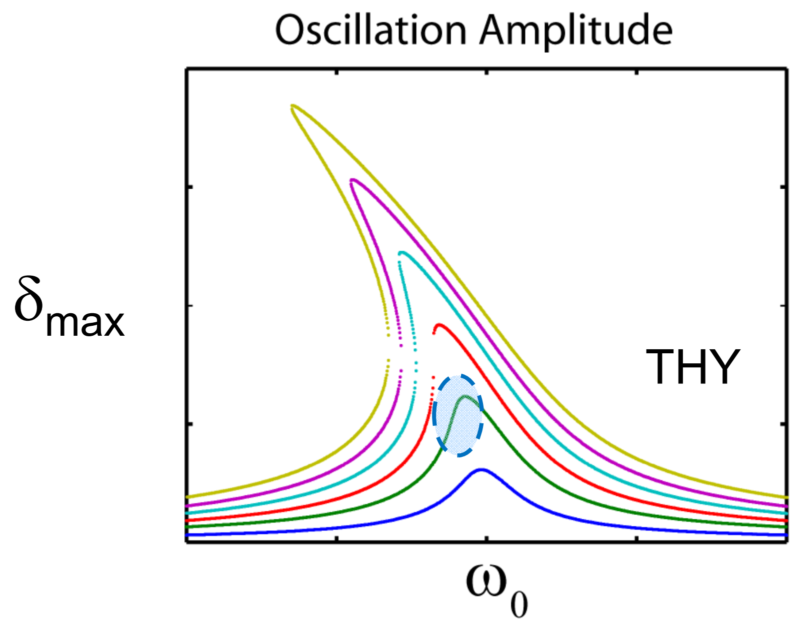
TWO STAGE READOUT



- QUBIT OSCILLATOR PROBED WITH A FEW PHOTONS
- SUERCONDUCTING PARAMETRIC AMPLIFIER SETS T_{sys}

PERIODIC DRIVE: PARAMP REGIME





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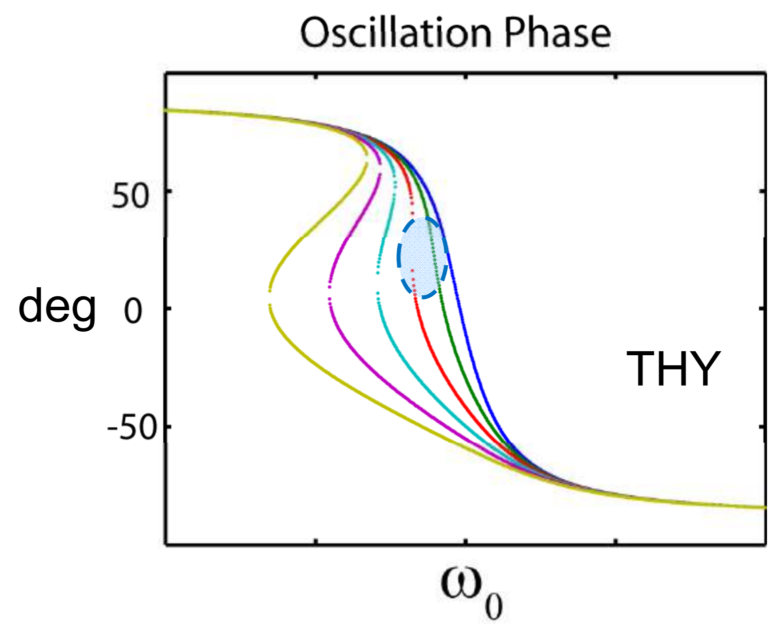
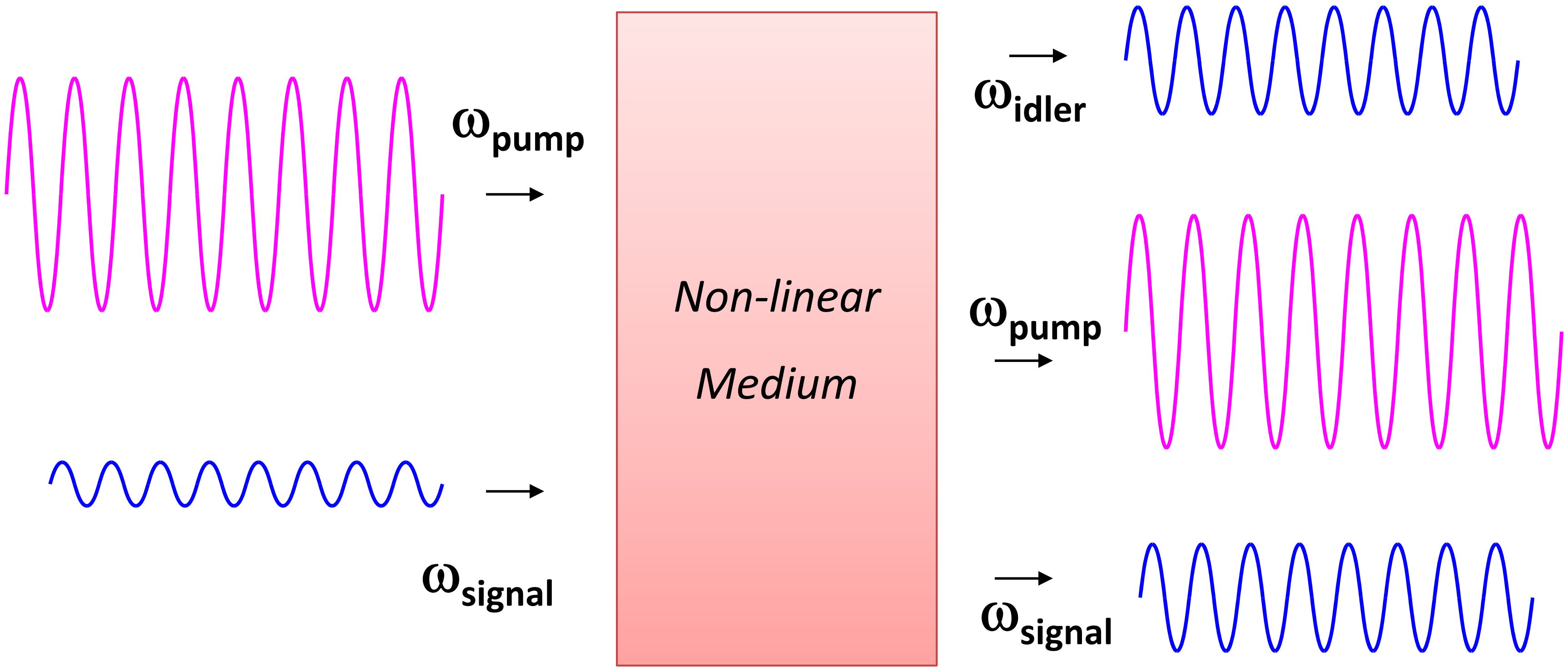
linear inductance

