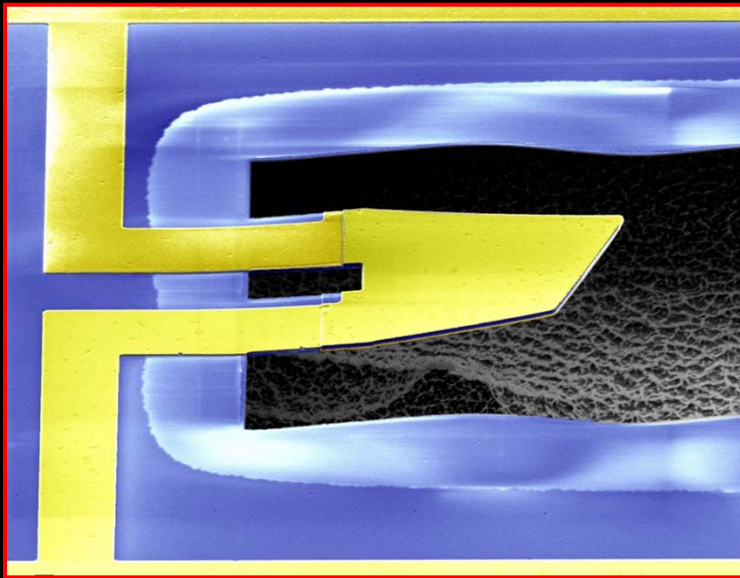

Quantum light & sound



Andrew N. Cleland
Department of Physics
University of California
Santa Barbara



Collaborators:

John M. Martinis (UC Santa Barbara)
Michael Geller (U Georgia - Athens)

IQC Colloquium
University of Waterloo
March 2011

Monday March 14 2011

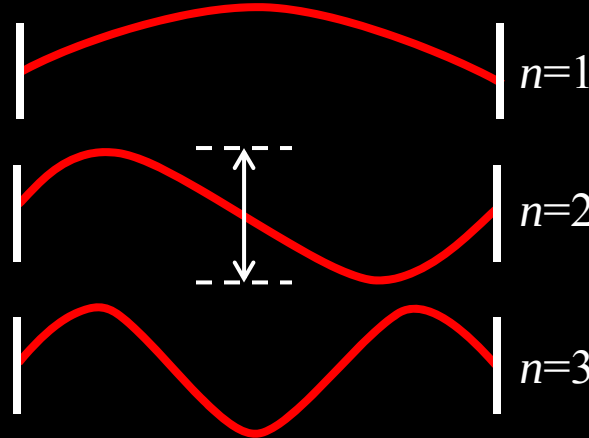
Classical and quantum physics

- **Classical physics is intrinsically analog**
 - Classical mechanics (simple harmonic oscillator)
 - Electromagnetism (transmission of light)
 - Thermodynamics (work, heat, entropy)
- **Quantum physics is intrinsically digital (binary)**
 - Photoelectric effect
 - Atomic transitions
 - Measurement process



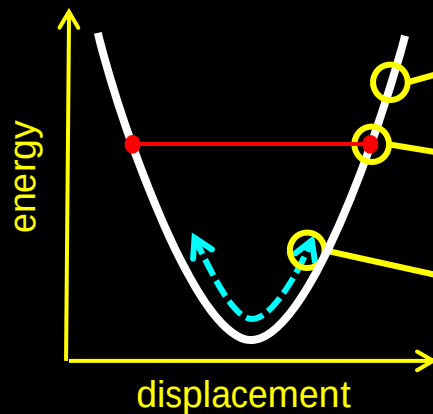
CLICK!

Classical mechanics



- Vibrational modes f_n
- Arbitrary amplitudes
- Frequency $\approx$ independent of amplitude

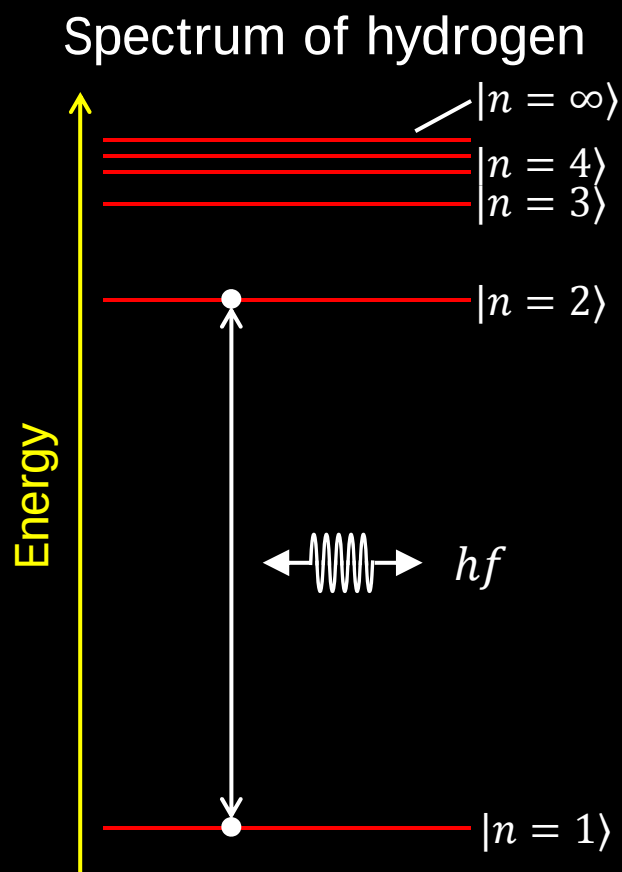
➤ Each vibrational mode:



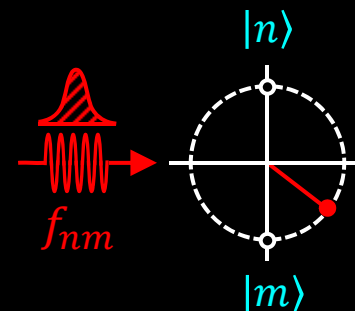
- Potential energy quadratic in displacement
- Total energy can take on any value
- Frequency f independent of energy

➤ Excitations at resonance f generate arbitrary amplitudes

Quantum mechanics

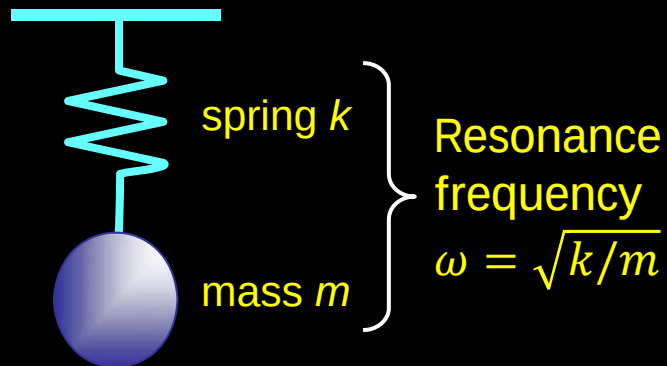


- Series of distinct spectral lines
- Bohr: Transitions between states involve photons: $E_n - E_m = hf_{nm}$
- A particular frequency generates a particular transition: $|m\rangle + hf_{nm} \Rightarrow |n\rangle$
- More photons induce further oscillations:
 $hf_{nm} + |m\rangle \Rightarrow |n\rangle, |n\rangle \Rightarrow |m\rangle + hf_{nm}$
- Resonant light pulses can control relative occupation:

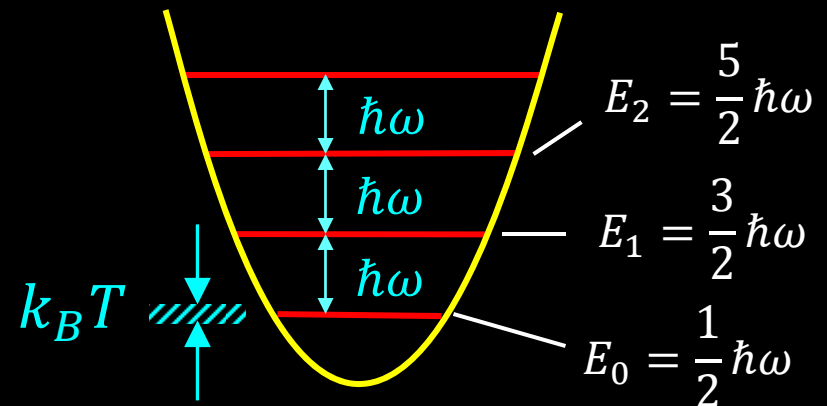


Phase & amplitude control of light allows arbitrary state preparation: $|\Psi\rangle = \alpha|m\rangle + \beta e^{i\phi}|n\rangle$

Harmonic oscillator in the quantum limit



Quantum solution:

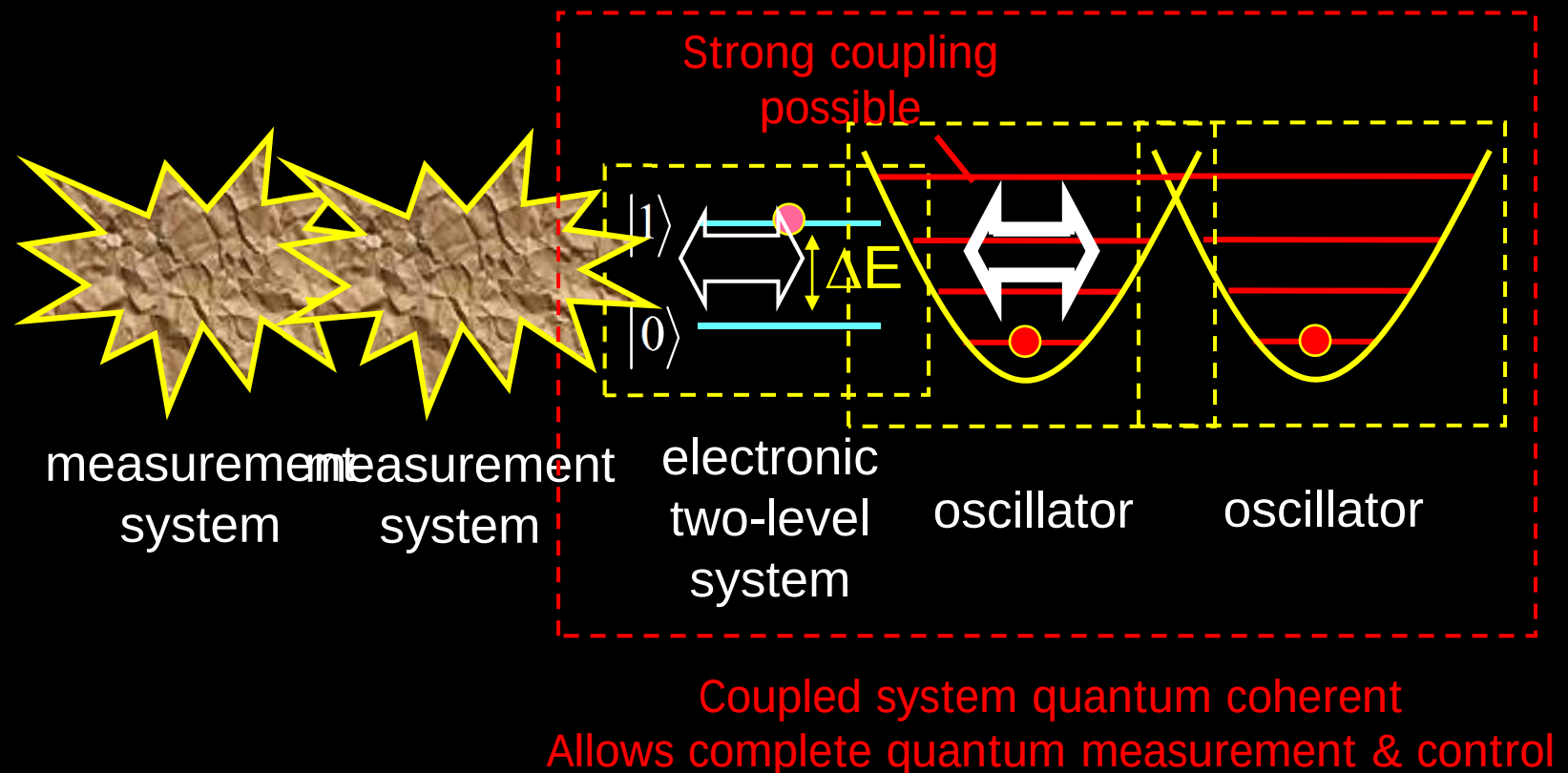


How to see quantum behavior?

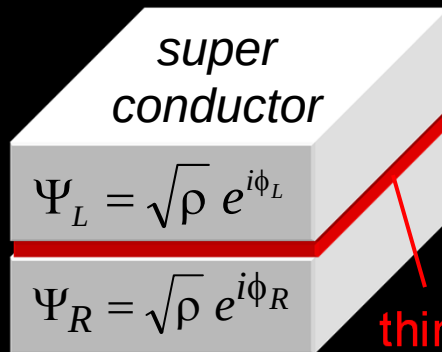
1. Cool to quantum ground state: $k_B T \ll \hbar\omega$
 - Conventional refrigeration: $T_{\min} = 20 \text{ mK} \Rightarrow \omega/2\pi > 1 \text{ GHz}$
2. Quantum-limited measurement
 - Need to detect single quanta – best without disturbing oscillator
3. Control of quantum state
 - How to inject single quanta? Classical signals generate coherent states
4. Sufficient oscillator lifetime
 - Finite quality factor means limited energy lifetime $T_1 = Q/\omega$

Measuring a harmonic oscillator in the quantum limit

1. Interpose a two-level system (electronic atom)
2. Electronic atom and oscillator form coherent system
3. Complete quantum control & measurement possible



Josephson phase qubit: Electronic atom/two-level system

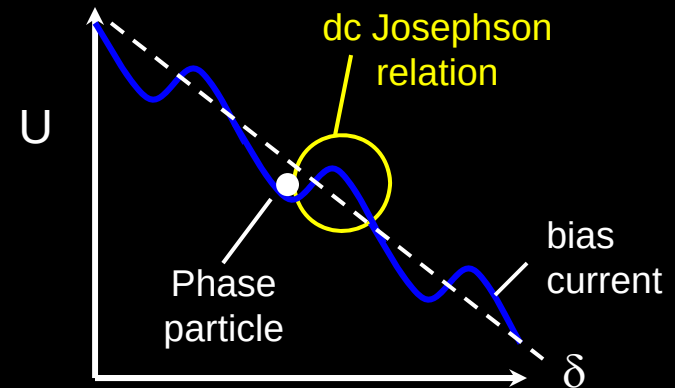


thin insulator (~ 1 nm)

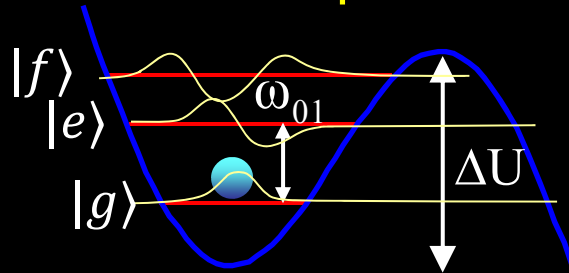
Phase difference

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

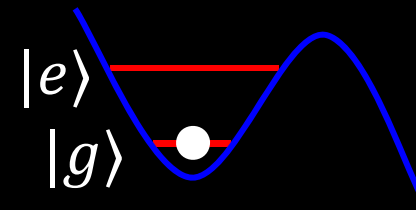
ac & dc
Josephson relations



At 20 mK δ is a quantum variable:



- Nonlinearity makes $\omega_{12} \sim 0.95 \omega_{01}$
Selectively address lowest two states
- ω_{01} tuned by bias current: 5-10 GHz
 $\hbar\omega \sim 30 k_B T$ at 20 mK

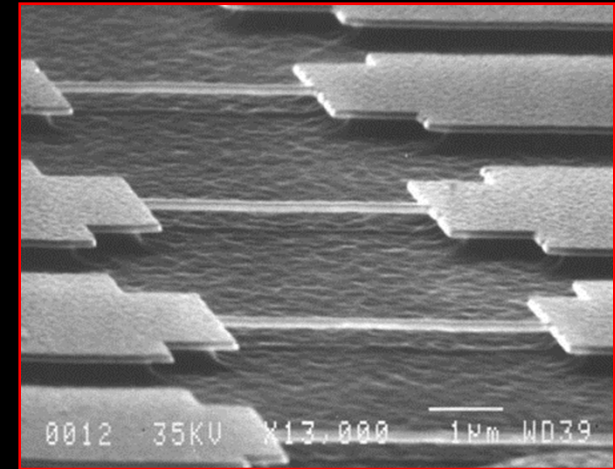


1. Electronic two-level system
2. Ground state below 100 mK
3. Complete quantum control
4. Strong coupling possible

Candidates for quantum harmonic oscillators

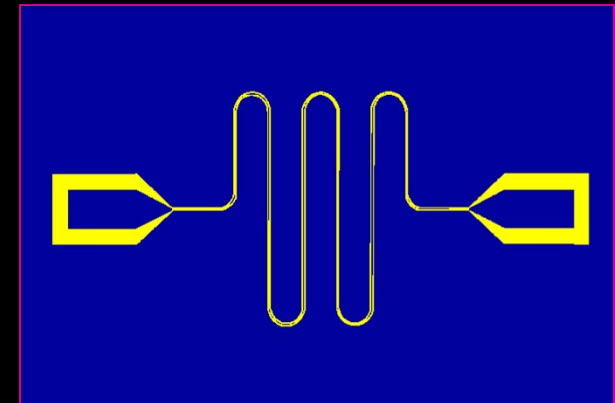
- Nanomechanical resonators

- Resonance frequencies up to ~ 10 GHz
- Integrable with phase qubit
- Quanta are *phonons*
- **Quality factors $\sim 10^3$: Short lifetime**



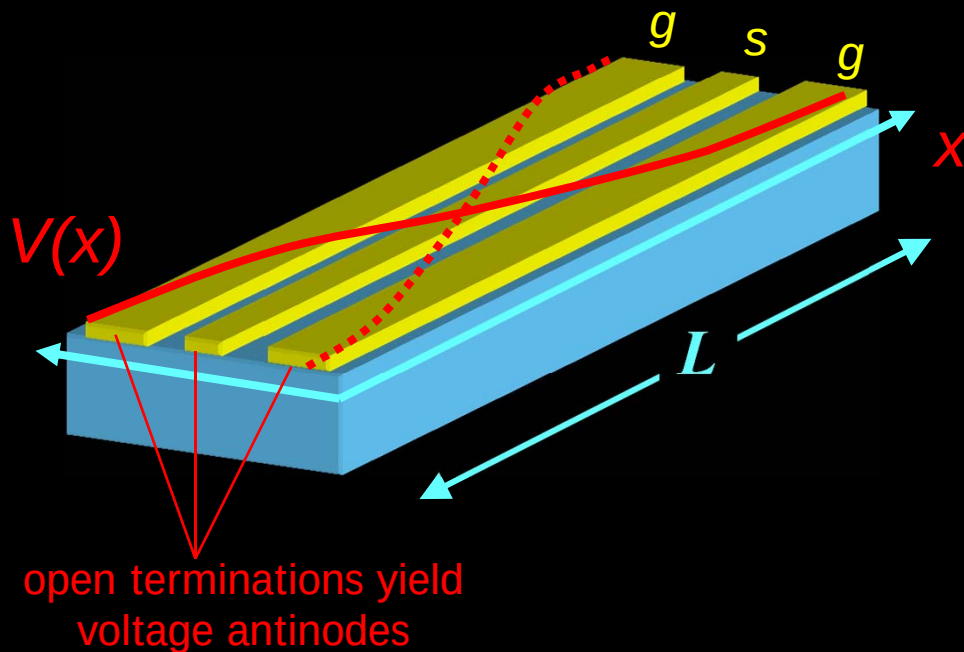
- Electromagnetic resonators

- Resonance frequencies up to ~ 100 GHz
- Integrable with phase qubit
- Quanta are *photons*
- **Quality factors $\sim 10^5$ - 10^6 : Long lifetime**

