The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA

2164-3

Workshop on Nano-Opto-Electro-Mechanical Systems Approaching the Quantum Regime

6 - 10 September 2010

Measuring the Quantum Harmonic Oscillator

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Measuring the quantum harmonic oscillator

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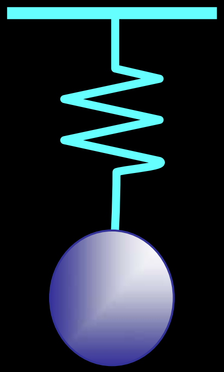
NOEMS in the quantum regime

Abdus-Salam ICTP
Trieste Italy
September 2010

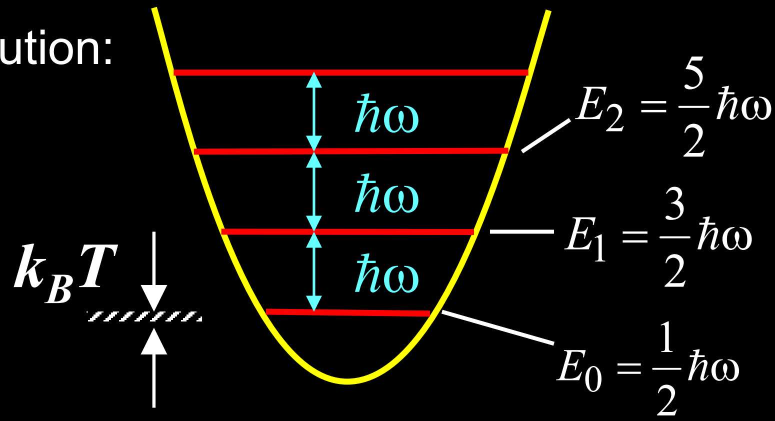
Monday September 6 9:40-10:20

Harmonic oscillator in the quantum limit



Resonance frequency: $\omega = \sqrt{\frac{k}{m}}$

Quantum solution:



Cooling to quantum ground state:

$\hbar\omega >> k_B T$

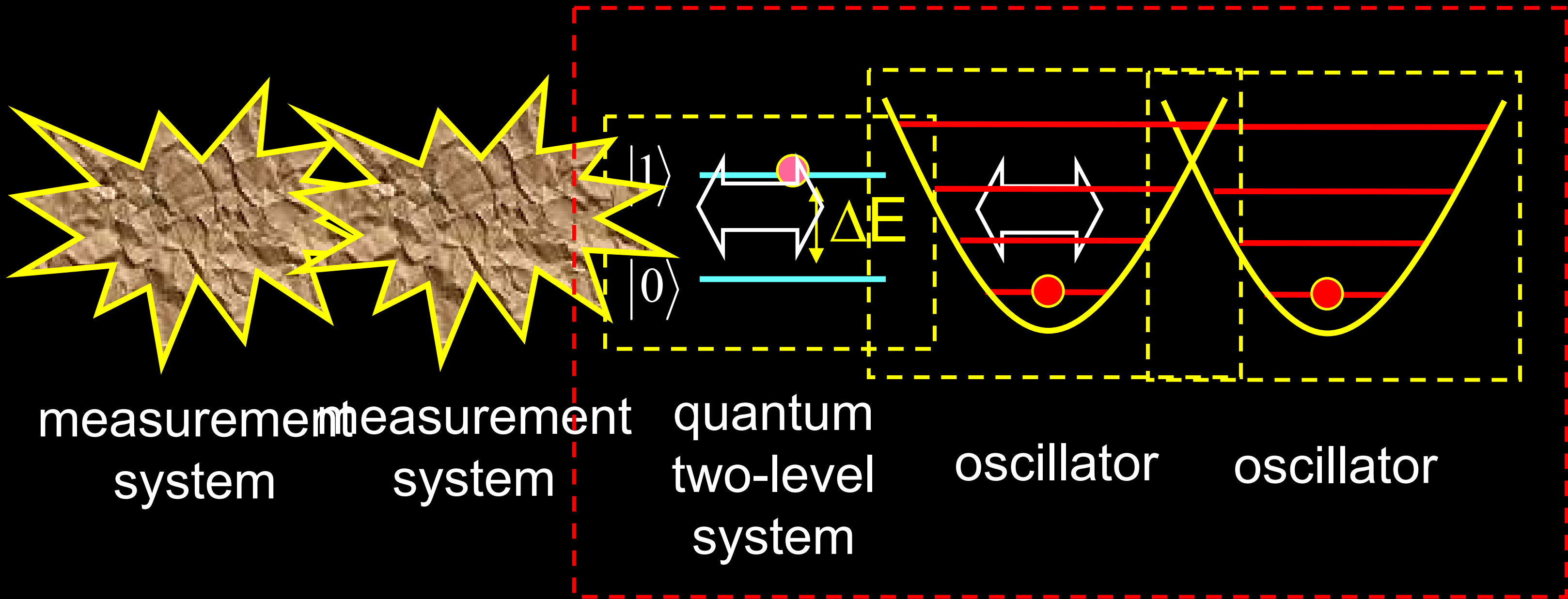
Conventional refrigeration: $T_{min} = 20$ mK ⇒ $\omega/2\pi > 1$ GHz

Control and measurement present significant challenges

- Detection:
  - $\langle x(t) \rangle$ identical in classical & quantum systems (correspondence limit)
- Detecting noise:
  - Amplifier noise & back-action noise dominate (Heisenberg uncertainty)
- Excitations:
  - A classical signal at $\omega/2\pi$ superposes many states (coherent state)

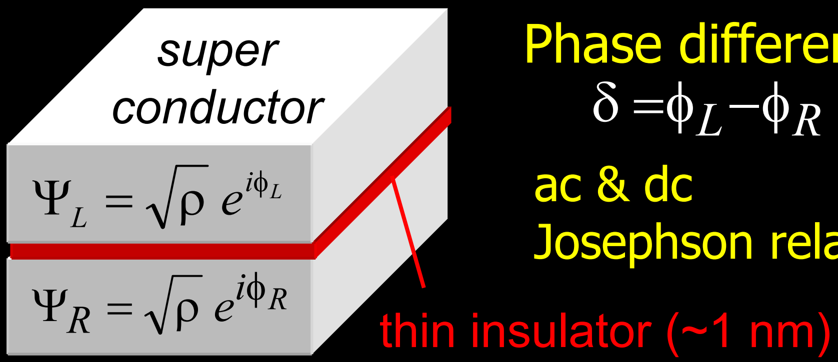
Measuring a harmonic oscillator in the quantum limit

- Measurement system destroys oscillator quantum state
- Interpose quantum two-level system



Coupled system quantum coherent
Allows complete quantum measurement & control

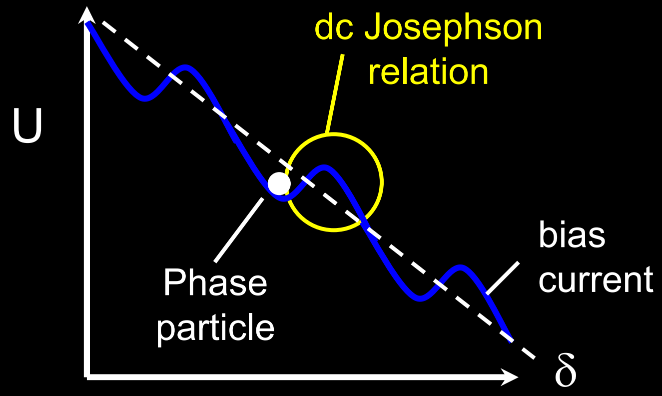
Josephson phase qubit: An electronic two-level system



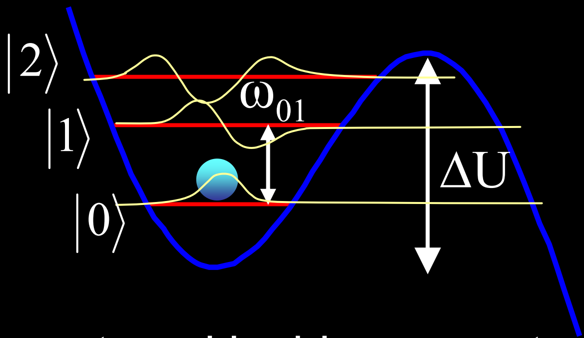
Phase difference

$$\delta = \phi_L - \phi_R$$

ac & dc Josephson relations

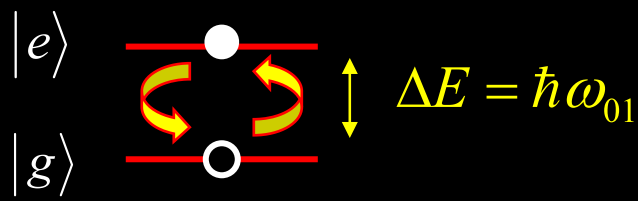


At 20 mK δ is a quantum variable:



- ω_{01} tuned by bias current: 4-10 GHz
- Nonlinearity makes $\omega_{12} \sim 0.95\ \omega_{01}$

Phase qubit for quantum computation

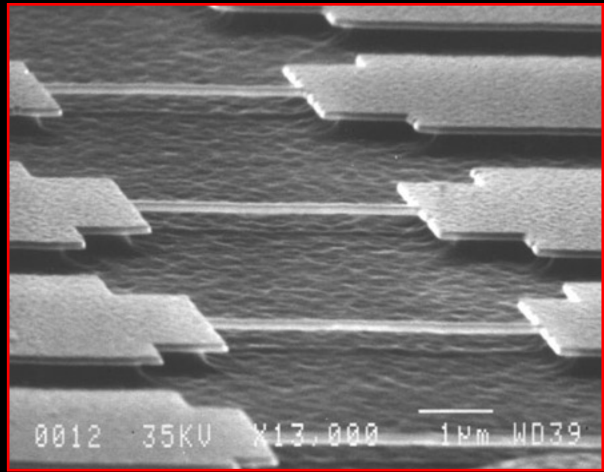


Tunable: 4-10 GHz

Josephson phase qubit ⟷ two-level system

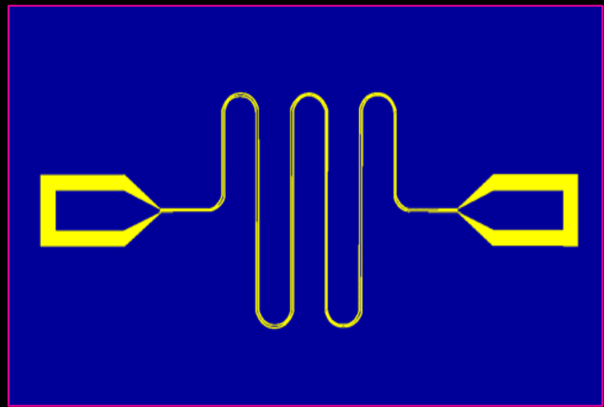
Candidates for quantum harmonic oscillators

- Nanomechanical resonators
  - Resonance frequencies up to ~ 10 GHz
  - Integrable with phase qubit
  - Quanta are *phonons*
  - **Quality factors ~10^3**

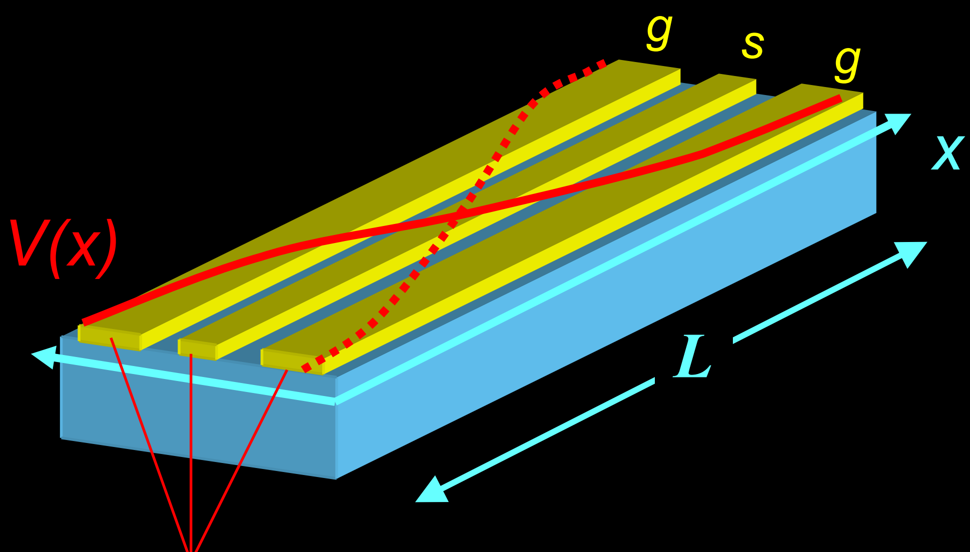


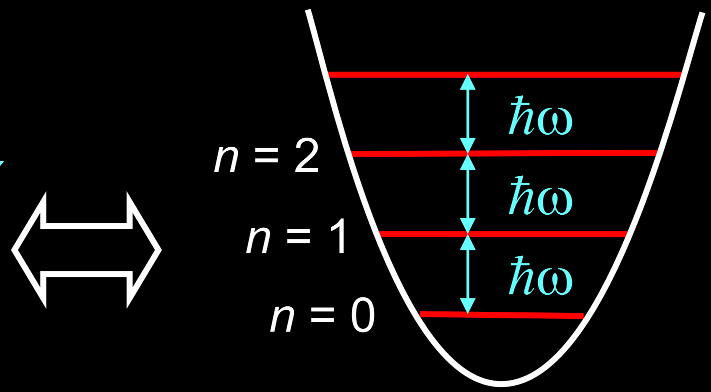
- Electromagnetic resonators
  - Resonance frequencies up to ~100 GHz
  - Integrable with phase qubit
  - Quanta are *photons*
  - **Quality factors ~10^5-10^6**

