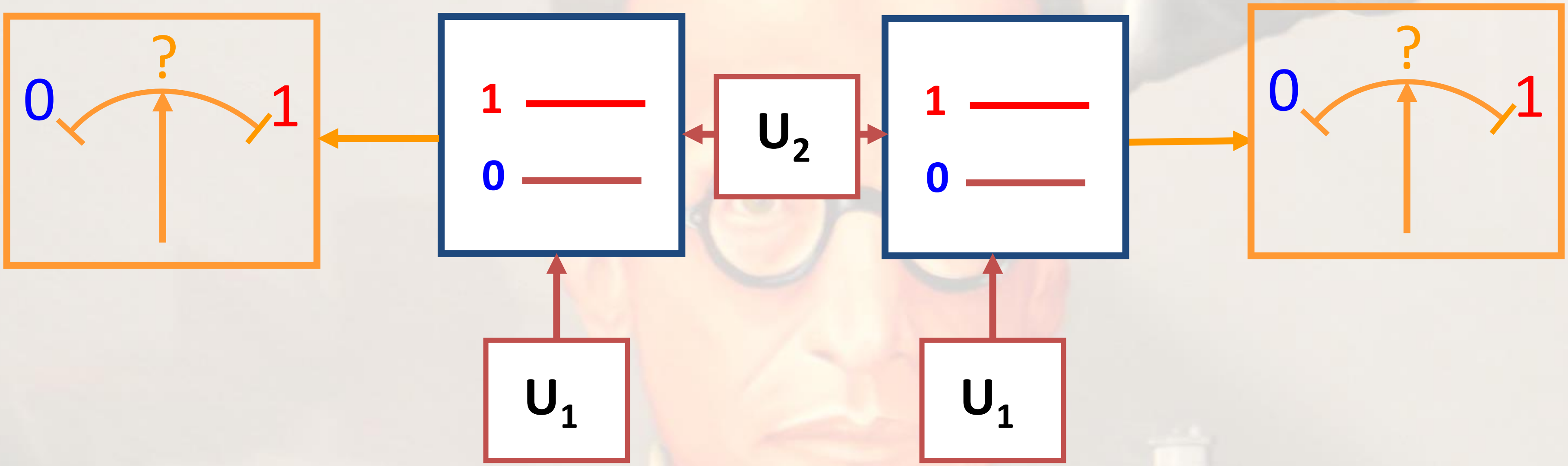
Routes towards quantum information processing with superconducting circuits



Daniel Estève

Quantronics
SPEC CEA Saclay

Quantum Mechanics: resources for information processing

1930s: quantum weirdness

1960s: Bell inequalities

1980s: quantum violation demonstrated

A. Aspect et al.

entangled states

$$\left|left+,right-\right\rangle+\left|left-,right+\right\rangle$$

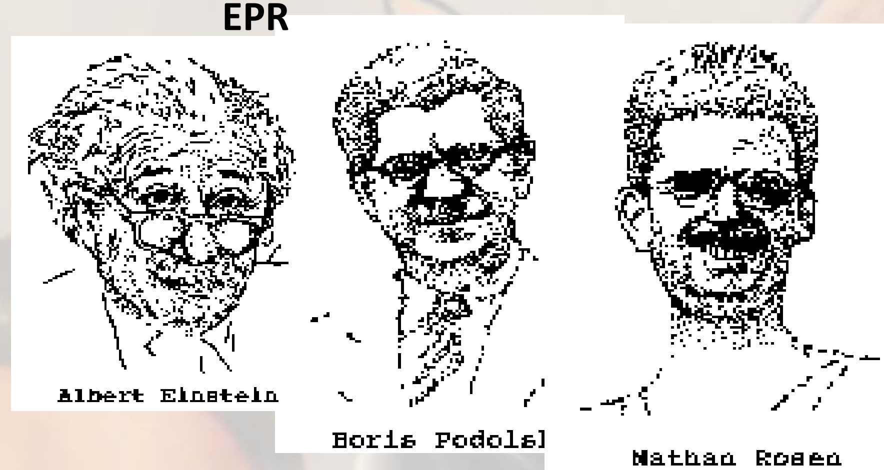
breakthrough:

a resource for computing

David Deutsch

Richard Jozsa

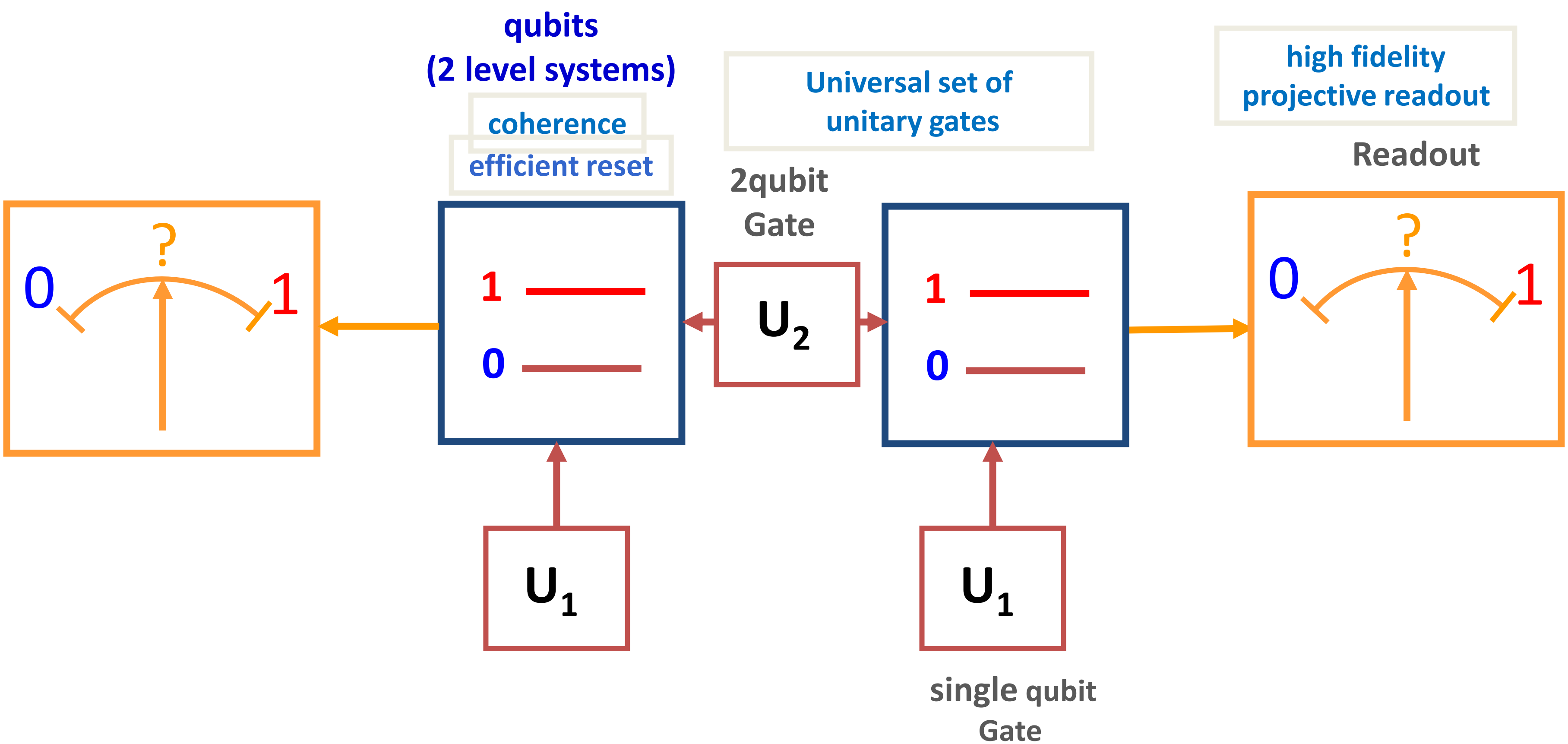
EPR



A second quantum revolution ?

Blueprint of a quantum processor based on quantum gates

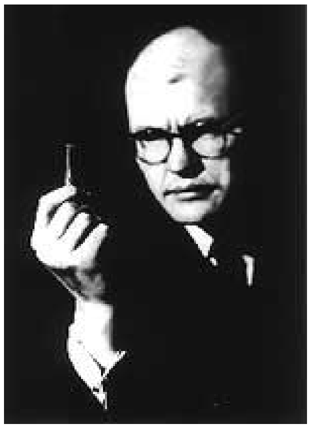
Specifications: "DiVincenzo criteria"



Electrical implementations ?

Can (macroscopic) electrical circuits be quantum (usually not !)

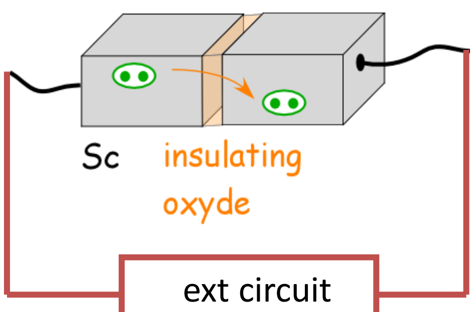
Jack S. Kilby handling the first integrated circuit

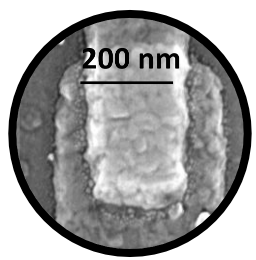


electrical variables
usually not quantum

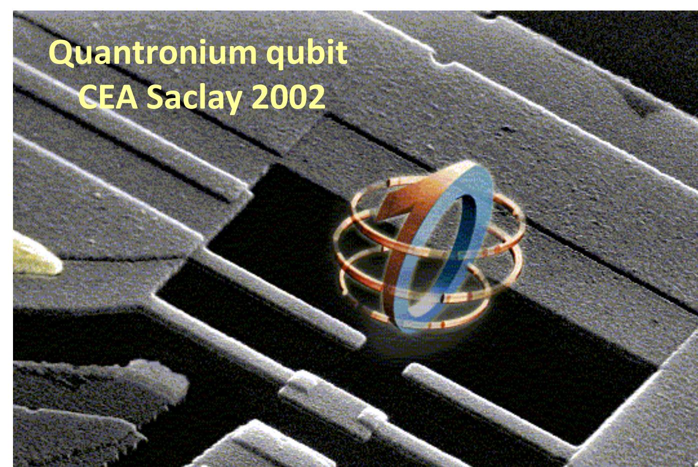
ALL OF THEM ?