non-linear inductance

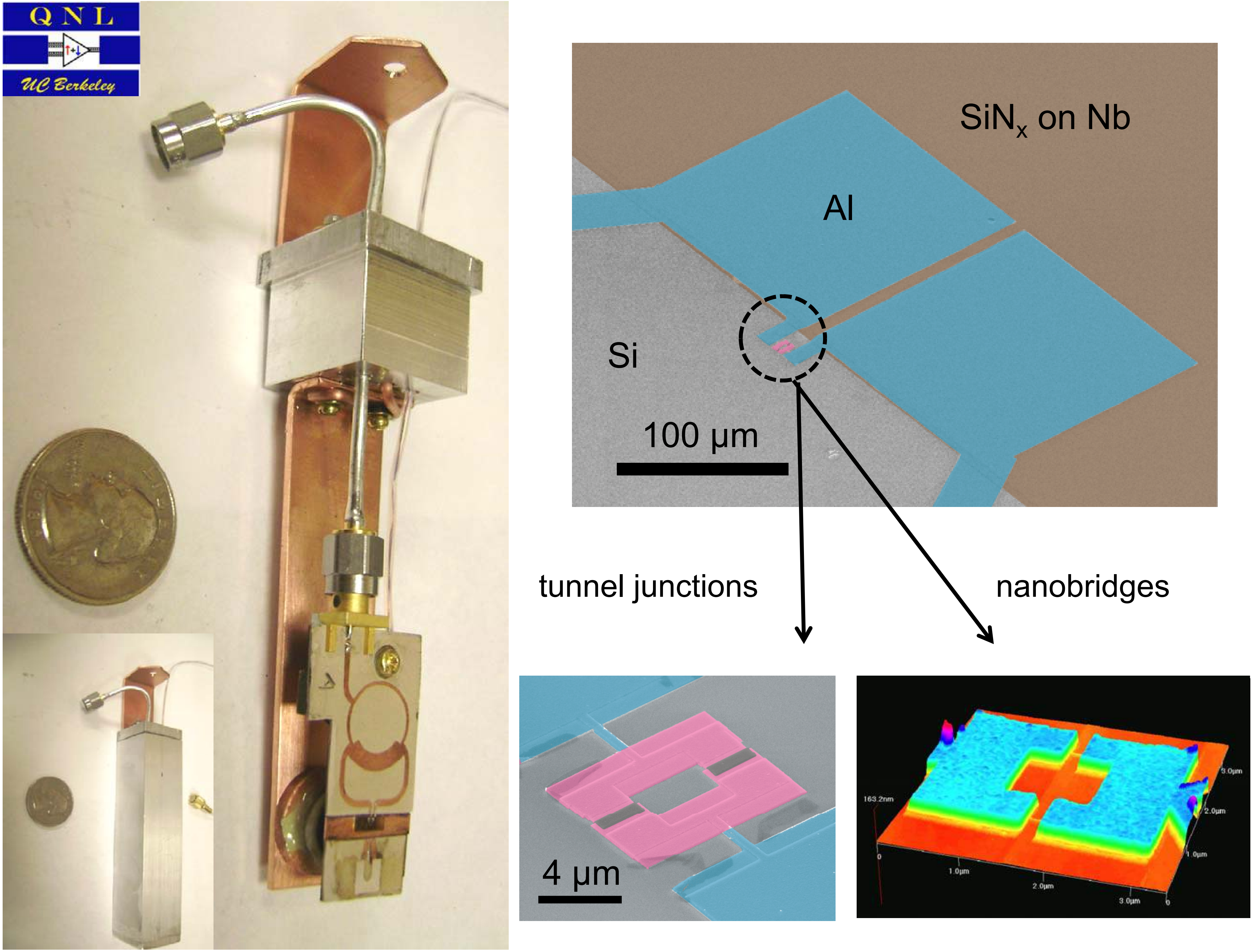


PARAMETRIC AMPLIFICATION



$$\omega_{pump} = \omega_{signal} + \omega_{idler}$$

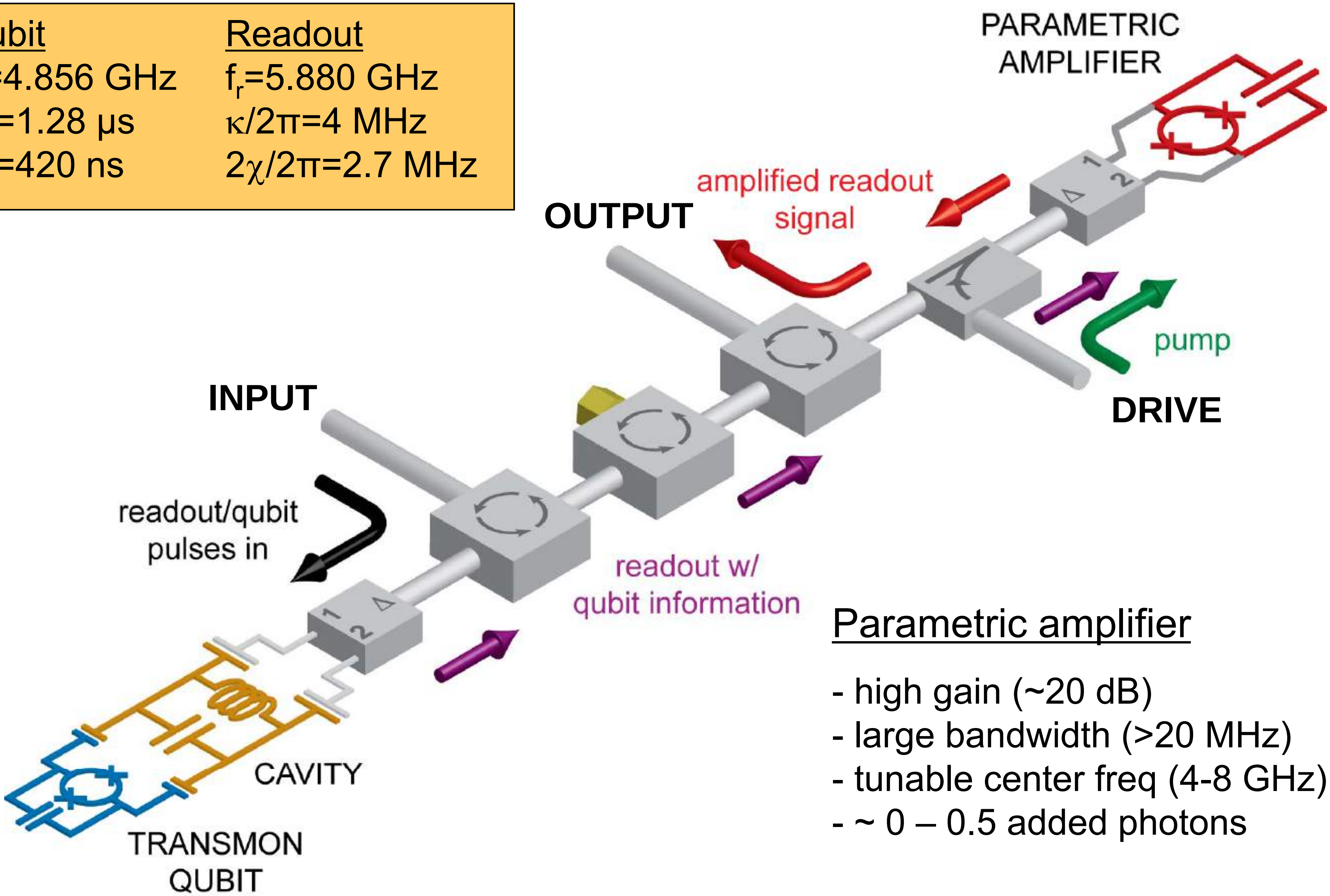
$$2\omega_{pump} = \omega_{signal} + \omega_{idler}$$



Q N L
UC Berkeley
SiN$_x$ on Nb
Al
Si
100 μm
tunnel junctions
nanobridges
4 μm
163.2nm
0
1.0μm
2.0μm
3.0μm

EXPERIMENTAL SETUP

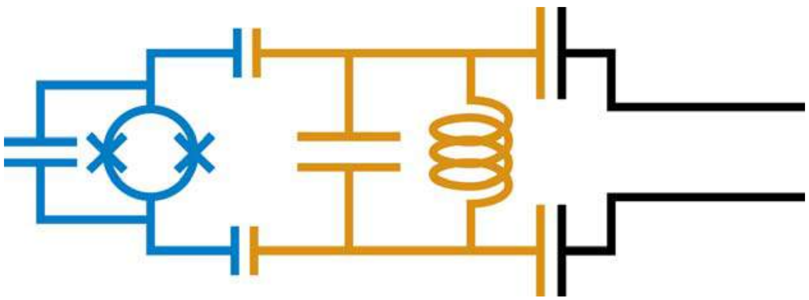
Qubit	Readout
f_q=4.856 GHz	f_r=5.880 GHz
T_1=1.28 μs	$\kappa/2\pi$=4 MHz
T_2=420 ns	$2\chi/2\pi$=2.7 MHz

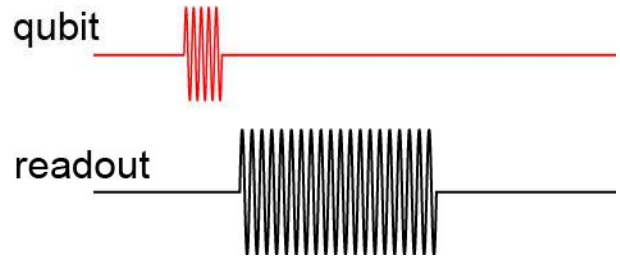


<u>Parametric amplifier</u>

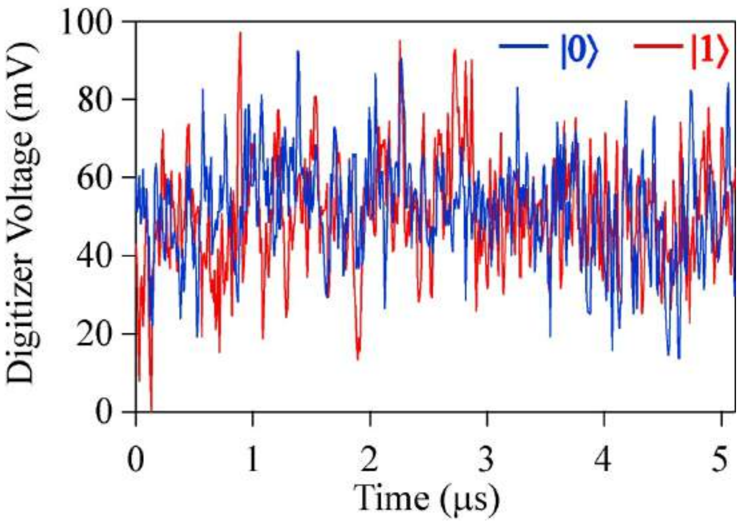
- high gain (~20 dB)
- large bandwidth (>20 MHz)
- tunable center freq (4-8 GHz)
- ~ 0 – 0.5 added photons

