# Superconducting circuits for Quantum Information Processing

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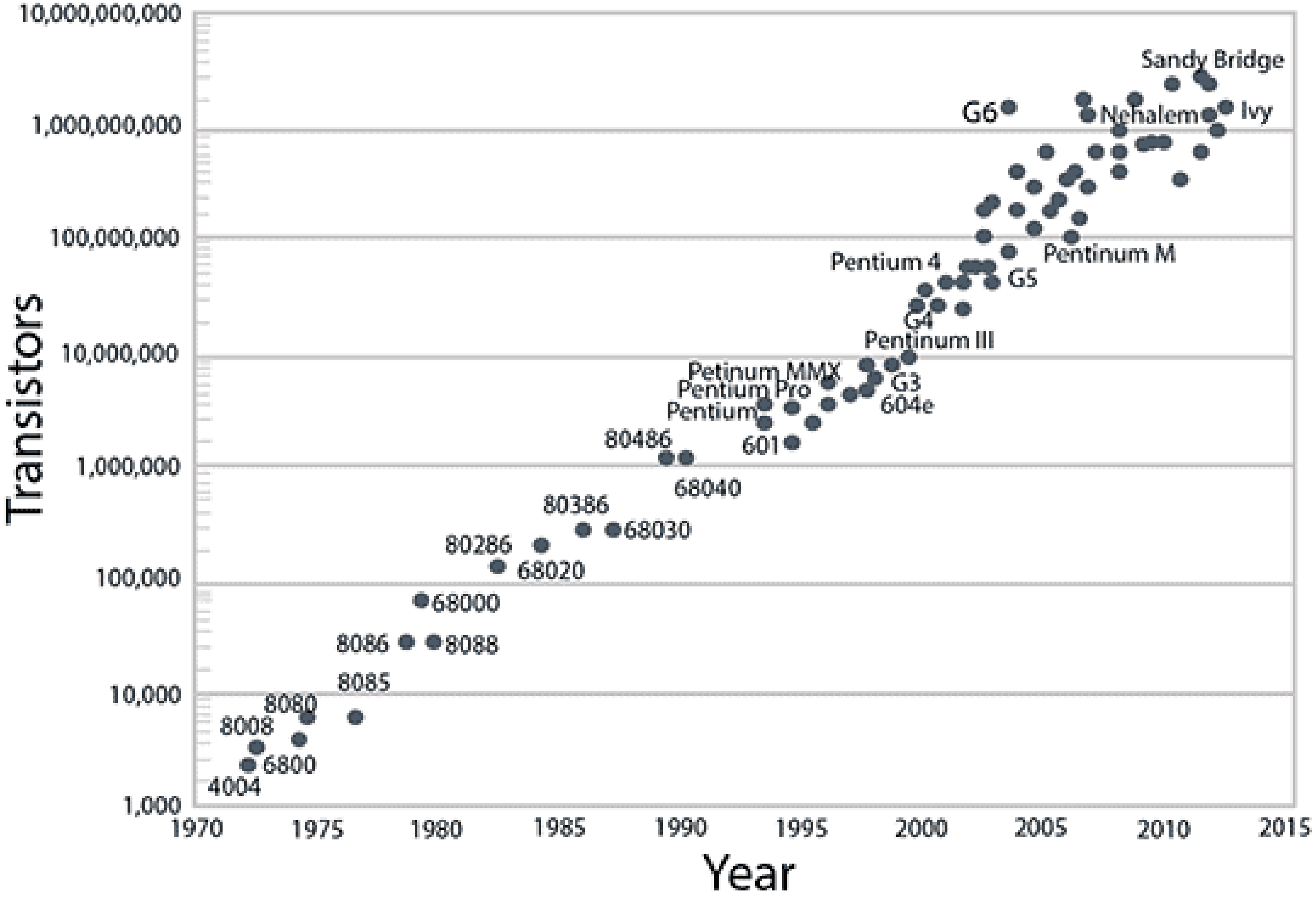
# The Incredible Growth of Computing: Moore’s Law



*Source: University of Wisconsin-Madison*

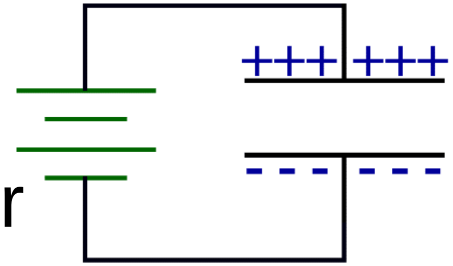
*picture from internet*

# Process Information Using Quantum Mechanics

Information encoded in the state of two-level systems

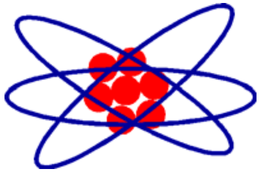
## Classical bit

charge
on
capacitor



values 0 or 1

## Quantum bit (or "qubit")



single
atom

define: $|g\rangle = |0\rangle$ and $|e\rangle = |1\rangle$

**superposition:** $\alpha|0\rangle + \beta|1\rangle$

# Quantum Superposition of States

*N*=1 qubit

$$|\psi\rangle = c_0|0\rangle + c_1|1\rangle$$

*N*=2 qubits

$$|\psi\rangle = c_0|00\rangle + c_1|01\rangle + c_2|10\rangle + c_3|11\rangle$$

*N*=3 qubits

$$|\psi\rangle = c_0|000\rangle + c_1|001\rangle + c_2|010\rangle + c_3|011\rangle + c_4|100\rangle + c_5|101\rangle + c_6|110\rangle + c_7|111\rangle$$

*Describing an N-qubit state requires $2(2^N-1)$ real numbers*

A 200 qubit register = more classical bits to describe than atoms in the universe!

# Quantum Parallelism

$$|\psi_{\text{in}}\rangle \longrightarrow \boxed{\;U\;} \longrightarrow |\psi_{\text{out}}\rangle$$

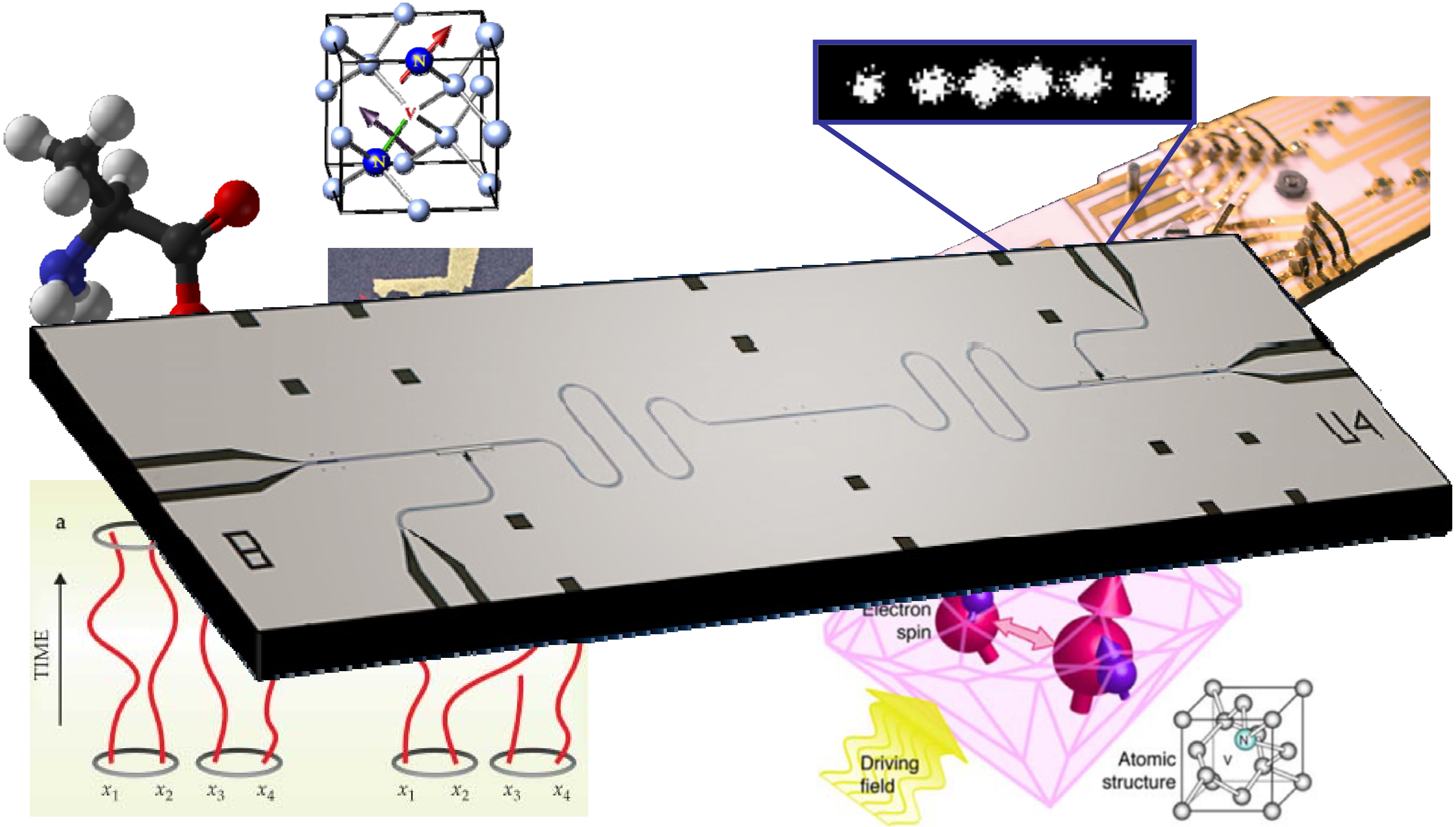
$$\begin{aligned} |\psi_{\text{in}}\rangle \;=\; & \;\;c_0\,|000\rangle \\ & +c_1\,|001\rangle \\ & +c_2\,|010\rangle \\ & \;\;\vdots \\ & +c_7\,|111\rangle \end{aligned} \quad \longrightarrow \quad \begin{aligned} \psi_{\text{out}}\rangle \;=\; & \;\;c_0U\,|000\rangle \\ & +c_1U\,|001\rangle \\ & +c_2U\,|010\rangle \\ & \;\;\vdots \\ & +c_7U\,|111\rangle \end{aligned}$$

Could evaluate a function, for all inputs, at once!

# Candidate Quantum Information Processors

**Nuclear / electron spins**

**Atomic Ions**

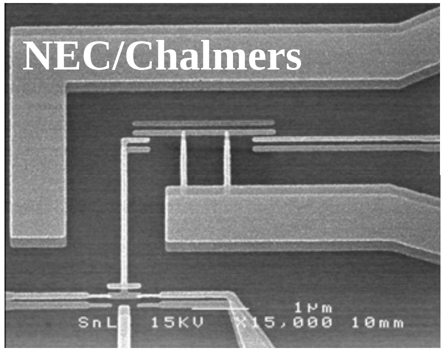


**Topological state**

**NV in diamond**

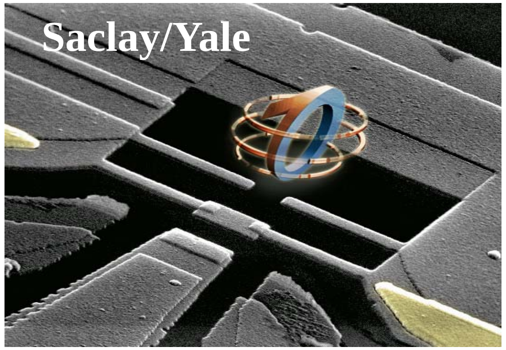
# Superconducting Qubits

### Charge CPB



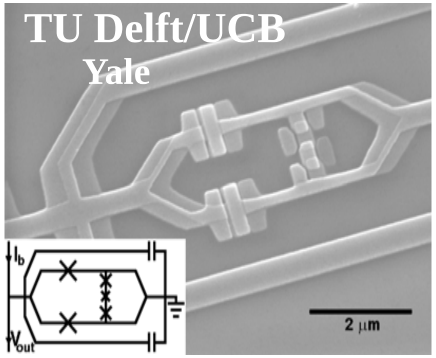
$E_J = E_C$

### Charge/Phase



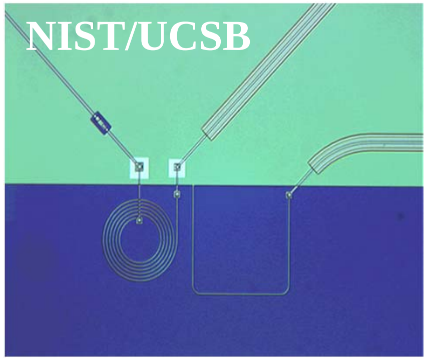
$E_J = E_C$

### Flux



$E_J = 40\text{-}100E_C$

### Phase

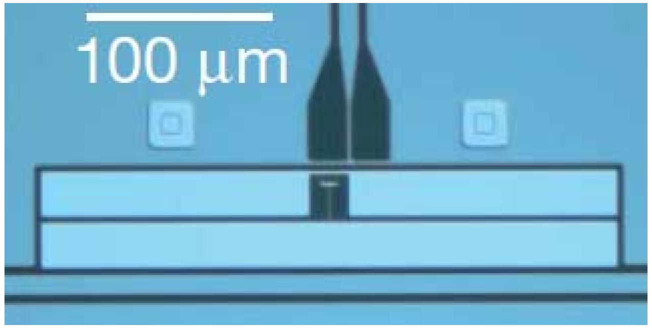


$E_J = 10{,}000E_C$

**Reviews:**

Yu. Makhlin, G. Schön, and A. Shnirman, Rev. Mod. Phys. **73**, 357 (2001)
M. H. Devoret, A. Wallraff and J. M. Martinis, cond-mat/0411172 (2004)
J. Q. You and F. Nori, Phys. Today, Nov. 2005, 42

**circuit QED:**
interaction with ***quantized*** fields



transmon

Charge

$E_J = 30\text{-}100E_C$

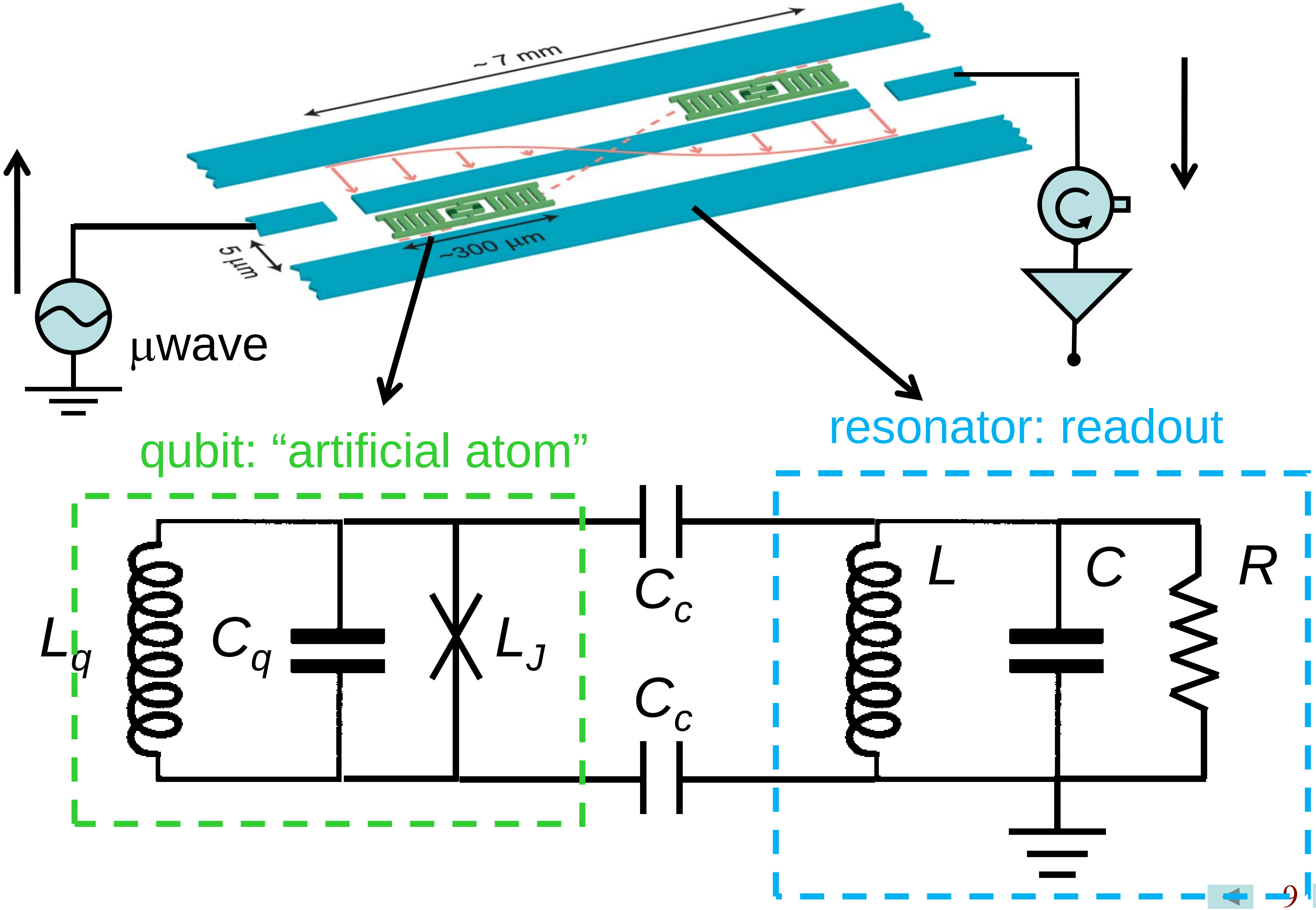
**Transmon:**

J. Koch, …, M. H. Devoret, S. M. Girvin, R. J. Schoelkopf, Phys. Rev. A **76**, 042319 (2007)

# Outline

1. Quantum computation based on circuit quantum electrodynamics (circuit QED)
2. Quantum error correction (QEC) based on Schrodinger cat states in circuit QED
   - ✓ The basics of QEC
   - ✓ Basic operations in circuit QED
   - ✓ Tracking photon parity jumps in real time
3. Recent progresses in our lab (Tsinghua Univ.):
   - A two-fold quantum delayed choice experiment
   - Generation of arbitrary Fock-state superpositions
4. Conclusions

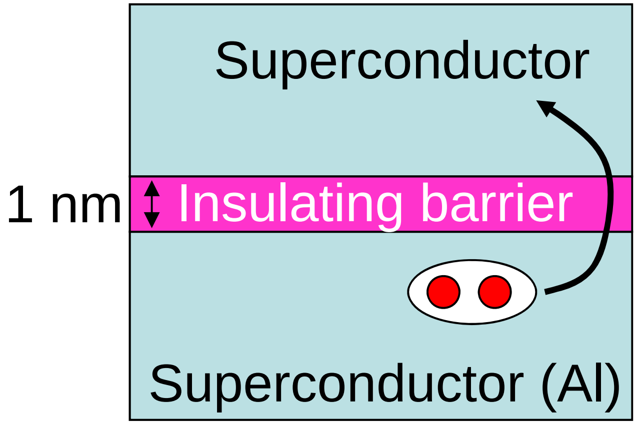
# Circuit Model for Circuit QED

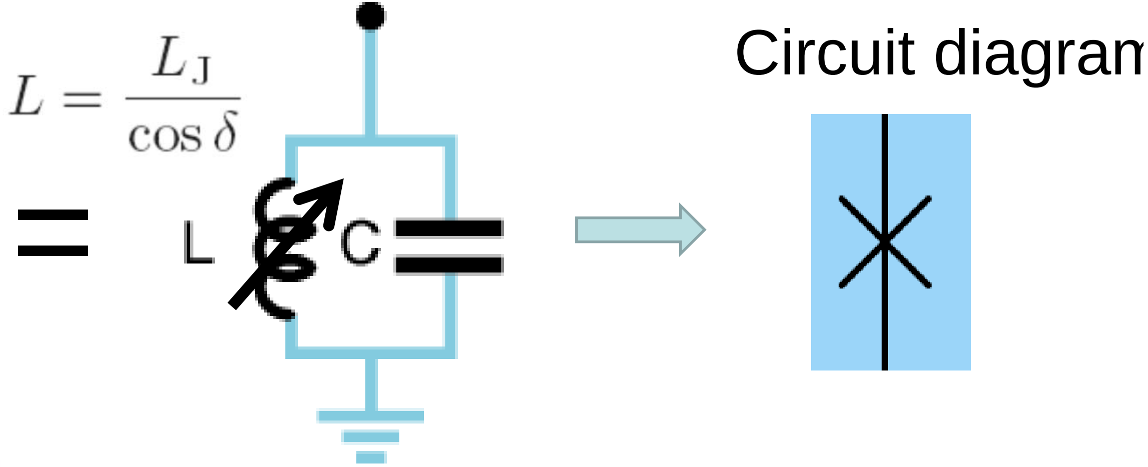


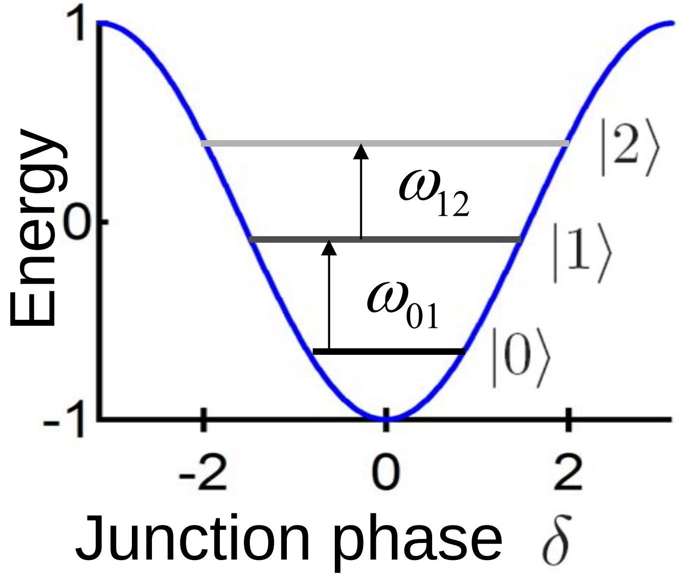
qubit: “artificial atom”

resonator: readout

# Superconducting Artificial Atoms




$$L = \frac{L_J}{\cos\delta}$$



(1 K ~ 21 GHz)

$$\hbar\omega_{01} \approx \sqrt{8E_C E_J(\Phi)} - E_C \sim 5-10\text{GHz}$$

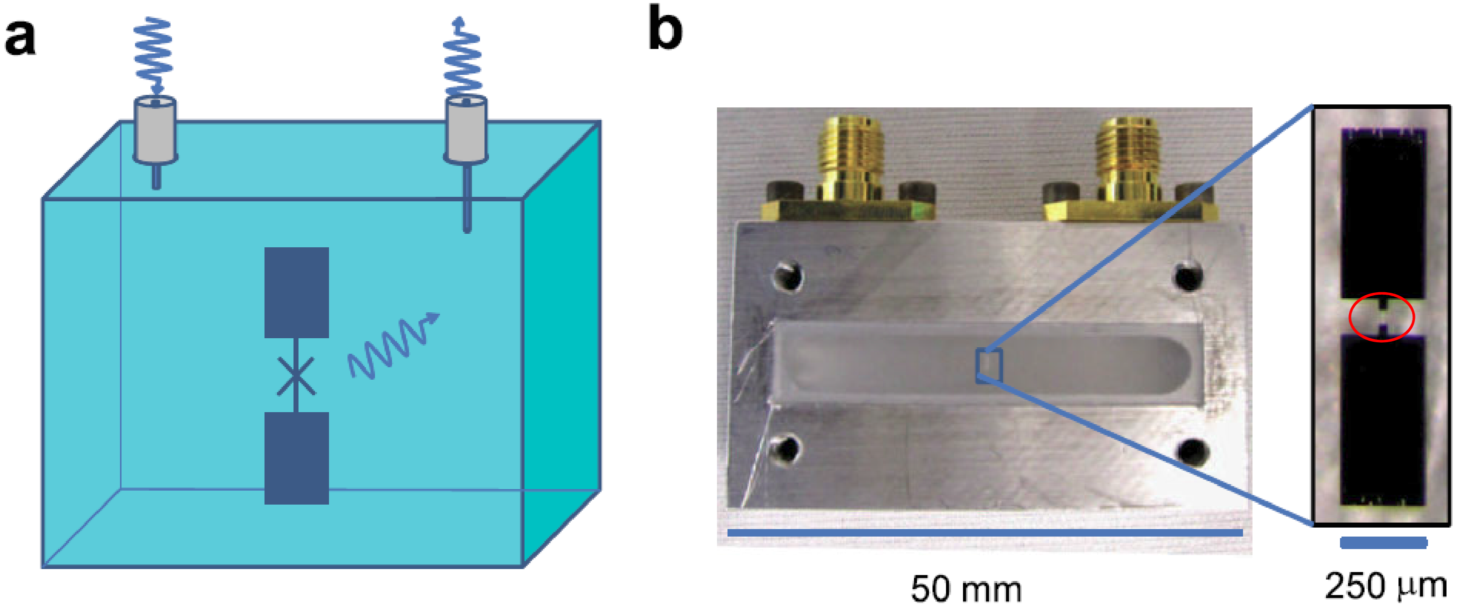
$$\hbar\omega_{12} - \hbar\omega_{01} \approx -E_C \sim -300\text{MHz}$$

→ fast gate operation, ~ 10 ns

Multi-level nature can be *useful* for computation!