Superconductor/insulator/Superconductor
JOSEPHSON JUNCTION

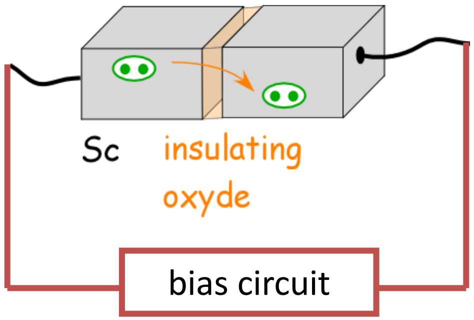


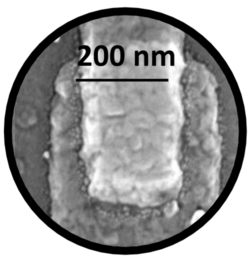


Al/AlOx/Al
junction

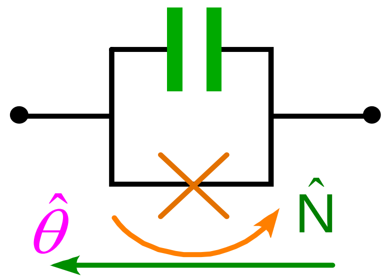


A quantum electrical component : the Josephson junction





Al/AlOx/Al
tunnel junction



1 single degree of freedom:

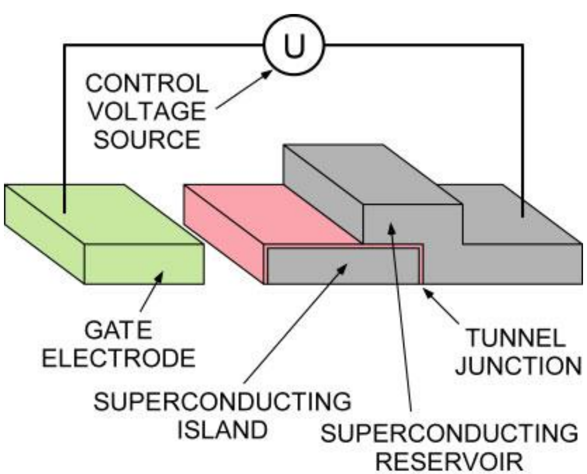
$$\Phi(t)=\int_{-\infty}^{t}V(t')dt' \quad Q(t)=\int_{-\infty}^{t}i(t')dt'$$

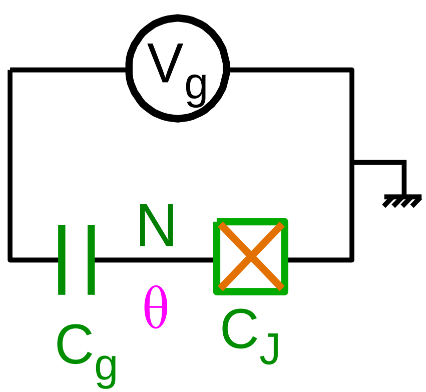
$$\left[\hat{\Phi},\hat{Q}\right]=i\hbar \Longrightarrow \left[\hat{\theta},\hat{N}\right]=i$$

θ and N conjugated variables

Hamiltonian: $$H=-E_J\cos\hat{\theta}+H_{ELM}$$

the single Cooper pair box



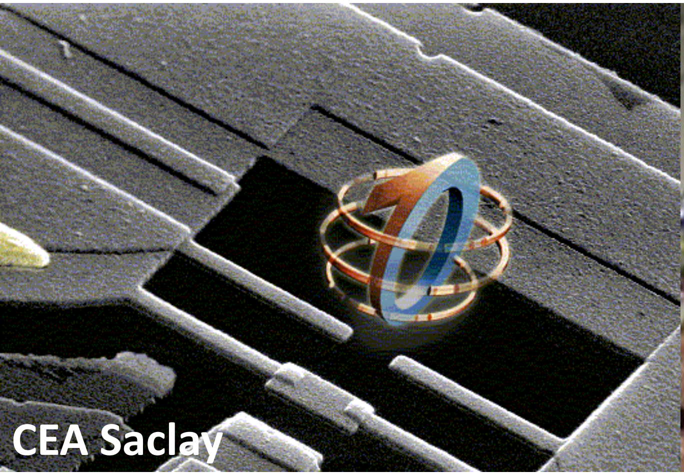


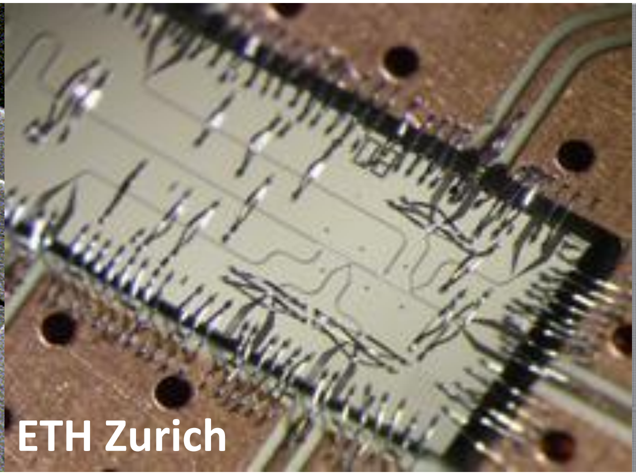
$$\hat{H}=E_C(\hat{N}-N_g)^2-E_J\cos\hat{\theta}$$

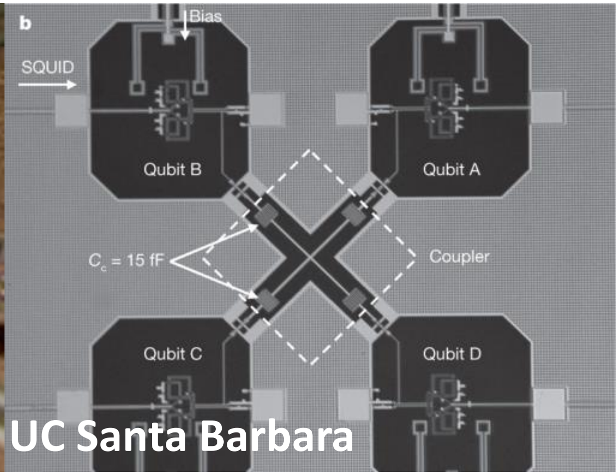
reduced gate charge: $N_g=C_gV_g/2e$

(Quantronics 1996, NEC 1999)

Superconducting Josephson quantum circuits







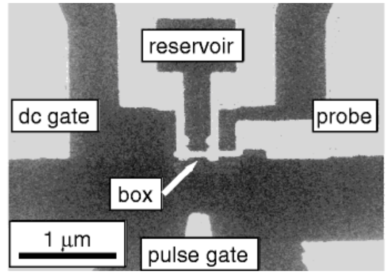
1. Quantum behavior demonstrated in 1980s
2. Since 1999 qubits with increasingly long coherence times.
3. Potentially scalable

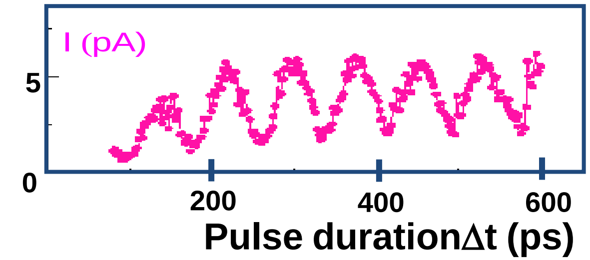
Other electrical implementations :
quantum dots in 2DEGs

The Cooper Pair Box: from charge to phase

first electrical qubit : Cooper pair box

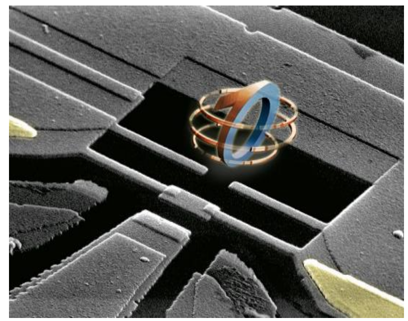
Nakamura, Pashkin &Tsai (NEC, 1999)

