Metrology of Entangled States

in Circuit QED

Applied Physics + Physics
Yale University

PI's:
Rob Schoelkopf
Michel Devoret
Steven Girvin

IARPA

Expt.
Leo DiCarlo
Andrew Houck
David Schuster
Hannes Majer
Jerry Chow
Joe Schreier
Blake Johnson
Luigi Frunzio

Theory
Lev Bishop
Jens Koch
Jay Gambetta
Alexandre Blais
Florian Marquardt
Eli Luberoff
Lars Tornberg
Terri Yu

Metrology of Entangled States in Circuit QED

Applied Physics + Physics
Yale University

PI's:
Rob Schoelkopf
Michel Devoret
Steven Girvin

IARPA

Expt.
Leo DiCarlo
Andrew Houck ← Princeton
David Schuster
Hannes Majer ← Vienna
Jerry Chow
Joe Schreier
Blake Johnson
Luigi Frunzio

Theory
Lev Bishop
Jens Koch
Jay Gambetta ← IQC/Waterloo
Alexandre Blais ← U. Sherbrooke
Florian Marquardt ← Munich
Eli Luberoff
Lars Tornberg ↔ Göteborg
Terri Yu

Recent Reviews

'Wiring up quantum systems'
R. J. Schoelkopf, S. M. Girvin
Nature **451**, 664 (2008)

'Superconducting quantum bits'
John Clarke, Frank K. Wilhelm
Nature **453**, 1031 (2008)

Quantum Information Processing **8** (2009)
ed. by A. Korotkov

Overview

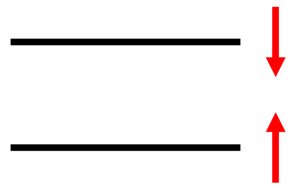
- ‘Transmon’ qubit, insensitive to charge noise
- Circuit QED: using cavity bus to couple qubits
- Two qubit gates and generation of Bell’s states
- “Metrology of entanglement” – using joint cQED msmt.
- Demonstration of Grover and Deutsch-Josza algorithms

  DiCarlo et al., cond-mat/0903.2030

  Nature, (in press, June 2009)

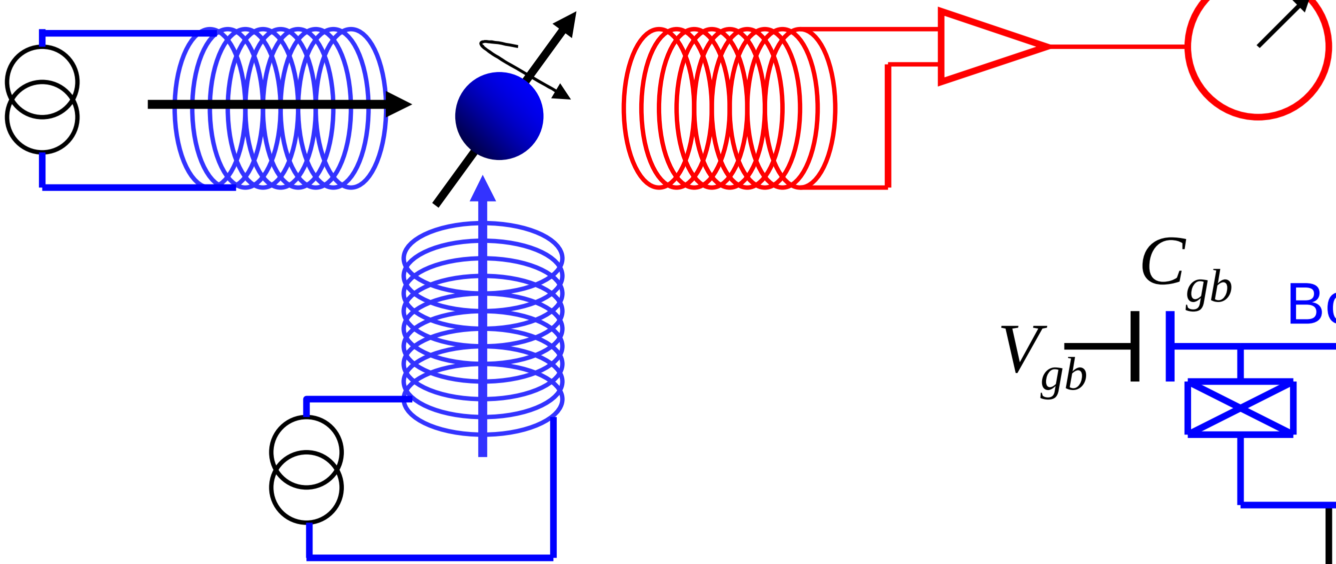
Quantum Computation and NMR of a Single 'Spin'

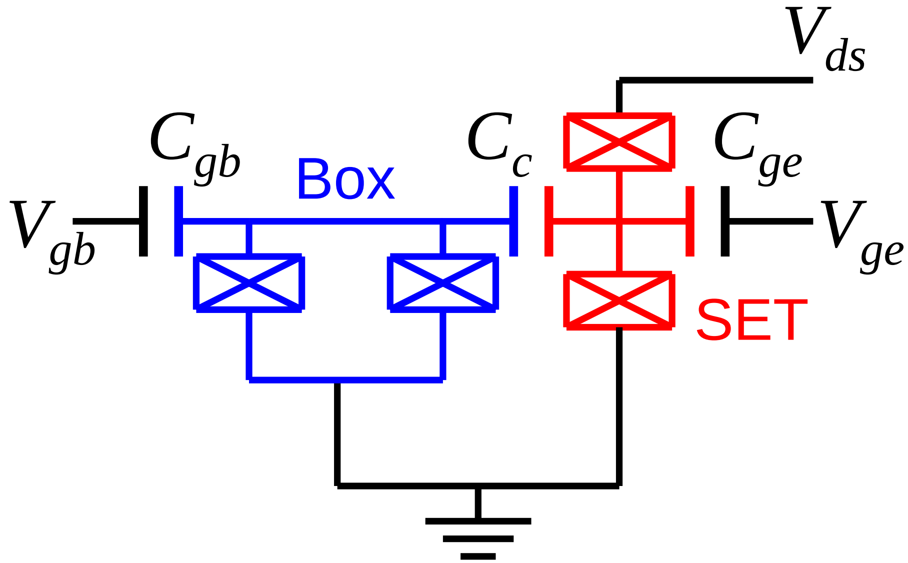
Electrical circuit with two quantized energy levels is like a spin -1/2.



Single Spin ½

Quantum Measurement



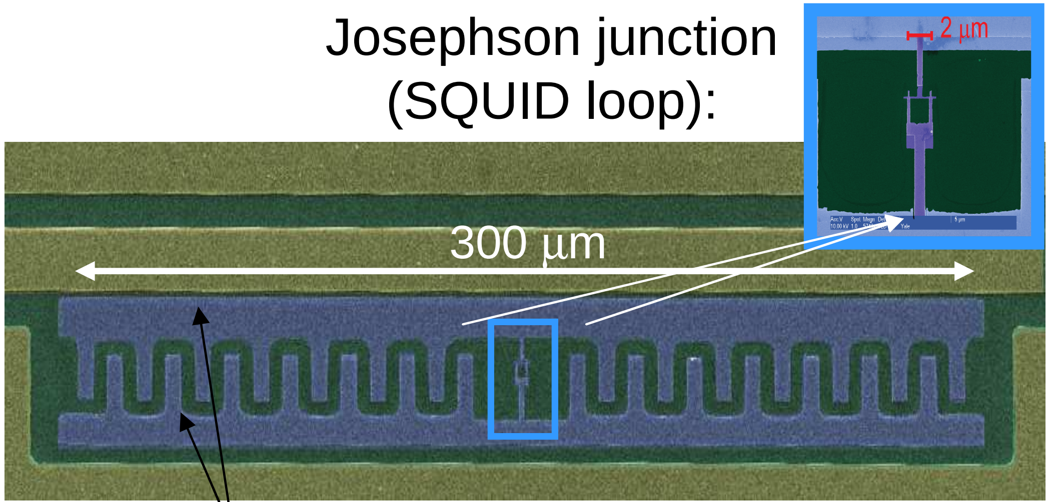


(After Konrad Lehnert)

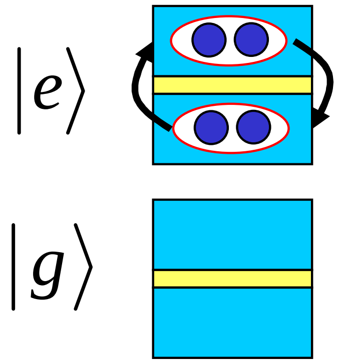
‘Transmon’ Cooper Pair Box: Charge Qubit that Works!

$E_J >> E_C$

Josephson junction
(SQUID loop):



Added metal
= capacitor & antenna



plasma oscillation of
2 or 3 Cooper pairs:
almost no static dipole

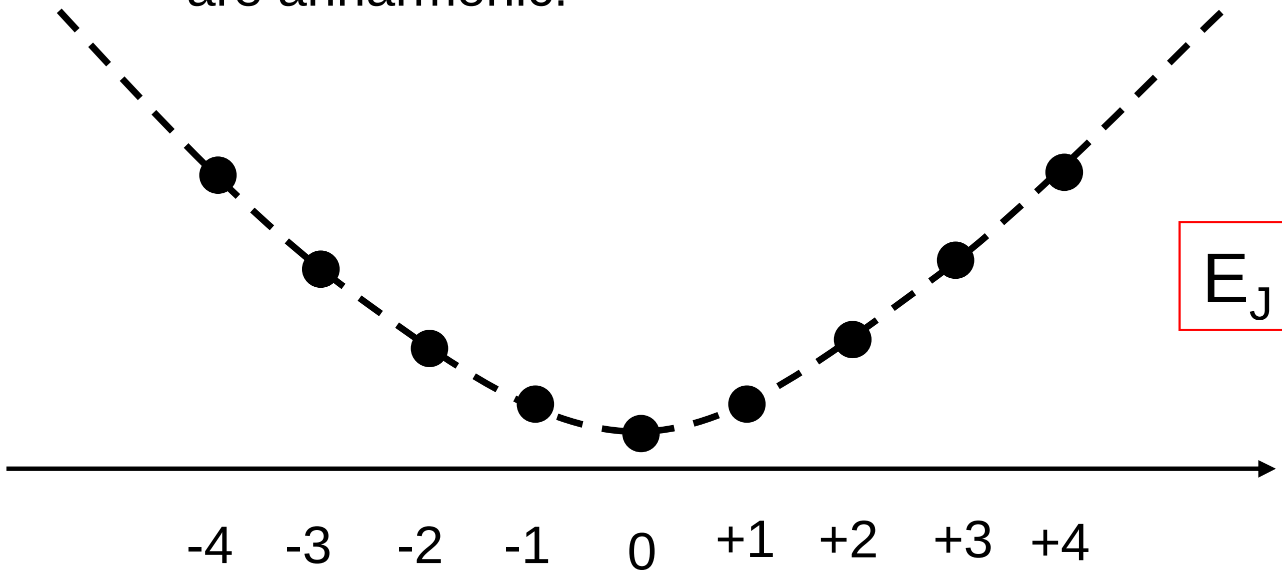
Transmon qubit insensitive to 1/f electric fields

* Theory: J. Koch et al., PRA (2007); Expt: J. Schreier et al., PRB (2008)

Flux qubit + capacitor: F. You et al., PRB (2006)

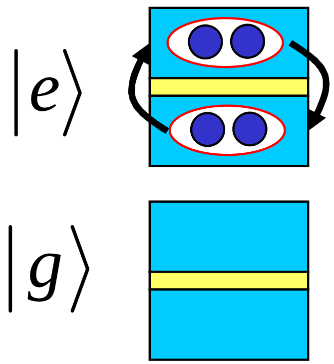
‘Transmon’ Cooper Pair Box: Charge Qubit that Works!

Josephson junction plasma oscillations are anharmonic:



n = Number of pairs that have tunneled

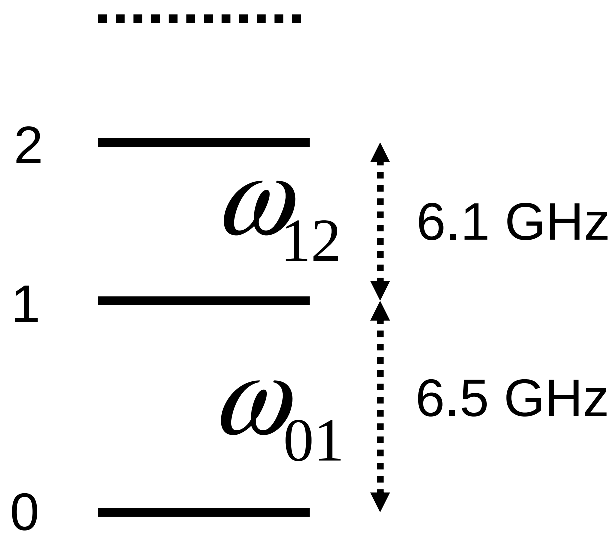
$E_J >> E_C$



$$H = -E_J\left[\text{tunneling}\right] + 4E_C\,(\hat{n} - n_{\text{offset}})^2$$

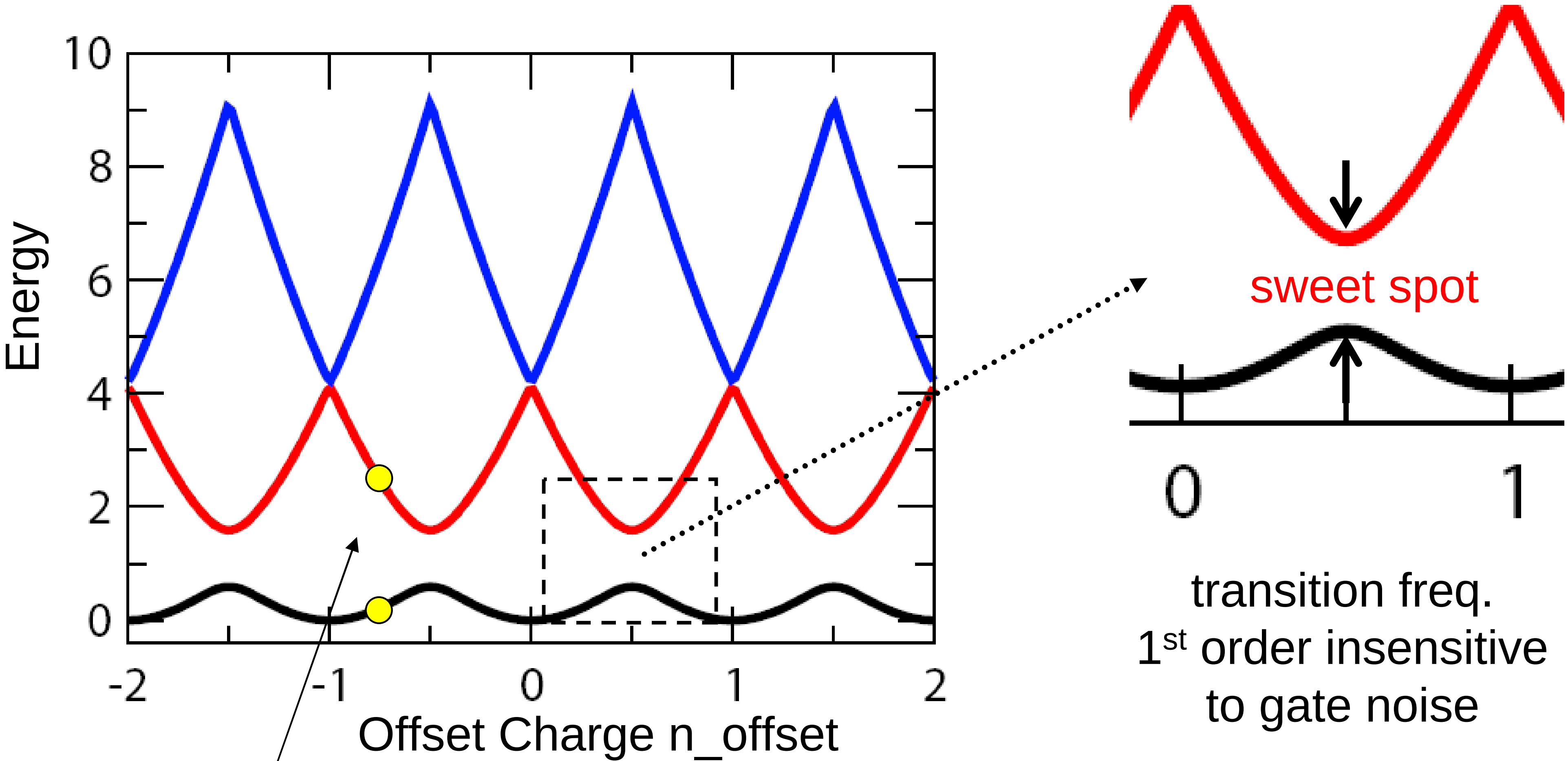
Transition frequency tunable via SQUID flux.

$$\hbar\omega_{01} \approx \sqrt{8E_J E_C}$$



Outsmarting Noise: Sweet Spot

1st coherence strategy: optimize design



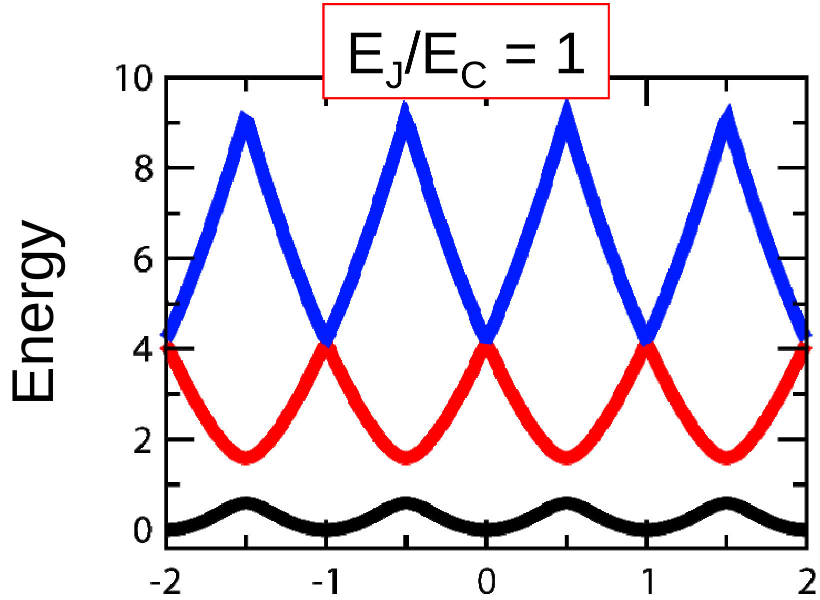
Strong sensitivity of frequency to charge noise

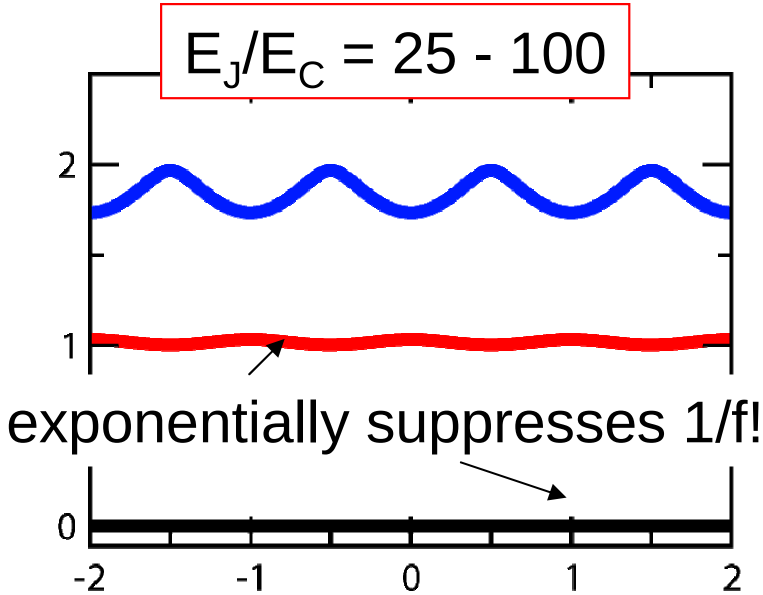
But T_2 still < 500 ns due to second-order noise!

Vion et al., Science **296**, 886 (2002)

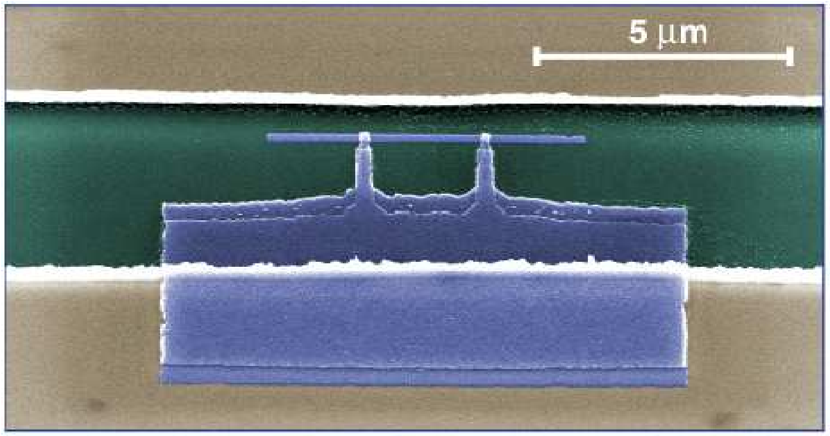
“Eliminating” Charge Noise with Better Design

$$\boxed{\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\varphi}}$$

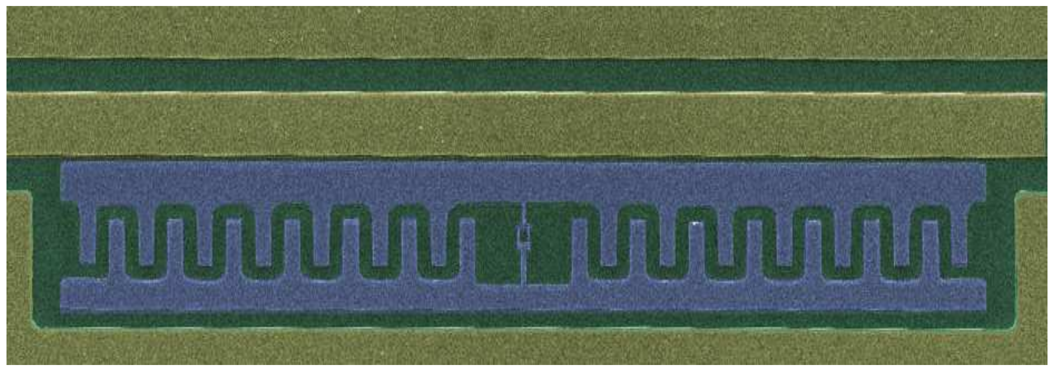




Cooper-pair Box



“Transmon”

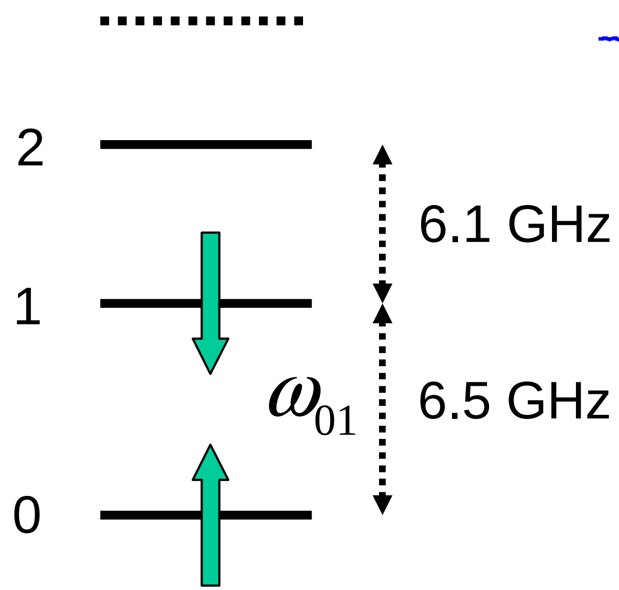


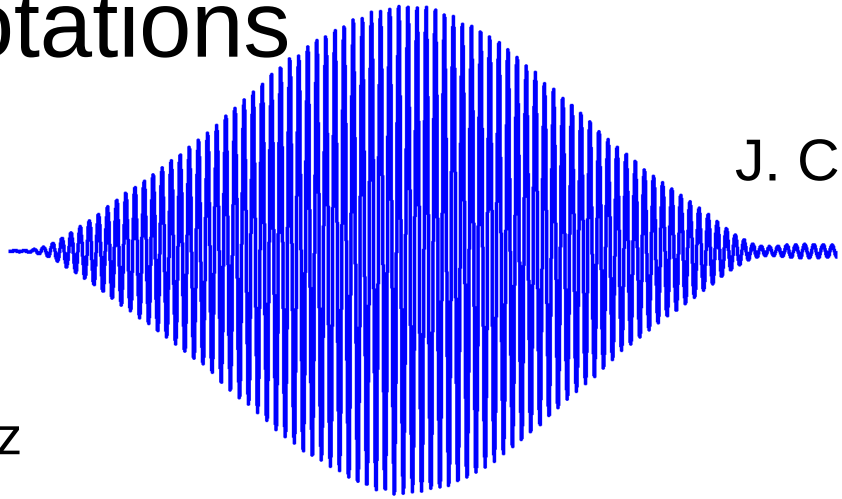
Koch et al., 2007; Houck et al., 2008

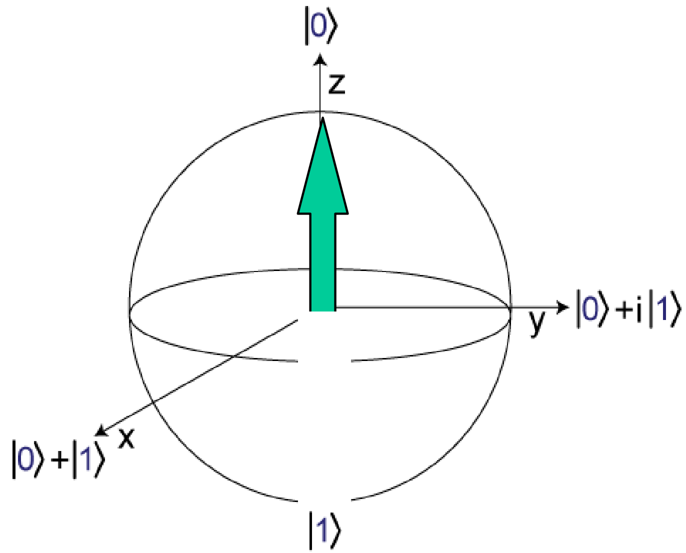
Single Qubit Rotations

Fidelity = 99%

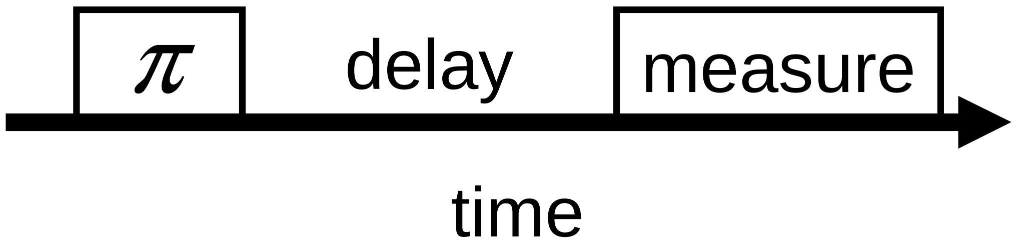
J. Chow *et al.*, PRL (2009):

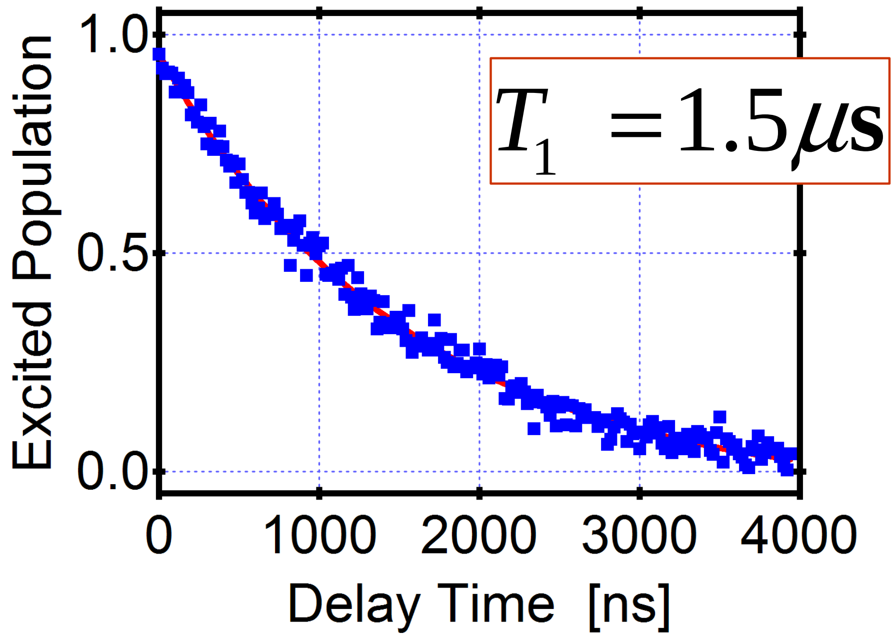




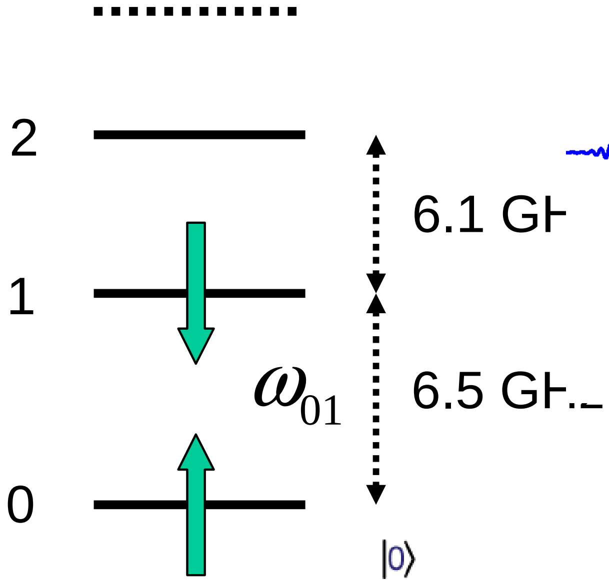


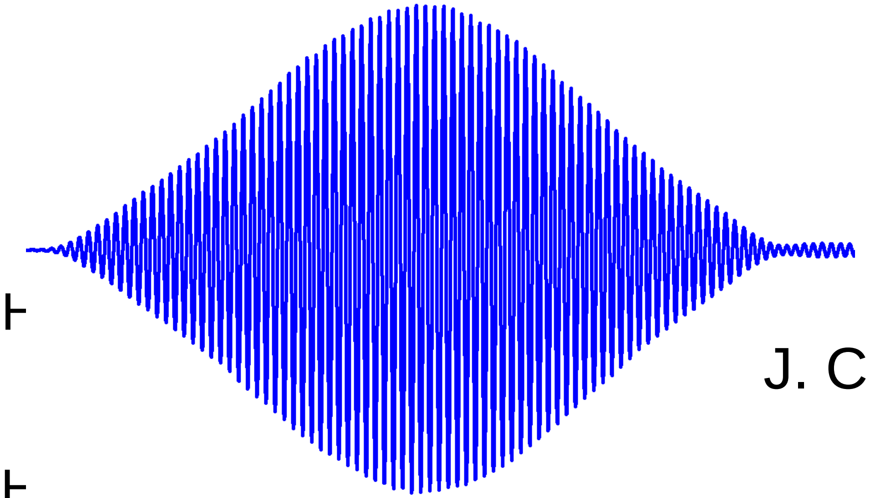
$$V = \Omega^{x}_{\text{Rabi}}(t)\cos(\omega_{01}t)\sigma^{x} + \Omega^{y}_{\text{Rabi}}(t)\sin(\omega_{01}t)\sigma^{y}$$





