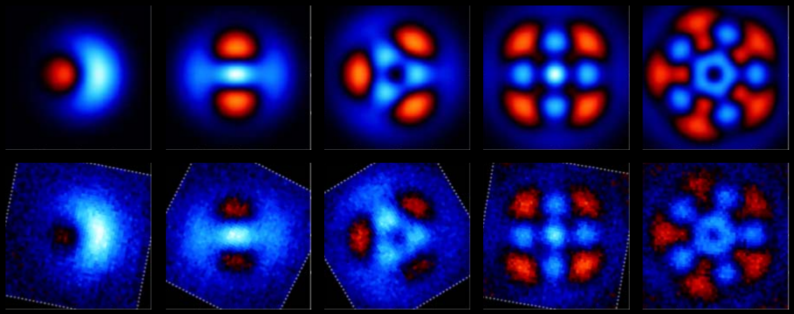
# images of quantum light

Andrew N Cleland
department of physics
university of california
santa barbara

collaborators:
John M Martinis (uc santa barbara)
Michael Geller (u georgia - athens)

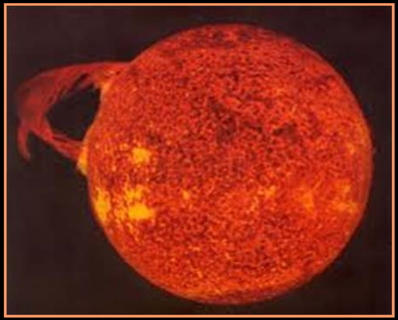

theory

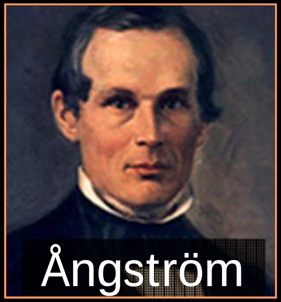
experiment

College de France
14 Juin 2011
11:00

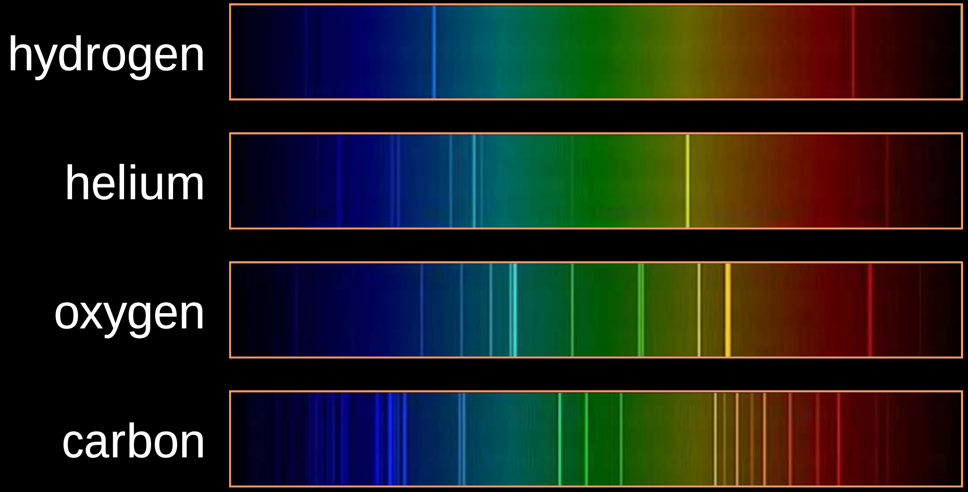
# historical perspective


Fraunhofer




Ångström

## Each atom has specific wavelengths




de Broglie

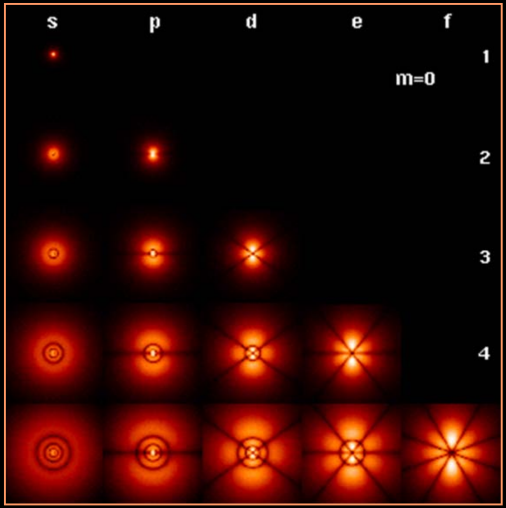

Bohr


Schrödinger

$$\lambda = \frac{h}{mv}$$

$$\hat{H}|\Psi\rangle = i\hbar \frac{\partial}{\partial t}|\Psi\rangle$$

wave
nature of
electrons
in atoms



# a precision theory

Quantum mechanics is the most precise physical theory :

atomic hydrogen 1S-2S transition frequency:

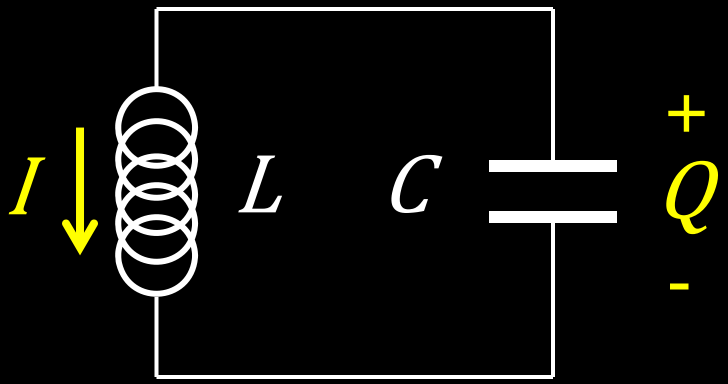
experiment: 2 466 061 413 187 103 Hz

theory: 2 466 061 413 2XX XXX Hz

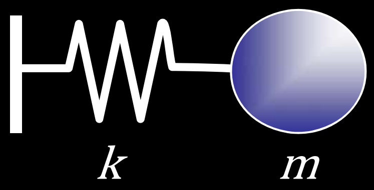
limited by precision of physical constants

“Measurement of the H 1*S*-2*S* transition”
M. Niering et al. *Phys. Rev. Lett.* (2000)
MPI Garching & Observatoire de Paris & LKB, Paris

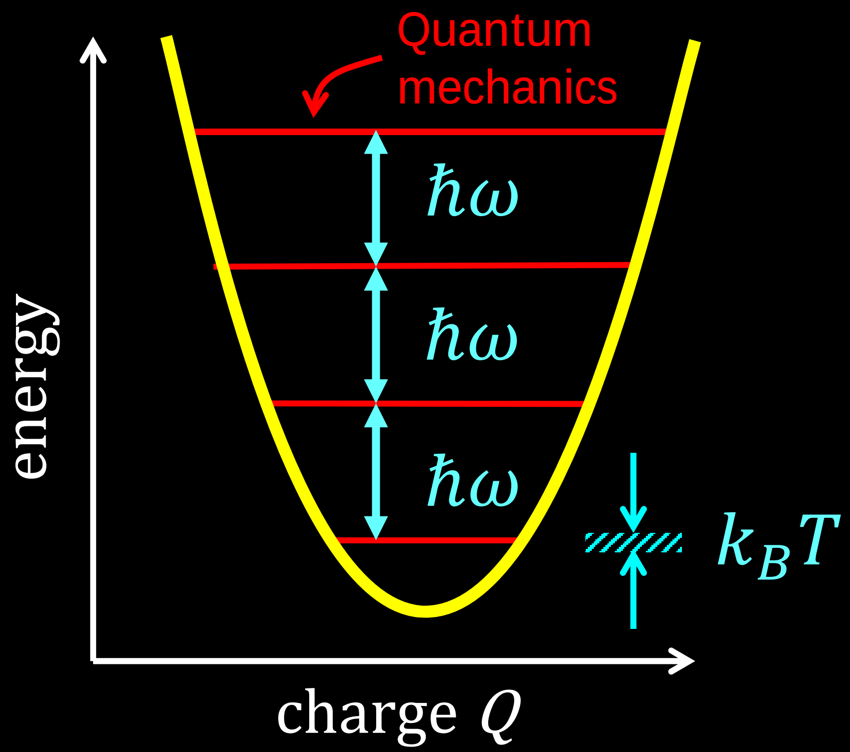
# not just for atoms



Resonance frequency: $\omega = \sqrt{L/C}$



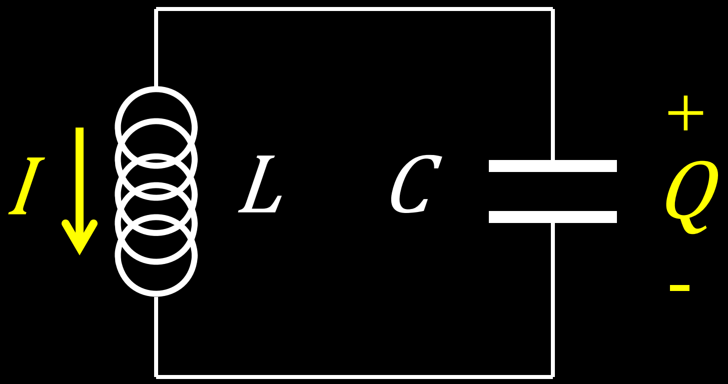
$\omega = \sqrt{k/m}$



Cool to quantum ground state:

- need $T \ll \hbar\omega/k_B$ $\quad \omega/2\pi \sim \text{GHz} \Longrightarrow T \ll 0.1\ \text{K}$
- dilution refrigerator: $T = 20\ \text{mK}$ ✓

# not just for atoms



However:

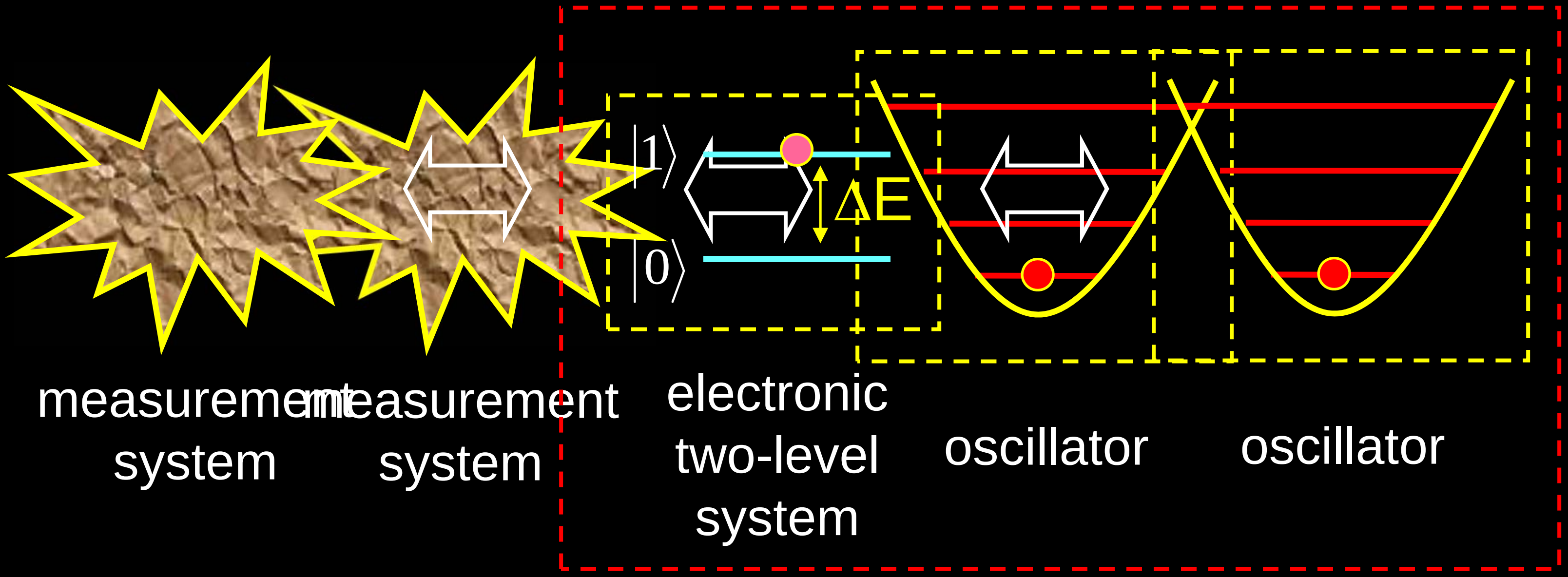
Harmonic oscillators are always in the correspondence limit

- ➢ Difficult to distinguish classical from quantum behavior
- ➢ Difficult to control at single photon level
- ➢ Difficult to measure at single photon level
- ➢ How to measure without destroying quantum effects?

# resonator quantum control

how to measure a harmonic oscillator in quantum limit?

