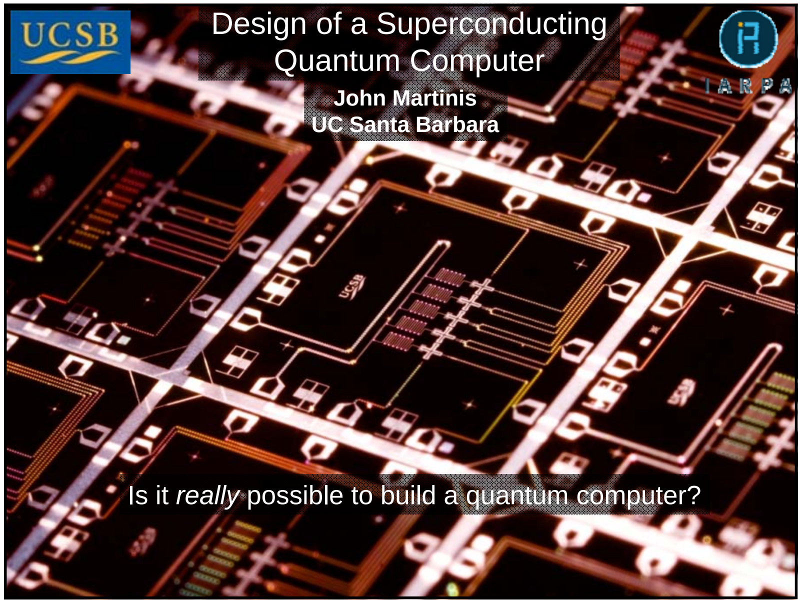
John Martinis : Suggested Reading

1) Overview of basic qubit physics
   Implementing Qubits with
   Superconducting Integrated Circuits
   Michel H. Devoret and John M. Martinis
   Quantum Information Processing **vol. 3**. (2004)

2) Recent review by Yale group
   Superconducting Circuits for Quantum Information: An Outlook
   M. H. Devoret and R. J. Schoelkopf
   Science **339**, 1169 (2013);

3) Architecture for a quantum computer
   Surface codes: Towards practical large-scale
   quantum computation
   Austin G. Fowler, Matteo Mariantoni,
   John M. Martinis, Andrew N. Cleland
   PRA **86**, 032324 (2012)



UCSB

Design of a Superconducting Quantum Computer

John Martinis
UC Santa Barbara

IARPA

Is it *really* possible to build a quantum computer?

Outline

1) Exponential computing power

2) Hardware Requirements

3) Review of qubit physics: Bloch sphere

4) Need for fault-tolerant computation

5) Surface code theory
   error-correction and architecture

6) Xmon superconducting qubits
   integrated circuits for scaling
   above fidelity threshold

Exponential Computation Power

- Classical computation power scales linearly:
  speed (GHz), size (RAM Mbytes), number processors

★ **1 GHz**
★★ **2 GHz**
★★★★ **2 GHz, Dual Processor**

- Quantum computer scales exponentially!

qubit 1 qubit 2 qubit 3

$$(|0\rangle+|1\rangle)(|0\rangle+|1\rangle)(|0\rangle+|1\rangle)$$

$$=|0\rangle|0\rangle|0\rangle+|0\rangle|0\rangle|1\rangle+|0\rangle|1\rangle|0\rangle+|0\rangle|1\rangle|1\rangle+|1\rangle|0\rangle|0\rangle+|1\rangle|0\rangle|1\rangle+|1\rangle|1\rangle|0\rangle+|1\rangle|1\rangle|1\rangle$$

3 qubits :
parallel processing of 2^3=8 states

Q-box 64 $\xrightarrow{2x}$ Q-box 65

200 bit quantum computer: More states than atoms in universe!

- HOWEVER: Only *measure* n qubits!
  Use only for certain algorithms (quantum simulation, factoring, optimization)

Classical Computing: Factoring 2048 bit number

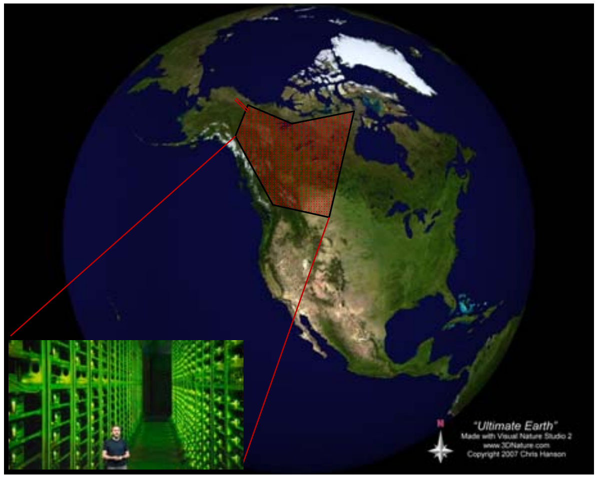
Exponential scale up from 640 bit: 30 CPU years

10 year run time

$\$10^6$ trillion

10^6 terrawatt
(world=10tw)

Consume all
earth's energy
in 1 day



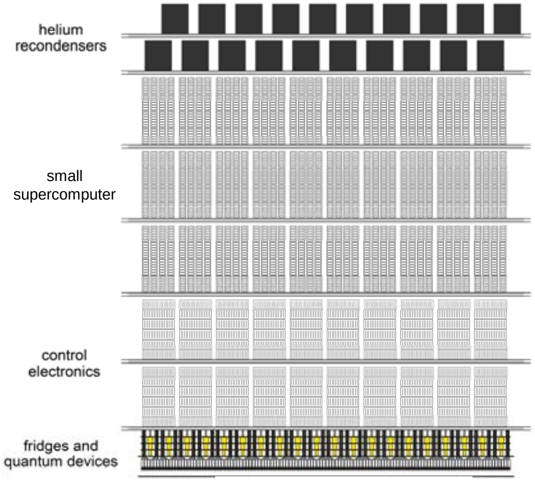
Quantum Computing: Factoring 2048 bit number

200M physical qubits
100k logical qubits

24 hour run time

(?)<$few satellites

(?)<10 Mwatt



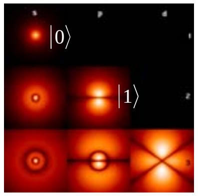
Brute force design for wiring

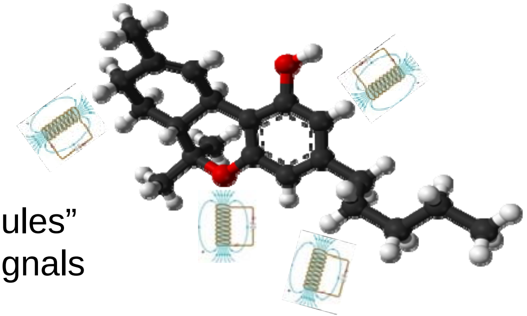
← 1 m - 10 m →
cells: 100 μm - 1 mm

Quantum Bits

$$|0\rangle + |1\rangle$$

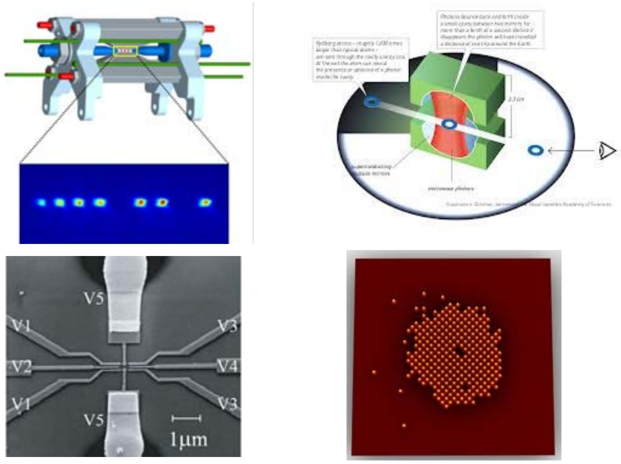
H atom wavefunctions:





Need
Large "Molecules"
for Control Signals

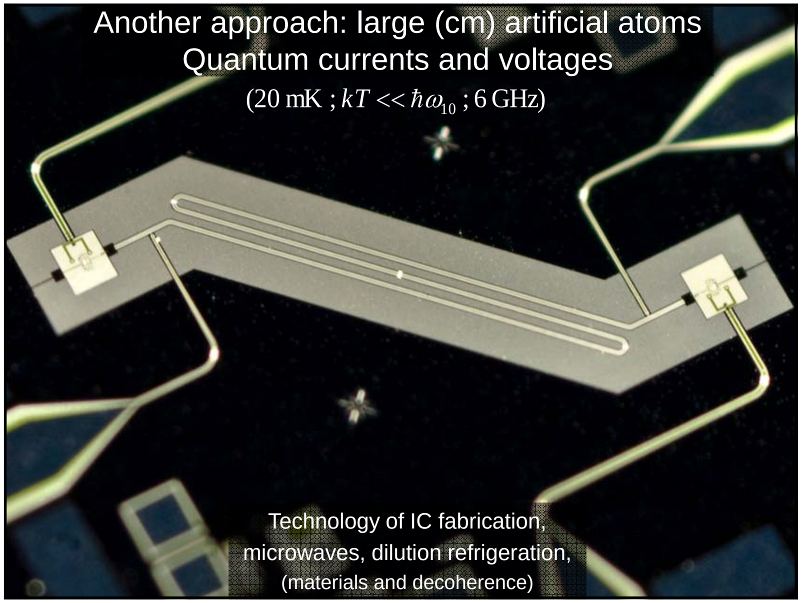
Manipulating atoms and electrons: μm length scale



For megascale quantum computer: need area for control

Another approach: large (cm) artificial atoms Quantum currents and voltages

$(20\text{ mK}\,;\,kT << \hbar\omega_{10}\,;\,6\text{ GHz})$

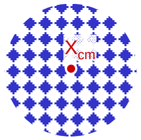


Technology of IC fabrication,
microwaves, dilution refrigeration,
(materials and decoherence)

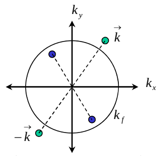
Macroscopic Variables

Single degree of freedom describing state of macroscopic number of atoms/electrons

Center of mass of ball
(single variable describes position)



Phase of superconductor
(Single phase for all Cooper pairs)



$$\Psi = \prod_k \left(u_k + v_k e^{i\phi} c_k^+ c_{-k}^+\right)\left|\Psi_0\right\rangle$$

$$I \propto \nabla\phi$$

Quantize macro-variables as for atomic variables

Qubit Physics: 2-level Quantum State

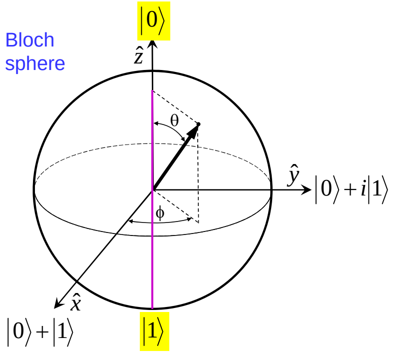
Spin in B field

B field is control!