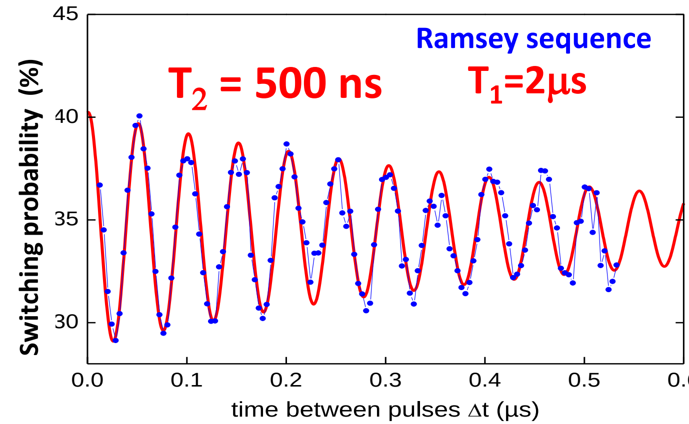




First operational qubit : quantronium, single-shot readout, protected against dephasing

Vion et al., (Quantronics, 2002)





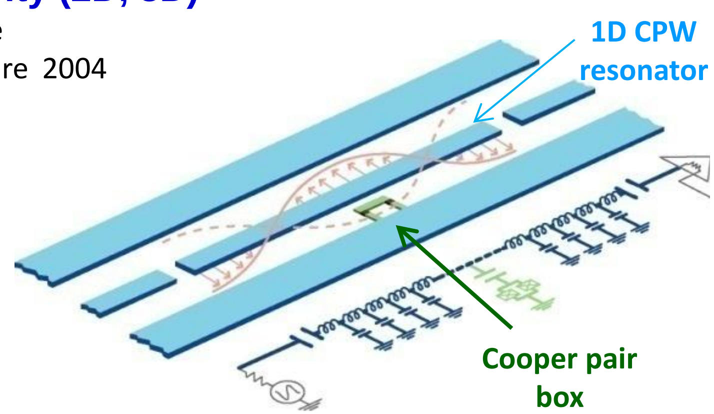
Circuit QED: Cooper pair box in a microwave cavity (2D, 3D)

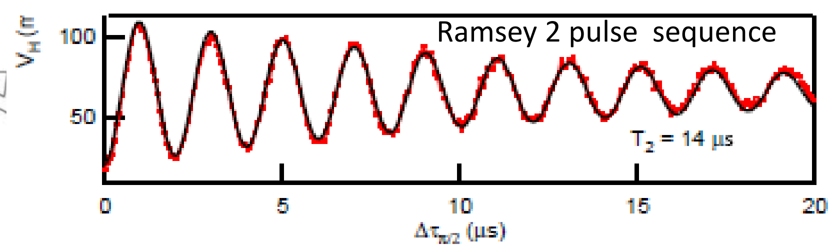
Schoelkopf lab., Yale

-Wallraff et al., Nature 2004

-Koch et al., 2007

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

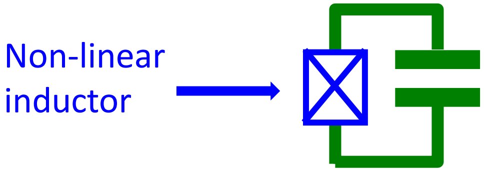




Longer coherence times, up to ~25μs (2D), 100 μs (3D)

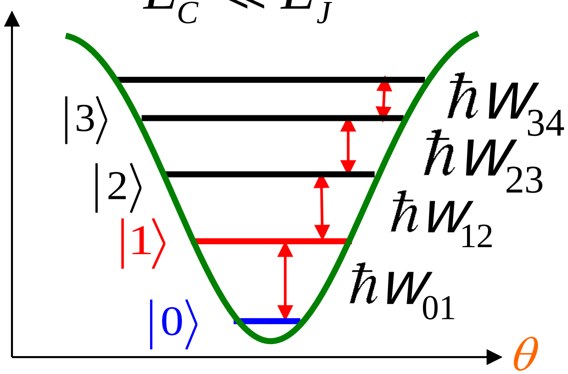
The transmon Cooper pair box: circuit QED (inspired from cavity QED)

Cooper pair box in the phase regime



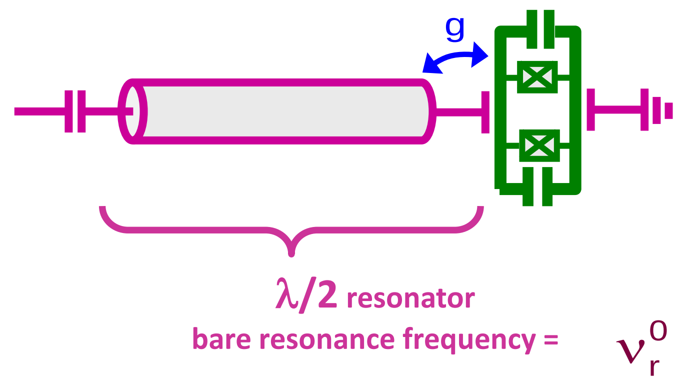
$$H_{transmon} = E_C \hat{N}^2 - E_J \cos\hat{q}$$

$$E_C \ll E_J$$

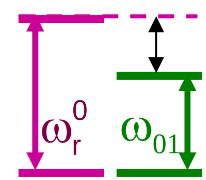


a non linear resonator at the **single** photon level

Circuit QED: dispersive regime



$$|\Delta| = |\omega_{01} - \omega_r^0| >> g$$



$$\hat{H}_{eff} = -\frac{\hbar}{2}(\omega_{01} + \chi)\hat{\sigma}_Z + \hbar(\omega_r^0 - \chi\hat{\sigma}_Z)\hat{a}^+\hat{a}$$

qubit Stark shift

qubit controlled Cavity pull

Status of SC quantum processors

Schoelkopf Lab, Yale University
DiCarlo et.al., Nature 2009
Two-Qubit Grover Search

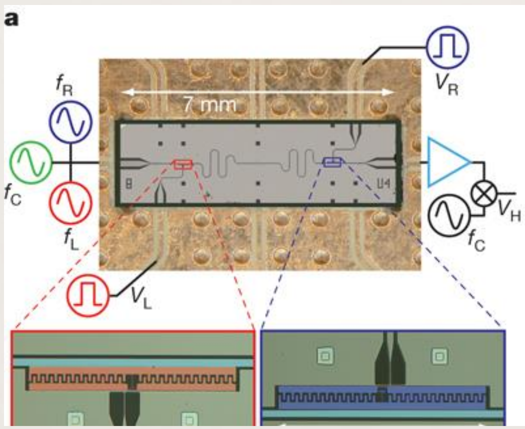
No individual readout:
not operational

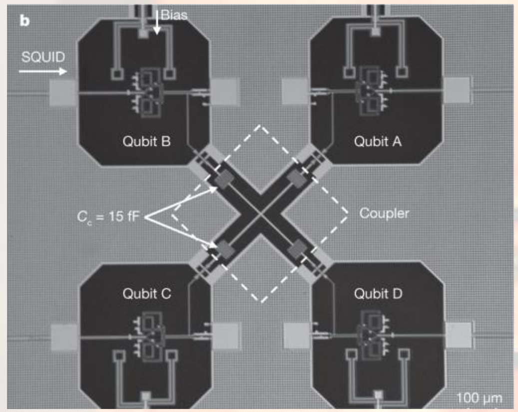
Martinis Lab, UC Santa Barbara
Yamamoto et.al. , PRB **82** 2010 , Nat Phys 2012
Two-Qubit Deutsch-Josza Algorithm
Factorization of 15

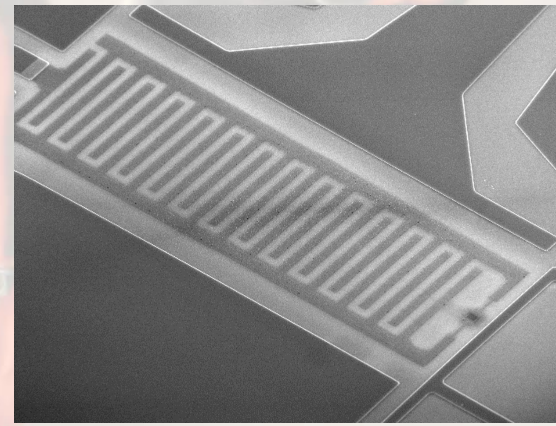
individual destructive readout

Quantronics, CEA
Dewes et. al., PRL & PRB 2012
Grover Search Algorithm on 4 items

Individual non-destructive readout







Quantum speedup demonstrated
on **elementary cases**

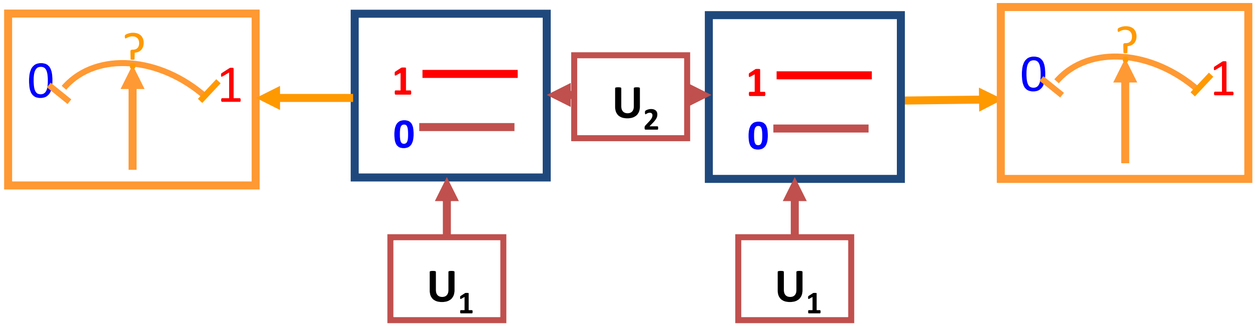
Why slow progress ?