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

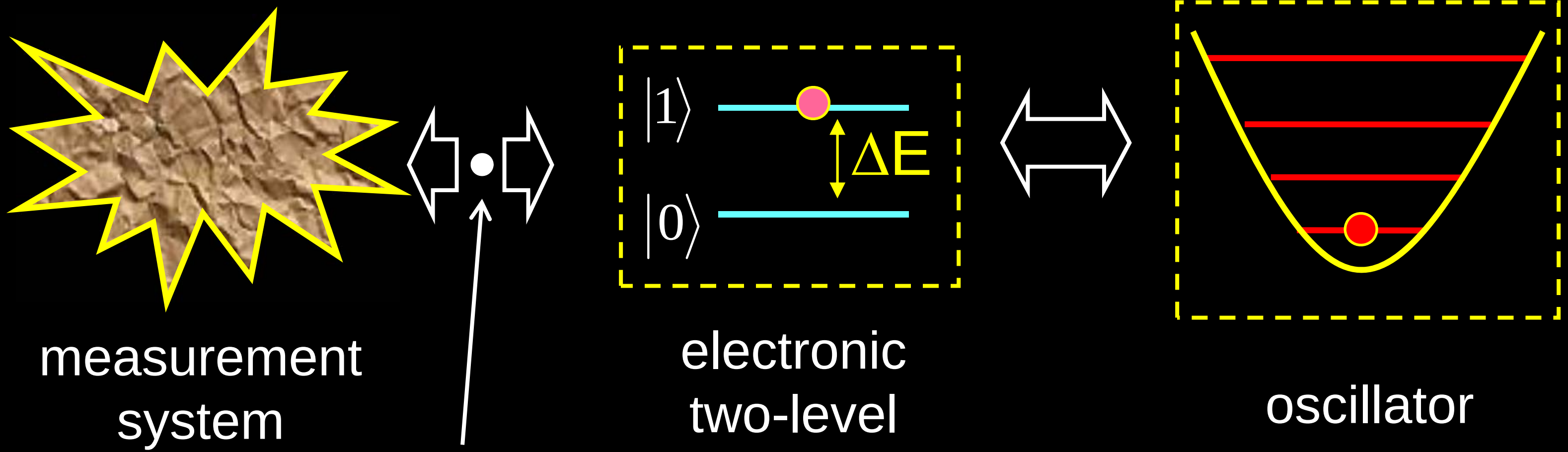


coupled system quantum coherent
measurement destroys quantum state

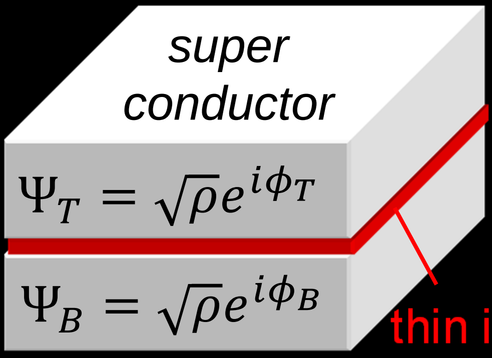
# resonator quantum control

how to measure a harmonic oscillator in quantum limit?

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



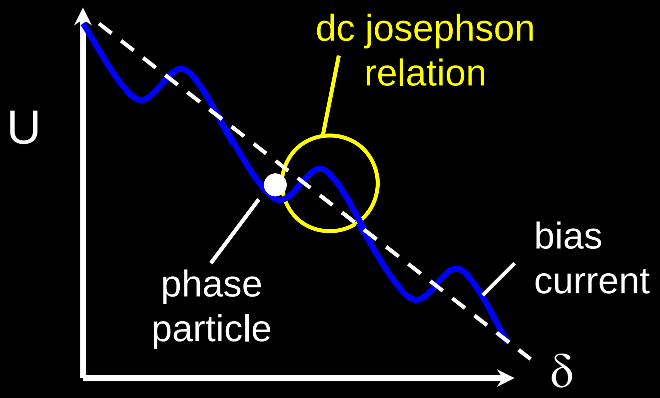
# electronic two-level atom



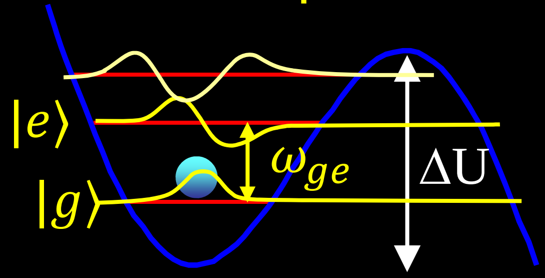
phase difference

$$\delta = \phi_T - \phi_B$$

ac & dc josephson relations

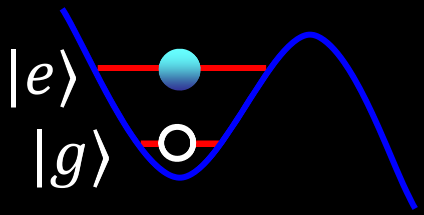


at 20 mK δ is a quantum variable:



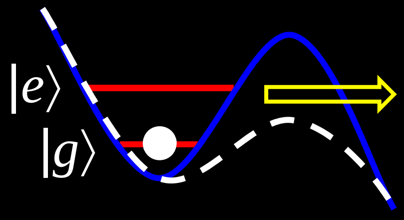
$$\frac{\omega_{ge}}{2\pi} \sim 6\ \mathrm{GHz}$$

- strong nonlinearity
  can address just $|g\rangle$ and $|e\rangle$
- energy splitting $\omega_{ge}$ tunable
  $\hbar\omega_{ge} \sim 30 k_B T$ at 20 mK



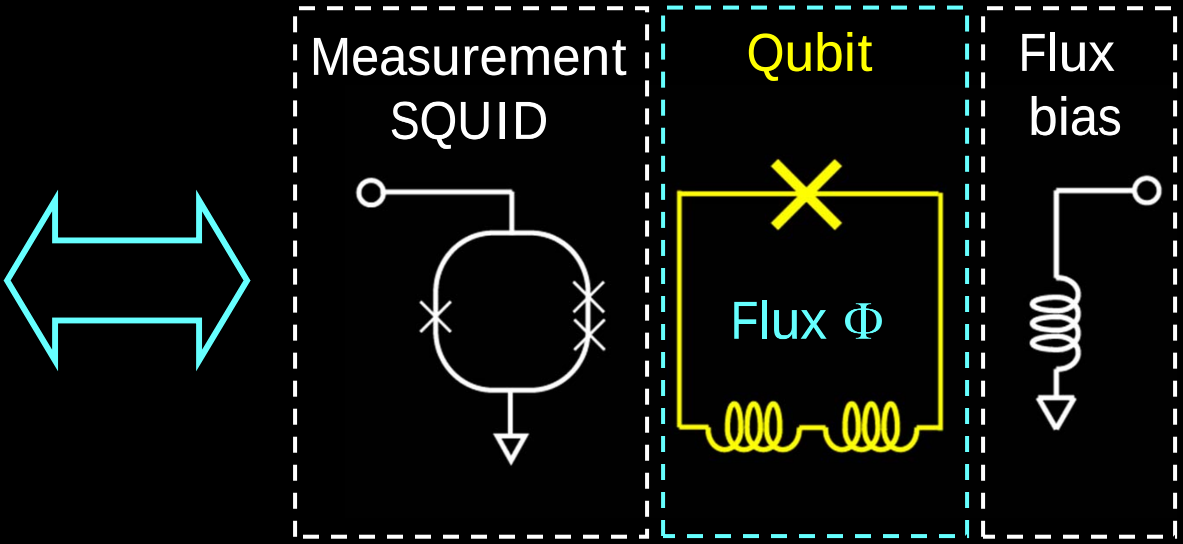
1. electronic two-level system
2. ground state below 300 mK
3. complete quantum control
4. single-shot measurement

# qubit measurement



**Vary barrier height**

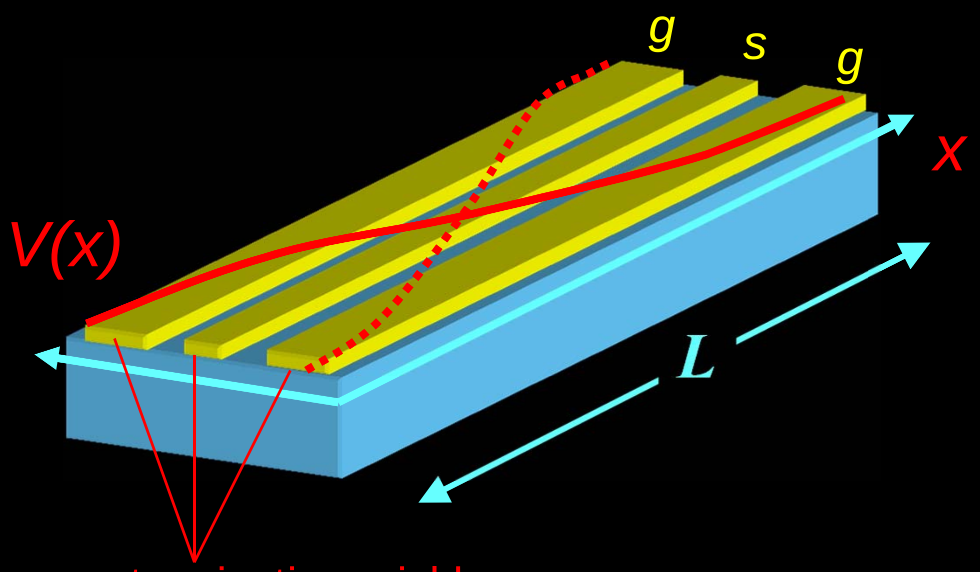
- $|e\rangle$ tunnels
- $|g\rangle$ trapped



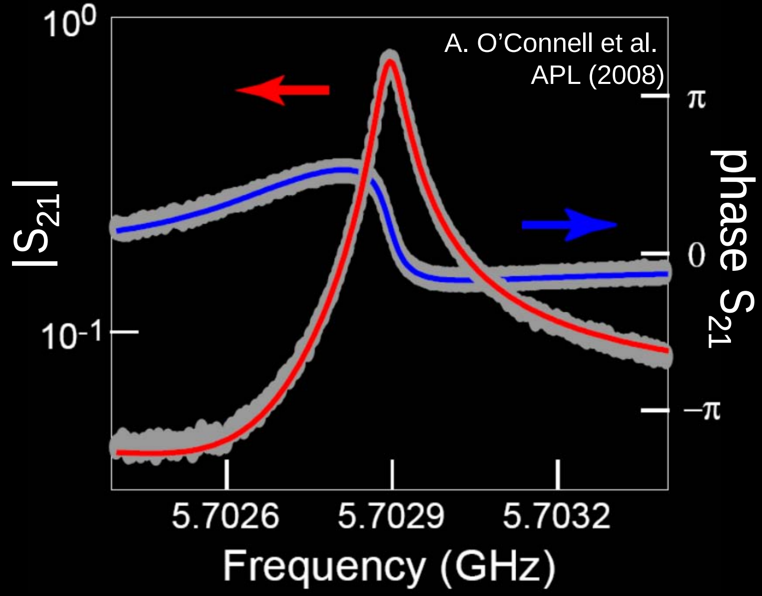
- State of qubit measured with SQUID at end of preparation
- Single shot measurement yields qubit state ($|g\rangle$ or $|e\rangle$)
- Repeated preparation & measurement (~1000X) yields $P(e)$
- External flux bias $\Phi$ used to adjust $|e\rangle - |g\rangle$ frequency,

  relative occupation & quantum phase

# half-wave coplanar stripline resonator



open terminations yield voltage antinodes

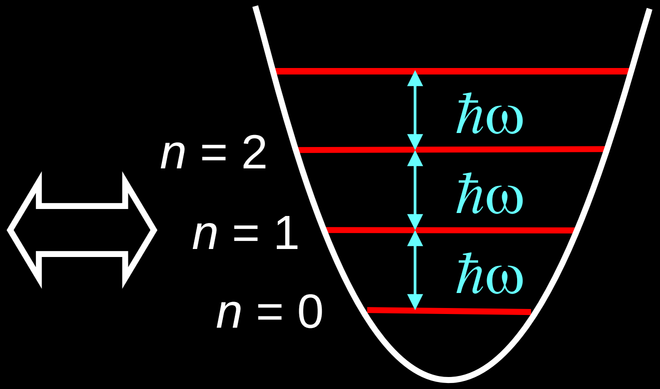


- wavelength $\lambda = 2L \sim 10$ mm
- resonance frequency $\omega/2\pi \sim$ 5-10 GHz