Ramsey Fringe and Qubit Coherence

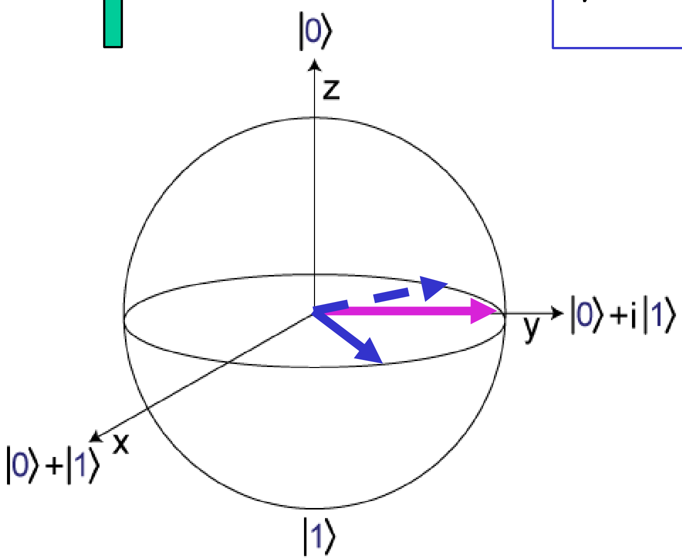


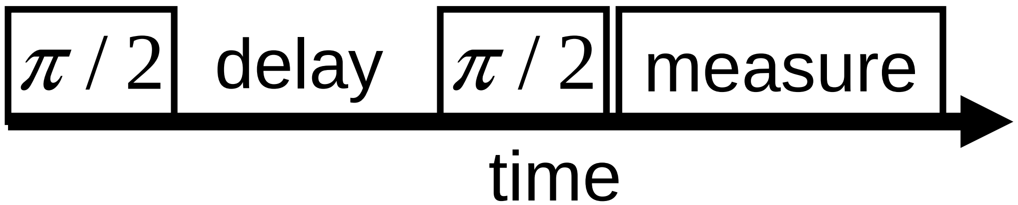


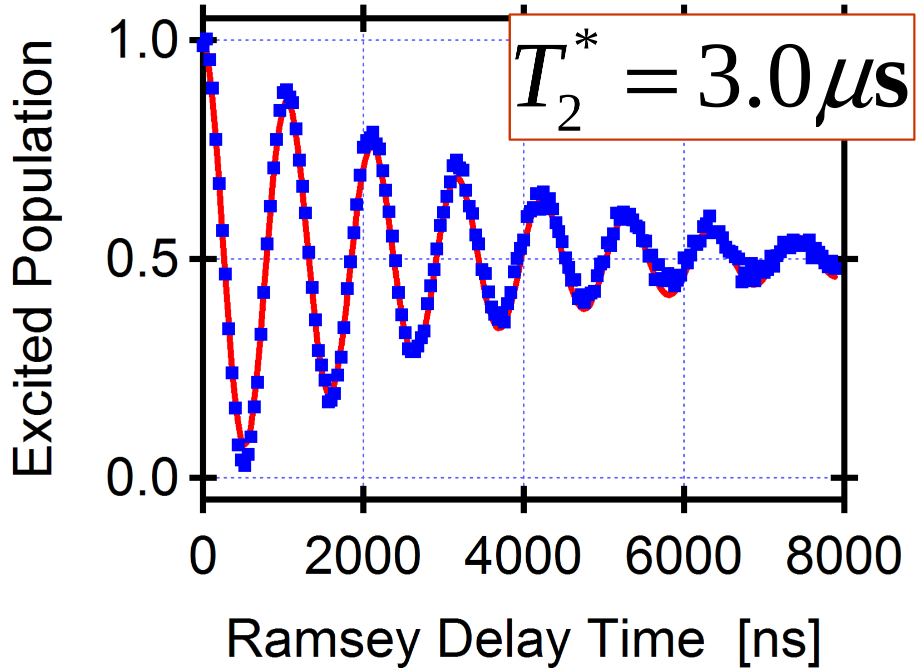
Fidelity = 99%

J. Chow *et al.*, *PRL* (2009):

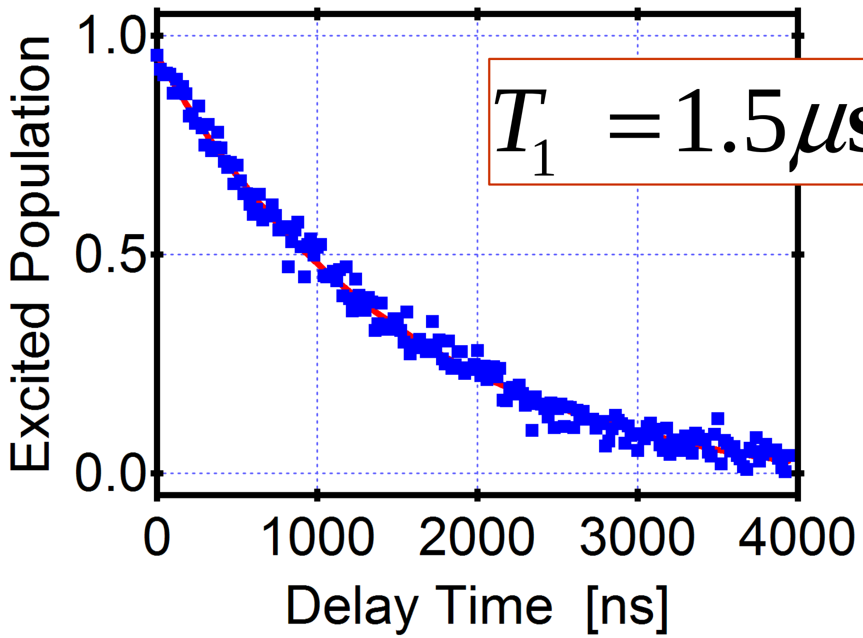
$$V = \Omega_{\text{Rabi}}(t)\cos(\omega_{01}t)\sigma^{x}$$



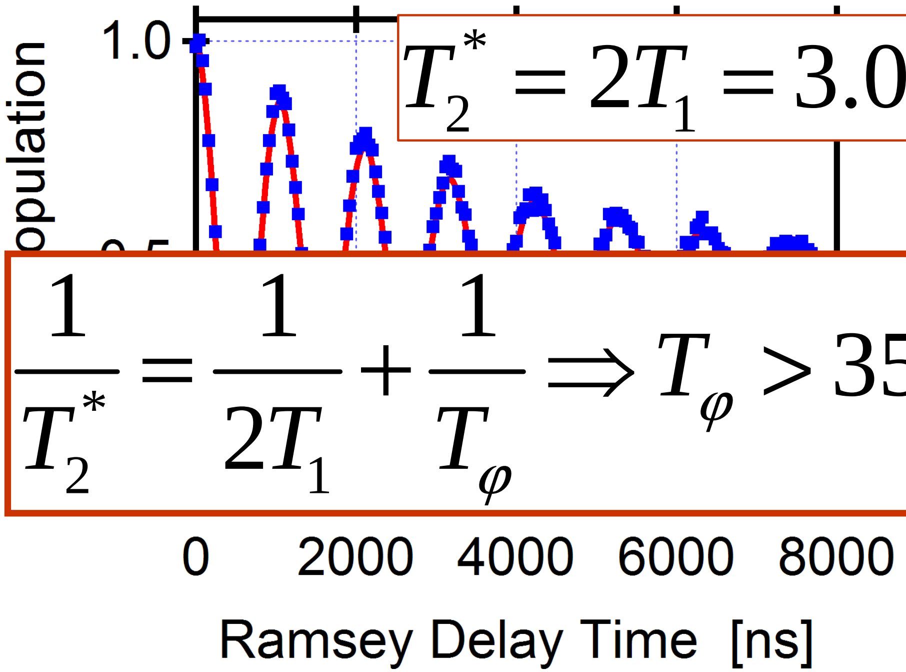




Coherence in Transmon Qubit



$$T_1 = 1.5\mu s$$

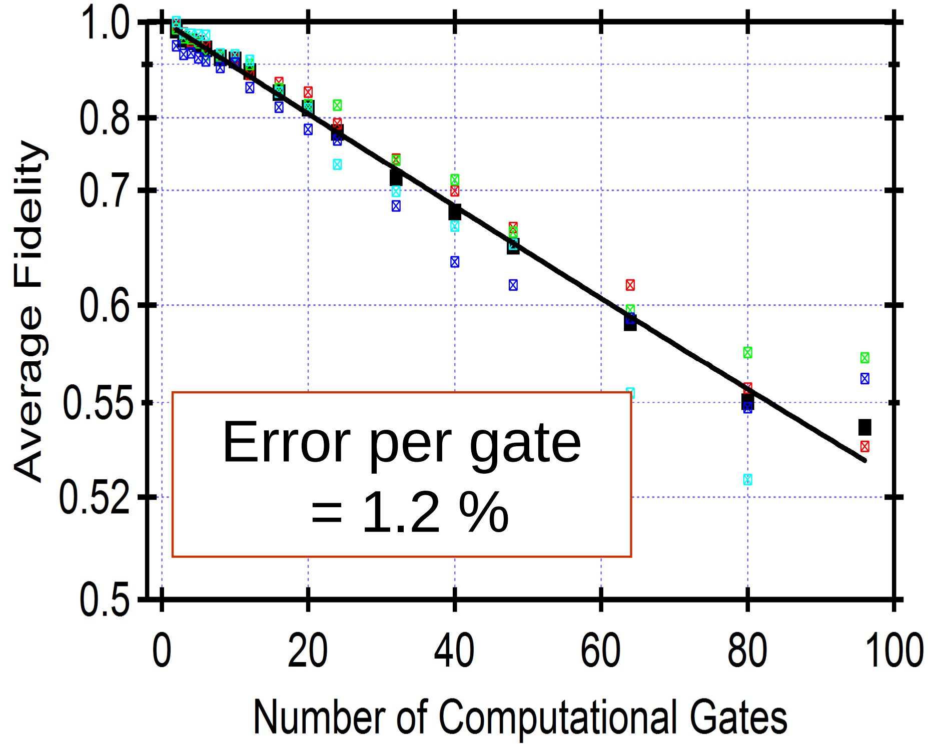


$$T_2^* = 2T_1 = 3.0\mu s$$

$$\frac{1}{T_2^*} = \frac{1}{2T_1} + \frac{1}{T_\varphi} \Rightarrow T_\varphi > 35\mu s$$

Random benchmarking of 1-qubit ops

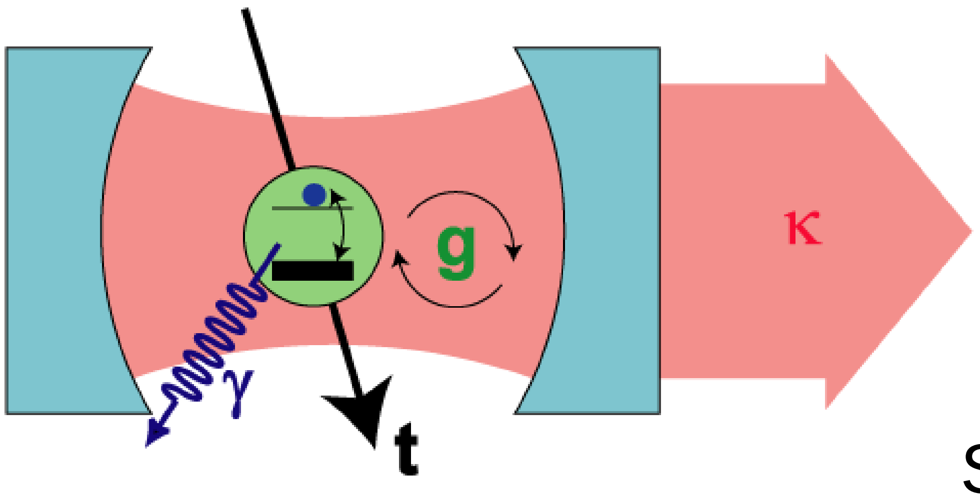
Chow et al. *PRL* 2009:
Technique from Knill et al. for ions



Error per gate
= 1.2 %

Similar error rates in phase qubits (UCSB):
Lucero et al. *PRL* 100, 247001 (2007)

Cavity Quantum Electrodynamics (cQED)



2g = vacuum Rabi freq.

κ = cavity decay rate

γ = "transverse" decay rate

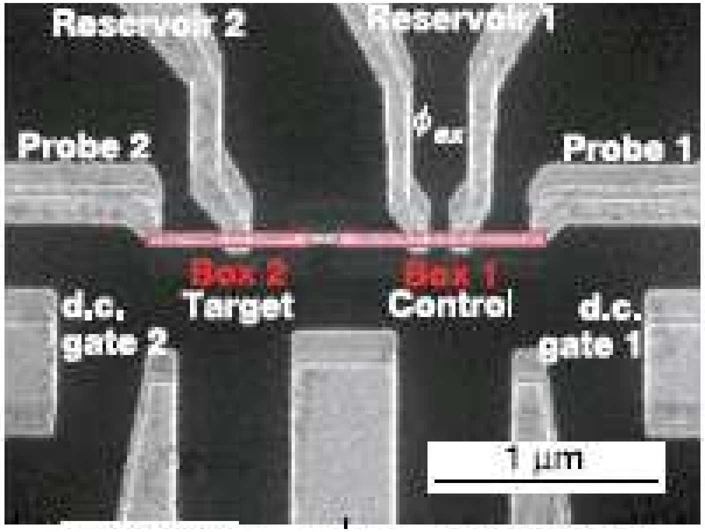
<u>Strong Coupling</u> = **g** > **κ** , **γ**

Jaynes-Cummings Hamiltonian

$$\hat{H} = \hbar\omega_r(a^\dagger a + \tfrac{1}{2}) - \frac{\hbar\omega_a}{2}\hat{\sigma}_z - \hbar g(a^\dagger\sigma^- + \sigma^+ a) + H_\kappa + H_\gamma$$

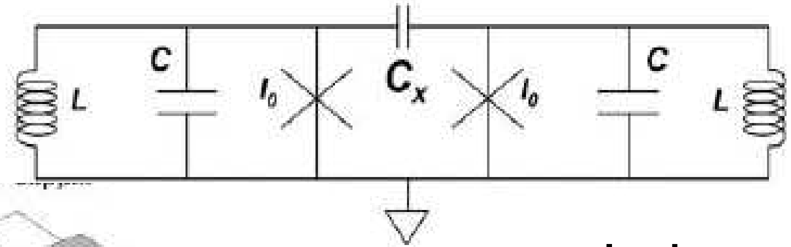
Quantized Field 2-level system Electric dipole Interaction Dissipation

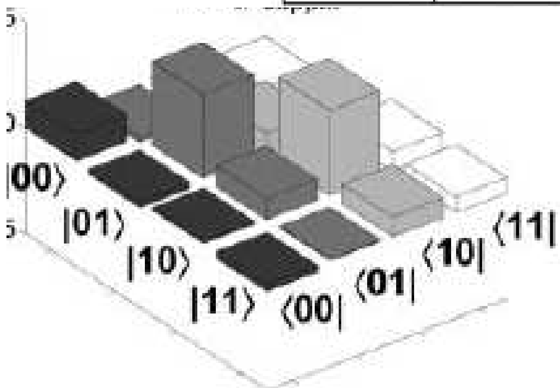
Coupling SC Qubits: Use a Circuit Element



Charge qubits: NEC 2003

a capacitor



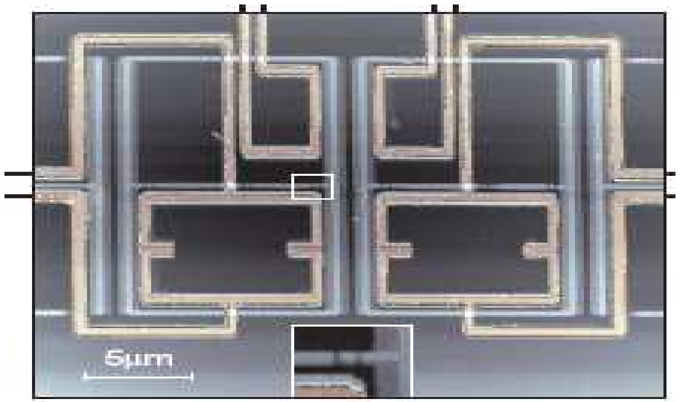


entangled states!

Concurrence ~ 55%

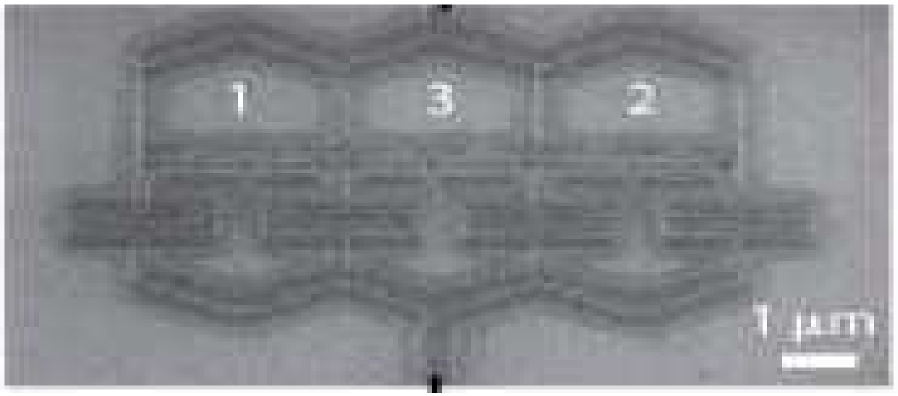
Phase qubits: UCSB 2006

an inductor



Flux qubits: Delft 2007

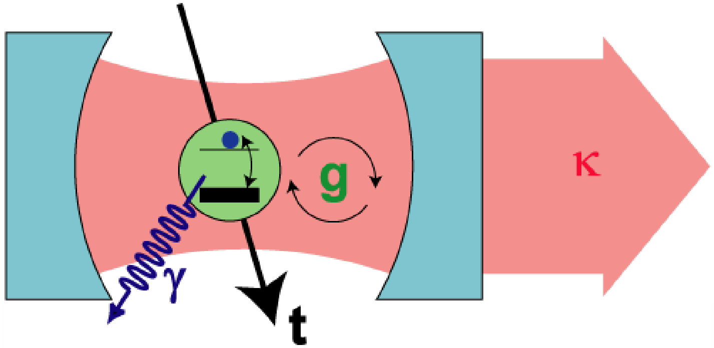
tunable (SQUID) element



Flux qubits: Berkeley 2006, NEC 2007
Or tunable bus, Chalmers

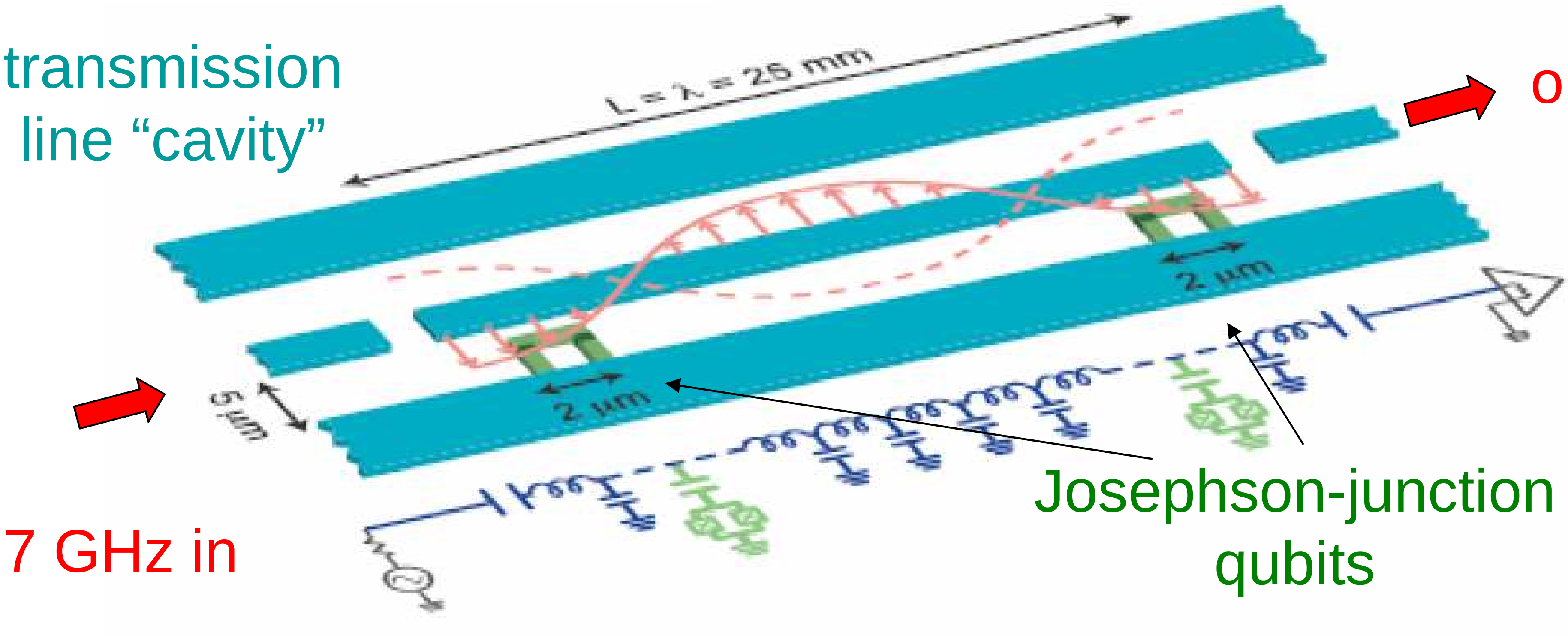
Qubits Coupled with a Quantum Bus

use microwave photons guided on wires!



"Circuit QED"

Blais *et al.*, *Phys. Rev. A* (2004)

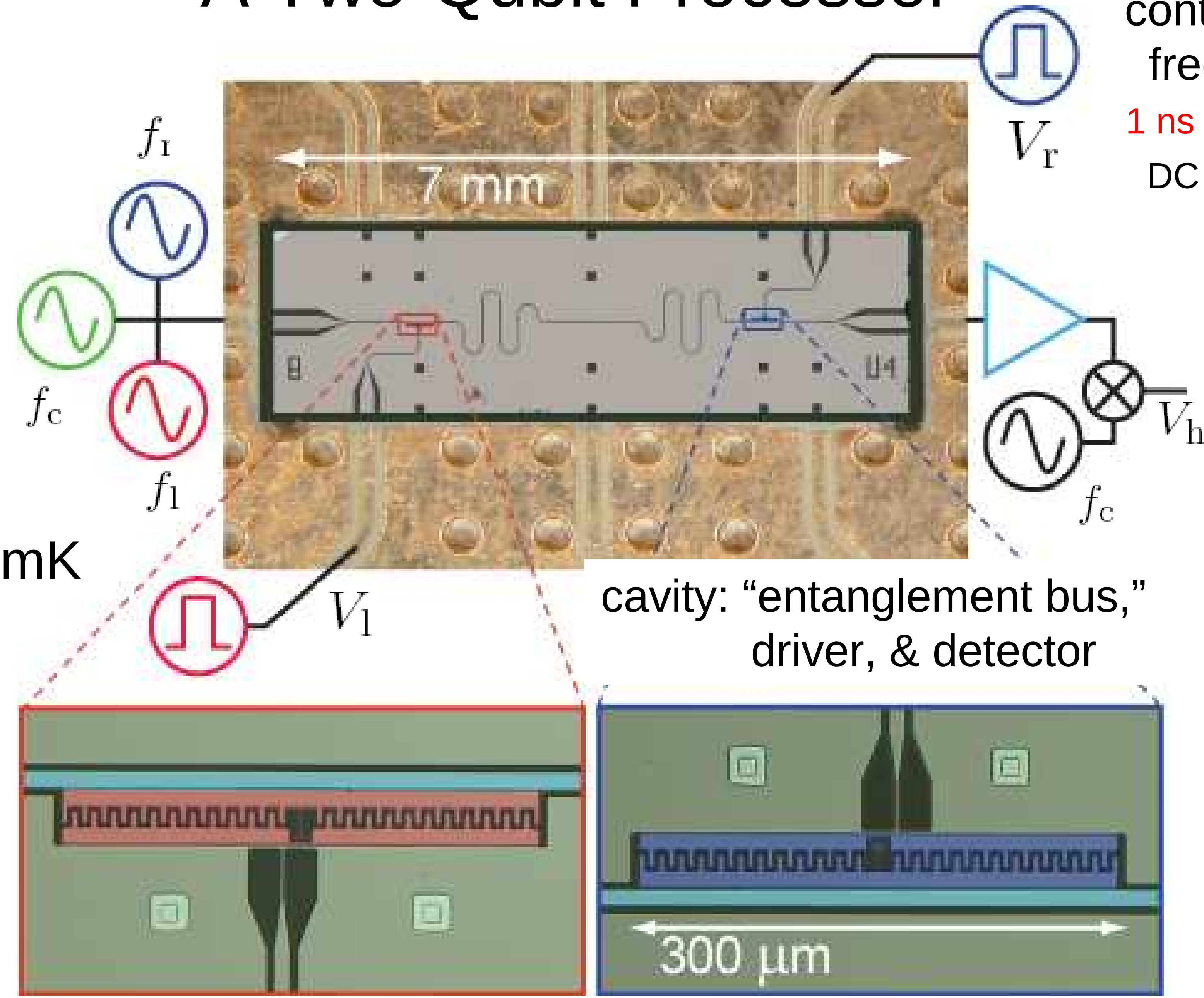


<u>Expts:</u> Majer et al., *Nature* 2007 (Charge qubits / Yale)
Sillanpaa et al., *Nature* 2007 (Phase qubits / NIST)

A Two-Qubit Processor

flux bias lines
control qubit
frequency
1 ns resolution
DC - 2 GHz

T = 10 mK



cavity: “entanglement bus,”
driver, & detector

transmon qubits

How do we entangle two qubits?

$R_Y(-\pi/2)$ rotation on each qubit yields superposition:

$$|\Psi\rangle = \frac{1}{2}\left(|0\rangle + |1\rangle\right) \otimes \left(|0\rangle + |1\rangle\right)$$

$$= \frac{1}{2}\left(|00\rangle + |10\rangle + |01\rangle + |11\rangle\right)$$

'Conditional Phase Gate' entangler:

$$\begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} |\Psi\rangle = \frac{1}{2}\left(|00\rangle + |10\rangle + |01\rangle - |11\rangle\right)$$

No longer a product state!

How do we entangle two qubits?

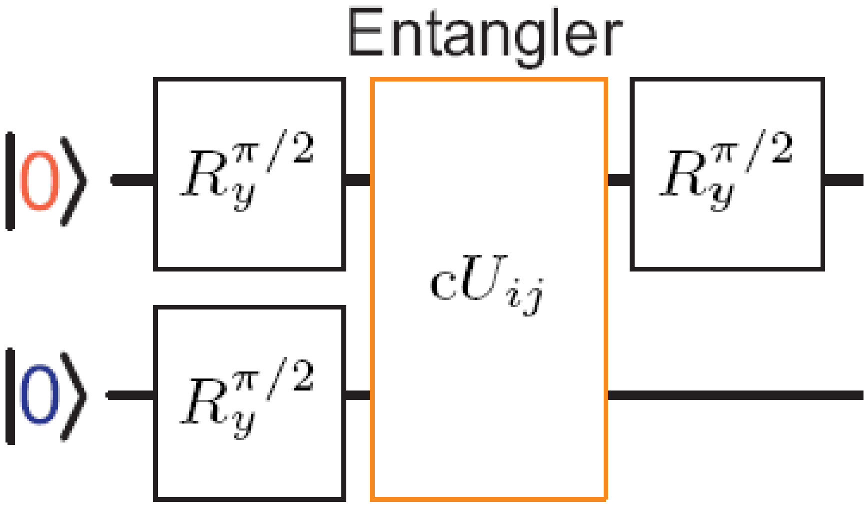
$$\begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} |\Psi\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle - |11\rangle\right) = \frac{1}{\sqrt{2}}\left(|0 \rightarrow\rangle + |1 \leftarrow\rangle\right)$$

$R_Y(+\pi/2)$ rotation on LEFT qubit yields:

$$\boxed{|\mathrm{Bell}\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle + |11\rangle\right)}$$

Other 3 Bell states similarly achieved.

Entanglement on Demand



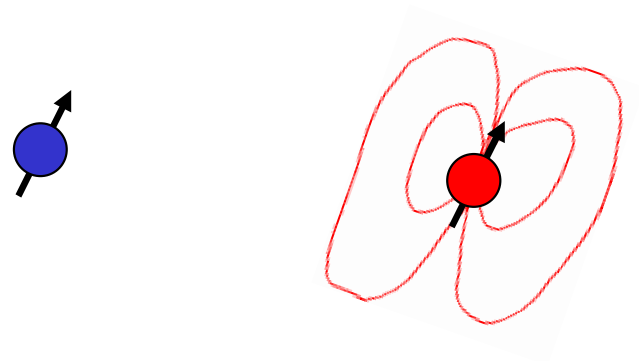
$\frac{1}{\sqrt{2}}\Big(\Big|$  $\Big\rangle + \Big|$  $\Big\rangle\Big)$

L’état quantique c’est Moi!

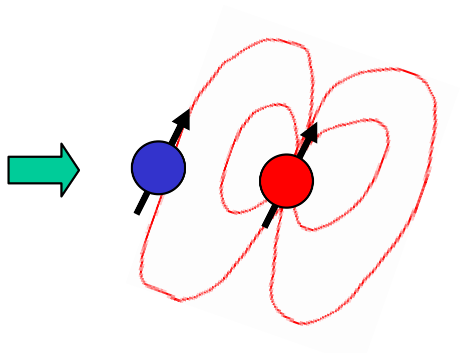
How do we realize the conditional phase gate?

$$\begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} |\Psi\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle - |11\rangle\right)$$

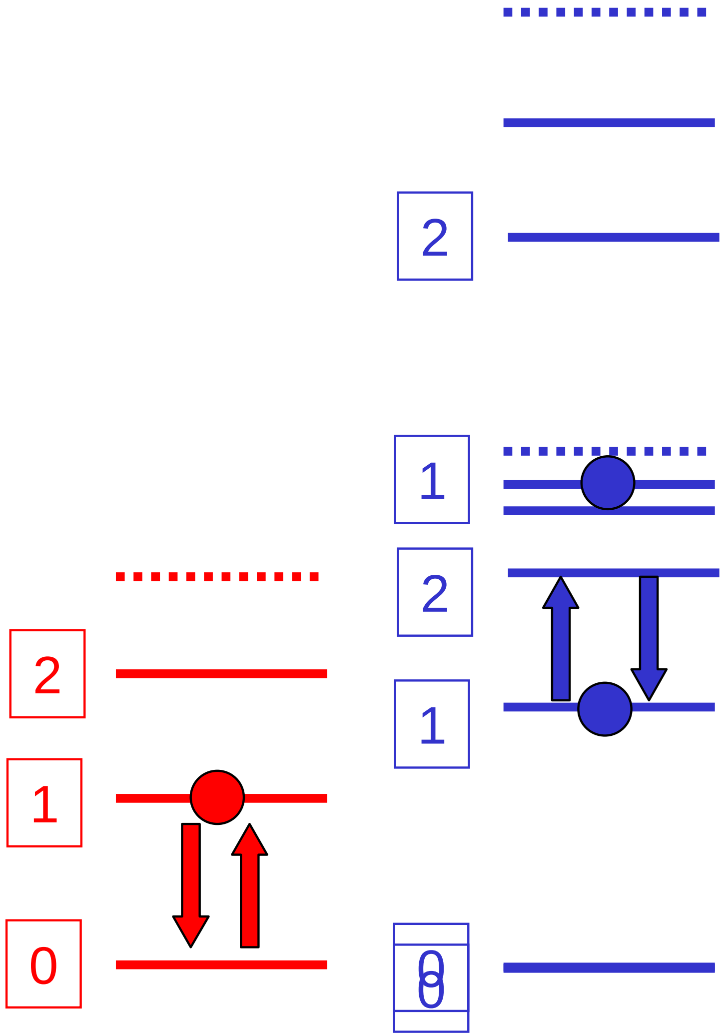
Use control lines to push qubits near a resonance:



A controlled z-z interaction also à la NMR



Key is to use 3rd level of transmon (outside the logical subspace)



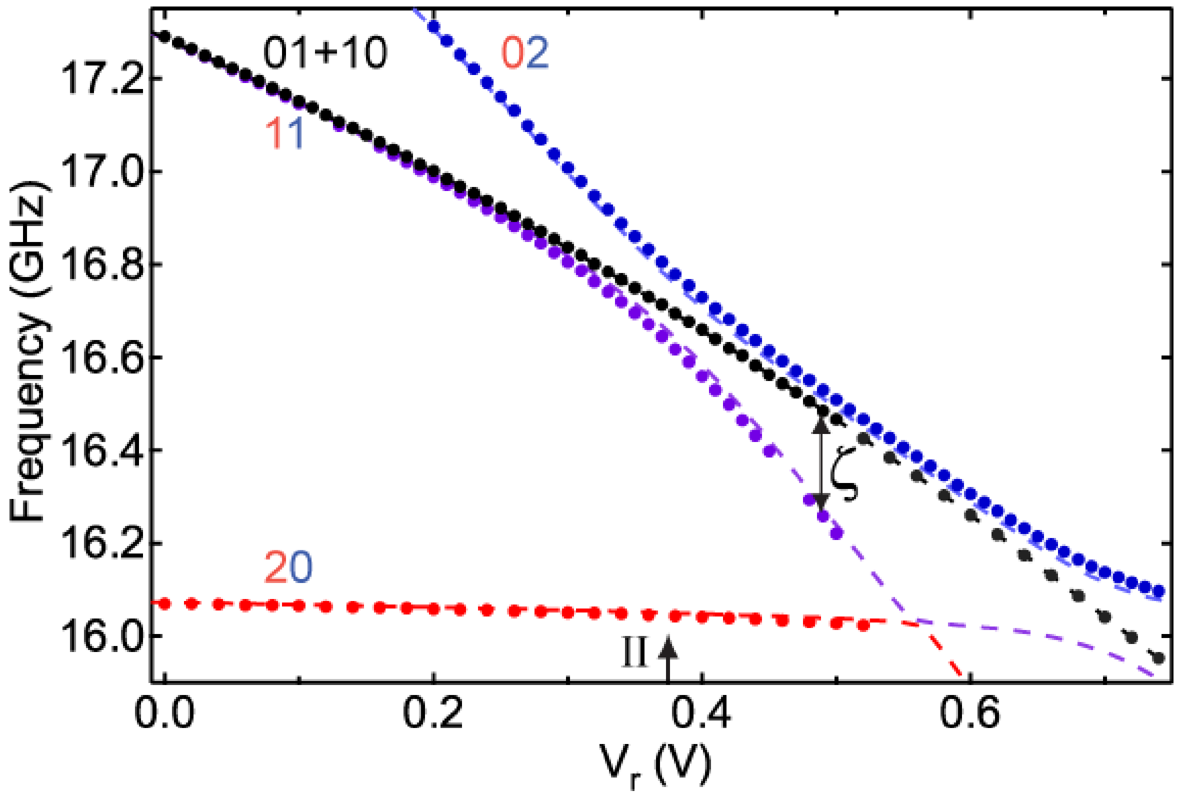
Coupling turned off.