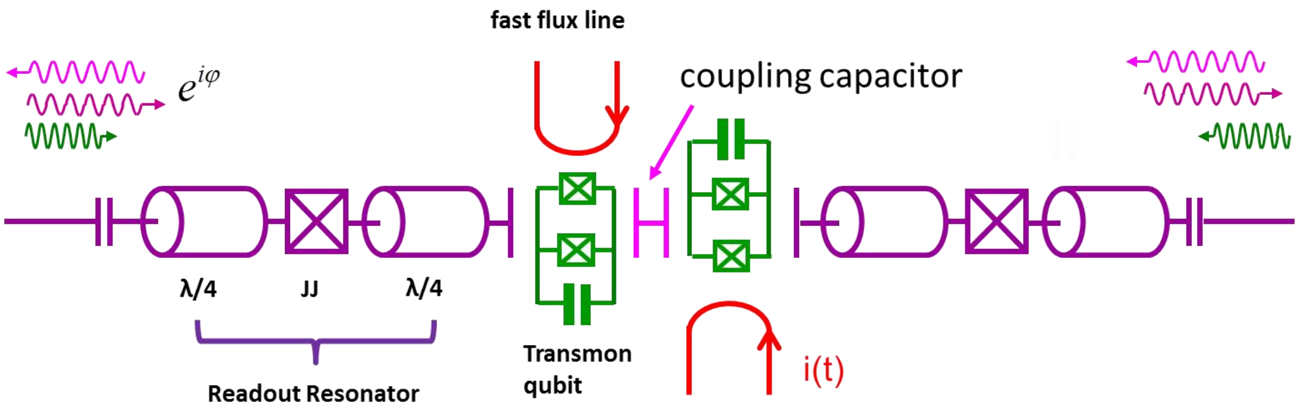
Difficult
scalability issues

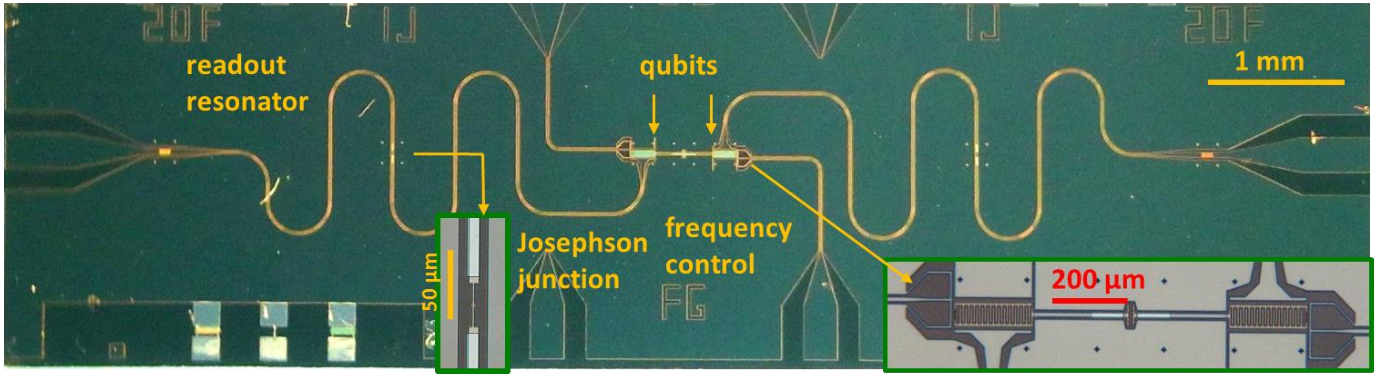
Quantum coherence in complex architecture
Hifi readout of qubit register
Quantum error Correction

An operational two-qubit (4 states) processor

Dewes et al., Phys. Rev. Lett. 108, 057002 (2012)

