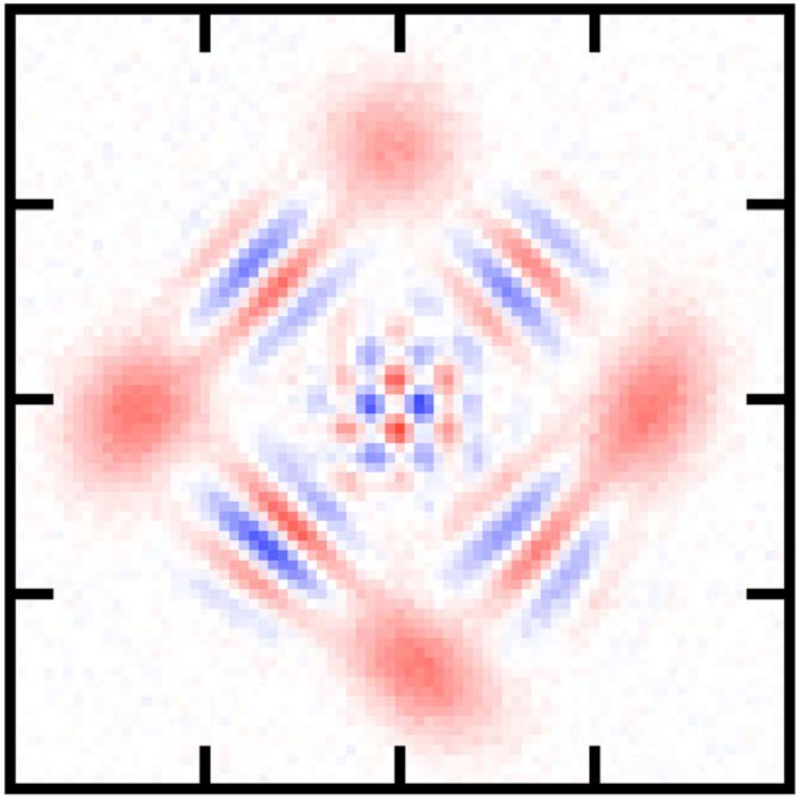


# “Putting the Bell on Schrodinger’s Cat”

**Rob Schoelkopf**

*Applied Physics, Yale University*

PI’s:

RS

Michel Devoret

Luigi Frunzio

Steven Girvin

Leonid Glazman

Liang Jiang

Mazyar Mirrahimi

Postdocs & students wanted!

# Overview

- A few remarks on quantum circuits, then and now…

- "Putting the Bell on a cat": efficient tomography and single-shot violation for a logical qubit

  CHSH for encoded qubit:
  Petrenko, Vlastakis, et al., submitted & arXiv (2015).

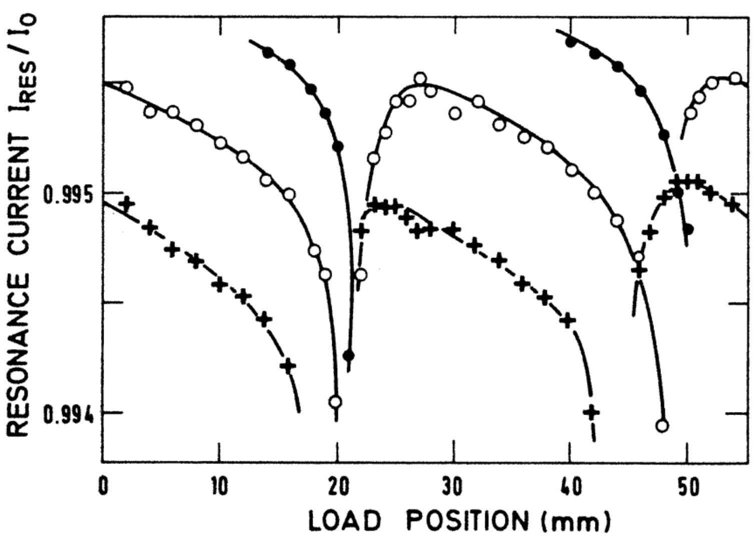
- Tracking photon parity of a cat state in real time

  Observing quantum jumps of photon parity:
  Sun, Petrenko et al., Nature **511**, 444 (2014).

# Before we met…

Some early influences:

- Koch, PhD thesis ~ 1985
- MQT:  Martinis, Devoret, Clarke,…
- Control/influence of EM environment!

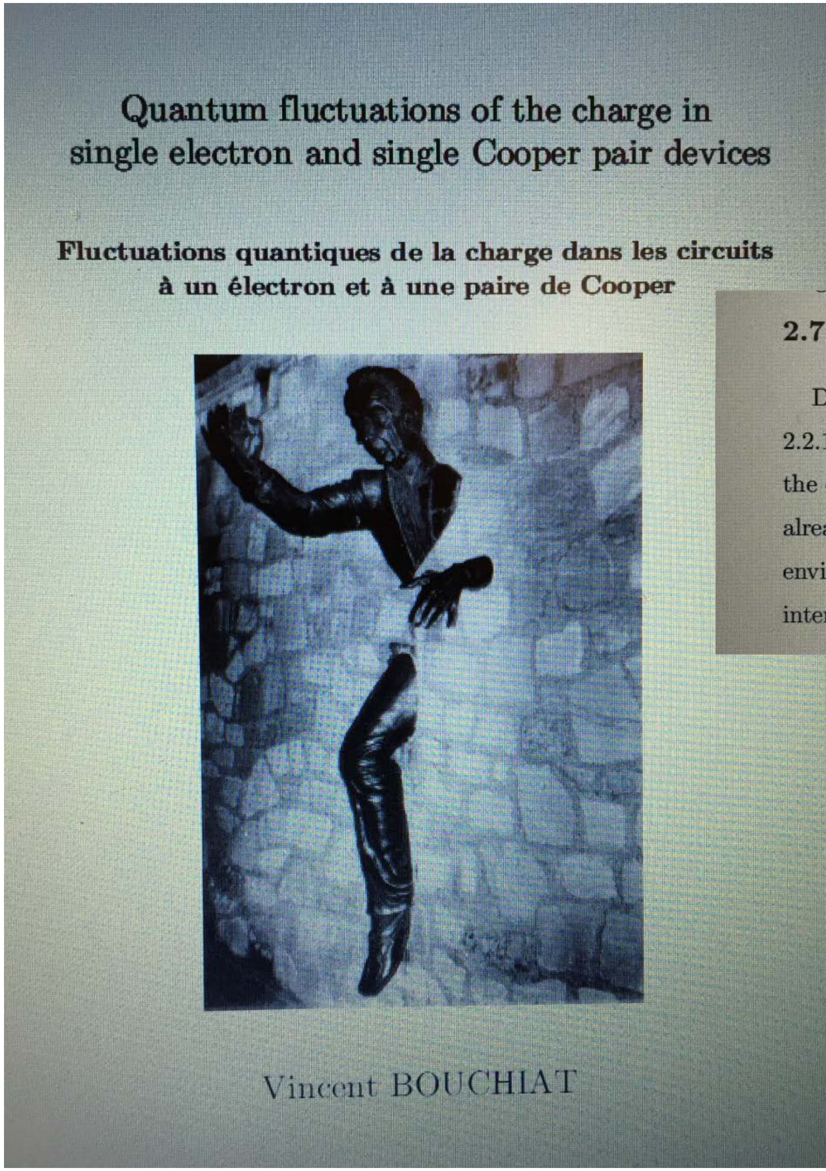



Devoret, Esteve, Martinis, and Urbina, 1989.

Forerunner of circuit QED!

In AMO language:
strong coupling, bad cavity limit

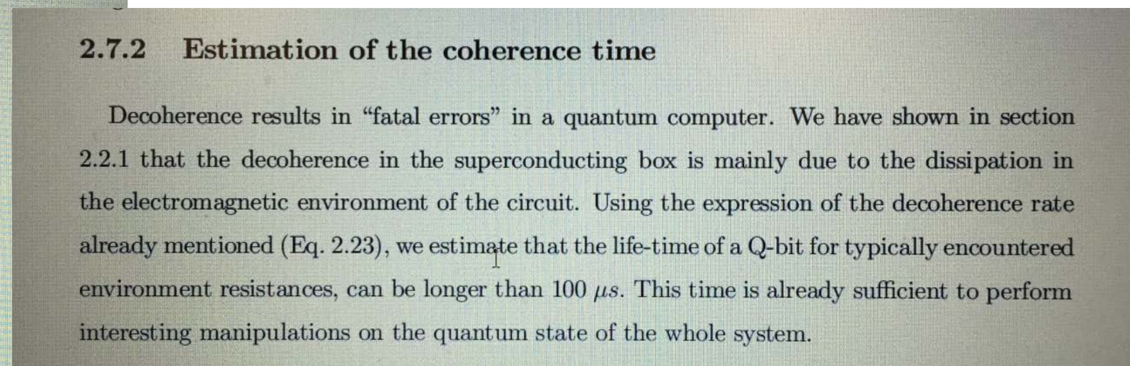
# Before we met…



Quantum fluctuations of the charge in single electron and single Cooper pair devices

**Fluctuations quantiques de la charge dans les circuits à un électron et à une paire de Cooper**

Vincent BOUCHIAT



**2.7.2 Estimation of the coherence time**

Decoherence results in "fatal errors" in a quantum computer. We have shown in section 2.2.1 that the decoherence in the superconducting box is mainly due to the dissipation in the electromagnetic environment of the circuit. Using the expression of the decoherence rate already mentioned (Eq. 2.23), we estimate that the life-time of a Q-bit for typically encountered environment resistances, can be longer than 100 $\mu s$. This time is already sufficient to perform interesting manipulations on the quantum state of the whole system.

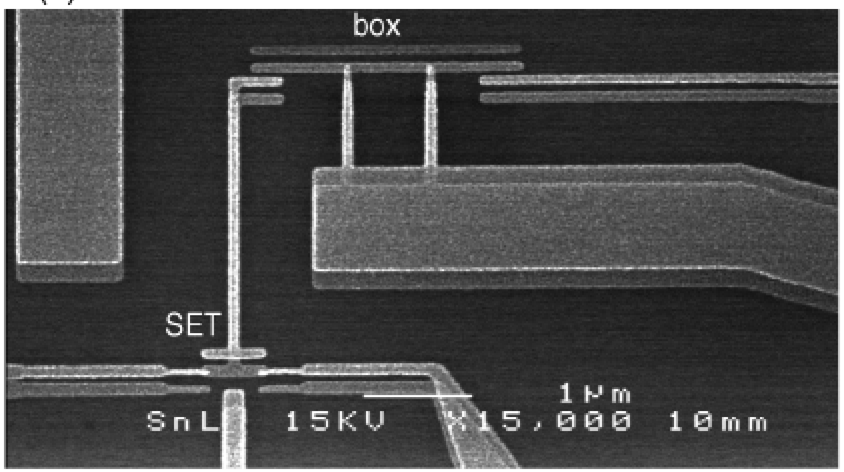
… decoherence…is mainly due to the… electromagnetic environment of the circuit. …we estimate that the life-time of a Q-bit …can be longer than 100 $\mu$s.

This is sufficient to perform interesting manipulations on the quantum state…

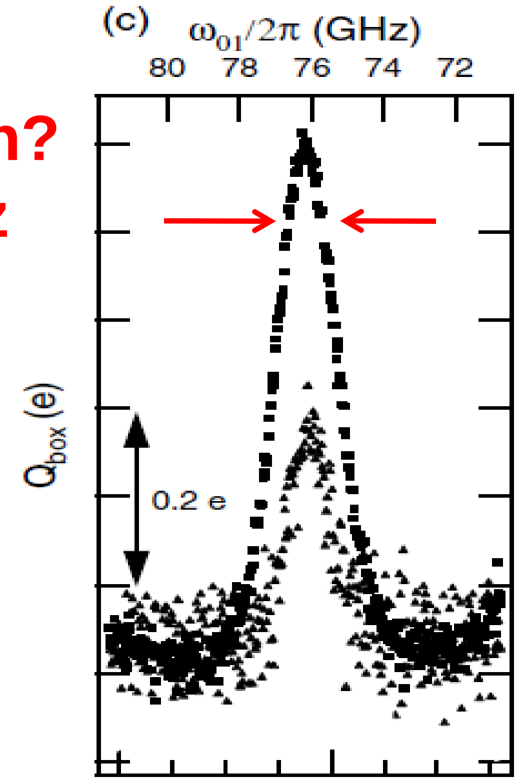
# When I began…

First Yale/Chalmers spectroscopy of Cooper-pair box, ca. 2000 -2002,
**aka Bouchiat + RF-SET**

(a)




**Linewidth?**
**~ 1 GHz**

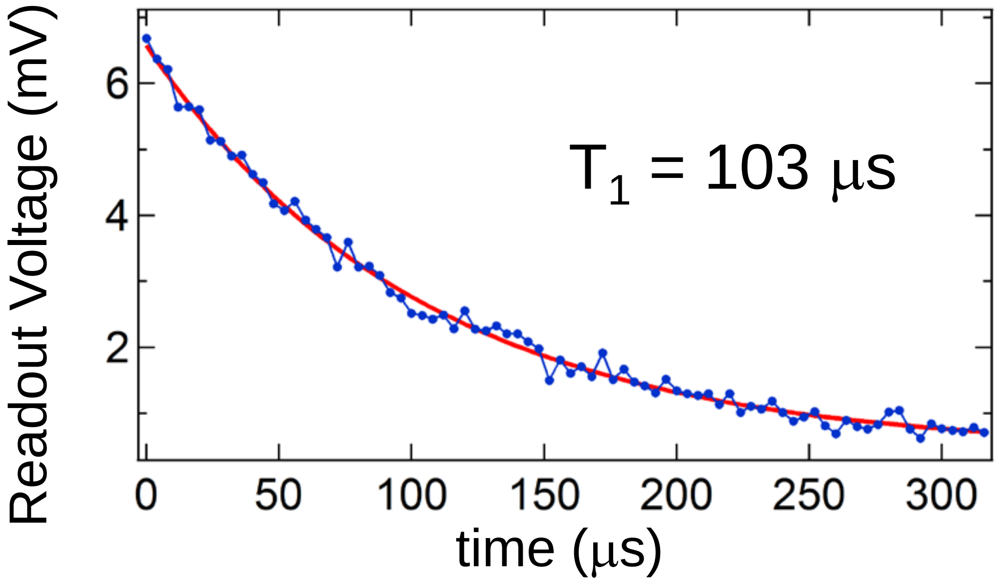



VOLUME 90, NUMBER 2 PHYSICAL REVIEW LETTERS week ending 17 JANUARY 2003

## Measurement of the Excited-State Lifetime of a Microelectronic Circuit

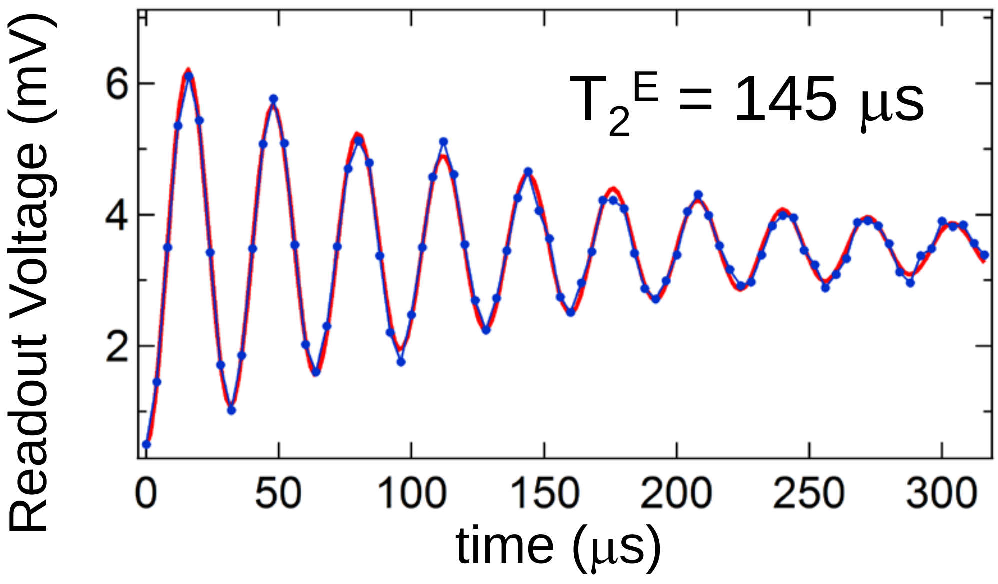
K. W. Lehnert,[1,*] K. Bladh,[2] L. F. Spietz,[1] D. Gunnarsson,[2] D. I. Schuster,[1] P. Delsing,[2] and R. J. Schoelkopf[1]
[1]*Department of Applied Physics and Physics, Yale University, New Haven, Connecticut 06511*
[2]*Microtechnology Center at Chalmers MC2, Department of Microelectronics and Nanoscience, Chalmers University of Technology and Göteborg University, SE-412 96, Göteborg, Sweden*
(Received 20 June 2002; published 17 January 2003)