Coupling turned on:
Near resonance with 3rd level

$$\omega_{01} \approx \omega_{12}$$

Energy is shifted if and only if both qubits are in excited state.

Adiabatic Conditional Phase Gate



- Avoided crossing (160 MHz)

$$|11\rangle \leftrightarrow |02\rangle$$

- A frequency shift

$$\boxed{\zeta/2\pi = f_{01} + f_{10} - f_{11}}$$

$$1.2\,\mathrm{MHz} \leqslant \zeta/2\pi \lesssim 150\,\mathrm{MHz}$$

On/off ratio ≈ 100:1

Use large on-off ratio of ζ to implement 2-qubit phase gates.

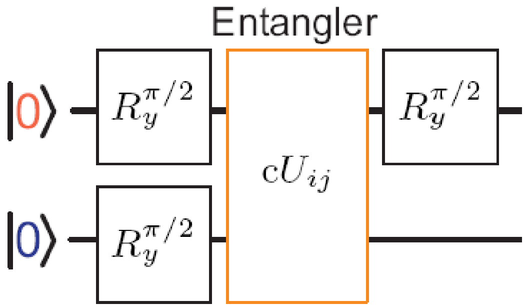
$$\int \zeta(t)\,\mathrm{d}t = (2n+1)\pi$$

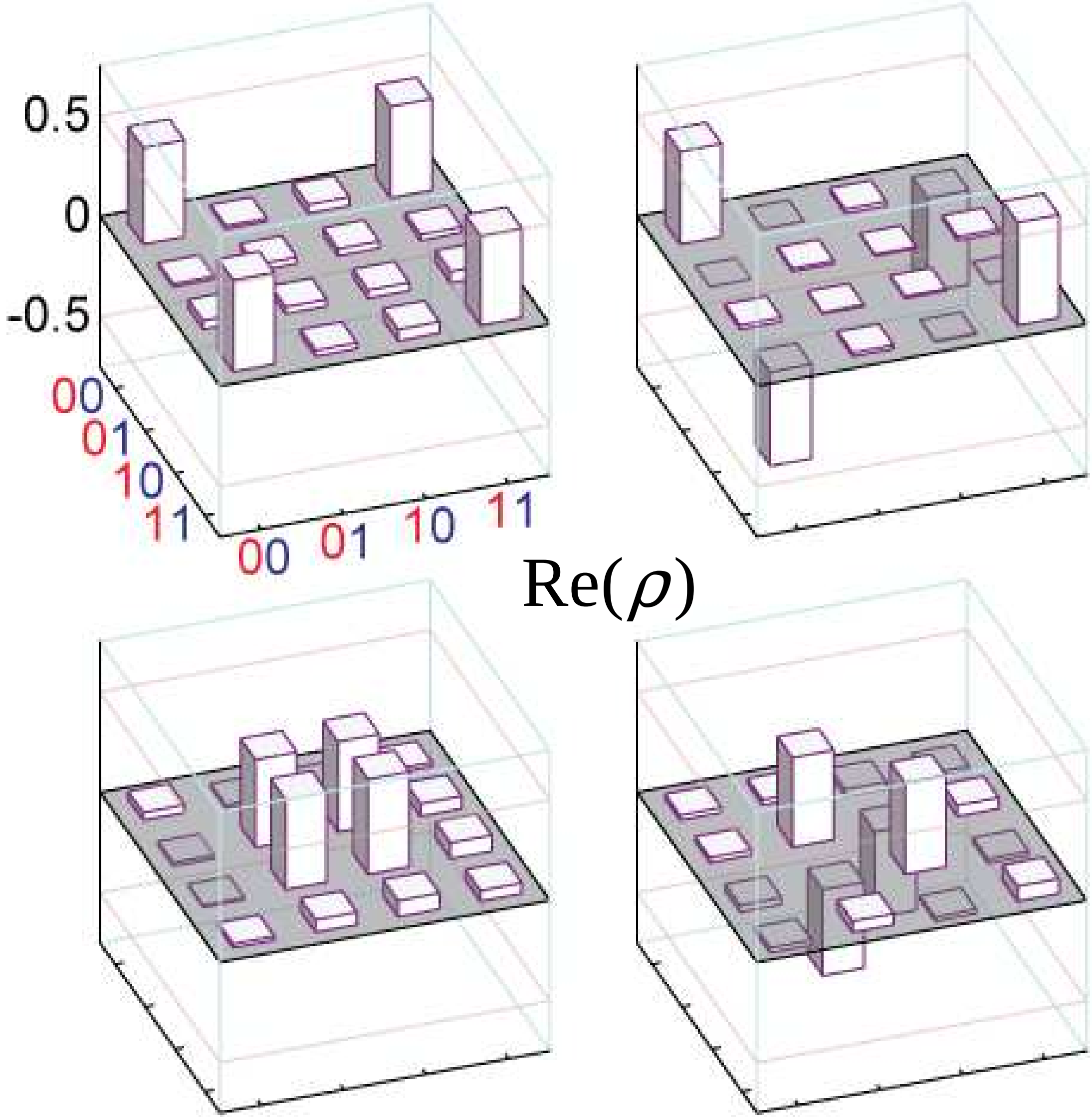
Strauch et al. *PRL* (2003): proposed use of excited states in phase qubits

Adjust timing so that amplitude for both qubits to be excited acquires a minus sign:

$$\begin{pmatrix} +1 & 0 & 0 & 0 \\ 0 & +1 & 0 & 0 \\ 0 & 0 & +1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix} |\Psi\rangle = \frac{1}{2}\left(|00\rangle + |10\rangle + |01\rangle - |11\rangle\right)$$

Entanglement on Demand



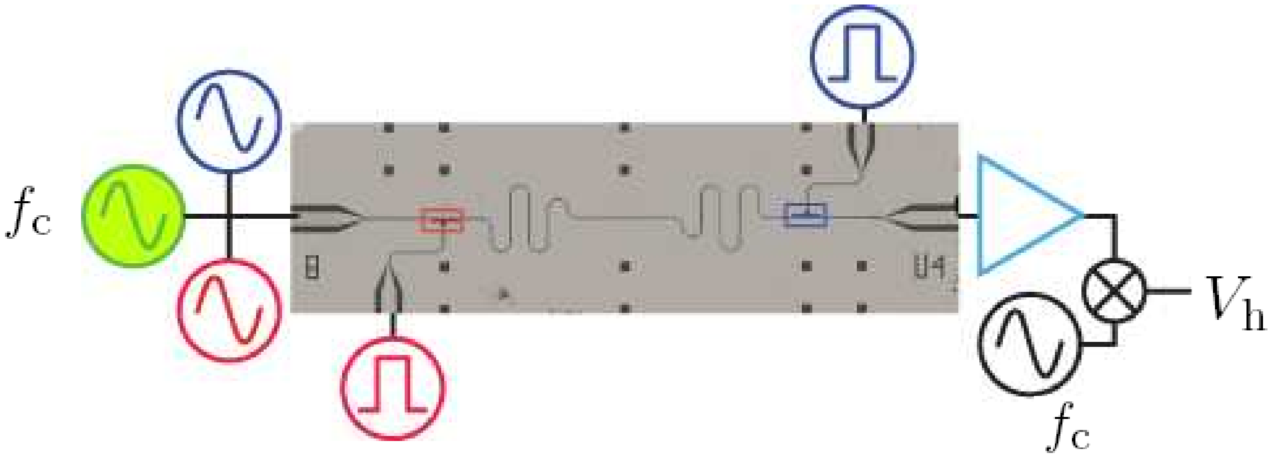


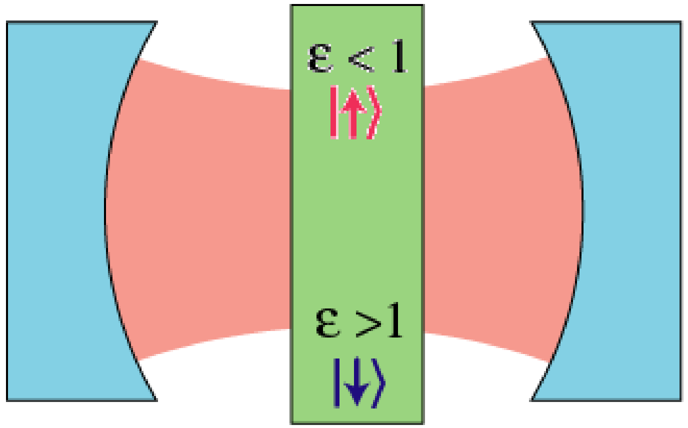
Bell state	Fidelity	Concurrence
$\|00\rangle + \|11\rangle$	91%	88%
$\|00\rangle - \|11\rangle$	94%	94%
$\|01\rangle + \|10\rangle$	90%	86%
$\|01\rangle - \|10\rangle$	87%	81%

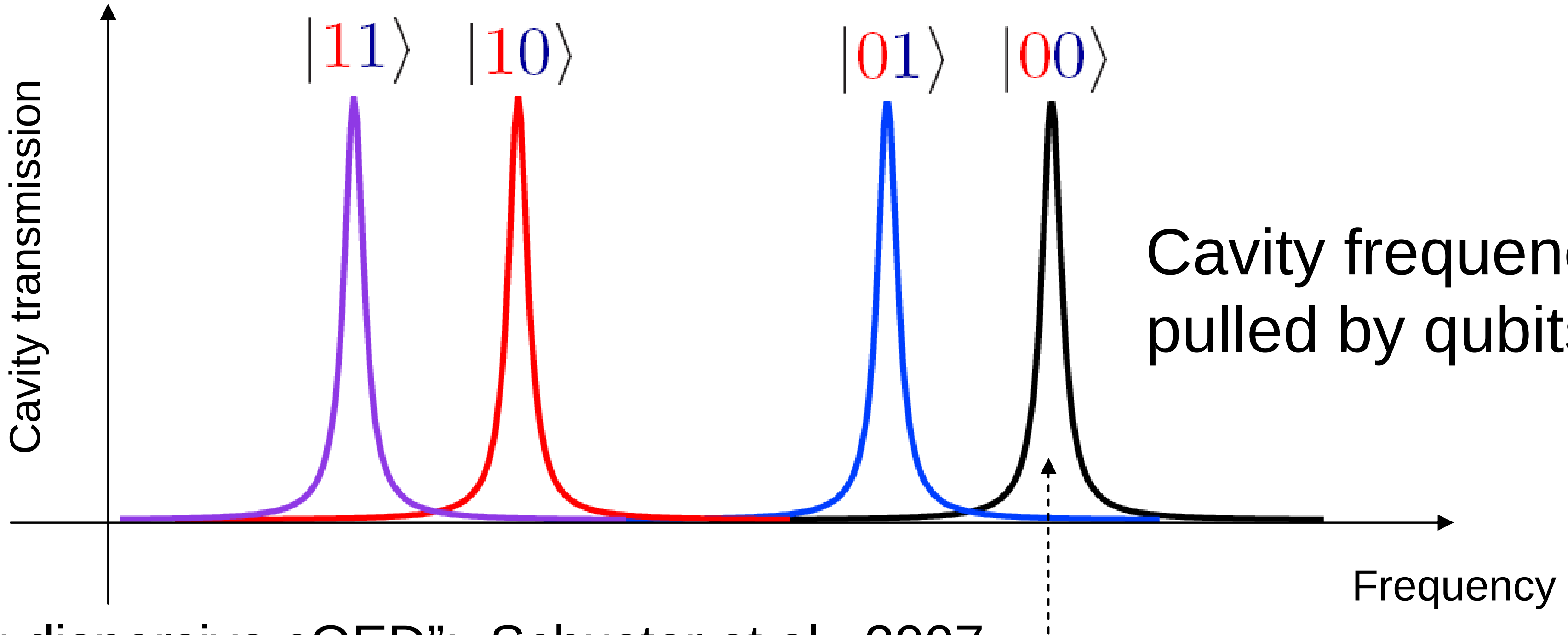
UCSB: Steffen *et al.*, Science (2006)
ETH: Leek *et al.*, PRL (2009)

How do we read out the qubit state and measure the entanglement?

Two Qubit Joint Readout via Cavity



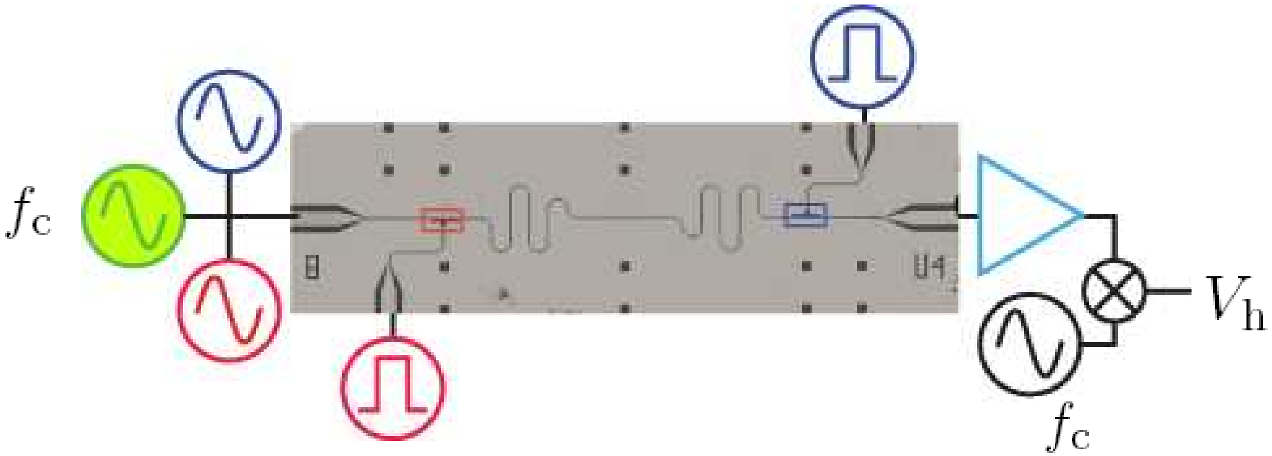


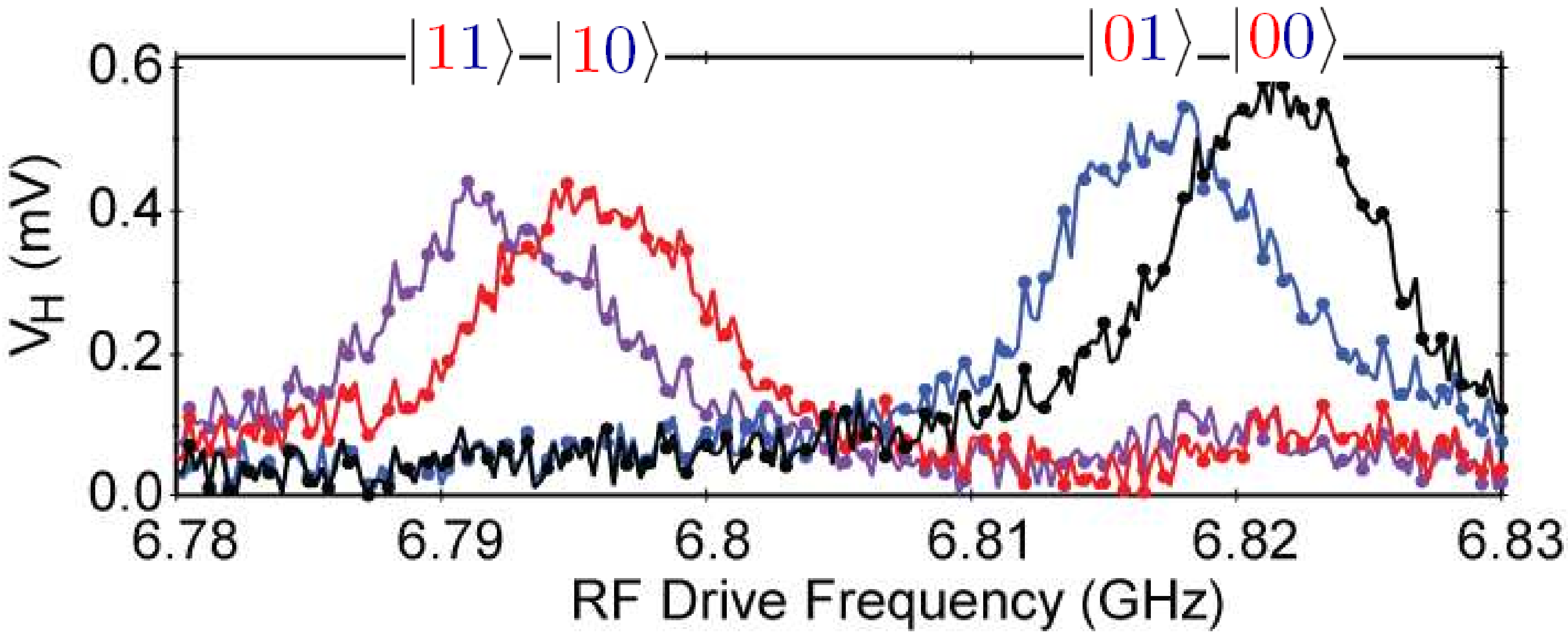


Cavity frequency pulled by qubits

“Strong dispersive cQED”: Schuster et al., 2007

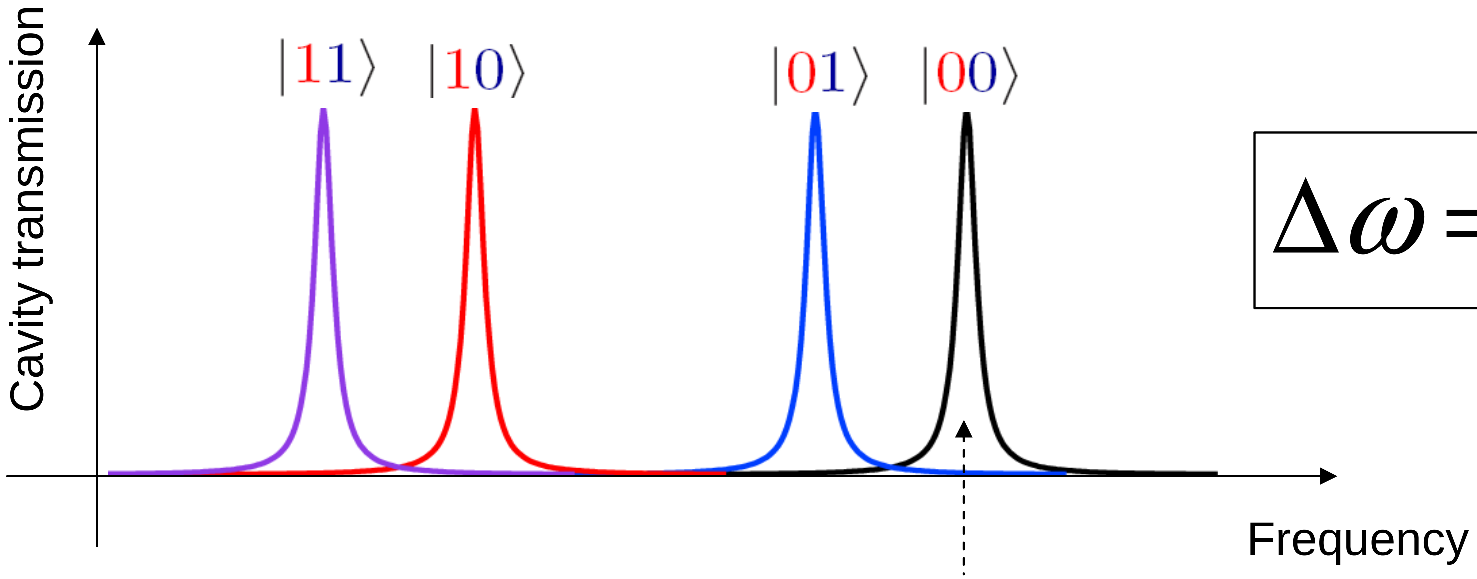
Two Qubit Joint Readout via Cavity





Initial polarization of qubit? > 99.7% (Bishop et al., 2009) -> reset fidelity is high!

Cavity Pull is linear in spin polarizations



$$\Delta\omega = a\sigma_{\mathrm{L}}^{z} + b\sigma_{\mathrm{R}}^{z}$$

Complex transmitted amplitude is non-linear in cavity pull:

$$\boxed{t = \frac{\kappa/2}{\omega_{\mathrm{drive}} - \omega_{\mathrm{cavity}} - \Delta\omega + i\kappa/2}}$$

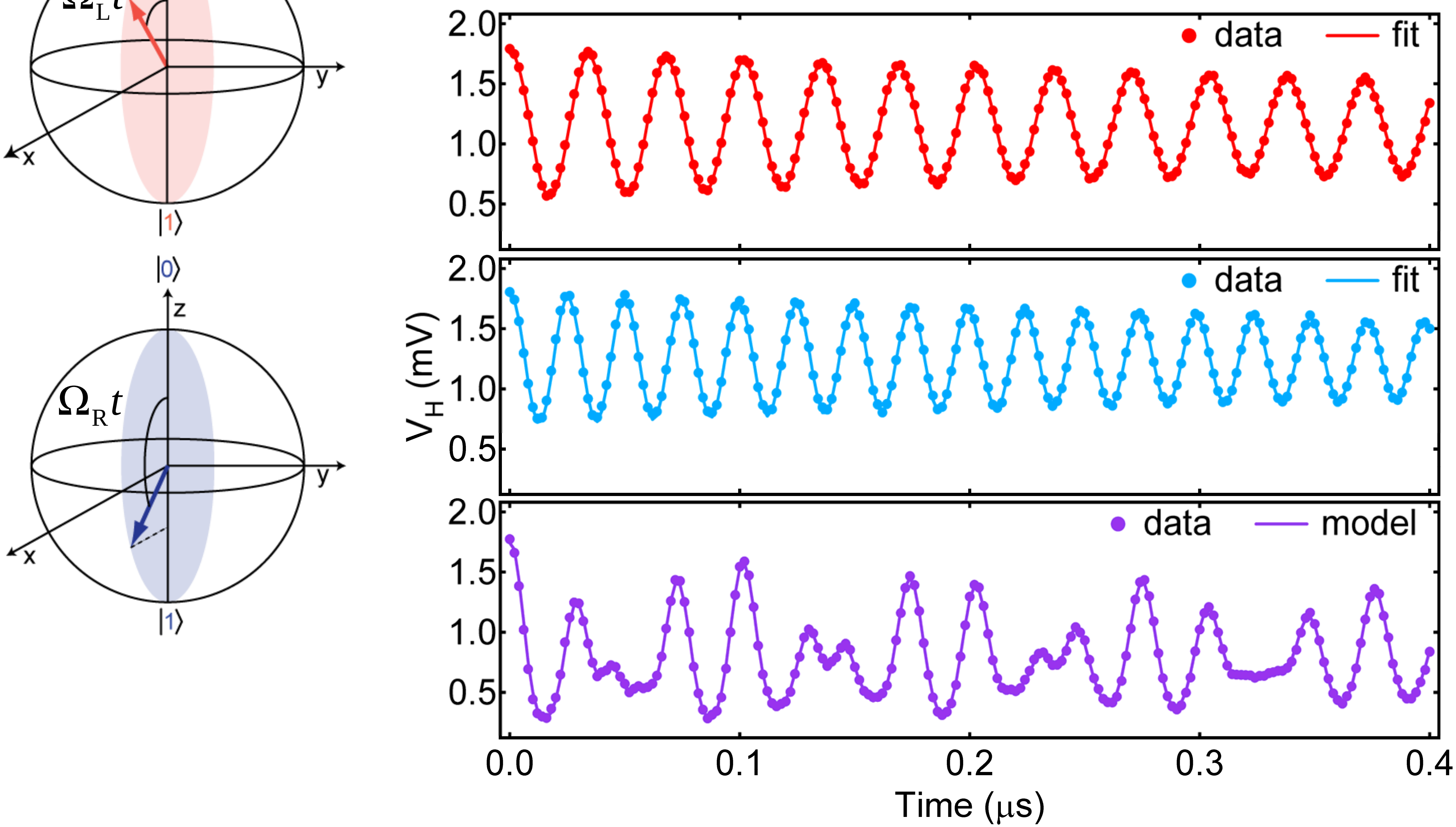
Most general non-linear function of two Ising spin variables:

$$\boxed{t = \cancel{\beta_0} + \beta_1\, \sigma_{\mathrm{L}}^{z} + \beta_2\, \sigma_{\mathrm{R}}^{z} + \beta_{12}\, \sigma_{\mathrm{L}}^{z} \otimes \sigma_{\mathrm{R}}^{z}}$$

Joint Readout

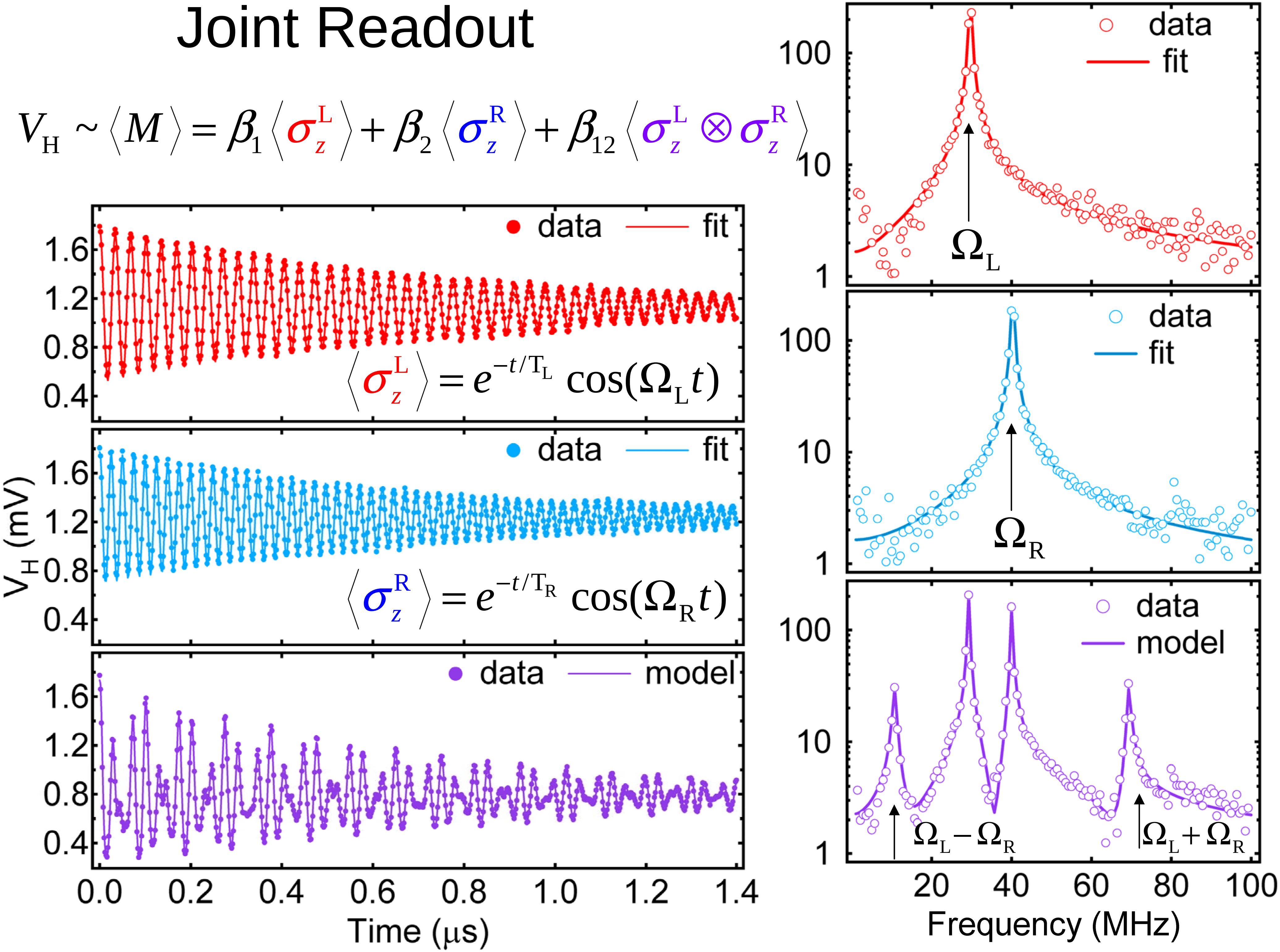
$$V_H \sim \langle M \rangle = \beta_1 \langle \sigma_z^L \rangle + \beta_2 \langle \sigma_z^R \rangle + \beta_{12} \langle \sigma_z^L \otimes \sigma_z^R \rangle$$

$$\beta_1 \sim 1; \quad \beta_2 \sim 0.8; \quad \beta_{12} \sim 0.5$$

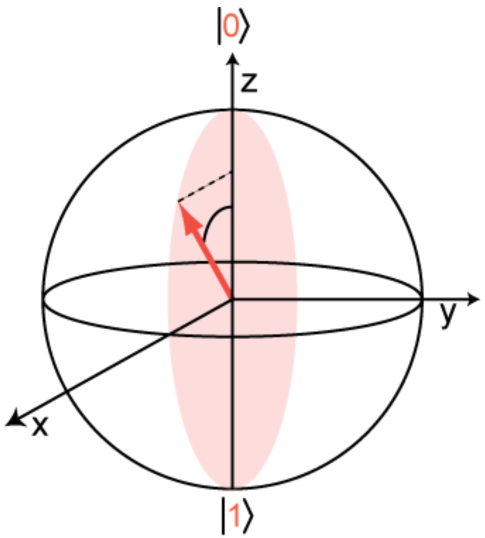


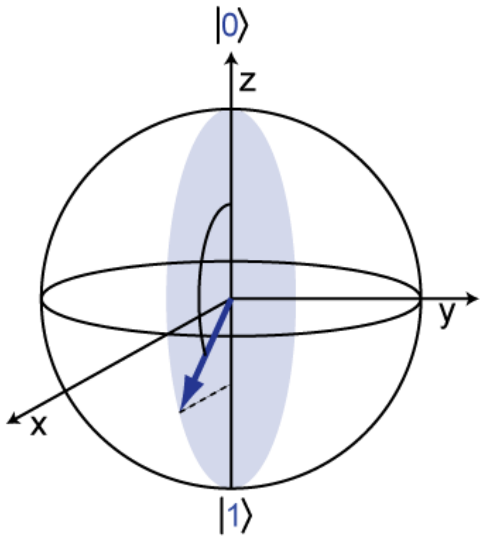
Joint Readout

$$V_H \sim \langle M \rangle = \beta_1 \langle \sigma_z^L \rangle + \beta_2 \langle \sigma_z^R \rangle + \beta_{12} \langle \sigma_z^L \otimes \sigma_z^R \rangle$$



State Tomography





$$V_{\mathrm{H}} \sim \langle M \rangle = \beta_1 \langle \sigma_z^{\mathrm{L}} \rangle + \beta_2 \langle \sigma_z^{\mathrm{R}} \rangle + \beta_{12} \langle \sigma_z^{\mathrm{L}} \otimes \sigma_z^{\mathrm{R}} \rangle$$

Combine joint readout with one-qubit “analysis” rotations

$$\langle \sigma_z^{\mathrm{L}} \rangle \sim V_H(Ident.) + V_H(Y_\pi^R) \longleftarrow$$ π-pulse on right

$$\langle \sigma_z^{\mathrm{R}} \rangle \sim V_H(Ident.) + V_H(\mathrm{Y}_\pi^L) \longleftarrow$$ π-pulse on left

$$\langle \sigma_z^{\mathrm{L}} \sigma_z^{\mathrm{R}} \rangle \sim V_H(Ident.) + V_H(Y_\pi^R, \mathrm{Y}_\pi^L) \longleftarrow$$ π on both

Possible to acquire correlation information even with single, ensemble averaged msmt.!