  $\hbar\omega \gg k_B T$ at 20 mK

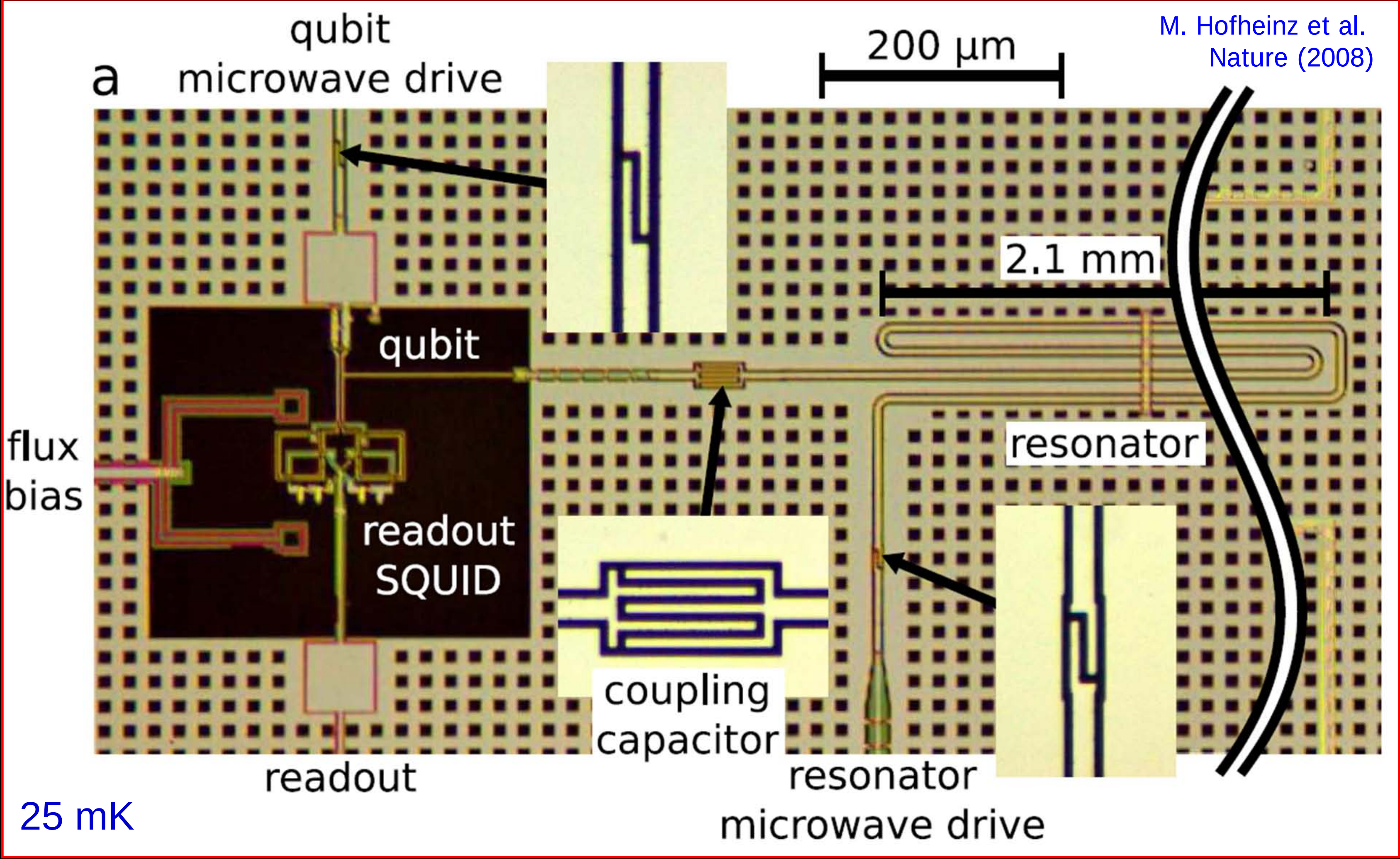
- quality factor Q ~ $10^5$-$10^6$

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



quantum control of microwave photons

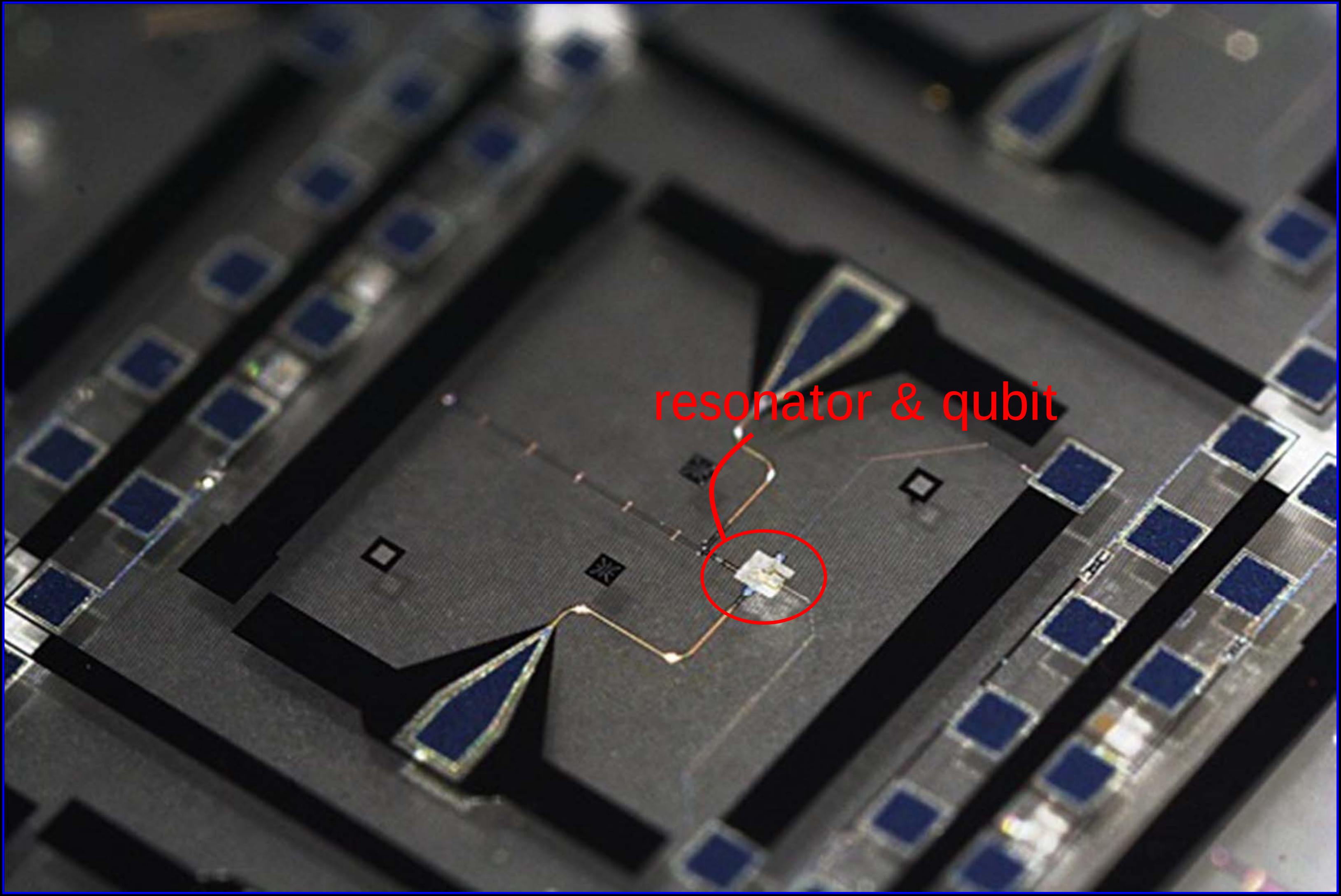
# coupled resonator & qubit



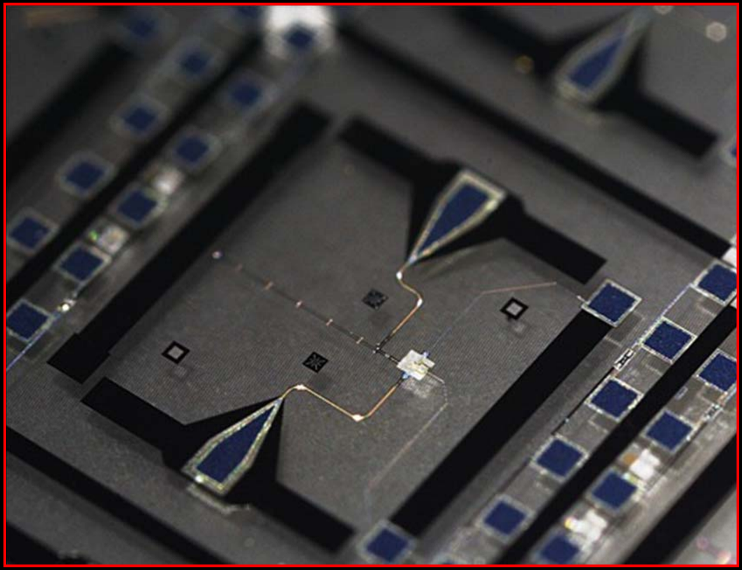
M. Hofheinz et al.
Nature (2008)