# We've come a long way together…




A 3D transmon qubit

$$\frac{1}{T_2} = \frac{1}{2T_1} + \frac{1}{T_\phi}$$

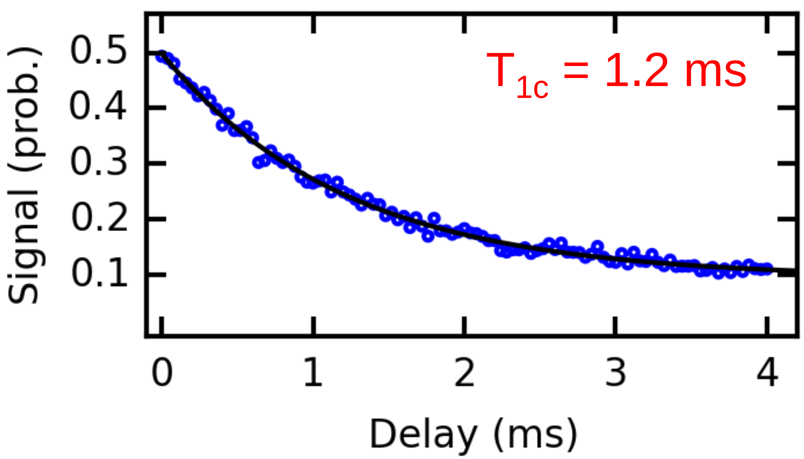


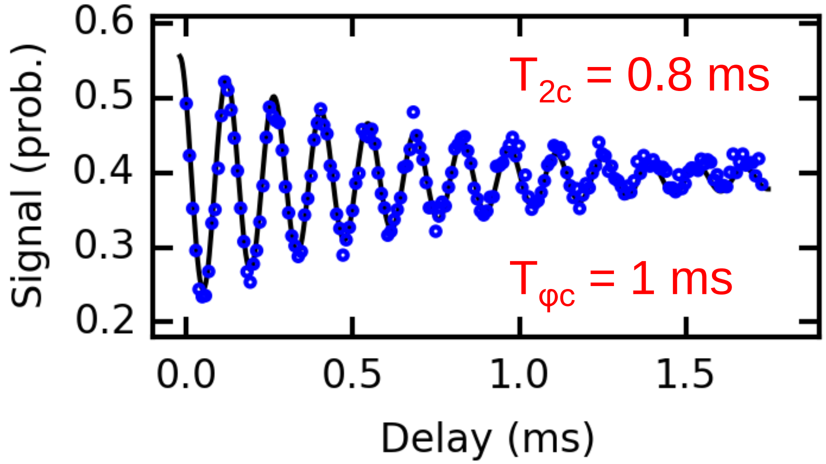

$$T_2^{\mathrm{echo}} \sim 1.5\, T_1$$

# Coherence of Photon States in Cavity


State preparation by SNAP:
*Heeres et al.,*
*arXiv:1503.01496,*
Thy: *Krastanov et al.,*
*arXiv: 1502.08015*

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



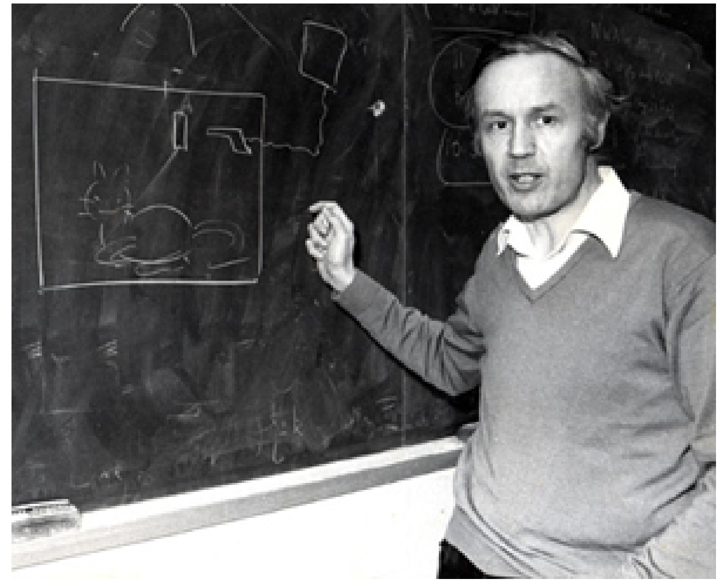

$\Delta f / f$ = 100 Hz / 4 GHz ~ 25 ppb !!

Reagor, Pfaff, et al., in preparation

Dephasing and relaxation actually limited by qubit…
(reverse Purcell and qubit thermal population)

# "Putting the Bell" on Schrodinger's Cat

"The mice in council"
Gustave Dore, ca. 1868



courtesy University of Illinois, Urbana-Champaign

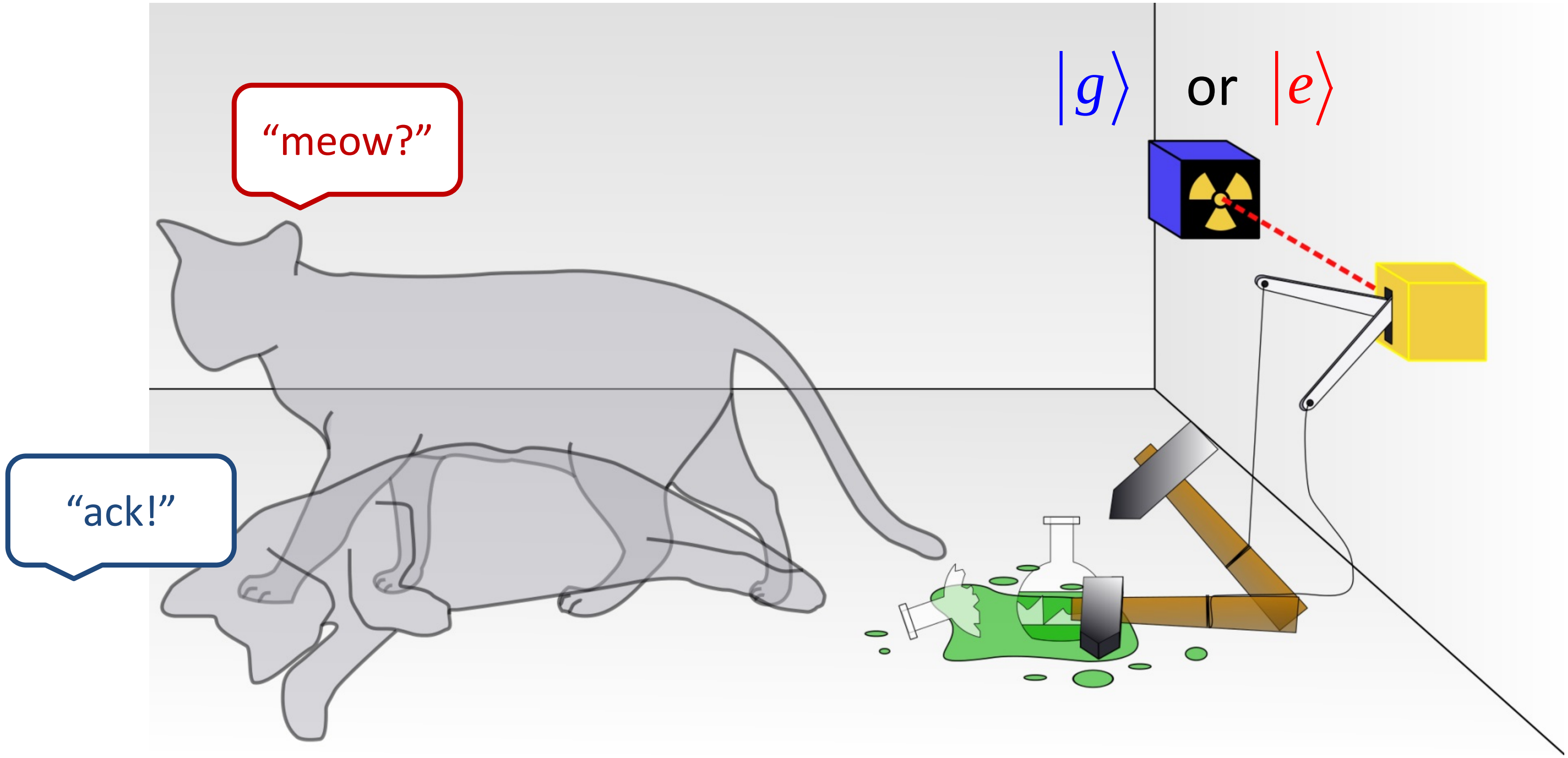
"But who will volunteer to place it?"

Violation of a CHSH inequality
for a macroscopic quantum state

Petrenko, Vlastakis, et al., submitted (2015).

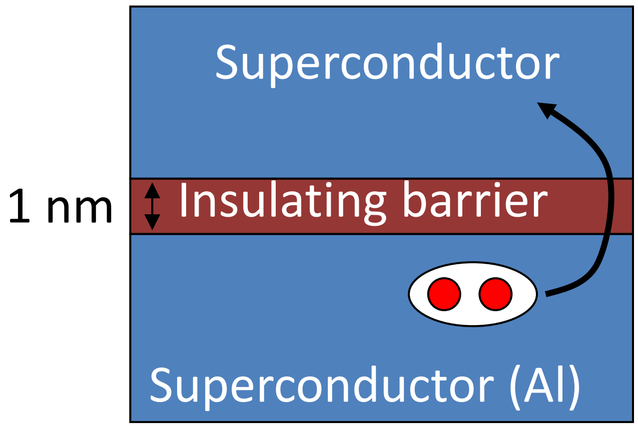
# Schrodinger's Cat

= an entangled state between a microscopic object (atom or qubit) and a macroscopic object (easily distinguished by "environment")

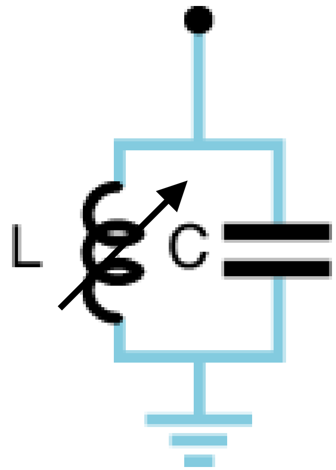



$$\Psi = \frac{1}{\sqrt{2}}\left(|e\rangle|\text{alive}\rangle + |g\rangle|\text{dead}\rangle\right)$$ ??

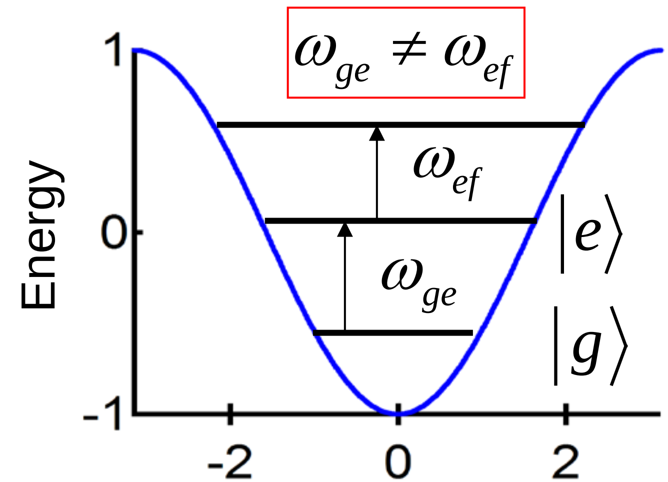
# Atom: The Transmon Qubit




Josephson junction
(dissipation-free?)




Non-linear
electromagnetic
oscillator




$\omega_{ge} \sim 5-10\,\mathbf{GHz}$

$\hbar\omega/\mathbf{k}_B \sim 0.25\,\mathbf{K}$

$$H = \frac{\hat{Q}^2}{2C} - E_J \cos\left(\frac{2\pi}{\Phi_0}\hat{\Phi}\right) = \hbar\omega_{ge}\; a^\dagger a - \lambda a^\dagger a^\dagger a a + \ldots$$

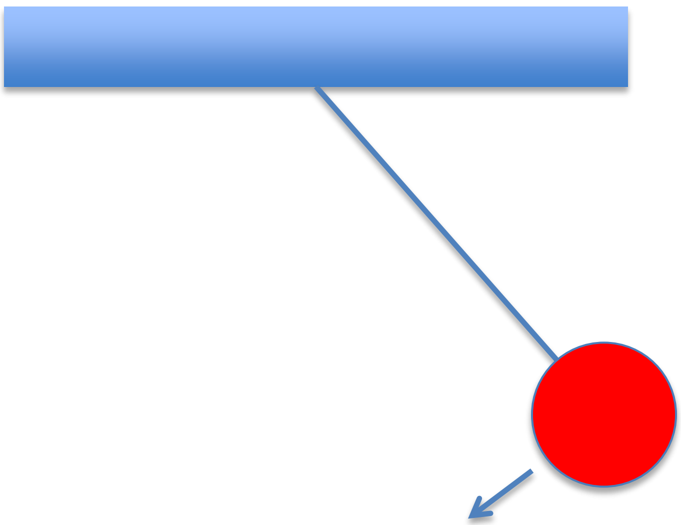
$$H \approx \hbar\omega_{ge} |e\rangle\langle e|$$

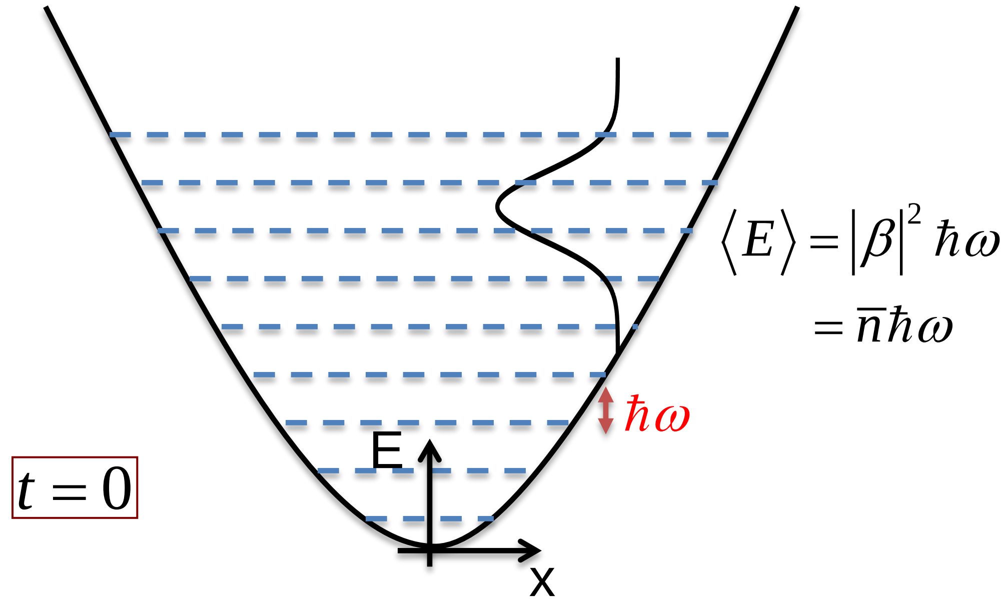
Koch et al., PRA, 2007; Houck et al., PRL, 2008

Other practitioners (many!): UCSB/Google, Berkeley, Princeton, Delft, Zurich, Chicago…

# The Cat: A Cavity Oscillator

if we can only apply classical controls (e.g. laser, force), can only make displacements