Max Hofheinz & Haohua Wang

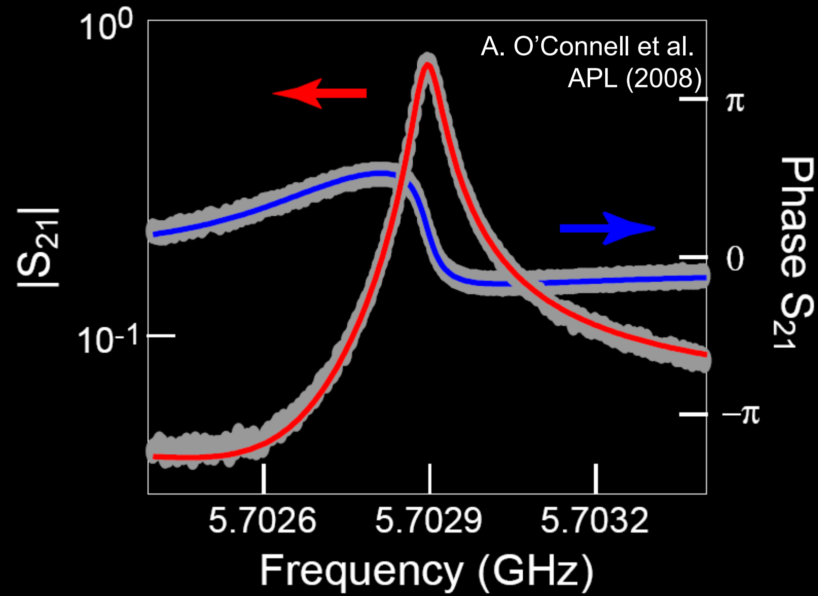


Half-wave coplanar stripline resonator





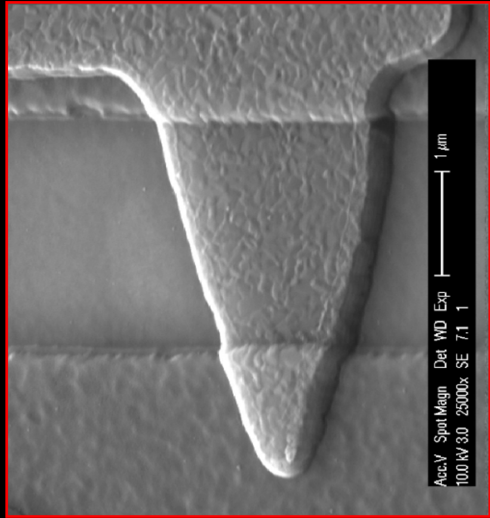
Photons in half-wave mode

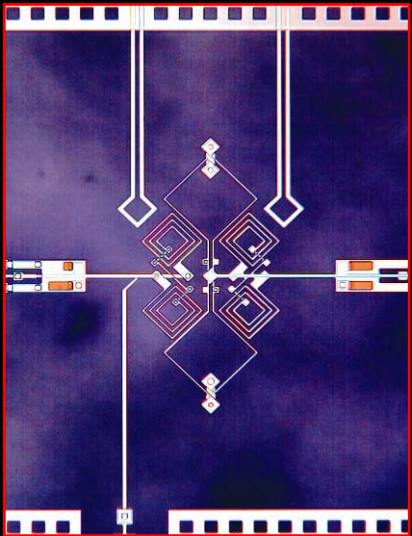


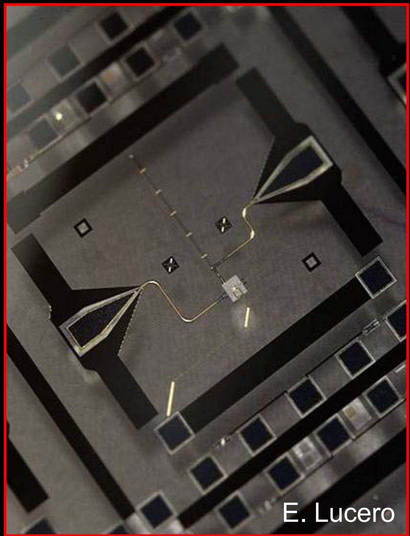
- Wavelength $\lambda = 2L \sim$ 10-15 mm
- Resonance frequency $\omega/2\pi \sim$ 5-10 GHz
- Quality factor $Q \sim 10^5$-10^6
  (determined by dielectric loss)
- Excitation lifetime ~ few μs

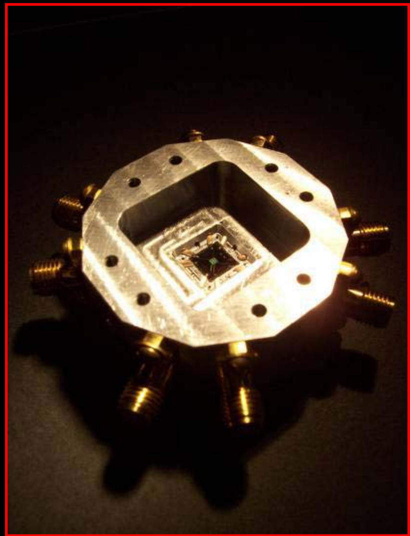
Making & measuring quantum devices

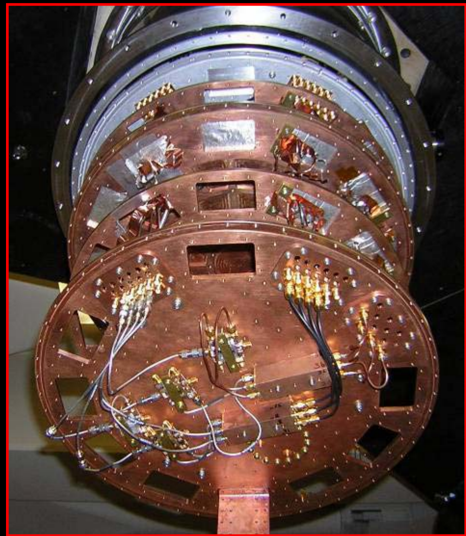
- 8 layers optical lithography, deposition, etching (UCSB Nanofabrication Facility)
- 3″ sapphire wafers
- Diced into ¼″ x ¼″ chips
- Mount on dilution refrigerator (25 mK)
- Control with custom electronics