*See reviews: Devoret and Martinis, 2004; Wilhelm and Clarke, 2008*

# Superconducting Qubit: Transmon



single
Al JJ
+
dipole
antenna

d ~ 0.01λ

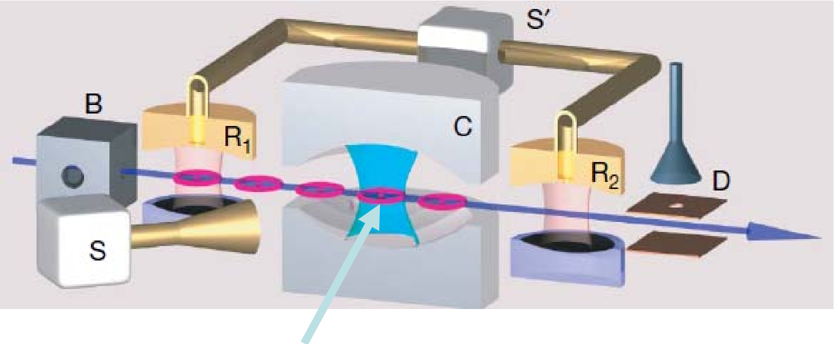
- Josephson junction(s) with a large shunt capacitor
- Dephasing from charge fluctuations suppressed:

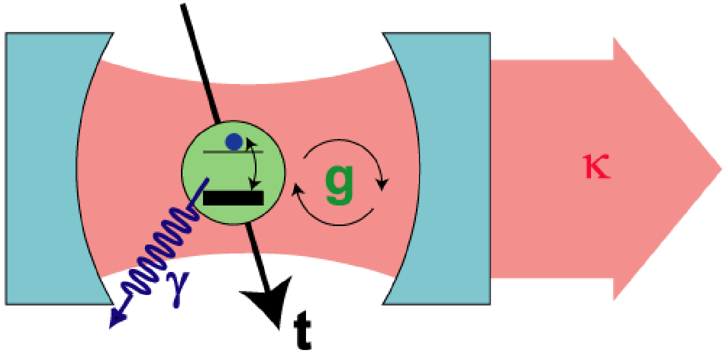
$E_J/E_c \sim 50$ to $100$

*J. Koch, et al. Phys. Rev. A **76**, 042319 (2007)*

*Paik et al., PRL **107**, 240501 (2011)*

# Interacting with SC qubits: circuit QED (A circuit implementation of cavity QED)





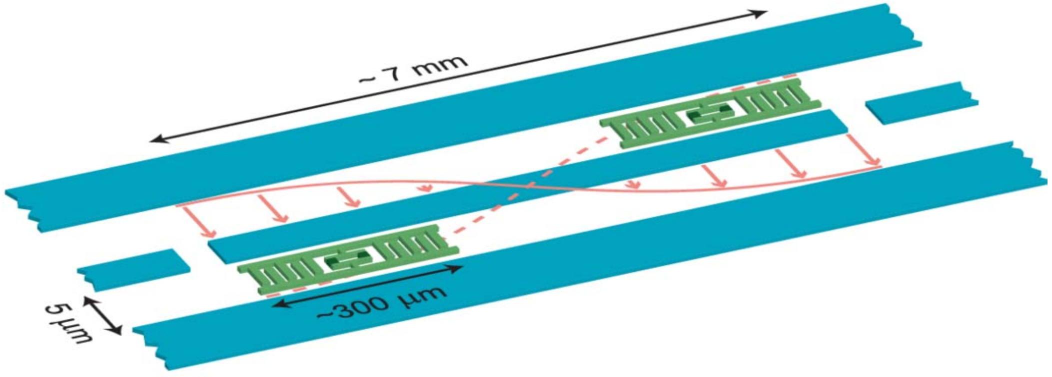
Rydberg atoms

*Nature 455, 510 (2008）*

Haroche (Nobel Prize 2012)

- Atoms are moving through the cavity
- there is a limited interaction time
- Interaction strength is strong, but not always strong enough

# Interacting with SC qubits: circuit QED (A circuit implementation of cavity QED)



Strong Coupling = $g \gg \kappa, \gamma$  g ~ 100 MHz (transmon)

Jaynes-Cummings Hamiltonian

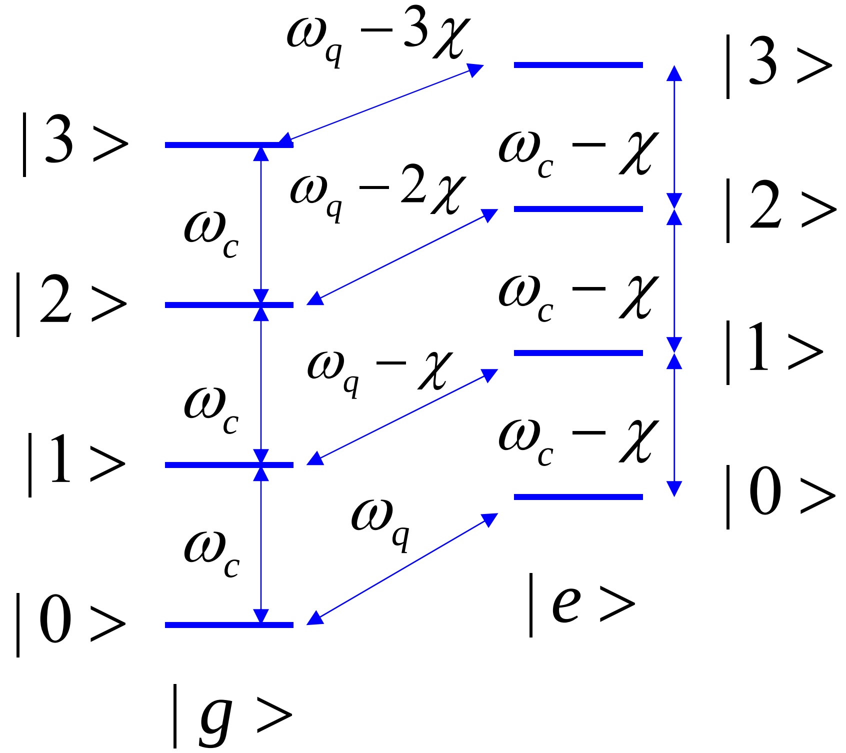
$$\hat{H} = \hbar\omega_r a^+ a + \frac{\hbar\omega_q}{2}\hat{\sigma}_z + \hbar g(a^\dagger\sigma^- + \sigma^+ a)$$

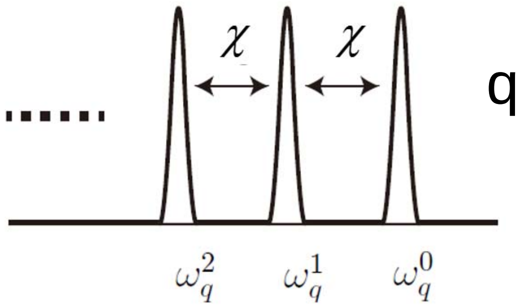
quantized Field

2-level system

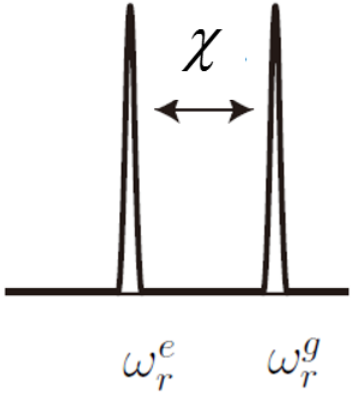
electric dipole interaction

# Interacting with SC qubits: circuit QED (A circuit implementation of cavity QED)





qubit frequency



cavity frequency

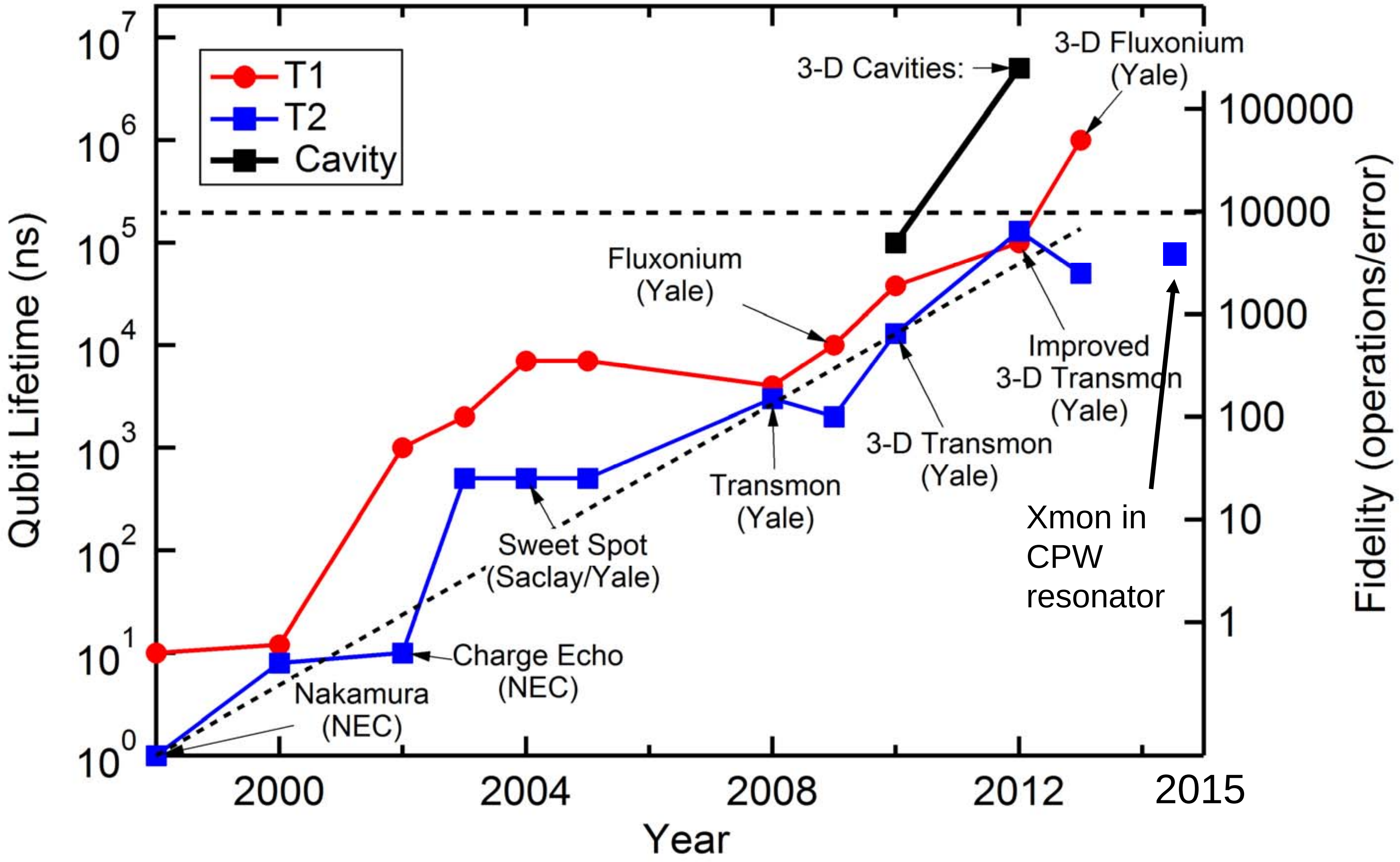
$$\hat{H} = \hbar\omega_r a^+ a + \frac{\hbar\omega_q}{2}\hat{\sigma}_z - \hbar\chi a^\dagger a \sigma_z \qquad \left(\Delta = \left|\omega_q - \omega_r\right| \gg g\right)$$

quantized Field

2-level system

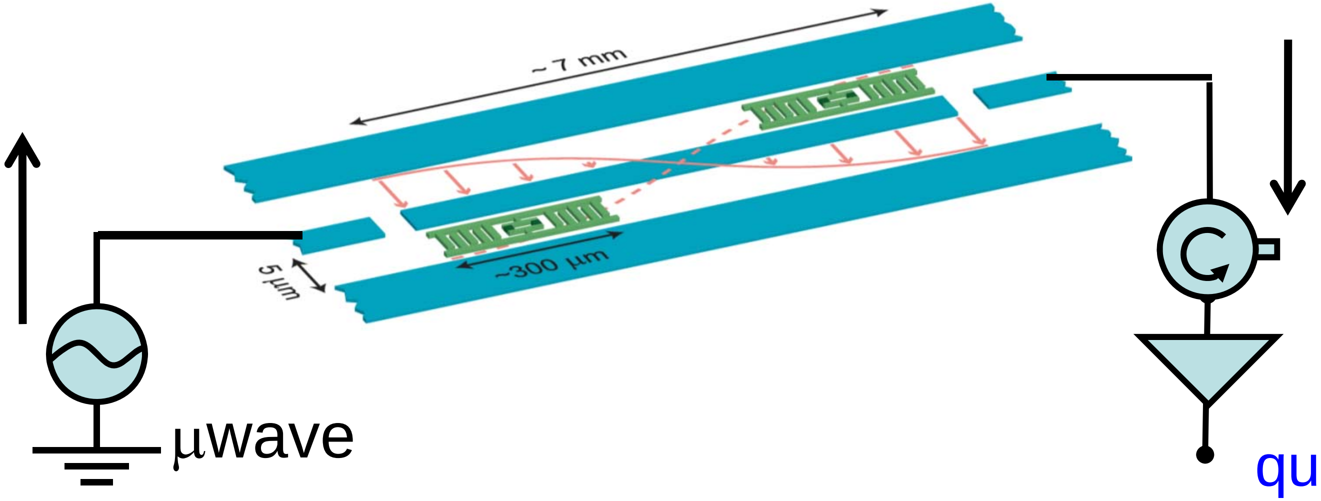
electric dipole interaction

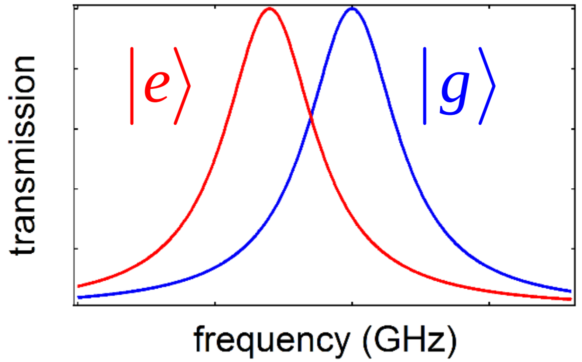
# “Coherence Law”



*Devoret and Schoelkopf, Science **339**, 1169 (2013)*

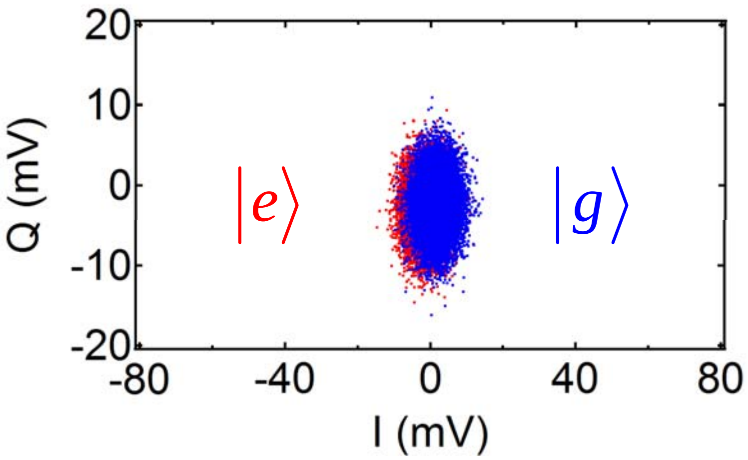
# High Fidelity and QND Readout



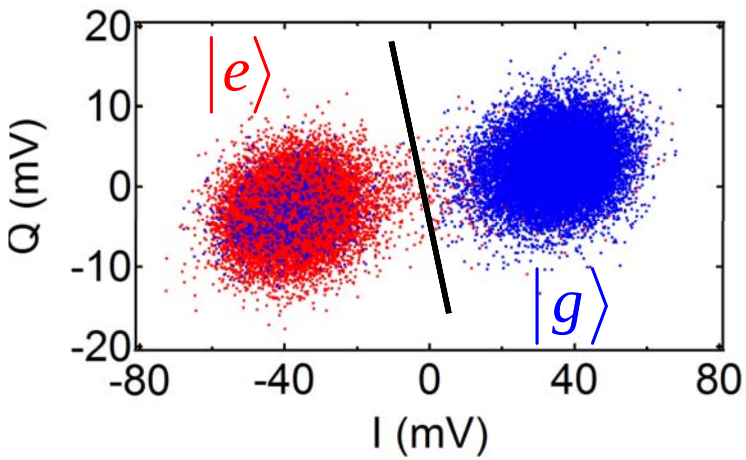


quantum-limited
parametric amplifier

amplifier off



amplifier on

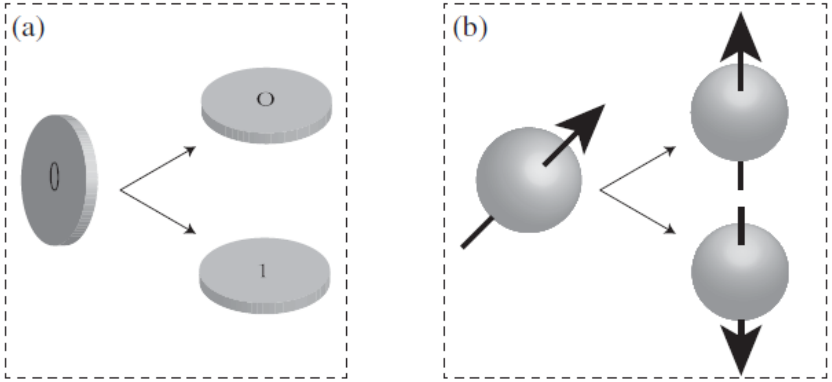


F > 99.6%

readout time
~ 200 ns

# High Fidelity and QND Readout

Bernoulli factory

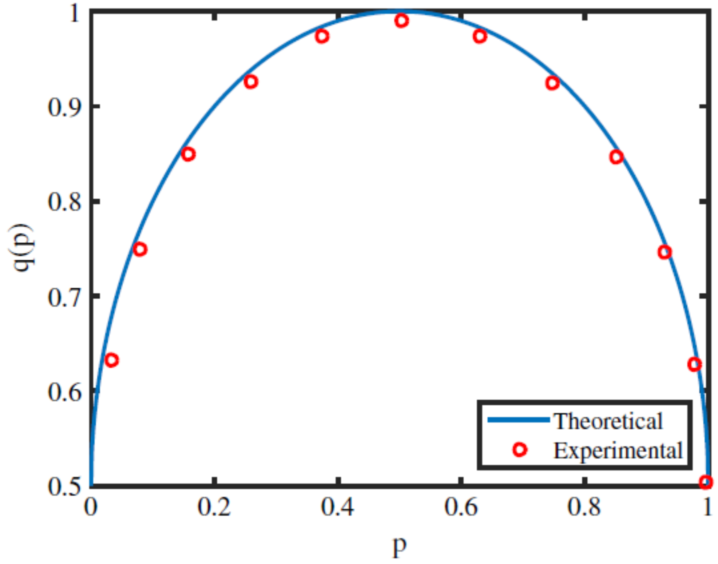


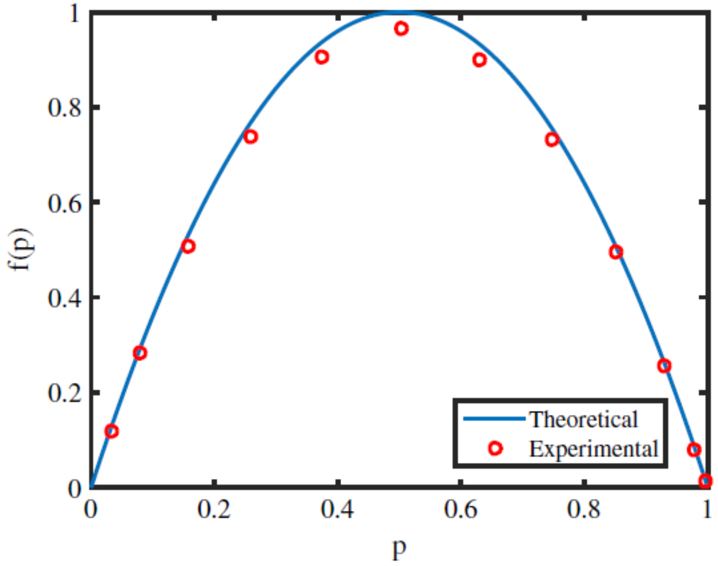
classical
coin

quantum
coin

Realize quantum advantage with the simplest quantum state.

Yuan and Liu *et al*., Experimental quantum randomness processing using superconducting qubits, PRL **117**, 010502 (2016)





# The DiVincenzo Criteria

**Requirements for a qubit:**

1. Well-defined scalable quantum two-level system
2. Initialization （high QND readout)
3. Universal quantum gates– single/two qubit gates
4. Qubit specific readout
5. Coherence time >> gate operation time

Advantages of superconducting circuits:

- ✓ Superconducting circuits can be designed!
- ✓ Based on solid state device, scalable.
- ✓ Long coherent times and fast gate operation.
- ✓ No known physical law prevents further improvements.

Leading candidate for quantum information processing.

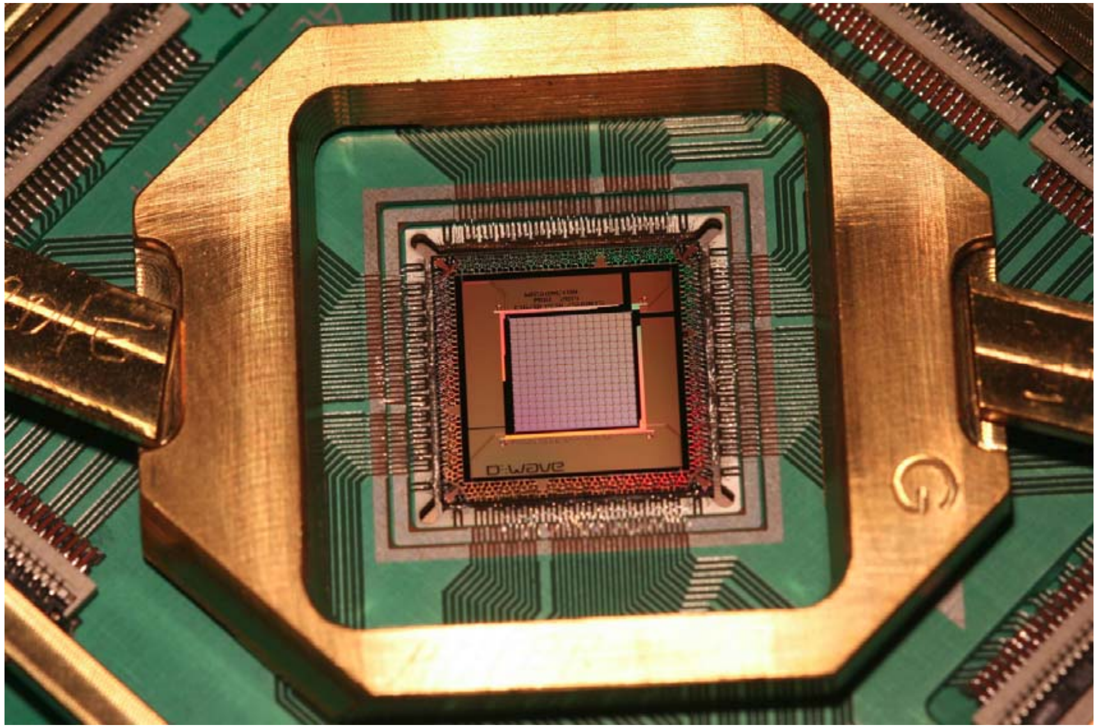
# Dwave’s 2X Quantum Annealer

PHYSICAL REVIEW X **6,** 031015 (2016)

## What is the Computational Value of Finite-Range Tunneling?

Vasil S. Denchev,[1,*] Sergio Boixo,[1,†] Sergei V. Isakov,[1] Nan Ding,[1] Ryan Babbush,[1]
Vadim Smelyanskiy,[1] John Martinis,[2] and Hartmut Neven[1]
[1]*Google Inc., Venice, California 90291, USA*
[2]*Google Inc., Santa Barbara, California 93117, USA*

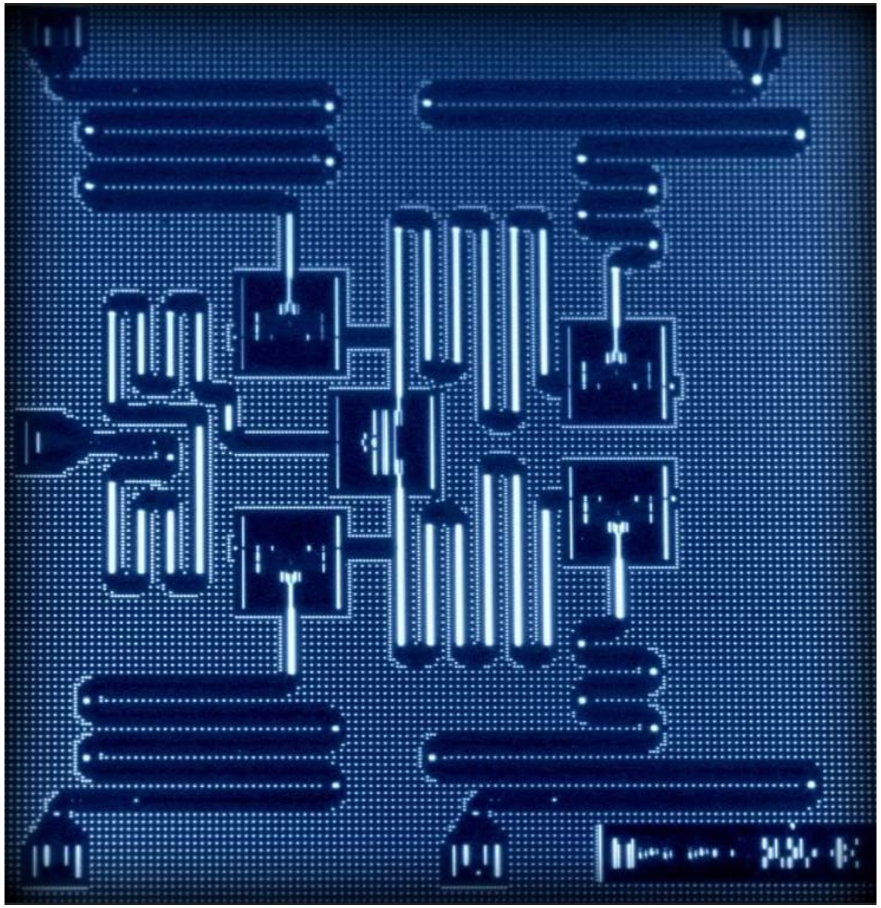
(Received 4 March 2016; revised manuscript received 22 June 2016; published 1 August 2016)



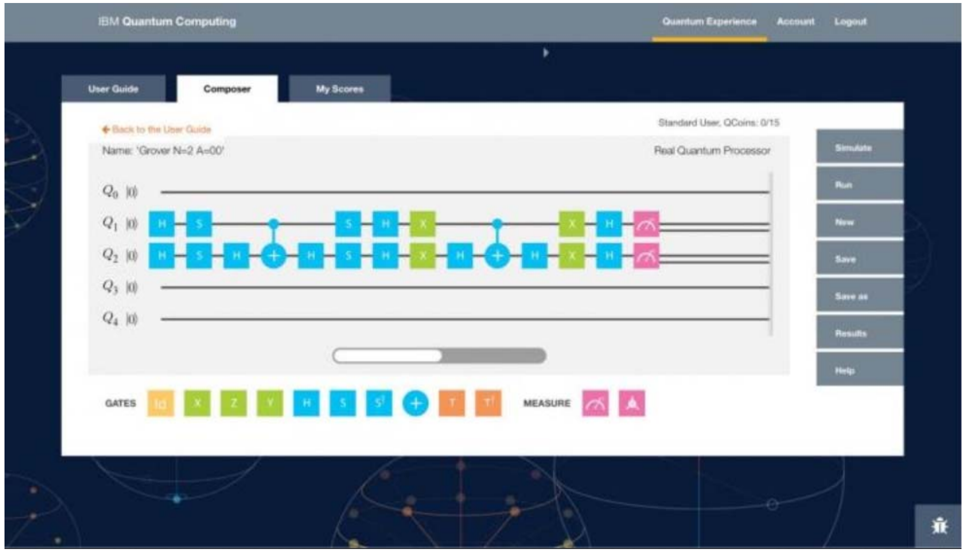
1000 qubits on chip!