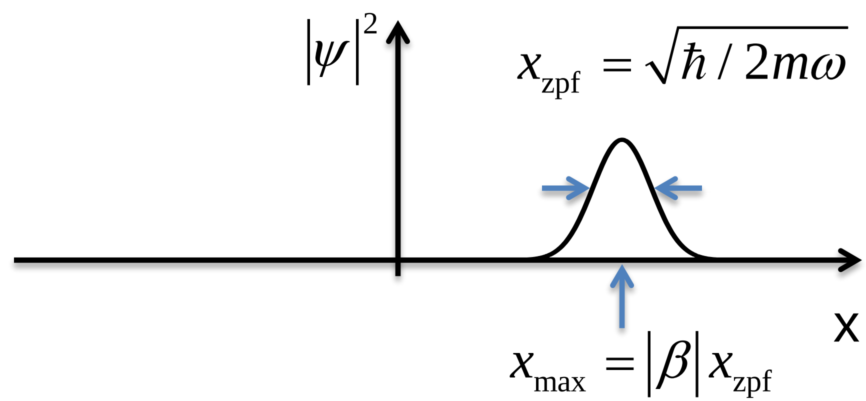




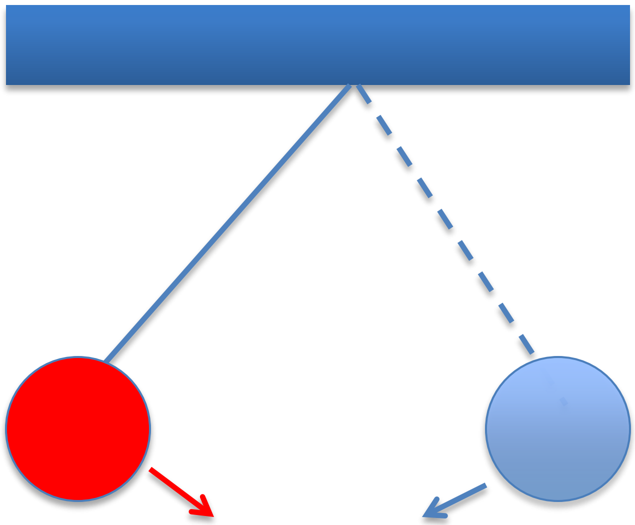

Glauber (coherent) state

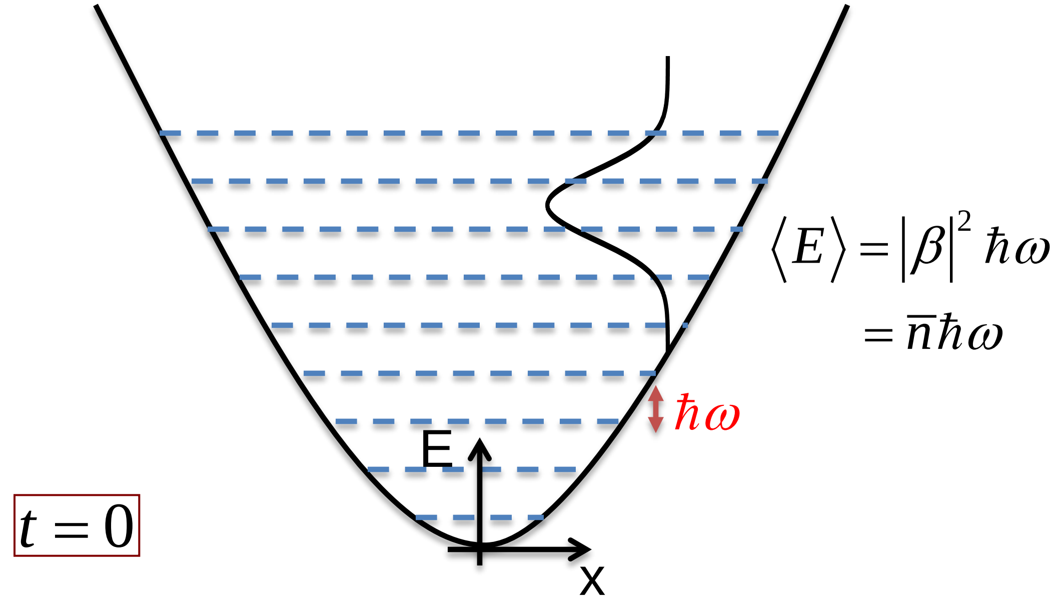
$$|\beta\rangle = e^{-\frac{|\beta|^2}{2}} \sum_{n=0}^{\infty} \frac{\beta^n}{\sqrt{n!}} |n\rangle$$

$$\hat{a}|\beta\rangle = \beta|\beta\rangle$$



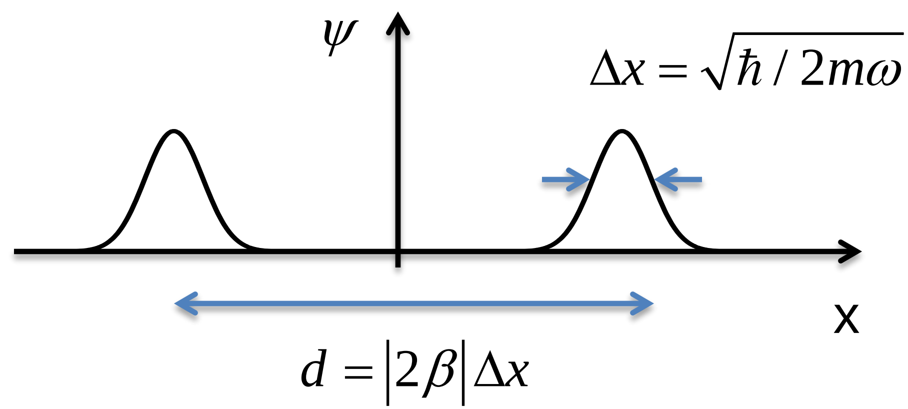
# What's a Cat State of an Oscillator?






Cat state of an oscillator (field)

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

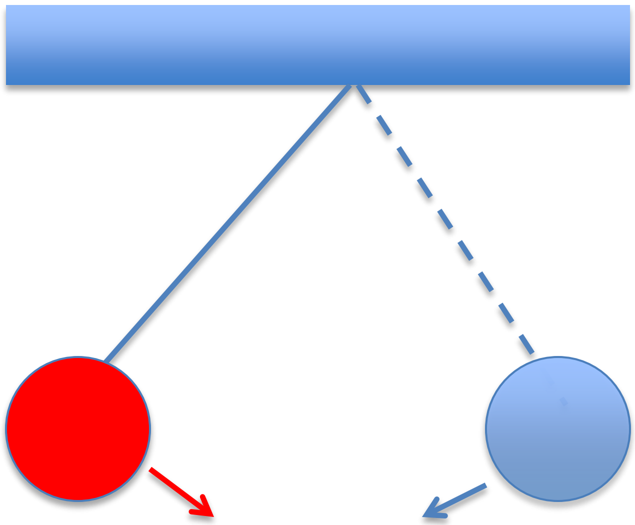


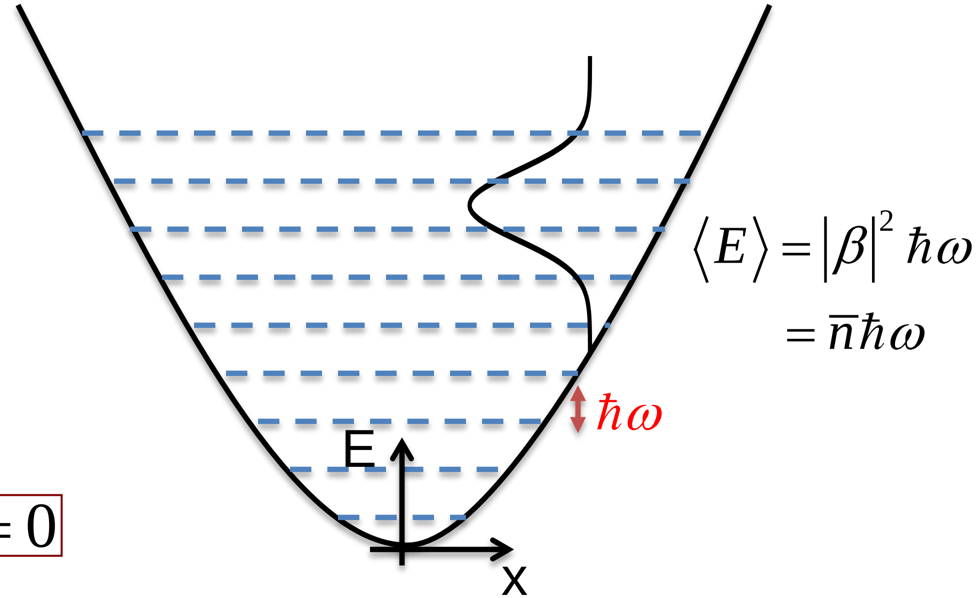

Size of the superposition, d:

$$d^2 = 4|\beta|^2 = 4\bar{n}$$

Bigger cats die faster: rate = $d^2\kappa$

# What's a Cat State of an Oscillator?



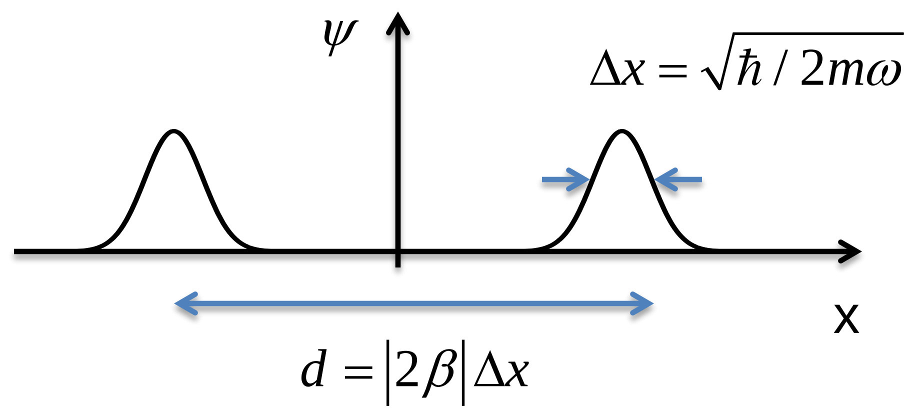



$t = 0$

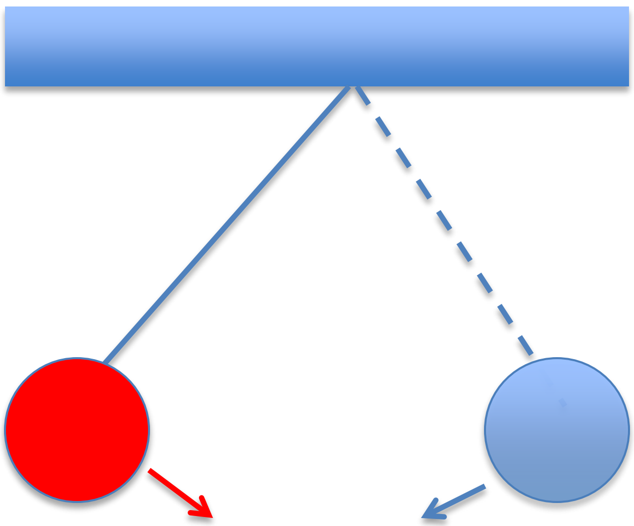
Cat state of an oscillator (field)

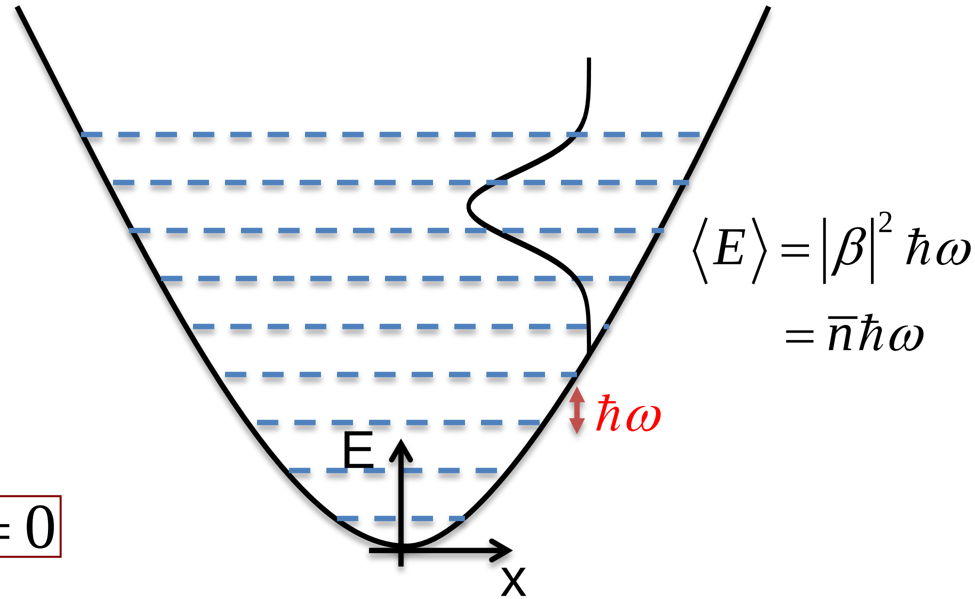
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\beta\rangle + |-\beta\rangle\right)$$

This one is **EVEN** parity!



# What's a Cat State of an Oscillator?



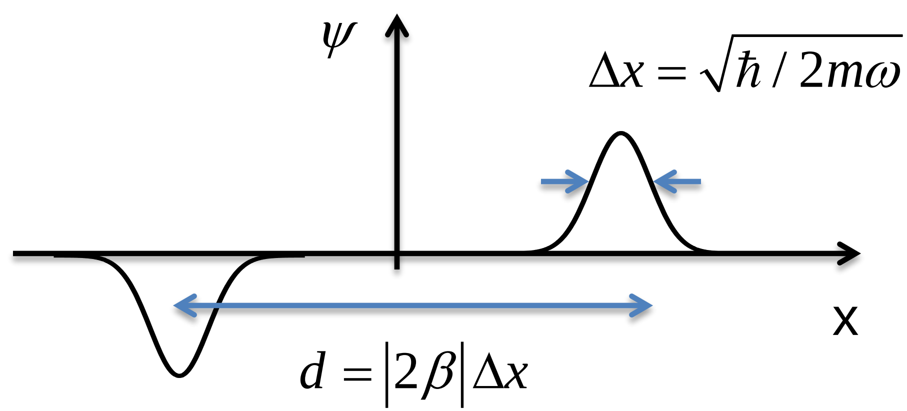



$t = 0$

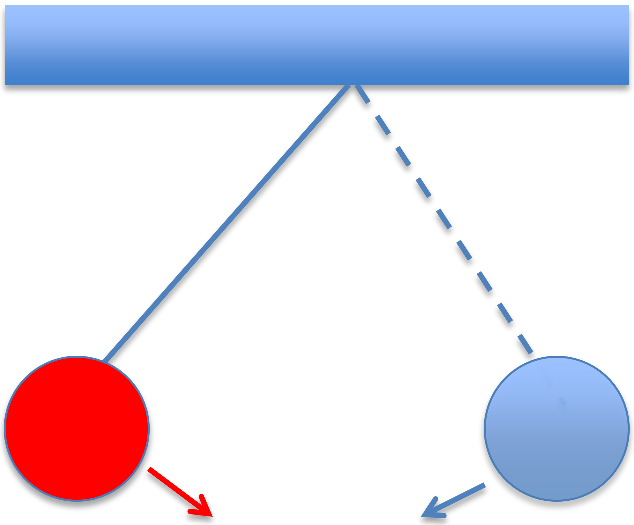
Cat state of an oscillator (field)

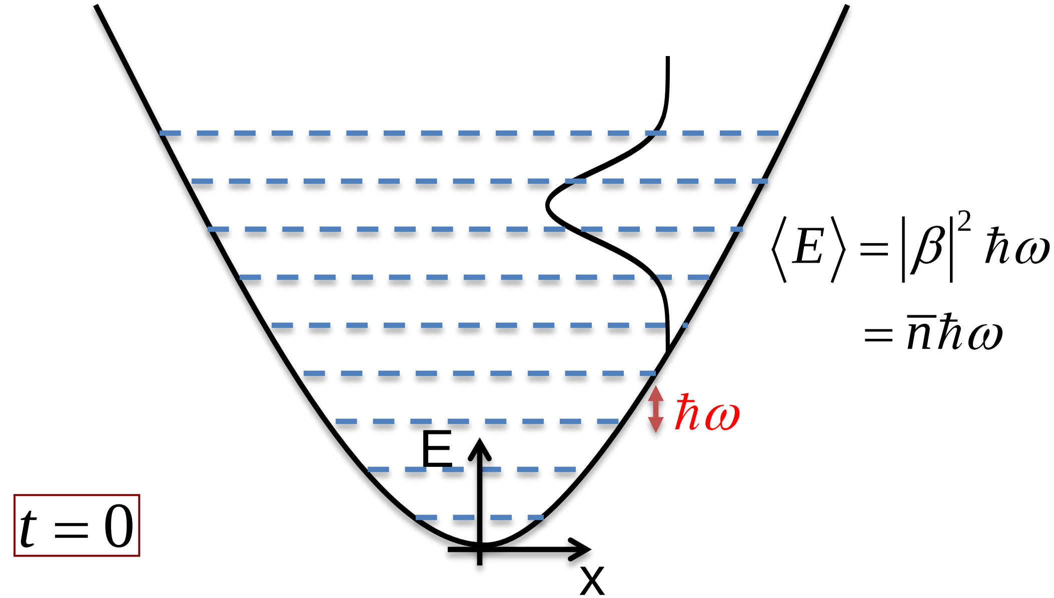
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|\beta\rangle - |-\beta\rangle\right)$$

This one is **ODD** parity!