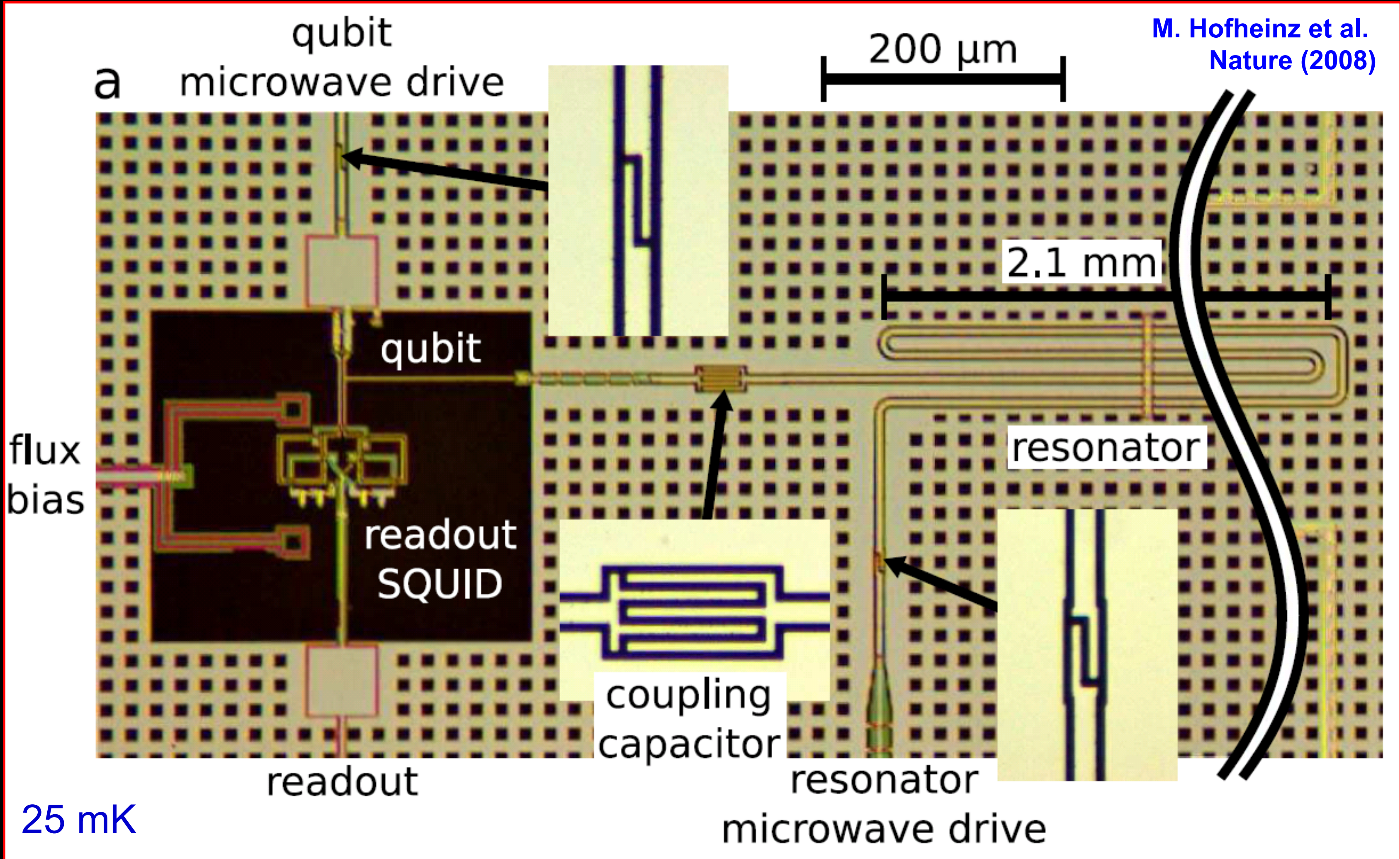




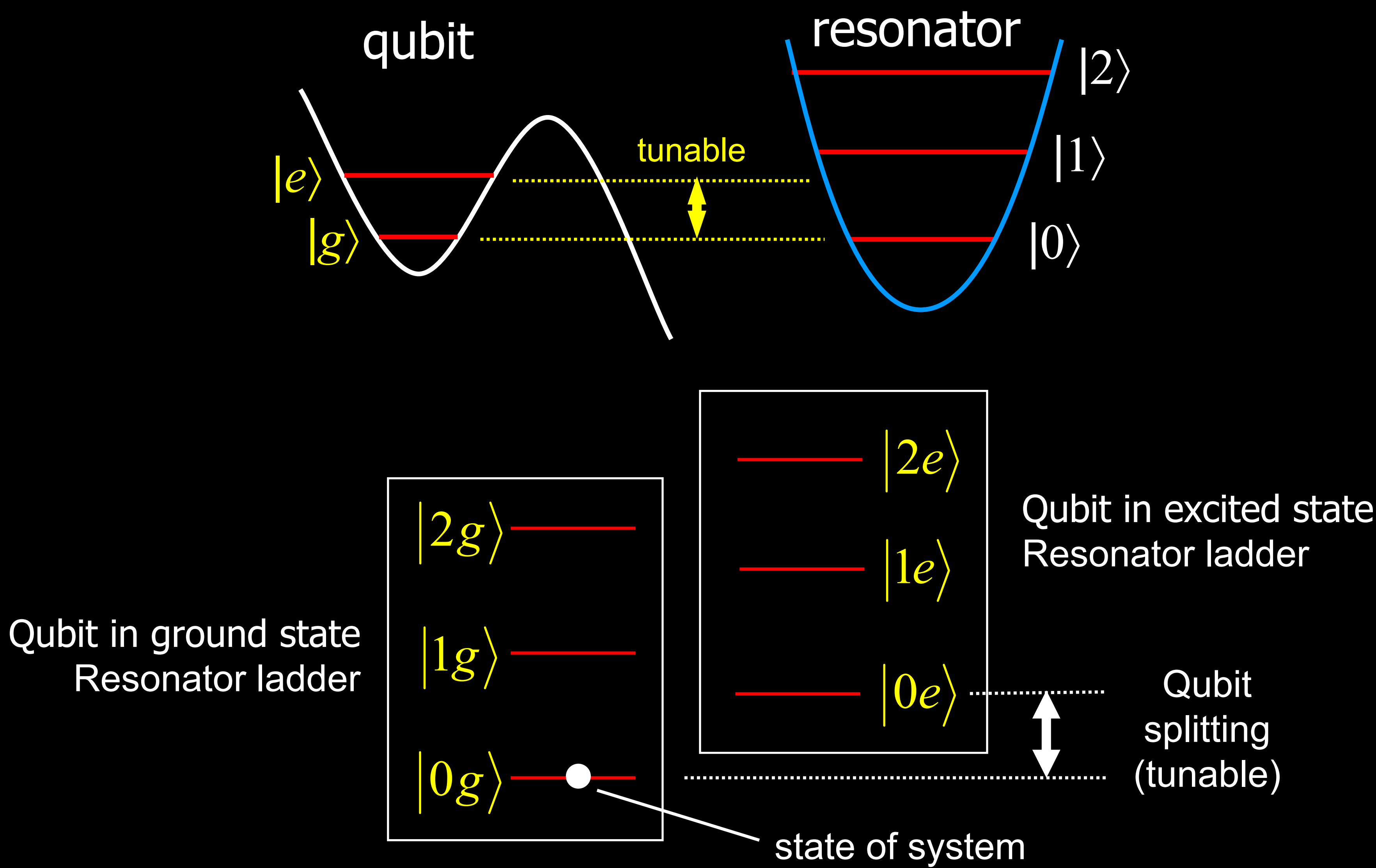




Coupled electromagnetic resonator & Josephson qubit

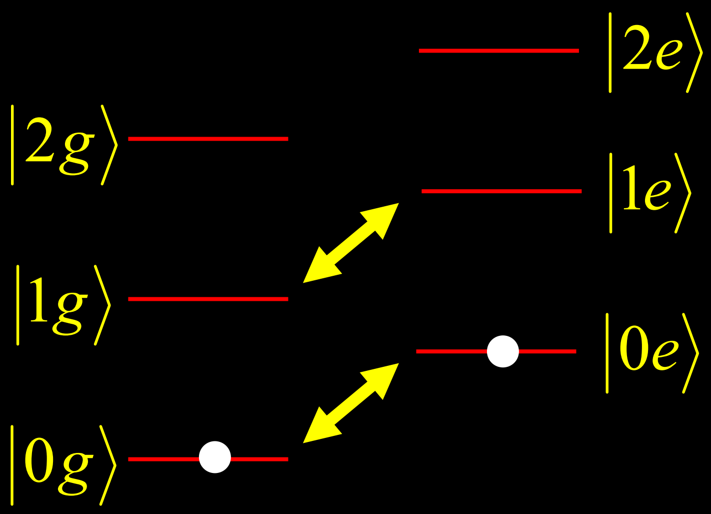


Coupled resonator-qubit energy levels



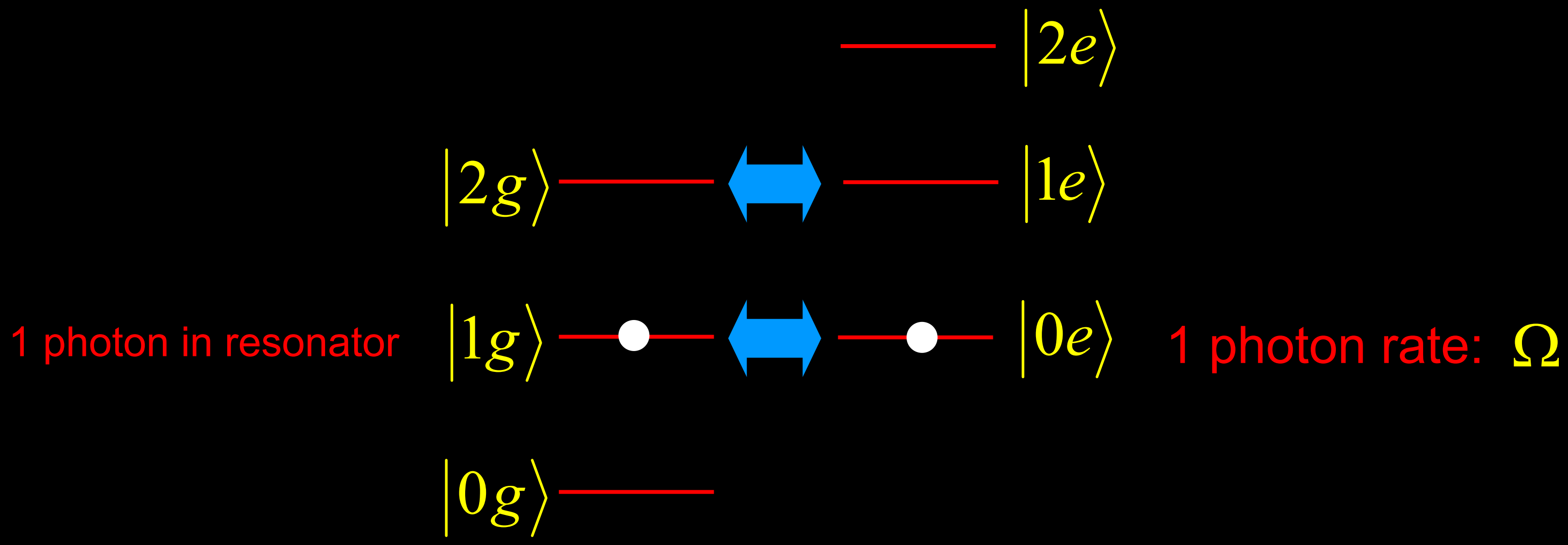
Resonator-qubit time-domain control

- Qubit off resonance (system in $|0g\rangle$ state)
- Apply microwave π pulse to qubit (goes to $|0e\rangle$ state)



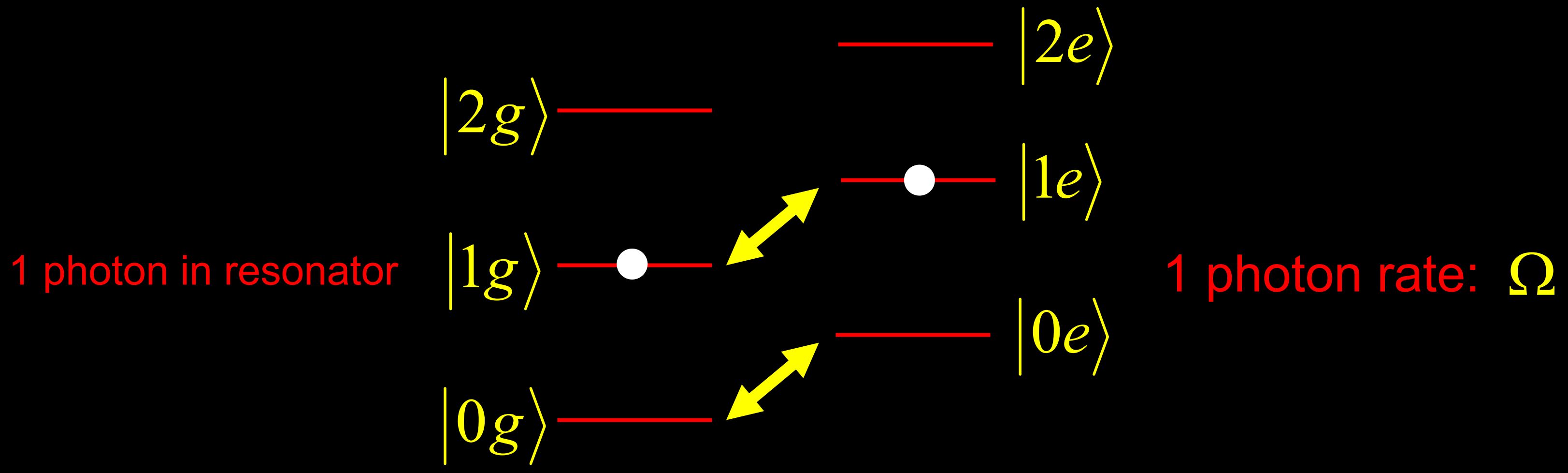
Resonator-qubit time-domain control

- Qubit off resonance (system in $|0g\rangle$ state)
- Apply microwave π pulse to qubit (goes to $|0e\rangle$ state)
- Tune qubit to resonator frequency
- Rabi oscillation: Transfer photon from qubit to resonator



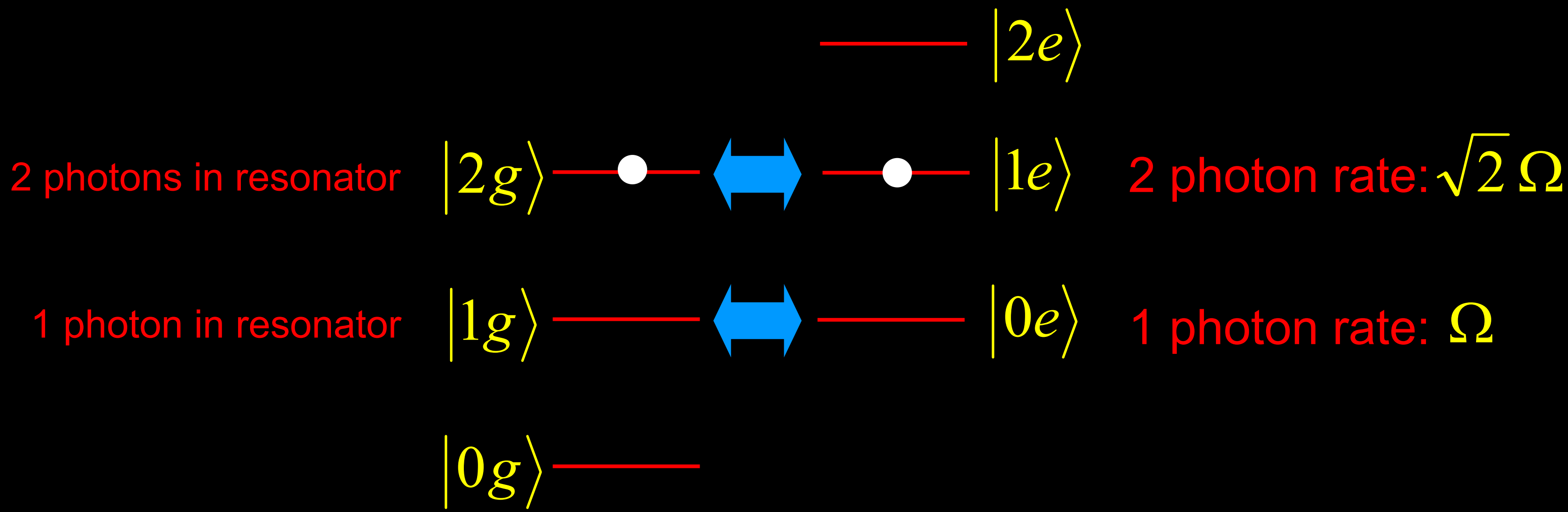
Adding more photons

- Detune qubit (system in $|1g\rangle$ state)
- Apply microwave π pulse to qubit (goes to $|1e\rangle$ state)



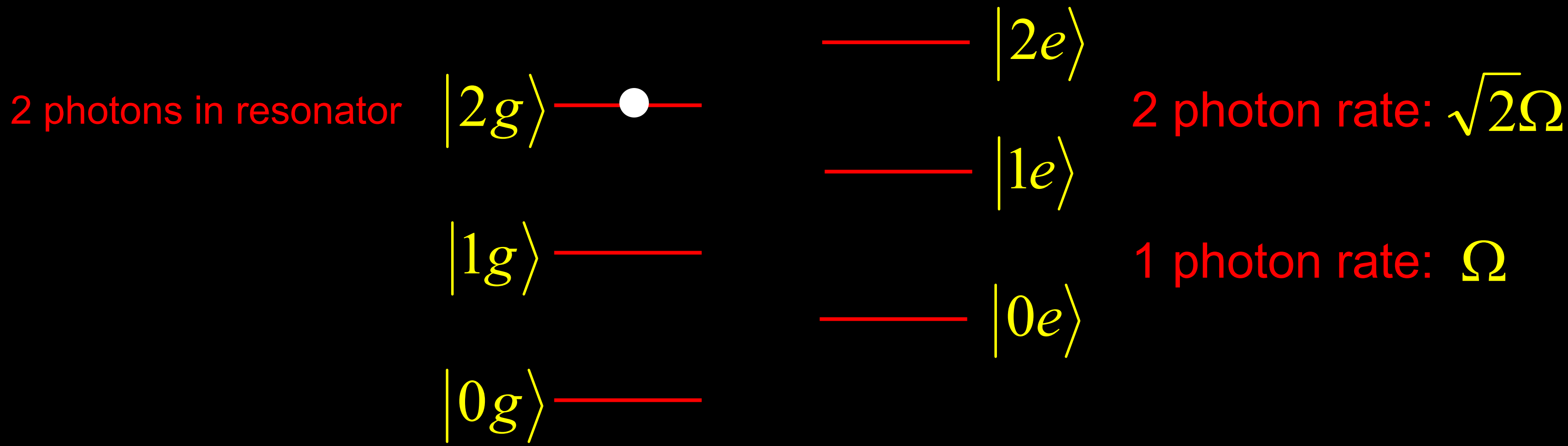
Adding more photons

- Detune qubit (system in $|1g\rangle$ state)
- Apply microwave π pulse to qubit (goes to $|1e\rangle$ state)
- Tune qubit to resonator, Rabi (goes to $|2g\rangle$ state)



Adding more photons

- Detune qubit (system in $|1g\rangle$ state)
- Apply microwave π pulse to qubit (goes to $|1e\rangle$ state)
- Tune qubit to resonator, Rabi (goes to $|2g\rangle$ state)
- Repeat for *n* photons: Each transfer $\sqrt{n}$ faster



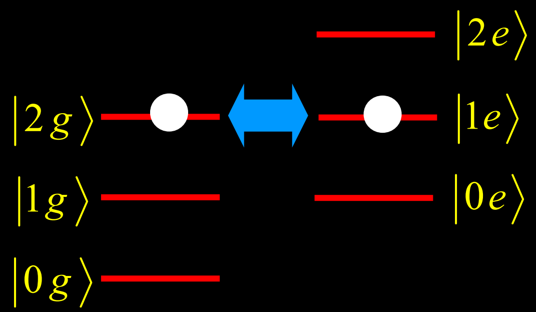
Pumping photons: n = 1 to 12 Fock states

Measurement of resonator state:

M. Hofheinz et al.
Nature (2008)

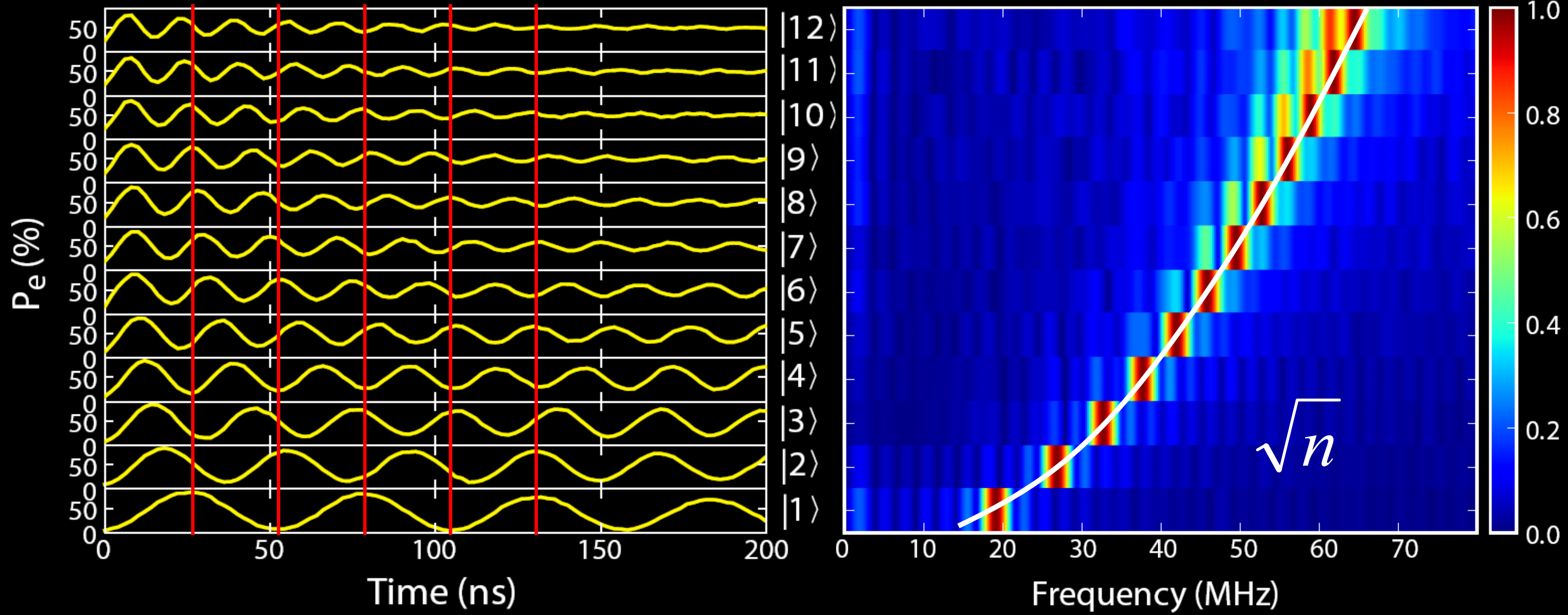
Bring ground-state qubit into resonance with resonator

2 photons in resonator
Qubit ground state



1 photon in resonator
Qubit excited state

Oscillation at $\sqrt{n}\,\Omega$

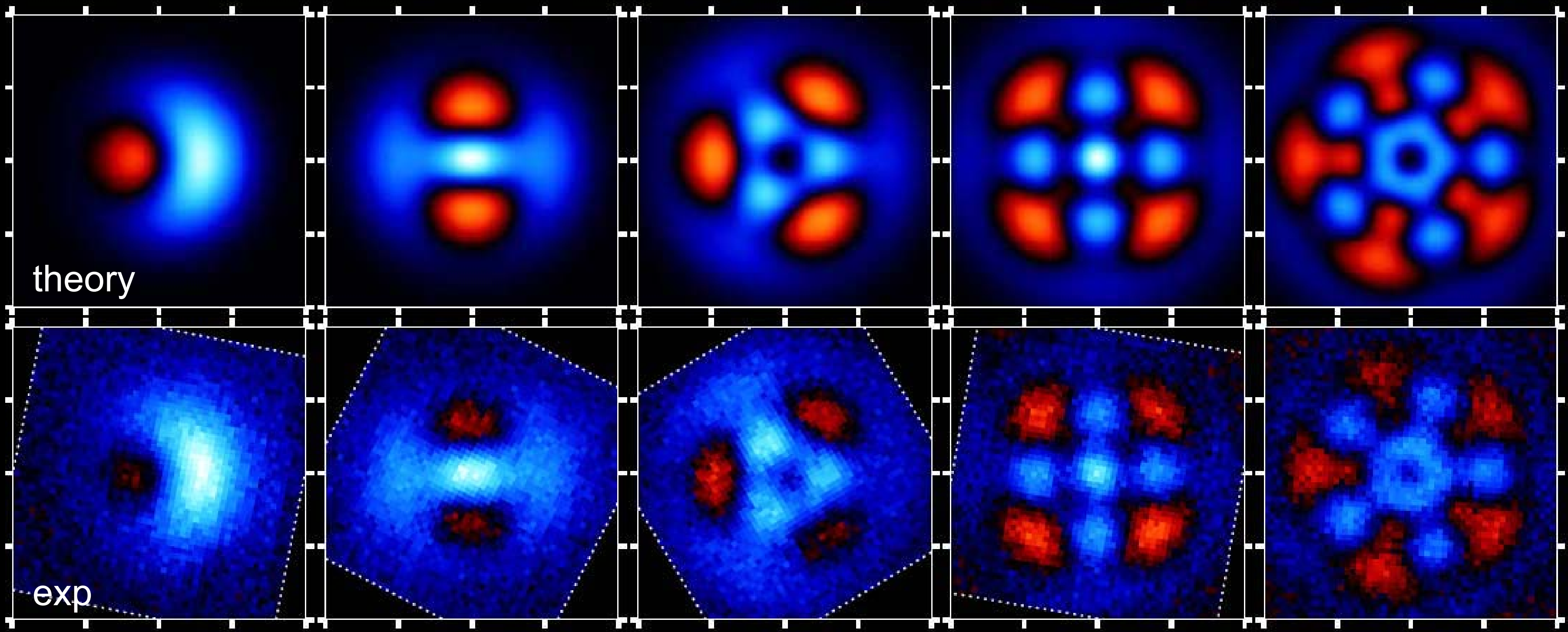


Superpositions by Wigner tomography

Prepare and measure $|0\rangle + |n\rangle$ states in resonator

M. Hofheinz et al.
Nature (2009)

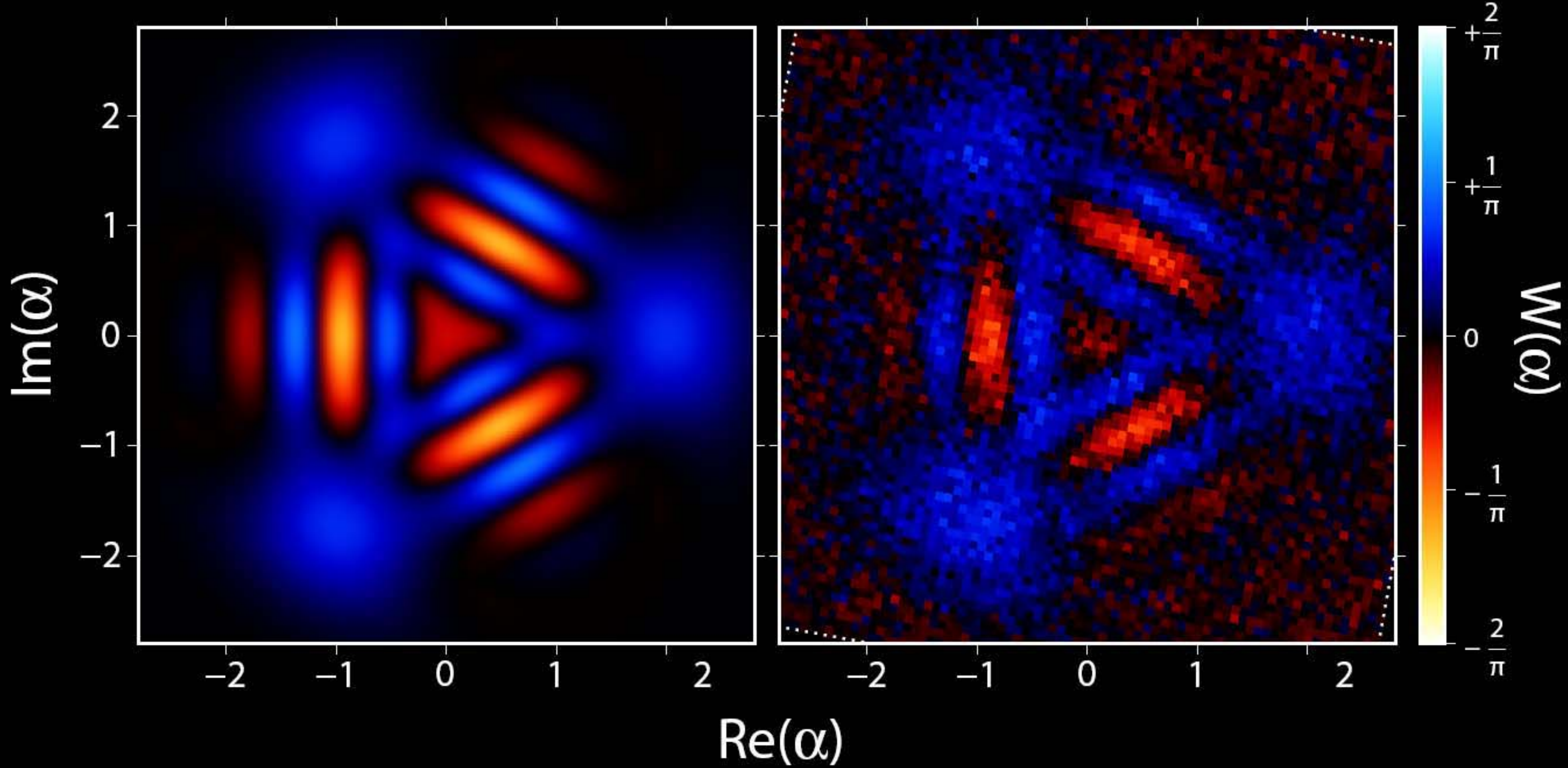
$|\psi\rangle = |0\rangle + |1\rangle$ $|\psi\rangle = |0\rangle + |2\rangle$ $|\psi\rangle = |0\rangle + |3\rangle$ $|\psi\rangle = |0\rangle + |4\rangle$ $|\psi\rangle = |0\rangle + |5\rangle$



“Voodoo” cat state: Alive + dead + zombie

alive dead zombie

$$|\psi\rangle = |\alpha = 2\rangle + |\alpha = 2e^{2\pi i3}\rangle + |\alpha = 2e^{4\pi i/3}\rangle$$



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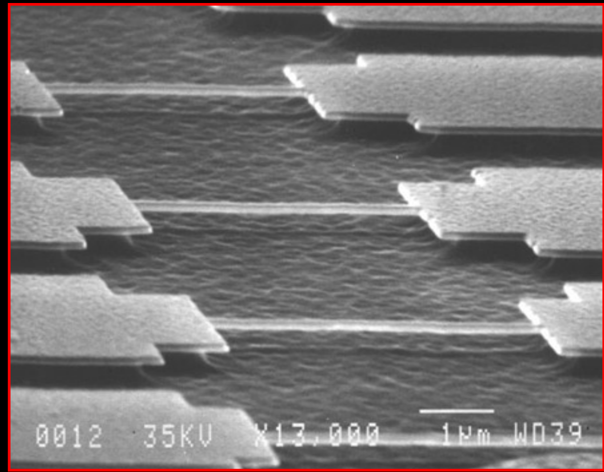

Aaron O'Connell

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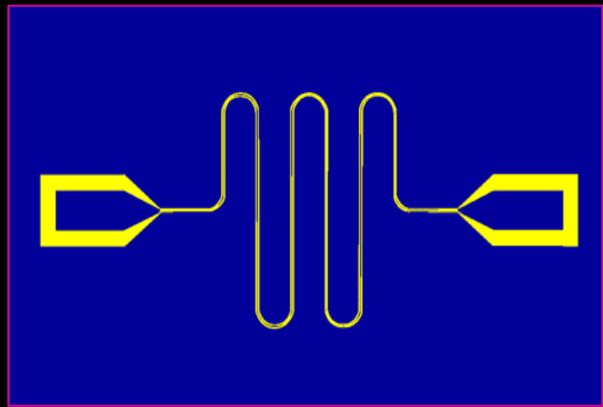