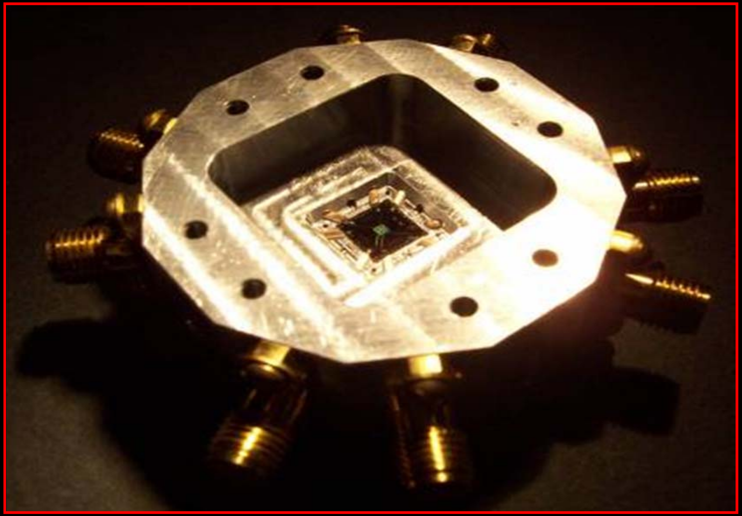
25 mK

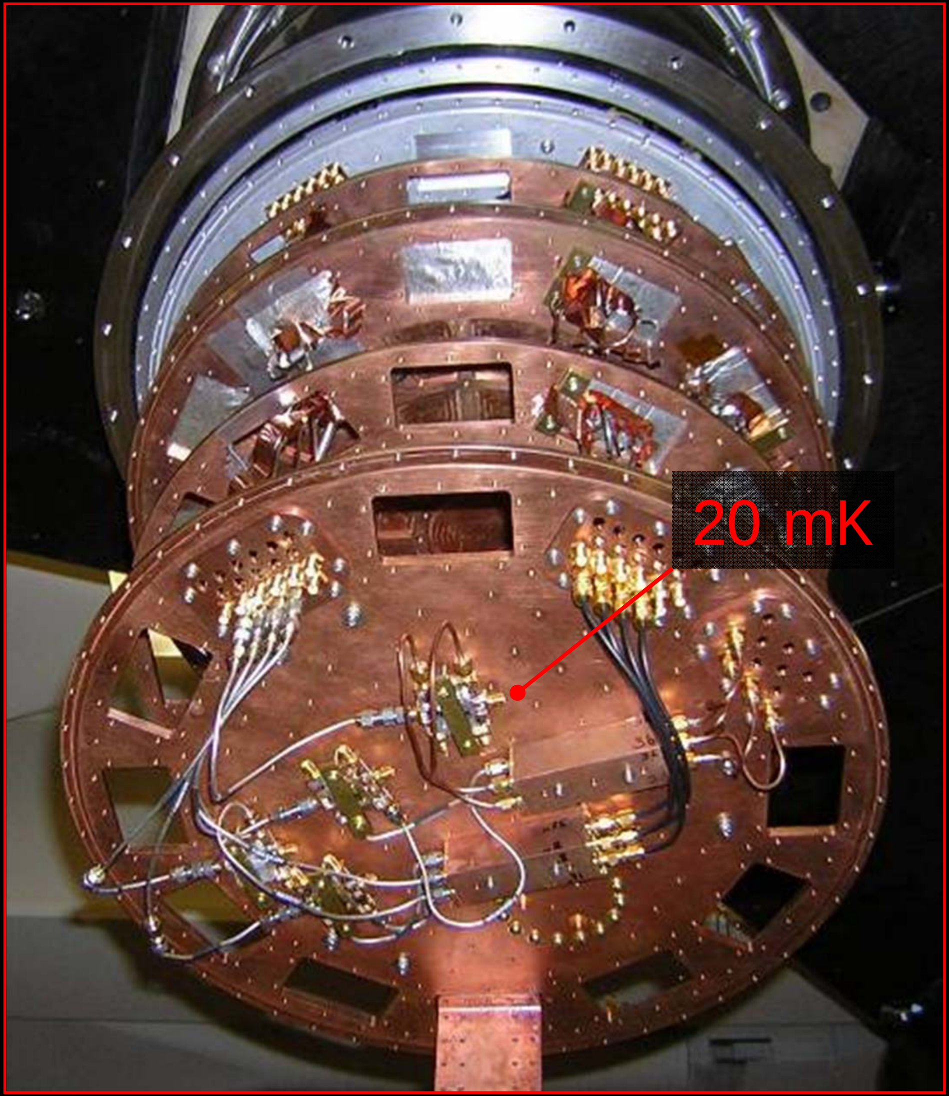
# quantum light & sound



# experimental system

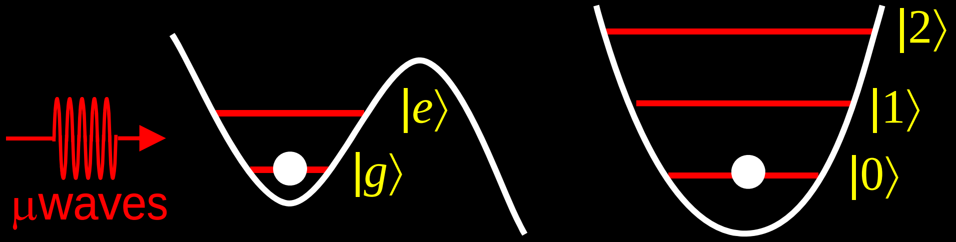


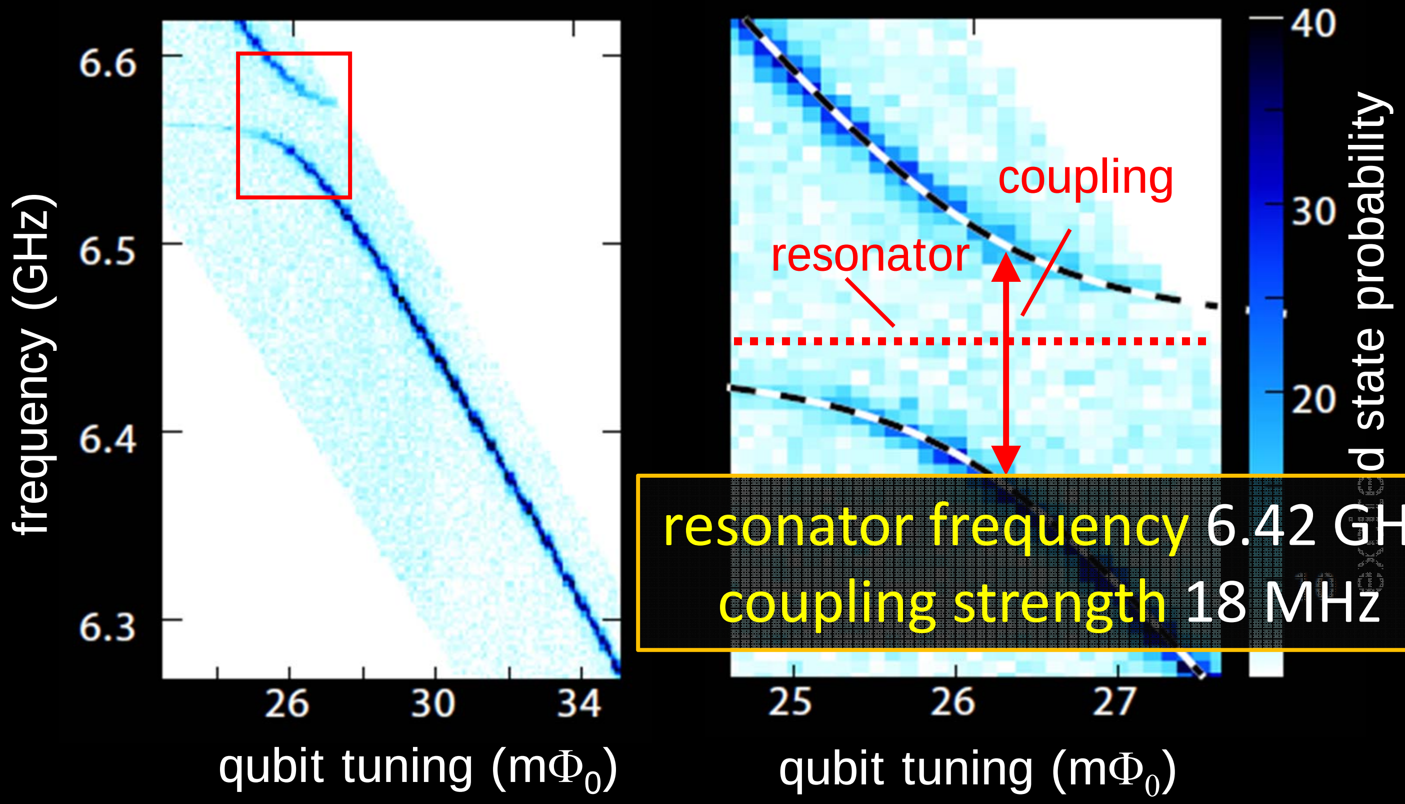




# coupled system spectroscopy

1. set qubit frequency
2. set microwave frequency
3. pulse & measure qubit

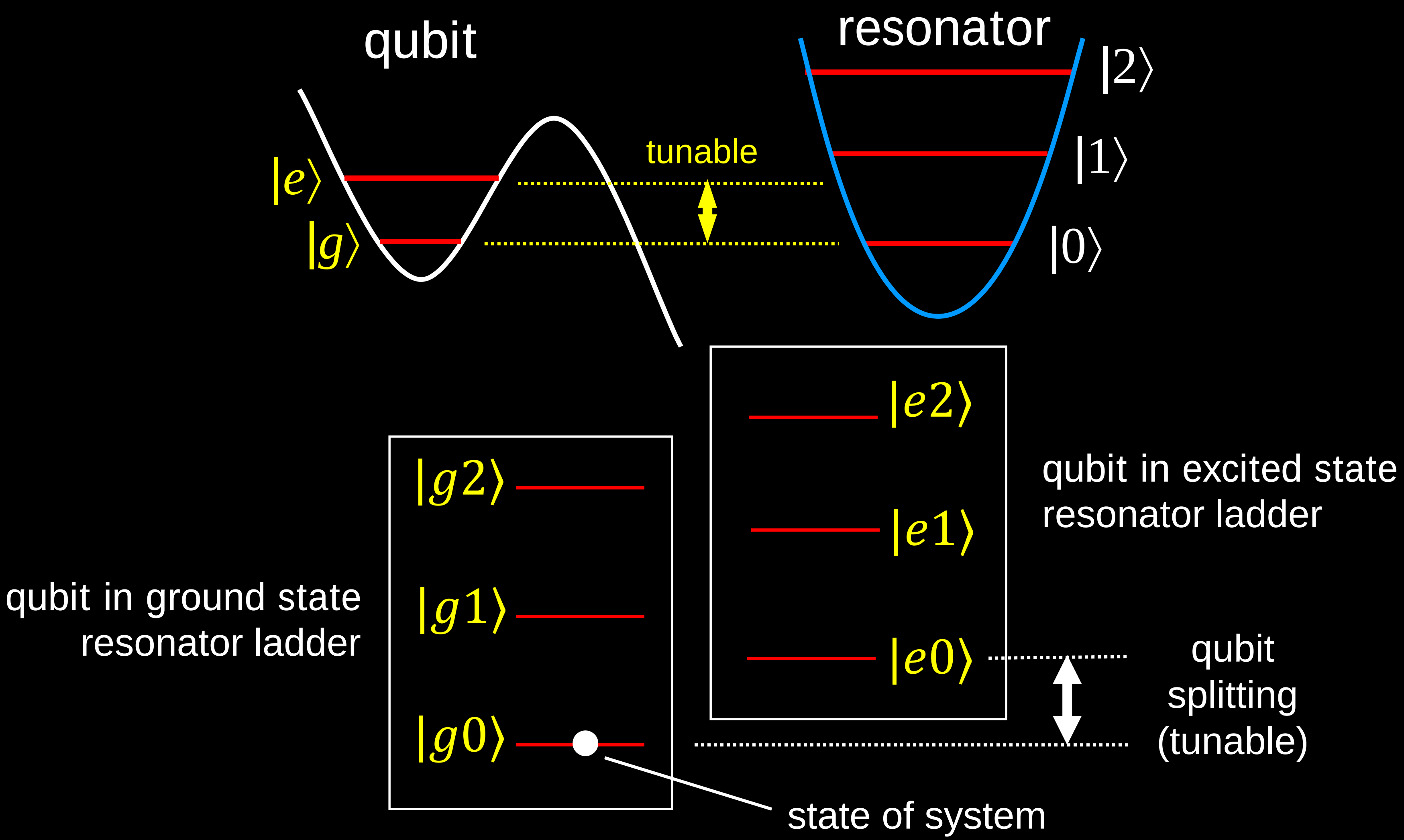




resonator frequency 6.42 GHz
coupling strength 18 MHz

m. hofheinz et al. nature (2008)

# coupled system energy levels



qubit in excited state
resonator ladder

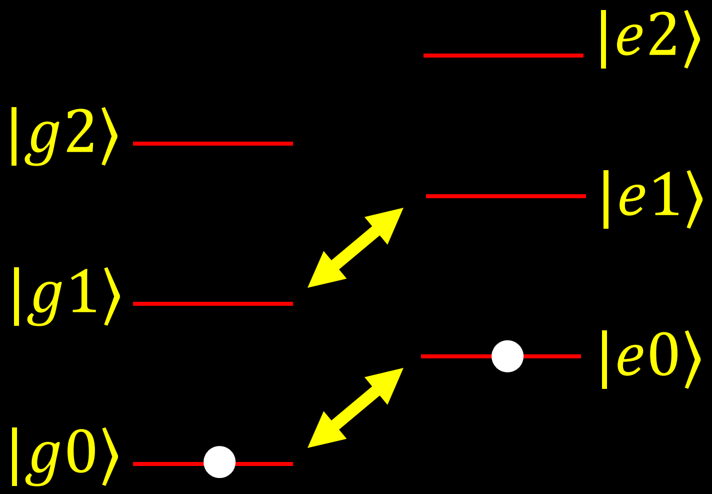
qubit in ground state
resonator ladder

qubit
splitting
(tunable)

state of system

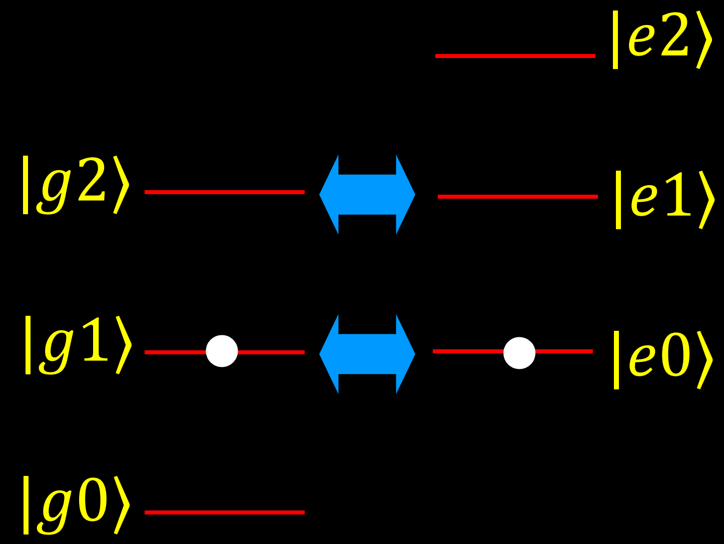
# time-domain control

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



# time-domain control

- qubit off resonance (system in $|g\rangle|0\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|0\rangle$ state)
- tune qubit to resonator frequency
- Rabi oscillation: transfer photon from qubit to resonator



$|e2\rangle$

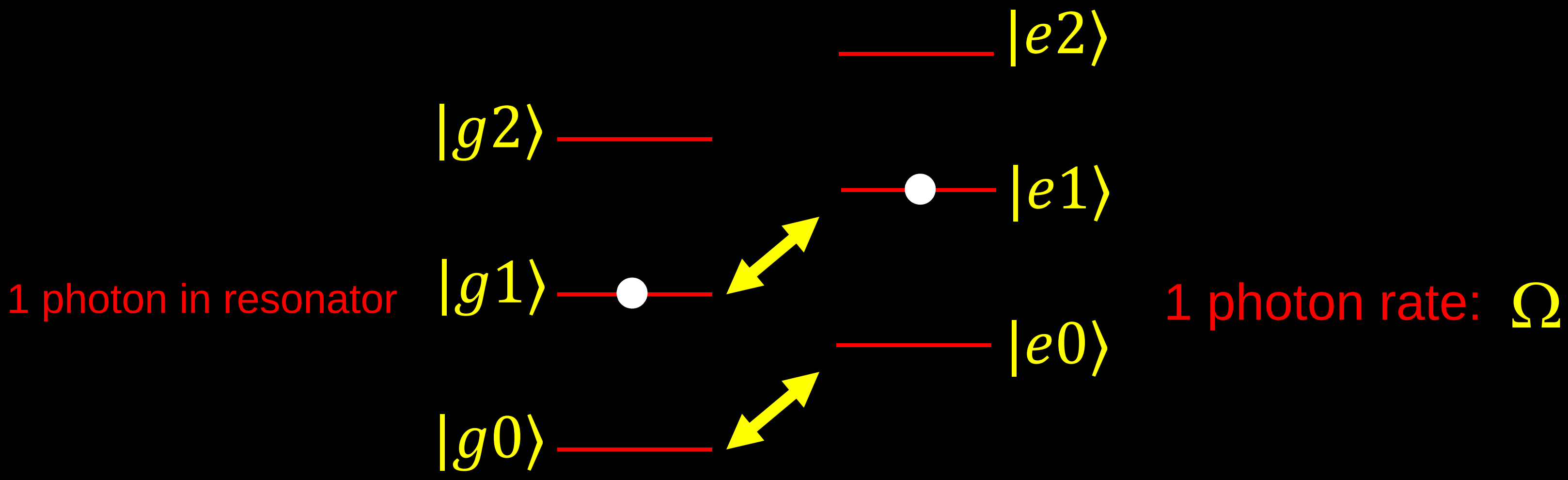
$|g2\rangle$ $|e1\rangle$

1 photon in resonator $|g1\rangle$ $|e0\rangle$ 1 photon rate: $\Omega$

$|g0\rangle$

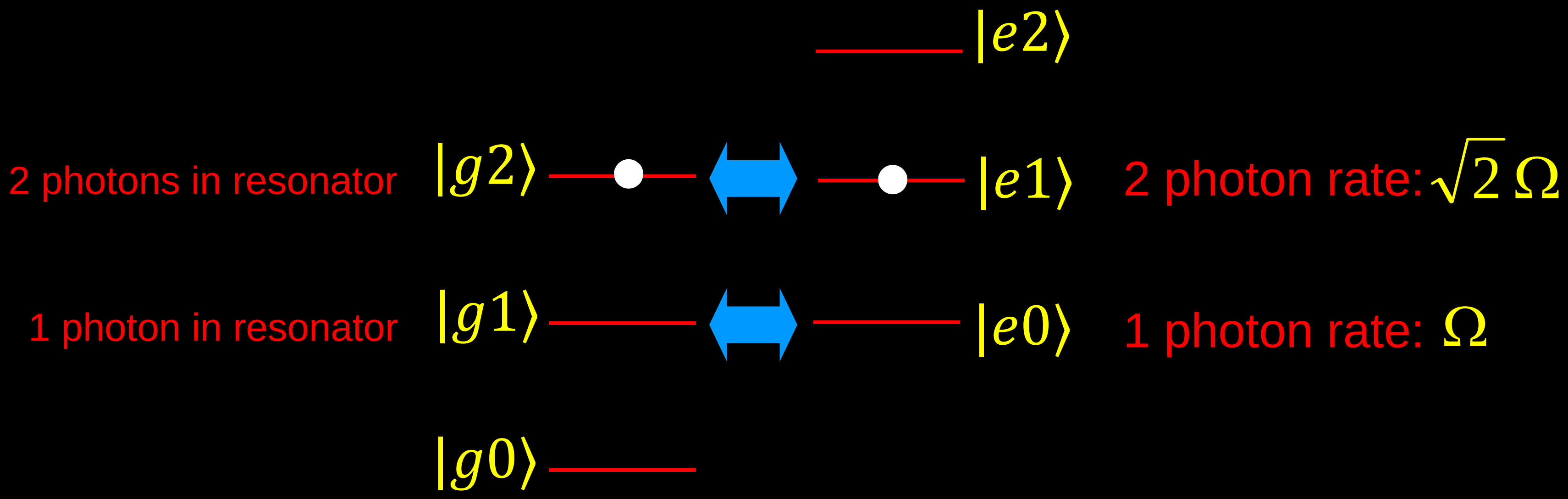
# adding more photons

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



# adding more photons

- detune qubit (system in $|g\rangle|1\rangle$ state)
- apply microwave $\pi$ pulse to qubit (goes to $|e\rangle|1\rangle$ state)
- rune qubit to resonator, Rabi (goes to $|g\rangle|2\rangle$ state)



