Title: Wiring up Quantum Systems: Fun with Artificial Atoms and Microwave Photons

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Abstract: A revolution is underway in the construction of â€˜artificial atomsâ€™ out
of superconducting electrical circuits.
These macroscopic â€˜atomsâ€™ have quantized energy levels and can emit and
absorb quanta of light (in this case microwave photons), just like ordinary
atoms. Unlike â€˜realâ€™ atoms, the
properties of these artificial atoms can be engineered to suit various
particular applications, and they can be connected together by wires to form
quantum â€˜computer chips.â€™ This so-called
â€˜circuit QEDâ€™ architecture has given us the ability to do non-linear quantum
optics in electrical circuits at the single photon level. It is now possible to entangle multiple
qubits, count individual microwave photons, create large â€˜SchrÃ¶dinger catâ€™
photon states and perform quantum feedback.
This talk will present an elementary introduction to the field.

Departments of Physics
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Circuit QED

EXPERIMENT

Rob Schoelkopf,
Michel Devoret
Luigi Frunzio

M. Hatridge
Shyam Shankar
G. Kirchmair
Brian Vlastakis
Matt Reed
Luyan Sun
Eric Holland
Matt Reagor
Andy Fragner
Joseph Schreier
Adam Sears

Alumni:
Hanhee Paik (BBN)
Andrew Houck (Princeton)
Andreas Wallraff (ETH Zurich)
Irfan Siddiqi (Berkeley)
Konrad Lehnert (JILA)
Johannes Majer (TU Vienna)
David Schuster (Chicago
V. Manucharyan (Harvard)
Chad Rigetti (IBM)
Jerry Chow (IBM)
Blake Johnson (BBN)

IARPA

THEORY

SMG, L. Glazman, Liang Jiang

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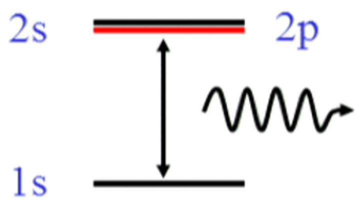
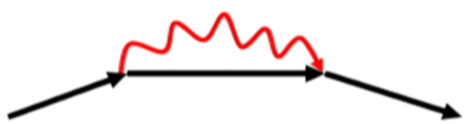
Alumni:
G. Catelani (Juelich)
Eran Ginossar (Surrey)
Andreas Nunnenkamp (Basel)
Jens Koch (Northwestern)
Lev Bishop (JQI)
Terri Yu
Dong Zhou (Weil Cornell)
Lars Tornberg (Göteborg)
Erkki Thuneberg (Oulu)
Alexandre Blais (Sherbrooke)
Jay Gambetta (IBM)
Florian Marquardt (Erlangen)
Aash Clerk (McGill)

QED: Atoms Coupled to Photons

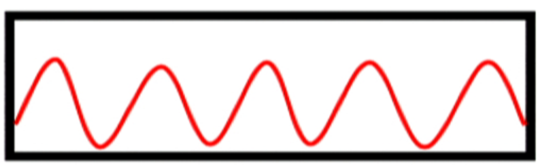


Irreversible spontaneous decay into the photon continuum:

$$2p \rightarrow 1s + \gamma \qquad T_1 \sim 1\text{ ns}$$



Vacuum Fluctuations:
(Virtual photon emission and reabsorption)
Lamb shift lifts 1s 2p degeneracy



Cavity QED: What happens if we trap the photons as discrete modes inside a cavity?

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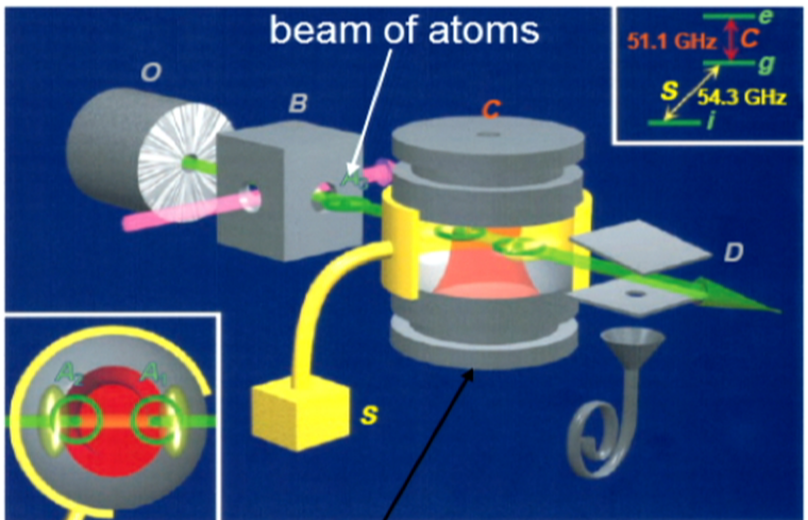
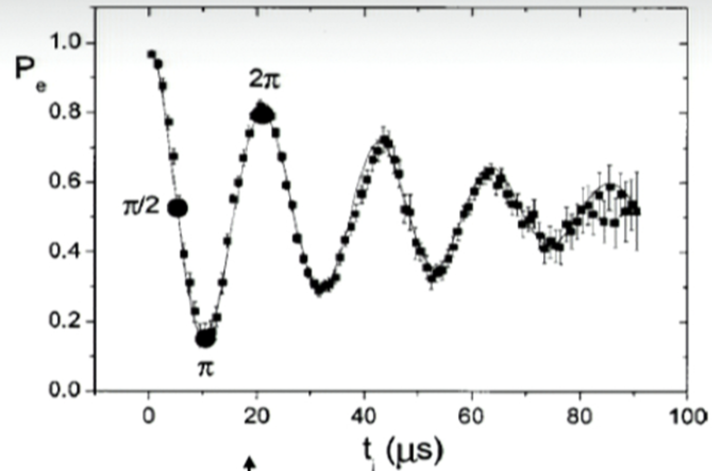
μwave cQED with Rydberg Atoms



3-d superconducting cavity
(50 GHz)

vacuum Rabi oscillations

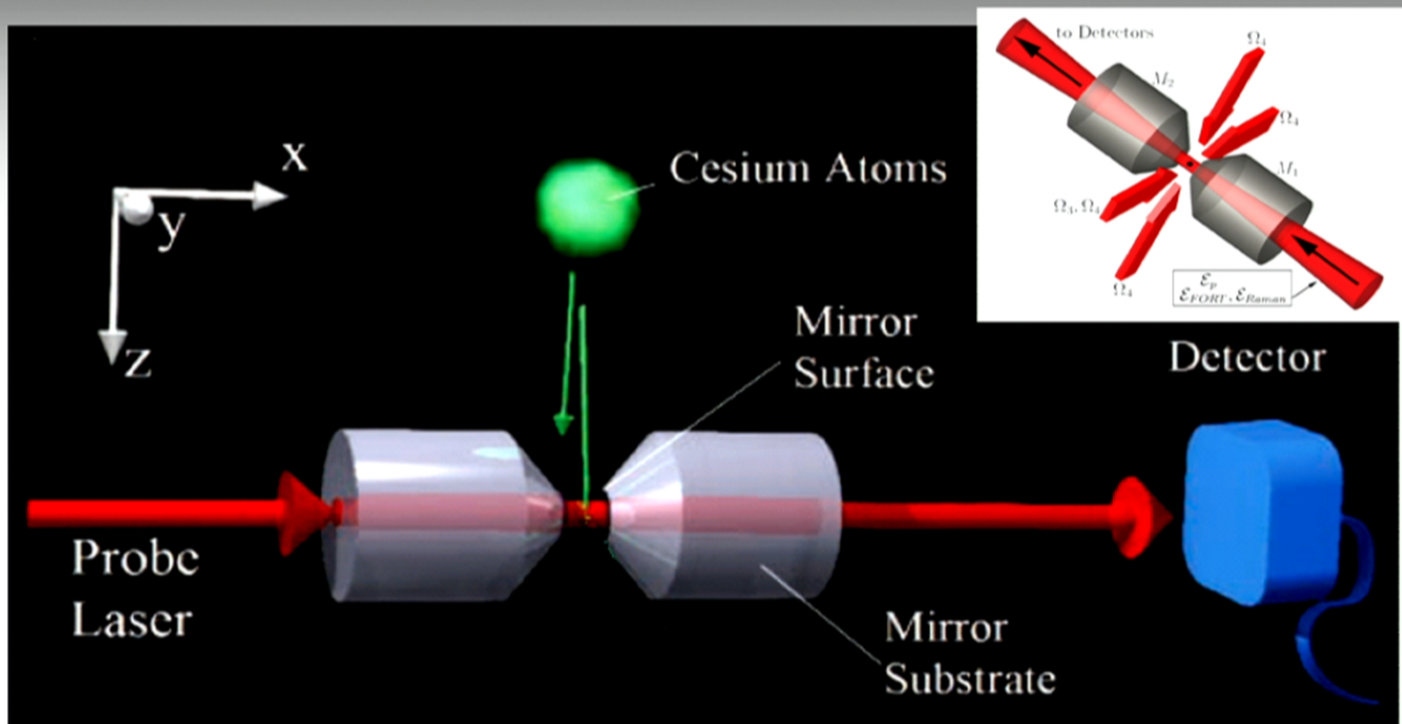


observe dependence of atom final state on time spent in cavity

measure atomic state, or …

Review: S. Haroche et al., Rev. Mod. Phys. **73** 565 (2001)

cQED at optical frequencies



state of photons is detected,
not atoms.

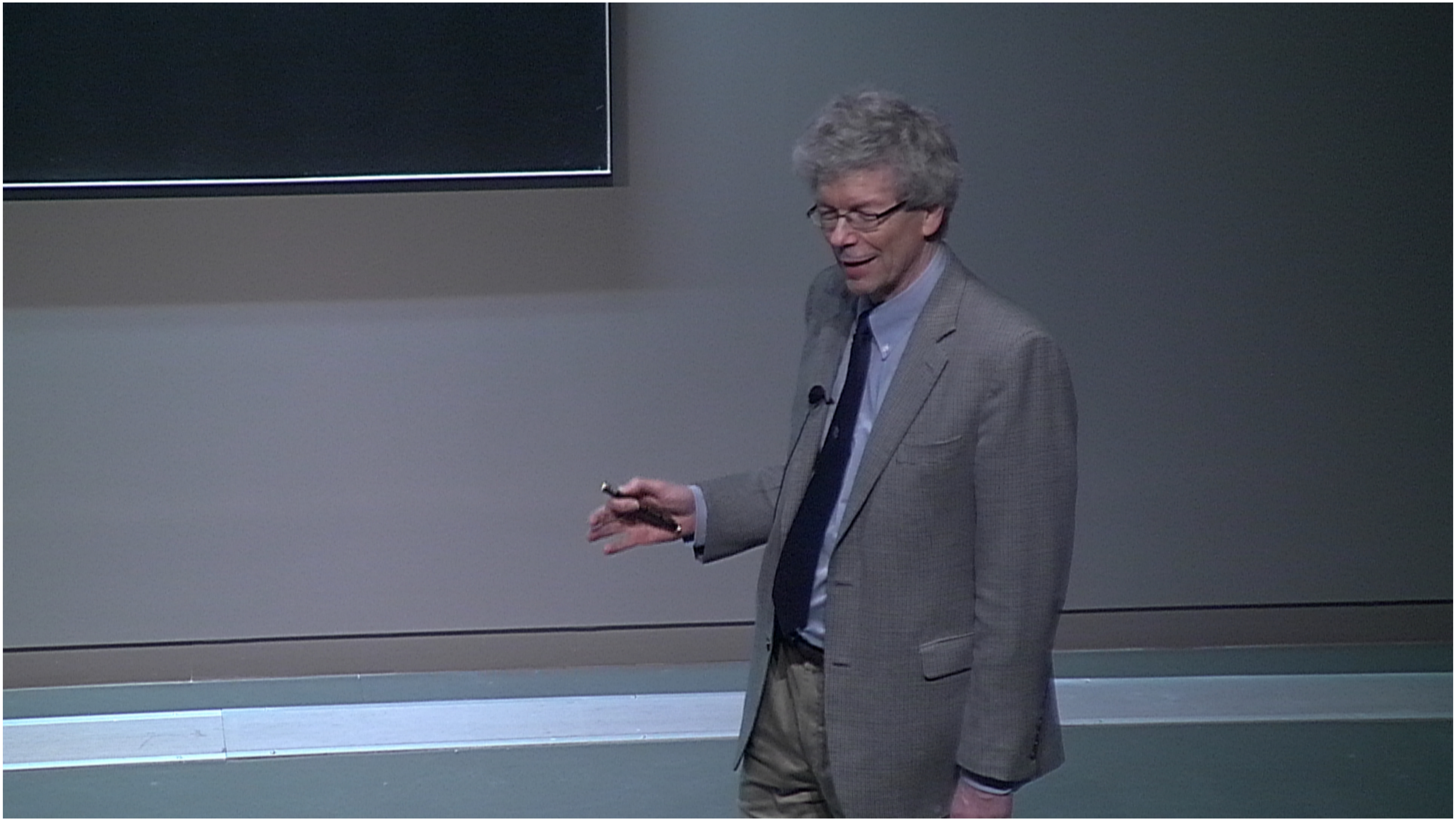
… measure changes in transmission of optical cavity

