Building a quantum computer: Opportunities & Challenges

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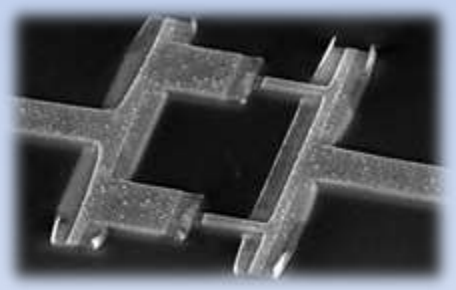

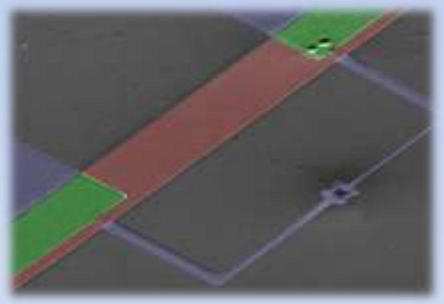

ASET Colloquium, TIFR, Mumbai
Dec 23, 2016

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Funding: Dept. of Atomic energy, Dept. of Science and Technology, India
Rigetti Quantum Computing, Berkeley, USA

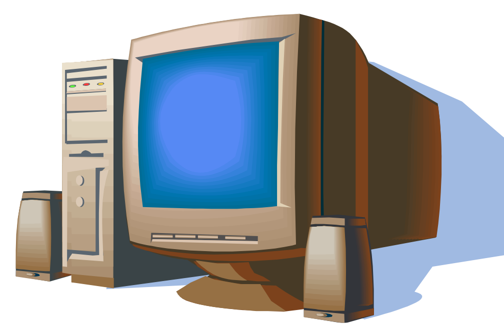
Outline

- Introduction
  - Quantum Information & Computing
- Superconducting Quantum Circuits
  - “Artificial atoms” using electrical circuits
- Some recent results & future directions

Classical digital information

bit

"0" or "1"



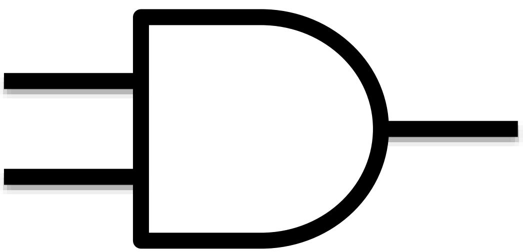
Digital gates

XOR GATE

A	B	X
0	0	0
0	1	1
1	0	1
1	1	0

SUM

AND GATE



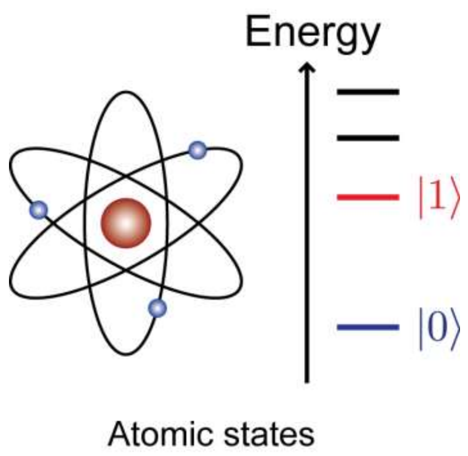
0	0	0
0	1	0
1	0	0
1	1	1

CARRY

OR GATE

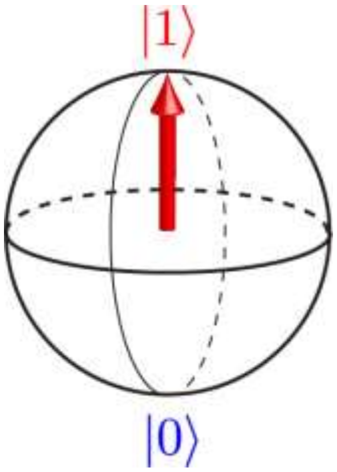
0	0	0
0	1	1
1	0	1
1	1	1

Quantum Information

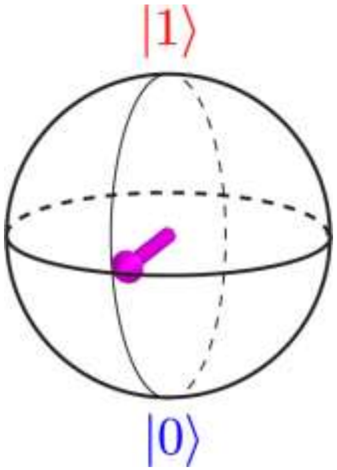


Superposition:

$$\alpha\,|0\rangle + \beta\,|1\rangle$$

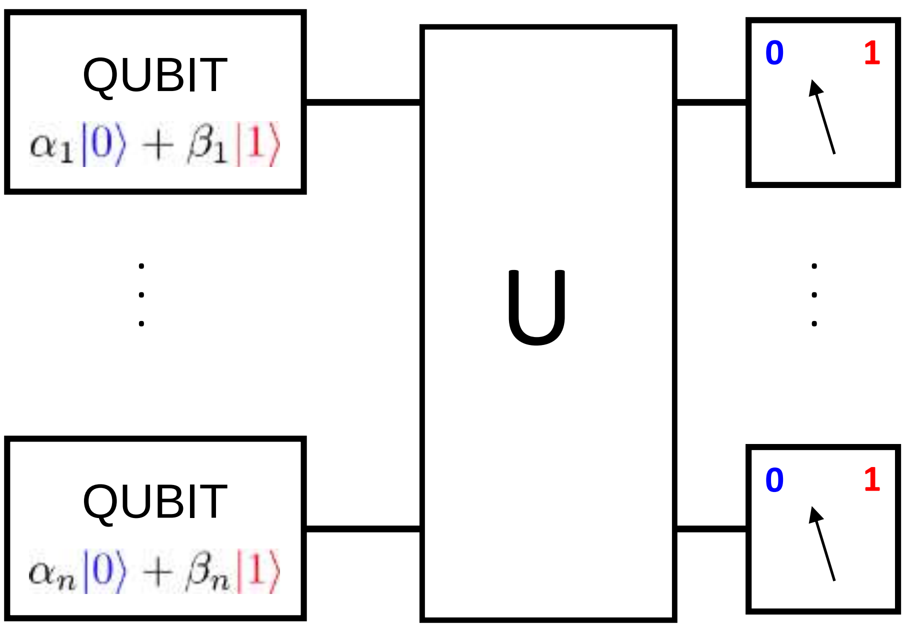


$$|\psi\rangle = \cos(\theta/2)\,|0\rangle + e^{i\phi}\sin(\theta/2)\,|1\rangle$$



Quantum Algorithms

- N classical bits : one of the 2^N possible states
- N qubits : all of the 2^N possible states
- Operate on all states simultaneously



What can we compute?

2038074743 X 4222234741

HARD

RSA ENCRYPTION

8605229984649246563

(mit.edu)

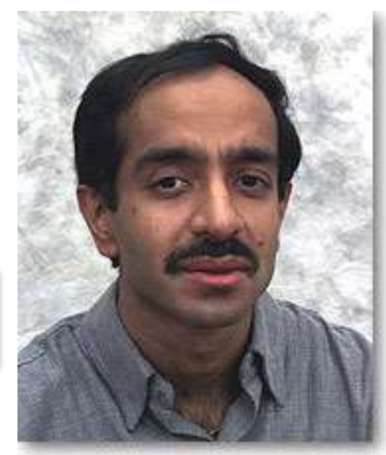
SHOR'S FACTORING ALGORITHM: 1994

1000 digit number: 10^{24} years -> minutes!

GROVER'S SEARCH ALGORITHM:1996

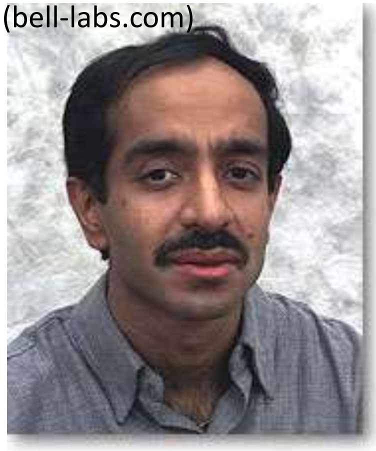
Algorithmic search

N vs $N^{1/2}$



(bell-labs.com)

(bell-labs.com)



Grover’s search

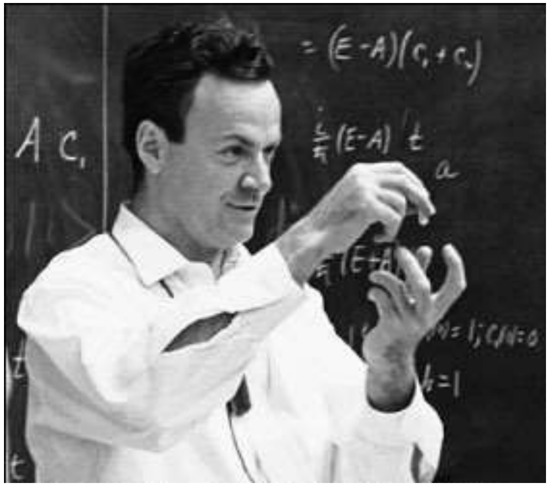
Input	Output
0001	0
0010	0
0011	0
0100	0
0101	1
0110	0
0111	0
1000	0
1001	0
1010	0
1011	0
1100	0
1101	0
1110	0
1111	0

1100 → 0

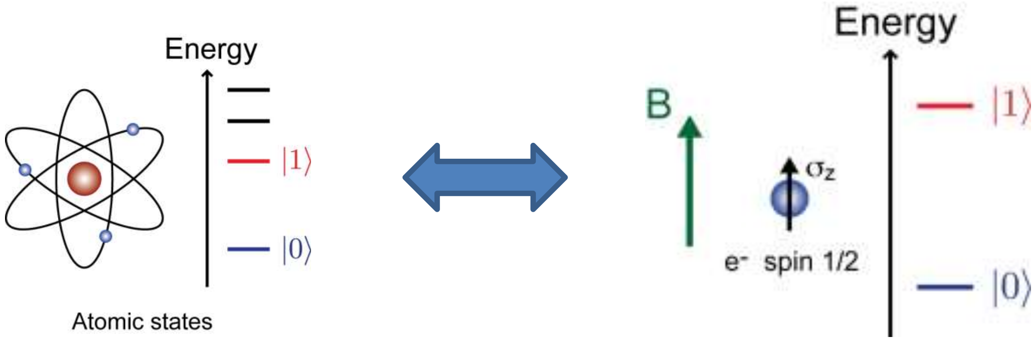
0101 → 1

How many steps before we find the special item?

Quantum simulation



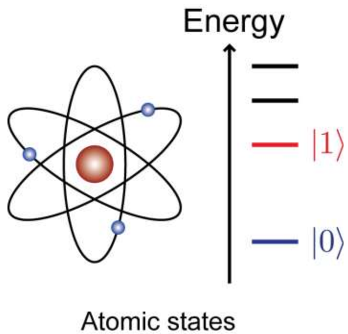
QM on classical computers is difficult



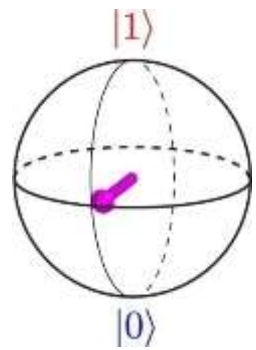
Simulate one type of QM system with another

Requirements

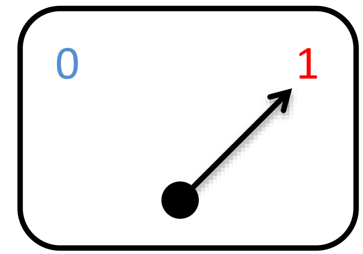
Quantum Two Level Systems



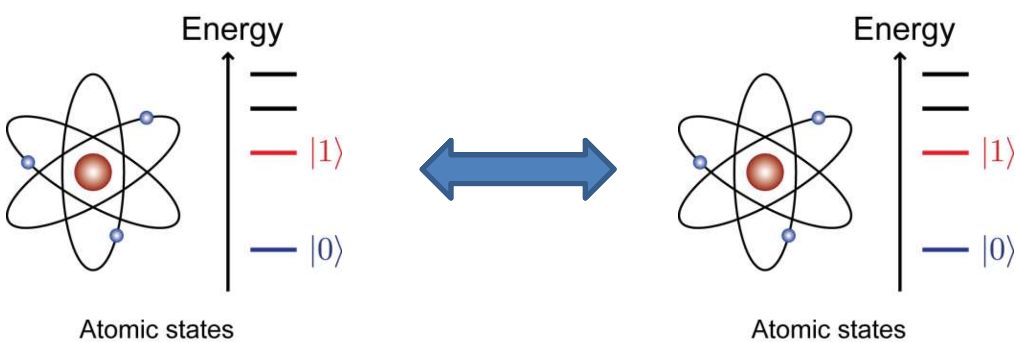
Create arbitrary states



Measure quantum state



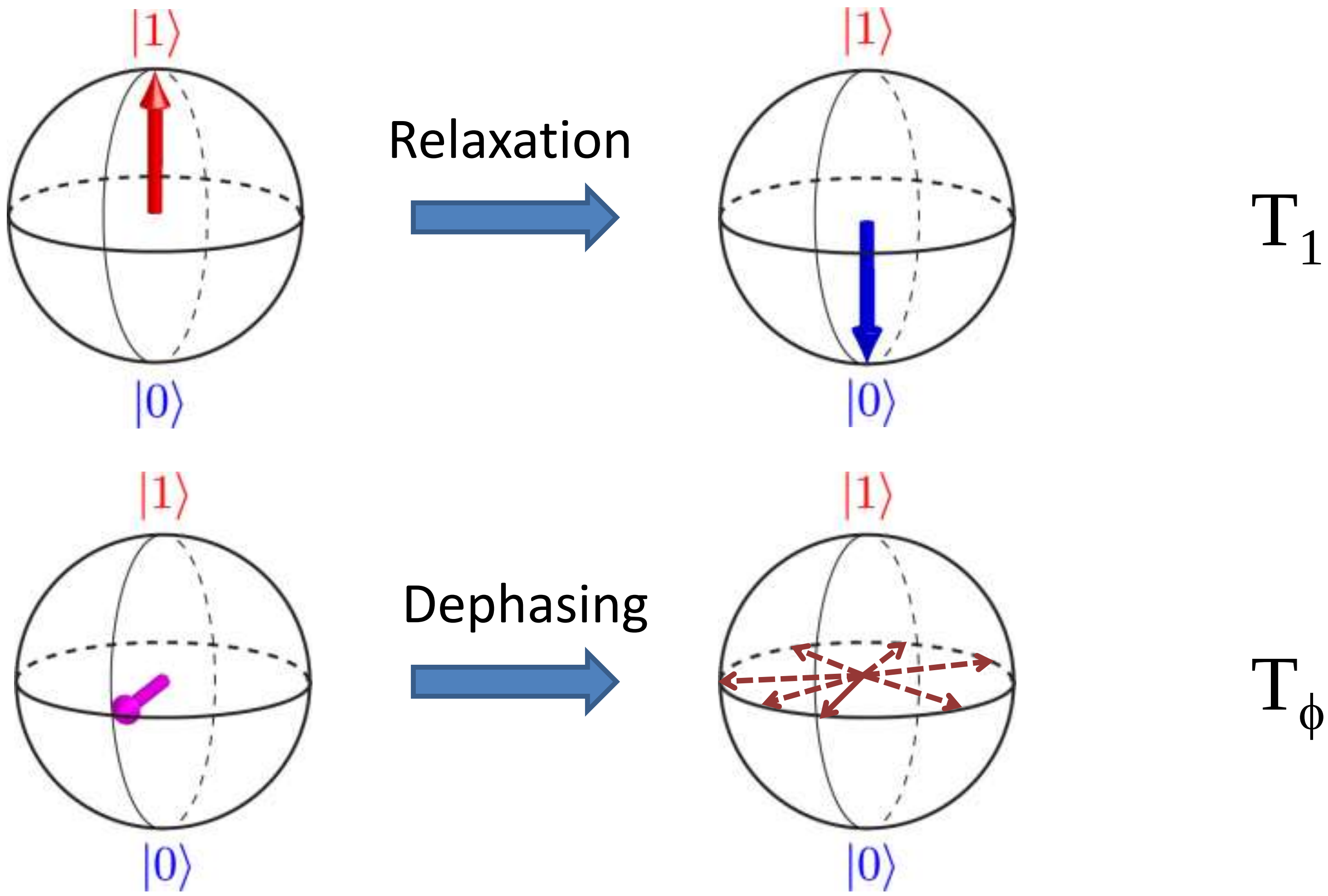
Coupling between qubits



Challenges:

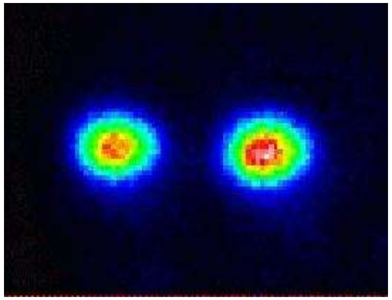
- Finite quantum coherence
- Scaling to large no. of qubits

Quantum coherence

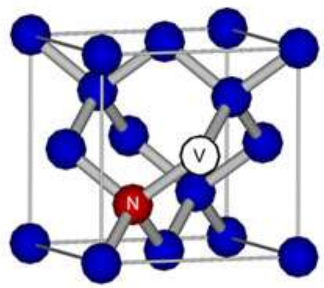


Choosing a quantum system

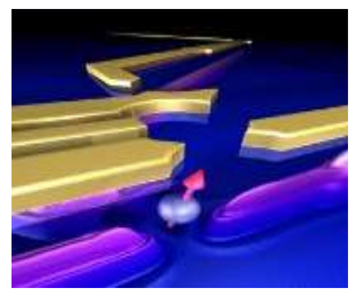
Trapped ions



NV Centers in diamond



Quantum dots



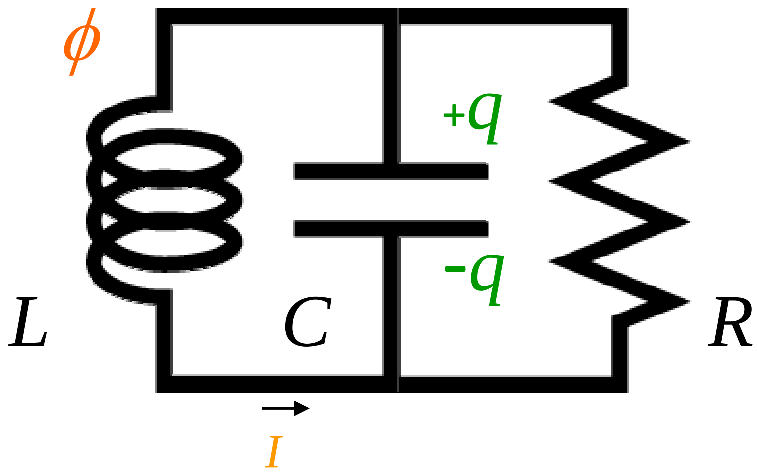
[Macroscopic electrical circuits]()