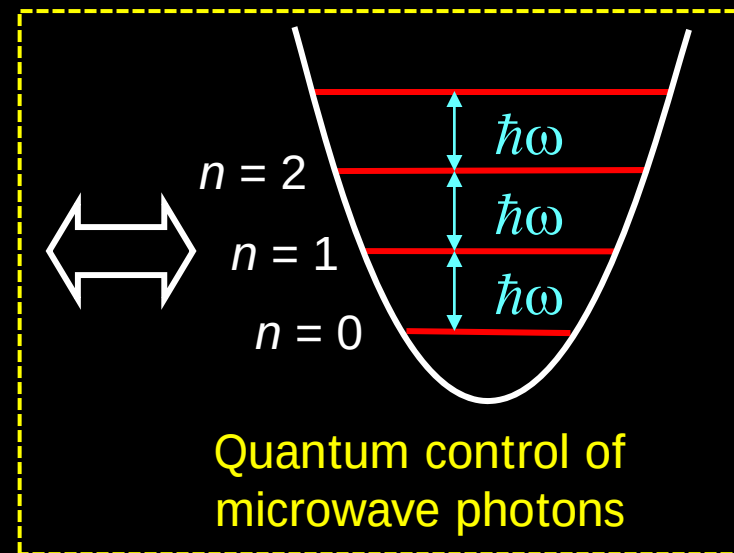
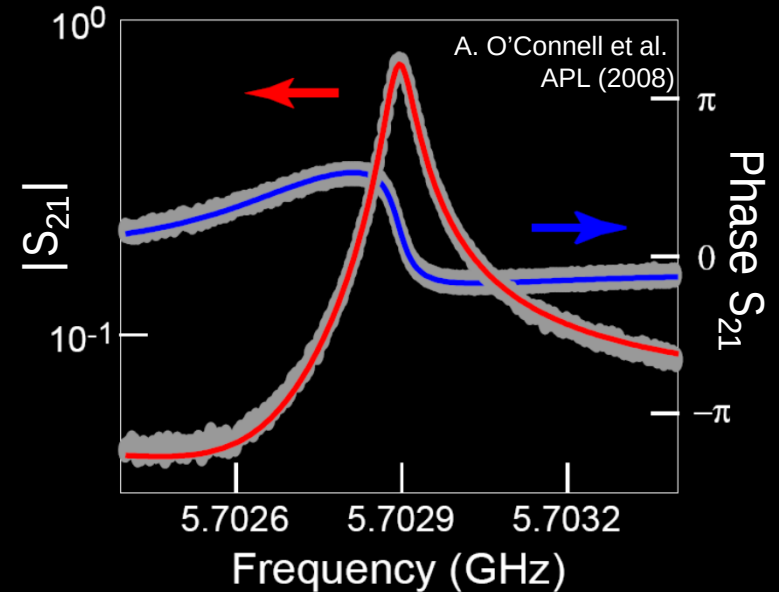


Max Hofheinz & Haohua Wang

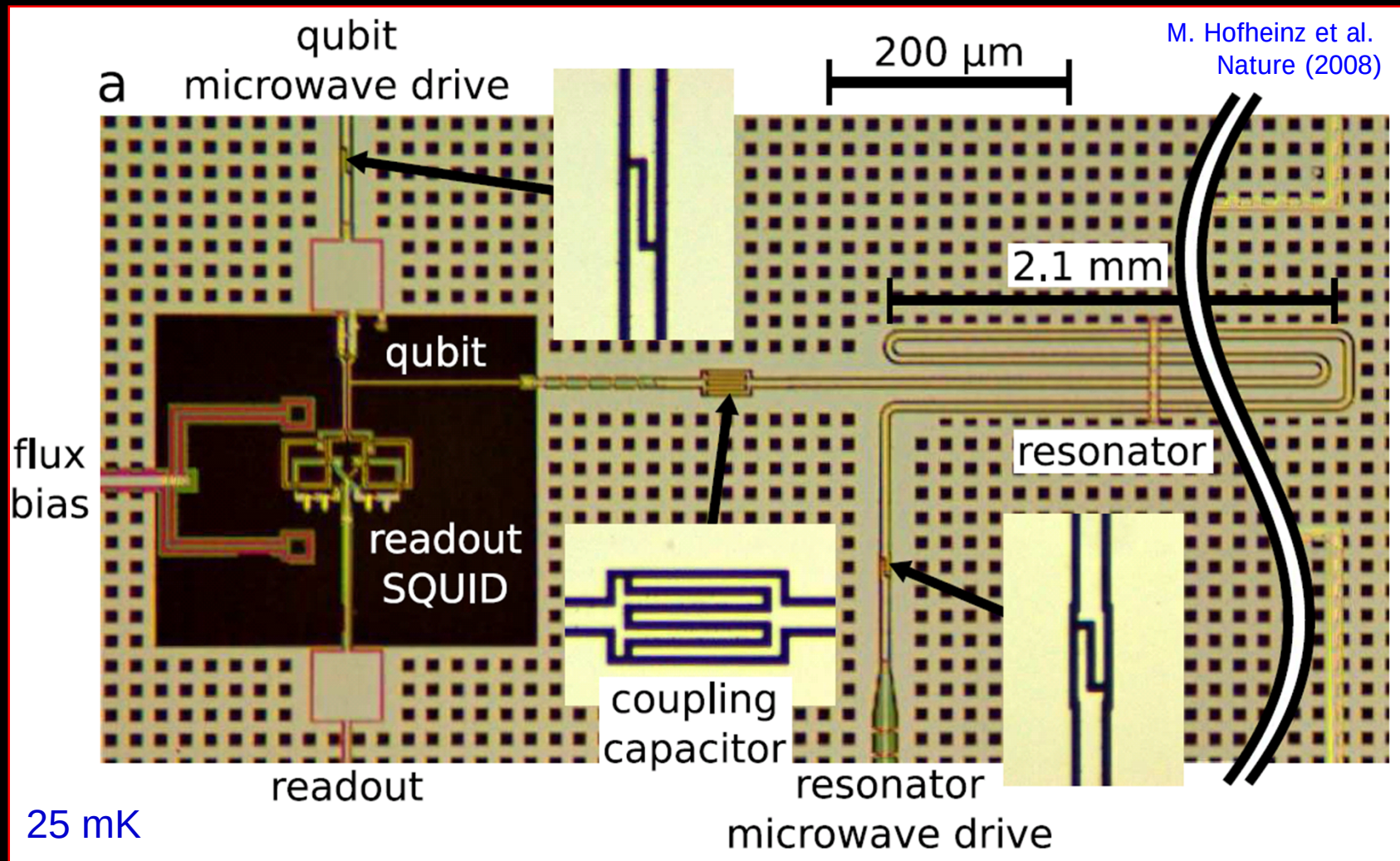
Half-wave coplanar stripline resonator



- Wavelength $\lambda = 2L \sim 10$ mm
- Resonance frequency $\omega/2\pi \sim 5$ -10 GHz
 $\hbar\omega \gg k_B T$ at 20 mK
- Quality factor $Q \sim 10^5$
 $T_1 = Q/\omega$ is a few microseconds

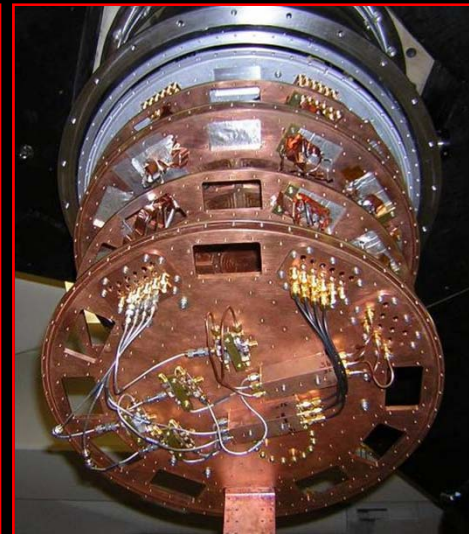
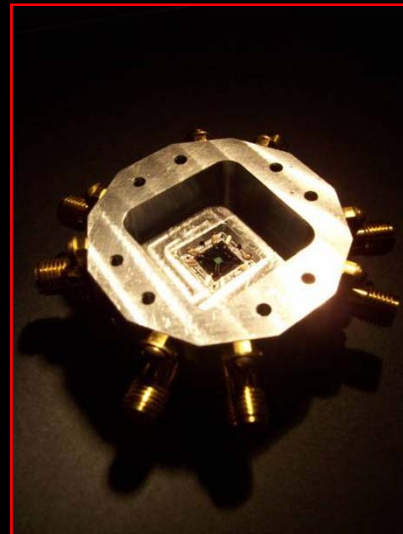
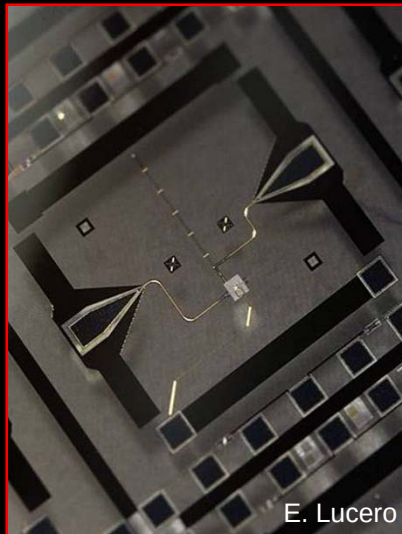
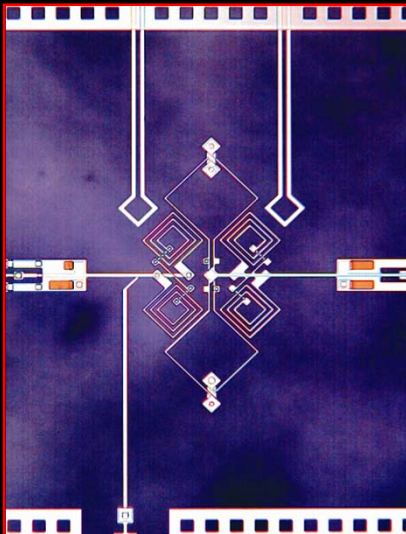
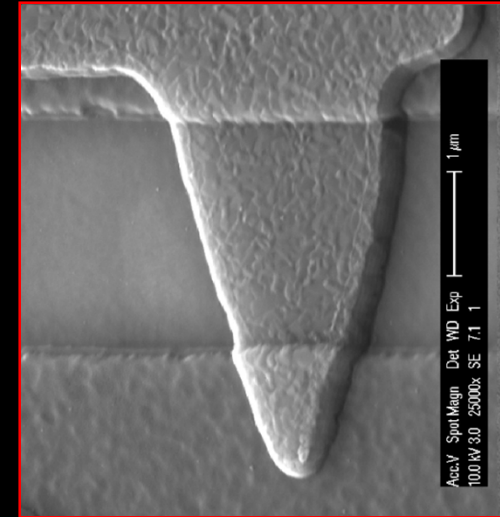


Coupled electromagnetic resonator & Josephson qubit



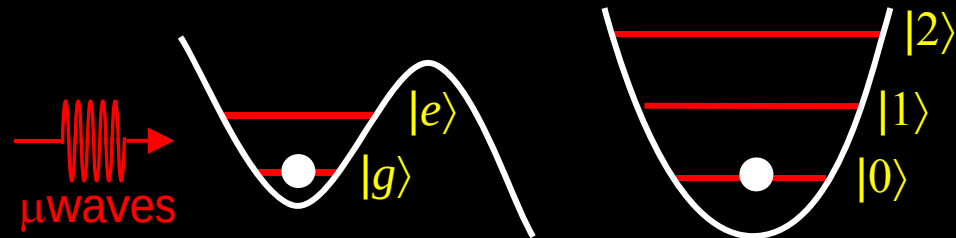
Making & measuring quantum devices

- 8 layers optical lithography, deposition, etching (UCSB Nanofabrication Facility)
- 3" sapphire wafers
- Diced into $\frac{1}{4}$ " x $\frac{1}{4}$ " chips
- Mount on dilution refrigerator (25 mK)
- Control with custom electronics

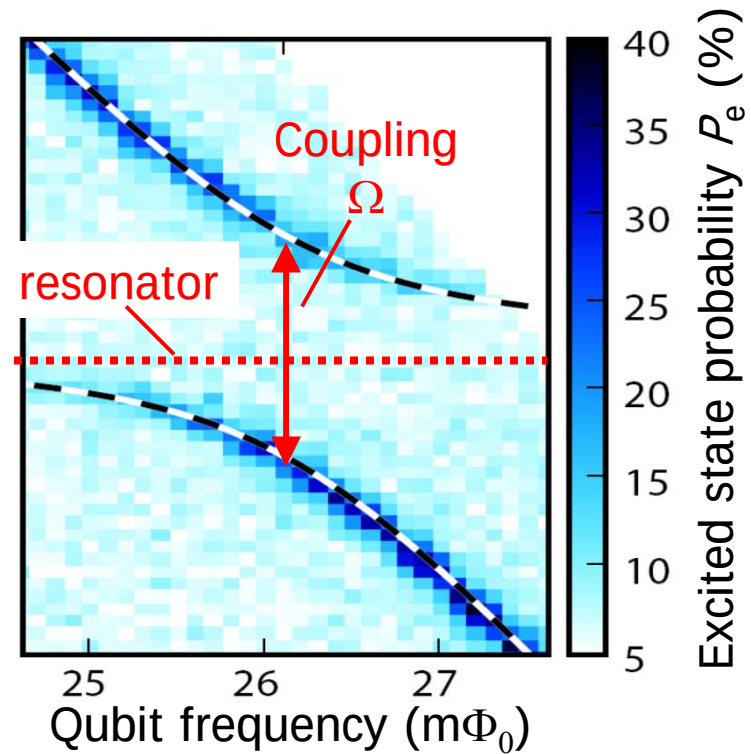
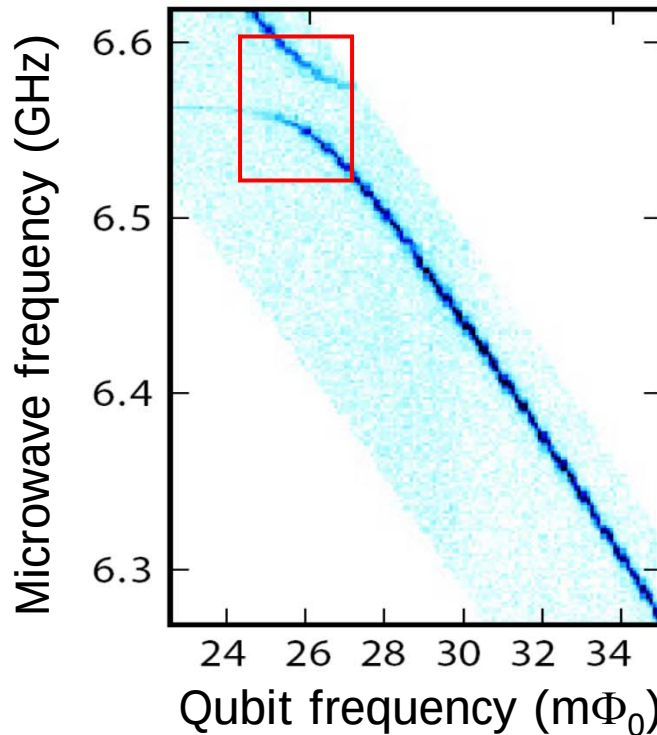


Spectroscopy of coupled system

1. Set qubit frequency
2. Set microwave frequency
3. Pulse & measure qubit

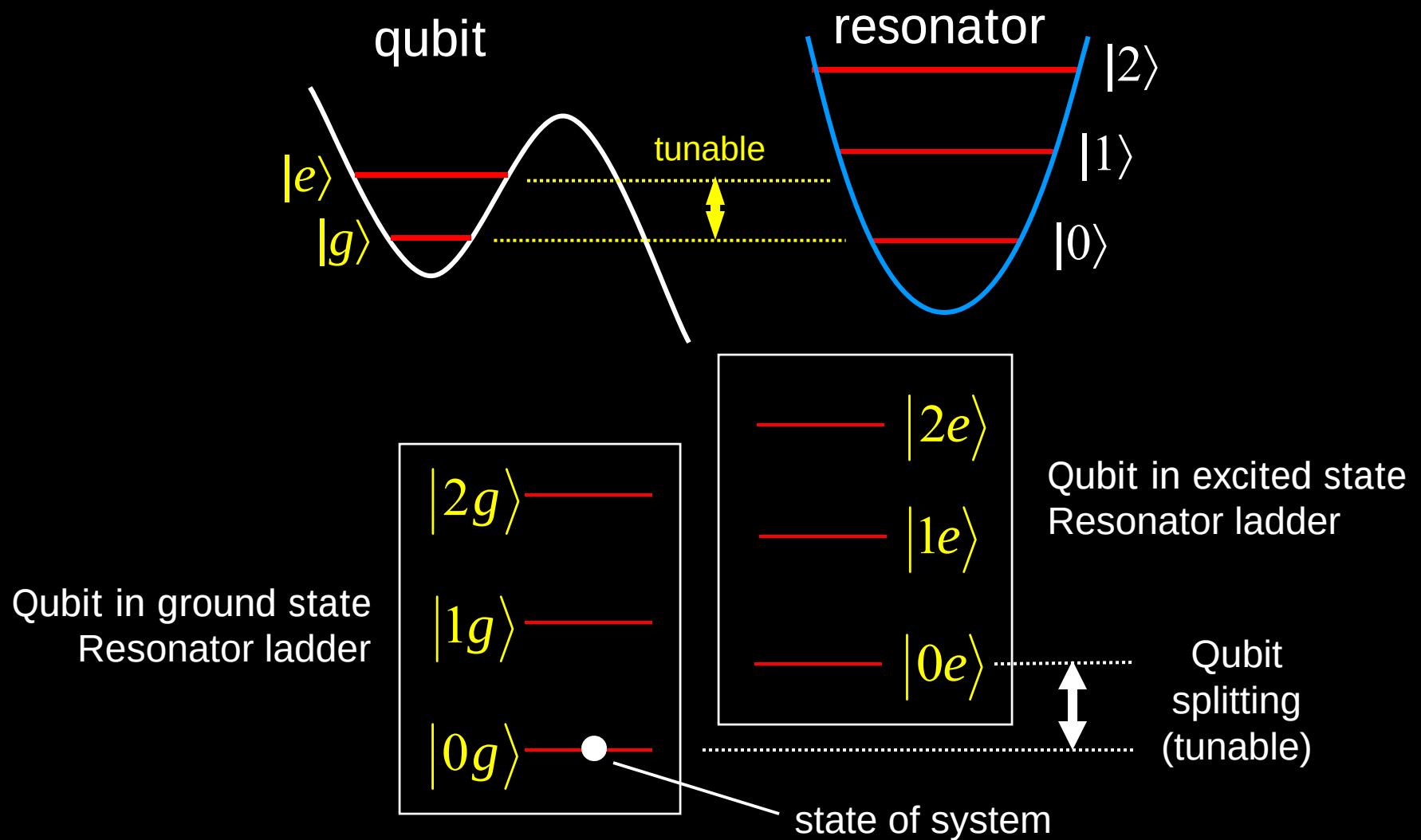


Spectroscopy



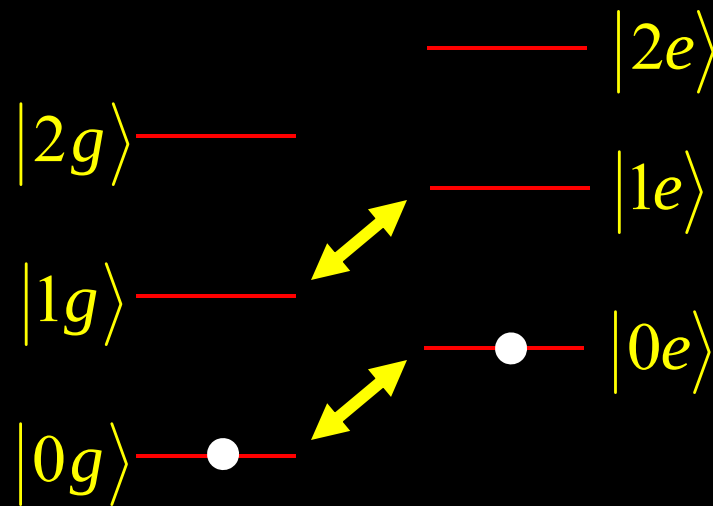
M. Hofheinz et al. Nature (2008)