(Caltech group H. J. Kimble, H. Mabuchi)

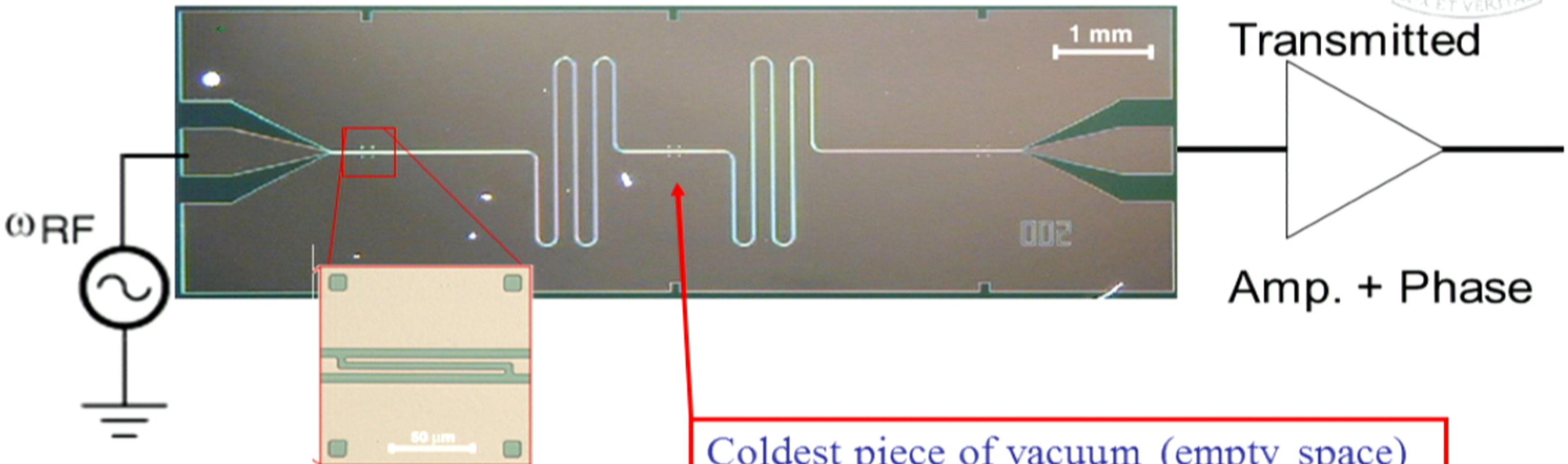
Quantum Electrodynamics (QED):
electrons/atoms coupled to photons

Circuit QED:
-microwave photons inside superconducting circuits
-artificial atoms (Josephson junction qubits)

Ultra-strong photon-‘atom’ coupling:
-non-linear quantum optics at the single photon level



Microwaves – Photons on a wire



Coldest piece of vacuum (empty space) in the universe?: T = 0.15 Kelvin

Microwaves are photons too!
…but they're very weak….

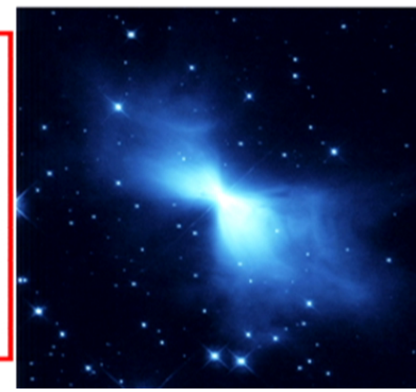
$$h \times 5\ \text{GHz} \approx 0.25\ \text{K}$$

$$P_{probe} = 10^{-17}\ \text{W} = \langle n \rangle \hbar \omega_r \kappa / 2$$

$$\Rightarrow \langle n \rangle \leq 1$$

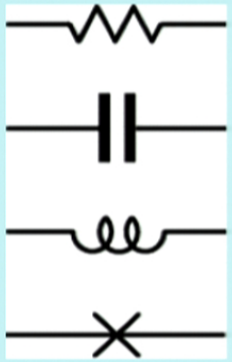
Boomerang Nebula
2nd coldest place in the universe
T = 1 Kelvin

CMB = 2.75 Kelvin



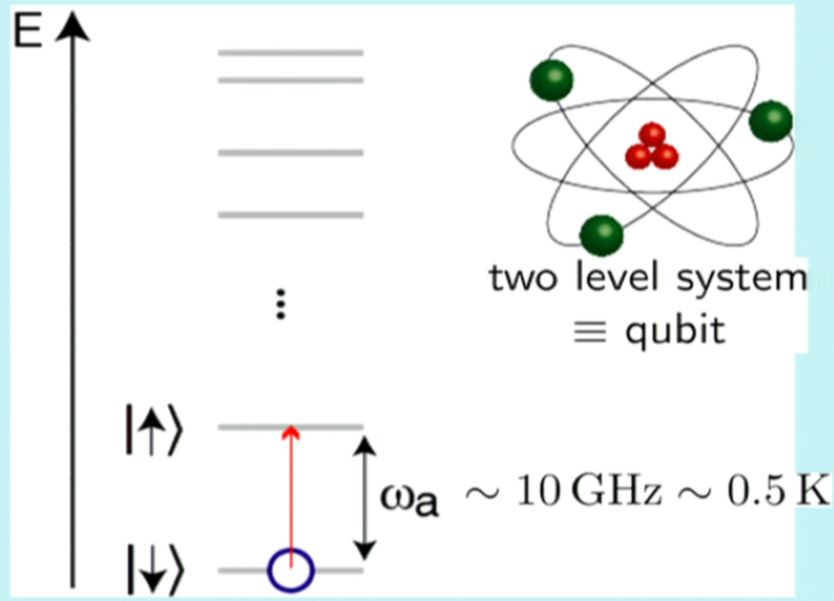
Building Quantum Electrical Circuits

circuit elements:



The Josephson Junction is the <u>only</u> known non-linear non-dissipative circuit element.

macroscopic artificial atom:



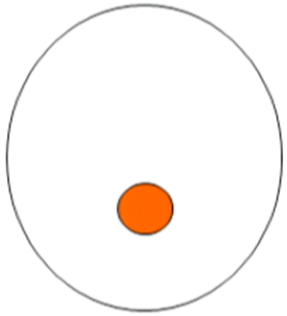
ingredients:

- nonlinearity
- low temperatures
- small dissipation
- isolation from environment

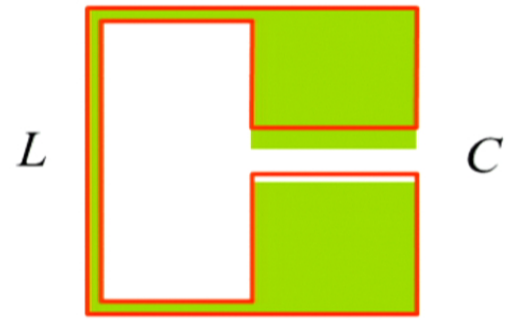
Review: M. H. Devoret, A. Wallraff and J. M. Martinis, *condmat/0411172* (2004)

ATOM vs CIRCUIT

Hydrogen atom

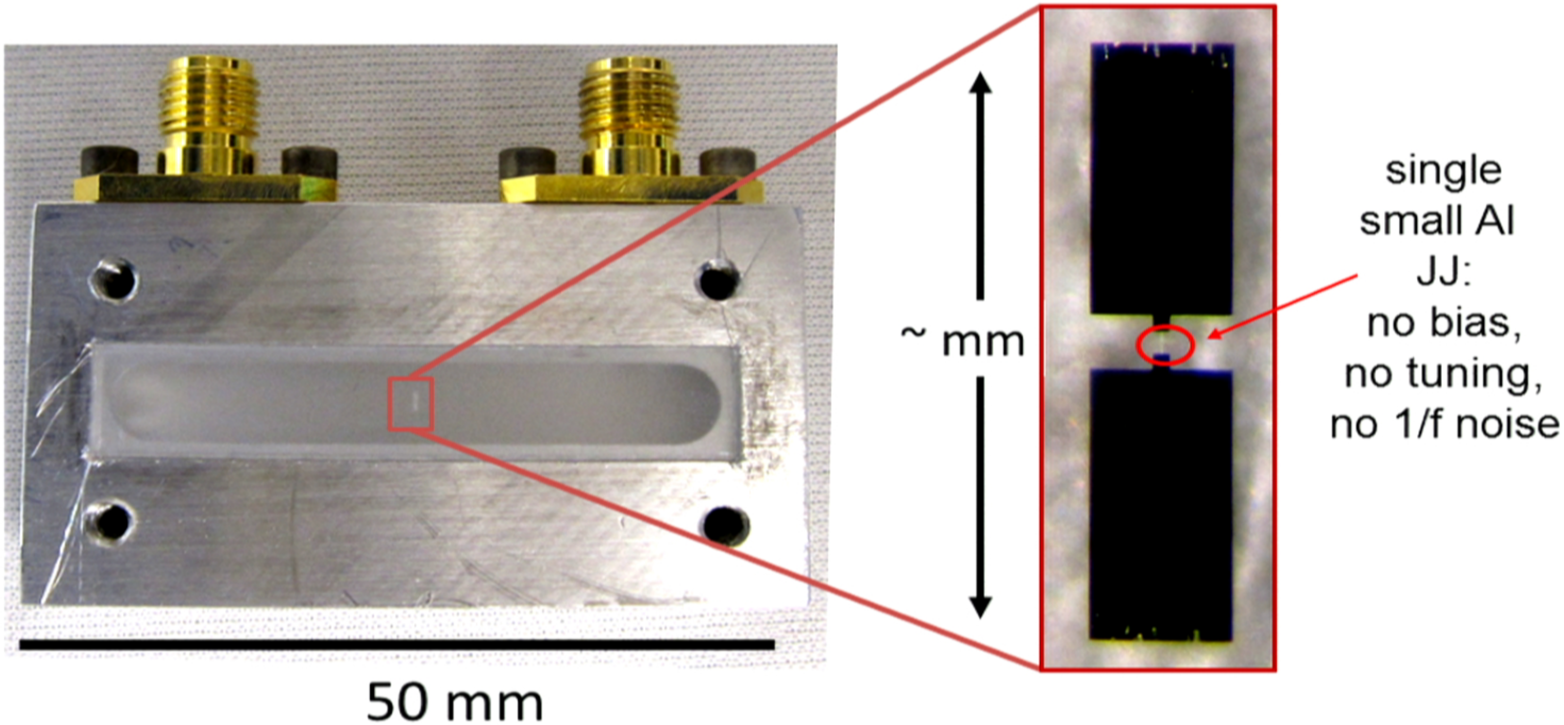


Superconducting
LC oscillator



(Not to scale!)

Transmon Qubit in 3D Cavity



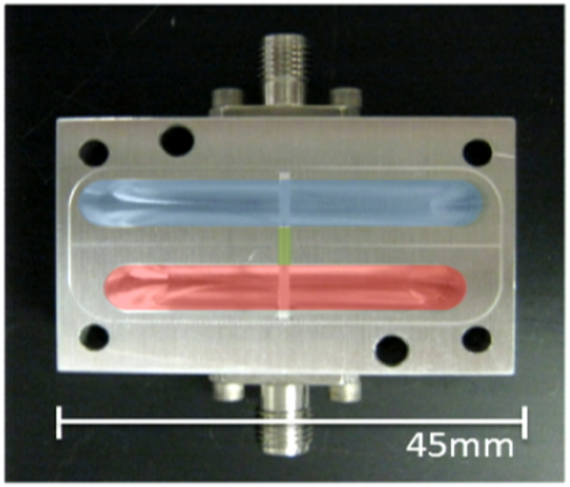
$$\left|\vec{d}\right| = 2e \times 1 \text{ mm} \approx 10^7 \text{Debye!!}$$

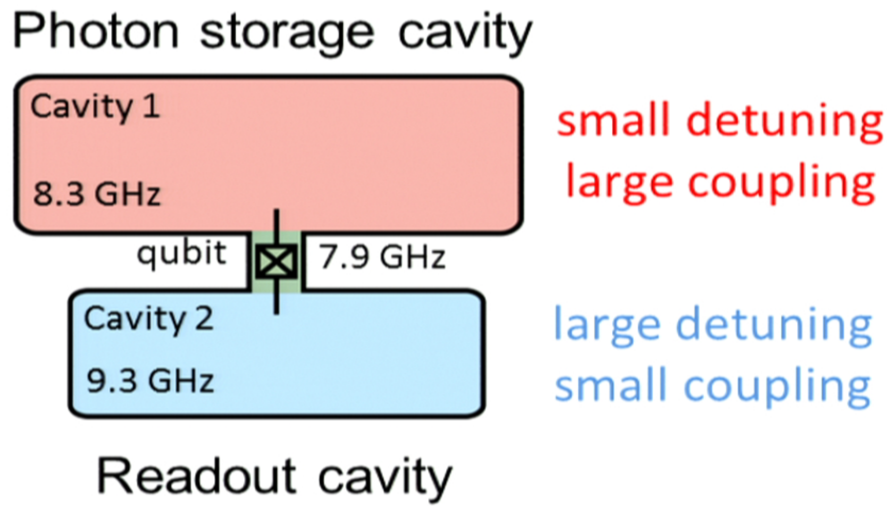
$$g = \frac{\vec{d} \bullet \vec{E}_{rms}}{h}$$