Rotate qubits to map other correlations onto z-z.

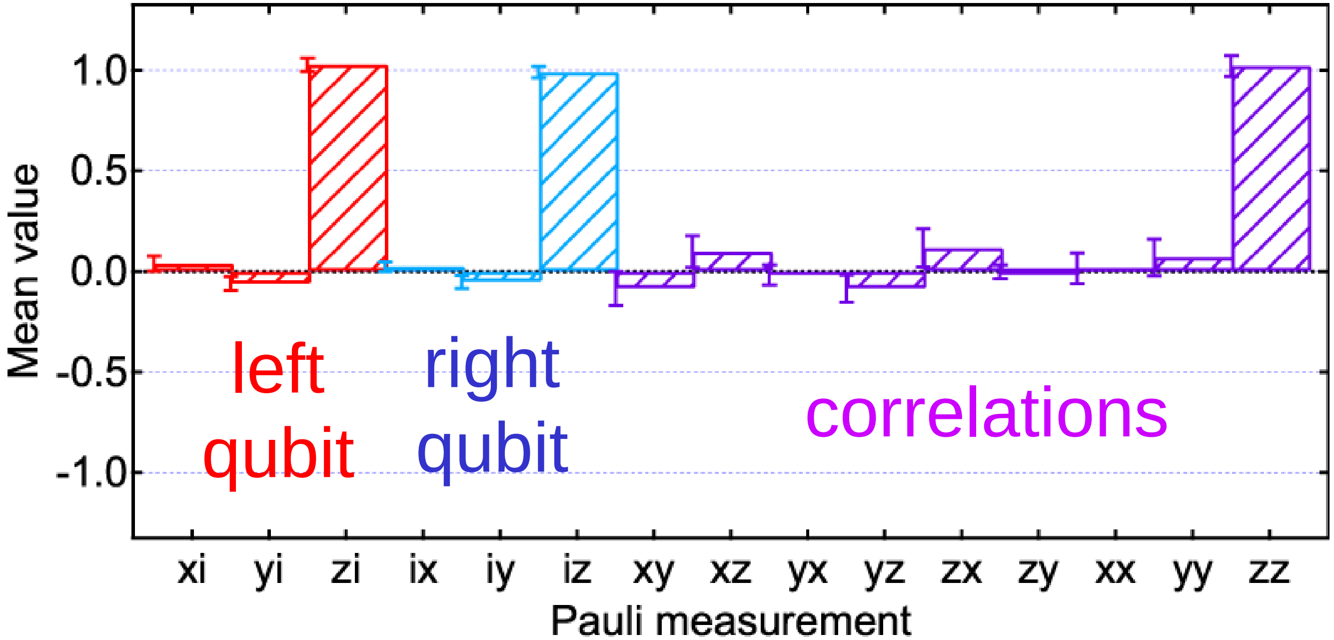
See similar from Zurich group: Fillip et al., PRL **102**, 200402 (2009).

Measuring the Two-Qubit State

Total of 16 msmts.: $I, Y_{\pi}^{L}, X_{\pi/2}^{L}, Y_{\pi/2}^{L}$ and combinations

$I, Y_{\pi}^{R}, X_{\pi/2}^{R}, Y_{\pi/2}^{R}$

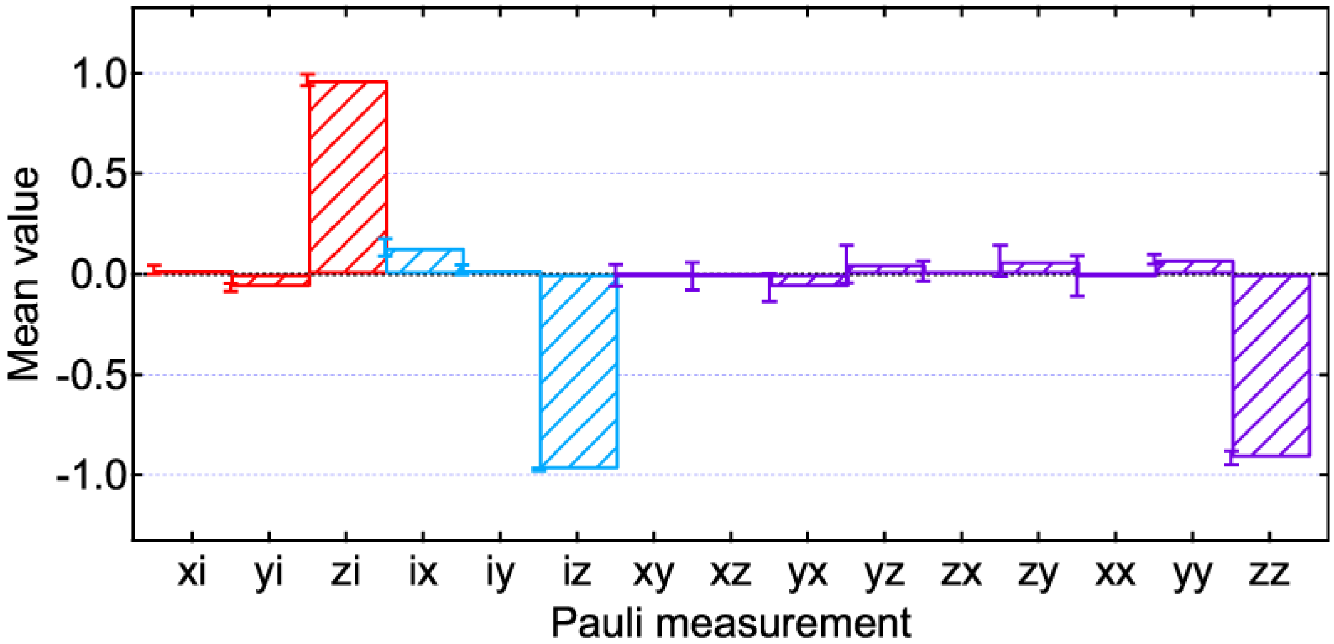
(almost) raw data



Ground state: $|\psi\rangle = |00\rangle = |\uparrow\uparrow\rangle$ $\boxed{\langle \sigma_{L}^{z} \rangle = \langle \sigma_{R}^{z} \rangle = \langle \sigma_{L}^{z} \sigma_{R}^{z} \rangle = 1}$

Measuring the Two-Qubit State

Apply π-pulse to invert state of right qubit



One qubit excited: $|\psi\rangle = |01\rangle = |\uparrow\downarrow\rangle$

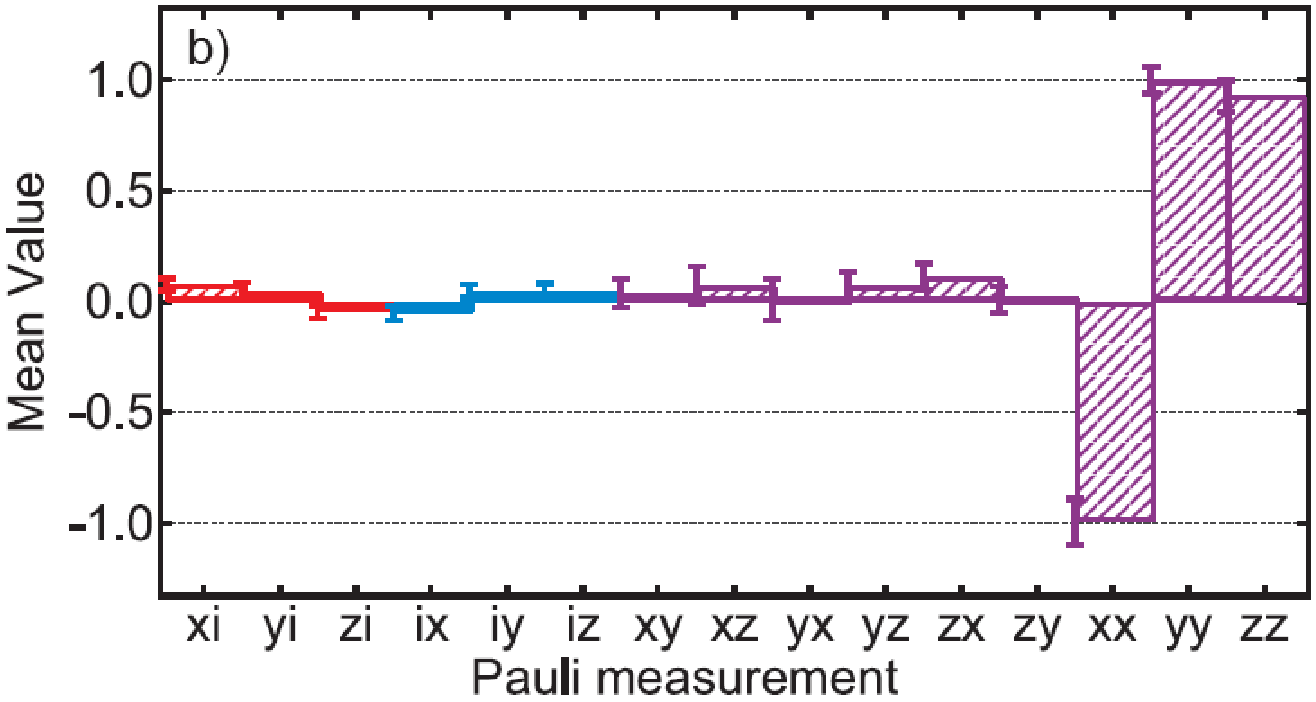
$$\langle \sigma_L^z \rangle = +1$$

$$\langle \sigma_R^z \rangle = \langle \sigma_L^z \sigma_R^z \rangle = -1$$

Measuring the Two-Qubit State

Now apply a two-qubit gate to *entangle* the qubits

Entangled state: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$



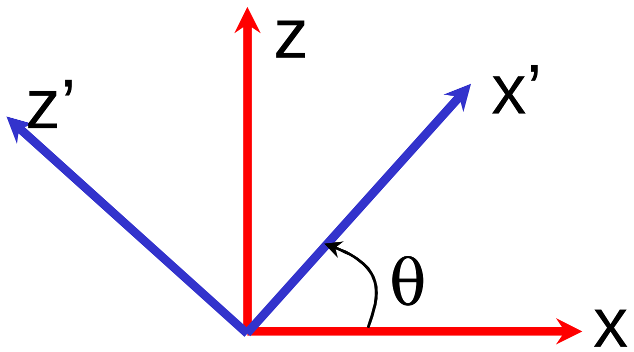
$$\left\langle \sigma_L^z \right\rangle = \left\langle \sigma_R^z \right\rangle = 0$$

$$\left\langle \sigma_L^z \sigma_R^z \right\rangle = +1$$

$$\left\langle \sigma_L^y \sigma_R^y \right\rangle = +1$$

$$\left\langle \sigma_L^x \sigma_R^x \right\rangle = -1$$

Witnessing Entanglement



Clauser, Horne, Shimony & Holt (1969)

CHSH operator = entanglement witness

$$CHSH = XX' - XZ' + ZX' + ZZ'$$

If variables take on the values ±1 and exist even independent of measurement then

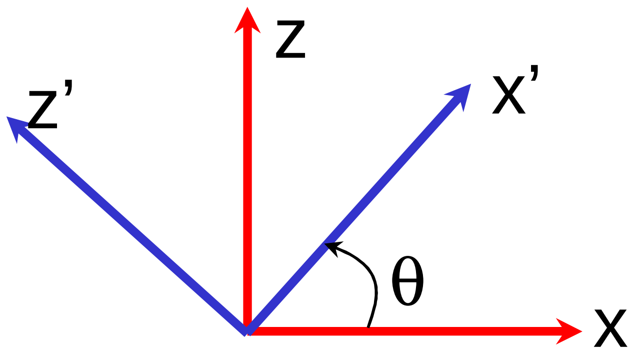
$$CHSH = X(X' - Z') + Z(X' + Z')$$

Either:	=0	=±2
Or:	=±2	=0

Classically:

$$\boxed{|CHSH| \le 2}$$

Witnessing Entanglement



CHSH operator = entanglement witness

$$\langle CHSH \rangle = \langle XX' \rangle - \langle XZ' \rangle + \langle ZX' \rangle + \langle ZZ' \rangle$$

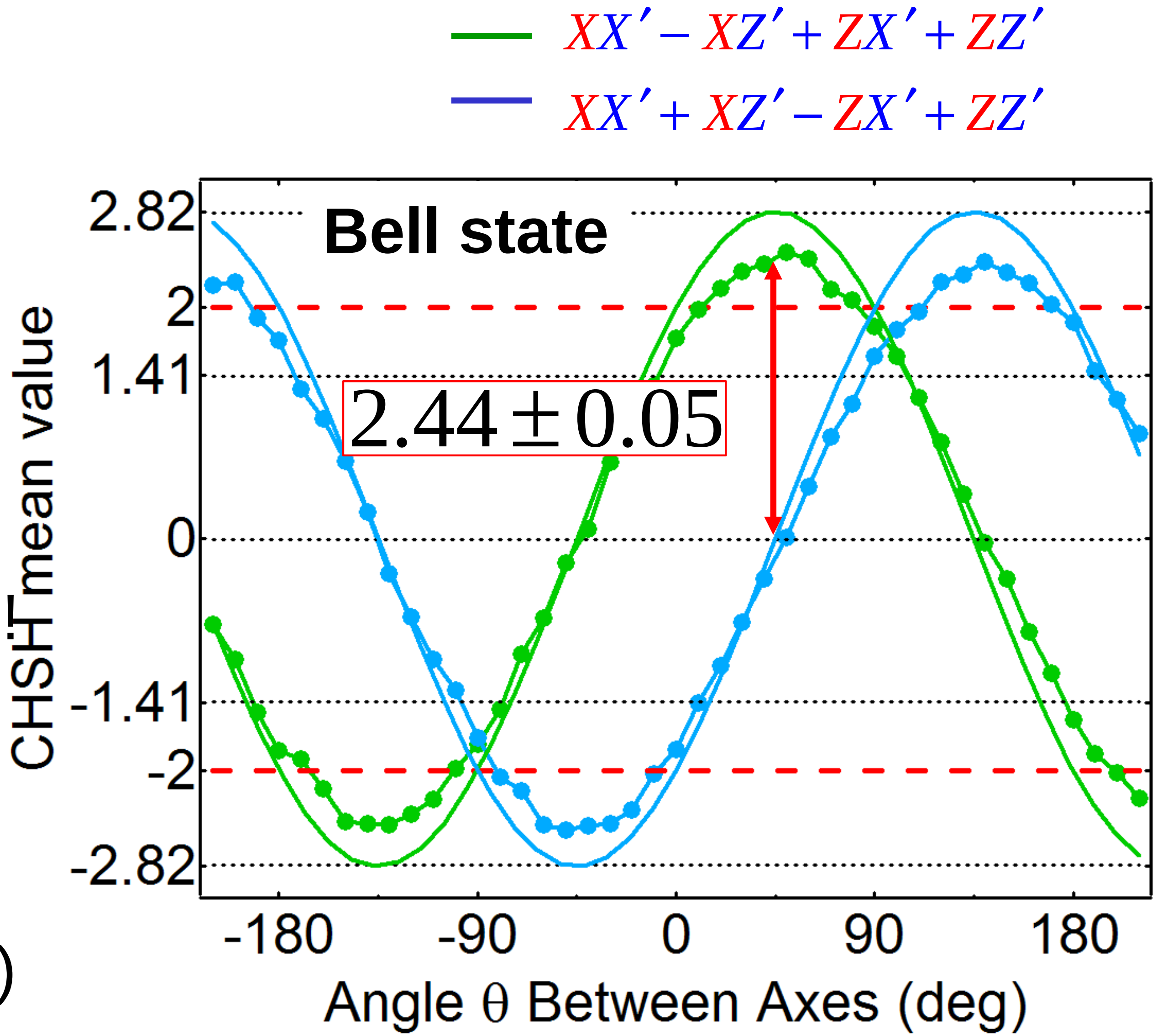
Clauser, Horne, Shimony & Holt (1969)

Separable bound:

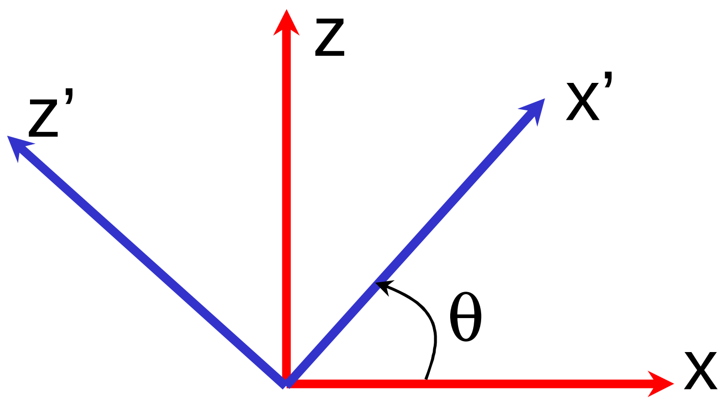
$$|CHSH| \leq 2$$

not ? Bell's violation!
(loopholes abound)

but state is clearly highly entangled!
(and no likelihood req.)



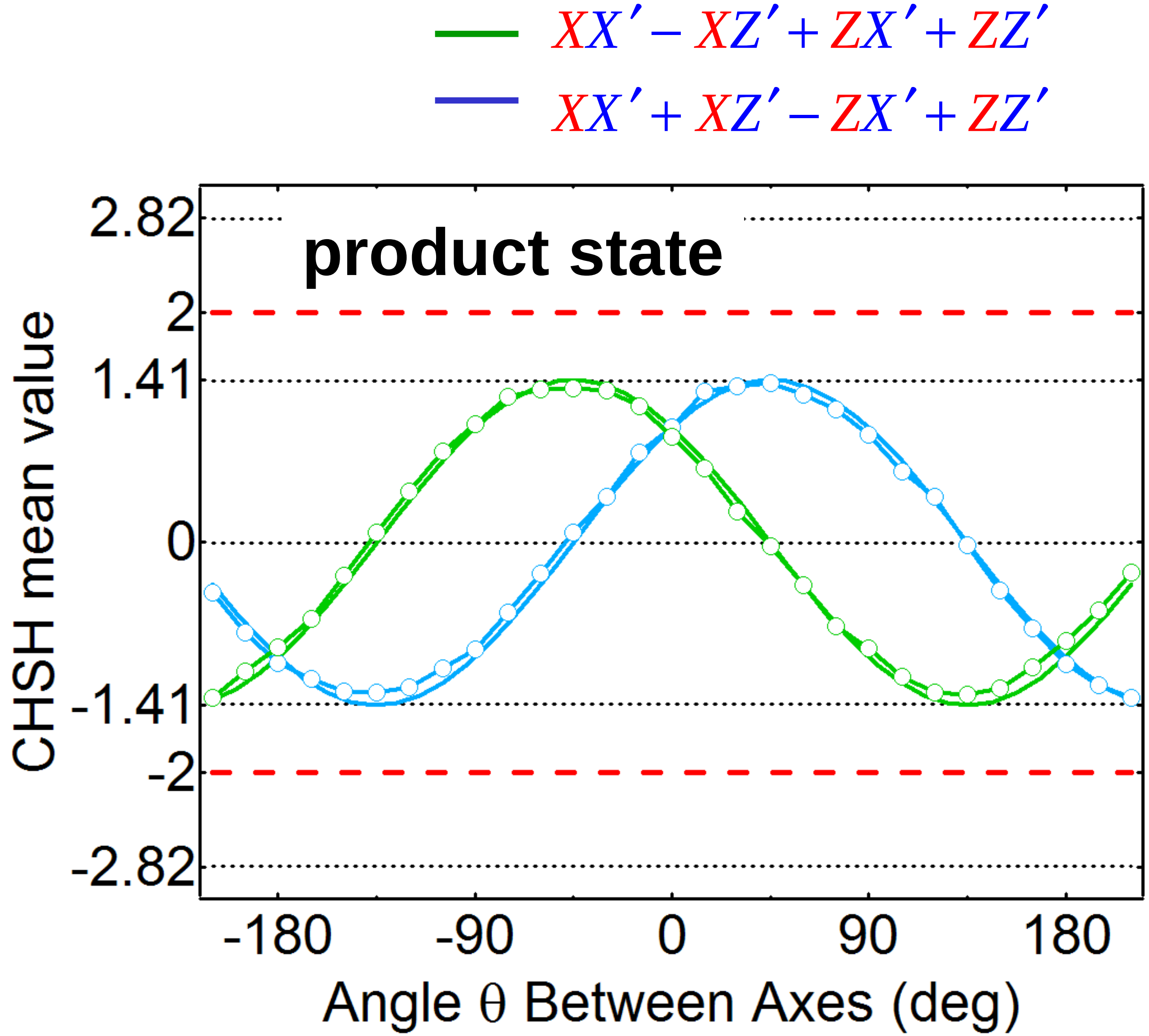
Control: Analyzing Product States



CHSH operator = entanglement witness

$$\langle CHSH \rangle = \langle XX' \rangle - \langle XZ' \rangle + \langle ZX' \rangle + \langle ZZ' \rangle$$

Clauser, Horne, Shimony & Holt (1969)

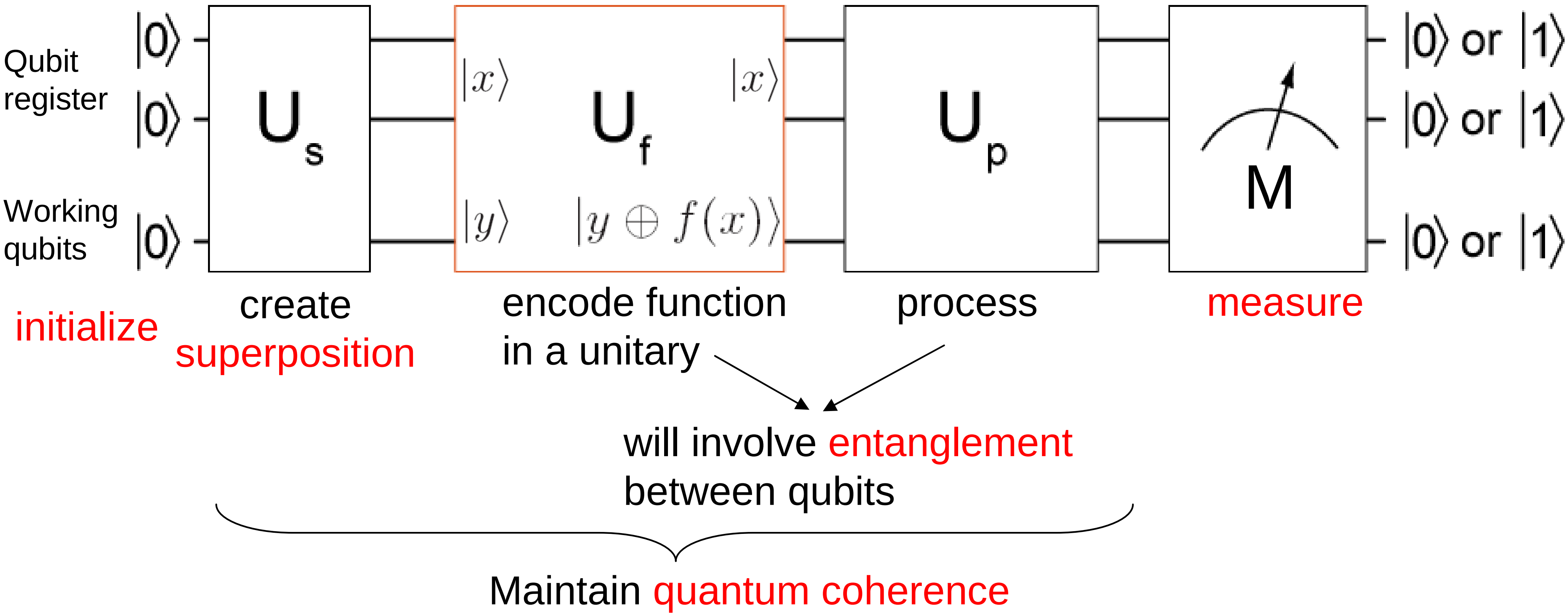


no entanglement!

Using entanglement on demand to run first quantum algorithm on a solid state quantum processor

Skip to Summary

General Features of a Quantum Algorithm



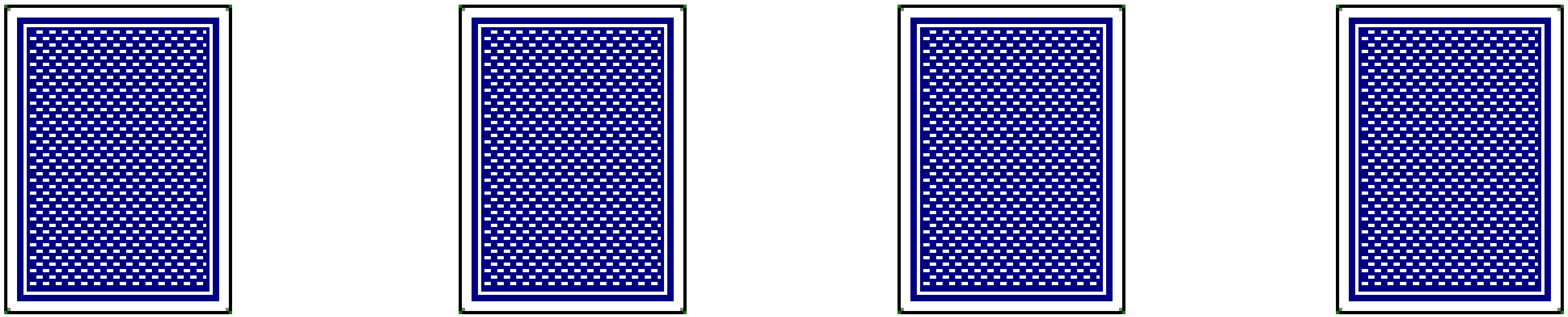
1) Start in superposition: all values at once!
2) Build complex transformation out of one-qubit and two-qubit “gates”
3) Somehow* make the answer we want result in a definite state at end!

*use interference: the magic of the properly designed algorithm

The Search Problem

$$f(x) = \begin{cases} -1, & x \neq x_0 \\ 1, & x = x_0 \end{cases}$$

“Find x_0!”



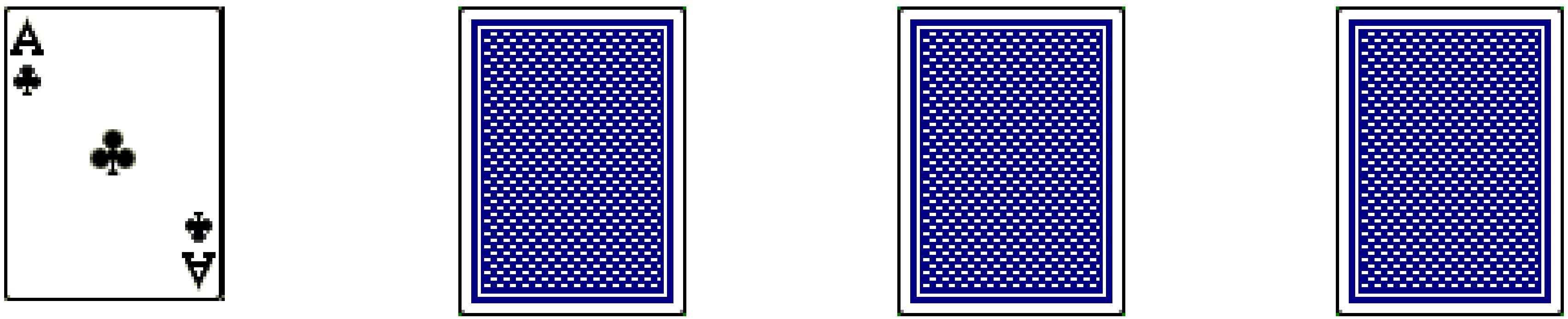
Position: 0 I II III

“Find the queen!”

The Search Problem

$$f(x) = \begin{cases} -1, & x \neq x_0 \\ 1, & x = x_0 \end{cases}$$

"Find x_0!"



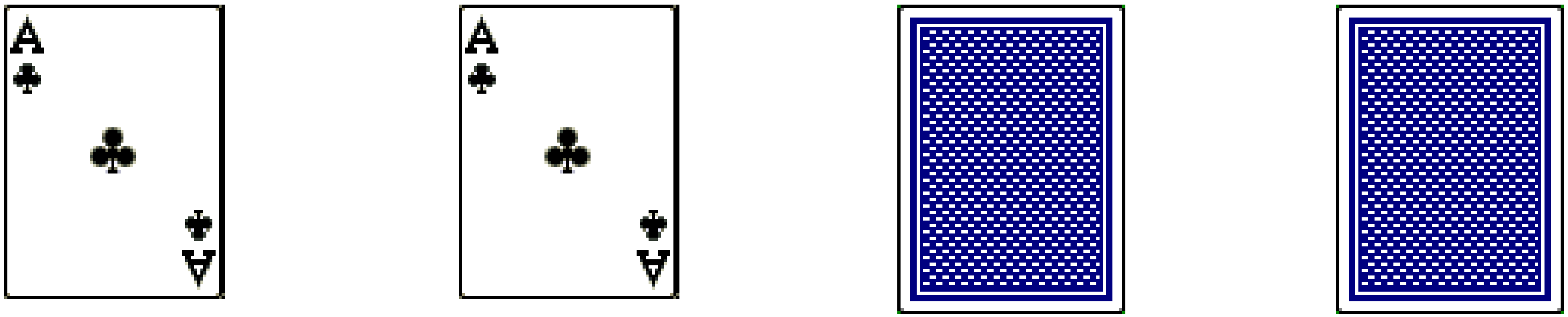
Position: 0 I II III

"Find the queen!"

The Search Problem

$$f(x) = \begin{cases} -1, & x \neq x_0 \\ 1, & x = x_0 \end{cases}$$

“Find x_0!”



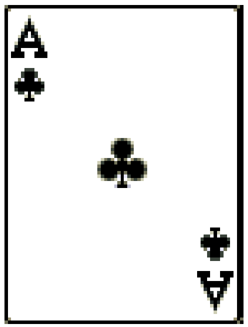
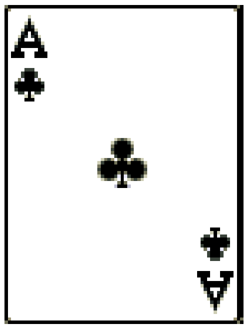
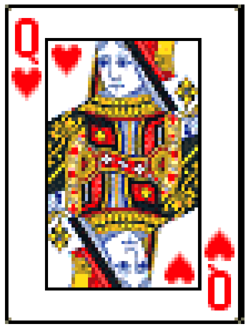
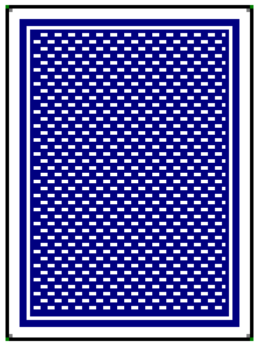
Position: 0 I II III

“Find the queen!”