QUBIT MEASUREMENTS: HOMODYNE SIGNAL



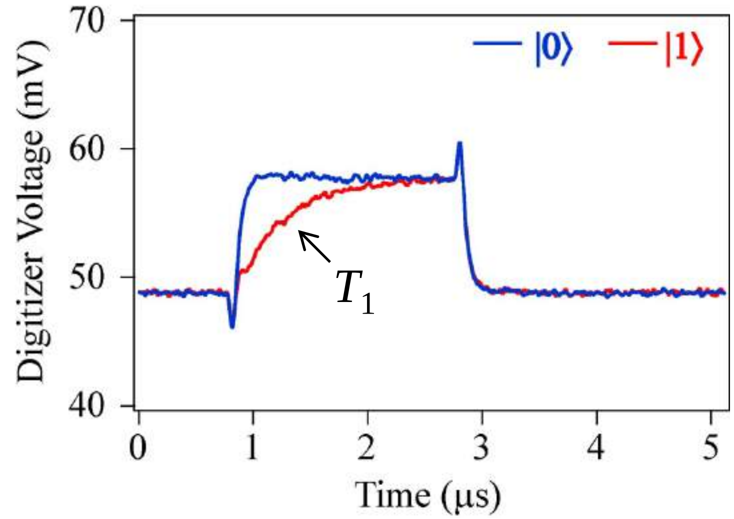


Single measurement trace



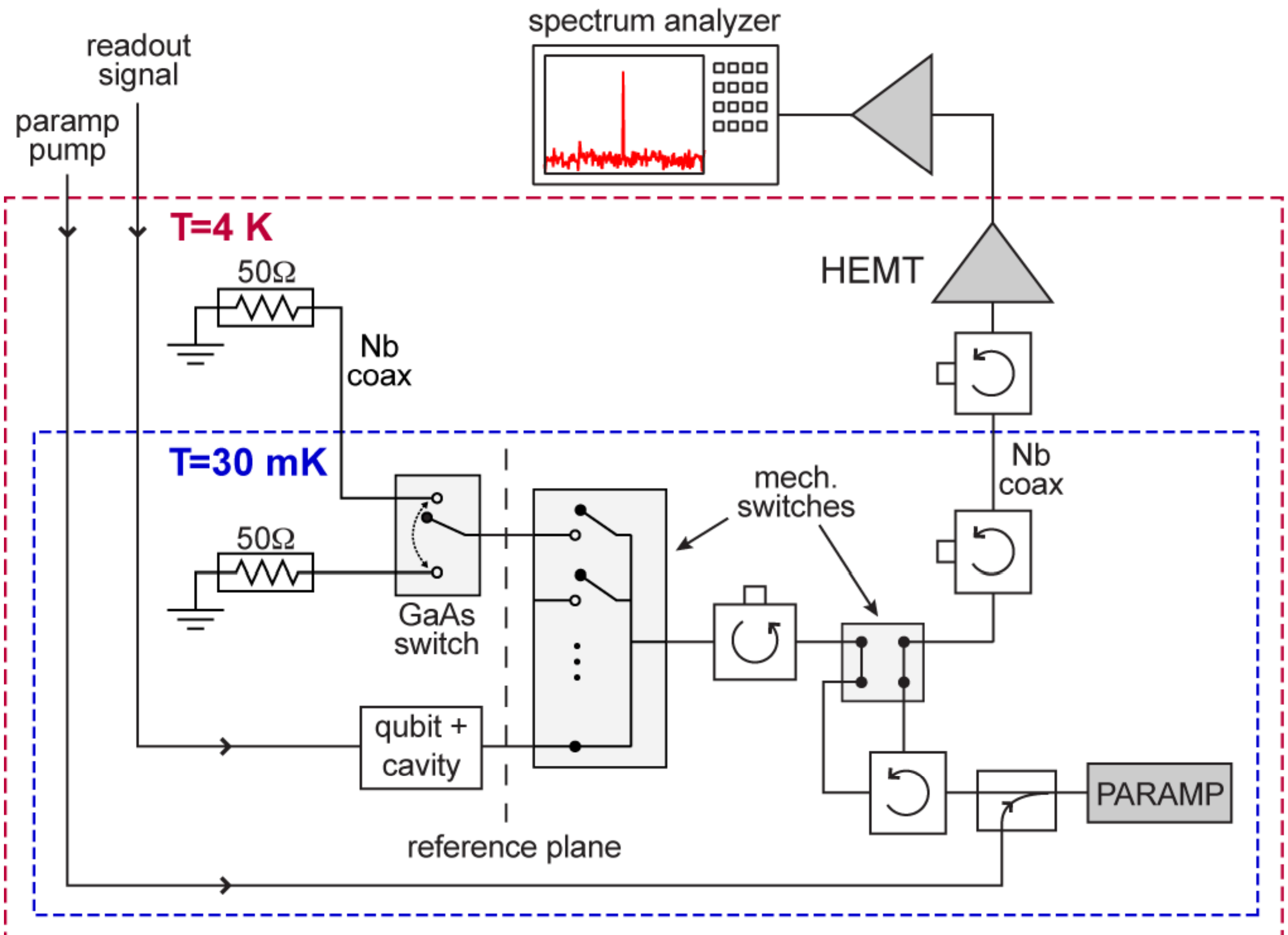
10^4 Averages

Averaged measurement trace



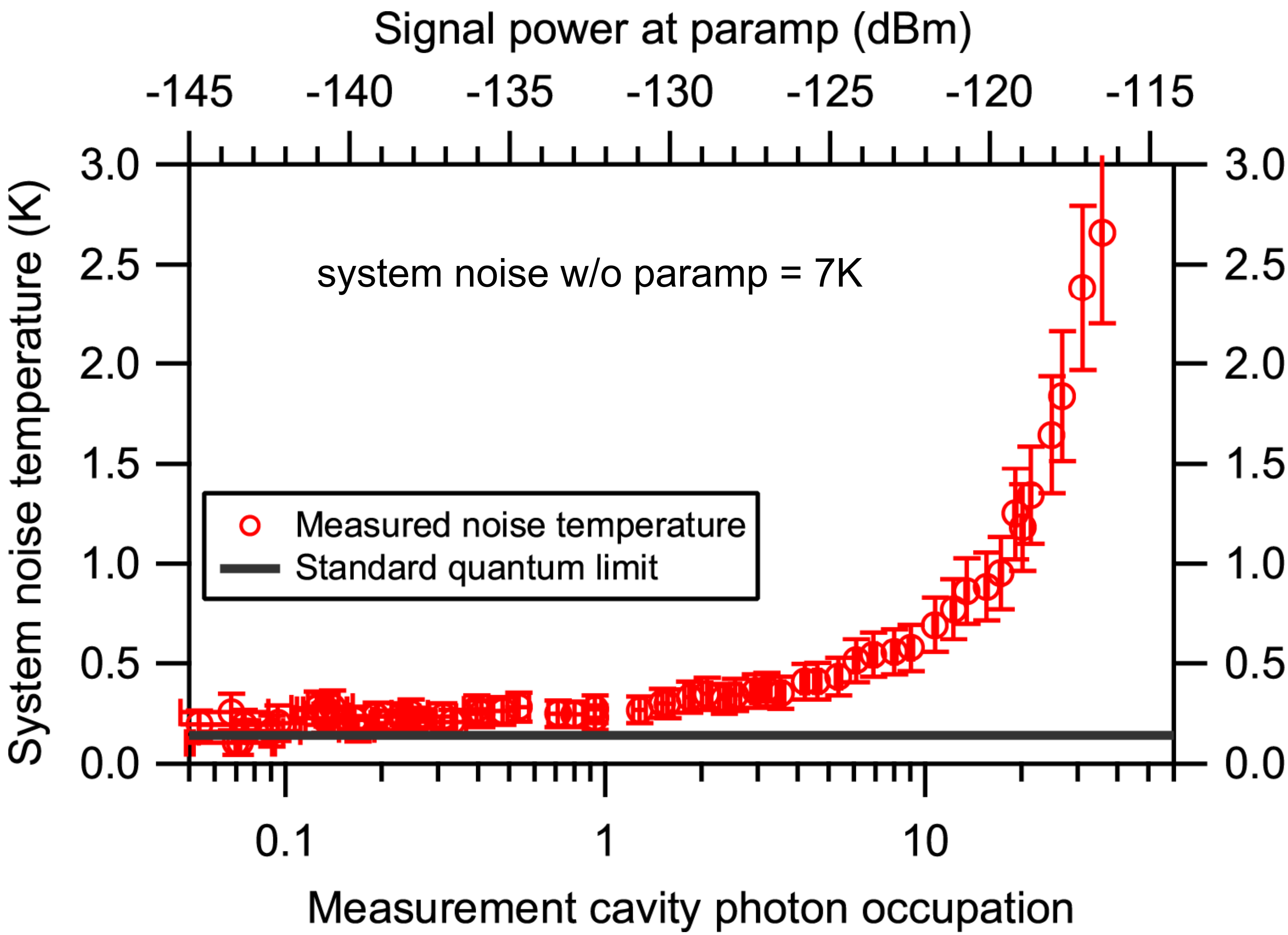
Amplifier (T_{SYS} = 7K) noise masks qubit state information

SYSTEM NOISE TEMPERATURE



$$T_N = \frac{T_H - \quad}{Y - \quad} \qquad T_{N,\mathrm{par}} = \frac{T_{N,\mathrm{nopar}}}{\text{SNR improvement}} \qquad \mathrm{K} + AT_L$$

SYSTEM NOISE TEMPERATURE



THE
LONDON, EDINBURGH, AND DUBLIN
PHILOSOPHICAL MAGAZINE
AND
JOURNAL OF SCIENCE.

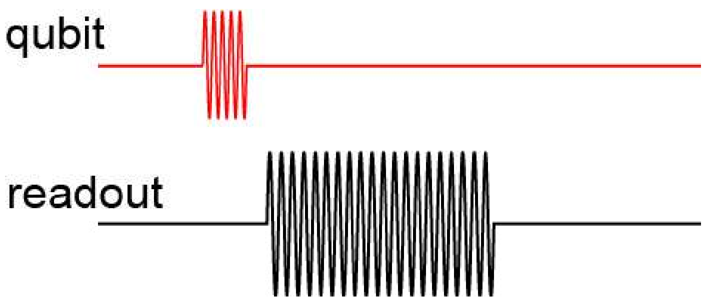
[SIXTH SERIES.]

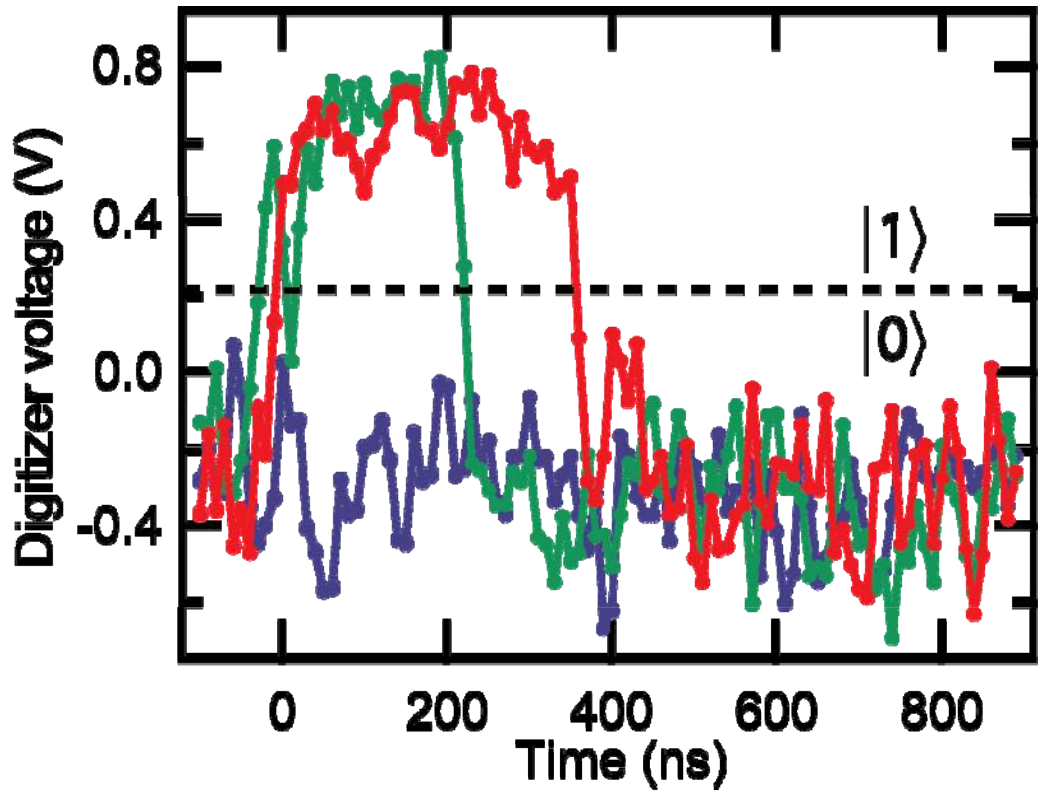
JULY 1913.

I. *On the Constitution of Atoms and Molecules.*

By N. BOHR, *Dr. phil. Copenhagen**.