Huge dipole moment: strong coupling

$g \sim 100$ MHz

One qubit two-cavity system





High Q cavity to store photons

Low Q cavity to readout state of qubit after

Dispersive 'cross-Kerr' Hamiltonian

$$H = \chi_{12}\hat{n}_1\hat{n}_2$$

Kirchmair et al. (Schoelkfopf Lab)

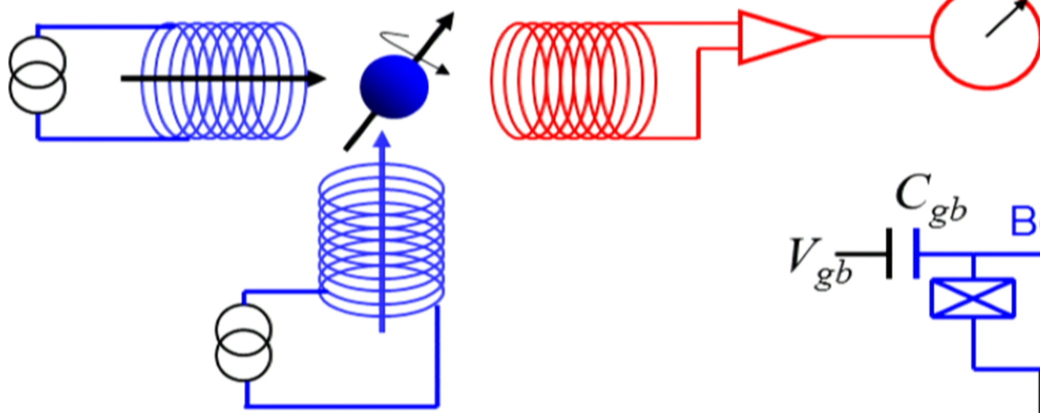
Quantum Control and NMR of a Single 'Spin'

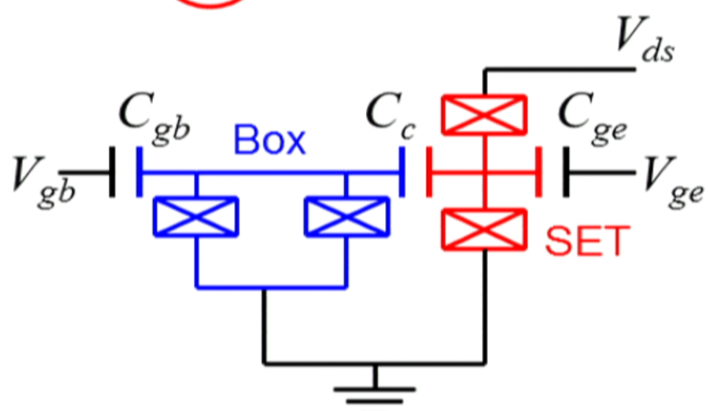
Electrical circuit with two quantized energy levels is like a spin -1/2.

$$|\rightarrow\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle + |\downarrow\rangle\right)$$

Quantum Measurement

Single Spin ½





(After Konrad Lehnert)

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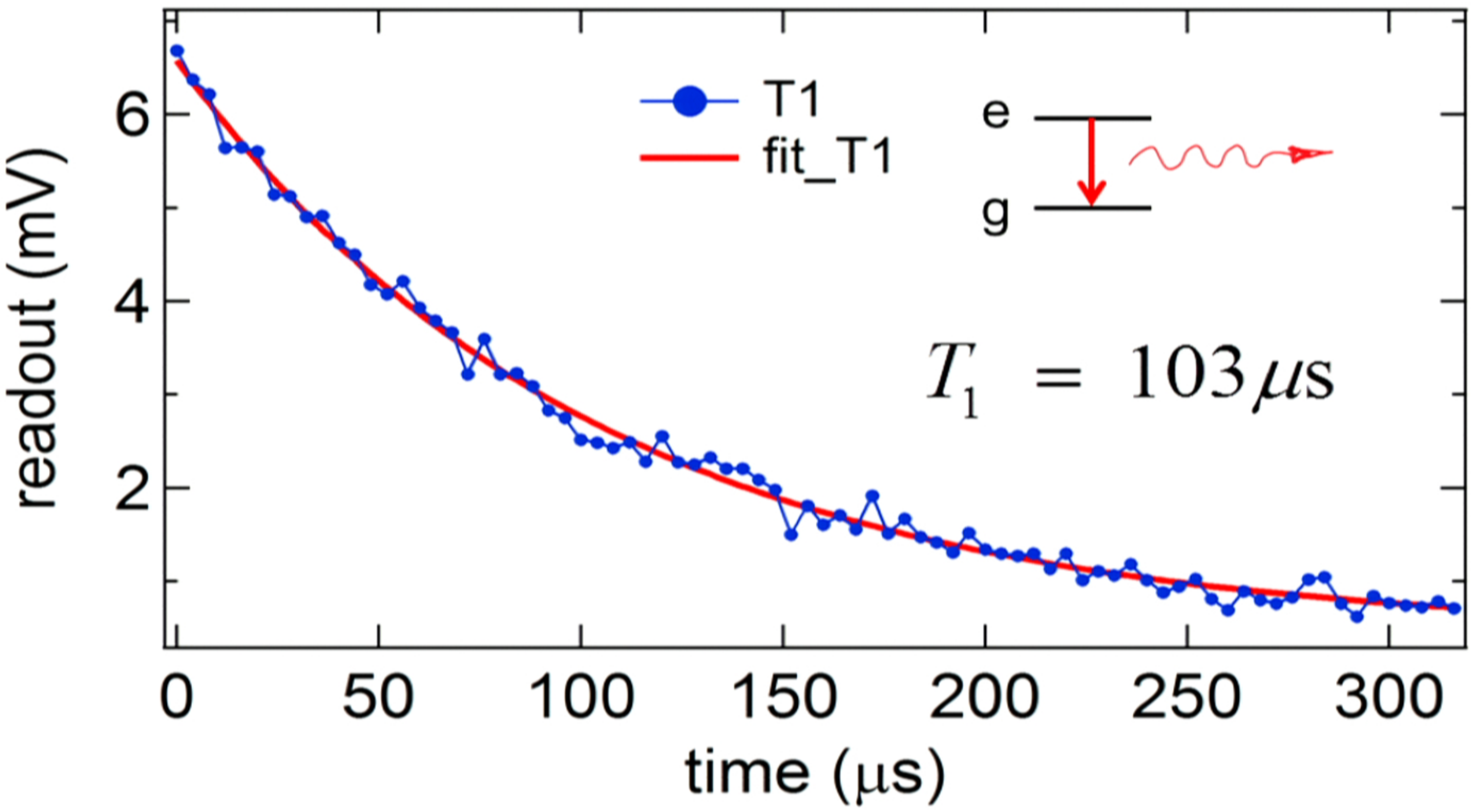
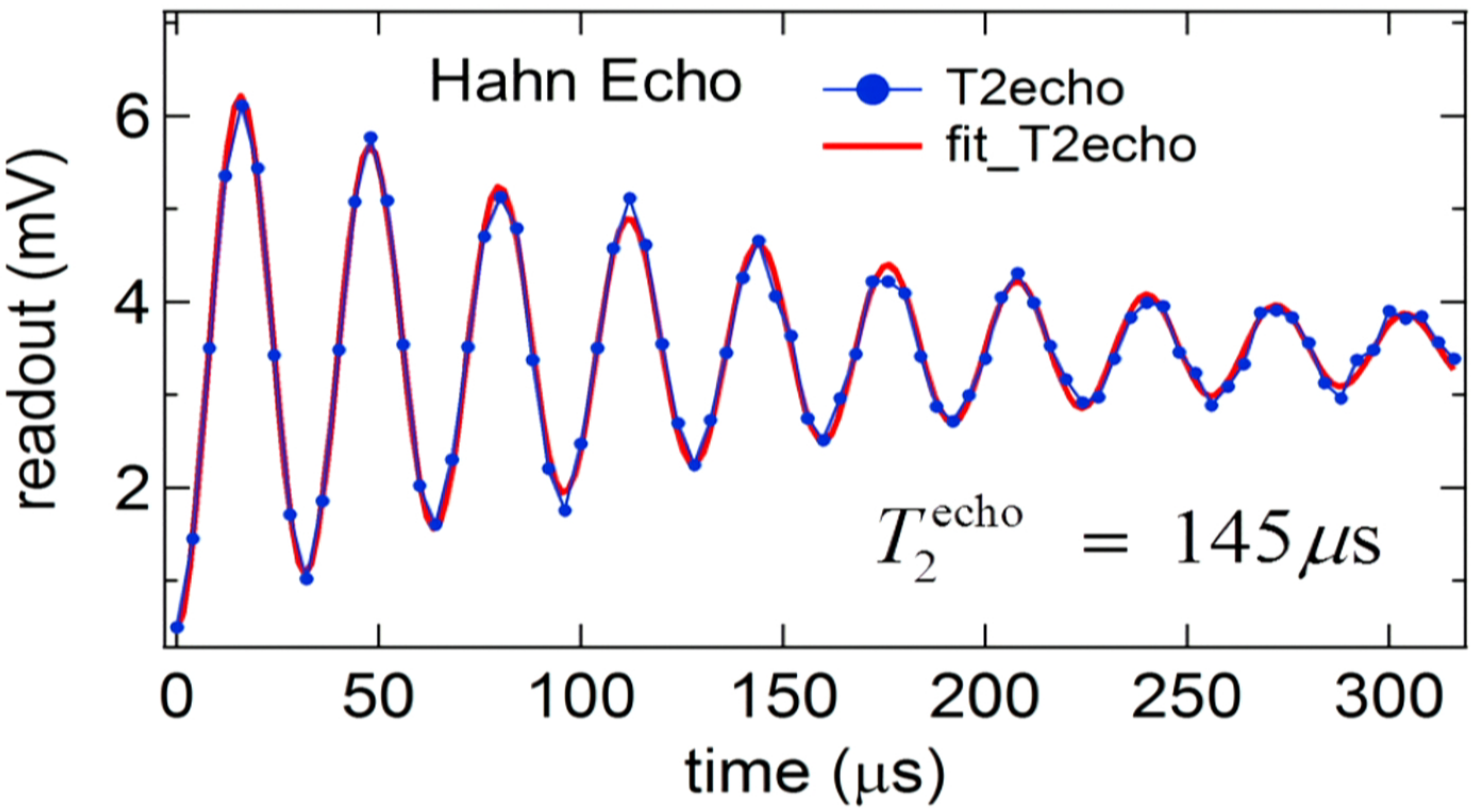
Relaxation Time (excited state lifetime)