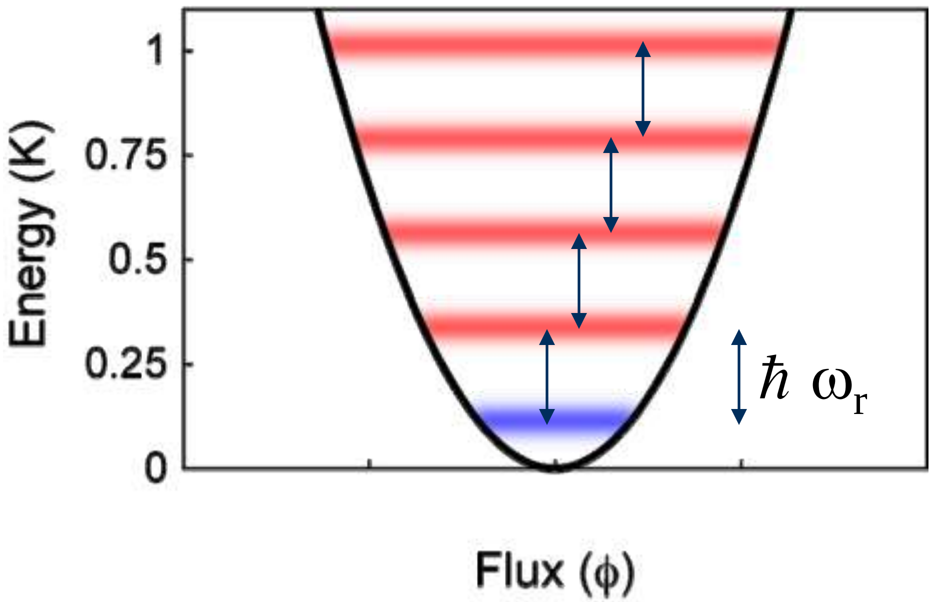
- **Highly tunable**
- **Strong coupling**
- **Coherence**
- **Scalable ?**

Superconducting Circuit

Quantum LC oscillator

$$\omega_r = \frac{1}{\sqrt{LC}}$$





$$[\phi, q] = i\hbar$$

$$\phi = LI$$

$$q = CV$$

$$k_B\, T << \hbar\, \omega_r$$

10 mK 5 GHz ~ 250 mK

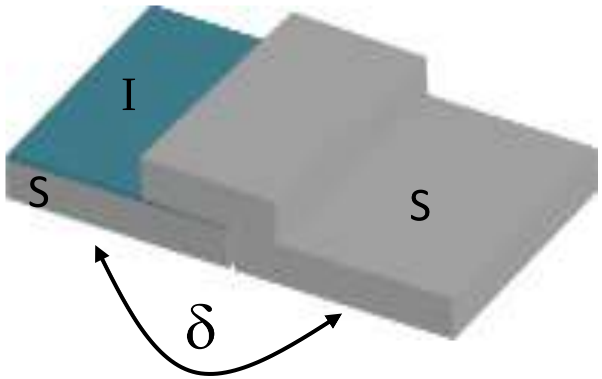
Superconductors

- ZERO DC RESISTANCE BELOW CERTAIN TEMPERATURE
- ZERO AC RESISTANCE BELOW CERTAIN TEMPERATURE/FREQUENCY

CONSTRUCT CIRCUITS WITH MINIMAL DISSIPATION

ACCESS TO A NON-DISSIPATIVE, NON-LINEAR CIRCUIT ELEMENT

Josephson junctions



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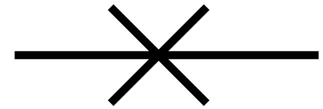
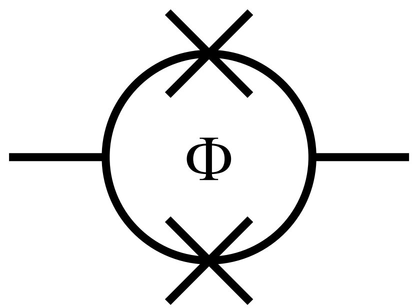


$$I = I_0 \sin \delta$$

SQUID



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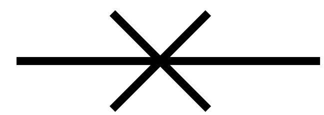
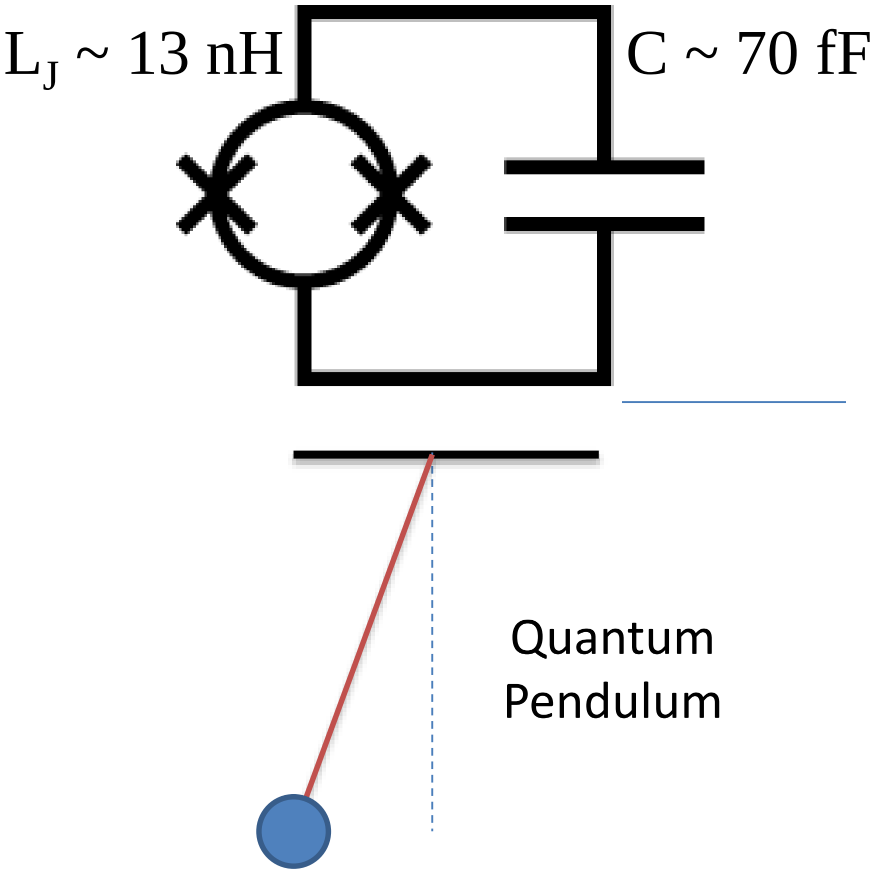


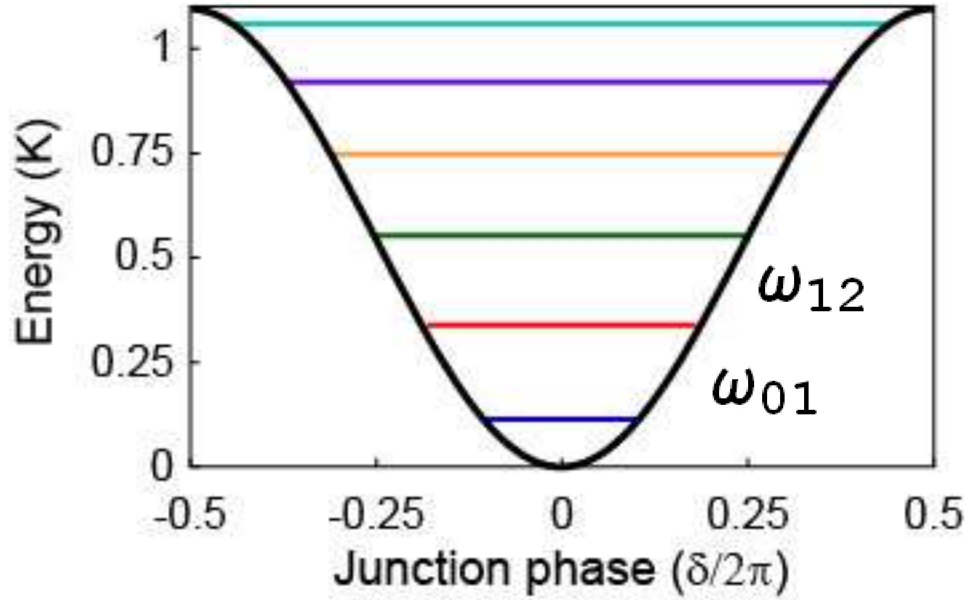
$L_J(\Phi)$

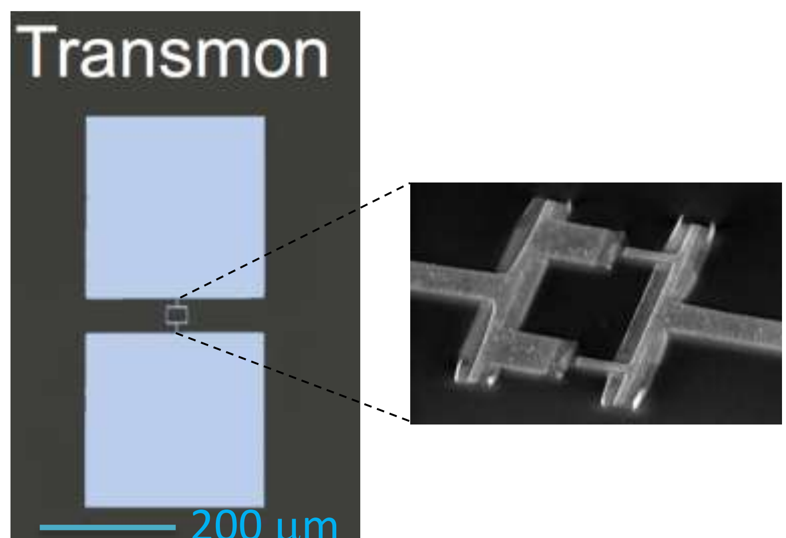
Flux tunable , Nonlinear , Non-dissipative , Inductor

Superconducting qubit: Anharmonic oscillator



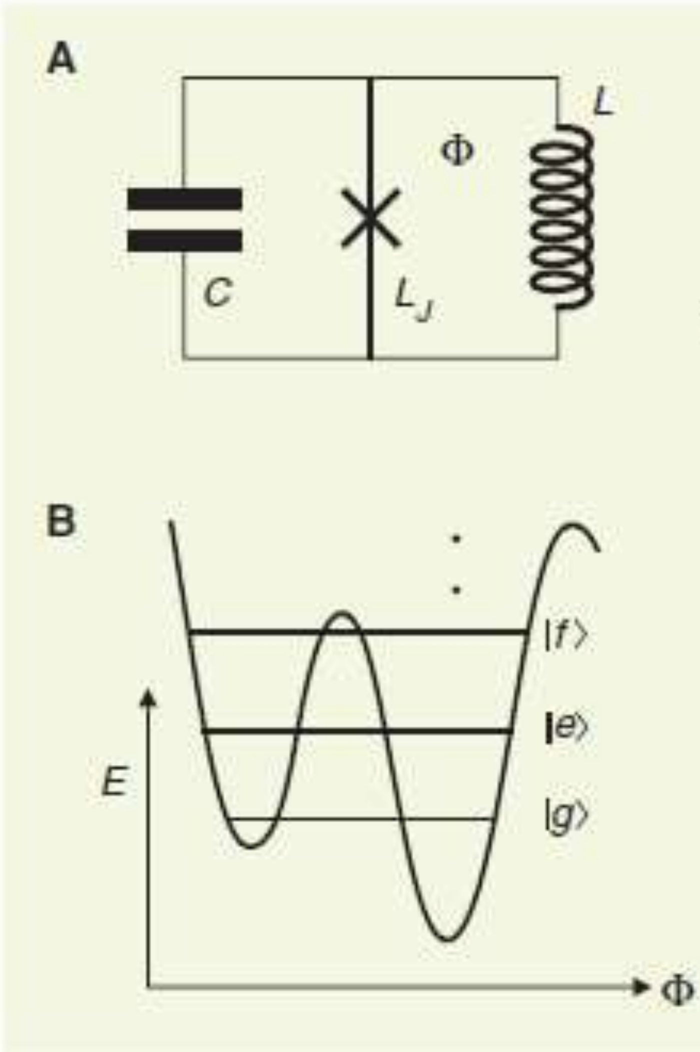
Quantum
Pendulum





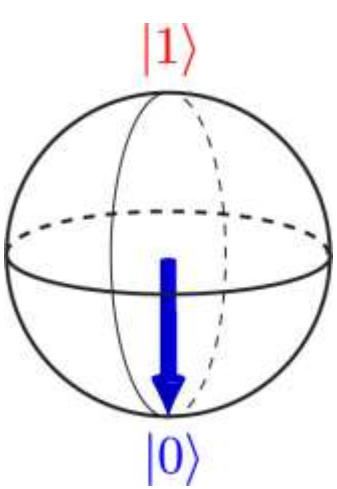
Koch et al. , Phys. Rev. A 76, 042319 (2007)

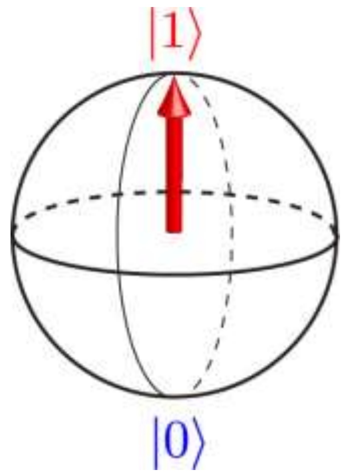
Qubit designs

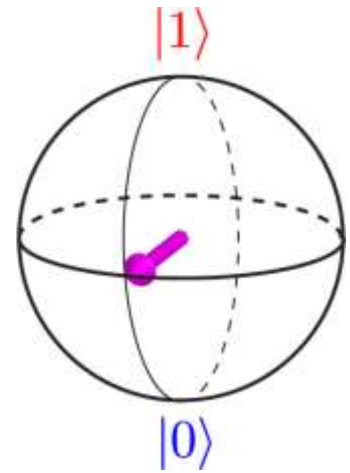


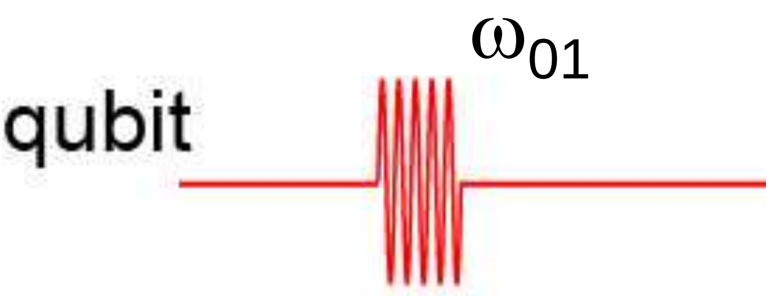
Devoret and Schoelkolpf, Science **339**, 1169 (2013)

