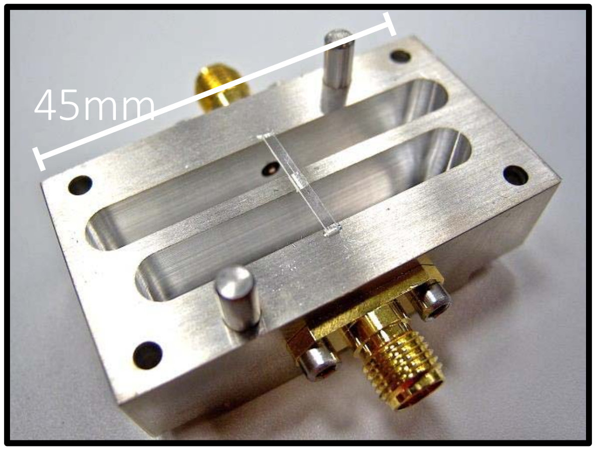
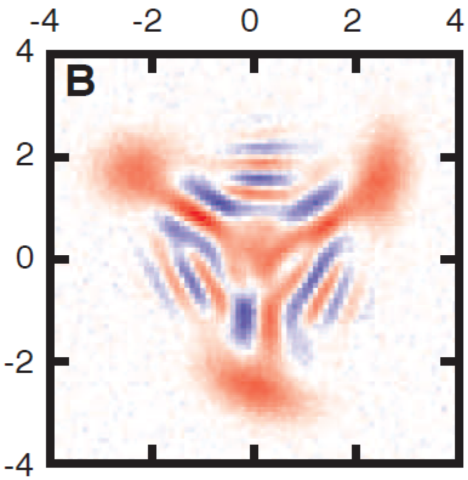
Quantum Control of Superconducting Circuits

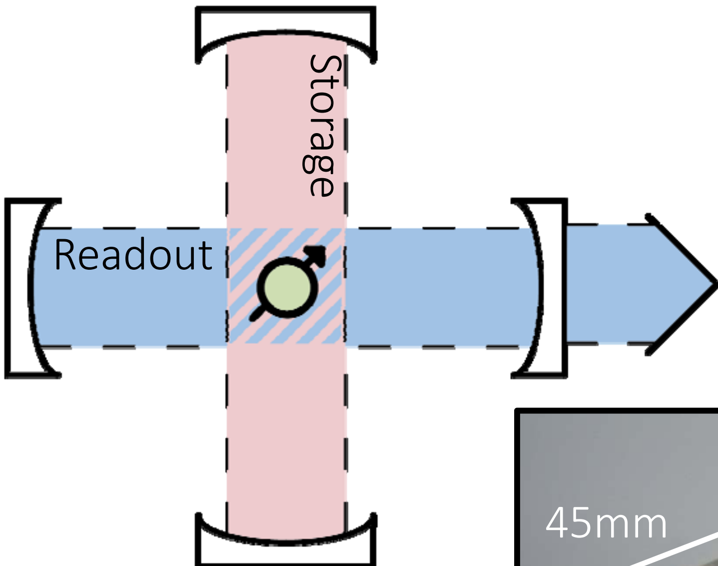




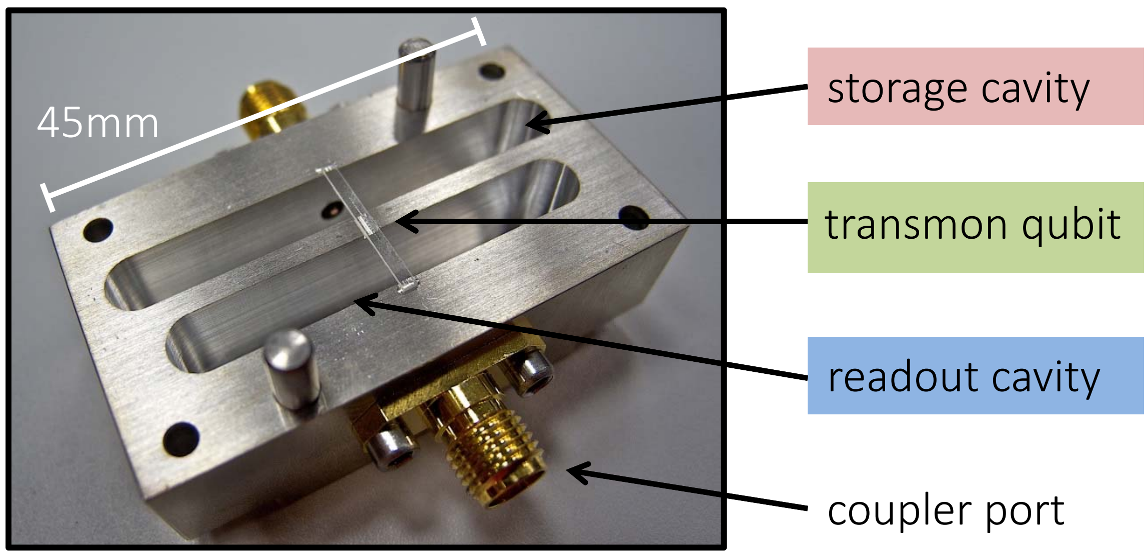
Liang Jiang
Yale University, Applied Physics
Benasque Workshop
2014.7.8

Two-cavity architecture

Cavity QED equivalent:



One fast probe cavity for qubit state detection and one long-lived cavity for photon manipulation/storage



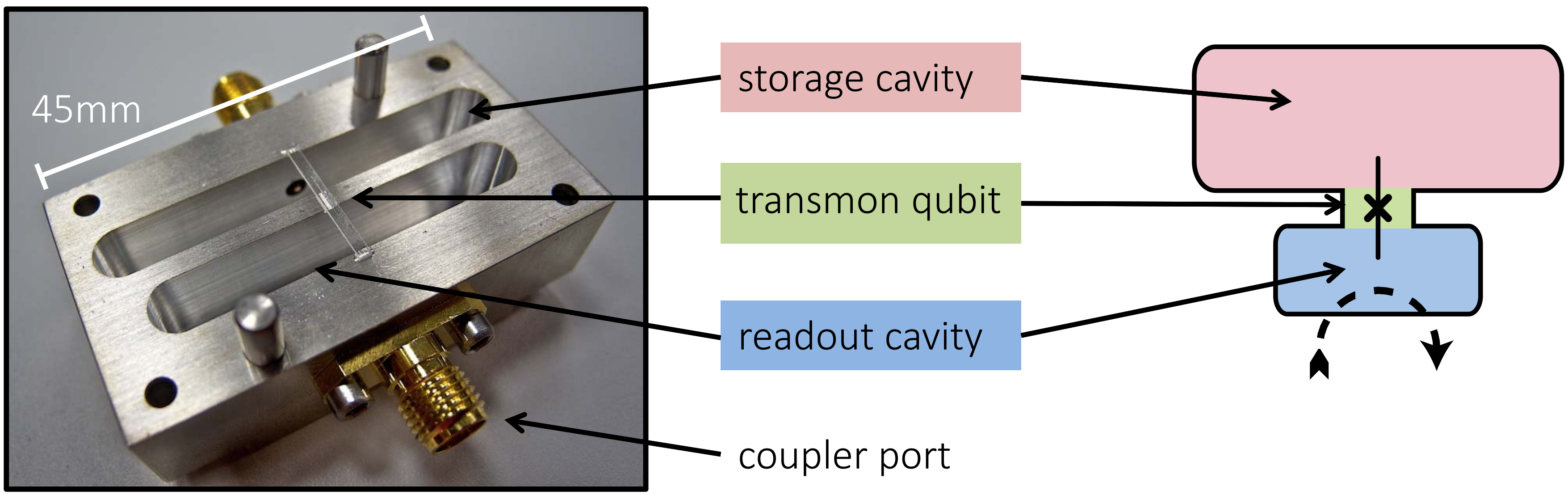
Two-cavity architecture

Effective Hamiltonian:

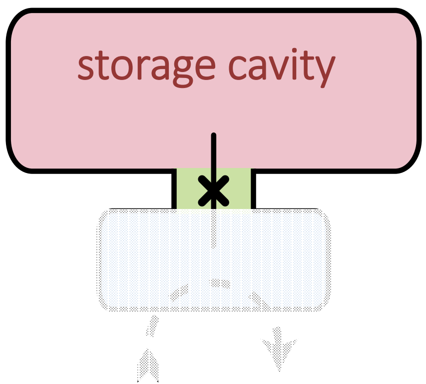
$$H/\hbar = \omega_s a^\dagger a + \omega_r b^\dagger b + \omega_q |e\rangle\langle e| - \chi_s a^\dagger a |e\rangle\langle e| - \chi_r b^\dagger b |e\rangle\langle e|$$

Interaction strength dominates photon loss: $\chi_s / \kappa_s > 300$

κ_s : storage photon decay rate

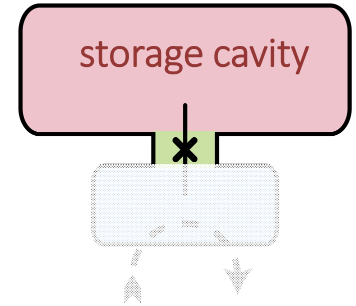


Coherent Operations

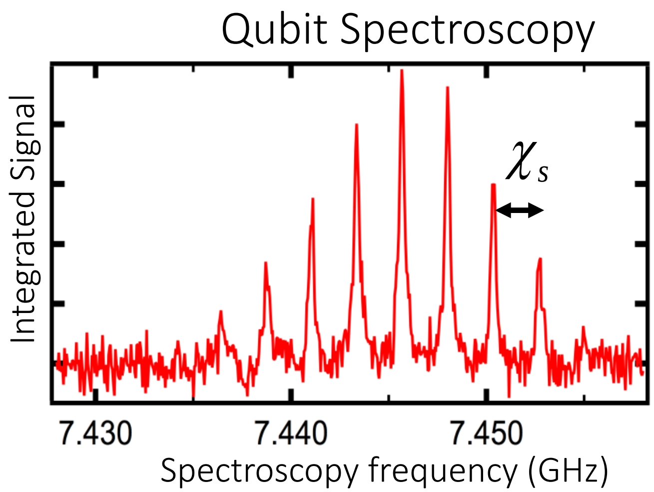


- Qubit Rotation (conditional & unconditional)
- Cavity displacement (conditional & unconditional)

Manipulating the qubit



$$H/\hbar = \omega_s a^\dagger a + \left(\omega_q - \chi_s a^\dagger a\right)|e\rangle\langle e|$$



Strong Drive:

Unconditional qubit rotation:

$$Y_\pi |n,g\rangle \Rightarrow |n,g\rangle$$

for all n

Weak Drive:

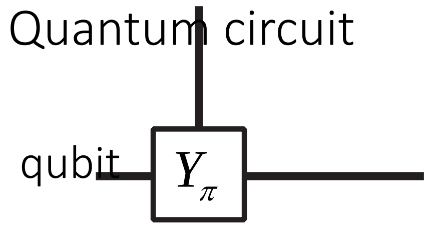
Conditional qubit rotation:

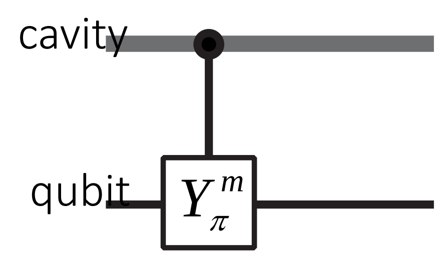
$$Y_\pi^m |m,g\rangle \Rightarrow |m,e\rangle$$

$$Y_\pi^m |n,g\rangle \Rightarrow |n,g\rangle$$

$n \neq m$

Quantum circuit



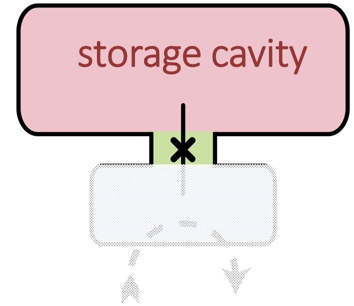


Query the qubit: 'Are there m photons in the cavity?'

Johnson B.R. et al. Nature Phys. 6, 663-667 2010

Kirchmair G. et al. Nature 495 205-209 2013

Manipulating the cavity



$$H / \quad = \left(\omega_s - \chi_s |e\rangle\langle e|\right) a^\dagger a + \omega_q |e\rangle\langle e|$$

Strong Drive:

Unconditional cavity displacement

$D_\beta |0\rangle \Rightarrow |\beta\rangle$

indep. of qubit state

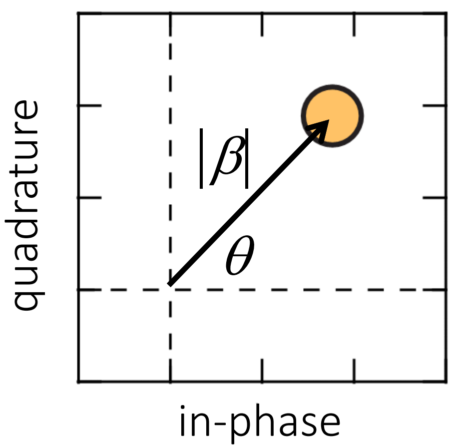
Weak Drive:

Conditional cavity displacement

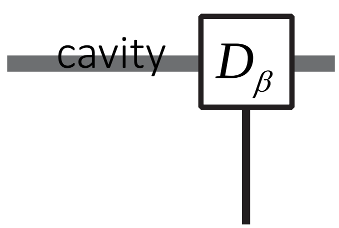
$D_\beta^g |0, g\rangle \Rightarrow |\beta, g\rangle$