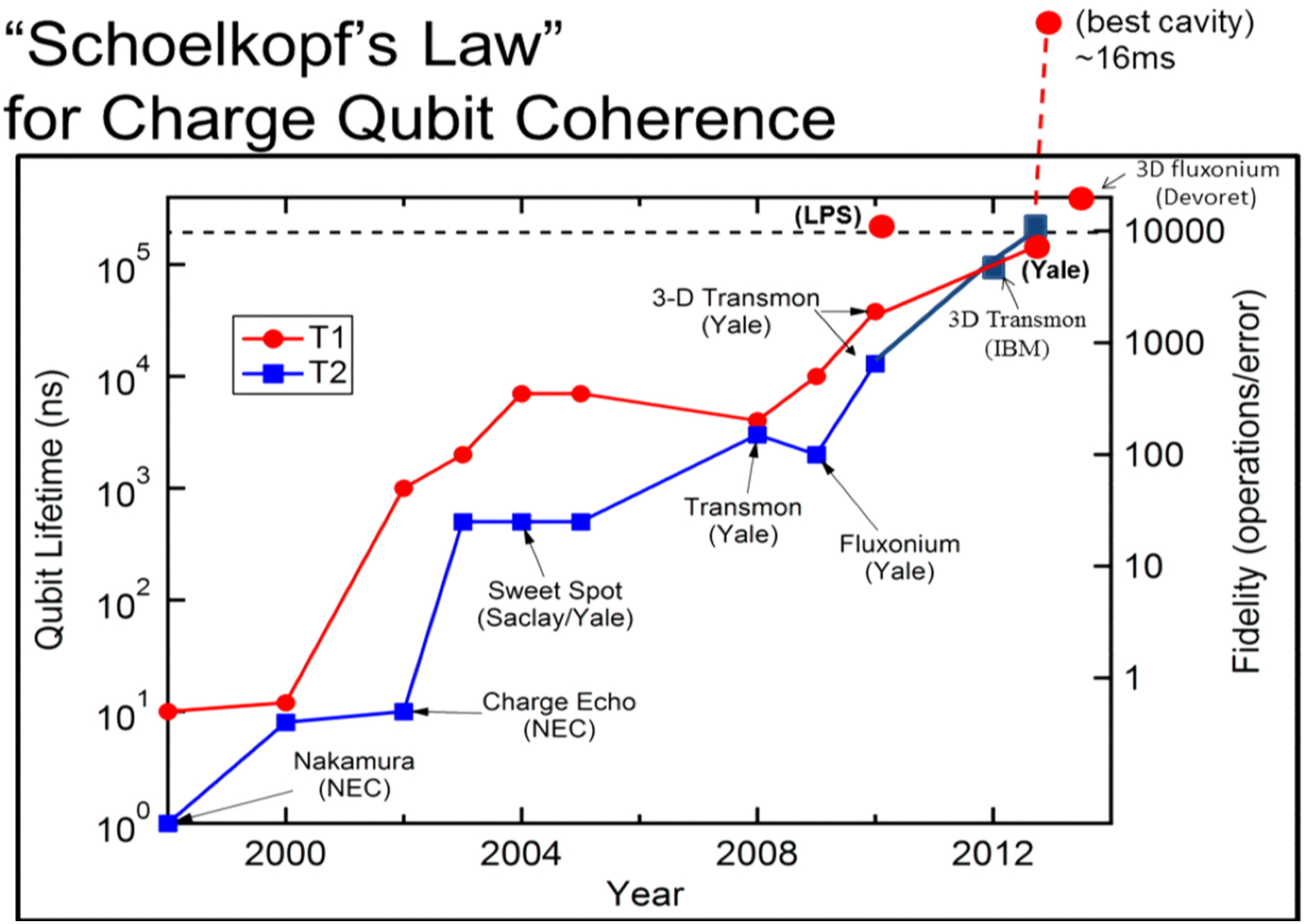
Protocol: Pi pulse, wait, measure Z

Current world record for phase coherence time:
(lifetime of quantum superposition state)



Protocol: Pi/2 pulse, wait, Pi pulse, wait, Pi/2 pulse, measure Z

“Schoelkopf’s Law” for Charge Qubit Coherence



Quantum optics at the single photon level

- Photon state engineering

- Photon cat states on demand
  -largest ‘macroscopic’ superposition ever created?

Quantum optics at the single photon level

- Photon state engineering

Goal: arbitrary photon Fock state superpositions

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle + \dots$$

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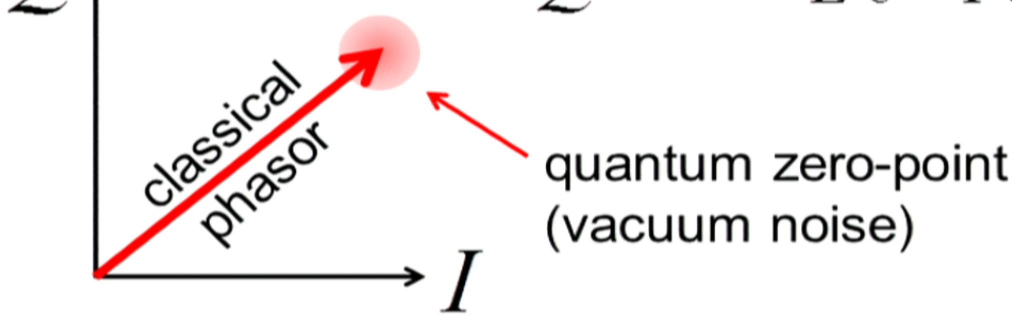
‘Coherent states’ of are essentially classical and <u>easy</u> to make with a signal generator by applying a microwave pulse to cavity

$$\left|\alpha\right\rangle = e^{-\frac{|\alpha|^2}{2}} e^{\alpha a^\dagger} \left|0\right\rangle$$

$$= e^{-\frac{|\alpha|^2}{2}} \left(\left|0\right\rangle + \frac{\alpha}{\sqrt{1!}}\left|1\right\rangle + \frac{\alpha^2}{\sqrt{2!}}\left|2\right\rangle + \frac{\alpha^3}{\sqrt{3!}}\left|3\right\rangle + \ldots \right)$$

$$\alpha = I + iQ$$



Electric field:

$$\vec{E}\cdot\hat{\epsilon} = I\cos(\omega t) + Q\sin(\omega t)$$

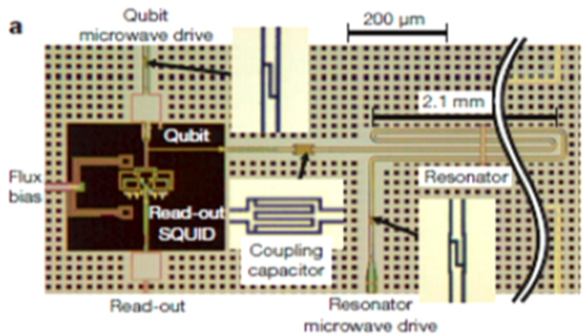
Arbitrary non-classical states
(photon Fock state superpositions):

$$|\psi\rangle = a_0|0\rangle + a_1|1\rangle + a_2|2\rangle + a_3|3\rangle + \ldots$$

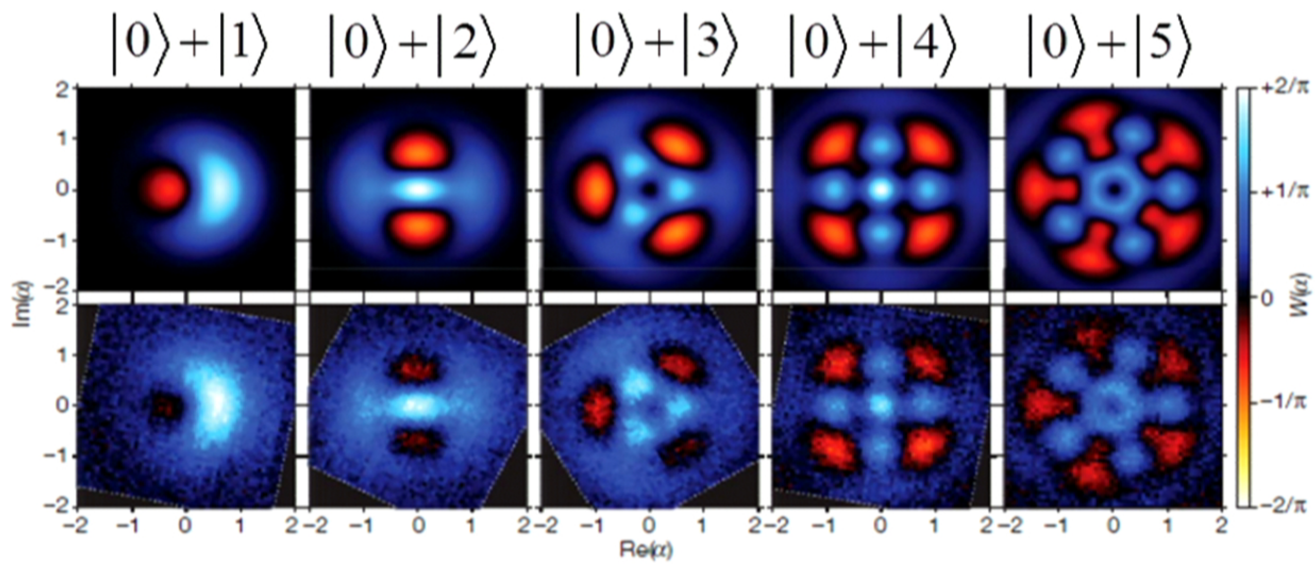
are much more difficult to make and require
coupling the cavity to a non-linear element (e.g. a qubit)

Paris group has used Rydberg atoms passing through a cavity

Quantum Superpositions of Photon Fock States



Phase qubit plus cavity: synthesize and analyze complex photon states (UCSB Cleland/Martinis groups)



Hofheinz et al., Nature 454 (2008) and Nature 459 (2009)

Quantum optics at the single photon level

- Quantum engineer's toolbox to make arbitrary states:

Dispersive Hamiltonian: qubit detuned from cavity
-qubit can only virtually absorb/emit photons

$$\boxed{H = \omega_{\mathrm{r}} a^{\dagger} a + \frac{\omega_{\mathrm{q}}}{2} \sigma^{z} + \chi \sigma^{z} a^{\dagger} a + H_{\mathrm{damping}}} \qquad \boxed{\omega_{\mathrm{r}} \neq \omega_{\mathrm{q}}}$$

resonator qubit dispersive coupling

Dispersive Hamiltonian

$$H = \omega_{\mathrm{r}} a^{\dagger} a + \frac{\omega_{\mathrm{q}}}{2}\sigma^{z} + \chi\sigma^{z} a^{\dagger} a + H_{\mathrm{damping}}$$

resonator   qubit   dispersive coupling

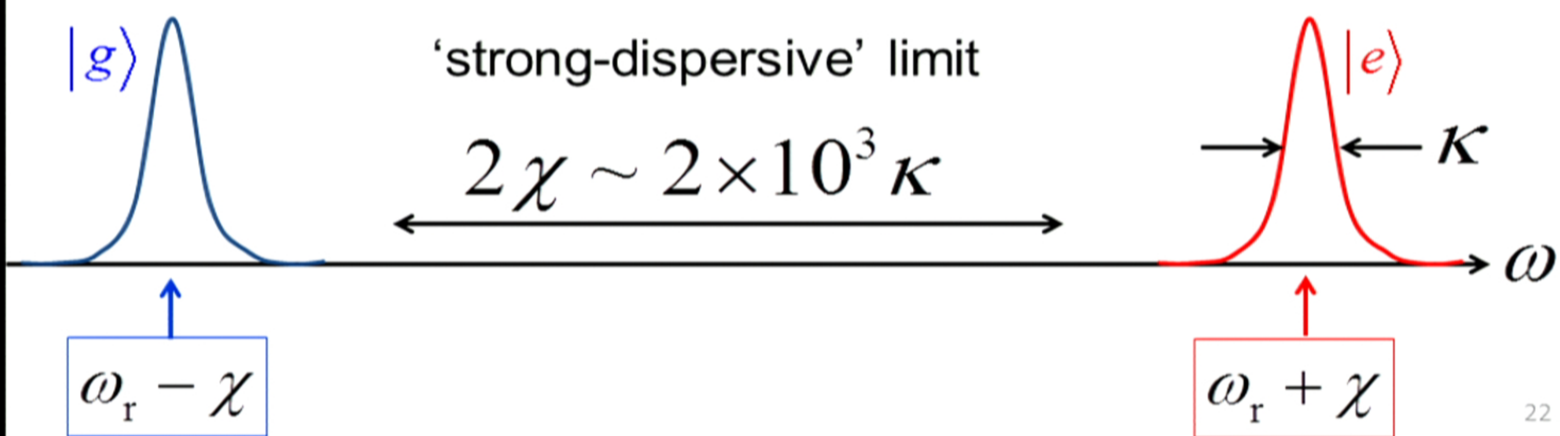
$$\text{cavity frequency} = \omega_{\mathrm{r}} + \chi\sigma^{z}$$

Dispersive Hamiltonian

$$H = \omega_{\mathrm{r}} a^{\dagger} a + \frac{\omega_{\mathrm{q}}}{2}\sigma^{z} + \chi\sigma^{z} a^{\dagger} a + H_{\mathrm{damping}}$$

resonator qubit dispersive coupling

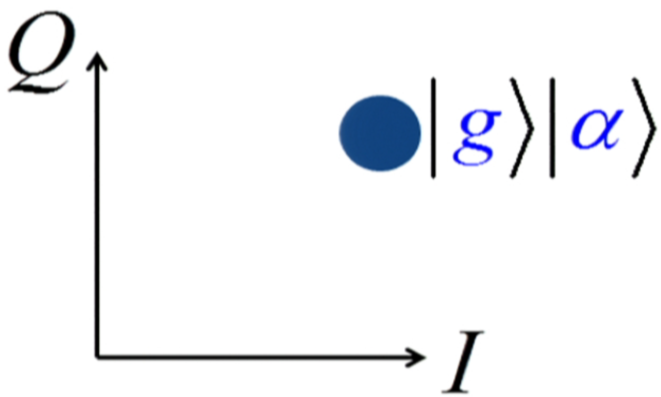
$$\text{cavity frequency} = \omega_{\mathrm{r}} + \chi\sigma^{z}$$



$\boxed{D_\alpha^g}$ Conditional displacement of cavity

If qubit starts in ground state: $|\psi\rangle = |g\rangle|0\rangle$

$$D_\alpha^g \, |\psi\rangle = |g\rangle|\alpha\rangle$$

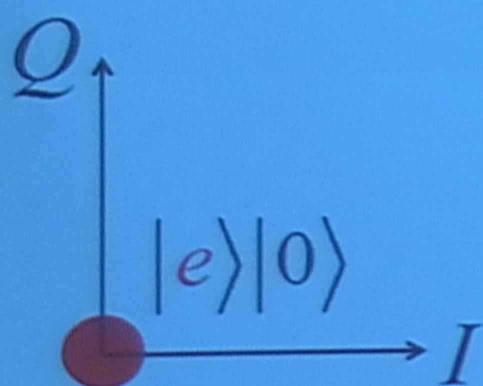


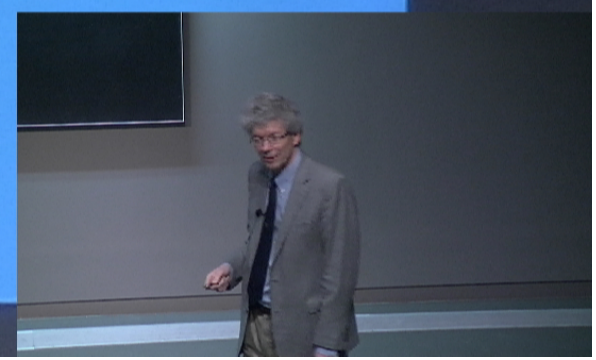
$$\boxed{D_\alpha^g}$$

Conditional displacement of cavity

If qubit starts in excited state: $|\psi\rangle = |e\rangle|0\rangle$

$$D_\alpha^g \; |\psi\rangle = |e\rangle|0\rangle$$





$$\boxed{D_\alpha^g}$$

Conditional displacement of cavity

What happens if qubit is in a superpostion state?