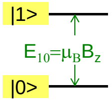
$$H = -\frac{\mu_B}{2}\vec{\sigma}\bullet\vec{B}$$

$$= -\frac{\mu_B}{2}\left[\underbrace{\begin{pmatrix}0 & 1\\ 1 & 0\end{pmatrix}}_{\sigma_x}B_x + \underbrace{\begin{pmatrix}0 & -i\\ i & 0\end{pmatrix}}_{\sigma_y}B_y + \underbrace{\begin{array}{c|cc} & \left|1\right\rangle & \left|0\right\rangle \\ \hline \left\langle 1\right| & 1 & 0\\ \left\langle 0\right| & 0 & -1\end{array}}_{\sigma_z}B_z\right]$$

Bloch
sphere



Example: strong B_z



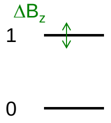
Arbitrary amplitude and phase

$$\Psi = \cos\tfrac{\theta}{2}\left|0\right\rangle + \sin\tfrac{\theta}{2}\,e^{i\phi}\underbrace{e^{-iE_{10}t/\hbar}\left|1\right\rangle}_{\rightarrow\left|1\right\rangle'}$$

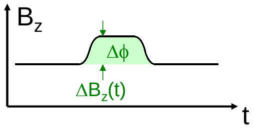
rotating
frame

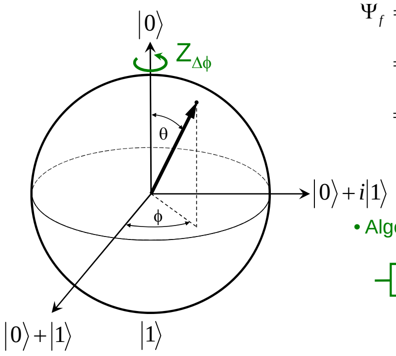
P_g : Measure prob. is projection z-axis

Qubits: B_z large; B_x, B_y, ΔB_z small controls



- Control field ΔB_z is z-axis rotation





$$\Psi_f = \exp(-iHt/\hbar)\,\Psi$$

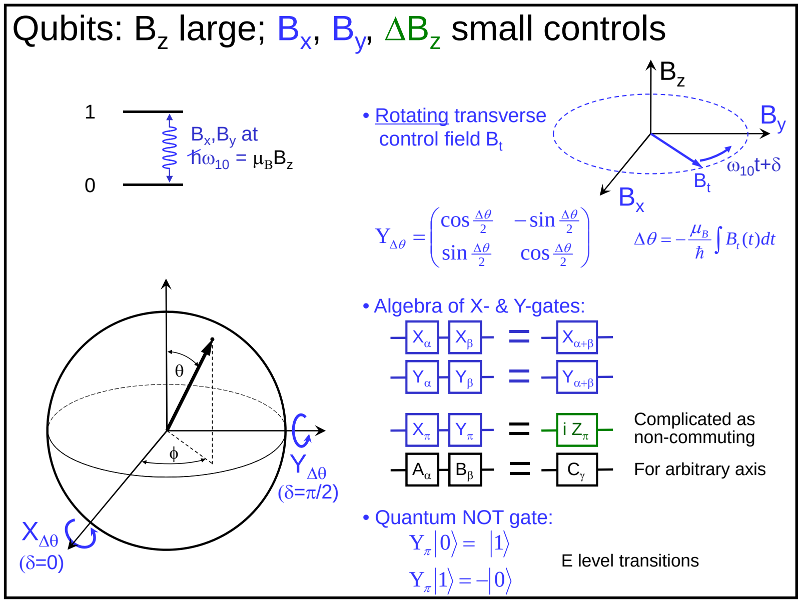
$$= \begin{pmatrix}e^{-i\Delta\phi/2} & 0\\ 0 & e^{i\Delta\phi/2}\end{pmatrix}\Psi \qquad \Delta\phi = -\frac{\mu_B}{\hbar}\int \Delta B_z(t)dt$$

$$= Z_{\Delta\phi}\Psi$$

- Algebra of Z-gates:

$$-\boxed{Z_\alpha}-\boxed{Z_\beta}- \;=\; -\boxed{Z_{\alpha+\beta}}-$$

$$Z_{2\pi} = -I$$



Qubits: B_z large; B_x, B_y, ΔB_z small controls

- Rotating transverse control field B_t

$$Y_{\Delta\theta} = \begin{pmatrix} \cos\frac{\Delta\theta}{2} & -\sin\frac{\Delta\theta}{2} \\ \sin\frac{\Delta\theta}{2} & \cos\frac{\Delta\theta}{2} \end{pmatrix} \qquad \Delta\theta = -\frac{\mu_B}{\hbar}\int B_t(t)dt$$

- Algebra of X- & Y-gates:

$$X_\alpha X_\beta = X_{\alpha+\beta}$$

$$Y_\alpha Y_\beta = Y_{\alpha+\beta}$$

$$X_\pi Y_\pi = i Z_\pi$$ Complicated as non-commuting

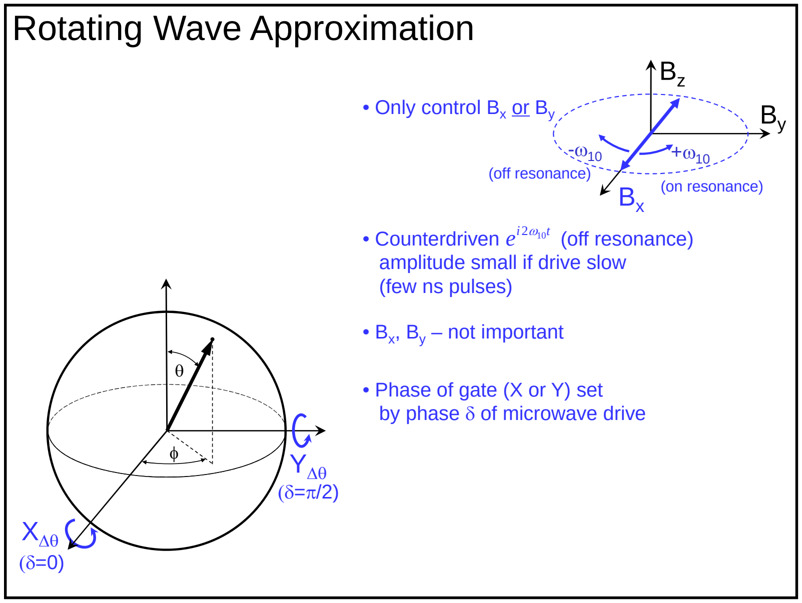
$$A_\alpha B_\beta = C_\gamma$$ For arbitrary axis

- Quantum NOT gate:

$$Y_\pi|0\rangle = \ |1\rangle$$

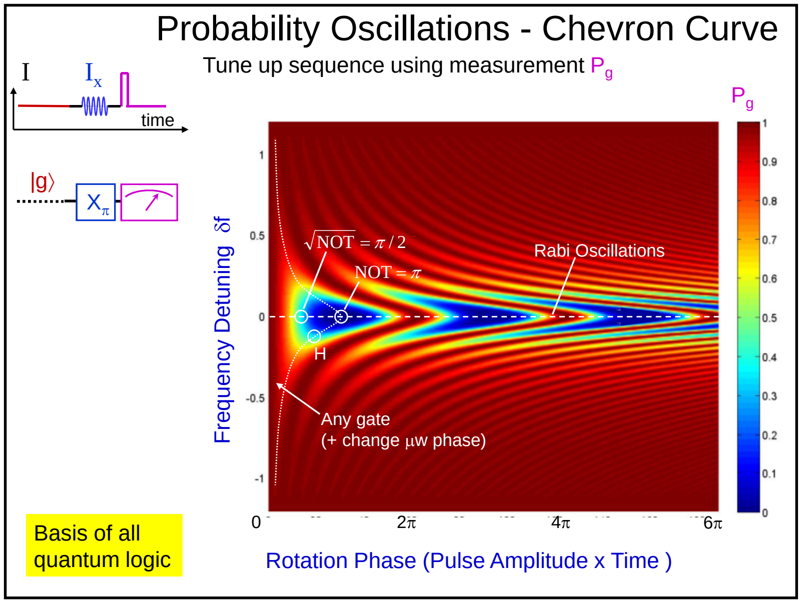
$$Y_\pi|1\rangle = -|0\rangle$$

E level transitions



Rotating Wave Approximation

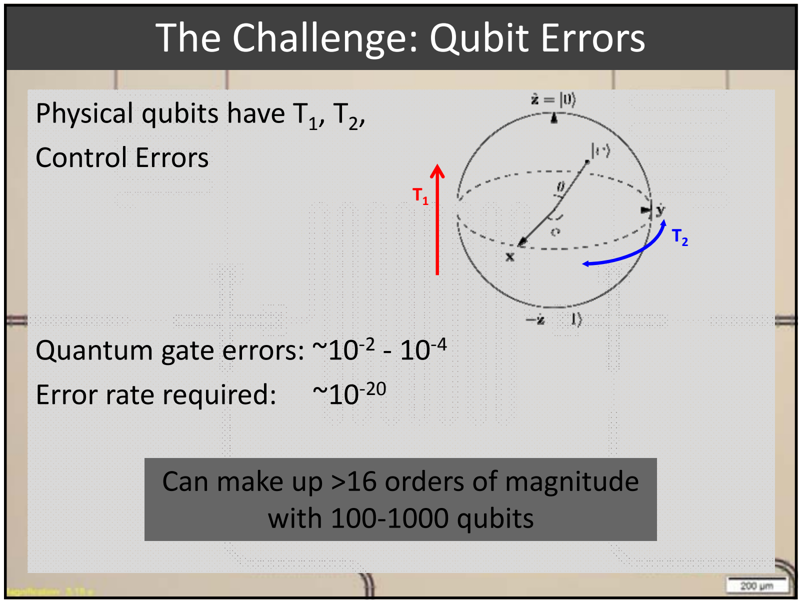
- Only control B_x or B_y
- Counterdriven $e^{i2\omega_{10}t}$ (off resonance) amplitude small if drive slow (few ns pulses)
- B_x, B_y – not important
- Phase of gate (X or Y) set by phase δ of microwave drive