# What's a Cat State of an Oscillator?



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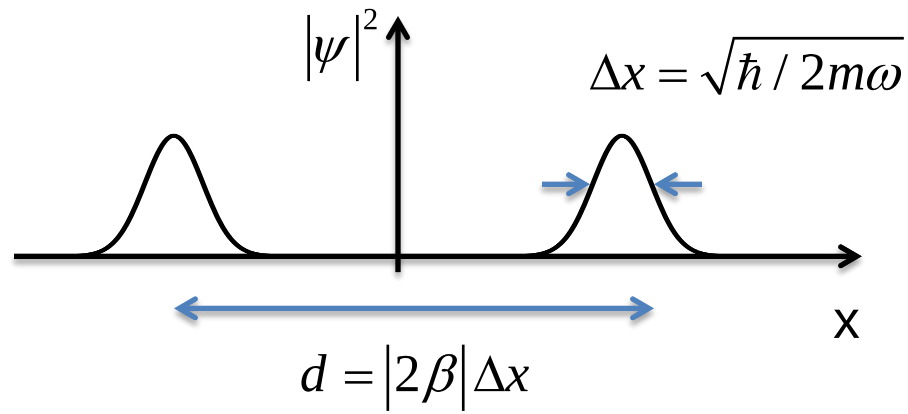
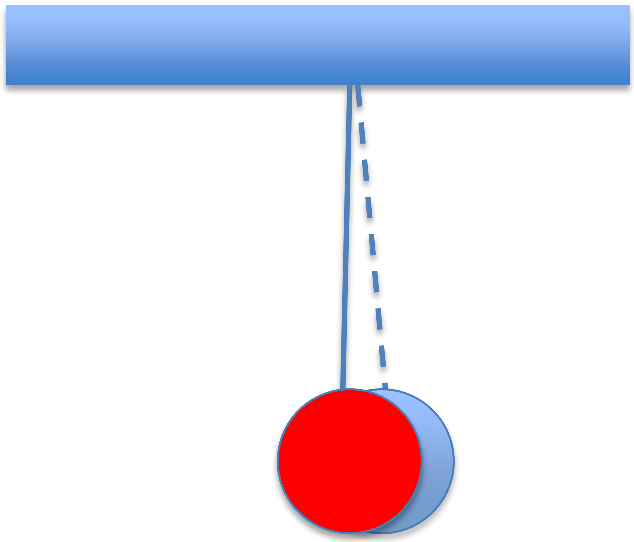
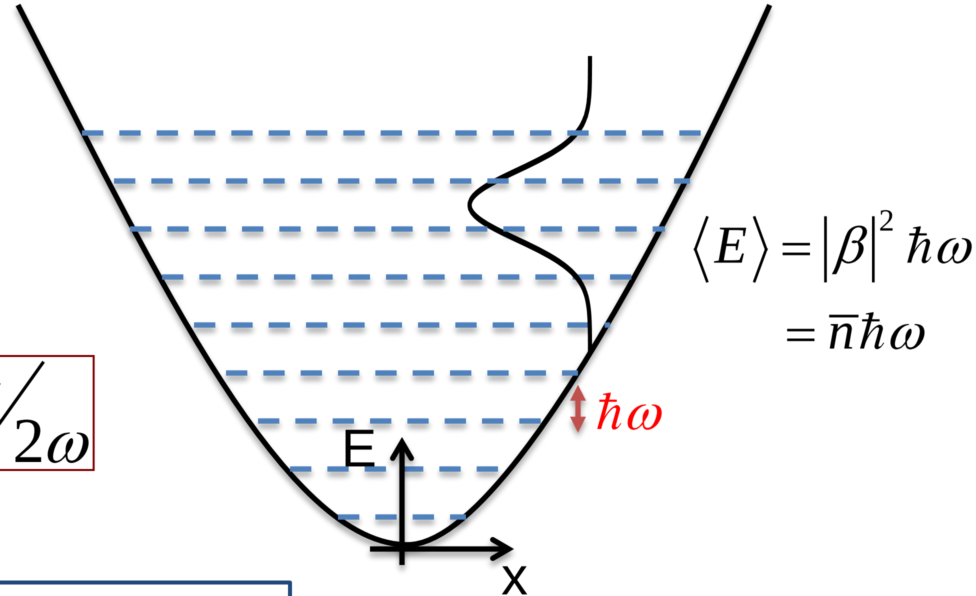


# What’s a Cat State of an Oscillator?



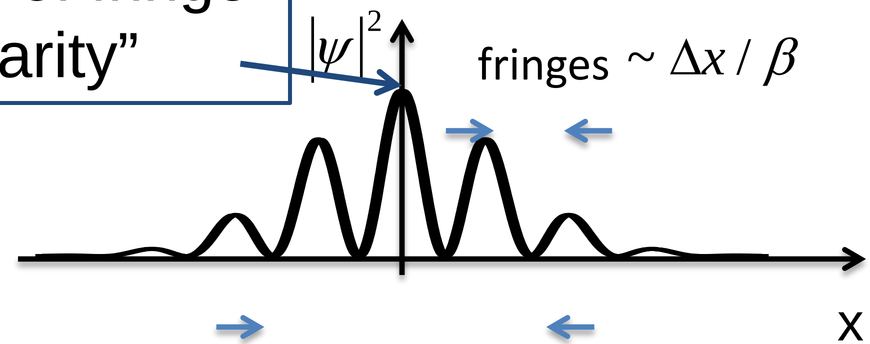
$$t = \pi / 2\omega$$




Schrödinger cat state

The sign of fringe = “parity”

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




What happens now, when packets collide?

$$\Delta x = \sqrt{\hbar / 2m\omega}$$

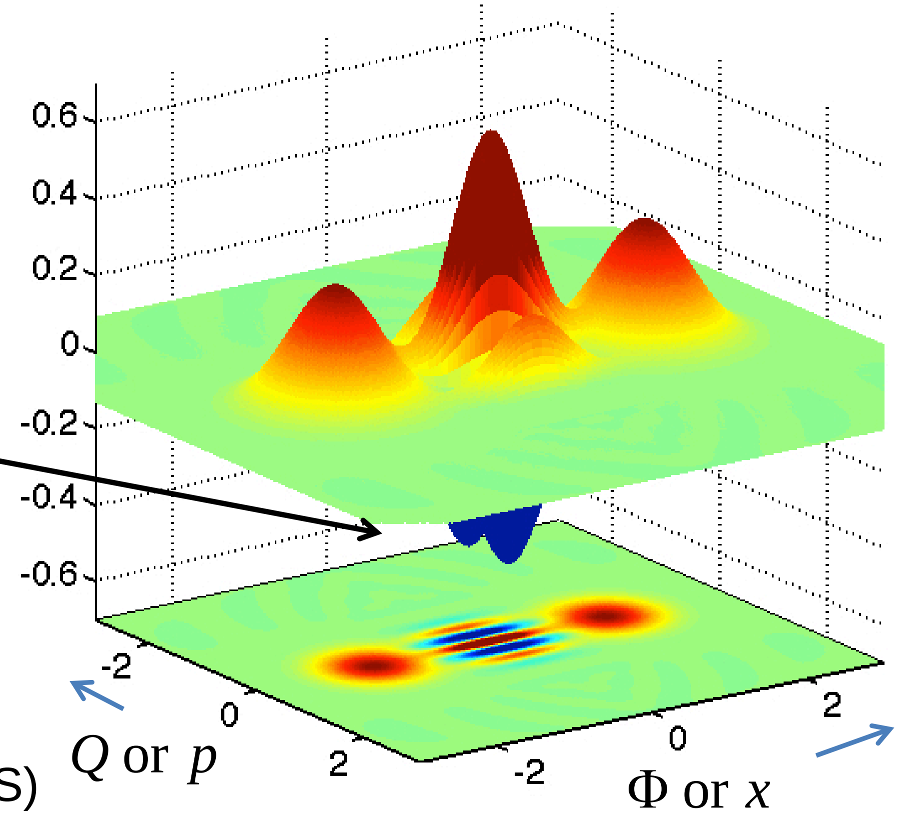
# Seeing the Interference: Wigner Function

$$W(\alpha_m) = \frac{2}{\pi} Tr\left\{D(-\alpha_m)\rho D(\alpha_m)P\right\}$$

Parity $P = e^{i\pi a^\dagger a} = \left(-1\right)^n$

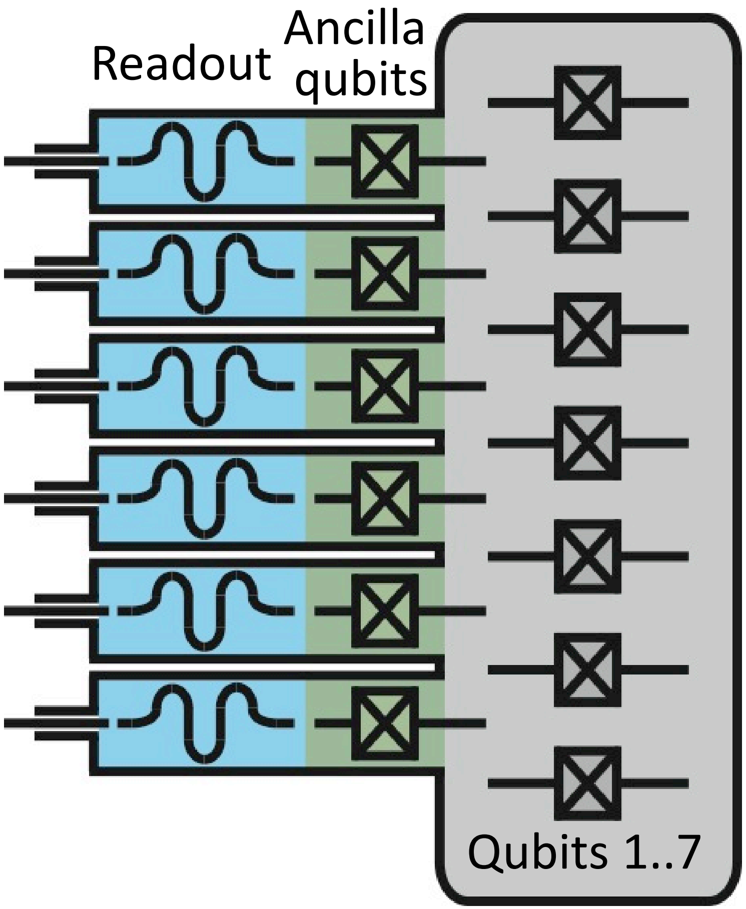
Thy:

Negative fringes = "whiskers"



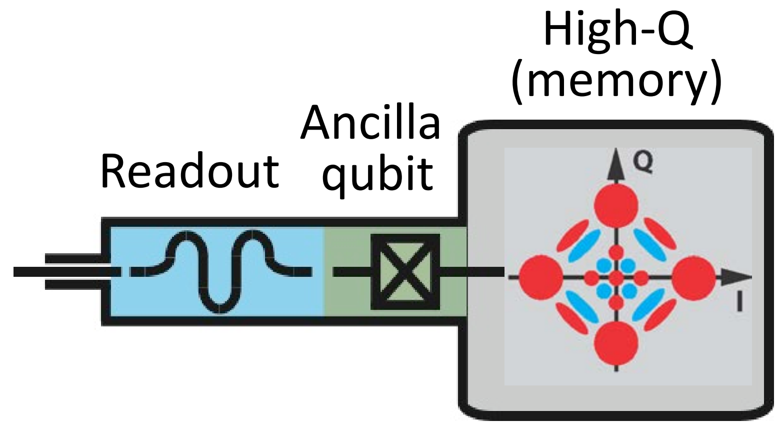

Expt'l. Wigner tomography:
Leibfried et al., 1996 ion traps (NIST)
Haroche/Raimond , 2008 Rydberg (ENS)
Hofheinz et al., 2009 in circuits (UCSB)

# Using a Cavity as a Logical Qubit?




"Hardware-efficient QEC"

Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).




Register as memory:

1. More qubits
2. More decay channels

Our approach :

- Cavity is the memory
- One error syndrome

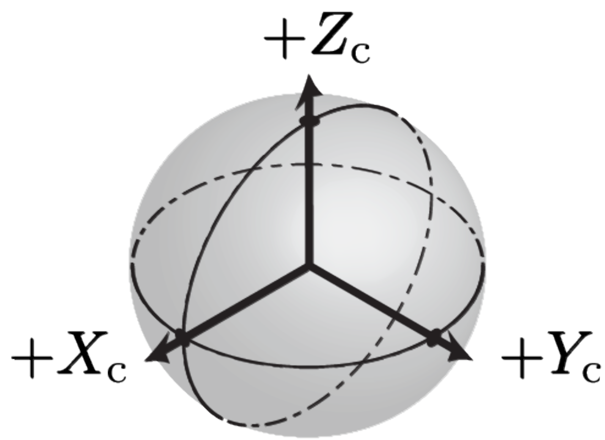
1. 1 qubit!
2. Single readout channel!

*earlier ideas: Gottesman, Kitaev & Preskill, PRA 64 , 012310 (2001)*

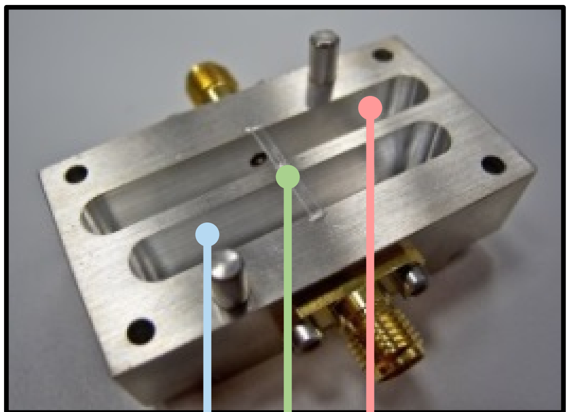
# Encoding a Quantum Bit in a Cavity State

Continuous Variable (e.g. cavity)

2-Level System (e.g. transmon)



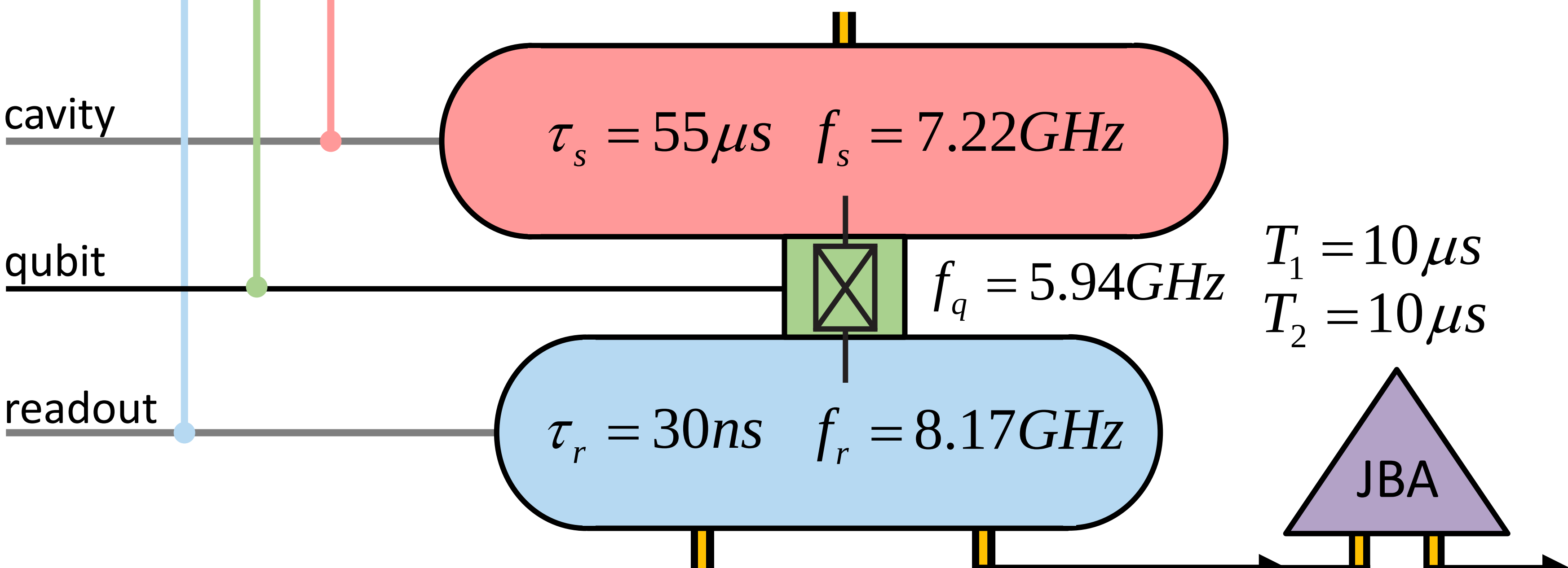
# Dispersive cQED Coupling:
# 2 Cavities + 1 Qubit + Paramp



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

$F_R = 98\%$ Readout Fidelity

$F_P = 95\%$ Parity Readout Fidelity



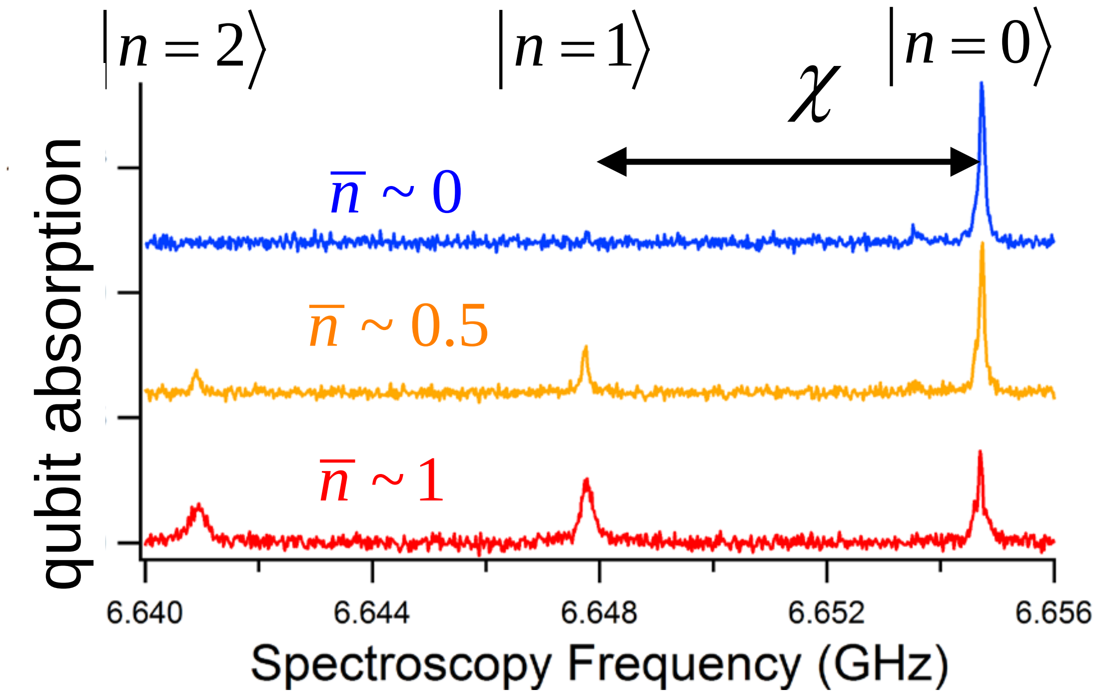
# Strong* Dispersive Regime

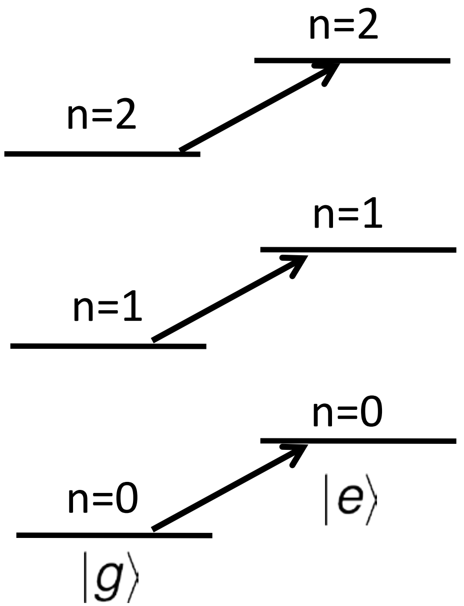
Dispersive Hamiltonian: $\chi \gg \gamma, \kappa$ $\qquad$ $\chi \sim g^2 / (\omega_s - \omega_q)$

$$H = \hbar\omega_q |e\rangle\langle e| + \hbar\omega_s a^\dagger a - \hbar\chi a^\dagger a |e\rangle\langle e|$$