Coupled resonator-qubit energy levels



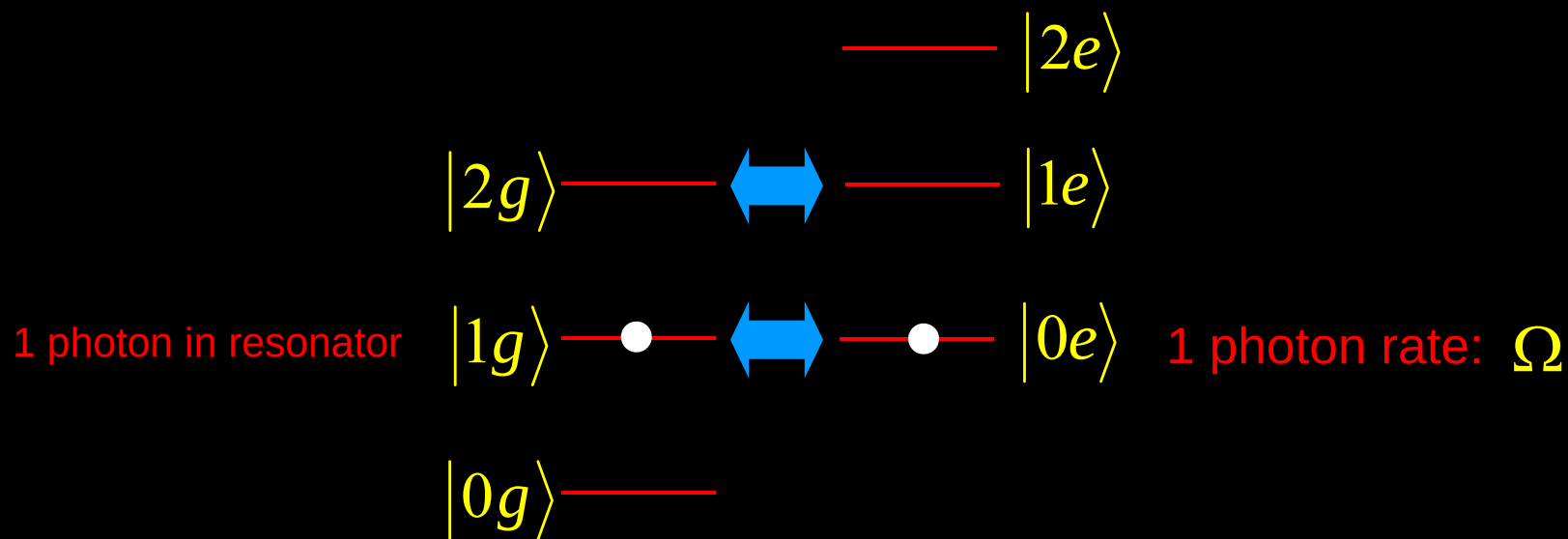
Resonator-qubit time-domain control

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



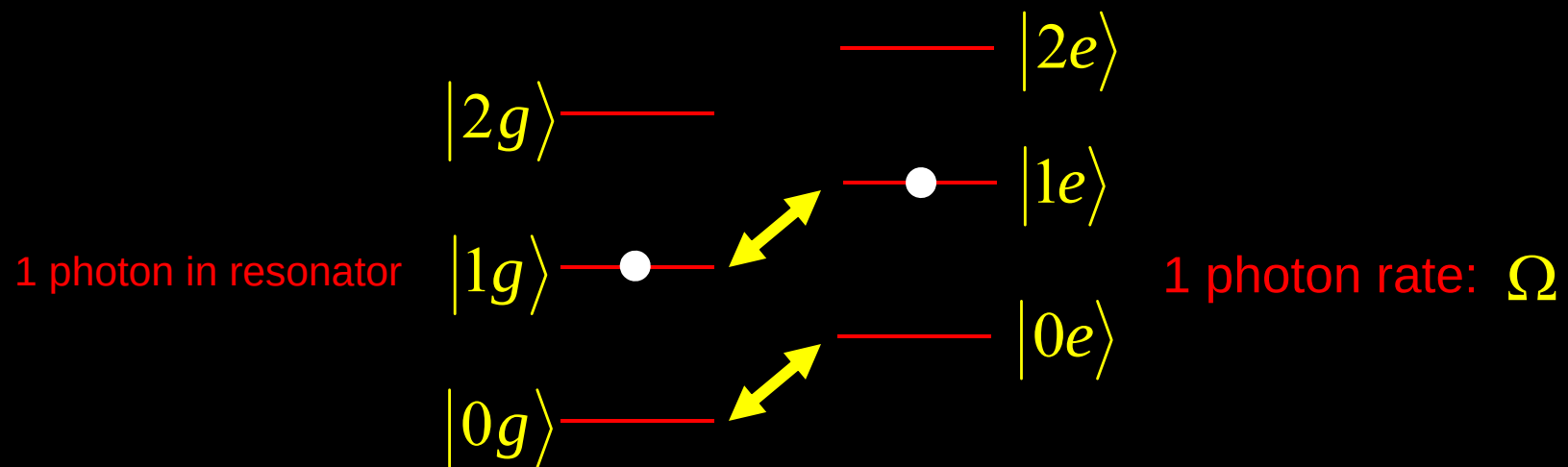
Resonator-qubit time-domain control

- 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



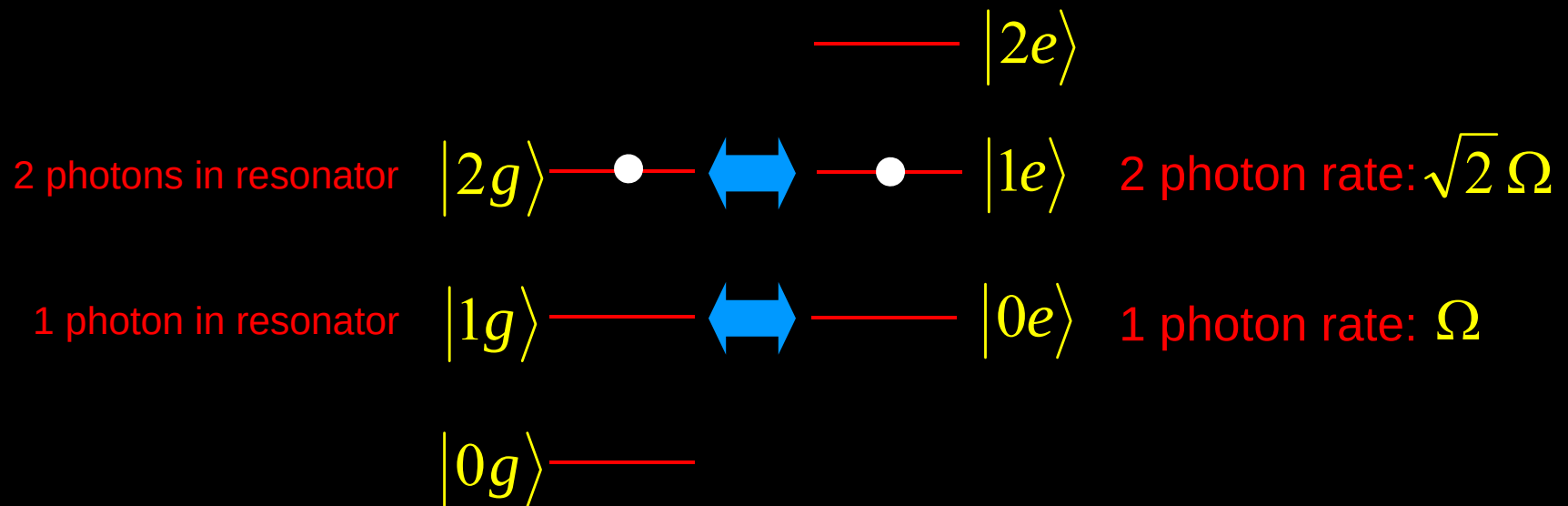
Adding more photons

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



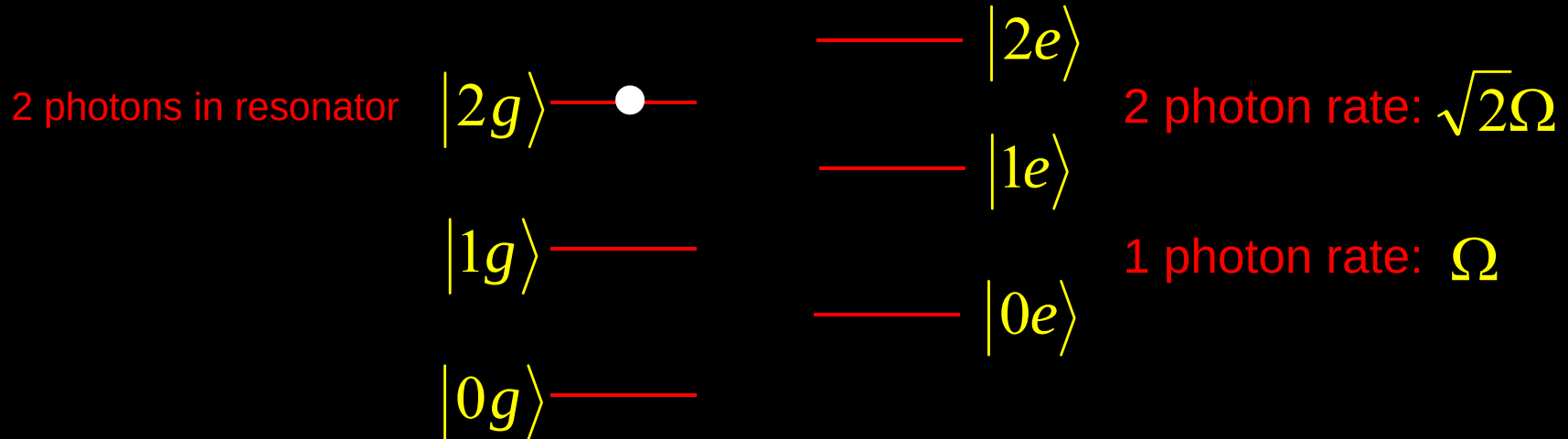
Adding more photons

- 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

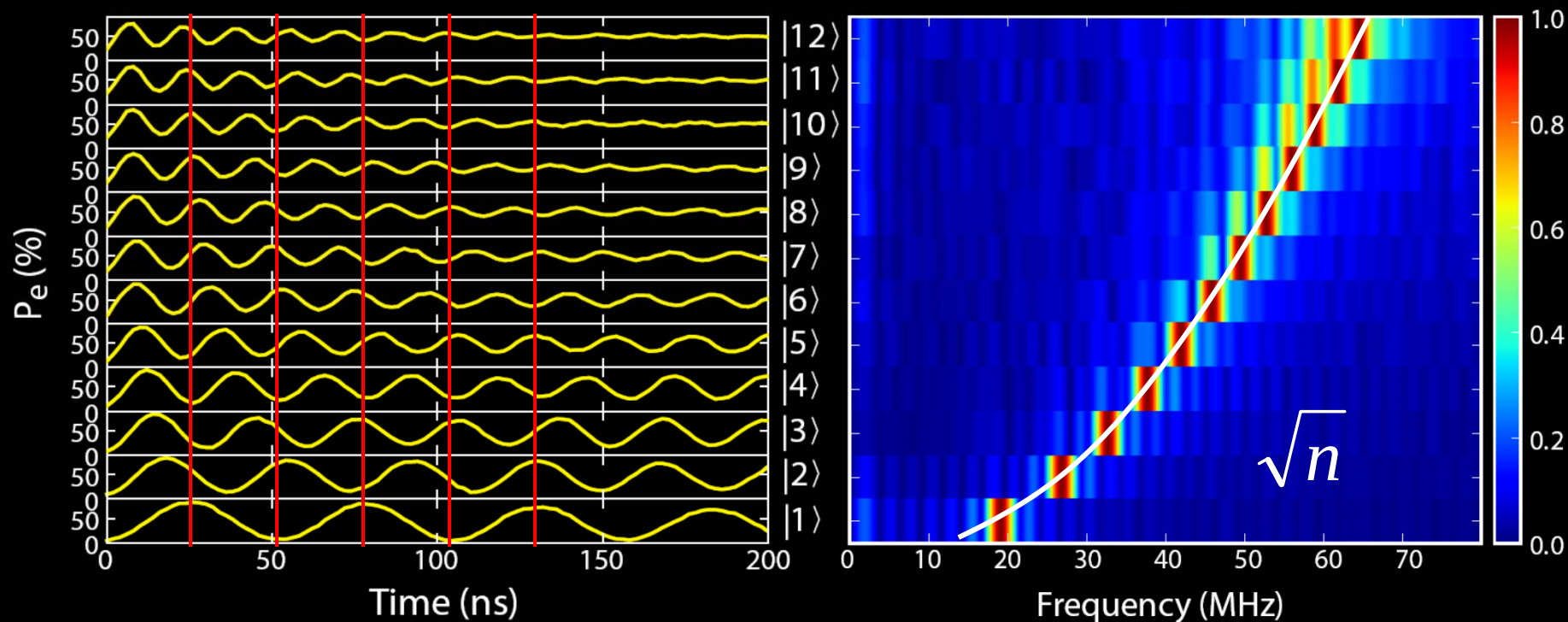
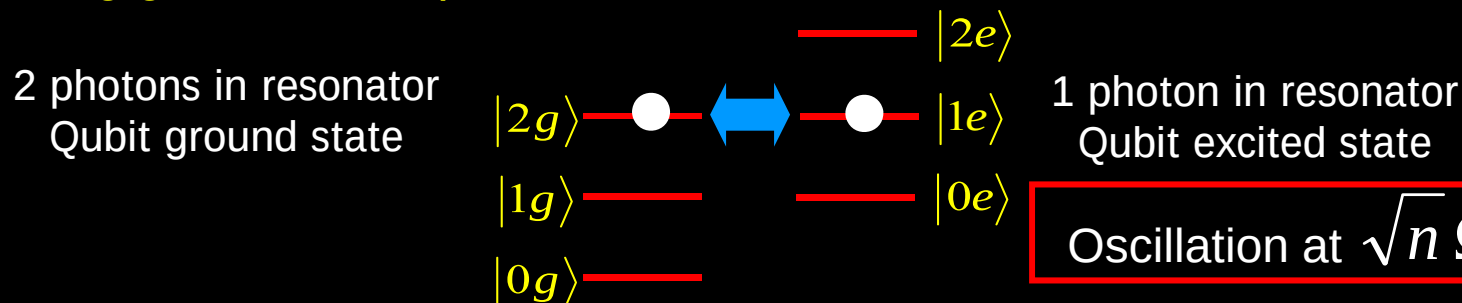


Resonator-qubit time-domain control

Measurement of resonator state:

M. Hofheinz et al.
Nature (2008)

Bring ground-state qubit into resonance with resonator



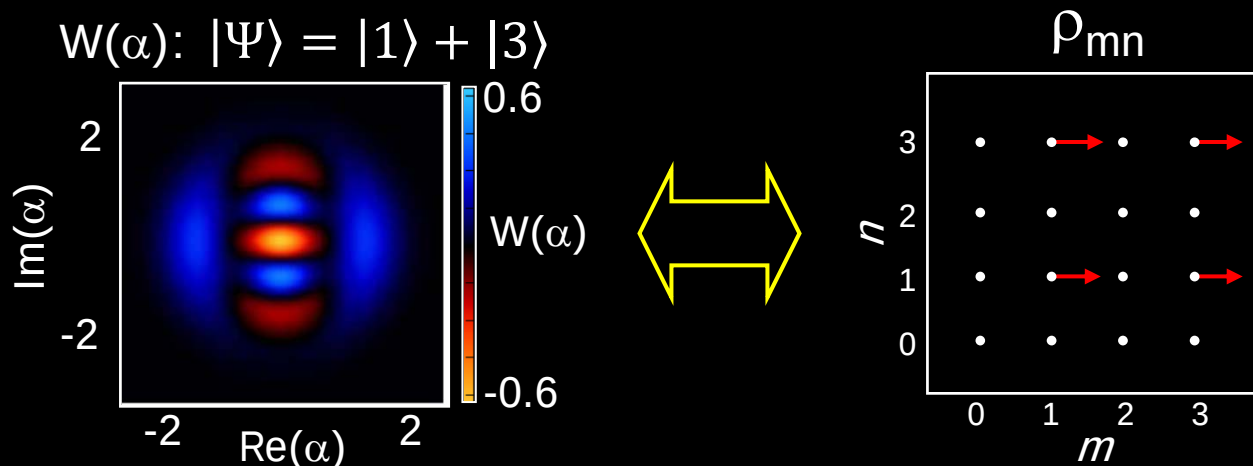
Arbitrary quantum states & Wigner tomography