Max Hofheinz

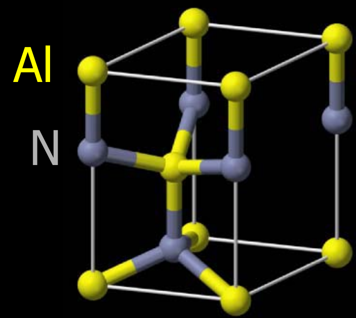
Mechanical quantum oscillator

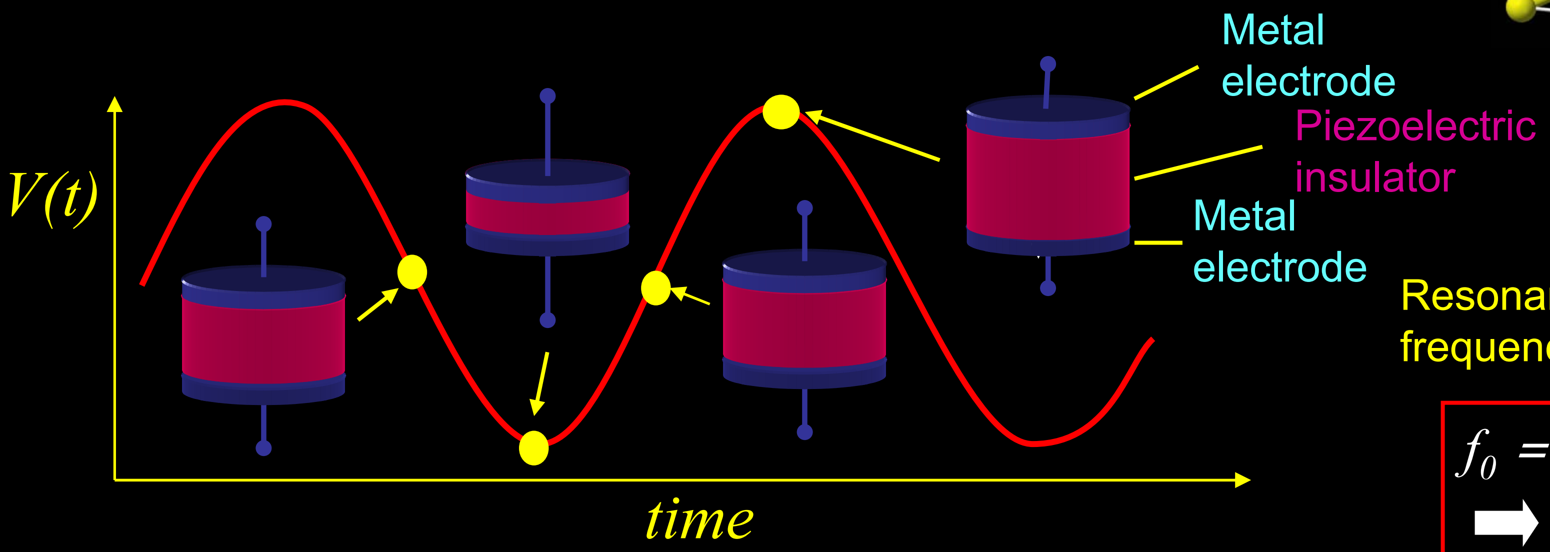
Requirements for mechanical oscillator:

- Resonance frequency >> 1 GHz (want 6-7 GHz)
- Strong coupling of mechanics to electronics
- Testable in classical regime

Our approach:

- Piezoelectric coupling: aluminum nitride
- Dilatational acoustic resonator (FBAR)





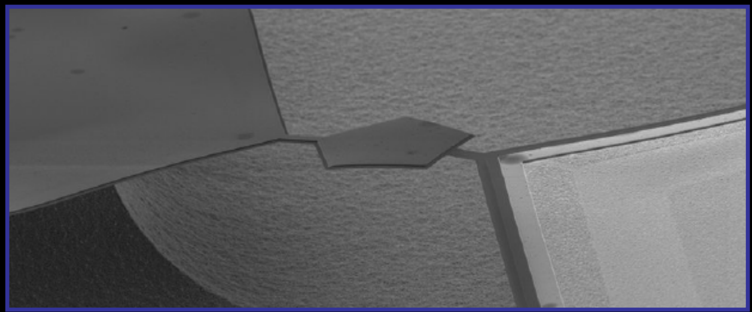
Resonance frequency $f_0 \approx \frac{c}{2t}$ (c: sound speed)

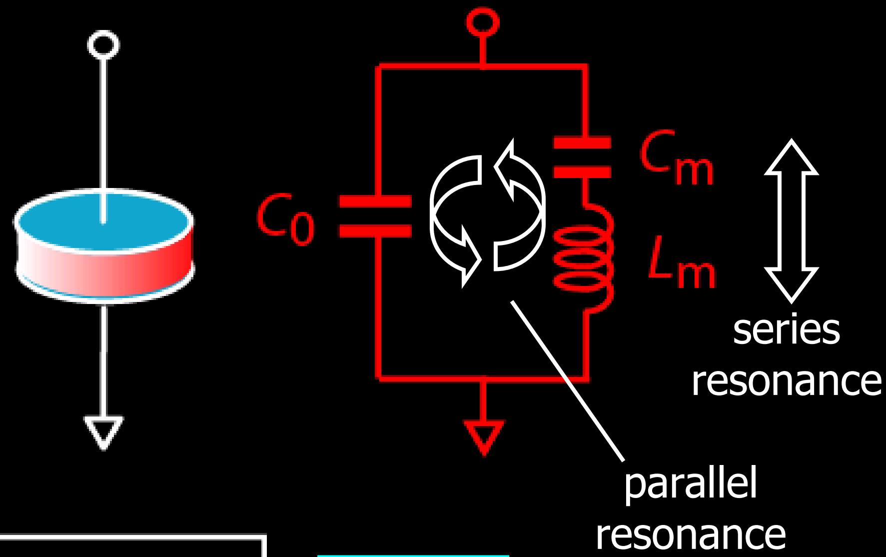
f_0 = 6 to 7 GHz

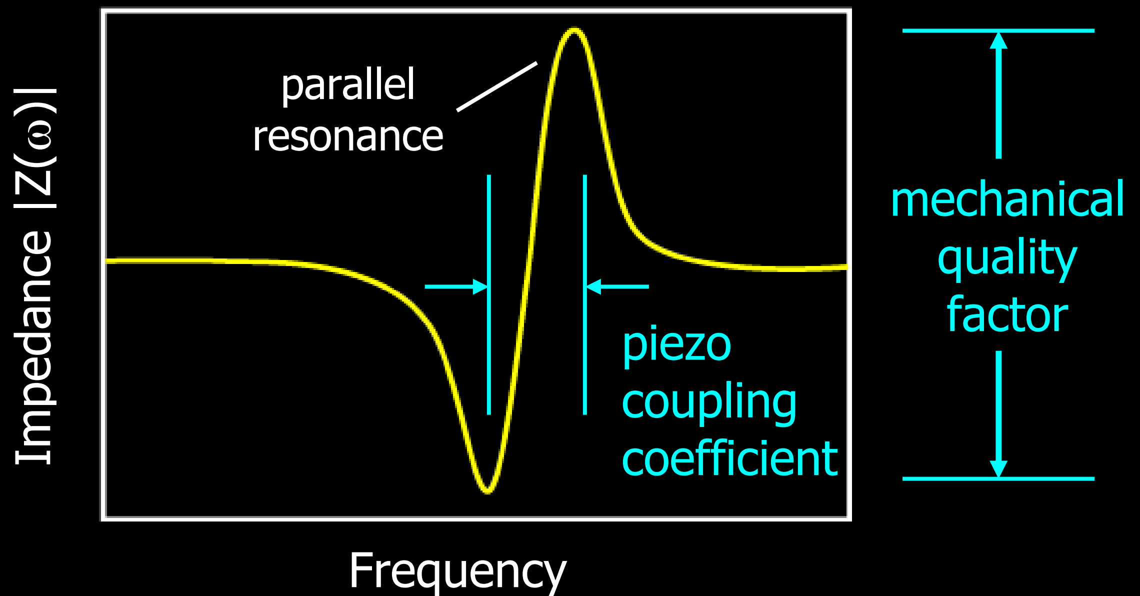
➡ t = 0.8 μm

Resonator equivalent circuit

Electrical equivalent circuit:





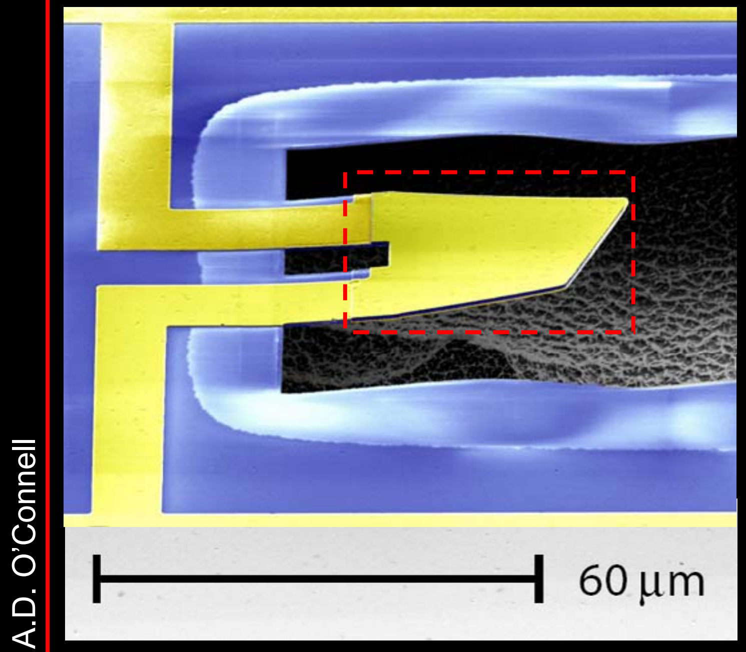


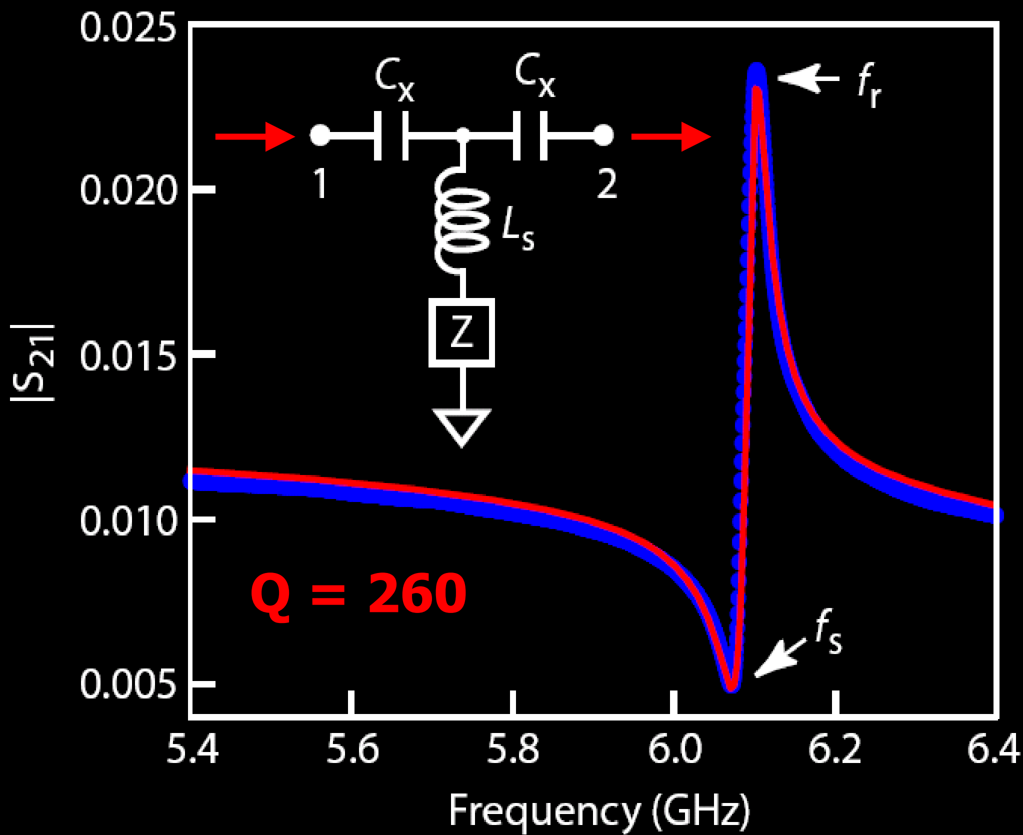
Mechanical quantum oscillator

- Al top & bottom electrodes
- Sputtered AlN piezoelectric
- XeF_2 substrate release
- 4-7 GHz fundamental resonance
- Integrable with qubit fabrication

A.D. O'Connell et al. Nature (2010)

diameter 35 μm mass 20 ng





Six billionths of a second

Electromagnetic resonator: Q ~ 10^5

Energy lifetime $T_1 = \frac{Q}{2\pi f_r} = 2\ \mu\text{s}$

Qubit-resonator photon transfer time ~25 ns (20 MHz coupling)

Lots of time for complex experiments (~40 gate operations)