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)|0\rangle$$

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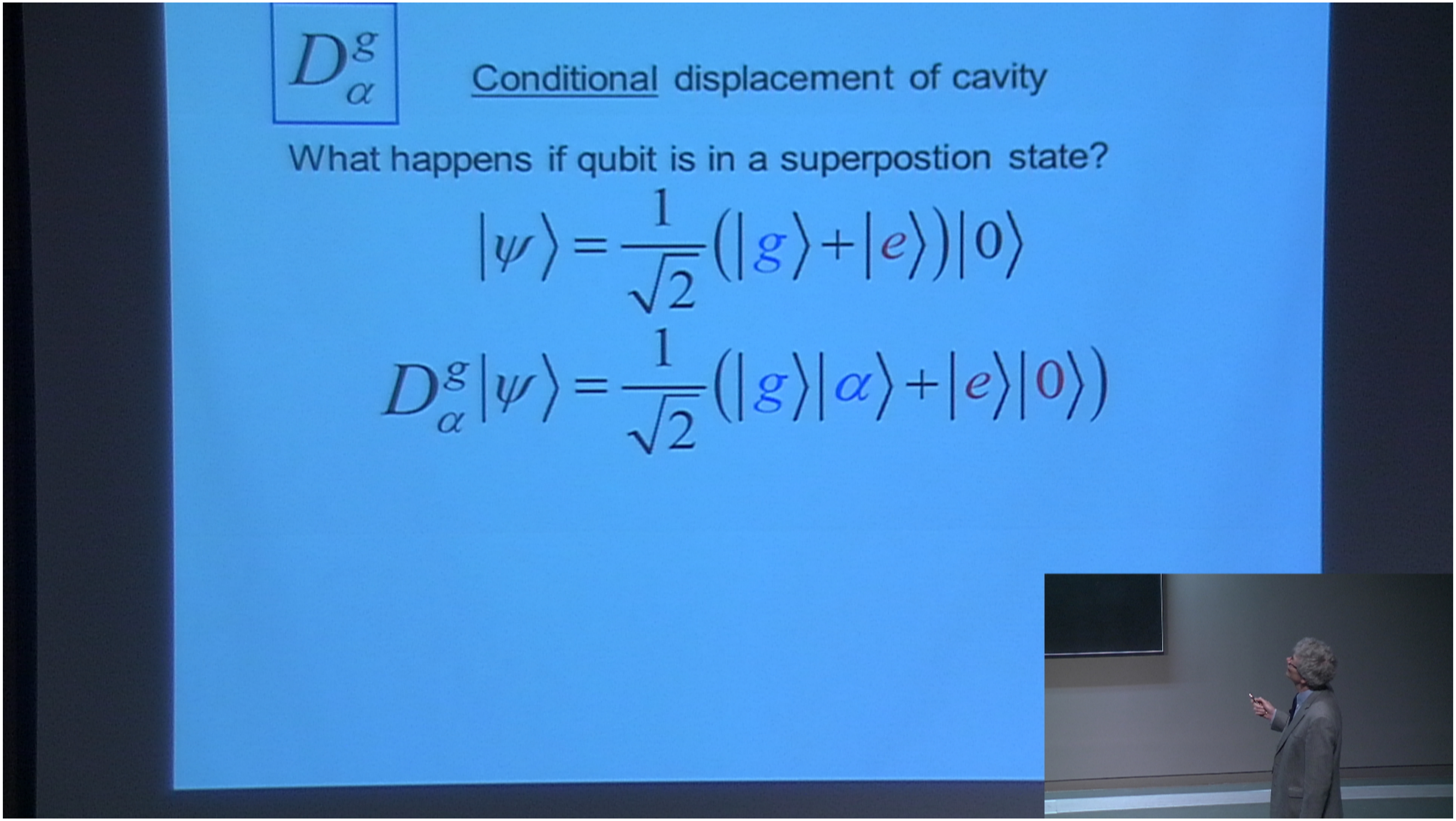
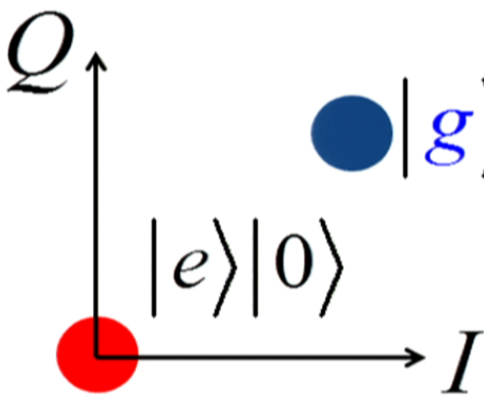

D_α^g
Conditional displacement of cavity
What happens if qubit is in a superpostion state?
$|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle + |e\rangle)|0\rangle$
$D_\alpha^g|\psi\rangle = \frac{1}{\sqrt{2}}(|g\rangle|\alpha\rangle + |e\rangle|0\rangle)$

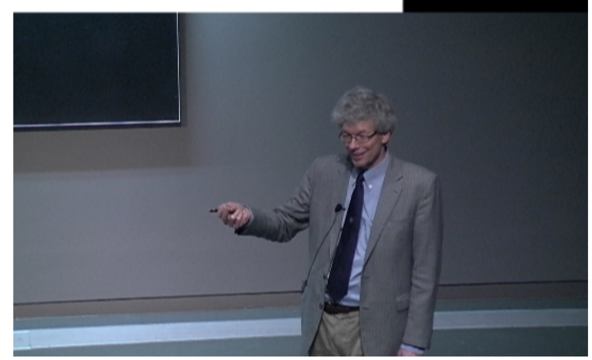
$\boxed{D_\alpha^g}$ Conditional displacement of cavity

What happens if qubit is in a superpostion state?

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)|0\rangle$$

$$D_\alpha^g|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle|\alpha\rangle + |e\rangle|0\rangle\right)$$



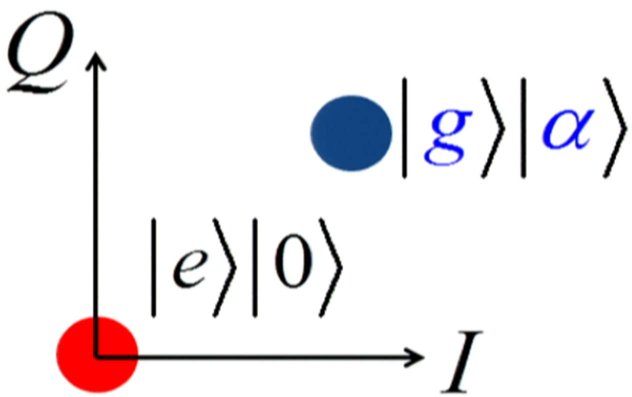


$\boxed{D_\alpha^g}$ <u>Conditional</u> displacement of cavity

What happens if qubit is in a superpostion state?

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)|0\rangle$$

$$D_\alpha^g|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle|\alpha\rangle + |e\rangle|0\rangle\right)$$



Qubit fully <u>entangled</u> with cavity

‘cat is dead; poison bottle open’

‘cat is alive; poison bottle closed’

$$\boxed{\pi_n}$$

Engineer's tool #2:

Conditional flip of qubit if exactly n photons

$$\boxed{H = \omega_r a^\dagger a + \frac{\omega_q}{2}\sigma^z + \chi\sigma^z a^\dagger a + H_{\text{damping}}}$$

resonator qubit dispersive coupling

Reinterpret dispersive term:

- quantized light shift of qubit frequency

$$\boxed{\frac{\omega_q + 2\chi a^\dagger a}{2}\sigma^z}$$

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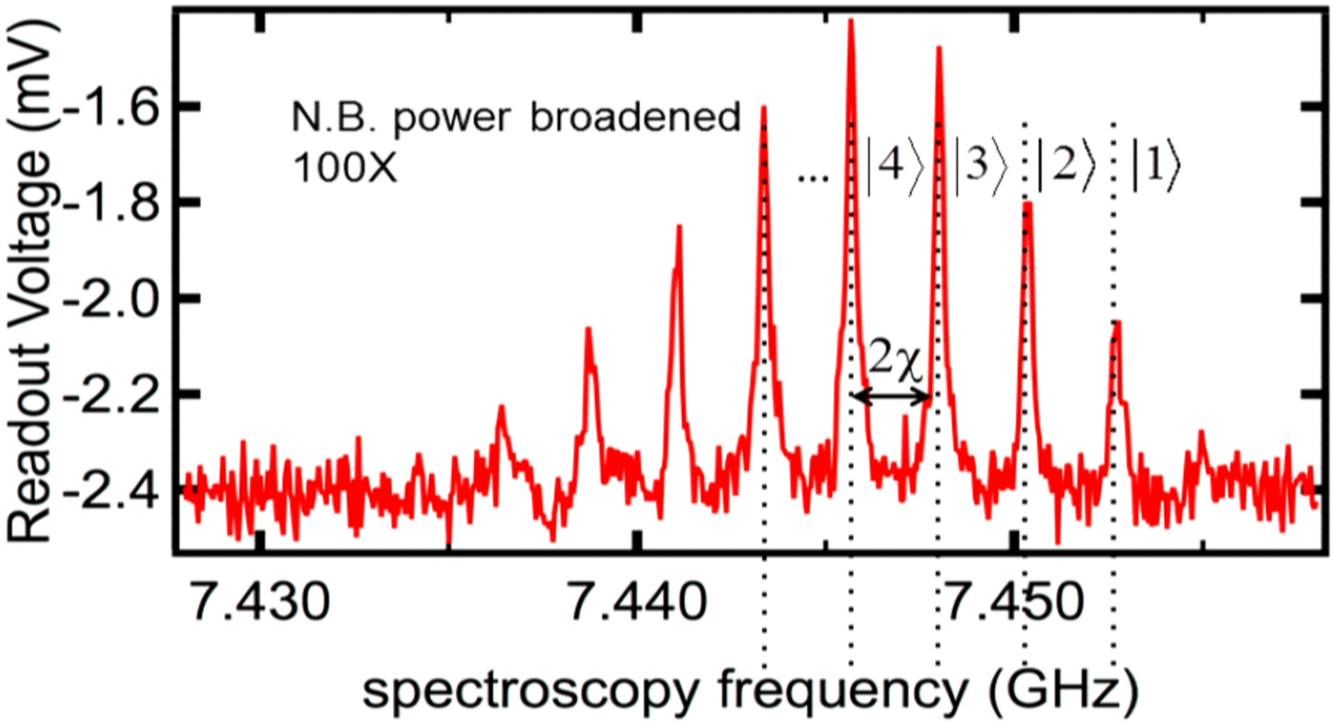
- quantized light shift of qubit frequency (coherent microwave state)

