Quantum light & sound

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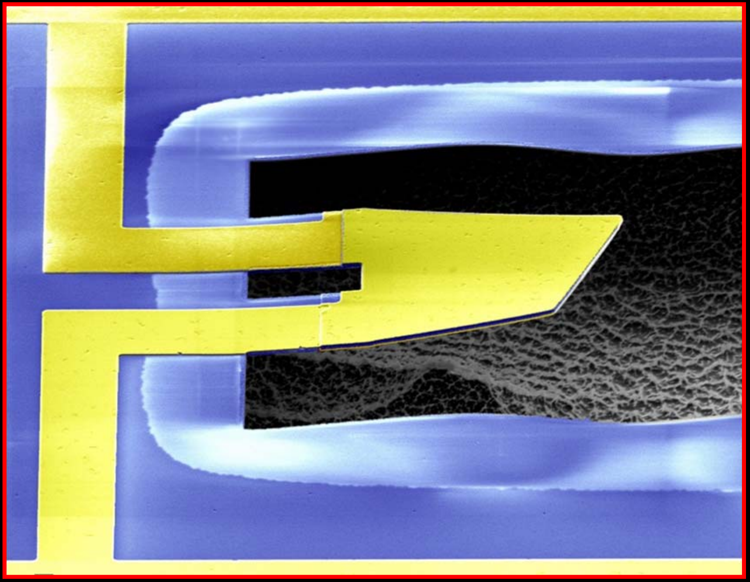

Collaborators:
- John M. Martinis (UC Santa Barbara)
- Michael Geller (U Georgia - Athens)

IQC Colloquium
University of Waterloo
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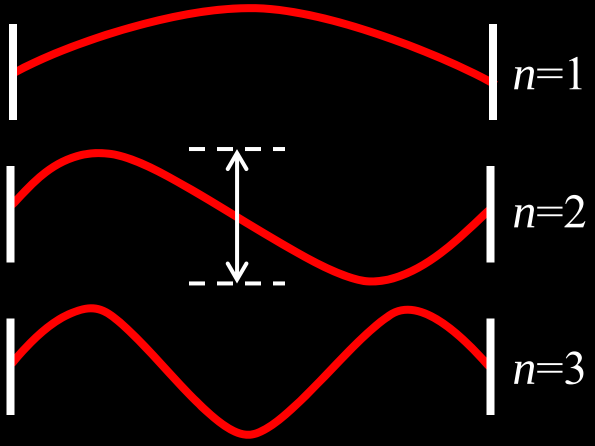
Monday March 14 2011

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

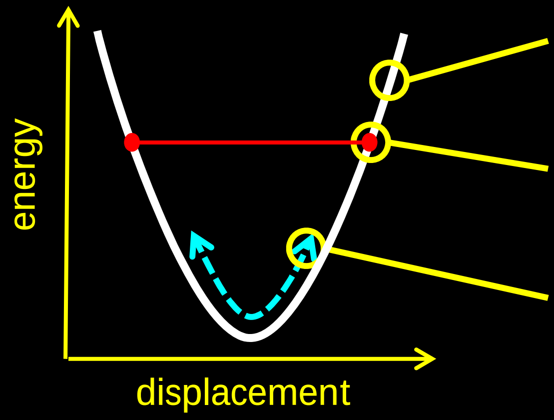
CLICK!

Classical mechanics



- Vibrational modes f_n
- Arbitrary amplitudes
- Frequency ≈ independent of amplitude

➢ Each vibrational mode:

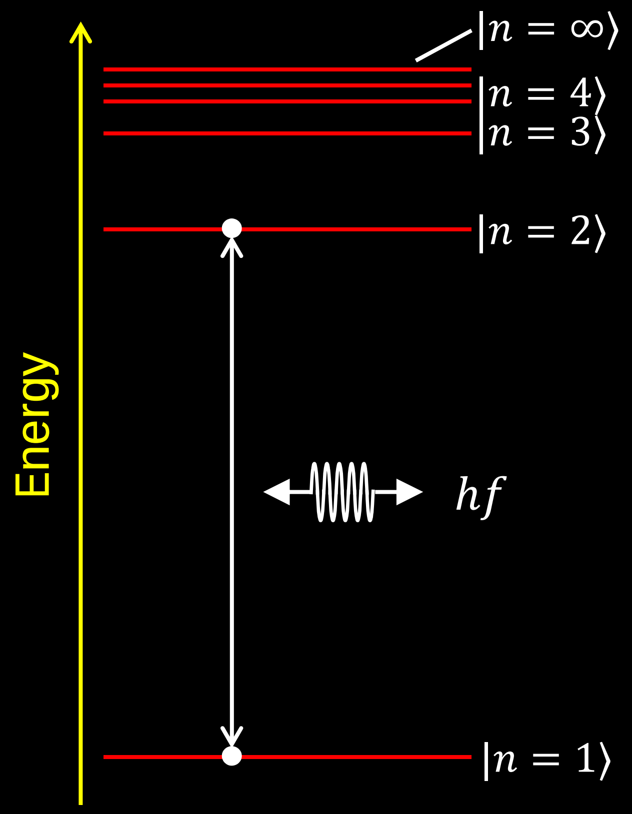


- Potential energy quadratic in displacement
- Total energy can take on any value
- Frequency f independent of energy

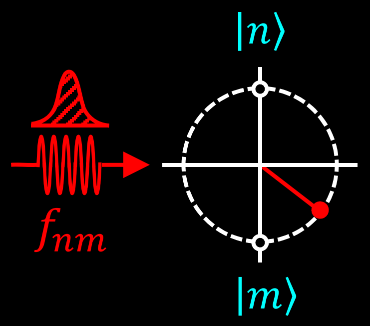
➢ Excitations at resonance f generate arbitrary amplitudes

Quantum mechanics

Spectrum of hydrogen

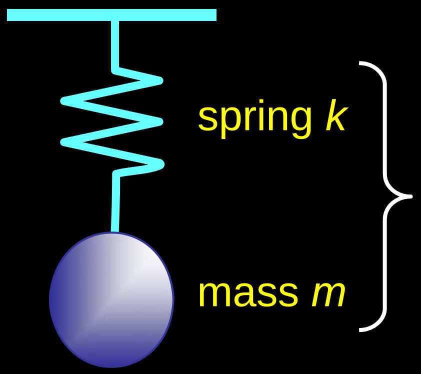


- Series of distinct spectral lines
- Bohr: Transitions between states involve photons: $E_n - E_m = hf_{nm}$
- A particular frequency generates a particular transition: $|m\rangle + hf_{nm} \Rightarrow |n\rangle$
- More photons induce further oscillations:
  $$hf_{nm} + |m\rangle \Rightarrow |n\rangle,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



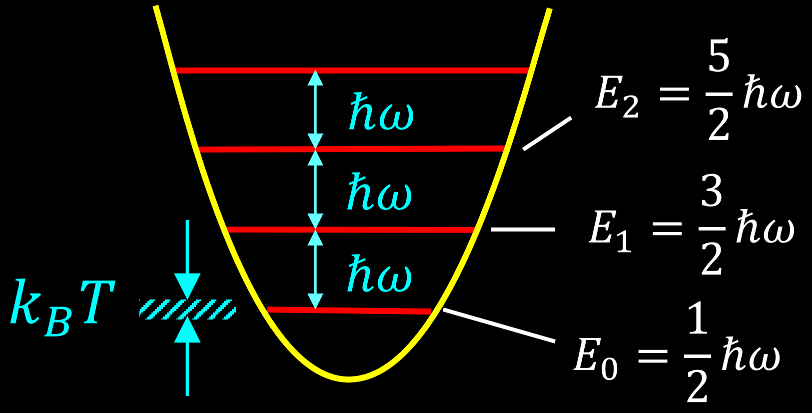
Phase & amplitude control of light allows arbitrary state preparation: $|\Psi\rangle = \alpha|m\rangle + \beta e^{i\phi}|n\rangle$

Harmonic oscillator in the quantum limit



Resonance frequency $\omega = \sqrt{k/m}$

Quantum solution:

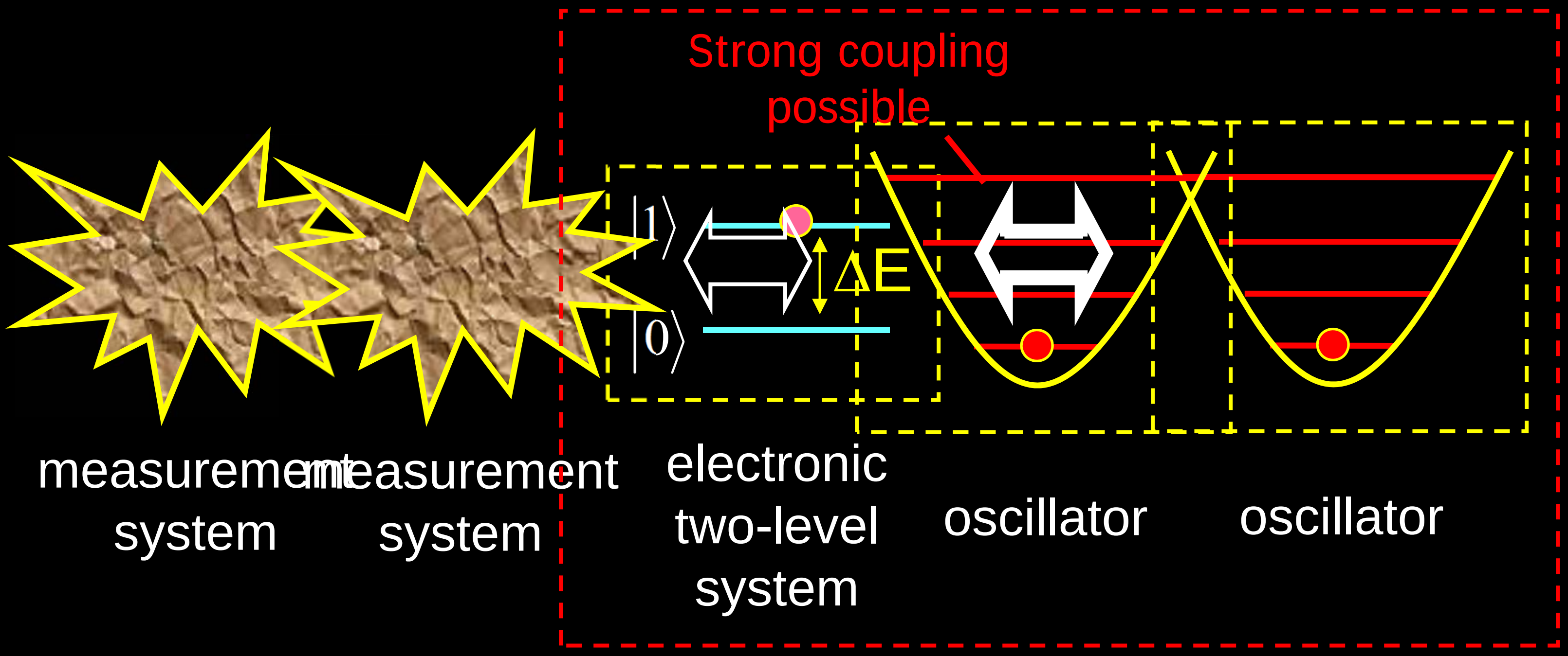


How to see quantum behavior?

1. Cool to quantum ground state: $k_B T \ll \hbar\omega$
   - Conventional refrigeration: $T_{min} = 20\ \mathrm{mK} \Longrightarrow \omega/2\pi > 1\ \mathrm{GHz}$
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 $T_1 = Q/\omega$

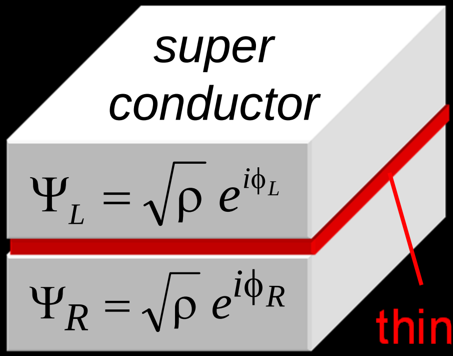
Measuring a harmonic oscillator in the quantum limit

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



Coupled system quantum coherent
Allows complete quantum measurement & control

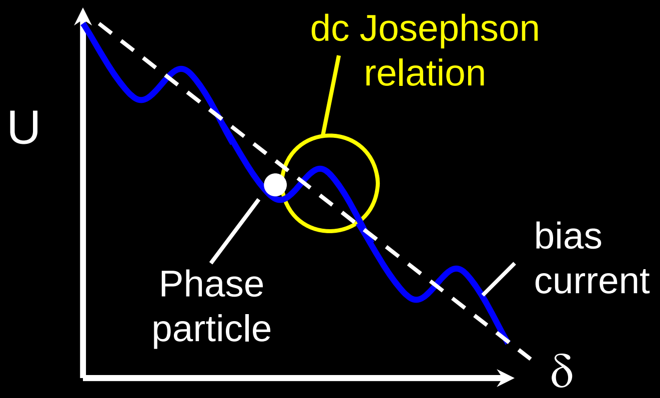
Josephson phase qubit: Electronic atom/two-level system



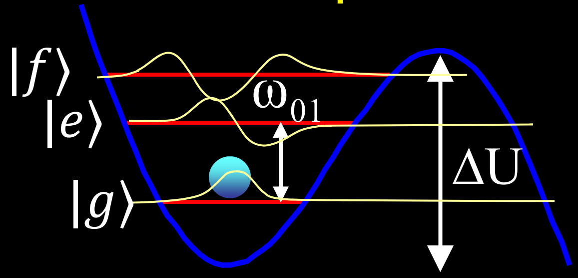
Phase difference

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

ac & dc Josephson relations



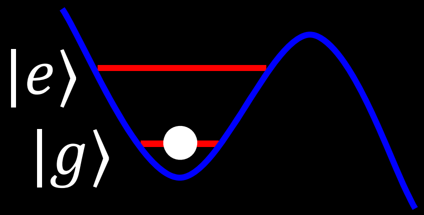
At 20 mK δ is a quantum variable:



- ➢ Nonlinearity makes $\omega_{12} \sim 0.95\, \omega_{01}$

  Selectively address lowest two states
- ➢ ω_{01} tuned by bias current: 5-10 GHz

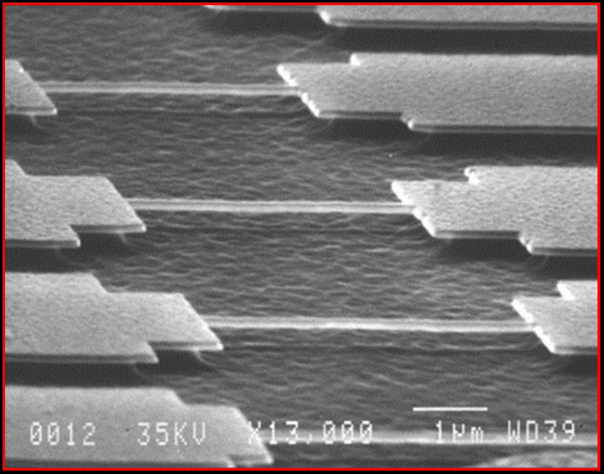
  $\hbar\omega \sim 30 k_B T$ at 20 mK



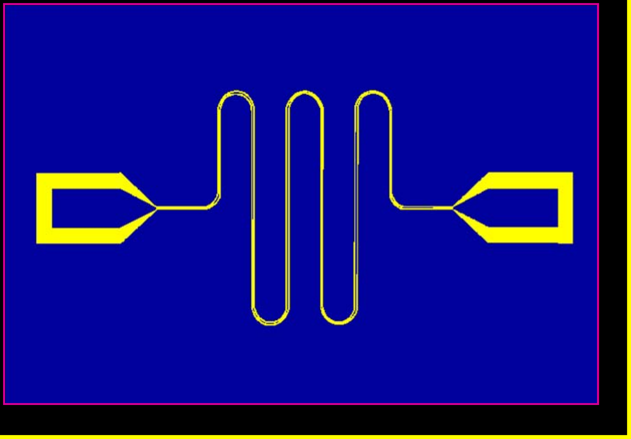
1. Electronic two-level system
2. Ground state below 100 mK
3. Complete quantum control
4. Strong coupling possible

Candidates for quantum harmonic oscillators

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

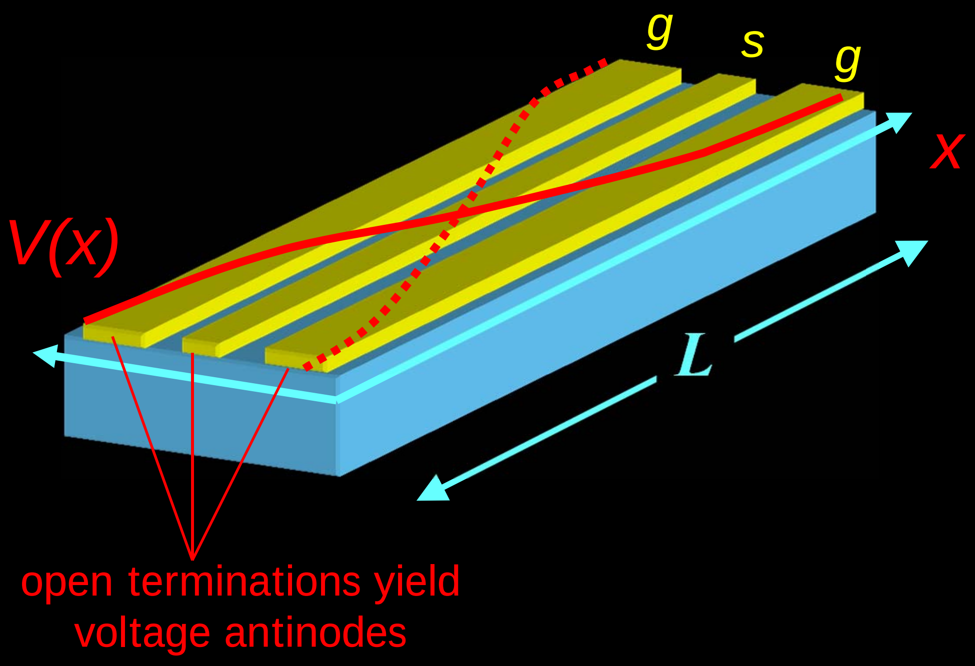


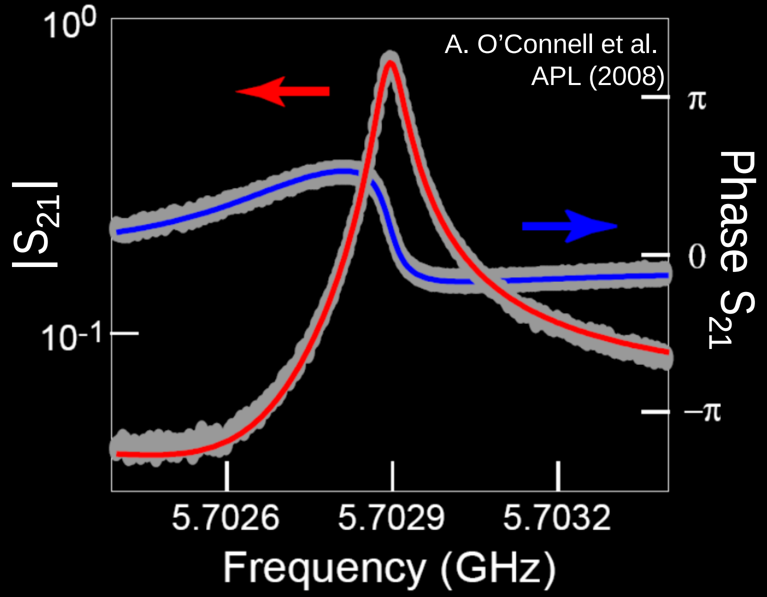
- Electromagnetic resonators
  - Resonance frequencies up to ~100 GHz
  - Integrable with phase qubit
  - Quanta are *photons*
  - **Quality factors ~10^5-10^6: Long lifetime**