$10^8 \times$ classical computer

# IBM’s Free Quantum Computing Cloud Service



5-qubit processor



Standard User, QCoins: 0/15

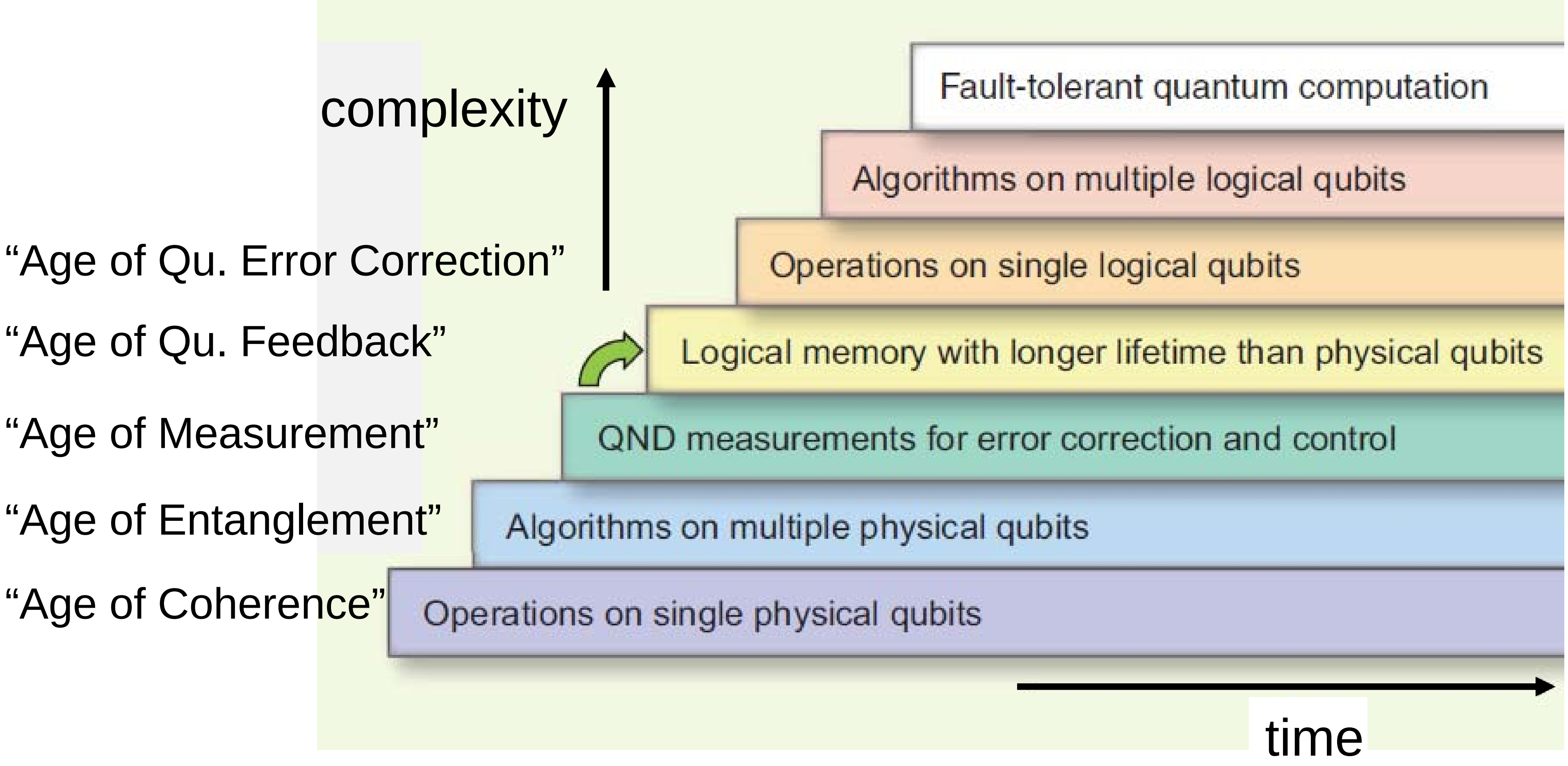
Name: 'Grover N=2 A=00'

Real Quantum Processor

**May 2016**

http://news.mydrivers.com/1/480/480952.htm

# Stages in the Development of Quantum Information Processing



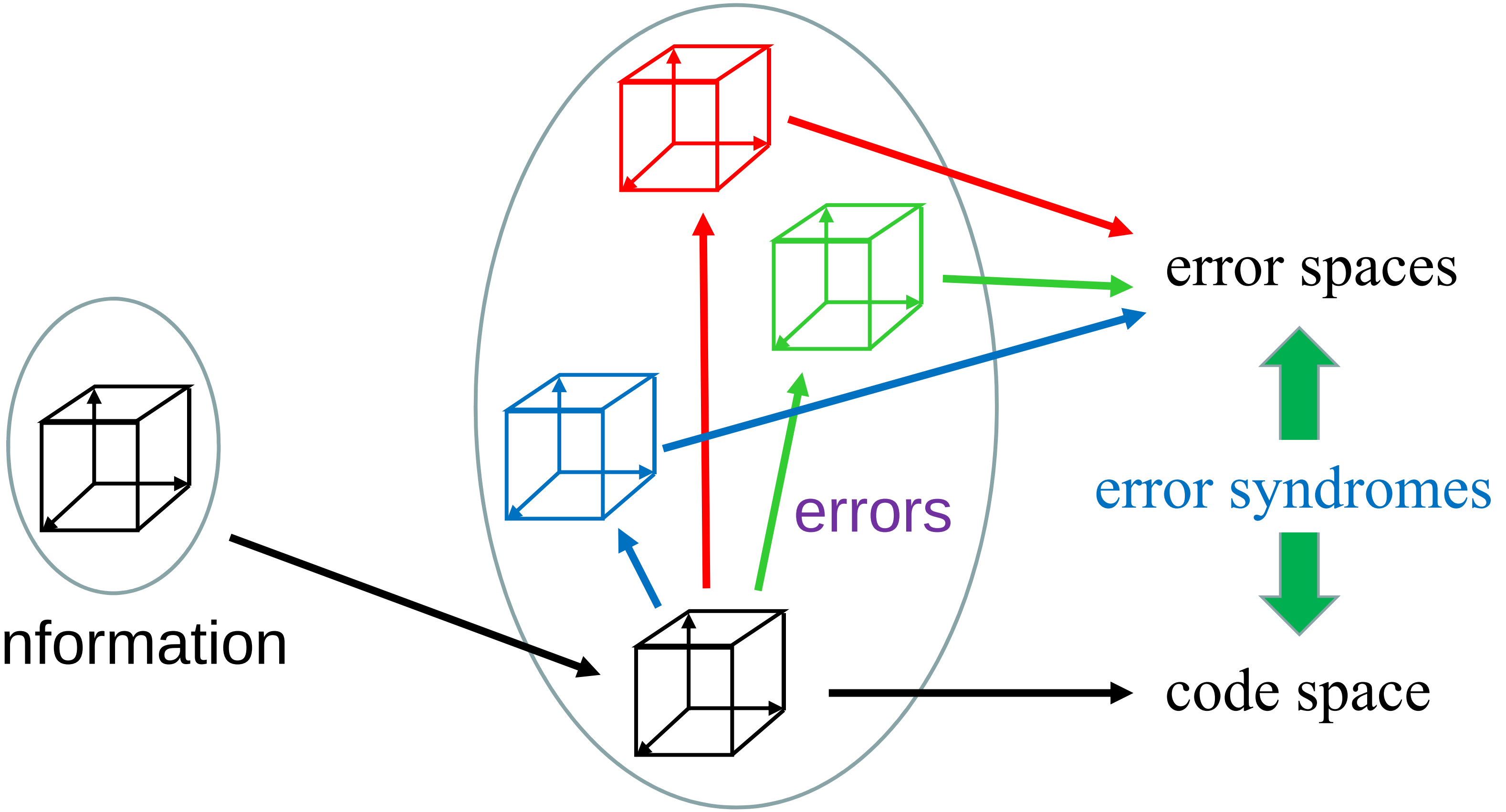
complexity

time

| | |
|---|---|
| | Fault-tolerant quantum computation |
| | Algorithms on multiple logical qubits |
| “Age of Qu. Error Correction” | Operations on single logical qubits |
| “Age of Qu. Feedback” | Logical memory with longer lifetime than physical qubits |
| “Age of Measurement” | QND measurements for error correction and control |
| “Age of Entanglement” | Algorithms on multiple physical qubits |
| “Age of Coherence” | Operations on single physical qubits |

*Devoret and Schoelkopf, Science* ***339****, 1169 (2013)*

# Quantum Error Correction Scheme

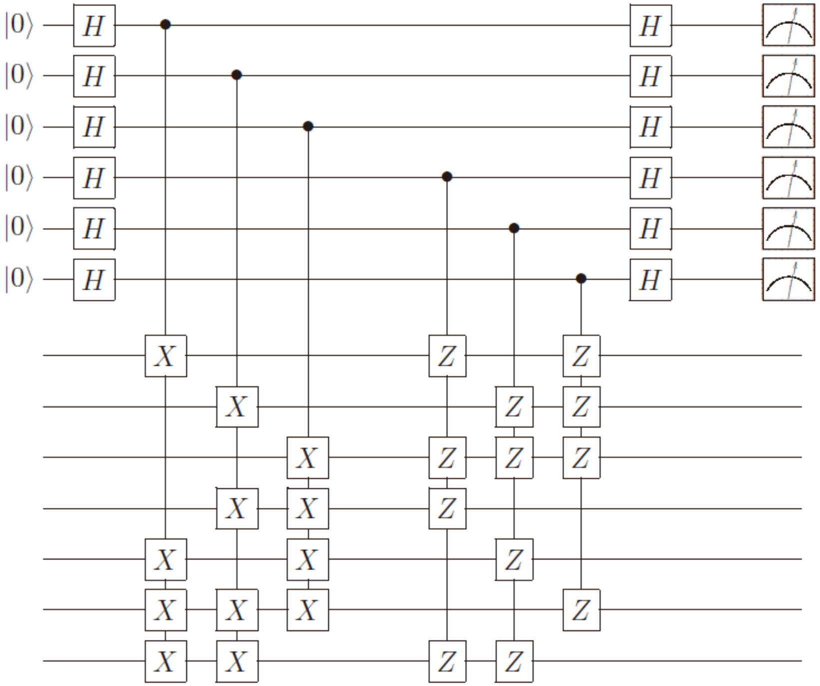


larger Hilbert space

Error syndrome measurements need to be quantum non-demolition!

# Quantum Error Correction Approaches

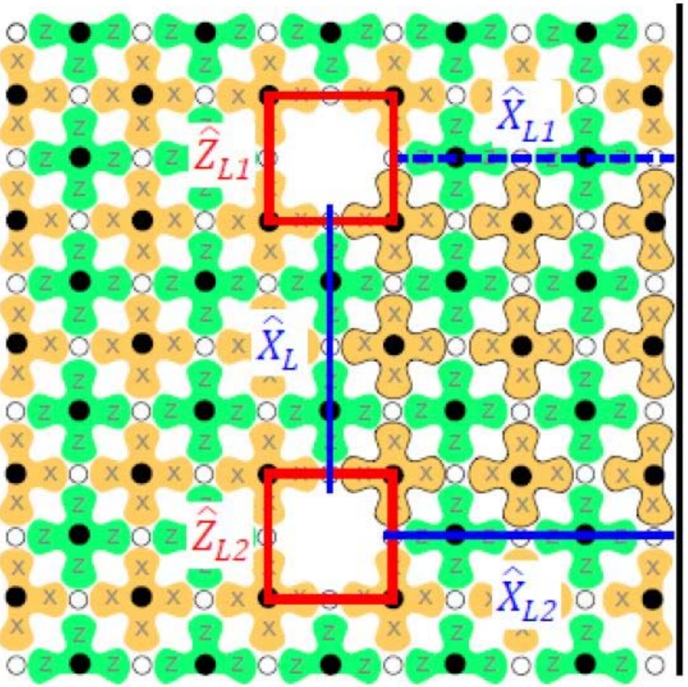
## classical



- Demanding low error rate <$10^{-4}$.
- Concatenated coding requires large resource overhead

- *Shor, Phys. Rev. A **52**, 2493 (1995)*
- *Steane, Proc. Roy. Lond. A **452**, 2551 (1996)*

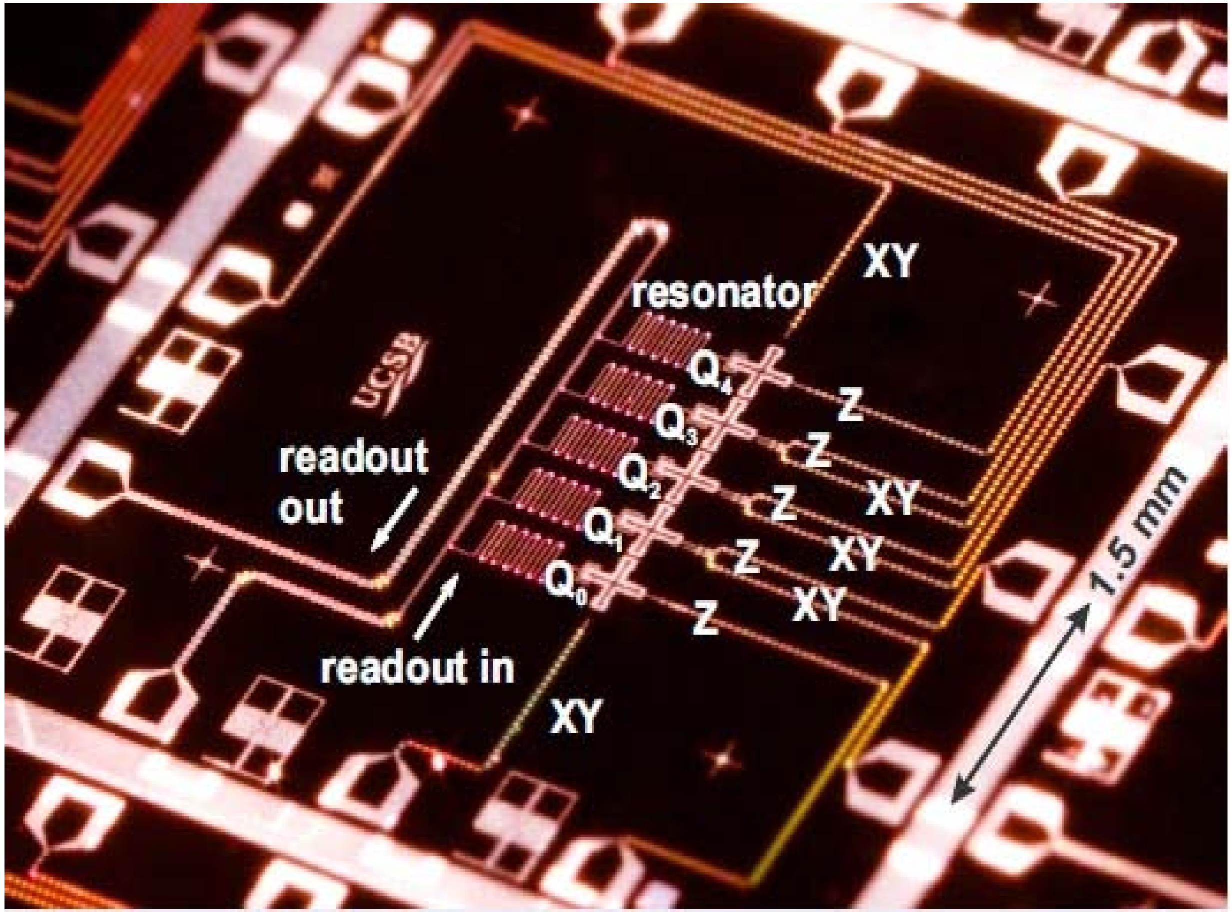
## surface code



- Low error rate ~ 1%
- Large resource overhead (3600 qubit for $10^{-3}$ error rate)

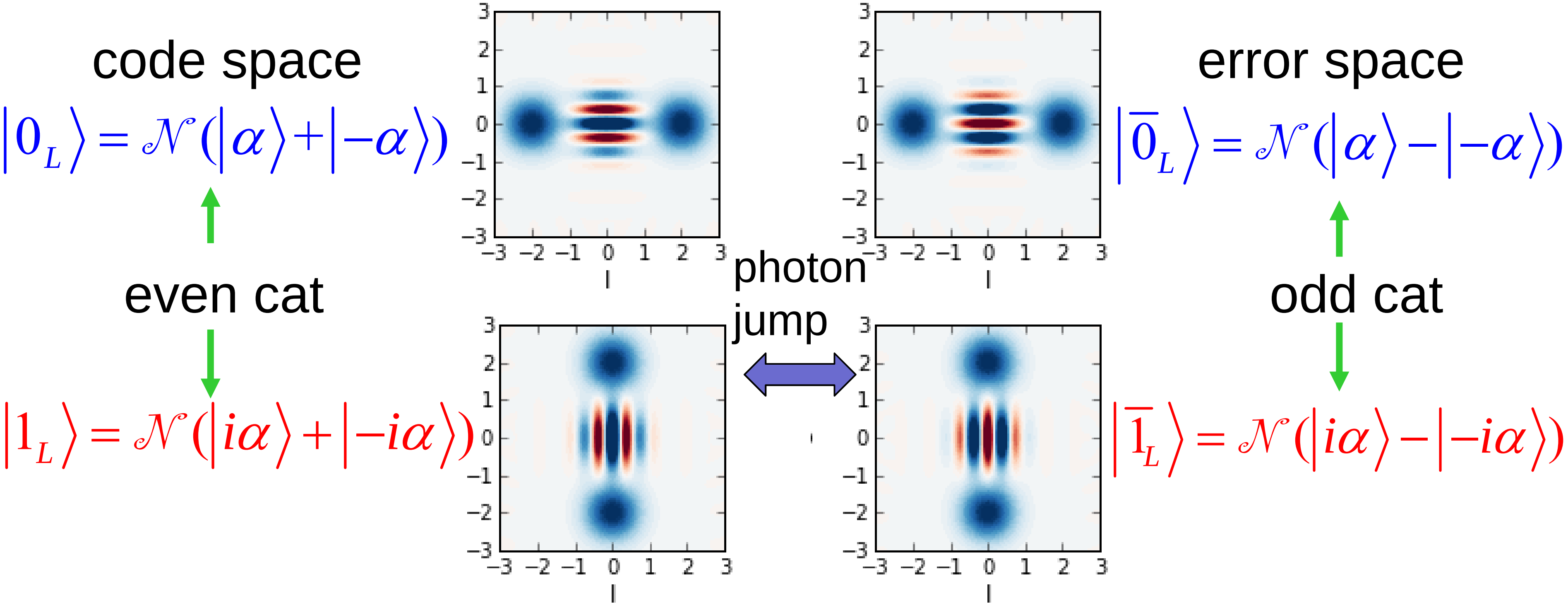
- *Fowler, Mariantoni, Martinis, and Cleland, PRA **86**, 032324 (2012)*

# Surface Code Threshold for Fault Tolerance



single qubit gate fidelity > 99.92%
two-qubit gate fidelity > 99.4%
Nature 508, 500-503 (2014) UCSB

# QEC Based on Schrodinger Cat States



code space

$|0_L\rangle = \mathcal{N}\left(|\alpha\rangle + |-\alpha\rangle\right)$

even cat

$|1_L\rangle = \mathcal{N}\left(|i\alpha\rangle + |-i\alpha\rangle\right)$

photon jump

error space

$|\bar{0}_L\rangle = \mathcal{N}\left(|\alpha\rangle - |-\alpha\rangle\right)$

odd cat

$|\bar{1}_L\rangle = \mathcal{N}\left(|i\alpha\rangle - |-i\alpha\rangle\right)$

parity = error syndrome

microwave cavities for QIP:

- large Hilbert space
- long lifetimes
- main decoherence channel: photon loss

- only one error syndrome -- the parity to measure

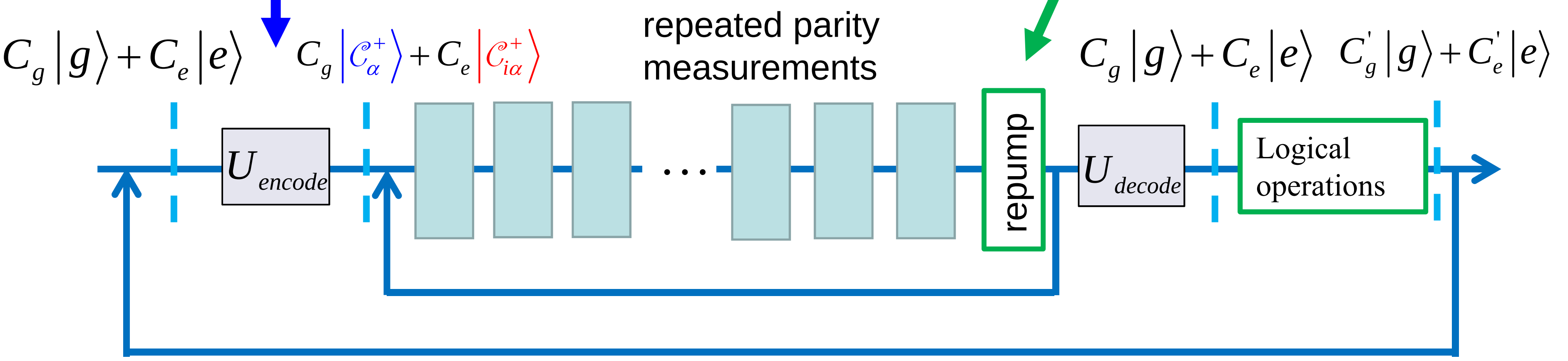
*Zaki Leghtas et al. PRL* ***111****, 120501 (2013)*

# QEC Protected Quantum Memory

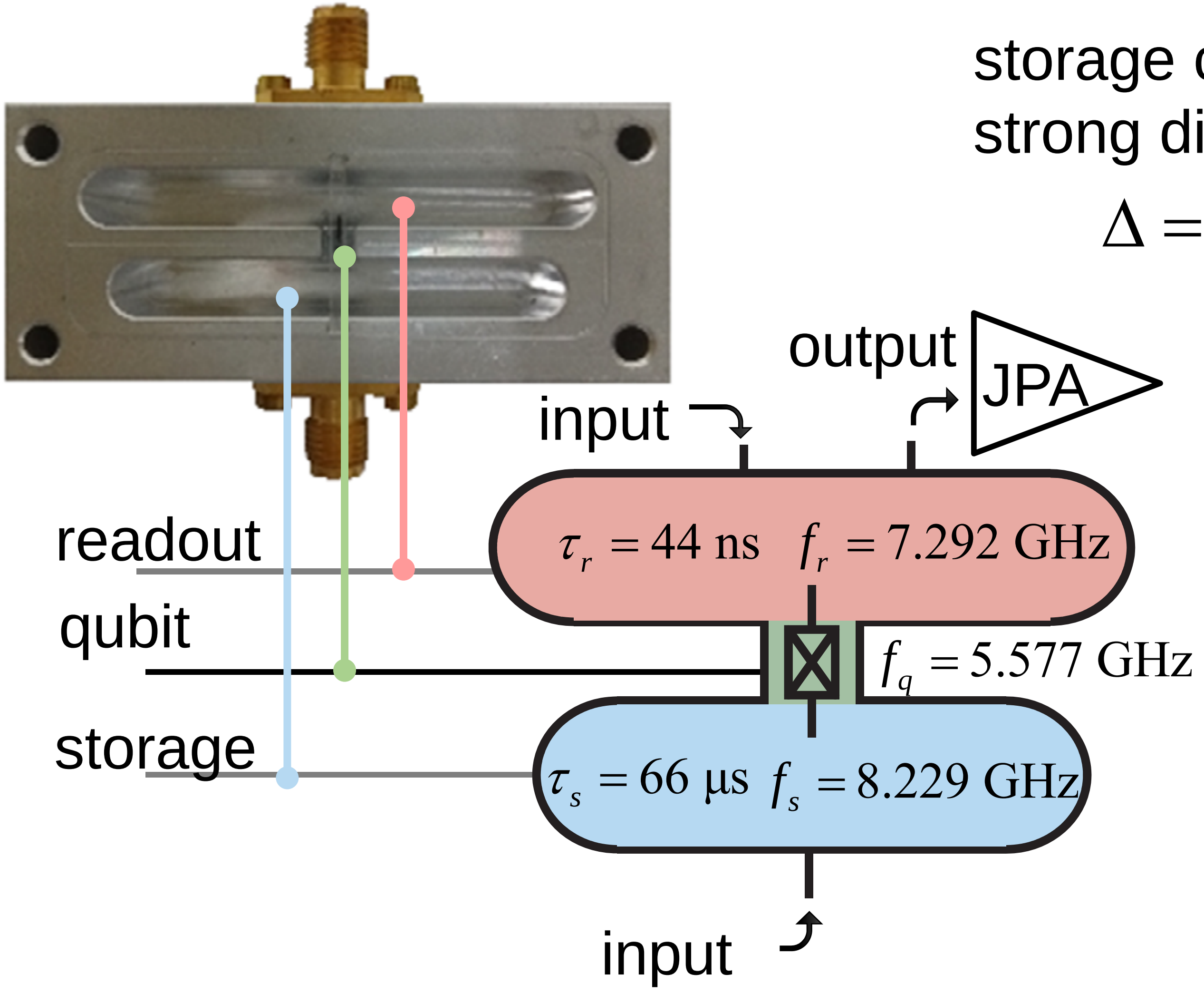
“Deterministically encoding quantum information using 100-photon Schrodinger cat states”, Vlastakis *et al.*, Science **342**, 607 (2013)