Mechanical resonator: Q ~ 260

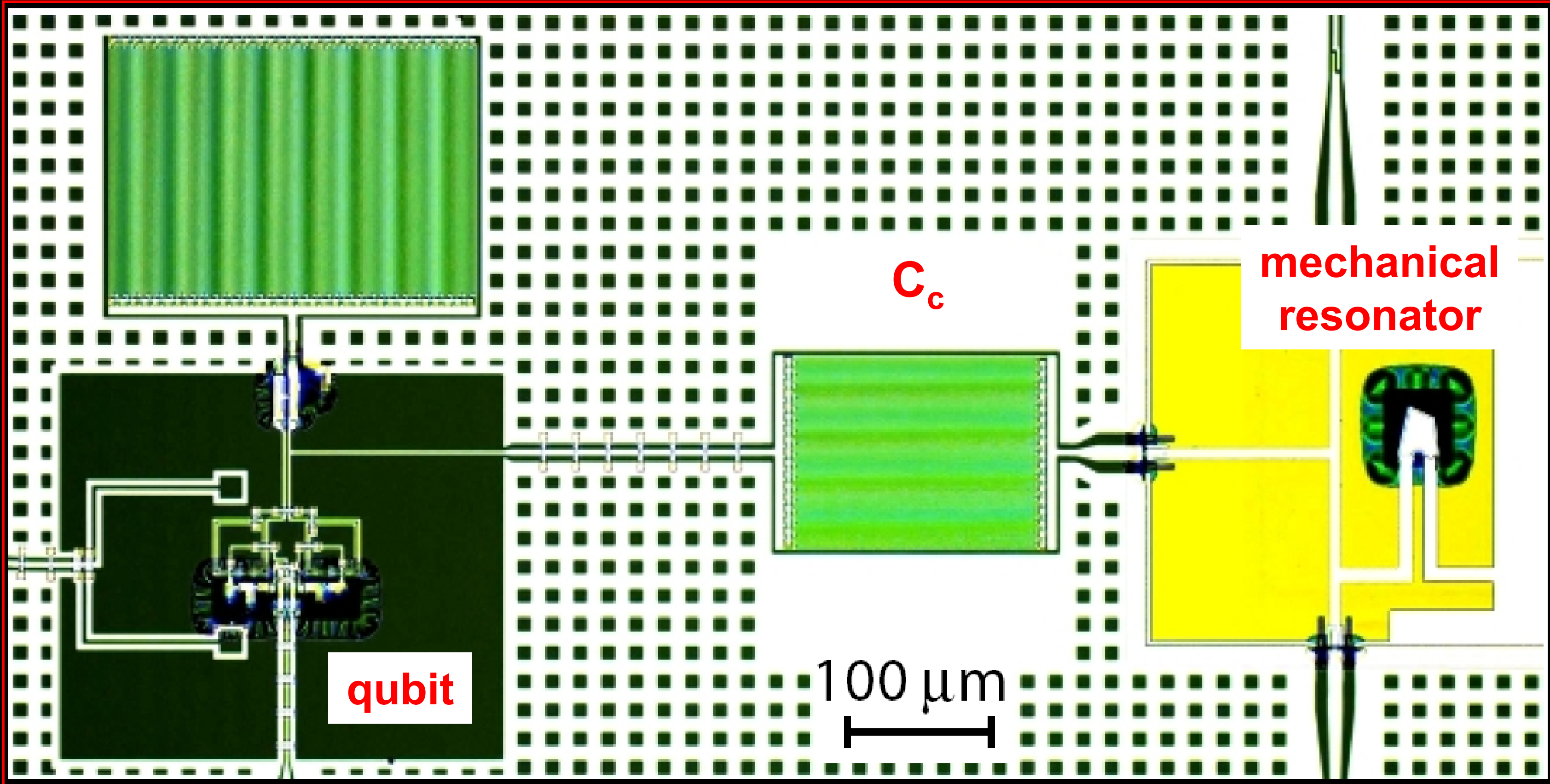
Energy lifetime $T_1 = \frac{Q}{2\pi f_r} = 6.7\ \text{ns}$

- Fast energy transfer
- Fast measurement
- Strong qubit-resonator coupling

➢ Target gate time: ~ 5 ns to transfer excitation (~100 MHz coupling)

Integrated resonator & qubit

A.D. O'Connell et al. Nature (2010)

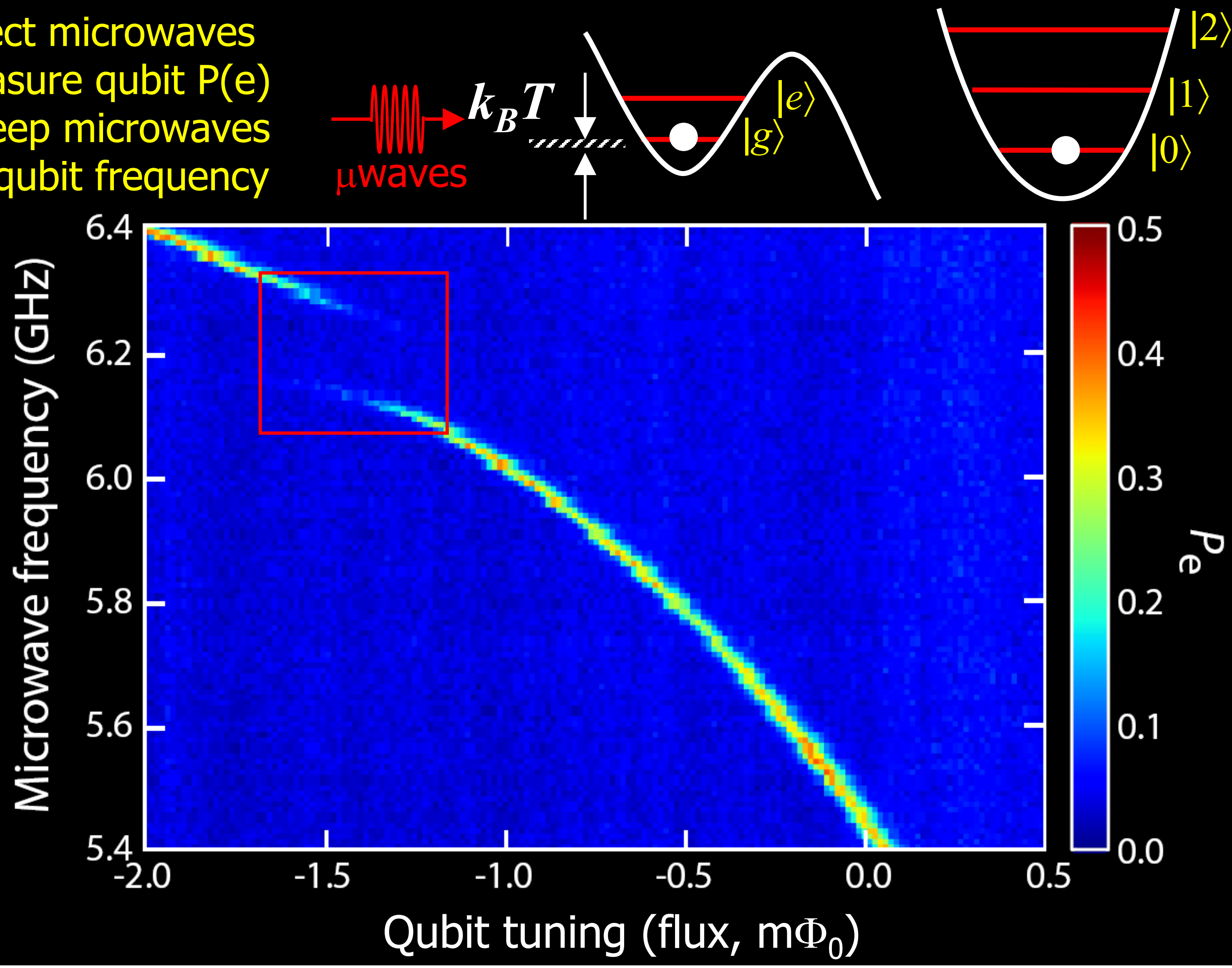


- Fabricate resonator, then qubit (13 layers)
- Suspend resonator at end
- Qubit & SQUID also mechanically suspended

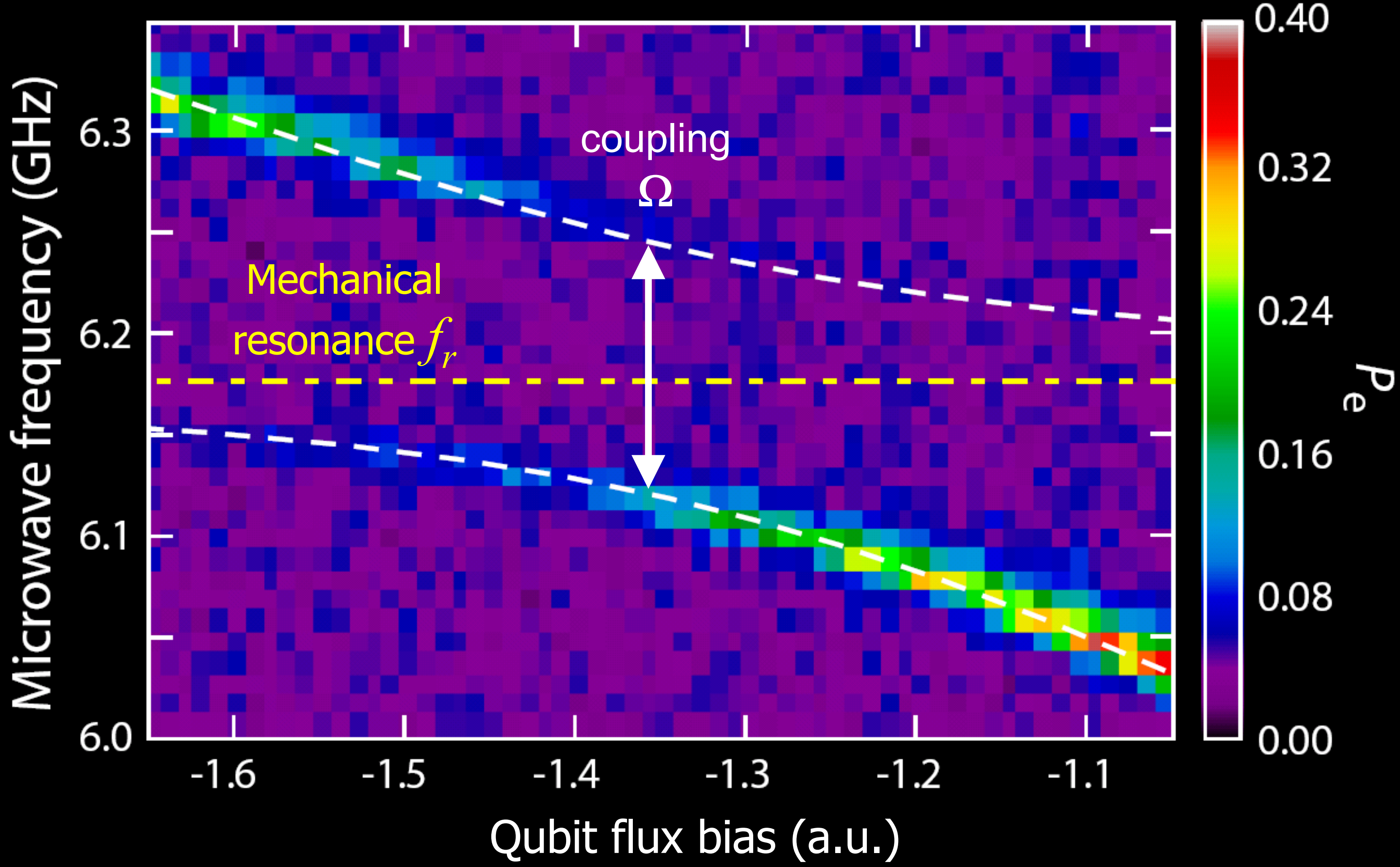
Design parameters:
Resonator 6.1 GHz
Coupling 110 MHz

Spectroscopy of coupled system

- Inject microwaves
- Measure qubit P(e)
- Sweep microwaves & qubit frequency



Spectroscopy of coupled system

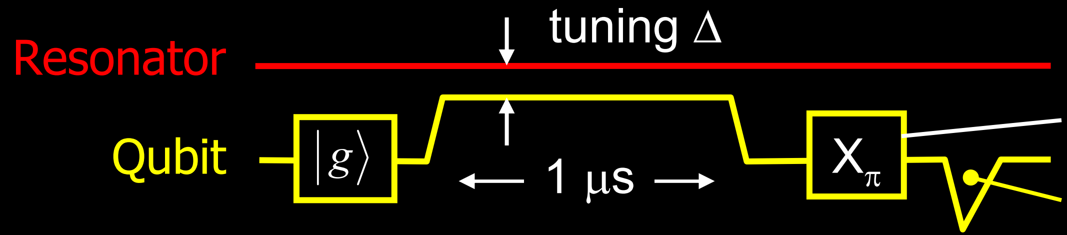


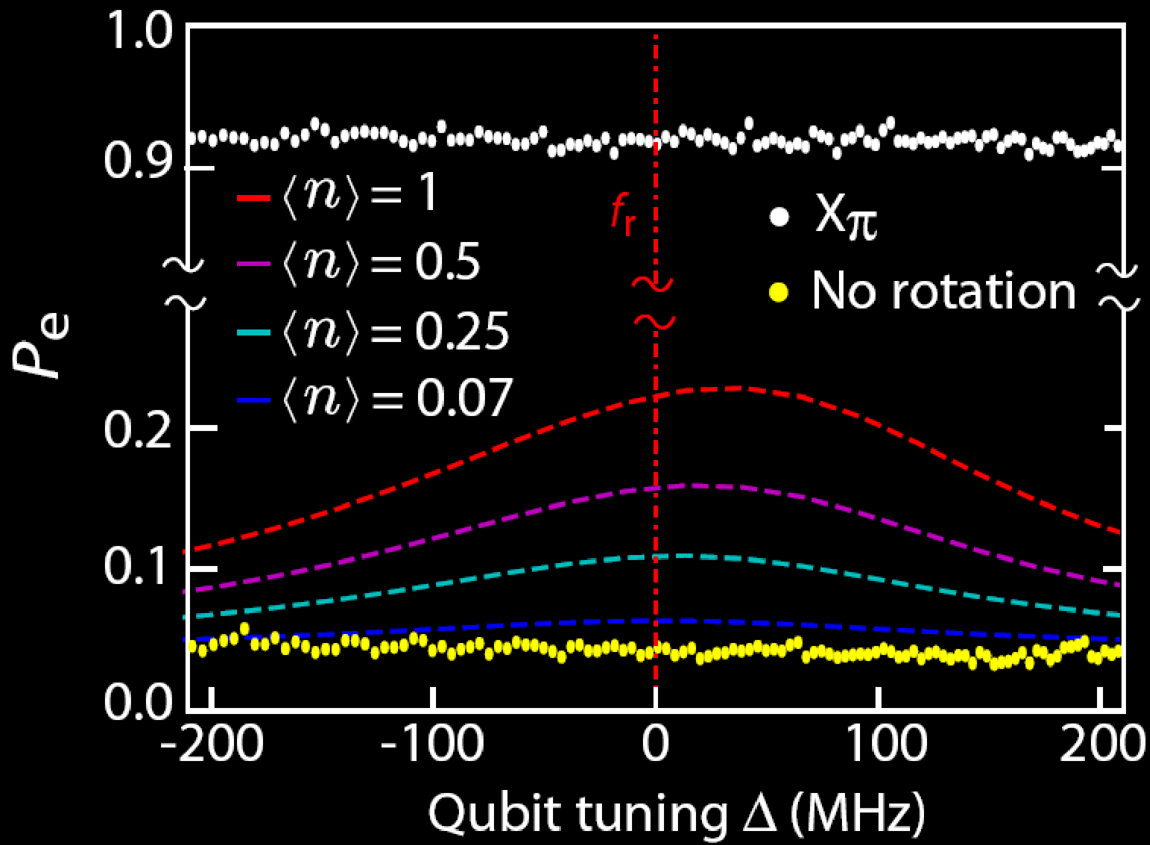
Mechanical resonance $f_r = 6.175$ GHz   Coupling strength $\Omega = 124$ MHz