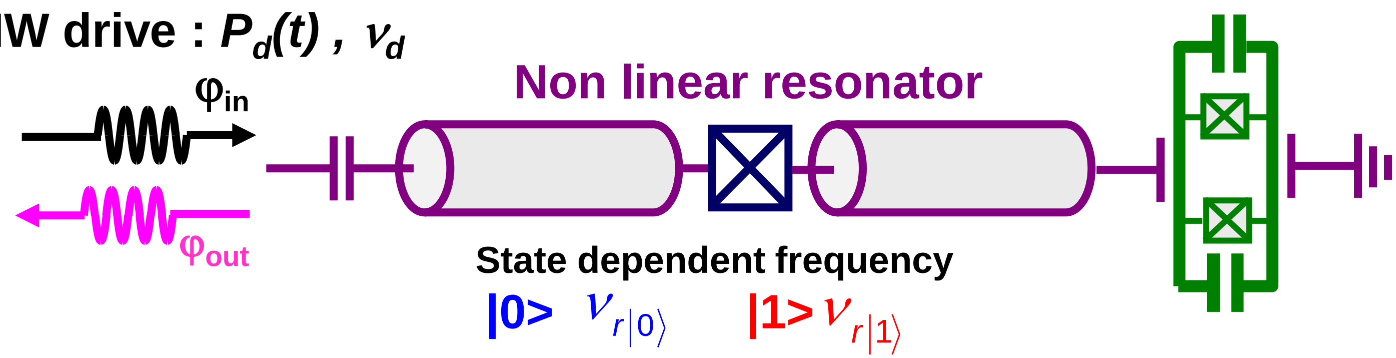


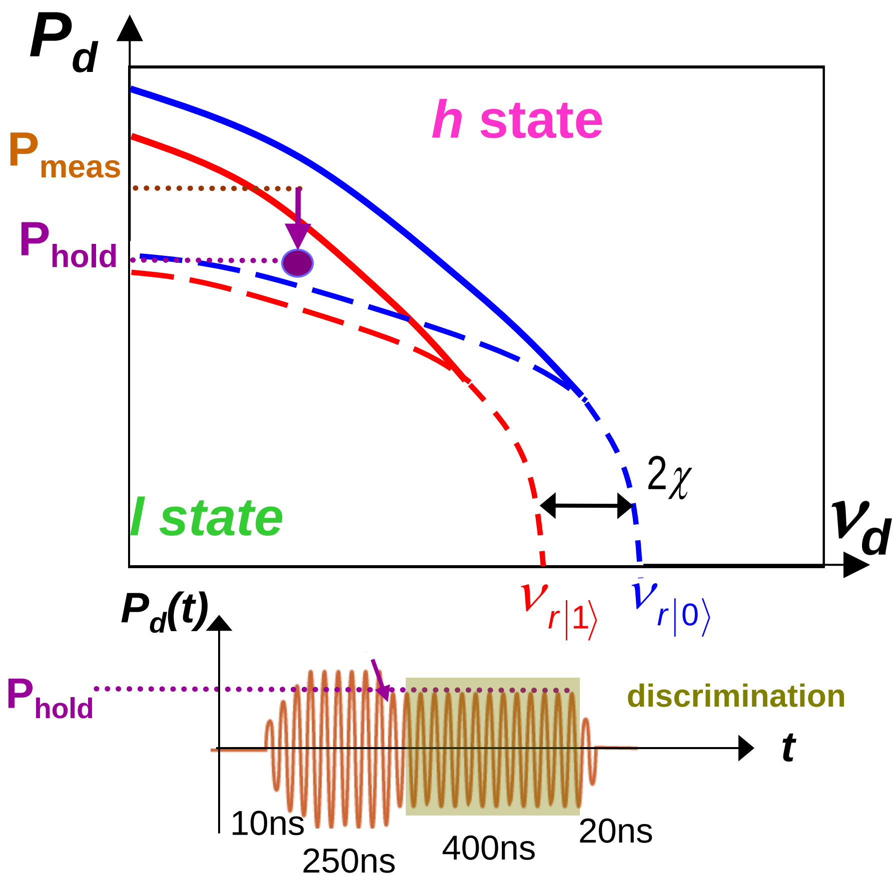


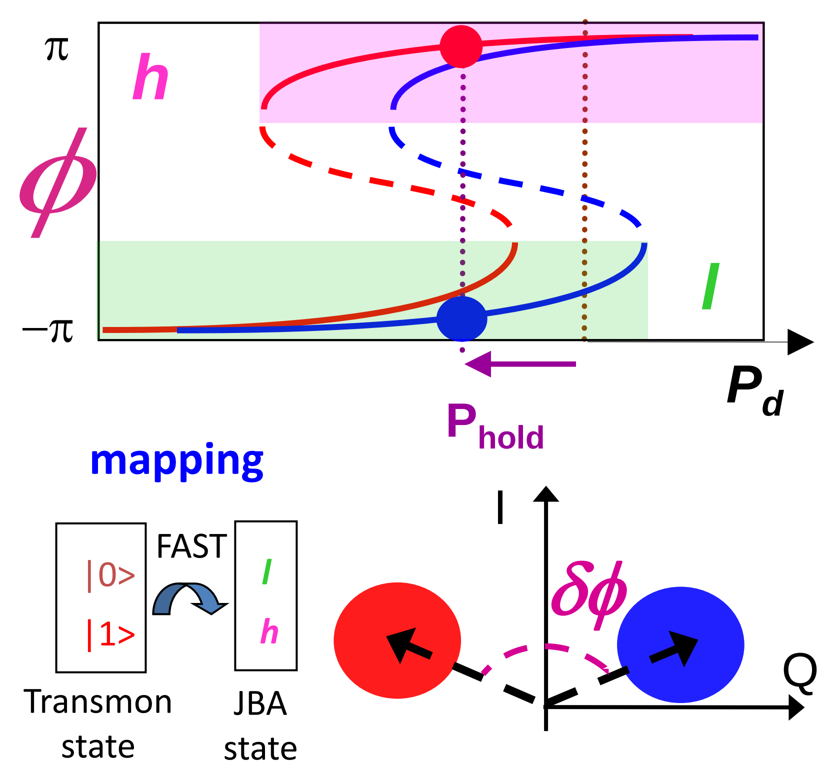


Transmon readout with a non-linear resonator

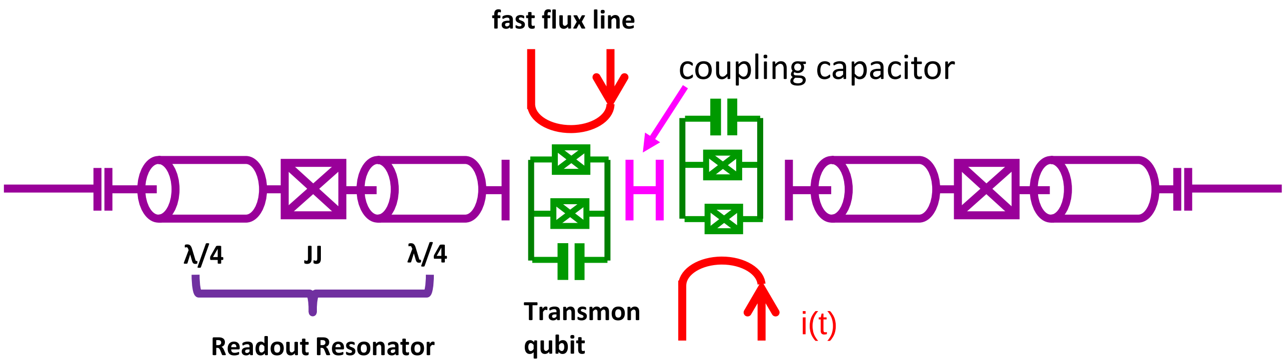
Josephson Bifurcation Amplifier: Siddiqi et al., Phys.Rev.Lett 93 (2004)
Transmon Readout: Mallet et al. *Nature Physics* 5, 791 - 795 (*2009*)







Switchable SWAP interaction



$$H/\hbar = -\frac{\omega_{01}^{I}}{2}\sigma_z^{I} - \frac{\omega_{01}^{II}}{2}\sigma_z^{II} + \overbrace{g\left(\sigma_+^{I}\sigma_-^{II} + \sigma_-^{I}\sigma_+^{II}\right)}^{H_{\text{int}}}$$

Off resonance: $\left|\omega_{01}^{I} - \omega_{01}^{II}\right| \gg g$ no effect of coupling

On resonance: $\omega_{01}^{I} = \omega_{01}^{II}$

00 10 01 11

$$U_{\text{int}}(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(gt) & -i\sin(gt) & 0 \\ 0 & -i\sin(gt) & \cos(gt) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad U_{\text{int}}\left(\frac{\pi}{2g}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{2} & -i/\sqrt{2} & 0 \\ 0 & -i/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \sqrt{i\mathrm{SWAP}}$$

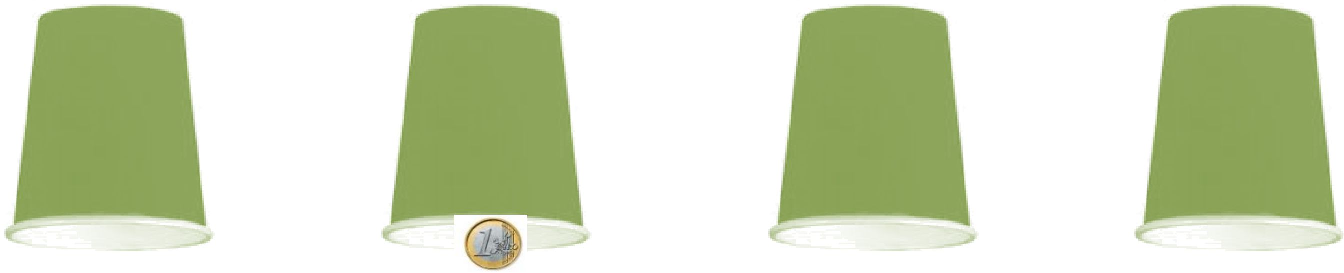
➡ universal gate : $\sqrt{iSWAP}$

A quantum algorithm for the search problem

The 4 state case: $x, y \in \{00, 01, 10, 11\}$

Game: find **y** by calling the discriminating function f once only

$$f_y(x) = \begin{cases} 1, & x = y \\ 0, & x \neq y \end{cases}$$



$f_{01}(00)=0$ $f_{01}(01)=1$ $f_{01}(10)=0$ $f_{01}(11)=0$

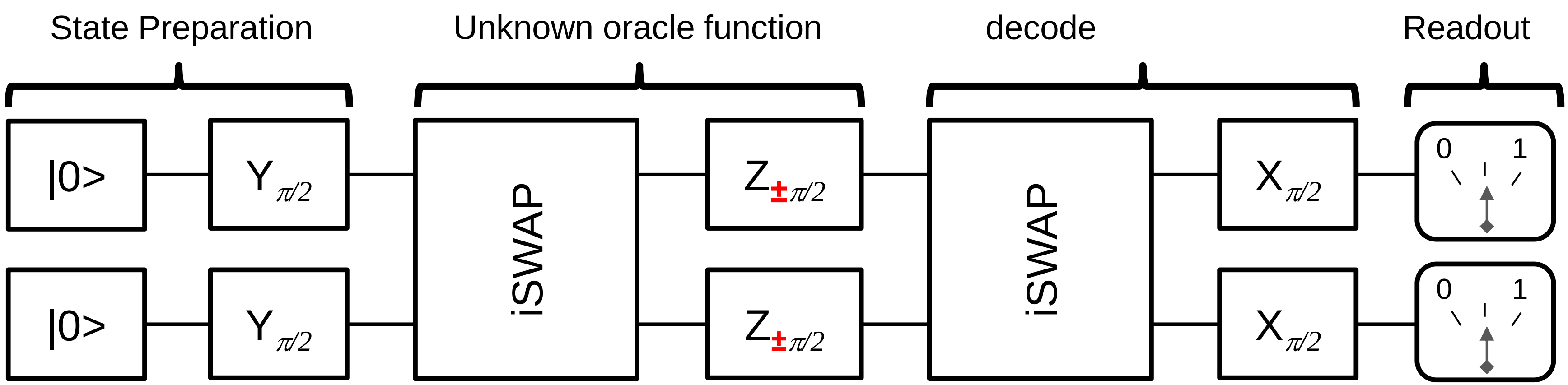
Classical "Guess and check strategy " success probability : 1/4

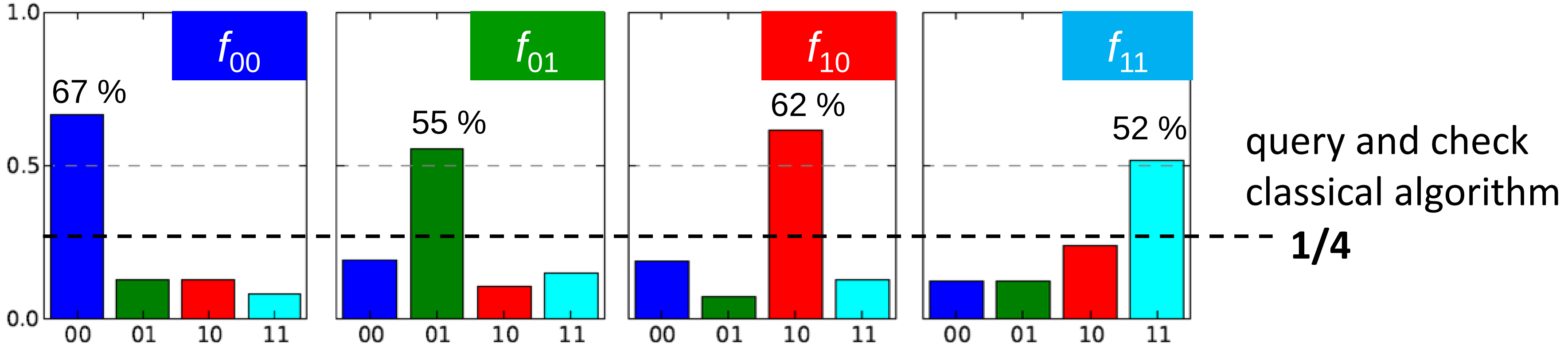
Quantum Grover search quantum algorithm finds in 1 call !