“Confining the state of light to a quantum manifold by engineered two-photon loss”, Leghtas *et al*., Science 347, 853 (2015)

“Tracking photon jumps with repeated quantum non-demolition parity measurements”, Sun *et at*., Nature **511**, 444 (2014)



# Our Setup – 2 Cavity + Ancilla Qubit



readout

qubit

storage

input

output

JPA

$\tau_r = 44\ \text{ns} \quad f_r = 7.292\ \text{GHz}$

$f_q = 5.577\ \text{GHz}$

$\tau_s = 66\ \mu\text{s} \quad f_s = 8.229\ \text{GHz}$

input

storage cavity – qubit:
strong dispersive regime

$$\Delta = \omega_s - \omega_q \gg g$$

$\kappa_r / 2\pi = 3.62\ \text{MHz}$

$\chi_{qr} / 2\pi = 4.71\ \text{MHz}$

$$\left\{ \begin{array}{l} T_1 = 9.5\ \mu\text{s} \\ T_2 = 7.5\ \mu\text{s} \end{array} \right.$$

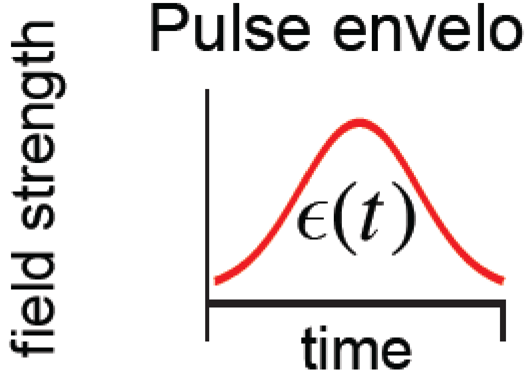
$\chi_{qs} / 2\pi = 1.64\ \text{MHz}$

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

# Manipulation of Qubit and Cavity State

cavity:

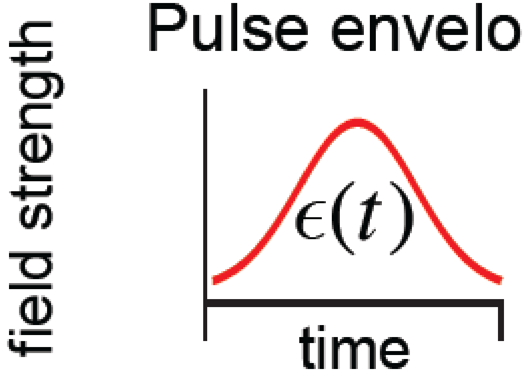
Pulse envelope:



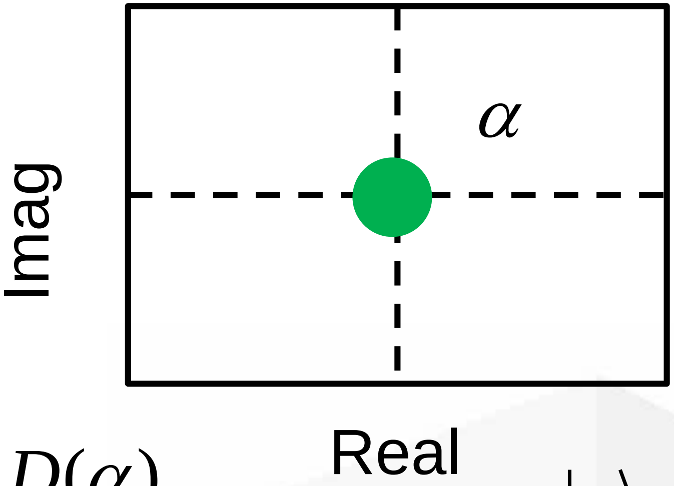
$$\alpha \propto \int \varepsilon(t)dt$$

qubit:

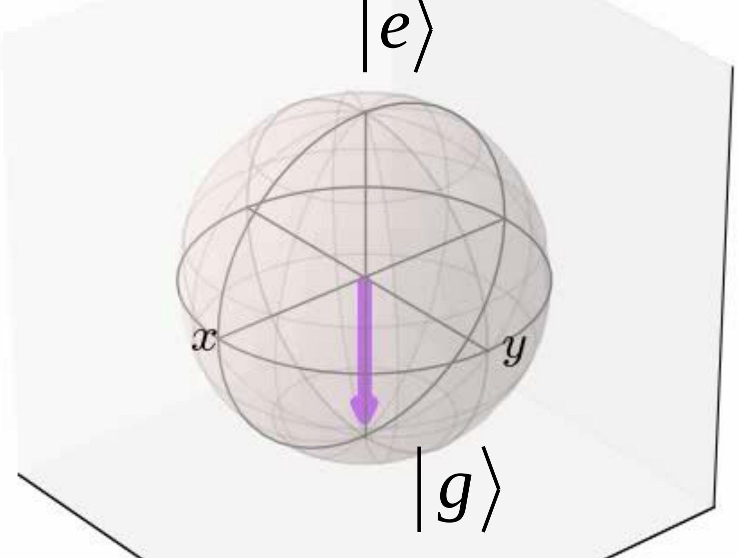
Pulse envelope:



$$\theta \propto \int \varepsilon(t)dt$$



$$D(\alpha)$$



$$|g\rangle \rightarrow \sin\frac{\theta}{2}|g\rangle + e^{i\varphi}\cos\frac{\theta}{2}|e\rangle$$

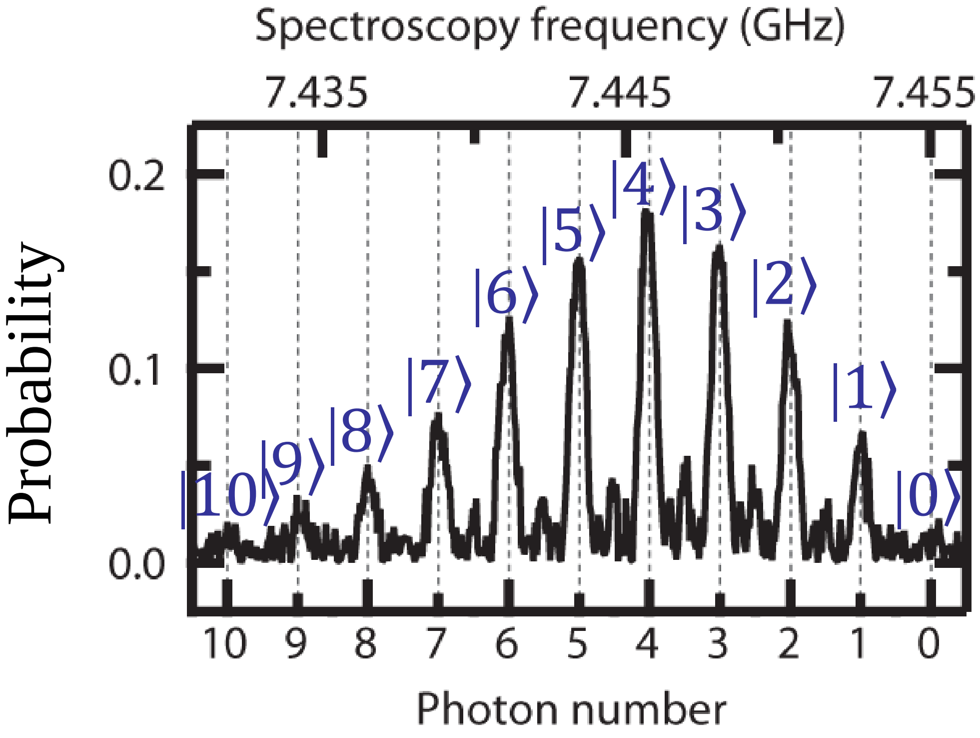
# Number Splitting Peaks

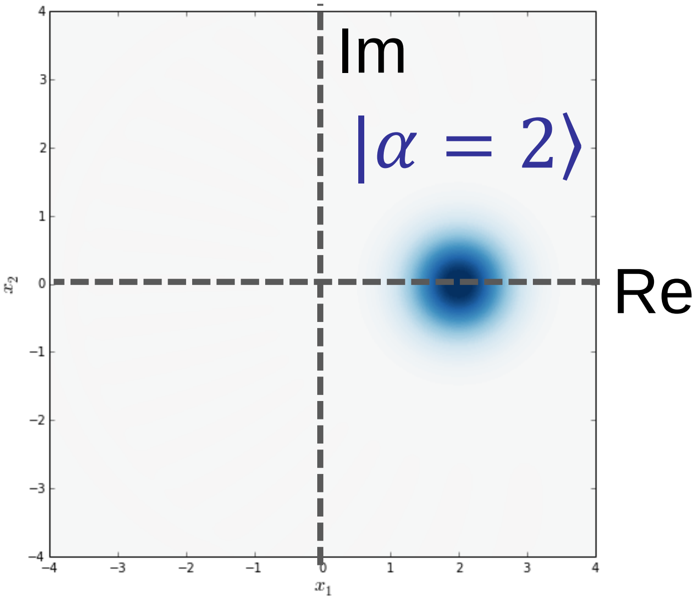
$$H/\hbar = \omega_q |e\rangle\langle e| + \omega_s a^+ a - \chi_{qs} a^+ a |e\rangle\langle e|$$

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

$|\alpha = 2\rangle \rightarrow \bar{n} = 4$

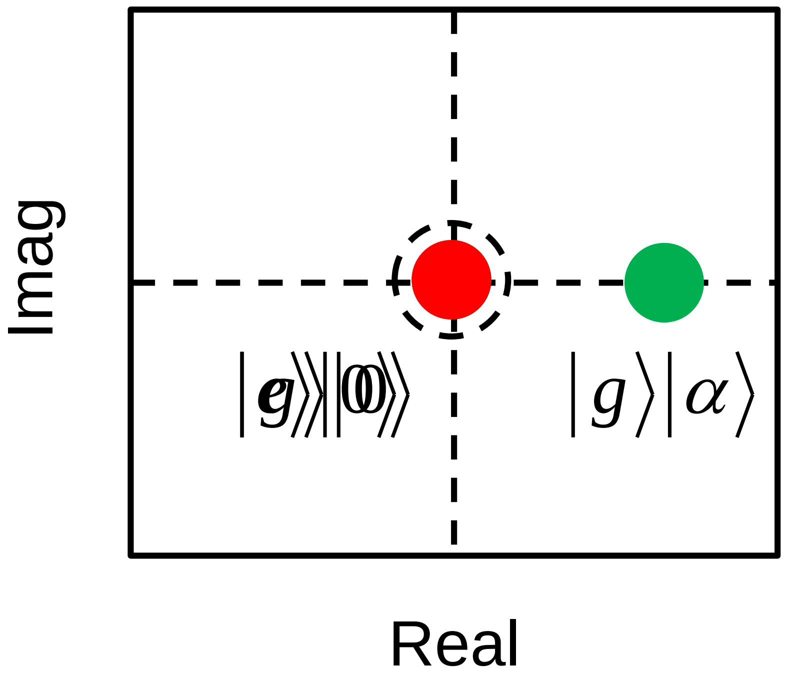
complex plane





*Vlastakis et al. Science 2013*

# Distinguish $|0\rangle$ From $|\alpha\rangle$



$$|\langle 0|\alpha\rangle| \approx 0$$

selective qubit π pulse $R_{\pi,0}$ on N=0

Is it a vacuum state?

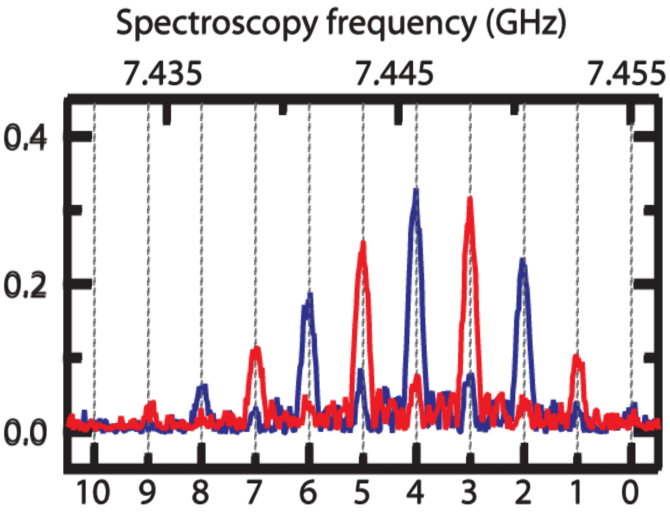
↓

Is it $|\alpha\rangle$ state?

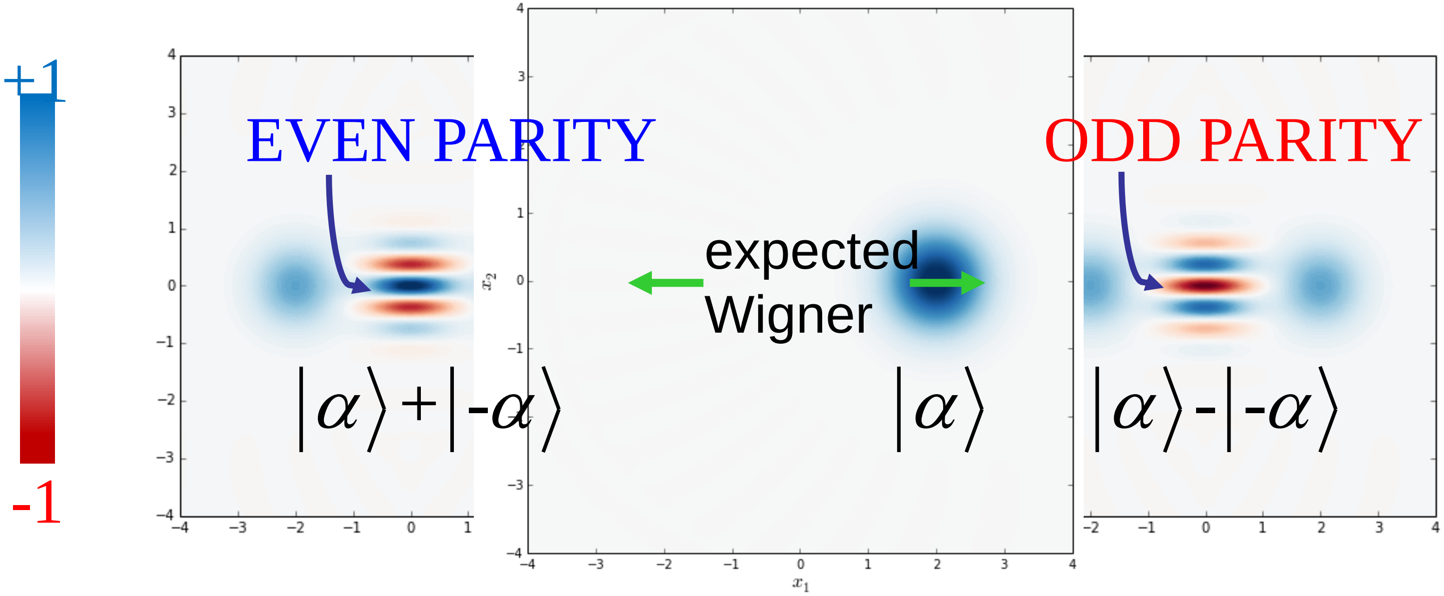
$D(-\alpha)$ and $R_{\pi,0}$

# A Parity Measurement Projects to Even/Odd Cat States

Probability



Parity



EVEN PARITY

expected Wigner

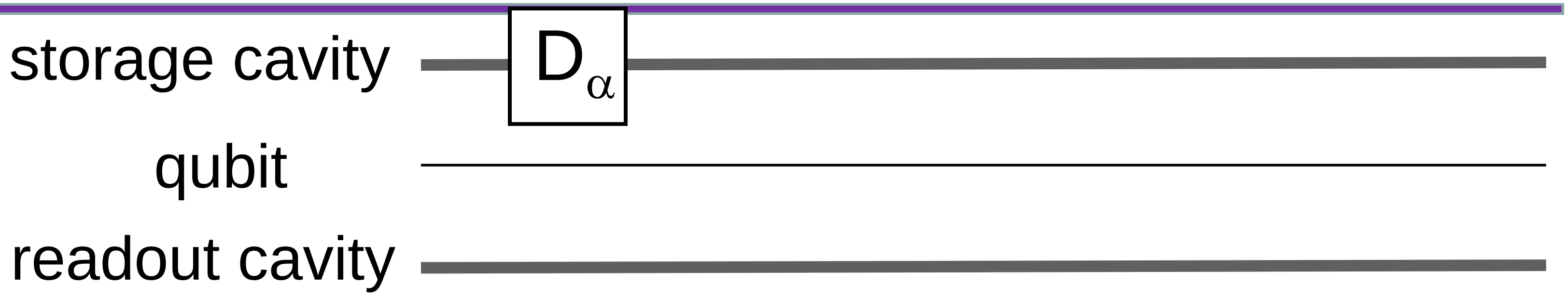
ODD PARITY

$|\alpha\rangle + |\text{-}\alpha\rangle$

$|\alpha\rangle$

$|\alpha\rangle - |\text{-}\alpha\rangle$

# Measuring Parity

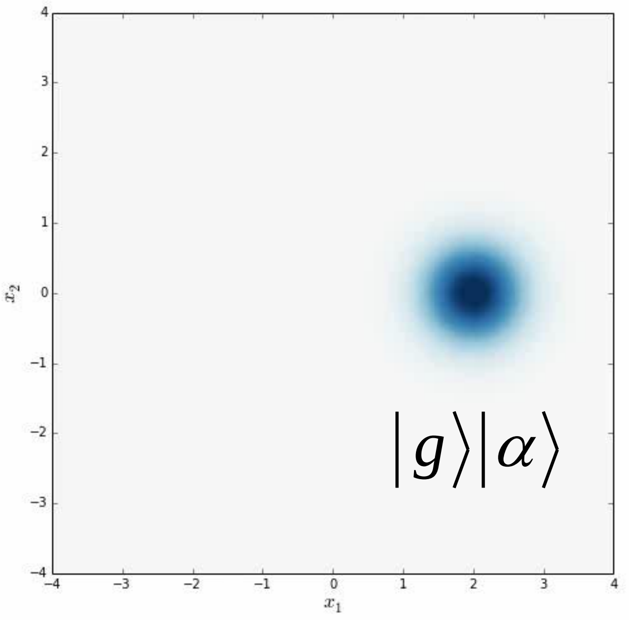


storage cavity

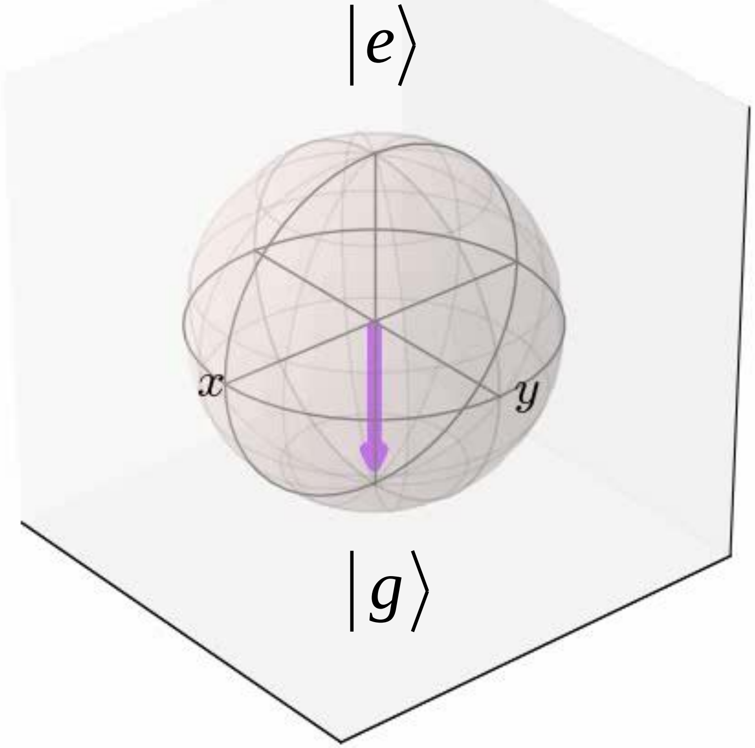
qubit

readout cavity

## What Cavity Does

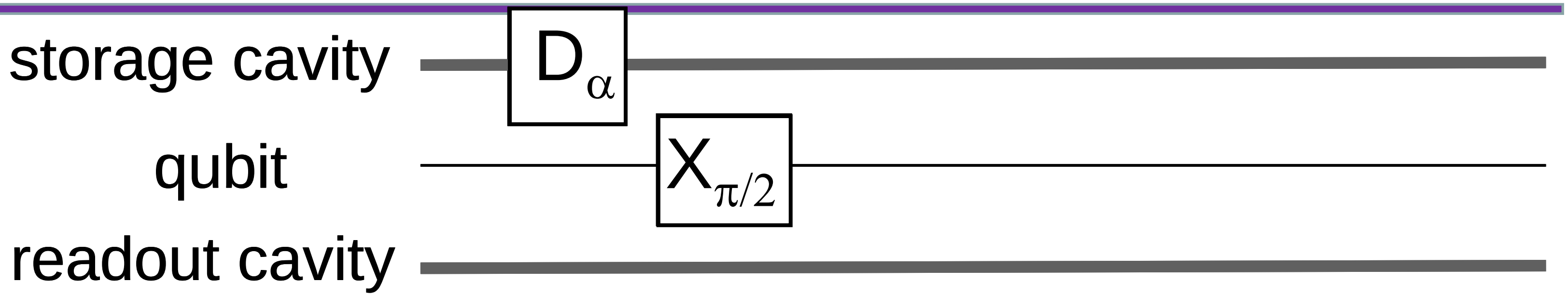


## What Qubit Does

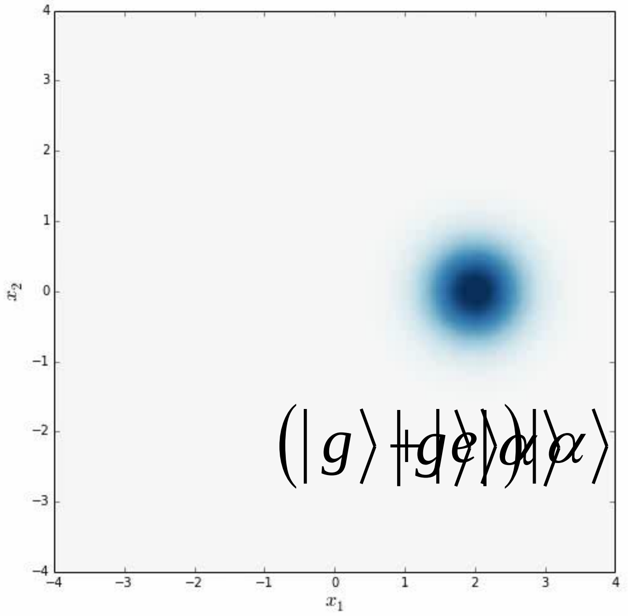


*Bertet et al. PRL 89, 200402 (2002)*

# Measuring Parity

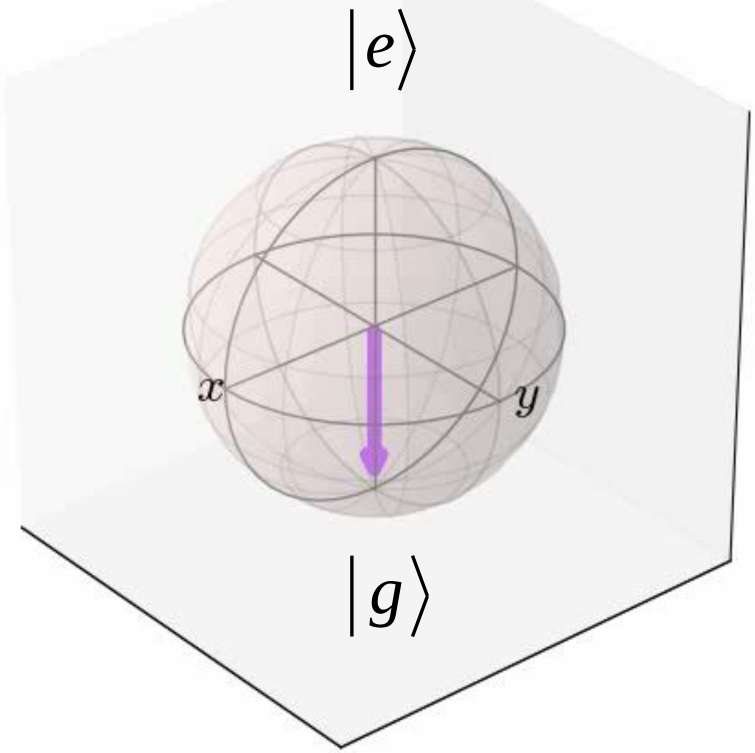


What Cavity Does



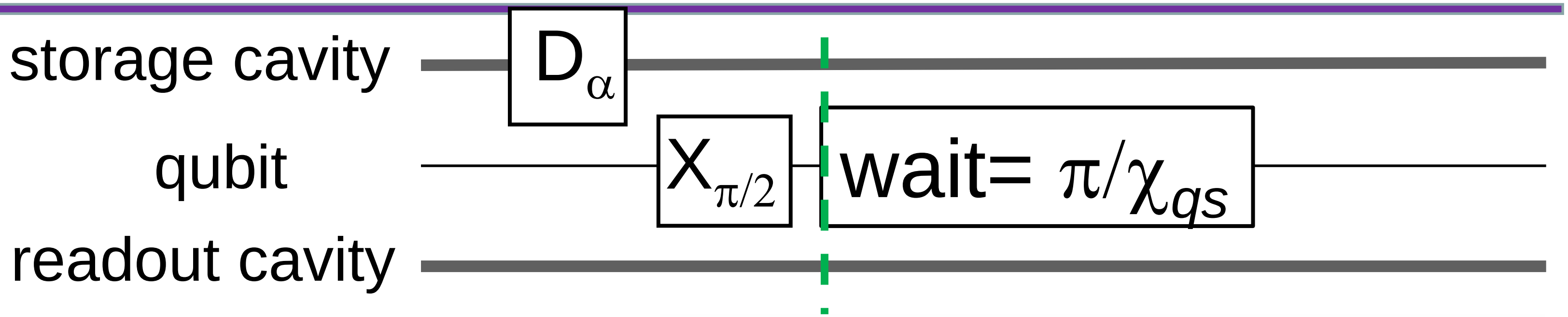
$(|g\rangle+|e\rangle)|\alpha\rangle$ $|g\rangle|\alpha\rangle$