Max Hofheinz & Haohua Wang

Half-wave coplanar stripline resonator

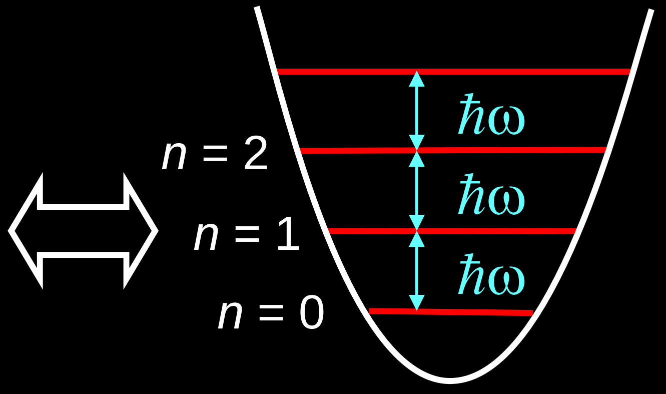




- Wavelength $\lambda = 2L \sim 10$ mm
- Resonance frequency $\omega/2\pi \sim$ 5-10 GHz

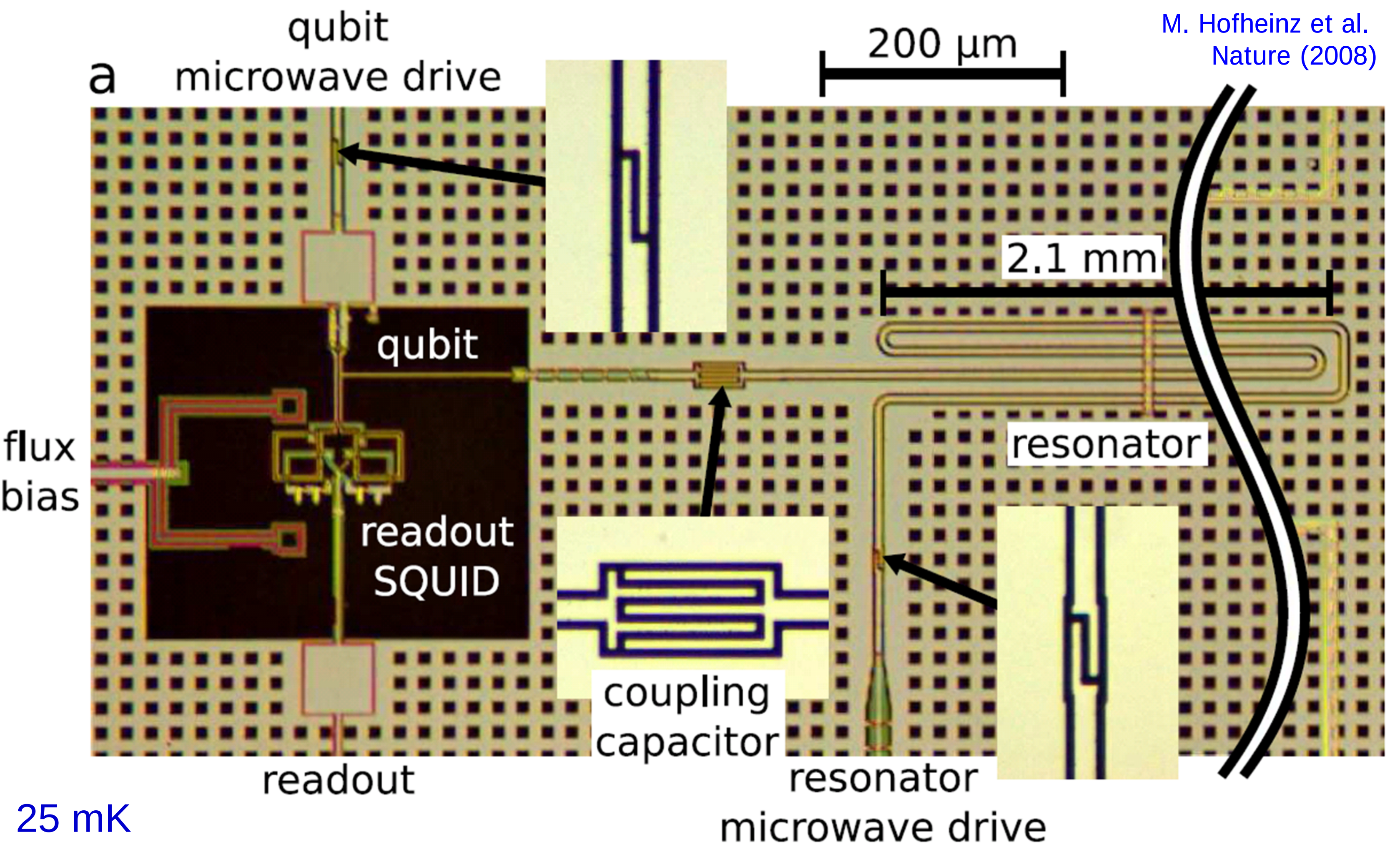
  $\hbar\omega \gg k_B T$ at 20 mK
- Quality factor Q ~ 10^5

  $T_1 = Q/\omega$ is a few microseconds



Quantum control of microwave photons

Coupled electromagnetic resonator & Josephson qubit

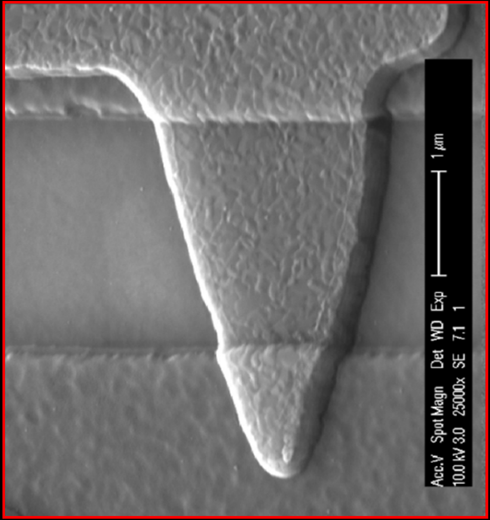


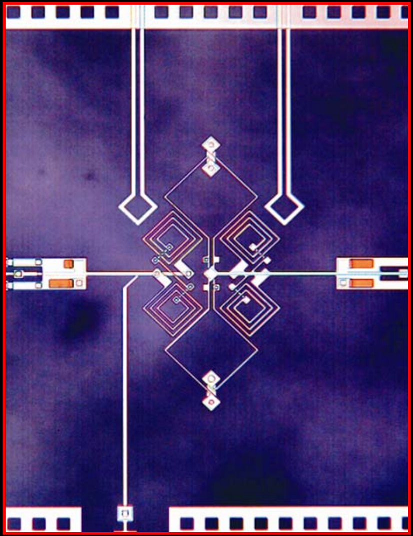
M. Hofheinz et al.
Nature (2008)

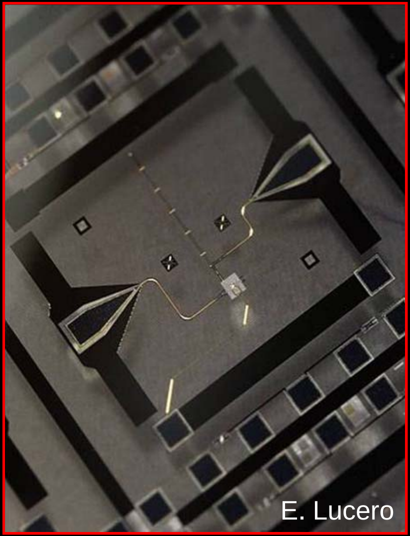
25 mK

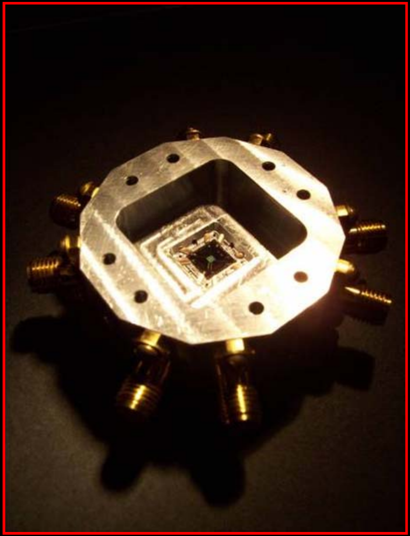
Making & measuring quantum devices

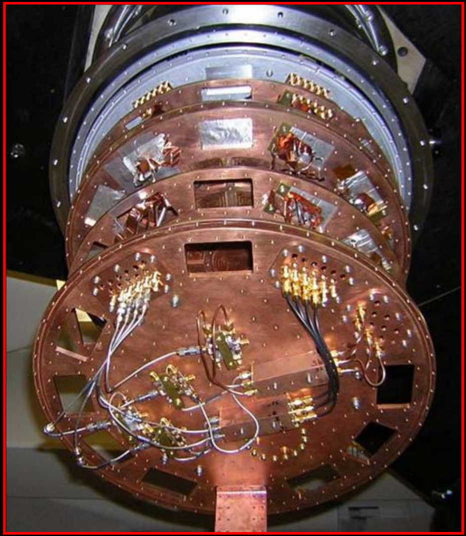
- 8 layers optical lithography, deposition, etching (UCSB Nanofabrication Facility)
- 3” sapphire wafers
- Diced into ¼” x ¼” chips
- Mount on dilution refrigerator (25 mK)
- Control with custom electronics





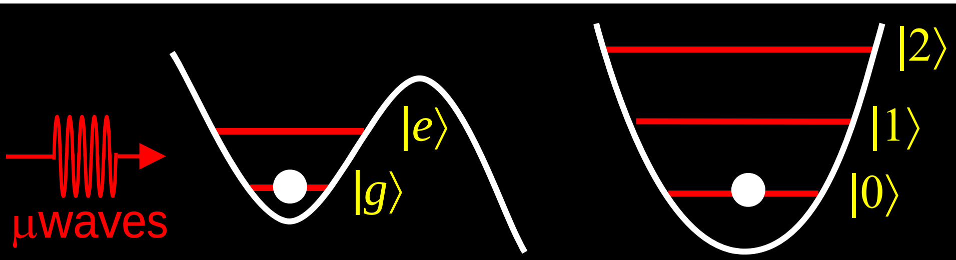


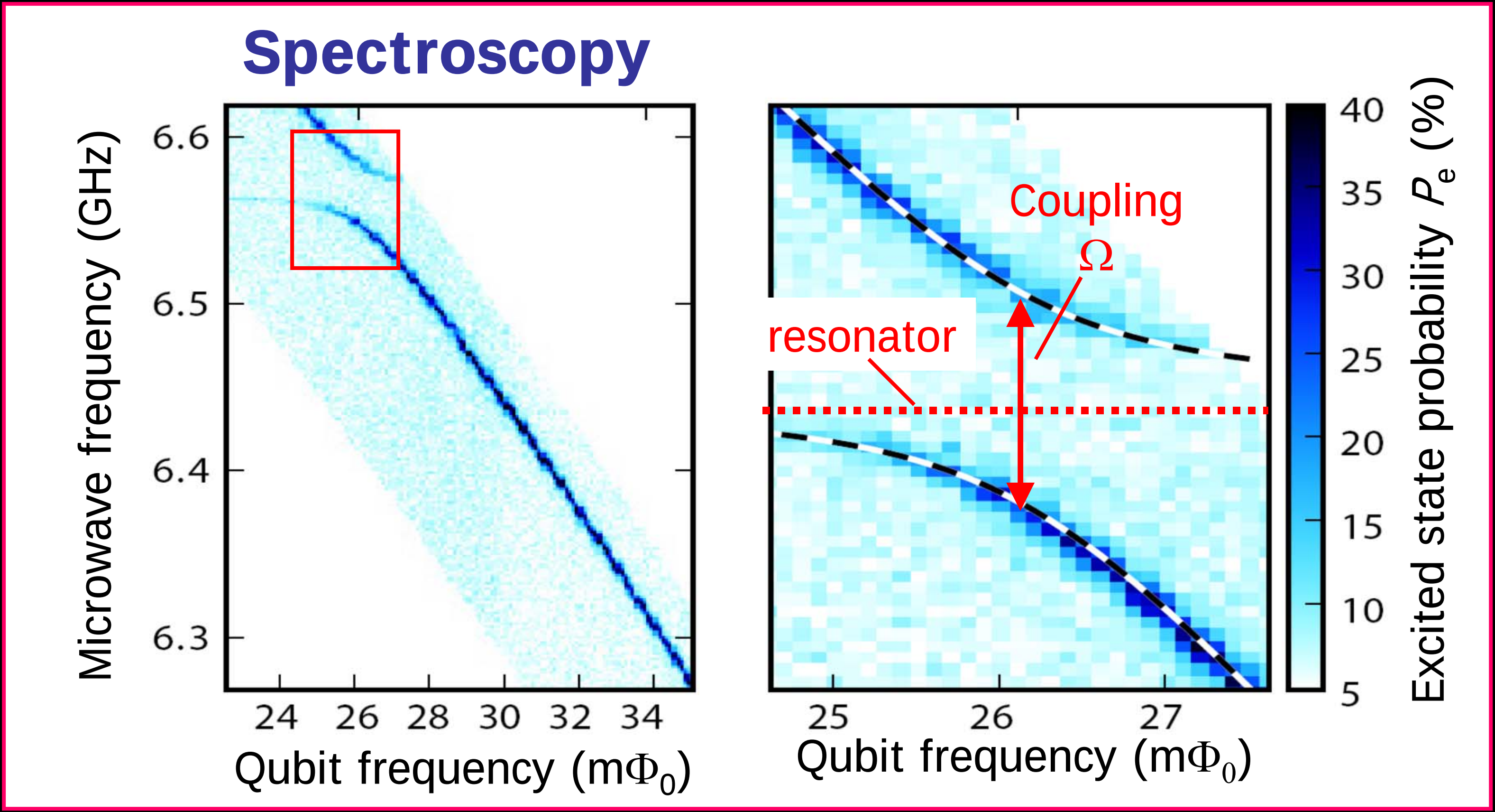




Spectroscopy of coupled system

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

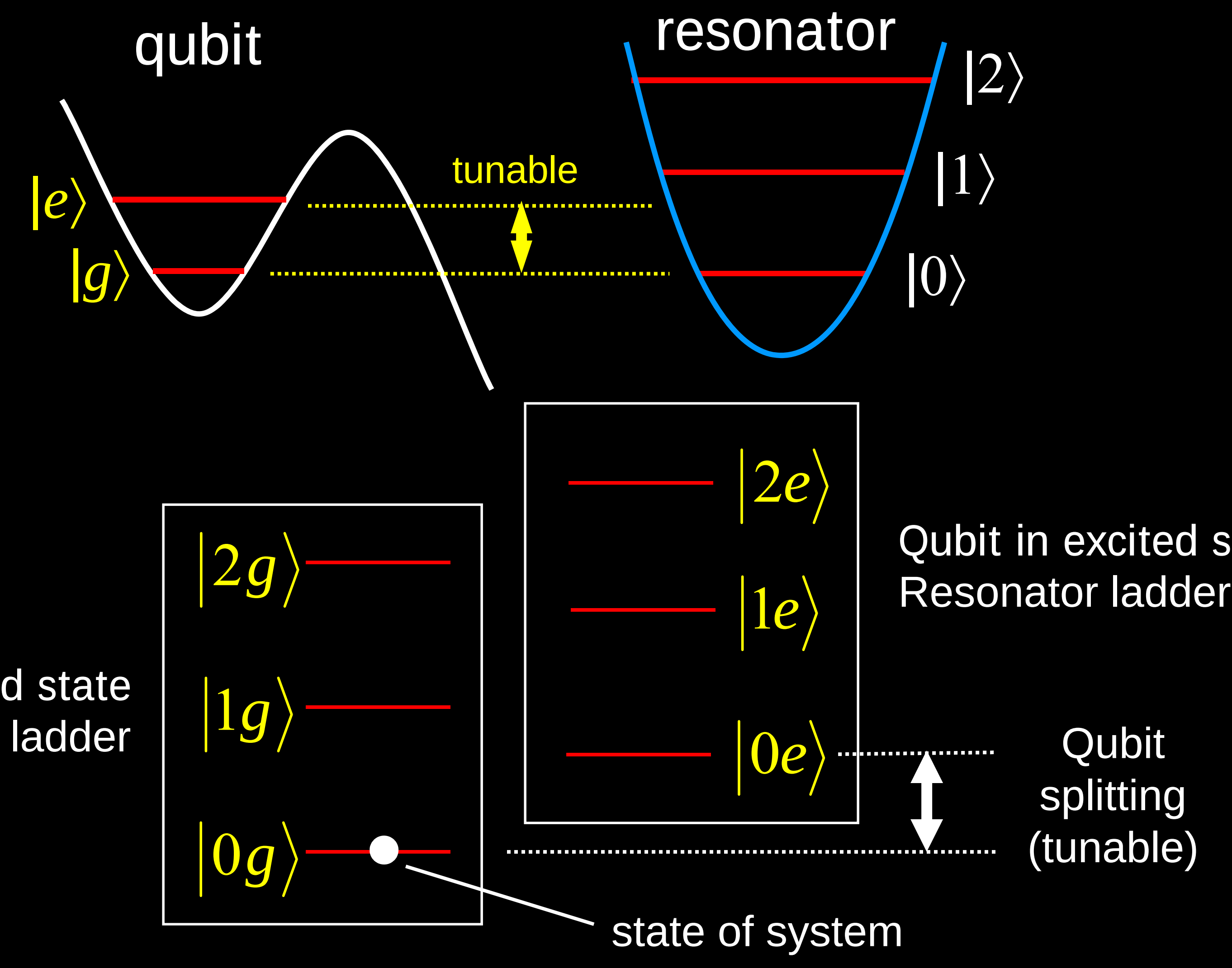




Spectroscopy

M. Hofheinz et al. Nature (2008)

Coupled resonator-qubit energy levels



Qubit in excited state
Resonator ladder

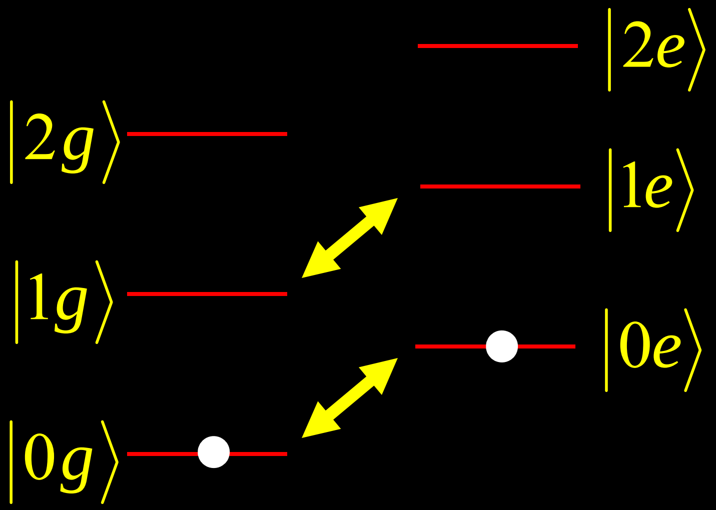
Qubit in ground state
Resonator ladder

Qubit
splitting
(tunable)