"doubly-QND" interaction

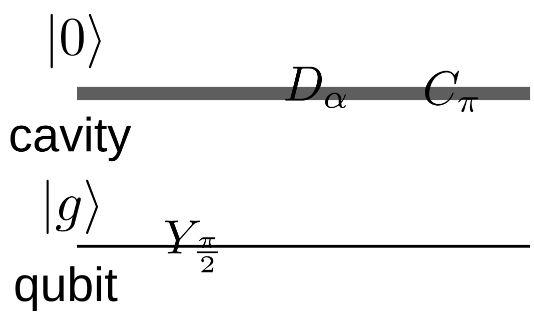
Allows qubit to control many photons at once (and vice-versa)



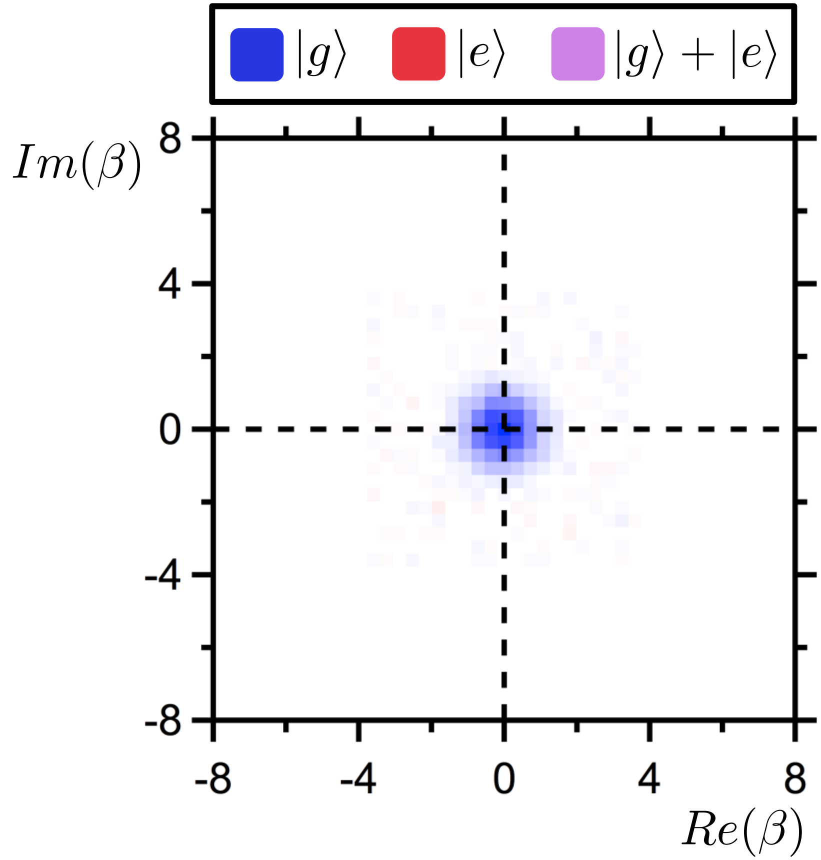

* Schuster et al., 2007; prev. attained only in Rydberg cQED (ENS-Paris)

# Deterministic Cat Creation: QCMAP Gate



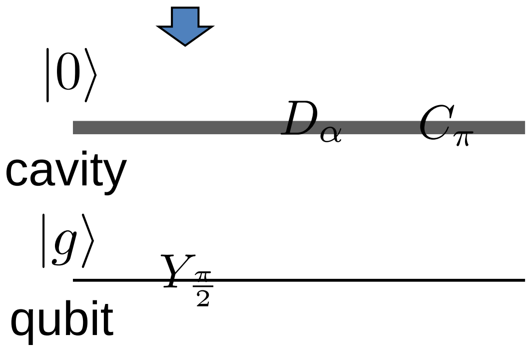

$$|\psi\rangle = |g\rangle \otimes |0\rangle$$

$$Q(\beta) = \langle \beta | \hat{\rho} | \beta \rangle$$



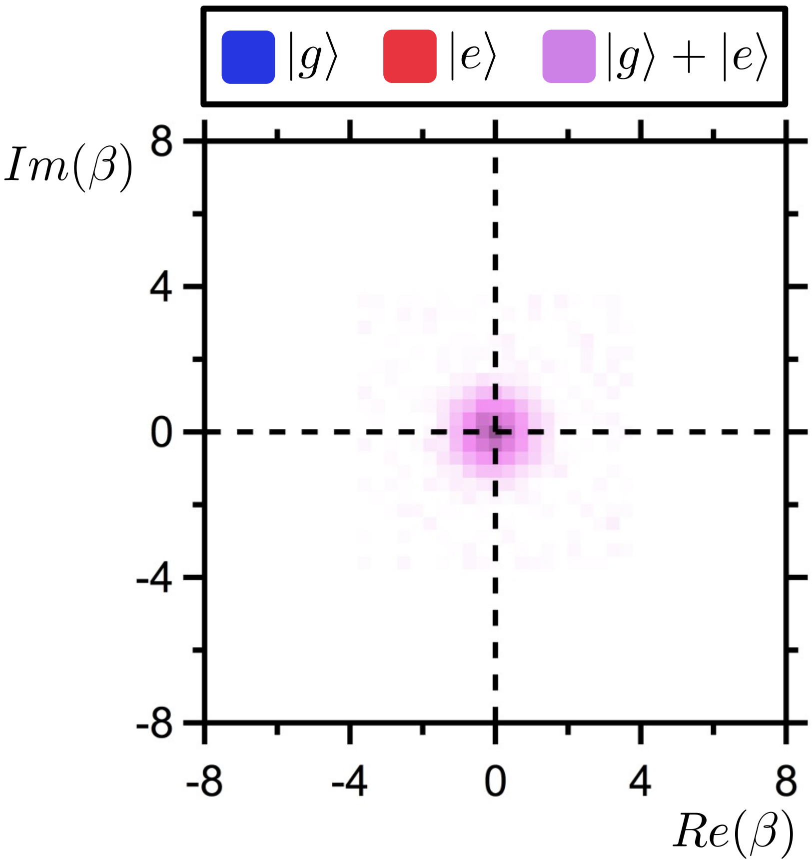

Theory:
Leghtas et al., Phys. Rev A 87, 042315 (2013)

# Deterministic Cat Creation: QCMAP Gate




$$|\psi\rangle = N\left(|g\rangle + |e\rangle\right) \otimes |0\rangle$$

$$Q(\beta) = \langle \beta | \hat{\rho} | \beta \rangle$$

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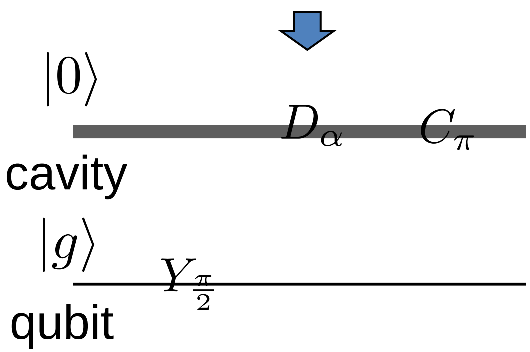
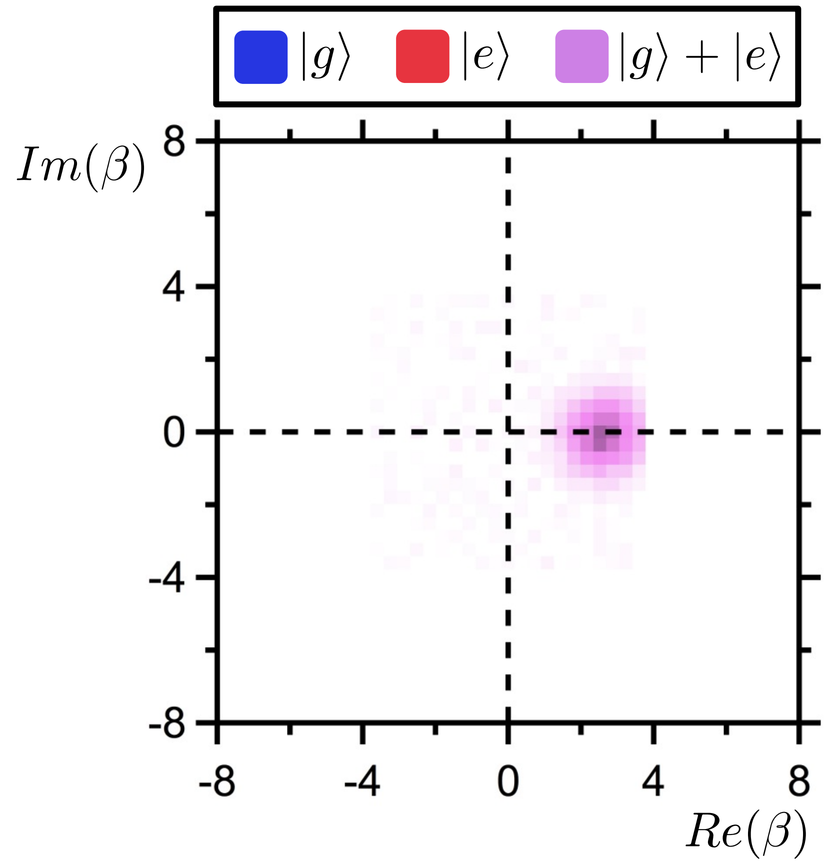
# Deterministic Cat Creation: QCMAP Gate




$$|\psi\rangle = N\left(|g\rangle + |e\rangle\right) \otimes |\beta\rangle$$

$$Q(\beta) = \langle\beta|\hat{\rho}|\beta\rangle$$

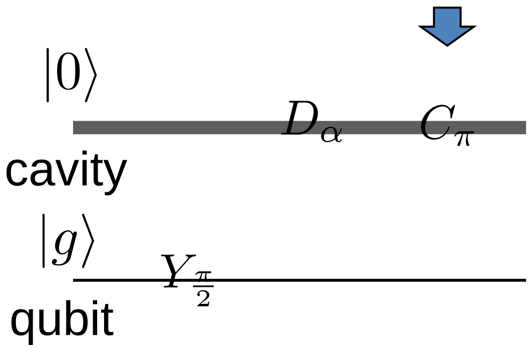


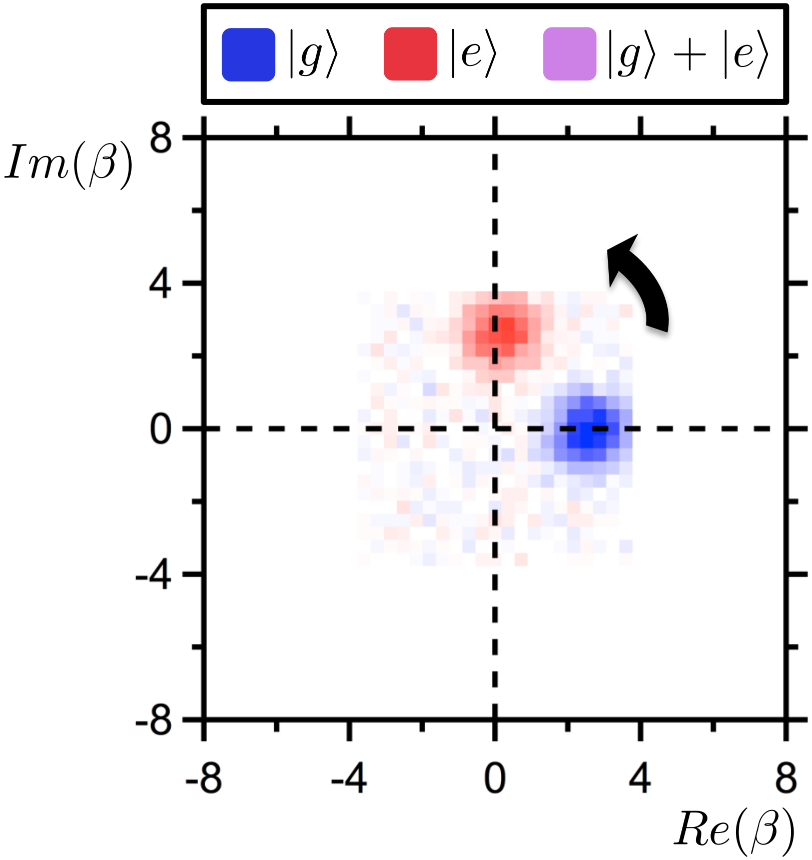

Theory:
Leghtas et al., Phys. Rev A 87, 042315 (2013)

# Deterministic Cat Creation: QCMAP Gate

$$H_{\text{int}} = \hbar\chi a^{\dagger}a|e\rangle\langle e|$$

$$Q(\beta) = \langle\beta|\hat{\rho}|\beta\rangle$$




$$|\psi\rangle = N\left(|g,\beta\rangle + |e,\beta e^{-i\chi t}\rangle\right)$$

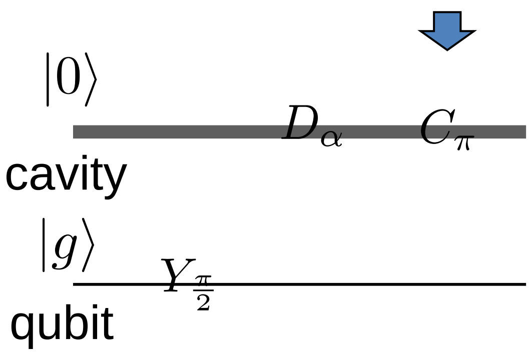
Theory:

Leghtas et al., Phys. Rev A 87, 042315 (2013)

# Deterministic Cat Creation: QCMAP Gate

$$H_{\text{int}} = \hbar\chi a^{\dagger} a |e\rangle\langle e|$$

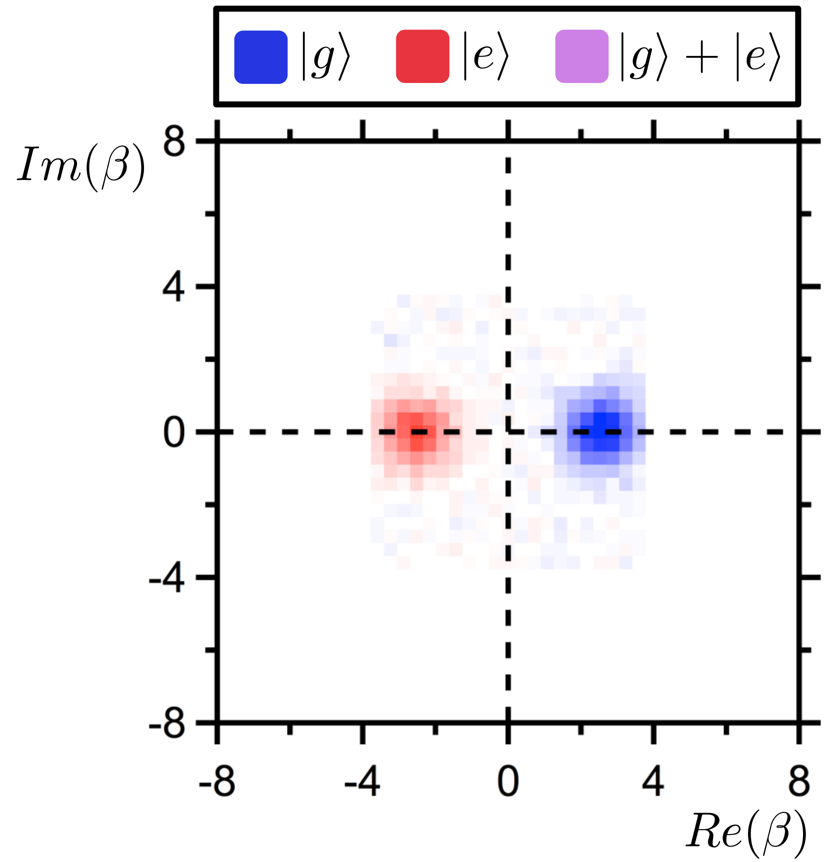
after time: $t = \pi/\chi$




$$|\psi\rangle = N\left(|g,\beta\rangle + |e,-\beta\rangle\right)$$

"Here be kittens!"