What Qubit Does



*Bertet et al. PRL 89, 200402 (2002)*

# Measuring Parity



storage cavity

qubit

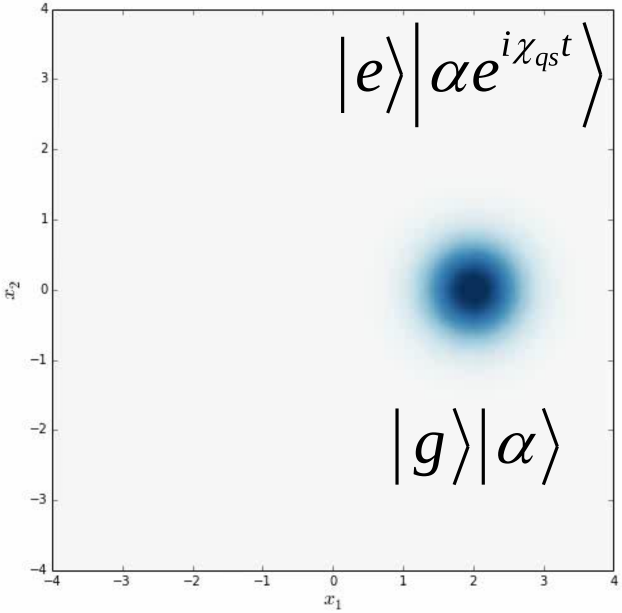
readout cavity

$D_\alpha$

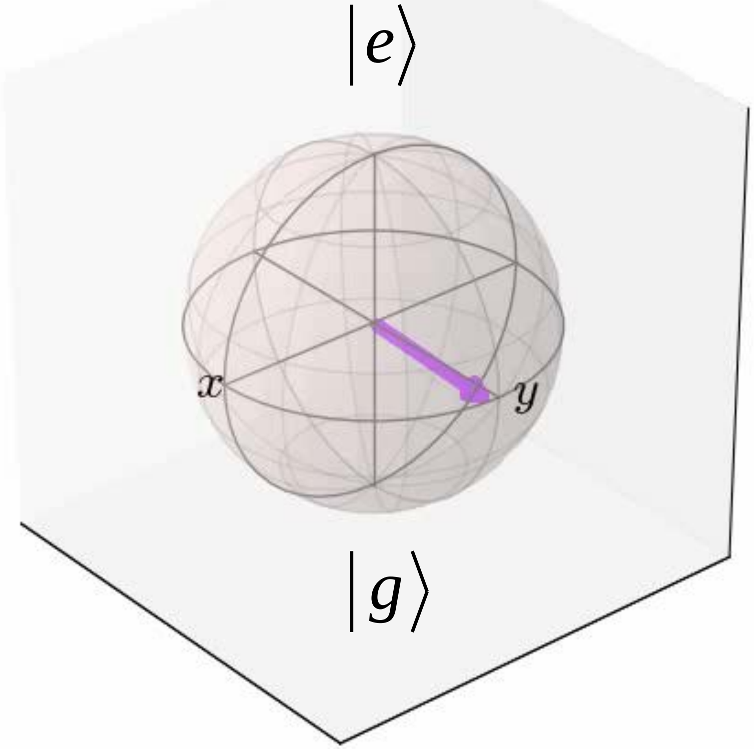
$X_{\pi/2}$

wait= $\pi/\chi_{qs}$

What Cavity Does

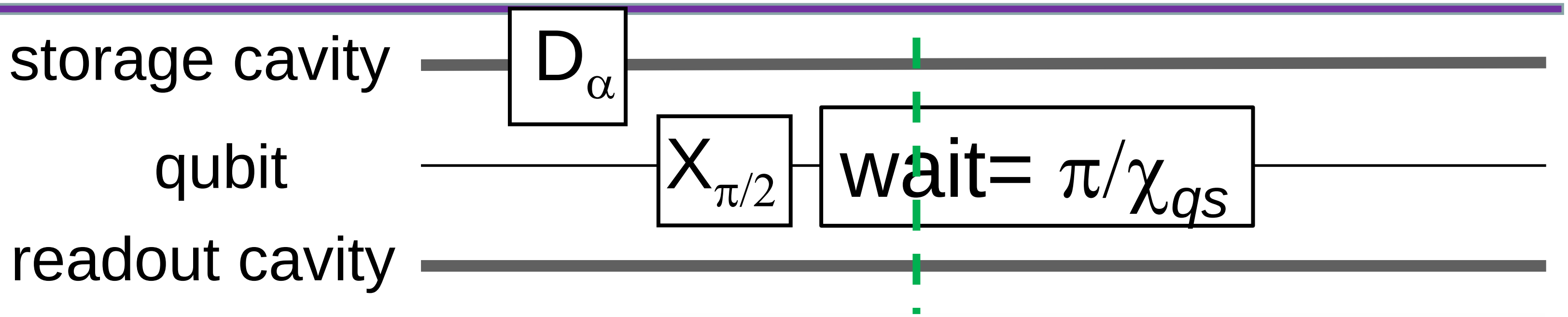


What Qubit Does



*Bertet et al. PRL 89, 200402 (2002)*

# Measuring Parity



storage cavity

qubit

readout cavity

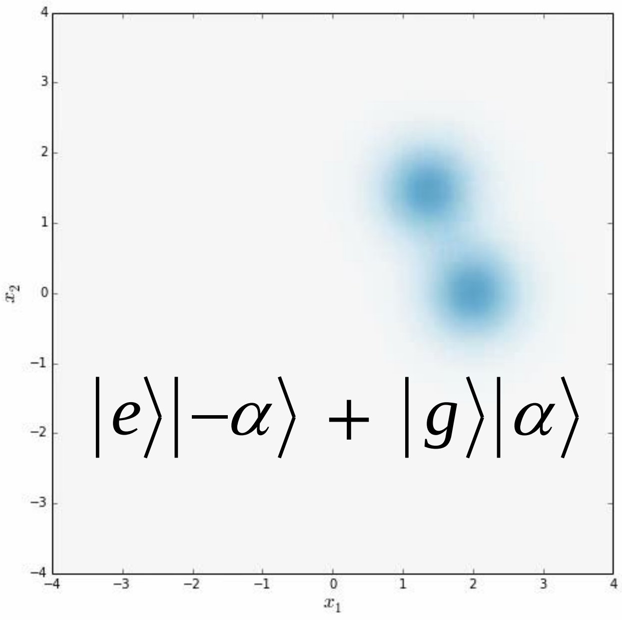
$D_\alpha$

$X_{\pi/2}$

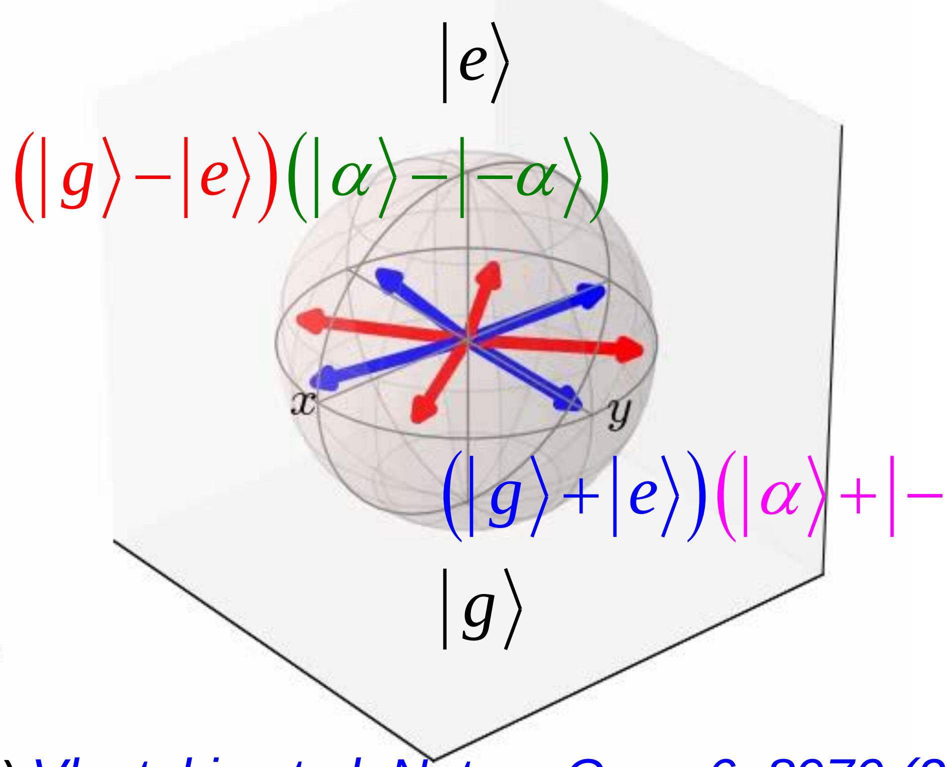
wait= $\pi/\chi_{qs}$

What Cavity Does

What Qubit Does



$|e\rangle|-\alpha\rangle + |g\rangle|\alpha\rangle$



$|e\rangle$

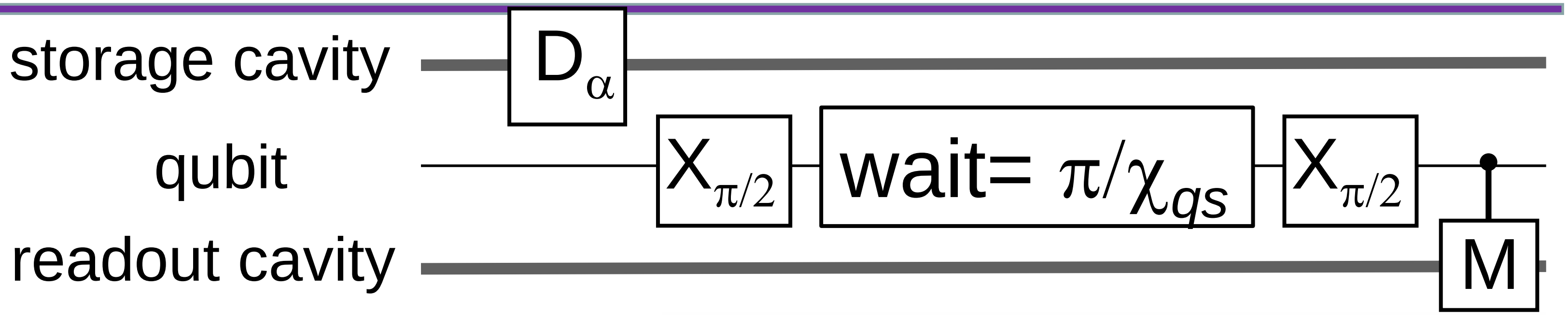
$(|g\rangle-|e\rangle)(|\alpha\rangle-|-\alpha\rangle)$

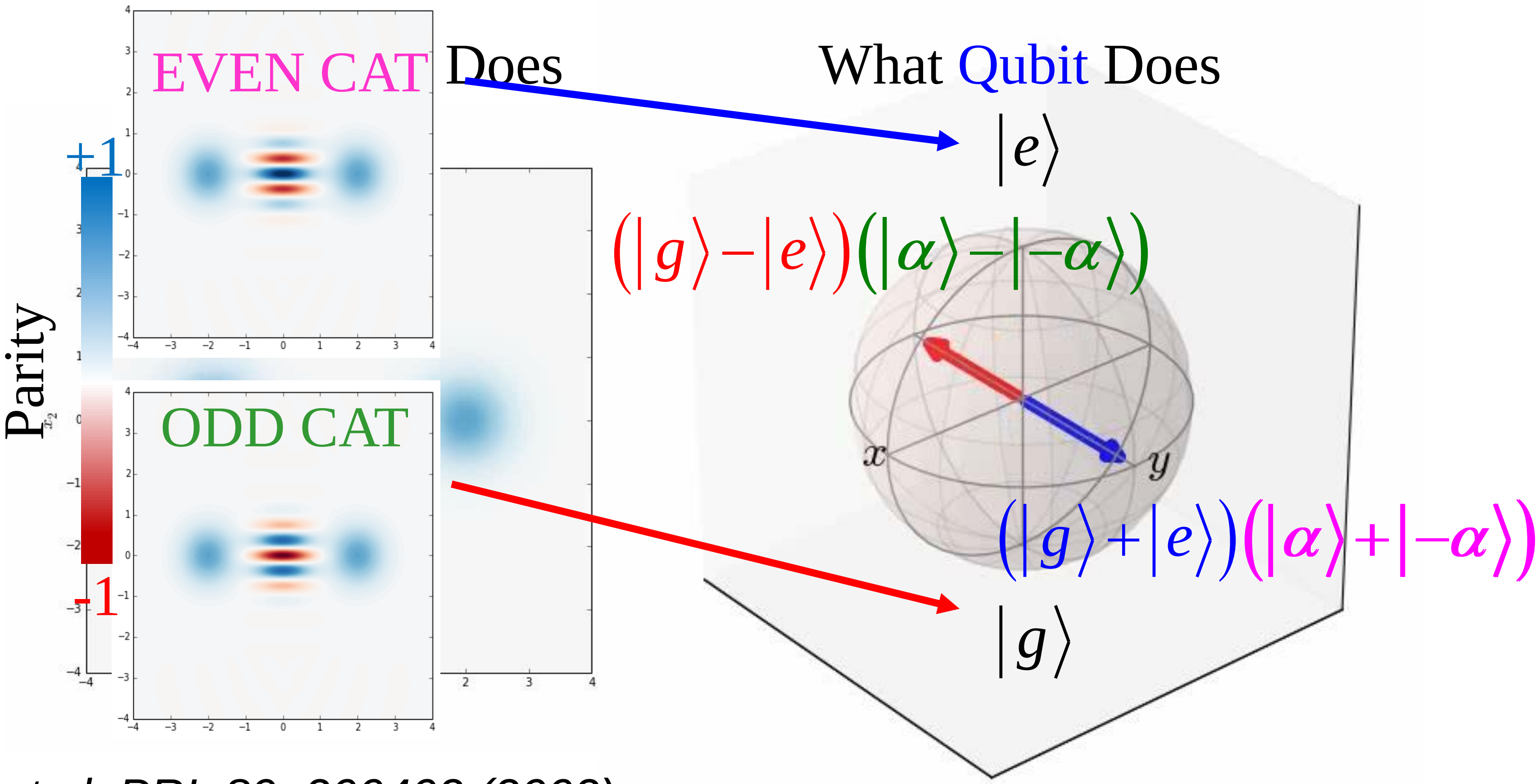
$(|g\rangle+|e\rangle)(|\alpha\rangle+|-\alpha\rangle)$

$|g\rangle$

*Bertet et al. PRL 89, 200402 (2002)* *Vlastakis et al. Nature Com. 6, 8970 (2015)*

# Measuring Parity



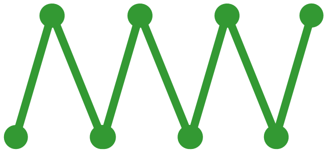


*Bertet et al. PRL 89, 200402 (2002)*

# Even/Odd Parity Measurement

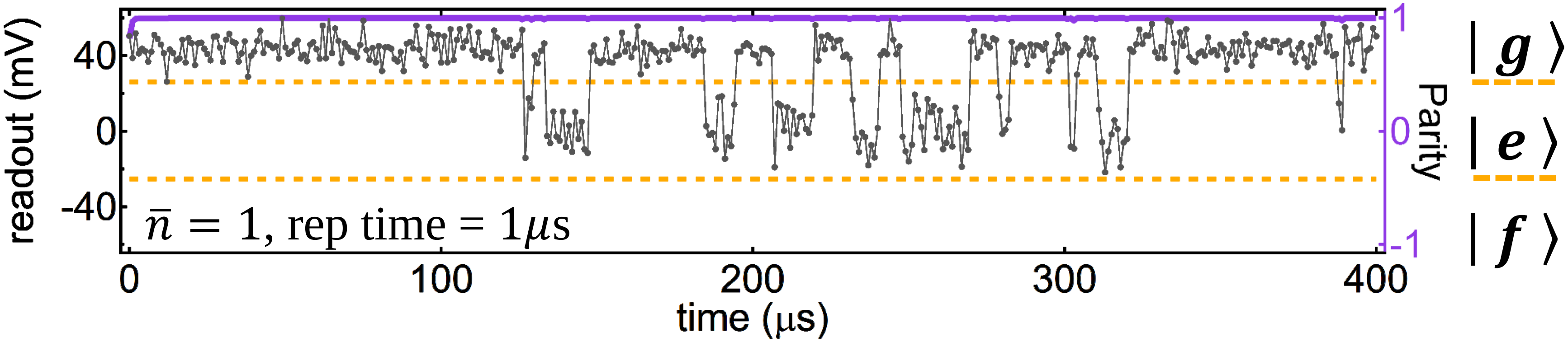
Parity measurement protocol: $X_{\pi/2}$, $\pi/\chi_{qs}$, $X_{-\pi/2}$

The protocol flips the qubit only if photon parity is odd.

| | before *P* meas. | | after *P* meas. | | meas. pattern |
|---|---|---|---|---|---|
| Even parity: | \|g> | → | \|g> | correlated |  |
| | \|e> | → | \|e> | | |
| Odd parity: | \|g> | → | \|e> | anti-correlated |  |
| | \|e> | → | \|g> | | |

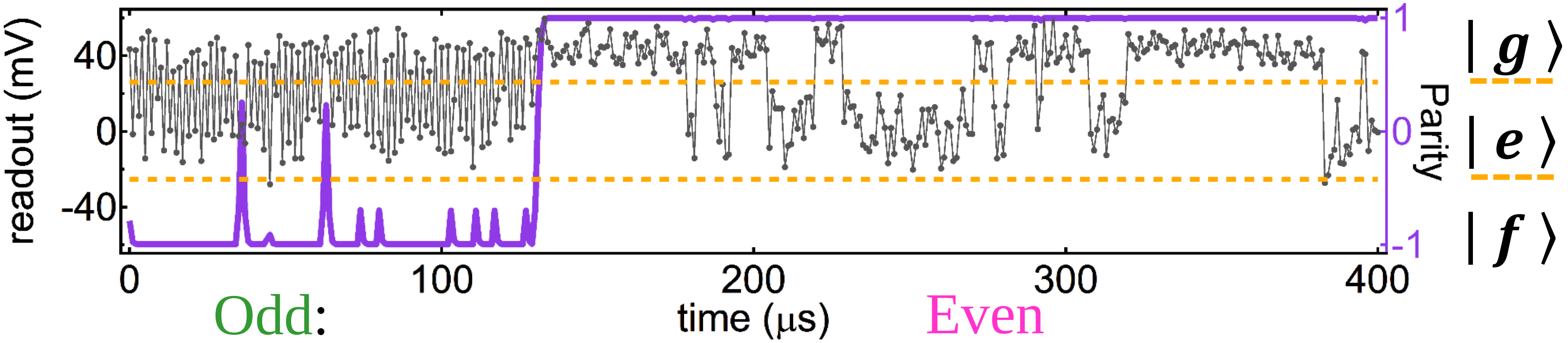
# Pattern of Signal Indicates Parity

1) Even: signal is mostly flat → correlated (g, g, …, or e, e, …)



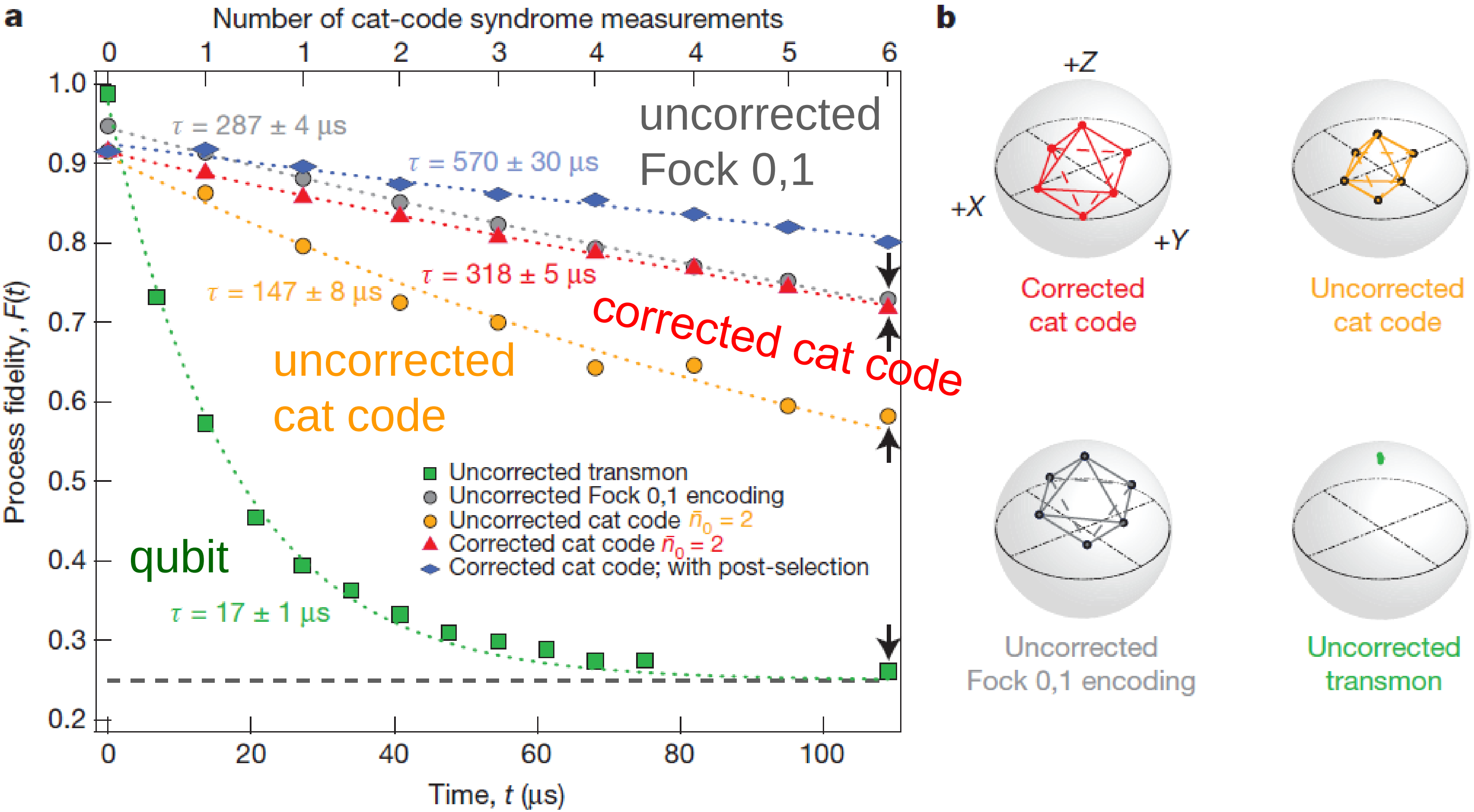
1) Odd: signal oscillates → anti-correlated (g, e, g, e, …)

2) Even: signal is mostly flat → correlated (g, g, …, or e, e, …)



L. Sun *et al.*, Nature **511**, 444 (2014)

# Break-Even Point of QEC



20× qubit lifetime

1.1× Fock 0, 1 encoding (the best physical qubit)

Ofek and Petrenko *et al*., “Extending the lifetime of a quantum bit with error correction in superconducting circuits”, Nature 536, 441 (2016)

Two recent experiments in our lab at Tsinghua University (not aim for quantum information processing):

- ✓ A two-fold quantum delayed choice experiment
  K. Liu *et al*., under review, arXiv:1608.04908

- ✓ Generation of arbitrary Fock-state superpositions in a superconducting cavity
  W. Wang *et al*., under review

# Wheeler’s Delayed-Choice Experiment

Wave-particle duality contains the “*only mystery*” of quantum mechanics (Feynman).