state of system

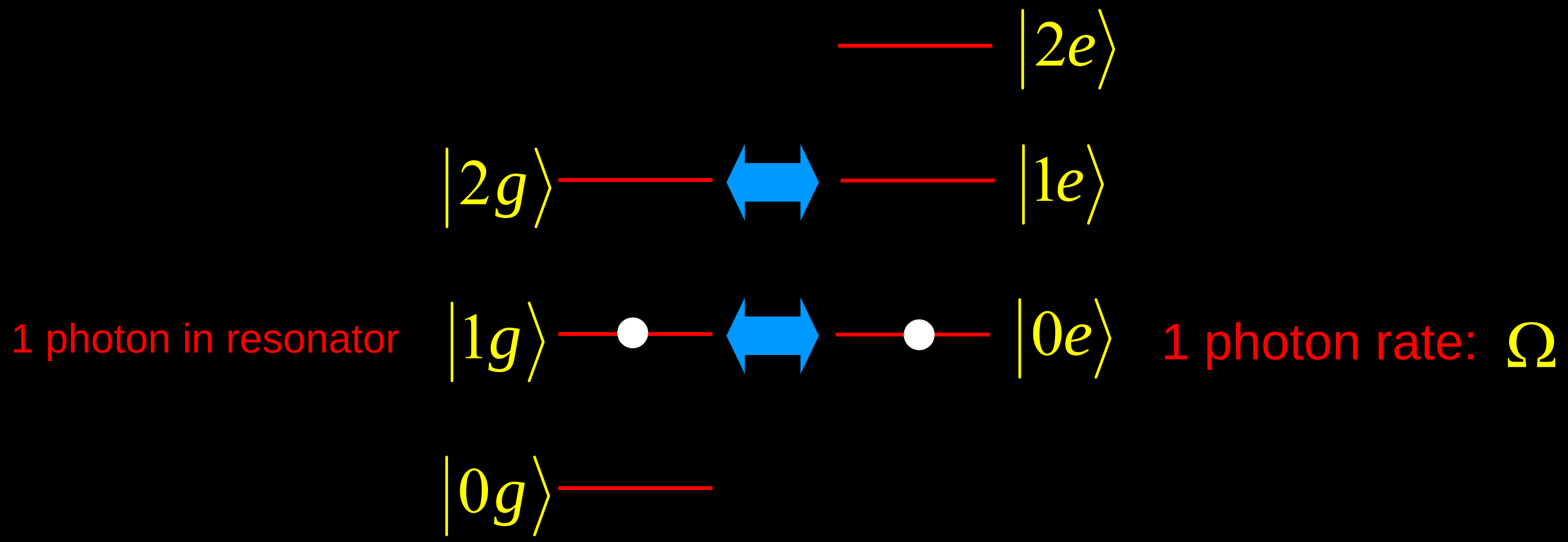
Resonator-qubit time-domain control

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



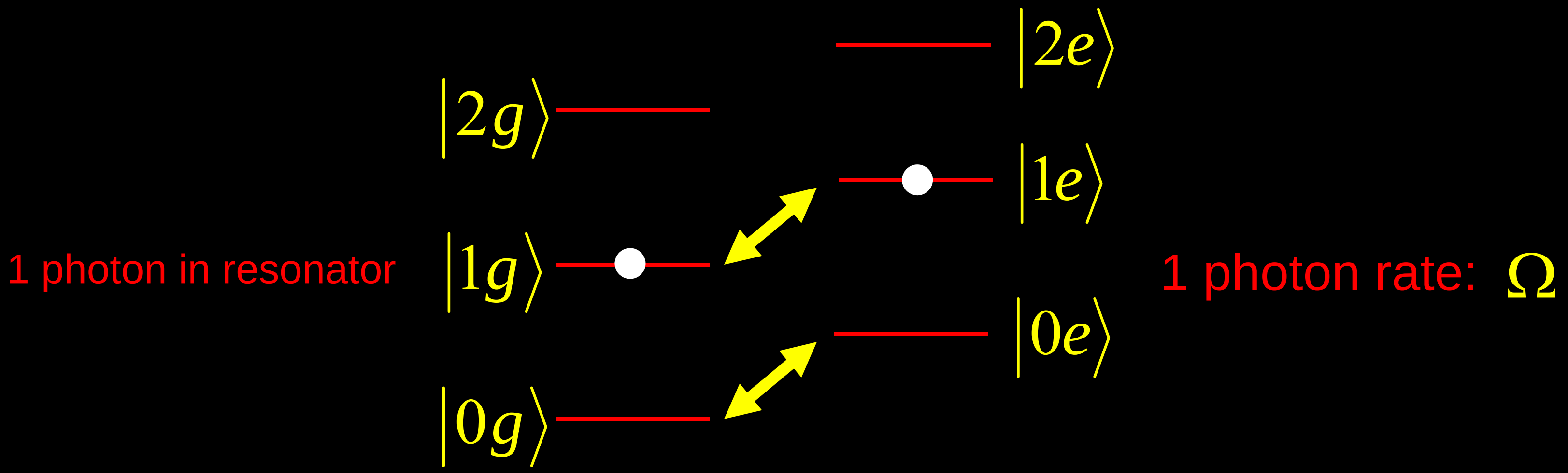
Resonator-qubit time-domain control

- 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



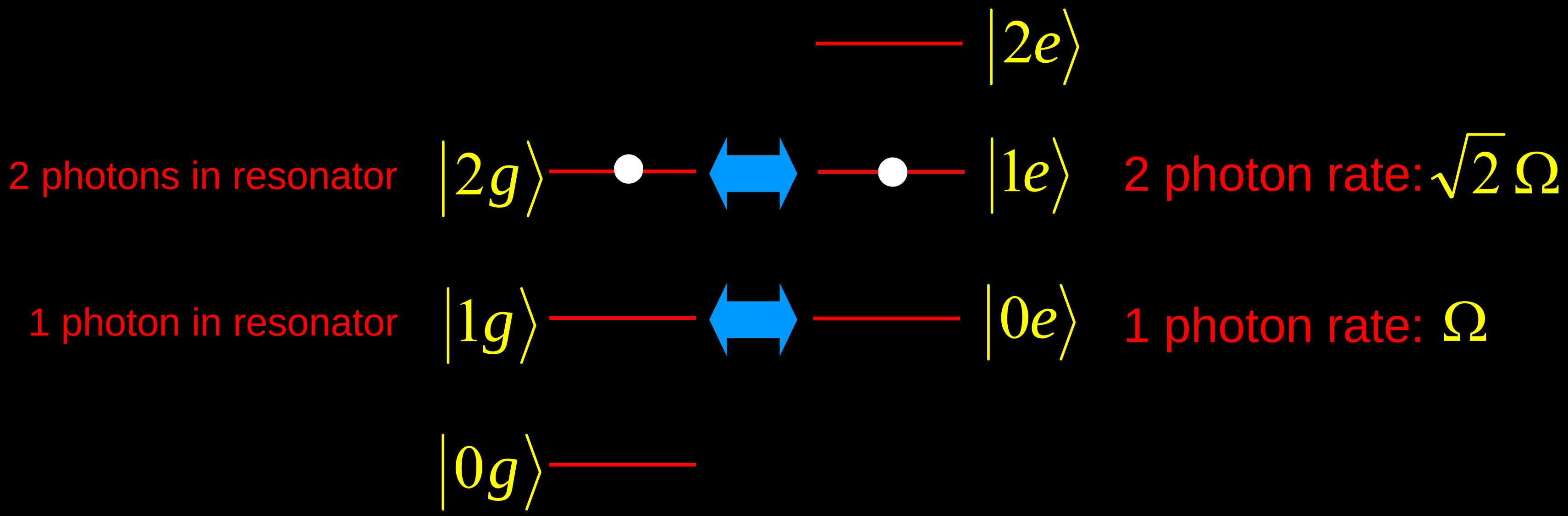
Adding more photons

- 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)



$|2e\rangle$

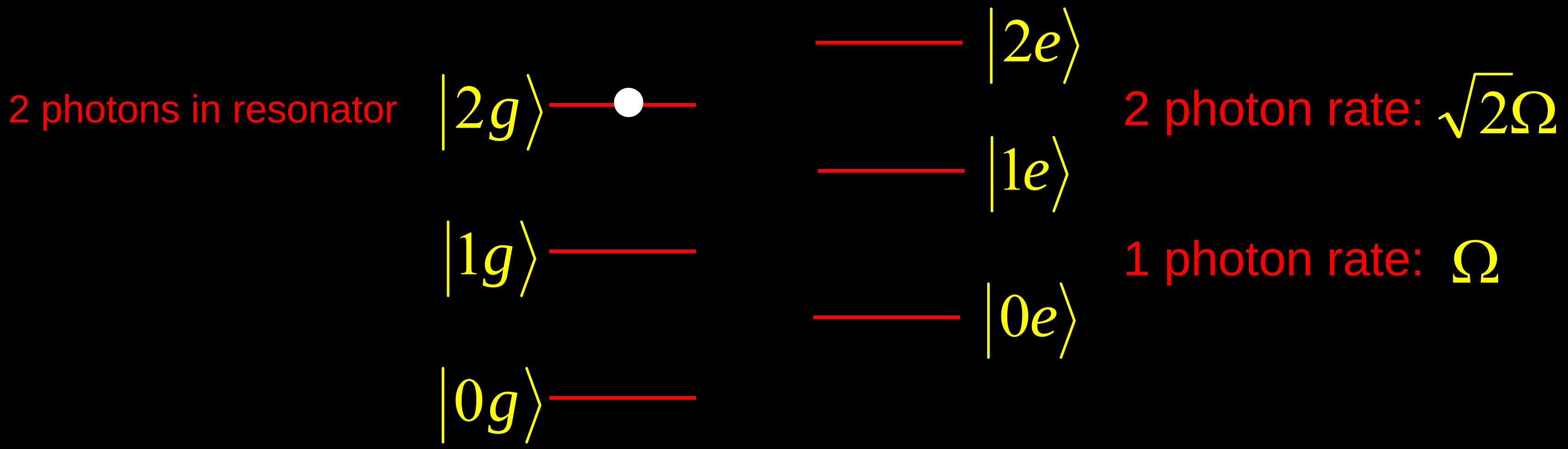
2 photons in resonator $|2g\rangle$ $|1e\rangle$ 2 photon rate: $\sqrt{2}\,\Omega$

1 photon in resonator $|1g\rangle$ $|0e\rangle$ 1 photon rate: Ω

$|0g\rangle$

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



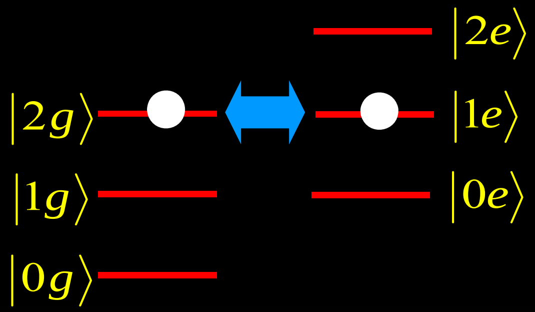
Resonator-qubit time-domain control

M. Hofheinz et al.
Nature (2008)

Measurement of resonator state:

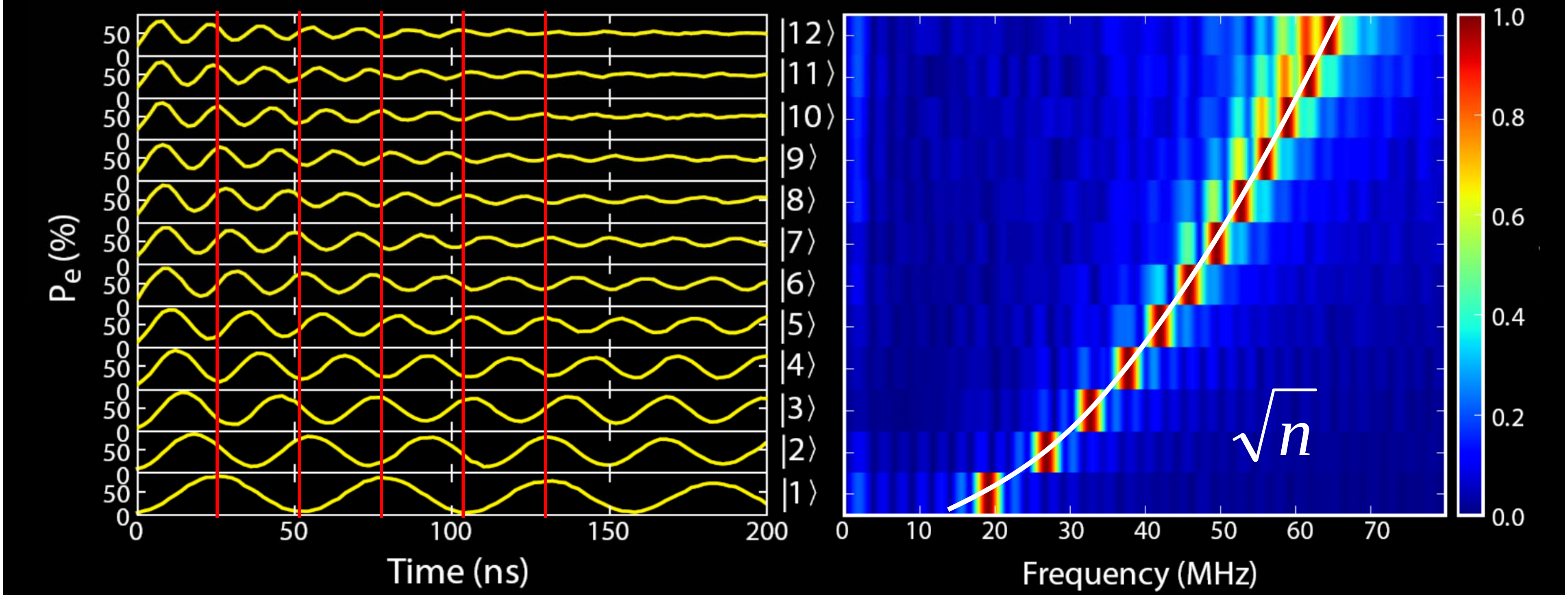
Bring ground-state qubit into resonance with resonator

2 photons in resonator
Qubit ground state



1 photon in resonator
Qubit excited state

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



Arbitrary quantum states & Wigner tomography

Prepare arbitrary superposition states:

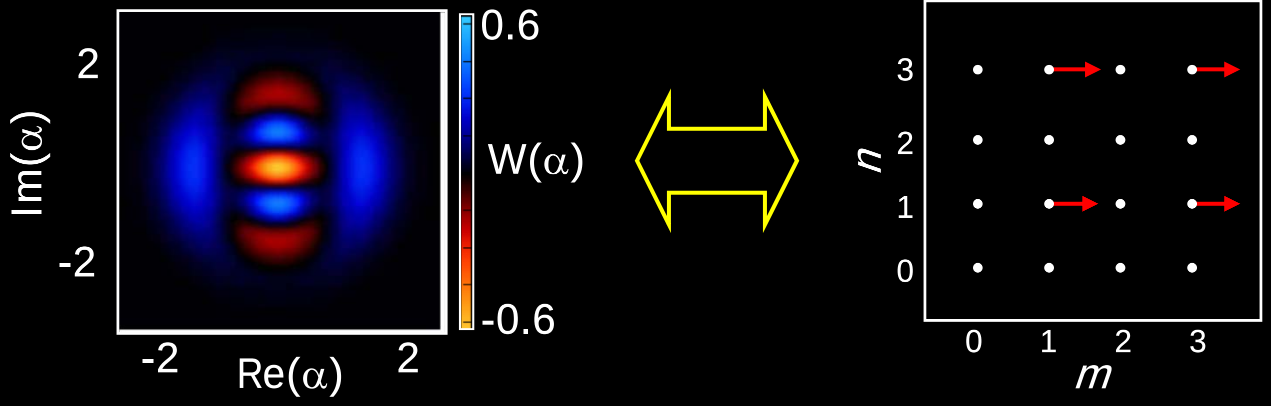
- Adapt Law & Eberly protocol (ion physics)
- Reverse engineering: Sequence from final state to ground state
- Apply sequence in reverse order: Ground state to final state

Measure Wigner function $W(\alpha)$:

- Quasiprobability distribution
- Negative values ⇔ quantum coherence
- Equivalent to measuring density matrix