The Search Problem

$$f(x) = \begin{cases} -1, & x \neq x_0 \\ 1, & x = x_0 \end{cases}$$

“Find x_0!”

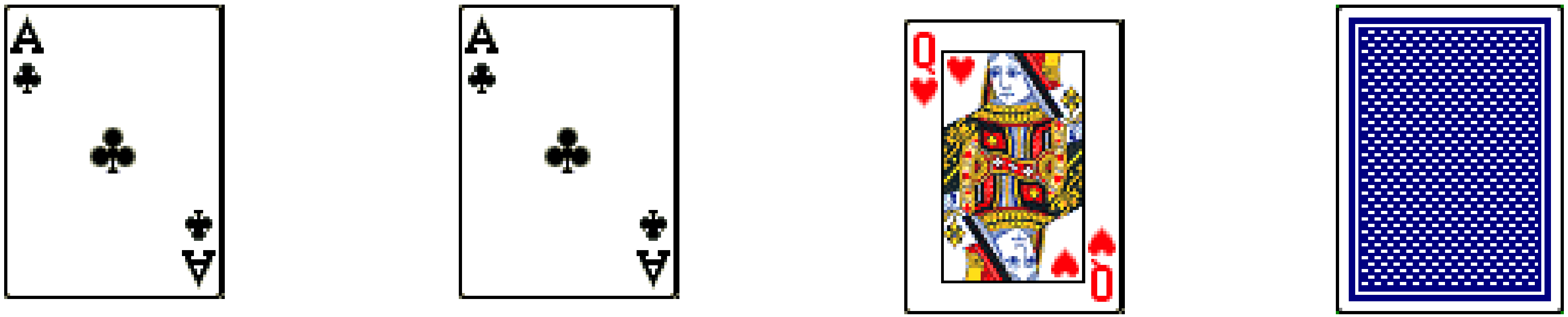
Position: 0 I II III

“Find the queen!”

The Search Problem

Classically, takes on average 2.25 guesses to succeed…

Use QM to “peek” under all the cards, find queen on first try!



Position: 0 I II III

“Find the queen!”

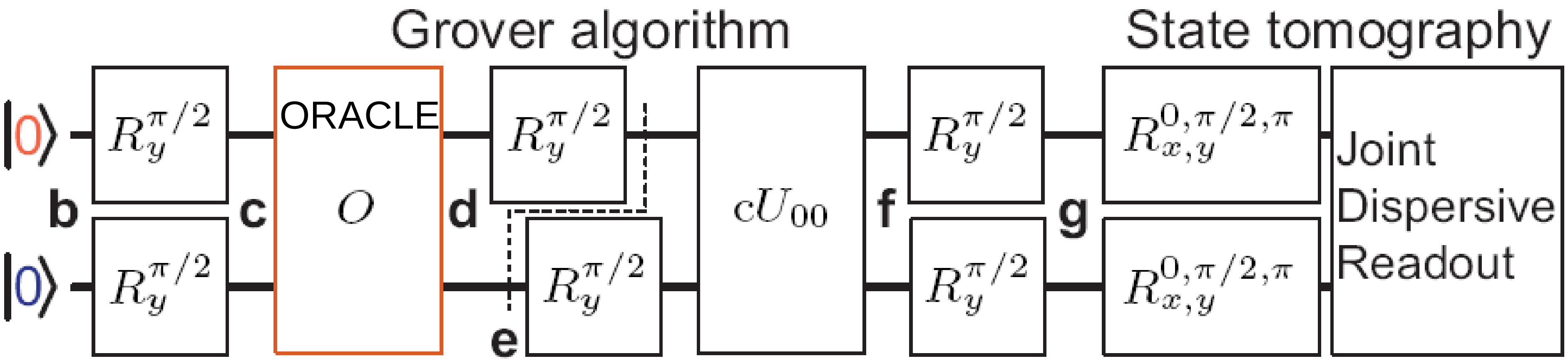
Grover's Algorithm

"unknown" unitary operation: →

$$O|\psi\rangle = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} |\psi\rangle$$

Challenge:
Find the location of the -1 !!!
(= queen)

Previously implemented in NMR: Chuang et al., 1998
Ion traps: Brickman et al., 2003

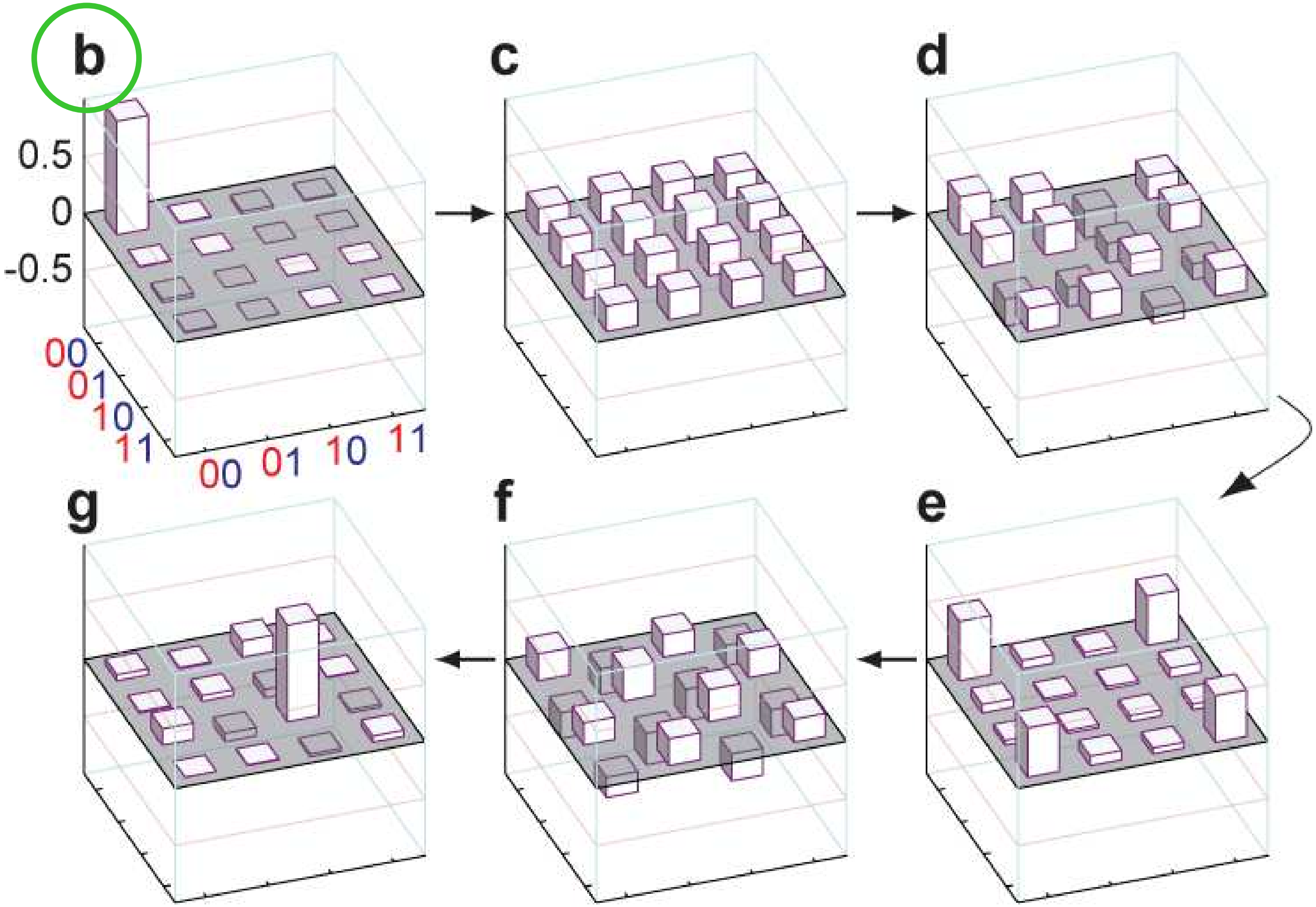


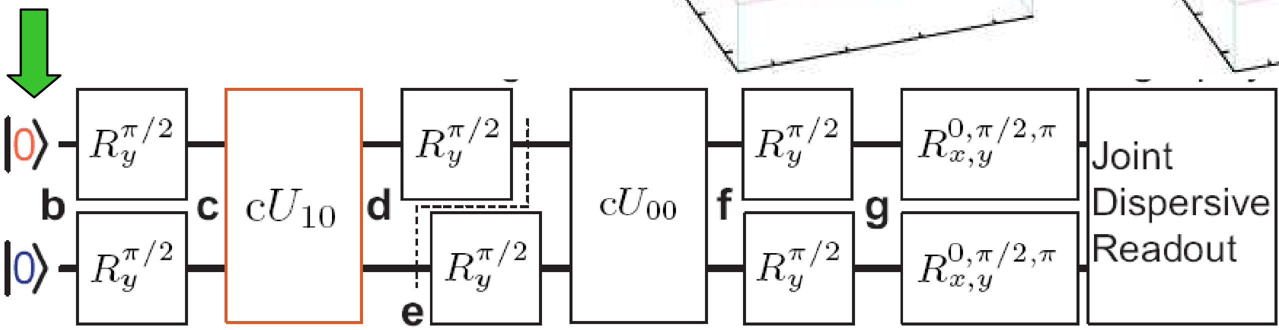
10 pulses w/ nanosecond resolution, total 104 ns duration

Grover Step-by-Step

$$|\psi_{\text{ideal}}\rangle = |00\rangle$$

Begin in ground state:

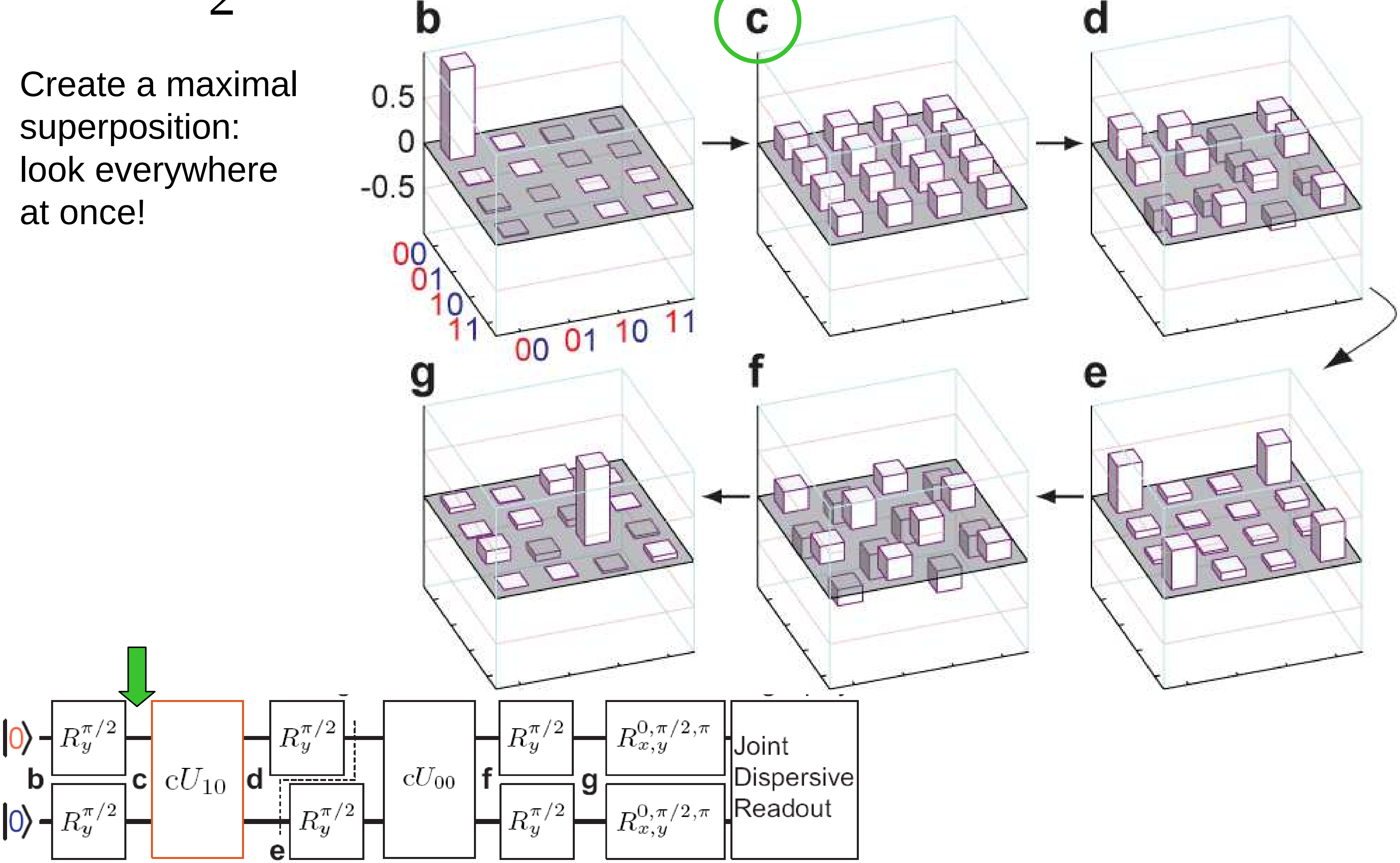




Grover Step-by-Step

$$|\psi_{\text{ideal}}\rangle = \frac{1}{2}\left(|00\rangle + |01\rangle + |10\rangle + |11\rangle\right)$$

Create a maximal superposition: look everywhere at once!

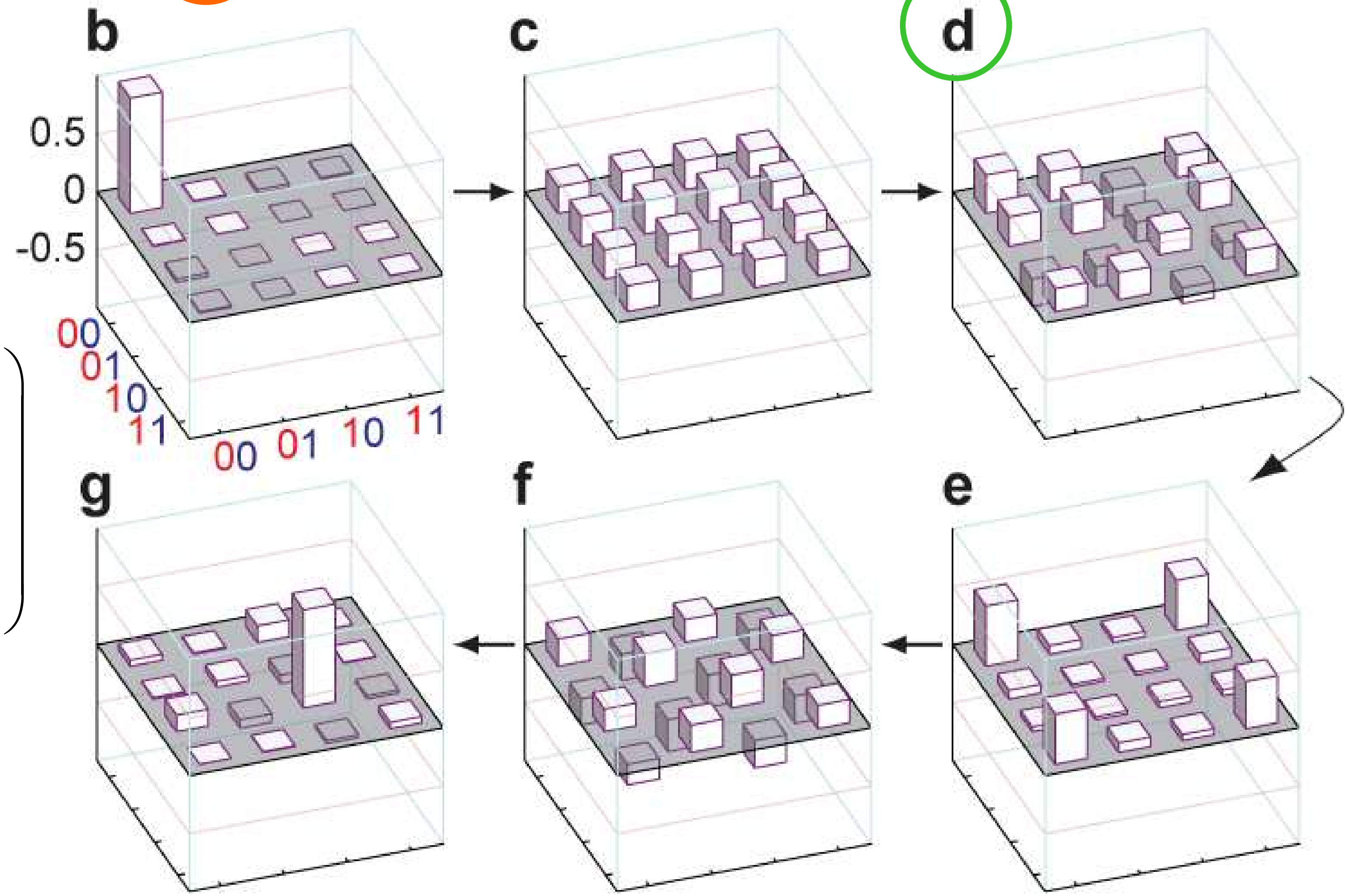


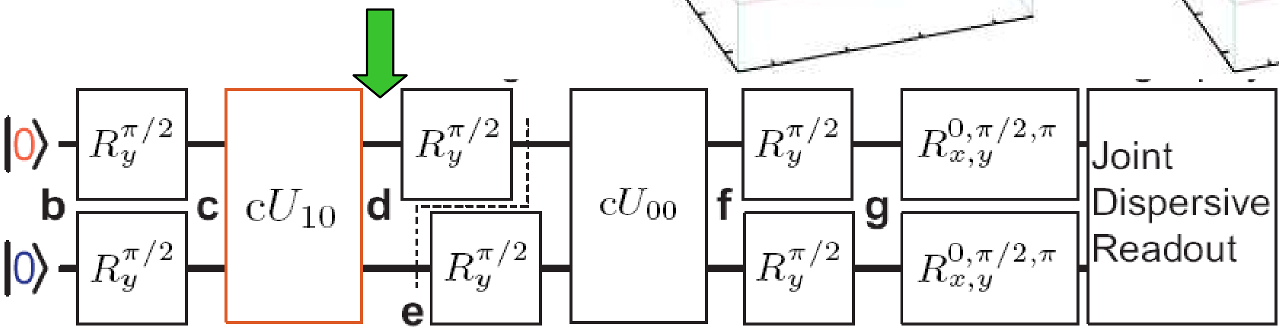
Grover Step-by-Step

$$\left|\psi_{\text{ideal}}\right\rangle = \frac{1}{2}\left(\left|00\right\rangle + \left|01\right\rangle - \left|10\right\rangle + \left|11\right\rangle\right)$$

Apply the "unknown" function, and mark the solution

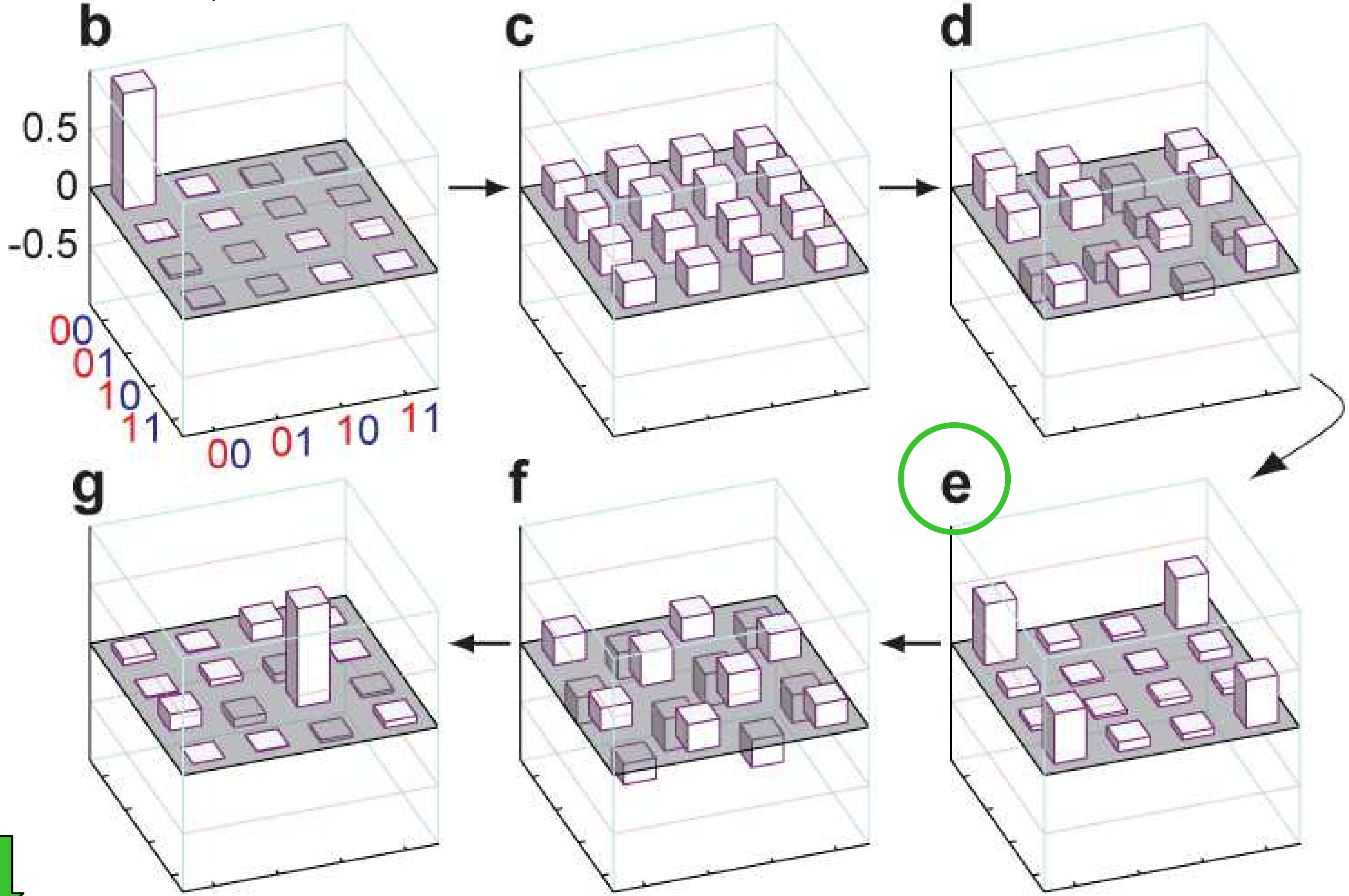
$$cU_{10} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$





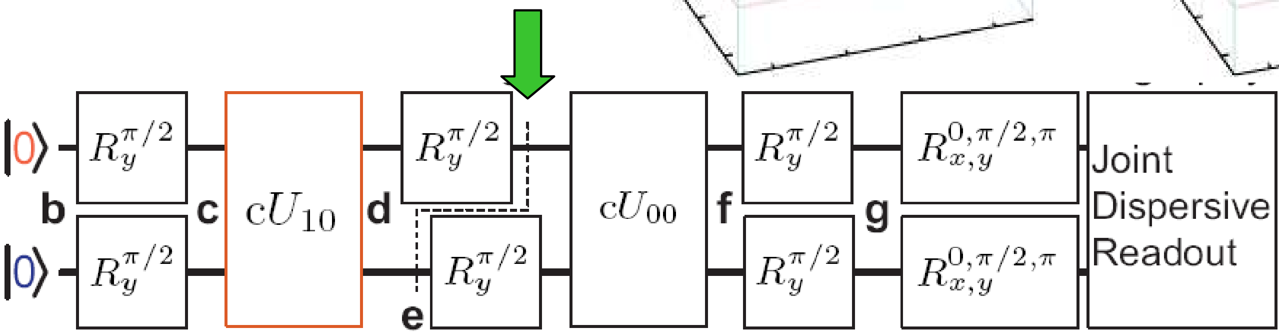
Grover Step-by-Step

$$\left|\psi_{\text{ideal}}\right\rangle = \frac{1}{\sqrt{2}}\left(\left|{\color{red}0}{\color{blue}0}\right\rangle + \left|{\color{red}1}{\color{blue}1}\right\rangle\right)$$



Some more 1-qubit rotations…

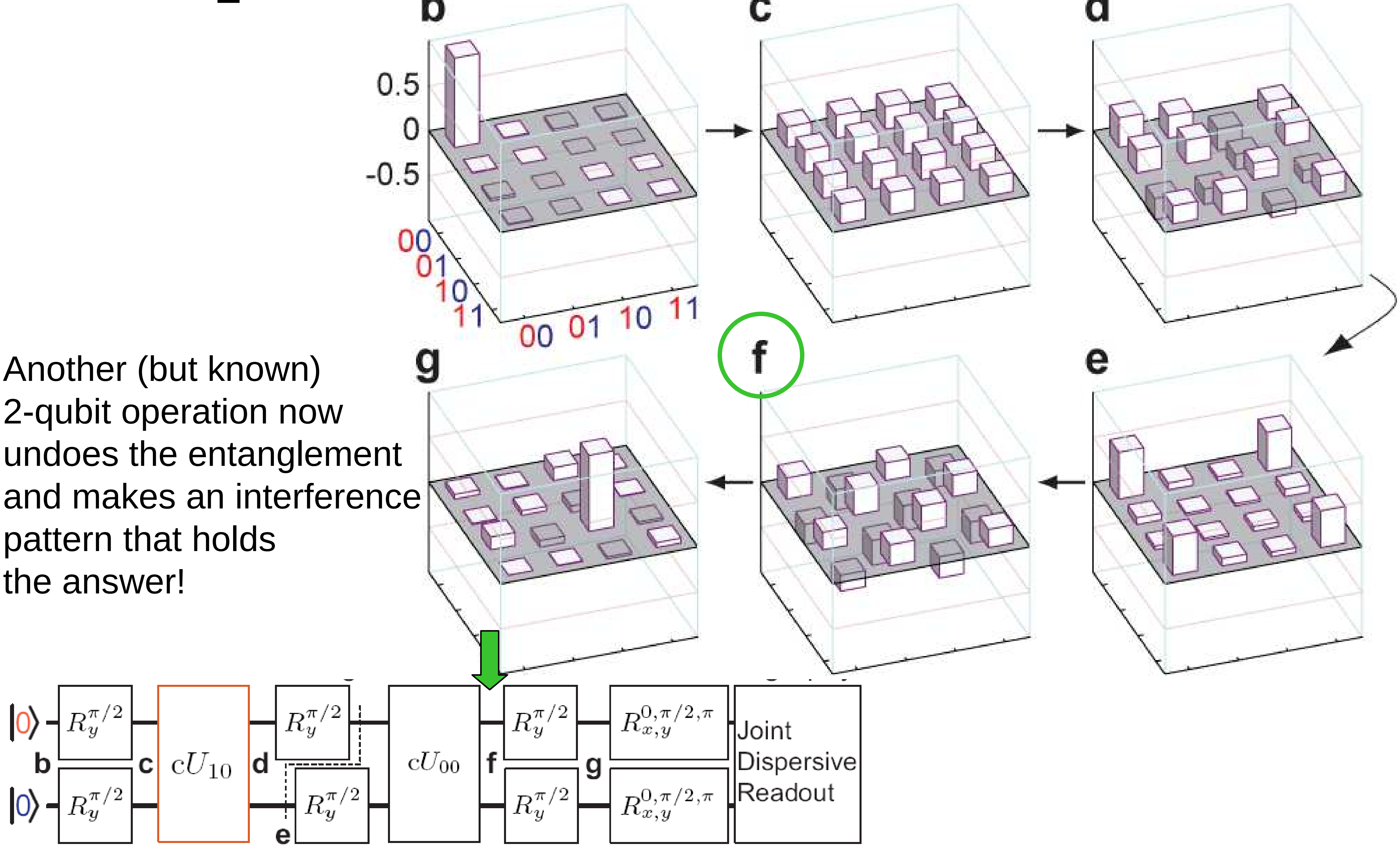
Now we arrive in one of the four Bell states



Grover Step-by-Step

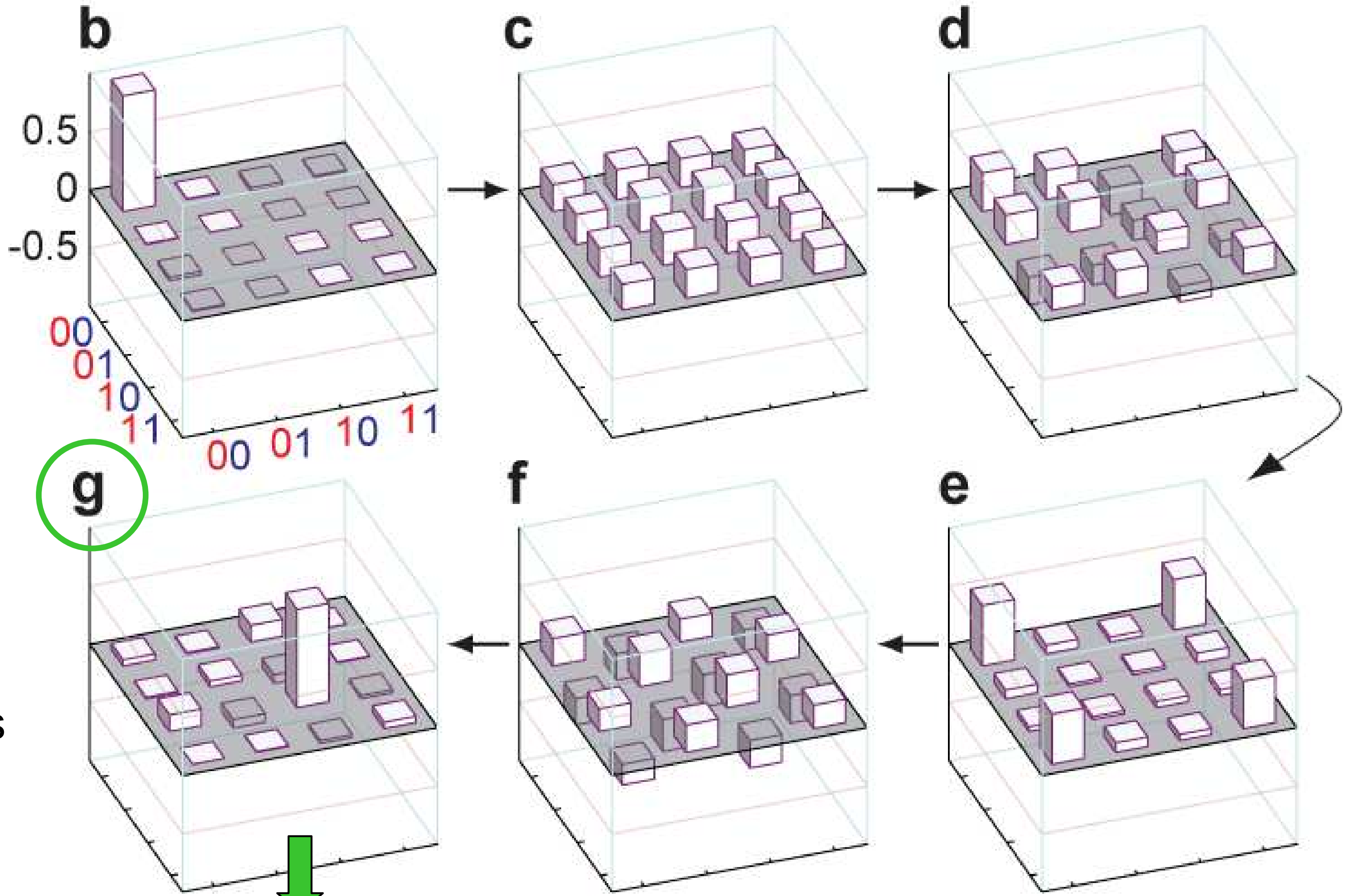
$$\left|\psi_{\text{ideal}}\right\rangle = \frac{1}{2}\left(\left|00\right\rangle - \left|01\right\rangle + \left|10\right\rangle - \left|11\right\rangle\right)$$

Another (but known) 2-qubit operation now undoes the entanglement and makes an interference pattern that holds the answer!