Prepare arbitrary superposition states:

- Adapt Law & Eberly protocol (ion physics)
- Reverse engineering: Sequence from final state to ground state
- Apply sequence in reverse order: Ground state to final state

Measure Wigner function $W(\alpha)$:

- Quasiprobability distribution
- Negative values $\Leftrightarrow$ quantum coherence
- Equivalent to measuring density matrix

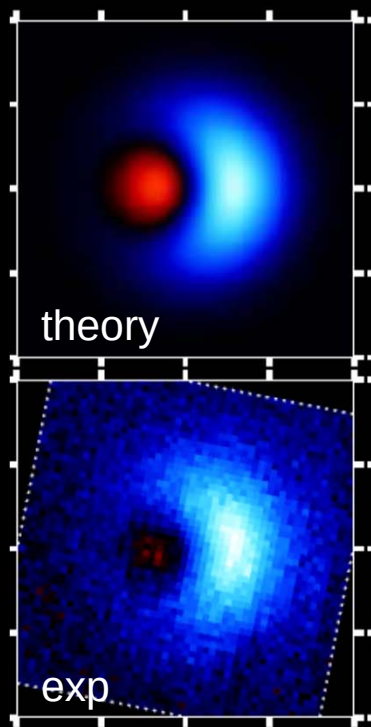


Superpositions by Wigner tomography

M. Hofheinz et al.
Nature (2009)

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

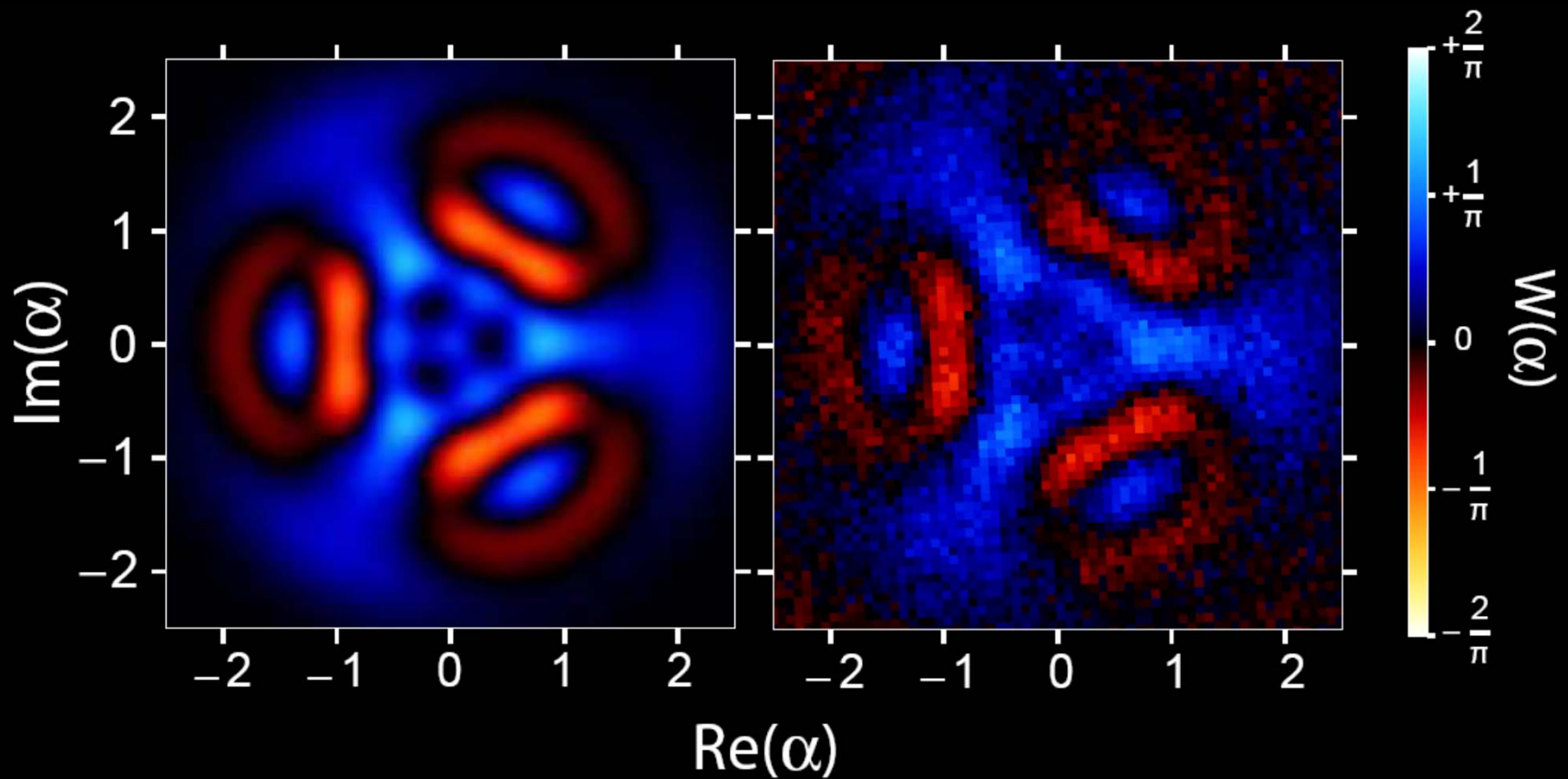
$$|\psi\rangle = |0\rangle + |1\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

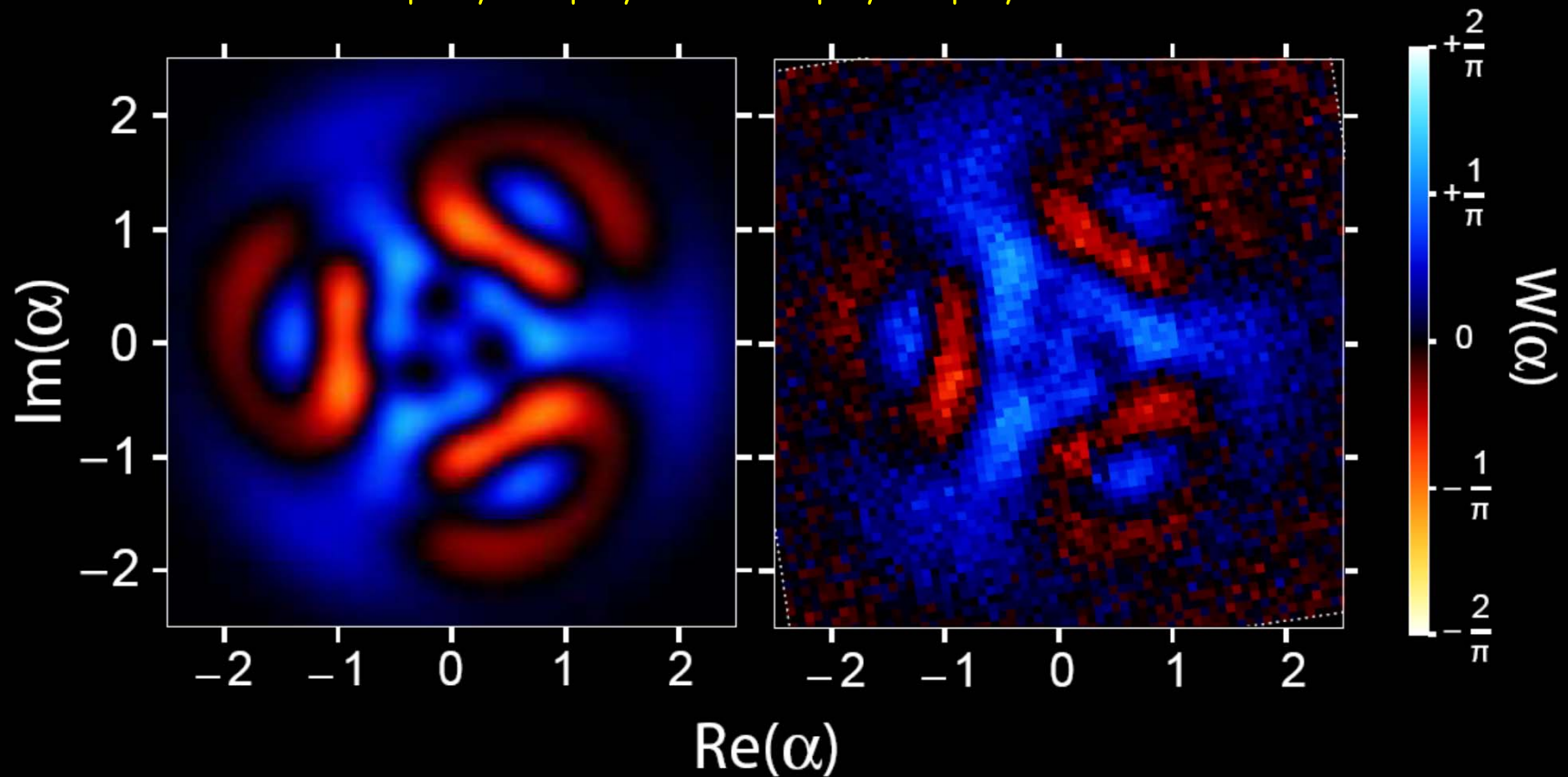
$$|\psi\rangle = |0\rangle + e^{\frac{0}{8}i\pi} |3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

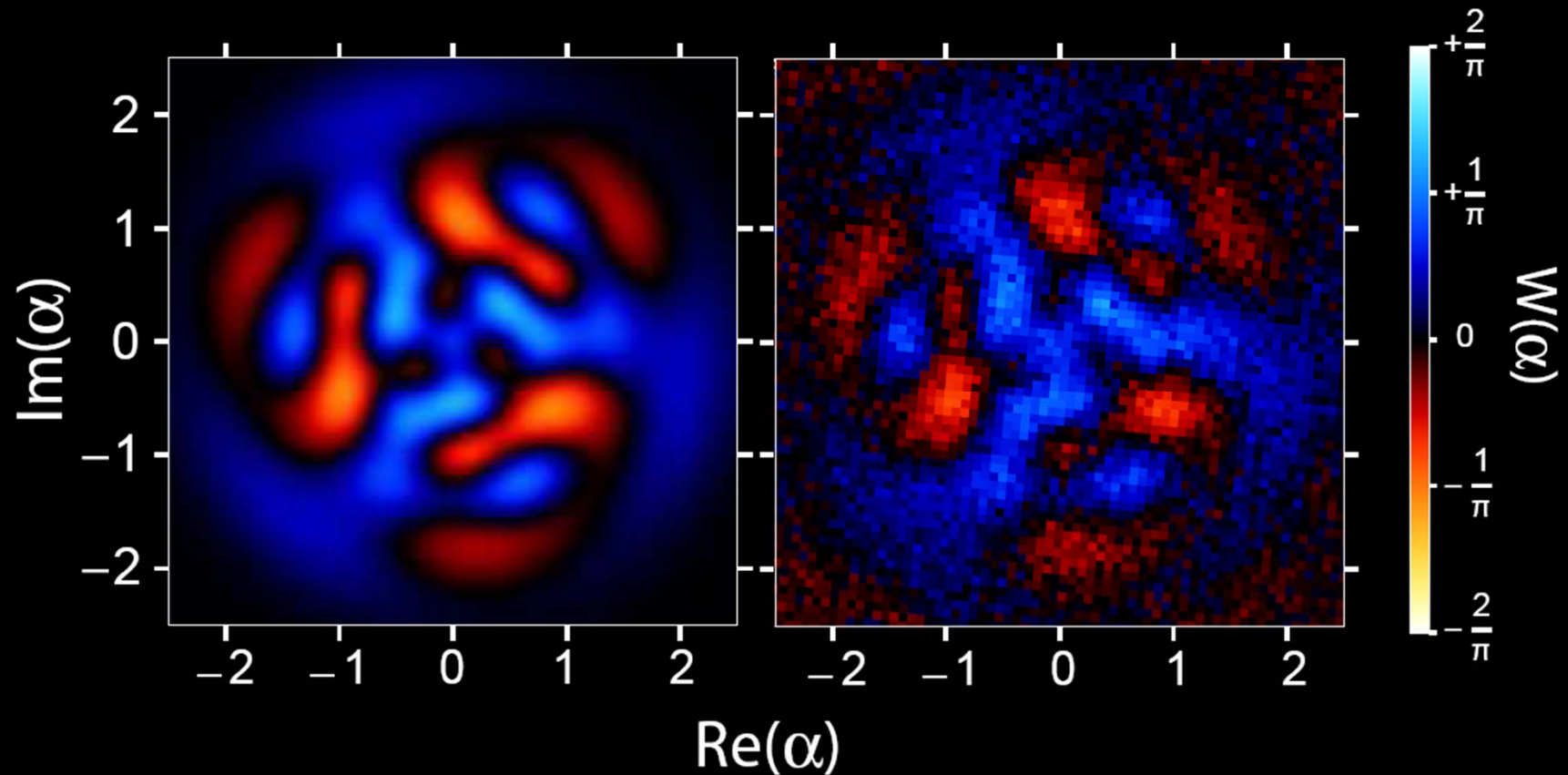
$$|\psi\rangle = |0\rangle + e^{\frac{1}{8}i\pi} |3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

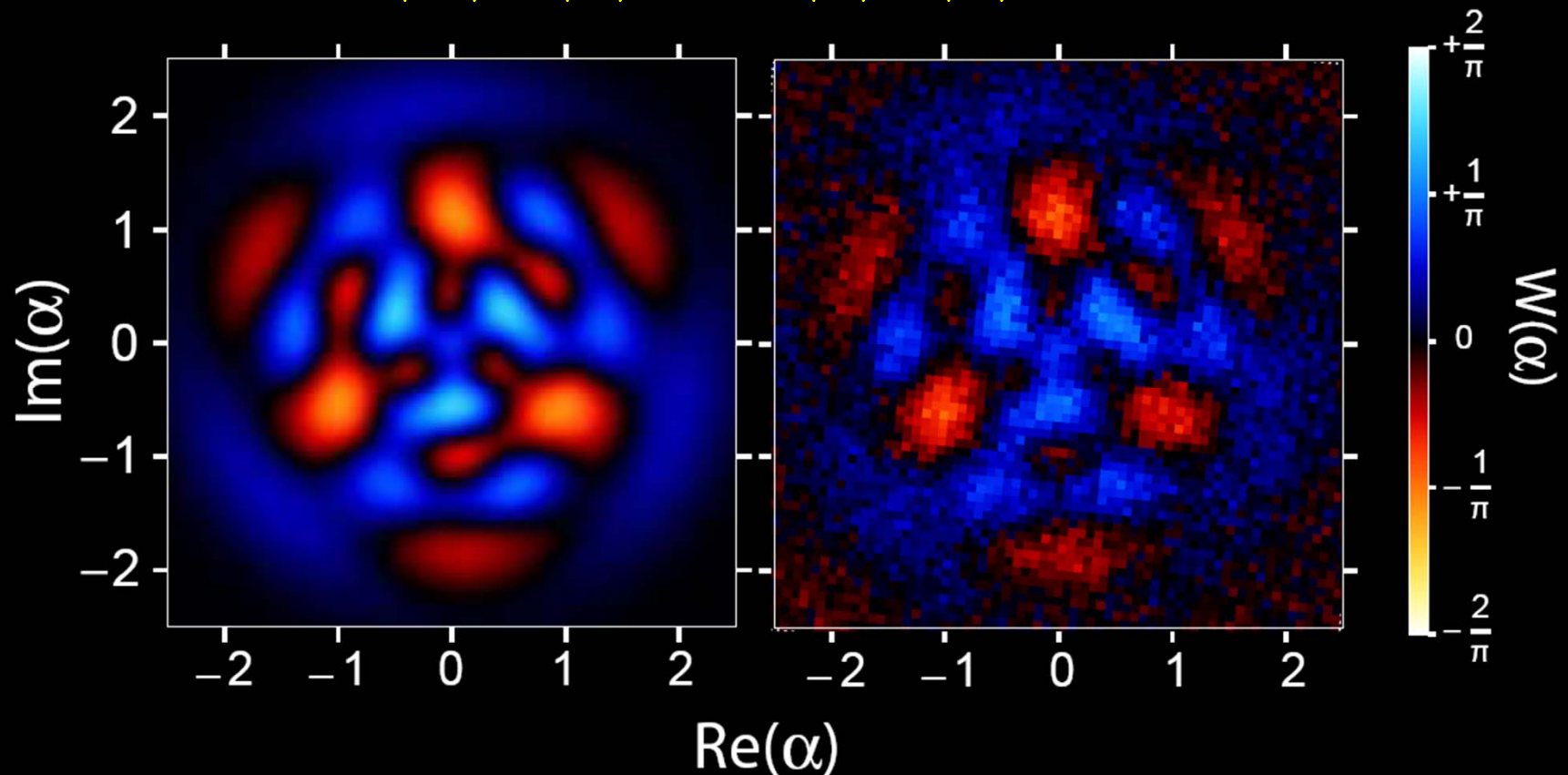
$$|\psi\rangle = |0\rangle + e^{\frac{2}{8}i\pi} |3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