$W(\alpha)$: $|\Psi\rangle = |1\rangle + |3\rangle$

ρ_{mn}

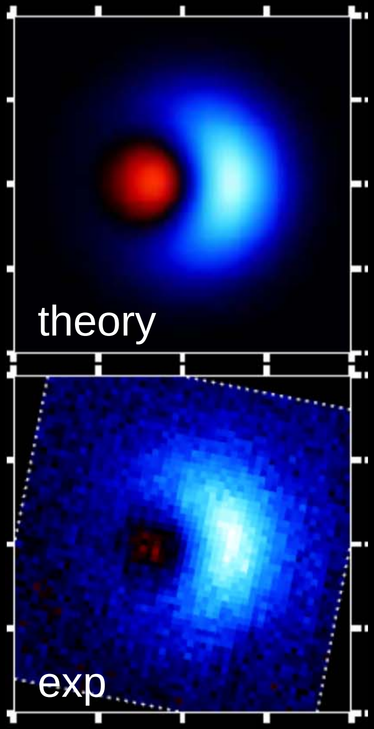


Superpositions by Wigner tomography

M. Hofheinz et al.
Nature (2009)

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

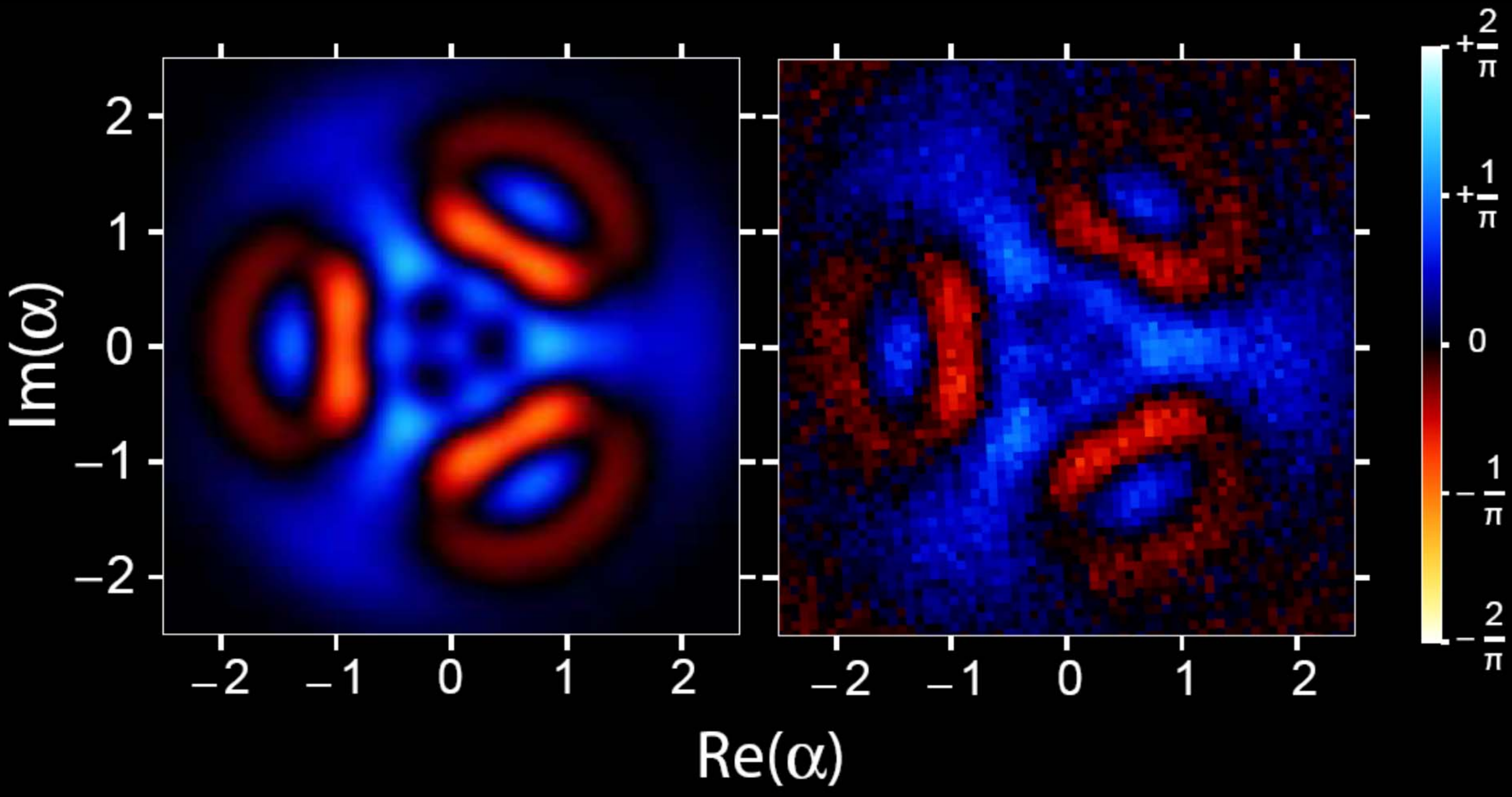
$$|\psi\rangle = |0\rangle + |1\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

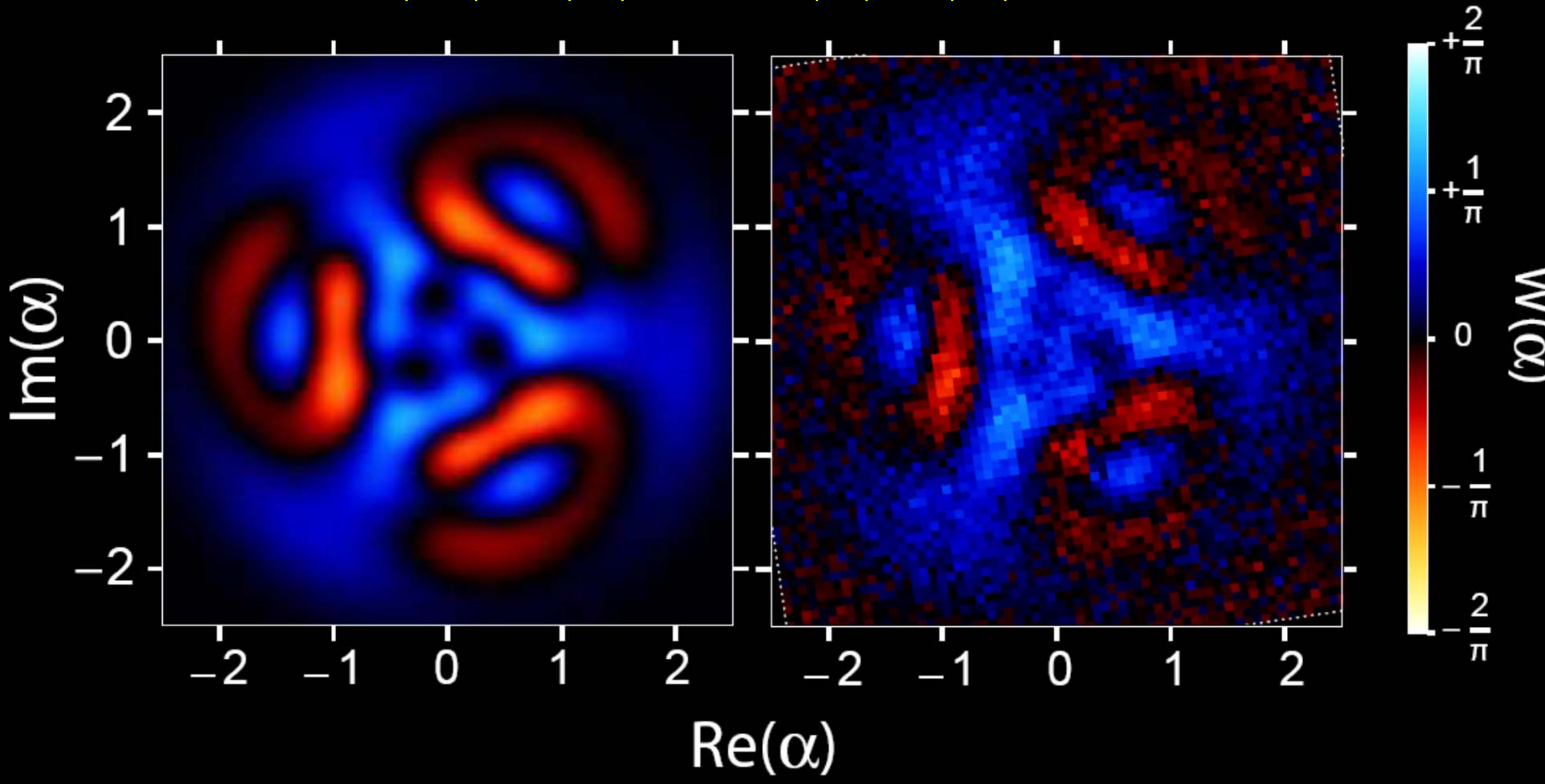
$$|\psi\rangle = |0\rangle + e^{\frac{0}{8}i\pi}|3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

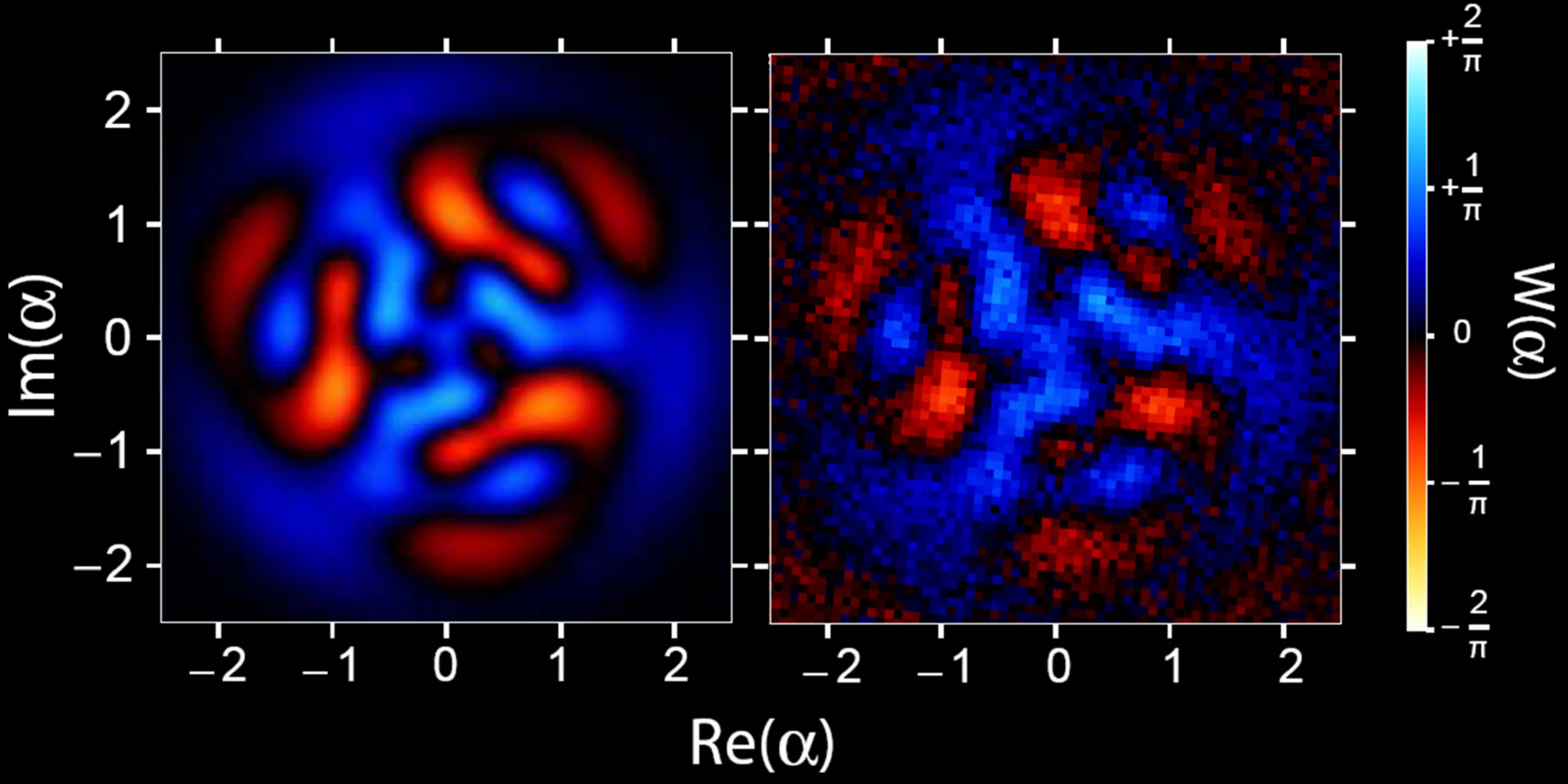
$$|\psi\rangle = |0\rangle + e^{\frac{1}{8}i\pi}|3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

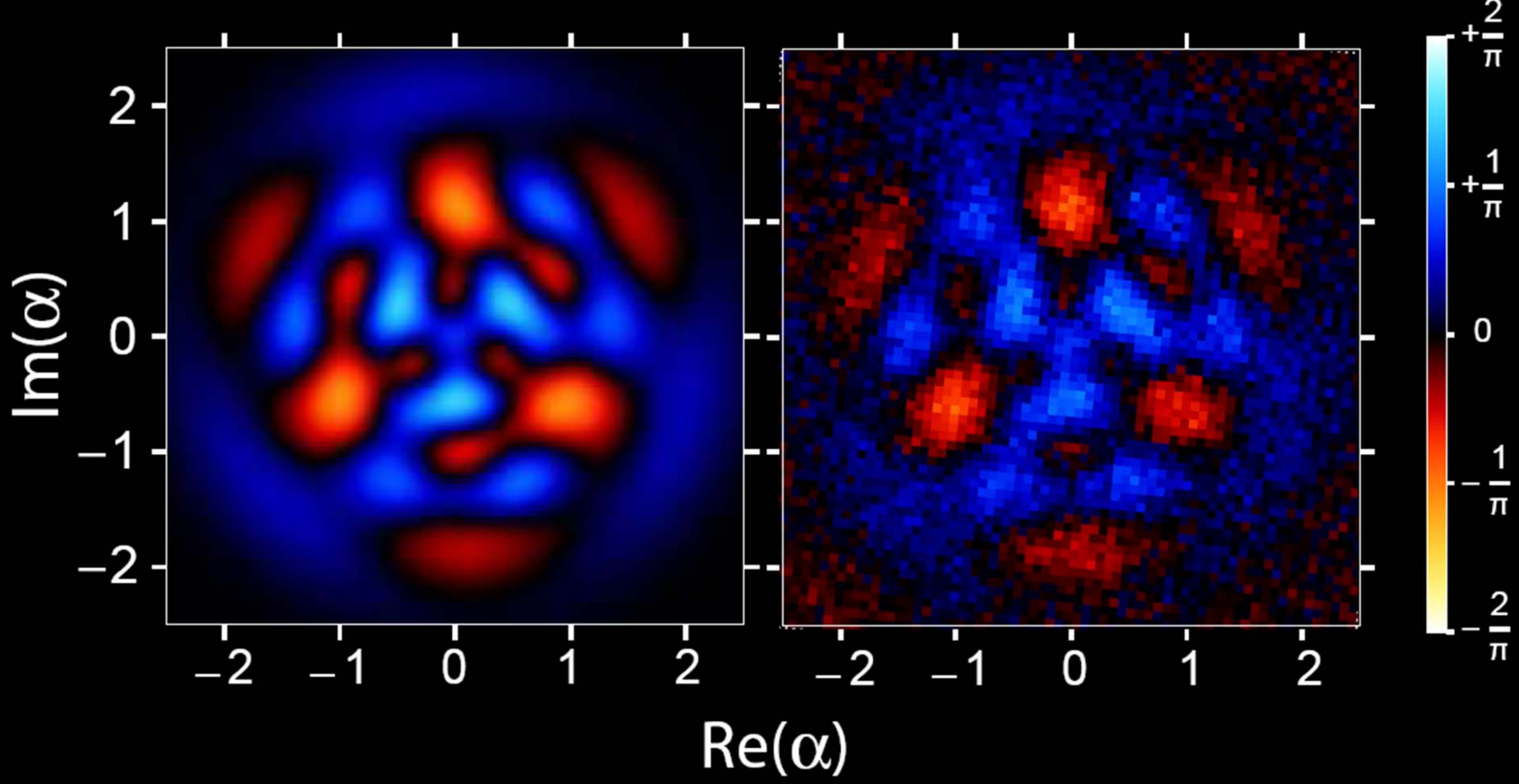
$$|\psi\rangle = |0\rangle + e^{\frac{2}{8}i\pi}|3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

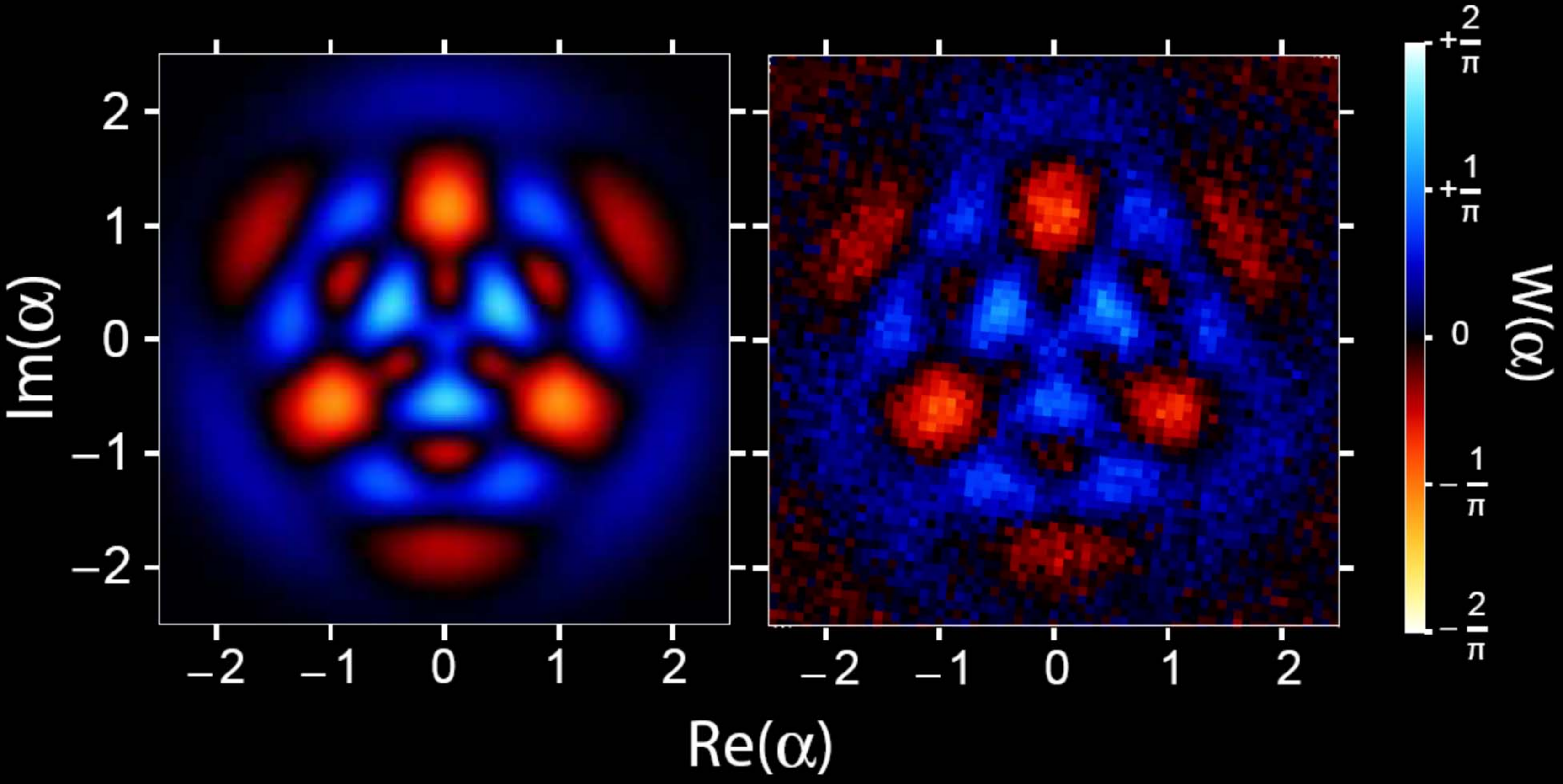
$$|\psi\rangle = |0\rangle + e^{\frac{3}{8}i\pi}|3\rangle + |6\rangle$$