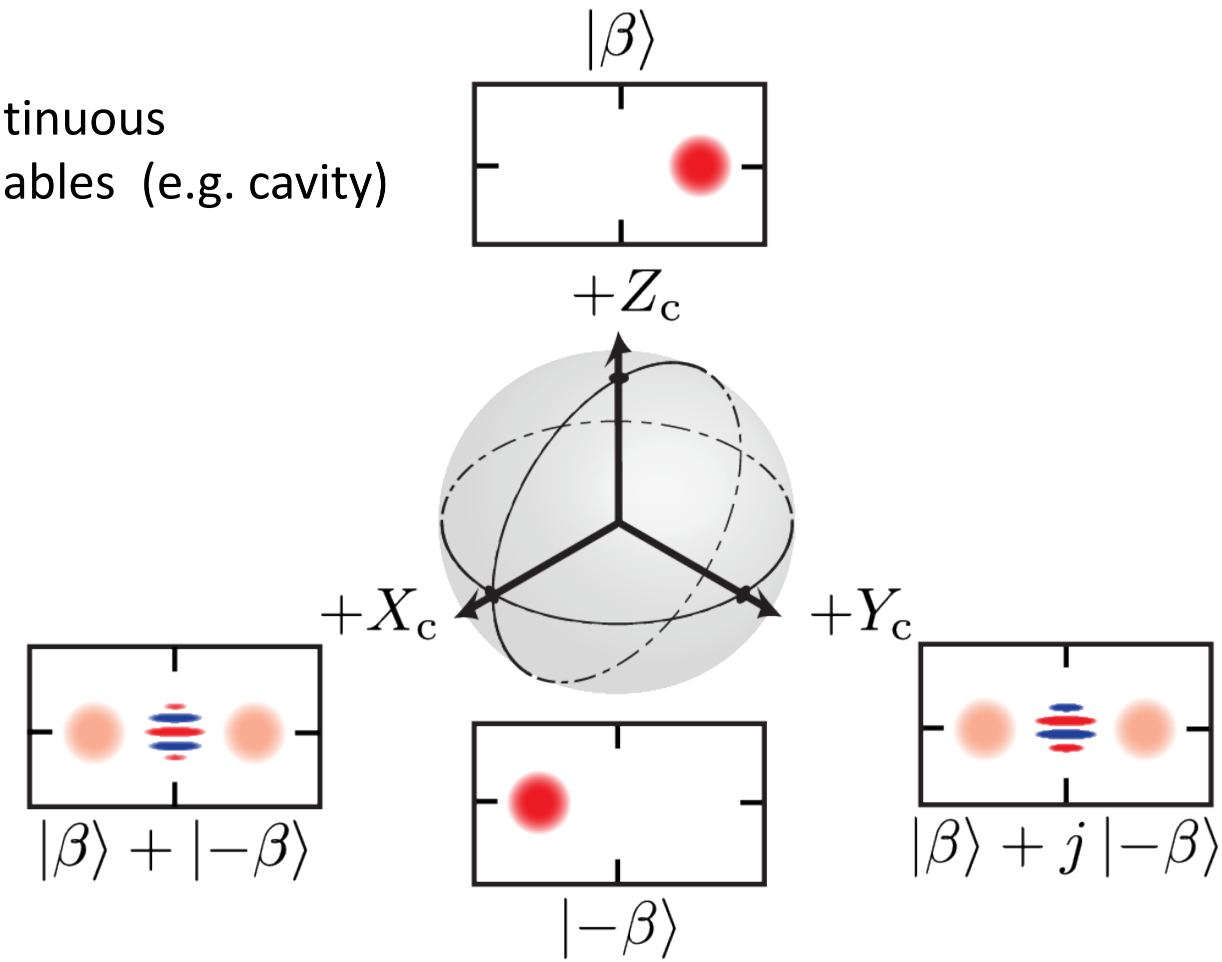
$$Q(\beta) = \langle\beta|\hat{\rho}|\beta\rangle$$




Theory:
Leghtas et al., Phys. Rev A 87, 042315 (2013)

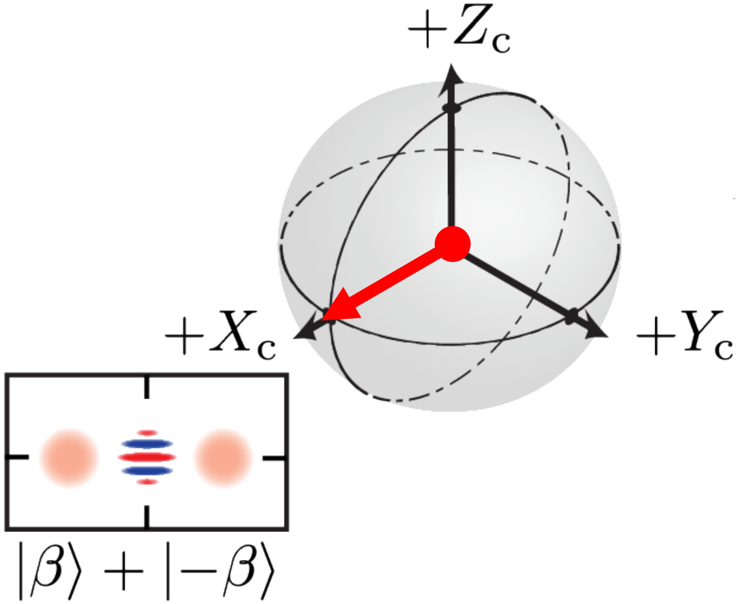
# Encoding a Quantum Bit in a Cavity State

Continuous
Variables (e.g. cavity)

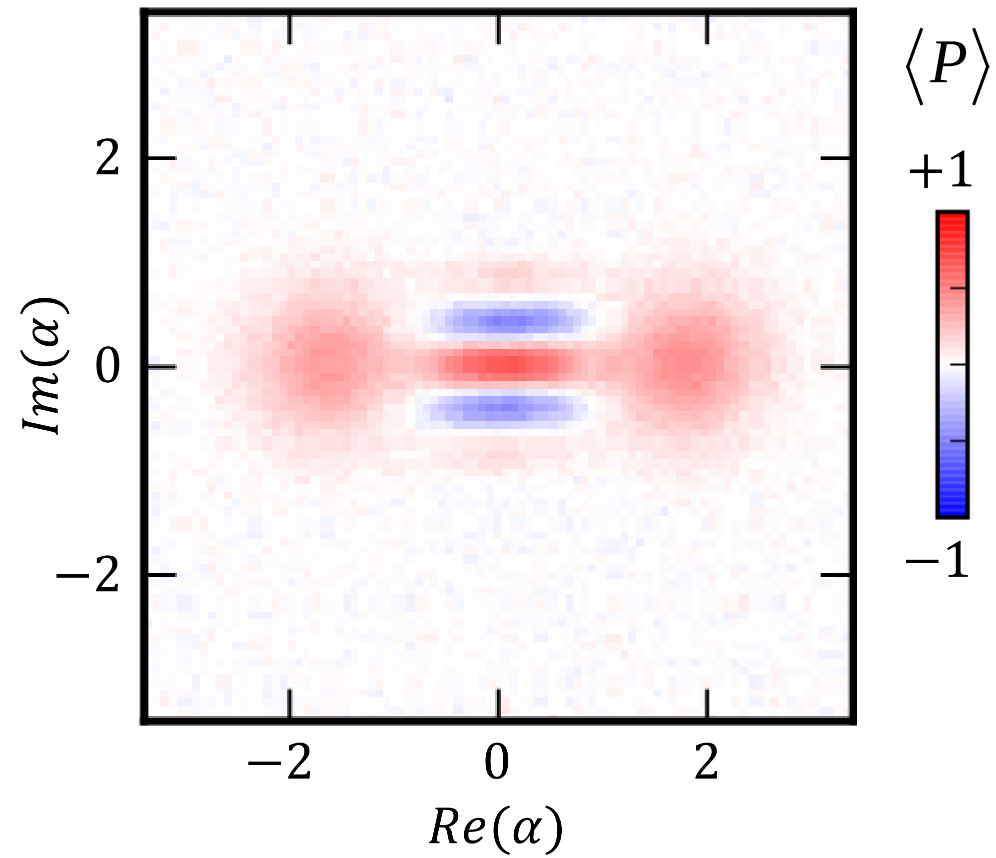


# Efficiently Measuring $X_c, Y_c, Z_c$

## Cavity state along $X_c$

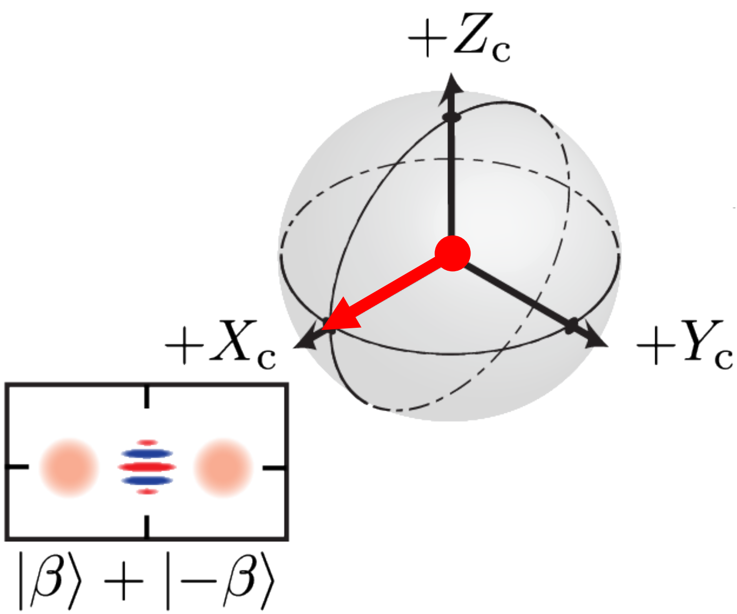


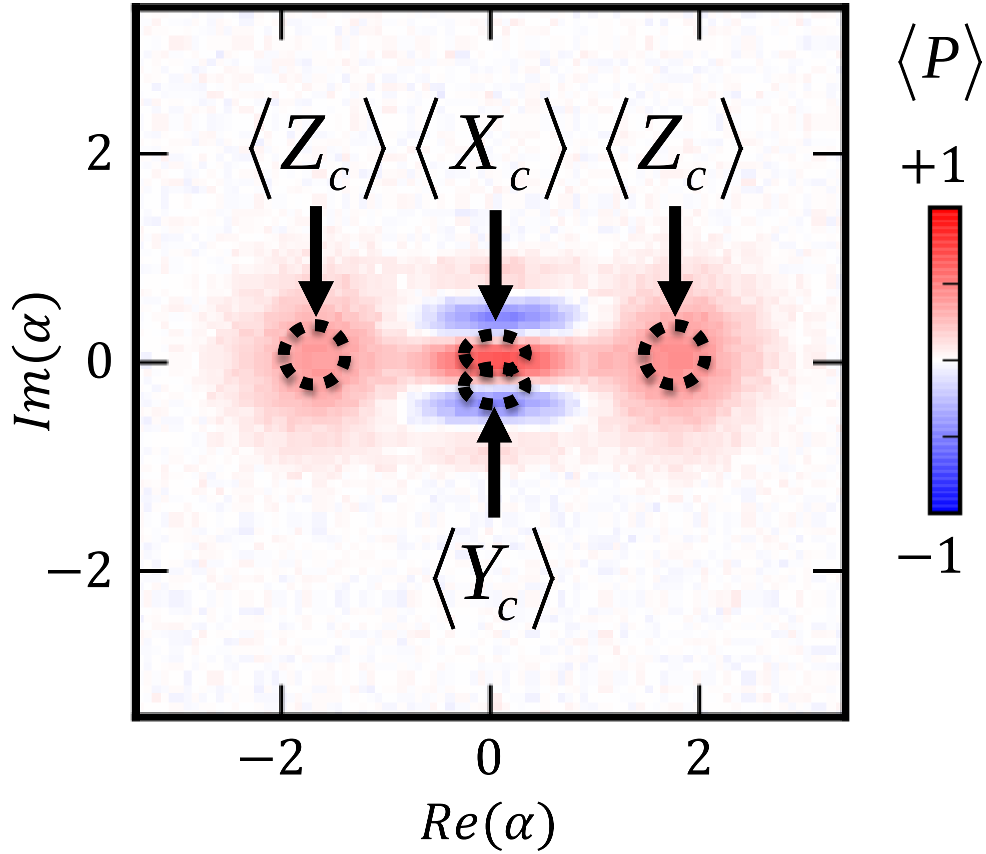

Measured Wigner function of cavity



# Efficiently Measuring $X_c, Y_c, Z_c$

Cavity state along $X_c$



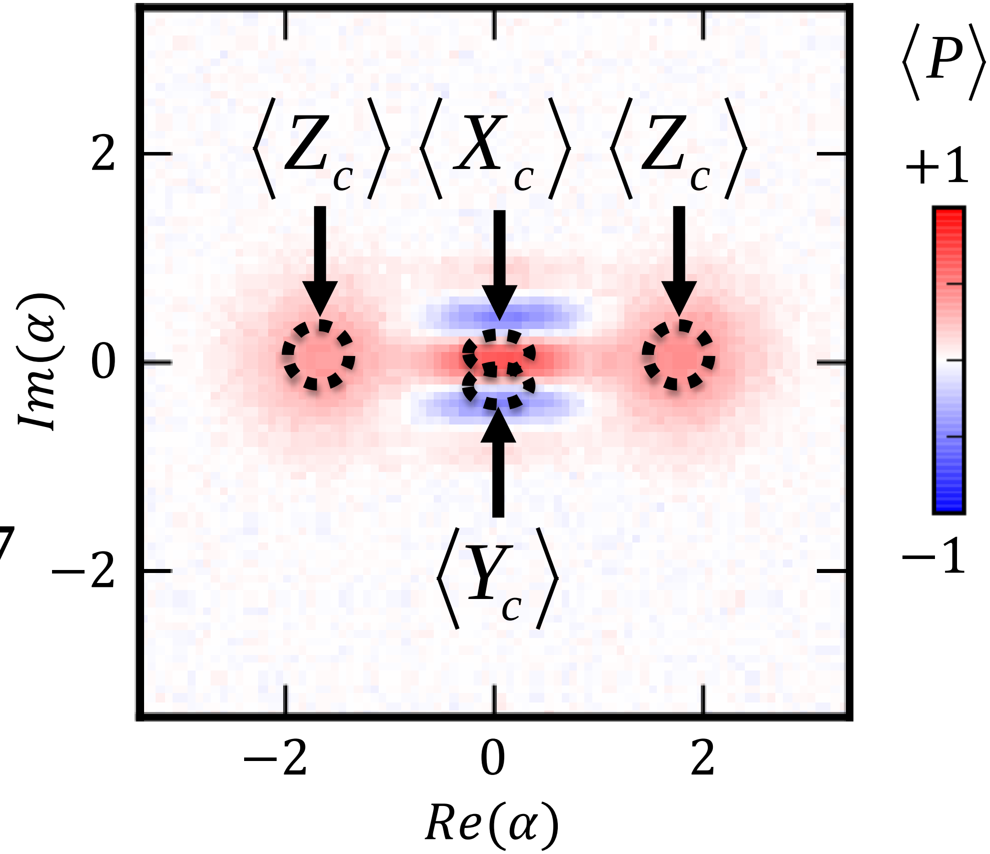
# Efficiently Measuring $X_c, Y_c, Z_c$

## Cavity state along $X_c$

$$\langle X_c \rangle = \langle P_0 \rangle = 0.76$$

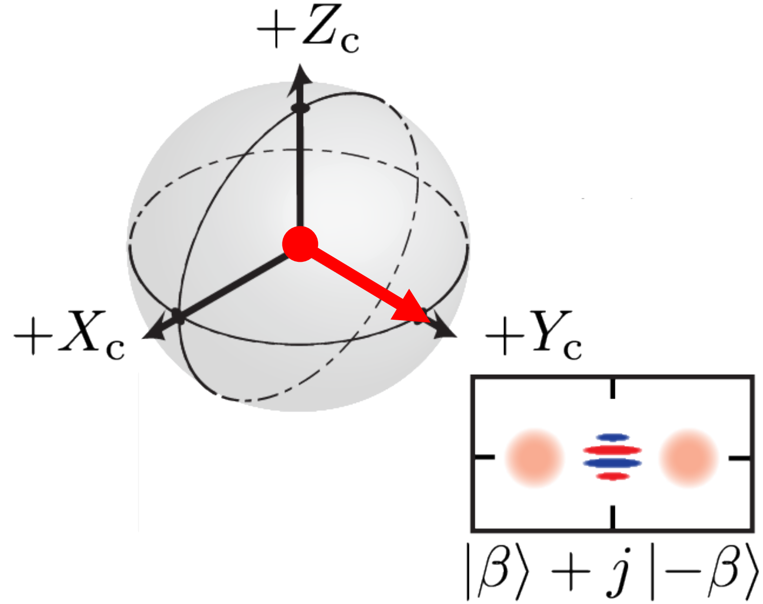
$$\langle Y_c \rangle = \left\langle P_{j\pi/8\beta} \right\rangle = 0.14$$