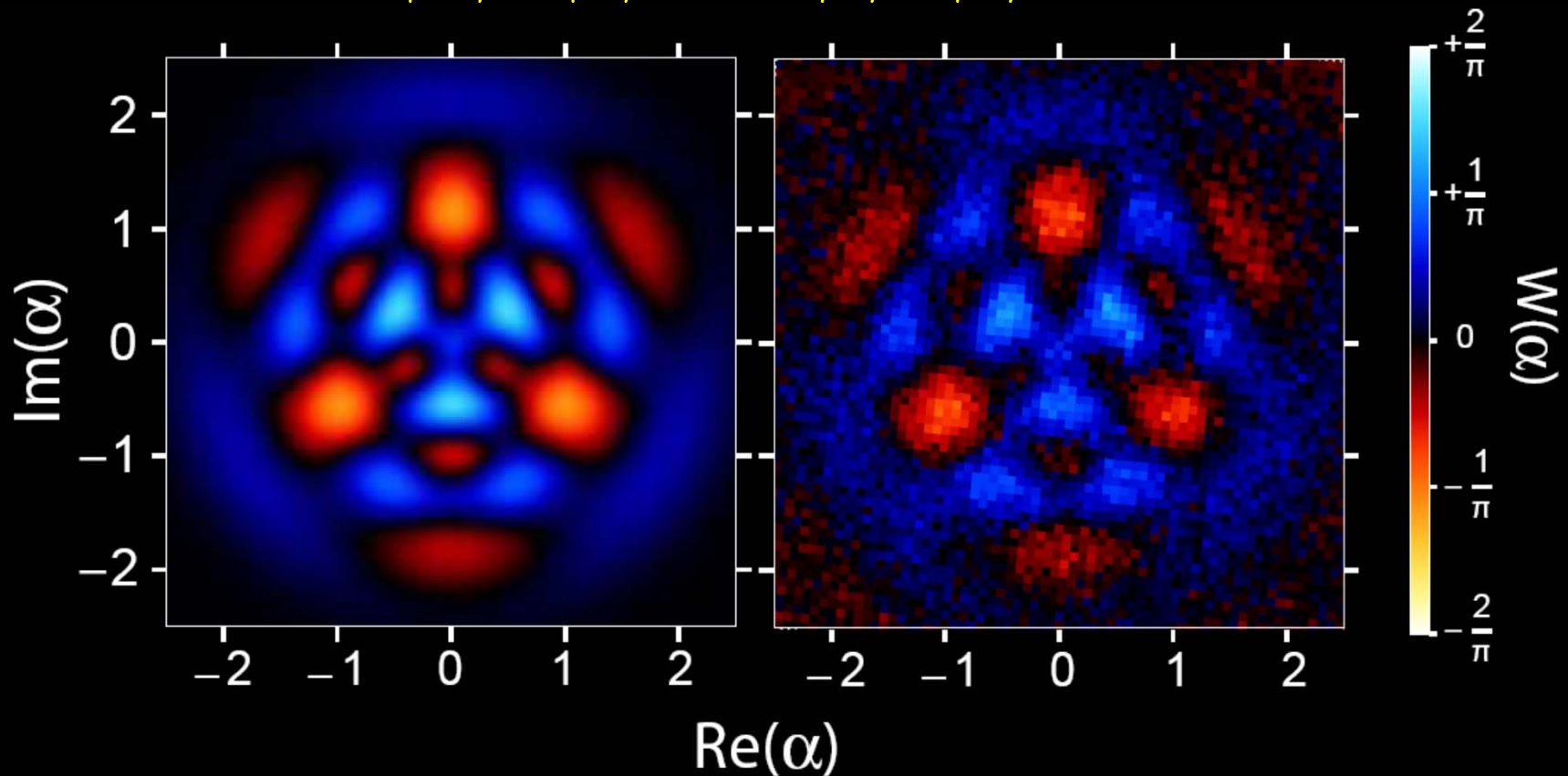
$$|\psi\rangle = |0\rangle + e^{\frac{3}{8}i\pi} |3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

$$|\psi\rangle = |0\rangle + e^{\frac{4}{8}i\pi} |3\rangle + |6\rangle$$



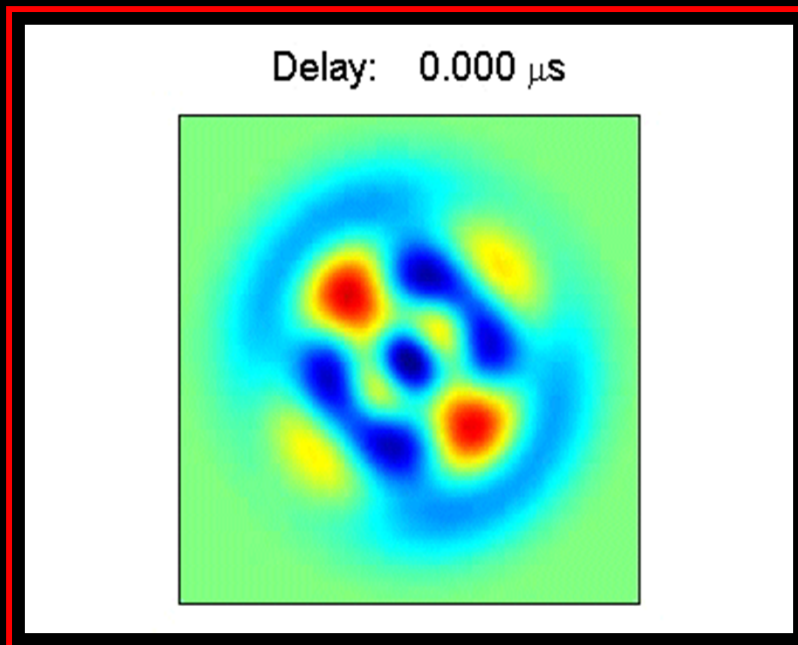
Decoherence as a movie

Evolution of superposed state $|\psi\rangle = |0\rangle + i|2\rangle + |4\rangle$

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

Watching
Schrodinger's cat
die

(note that no cats were
actually harmed in this
experiment, nor were any
cats directly involved)



H. Wang et al.
PRL (2009)

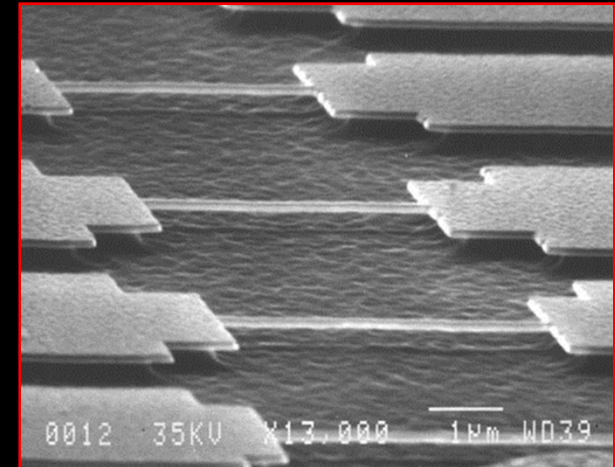
Quantitative
agreement with
Markovian master
equation

Candidates for quantum harmonic oscillators

- Nanomechanical resonators

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

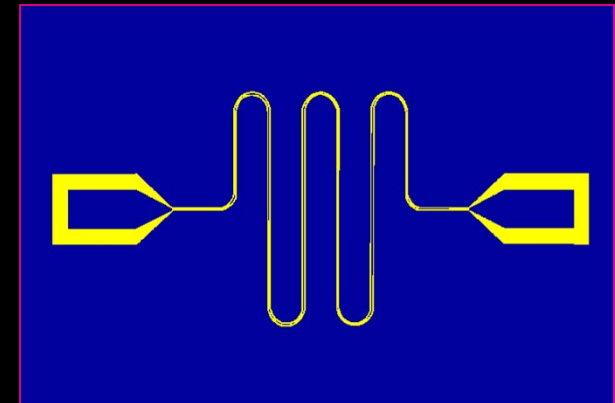
Aaron O'Connell



- Electromagnetic resonators

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

Max Hofheinz



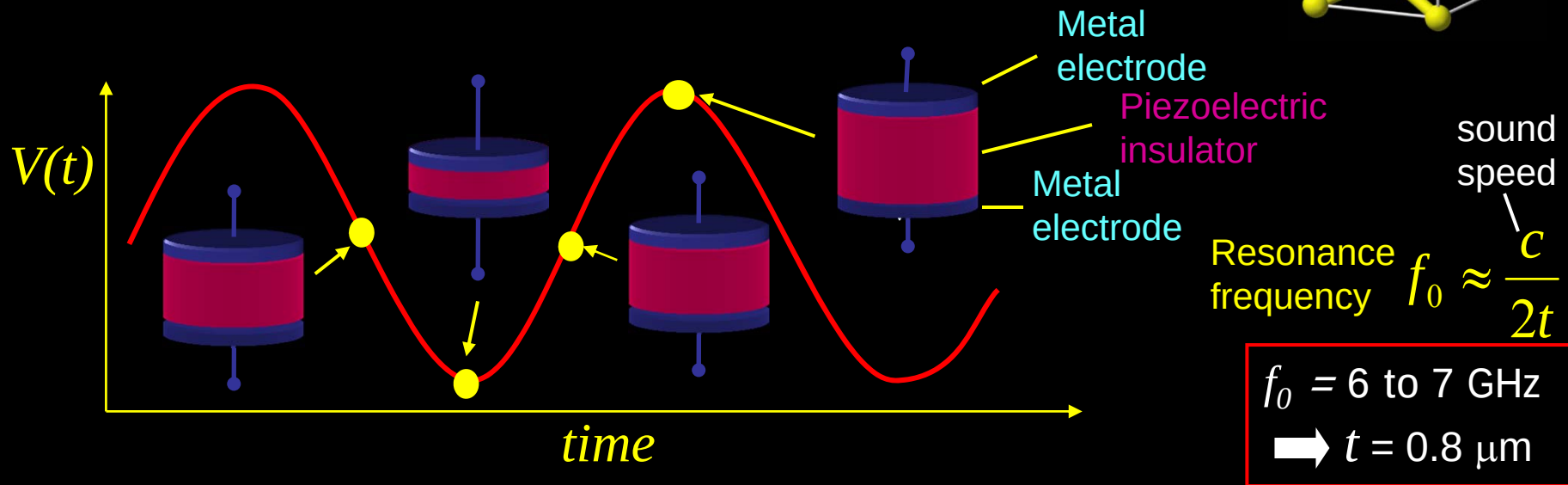
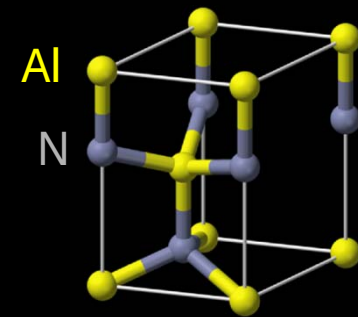
Mechanical quantum oscillator

Requirements for mechanical oscillator:

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

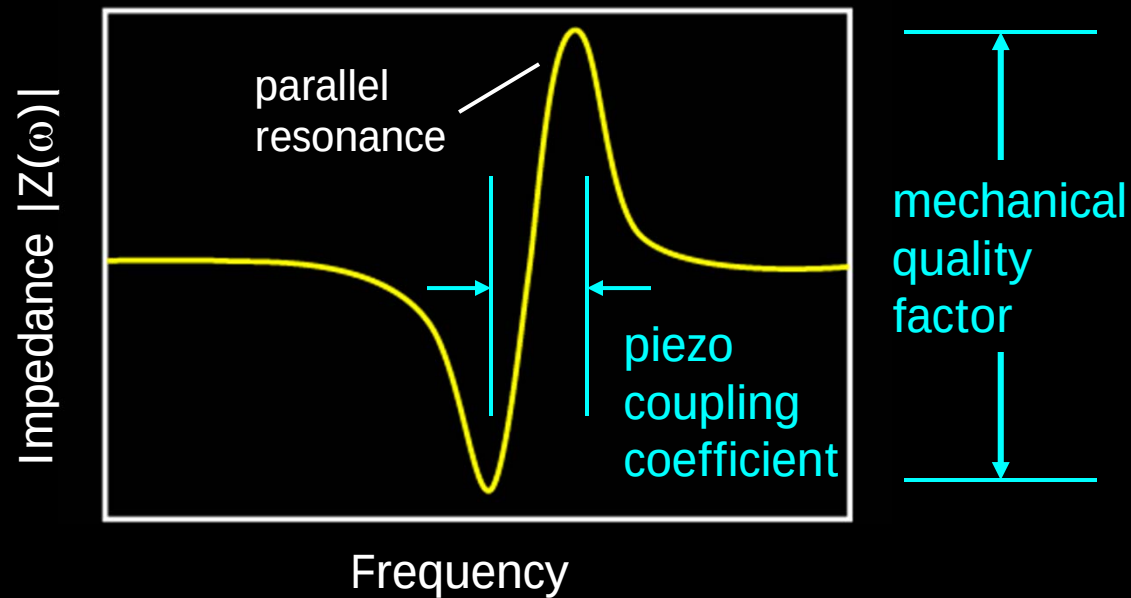
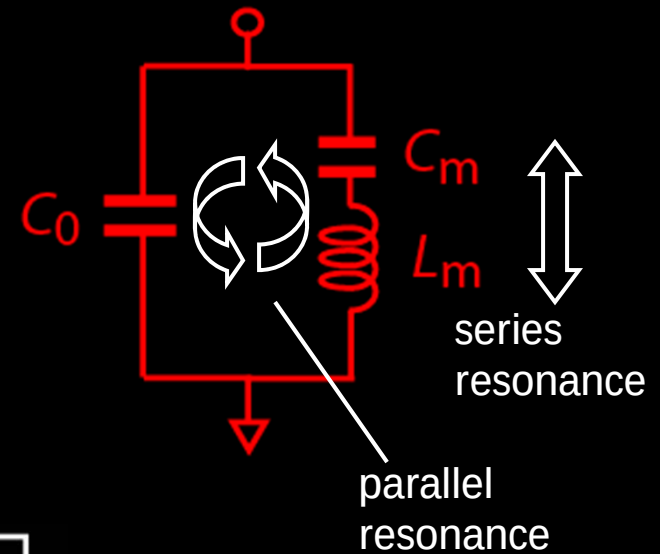
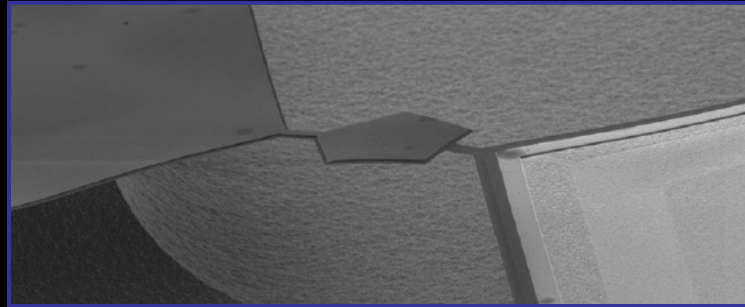
Our approach:

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



Resonator equivalent circuit

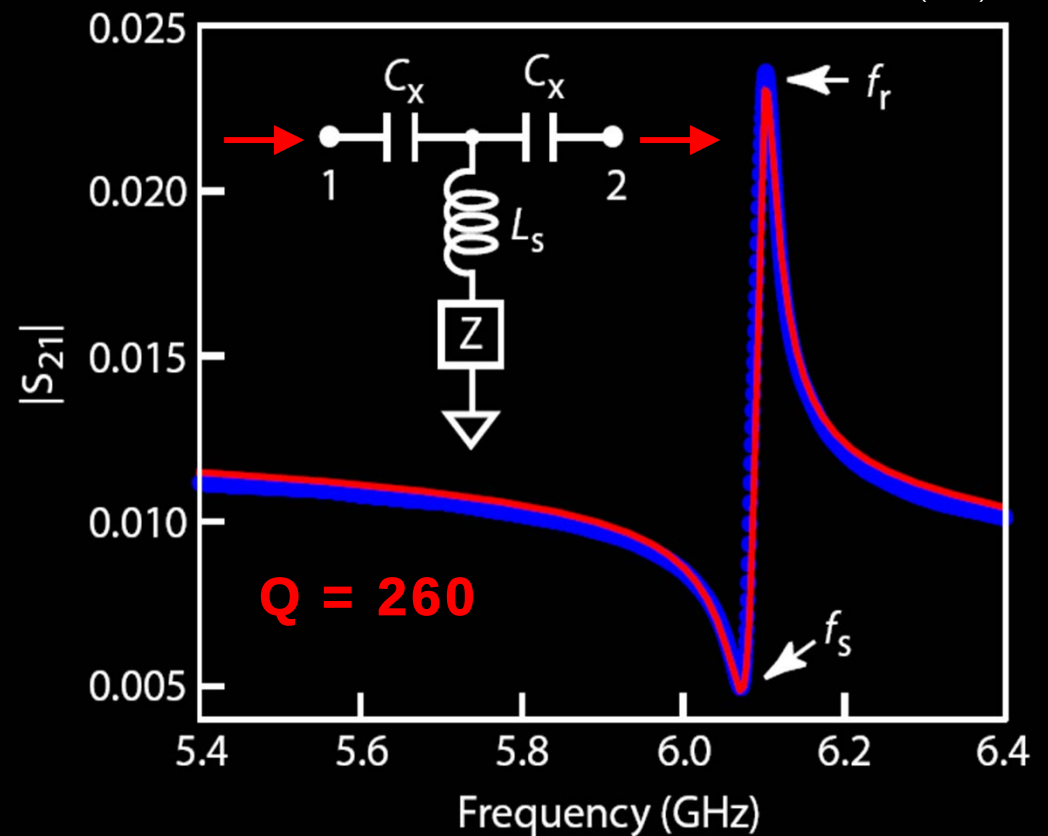
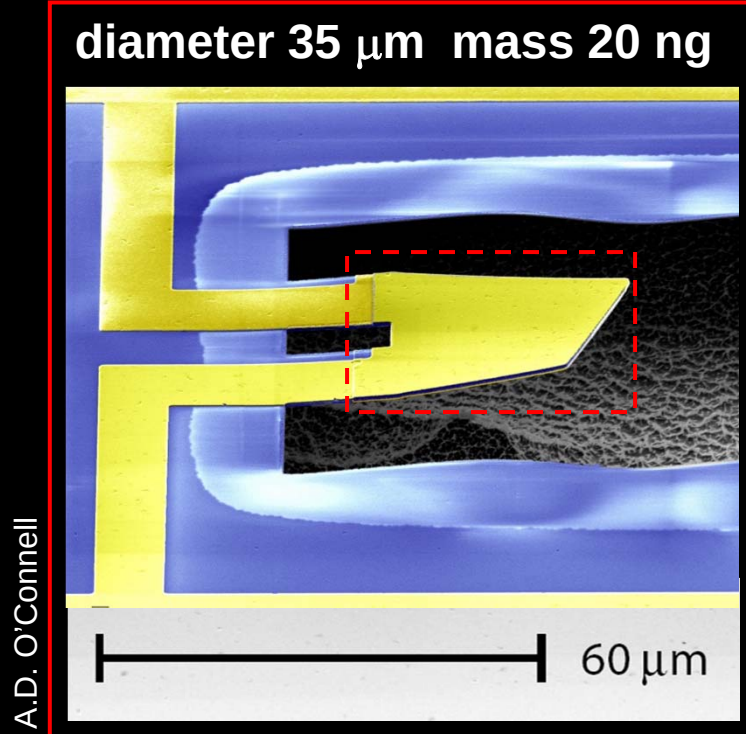
Electrical equivalent circuit:



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)



Six billionths of a second

Electromagnetic resonator: $Q \sim 10^5$

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

Qubit-resonator photon transfer time $\sim 25 \text{ ns}$ (20 MHz coupling)