Phase control of triple state superpositions

M. Hofheinz et al.
Nature (2009)

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

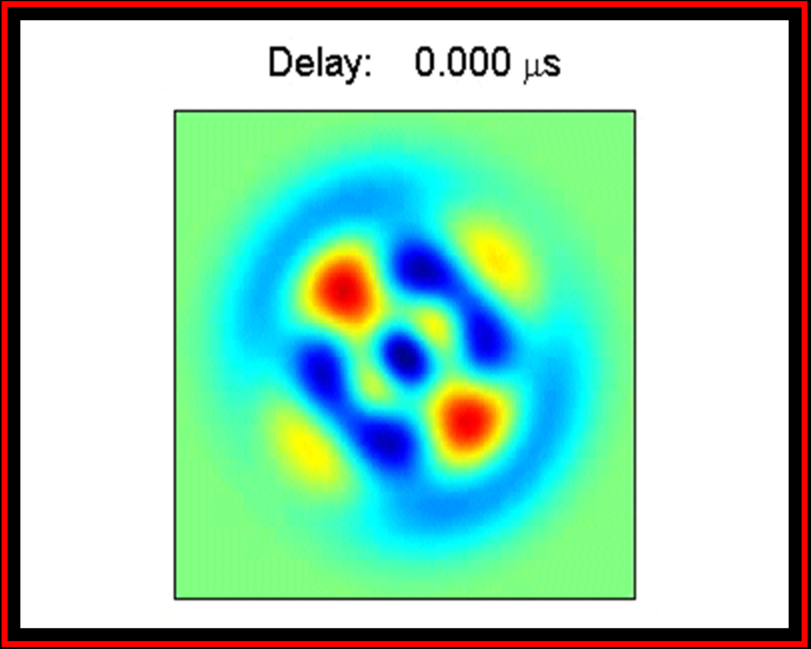


Decoherence as a movie

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



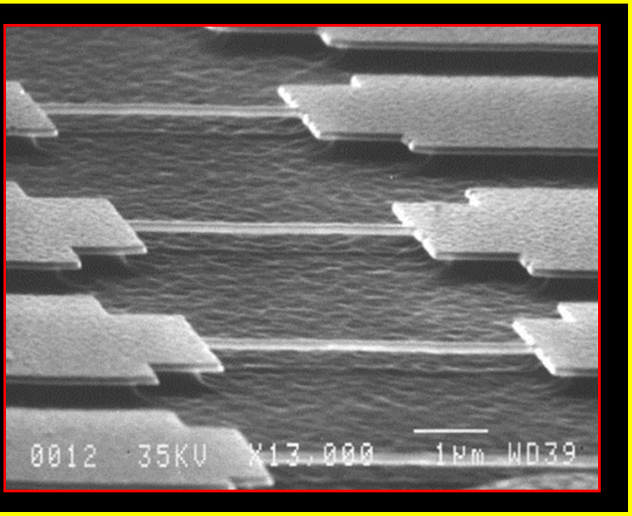
H. Wang et al.
PRL (2009)

Quantitative agreement with Markovian master equation

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

Candidates for quantum harmonic oscillators

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



Aaron O’Connell

- Electromagnetic resonators
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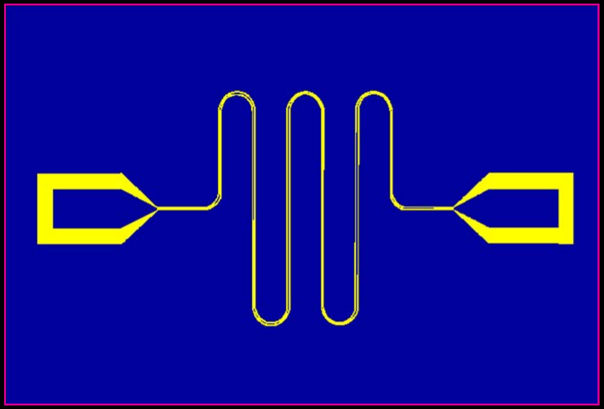


Max Hofheinz

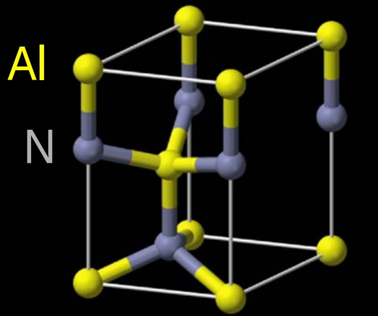
Mechanical quantum oscillator

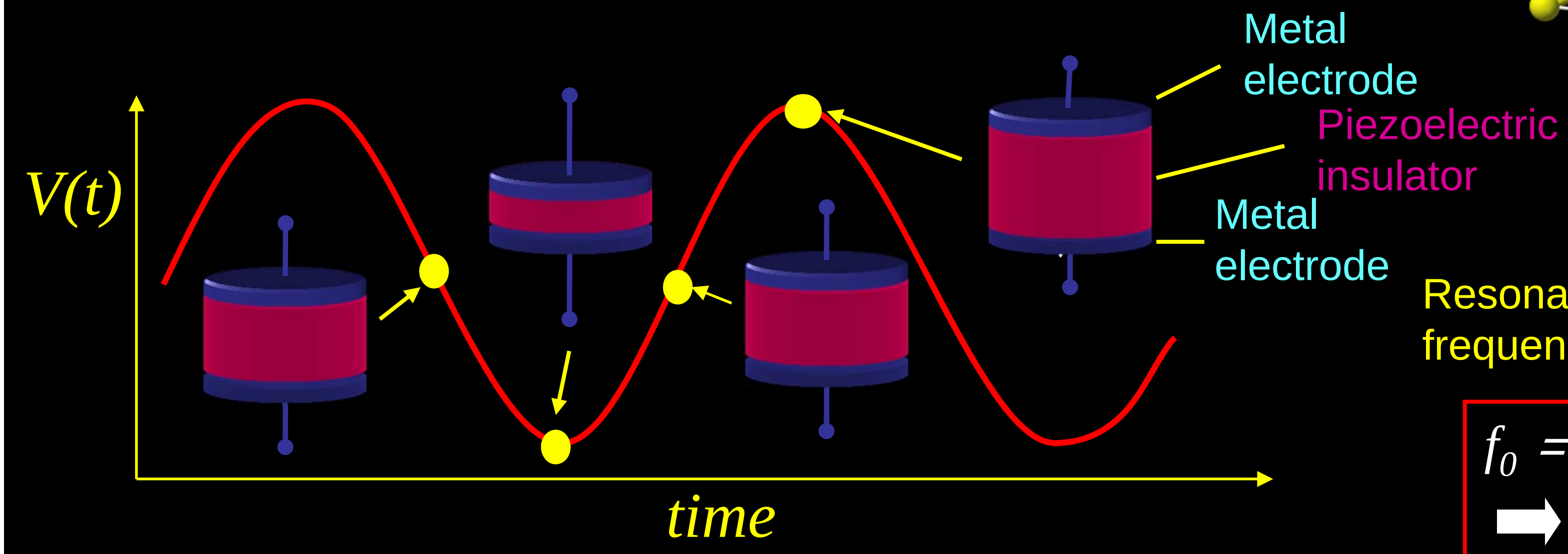
Requirements for mechanical oscillator:

- ➢ 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

sound speed

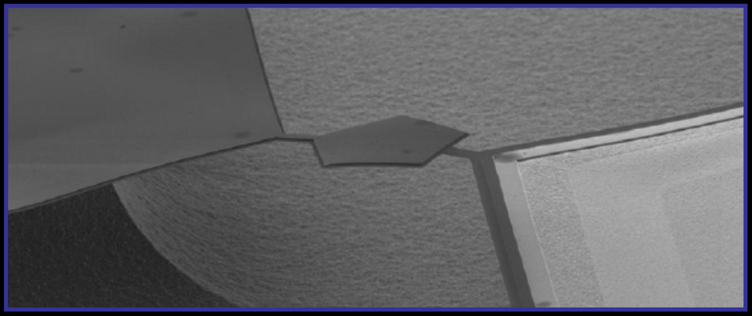
$$f_0 \approx \frac{c}{2t}$$

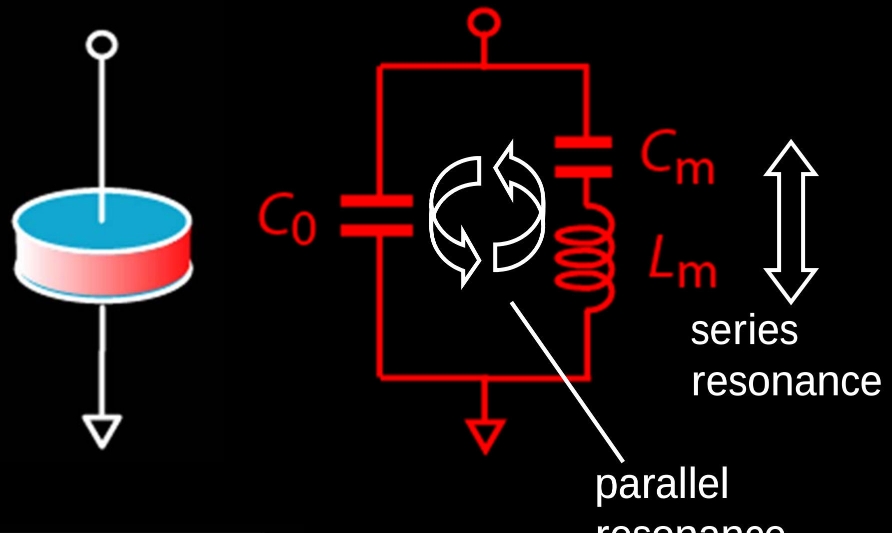
f_0 = 6 to 7 GHz

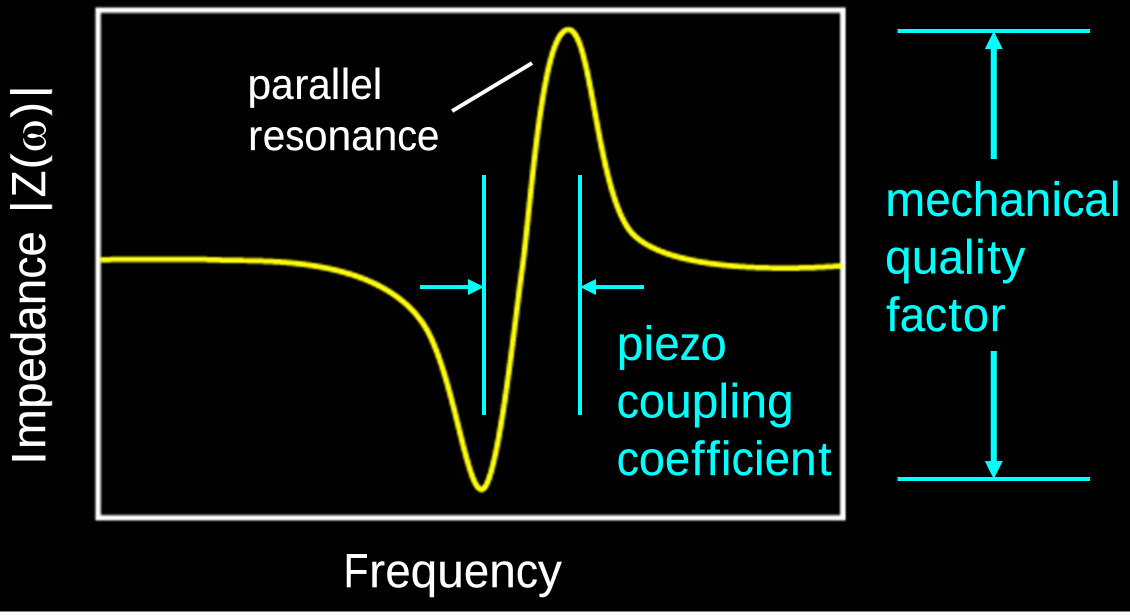
➡ t = 0.8 μm

Resonator equivalent circuit

Electrical equivalent circuit:



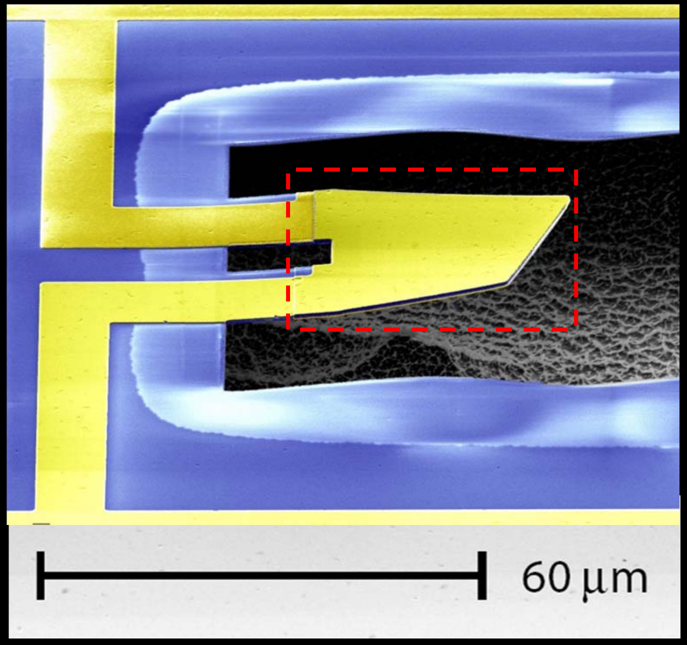




Mechanical quantum oscillator

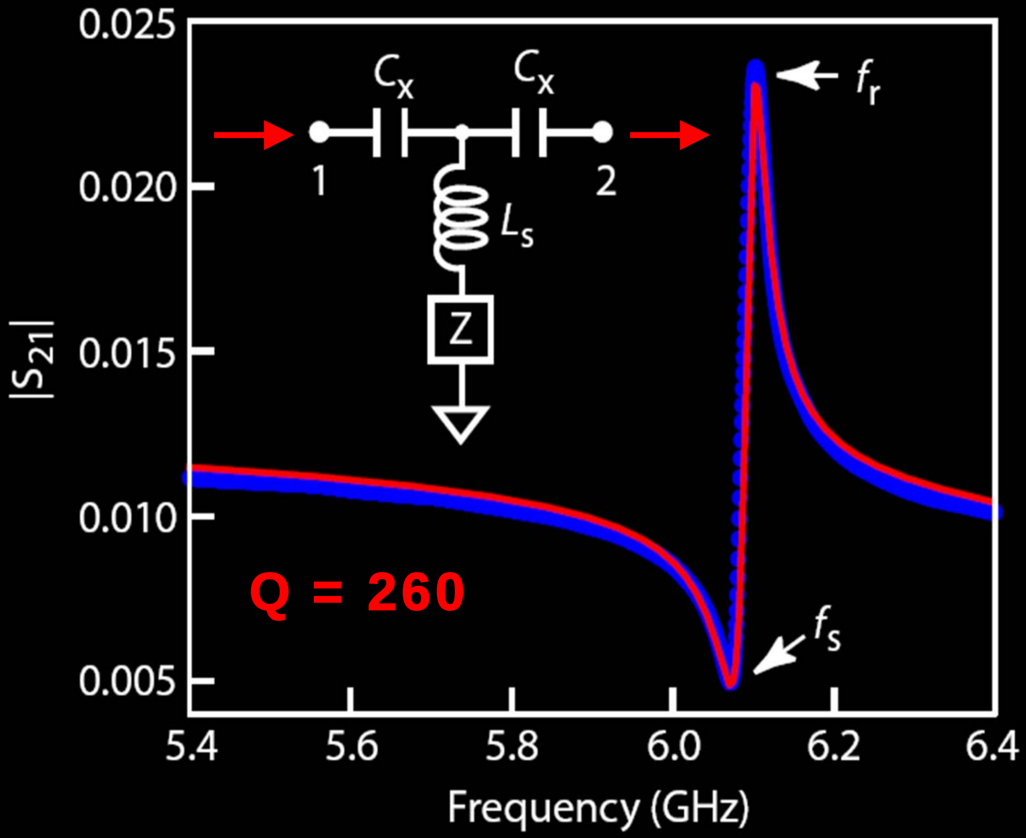
- Al top & bottom electrodes
- Sputtered AlN piezoelectric
- XeF$_2$ substrate release
- 4-7 GHz fundamental resonance
- Integrable with qubit fabrication

diameter 35 μm mass 20 ng



A.D. O'Connell

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



Six billionths of a second

Electromagnetic resonator: Q ~ 10^5

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

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 $T_1 = \frac{Q}{2\pi f_r} = 6.7\ \mathrm{ns}$

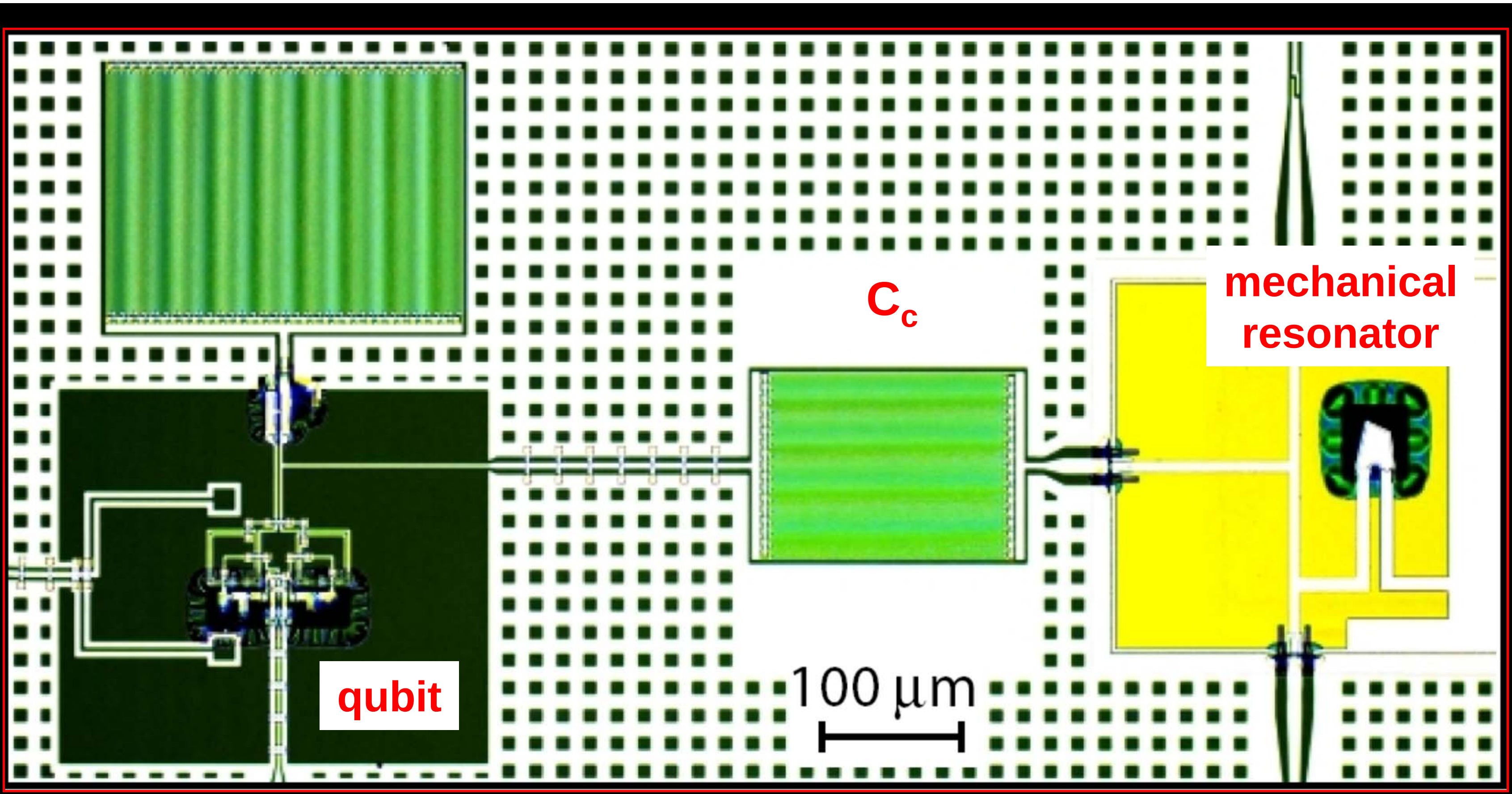
Requirements {

- 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)