Wave: able to interfere
Particle: unable to interfere

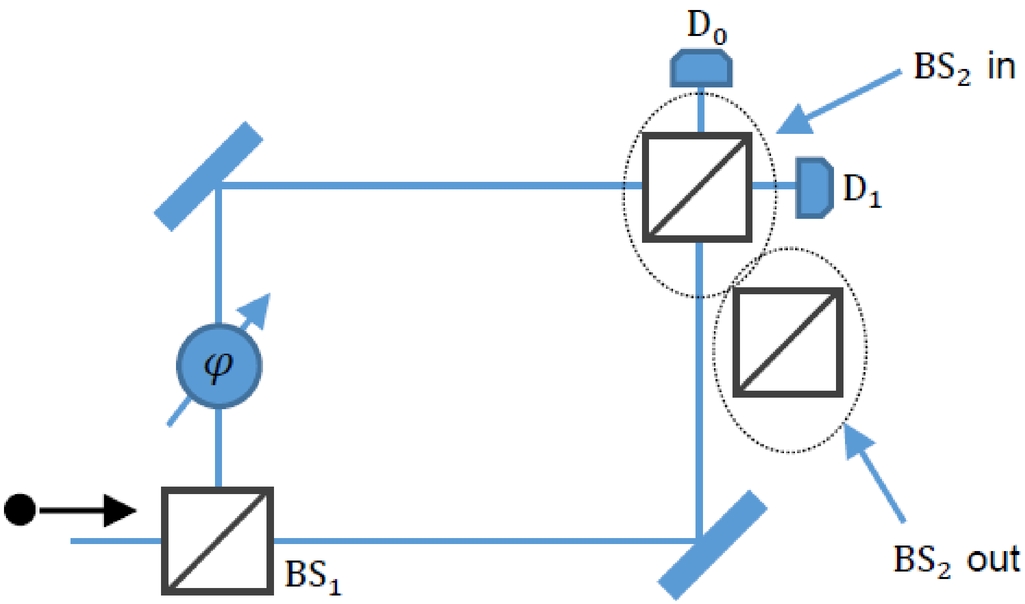
Quantum interference:

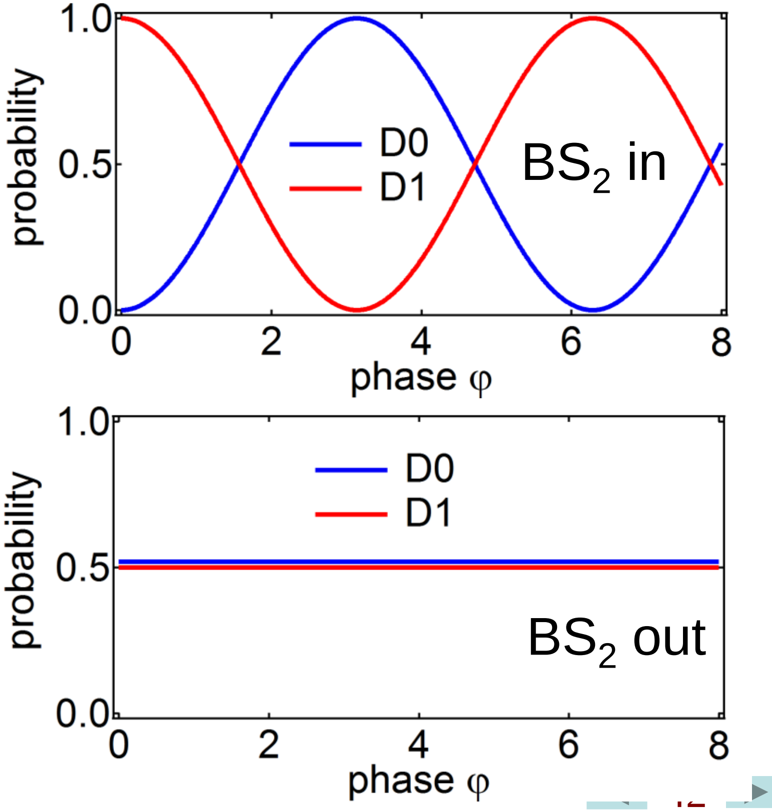
- ordinary space
- abstract space of quantum states

# Wheeler's Delayed-Choice Experiment

According to Bohr's complementarity, test of these two complementary phenomena (wave and particle) needs experimental arrangements that are mutually exclusive.

This is well illustrated by the Mach-Zehnder interferometer.





# Wheeler’s Delayed-Choice Experiment

Local hidden variable model: the photon knows in advance the experimental arrangement.

To exclude this possible causal link, Wheeler proposed the delayed-choice experiment:

the observer randomly chooses to insert BS2 or not after the photon has passed through BS1.

# Wheeler's Delayed-Choice Experiment

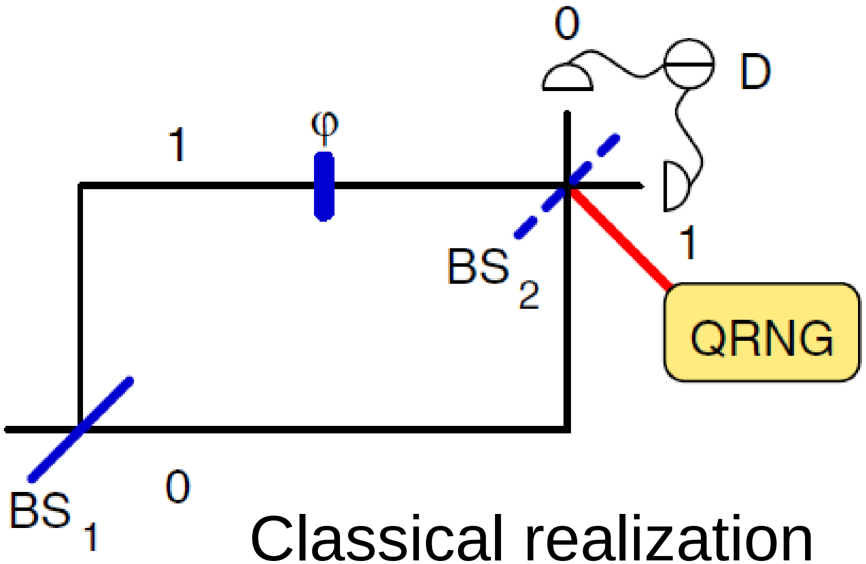
According to quantum mechanics, the delayed choice makes no difference on the outcomes of measurement.

In Wheeler's words: "*one decides whether the photon shall have come by one route or by both routes after it has already done its travel*".

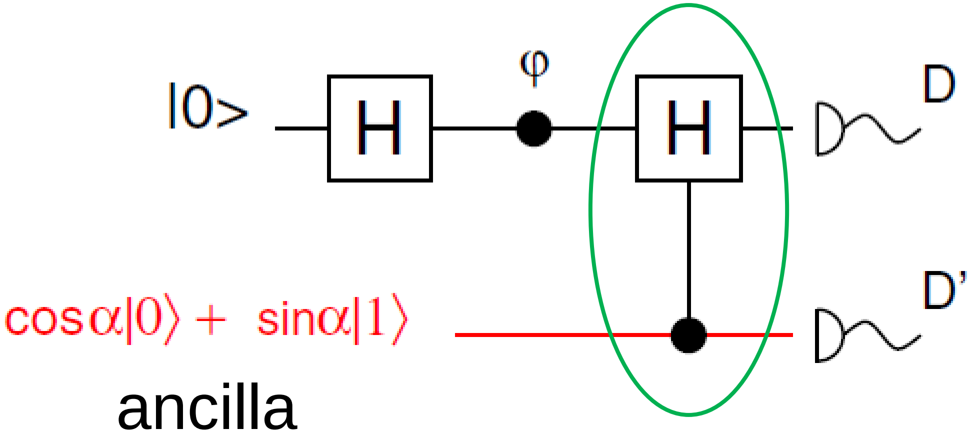
"*In this sense, we have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the already past history of that photon*."

# Quantum Delayed-Choice Experiments

Ionicioiu and Terno, *Proposal for a quantum delayed-choice experiment*, PRL 107, 230406 (2011)



Classical realization in 2007



quantum beam splitter

$$|\psi\rangle = \cos\alpha\,|\,particle\rangle|0\rangle_a + \sin\alpha\,|\,wave\rangle|1\rangle_a$$

# Quantum Delayed-Choice Experiments

To distinguish between the wave-like and particle-like components, one should measure the ancilla, and correlate the measurement data of the photon with the ancilla.

When the ancilla is detected in

$$|\pm\rangle_a = \left(|0\rangle_a \pm |1\rangle_a\right)/\sqrt{2},$$

the photon collapses to

$$\cos\alpha\,|particle\rangle \pm \sin\alpha\,|wave\rangle$$

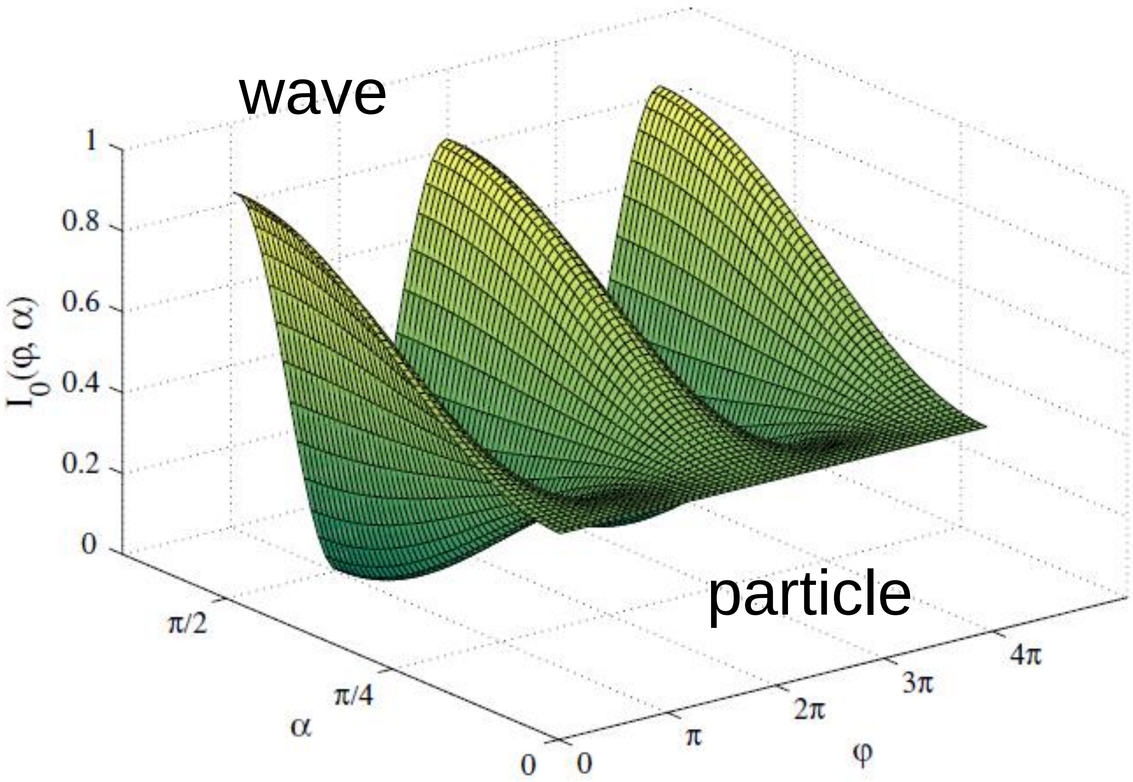
a superposition without a classical analog

# Quantum Delayed-Choice Experiments

The importance includes:

(1) The complementary phenomena can be observed with a single experiment.

(2) The morphing between particle and wave can be observed.



# Previous Quantum Delayed-Choice Experiments

- NMR implementation of a quantum delayed-choice experiment, Phys. Rev. A **85**, 022109 (2012)
- Experimental analysis of the quantum complementarity principle, Phys. Rev. A **85**, 032121 (2012)
- Realization of quantum Wheeler’s delayed-choice experiment, Nature Photonics **6**, 600 (2012)
- Entanglement-enabled delayed-choice experiment, Kaiser *et al.*, Science **338**, 637 (2012)
- A quantum delayed choice experiment, Science **338**, 634, (2012)
- Quantum delayed choice experiment with a genuine quantum beam splitter, Phys. Rev. Lett. **115**, 260403 (2015)

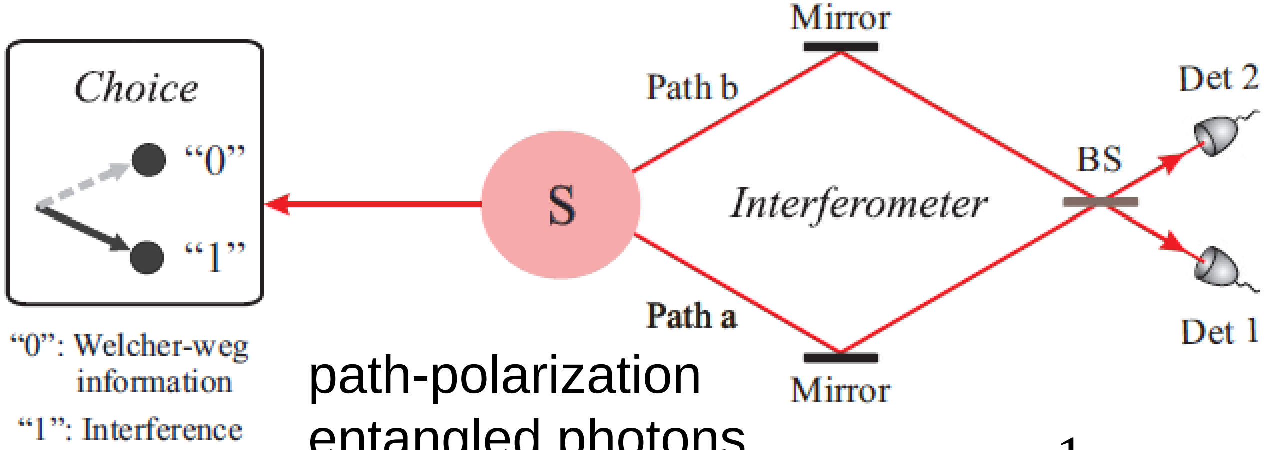
# Delayed-Choice Quantum Eraser

- M. O. Scully and K. Druhl, *Quantum eraser: A proposed photon correlation experiment concerning observation and "delayed choice" in quantum mechanics*, Phys. Rev. A 25, 2208 (1982).
- M. O. Scully, B. G. Englert, and H. Walther, *Quantum optical tests of complementarity*, Nature 351, 111 (1991).
- C. C. Gerry, *Complementarity and quantum erasure with dispersive atom-field interactions*, Phys. Rev. A 53, 1179 (1996)
- ……

# Previous Delayed-Choice Quantum Eraser Experiment

environment photon

system photon



path-polarization entangled photons

$$|\psi\rangle = \frac{1}{\sqrt{2}}\left(|b\rangle_s |V\rangle_e + |a\rangle_s |H\rangle_e\right)$$

$$\begin{cases} |R/L\rangle = \frac{1}{\sqrt{2}}\left(|V\rangle_e \pm |H\rangle_e\right) \\ |\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle_s \pm |b\rangle_s\right) \end{cases}$$

Ma *et al.*, *Quantum erasure with causally disconnected choice*, Proc. Natl. Acad. Sci. USA 110, 1221 (2013).

Also realized e.g. Herzog *et al.*, *Complementarity and the quantum eraser*, Phys. Rev. Lett. 75, 3034 (1995); Kim *et al.*, *Delayed "choice" quantum eraser*, Phys. Rev. Lett. 84, 1 (2000).

# Previous Quantum Delayed-Choice Experiments

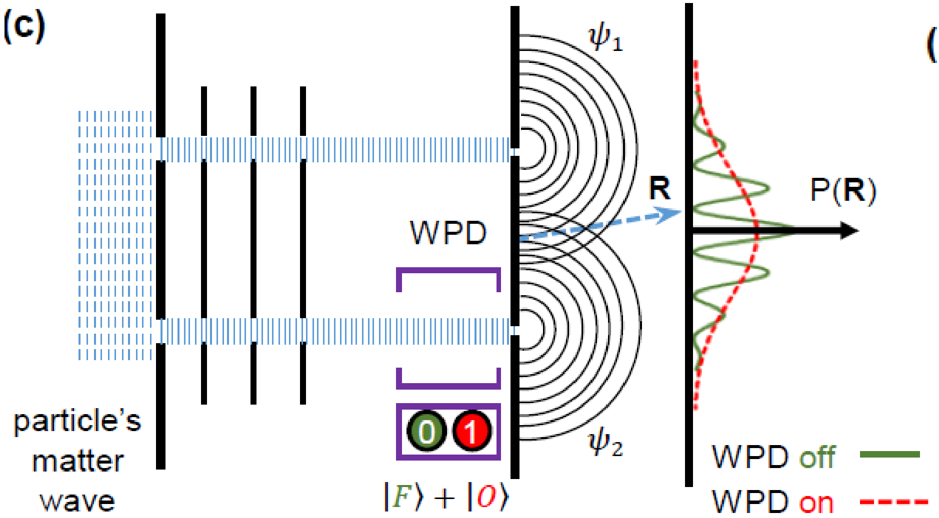
A short summary:

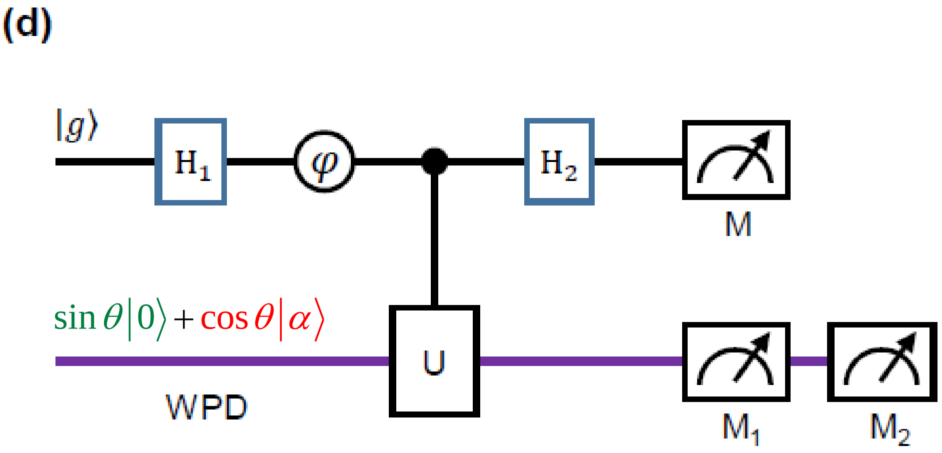
1. The wave and particle behaviors were simultaneously observed by using **a quantum beam splitter** or **quantum interferometer** that was in a superposition of being closed and open.
2. Either demonstrated that the behavior of the test system depends on the delayed choice of the detecting device’s configuration (interferometer is closed or open).
3. Or showed that one can *a posteriori* choose if the system behaves as a wave or as a particle by erasing or marking the which-path information (delayed-choice quantum eraser).

# Our Quantum Delayed-Choice Experiment

1. Demonstrated both (summary 2 and 3) with the same measurement apparatus.
2. This was achieved by introducing a which-path detector (WPD), but the interferometer itself was classical and always closed.
3. The first two-fold delayed-choice experiment is only enabled by our unique design.

# Our Quantum Delayed-Choice Experiment





$$|\Phi(\mathbf{r})\rangle = \frac{1}{2}\left[\begin{array}{l}\left(|\psi_1(\mathbf{r})\rangle|O_1\rangle + |\psi_2(\mathbf{r})\rangle|O_2\rangle\right)\\ +\left(|\psi_1(\mathbf{r})\rangle + |\psi_2(\mathbf{r})\rangle\right)|F\rangle\end{array}\right]$$

WPD is in a large Hilbert space

$|F\rangle$ → interference

$|O\rangle$ → no interference

$\frac{1}{\sqrt{2}}\left(|O\rangle_1 \pm |O\rangle_2\right)$ → interference

$\left\{|O\rangle_1, |O\rangle_2\right\}$ → no interference

# Which-Path Detector

$|g\rangle, |e\rangle:$ two paths in the interferometer in the abstract quantum space

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

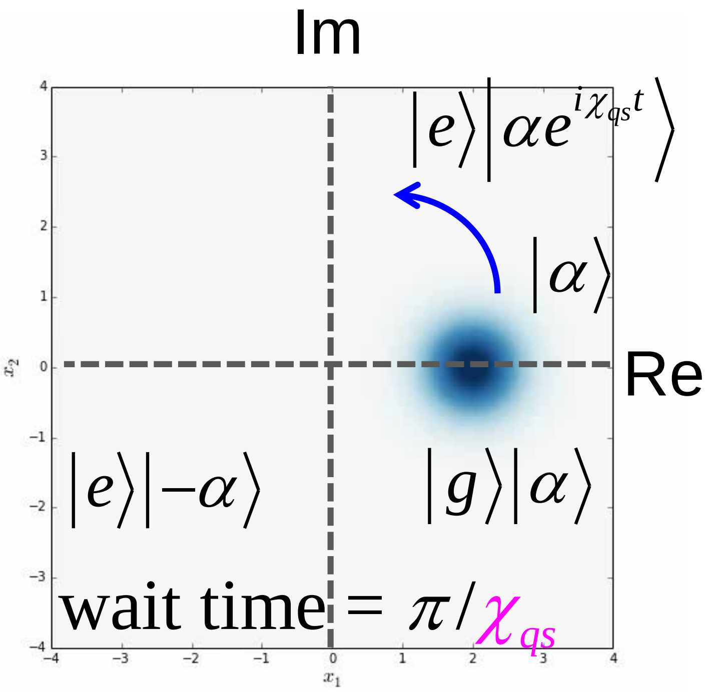
$$= \omega_q |e\rangle\langle e| + \left(\omega_s - \chi_{qs} |e\rangle\langle e|\right) a^{+} a$$