For searching 1 object out of N: sqrt(N) steps

sqrt(N) gain/ classical search algorithm

The Grover search algorithm

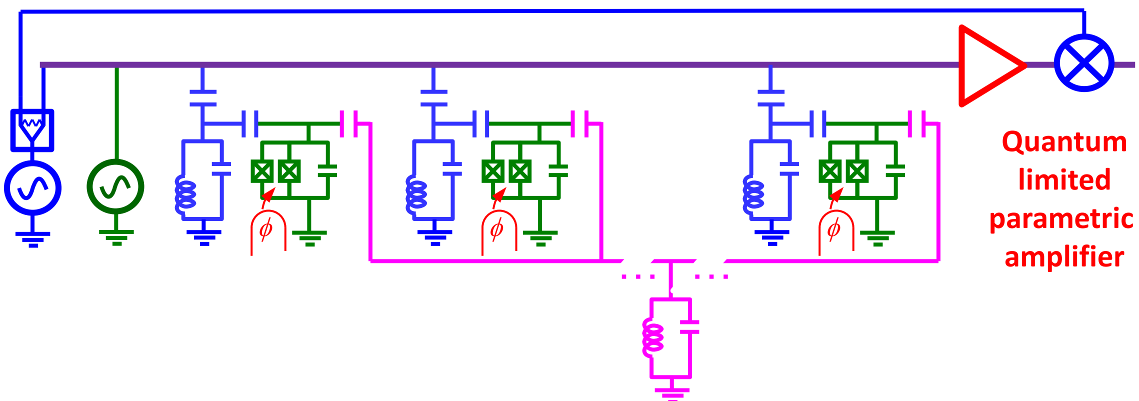


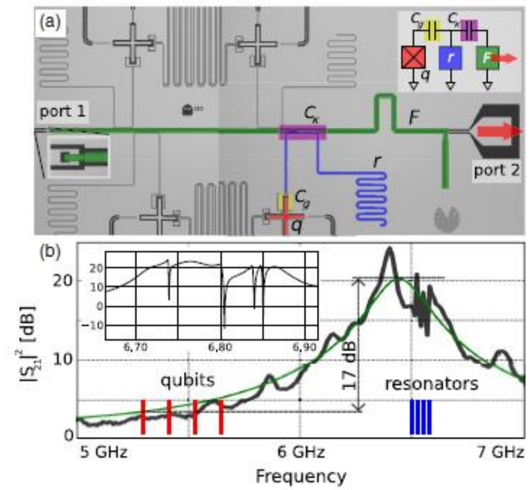


Single run success rate > ¼ demonstrates
Quantum Speedup

The readout scalability issue in circuit QED

Linear dispersive readout



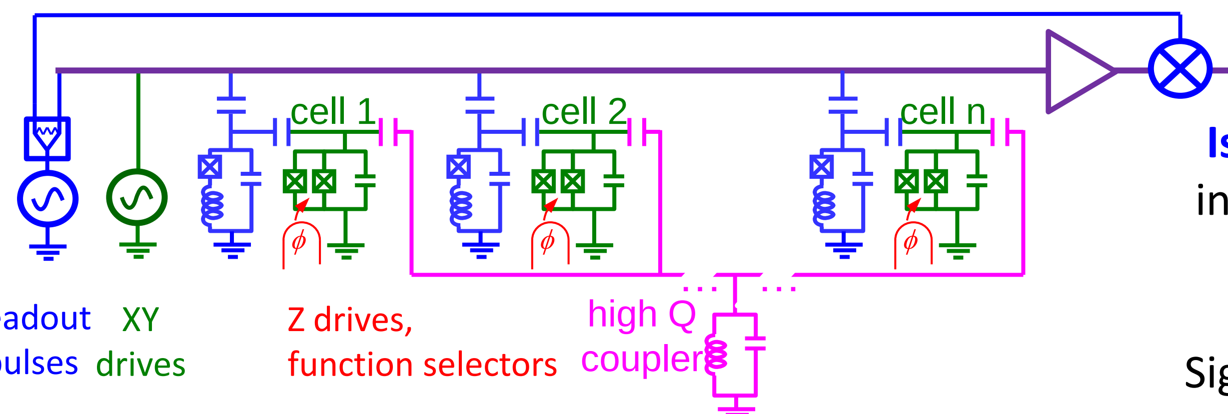


E. Jeffrey et al.
PRL **112**, 190504 (2014)

Issues: limited bandwidth, low saturation power

many groups at work

A N+1 architecture based on multiplexed JBA-readout

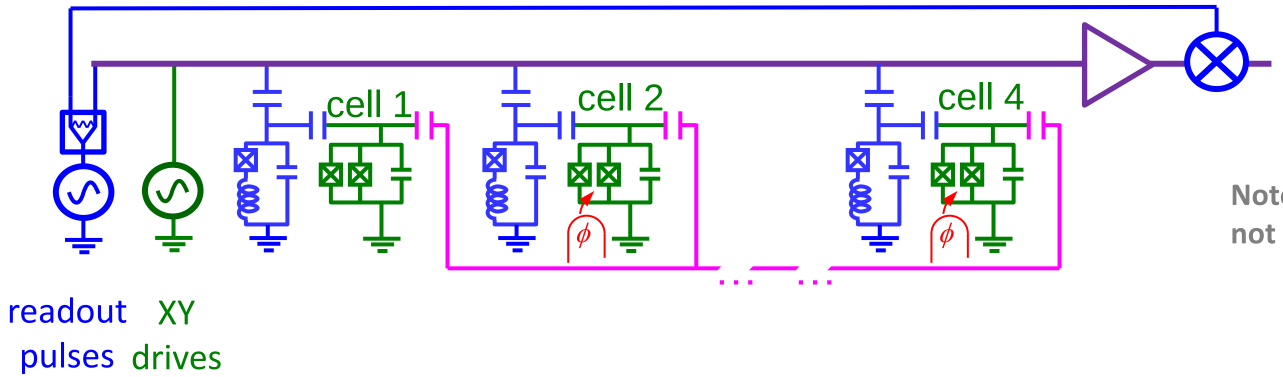


Issues:

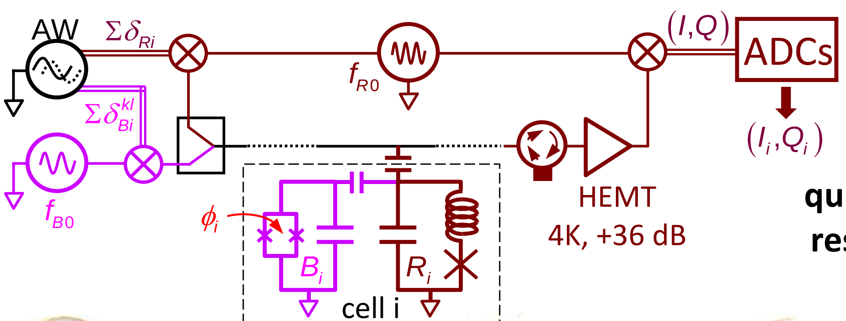
interactions btw non-linear readout resonators

Signal processing

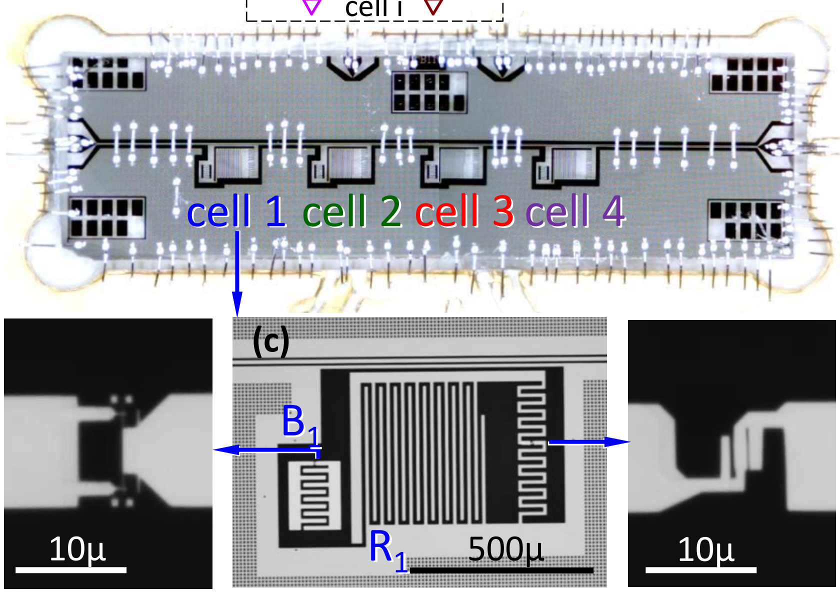
Demonstrating multiplexed JBA-readout



Note:
not a full processor !



qubit – readout resonator cell

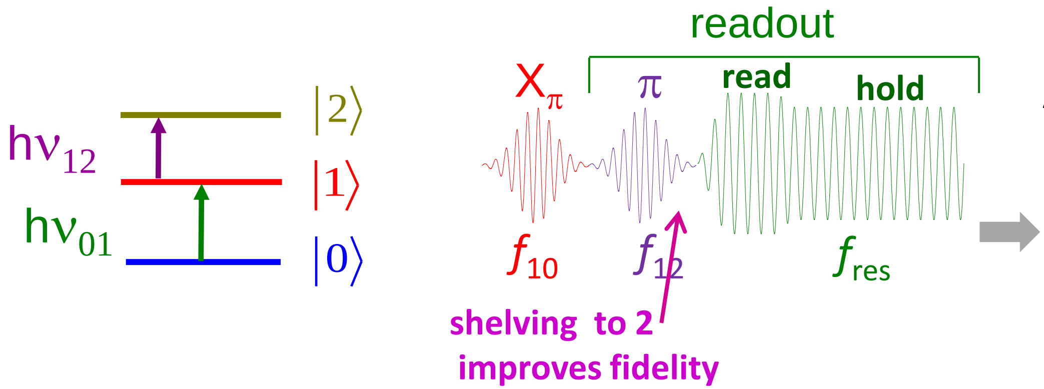


Flux tunable junction

readout resonator junction

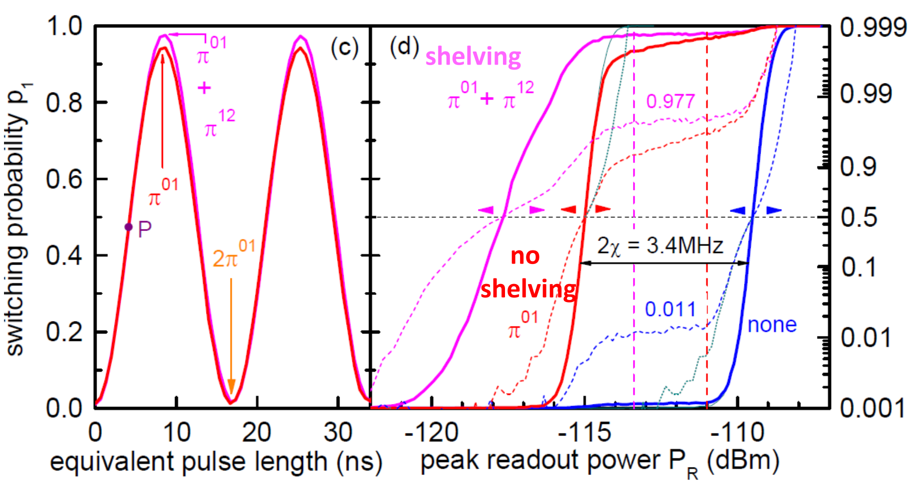
V. Schmitt et al., 2014; CMD25 poster, submitted