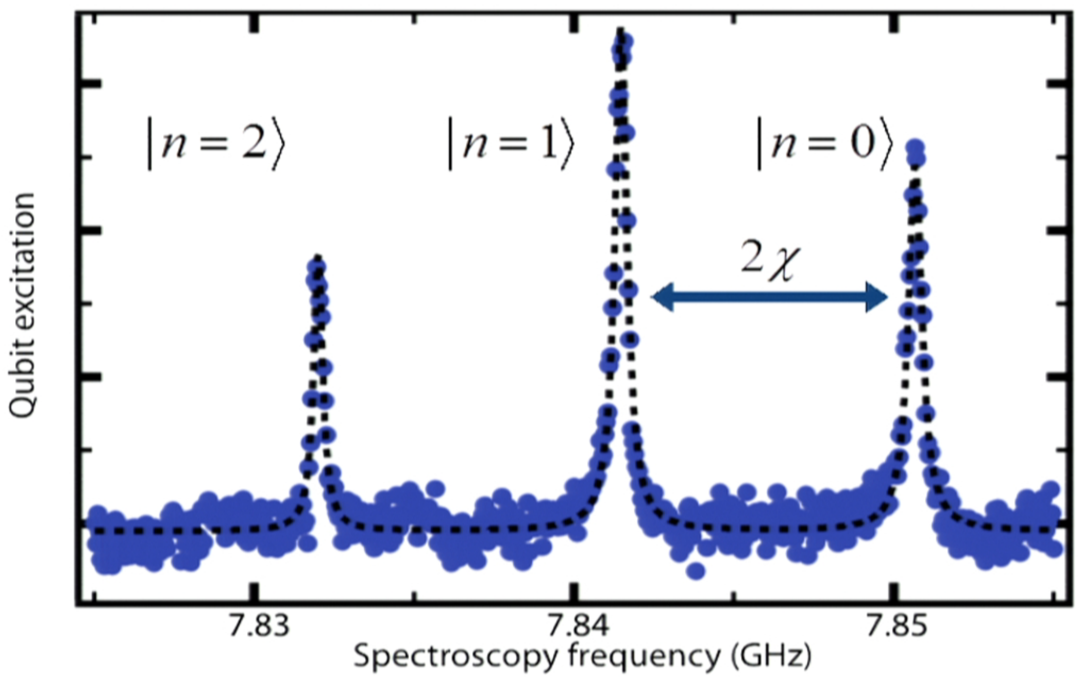
$$\frac{\omega_q + 2\chi a^\dagger a}{2}\sigma^z$$



strong dispersive coupling I

$$V_{\mathrm{DISPERSIVE}} \approx \chi a^{\dagger} a \sigma^{z}$$

Qubit Spectroscopy



Coherent state
in the cavity

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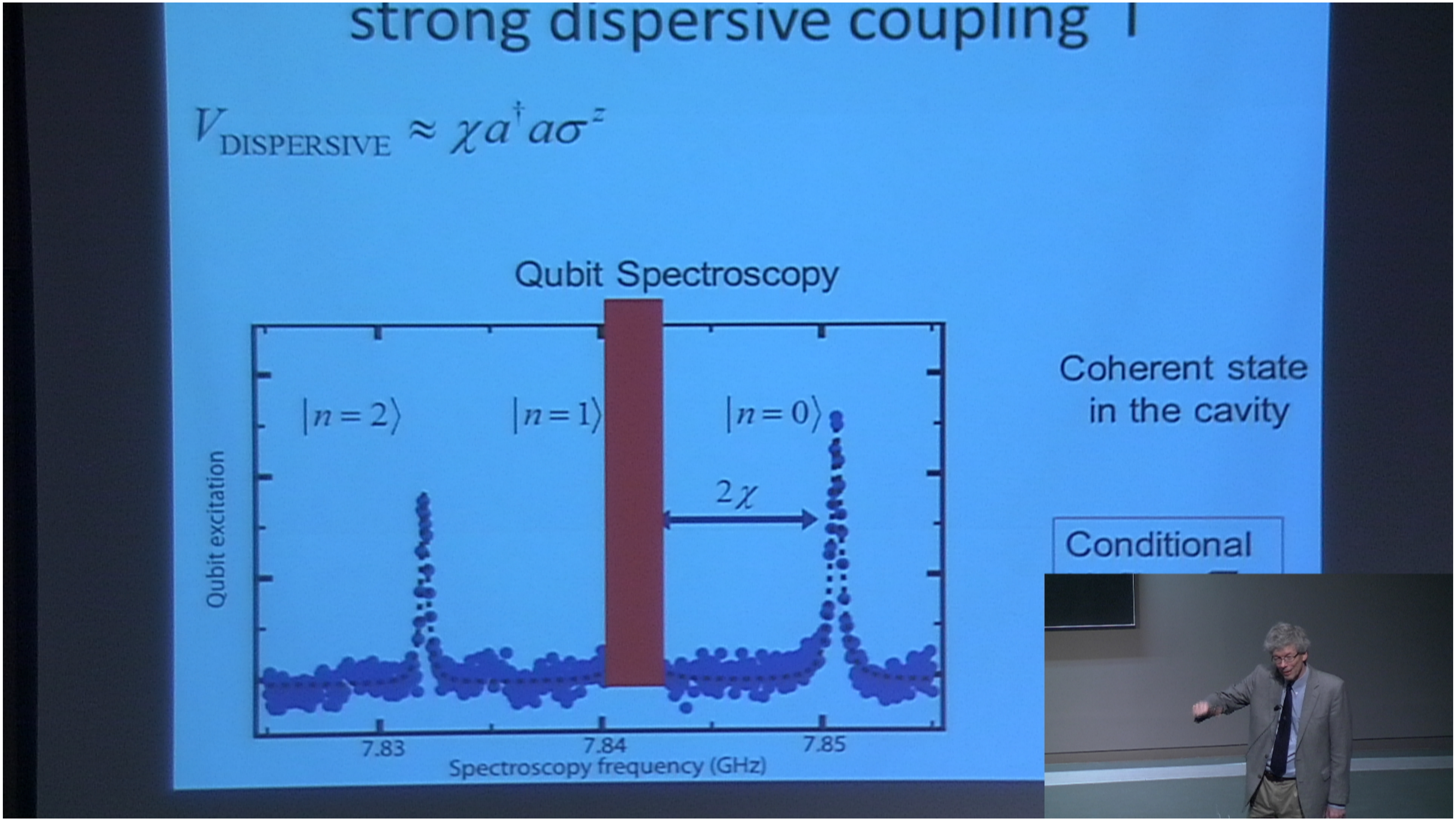
strong dispersive coupling I
$V_{\text{DISPERSIVE}} \approx \chi a^\dagger a \sigma^z$
Qubit Spectroscopy
$|n=2\rangle$
$|n=1\rangle$
$|n=0\rangle$
2χ
Qubit excitation
7.83
7.84
7.85
Spectroscopy frequency (GHz)
Coherent state
in the cavity
Conditional

Strong Dispersive Coupling Gives Powerful Tool Set

Cavity conditioned bit flip $\boxed{\pi_n}$

Qubit-conditioned cavity displacement $\boxed{D_\alpha^g}$

- multi-qubit geometric entangling phase gates (Paik et al.)
- Schrödinger cats are now 'easy' (Kirchmair et al.)

Photon Schrödinger cats on demand

<u>experiment</u>
G. Kirchmair
B. Vlastakis

<u>theory</u>
M. Mirrahimi
Z. Leghtas

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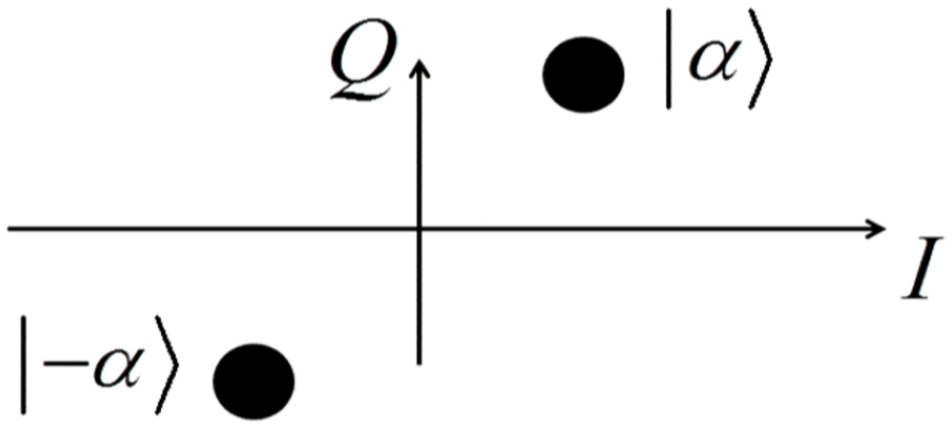
Photon Schrödinger cat

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\alpha\rangle + |-\alpha\rangle\right)$$

Superposition of two different coherent states

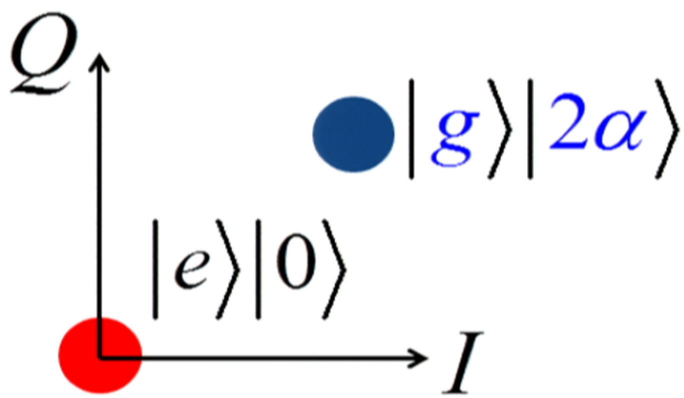


How do we construct it?

Start with previous qubit-cavity entangled state:

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle + |e\rangle\right)|0\rangle$$

$$D_{2\alpha}^{g}|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle|2\alpha\rangle + |e\rangle|0\rangle\right)$$



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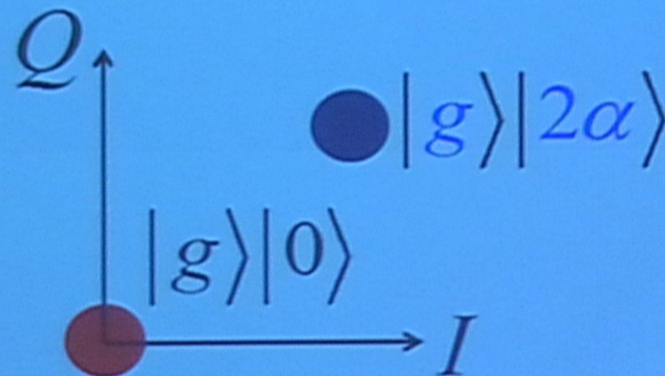
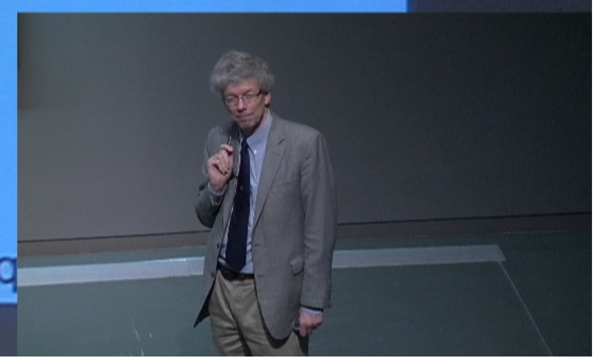
Now flip qubit only if zero photons present:

$$D_{2\alpha}^{g}|\psi\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle|2\alpha\rangle + |e\rangle|0\rangle\right)$$

$$\pi_0\, D_{2\alpha}^{g}\;|\psi\rangle = \frac{1}{\sqrt{2}}|g\rangle\left(|2\alpha\rangle + |0\rangle\right)$$



This unentangles the q



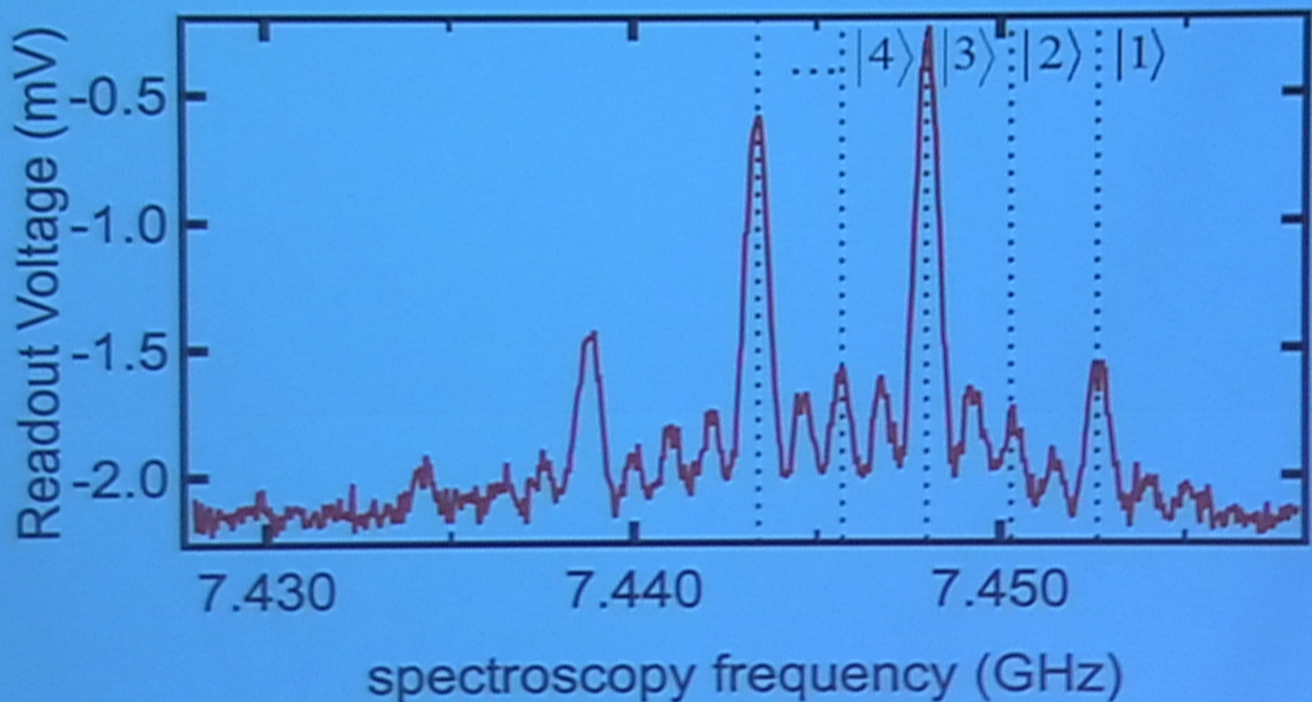
Does it work in practice?