Probability Oscillations - Chevron Curve

Tune up sequence using measurement P_g

Basis of all quantum logic



The Challenge: Qubit Errors

Physical qubits have T_1, T_2,

Control Errors

Quantum gate errors: ~10^{-2} - 10^{-4}

Error rate required: ~10^{-20}

Can make up >16 orders of magnitude with 100-1000 qubits

Error Digitization with Measurement

Example: error from small X rotation:

$$|\Psi\rangle \rightarrow (\hat{I}+\varepsilon\hat{X})|\Psi\rangle$$

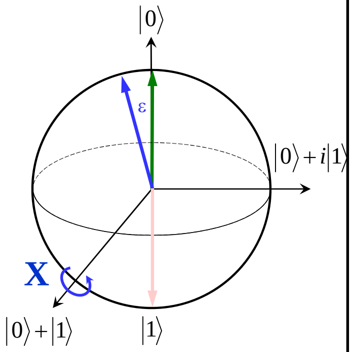
When measure Z, 2 outcomes:

1. Prob = 1-ε² : erases error

$$(\hat{I}+\varepsilon\hat{X})|\Psi\rangle \rightarrow |\Psi\rangle$$

2. Prob = ε² : X error

$$(\hat{I}+\varepsilon\hat{X})|\Psi\rangle \rightarrow \hat{X}|\Psi\rangle$$

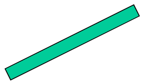


Understanding Qubit Errors

Classical bit:
Coin on table

restoring force makes bit stable

Quantum bit (analogy):
Coin in space



rotation errors from any small force

Quantum bit (physics):

Qubit state $\psi = \cos\theta|0\rangle + \sin\theta e^{i\phi}|1\rangle$ described by amplitude and phase

$\hat{X}\hat{Z} - \hat{Z}\hat{X} \neq 0$ Order of amplitude/phase flips matter
Measuring amplitude randomizes phase

$\hat{X}\hat{Z} + \hat{Z}\hat{X} = 0$ Quantum anticommutation relation

Error Detection Basics

1) Consider 2 qubits, with parity-type measurement

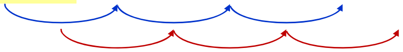
simultaneous bit flip: $\hat{X}_{12} = \hat{X}_1\hat{X}_2$

simultaneous phase flip: $\hat{Z}_{12} = \hat{Z}_1\hat{Z}_2$

new operators commute:
$$\begin{aligned}[\hat{X}_{12},\hat{Z}_{12}] &= \hat{X}_1\hat{X}_2\ \hat{Z}_1\hat{Z}_2 - \ \hat{Z}_1\hat{Z}_2\ \hat{X}_1\hat{X}_2 \\ &= \hat{X}_1\hat{Z}_1\ \hat{X}_2\hat{Z}_2 - (-\hat{X}_1\hat{Z}_1)(-X_2\hat{Z}_2) \\ &= 0\end{aligned}$$

2) Behaves classically. Simultaneous eigenstates:
Stable outcomes when both $\hat{X}_{12}$ and $\hat{Z}_{12}$ measured

measurement:	$\hat{Z}_{12}$	$\hat{X}_{12}$	$\hat{Z}_{12}$	$\hat{X}_{12}$	$\hat{Z}_{12}$	$\hat{X}_{12}$	$\hat{Z}_{12}$	$\hat{X}_{12}$
outcome:	$+1$	-1	$+1$	-1	$+1$	-1	$+1$	-1



3) From detection to identification:
more qubits needed

① ② ③
$\hat{Z}_{12}$ $\hat{Z}_{23}$

id. single flips!

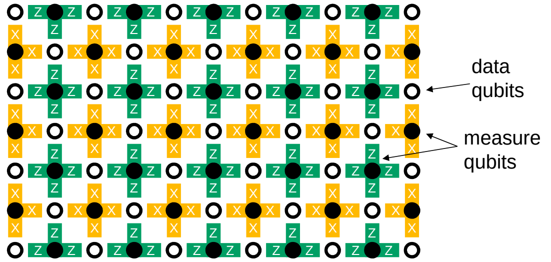
Surface Code Hardware

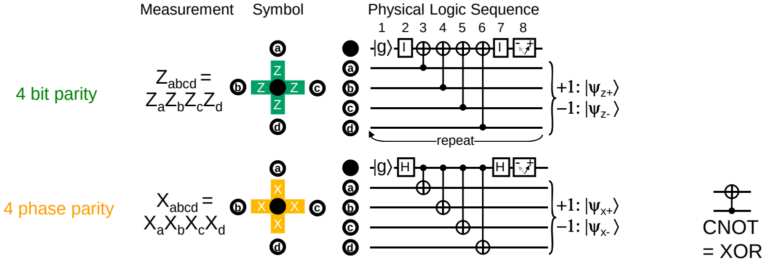
Toric code: Bravyi & Kitaev
arXiv:quant-ph/9811052 (1998)

Logical CNOT: Raussendorf et. al.,
PRL **98,** 190504 (2007)

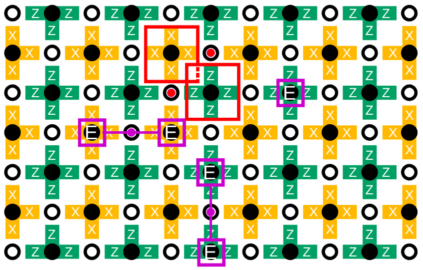
Theory review: A. Fowler et. al.,
PRA **80**, 052312 (2009)

Surface code for mortals: Fowler,
Mariantoni, Martinis, Cleland
PRA **86**, 032324 (2012)





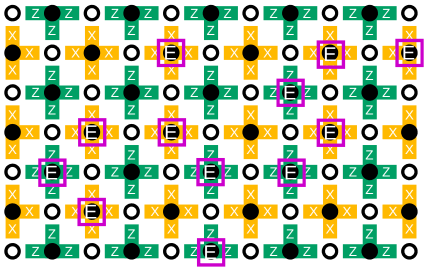
Stabilized State and Identifying Qubit Errors



All measurements XXXX and ZZZZ commute:
  Measurement outcomes unchanging

When errors:
  Data qubit errors – pairs in space
  Measure errors – pairs in time

Stabilized State and Identifying Qubit Errors

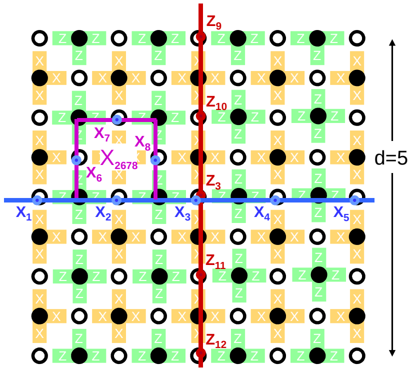


When large density -
  Backing out errors may not be unique

Logical Qubit: 41 data qubits, 40 measure qubits

$Z_L = Z_9 Z_{10} Z_3 Z_{11} Z_{12}$

$X_L =$
$X_1 X_2 X_3 X_4 X_5$



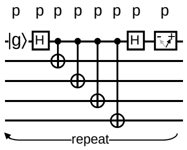
$X_L Z_L = - Z_L X_L$ (so acts like qubit)

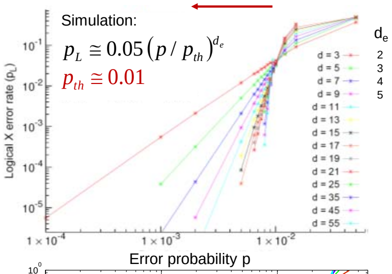
X_L and Z_L commute with measures (so stabilized)
acts as extra degree of freedom

Logical Error Probability

logical error
improves with size

Model: error p each step



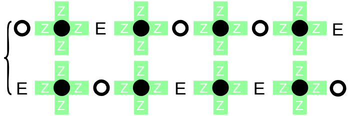


$p_L \cong 0.05 \left(p / p_{th} \right)^{d_e}$

$p_{th} \cong 0.01$

measured error chain:

computed error of data qubits:

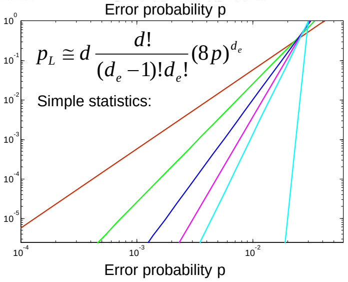


p_L

p^2

p^3

$$P_L \cong \frac{5 \cdot 4 \cdot 3}{3 \cdot 2 \cdot 1} (8p)^3$$

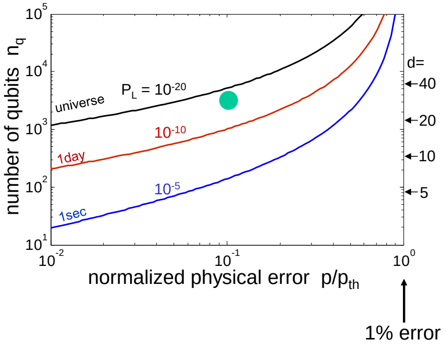


$$p_L \cong d \frac{d!}{(d_e - 1)! d_e!} (8p)^{d_e}$$

Simple statistics:

Size of Logical Qubits

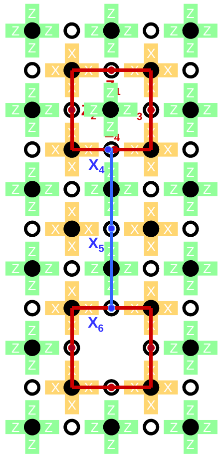
$$p_L \cong 0.05\left(p/p_{th}\right)^{\frac{d+1}{2}}$$