Grover Step-by-Step

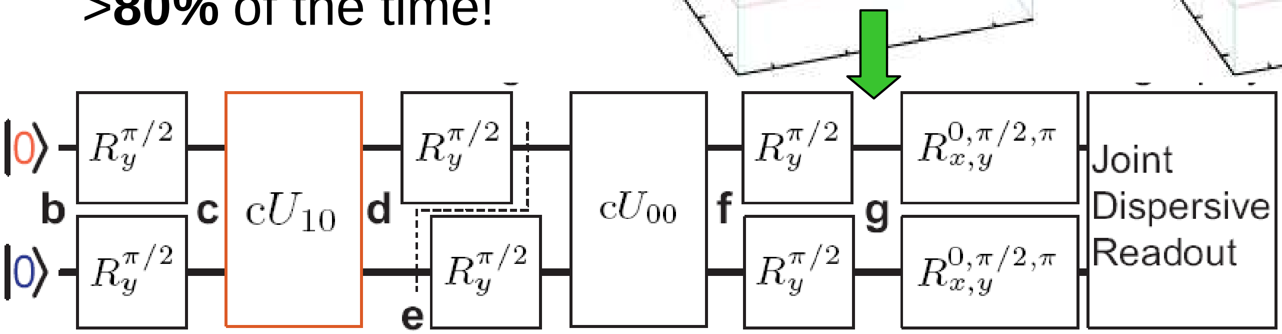
$$|\psi_{\text{ideal}}\rangle = |10\rangle$$



Final 1-qubit rotations reveal the answer:

The binary representation of “2”!

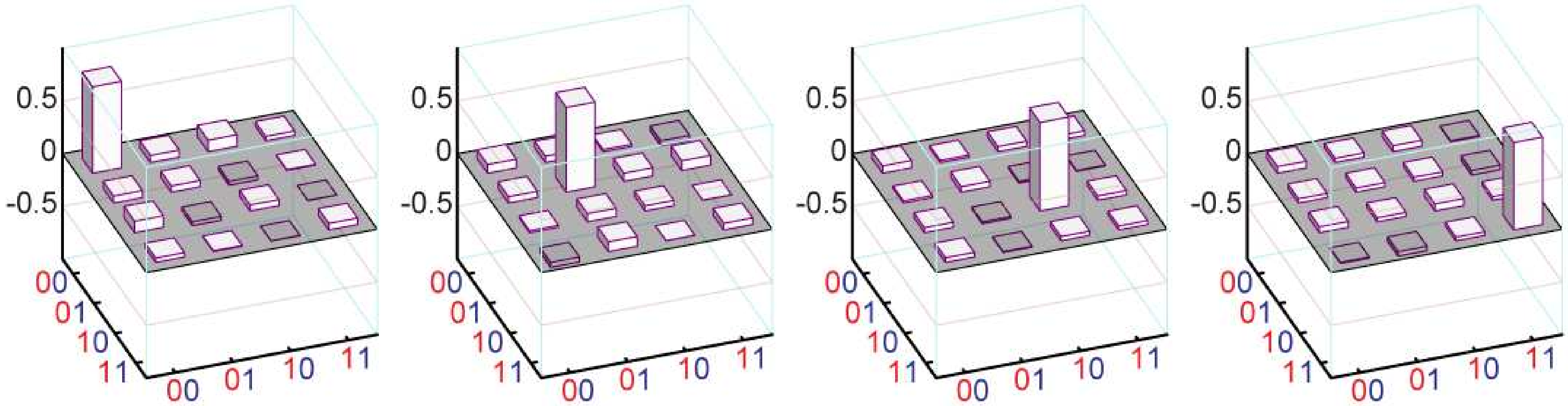
The correct answer is found >**80%** of the time!



Grover with Other Oracles

Oracle

$\hat{O} = cU_{00}$ cU_{01} cU_{10} cU_{11}

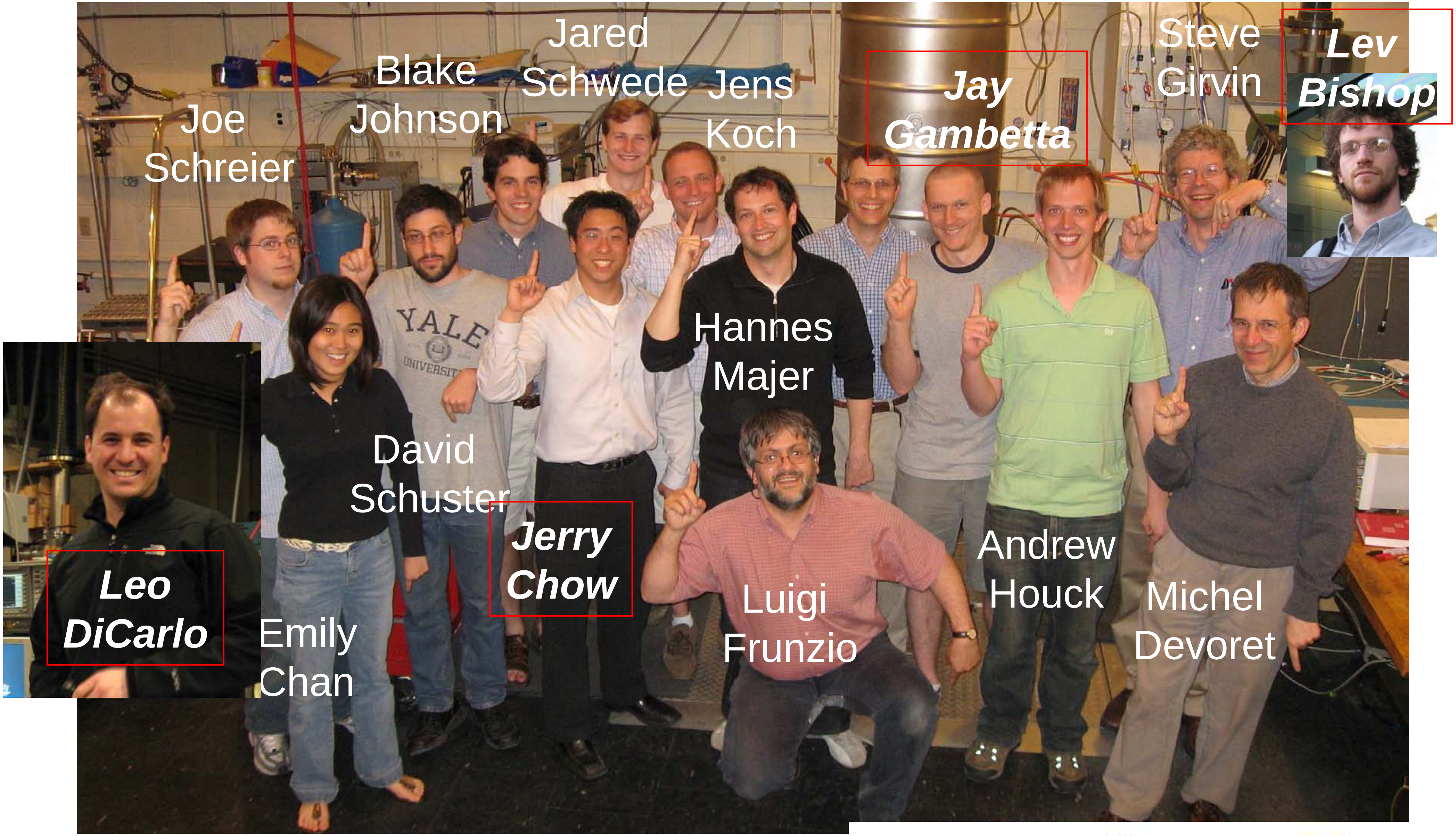


$\overline{F} = 81\%$ 80% 82% 81%

Fidelity $F = \langle \psi_{\text{ideal}} | \rho | \psi_{\text{ideal}} \rangle$ to ideal output

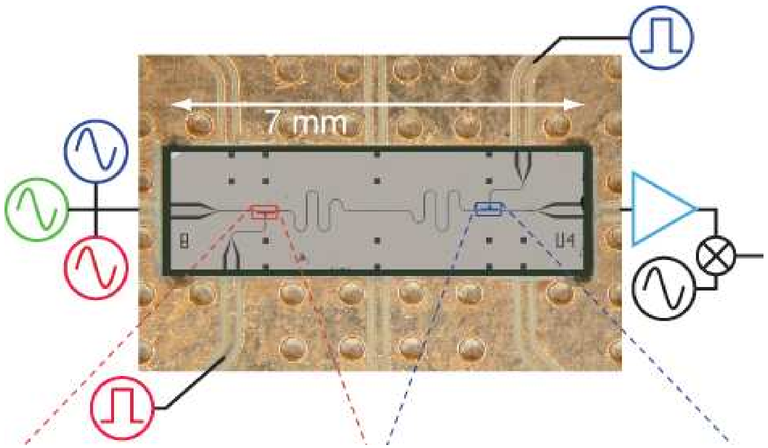
(average over 10 repetitions)

Circuit QED Team Members

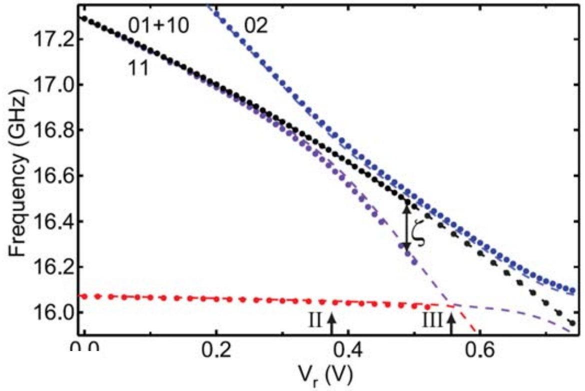


Funding:

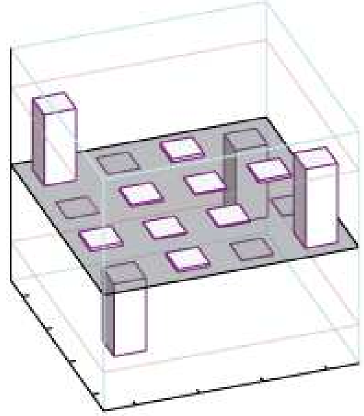
Summary



Rudimentary two-qubit processor



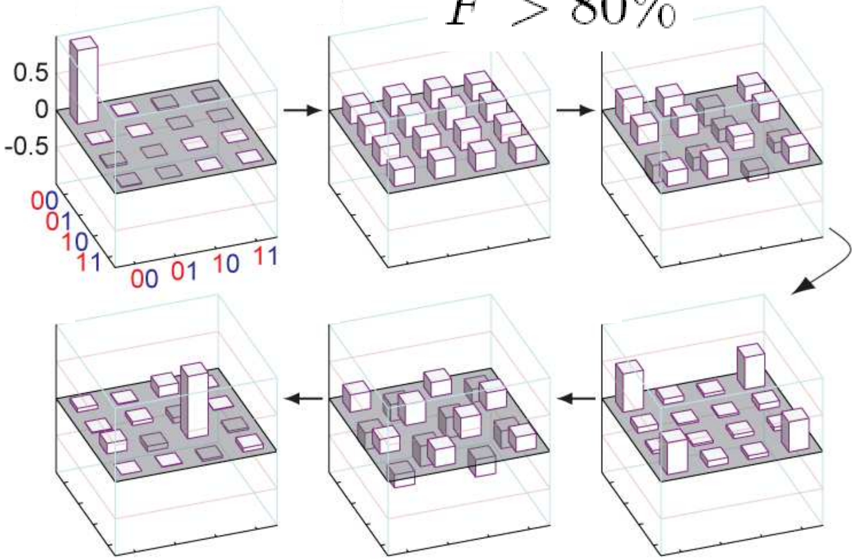
Adiabatic C-phase gate



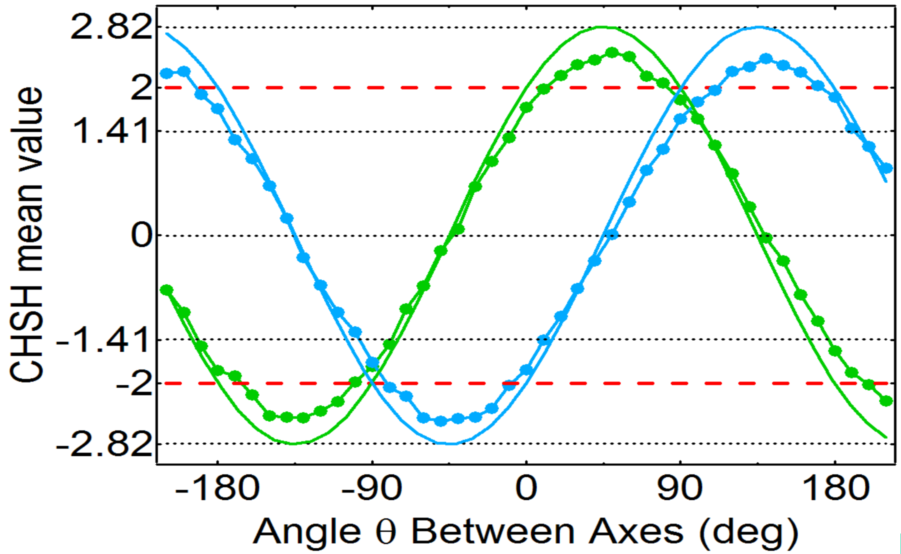
Entanglement on demand

$$F = 87\text{–}94\%$$
$$C = 81\text{–}94\%$$

- Grover algorithm with Fidelity $F > 80\%$



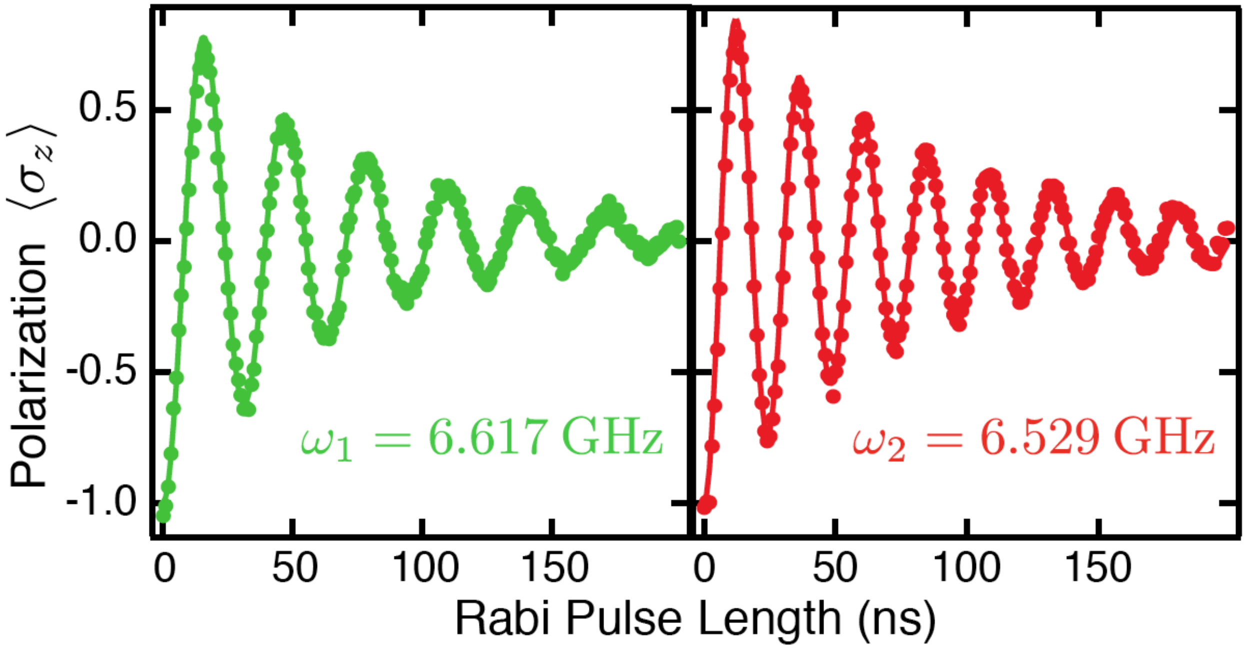
CHSH as entanglement witness



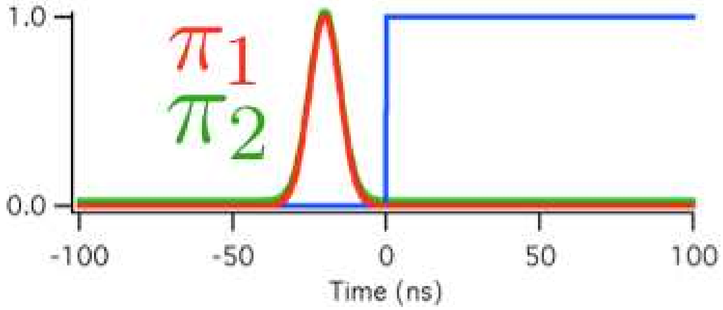
DiCarlo et al., cond-mat 0903.2030, *Nature* in press

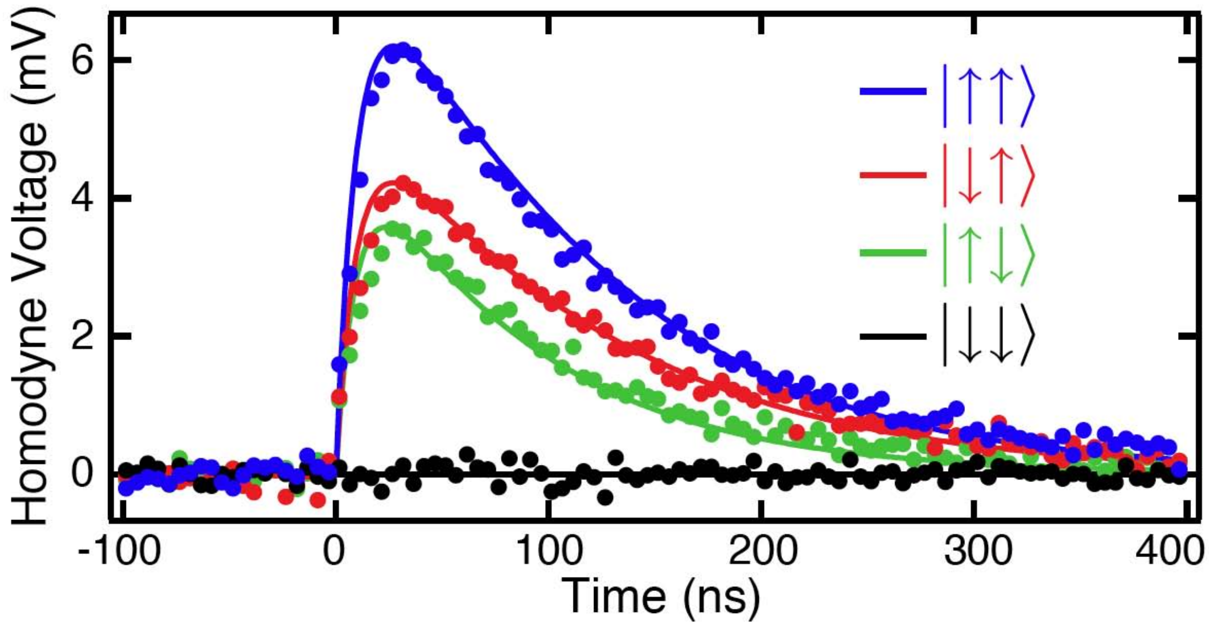
Additional Slides Follow

Multiplexed Qubit Control and Read-Out

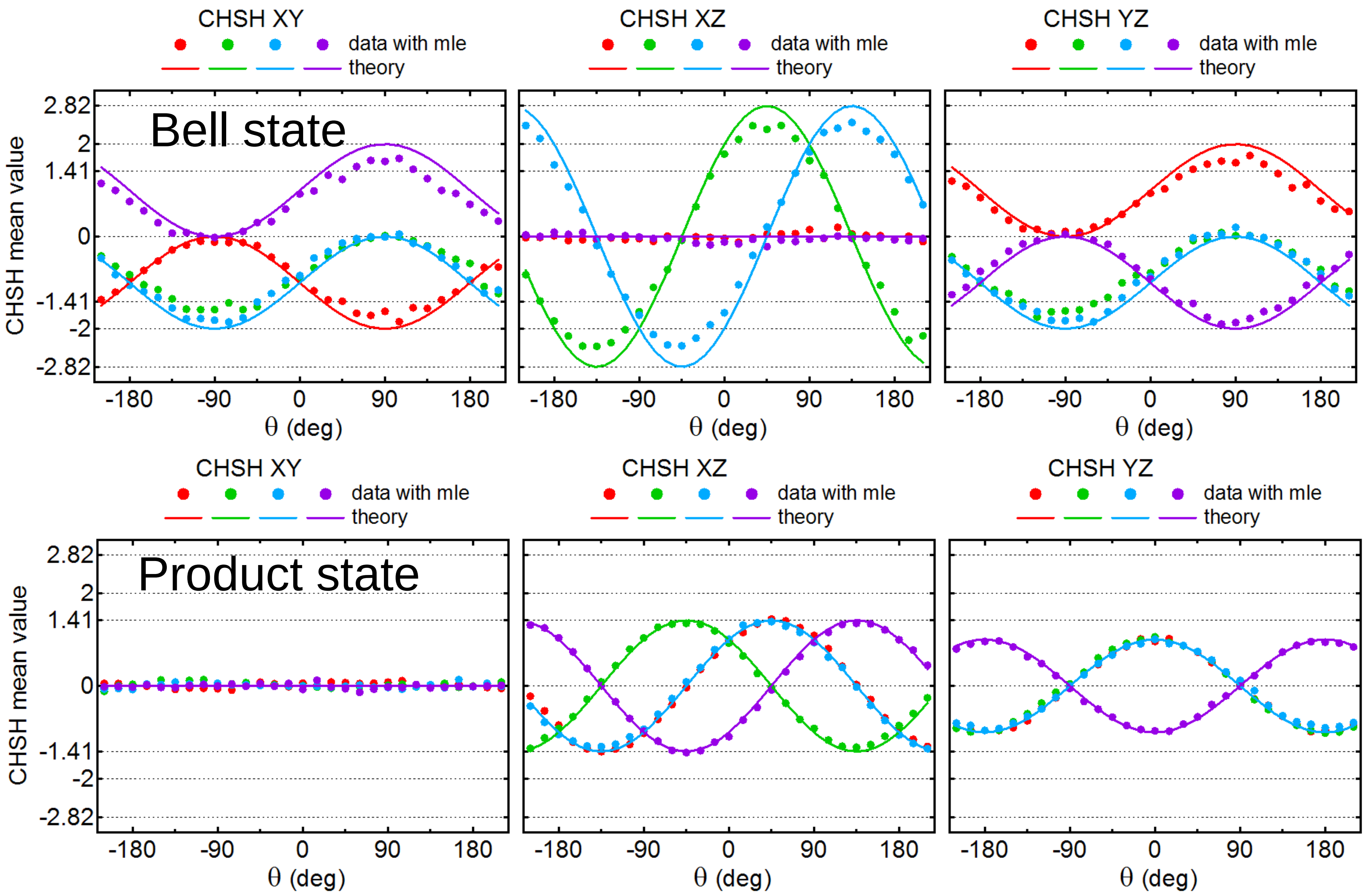


Single Oscillation



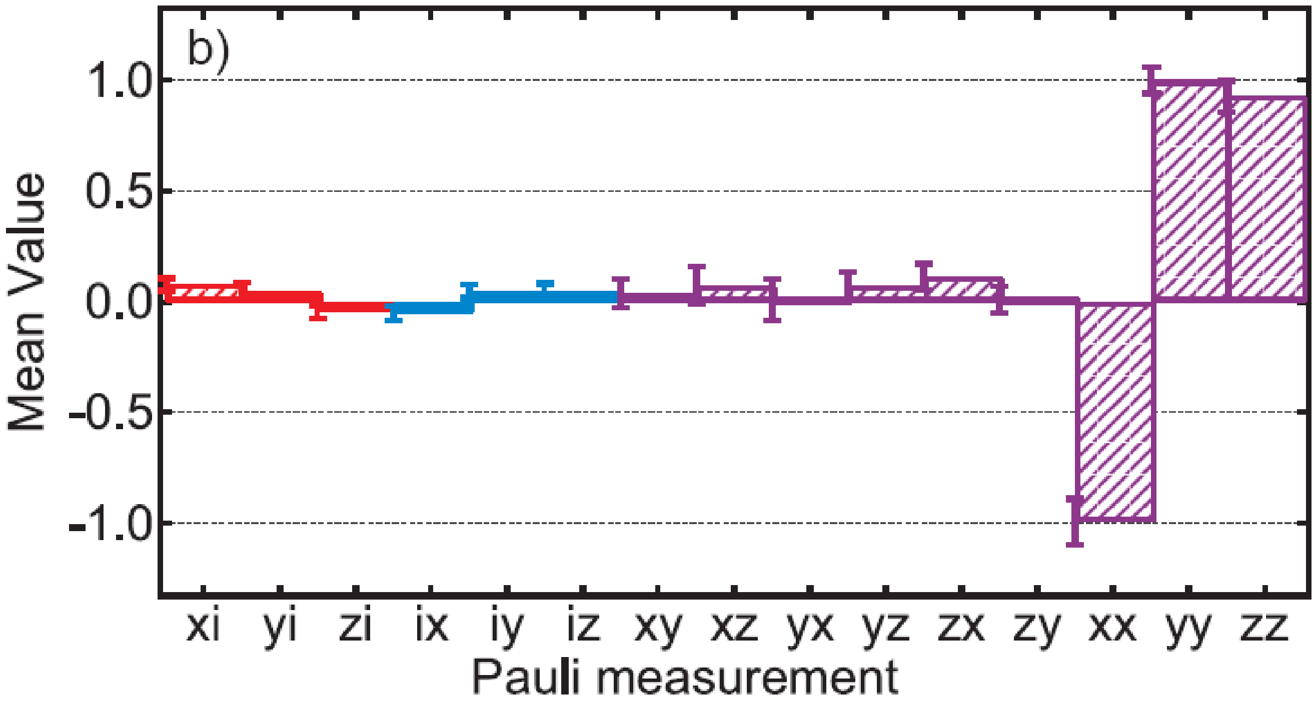


Witnessing Entanglement



Measuring the Two-Qubit State

Now apply a two-qubit gate to entangle the qubits



Concurrence ***directly***:
(for pure states)

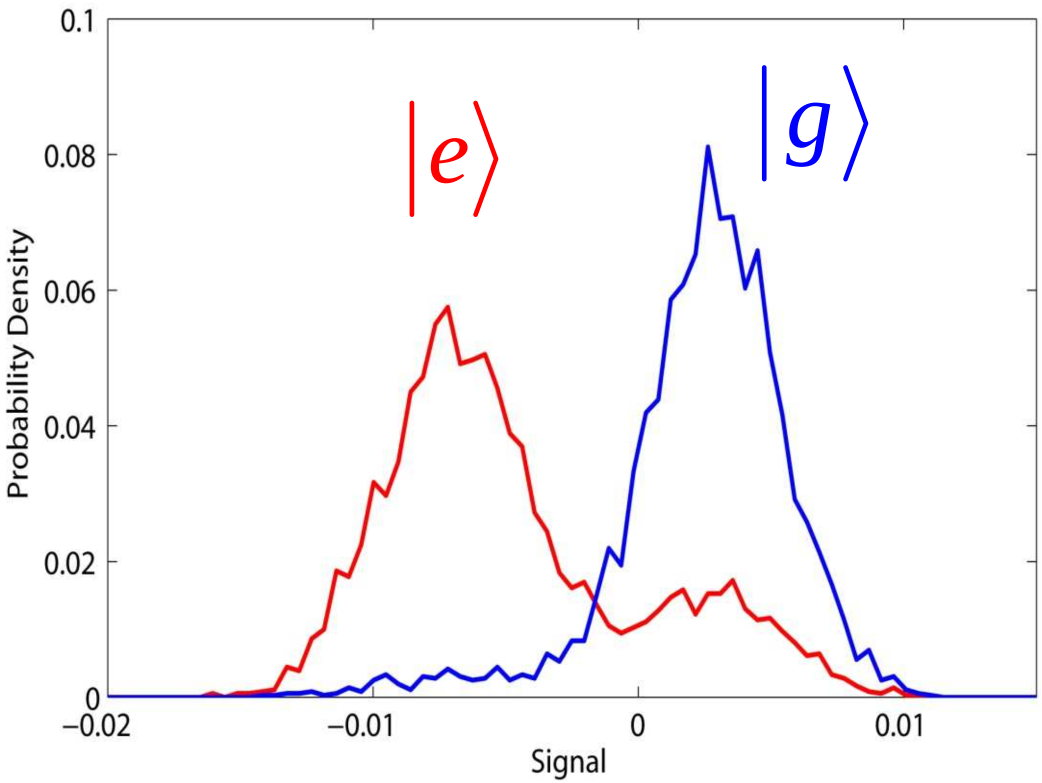
$$C = \sqrt{\frac{Q-1}{2}}$$

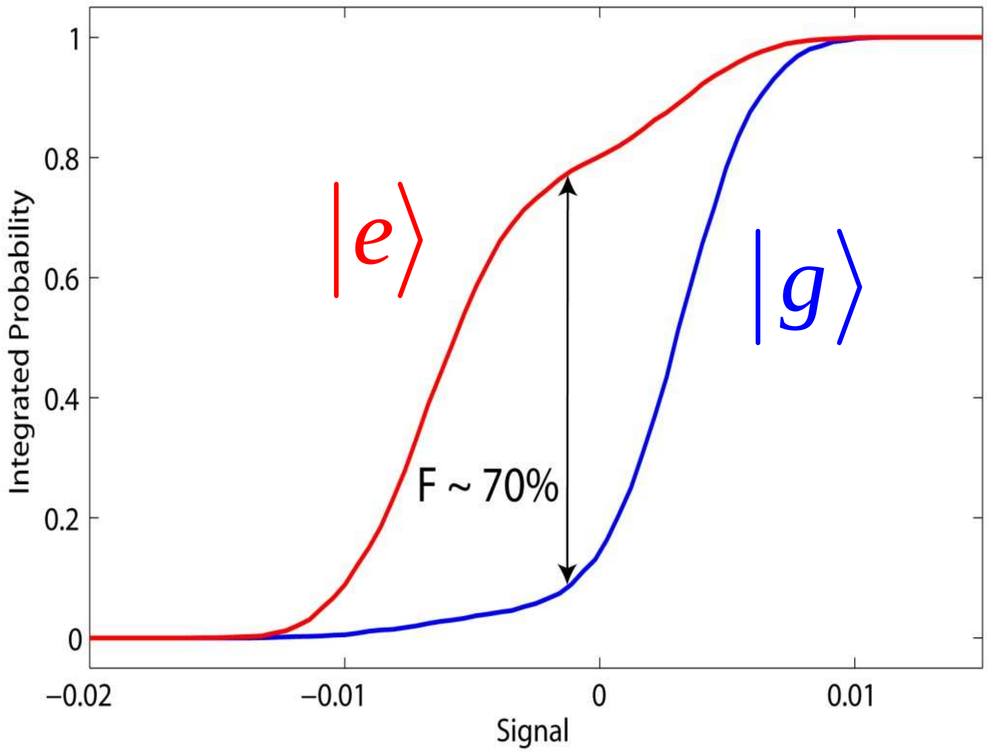
$$Q = \langle XX \rangle^2 + \langle XY \rangle^2 + \langle XZ \rangle^2 + \langle YX \rangle^2 + \langle YY \rangle^2 + \ldots + \langle ZZ \rangle^2$$