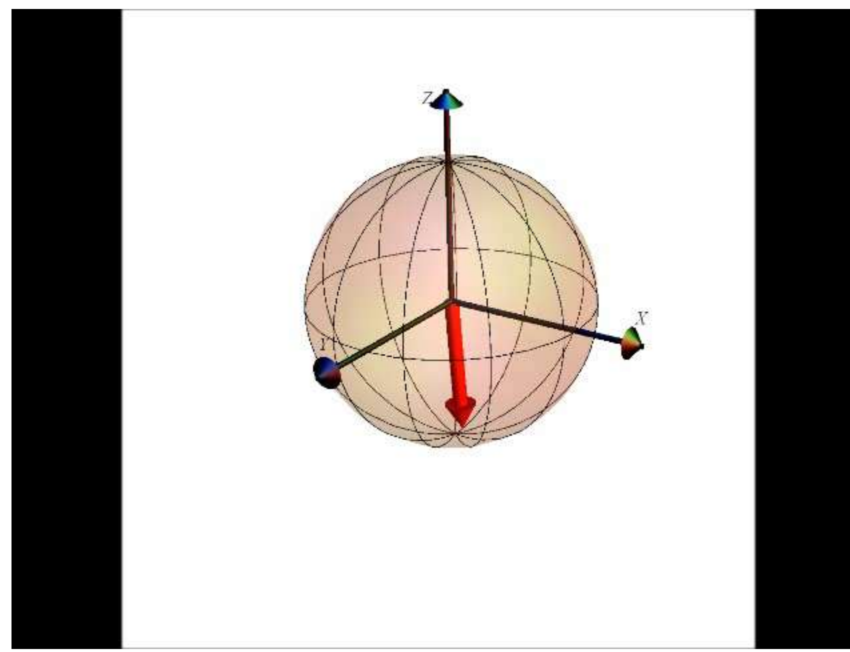
Quantum State Preparation





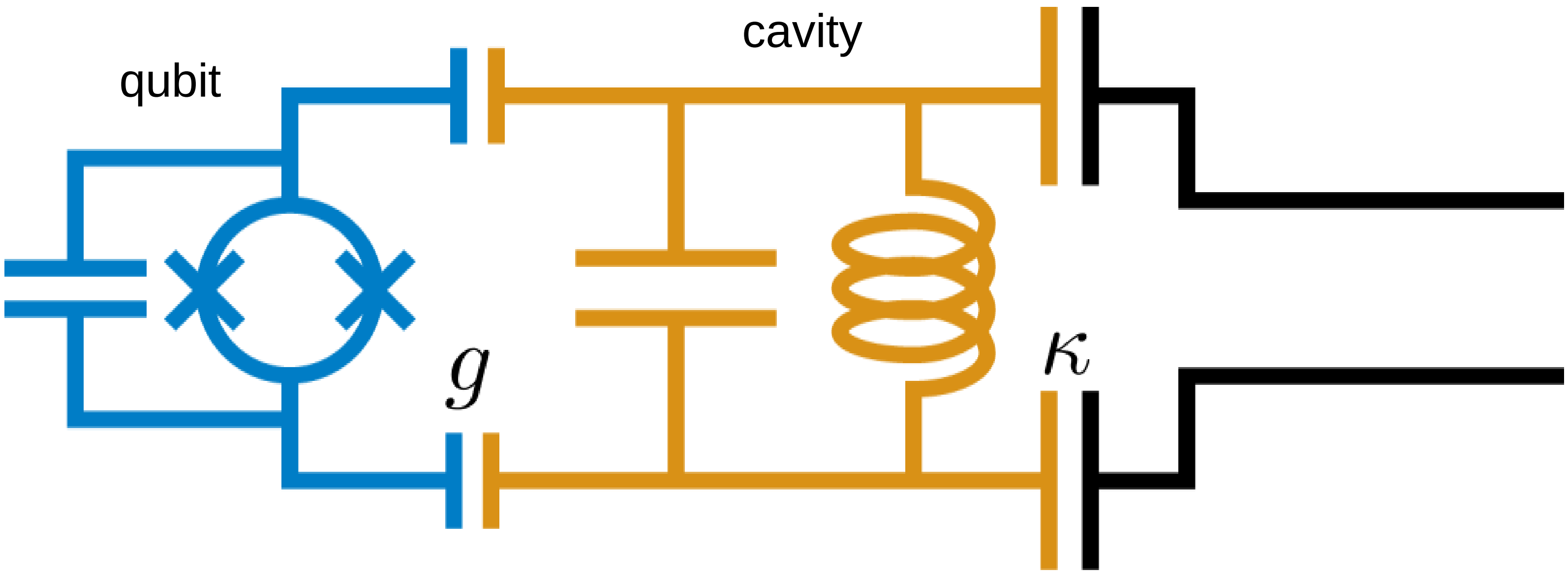


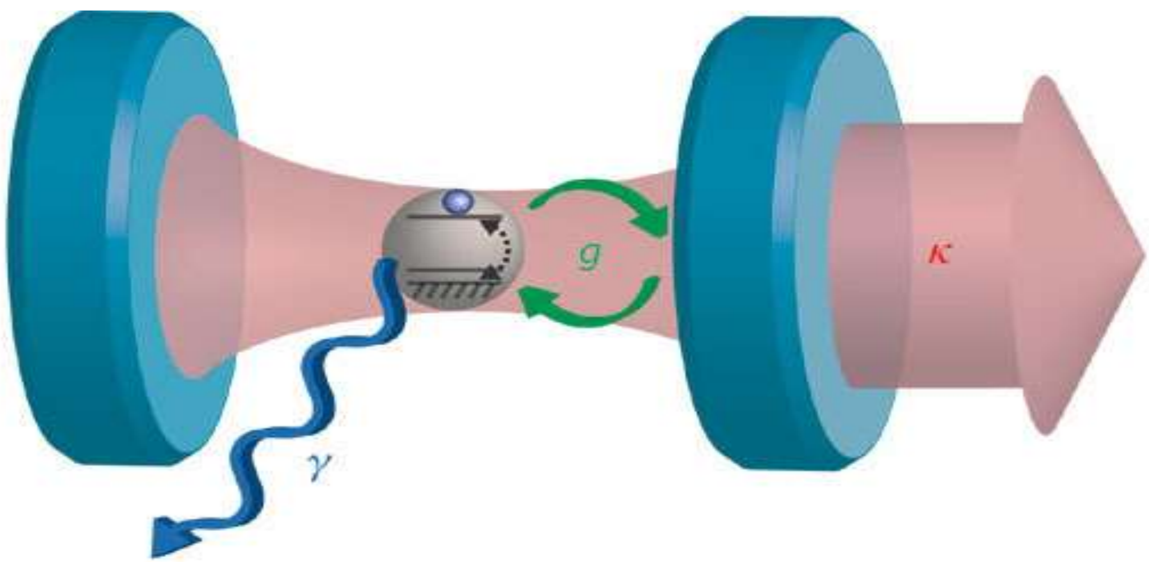




Control amplitude , length and phase of microwave pulse

Measurement architecture

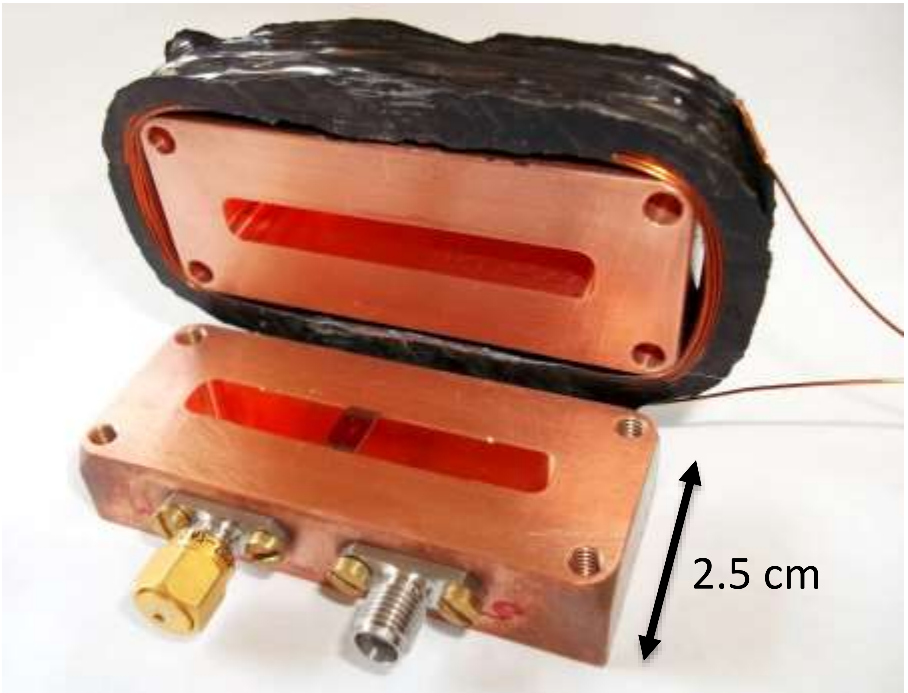


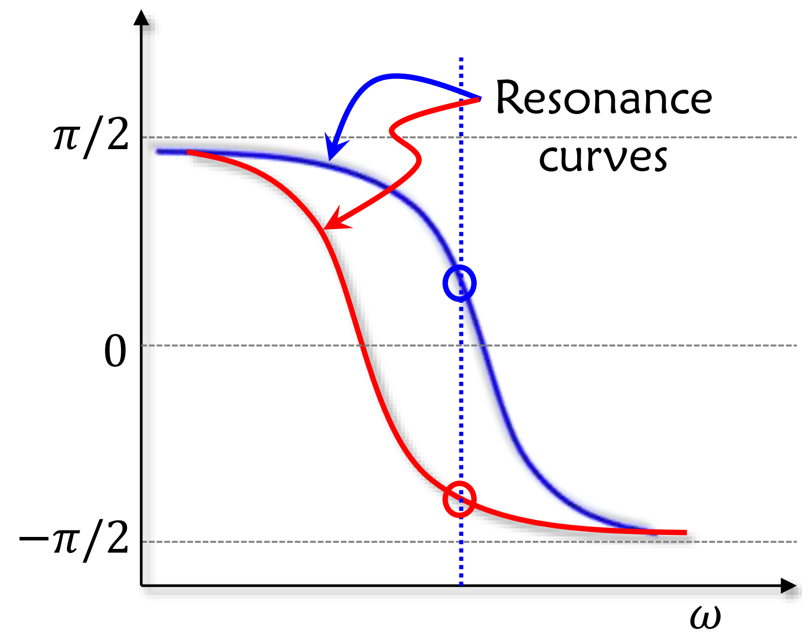


Blais et al. , Phys. Rev. A 69, 062320 (2004)

"Artificial" atom in a cavity

"3D Transmon"





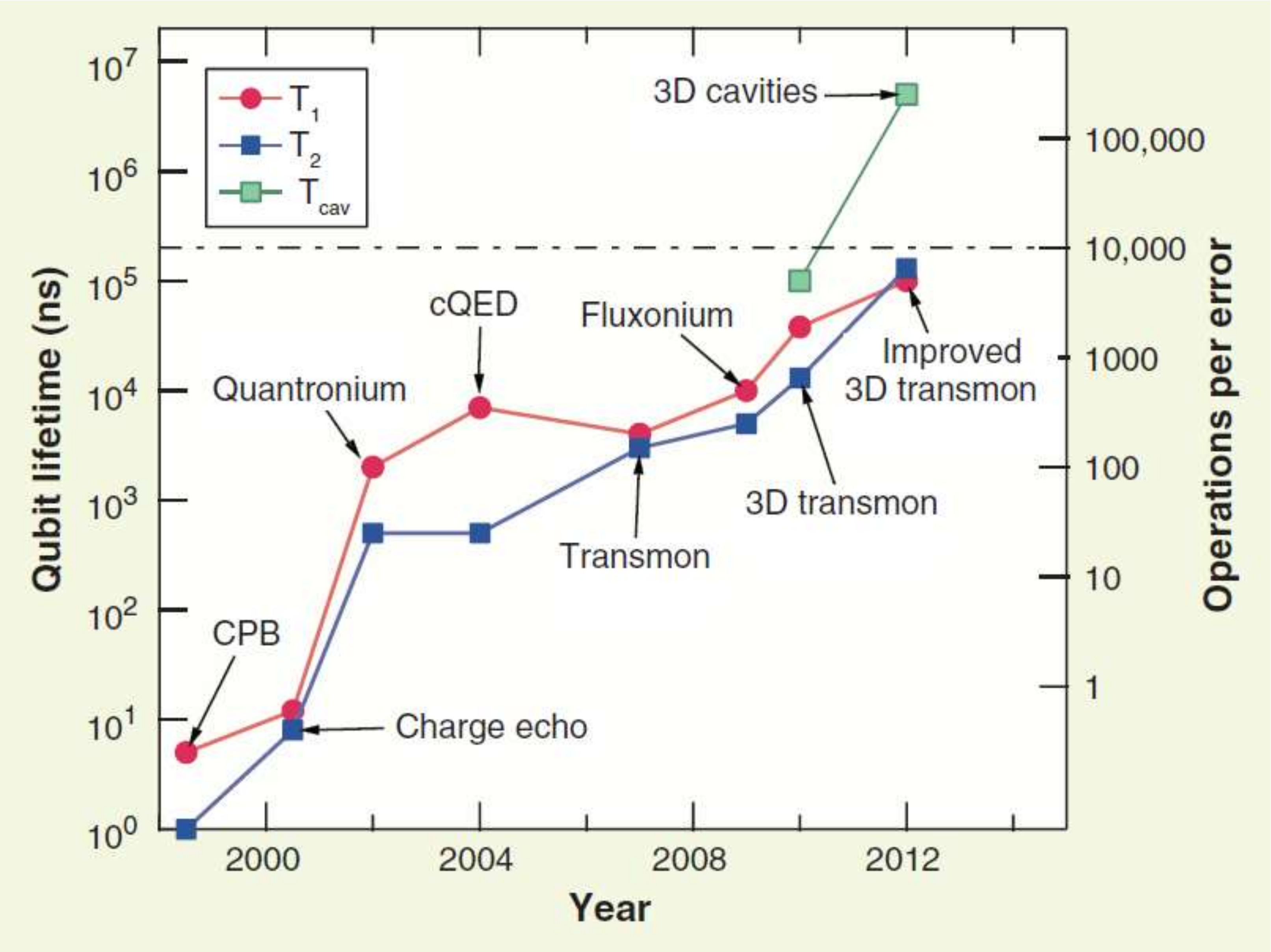
Transmitted Signal Phase shifts

- Cavity protects the qubit
- Manipulate and measure using microwave signals

H. Paik et al. Phys. Rev. Lett. **107**, 240501 (2011)

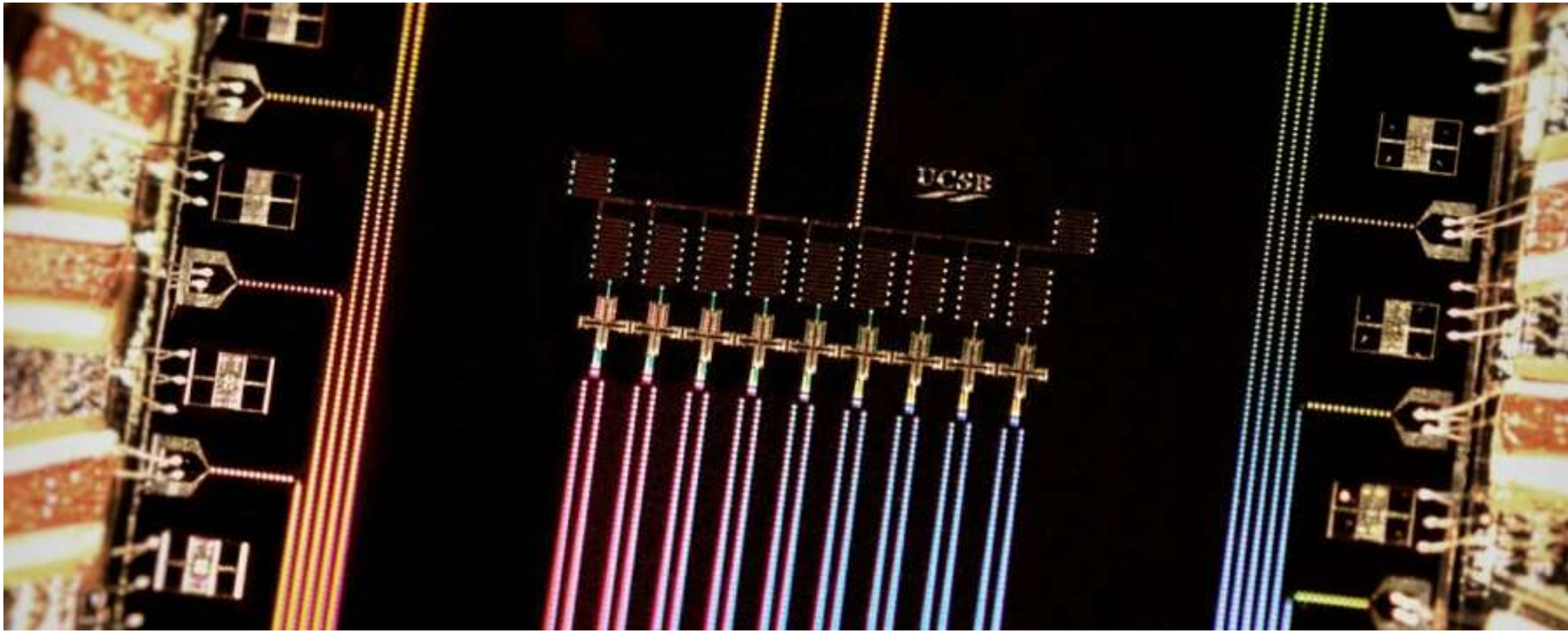
Progress using superconducting circuits

Qubit coherence



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

Multi-qubit sytems



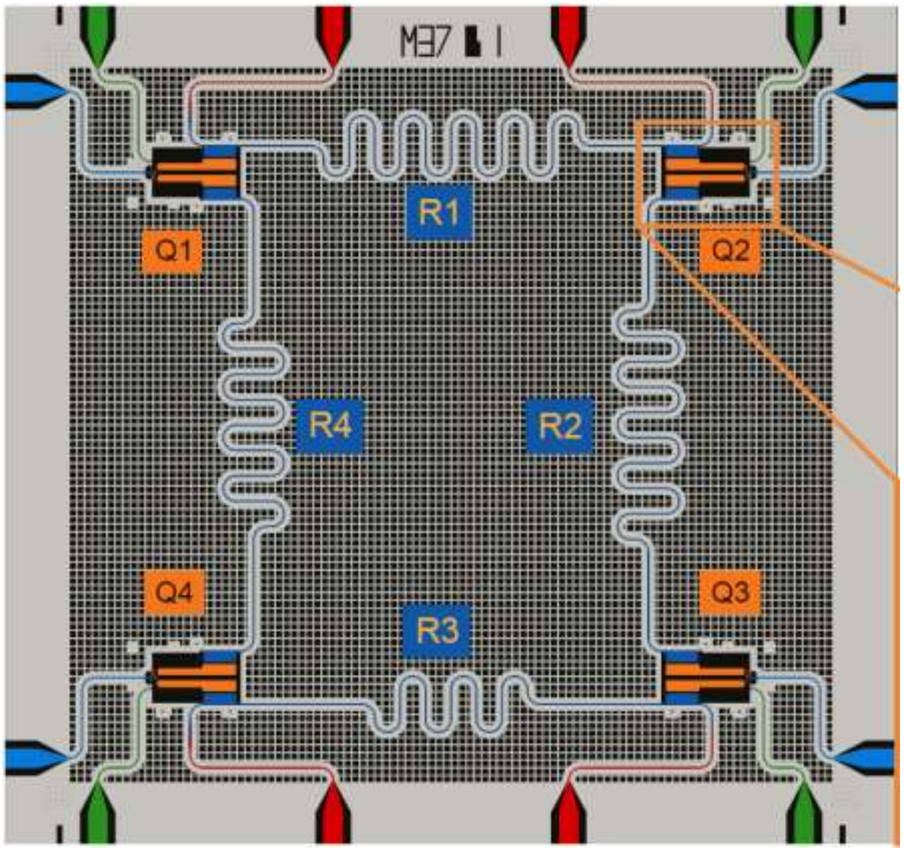
9-qubit processor

Martinis Group, UCSB (Now Google)

State preservation by repetitive error detection in a superconducting quantum circuit