$|e2\rangle$

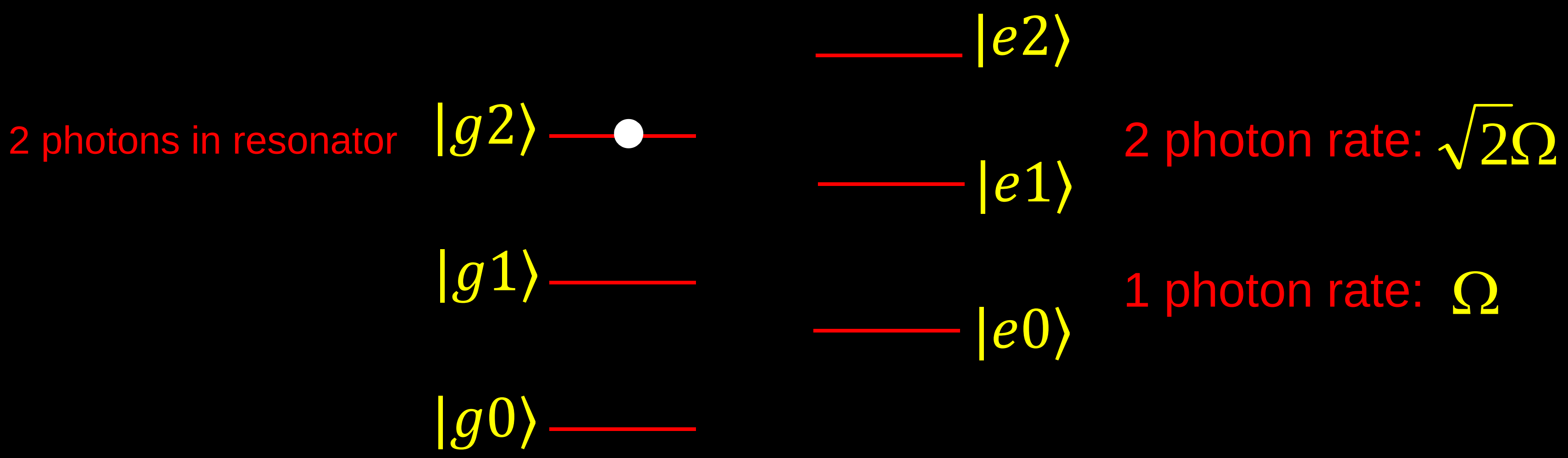
2 photons in resonator $|g2\rangle$ ⟺ $|e1\rangle$ 2 photon rate: $\sqrt{2}\,\Omega$

1 photon in resonator $|g1\rangle$ ⟺ $|e0\rangle$ 1 photon rate: $\Omega$

$|g0\rangle$

# adding more photons

- detune qubit (system in $|g\rangle|1\rangle$ state)
- apply microwave π pulse to qubit (goes to $|e\rangle|1\rangle$ state)
- tune qubit to resonator, Rabi (goes to $|g\rangle|2\rangle$ state)
- repeat for *n* photons: each transfer $\sqrt{n}$ faster



2 photons in resonator

$|g2\rangle$

$|g1\rangle$

$|g0\rangle$

$|e2\rangle$

$|e1\rangle$

$|e0\rangle$

2 photon rate: $\sqrt{2}\Omega$

1 photon rate: $\Omega$

# time-domain control

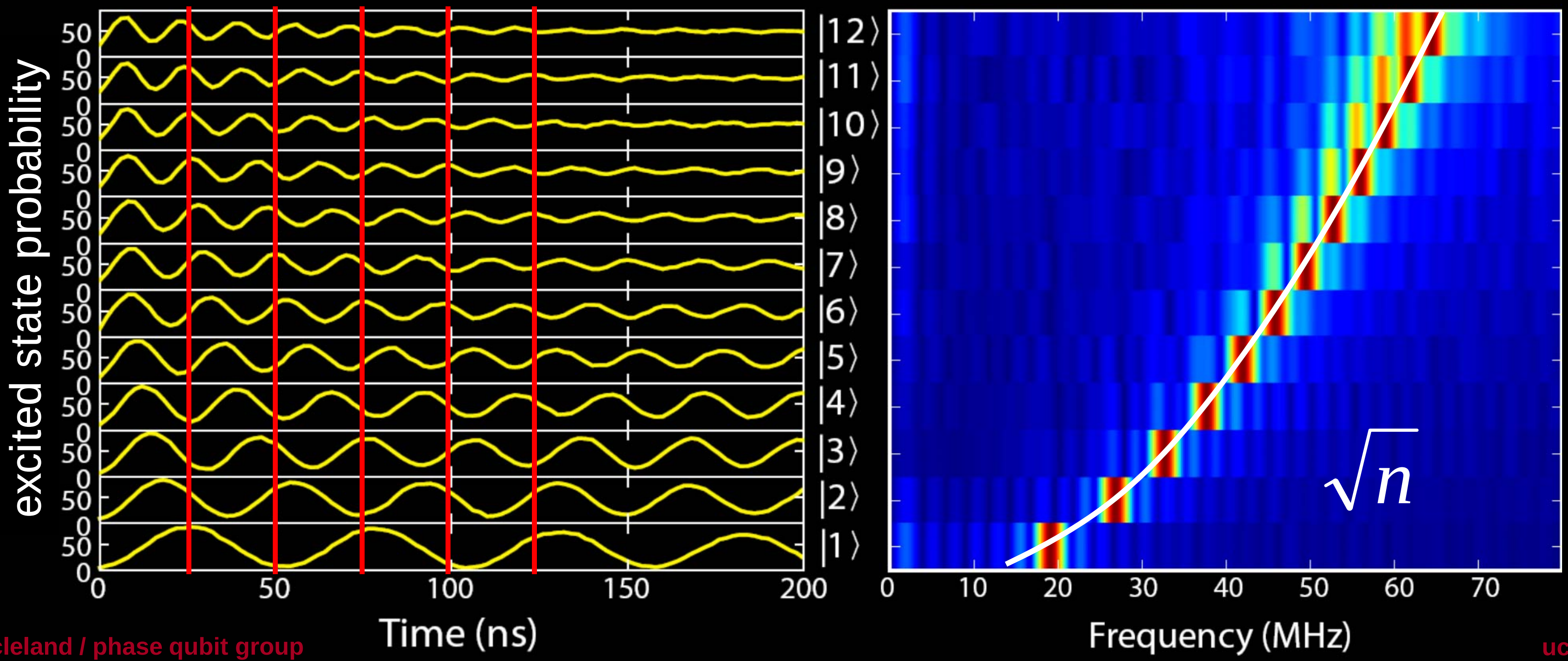
m. hofheinz et al.
nature (2008)

## measure resonator state with qubit

- qubit in $|g\rangle$
- resonator in $|n\rangle$
- tune qubit into resonance

Rabi oscillation:
$|g\rangle|n\rangle \Leftrightarrow |e\rangle|n-1\rangle$

Rabi frequency scales as $\sqrt{n}$



# quantum state tomography

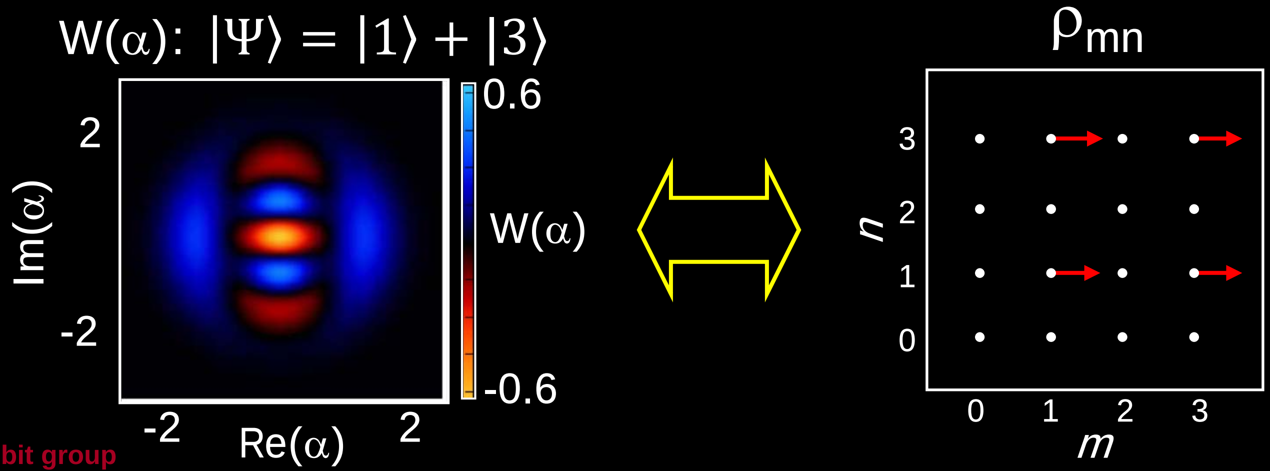
arbitrary superposition states:

$$|g\rangle|0\rangle \Rightarrow |g\rangle(a|0\rangle + b|1\rangle + c|2\rangle + \cdots)$$

- 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(α):

- quasiprobability distribution
- negative values $\Leftrightarrow$ quantum coherence
- equivalent to measuring density matrix



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

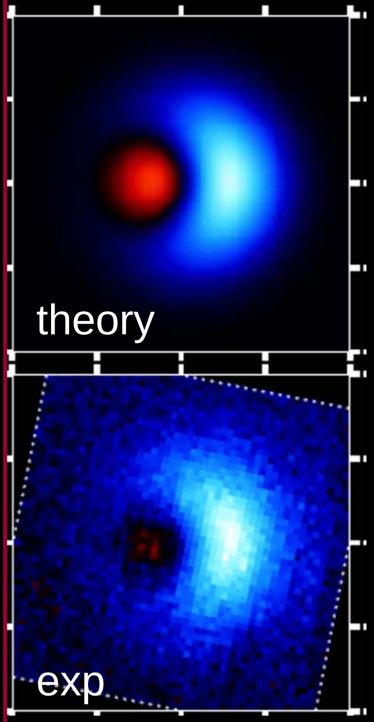
$\rho_{mn}$

# superpositions

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

M. Hofheinz et al.
Nature (2009)

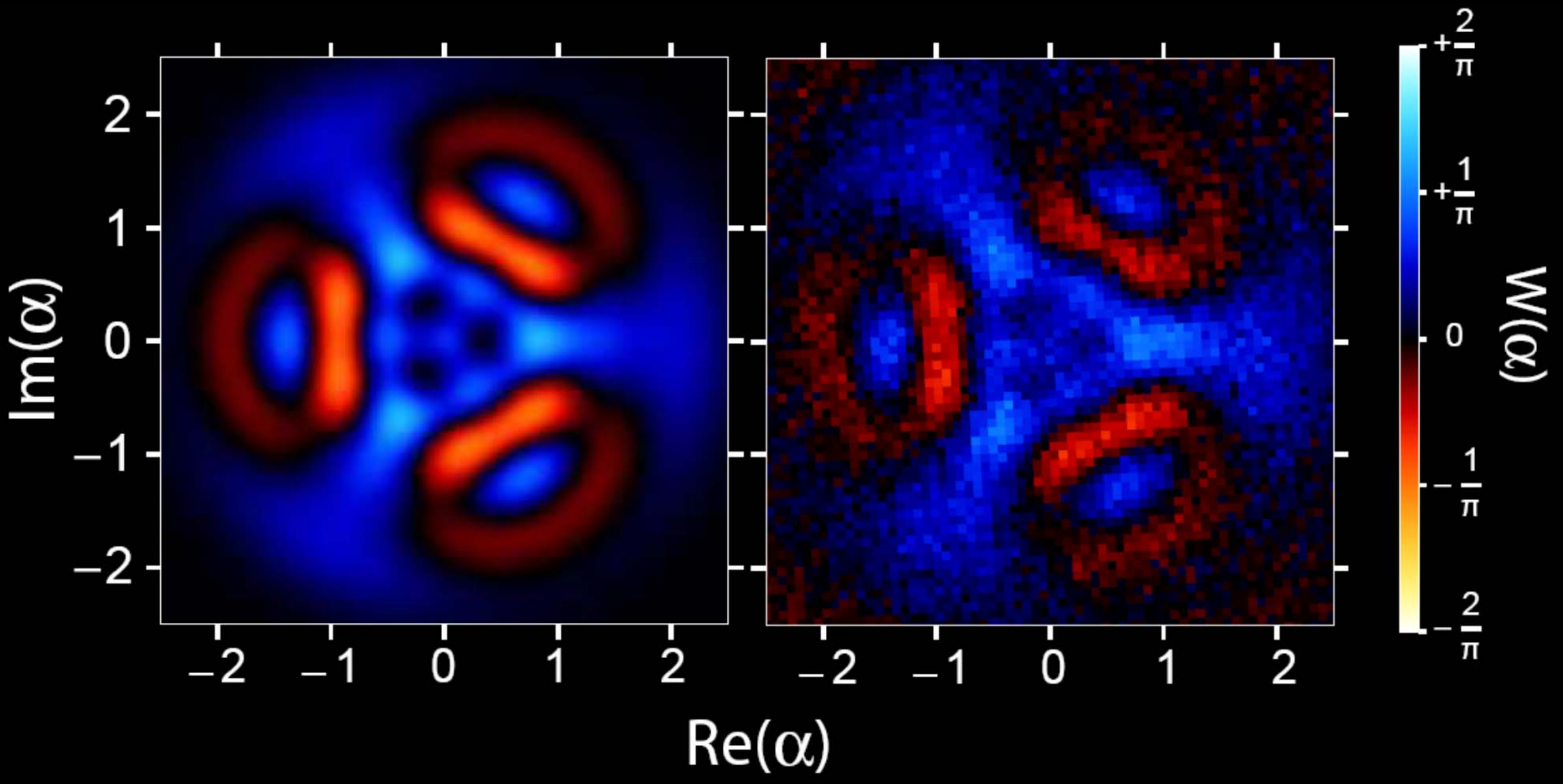
$$|\psi\rangle = |0\rangle + |1\rangle$$