Quantum thermometry of mechanical resonator

A.D. O'Connell et al., Nature (April 1 2010)

Pulse sequence:





With no X_π swap:

- Qubit always in $|g\rangle$ state

With X_π swap:

- Qubit always in $|e\rangle$ state

Thermal occupation:

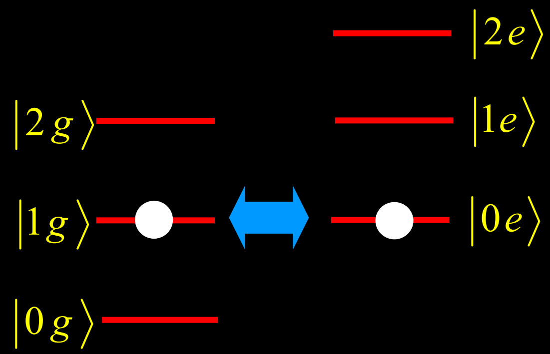
- Less than 0.07 phonons
- Maximum ~ 0.01 phonons

Mechanical resonator in quantum ground state

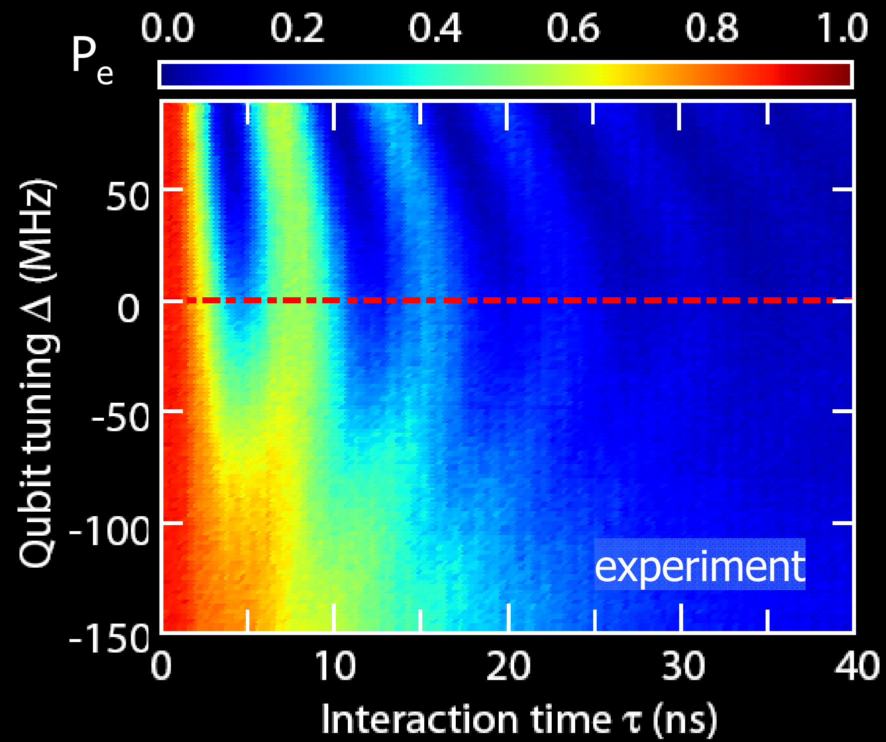
Electromechanical Rabi oscillations

A.D. O'Connell et al., Nature (April 1 2010)

- **Qubit in $|g\rangle$**
- **Tune to Δ of resonator**
- **Wait & measure:**



Oscillation period: $T = \dfrac{1}{\sqrt{\Omega^2 + \Delta^2}}$



Electromechanical Rabi oscillations

A.D. O'Connell et al., Nature (2010)

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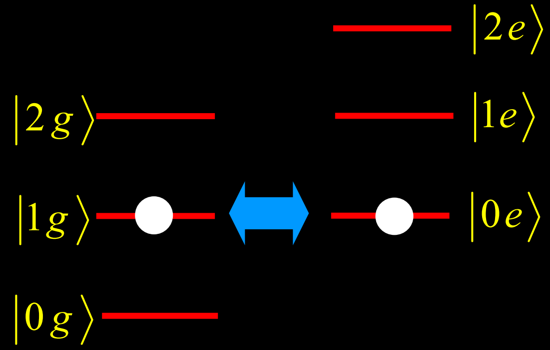

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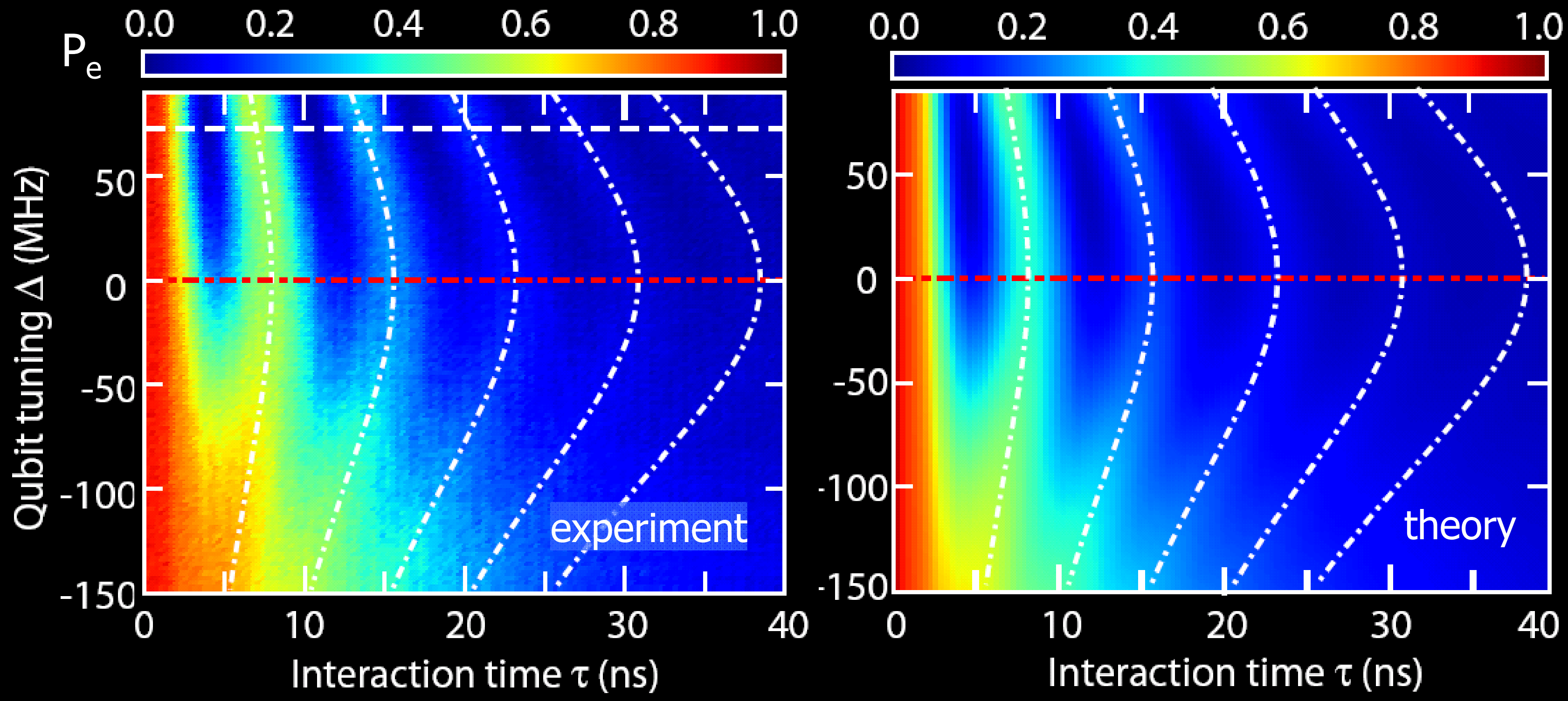

Electromechanical Rabi oscillations

A.D. O'Connell et al.,
accepted, Nature (2010)

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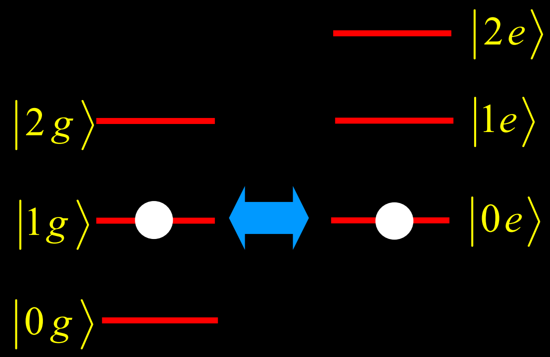

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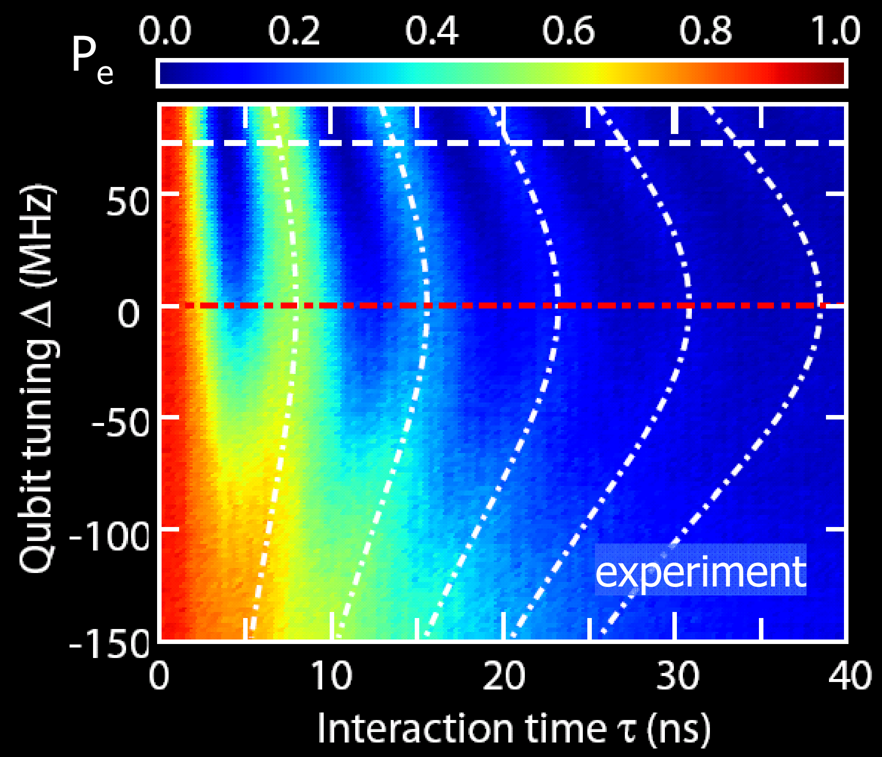
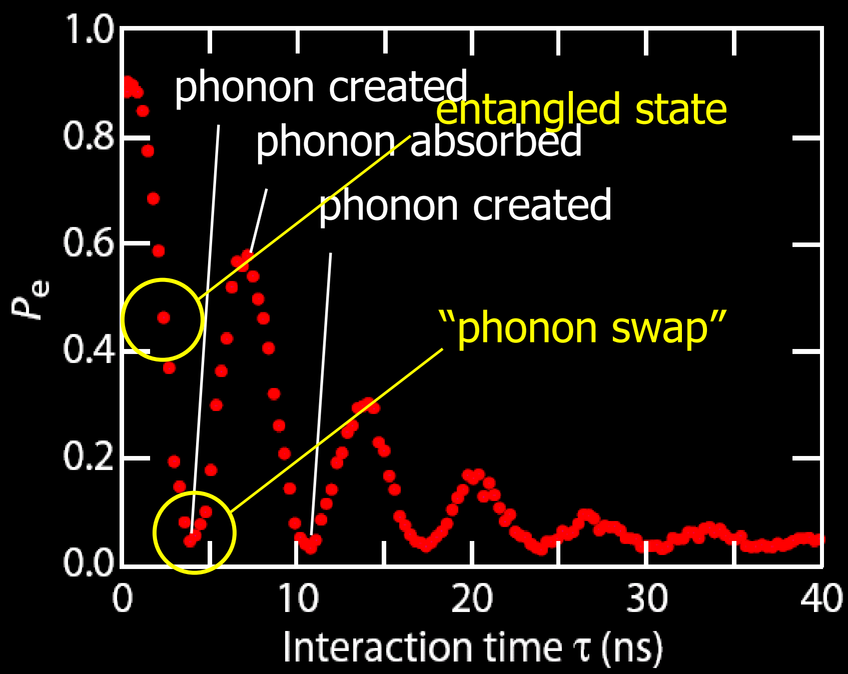