Nature 519, 66–69 (05 March 2015)

Multi-qubit sytems



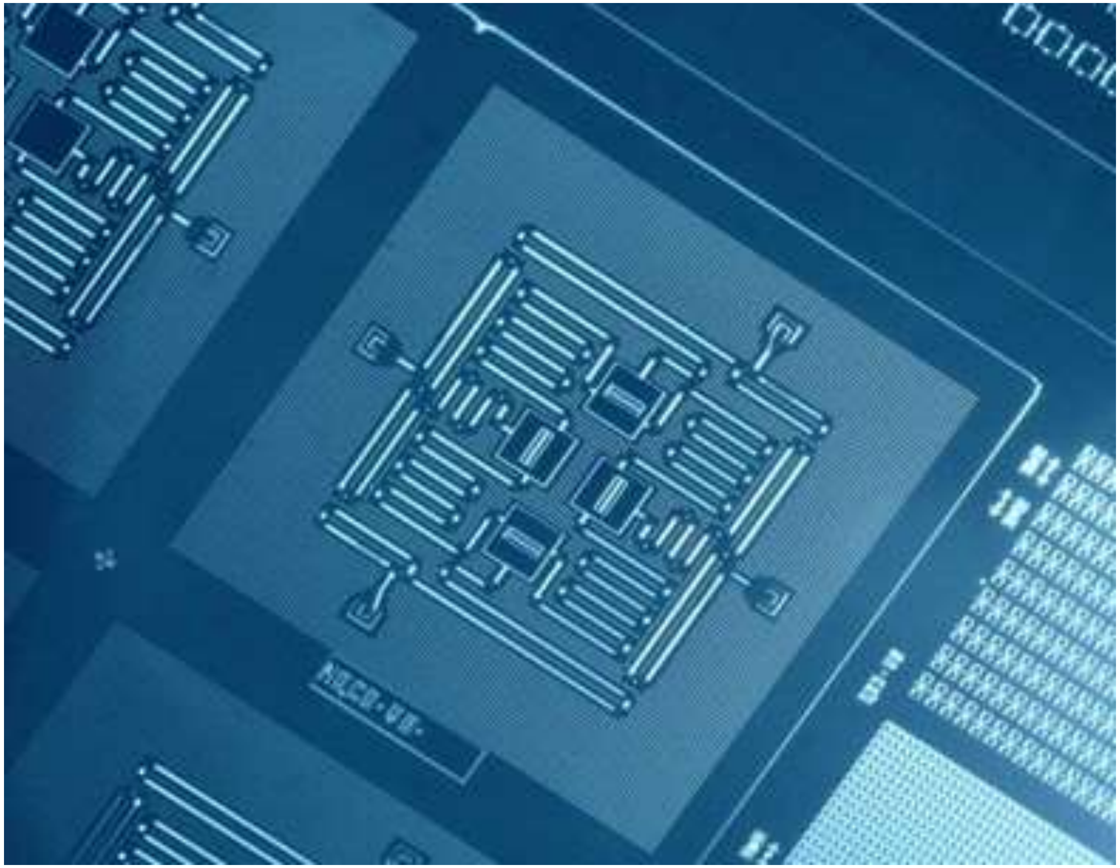
4-qubit processor

Wallraff Group ,
ETH, Zurich

Digital quantum simulation of spin models

Phys. Rev. X 5, 021027 (2015)

Multi-qubit sytems



4-qubit processor

IBM Group
USA

Have put a 5-qubit quantum processor on the cloud for public access

Demonstration of a quantum error detection code

Nature Communications **6**, Article number: 6979 (2015)

http://www.research.ibm.com/quantum/

Industrial Ventures

D-Wave Systems :

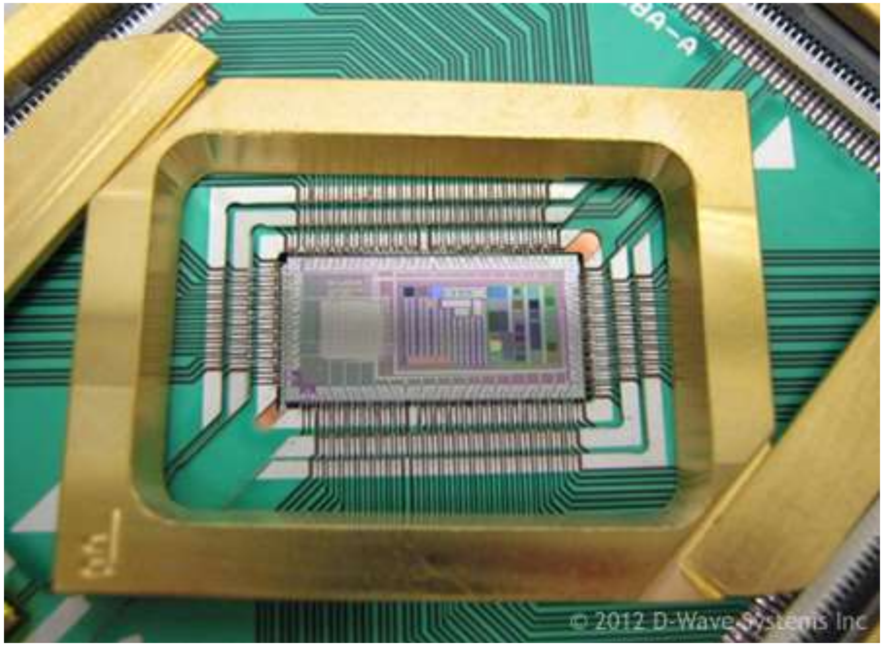
- Launched the first commercial system called D-Wave One
- Superconducting circuit technology operating at 10 mK
- Latest machine D-Wave Two has 512 "qubits"
- Adiabatic computing
- Many are using this machine including NASA & Google

IBM Research

Google

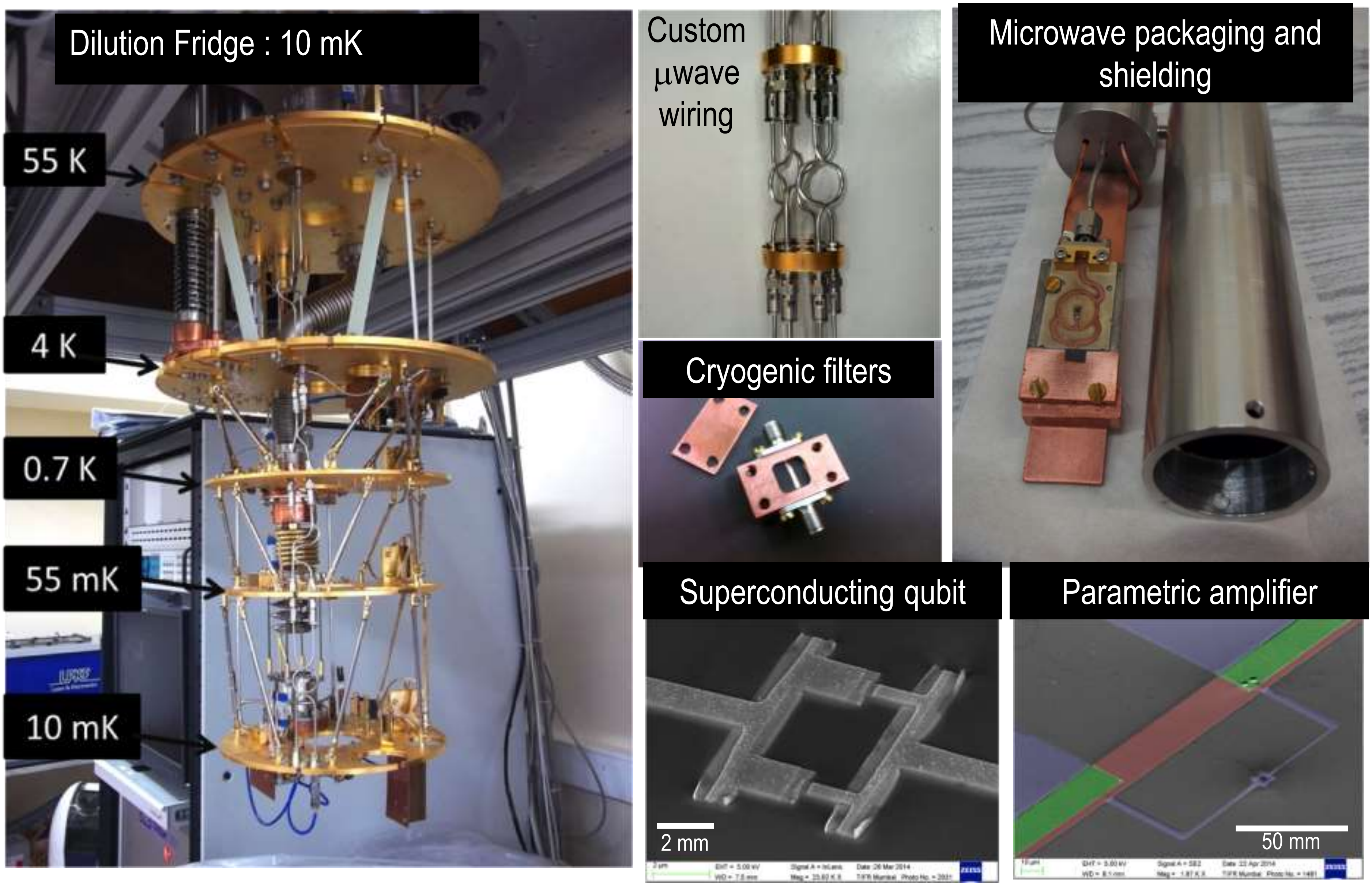
Startups (USA):

1. Rigetti Quantum Computing
2. Quantum Circuits Incorporated

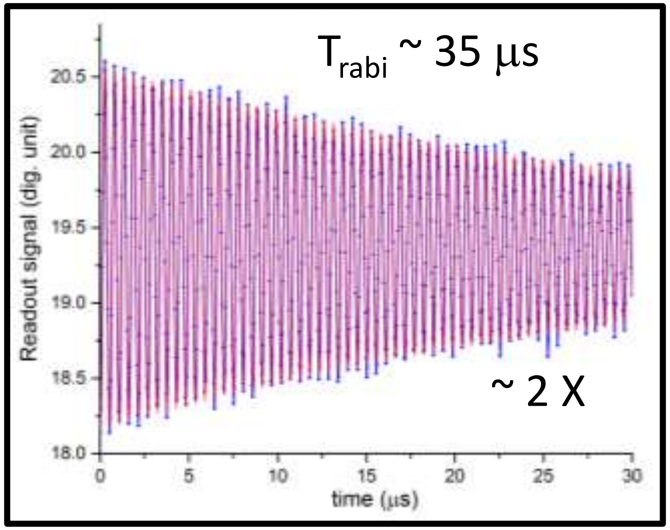


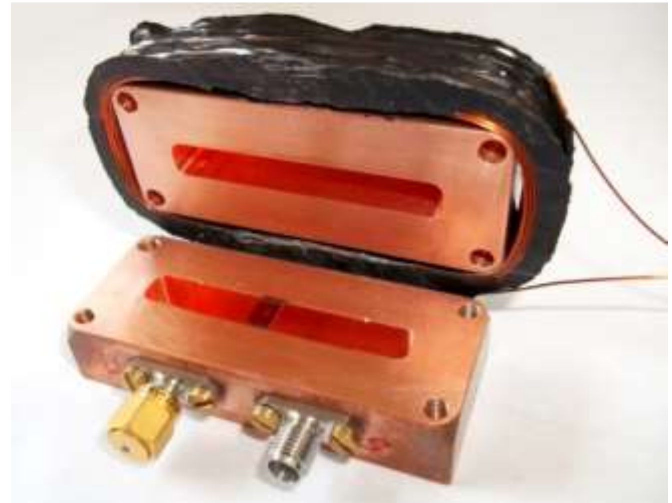
Quantum Computing
at the
Quantum Measurement and Control Lab
TIFR, Mumbai