Need ~3000 physical qubits per logical qubit

Logical Qubits and Gates

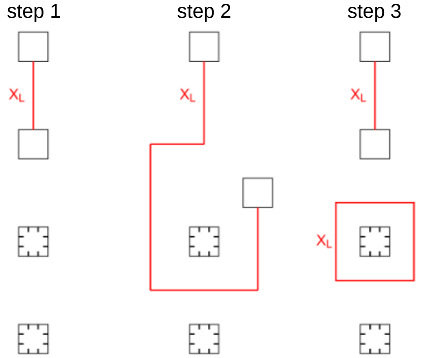
Interior surface qubit



$Z_L=Z_1Z_2Z_3Z_4$
$X_L=X_4X_5X_6$

- Initialize Z_L with Z measurement
- Measure Z_L with Z measurement

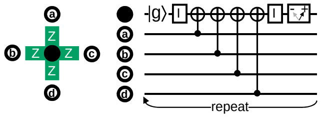
- CNOT from braiding:



- Single gates: $(X, Z),\ H,\ S=\sqrt{Z},\ T=\sqrt{S}$

Review of Hardware & Requirements

Presently, surface code only fault-tolerant architecture



Unit cell requirements:
Single gate
CNOT or CZ (nn)
Fast measurement
Nearest neighbor

Performance needed:
(99.3% threshold)

Target of 10-30x below threshold:
99.97% single gate
99.9% 2-qubit gate
99% measurement

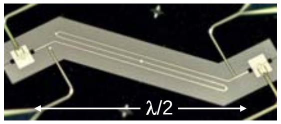
Experiments (# qubits):
9 - basic test
20 - full test
200 - low error
1000 - logical op's
1 M - algorithm

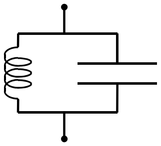
Scalability:
Qubits made reliably
(IC fabrication)
Need room for control wiring
Eventually need control system

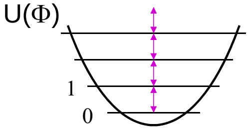
Superconducting Qubits

- Macroscopic "atom": quantize I and V, 5 GHz >> 20 mK

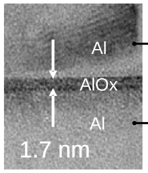
- LC oscillator (linear): memory and communication

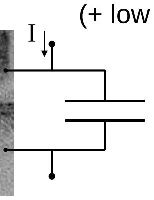


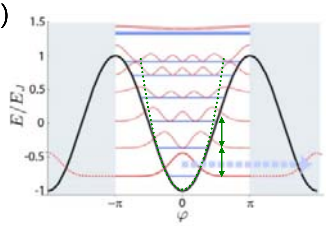




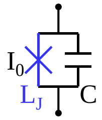
- Josephson junction: non-linear inductance with 1 photon
(+ low loss)







Qubit: Nonlinear LC resonator



$I = I_0 \sin\delta$ δ is dimensionless flux

$V = \frac{\Phi_0}{2\pi}\dot{\delta}$ $(V = \dot{\Phi})$

Junction response: $\dot{I}_j = I_0 \cos\delta\ \dot{\delta}$

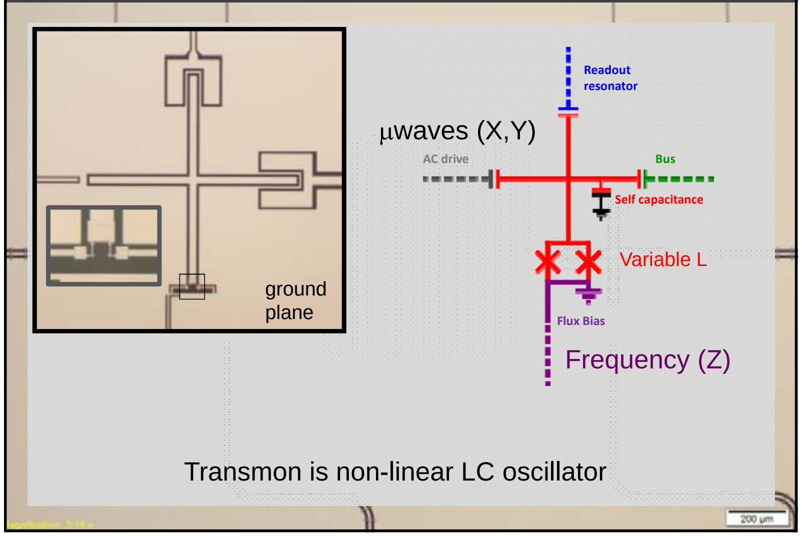
$\equiv (1/L_J)V$

$L_J = \Phi_0/2\pi I_0 \cos\delta$
nonlinear inductor

Junction energy:
$$U(\delta) = \int dt\, I\, V$$
$$= (I_0\Phi_0/2\pi)\int dt \sin\delta\, d\delta/dt$$
$$= -(I_0\Phi_0/2\pi)\cos\delta$$

QM commutator: $[\hat{\Phi}, \hat{Q}] = i\,\hbar\,,\quad [\hat{\delta}, \hat{q}] = 2i$

Xmon Circuit

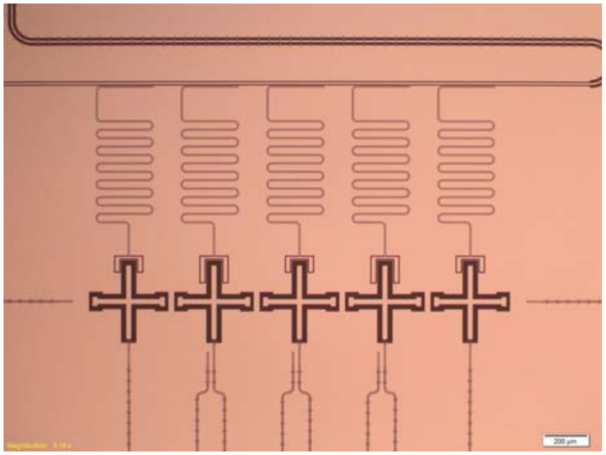


Transmon is non-linear LC oscillator

Xmon: Superconducting Qubit Fabrication

Al metal & Josephson junctions
Sapphire substrate
IC fabrication technology

10+ years
50+ researchers

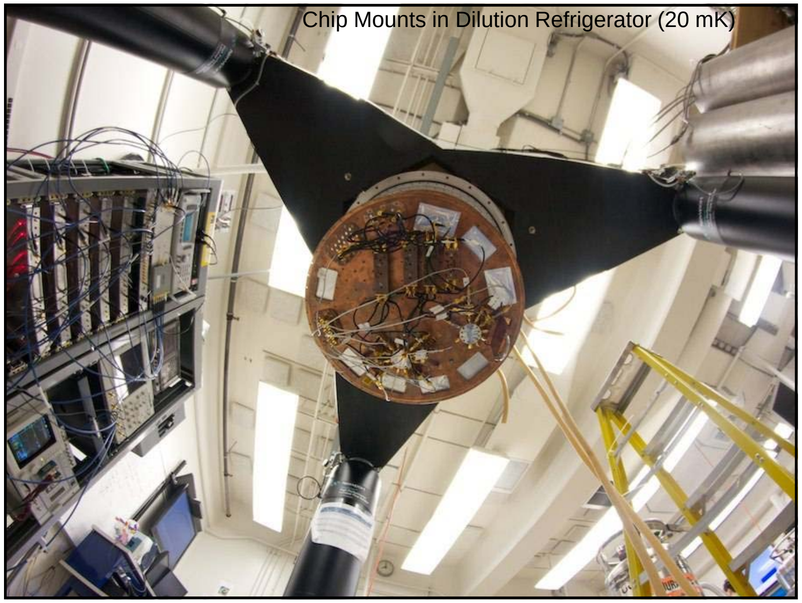


qubit readout (freq. mux'd)

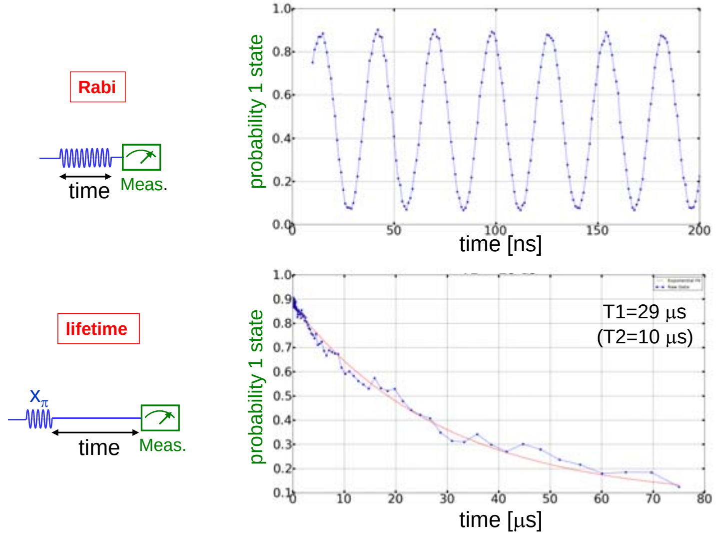
5 Xmon qubits, C coupling

qubit control

Chip Mounts in Dilution Refrigerator (20 mK)



Qubit Characterization



Harmonic Oscillators

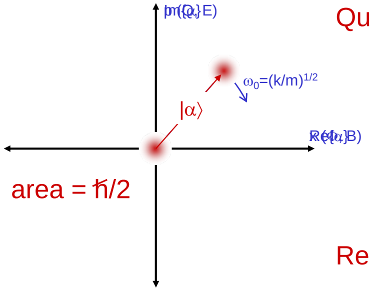
Examples: Mass on spring, $H = (1/2m)p^2 + (k/2)x^2$

LC resonator, $H = (1/2C)Q^2 + (1/2L)\Phi^2$

photons, phonons … $H = (\varepsilon_0/2)E^2 + (1/2\mu_0)B^2$

Dynamics: (1) Circular motion in phase space

(2) Linear response (α proportional to drive force)



area = ħ/2

Quantum: Ground state |0⟩ (Gaussian)

Driven state |α⟩ (Gaussian)

with classical trajectory

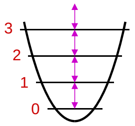
Relax to |0⟩ with classical trajectory

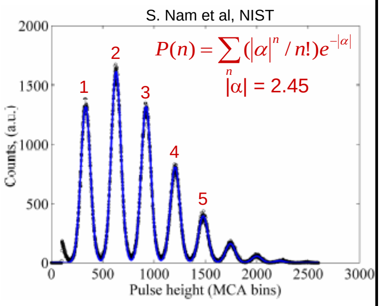
Response: Quantum = Classical

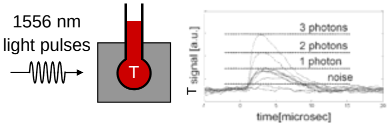
Quantum Effects Seen with Nonlinearity

Measurement:

Energy
(photon number n)





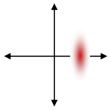


Microcalorimeter measures T pulses

Generation: Non-classical states

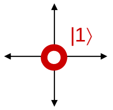
Photon squeezed states

Non-linearity from modulating k



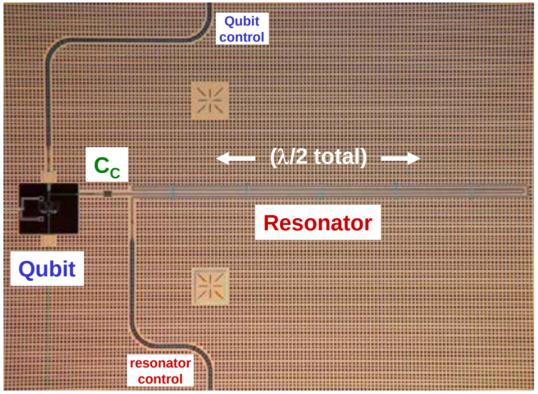
Qubit non-linearity

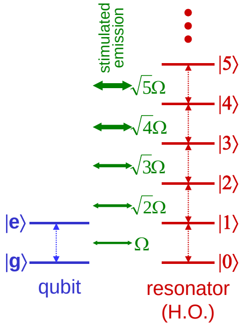
Rydberg atoms (ENS) / microwave cavity

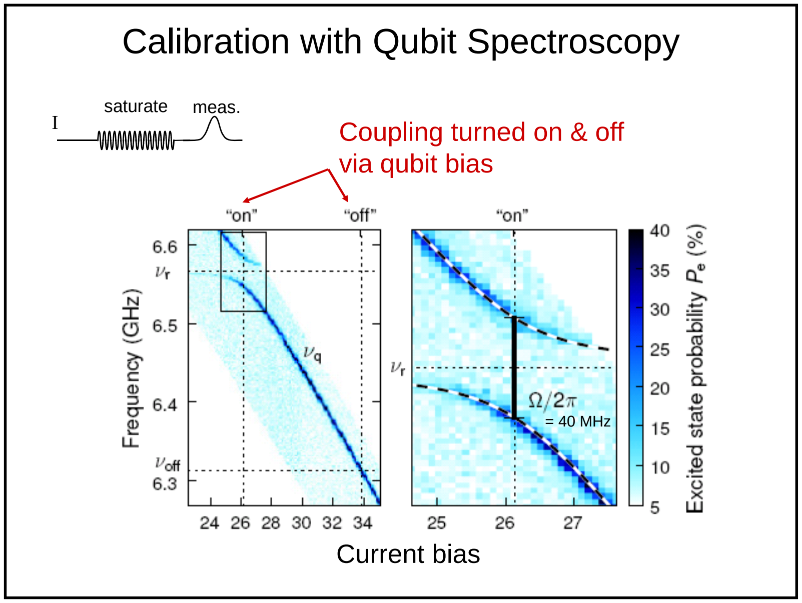


Qubit Coupled to Photons (Harmonic Oscillator)

Design similar to Yale experiments

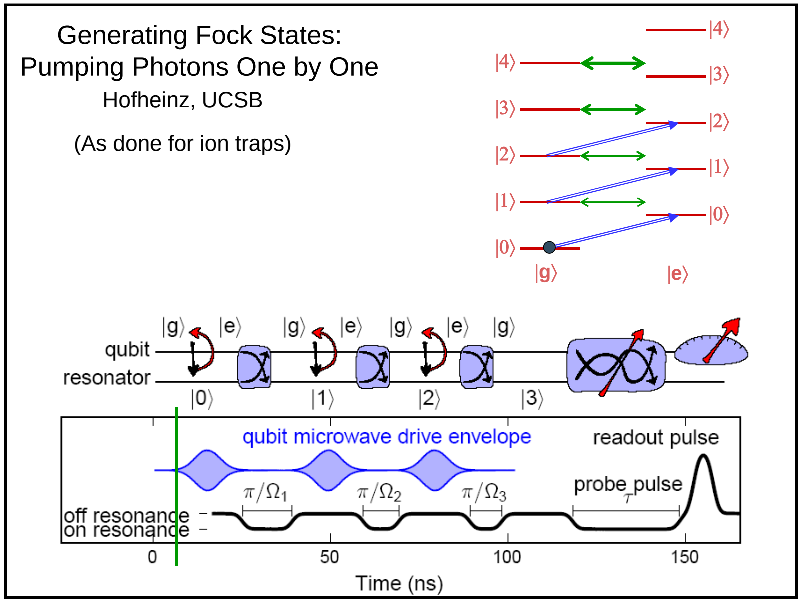






Calibration with Qubit Spectroscopy

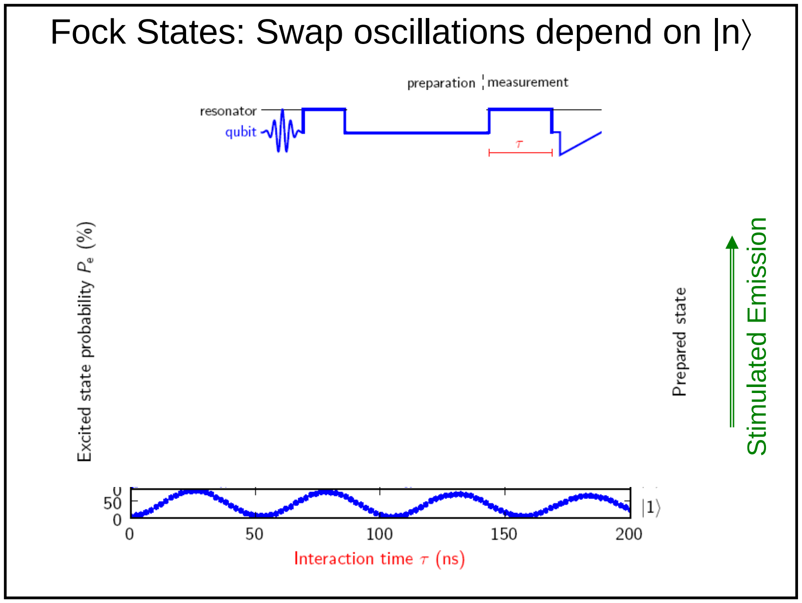
Coupling turned on & off via qubit bias



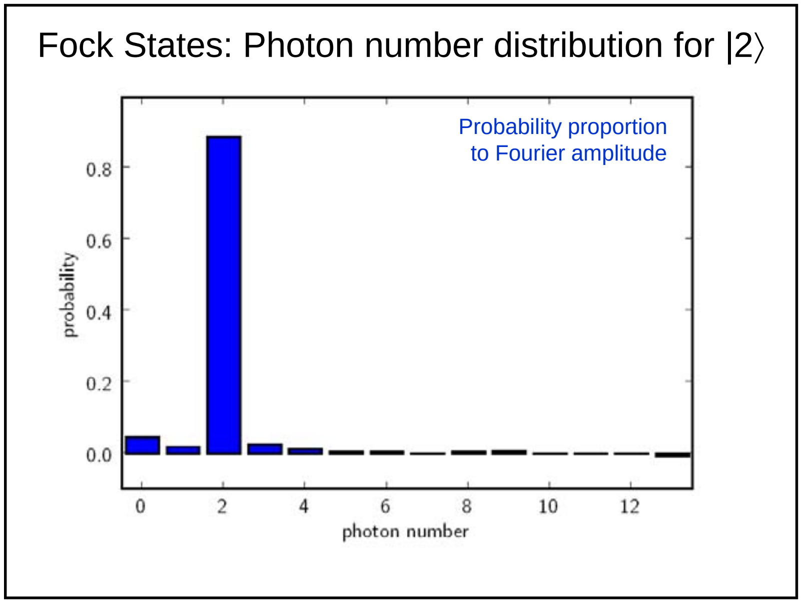
Generating Fock States: Pumping Photons One by One

Hofheinz, UCSB

(As done for ion traps)



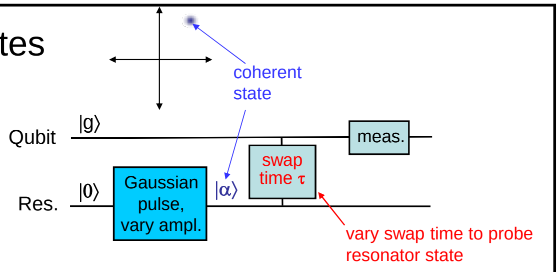
Fock States: Swap oscillations depend on |n⟩



Fock States: Photon number distribution for |2⟩

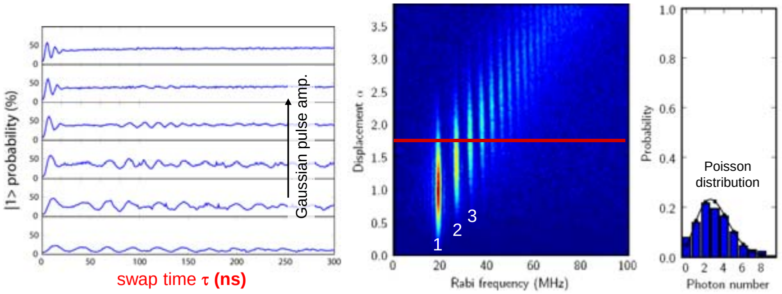
Probability proportion to Fourier amplitude

Coherent states



State preparation:

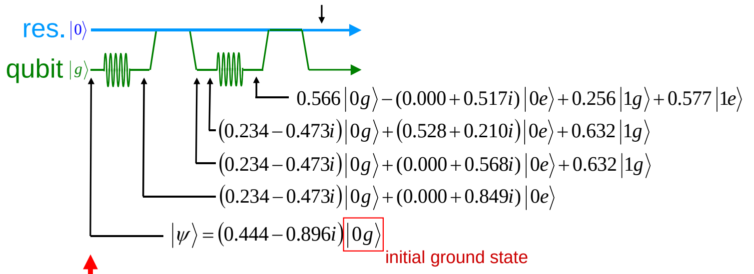
vary swap time to probe resonator state



Generating Arbitrary States

Hofheinz & Wang, UCSB

Desired final state ➡ $|\psi\rangle = 0.577\left(|0\rangle + |1\rangle + i|2\rangle\right)\otimes|g\rangle$