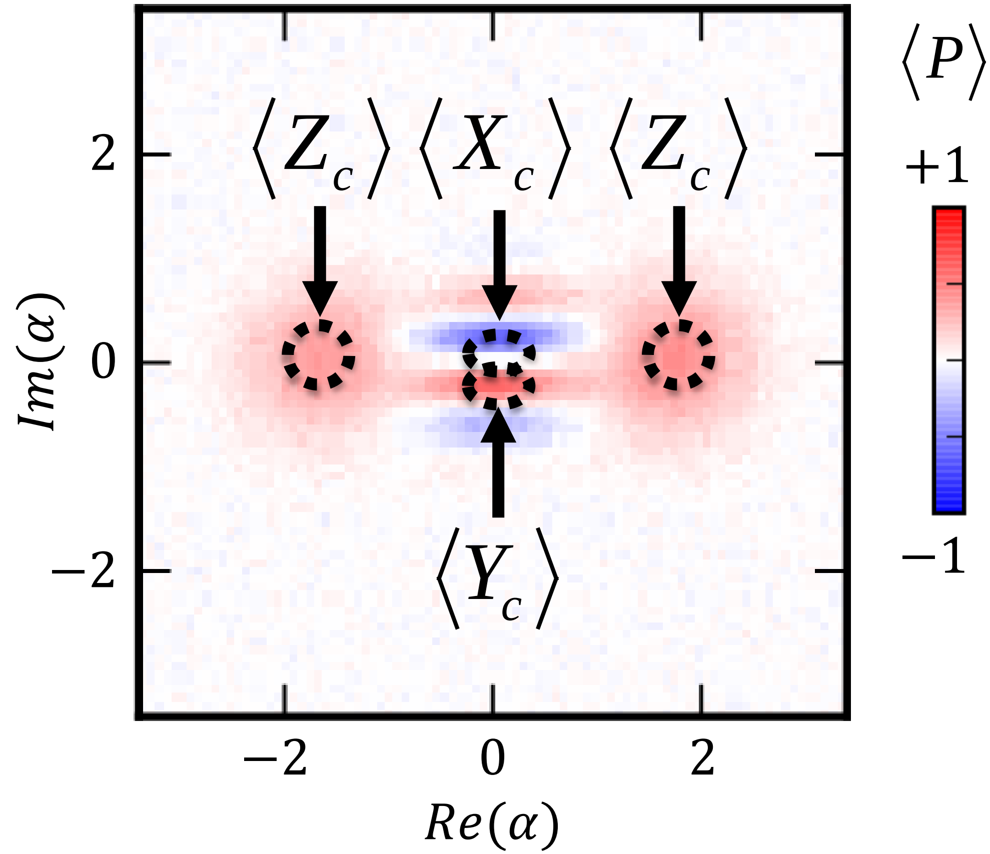
$$\langle Z_c \rangle = \langle P_\beta \rangle - \langle P_{-\beta} \rangle = 0.07$$



# Efficiently Measuring $X_c, Y_c, Z_c$

Cavity state along $Y_c$

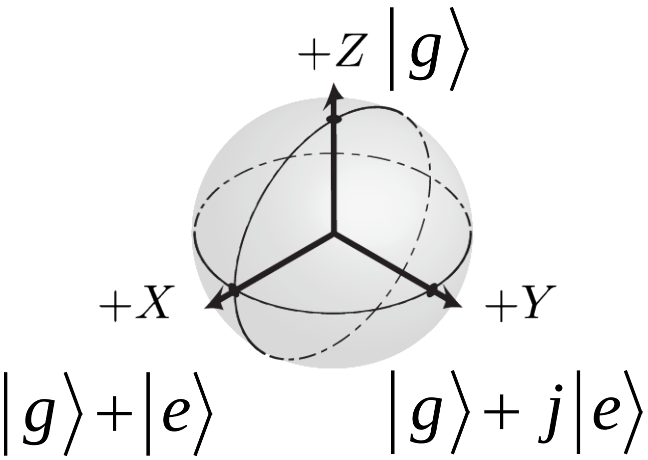


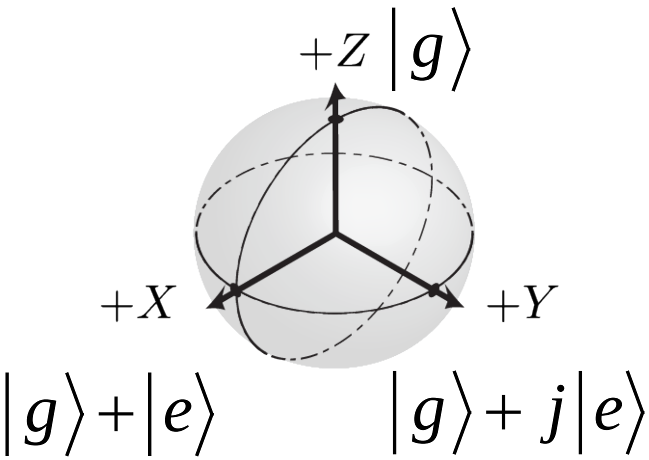
# A Bell State

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

2-Level System
(e.g. transmon)



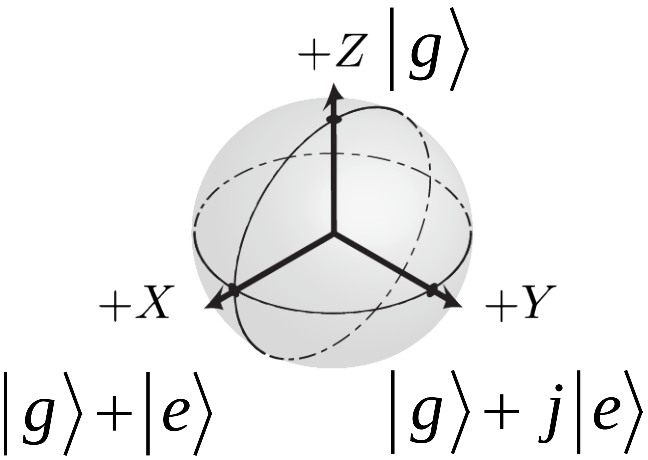

2-Level System
(e.g. transmon)



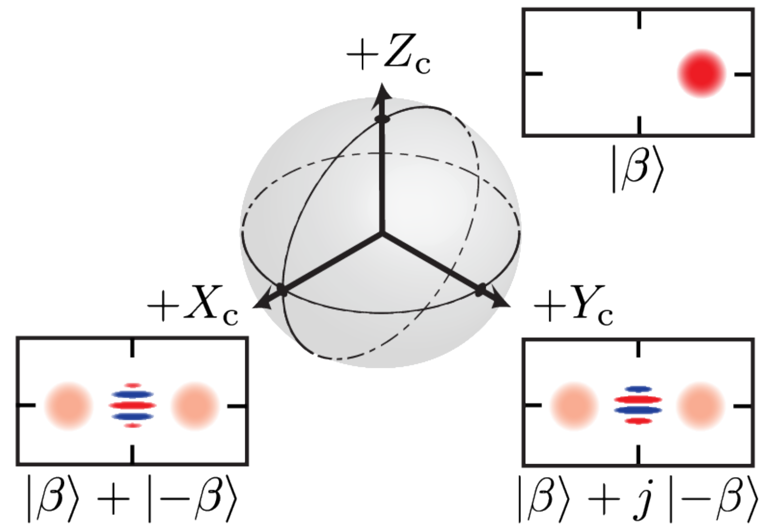
# The Schrodinger Cat or "Bell-Cat"

$$|\psi_B\rangle = \frac{1}{\sqrt{2}}\left(|g\rangle|\beta\rangle + |e\rangle|-\beta\rangle\right)$$

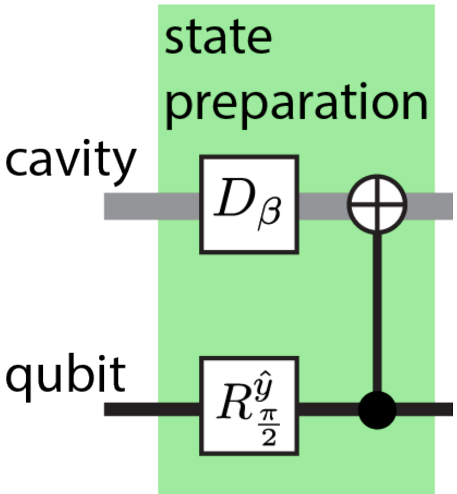
2-Level System
(e.g. transmon)




Continuous
Variables (e.g. cavity)



# Measuring Bell-Cat Correlations

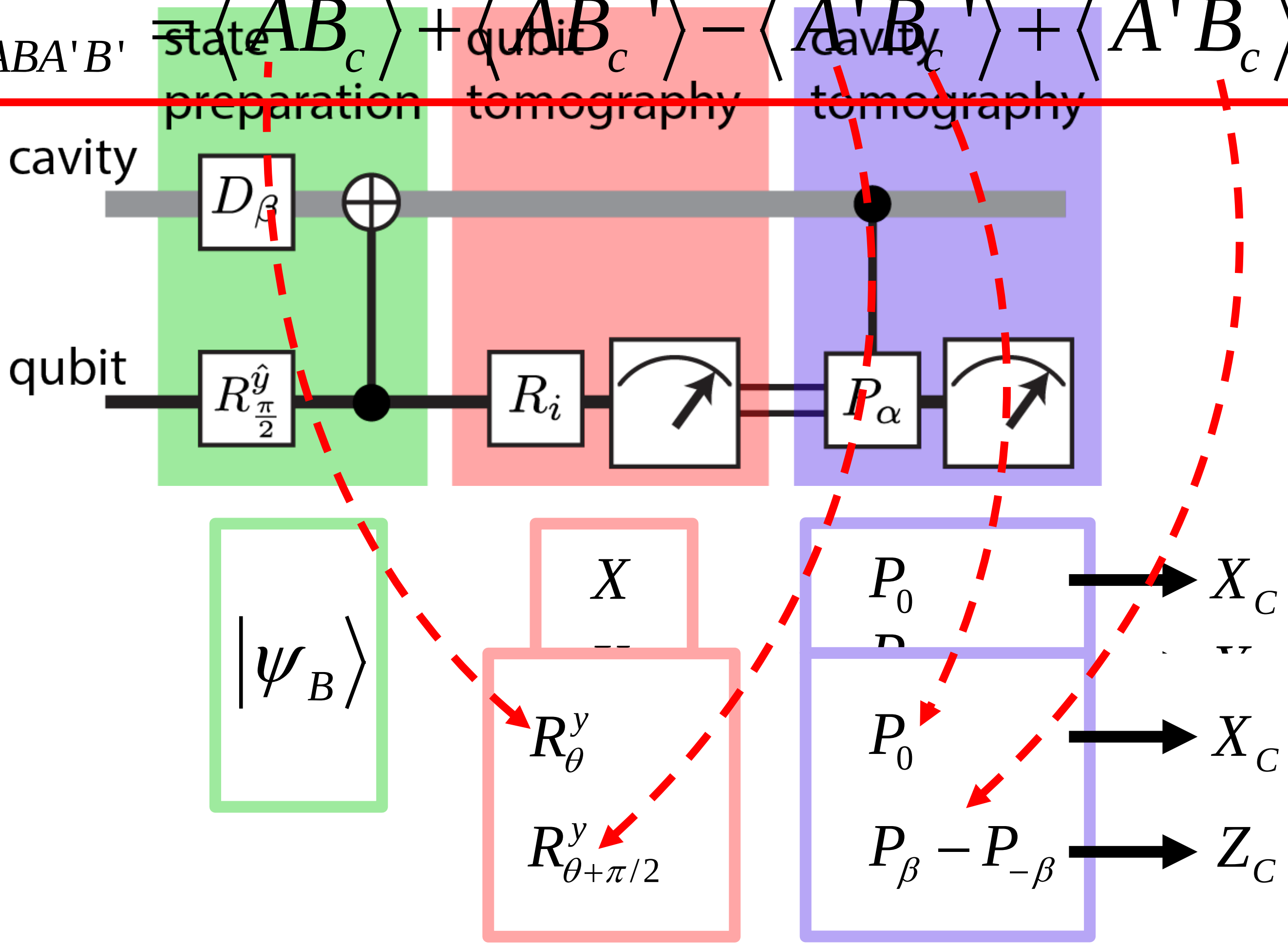



$|\psi_B\rangle$

*Vlastakis et.al. Science 2013*

# Performing a CHSH Measurement

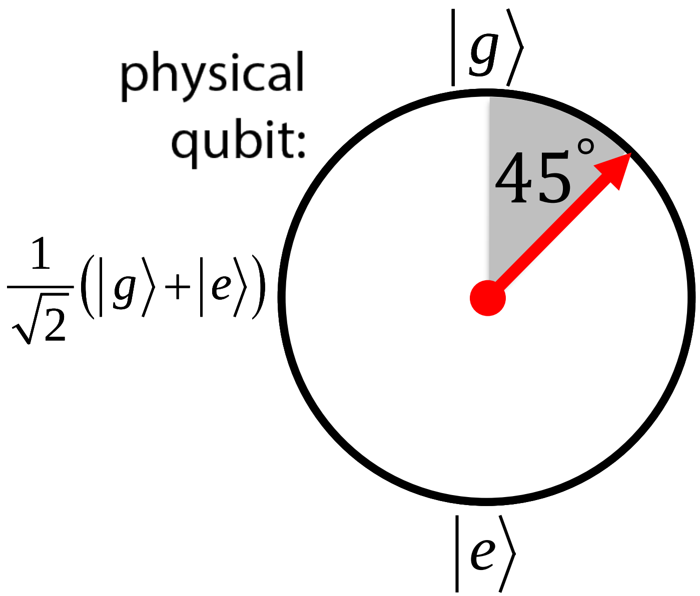
$$O_{ABA'B'} = \langle AB_c \rangle + \langle AB_c' \rangle - \langle A'B_c' \rangle + \langle A'B_c \rangle$$