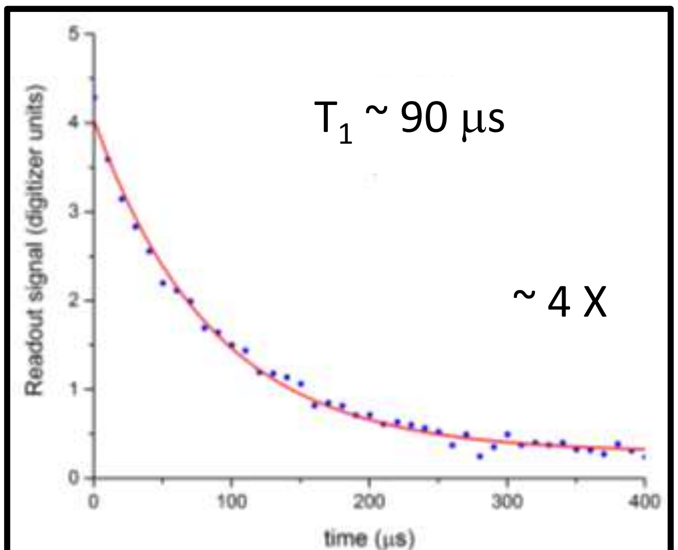
Ultra-low noise cryogenic setup

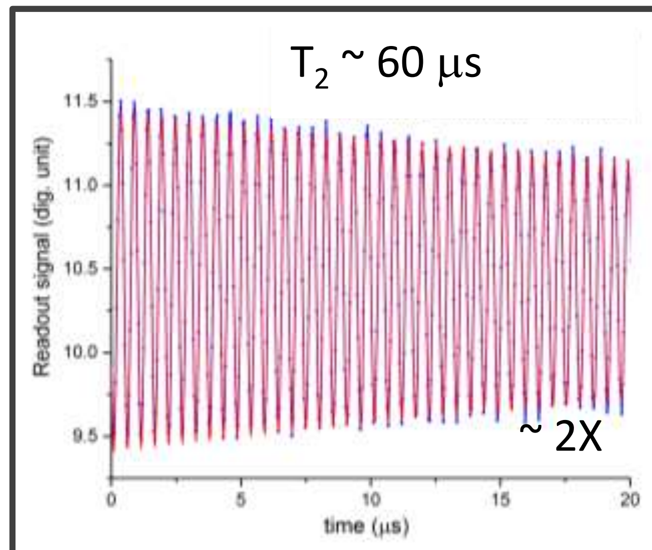


Good Qubit Coherence

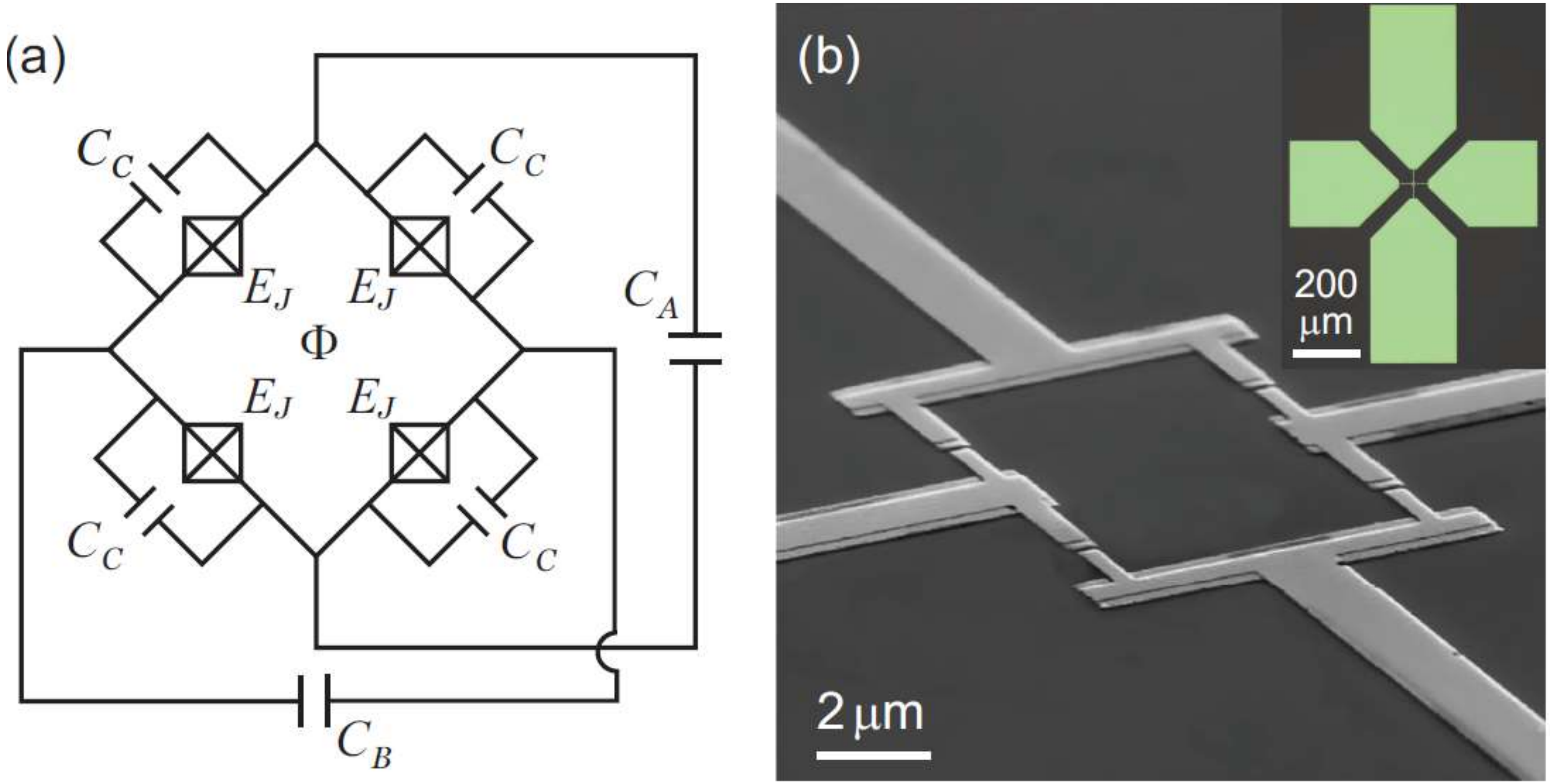






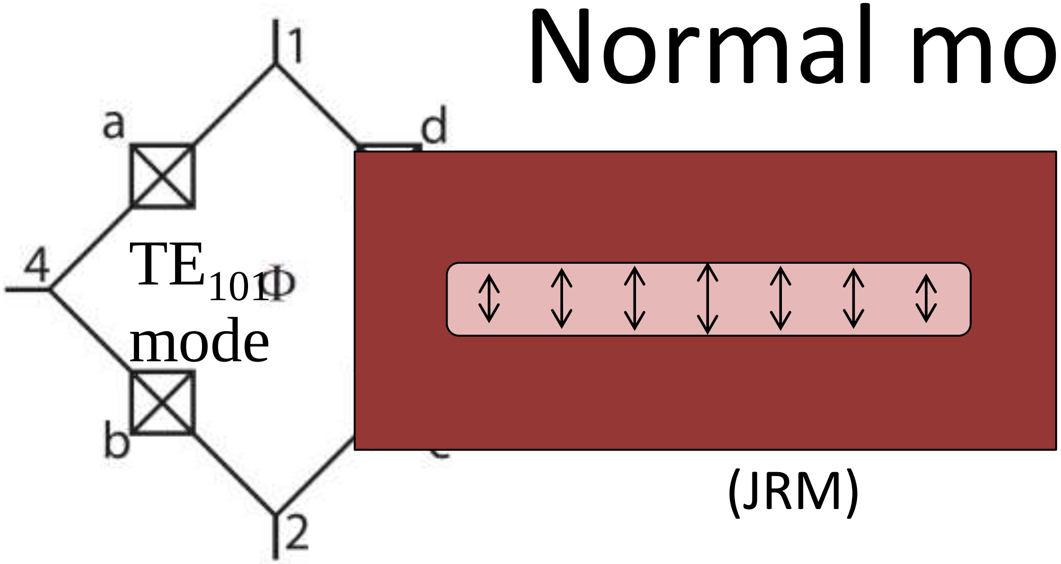


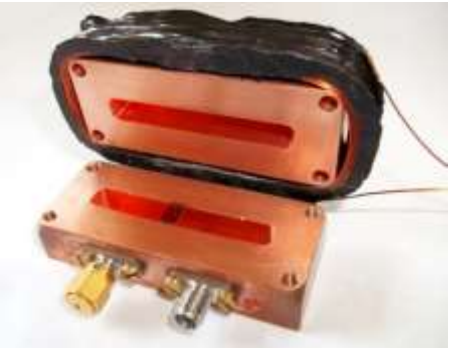
A novel three-qubit circuit: **Trimon**



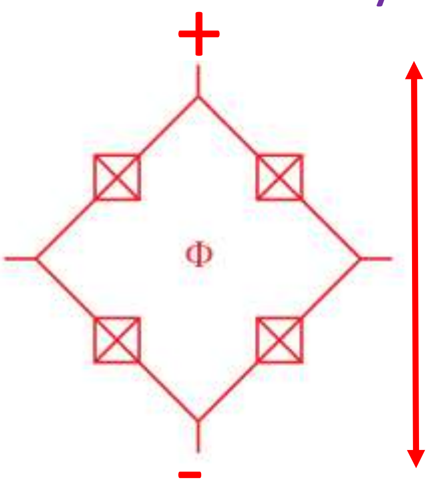
Tanay Roy, Suman Kundu et al., arXiv:1610.07915v1 (2016)

Normal modes

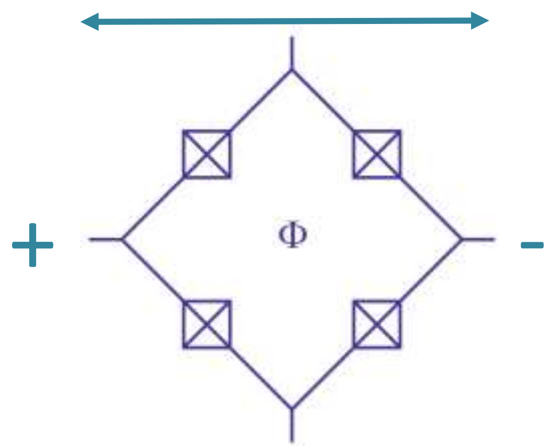




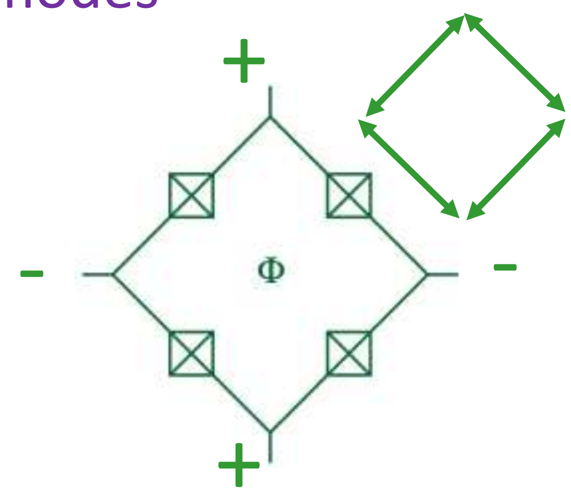
Symmetry of the circuit: 3 normal modes



A: dipolar mode



B: dipole orthogonal to A



C: quadrupolar mode

N. Bergeal et al, Nat. Phys. **6** 296 (2010)

System Hamiltonian

$H_{coupled\ qubit\ system}$

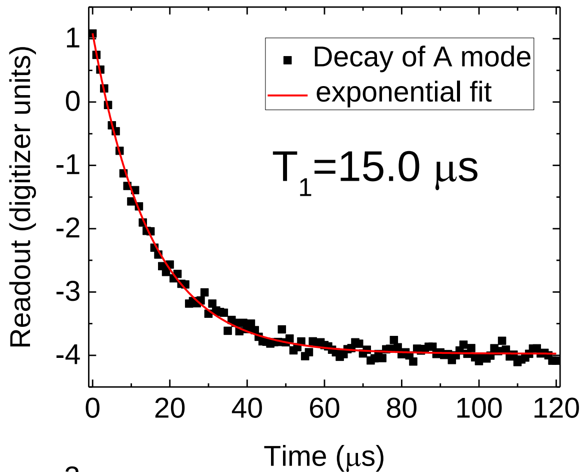
$= \omega^A \sigma_Z^A + \omega^B \sigma_Z^B + \omega^C \sigma_Z^C + \cdots$ 3 qubits

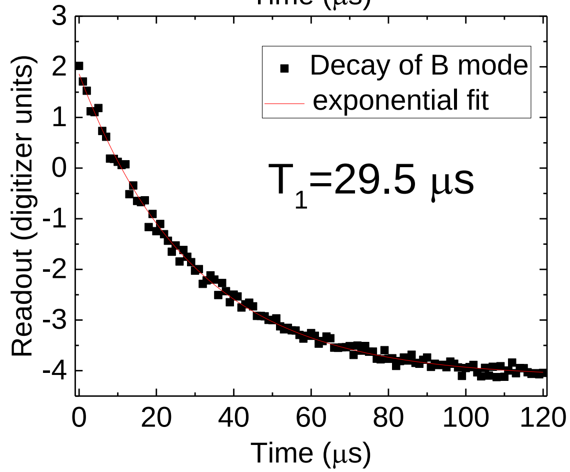
$+a^\dagger a\ (\omega_{cavity} + \chi^A \sigma_Z^A + \chi^B \sigma_Z^B + \chi^C \sigma_Z^C)$ Coupling to the cavity (measurability)

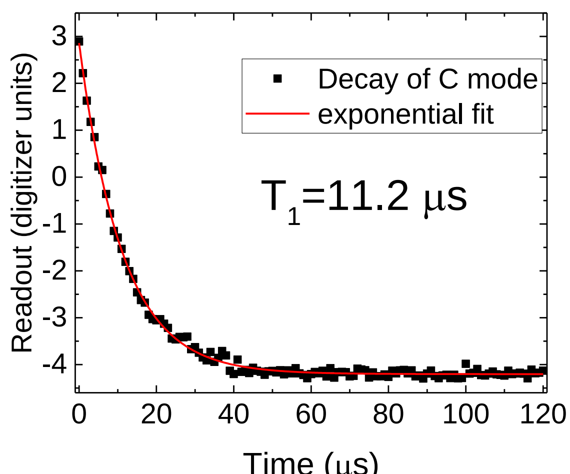
$+g_{AB}\sigma_Z^A\sigma_Z^B + g_{BC}\sigma_Z^B\sigma_Z^C + g_{CA}\sigma_Z^C\sigma_Z^A$ Pairwise $\sigma_Z\sigma_Z$ coupling

Tanay Roy, Suman Kundu et al., arXiv:1610.07915v1 (2016)

Coherence







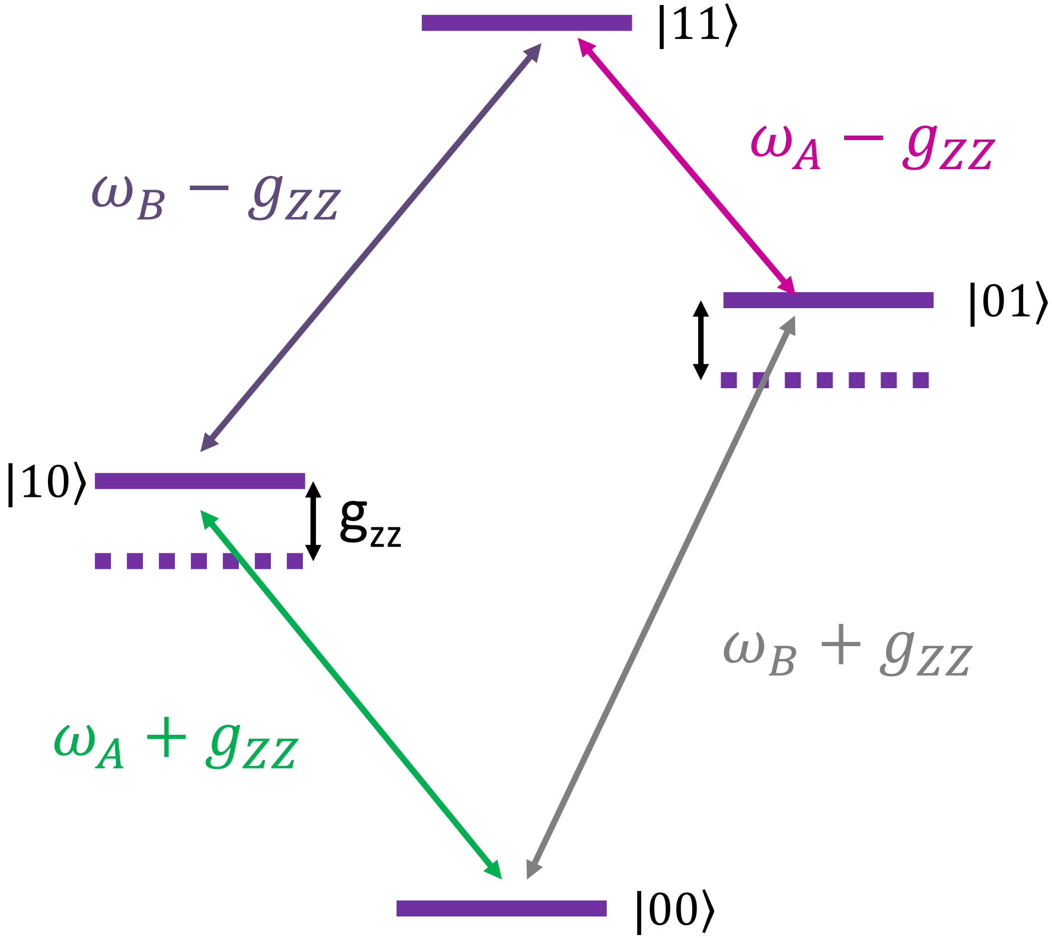
RT15_1 measured at cavity frequency = 7.267 GHz

Mode	Frequency (GHz)	T_1 (μs)
A	5.687	15.0
B	6.290	29.5
C	7.175	11.2

RT15_2 measured at cavity frequency = 7.2354GHz

Mode	Frequency (GHz)	T_1 (μs)
A	5.5585	20.46
B	6.14682	51.42
C	7.018	20.6

Pairwise $\sigma_z\sigma_z$ coupling

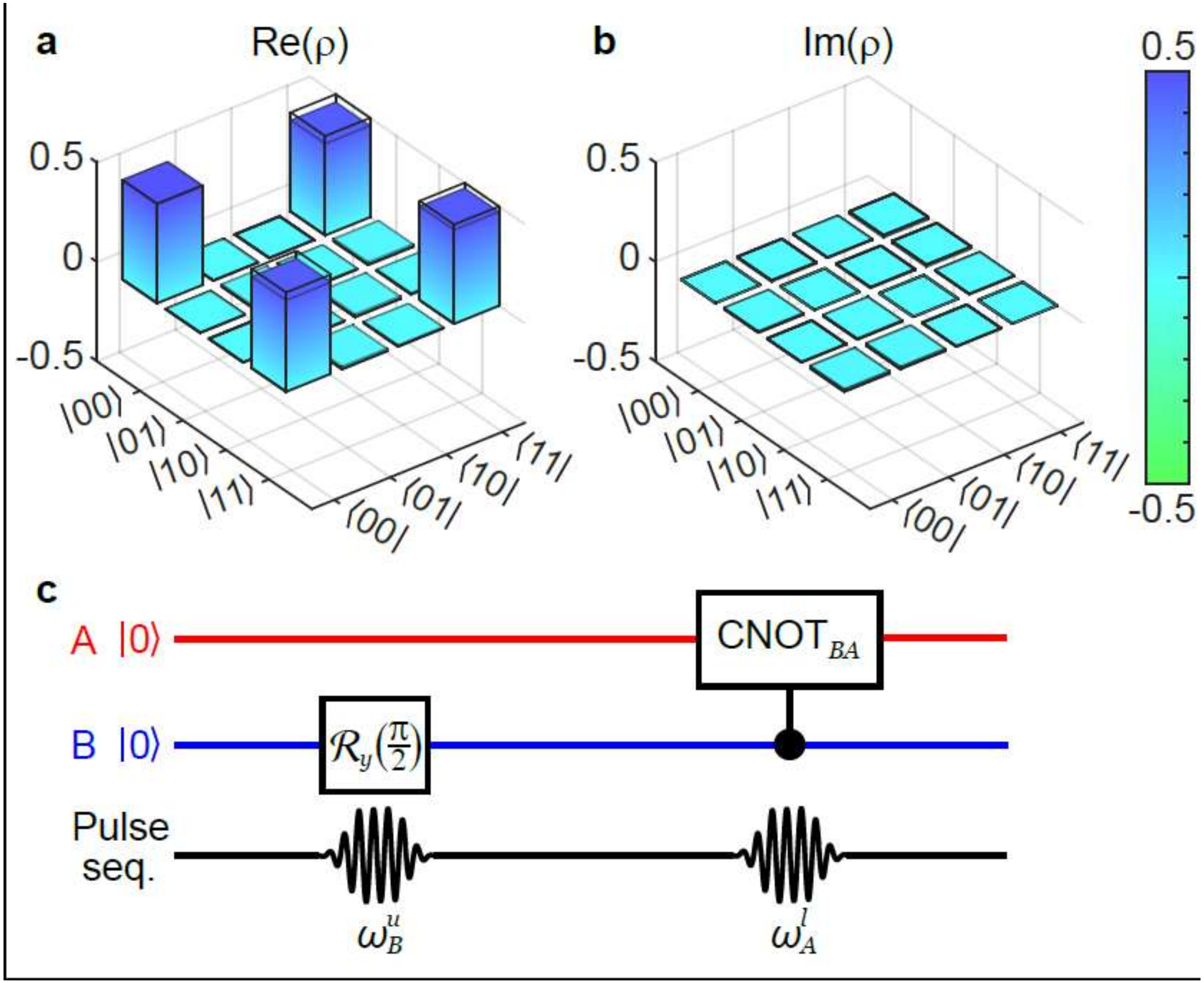


Address specific transitions

Not individual qubits

$\sigma_Z\sigma_Z$ enables CNOT

Bell state preparation

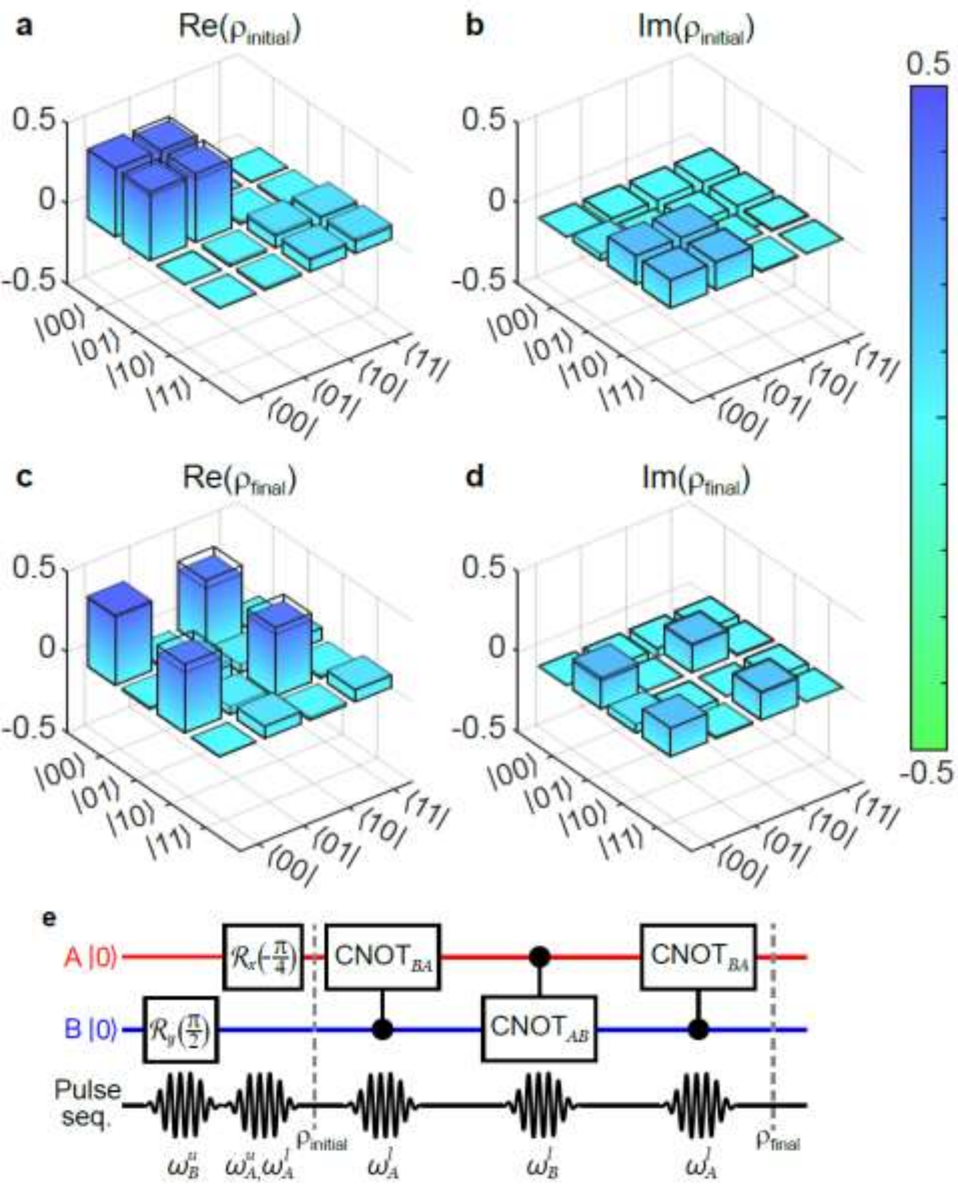


$$\frac{|\mathbf{00}\rangle + |\mathbf{11}\rangle}{\sqrt{2}}$$

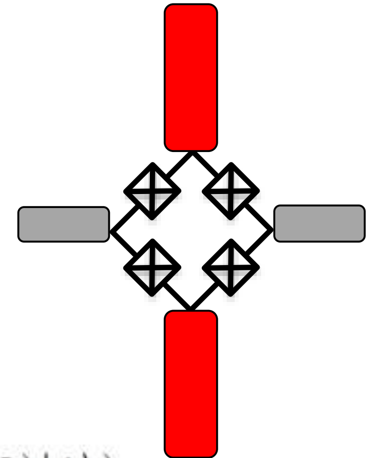
Fidelity: 97.4 %

Tanay Roy, Suman Kundu et al., arXiv:1610.07915v1 (2016)