# superpositions

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

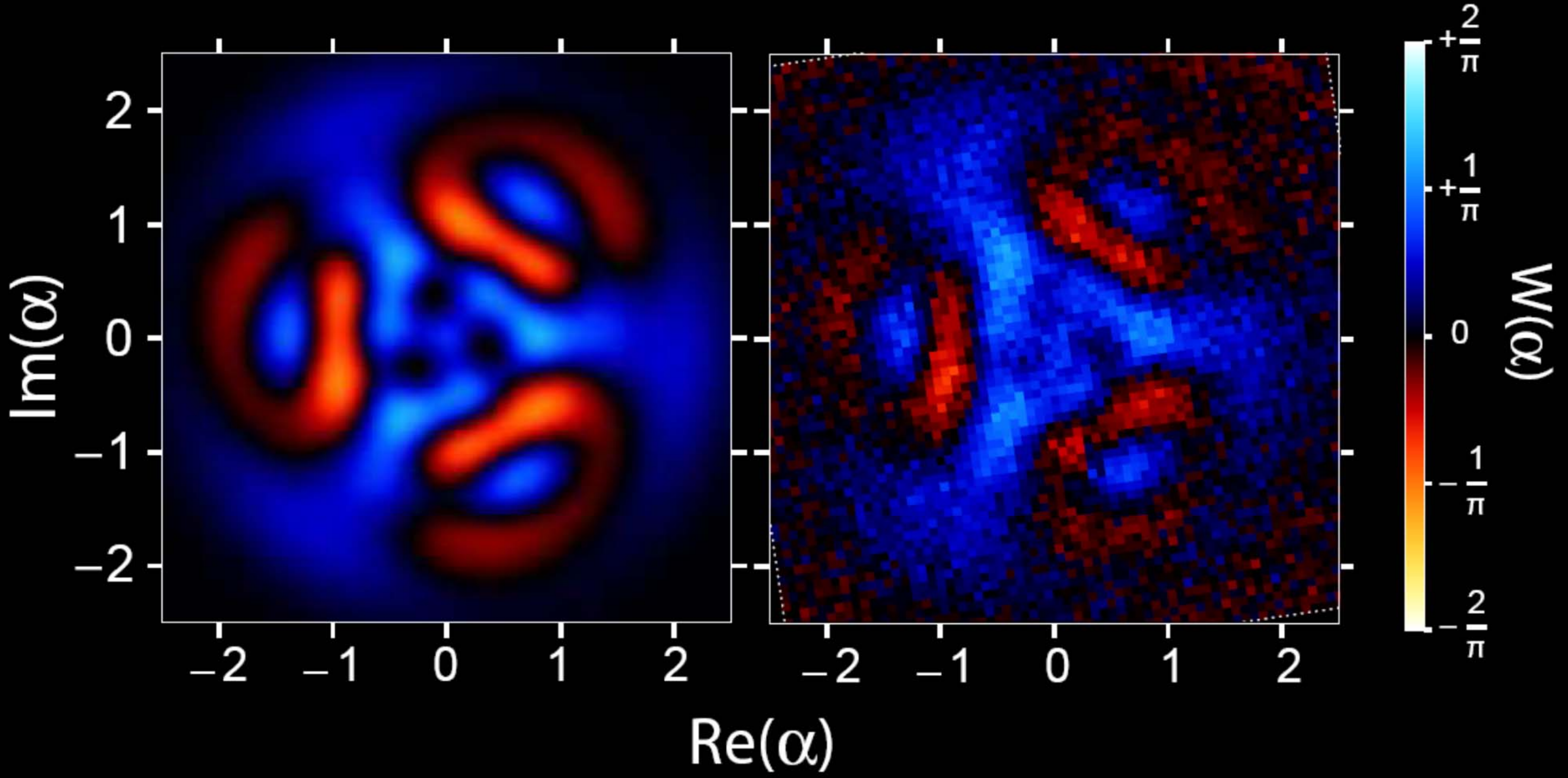
M. Hofheinz et al.
Nature (2009)



# superpositions

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

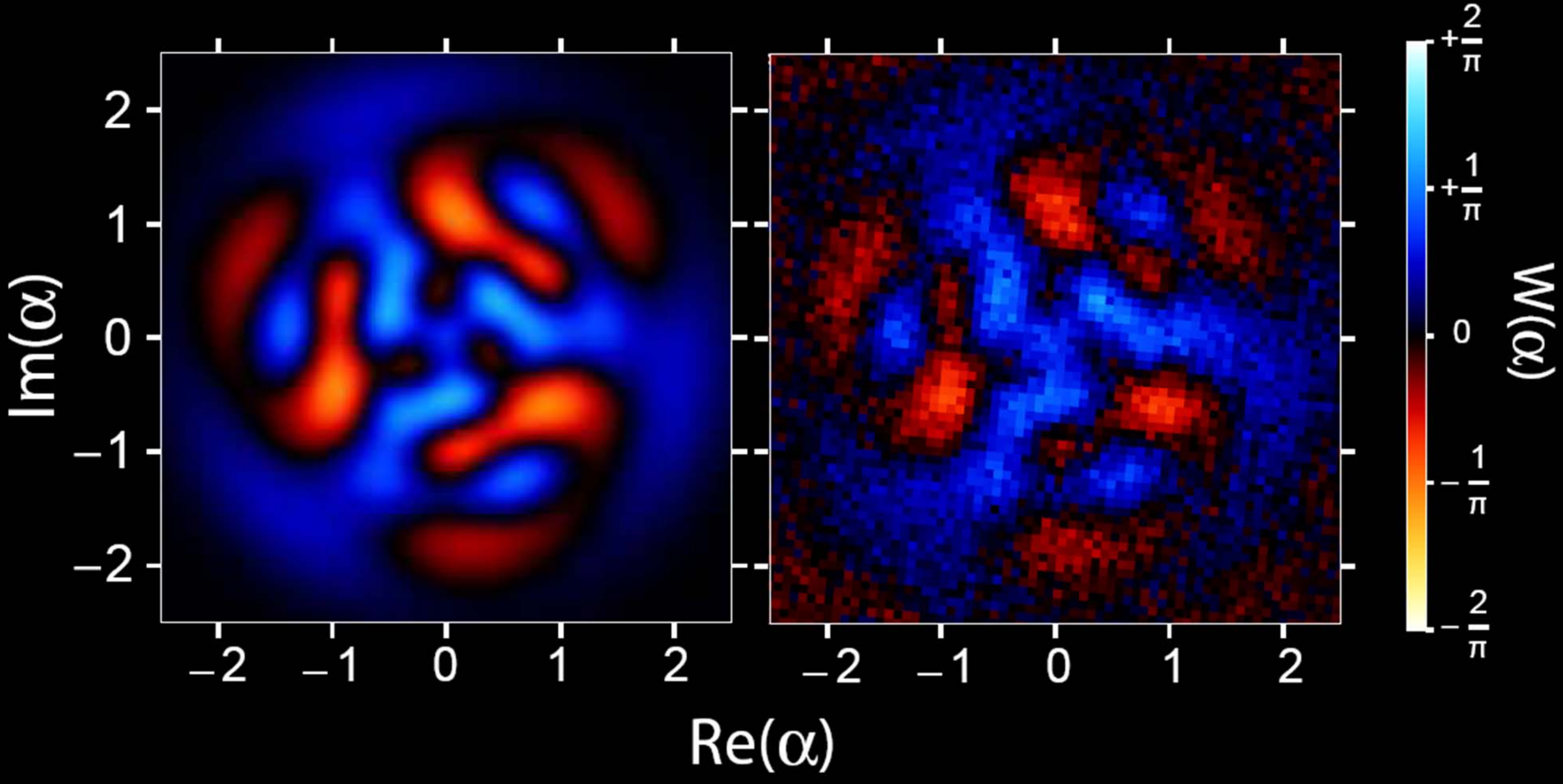
M. Hofheinz et al.
Nature (2009)



# superpositions

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

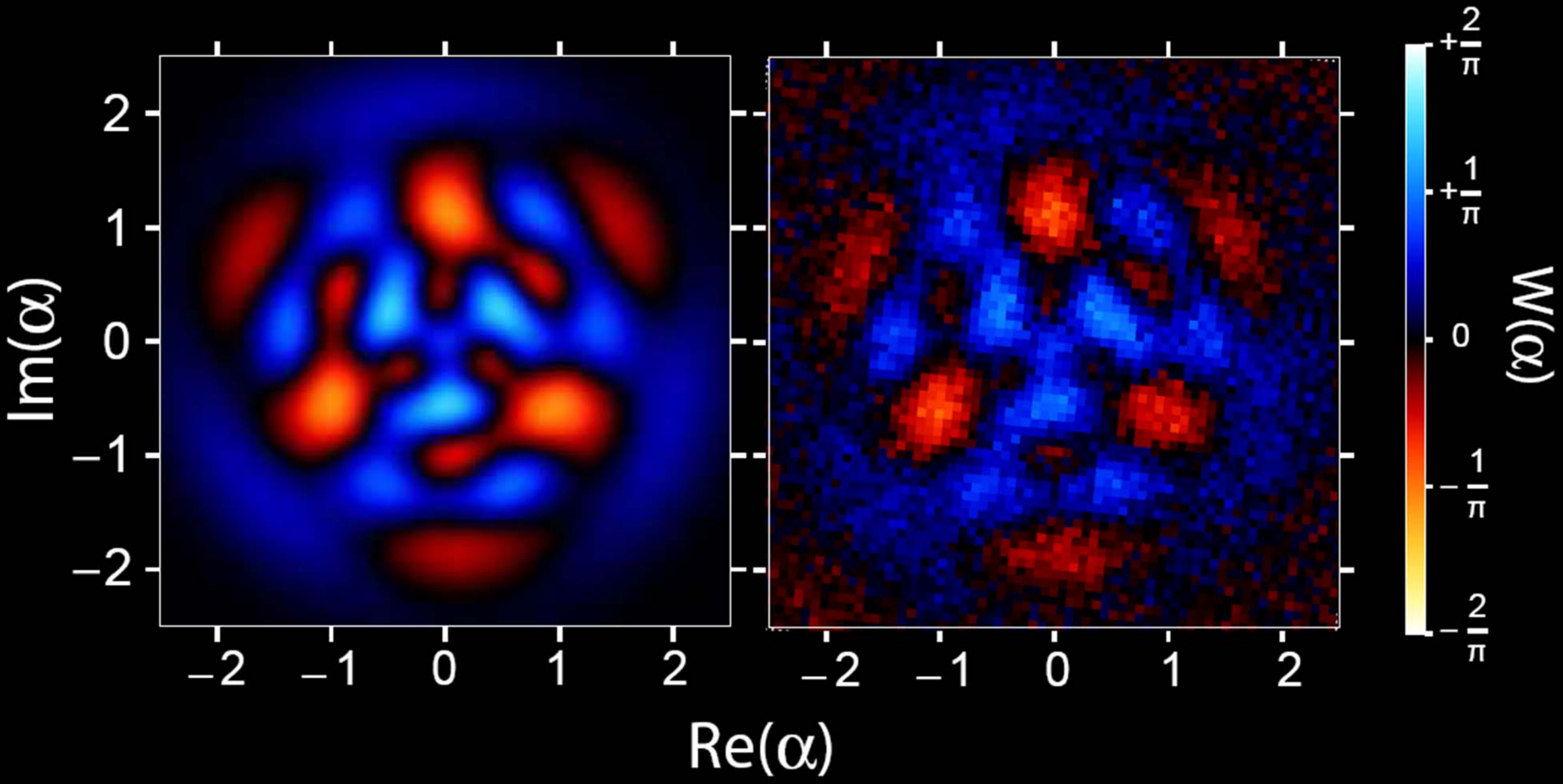
M. Hofheinz et al.
Nature (2009)