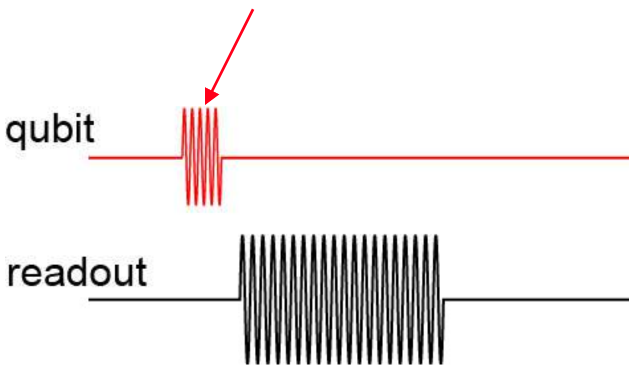
SINGLE SHOT MEASUREMENTS

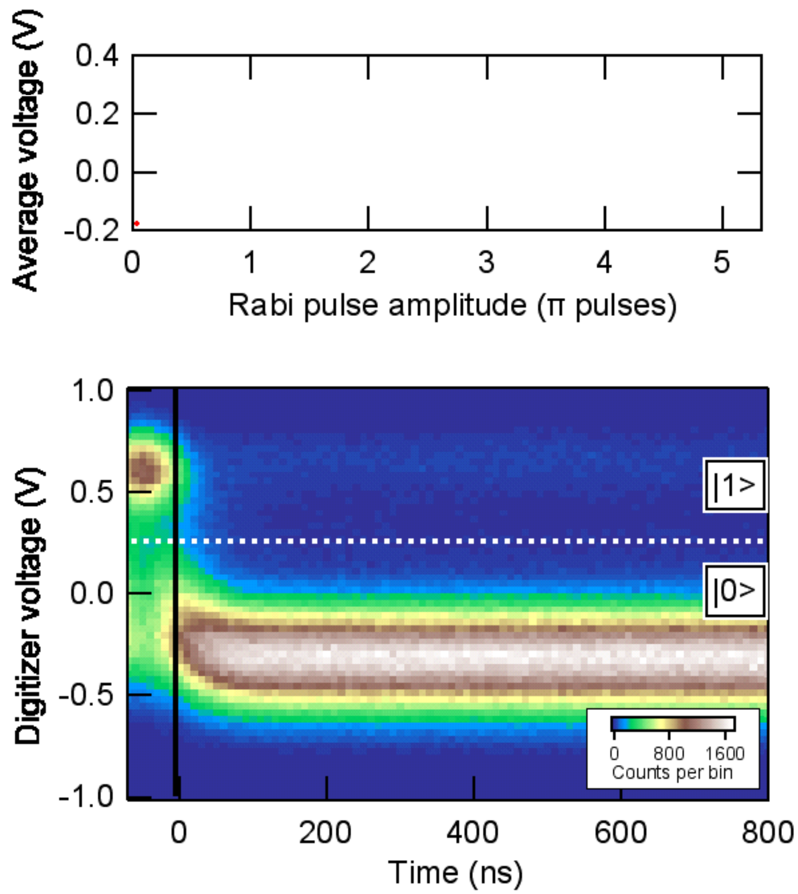




Real time observation of quantum jumps due to spontaneous decay

SINGLE SHOT HISTOGRAMS

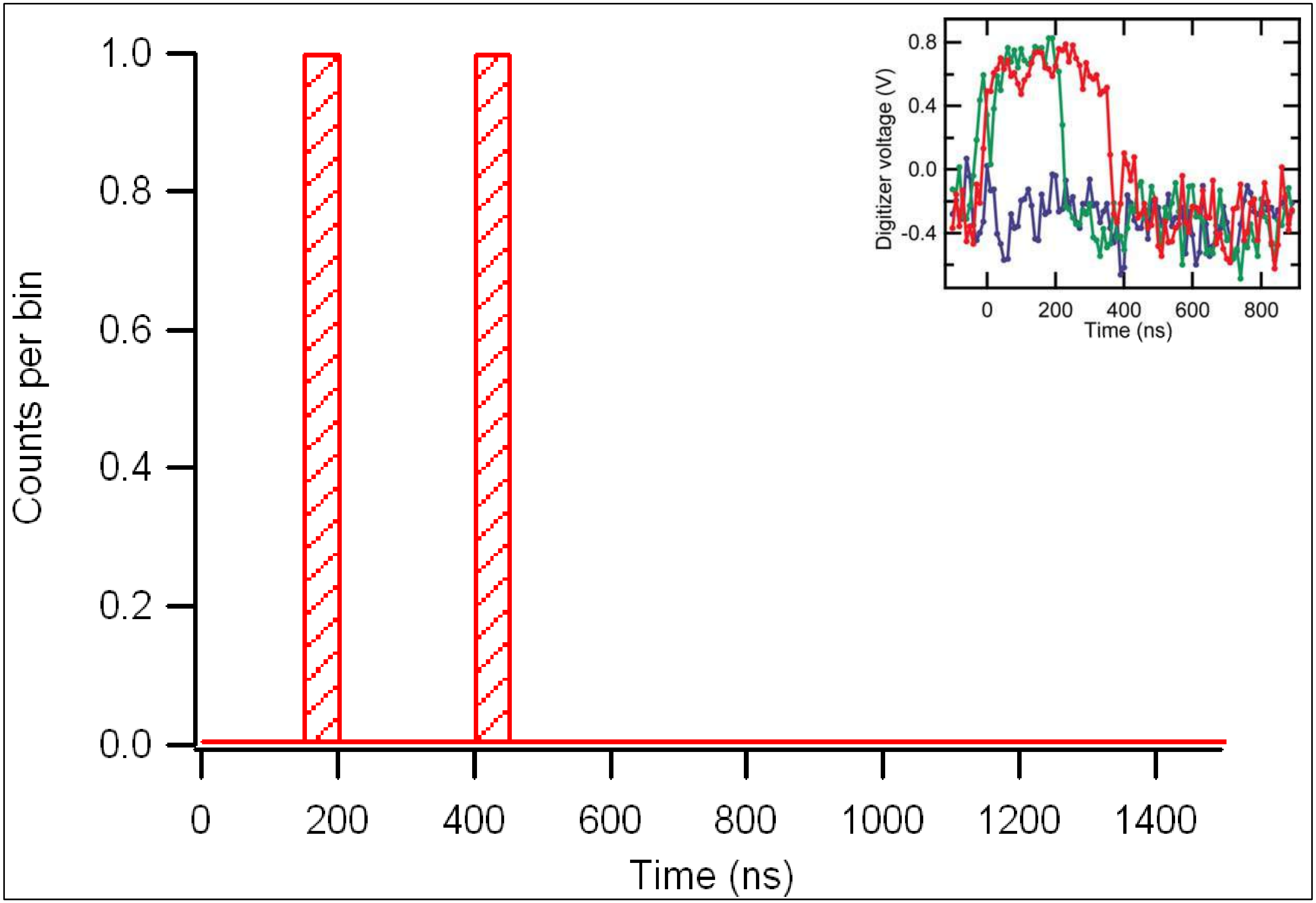




State discrimination fidelity > 95-99 %

Single shot fidelity: 70 -90%

JUMP STATISTICS

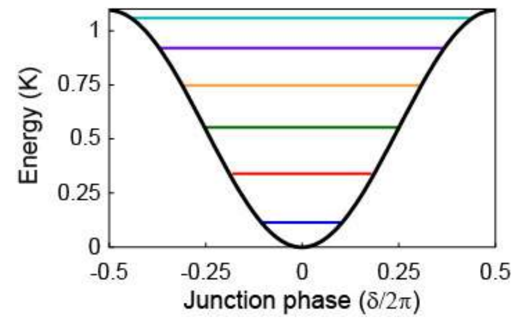


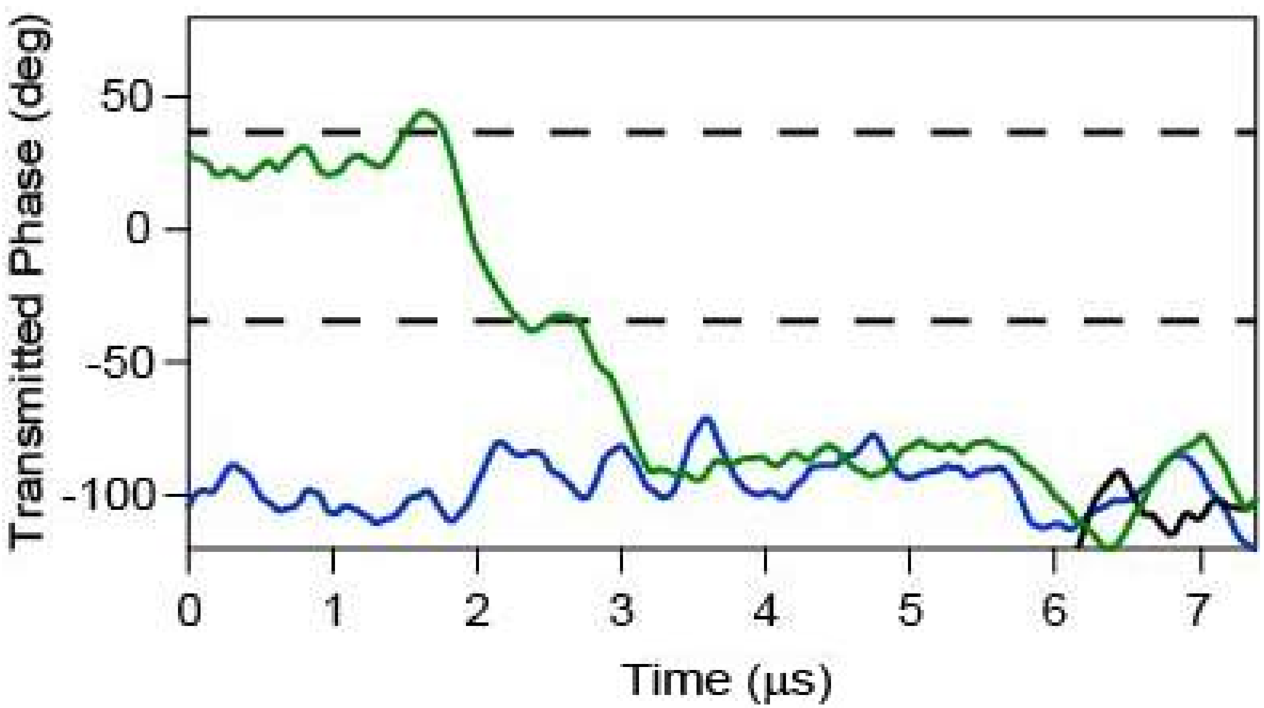
JUMPS FROM HIGHER QUBIT LEVELS

Paramp in phase insensitive mode

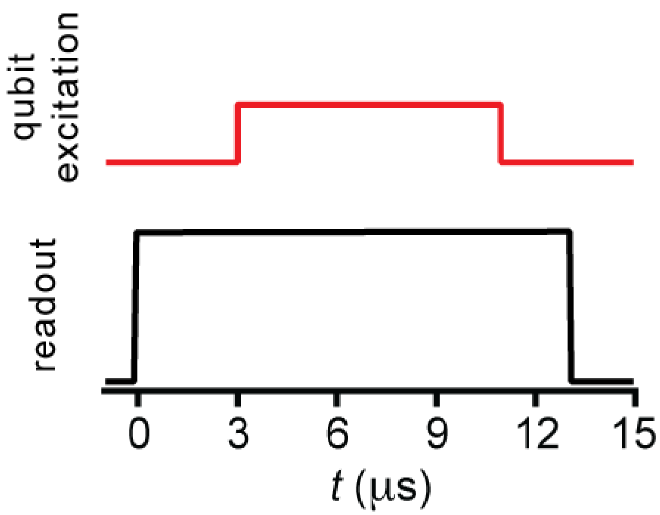