State swap operation

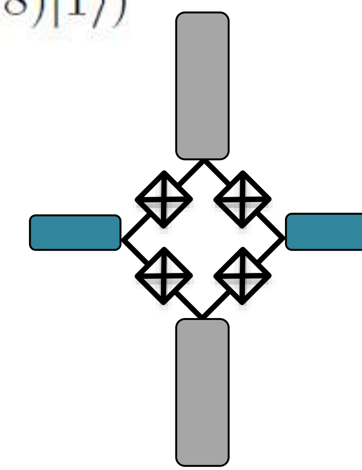


Fidelity: 98.3 %



$$(\cos(\pi/8)|0\rangle + i\sin(\pi/8)|1\rangle)$$

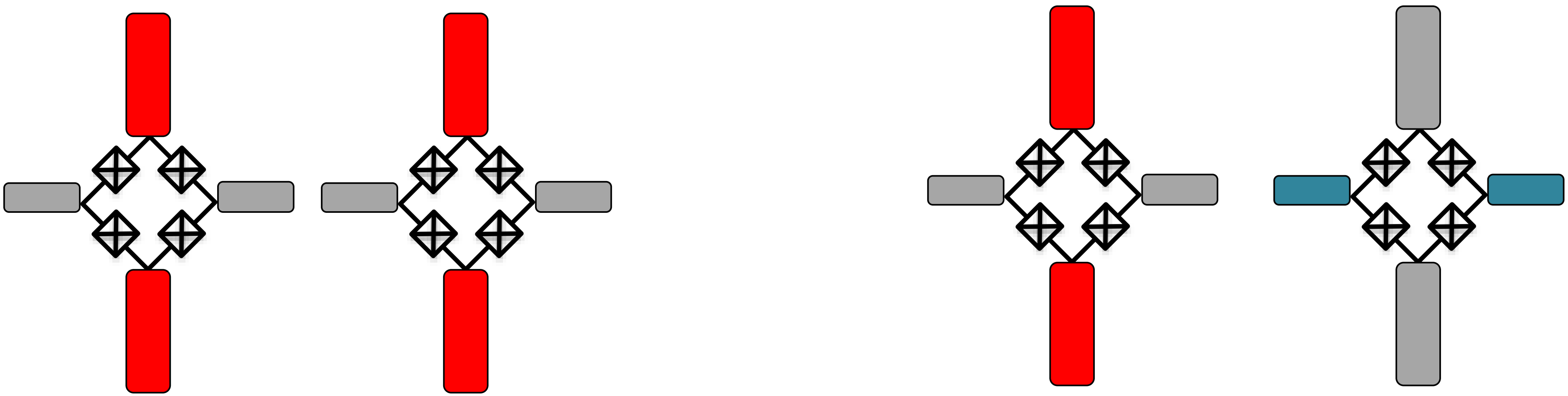
Fidelity: 97.1 %



Tanay Roy, Suman Kundu et al., arXiv:1610.07915v1 (2016)

Live Demo

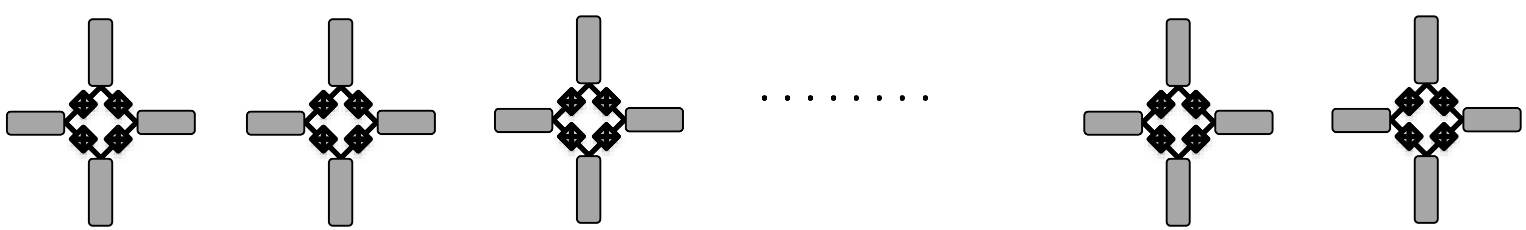
Coupling Trimons



Strongly Coupled

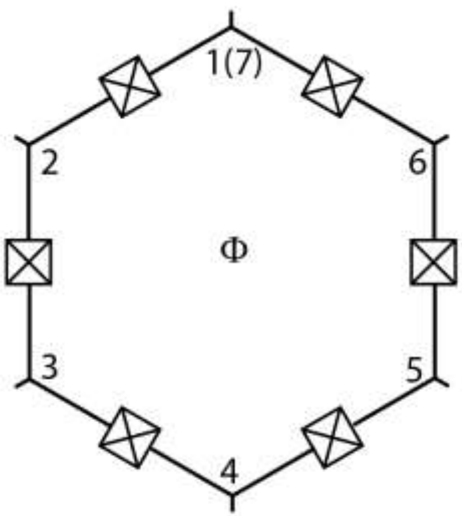
Weakly Coupled

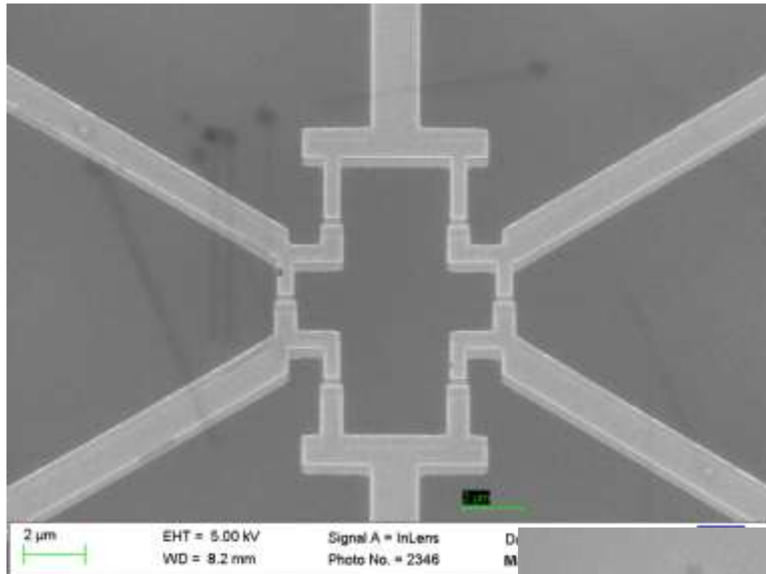
Spin chains: Mode switching can turn coupling ON/OFF

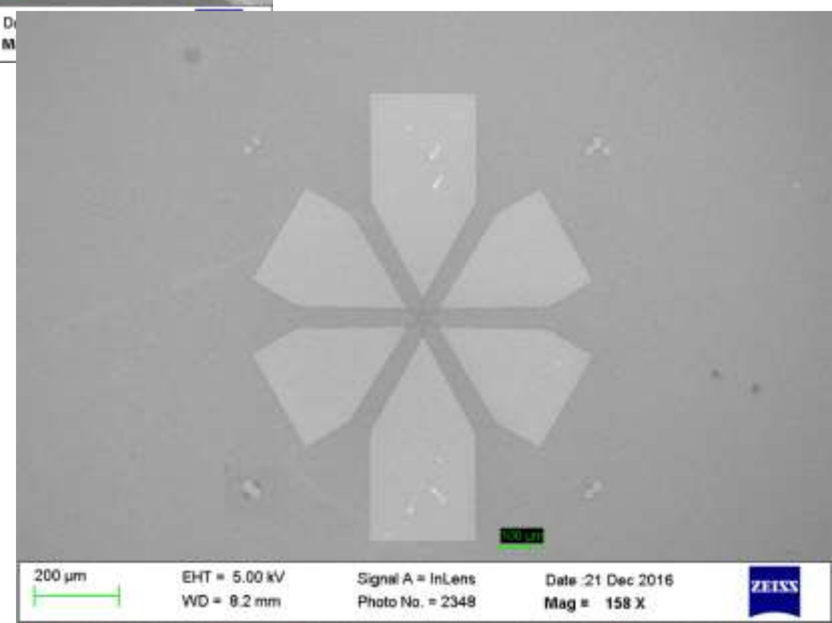


Expansion to more junctions

Six Junction Ring: 5 coupled qubits







Preliminary results look promising

Madhavi Chand et al. , (in progress)

In collaboration with Kedar Damle

Quantum Error Correction

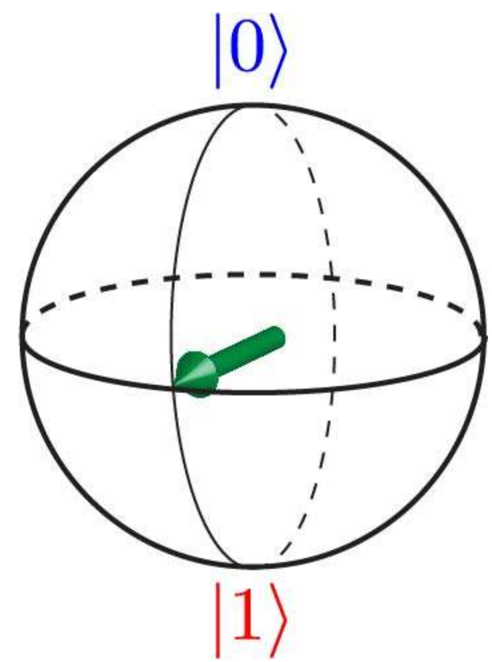
CLASSICAL ERROR CORRECTION:

0 → 000 1 → 111

REDUDANCY , MAJORITY VOTE

CAN WE DO THIS WITH QUANTUM BITS?

- NO CLONING THEOREM
- CONTINUOUS ERRORS
- MEASUREMENT DESTROYS STATE



Quantum Error Correction

Multiple physical qubits for one logical qubit

Example: Shor's three qubit bit-flip code

$\Psi = \alpha\,|0\rangle + \beta\,|1\rangle$ → $\Psi = \alpha\,|000\rangle + \beta\,|111\rangle$

<u>Protects against single bit flip errors</u>

$\Psi = \alpha\,|000\rangle + \beta\,|111\rangle$

$\Psi = \alpha\,|\underline{1}00\rangle + \beta\,|\underline{0}11\rangle$

$\Psi = \alpha\,|0\underline{1}0\rangle + \beta\,|1\underline{0}1\rangle$

$\Psi = \alpha\,|00\underline{1}\rangle + \beta\,|11\underline{0}\rangle$

Distinguish these four possibilities

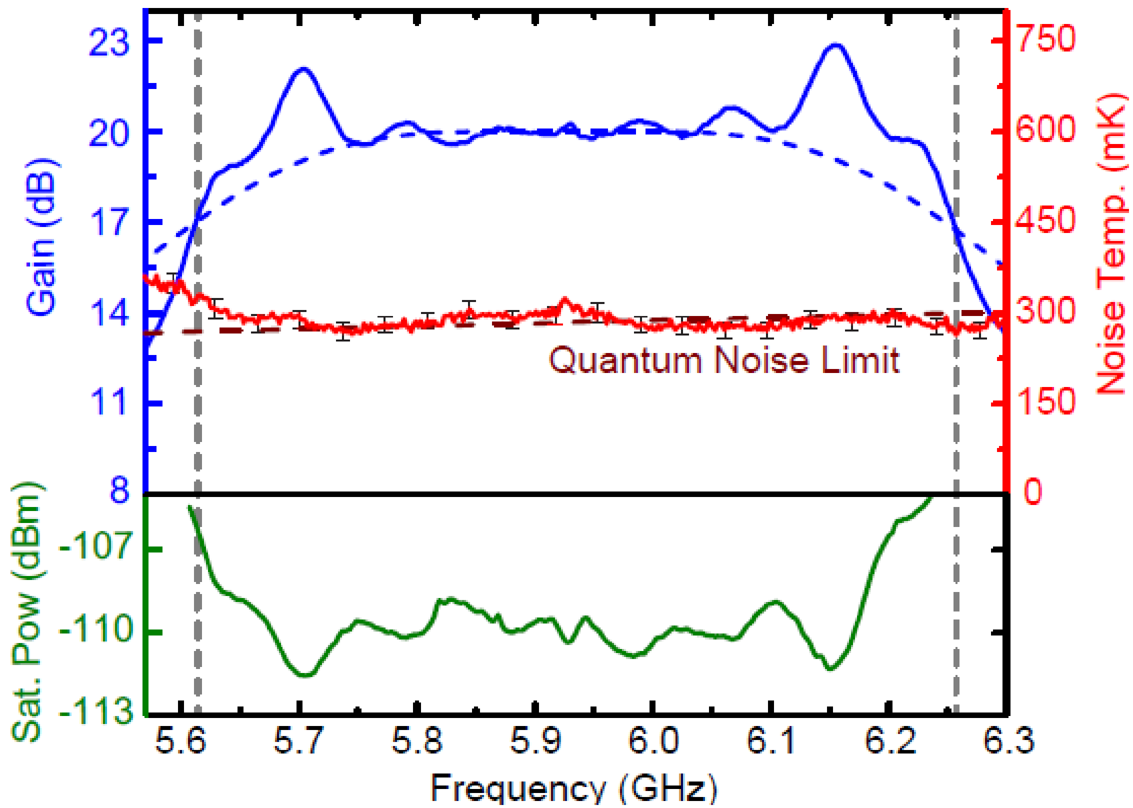
MEASURE THE ERROR, NOT THE STATE : PARITY MEASUREMENTS

THREE-QUBIT BUILDING BLOCK NATURALLY SUITED FOR QEC

Suman Kundu et al. , (in progress)

Other projects

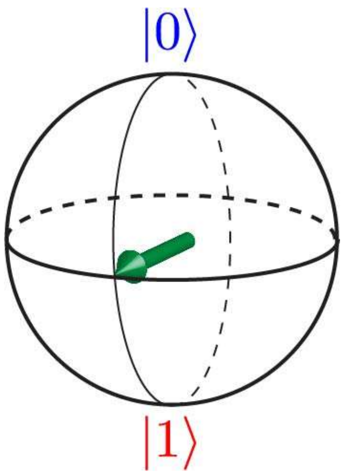
Broadband, ultra-low noise superconducting amplifiers