$D_\beta^g |0, e\rangle \Rightarrow |0, e\rangle$

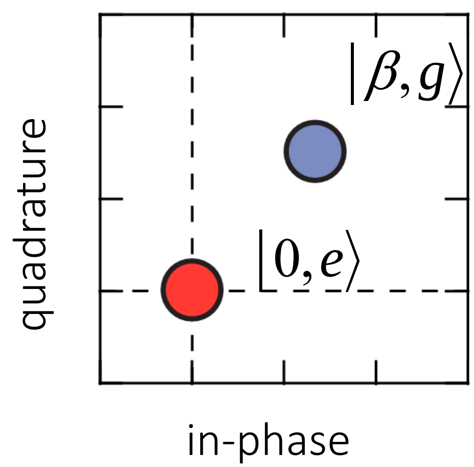
Phase-space diagram



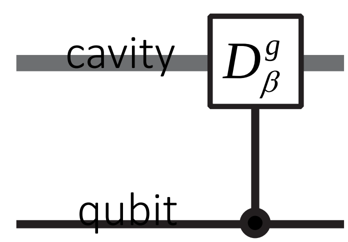
Quantum circuit



Phase-space diagram

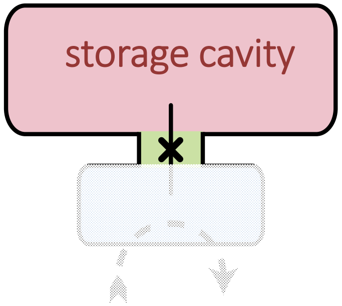


Quantum circuit

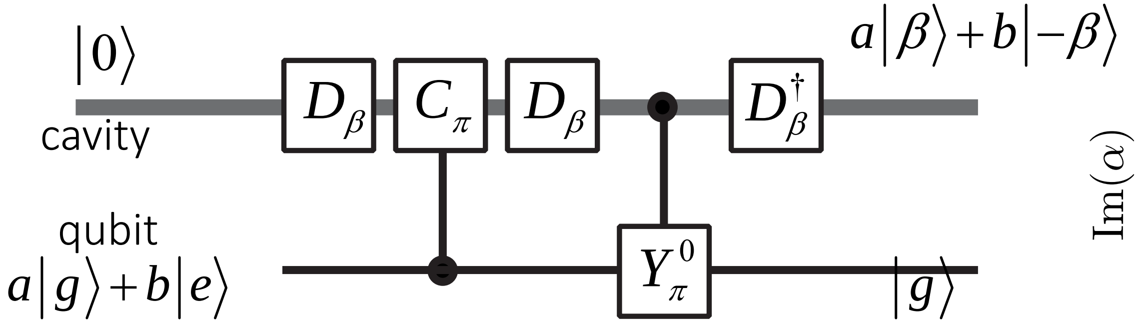


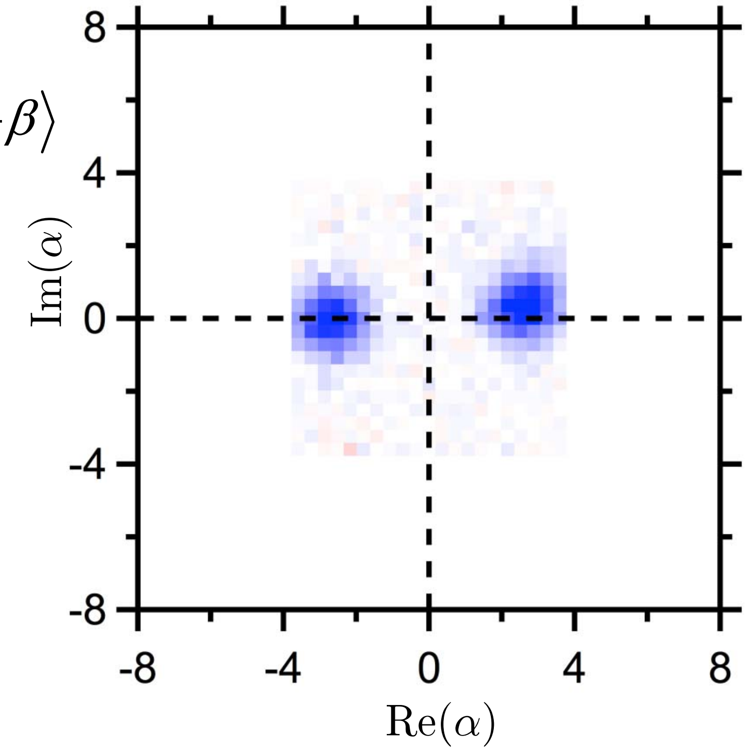
Create ***superposition*** of cavity state depending on the qubit.

Deterministic qubit-cavity mapping



Transfer arbitrary state from qubit to cavity

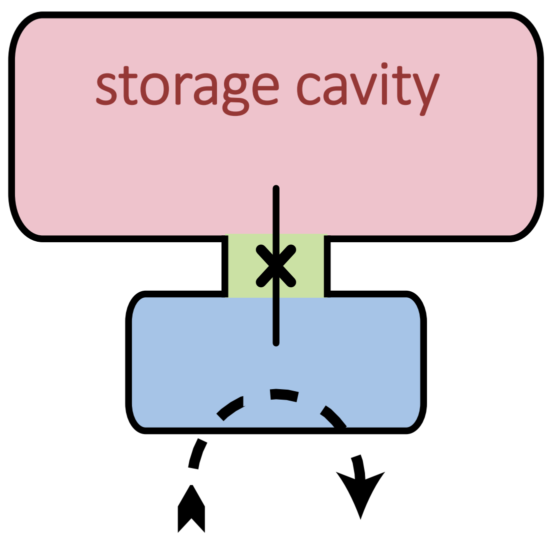




Theory:
Leghtas et. al PRA 87, 042315 (2013)

Experiment:
Vlastakis et. al Science 342, 6158 (2013)