Qubit prepared in first excited state

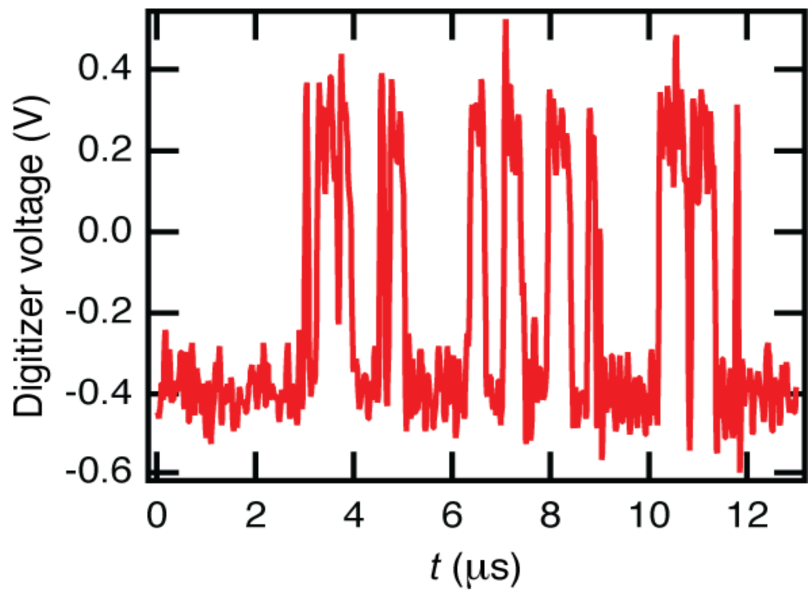
Qubit prepared in second excited state





MEASUREMENT PINNING





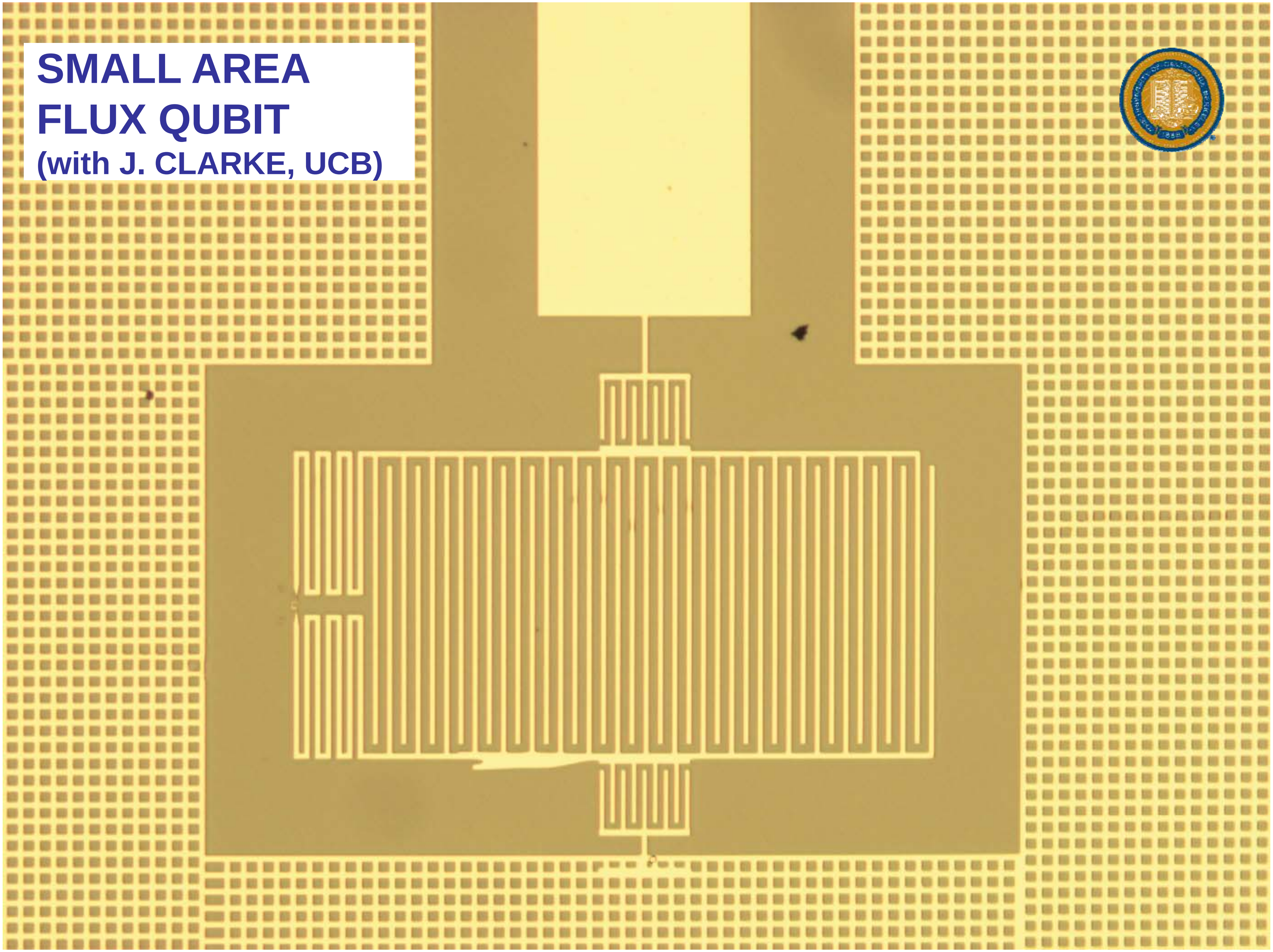
Measurement pinning
vs. qubit evolution

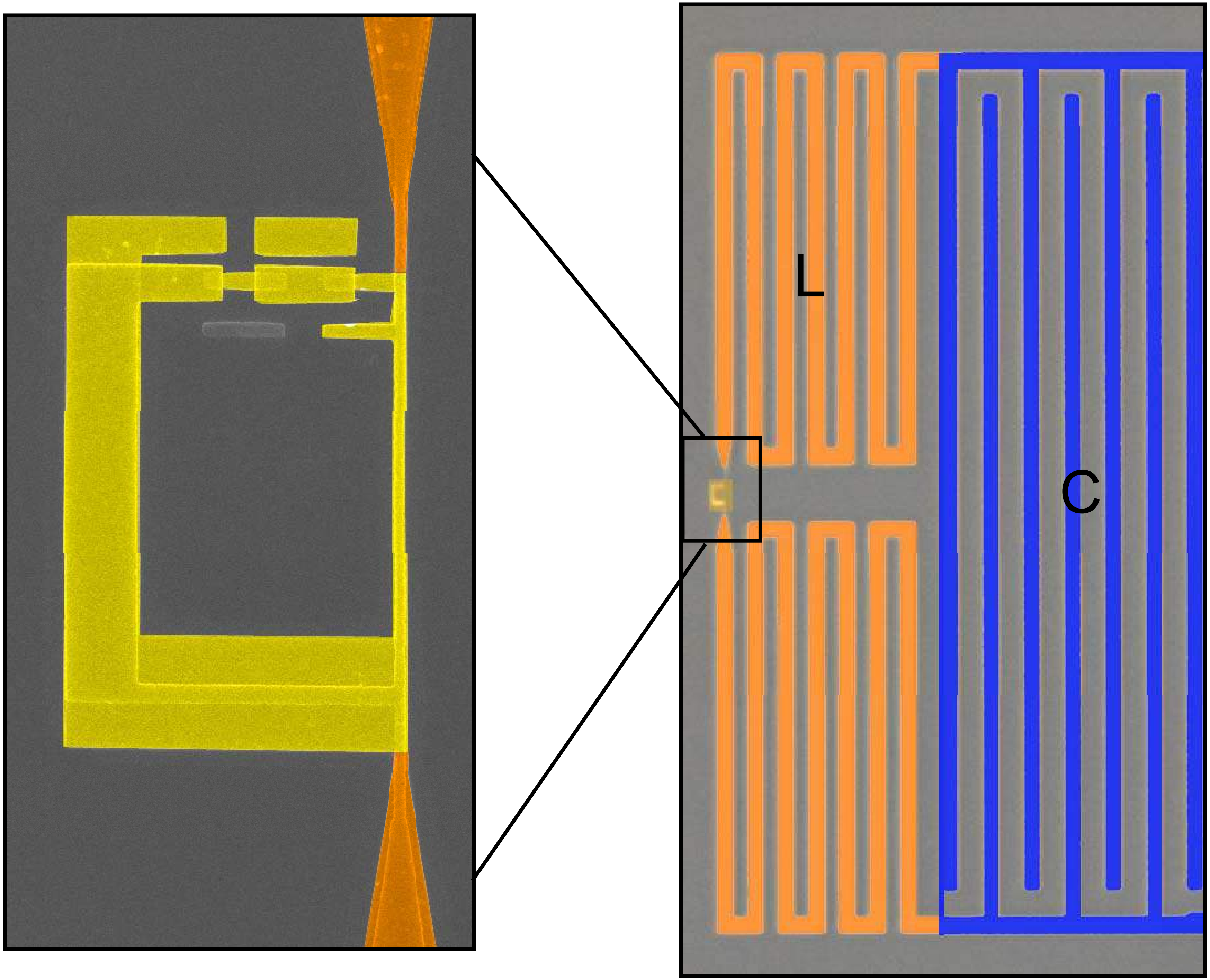
==> random telegraph signal

Quantum Zeno

SMALL AREA FLUX QUBIT

(with J. CLARKE, UCB)




L
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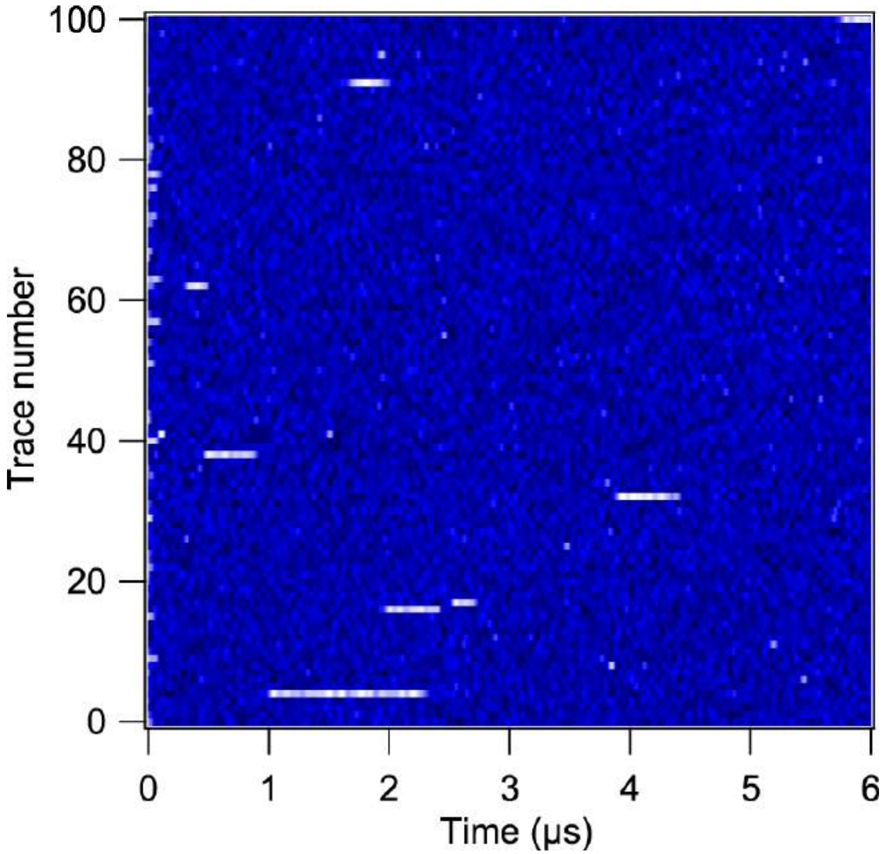
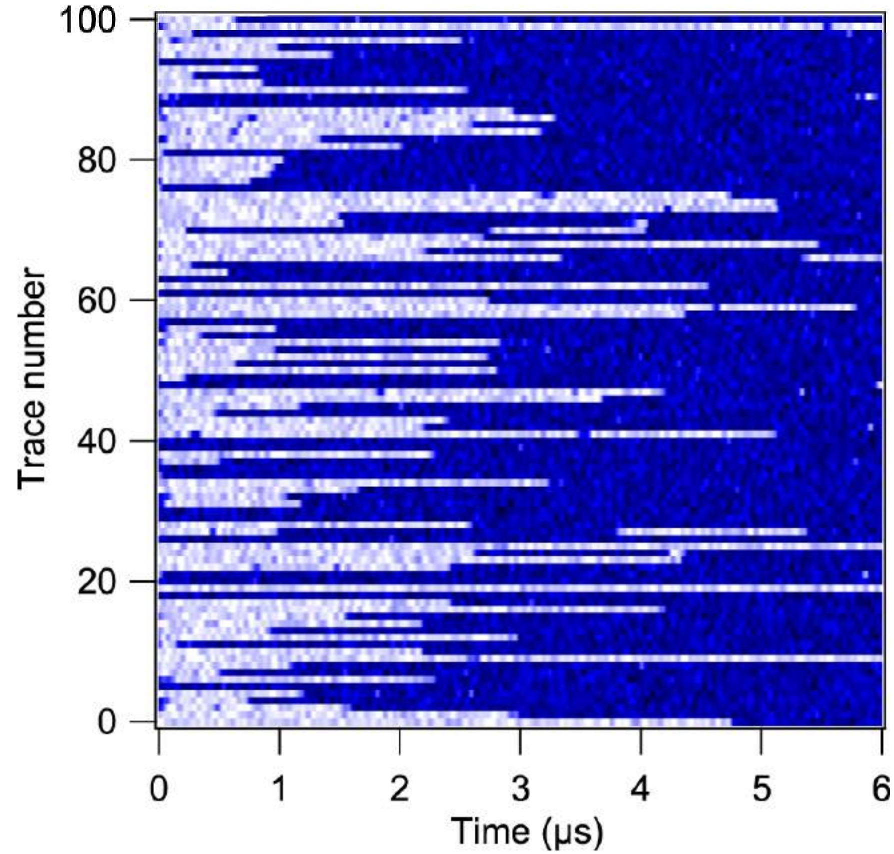
QUANTUM JUMPS IN A FLUX QUBIT