# superpositions

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

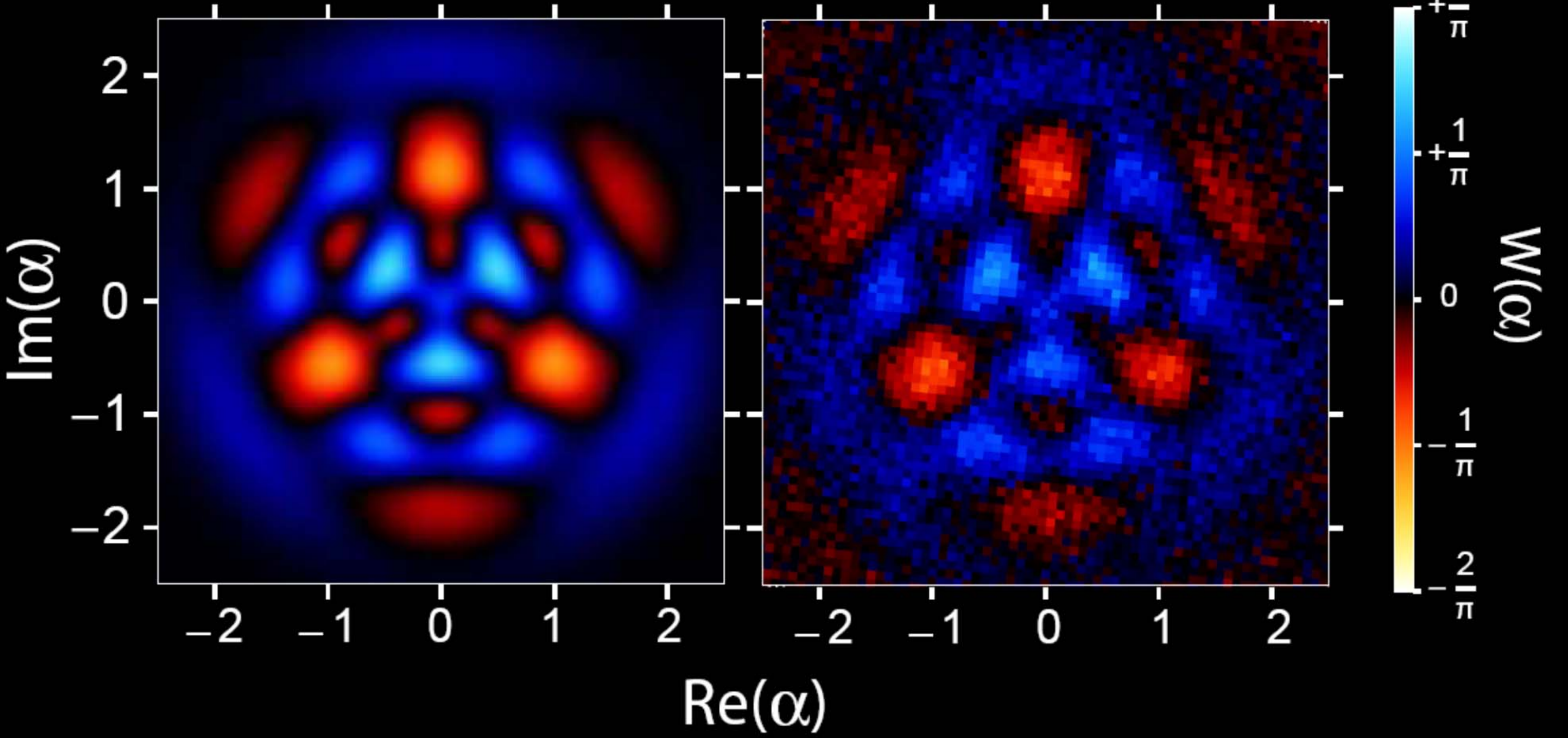
M. Hofheinz et al.
Nature (2009)



# superpositions

M. Hofheinz et al.
Nature (2009)

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

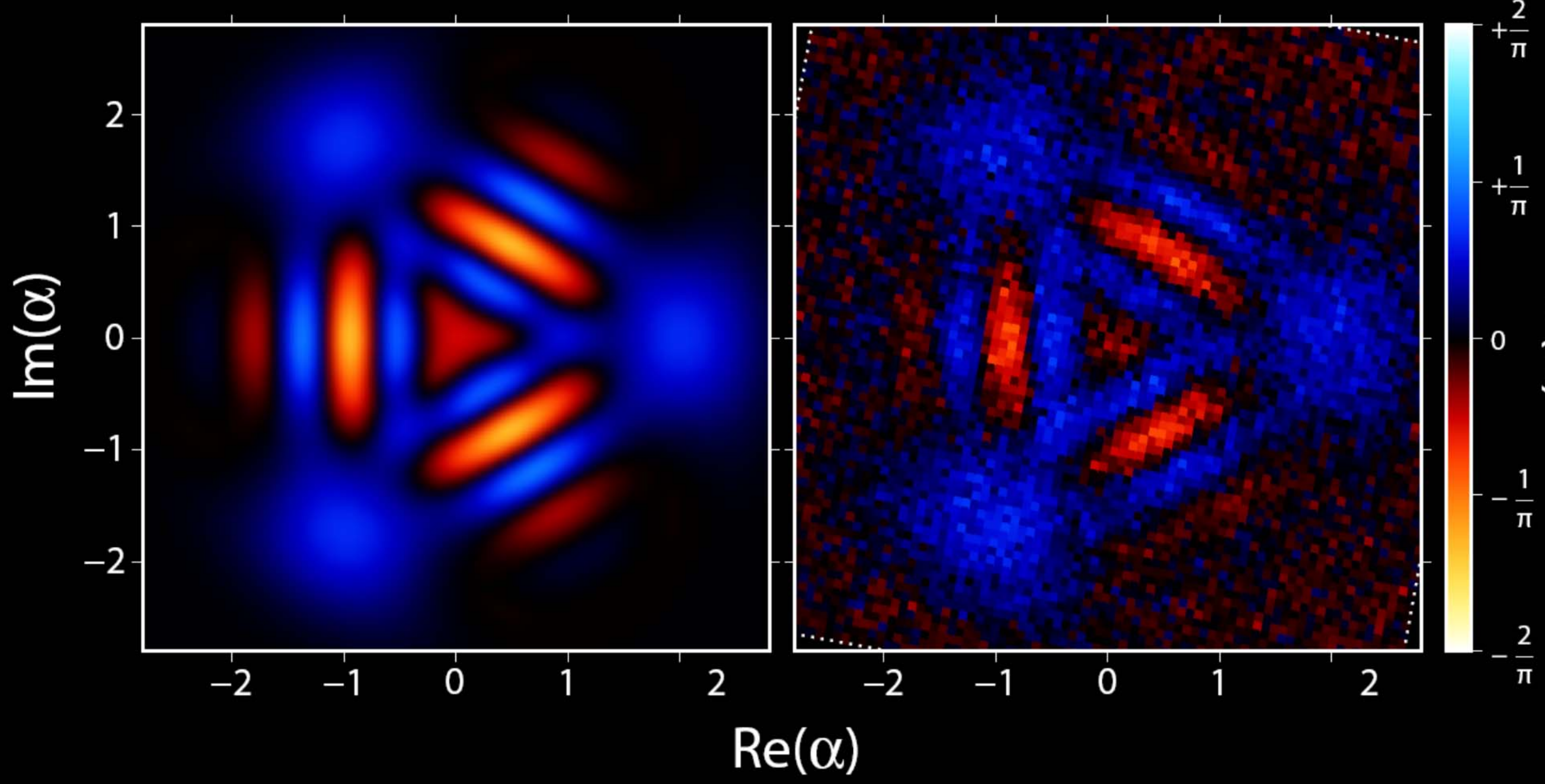


# the voodoo cat

M. Hofheinz et al.
Nature (2009)

alive dead zombie

$$|\psi\rangle = |\alpha = 2\rangle + |\alpha = 2e^{i2\pi/3}\rangle + |\alpha = 2e^{i4\pi/3}\rangle$$



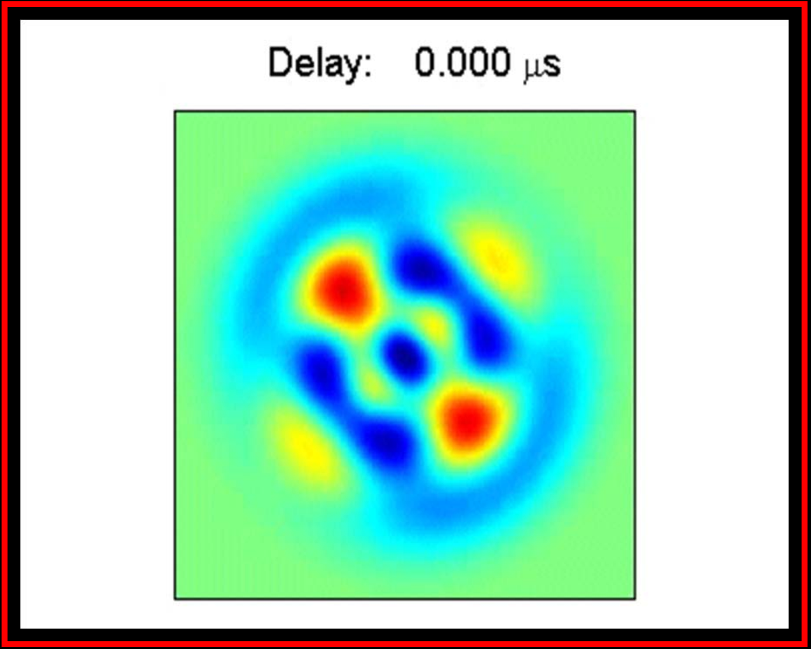
# the ex-voodoo cat

H. Wang et al.
PRL (2009)

## time evolution of a superposed state

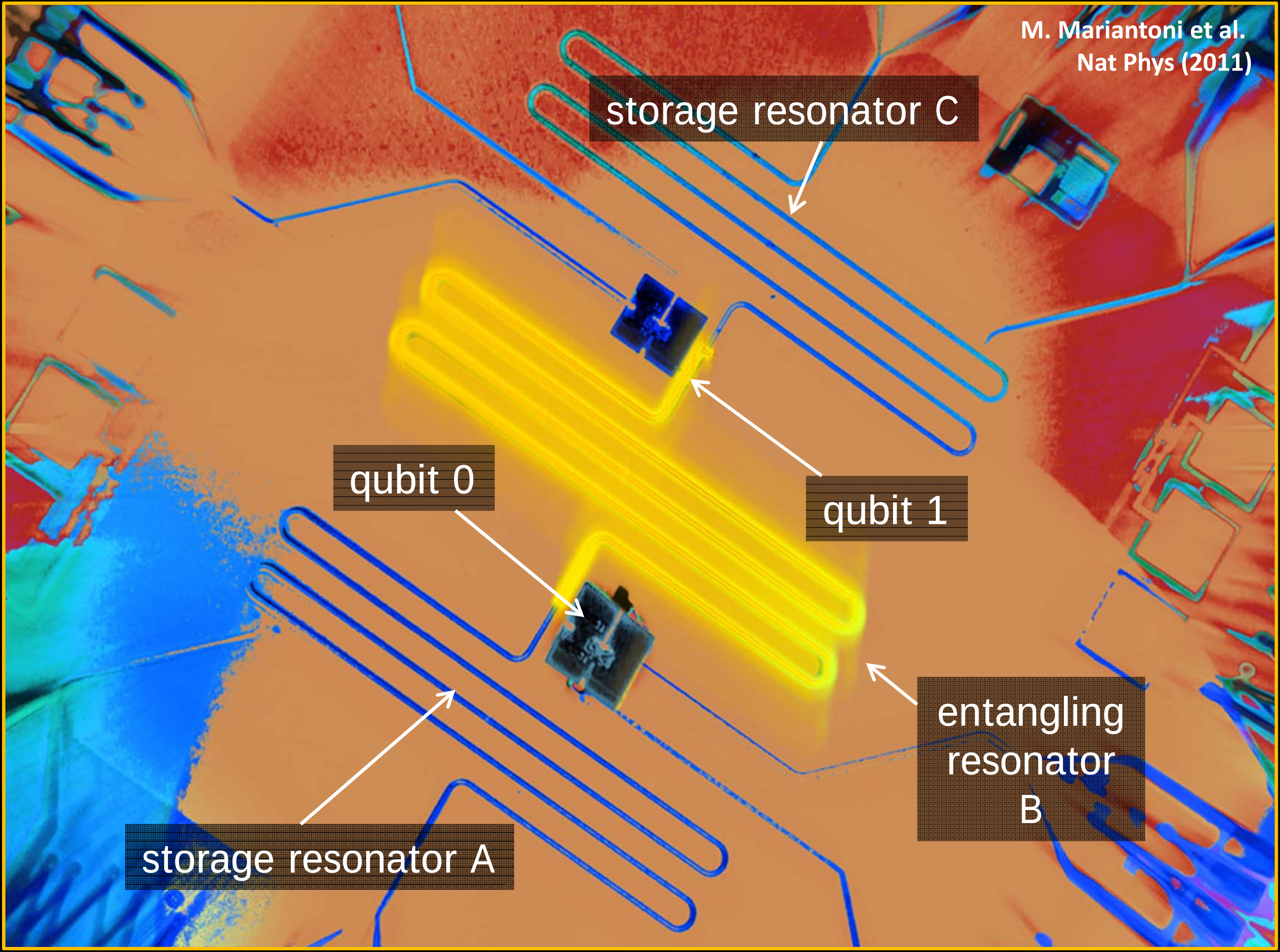
$$|\psi\rangle = |0\rangle + i\,|2\rangle + |4\rangle$$

watching
schrödinger's cat
die



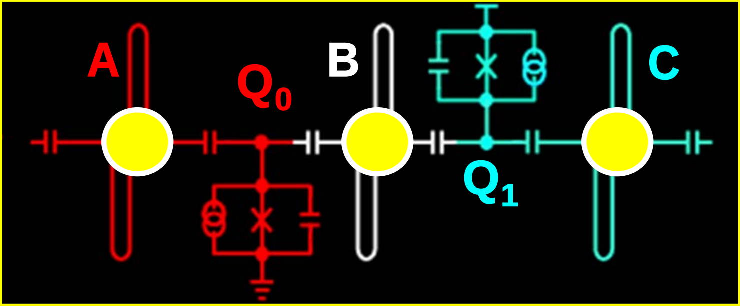
(note that no cats were actually harmed in this experiment, nor were any cats directly involved)