Measurement of Qubit & Cavity



Two-cavity architecture

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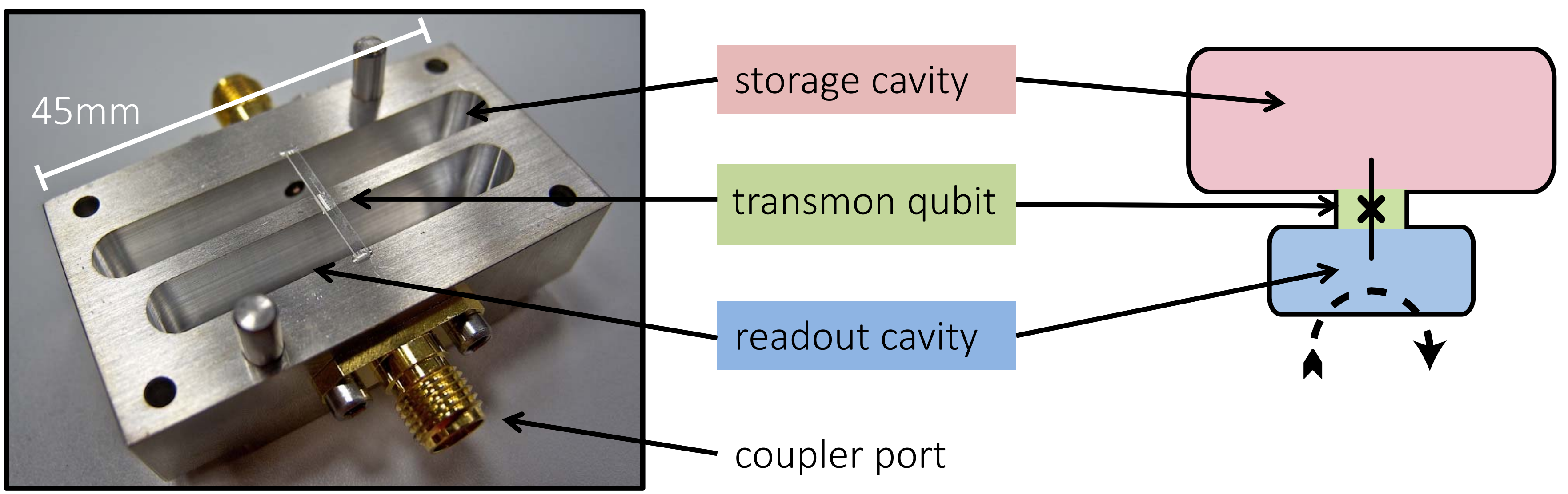
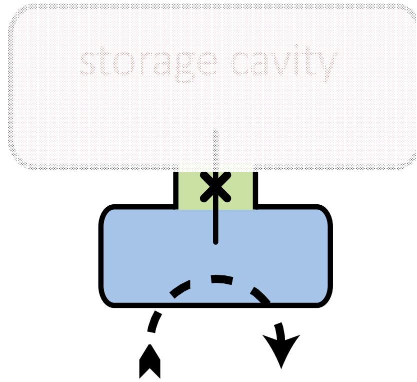
Interaction strength dominates photon loss: $\chi_s / \kappa_s > 300$

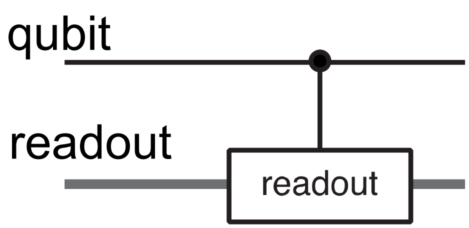
κ_s : storage photon decay rate

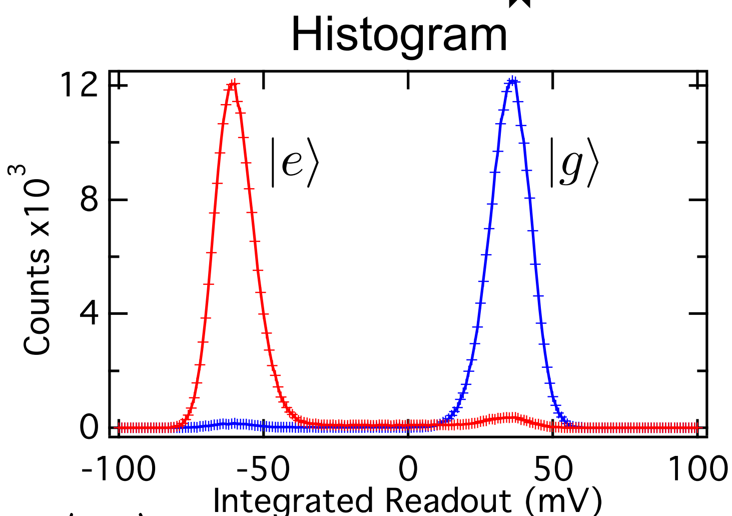


Dispersive qubit state readout



$$H/\hbar = (\omega_r - \chi_r |e\rangle\langle e|)b^\dagger b$$





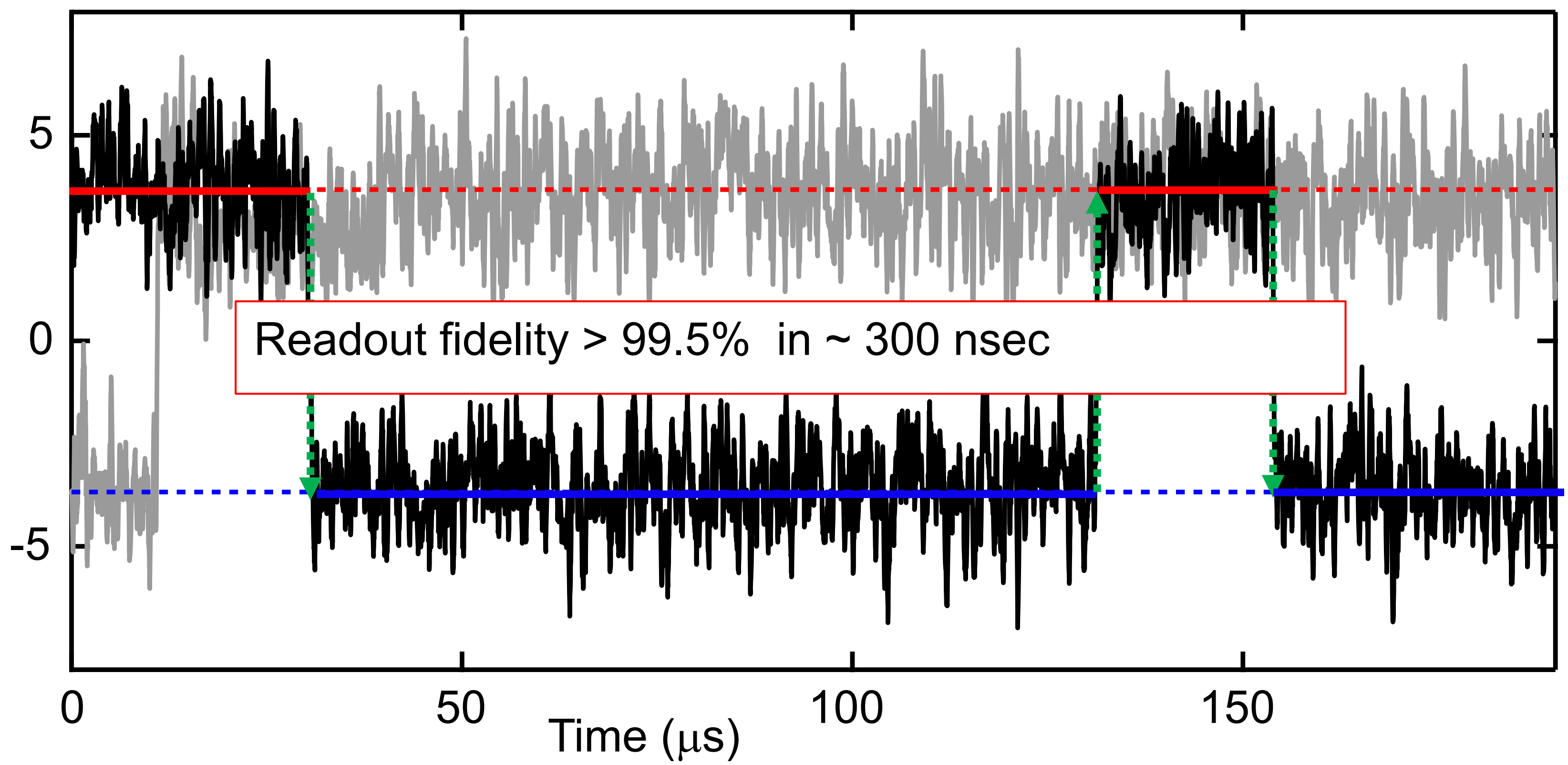
Single-shot qubit state detection, $\langle Z\rangle$

- Readout fidelity: 95%
- Readout repetition rate: 600ns

QND Measurement of Qubit!