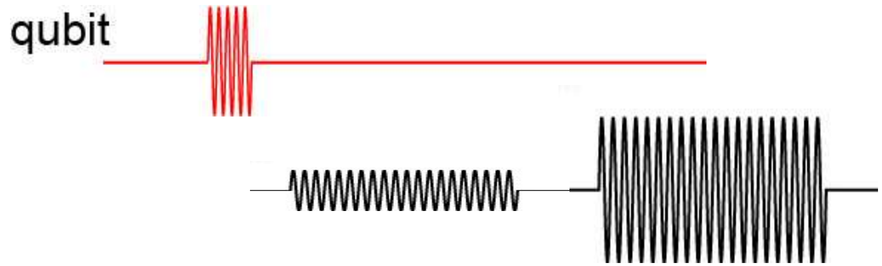


- ~ 600 MHz bandwidth (~ 10 X improvement)
- Quantum limited noise

Tanay Roy et al., *Appl. Phys. Lett. 107, 262601 (2015)*

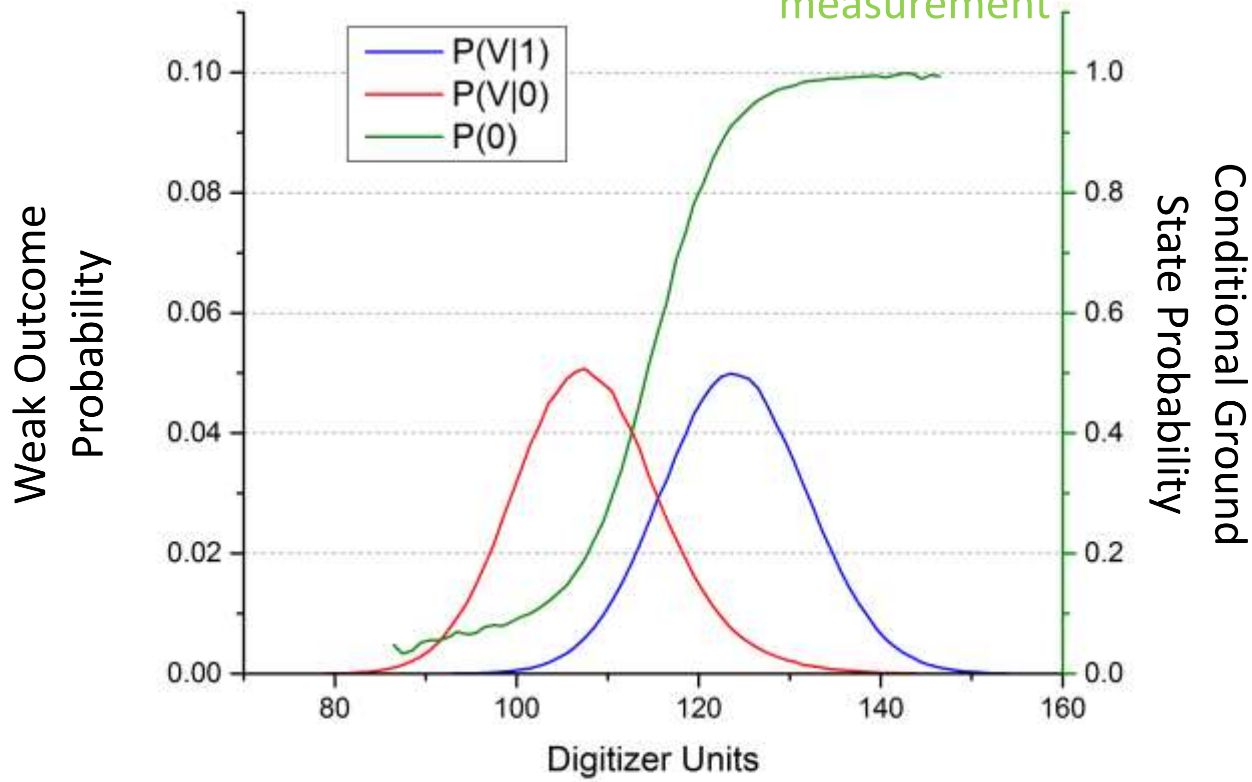
Weak measurements



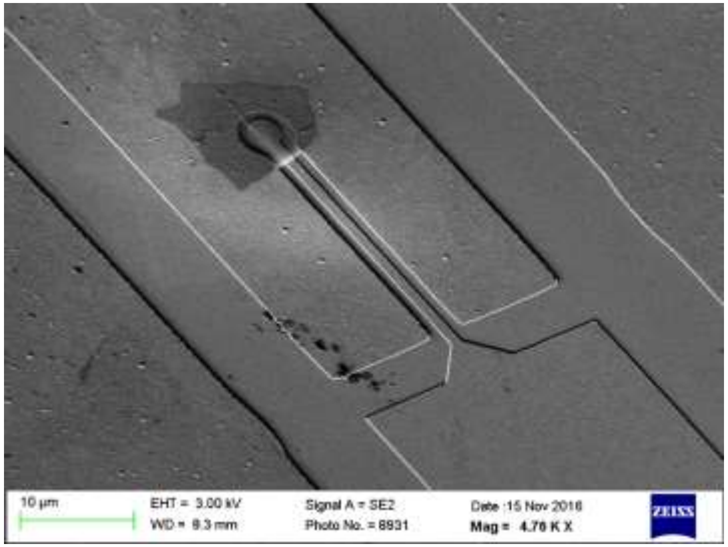


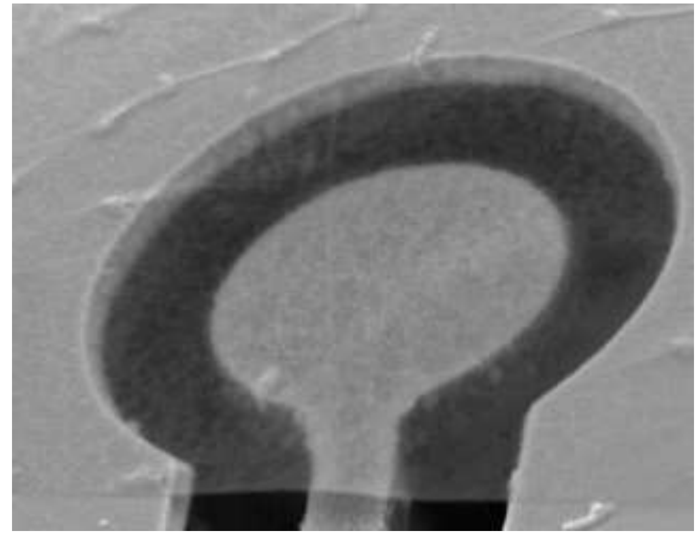
Weak measurement

Strong measurement



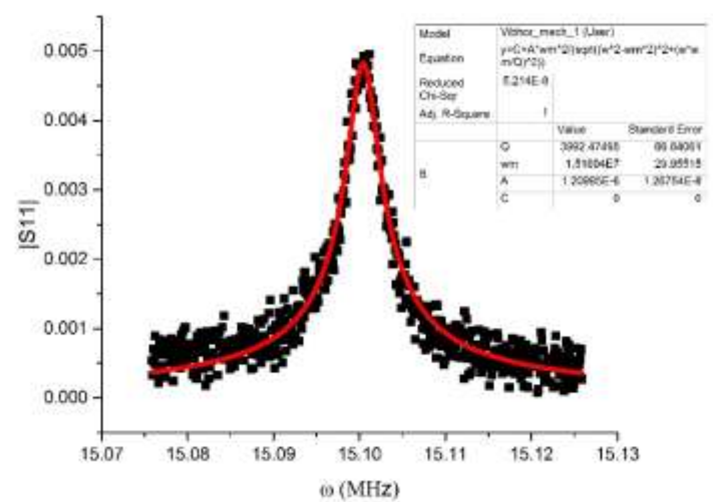
Nano-mechanical resonators





Graphene mechanical resonator coupled to superconducting microwave cavity

To study measurement backaction in the non-linear regime



U. Chandni, Ameya Riswadkar et al. , (in progress)   Collaboration: Mandar Deshmukh

Summary

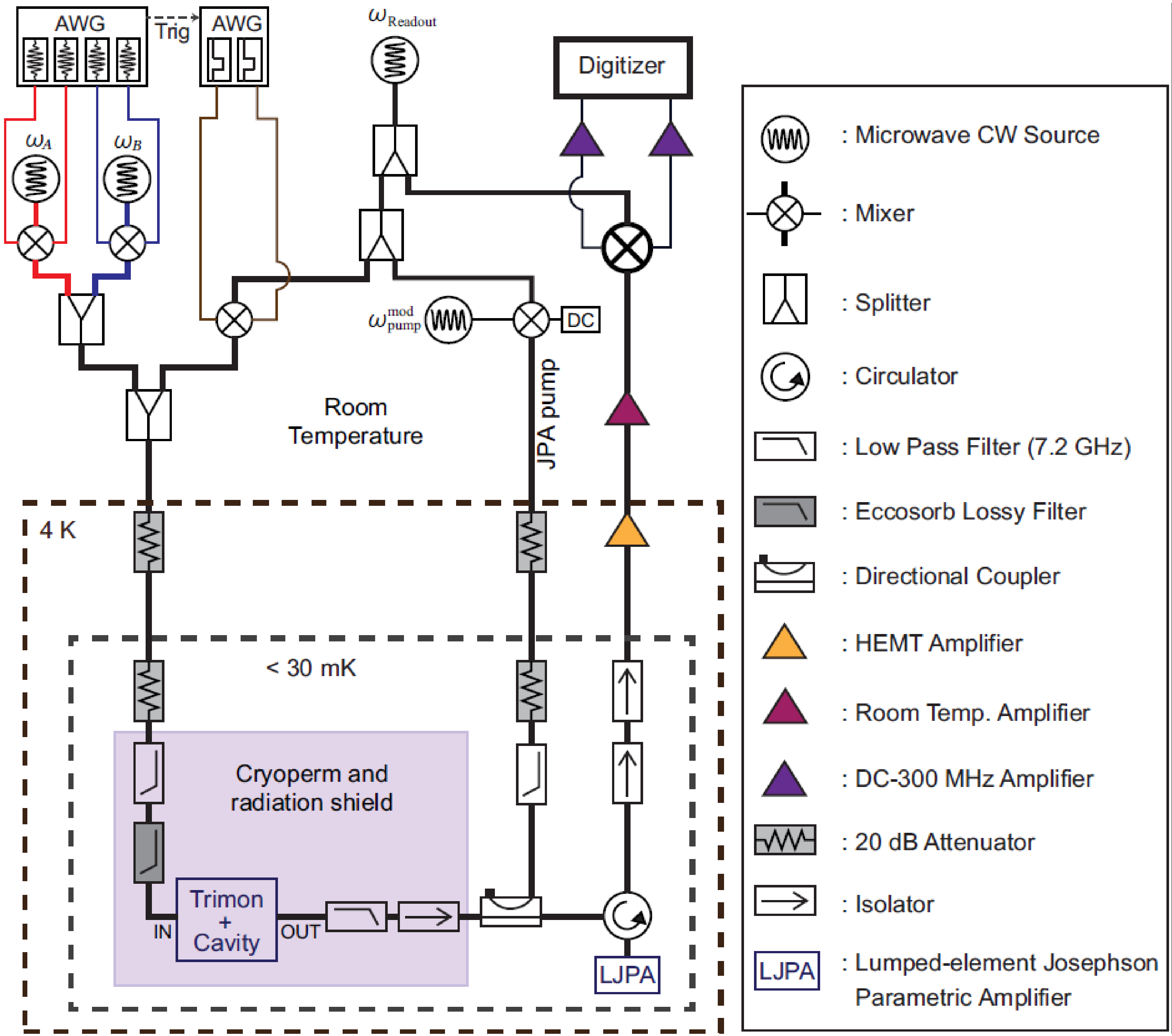
- Computing with quantum bits can provide tremendous computing power
- Superconducting circuits appear to be a strong candidate for building a practical quantum processor
- This is just the beginning: lots of new ideas required
- Small scale quantum processors demonstrating quantum advantage are around the corner

Quantum Measurement and Control Lab

www.tifr.res.in/~quantro/

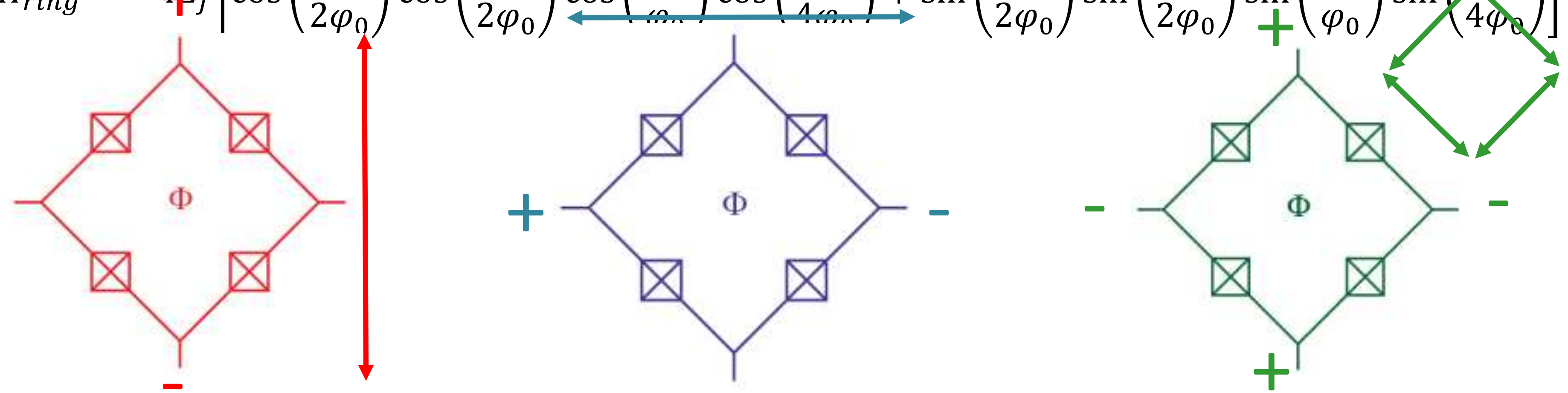
1. Quantum error correction
2. Weak measurements
3. Novel qubit designs
4. Ultra-low noise amplifiers
5. High speed digital/analog signal processing e.g. FPGA
6. Opto-mechanical systems with Graphene
7. Quantum Simulations

Additional Slides



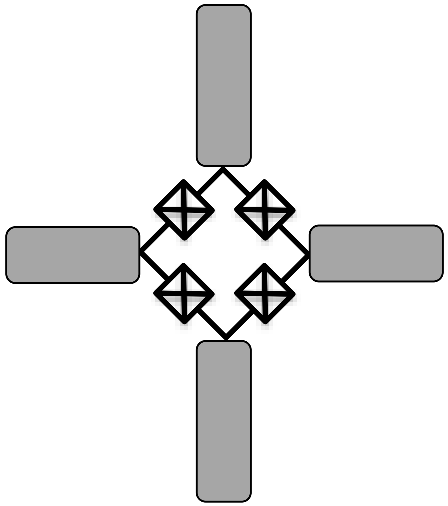
AWG
Trig
AWG
$\omega_{\mathrm{Readout}}$
Digitizer
ω_A
ω_B
$\omega_{\mathrm{pump}}^{\mathrm{mod}}$
DC
JPA pump
Room Temperature
4 K
< 30 mK
Cryoperm and radiation shield
Trimon + Cavity
IN
OUT
LJPA
: Microwave CW Source
: Mixer
: Splitter
: Circulator
: Low Pass Filter (7.2 GHz)
: Eccosorb Lossy Filter
: Directional Coupler
: HEMT Amplifier
: Room Temp. Amplifier
: DC-300 MHz Amplifier
: 20 dB Attenuator
: Isolator
LJPA
: Lumped-element Josephson Parametric Amplifier

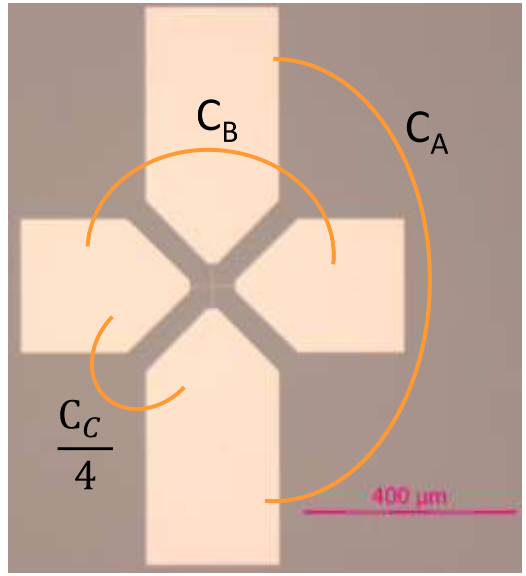
$$H_{ring} = -4E_J\left[\cos\left(\frac{\Phi_A}{2\varphi_0}\right)\cos\left(\frac{\Phi_B}{2\varphi_0}\right)\cos\left(\frac{\Phi_C}{\varphi_0}\right)\cos\left(\frac{\Phi}{4\varphi_0}\right) + \sin\left(\frac{\Phi_A}{2\varphi_0}\right)\sin\left(\frac{\Phi_B}{2\varphi_0}\right)\sin\left(\frac{\Phi_C}{\varphi_0}\right)\sin\left(\frac{\Phi}{4\varphi_0}\right)\right]$$



A: dipolar mode   B: dipole orthogonal to A   C: quadrupolar mode

N. Bergeal et al, Nat. Phys. **6** 296 (2010)





Operate at zero flux $\Phi=0$

Include shunting capacitances

Expand to quartic order

$$H_{ring} = -4E_J \left[\cos\left(\frac{\Phi_A}{2\varphi_0}\right)\cos\left(\frac{\Phi_B}{2\varphi_0}\right)\cos\left(\frac{\Phi_C}{\varphi_0}\right)\right]\cos\left(\frac{\Phi}{4\varphi_0}\right) + \sin\left(\frac{\Phi_A}{2\varphi_0}\right)\sin\left(\frac{\Phi_B}{2\varphi_0}\right)\sin\left(\frac{\Phi_C}{\varphi_0}\right)\sin\left(\frac{\Phi}{4\varphi_0}\right)\Big]$$