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

Mechanical resonator: $Q \sim 260$

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

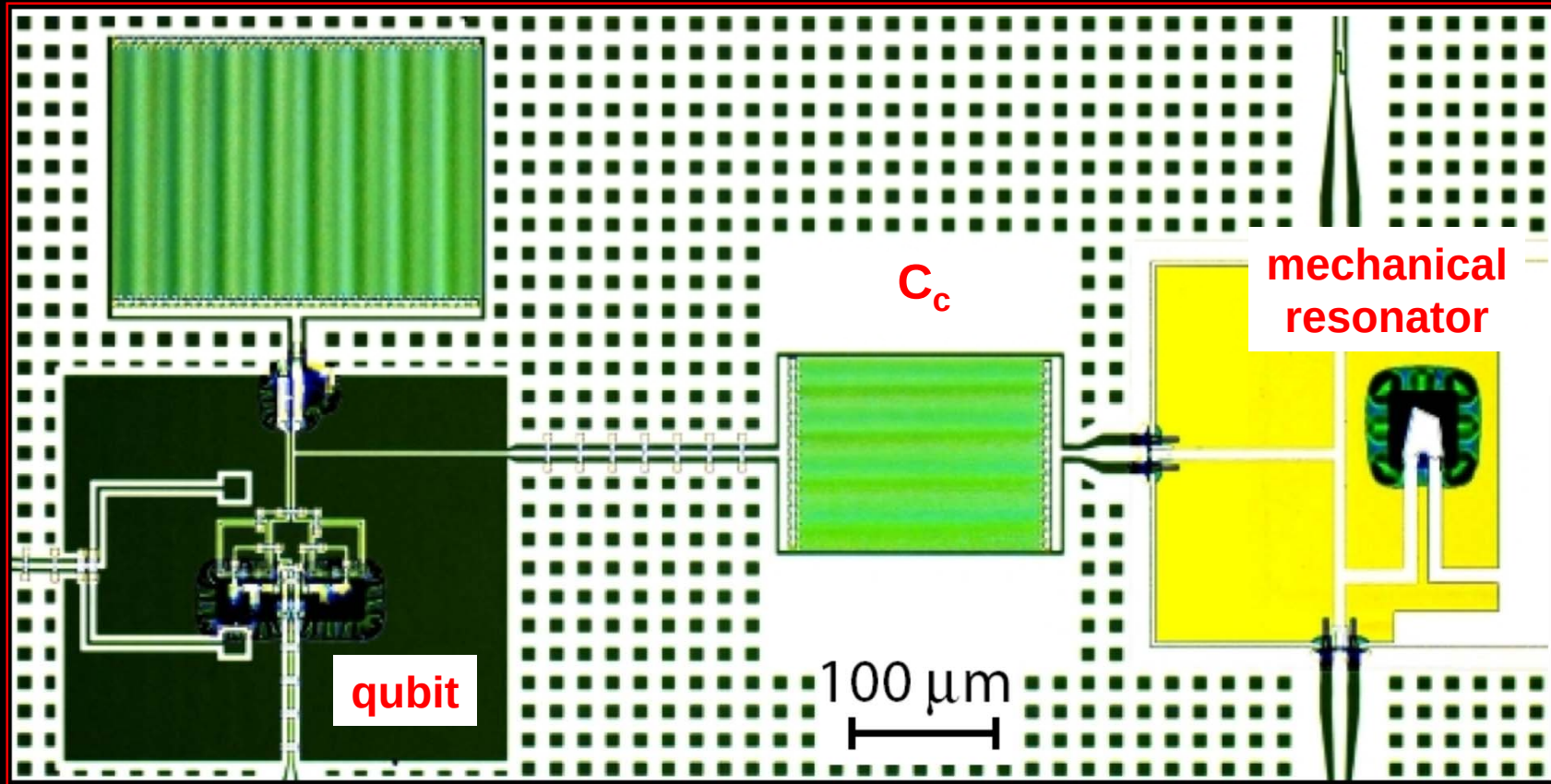
Requirements

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

➤ Target gate time: $\sim 5 \text{ ns}$ to transfer excitation ($\sim 100 \text{ MHz}$ coupling)

Integrated resonator & qubit

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

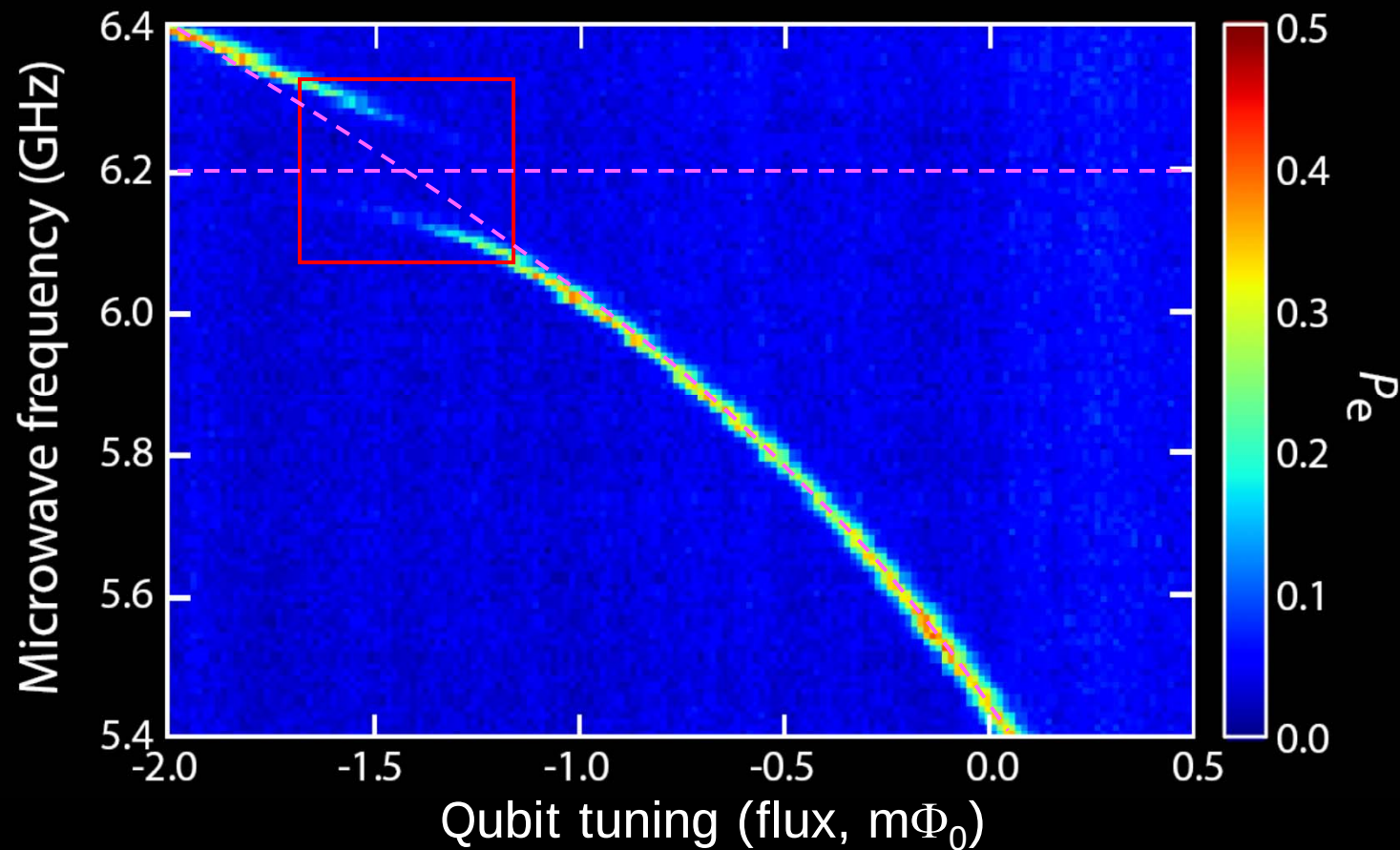
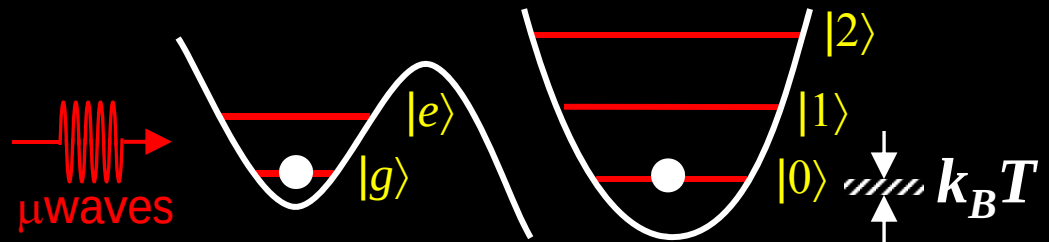


- Fabricate resonator, then qubit (13 layers)
- Suspend resonator at end
- Qubit & SQUID also mechanically suspended

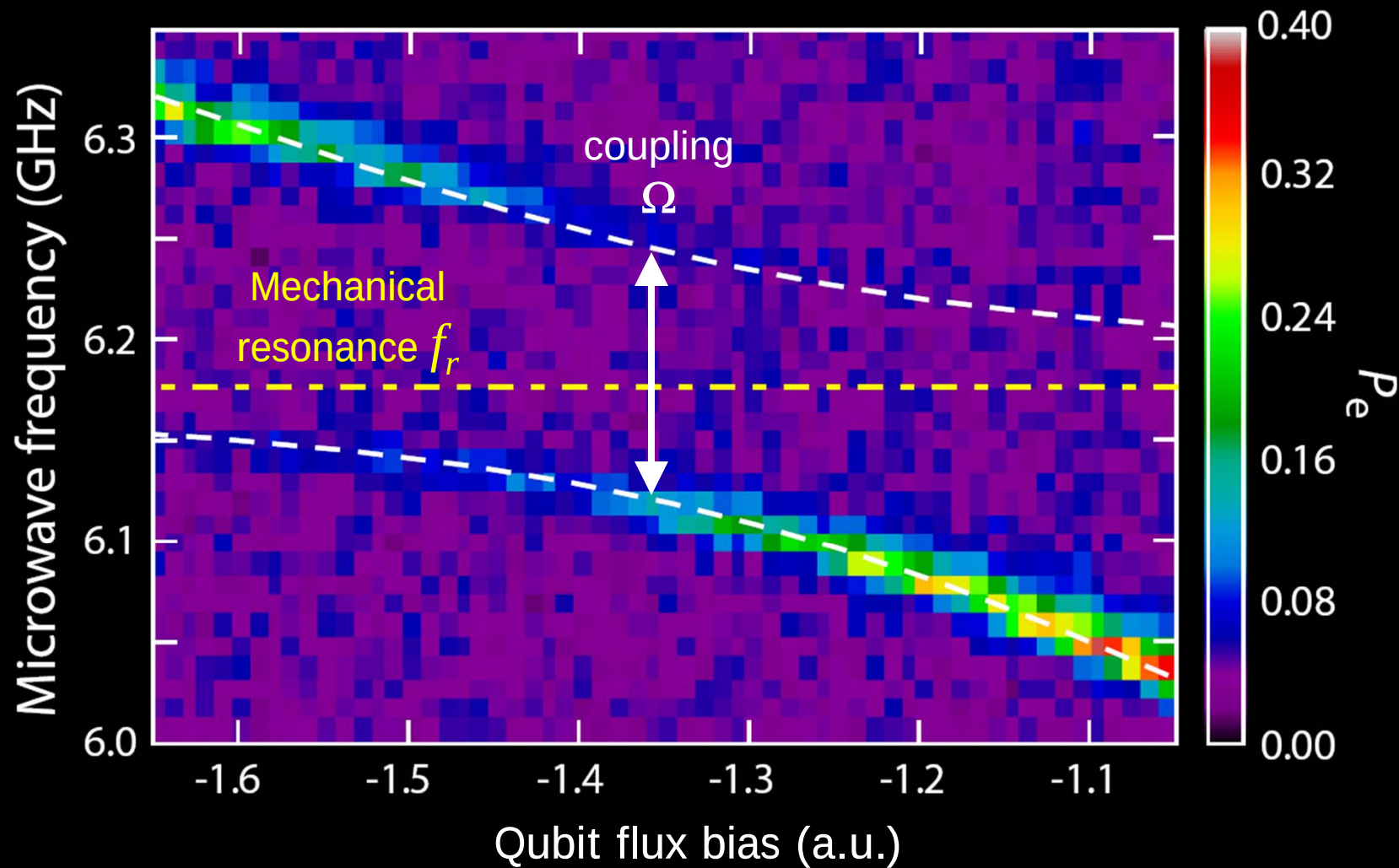
Design parameters:
Resonator 6.1 GHz
Coupling 110 MHz

Spectroscopy of coupled system

1. Set qubit frequency
2. Set microwave frequency
3. Pulse & measure qubit



Spectroscopy of coupled system

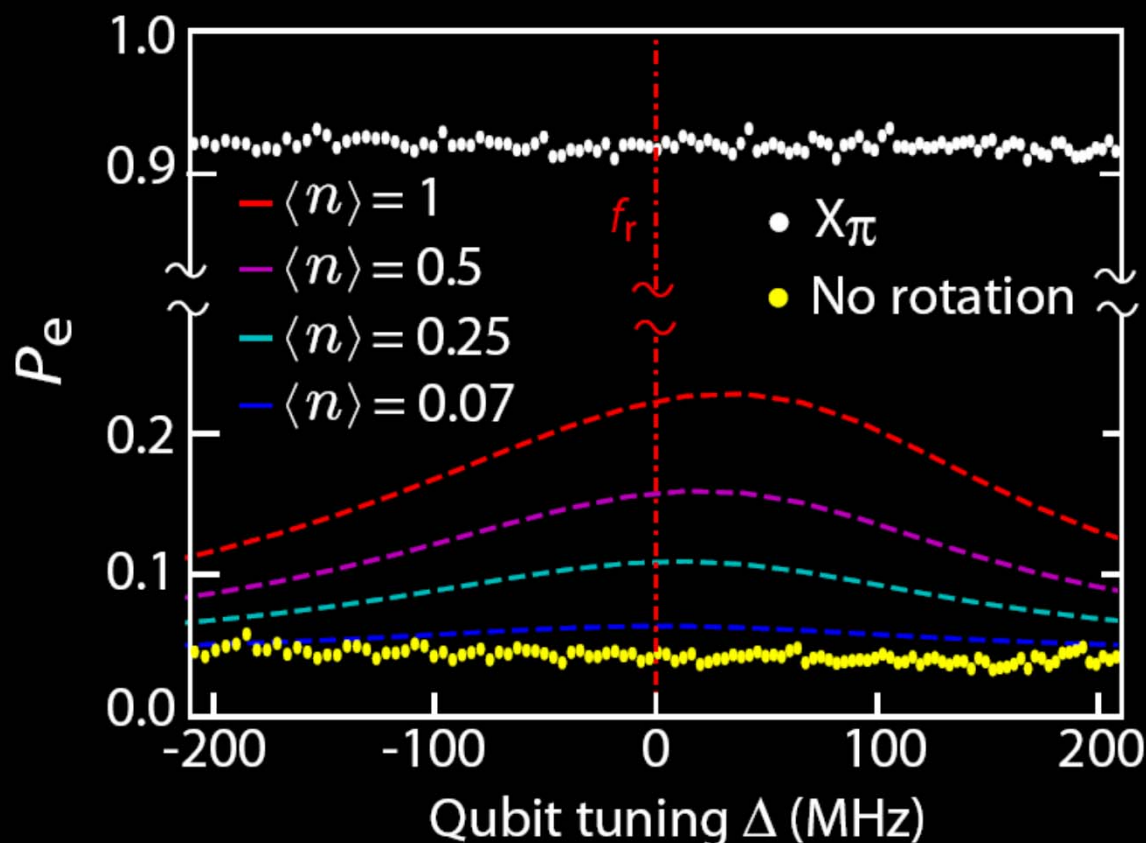
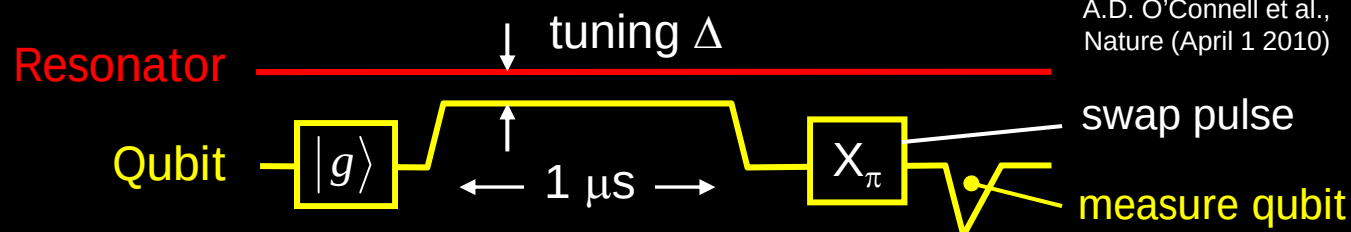


Mechanical resonance $f_r = 6.175$ GHz Coupling strength $\Omega = 124$ MHz

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:

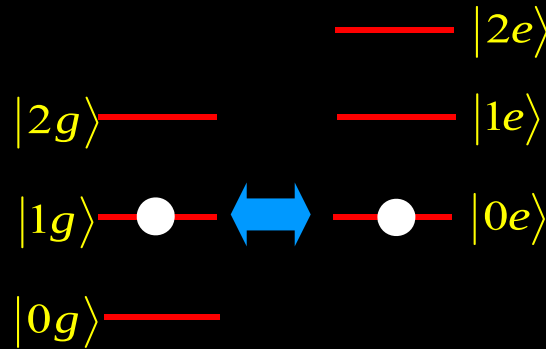
- Less than 0.07 phonons
- Maximum ~ 0.01 phonons

Mechanical resonator in
quantum ground state

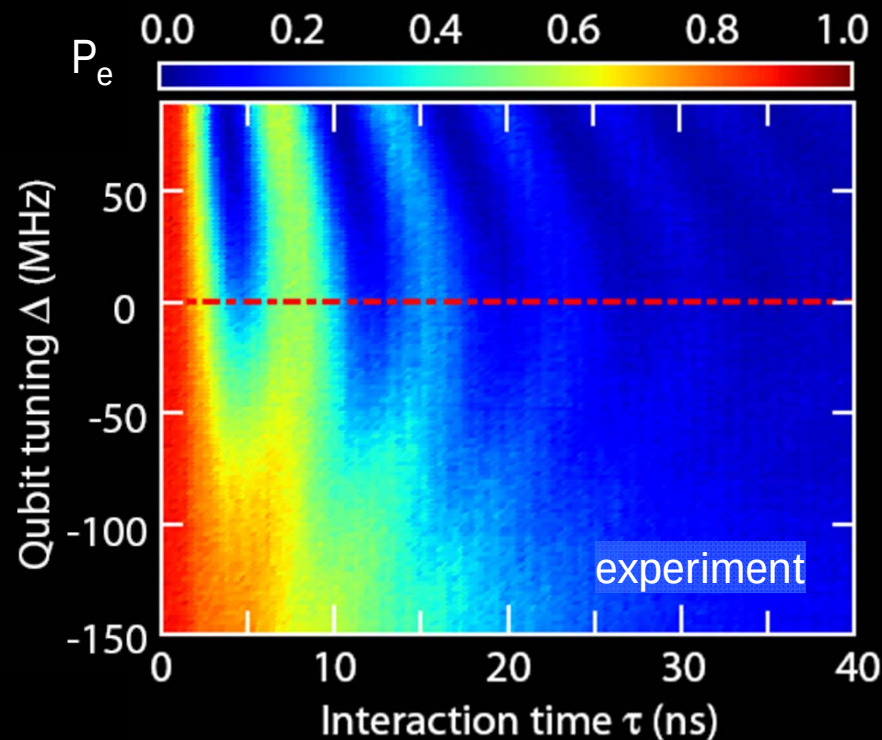
Electromechanical Rabi oscillations

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

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



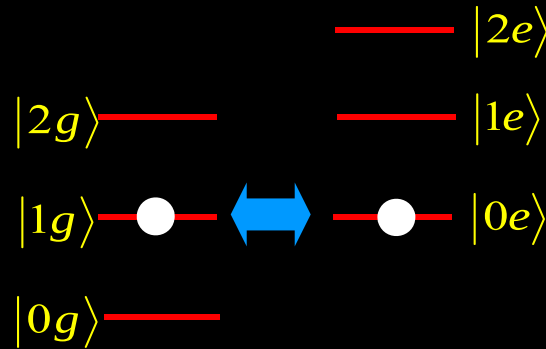
Oscillation period: $T = \frac{1}{\sqrt{\Omega^2 + \Delta^2}}$