Results from Devoret group, Yale: Hatridge et al., Science 2013*

dispersive circuit QED readout + JJ paramp



Many groups now working with JJ paramps & feedback, including:
Berkeley, Delft, JILA, ENS/Paris, IBM, Wisc., Saclay, UCSB, …

*First jumps: R. Vijay et al., (UCB)

Measurement of Cavity

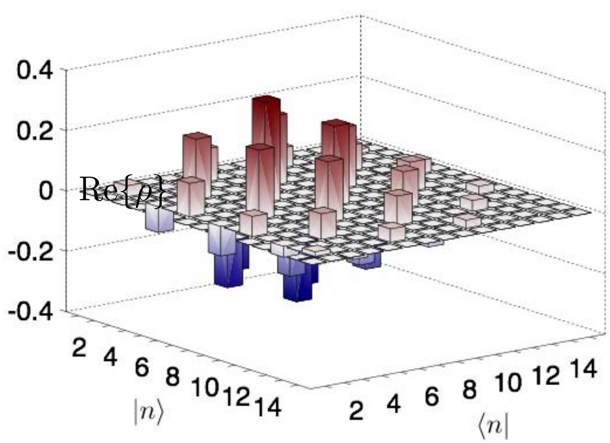
- Density Matrix:
  (in discrete Fock basis)

$$\langle \hat{O} \rangle = Tr\left[\hat{O}\rho \right]$$

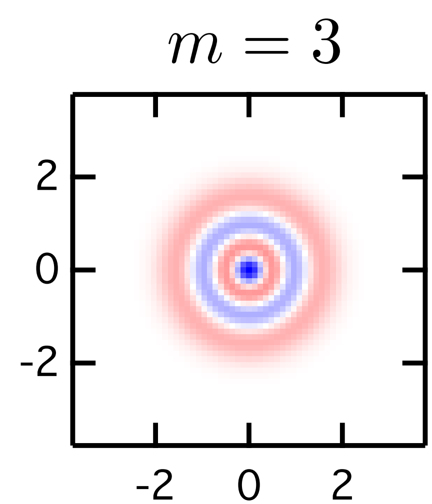
- "Distribution" function
  (continuous variable)

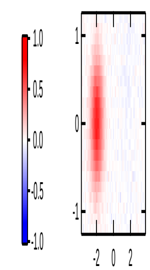
$$\langle \hat{O} \rangle = \int O(\alpha) P(\alpha) d^2\alpha$$

An example cavity density matrix:

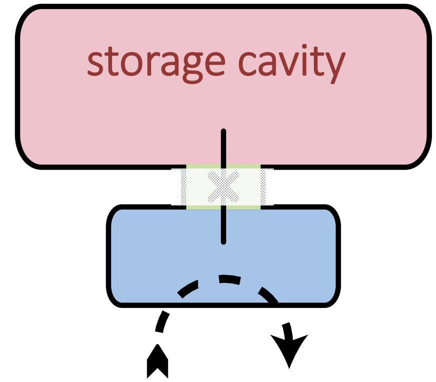


An example of "distribution" functions





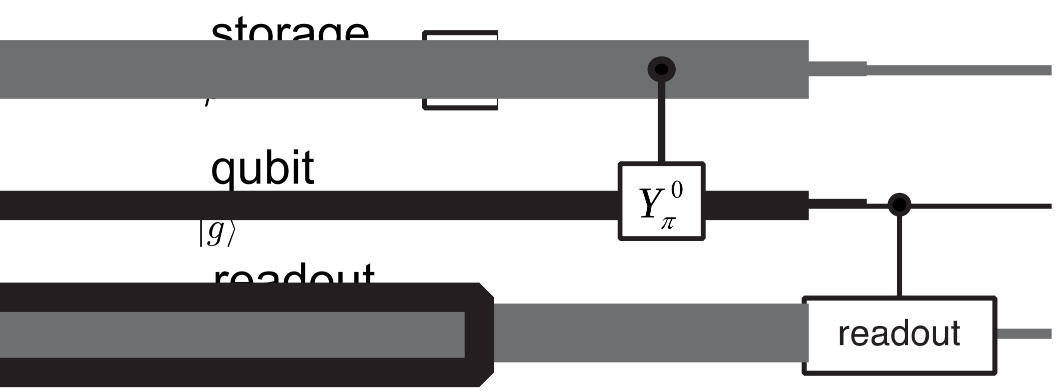
Cavity Q-function

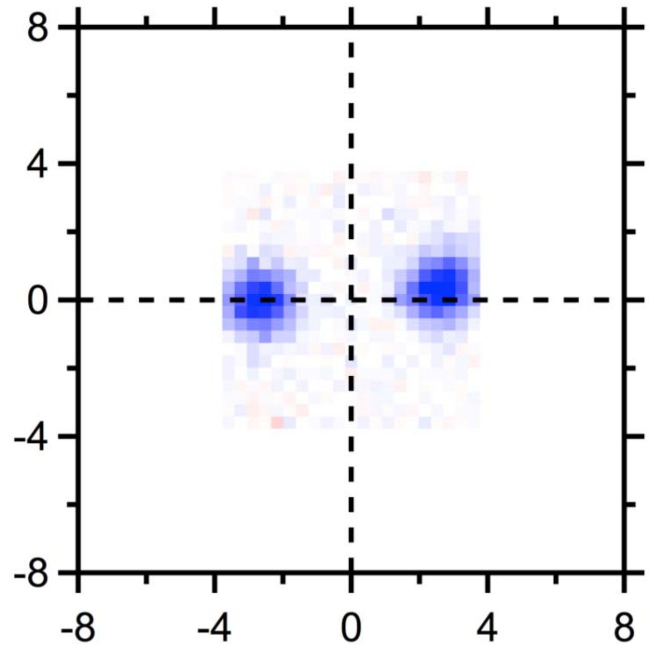


Husimi-Q distribution:

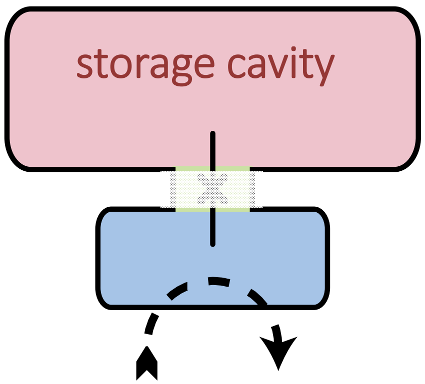
$$Q(\alpha) \propto \langle \alpha | \rho | \alpha \rangle$$
$$= Tr\left[|0\rangle\langle 0| D(\alpha)^{\dagger} \rho D(\alpha) \right]$$

Overlap of a state ρ with a coherent state $|\alpha\rangle$





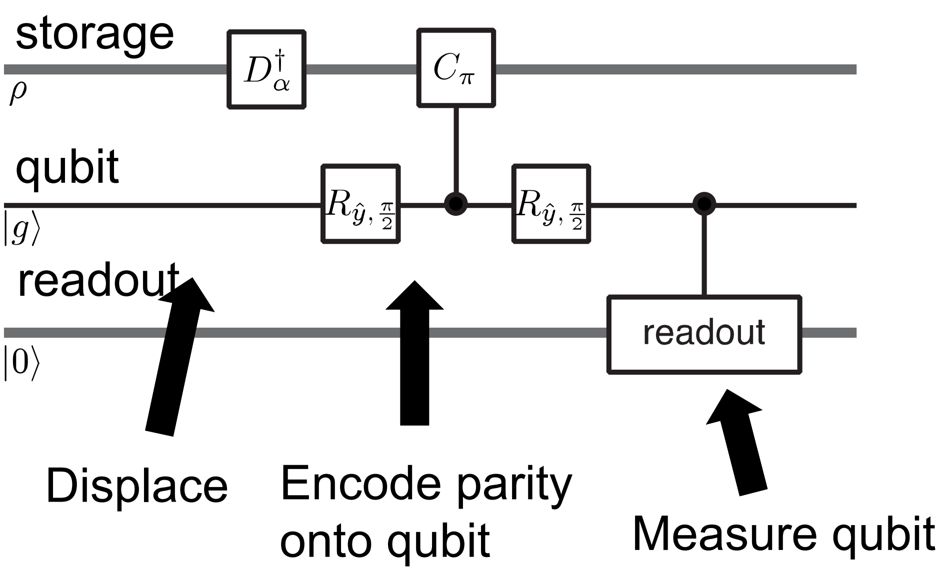
Cavity Wigner function



$$W(\alpha) = Tr\left[(-1)^{a^\dagger a} D(\alpha)^\dagger \rho D(\alpha)\right]$$

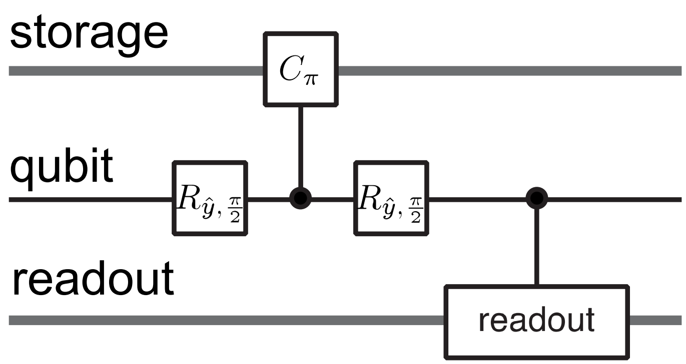
Mean value of photon parity for a displaced cavity state

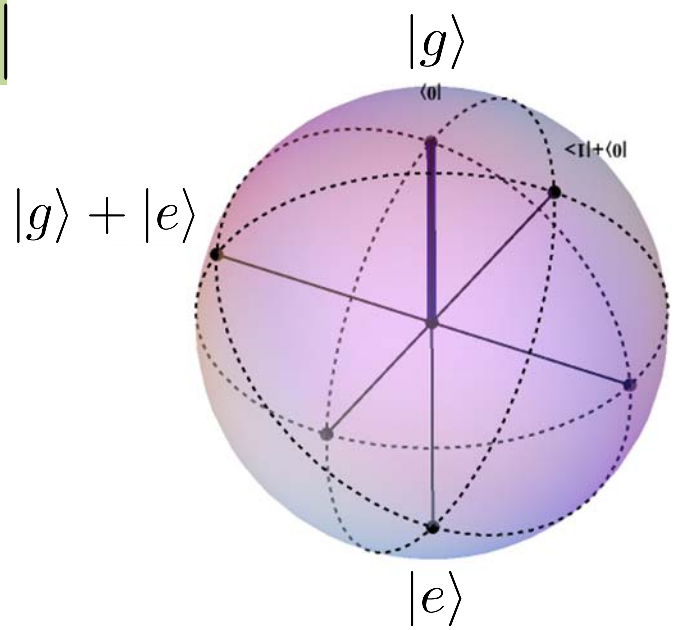
Q-Circuit for measuring $W(\alpha)$



Photon number parity detection

$$H/\hbar = (\omega_q - \chi_s a^\dagger a) |e\rangle \langle e|$$





Kirchmair, RS, et al, Nature 495, 205 (2013)

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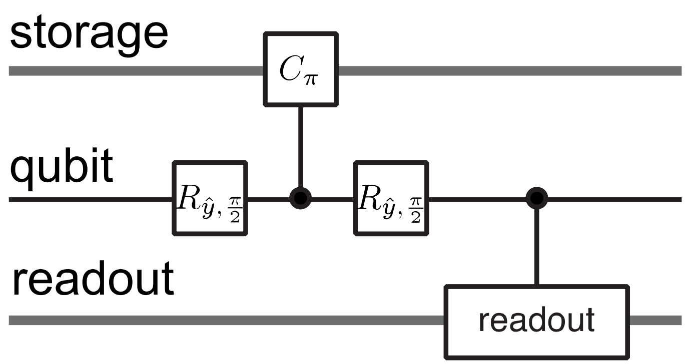