$0.566|0g\rangle - (0.000+0.517i)|0e\rangle + 0.256|1g\rangle + 0.577|1e\rangle$

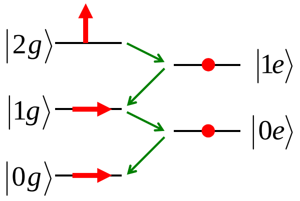
$(0.234-0.473i)|0g\rangle + (0.528+0.210i)|0e\rangle + 0.632|1g\rangle$

$(0.234-0.473i)|0g\rangle + (0.000+0.568i)|0e\rangle + 0.632|1g\rangle$

$(0.234-0.473i)|0g\rangle + (0.000+0.849i)|0e\rangle$

$|\psi\rangle = (0.444-0.896i)\boxed{|0g\rangle}$

initial ground state

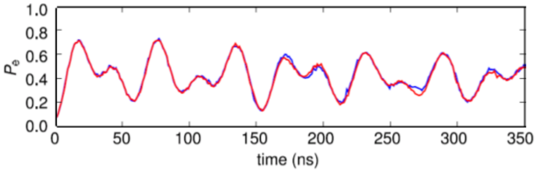


Law / Eberly protocol:
Build pulse sequence backwards
by zeroing highest state

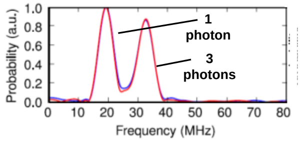
Generating Arbitrary States: Quantum Digital to Analog Converter

$|\psi_a\rangle = |1\rangle + |3\rangle$ Now try: $|\psi_b\rangle = |1\rangle + \boldsymbol{i}\,|3\rangle$

Measure using qubit and watching evolution (usual method):



Fourier transform yields number composition:



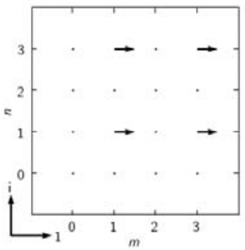
Cannot distinguish based on this measure!

State Tomography of Harmonic Oscillator

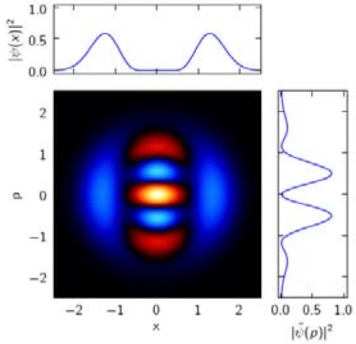
Example: $|\psi\rangle = |1\rangle + |3\rangle$

Density matrix:

$\rho = |\psi\rangle\langle\psi|$

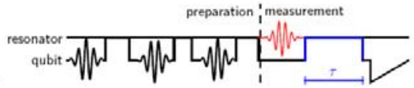


Wigner function:



State Tomography of Harmonic Oscillator

Example: $|\psi\rangle = |1\rangle + |3\rangle$



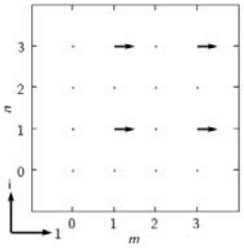
$\langle P\rangle = \sum p_n(-)^n$

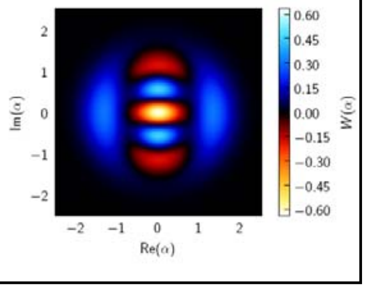
Density matrix:

$\rho = |\psi\rangle\langle\psi|$

Wigner function:

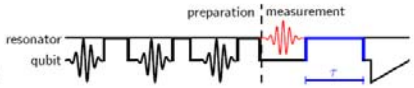
$W(\alpha) = \frac{2}{\pi}\langle\psi|D(\alpha)PD(-\alpha)|\psi\rangle$





State Tomography of Harmonic Oscillator

Example: $|\psi\rangle = |1\rangle + i|3\rangle$



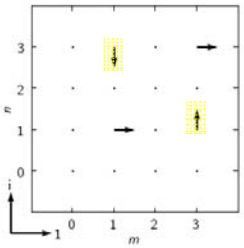
$\langle P\rangle = \sum p_n(-)^n$

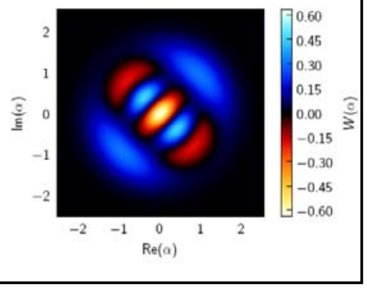
Density matrix:

$\rho = |\psi\rangle\langle\psi|$

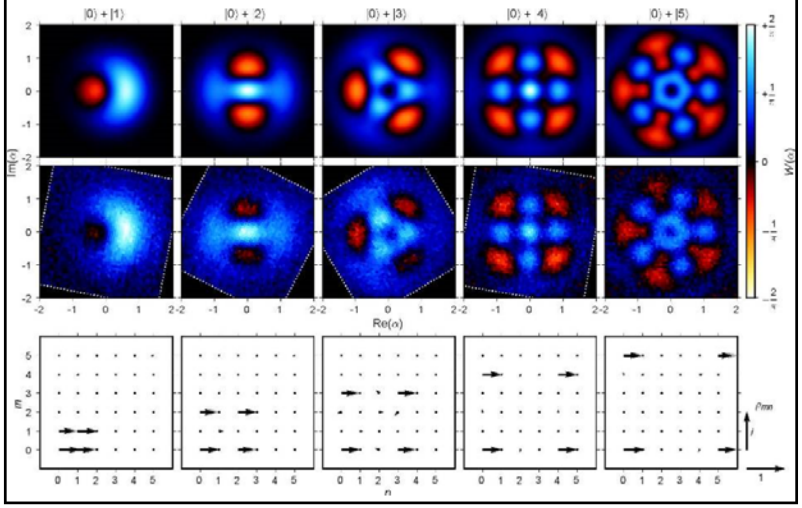
Wigner function:

$W(\alpha) = \frac{2}{\pi}\langle\psi|D(\alpha)PD(-\alpha)|\psi\rangle$





Wigner Tomography, $|0\rangle+|N\rangle$ states:



Collapse of Schrodinger Cat State

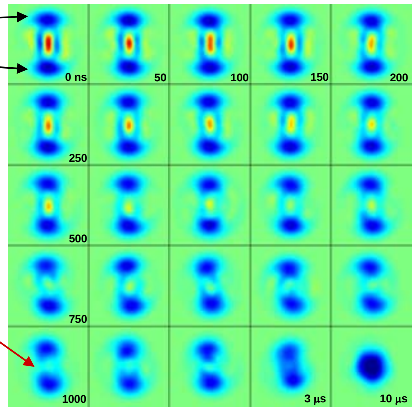
time sequence: delay before measure

$\Psi_{\text{dead}} + \Psi_{\text{alive}} = |2\rangle + |-2\rangle$

Projection (collapse) by dissipation

Interference gone!

Ψ_{dead} or Ψ_{alive}

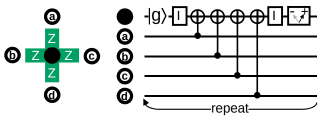


Collapse rate scales with distance between Ψ_{dead} & Ψ_{alive}

See “Exploring the Quantum”, Haroche & Raimond

Review of Hardware & Requirements

Presently, surface code only realistic fault-tolerant architecture



Unit cell requirements:
- Single gate
- CNOT or CZ (nn)
- Fast measurement
- Nearest neighbor

Performance needed:
(99.3% threshold)

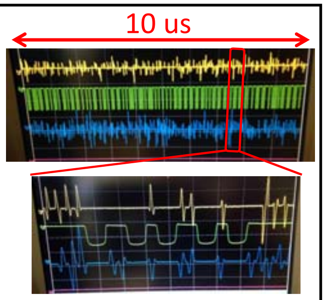
Target of 10-30x below threshold:
- 99.97% single gate
- 99.9% 2-qubit gate
- 99% measurement

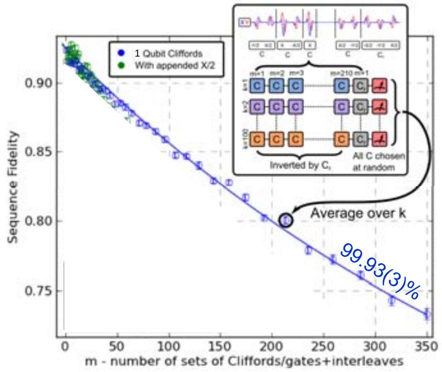
Experiments (# qubits):
- 9 - basic test
- 20 - full test
- 200 - low error
- 1000 - logical op's
- 1 M - algorithm

Scalability:
- Qubits made reliably
  - (IC fabrication)
- Need room for control wiring
- Eventually need control system

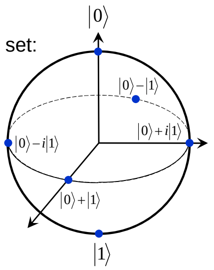
Randomized Benchmarking*

Realistic multi-qubit test of ***long*** algorithm
(1000+ gates)





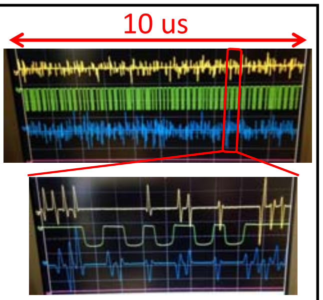
Clifford gate set:
"rotation" to
6 states

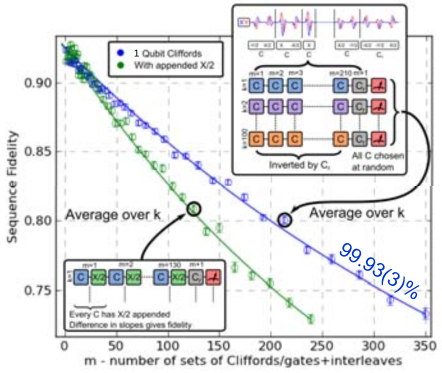


*Magesan et. al., *PRL* 106.18 (2011): 180504

Randomized Benchmarking*

Realistic multi-qubit test of ***long*** algorithm
(1000+ gates)