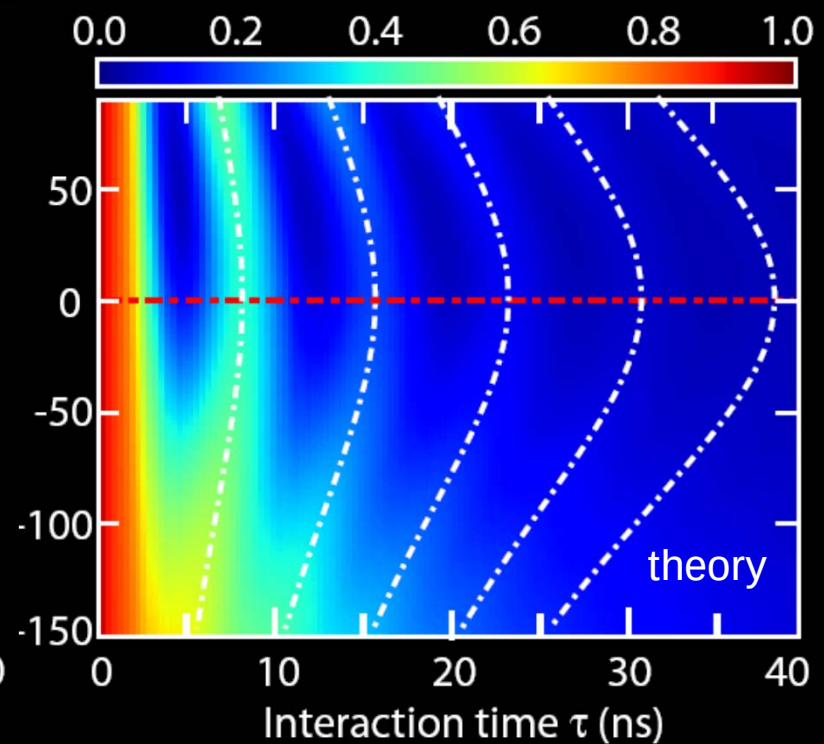
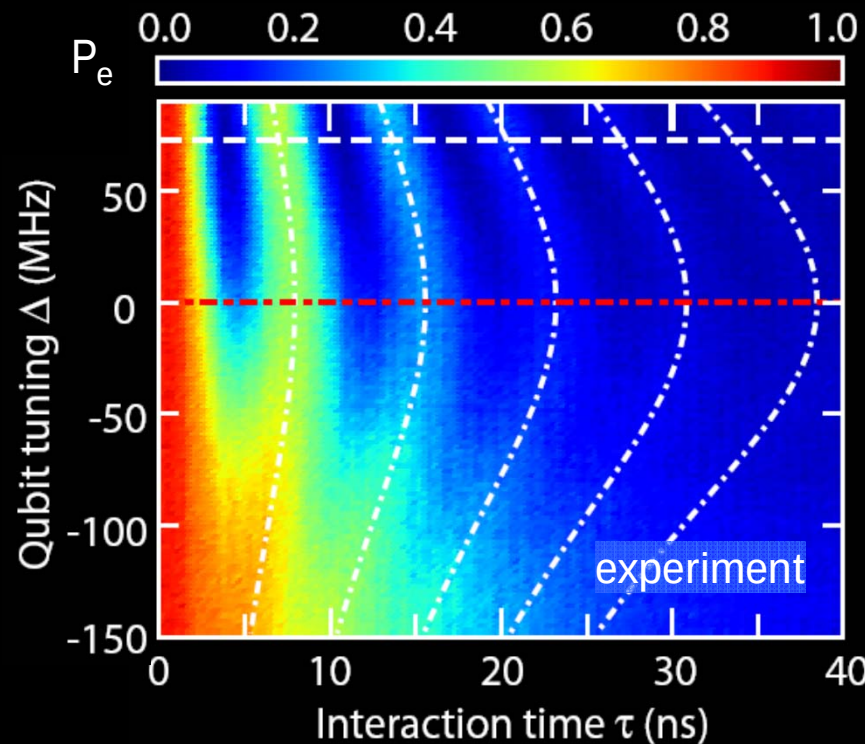
Electromechanical Rabi oscillations

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

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



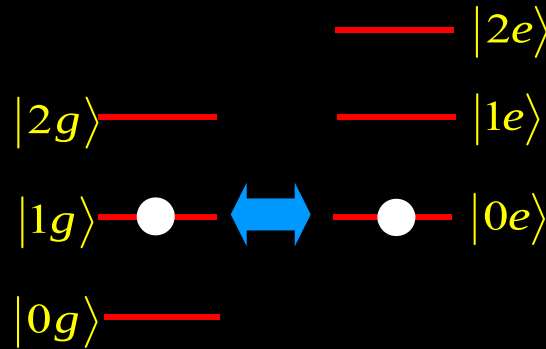
Oscillation period: $T = \frac{1}{\sqrt{\Omega^2 + \Delta^2}}$



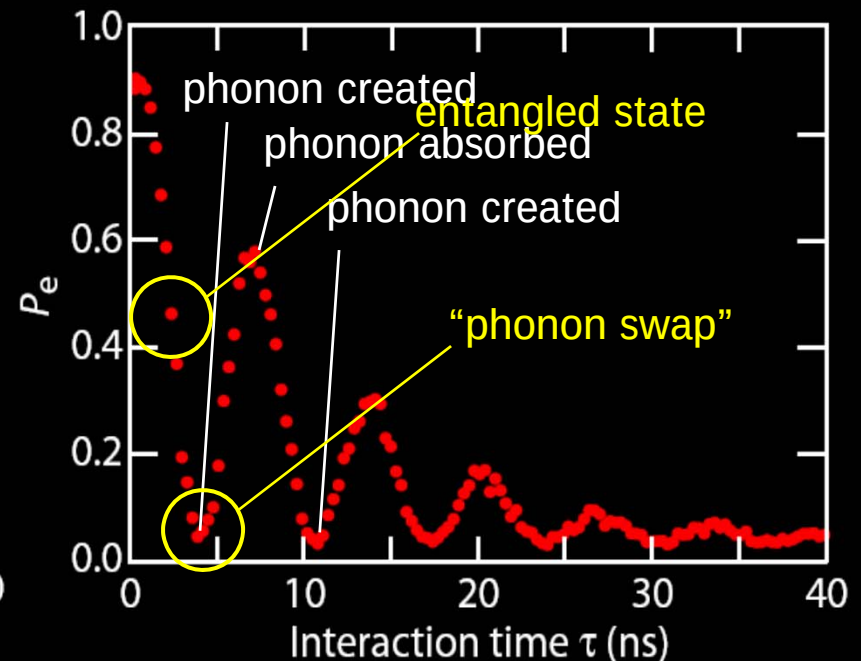
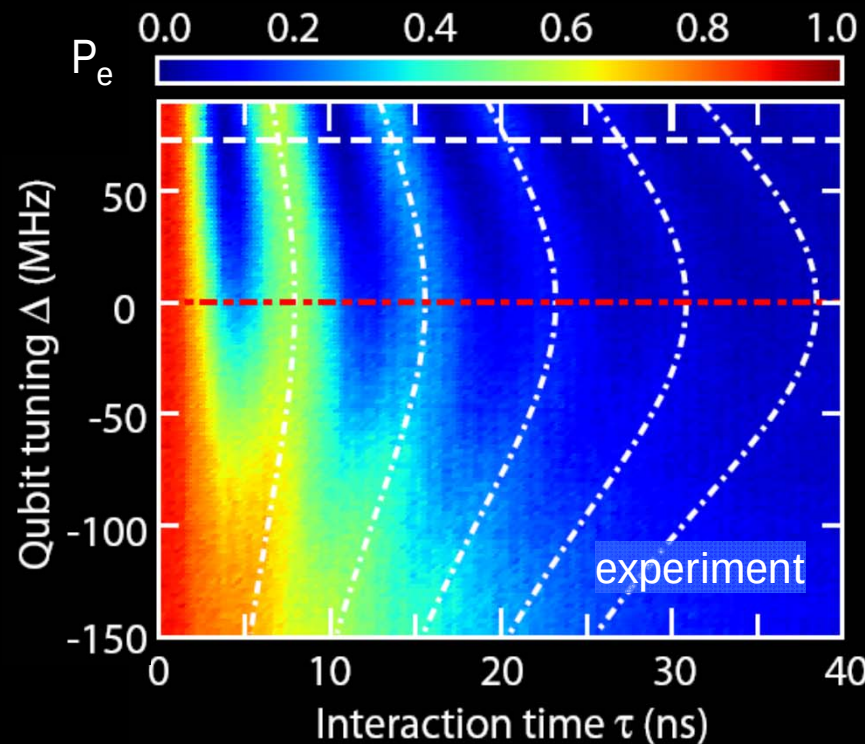
Electromechanical Rabi oscillations

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

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



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



Single phonon lifetime & phase coherence time

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

$$T_1 = 6.1 \text{ ns}$$

(agrees with $Q = 260$)

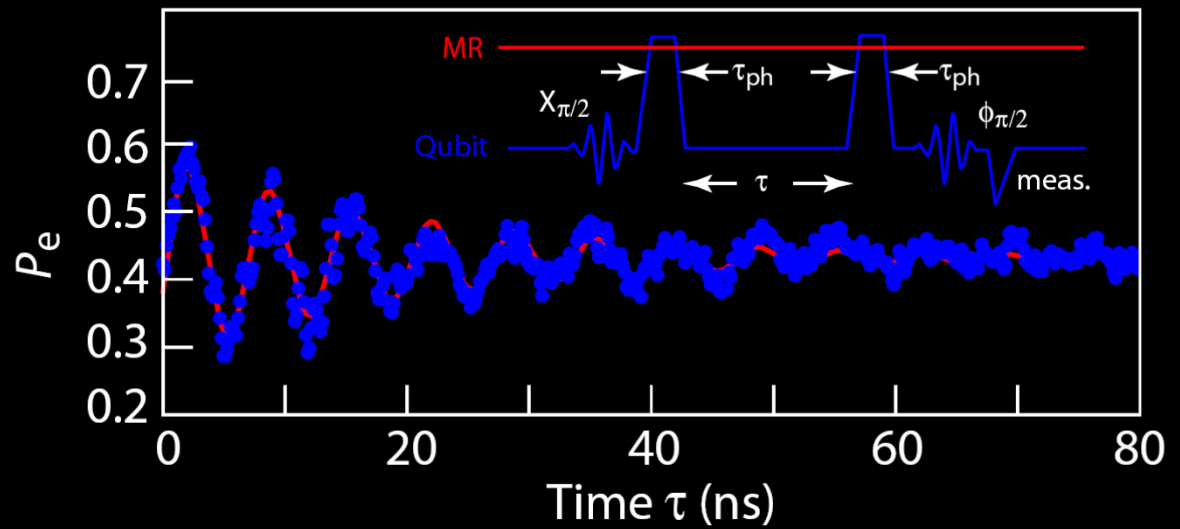
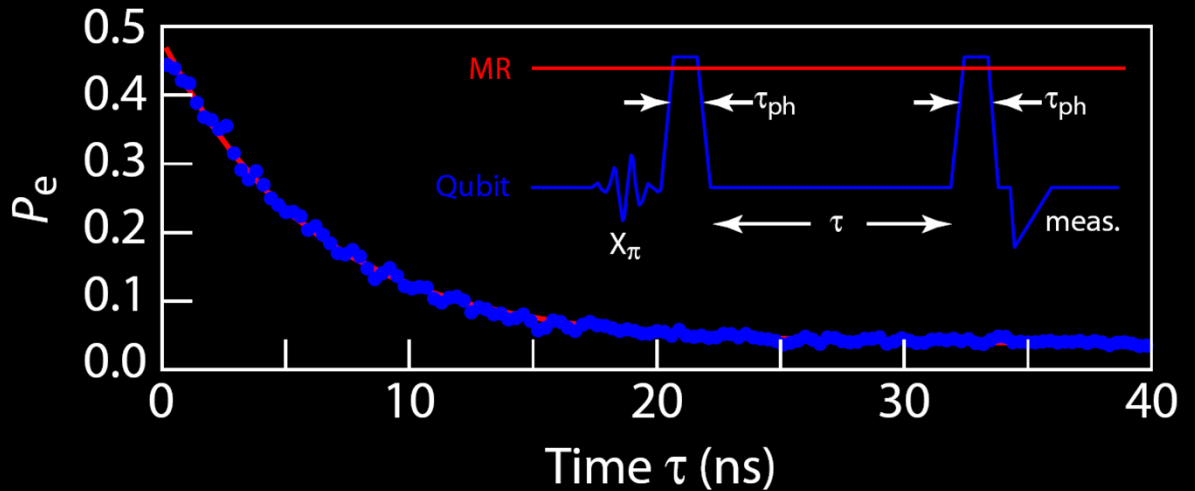
→ $T_1 = 6.7 \text{ ns}$

- Create superposition

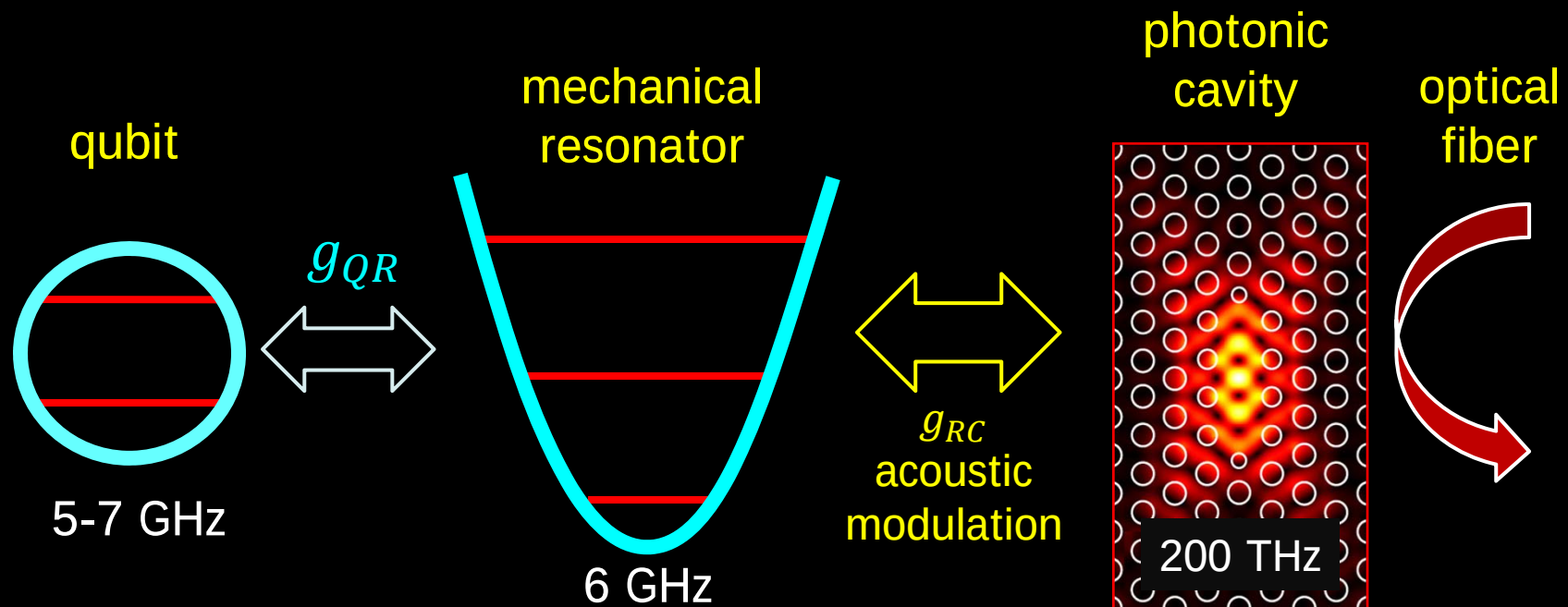
$$|0\rangle + |1\rangle$$

- Watch as it decays
(Ramsey fringe)
- Extract single phonon T_2

$$T_2 \sim 2 T_1$$

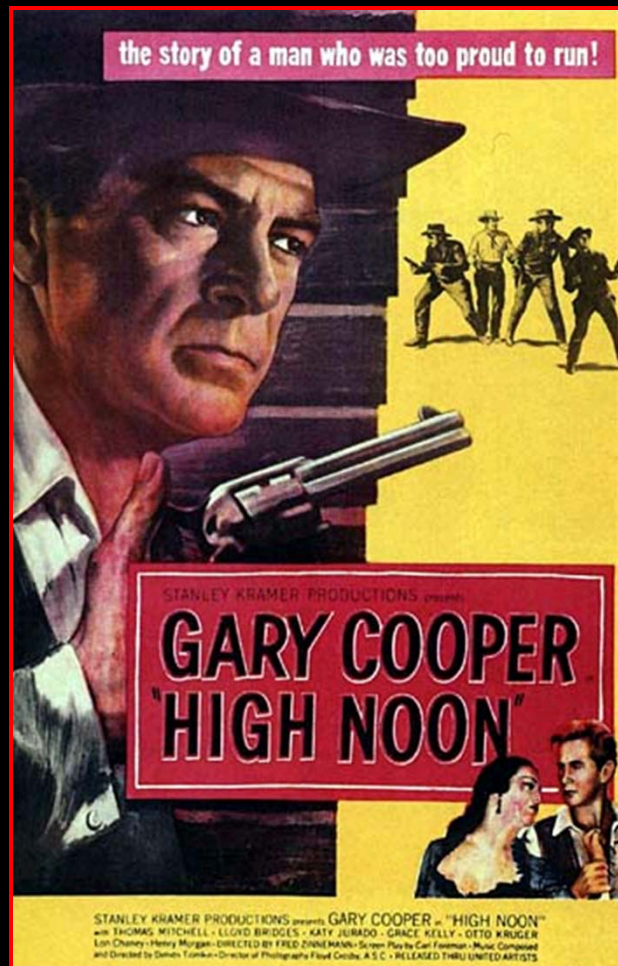


What's next? Qubit coupled to optomechanical system



- Strongly couple photonic cavity to mechanical resonator
- Laser sideband-couple resonator mode to cavity field
- Quantum transfer: Qubit to resonator to cavity, then to optical fiber