- measure photon number parity in the cat

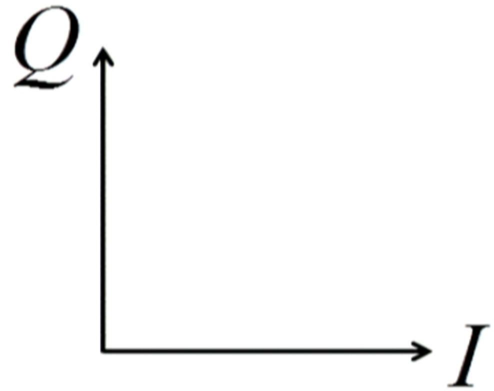
- measure the Wigner function
  (phase space distribution of cat)

quantized light shift in ‘odd’ cat

odd cat state: $\Psi = \frac{1}{\sqrt{2}}\left(|\beta\rangle - |-\beta\rangle\right)$ $\quad P = \sum_n p_n (-1)^n = -1$



Wigner Functions for Cats



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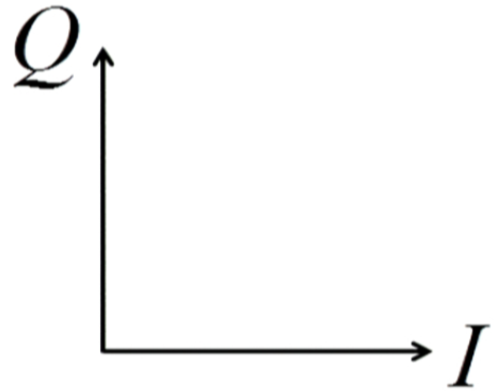
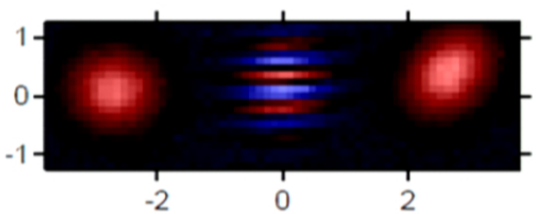
Wigner Functions for Cats





$$|\alpha|^2 = \bar{n} = 7$$

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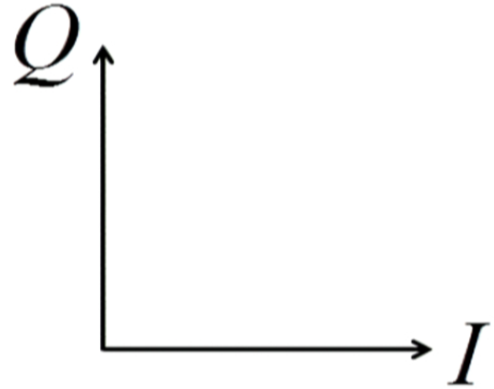
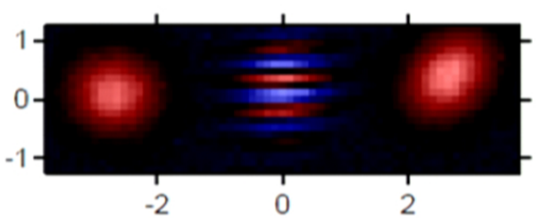
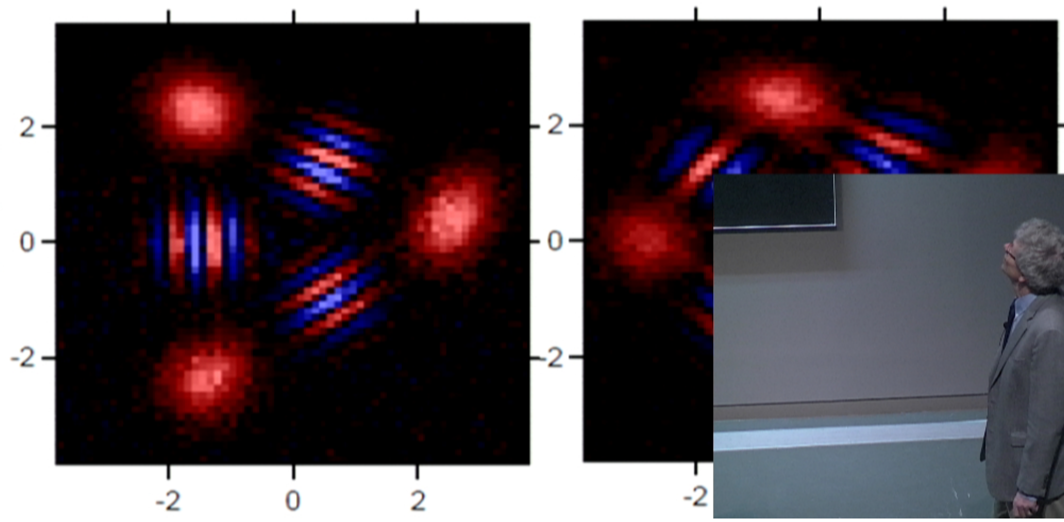




$$|\alpha|^2 = \overline{n} = 7$$



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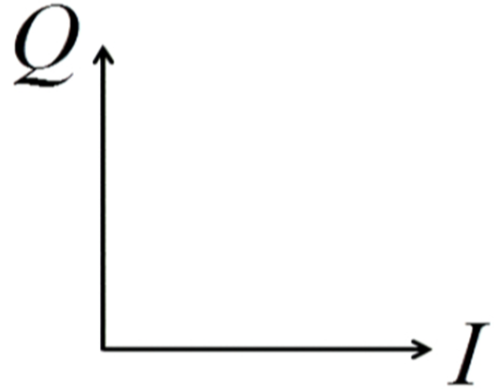
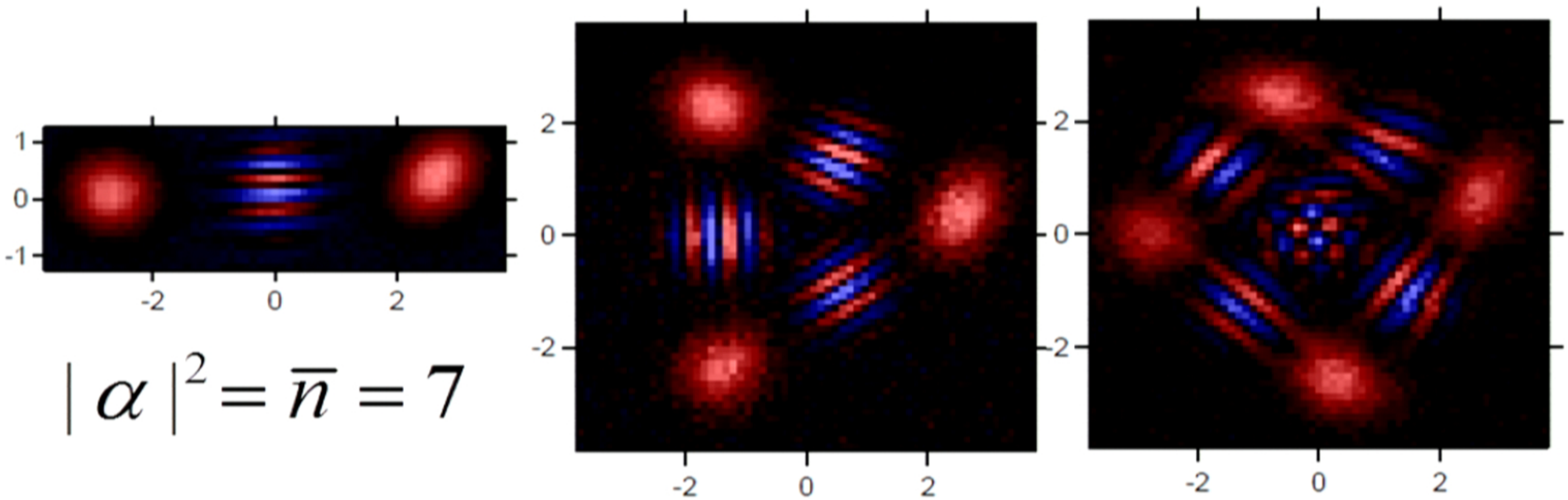
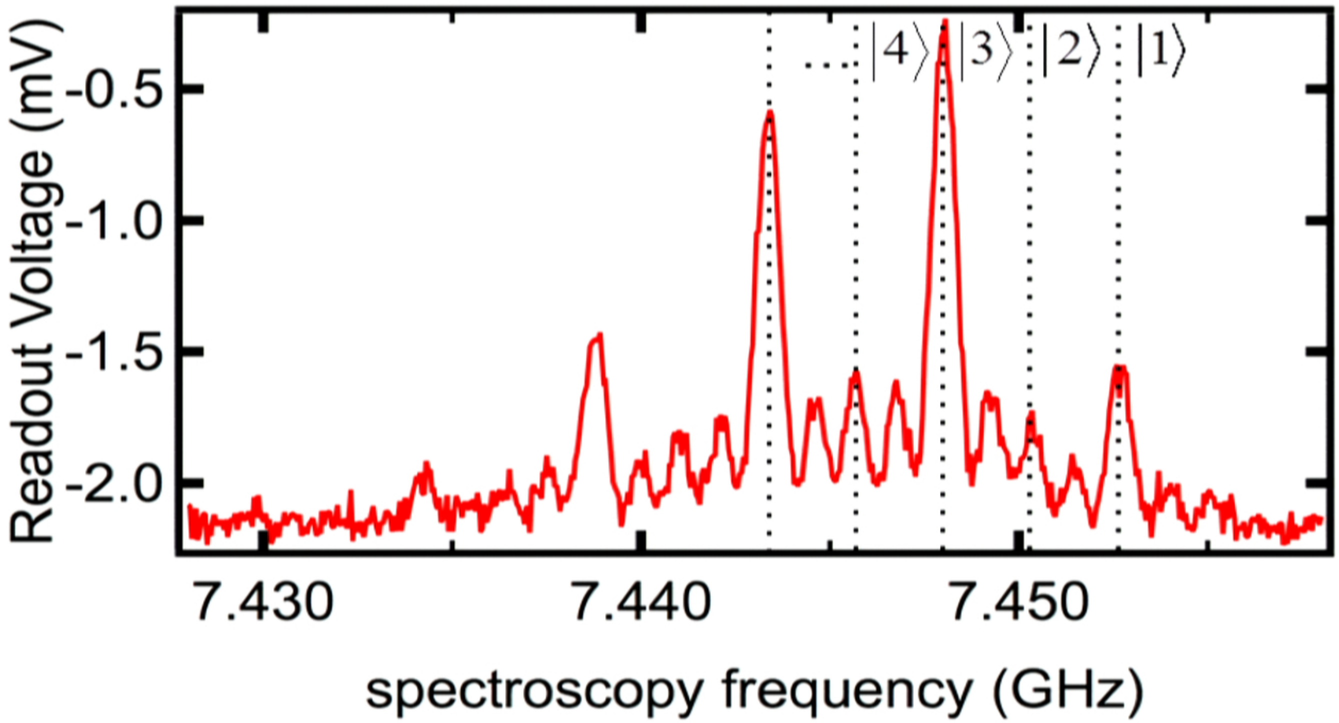




$$|\alpha|^2 = \bar{n} = 7$$

quantized light shift in ‘odd’ cat

odd cat state: $\Psi = \frac{1}{\sqrt{2}}\left(|\beta\rangle - |-\beta\rangle\right)$ $\quad P = \sum_n p_n(-1)^n = -1$