Individual qubit readout

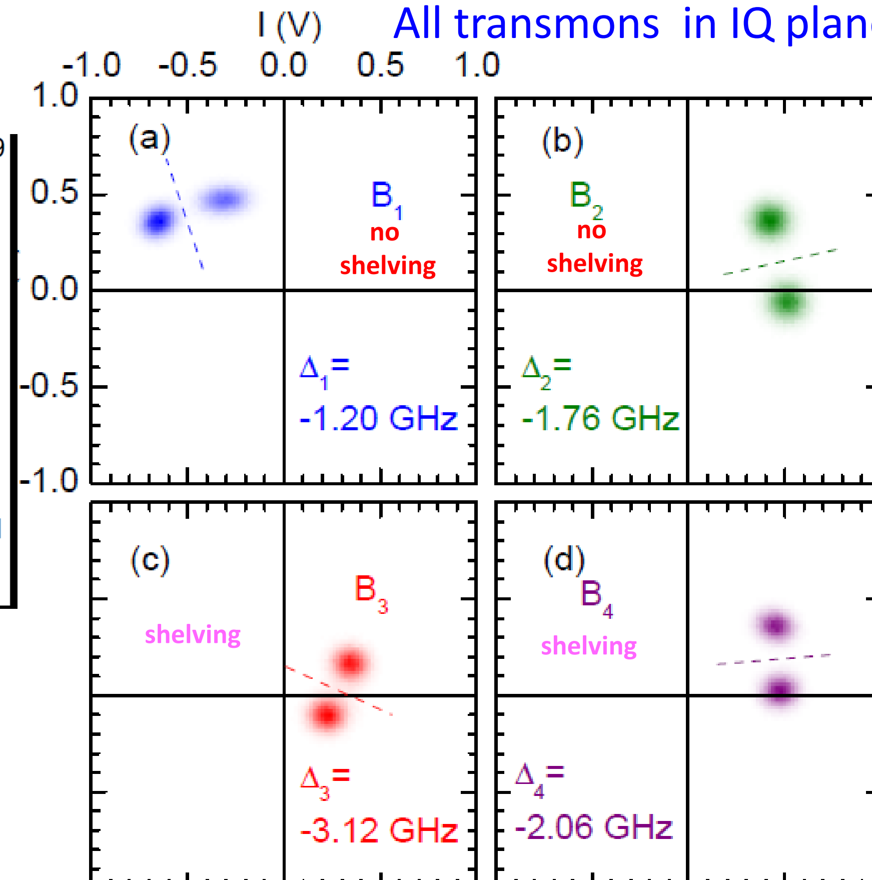


Analysis of reflected pulse yields
in-phase I
quadrature Q
bifurcated/non-bifurcated state

single transmon readout performance



All transmons in IQ planes

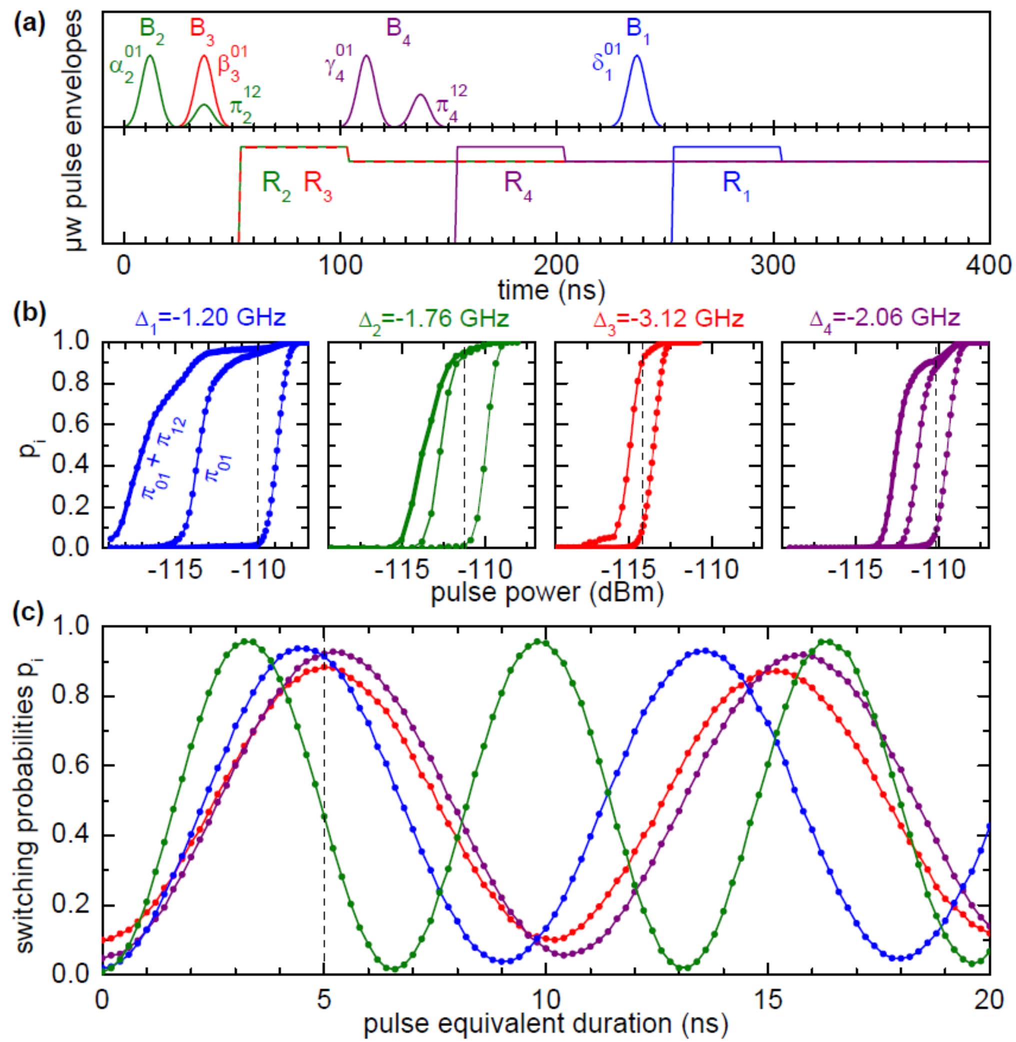


multiplexed qubit readout

drive & readout timing

switching curves

simultaneous Rabi oscillations



Note: lack of local flux tuning lines prevents getting best readout performance simultaneously.

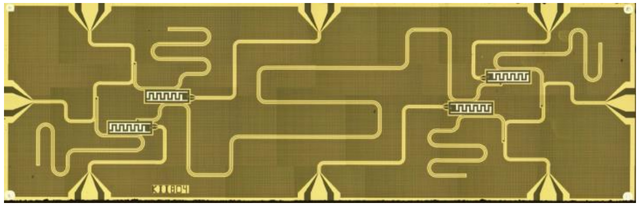
Scalability issues: quantum error correction

QC: > 100s of robust logical qubits needed

(1) Quantum error correction codes: demanding threshold for gate errors < 10^{-4}
huge resource overhead x50 ?

Measure syndroms for assigning errors without qubit projection

Di Carlo, TUD
parity measurements for bit-flip detection + FPGA feedback



bit-flip correction of a single qubit within reach

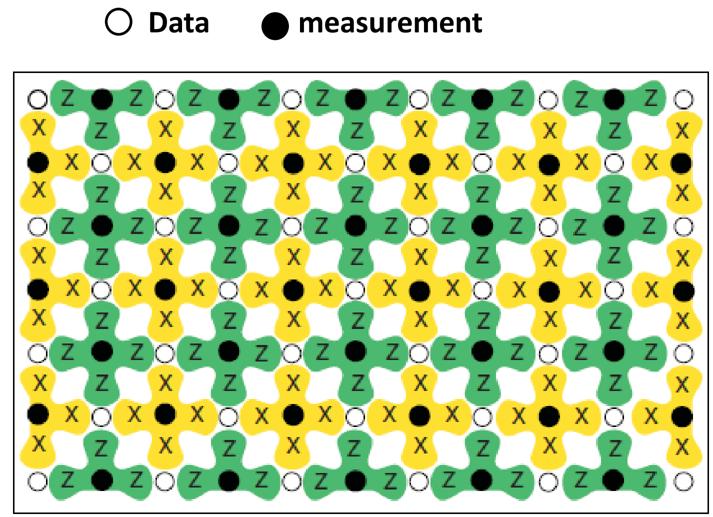
(2) Surface codes: less demanding threshold for gate errors < 10^{-2}
extreme resource overhead x 10^3 x 10^4

(3) Other paradigms:
spins, Schrödinger cat states in high Q resonators, Adiabatic Quantum Computing

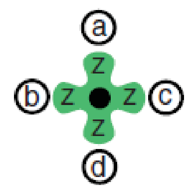
(2) The surface code

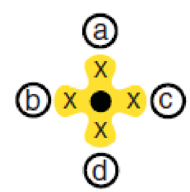
Kitaev, 2002, Preskill 2003,
Gottesman stabilizers ….