coherent state: WPD

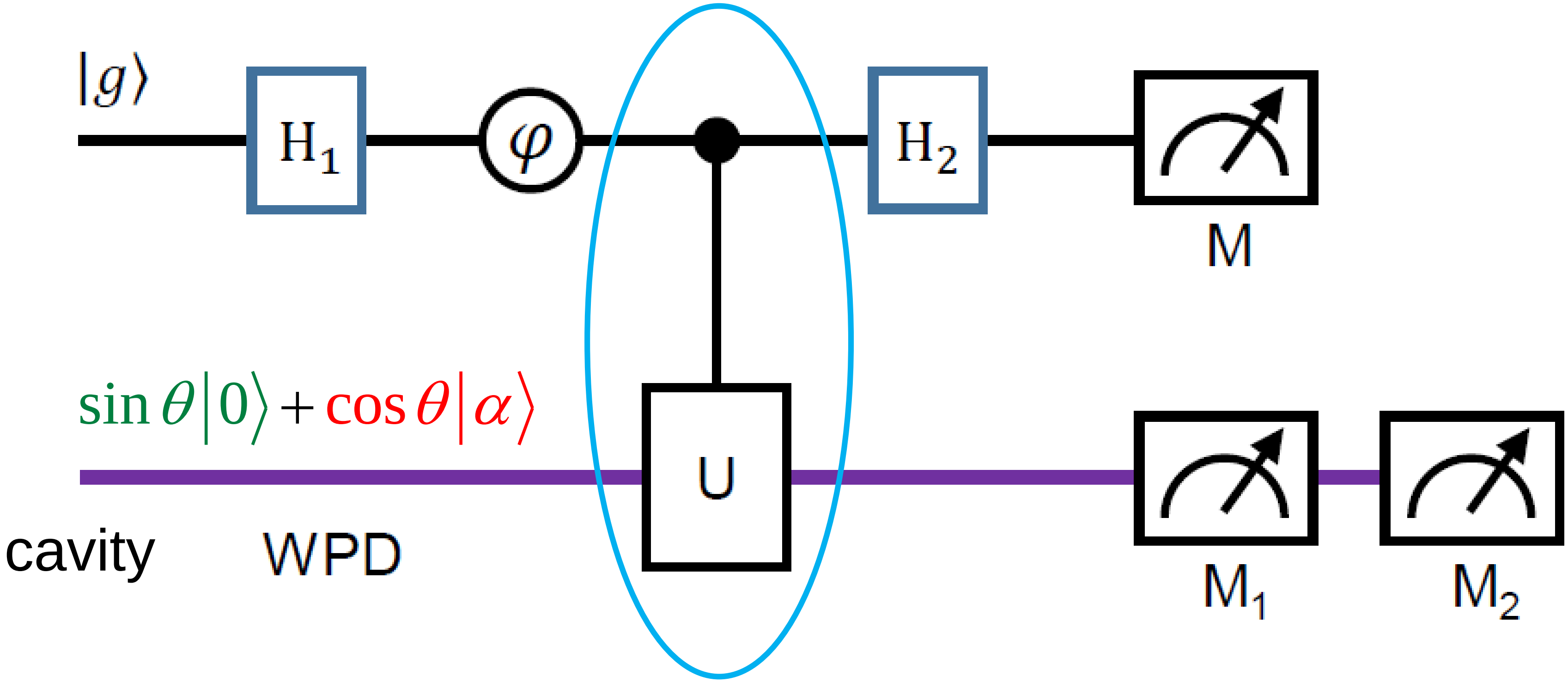
$|\alpha\rangle:$ WPD on

$|0\rangle:$ WPD off

$|qubit\rangle |photon\rangle$



# Which-Path Detector

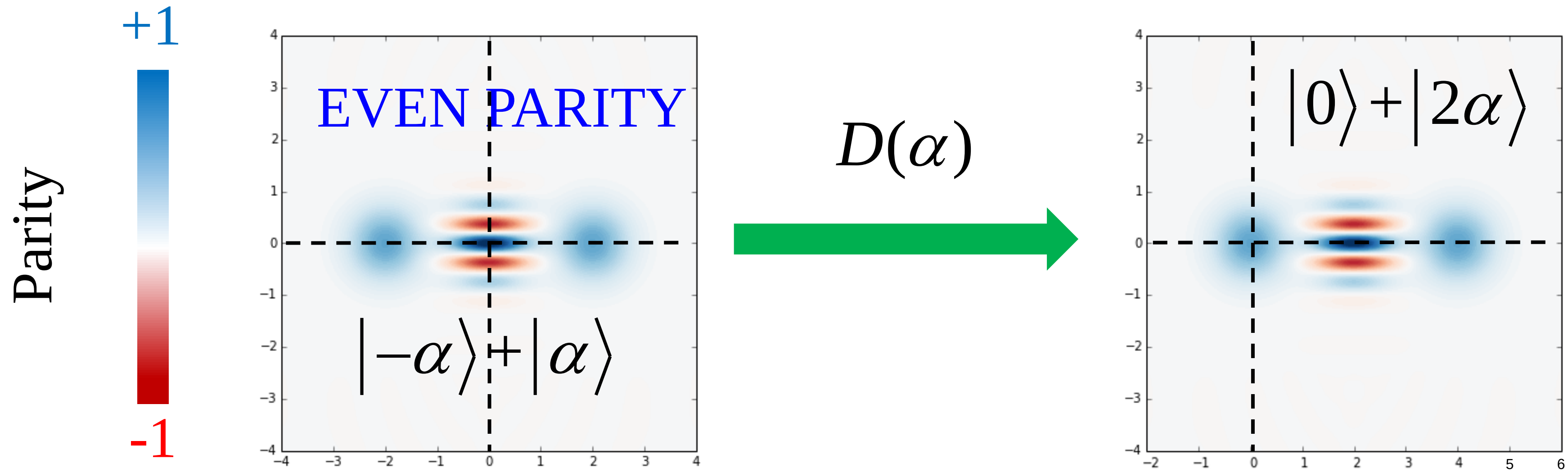


$$U = e^{i\pi a^{+}a \otimes |e\rangle\langle e|}$$

$$e^{i\pi a^{+}a}|\alpha\rangle = |-\alpha\rangle$$

$$e^{i\pi a^{+}a}|0\rangle = |0\rangle$$

# Creation of Initial WPD State



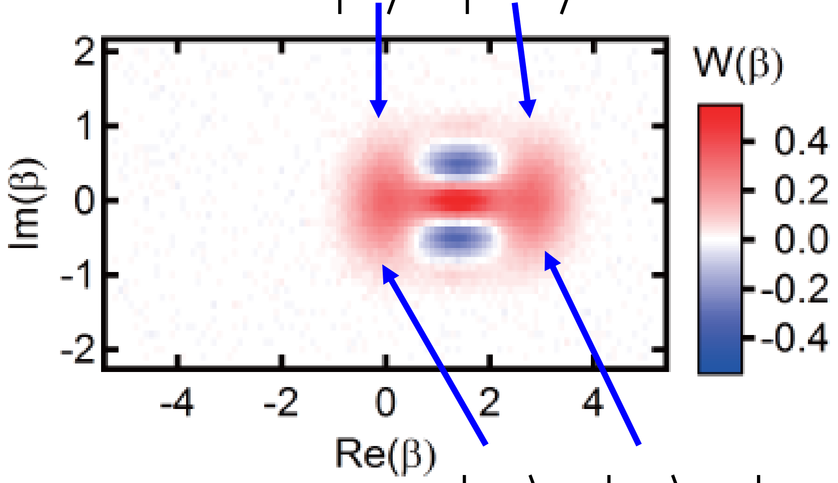
EVEN PARITY

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

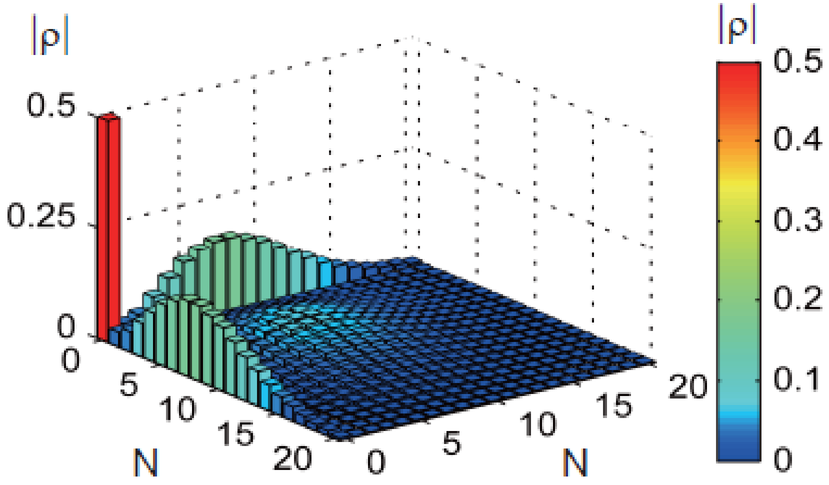
$D(\alpha)$

$|0\rangle+|2\alpha\rangle$

$|0\rangle+|2\alpha\rangle$

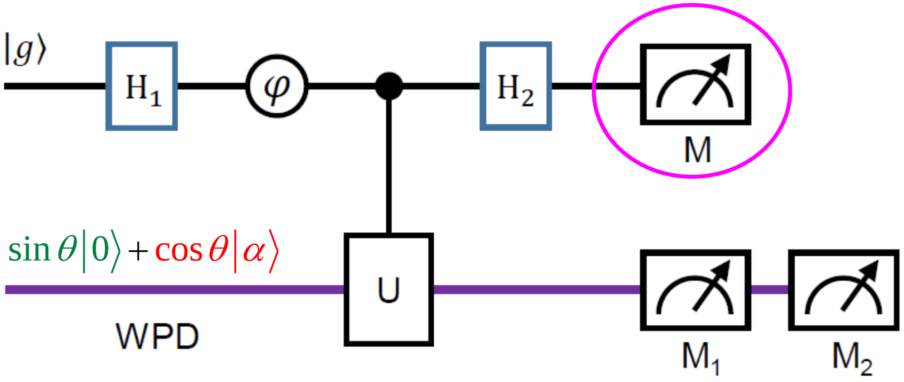


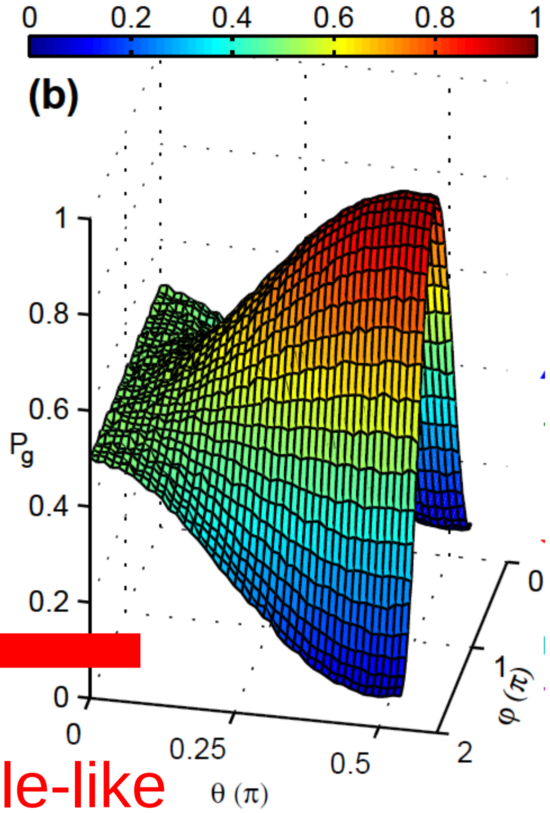
$|F\rangle+|O\rangle=|WPD\rangle$



$|2\alpha\rangle=|2\sqrt{2}\rangle$

# Transition of Particle and Wave Behaviors





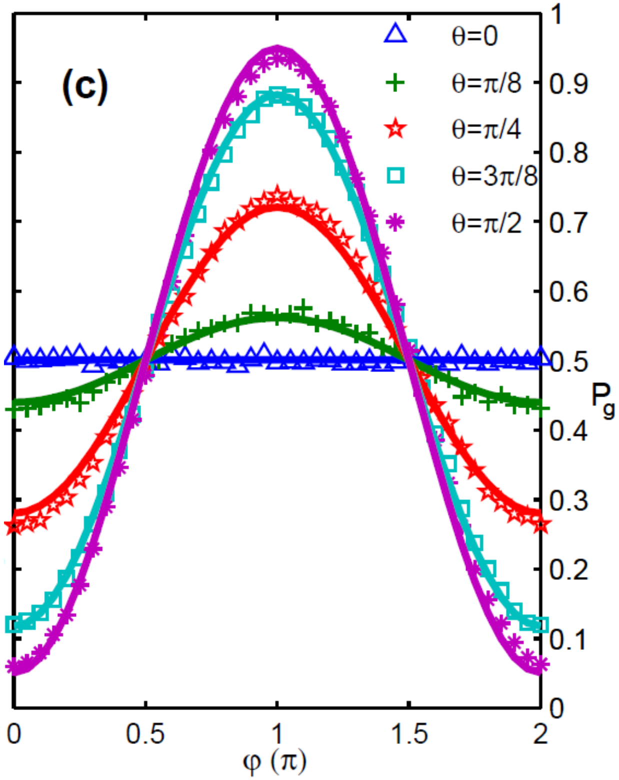
WPD
“on”

particle-like

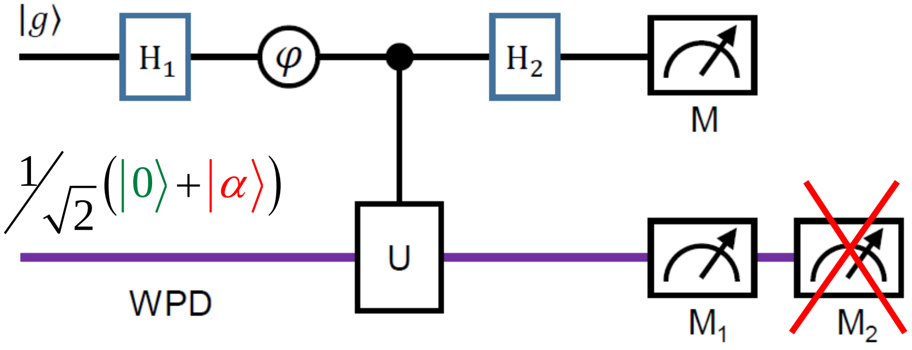
WPD
“off”

wave-like

cross-section at different θ

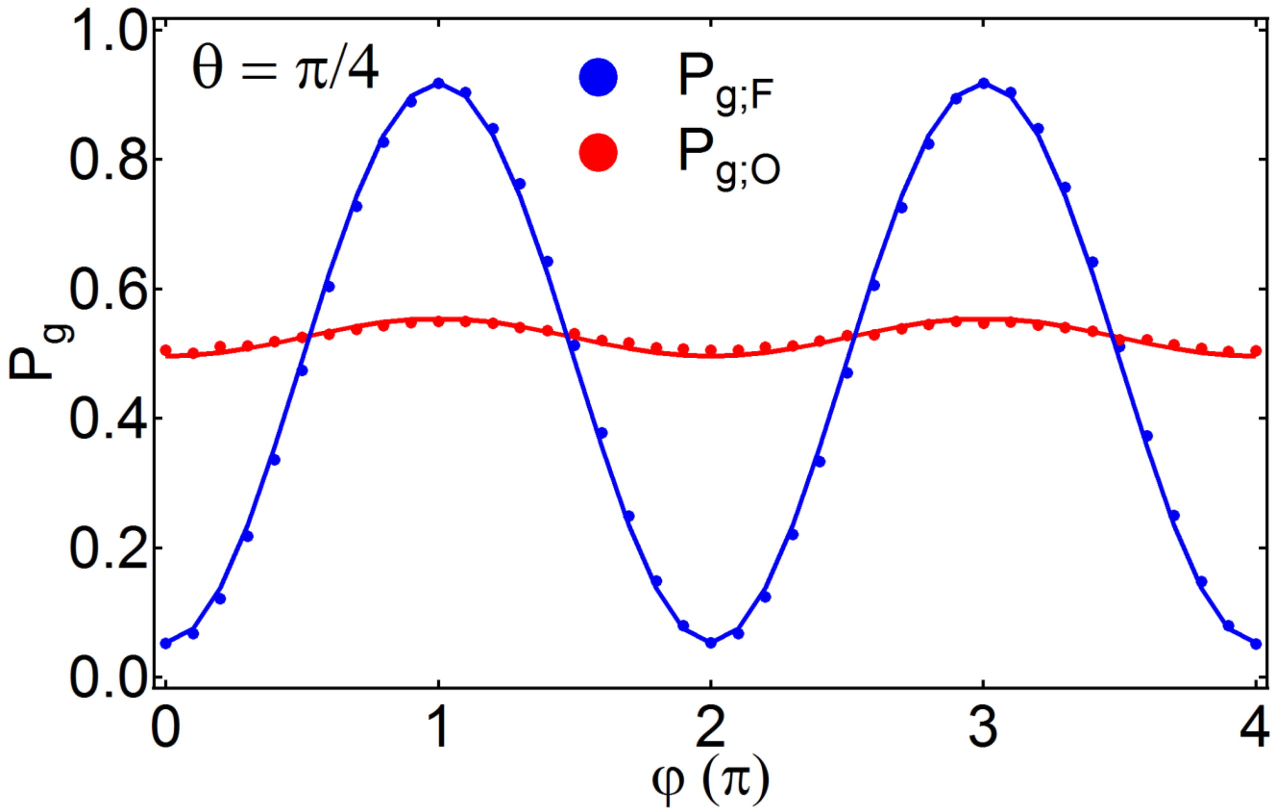


# Experimental Results

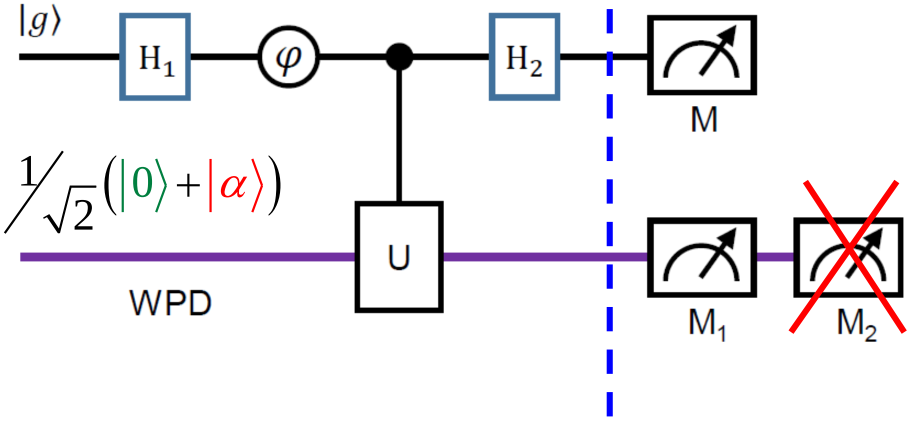


$M_1$= WPD
on/off selection

selective qubit π
pulse $R_{\pi,0}$ on N=0

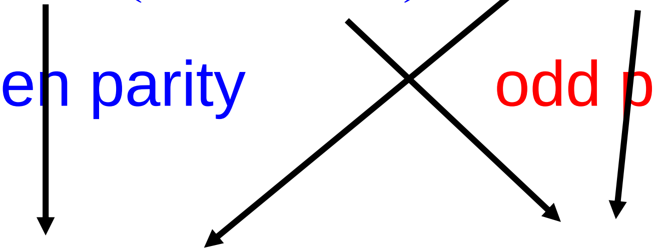


# Delayed-Choice Quantum Eraser



$M_1$= WPD
parity selection

$$|\psi\rangle = |\phi_+\rangle\left(|0\rangle + \frac{|\Phi_+\rangle}{\sqrt{2}}\right) + |\phi_-\rangle\frac{|\Phi_-\rangle}{\sqrt{2}}$$



even parity

odd parity

$$|\phi_\pm\rangle = \frac{1}{2}\left[\left(|g\rangle+|e\rangle\right)\pm e^{i\varphi}\left(|e\rangle-|g\rangle\right)\right]$$

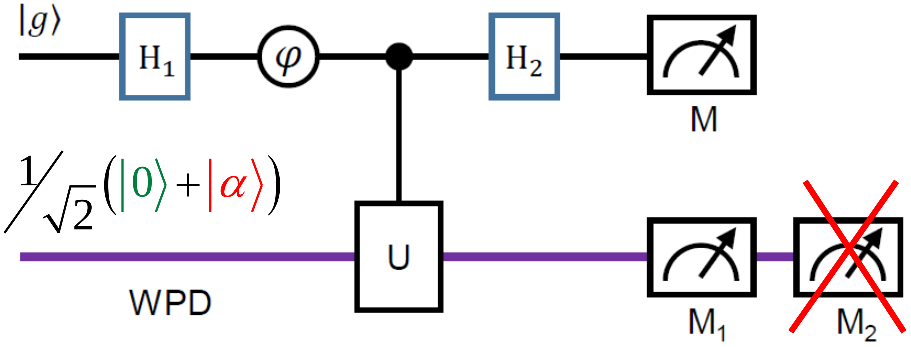
$$|\Phi_\pm\rangle = \frac{1}{2}\left(|\alpha\rangle\pm|-\alpha\rangle\right)$$

qubit

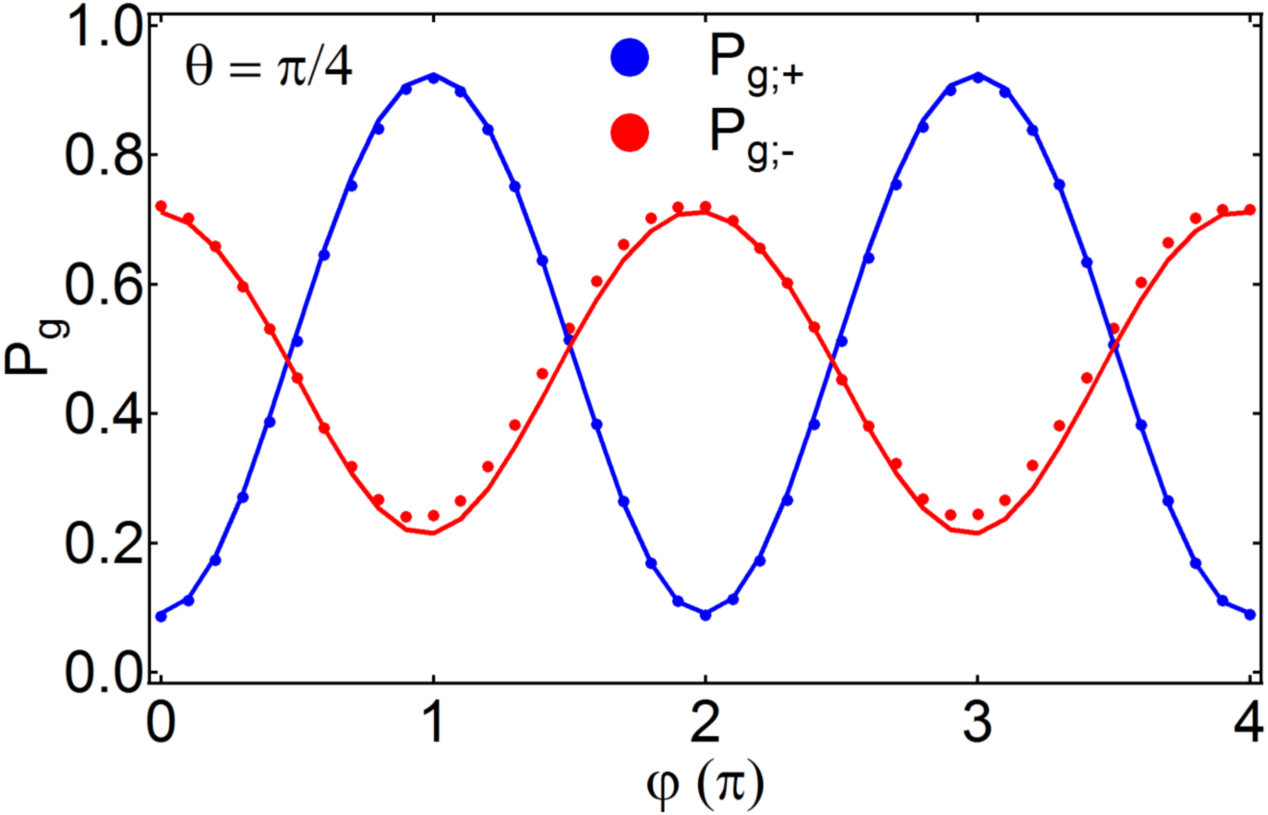
WPD

erase the path information

# Delayed-Choice Quantum Eraser

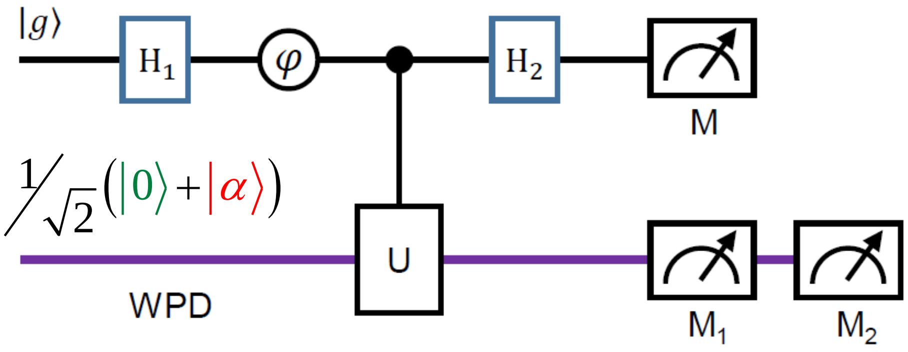


$M_1$= WPD
parity selection



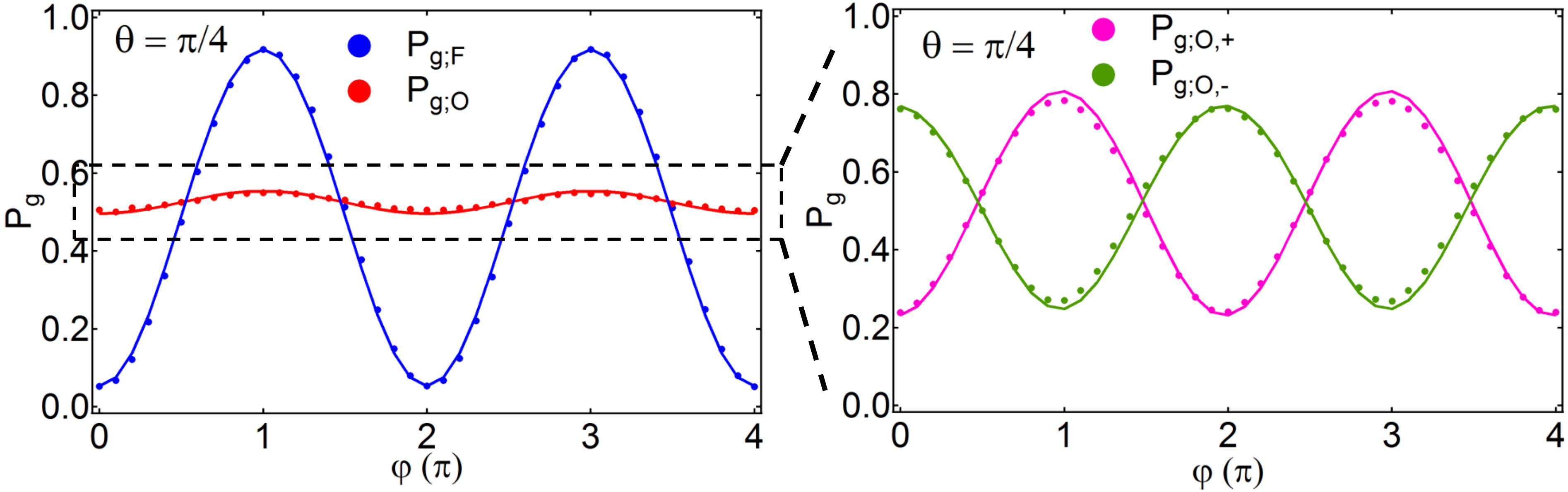
$$|\psi\rangle = |\phi_+\rangle\left(|0\rangle + \frac{|\Phi_+\rangle}{\sqrt{2}}\right) + |\phi_-\rangle\frac{|\Phi_-\rangle}{\sqrt{2}}$$

# Two-Fold Delayed Choice

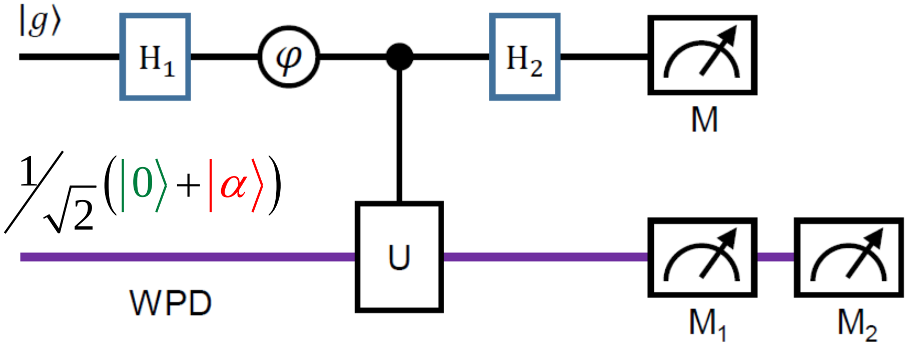


$M_1$= WPD
on selection

$M_2$= WPD
parity selection

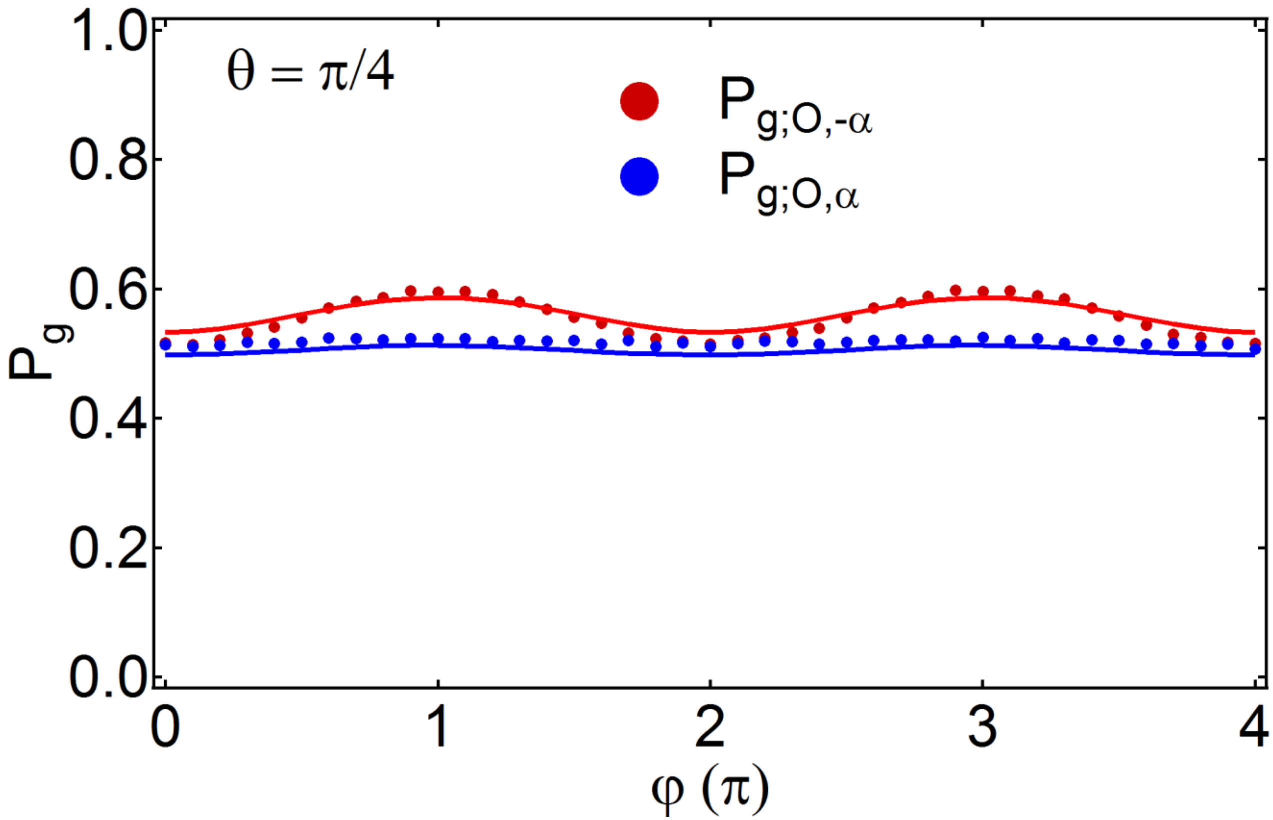


# Two-Fold Delayed Choice



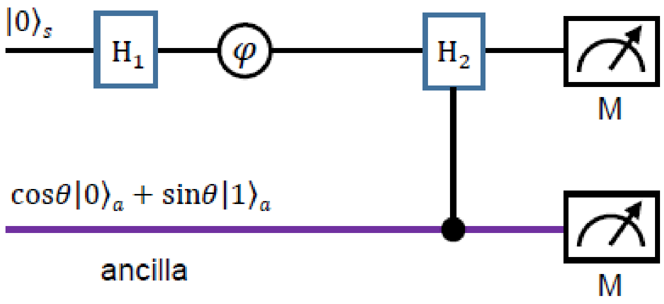
$M_1$= WPD
on selection

$M_2$= WPD
$|\alpha\rangle$ selection

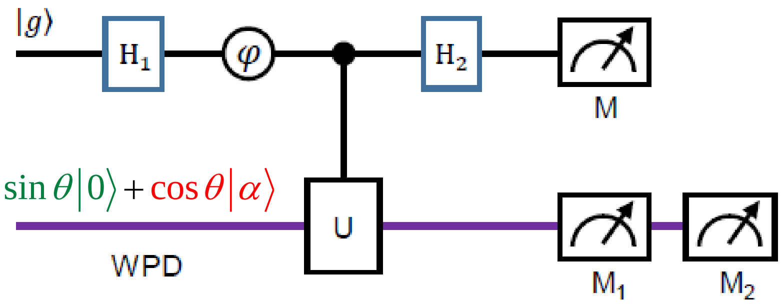


# Remarks

Previous experiments:



Our experiments:



- First experiment to realize a quantum delayed-choice experiment with a classical interferometer.
- First experiment to demonstrate with the same measurement apparatus both :
  - ✓ the behavior of the test system depends on the delayed choice of the detecting device’s configuration
  - ✓ one can *a posteriori* choose if the system behaves as a wave or as a particle by erasing or marking the which-path information stored in the WPD (delayed-choice quantum eraser)
- First two-fold delayed-choice experiment.