NOON states

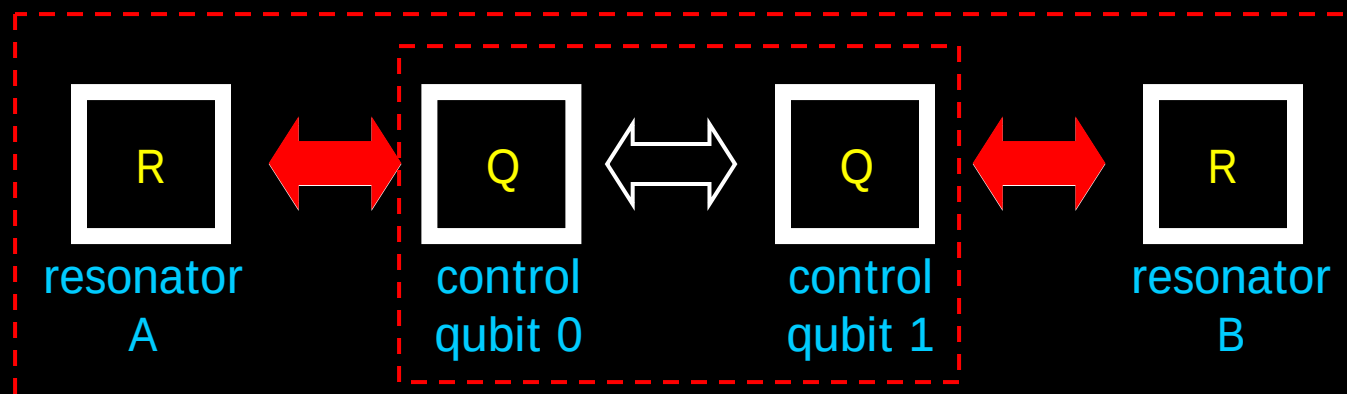


Coherent superposition of N and zero photons in two physically separated resonators:

$$|\Psi_{NOON}\rangle = |N\rangle_A |0\rangle_B + |0\rangle_A |N\rangle_B$$

NOON states

Topology for NOON state generation:

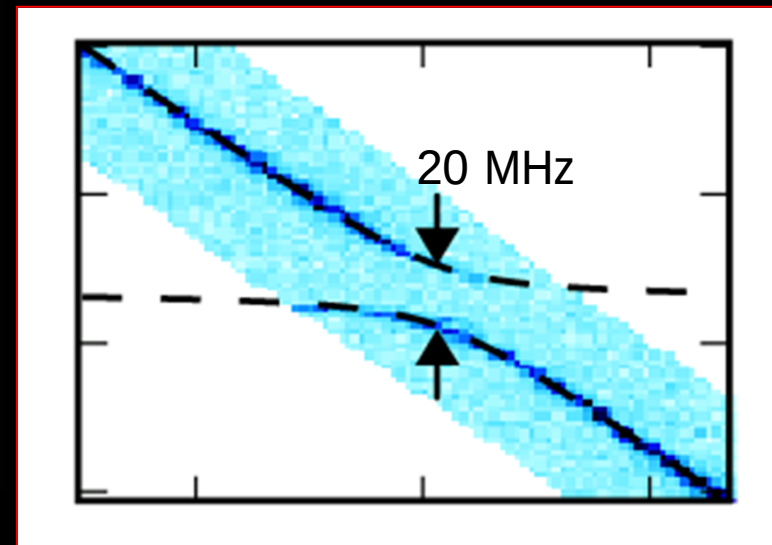
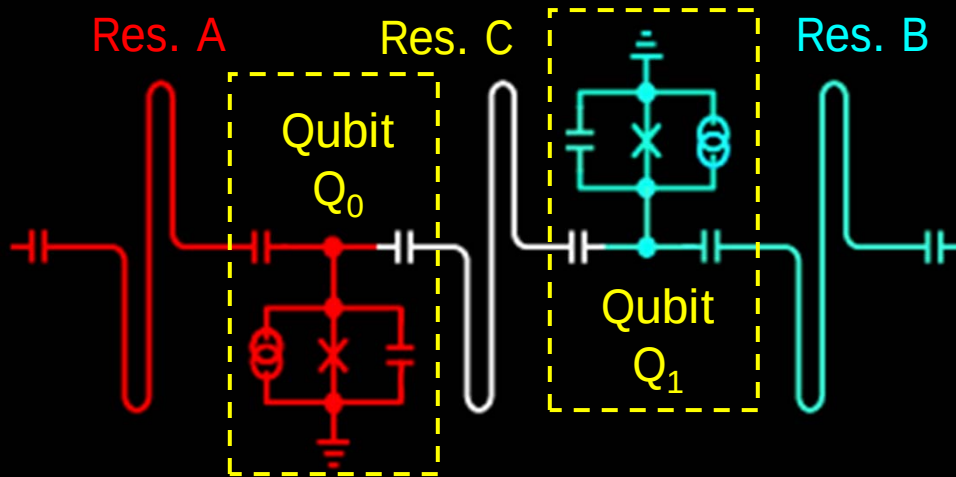
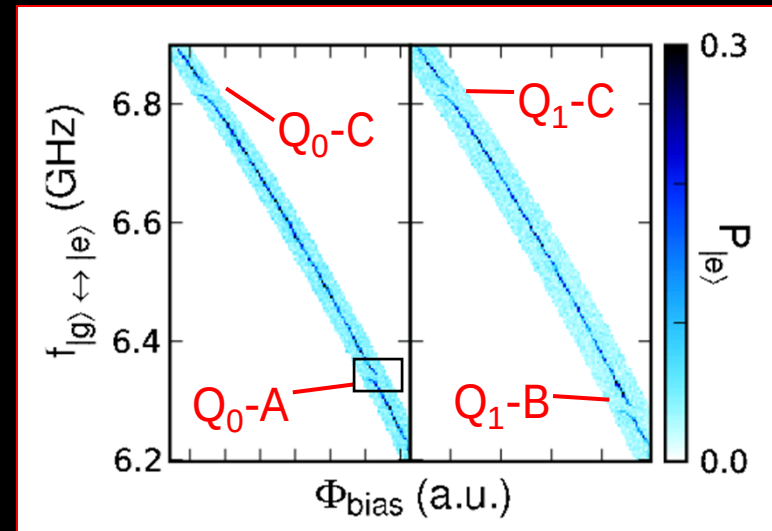
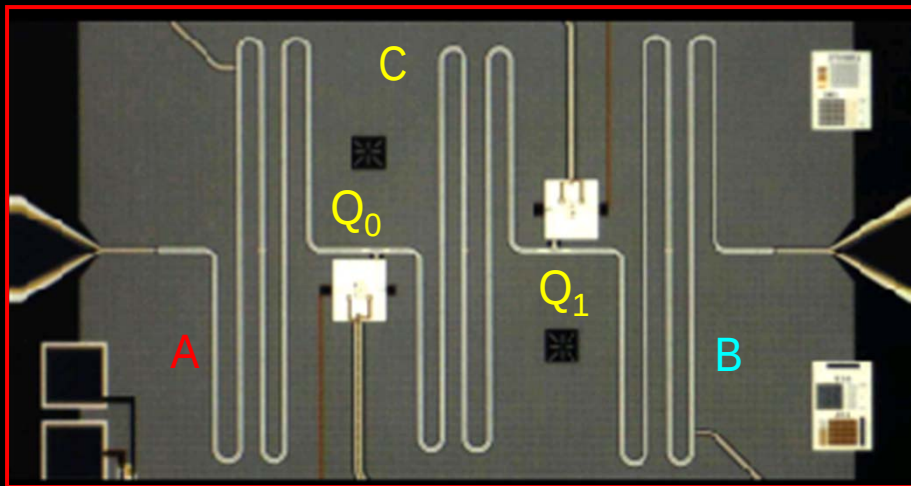


Procedure:

1. Entangle the two control qubits in a Bell state
2. Transfer entanglement (once) to the two resonators
3. “Amplify” by boosting photon number
4. Measure resonators & control qubits

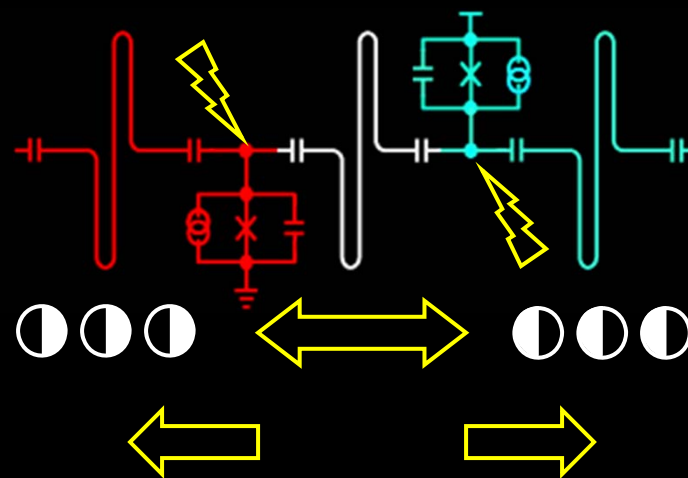
Also: Merkel & Wilhelm (NJP 2010)

NOON states



NOON states

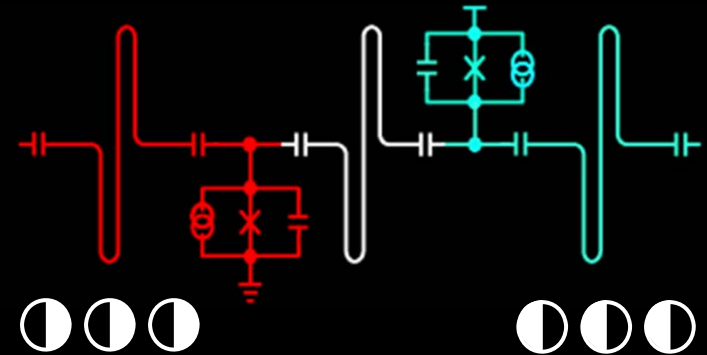
1. Excite & entangle qubits: $\overset{Q_0}{|e\rangle} \overset{Q_1}{|g\rangle} + \overset{Q_0}{|g\rangle} \overset{Q_1}{|e\rangle}$
2. Excite qubits e - f : $|fg\rangle + |gf\rangle$
3. ef transfer to resonators: $\overset{Q_0}{|e\rangle} \overset{Q_1}{|g\rangle} 10 + \overset{Q_0}{|g\rangle} \overset{Q_1}{|e\rangle} 01$
4. Excite qubits e - f : $\overset{R_A}{|f\rangle} \overset{R_B}{|g\rangle} 10 + \overset{R_A}{|g\rangle} \overset{R_B}{|f\rangle} 01$
5. ef transfer to resonators: $|eg20\rangle + |ge02\rangle$
6. ge transfer to resonators: $|gg30\rangle + |gg03\rangle = |gg\rangle \otimes (|30\rangle + |03\rangle)$



N=3 NOON state

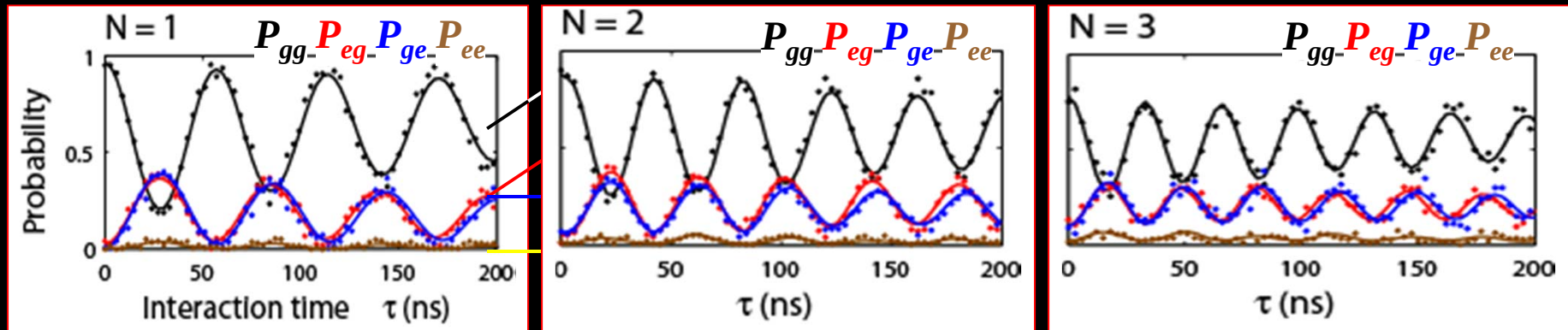
NOON state analysis

$$|\psi\rangle = |gg\rangle \otimes (|30\rangle + |03\rangle)$$



Coincidence measurement:

- Bring qubits into *eg* resonance and measure as photons swap



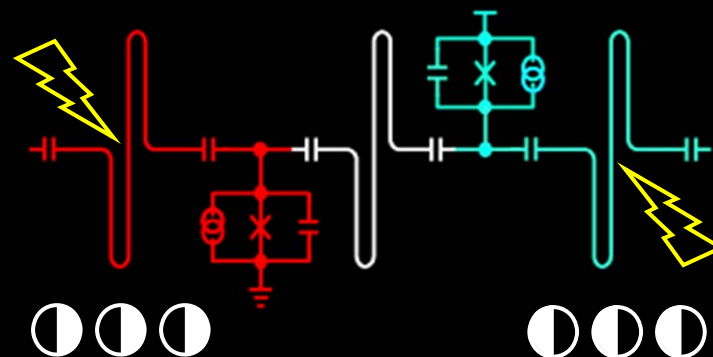
$$|\psi\rangle = |10\rangle + |01\rangle$$

$$|\psi\rangle = |20\rangle + |02\rangle$$

$$|\psi\rangle = |30\rangle + |03\rangle$$

NOON state analysis

$$|\psi\rangle = |gg\rangle \otimes (|30\rangle + |03\rangle)$$



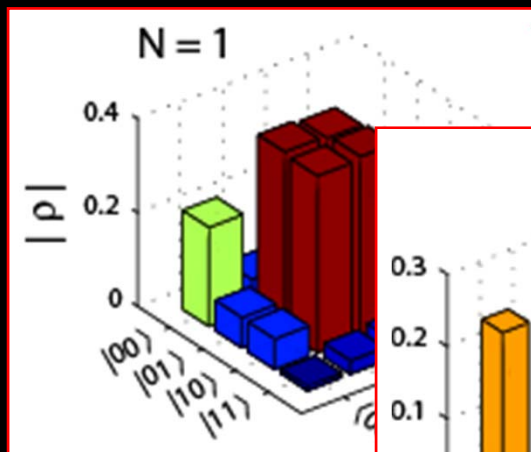
Bi-partite Wigner tomography:

- Bring qubits into e - g resonance and measure as photons swap (1000x)
- Inject coherent pulses (amplitude & phase) into resonators A and B
(this displaces states in resonator phase space)
- Bring qubits into e - g resonance and measure as photons swap (1000x)

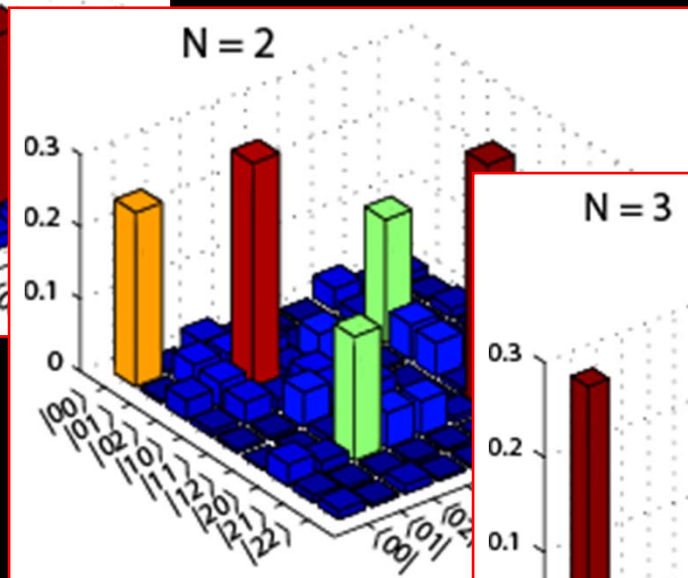
... Repeat ~200-400 times for different pulse amplitudes & phases

Calculate bi-partite Wigner tomogram $\Rightarrow$ Two-resonator density matrix

NOON state tomography



$$|\psi\rangle = |10\rangle + |01\rangle$$



$$|\psi\rangle = |20\rangle + |02\rangle$$

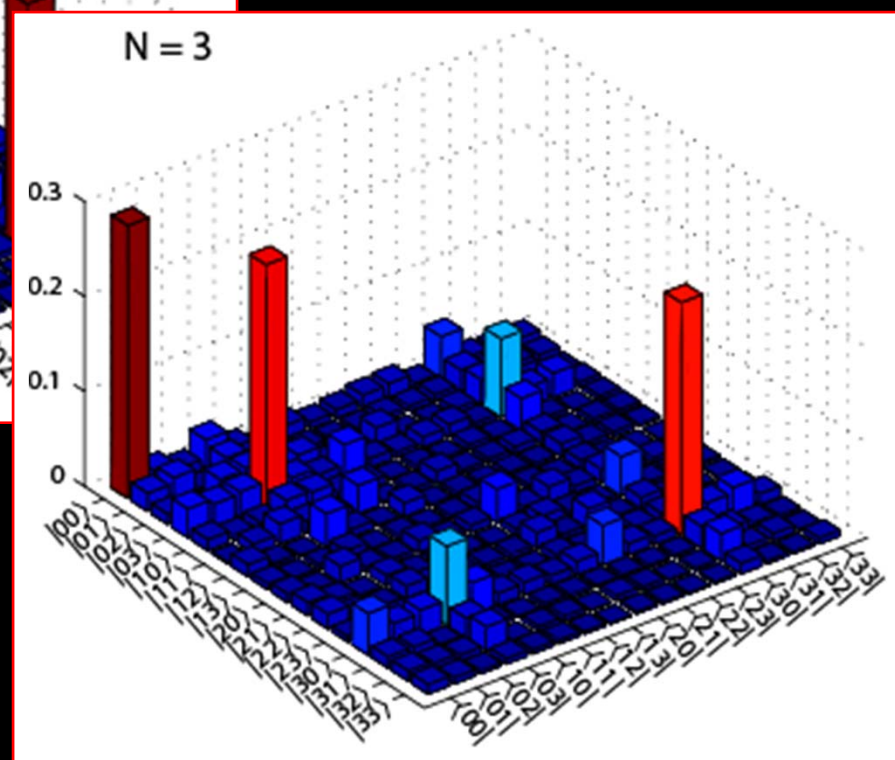
N=1 fidelity: $F = \langle\psi|\rho|\psi\rangle = 0.76$

N=2 fidelity: $F = 0.50$

N=3 fidelity: $F = 0.33$

Bipartite Wigner tomography yields two-resonator density matrix

$$\rho = |mn\rangle\langle pq|$$



$$|\psi\rangle = |30\rangle + |03\rangle$$

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
- NOON states in two superconducting resonators

Quantum light & sound



Andrew N. Cleland
John M. Martinis

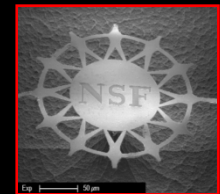
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