Readable ref: Fowler et al., PRA 86, 032324 2012)



- 2D array of qubits (measure (x and Y types), data) with CNOT gates , Z measurements.
- nearest-neighbor coupling
- Forgiving threshold (~0.99)
- Error detection is enough, correction handled by classical post-processing
- **Extreme** resource overhead (*irrealistic ?*)

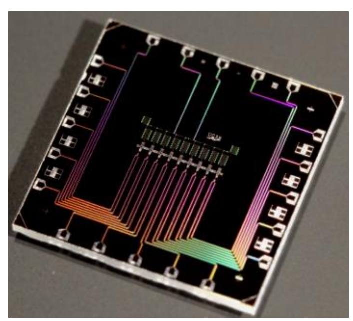


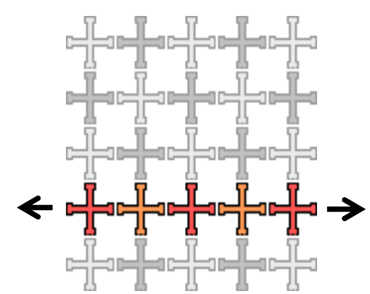


Preliminary 9 qubit test circuit

J. Martinis team

UCSB- **Google**





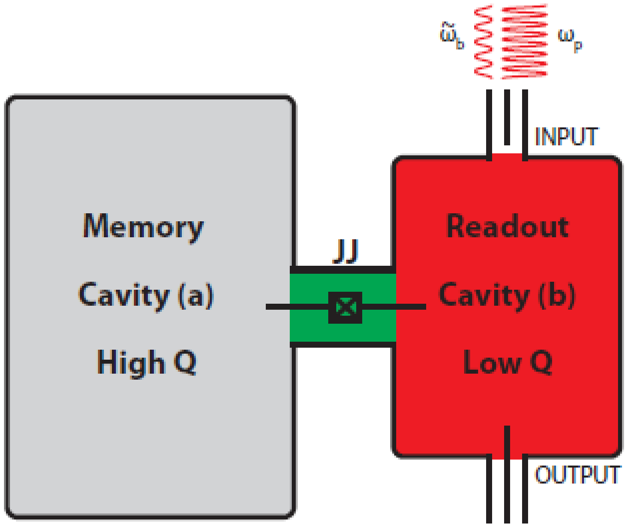
(3) Engineered dissipation for robust logical qubits with simple errors that can be detected and corrected

See: Dynamically protected cat-qubits:
a new paradigm for universal quantum computation

Mirrahimi, Leghtas, Albert, Touzard, Schoelkopf, Liang ,Devoret

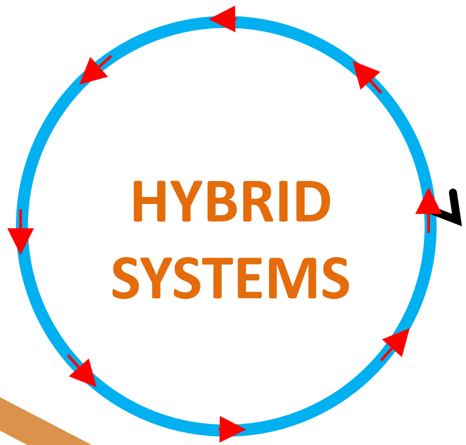
NEW JOURNAL OF PHYSICS 16 045014 (2014) arXiv:1312.201

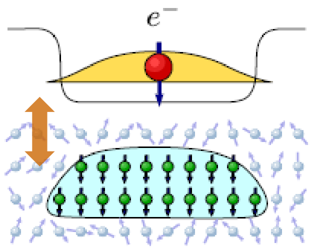
Pumping + non-linear element yield 2photon dissipation for memory



Cat states built with coherent states are robust
Parity measurements detect errors.
Gates based on Zeno effect

(3) Beyond hybrids

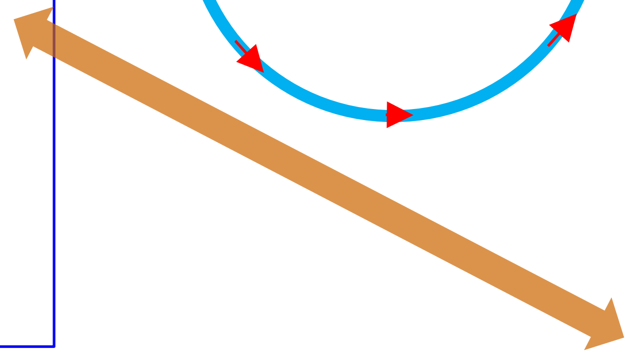




Nuclear spins

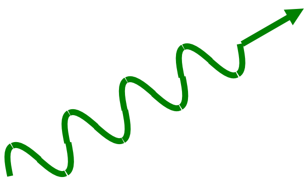
>1s coherence time

Very hard to couple



Optical photons

for communication



Superconducting qubits

See:

Kubo et al., PRL 107, 220501, 2011

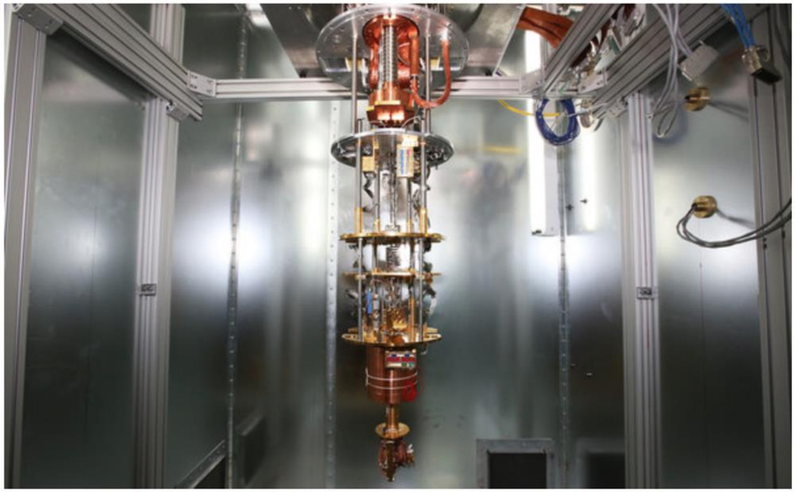
Grèzes et al., PRX 2, 021049, 2014

Julsgaard et al., PRL 110, 250503 2012

The Dwave strategy & machine (10 M$)

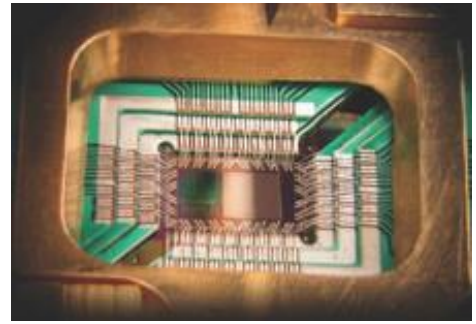
The New York Times   March 22 2013

A Strange Computer Promises Great Speed



Kim Stallknecht for The New York Times

512 qubits



??

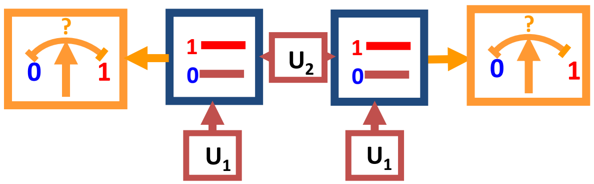
Adiabatic Quantum computing (?)

An annealing machine assisted by quantum effects ? ?

QC with gates versus Adiabatic Quantum Computation

The QC way:

unitary evolution of a qubit register (according to algorithm) & readouts



Difficulties:

unitary evolution
quantum error correction
readout
scalability

overcoming standard computers:

N=50-100 robust qubits
(i.e. corrected from errors)

State of the art:

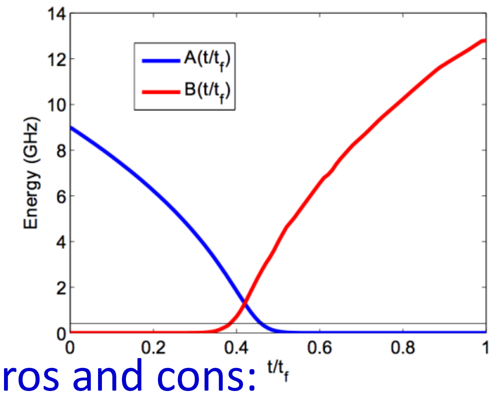
N=2-4 , errors, no QEC
N=10 in view, without QEC

Proof of principle for quantum speedup on elementary problem

(3) The AQC way:

finding the ground state of a Ising spin Hamiltonian $H^z(t)$ (that encodes the problem) starting from a trivial one following an adiabatic evolution

$$H(t) = B(t)H^z(t) - A(t)\sum \sigma_i^x$$



Pros and cons:

Evolution is simple
Problem encoding not easy, good for optimization
role of decoherence and temperature not understood

overcoming standard computers:

N=4000-8000 qubits

State of the art (Dwave machine):

N=500, operational , not perfect, N=2000 in view

Ising spin-glass problem solved on 100 spins but quantum speedup not demonstrated

Ronnow ,..., Troyer Science 334, 420 (2014)

cea

QUANTUM ELECTRONICS GROUP

SPEC

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