# entangling two resonators

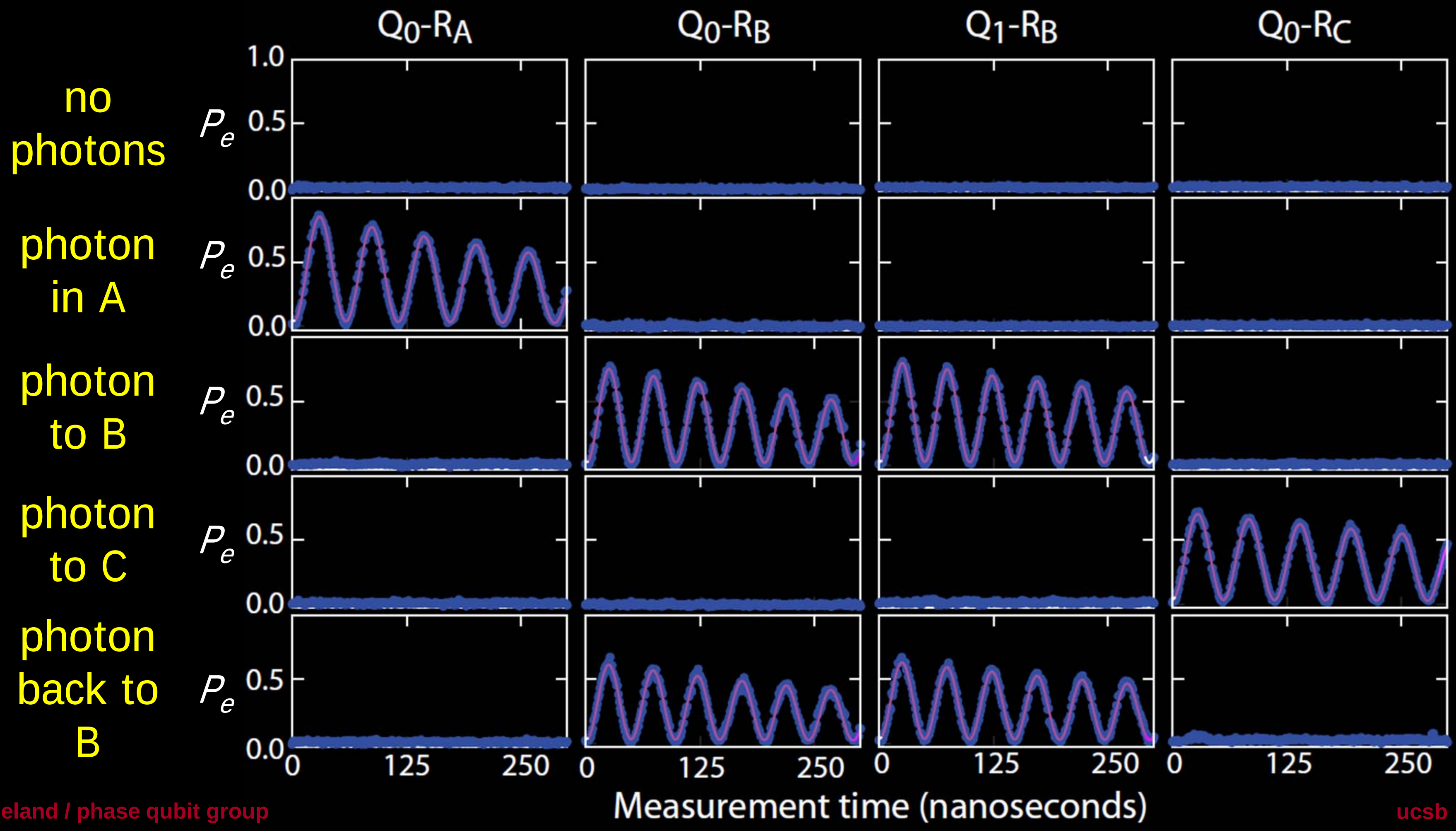


M. Mariantoni et al. Nat Phys (2011)

# entangling two resonators



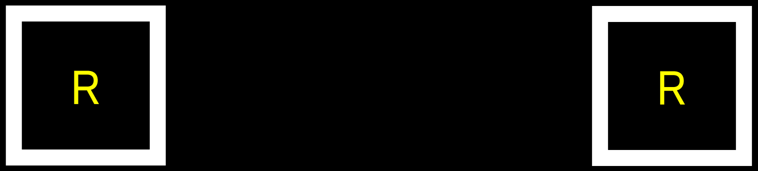
M. Mariantoni et al.
Nat Phys (2011)



# entangling two resonators

H. Wang et al.
PRL (2011)

## Storing delocalized photons in two resonators



resonator A — one photon — $|1\rangle_A$

resonator C — zero photons — $|0\rangle_C$

superposed with

zero photons — $|0\rangle_A$

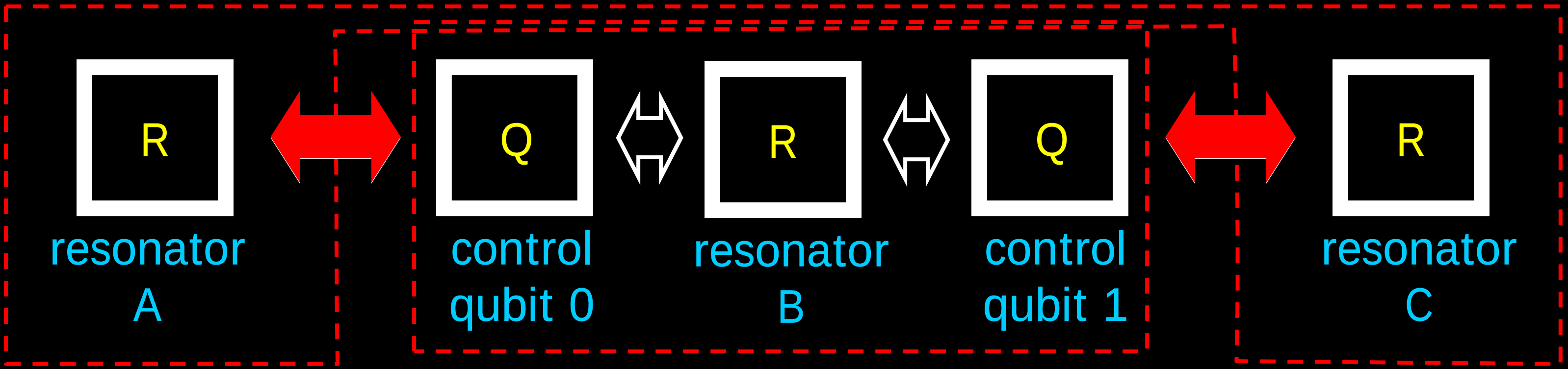
one photon — $|1\rangle_C$

$$\boxed{|\Psi\rangle = |1\rangle_A|0\rangle_C + |0\rangle_A|1\rangle_C}$$

# entangling two resonators

H. Wang et al.
PRL (2011)

## Storing delocalized photons in two resonators



R
resonator
A

Q
control
qubit 0

R
resonator
B

Q
control
qubit 1

R
resonator
C

Procedure:

1. Entangle qubits through resonator B: $|e\rangle_0|g\rangle_1 + |g\rangle_0|e\rangle_1$
2. Transfer state to resonators A & C: $|1\rangle_A|0\rangle_C + |0\rangle_A|1\rangle_C$
3. “Amplify” by boosting photon number to *N*

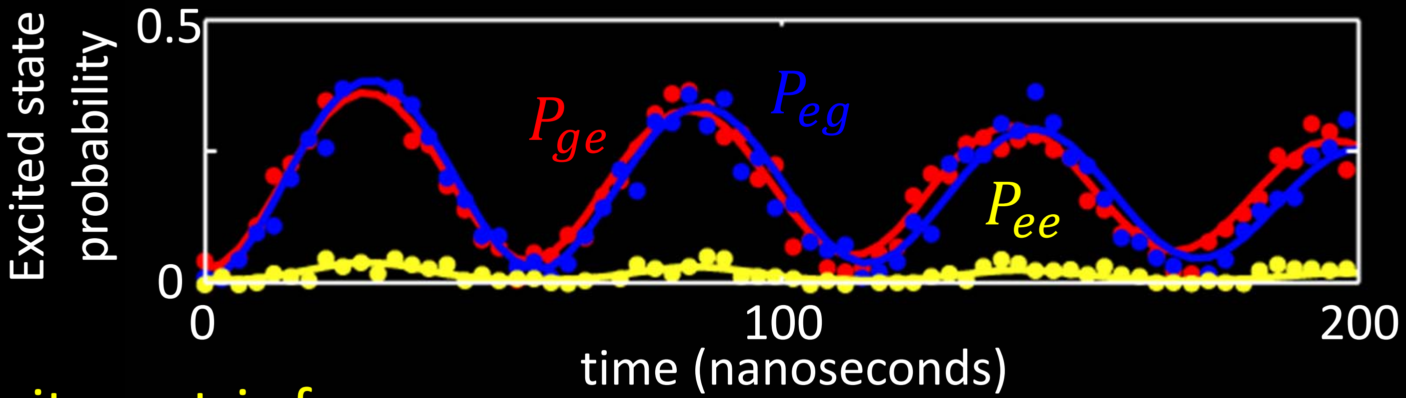
$$|\Psi\rangle \Longrightarrow |N\rangle_A|0\rangle_C + |0\rangle_A|N\rangle_C$$

# entangling two resonators

Coincidence measurement:

H. Wang et al.
PRL (2011)

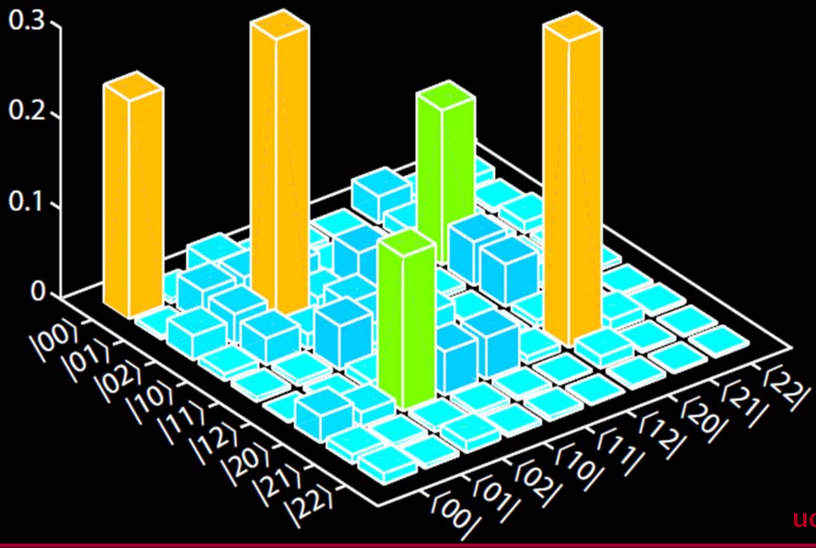
$$N=1:\ |1\rangle_A|0\rangle_C + |0\rangle_A|1\rangle_C \quad \Rightarrow |e\rangle_0|g\rangle_1 + |g\rangle_0|e\rangle_1$$



Density matrix from bipartite Wigner tomogram:

$$|2\rangle_A|0\rangle_C + |0\rangle_A|2\rangle_C$$

- strong off-diagonal terms
- good fidelity with target
- clear entanglement



# quantum oscillators

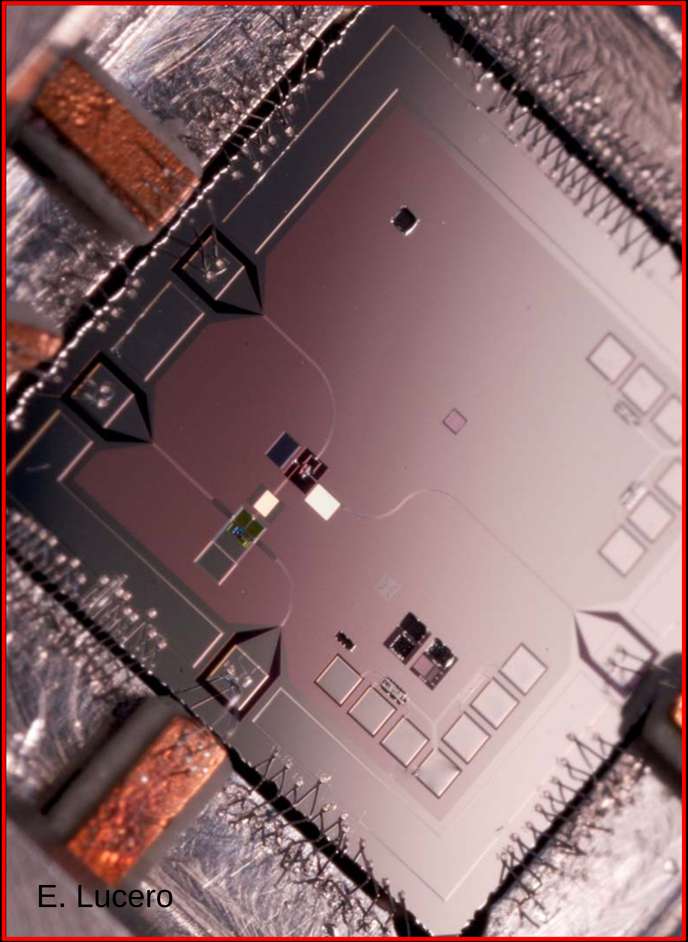
summary:

- generation & detection of photon Fock states
- synthesis of arbitrary synthesis
- movies of decoherence
- delocalized photons in two resonators

we are still very far from an
actual quantum computer

scientific american

# images of quantum light


E. Lucero

Andrew N Cleland
John M Martinis

Rami Barends
Jörg Bochmann
Yu Chen
(Max Hofheinz)
Matteo Mariantoni
(Haohua Wang)
Yi Yin

postdocs

Julian Kelly
Erik Lucero
Peter O’Malley
Daniel Sank
James Wenner
Ted White

Anthony Megrant
Charles Neill
Amit Vainsencher

graduate
students

support:
NSF
DARPA
IARPA