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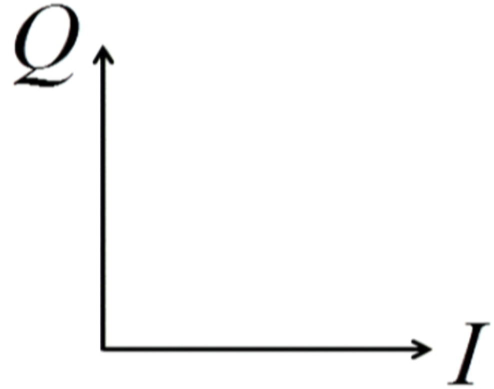
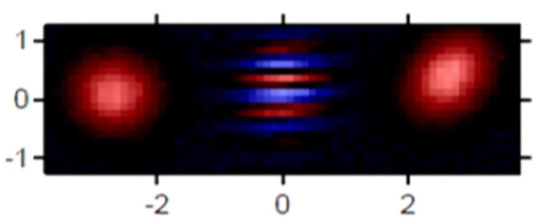
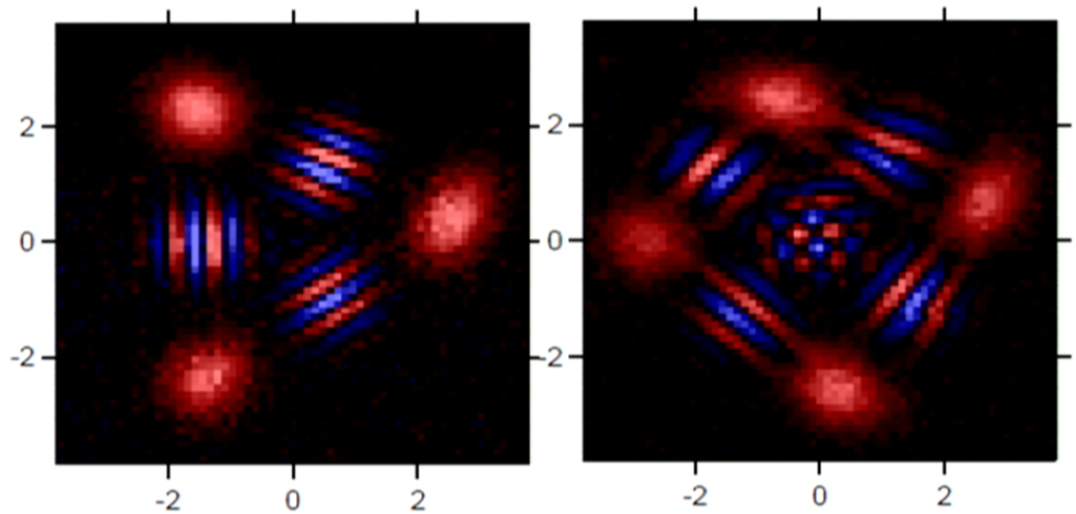
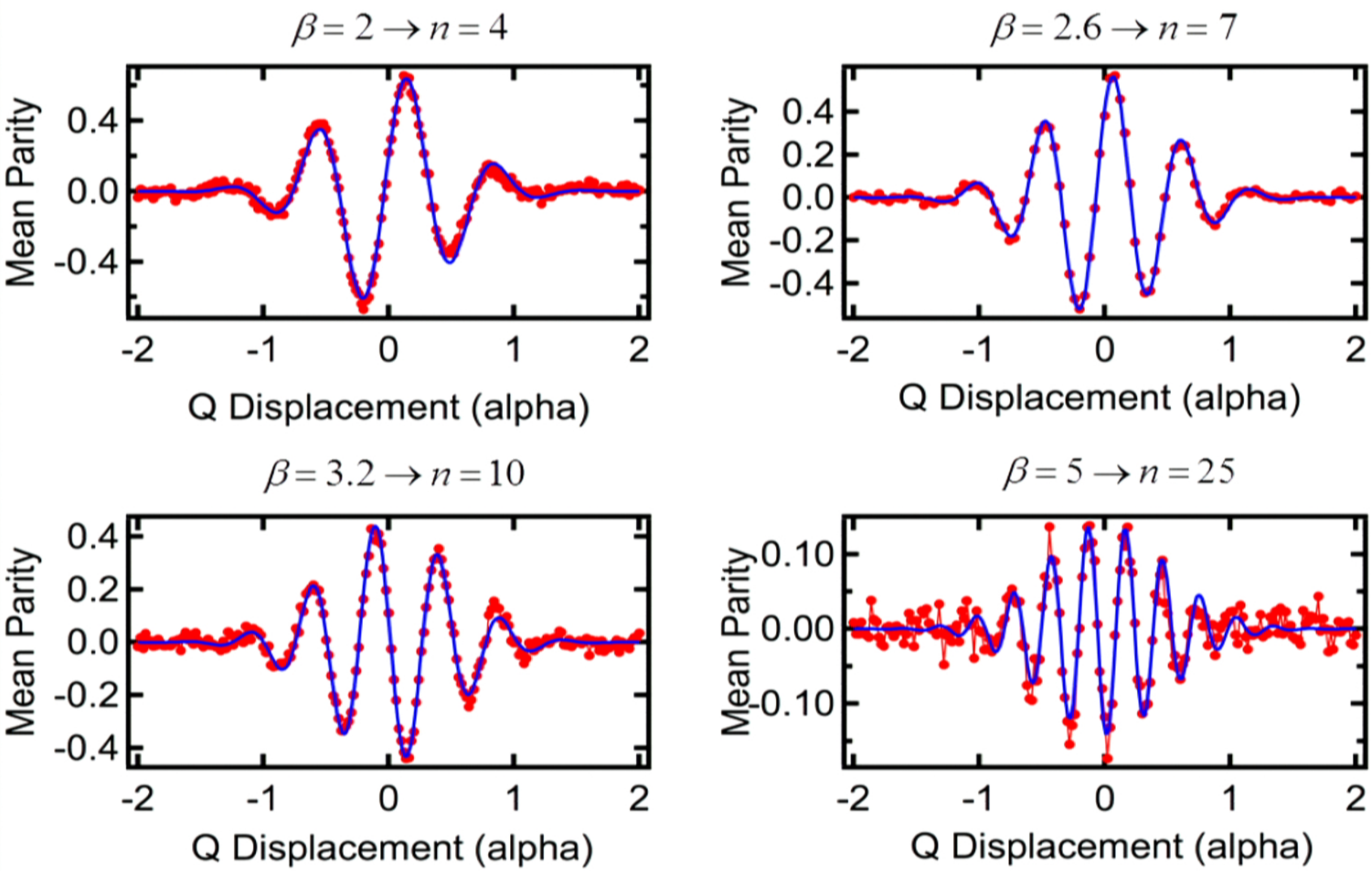




$$|\alpha|^2 = \bar{n} = 7$$



Fringes for different cat sizes



$$H = \omega_r a^\dagger a + \frac{\omega_q}{2}\sigma^z + \chi\sigma^z a^\dagger a + H_{\text{damping}}$$

resonator qubit dispersive coupling

For the future:

-map qubit states to storage cavity for quantum memory
-memory error correction using cat state encoding
-stabilizer pumping for Kitaev toric code (Simon Nigg)
-microwave photomultiplier for axion dark matter searches

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Hardware-efficient autonomous quantum error correction
Zaki Leghtas et al.

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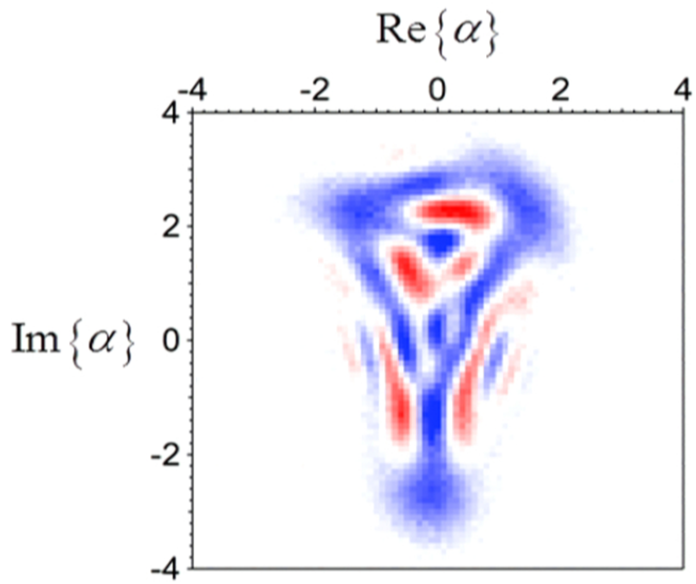
Last but not least: The Yale cat



$$\Psi_4 = \frac{1}{2}\left(\left| -i\beta \right\rangle + \left| e^{i5\pi/6}\beta \right\rangle + \left| e^{i7\pi/6}\beta \right\rangle + \left| 0 \right\rangle \right)$$

Circuit QED Team Members 2012

$$\dot{\bar{n}} = -\Gamma \bar{n}$$

$$\omega_R a^\dagger a$$

$$\bar{n} = |\alpha|^2$$

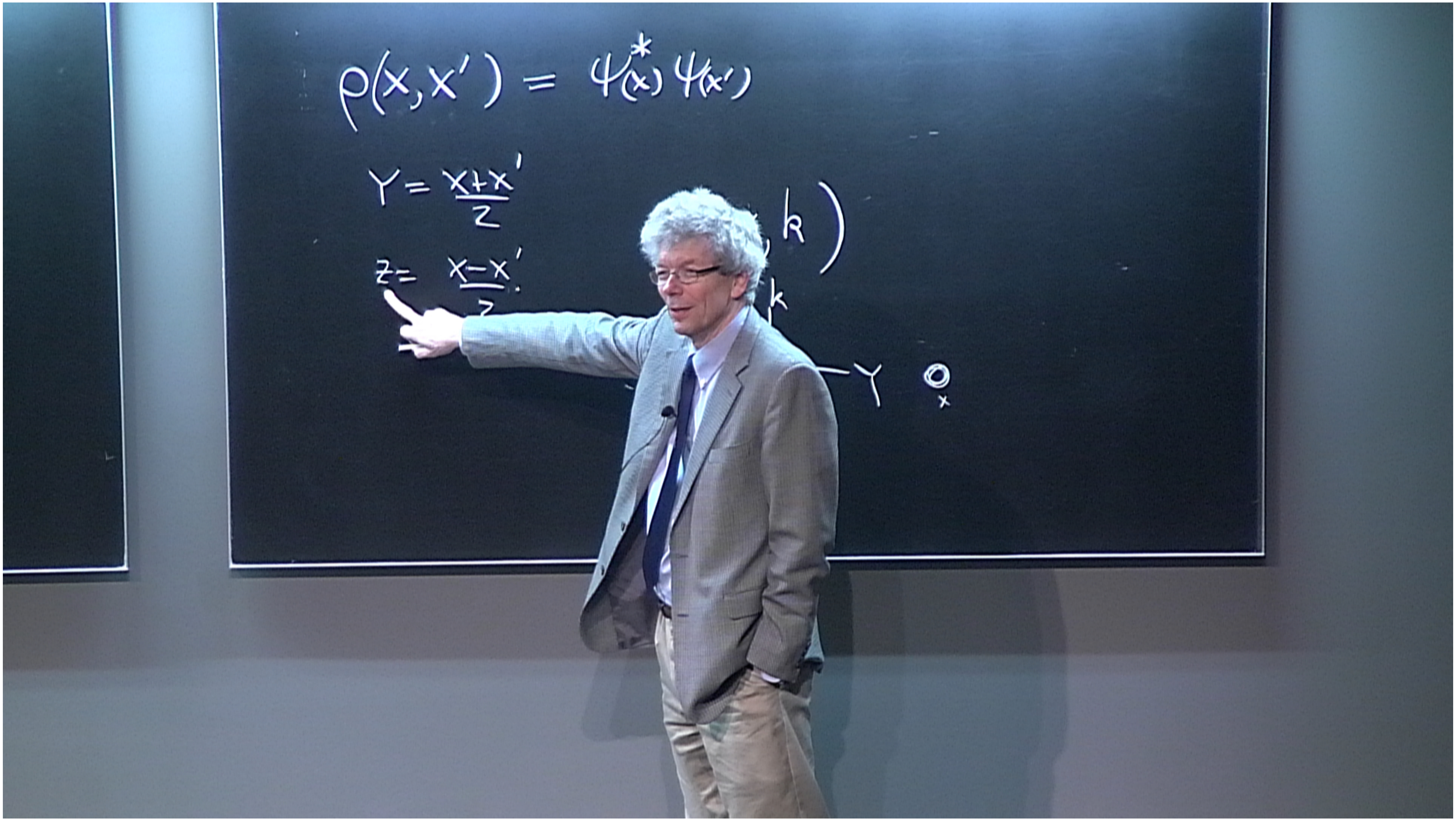
$$a|\alpha\rangle = \alpha|\alpha\rangle$$

$$a|-\alpha\rangle = -\alpha|\alpha\rangle$$

$$|\alpha\rangle + |-\alpha\rangle$$

$$\downarrow$$

$$-$$


$\rho(x, x') = \psi^*(x)\,\psi(x')$
$Y = \frac{x+x'}{2}$
$z = \frac{x-x'}{2}$


Steve Girvin
Kevin Chou
Andreas Fragner
Z. Leghtas
M. Mirrahimi
Michel Devoret
Leonid Glazman
Funding:
PI

$$\rho(x,x') = \psi^*(x)\,\psi(x')$$

$$Y = \frac{x+x'}{2}$$

$$z = \frac{x-x'}{2}$$

$$\int dz\, e^{ikz}$$

$$\rho(Y,k)$$