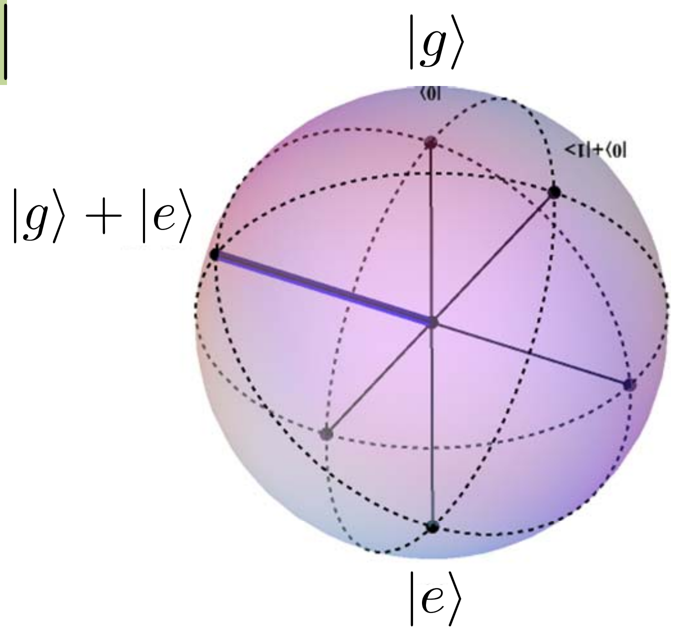

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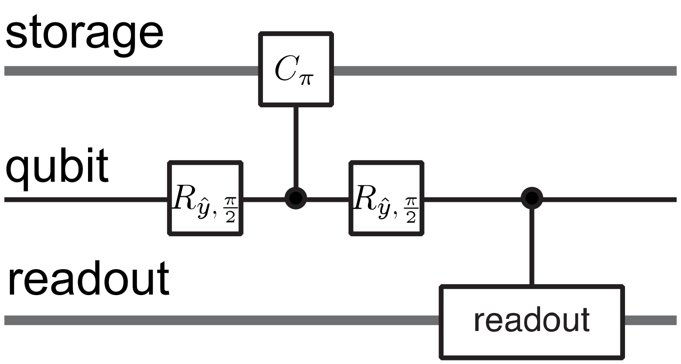

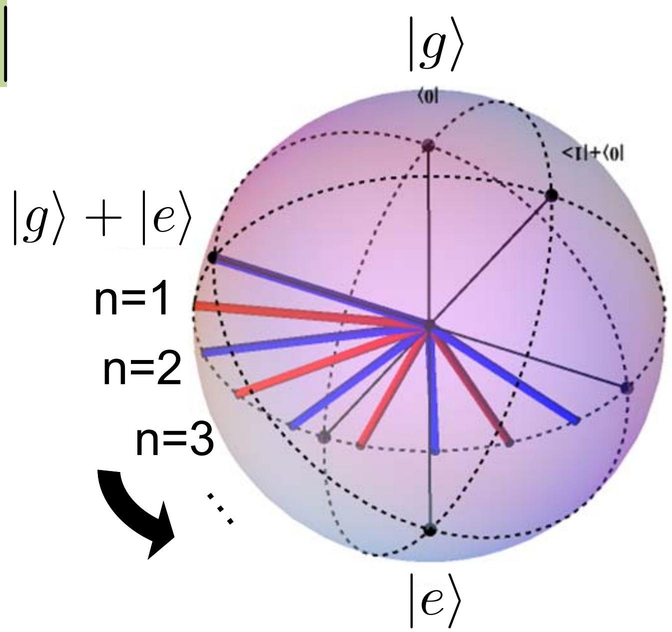

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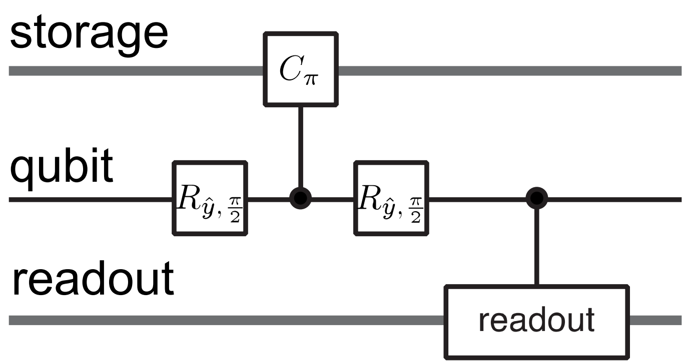

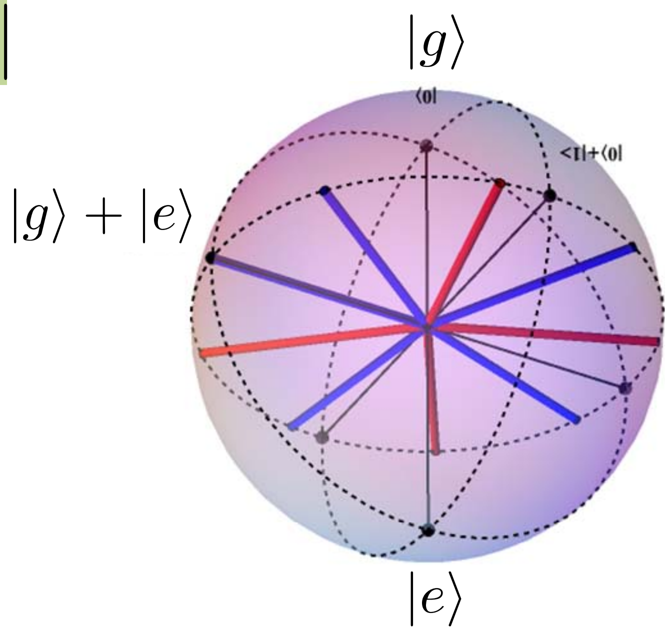

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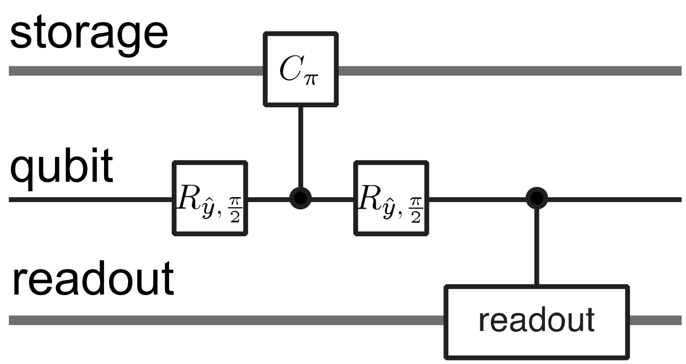