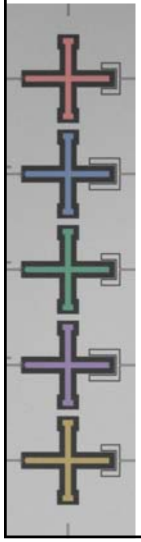


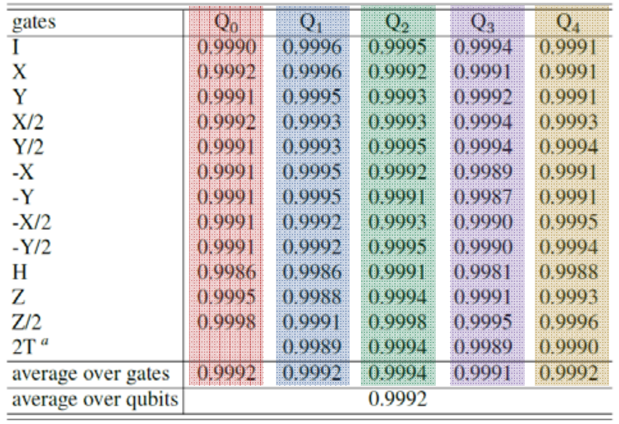


Gate	Fidelity (%)	Gate Time
X	99.95	20ns
Y	99.95	20ns
X/2	99.93	20ns
Y/2	99.93	20ns
-X	99.92	20ns
-Y	99.90	20ns
-X/2	99.93	20ns
-Y/2	99.93	20ns
H	99.91	40ns
Z	99.97	10ns
Z/2	99.98	10ns

*Magesan et. al., *PRL* 106.18 (2011): 180504

Single qubit gate fidelities

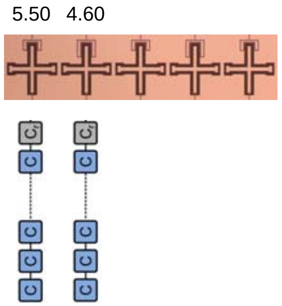




gates	Q_0	Q_1	Q_2	Q_3	Q_4
I	0.9990	0.9996	0.9995	0.9994	0.9991
X	0.9992	0.9996	0.9992	0.9991	0.9991
Y	0.9991	0.9995	0.9993	0.9992	0.9991
X/2	0.9992	0.9993	0.9993	0.9994	0.9993
Y/2	0.9991	0.9993	0.9995	0.9994	0.9994
-X	0.9991	0.9995	0.9992	0.9989	0.9991
-Y	0.9991	0.9995	0.9991	0.9987	0.9991
-X/2	0.9991	0.9992	0.9993	0.9990	0.9995
-Y/2	0.9991	0.9992	0.9995	0.9990	0.9994
H	0.9986	0.9986	0.9991	0.9981	0.9988
Z	0.9995	0.9988	0.9994	0.9991	0.9993
Z/2	0.9998	0.9991	0.9998	0.9995	0.9996
2T [a]		0.9989	0.9994	0.9989	0.9990
average over gates	0.9992	0.9992	0.9994	0.9991	0.9992
average over qubits	0.9992				

Simultaneous Benchmarking

Frequency (GHz):



Gate Fidelity (%):

Q0	Q1
99.94	
	99.95
99.91	

Operation of Q0 & Q1 simultaneously has same errors as Q0+Q1
→negligible crosstalk

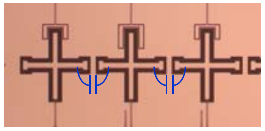
(Detuning turns off interaction)

Coupled Qubits: Thinking Outside the Cavity

Conventional thinking:
(1) Operate qubits at fixed frequency
(gives longest memory)
(2) Couple qubits through “quantum bus”
(long distance communication)
(3) Use complex photon drive/control
(need tuning for proper gate)

SC qubits: 200ns, 90-98% fidelity

New coupler design:
(1) Adjustable frequency qubit
(use to turn on/off interaction)
(2) Direct qubit-qubit coupling
(no extra mode giving decoherence)
(3) DC drive for qubit frequency
(need accurate, but 1 param. tuning)

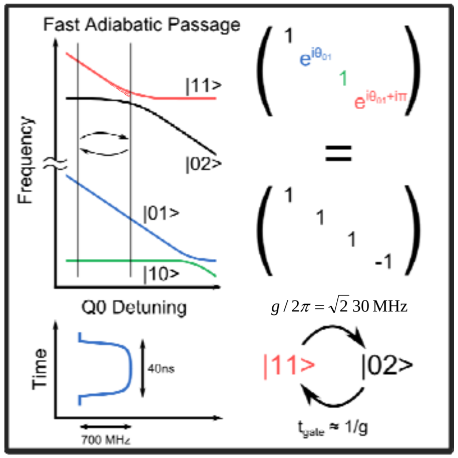


Theory: 40ns, 99.99% intrinsic fidelity (no decoherence)

Tune up of Controlled-Z

truth table

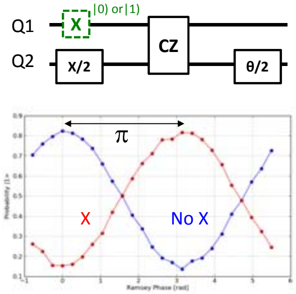
$$\begin{cases} |00\rangle \to |00\rangle \\ |01\rangle \to |01\rangle \\ |10\rangle \to |10\rangle \\ |11\rangle \to -|11\rangle \end{cases}$$



$$\begin{pmatrix} 1 & & & \\ & e^{i\theta_{01}} & & \\ & & 1 & \\ & & & e^{i\theta_{01}+i\pi} \end{pmatrix} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1 \end{pmatrix}$$

$g/2\pi = \sqrt{2}\ 30\ \text{MHz}$

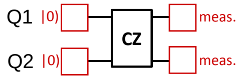
Functionality Check (truth table)

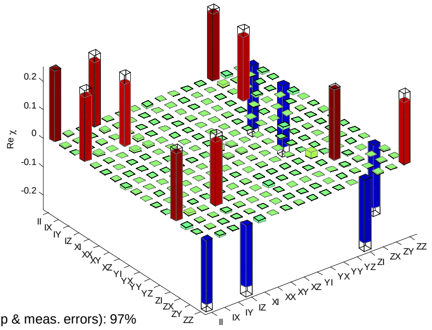


*Similar to Strauch; DiCarlo; Yamamoto

Controlled-Z QPT Fidelity

Quantum Process Tomography

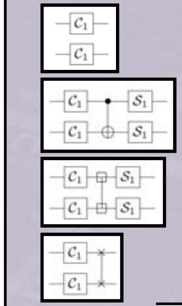




total fidelity (with state prep & meas. errors): 97%

Two qubit Clifford group C_2

Classes of C_2



single qubit class: 576

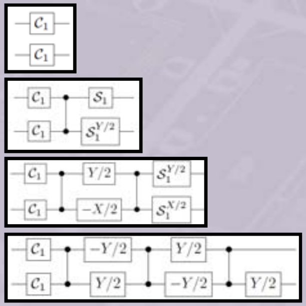
CNOT-like class: 5184

iSWAP-like class: 5184

SWAP-like class: 576 +

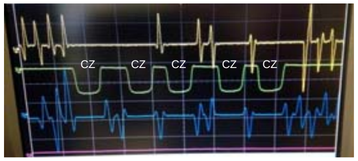
total : 11520

Classes of C_2: CZ



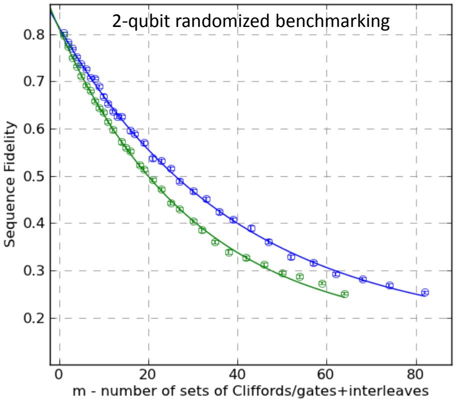
S_1= { [I], [Y/2, X/2], [-X/2, –Y/2] }

A. Corcoles *et al.*, PRA 2013



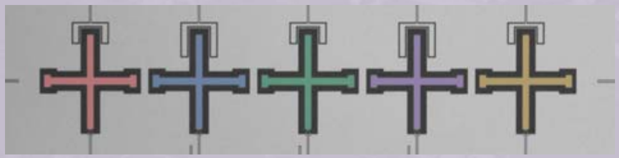
Performance of CZ gate

Fast (40ns)
Accurate F_{CZ} =99.45(5)%



At best in world

CZ fidelity for all pairs

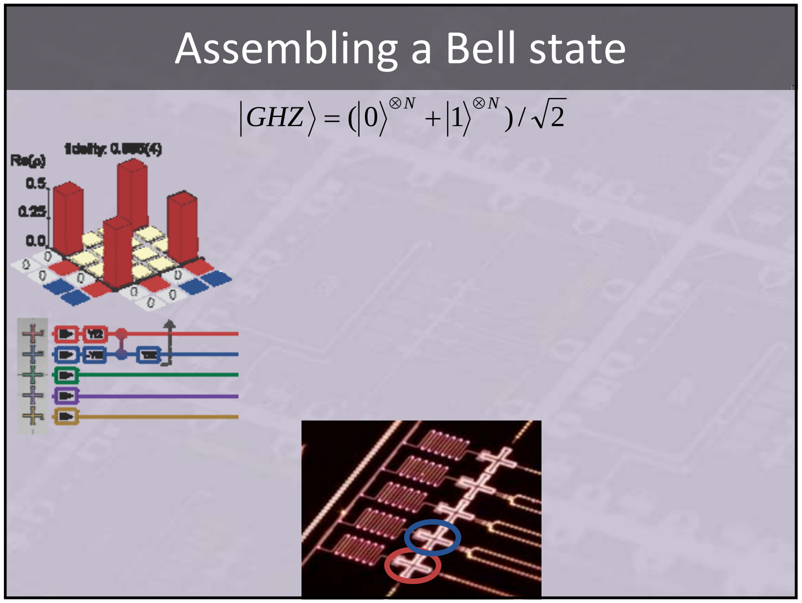


qubits	Q_0	Q_1	Q_2	Q_3	Q_4
$CZ_{Q_0-Q_1}$	0.9924 ± 0.0005				
$CZ_{Q_1-Q_2}$		0.9936 ± 0.0004			
$CZ_{Q_2-Q_3}$			0.9944 ± 0.0005		
$CZ_{Q_3-Q_4}$				0.9900 ± 0.0006	