# Remarks

Delayed-choice experiments play an important role in understanding fundamental aspects of quantum physics:

- ✓ Wheeler's delayed-choice experiments challenge a realistic explanation of the wave-particle duality (hidden variable model).
- ✓ Quantum delayed-choice experiments suggest a reinterpretation of the complementarity principle: complementarity of the experimental data, rather than complementarity of the experimental setups.

Our proposal can also be realized in a microwave cavity QED and ion-trap setups.

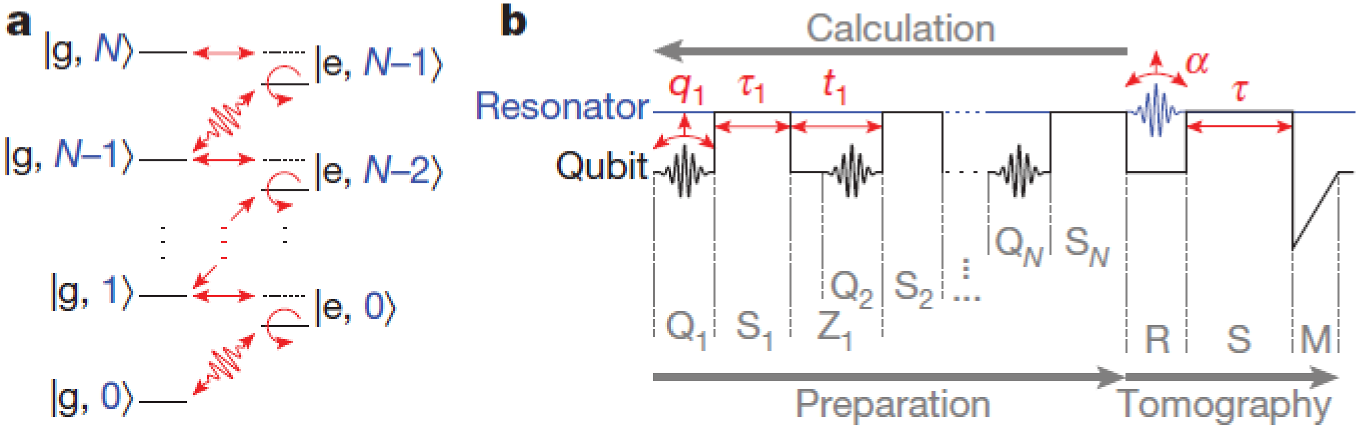
Two recent experiments in our lab at Tsinghua University (not aim for quantum information processing):

- ✓ A two-fold quantum delayed choice experiment
  K. Liu *et al*., under review, arXiv:1608.04908

- ✓ Generation of arbitrary Fock-state superpositions in a superconducting cavity
  W. Wang *et al*., under review

# Generation of Arbitrary Fock-state Superpositions

1)



Hofheinz *et al*., Nature **459**, 546 (2009); Vogel *et al*., PRL **71**, 1816 (1993); Law and Eberly, PRL **76**, 1055 (1996)

2) $D(\alpha_{n+1})R(\theta_n)D(\alpha_n)...R(\theta_2)D(\alpha_2)R(\theta_1)D(\alpha_1)$

2N selective number-dependent arbitrary phase gate (SNAP)
+ 2N+1 displacement operations

Krastanov et al., PRA **92**, 04303 (R) (2015); Heeres et al., PRL **115**, 137002 (2015)

Deterministic but requires multi-step

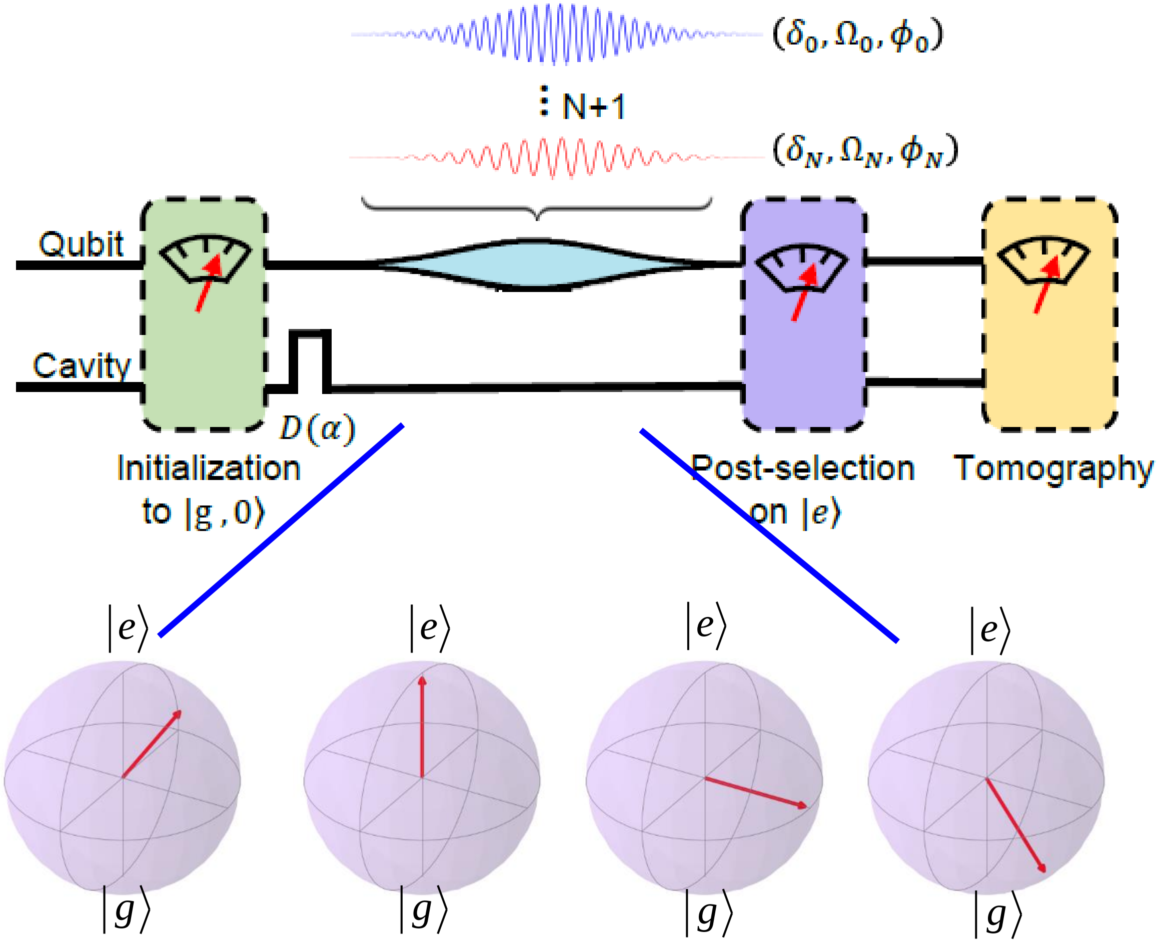
# Generation of Arbitrary Fock-state Superpositions

$$|\alpha\rangle|g\rangle = \sum_0^\infty c_n|n\rangle|g\rangle \longrightarrow |\alpha\rangle|g\rangle = \sum_0^\infty \boxed{c_n|n\rangle(\sin\beta_n e^{i\theta_n}|e\rangle} + \cos\beta_n|g\rangle)$$

$\downarrow$ projective measurement

$$|\psi_d\rangle = \sum_0^\infty d_n|n\rangle$$

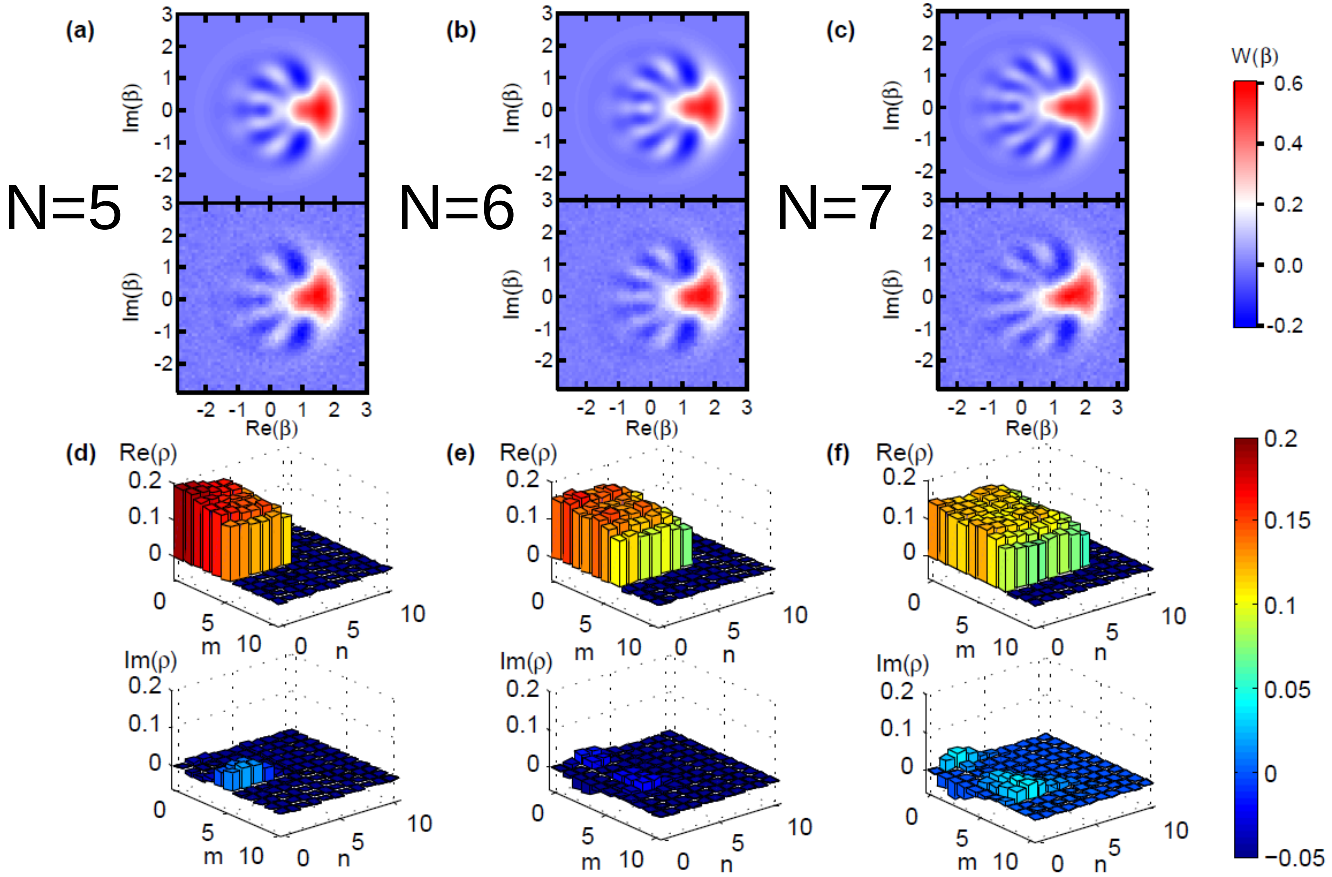
photon-number selective pulses



Probabilistic but requires only one single step: robust to noise and accumulation of errors

# Truncated Phase States

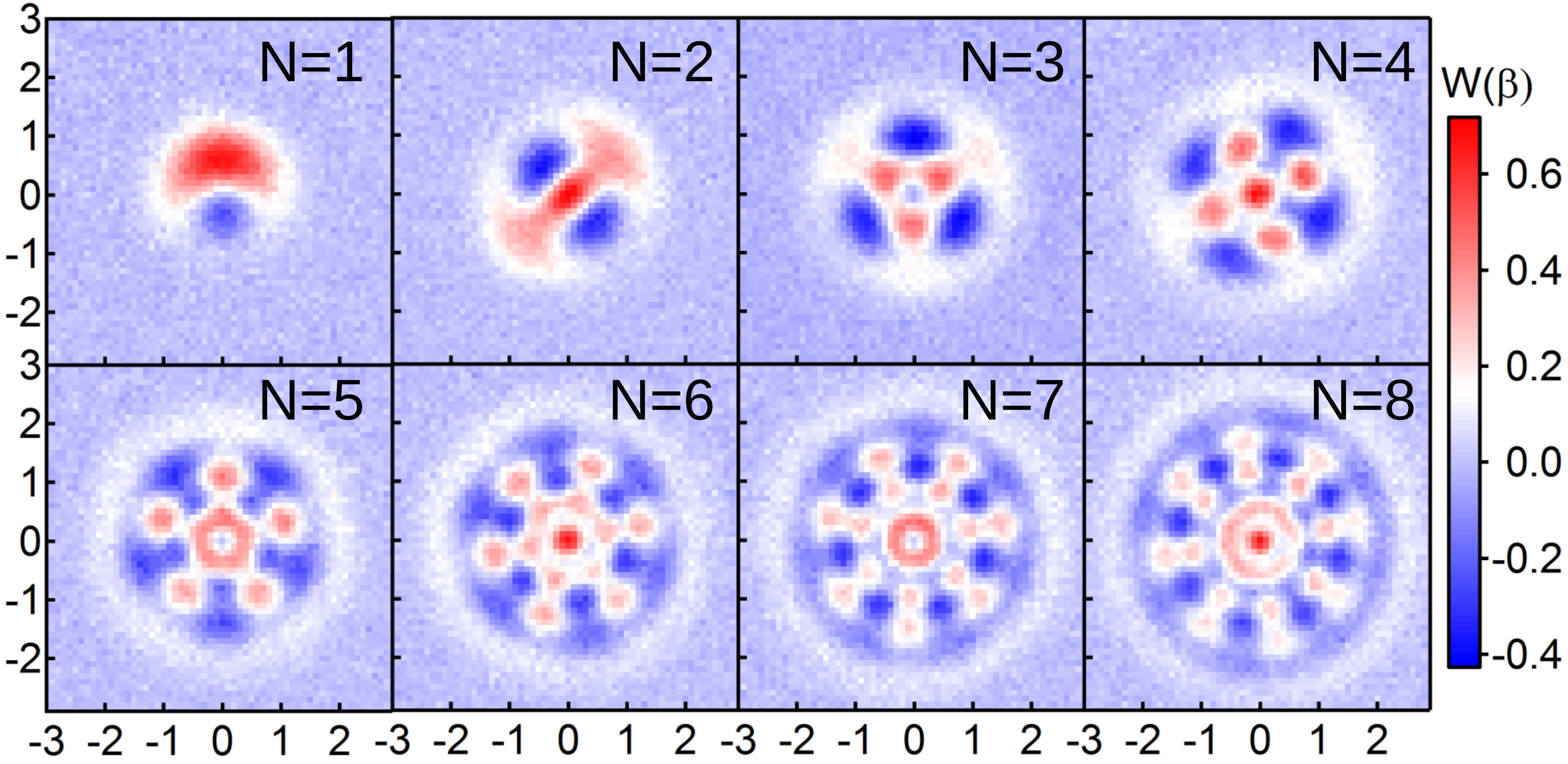
$$\left|\theta_{N,\mathrm{K}}\right\rangle = \frac{1}{\sqrt{N+1}} \sum_0^\infty e^{in\theta_{N,K}} \left|n\right\rangle \qquad \theta_{N,\mathrm{K}} = 2K\pi/(N+1)$$



| | | | |
|---|---|---|---|
| Fidelity: | 0.97±0.01 | 0.96±0.01 | 0.98±0.01 |
| Probability: | 0.37 | 0.31 | 0.23 |

# High Precision Measurements

$$|\psi_0\rangle = \left(|0\rangle + ie^{iN\theta}|N\rangle\right)/\sqrt{2}$$

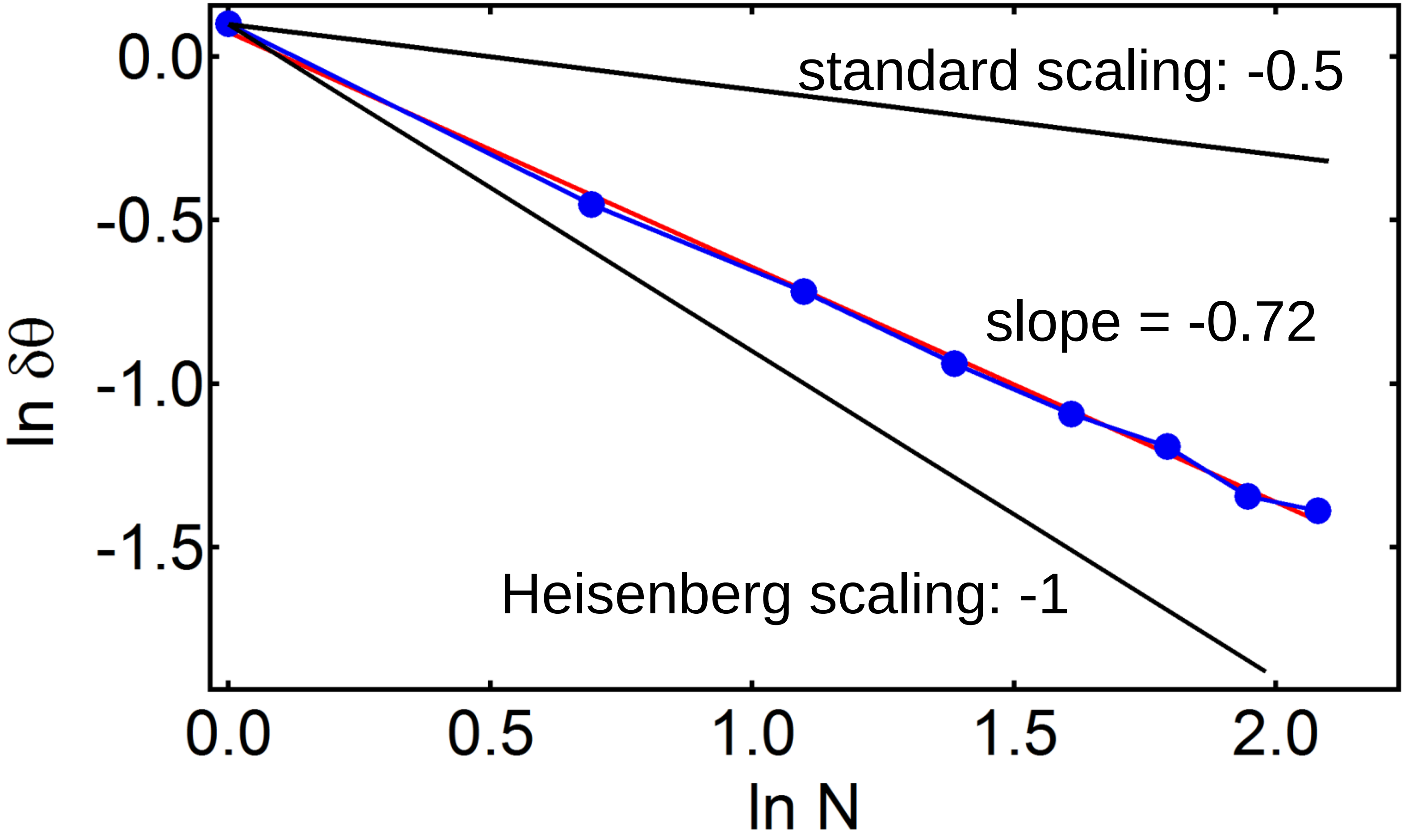


All measured Wigner functions

# High Precision Measurements

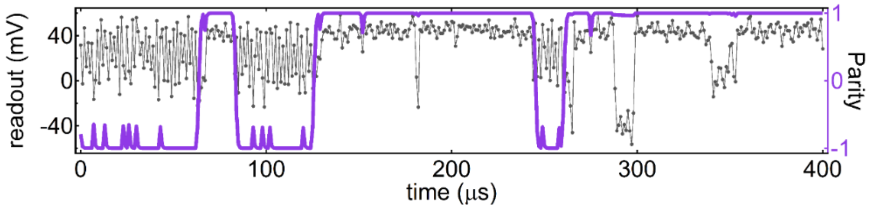
standard scaling: $1/\sqrt{N}$

Heisenberg scaling: $1/N$

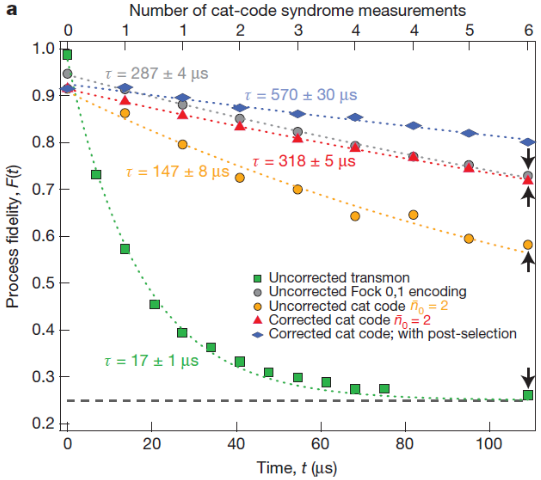


# Conclusions

- ✓ Schrodinger cat states are promising towards realizing a quantum memory with enhanced lifetimes.
- ✓ Break-even point has been reached.

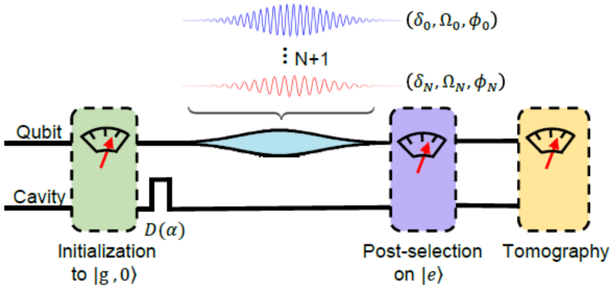


*Sun et al. Nature* ***511****, 444 (2014)*

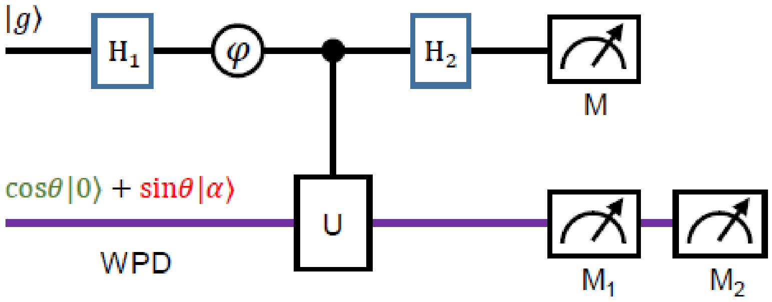


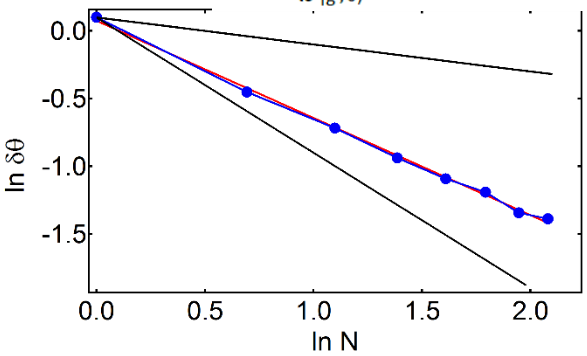
Ofek *et al*., Nature 536, 441 (2016)

- ✓ Generation of arbitrary Fock-state superpositions



- ✓ A two-fold quantum delayed-choice experiment, arXiv:1608.04908





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