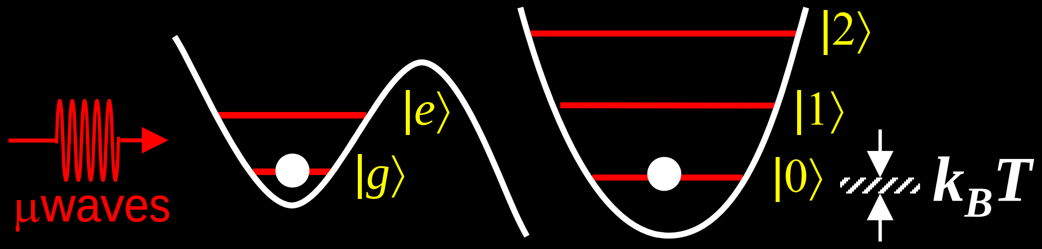


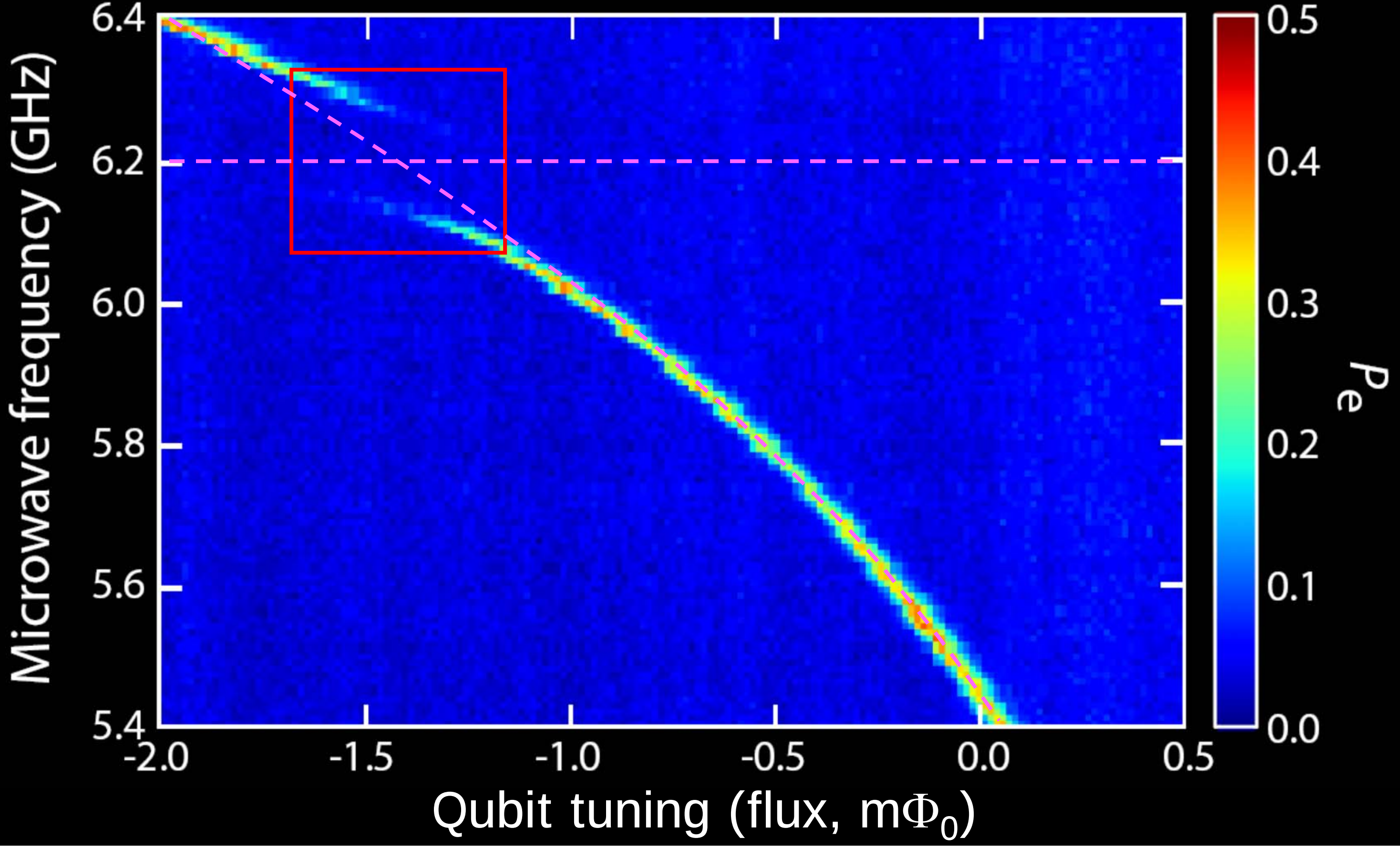
- ➢ Fabricate resonator, then qubit (13 layers)
- ➢ Suspend resonator at end
- ➢ Qubit & SQUID also mechanically suspended

Design parameters:
Resonator 6.1 GHz
Coupling 110 MHz

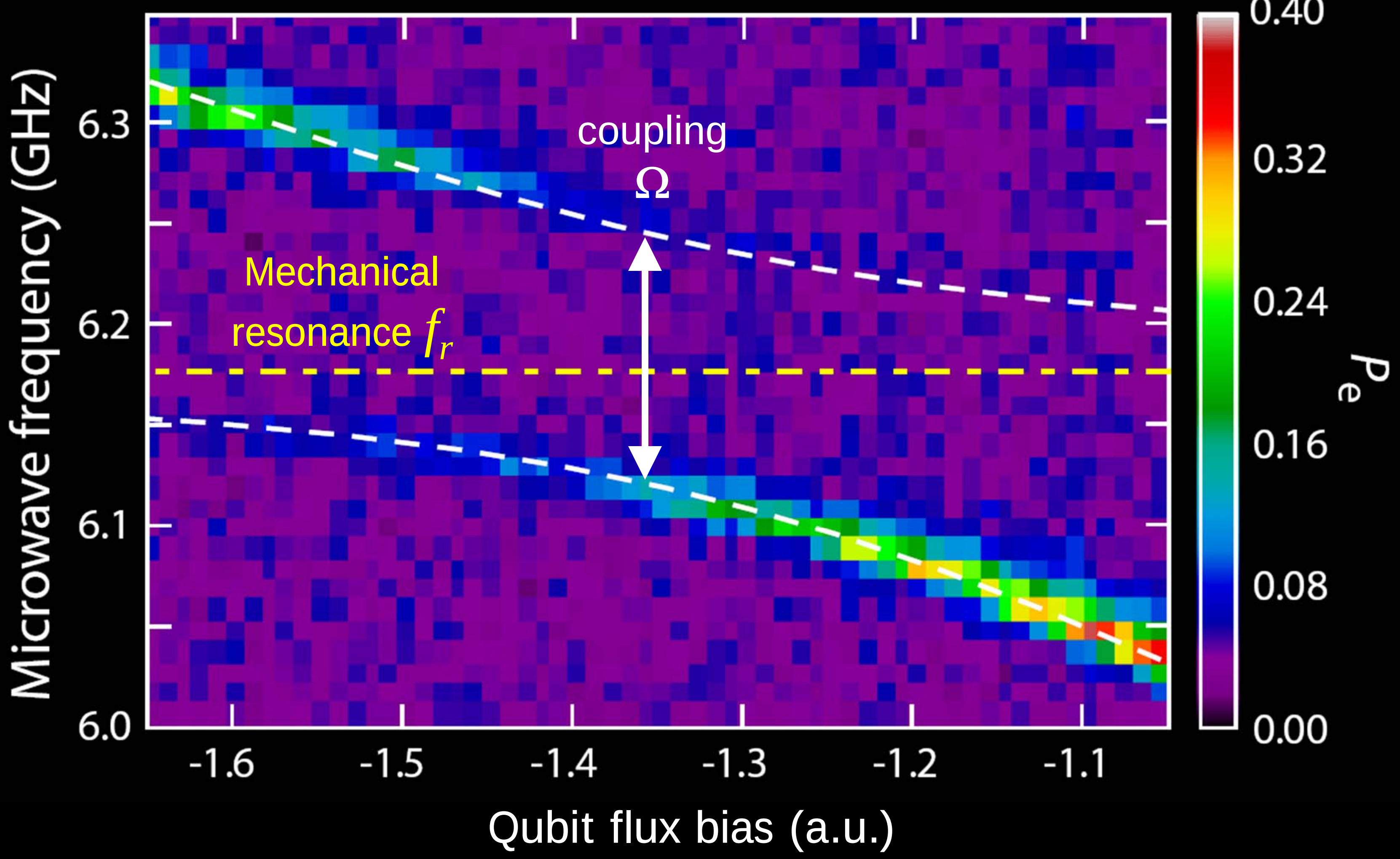
Spectroscopy of coupled system

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





Spectroscopy of coupled system

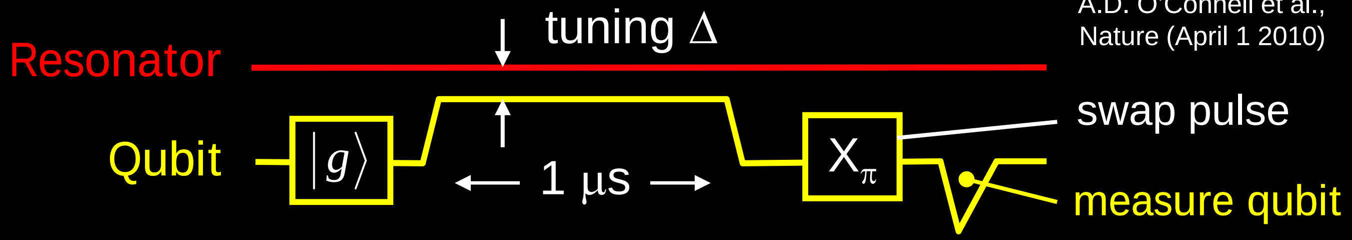


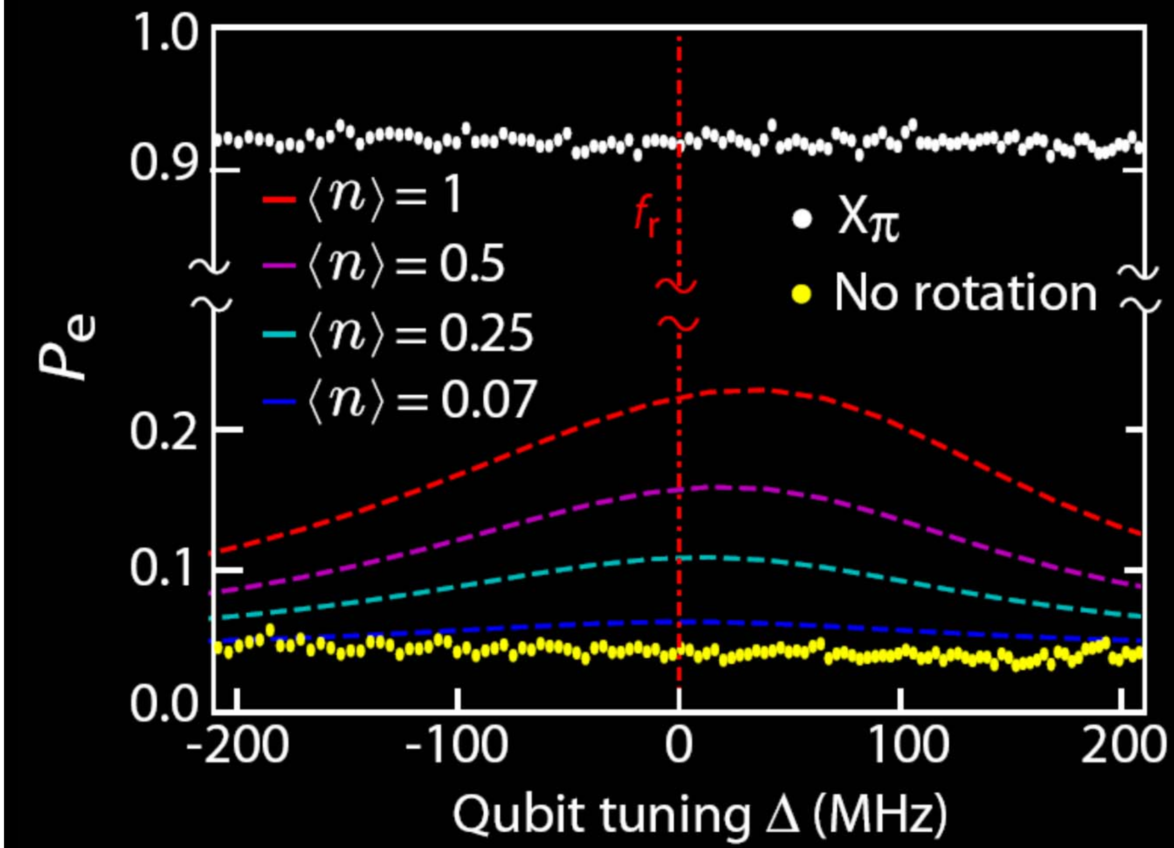
Mechanical resonance $f_r = 6.175$ GHz   Coupling strength $\Omega = 124$ MHz

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:

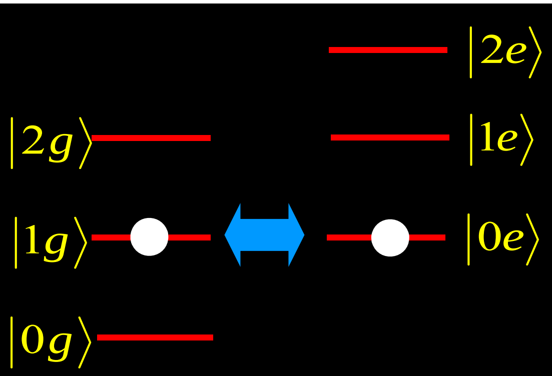
- Less than 0.07 phonons
- Maximum ~ 0.01 phonons

Mechanical resonator in quantum ground state

Electromechanical Rabi oscillations

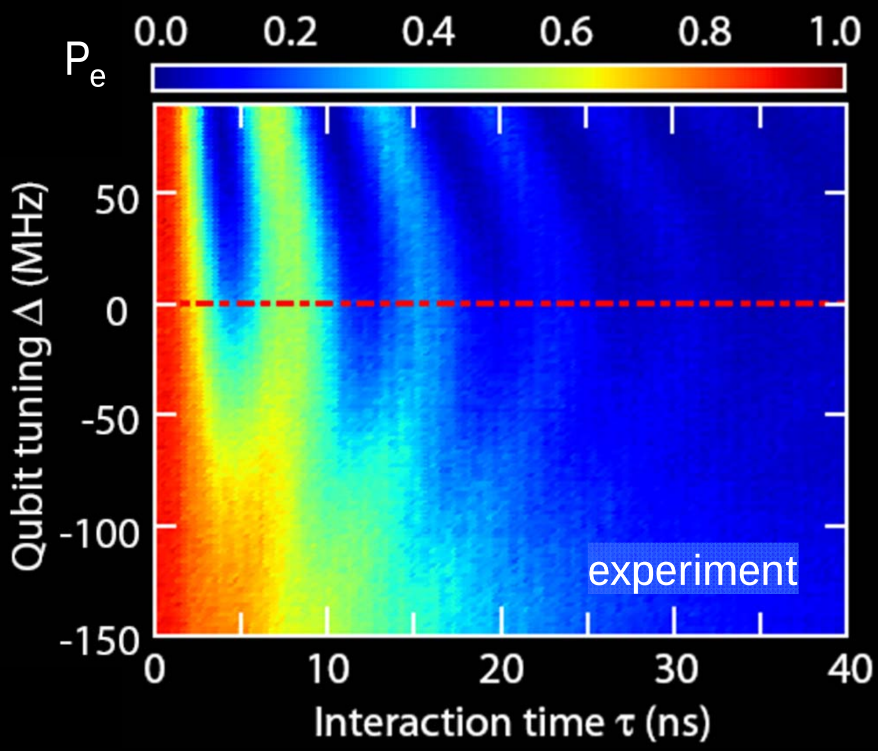
A.D. O'Connell et al., Nature (April 1 2010)

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



Oscillation period:

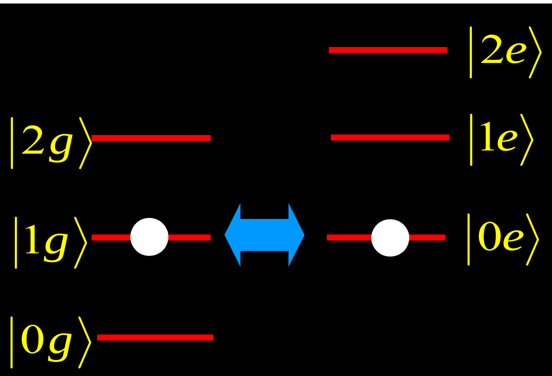
$$T = \frac{1}{\sqrt{\Omega^2 + \Delta^2}}$$