Single shot readout fidelity

<u>Histograms of single shot msmts.</u>

<u>Integrated probabilities</u>



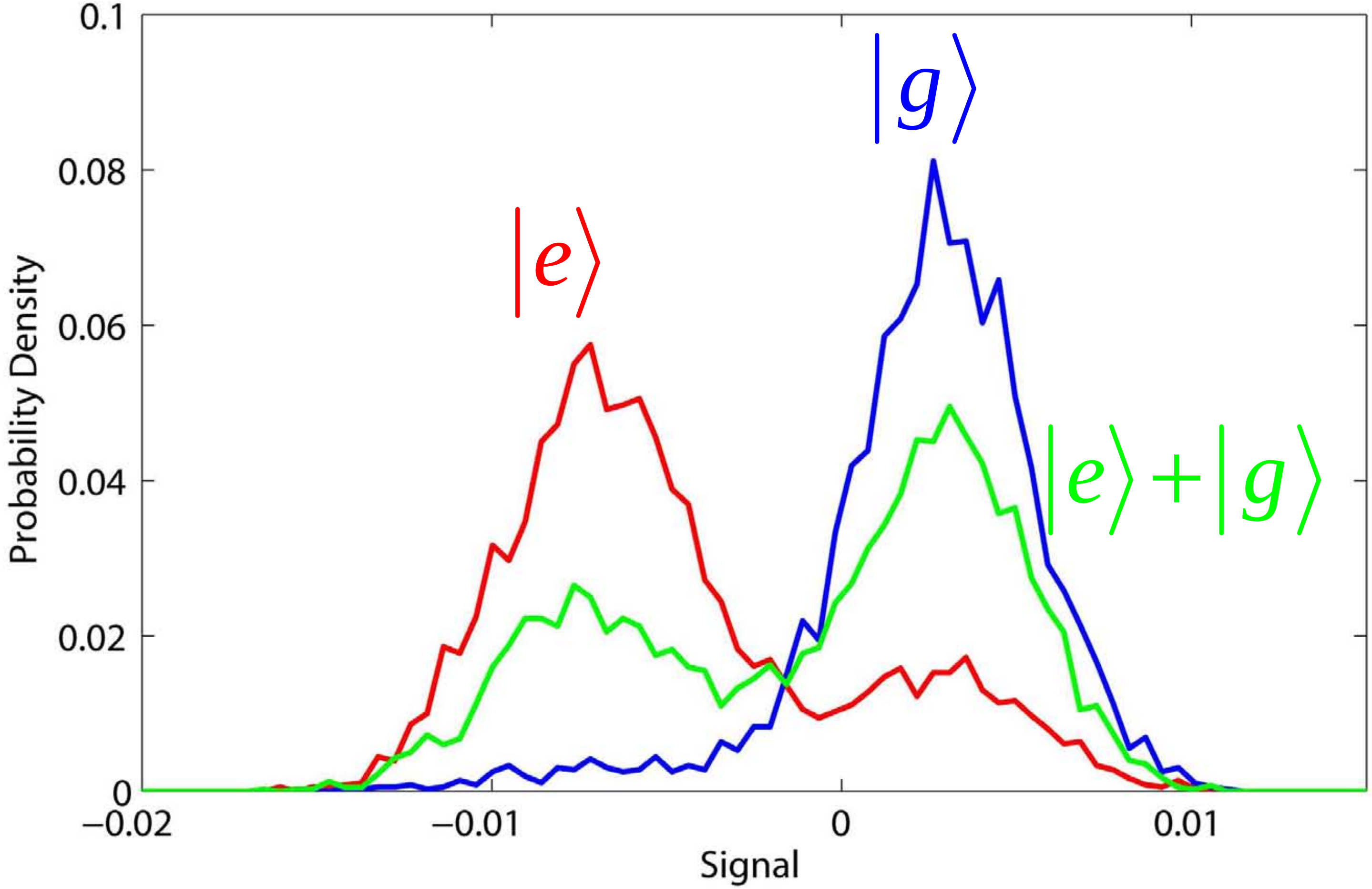


Measurement with ~ 5 photons in cavity;

SNR ~ 4 in one qubit lifetime (T_1)

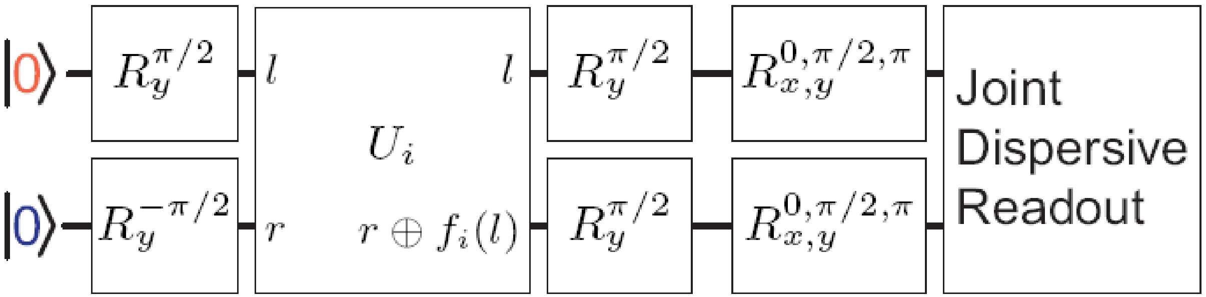
T1 ~ 300 ns, low Q cavity on sapphire

Projective measurement



- Measurement after pi/2 pulse bimodal, halfway between

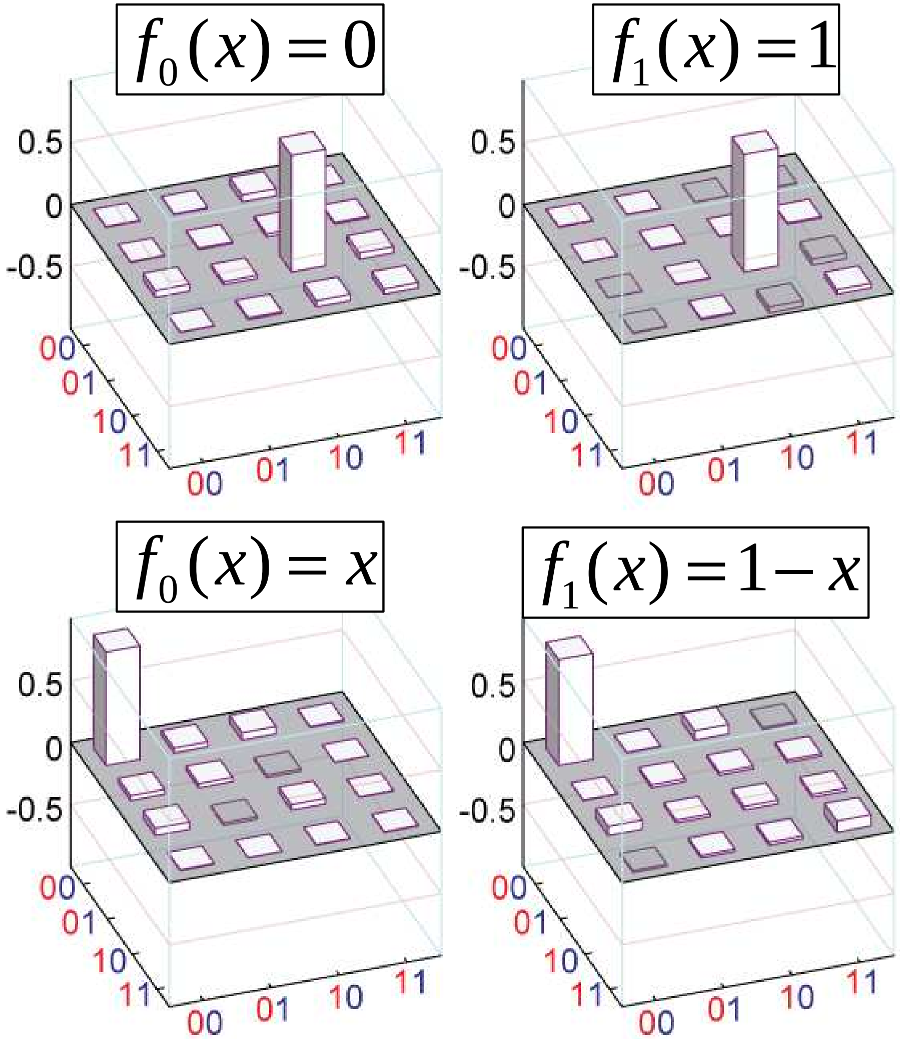
Deutsch-Jozsa Algorithm



Constant functions → $|10\rangle$

Answer is encoded in the state of left qubit

Balanced functions → $|00\rangle$

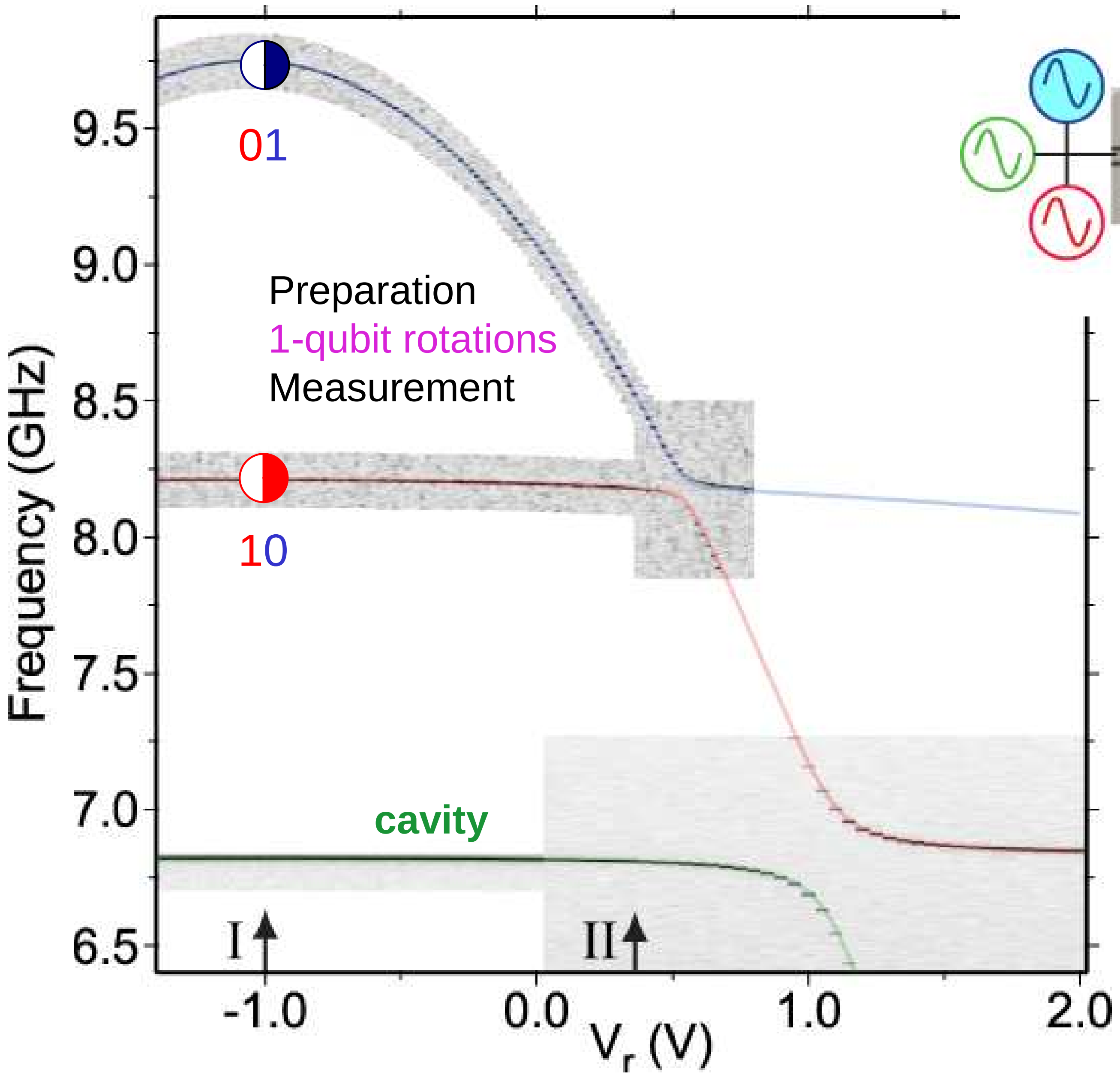


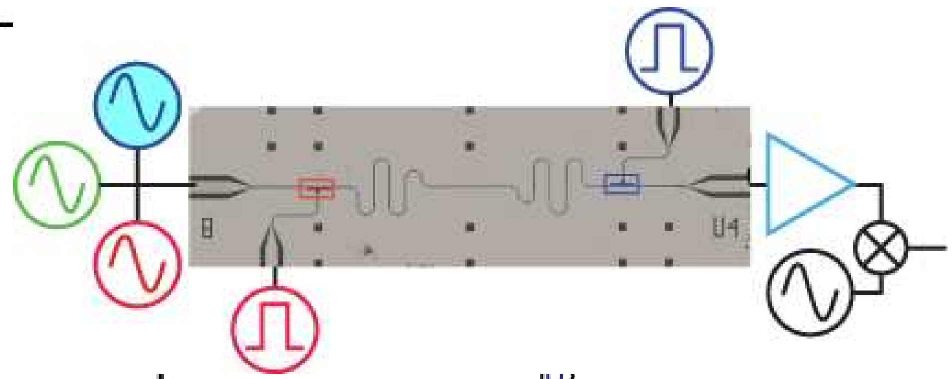
The correct answer is found >**84%** of the time.

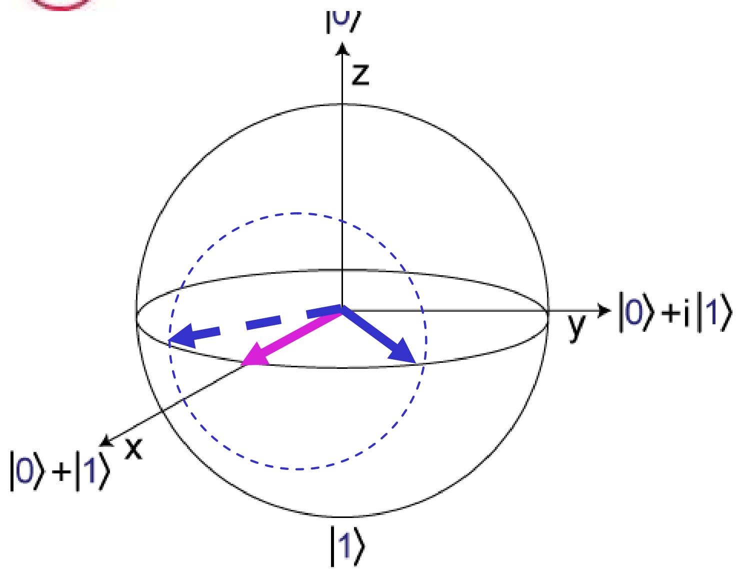
The cost of entanglement

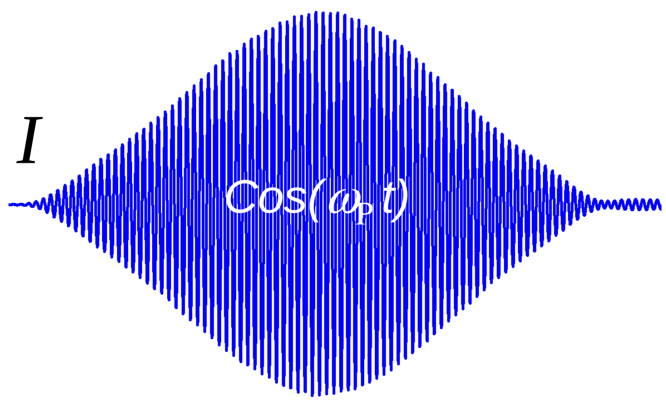
1 Cryogenic HEMT amp
2 Room Temp Amps
1 Two-channel digitizer
1 Two-channel AWG
1 Four-channel AWG
2 Scalar signal generators
2 Vector signal generators
1 Low-frequency generator
1 Rubidium frequency standard
2 Yokogawa DC sources
1 DC power supply
1 Amp biasing servo
1 Computer
10^3 Coffee pods

One-Qubit Gates



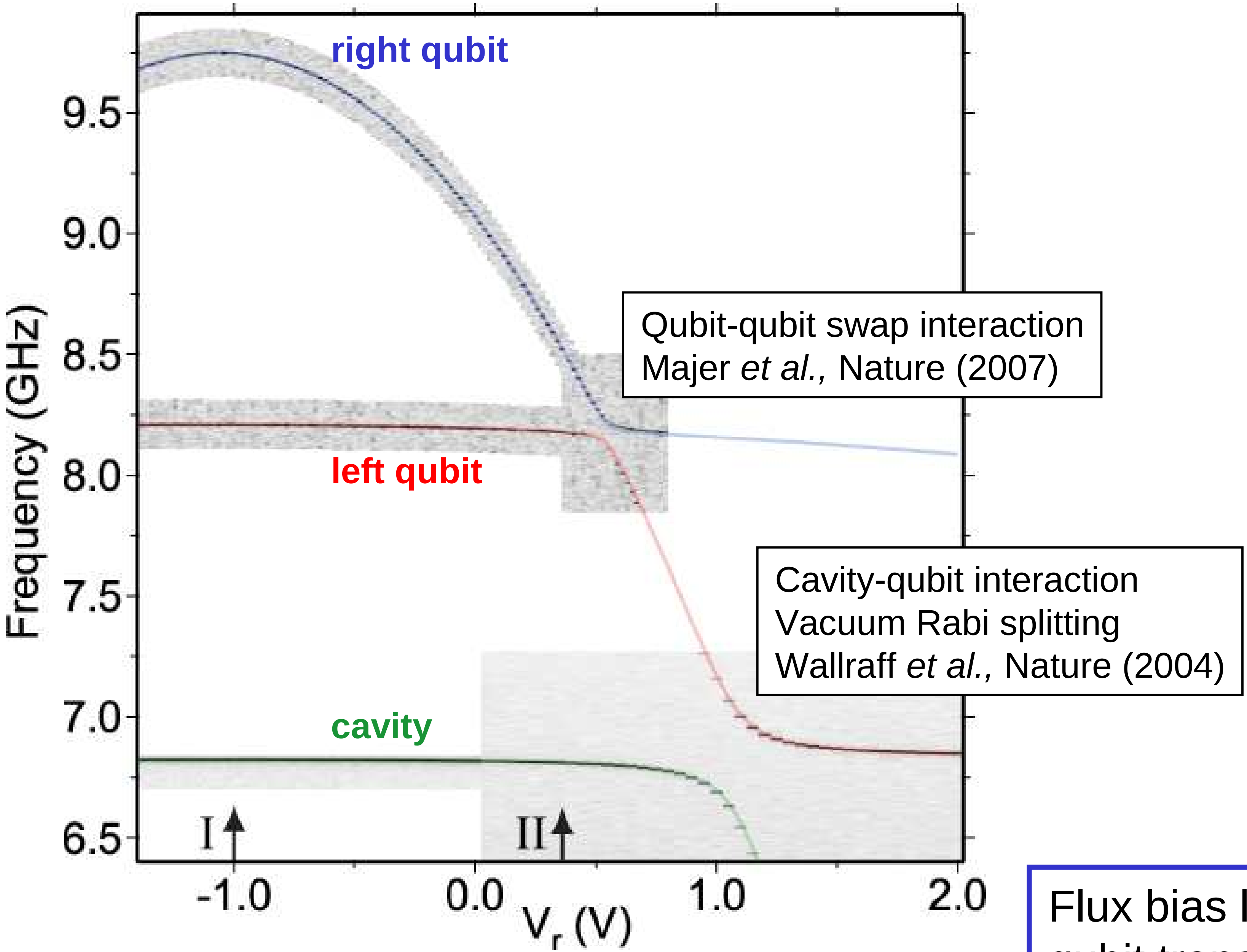






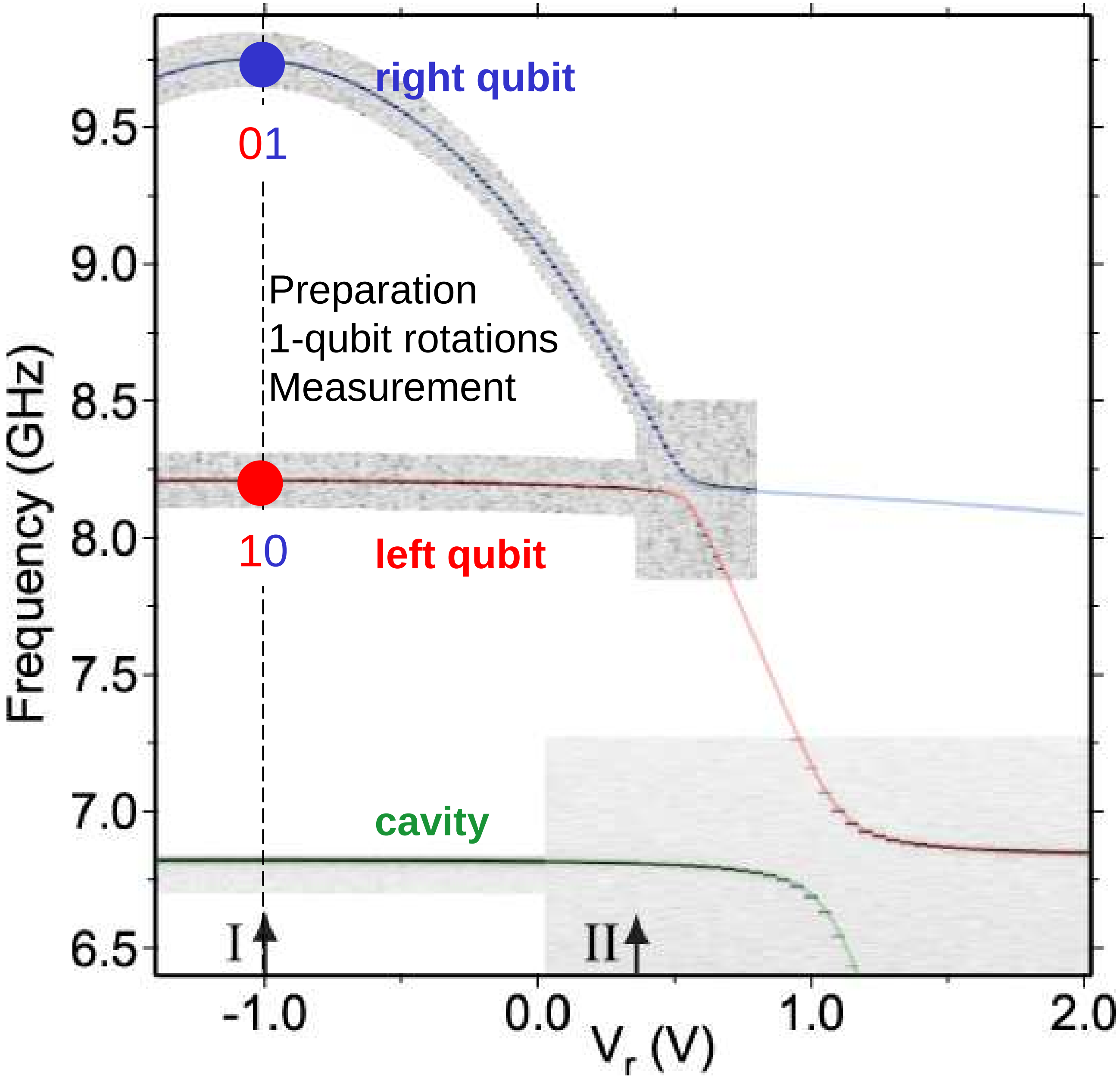
Apply microwave pulse resonant with qubit

Spectroscopy of Qubits Interacting with Cavity



Flux bias line controls qubit transition frequency

Spectroscopy of Qubits Interacting with Cavity

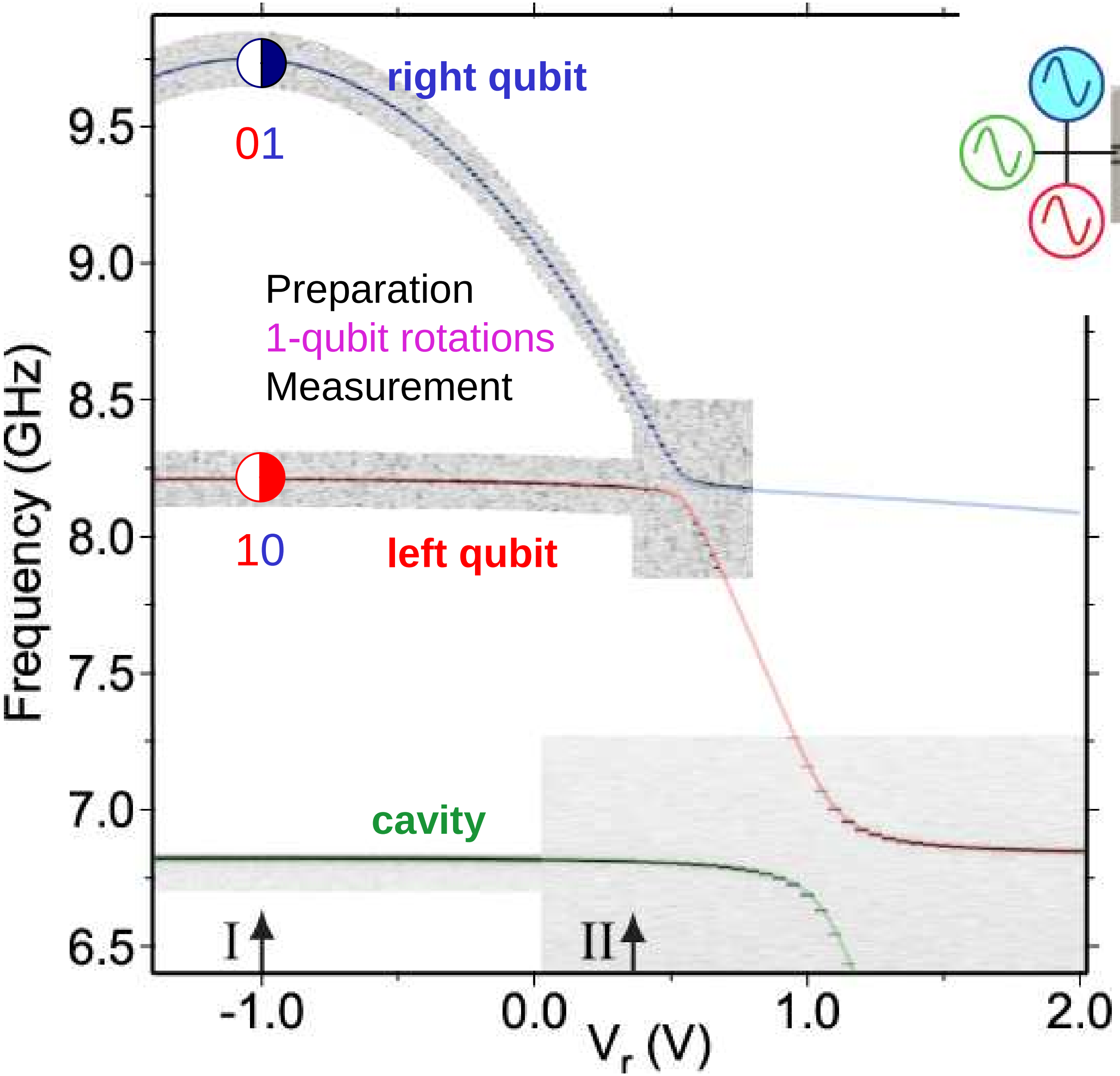


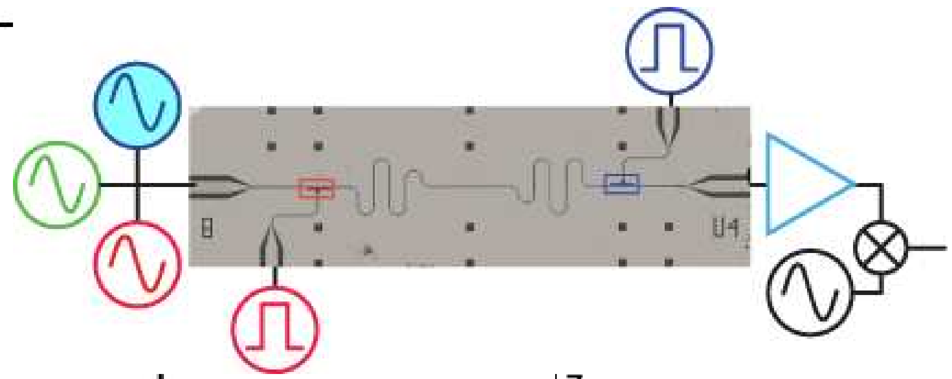
Qubits mostly separated
and non-interacting
due to frequency difference

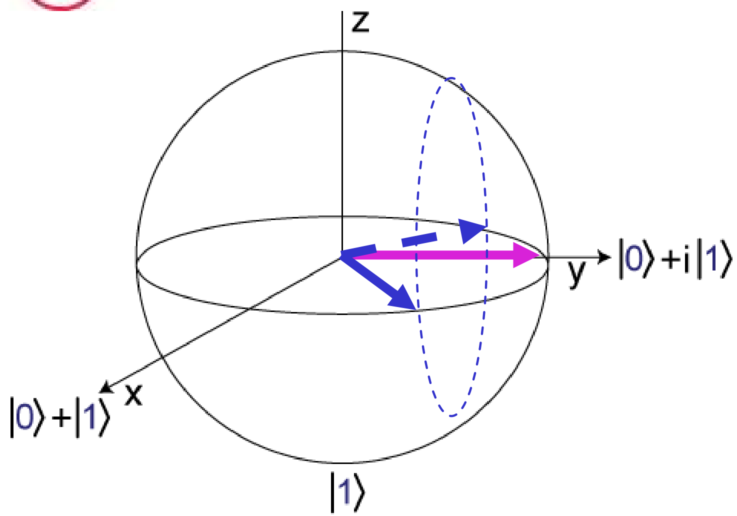
$$T_{1,\mathrm{r}} = 0.79\,\mu\mathrm{s}$$
$$T_{2,\mathrm{r}}^{*} = 1.15\,\mu\mathrm{s}$$

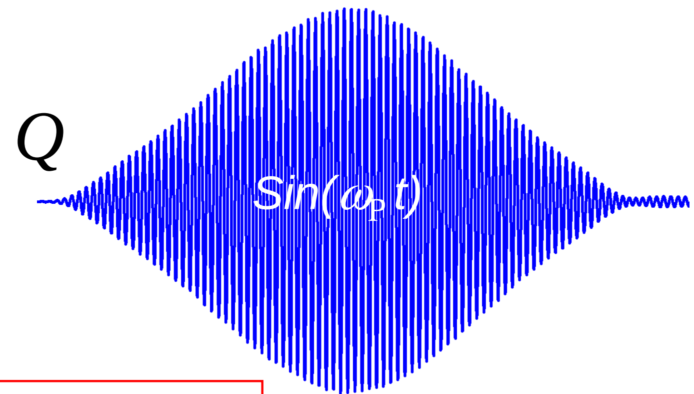
$$T_{1,\mathrm{l}} = 1.3\,\mu\mathrm{s}$$
$$T_{2,\mathrm{l}}^{*} = 1.8\,\mu\mathrm{s}$$