$\bar{n} \approx 10$

$T_2 = 2\ \mu s$



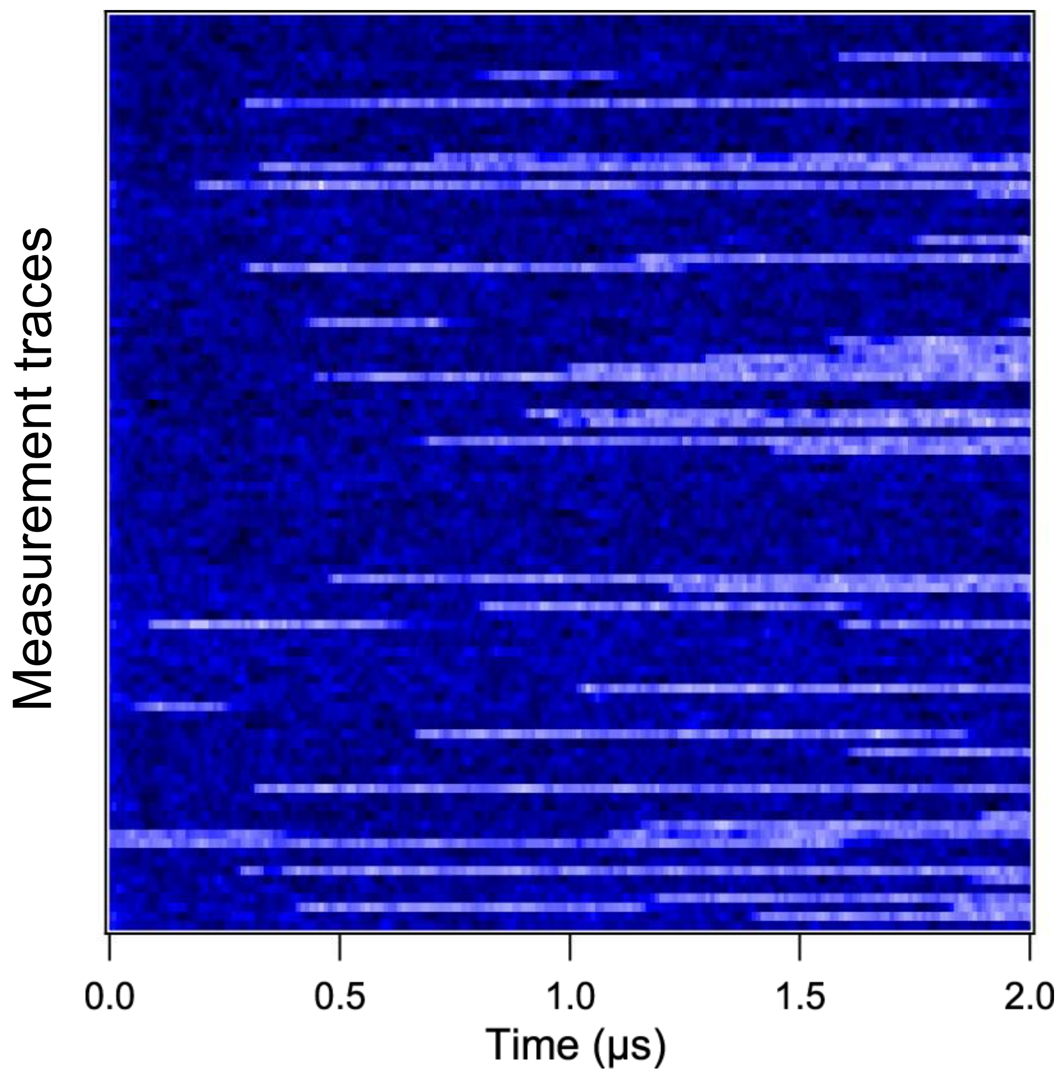
prepare |0>



prepare |1>

BACKACTION OF THE TANK CIRCUIT

NON-IDEALITIES IN MEASUREMENT



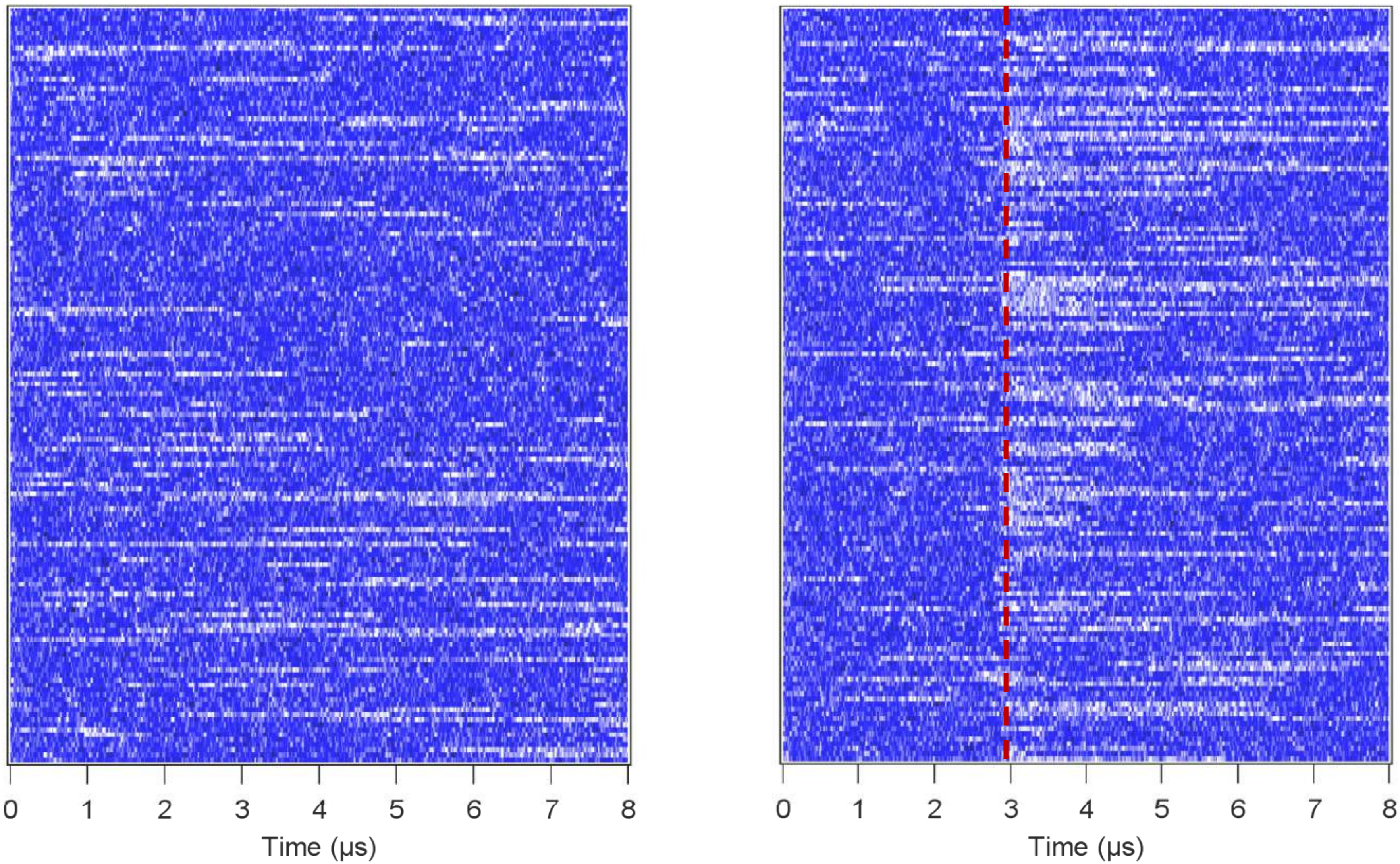
Qubit prepared in ground state

Blue: Ground state
White: Excited state

$$\bar{n} \approx 5$$

$\bar{n} \approx 60$

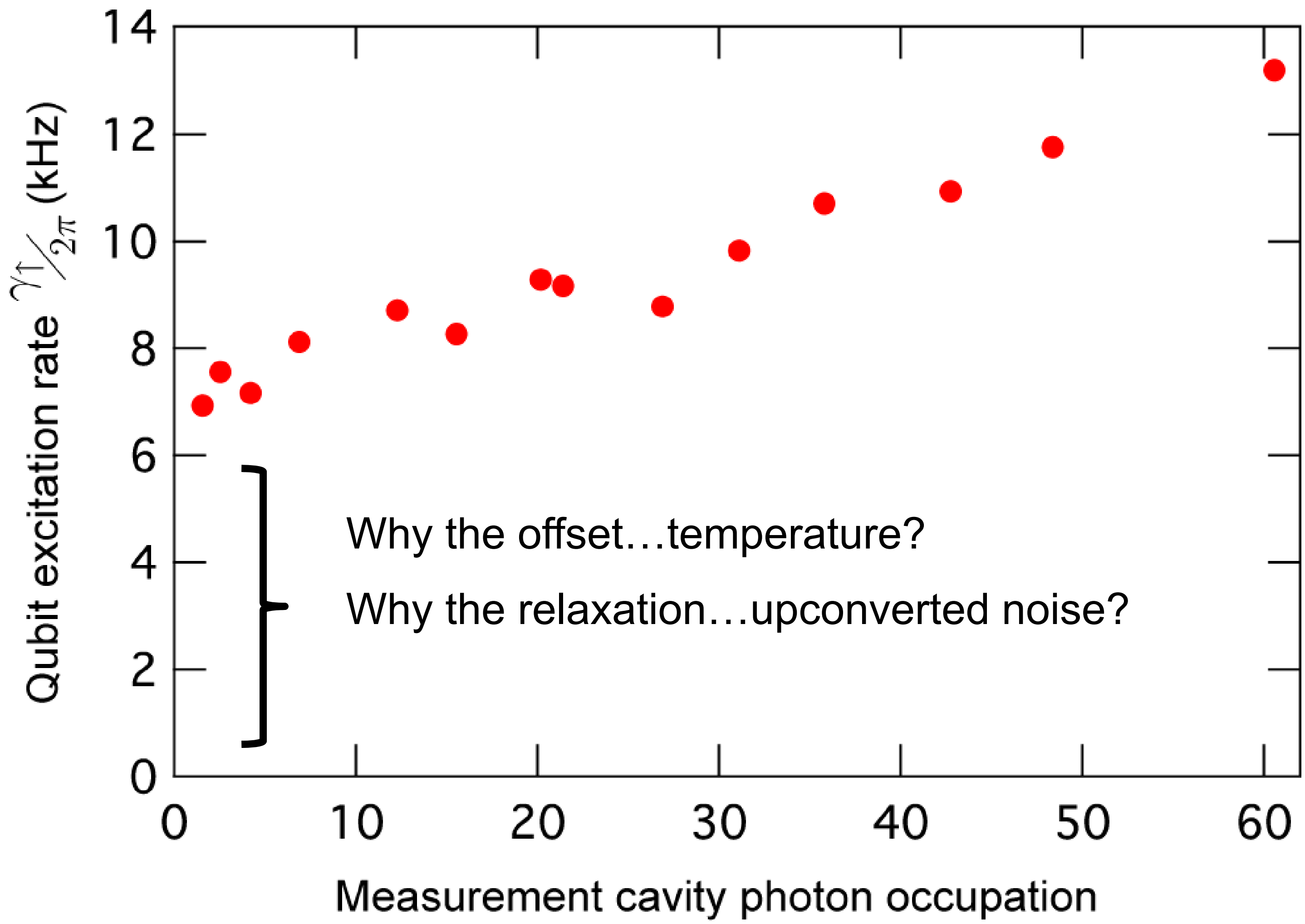
JUMPS WITHOUT PARAMP

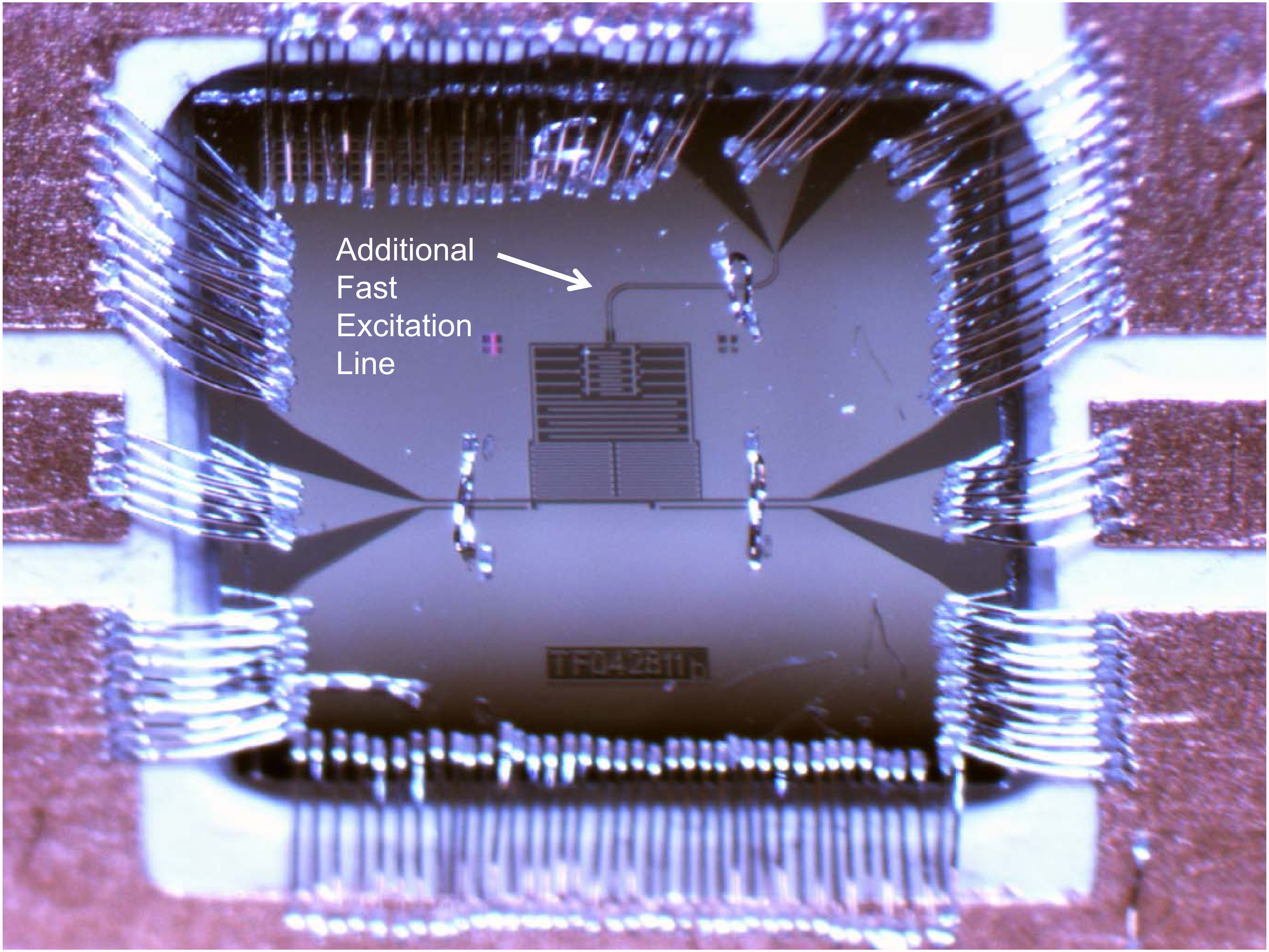


no π pulse