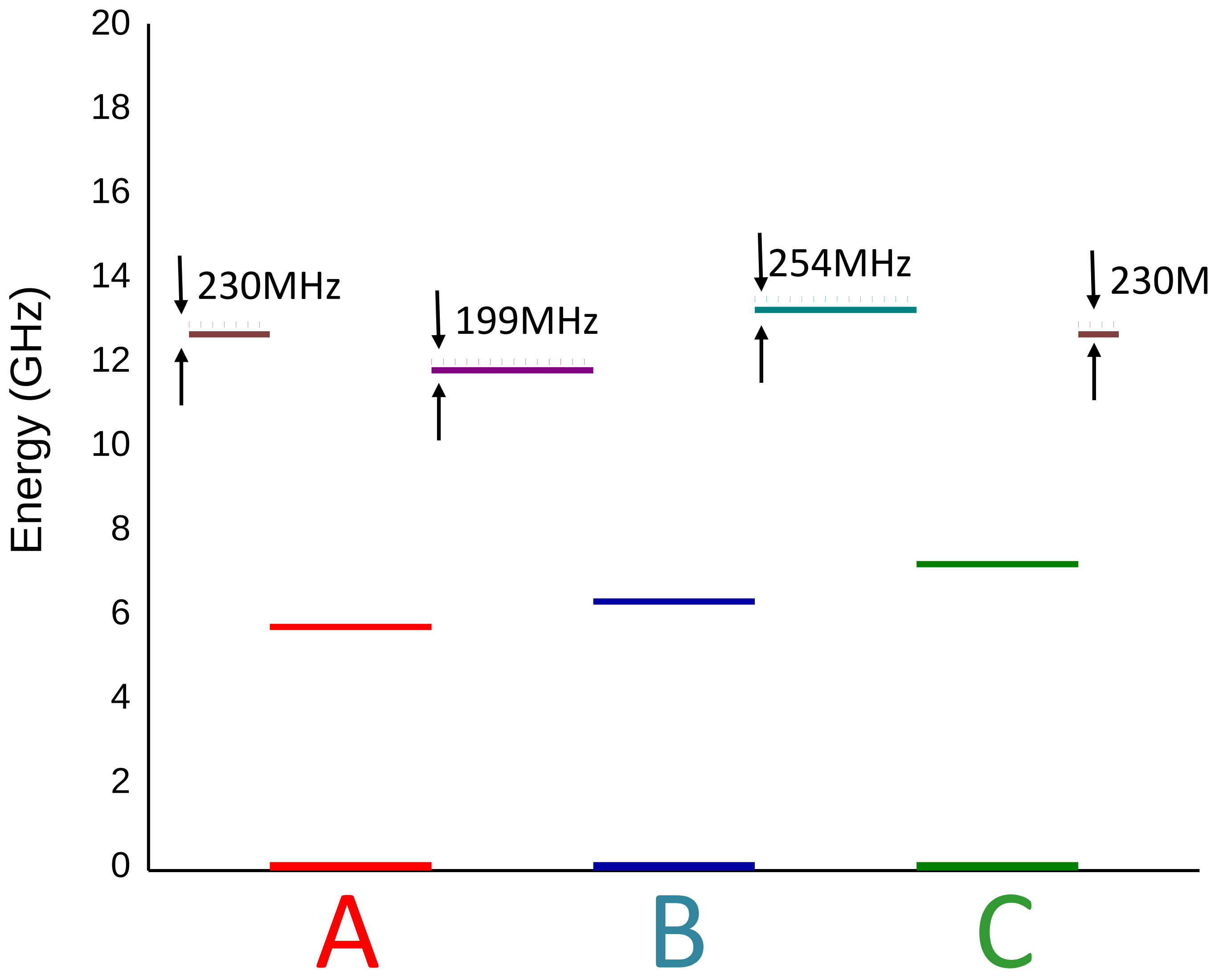
$$H_{circuit} = \frac{\Phi_A^2}{2L_J(\Phi)} + \frac{Q_A^2}{2C_A} - \delta_A\Phi_A^4 + \frac{\Phi_B^2}{2L_J(\Phi)} + \frac{Q_B^2}{2C_B} - \delta_B\Phi_B^4 + \frac{2\Phi_C^2}{L_J(\Phi)} + \frac{Q_C^2}{2C_C} + \delta_C\Phi_C^4$$

$$-g[\Phi_A^2\Phi_B^2 + 4\Phi_B^2\Phi_C^2 + 4\Phi_C^2\Phi_A^2]$$

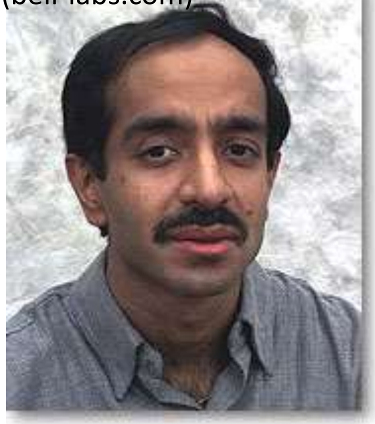
Transmon-like qubit

Energy levels: Coupling between qubits

$$+g_{AB}\sigma_Z^A\sigma_Z^B + g_{BC}\sigma_Z^B\sigma_Z^C + g_{CA}\sigma_Z^C\sigma_Z^A$$



Grover's search



(bell-labs.com)

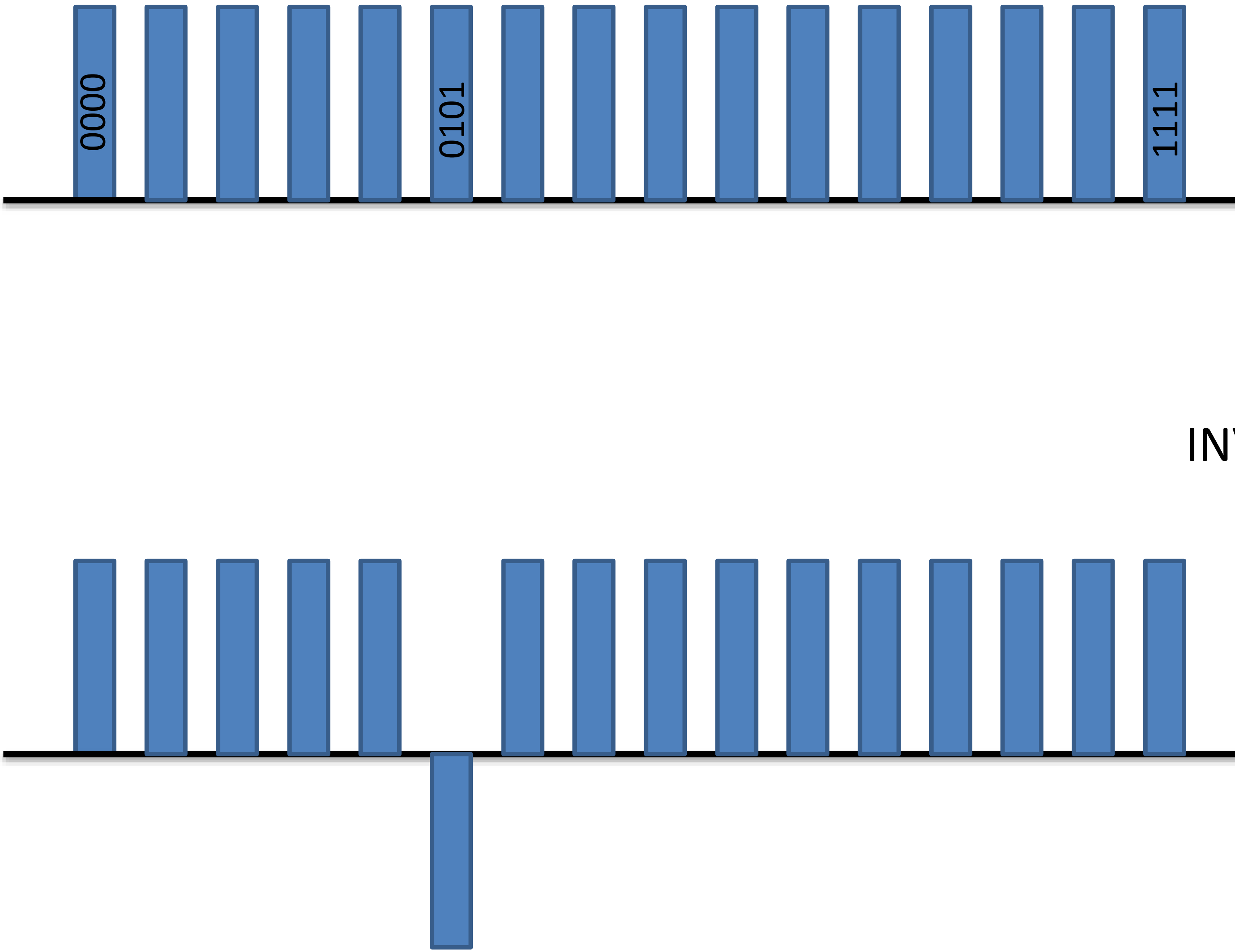
Input	Output
0001	0
0010	0
0011	0
0100	0
0101	1
0110	0
0111	0
1000	0
1001	0
1010	0
1011	0
1100	0
1101	0
1110	0
1111	0

1100 → 0

0101 → 1

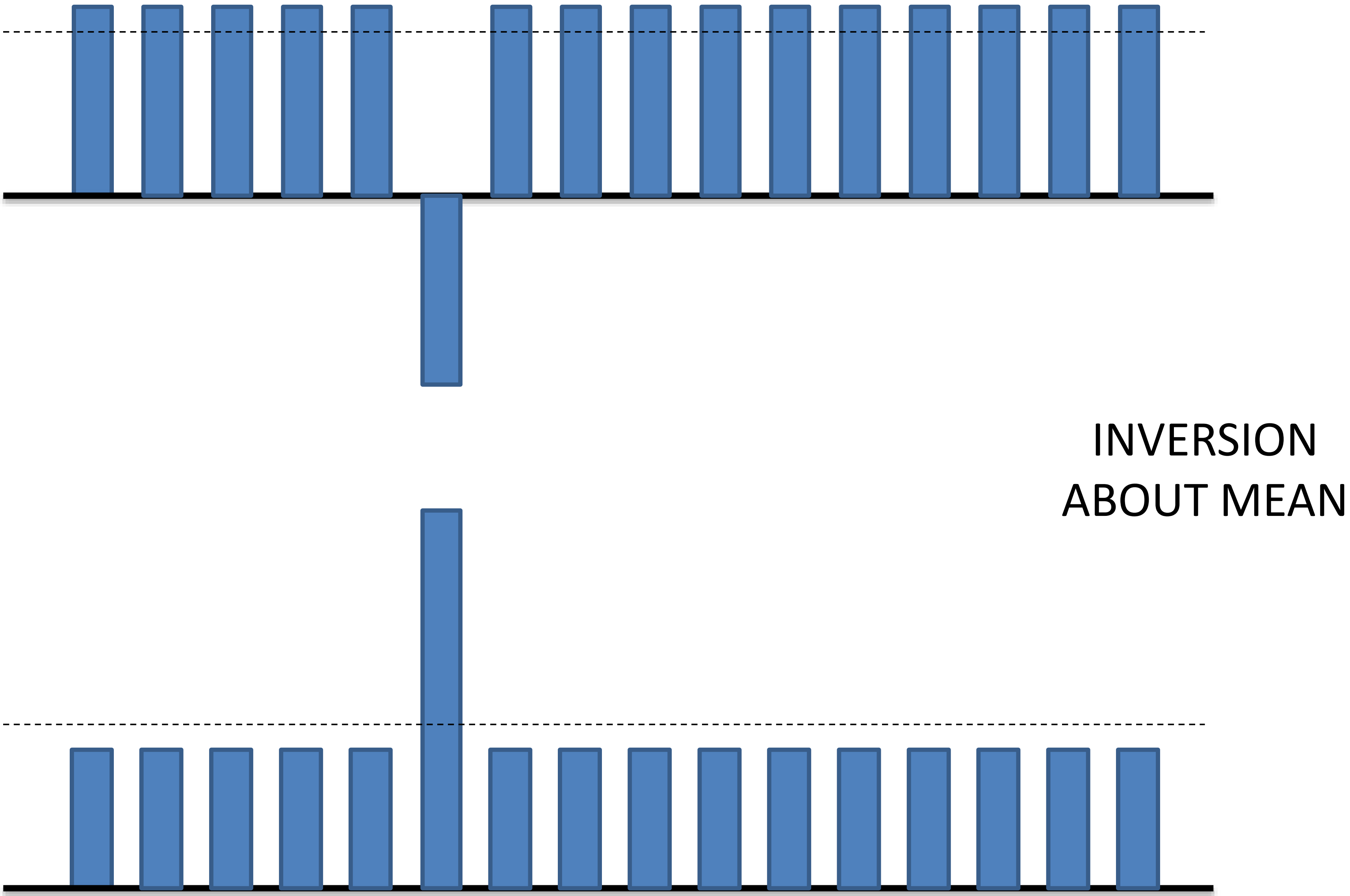
How many steps before we find the special item?

Grover’s search

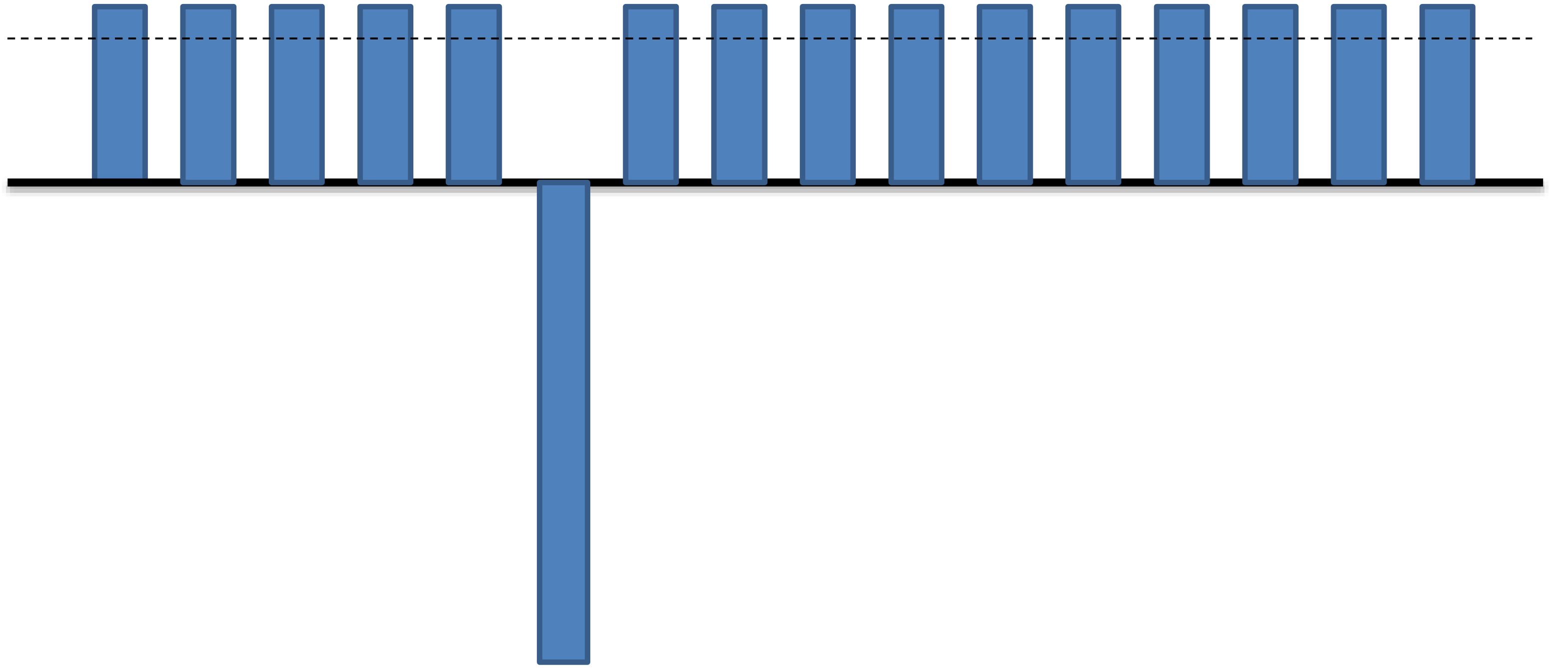


PHASE INVERSION

Grover's search

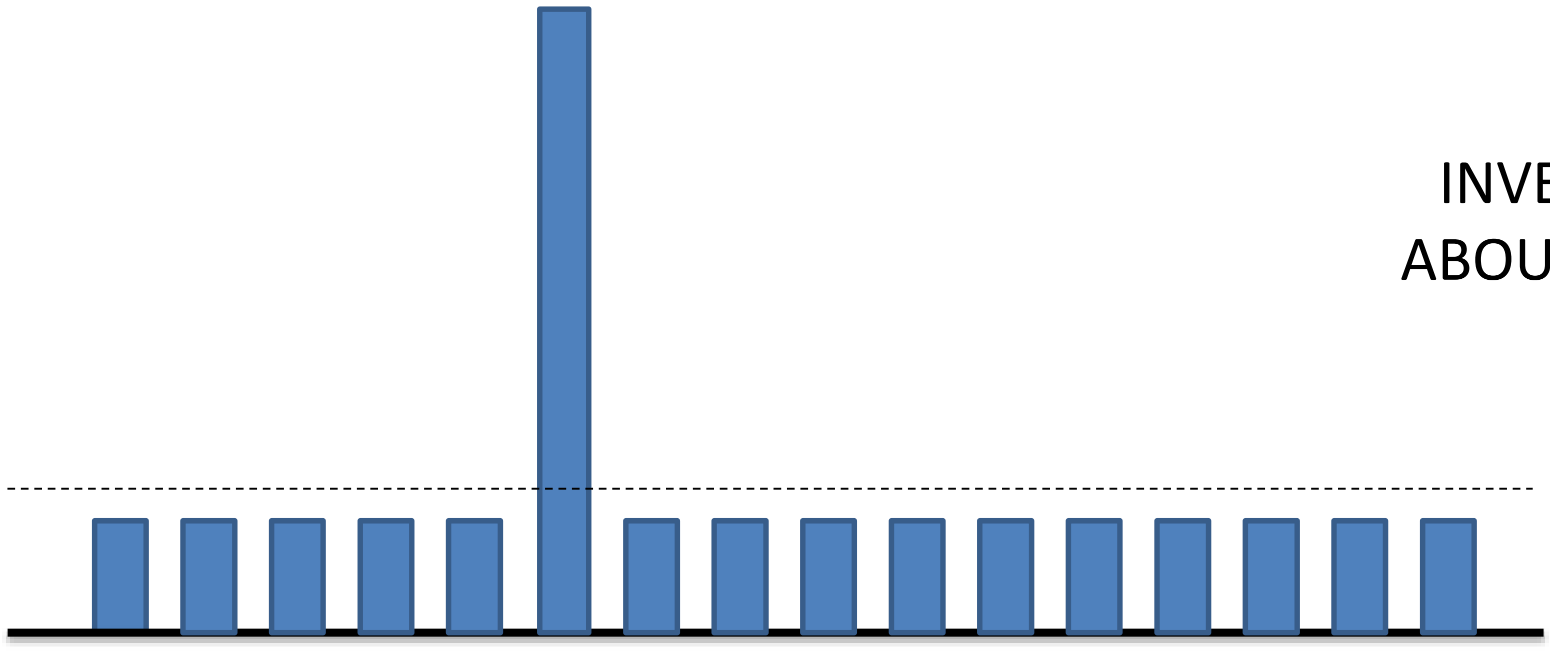


Grover's search



PHASE INVERSION

Grover's search



INVERSION
ABOUT MEAN

After roughly $\sqrt{N}$ steps : Measure

Get the correct result with high probability