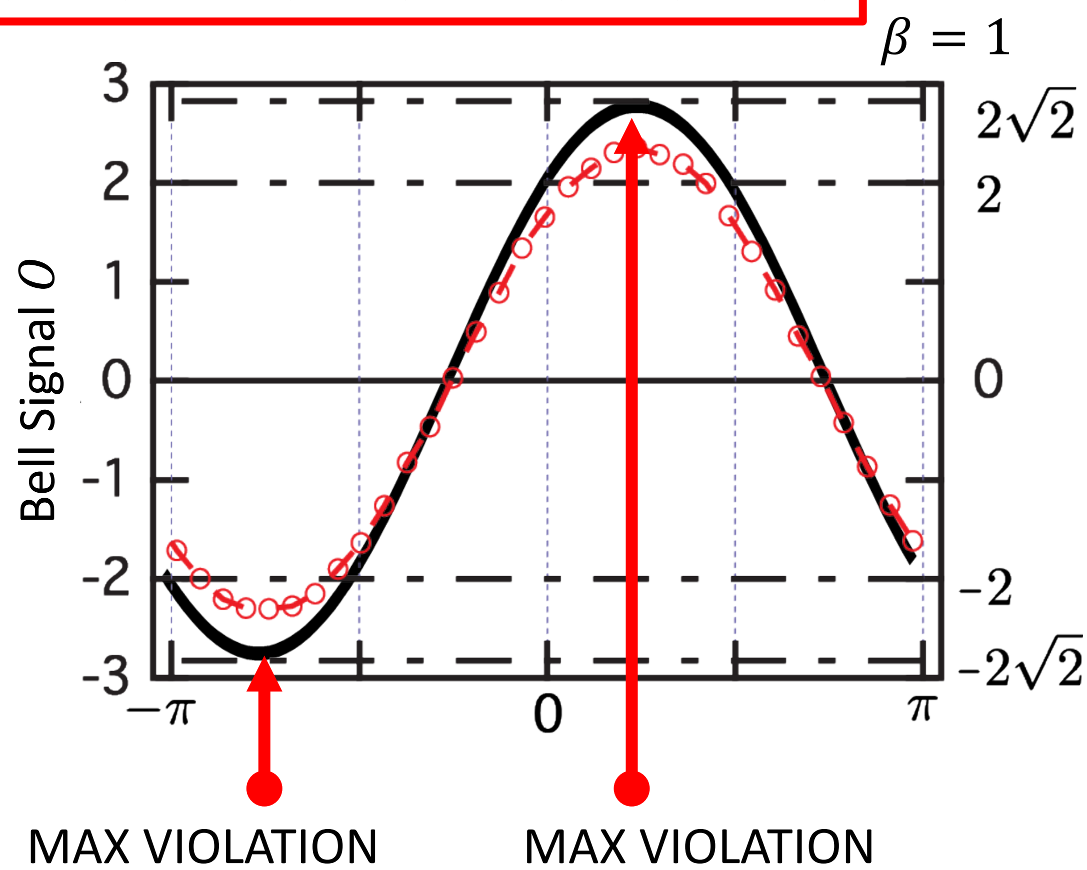



*Vlastakis et al. Science 2013*

# Violating the CHSH Inequality

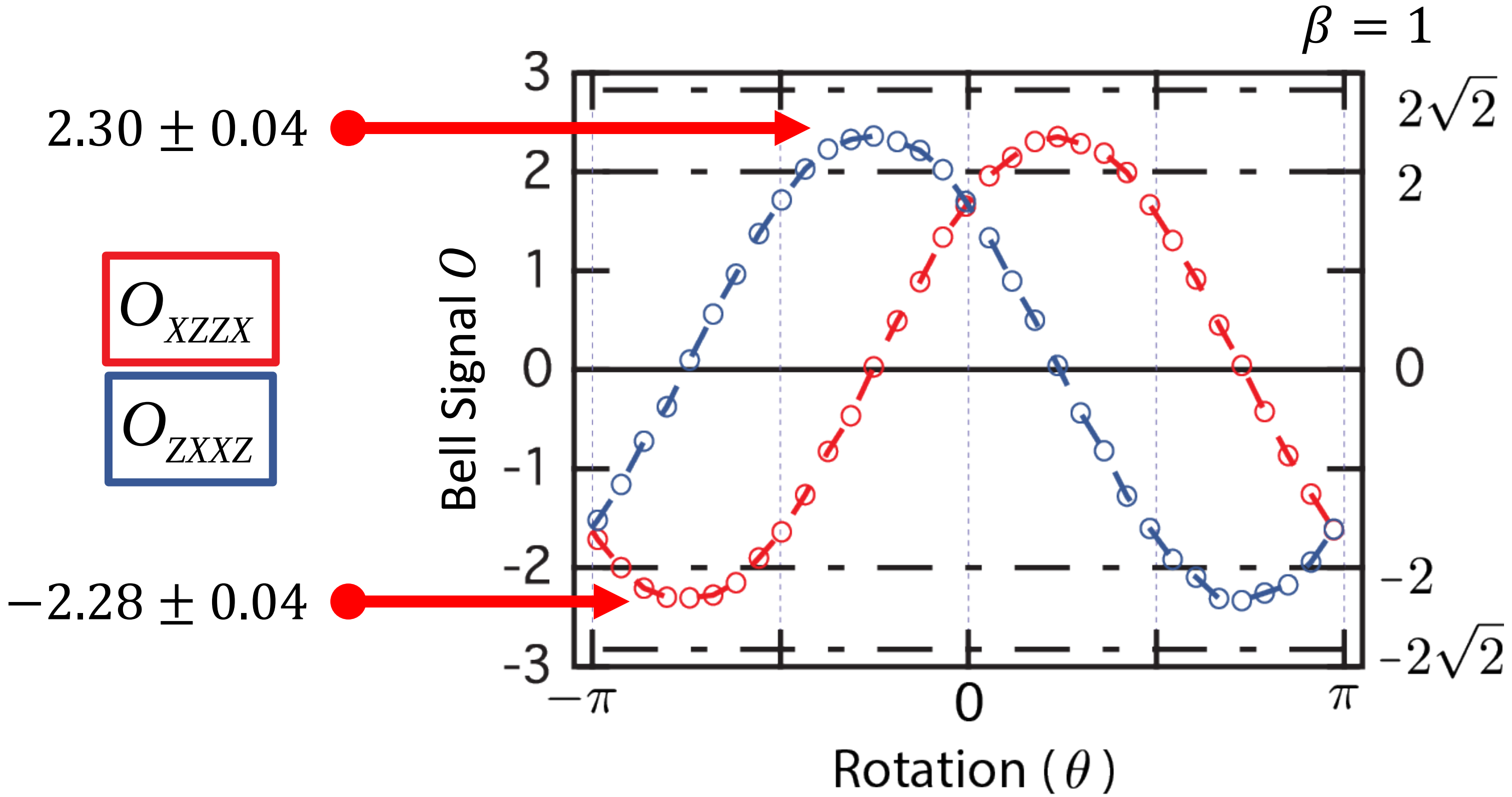
$$O_{XZZX} = \langle XZ_c \rangle + \langle XX_c \rangle - \langle ZX_c \rangle + \langle ZZ_c \rangle$$



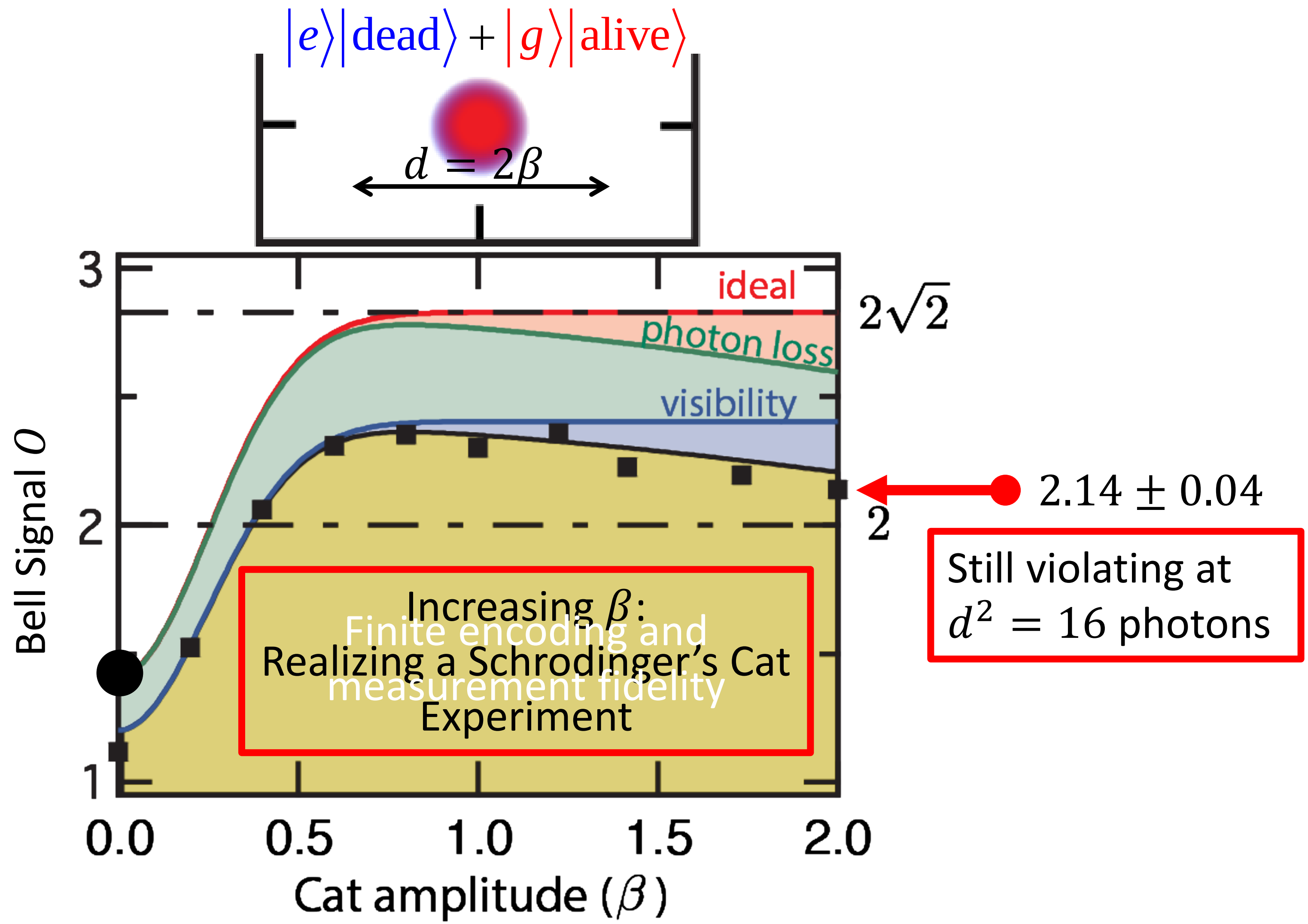



# Violating the CHSH Inequality

**WE TAKE ALL MEASUREMENTS:**
No correction for detector inefficiency



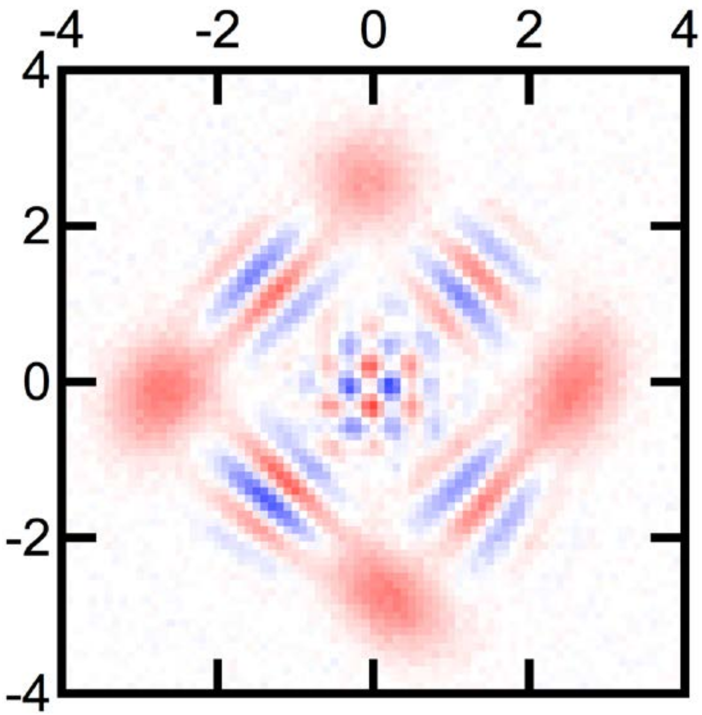
# Continuously Varying Bell-Cat Size



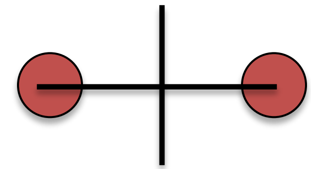

see also Brune et al., 1996

# What Comes Next?

# Cavity as a Correctable Memory?

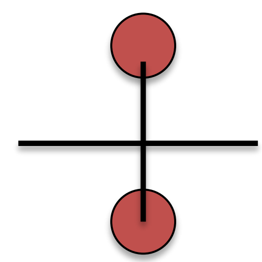



Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).



$$|0_L\rangle = |\mathcal{C}_\alpha^+\rangle = \mathcal{N}(|\beta\rangle + |-\beta\rangle)$$

$$|1_L\rangle = |\mathcal{C}_{i\alpha}^+\rangle = \mathcal{N}(|i\beta\rangle + |-i\beta\rangle)$$



$$c_g|\downarrow\rangle + c_e|\uparrow\rangle \Rightarrow c_g|0_L\rangle + c_e|1_L\rangle$$

Store a ***qubit*** as a ***superposition*** of two cats of same parity

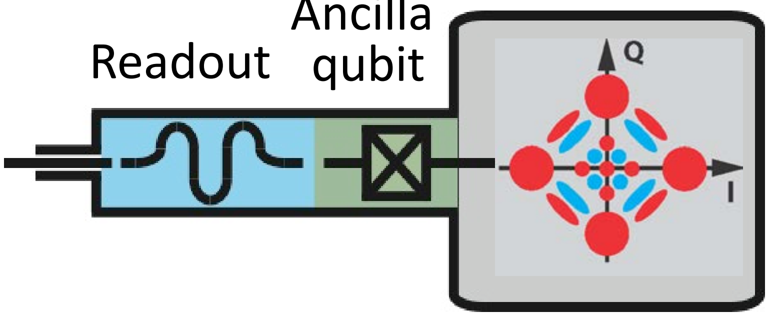
Z. Leghtas

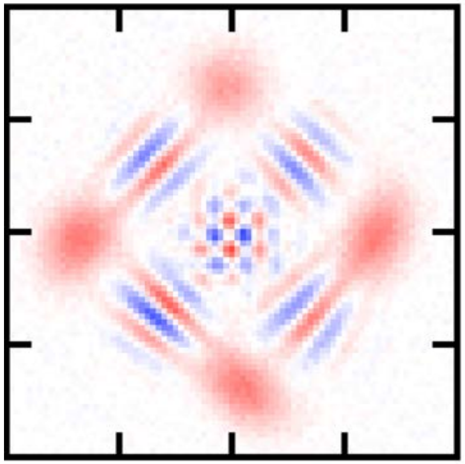
M. Mirrahimi

# Cat States for Hardware-Efficient QEC?

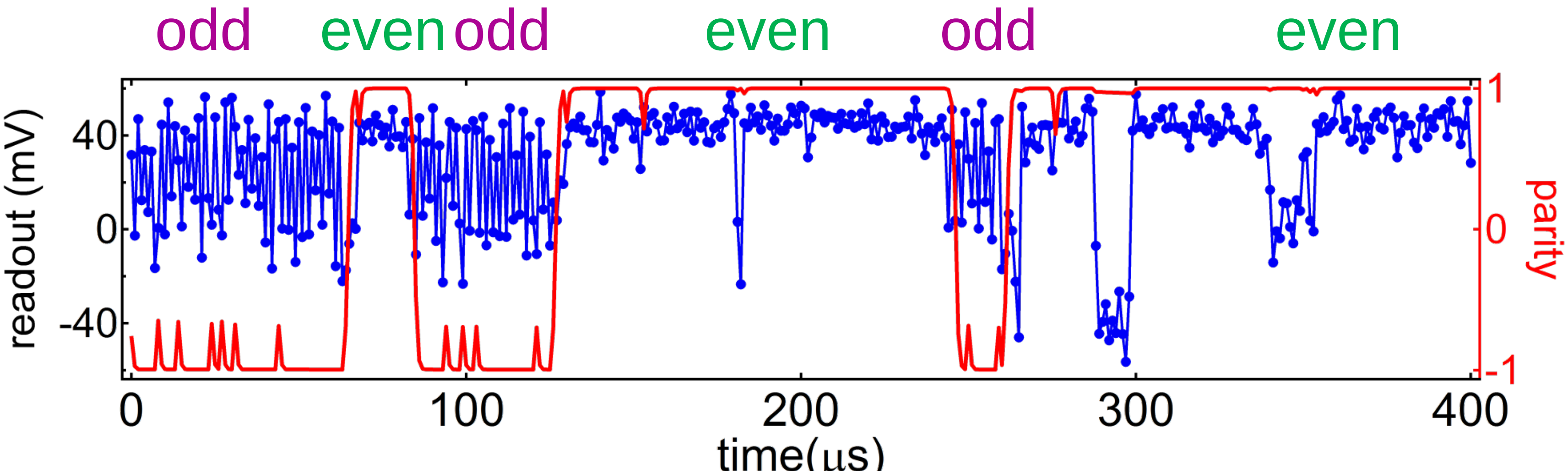
"Cat codes": much less hardware required

Leghtas, Mirrahimi, et al., PRL **111**, 120501(2013).



1st tracking of a parity or error syndrome in real-time:




parity msmt. ala' Bertet et al.,

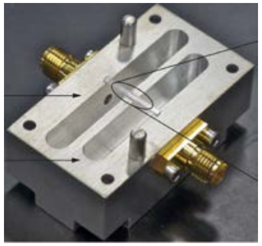
Sun, Petrenko et al., Nature 511, 444 (2014).

Bon anniversaire Quantronics!

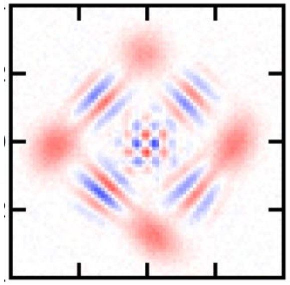

Merci!  … and my apologies

# Summary

- Coherence in circuit QED passing the QEC threshold.



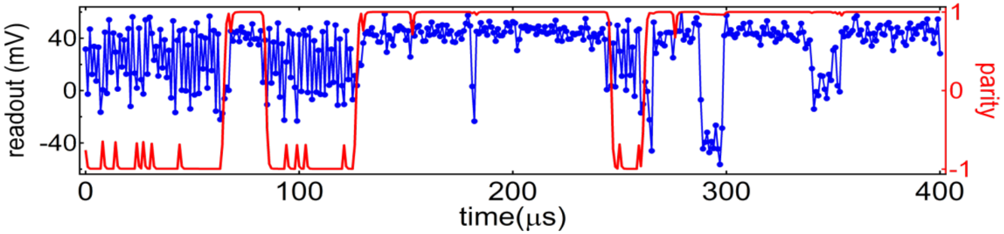
Qubits: T2 ~ 2*T1 ~ 0.0001 sec
Cavities: T2 ~ 2*T1 ~ 0.001 sec



- Cat-codes: a new shortcut for QEC?

- Tracking the jumps of an error syndrome: photon parity

Next challenge:
"breakeven" for error correction!




- Bell violation between qubit and continuous variable system: benchmarking a module

Leghtas, Mirrahimi et al., PRL 2013.
Sun, Petrenko et al., Nature **511**, 444 (2014).
Petrenko, Vlastakis et al., submitted & arXiv (2015)