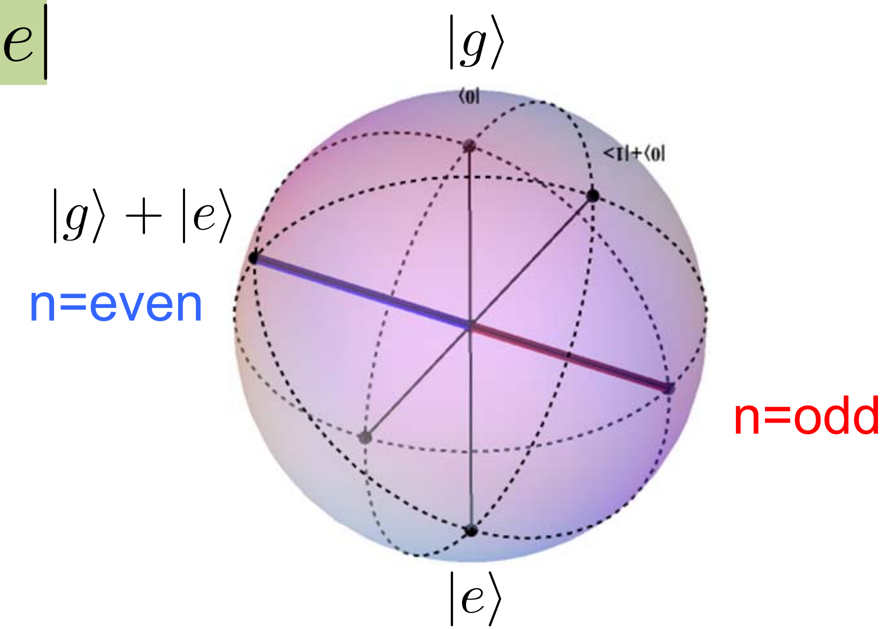

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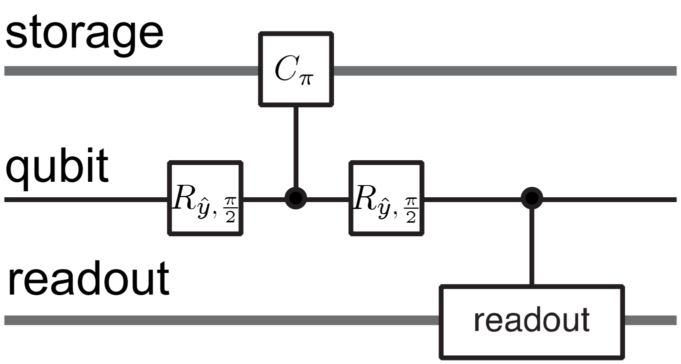
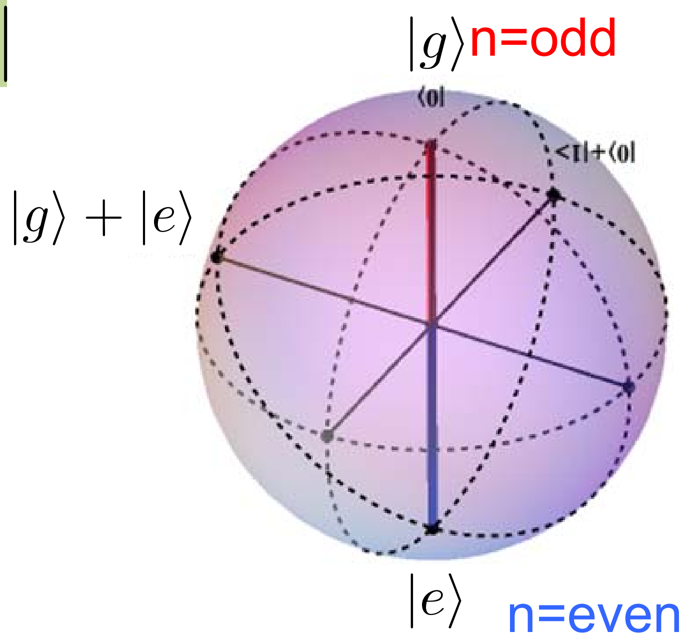




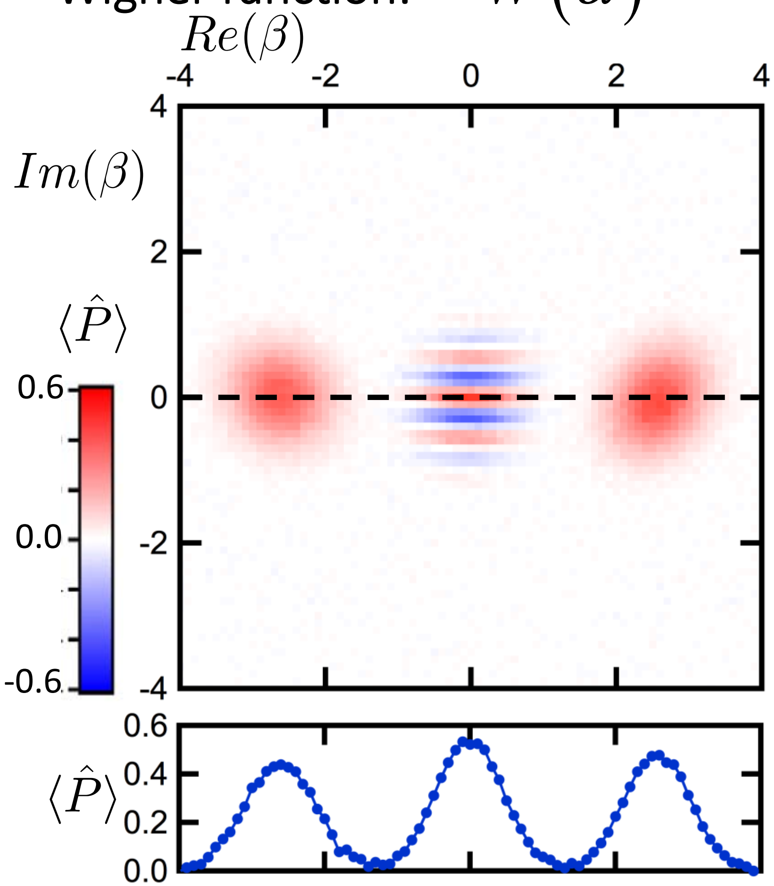
- Detect photon number parity, $\langle \Pi = e^{i\pi a^\dagger a} \rangle$
  - Ideally no direct cavity detection
  - Readout fidelity: ~80%

Kirchmair, RS, et al, Nature 495, 205 (2013)

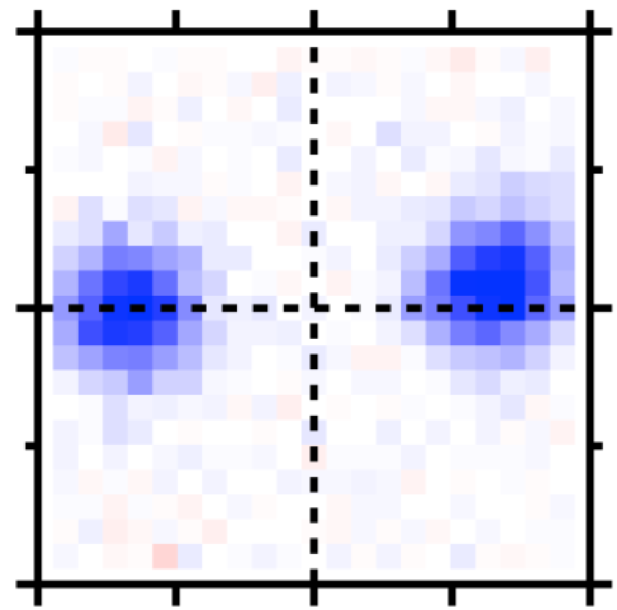
Wigner tomography of a cat state

Cavity state: $\cos(\frac{\theta}{2})\,|\alpha\rangle + \sin(\frac{\theta}{2})e^{i\phi}\,|-\alpha\rangle$

Wigner function: $W(\alpha)$



Q function



Expt'l. Wigner tomography:
Monroe, et al., 1996 ion traps (NIST)
Haroche/Raimond , 2008 Rydberg (ENS)
Hofheinz et al., 2009 in circuits (UCSB)