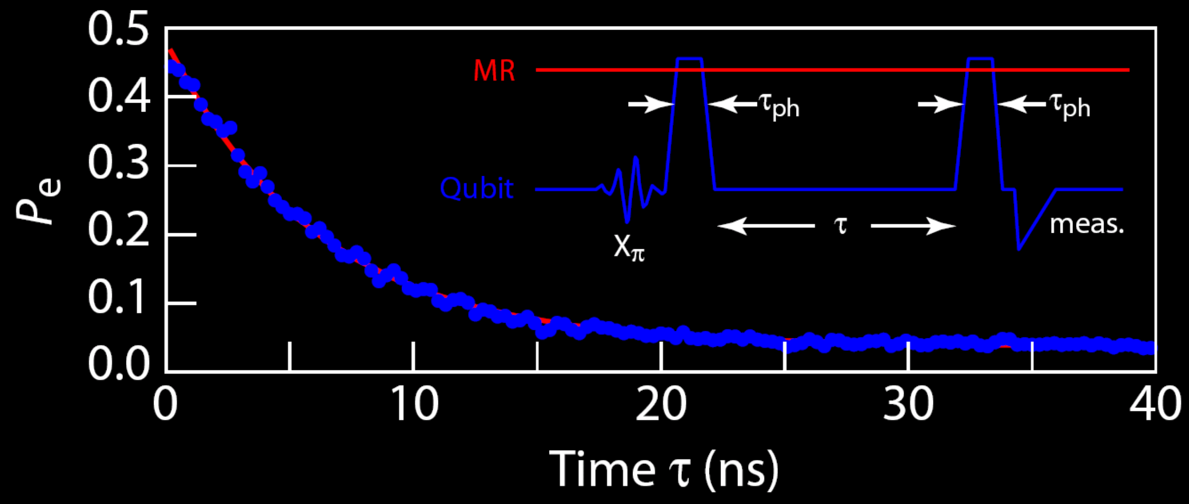


Single phonon lifetime & phase coherence time

- Create a single phonon
- Watch as it decays
- Extract single phonon T_1

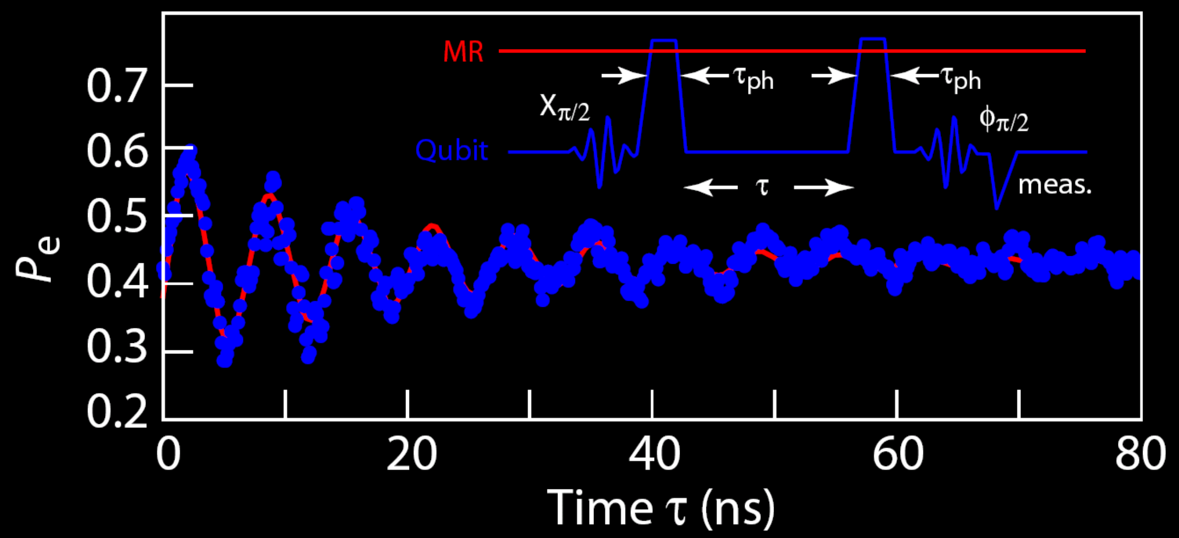
$T_1 = 6.1$ ns

(agrees with Q = 260 ⇨ T_1 = 6.7 ns)



- Create superposition
  $|0\rangle + |1\rangle$
- Watch as it decays
  (Ramsey fringe)
- Extract single phonon T_2

$T_2 \sim 2\ T_1$

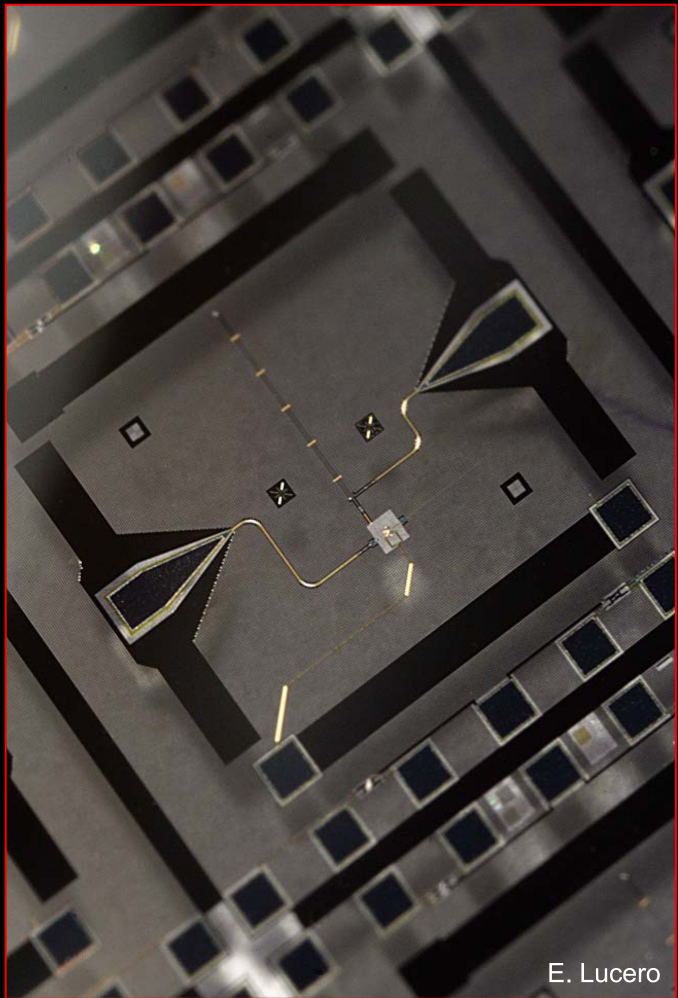


Quantum control of harmonic oscillators

Summary:

- Photon Fock $|n\rangle$ states
- Arbitrary superpositions of photon Fock states
- Cooling a mechanical resonator to its quantum ground state
- Creating and measuring a single mechanical phonon

Measuring the quantum harmonic oscillator



Cleland & Martinis groups:

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John M. Martinis

(Max Hofheinz)
Matteo Mariantoni
Haohua Wang
Martin Weides
(Eva Weig)
Yi Yin

postdocs

Radek Bialczak
Michael Lenander
Erik Lucero
Matthew Neeley
Daniel Sank
James Wenner
Jean-Luc Fraikin
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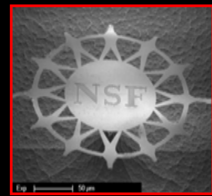
graduate students

Support:
NSF
iARPA



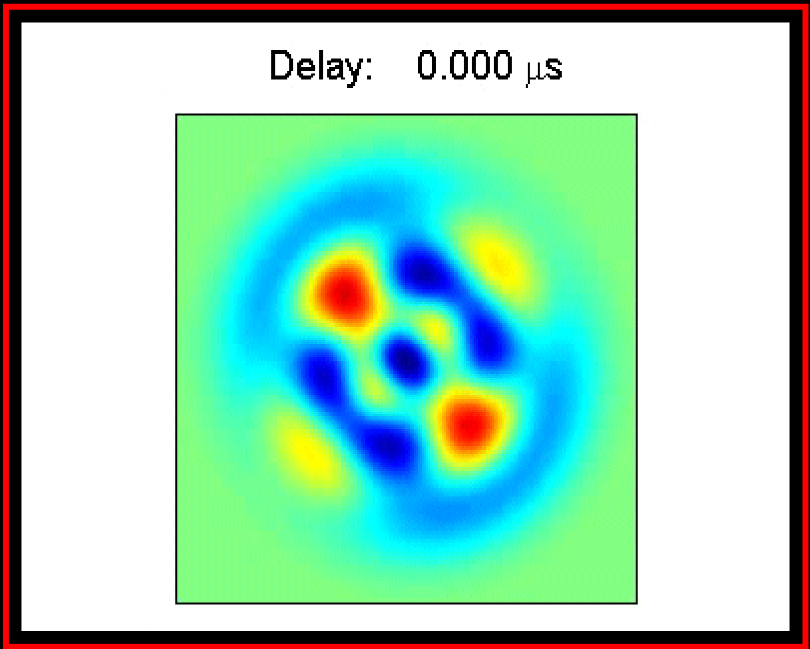
Decoherence as a movie

- Create superposed state using Law & Eberly protocol

$$|\psi\rangle = |0\rangle + i|2\rangle + |4\rangle$$

- Measure Wigner function using limited set of points
- Reconstruct full Wigner function using intrinsic symmetries

as a function of time



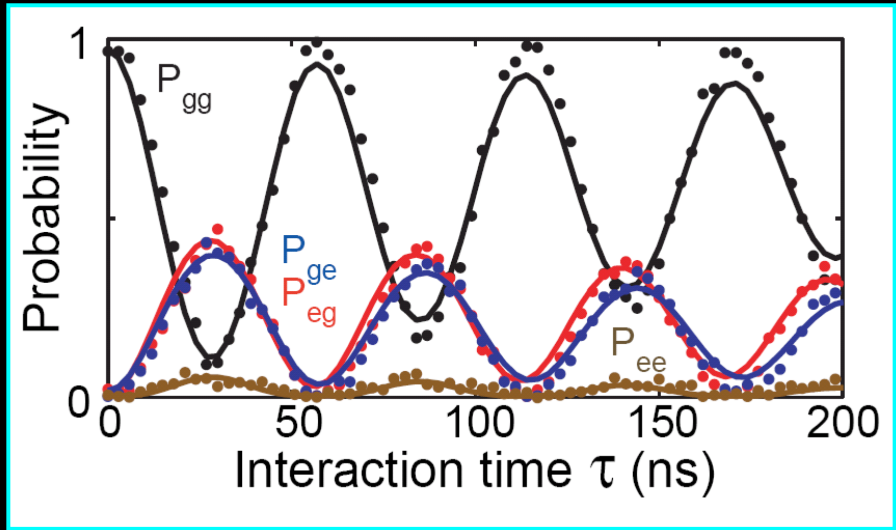
H. Wang et al. PRL (2009)

Quantitative agreement with Markovian master equation

Entangling photons in two separate resonators

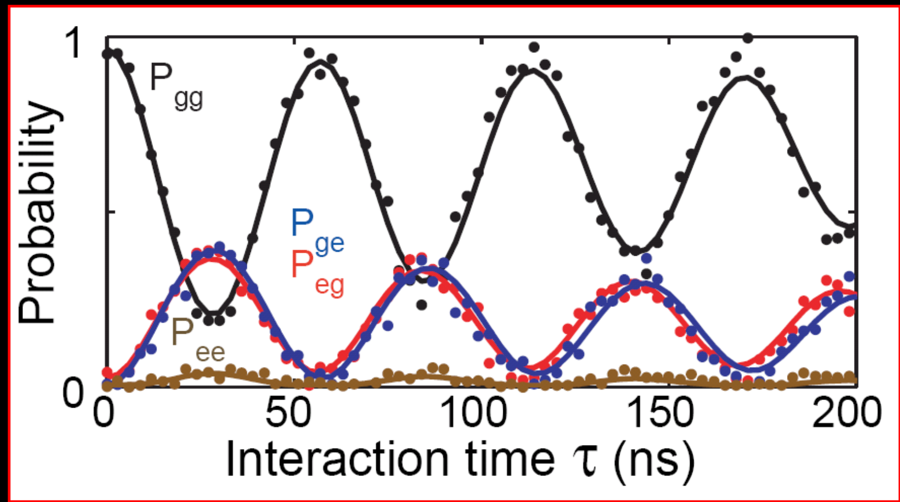
N=1 mixed state
Coincidence measurement

$$50\%\,|10\rangle \text{ and } 50\%\,|01\rangle$$



N=1 NOON state

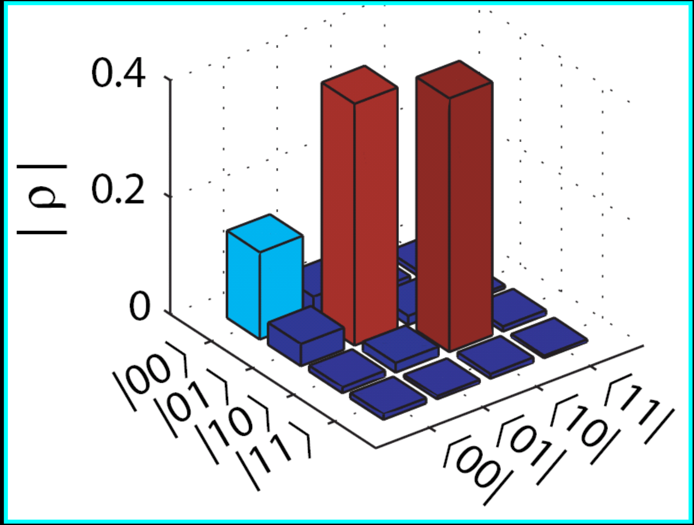
$$|10\rangle + |01\rangle$$



Entangling photons in two separate resonators

N=1 mixed state
Wigner tomography

$$50\% \left|10\right\rangle \text{ and } 50\% \left|01\right\rangle$$



N=1 NOON state

$$\left|10\right\rangle + \left|01\right\rangle$$