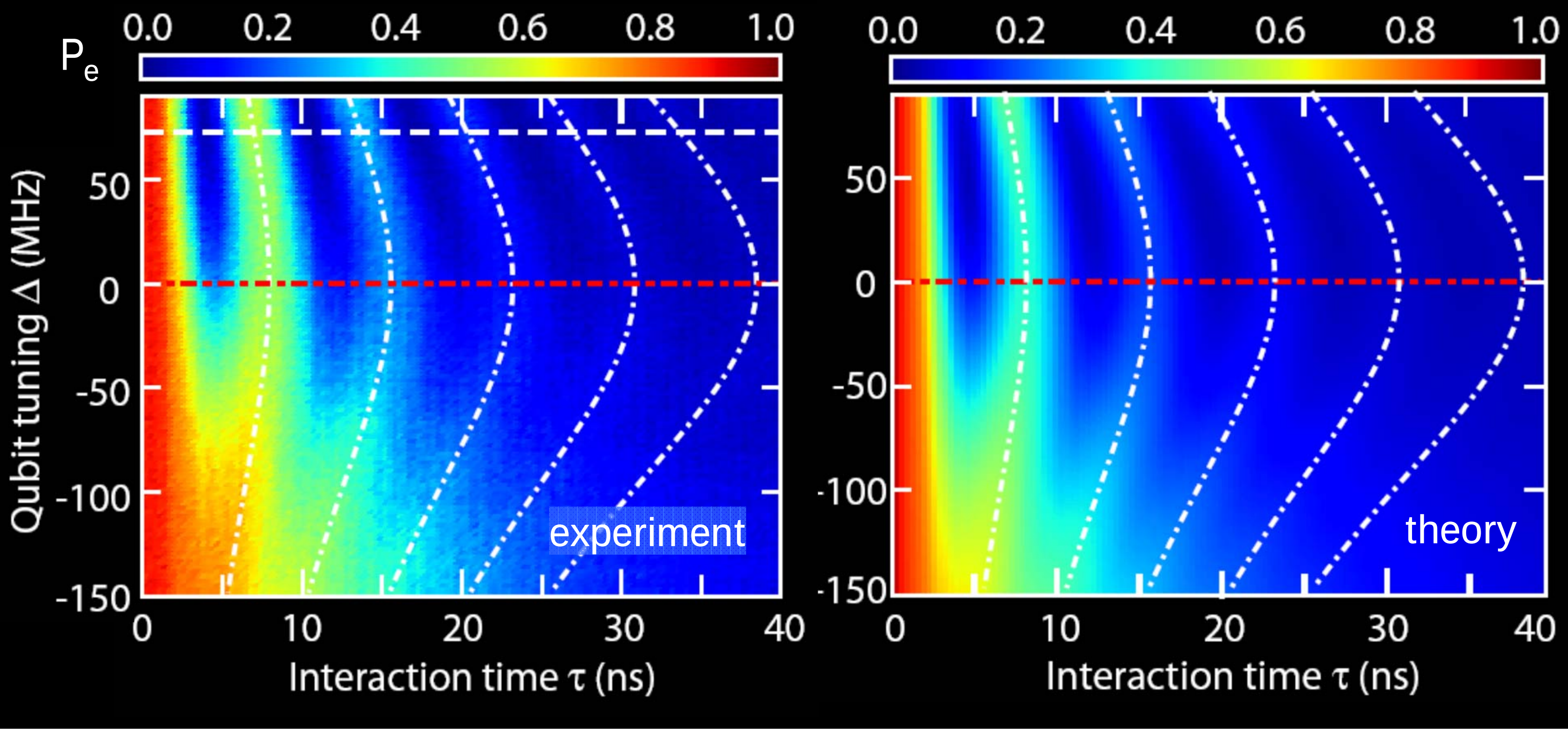
Electromechanical Rabi oscillations

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

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



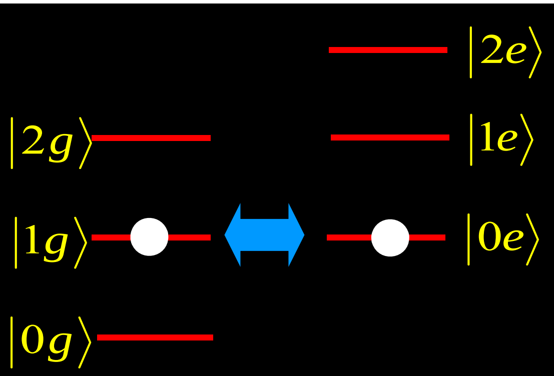
Oscillation period: $T = \frac{1}{\sqrt{\Omega^2 + \Delta^2}}$



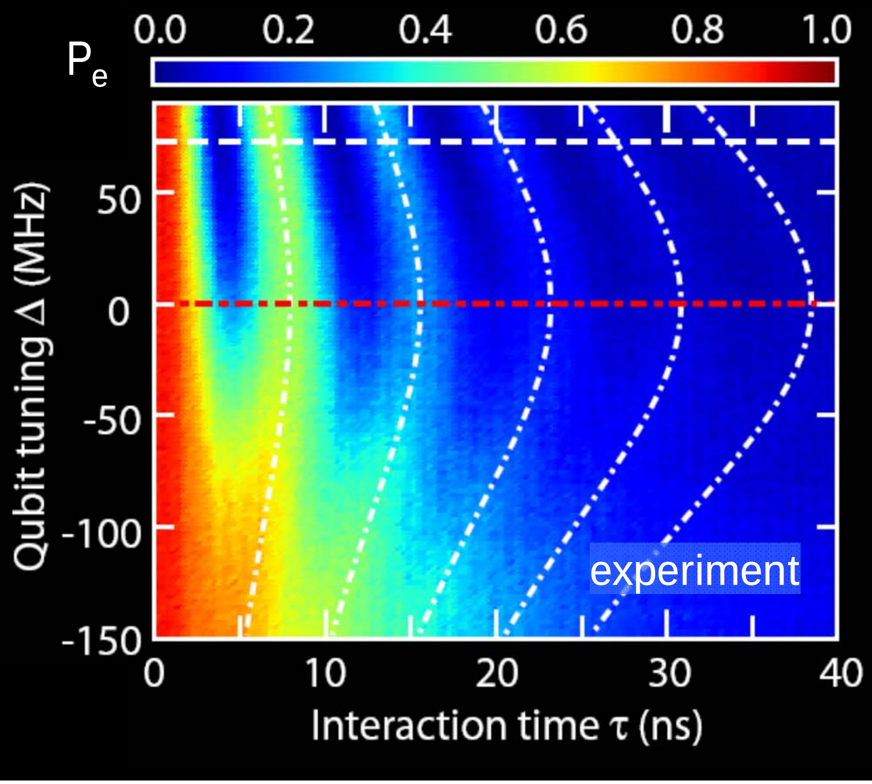
Electromechanical Rabi oscillations

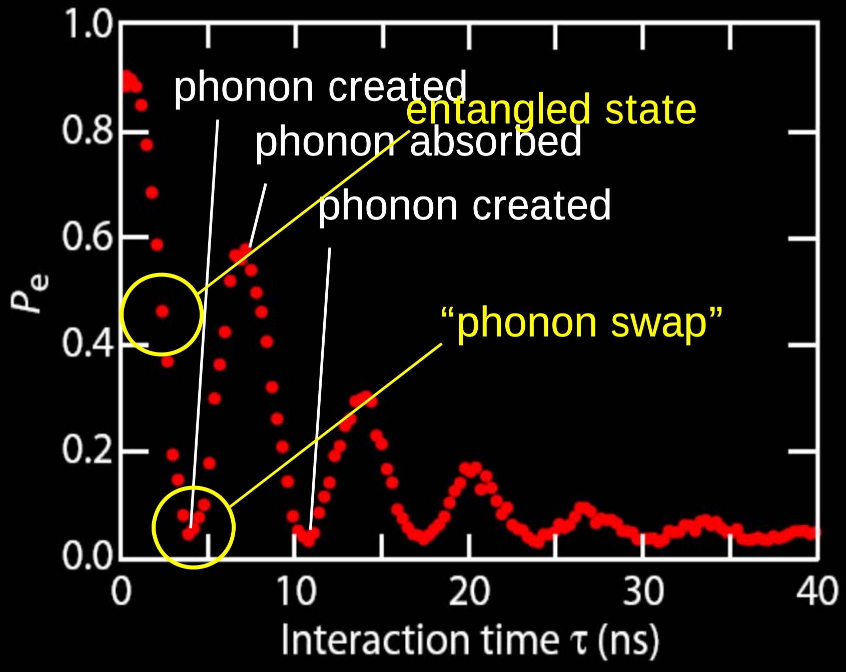
A.D. O'Connell et al.,
accepted, Nature (2010)

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



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



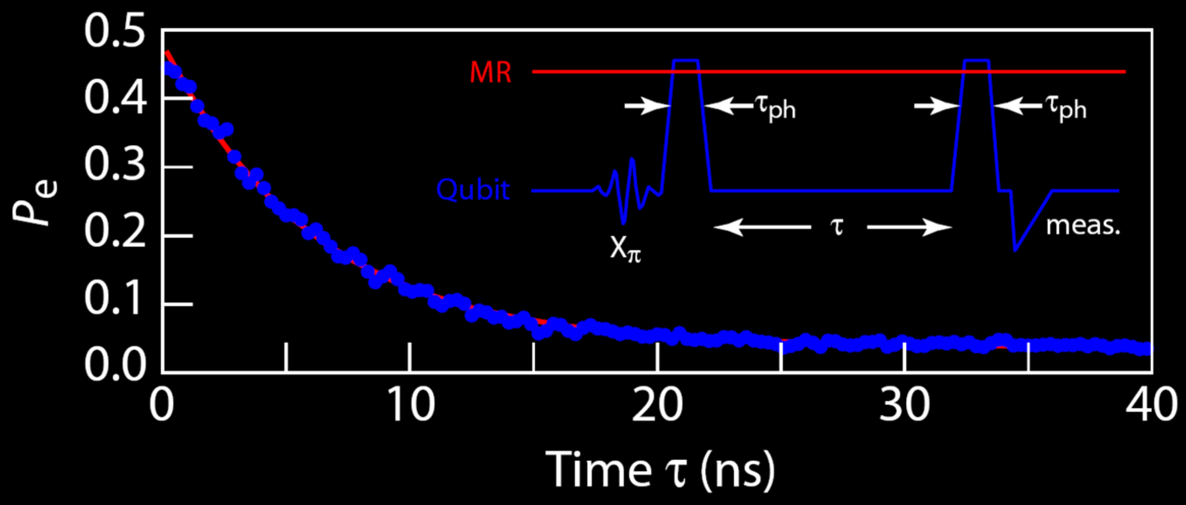


Single phonon lifetime & phase coherence time

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

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

(agrees with $Q = 260$
⇨ $T_1 = 6.7$ ns)

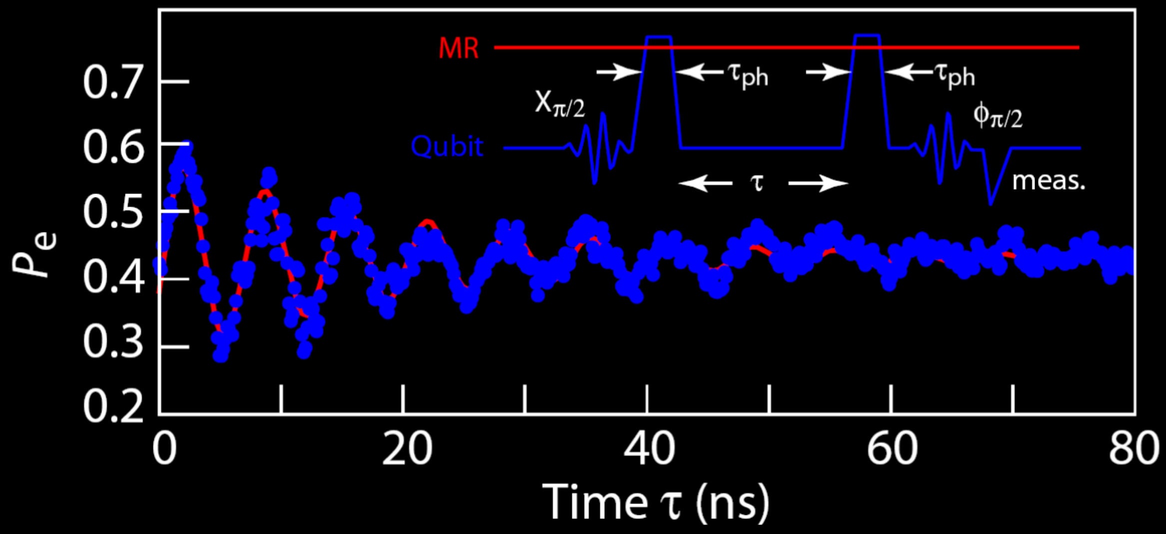


- Create superposition

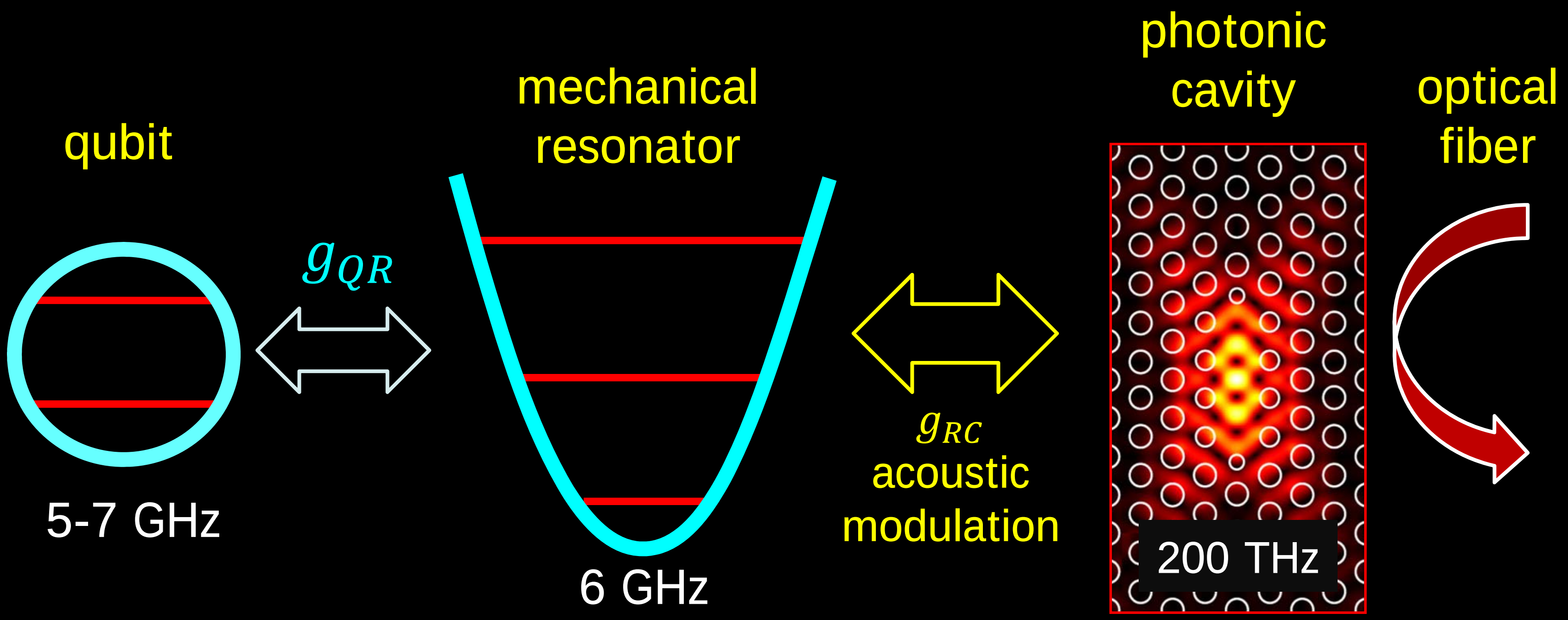
$$|0\rangle + |1\rangle$$

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

$$\boxed{T_2 \sim 2\, T_1}$$



What’s next? Qubit coupled to optomechanical system



qubit

g_{QR}

mechanical resonator

photonic cavity

optical fiber

5-7 GHz

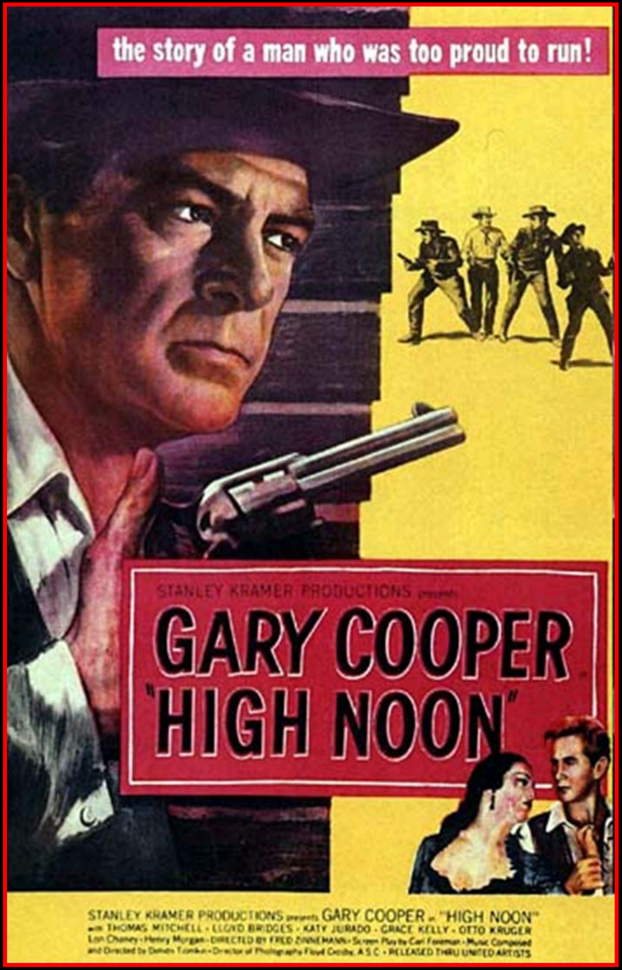
6 GHz

g_{RC} acoustic modulation

200 THz

- ➢ 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

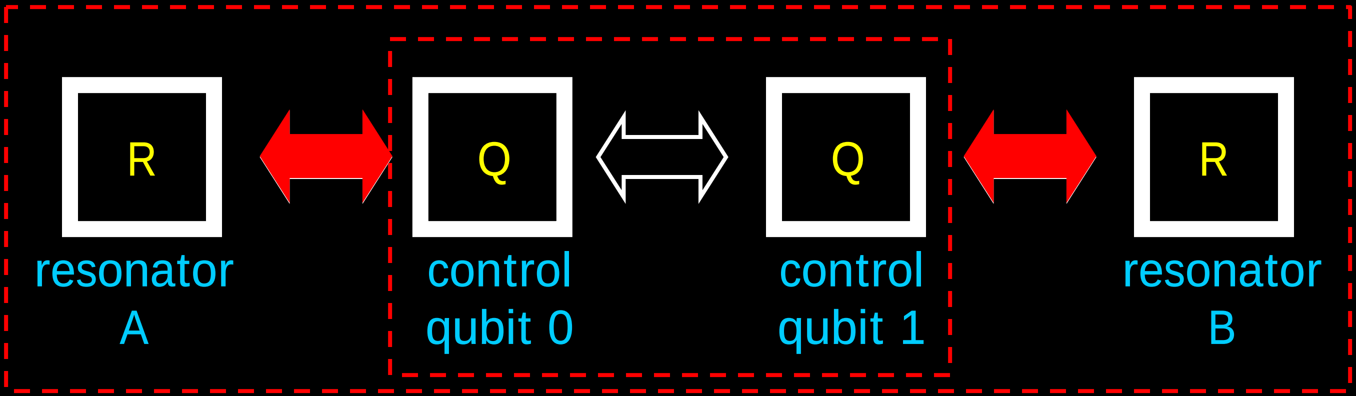


Coherent superposition of N and zero photons in two physically separated resonators:

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

NOON states

Topology for NOON state generation:

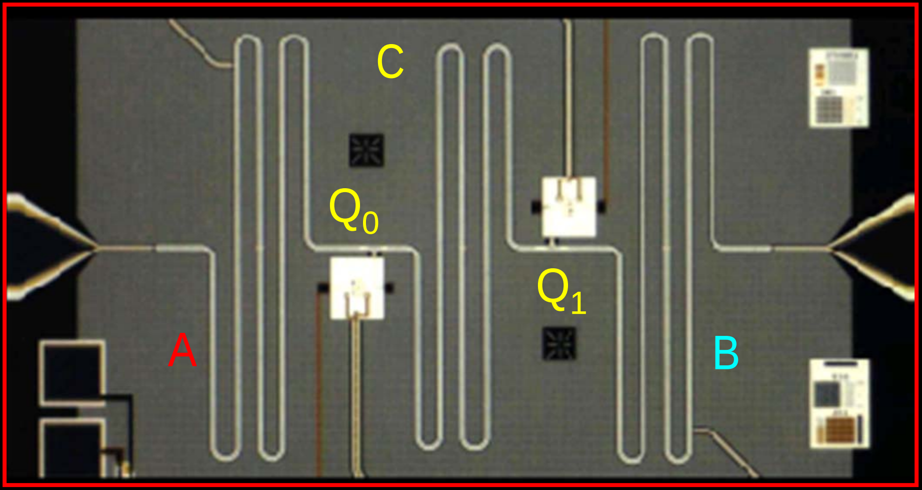


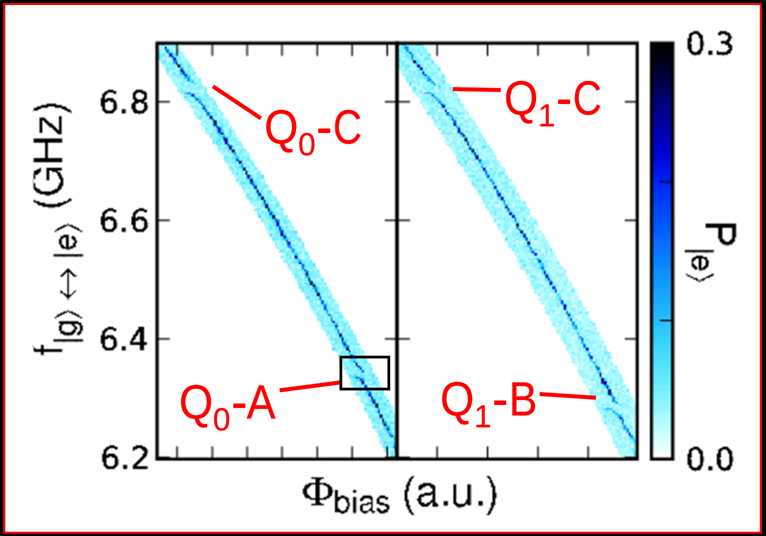
Procedure:

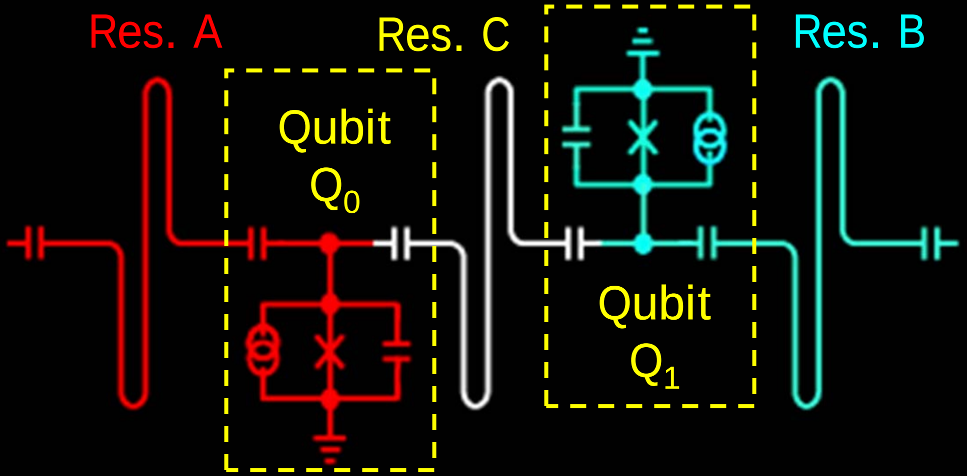
1. Entangle the two control qubits in a Bell state
2. Transfer entanglement (once) to the two resonators
3. “Amplify” by boosting photon number
4. Measure resonators & control qubits

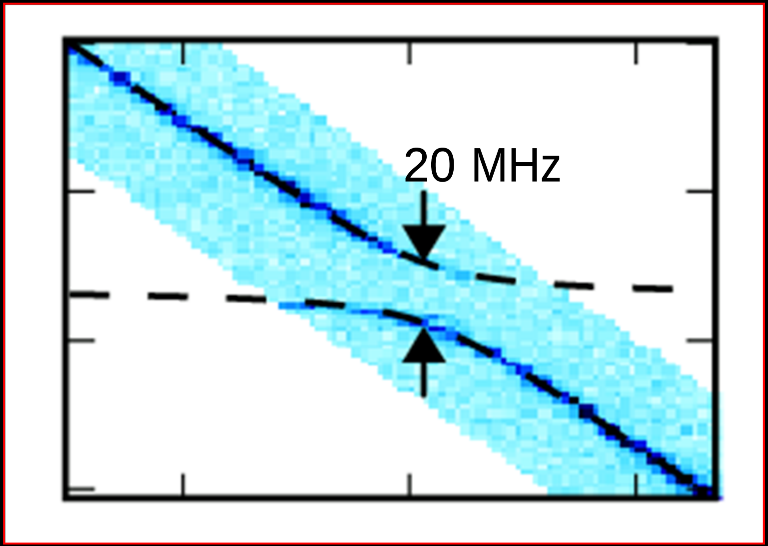
Also: Merkel & Wilhelm (NJP 2010)

NOON states

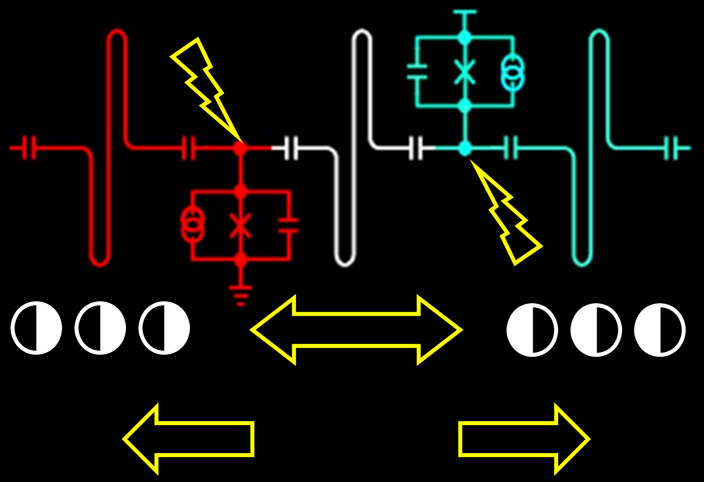

C
Q0
Q1
A
B


6.8
6.6
6.4
6.2
f|g⟩↔|e⟩ (GHz)
Q0-C
Q1-C
Q0-A
Q1-B
Φbias (a.u.)
0.3
0.0
P|e⟩


Res. A
Res. C
Res. B
Qubit
Q0
Qubit
Q1


20 MHz

NOON states



1. Excite & entangle qubits: $|\overset{Q_0}{e}\overset{Q_1}{g}\rangle + |\overset{Q_0}{g}\overset{Q_1}{e}\rangle$

2. Excite qubits *e*-*f*: $|fg\rangle + |gf\rangle$

3. *ef* transfer to resonators: $|eg\underset{R_A}{1}\underset{R_B}{0}\rangle + |ge\underset{R_A}{0}\underset{R_B}{1}\rangle$

4. Excite qubits *e*-*f*: $|fg10\rangle + |gf01\rangle$

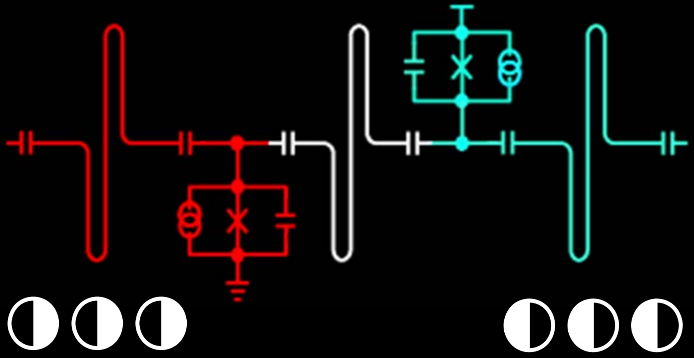
5. *ef* transfer to resonators: $|eg20\rangle + |ge02\rangle$

6. *ge* transfer to resonators: $|gg30\rangle + |gg03\rangle = |gg\rangle \otimes \underline{\left(|30\rangle + |03\rangle\right)}$

N=3 NOON state

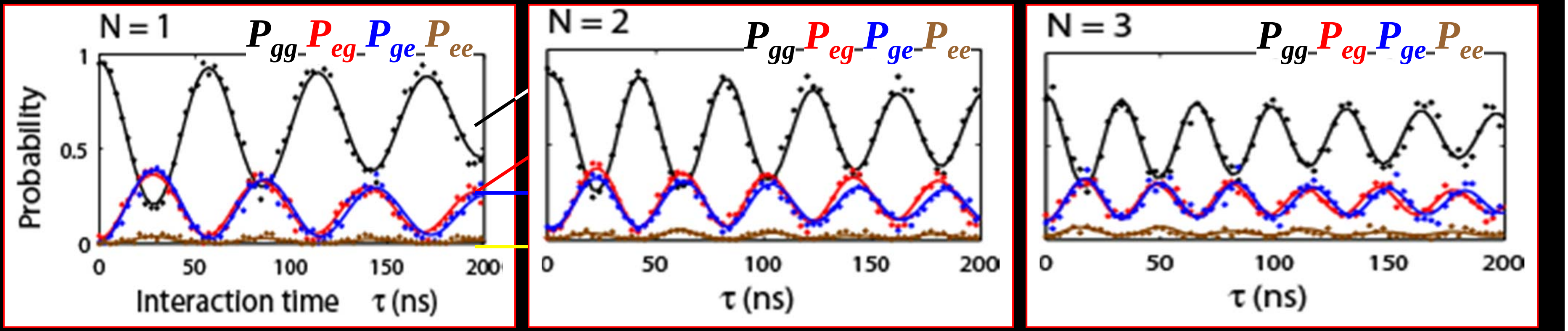
NOON state analysis

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



Coincidence measurement:

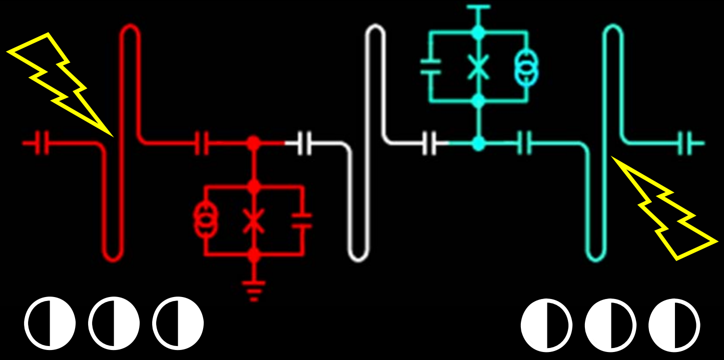
- Bring qubits into eg resonance and measure as photons swap



$$|\psi\rangle = |10\rangle + |01\rangle \qquad |\psi\rangle = |20\rangle + |02\rangle \qquad |\psi\rangle = |30\rangle + |03\rangle$$

NOON state analysis

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



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)

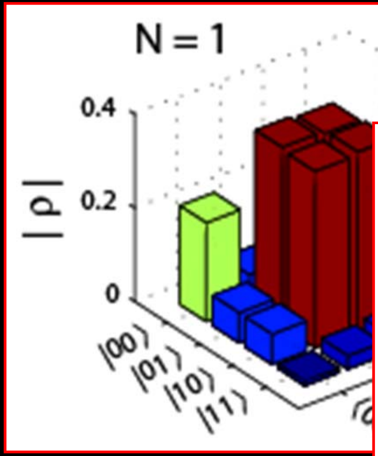
… Repeat ~200-400 times for different pulse amplitudes & phases

Calculate bi-partite Wigner tomogram ⟹ Two-resonator density matrix

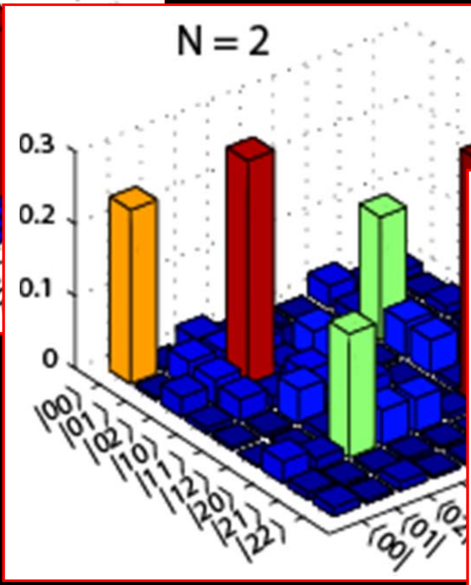
NOON state tomography

Bipartite Wigner tomography yields two-resonator density matrix

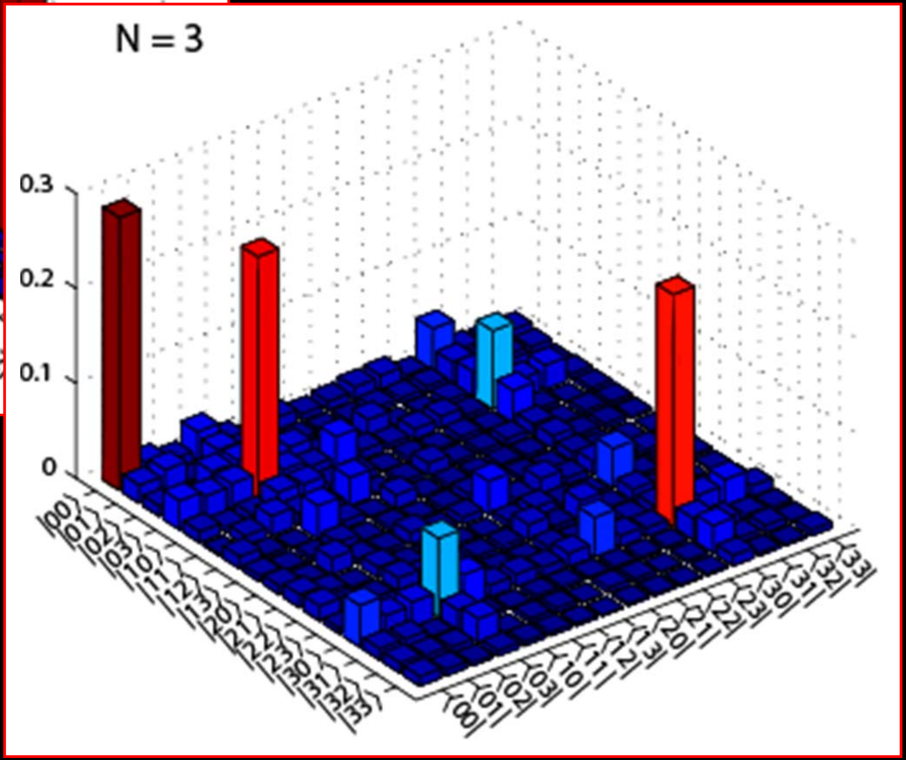
$$\rho = |mn\rangle\langle pq|$$



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



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



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

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

N=2 fidelity: $F = 0.50$

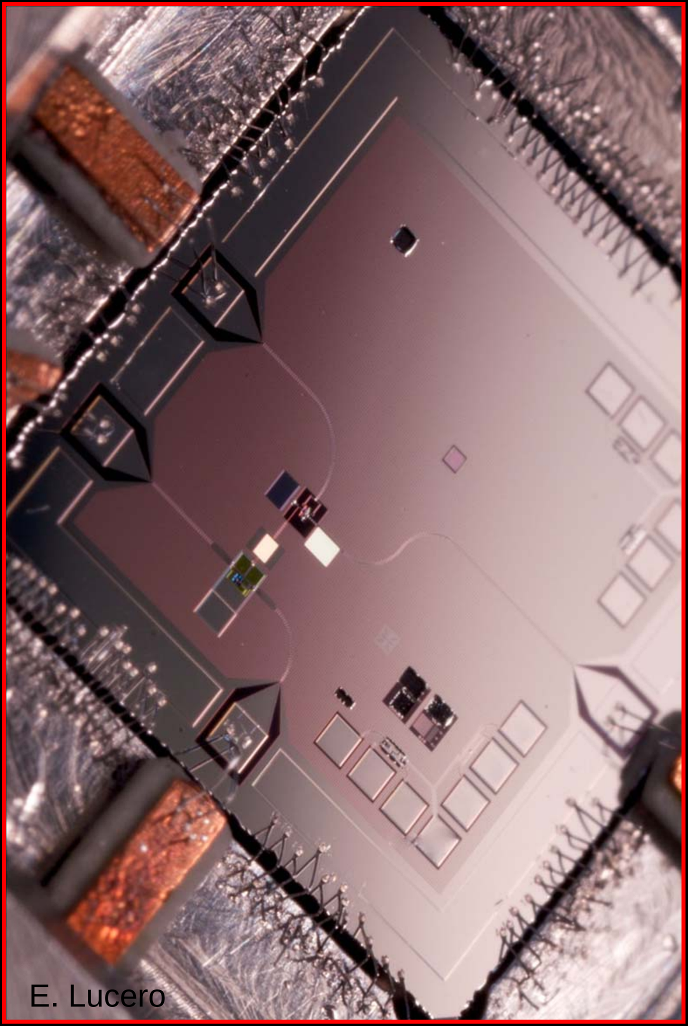
N=3 fidelity: $F = 0.33$

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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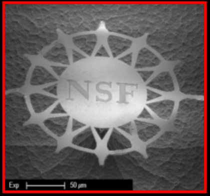
DARPA
iARPA



Positions available!