π pulse @ 3 μs

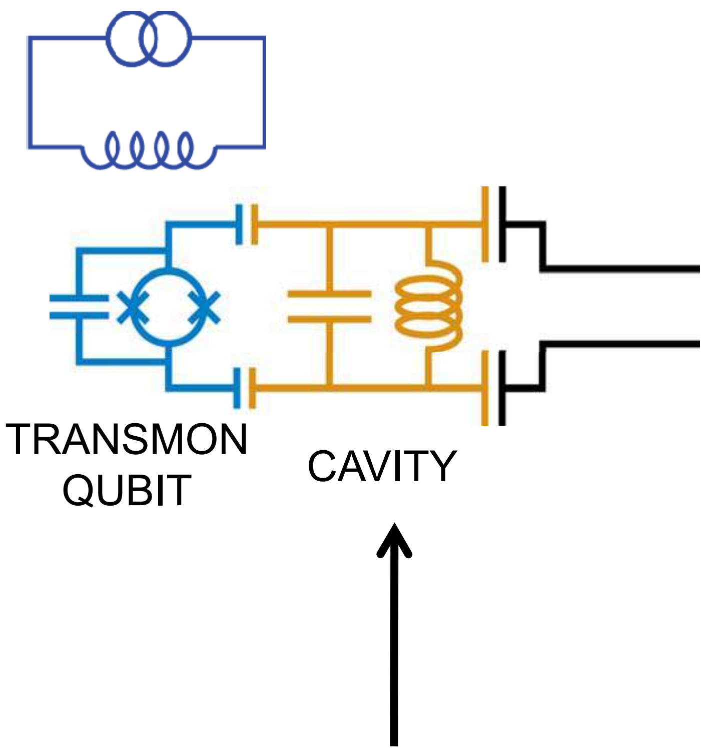
QUBIT EXCITATION RATES



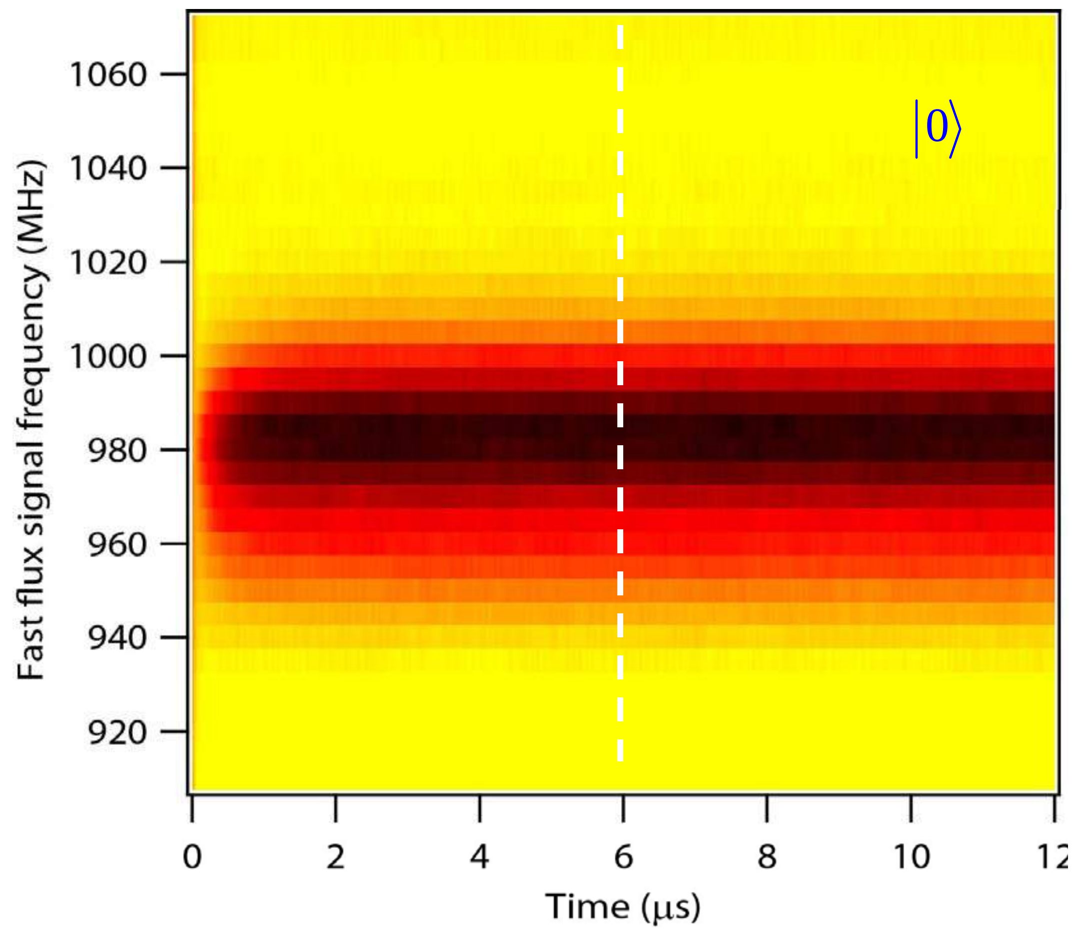

Additional
Fast
Excitation
Line
TF042811b

AVERAGE QUBIT EXCITATION WITH ADDITIONAL FLUX SIGNAL

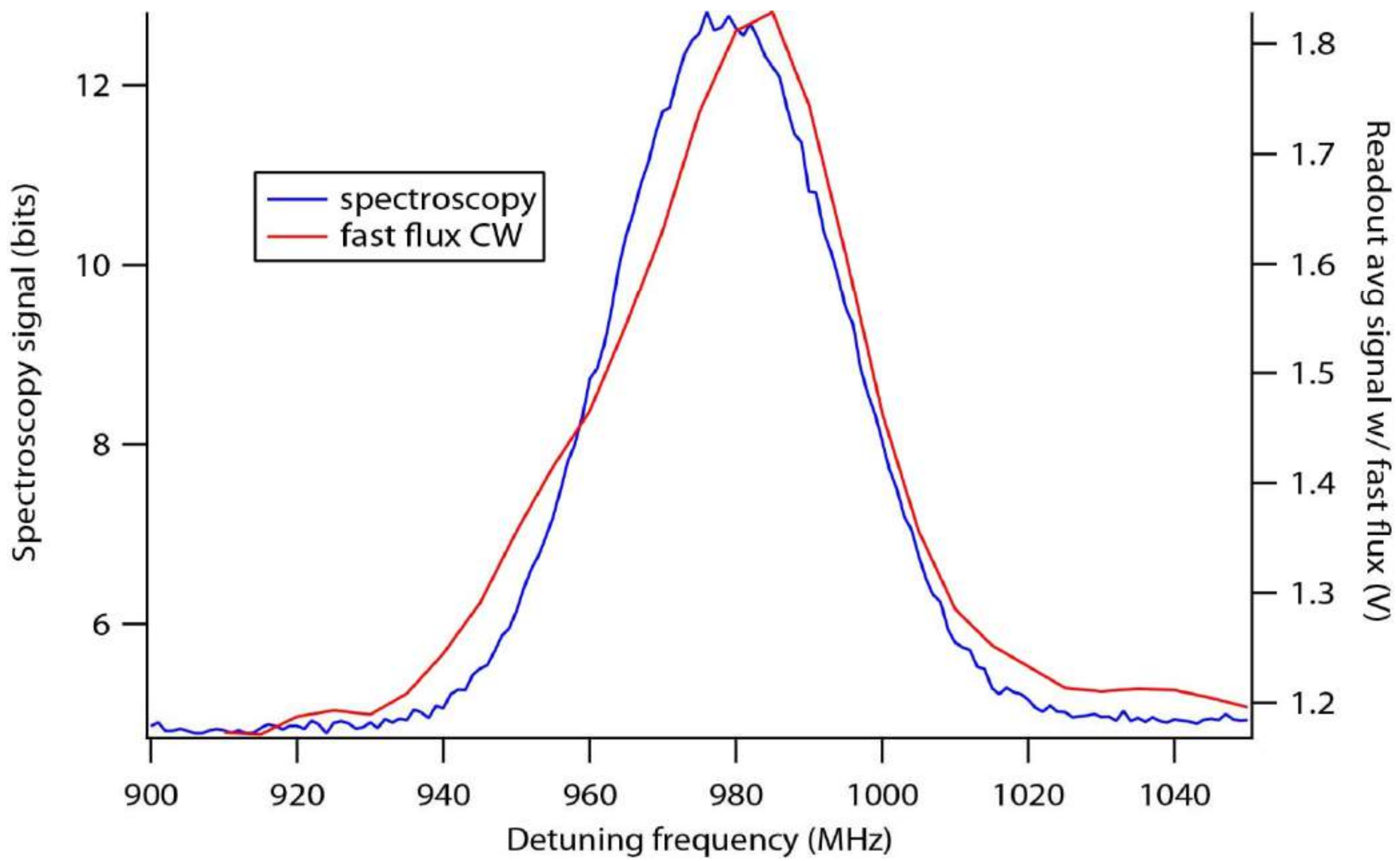
Sweep Fast flux signal



$\bar{n} \approx 10$



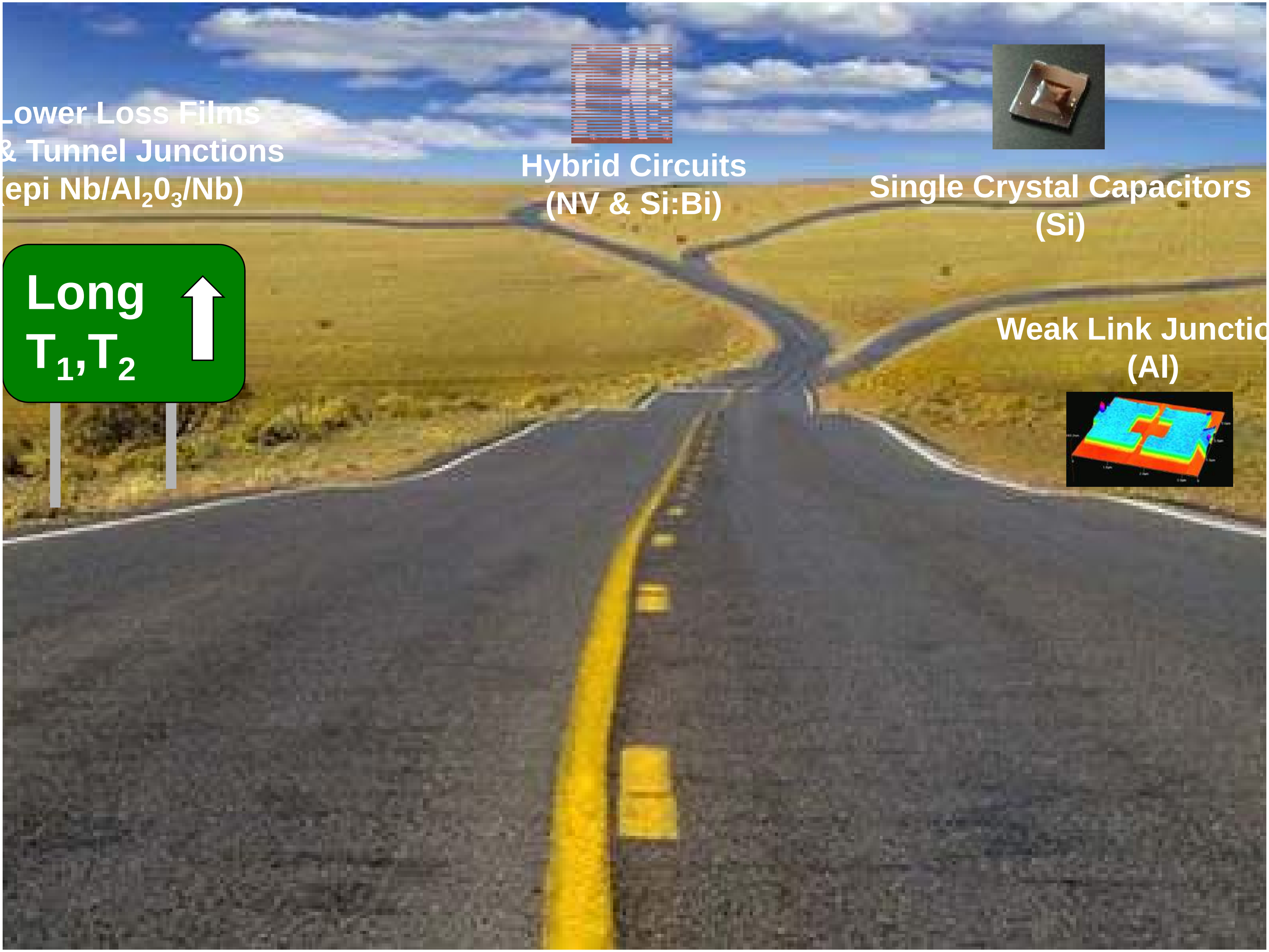
EXCITATION OBSERVED AT CAVITY DETUNING FREQUENCY



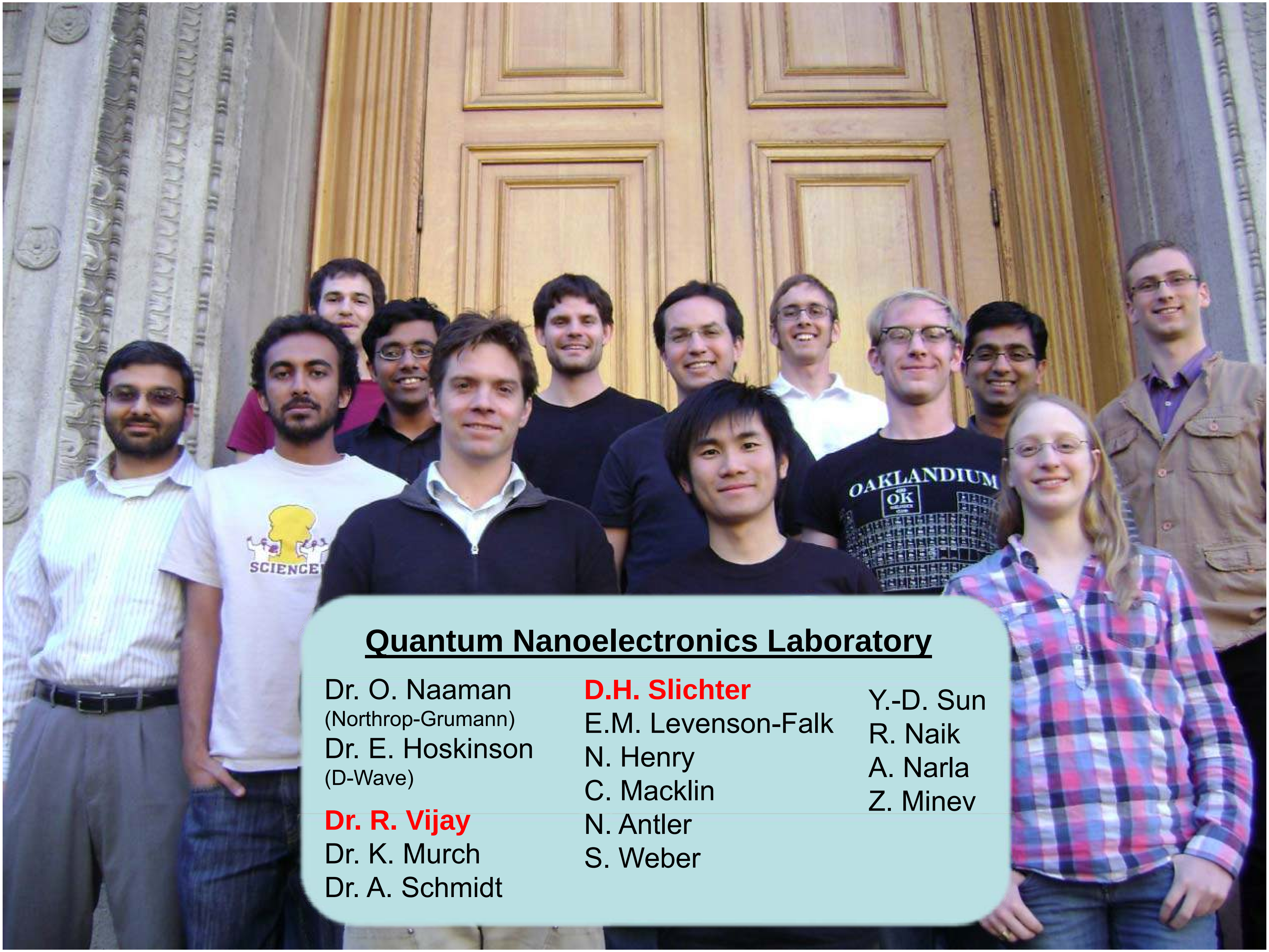
- Model for noise upconversion ? (dressed dephasing)
- Measure noise ~ 1 GHz

FUTURE DIRECTIONS

- DRESSED DEPHASING & QUANTUM ZENO
- QUANTUM FEEDBACK/CONTROL
- MULTIPLEXED QUBIT READOUT
- ON-CHIP PARAMP
  - BACKACTION OF NONLINEAR TANK CIRCUIT



Lower Loss Films
& Tunnel Junctions
(epi Nb/Al_20_3/Nb)
Hybrid Circuits
(NV & Si:Bi)
Single Crystal Capacitors
(Si)
Long
T_1,T_2
Weak Link Junctio
(Al)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