Comparison to other technologies

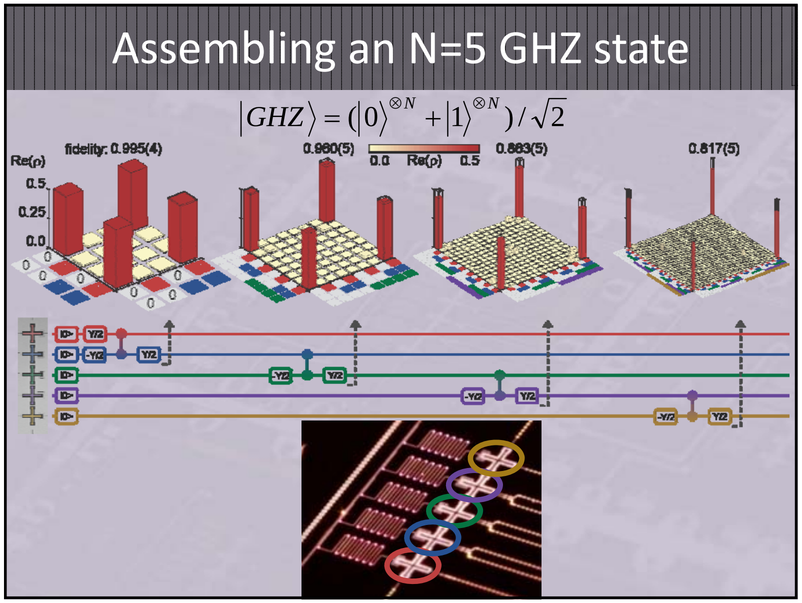
system	# qubits	entangling gate fidelity	single qubit gate fidelity
liquid NMR [1]	3,1	0.995	0.9999
UCSB Xmon	**5**	**0.994**	**0.9992**
ion traps [2]	1		0.99998
ion traps [3] (QPT,1/2 CNOT)	2	0.993	
ion traps [4]	5	0.95	
sup MIT LL, planar [5]	1		0.998
sup IBM, planar [6]	2	0.98	
sup IBM, planar [7]	2	0.93	0.998
sup IBM, planar [8]	3	0.96	0.997

1. Ryan et al., New J. Phys 2009
2. Brown et al., PRA 2011
3. Benhelm et al., Nat Phys 2008
4. Choi et al., arxiv 2014
5. Gustavsson et al., PRL 2013
6. Chow et al., PRL 2012
7. Corcoles et al., PRA 2013
8. Chow et al., arxiv 2013



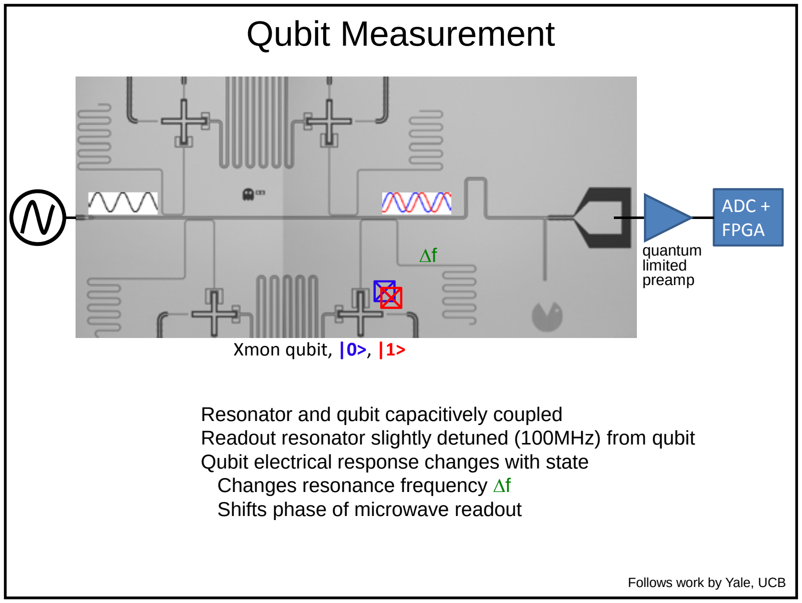
Assembling a Bell state

$$|GHZ\rangle = (|0\rangle^{\otimes N} + |1\rangle^{\otimes N})/\sqrt{2}$$



Assembling an N=5 GHZ state

$$|GHZ\rangle = (|0\rangle^{\otimes N} + |1\rangle^{\otimes N})/\sqrt{2}$$

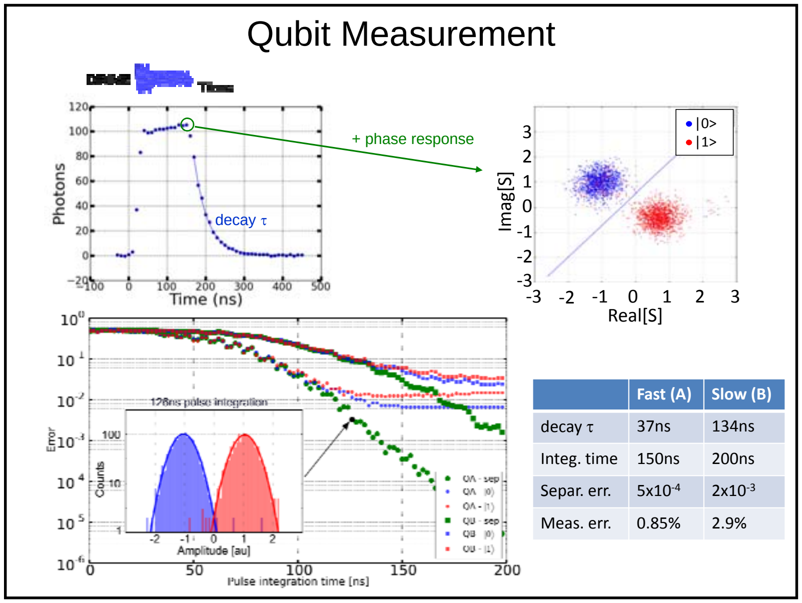


Qubit Measurement

Xmon qubit, |0>, |1>

Resonator and qubit capacitively coupled
Readout resonator slightly detuned (100MHz) from qubit
Qubit electrical response changes with state
  Changes resonance frequency Δf
  Shifts phase of microwave readout

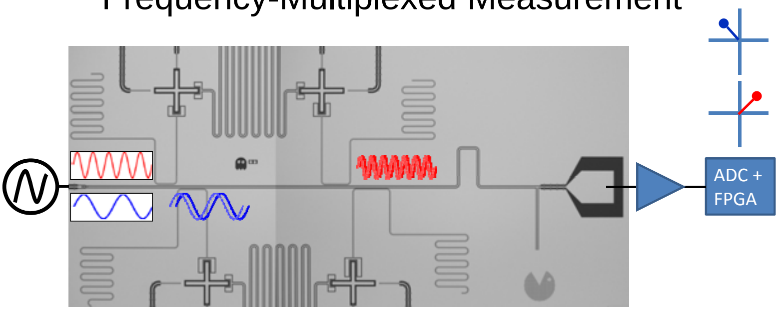
Follows work by Yale, UCB



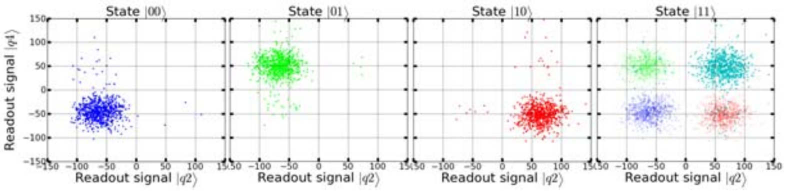
Qubit Measurement

	Fast (A)	Slow (B)
decay τ	37ns	134ns
Integ. time	150ns	200ns
Separ. err.	5×10^{-4}	2×10^{-3}
Meas. err.	0.85%	2.9%

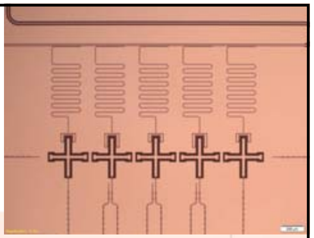
Frequency-Multiplexed Measurement



Inject multiple microwave tones, readout resonators at different frequencies



Summary & Outlook



Xmon qubits are high-fidelity technology
- 1 qubit: 99.93(3)%
- 2 qubit: 99.45(5)%
- Measure: 99-99.9%
- Improvements likely

Now understand path to fault-tolerant computation
- Surface code: at needed fidelity of 99%
- SC qubits are IC scalable

Surface code project to test science of error correction:
- 100-1000 qubit, surface code architecture
- Logical error rate 10^{-15}
- Logical operations (H, CNOT, …) at 10^{-6} errors

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Yu Chen
Daniel Sank
Austin Fowler

Chris Quintana
Anthony Megrant
Jimmy Chen
Peter O'Malley

James Wenner
Evan Jeffrey
Pedram Roushan
Julian Kelly (+qubit)

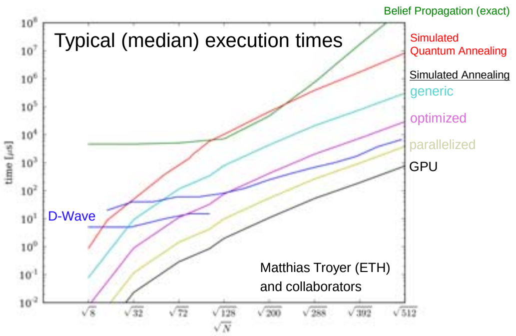
Andrew Dunsworth
Rami Barends
Josh Mutus
Charles Neill

Ted White
Ben Chiaro
John Martinis
Andrew Cleland

Market: Solve optimization problems (spin glass)
Conjecture: Build QC without much coherence
Technology: Use standard Josephson fabrication

Machine has superb engineering

Physicists: No exponential computing power
What does Nature have to say?



Matthias Troyer (ETH) and collaborators

Preliminary Results:
No faster than classical code