One-Qubit Gates





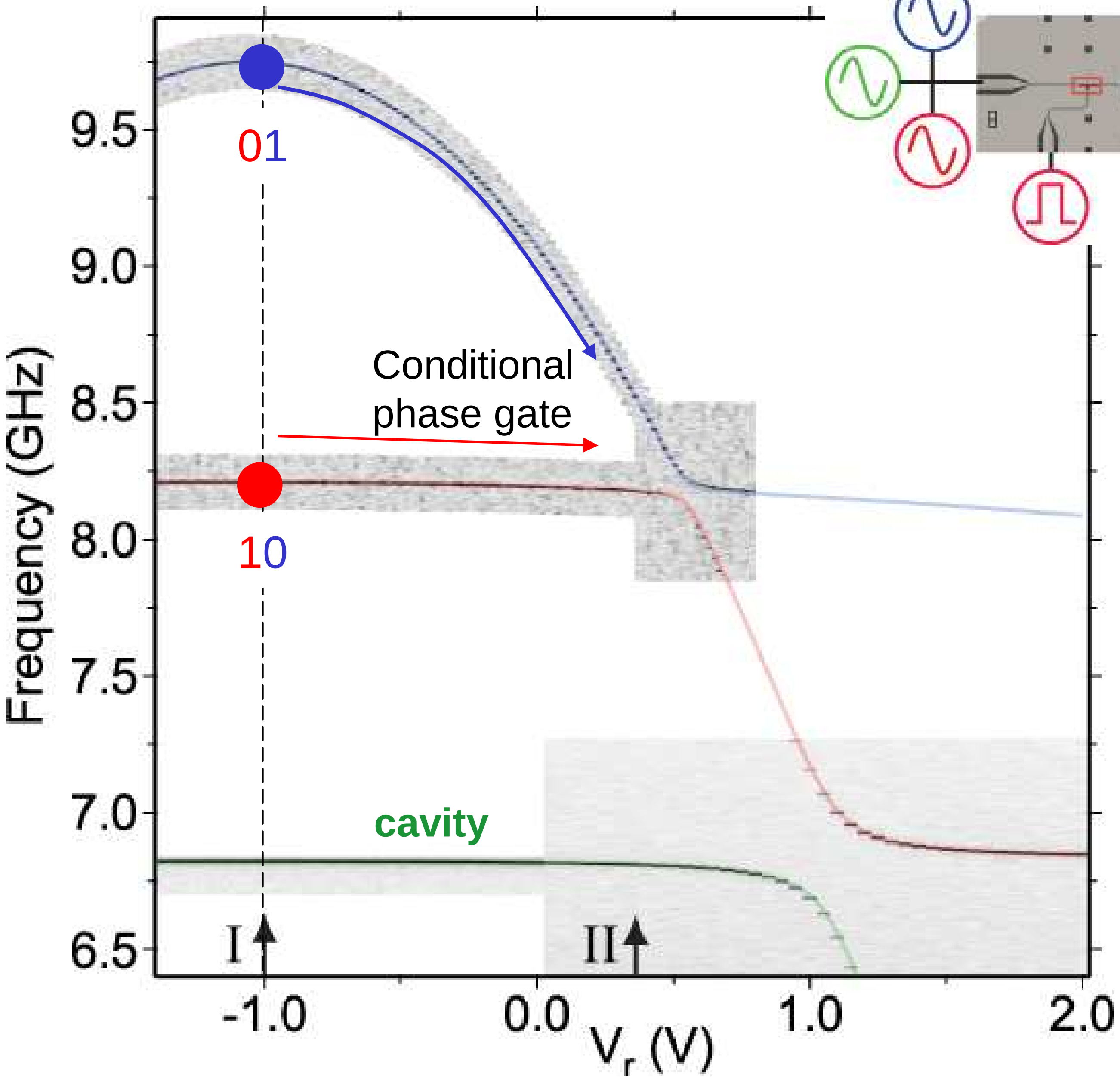


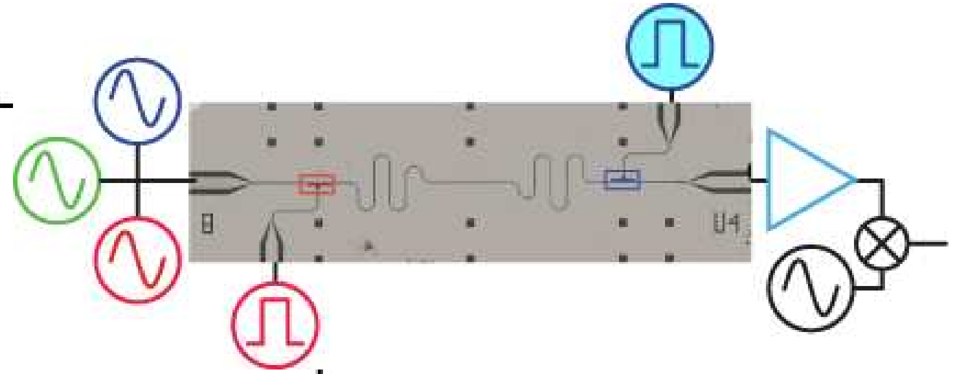


J. Chow *et al.*, PRL (2009):

Fidelity = 99%

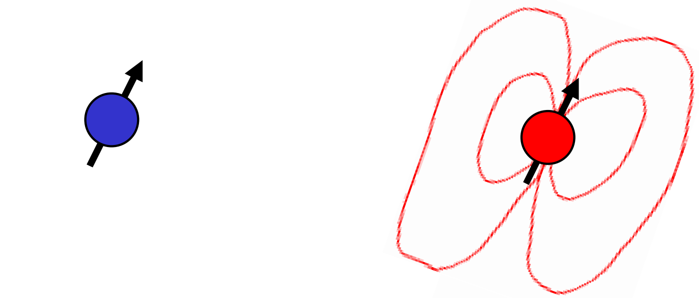
Two-Qubit Gate: Turn On Interactions

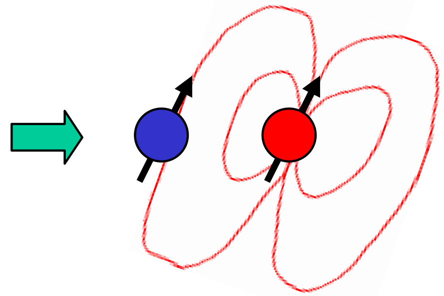




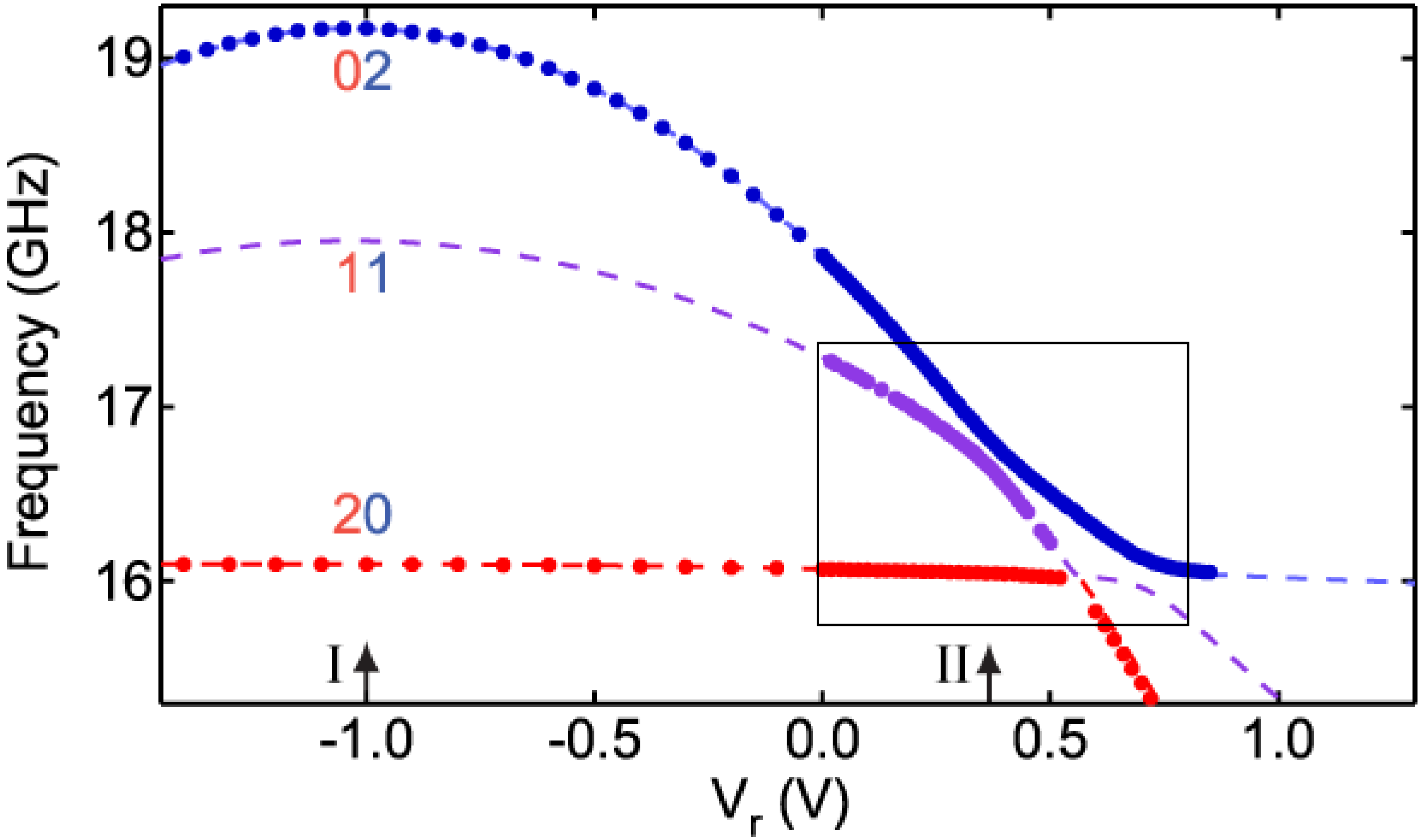
Use control lines to push qubits near a resonance:

A controlled z-z interaction also ala NMR



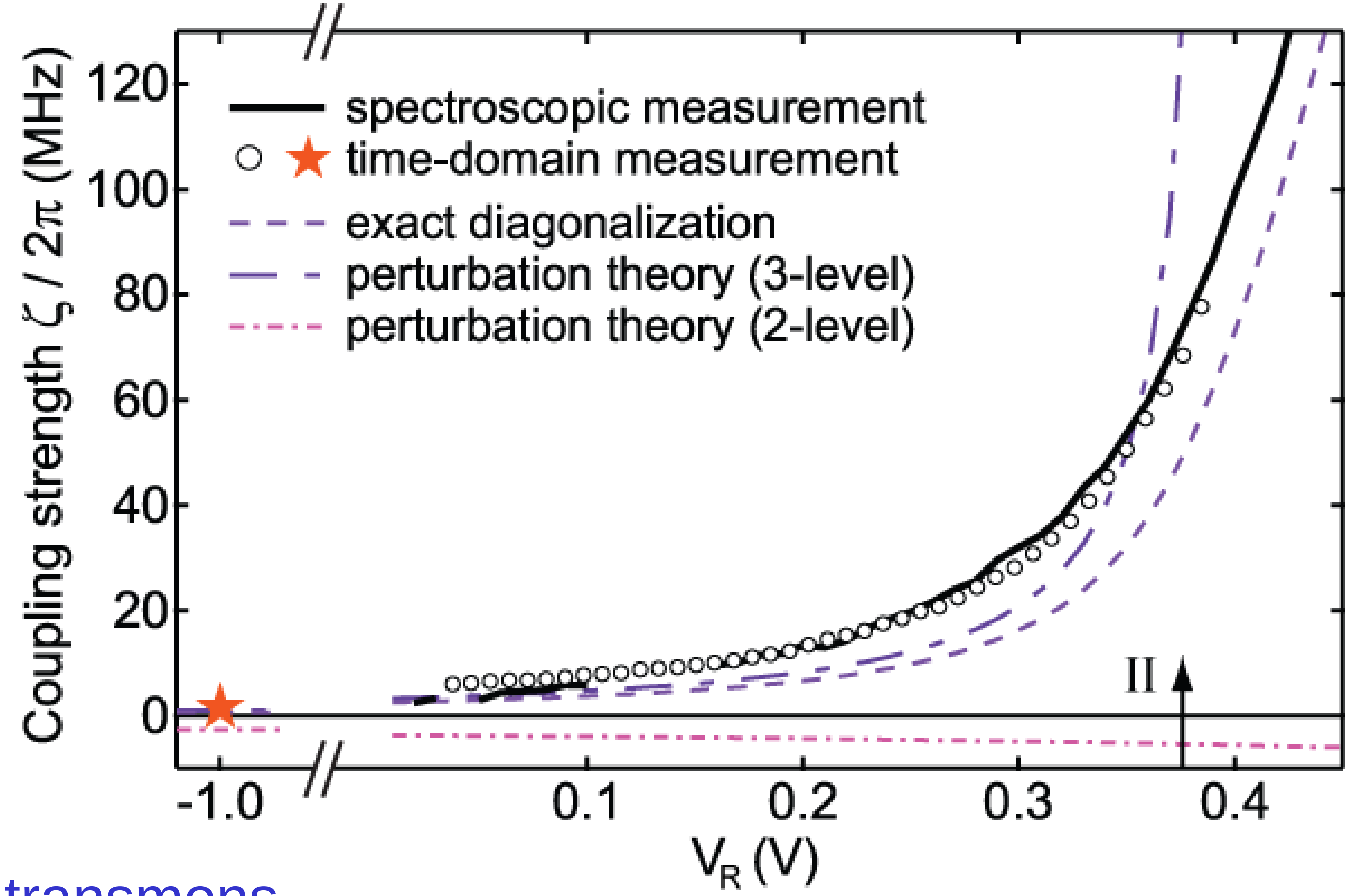


Two-Excitation Manifold of System



"Qubits" and cavity both have multiple levels…

On/Off Ratio for Two-Qubit Coupling



← > 100 MHz

← 1 MHz

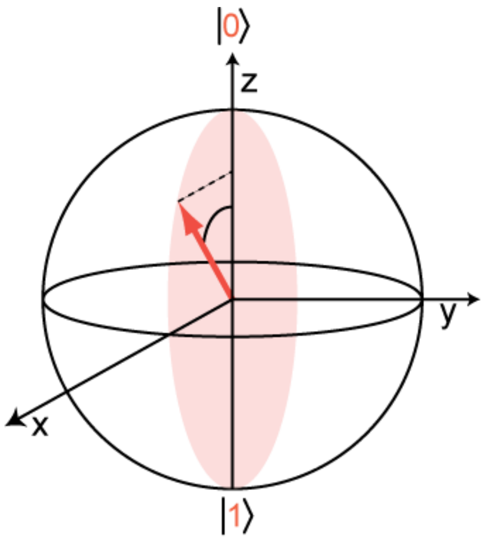
3-level transmons

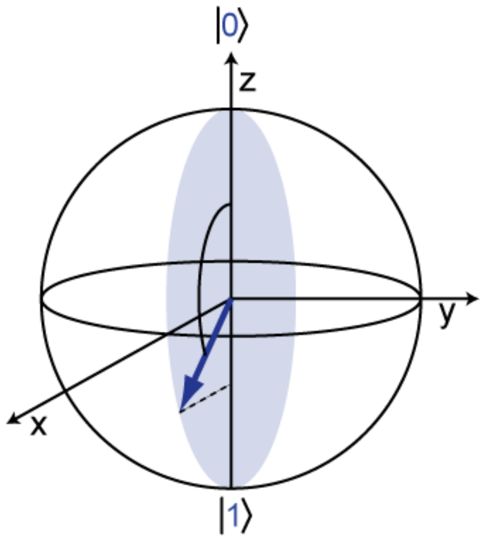
$$\zeta = -2g_L^2 g_R^2 \left(\frac{1}{(\omega_{01}^L - \omega_C)(\omega_{01}^R - \omega_C)^2} + \frac{1}{(\omega_{01}^R - \omega_C)(\omega_{01}^L - \omega_C)^2} + \frac{1}{(\omega_{01}^R - \omega_{12}^L)(\omega_{01}^L - \omega_C)^2} + \frac{1}{(\omega_{01}^L - \omega_{12}^R)(\omega_{01}^R - \omega_C)^2} \right)$$

Diverges at Point II

4th-order in qubit-cavity coupling!

State Tomography





$$V_{\mathrm{H}} \sim \langle M \rangle = \beta_1 \langle \sigma_z^{\mathrm{L}} \rangle + \beta_2 \langle \sigma_z^{\mathrm{R}} \rangle + \beta_{12} \langle \sigma_z^{\mathrm{L}} \otimes \sigma_z^{\mathrm{R}} \rangle$$

Combine joint readout with one-qubit "analysis" rotations

$$\langle \sigma_z^{\mathrm{L}} \rangle \sim V_H(Ident.) + V_H(Y_\pi^R) \longleftarrow$$ π-pulse on right

$$\langle \sigma_z^{\mathrm{R}} \rangle \sim V_H(Ident.) + V_H(Y_\pi^L) \longleftarrow$$ π-pulse on left

$$\langle \sigma_z^{\mathrm{L}} \sigma_z^{\mathrm{R}} \rangle \sim V_H(Ident.) + V_H(Y_\pi^R, Y_\pi^L) \longleftarrow$$ π on both

Possible to acquire correlation info.,
even with single, ensemble averaged msmt.!

See similar from Zurich group: Fillip et al., PRL **102**, 200402 (2009).

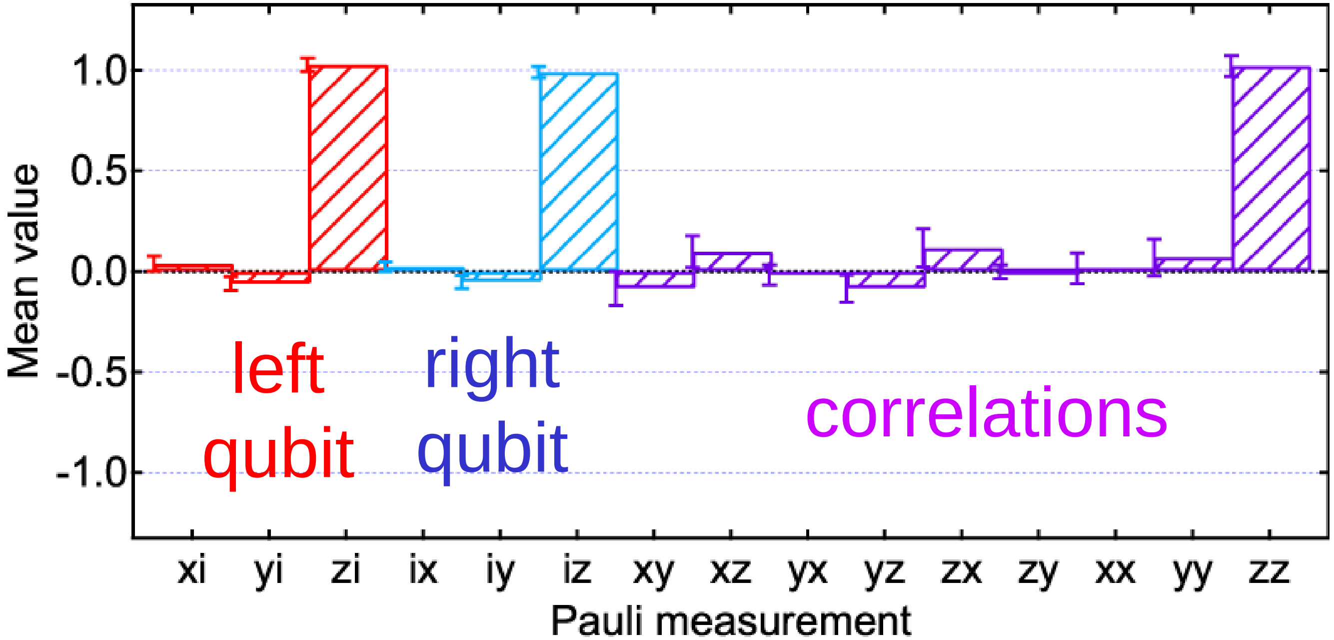
Measuring the Two-Qubit State

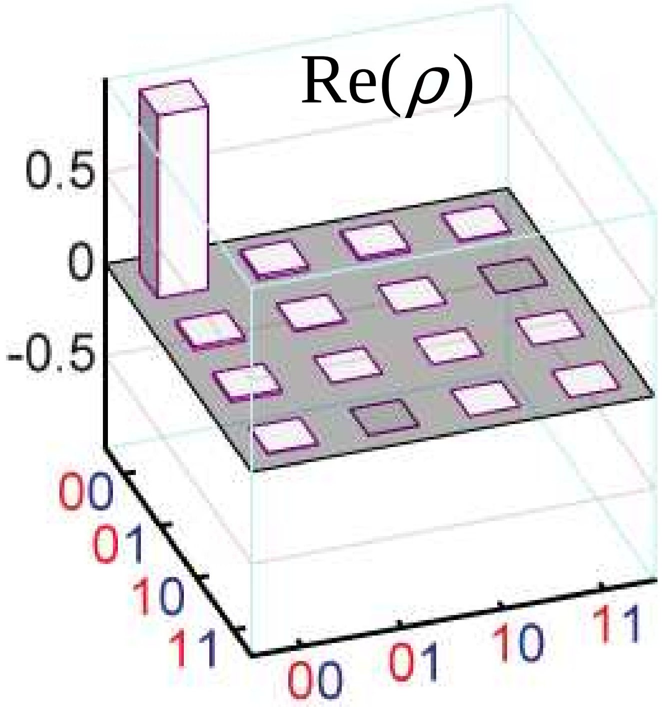
Total of 16 msmts.: $I, Y_{\pi}^{L}, X_{\pi/2}^{L}, Y_{\pi/2}^{L}$ and combinations

$I, Y_{\pi}^{R}, X_{\pi/2}^{R}, Y_{\pi/2}^{R}$

max. likelihood (nonlinear!)

(almost) raw data



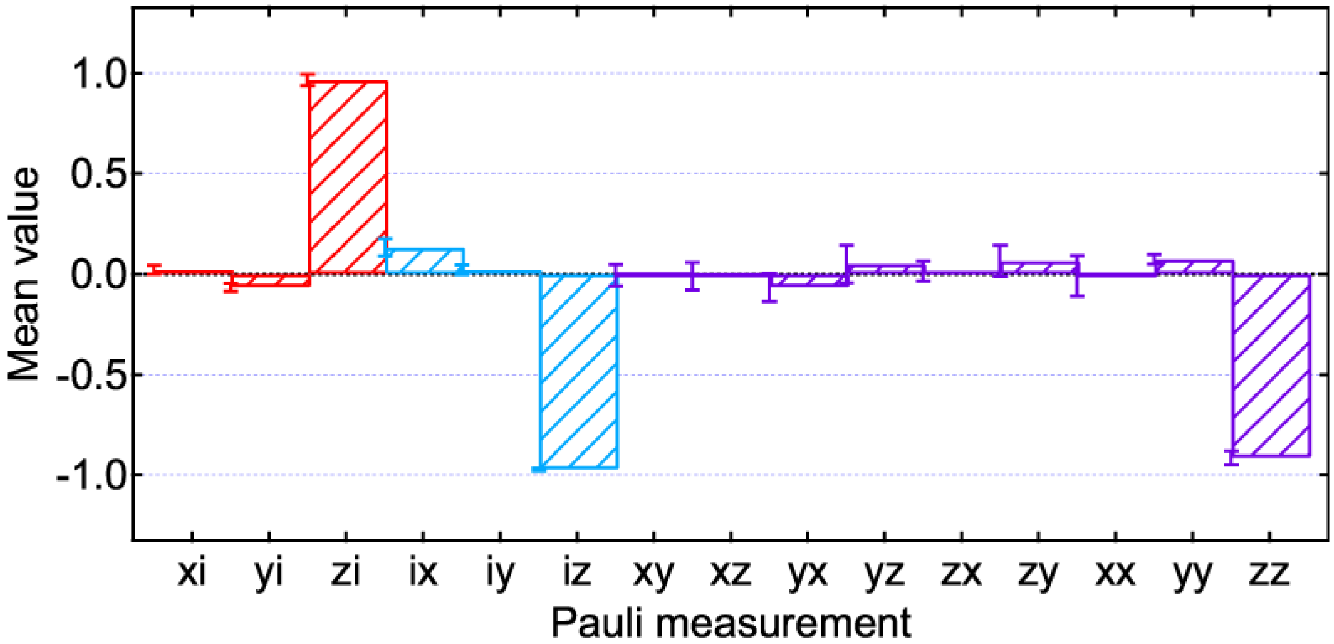


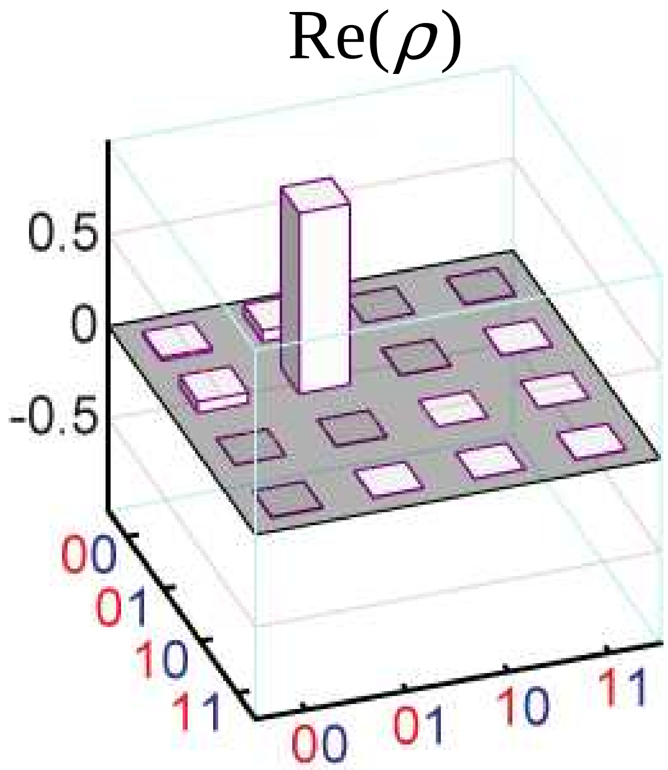
Density matrix

Ground state: $|\psi\rangle = |00\rangle$

Measuring the Two-Qubit State

Apply π-pulse to invert state of right qubit



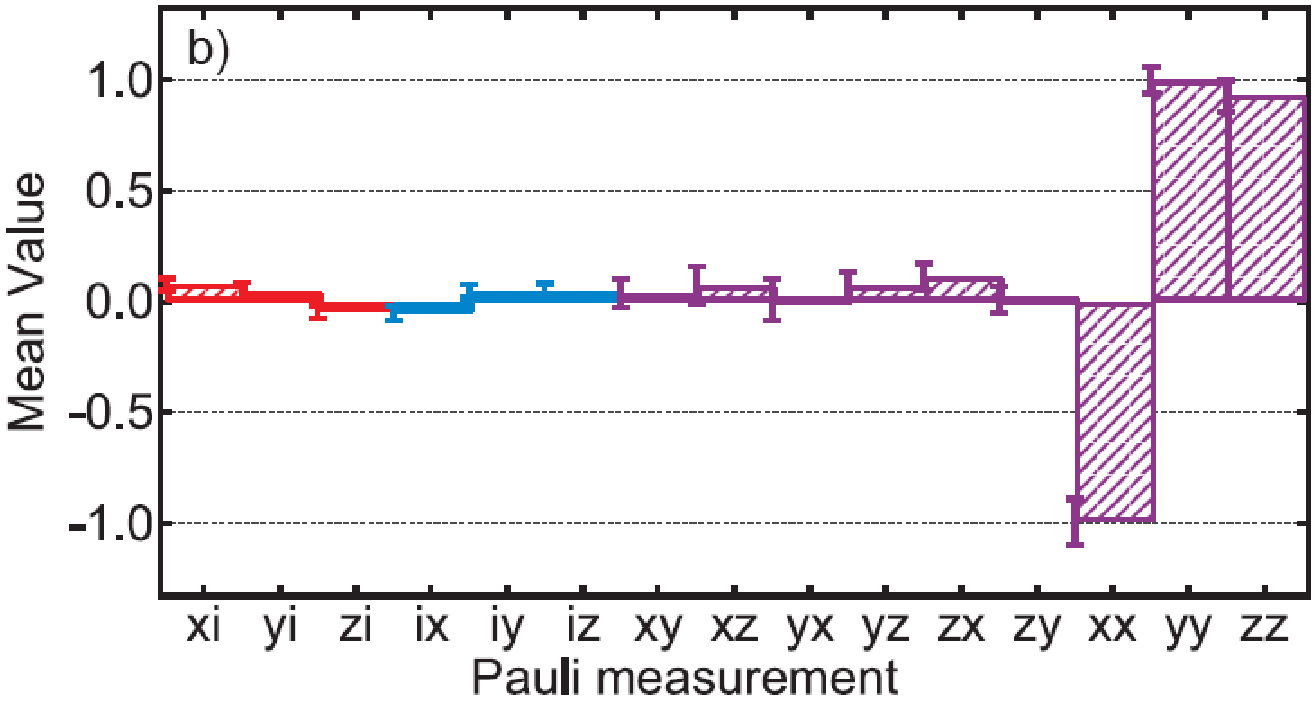


One qubit excited: $|\psi\rangle = |01\rangle$

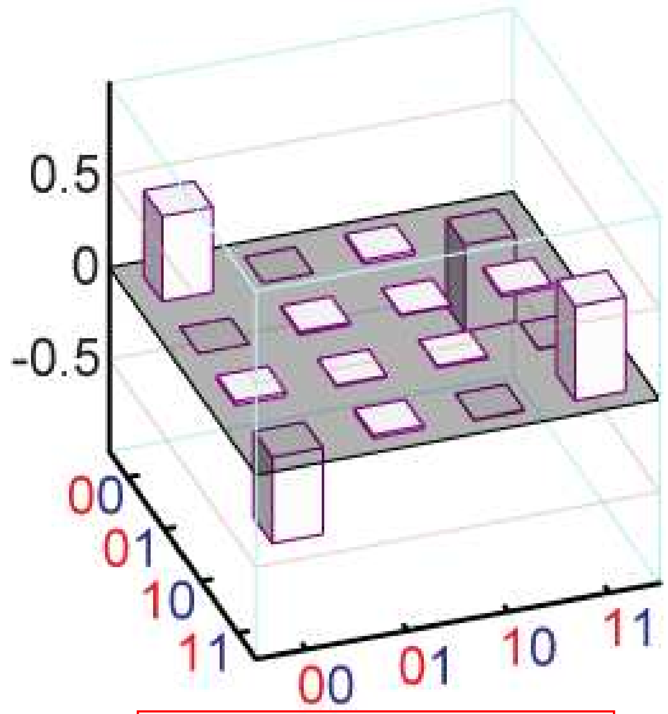
Measuring the Two-Qubit State

Now apply a two-qubit gate to *entangle* the qubits

Entangled state: $|\psi\rangle = \frac{1}{\sqrt{2}}\left(|00\rangle - |11\rangle\right)$



$\mathrm{Re}(\rho)$



C = 0.94 +-??

"Concurrence":

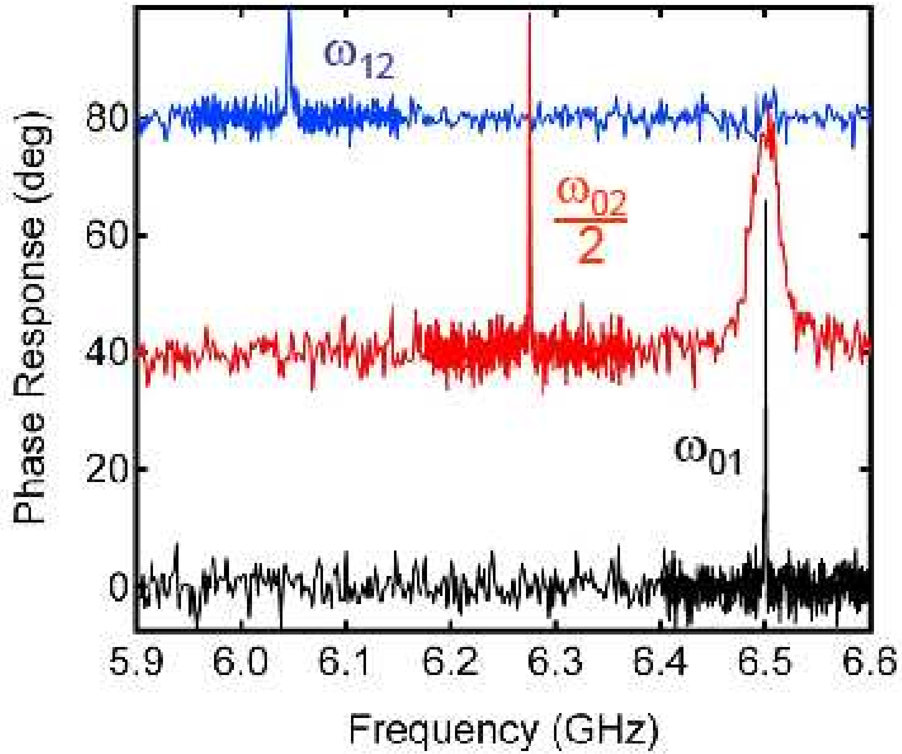
$$C(\rho) = \max\{0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4\}$$

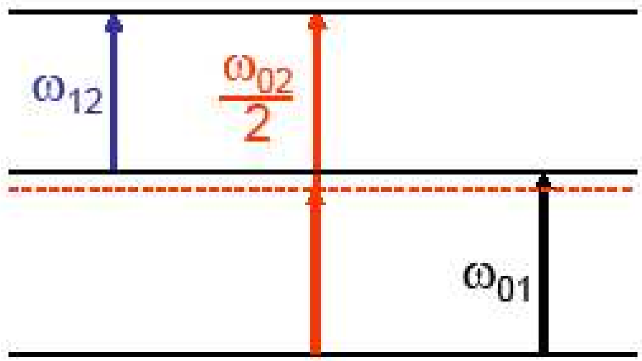
What's the entanglement metric?

λ are e-values of $\sqrt{\rho\tilde{\rho}}$

SPECTROSCOPY OF A JOSEPHSON ATOM

J. Schreier et al., Phys. Rev. B '08





Microwave pulses at ω_{01} can be used for single qubit rotations.

Anharmonicity:

$$\omega_{01} - \omega_{12} = 455\text{MHz} \simeq E_C$$

Sufficient to control the artificial atom as a two level system: Qubit

Slide courtesy of J. Schreier and R. Schoelkopf