Quantum Computing: how to fabricate and assemble quantum bits

Saclay ESNT workshop: QC&Nuclear Physics
June 12-14 2019

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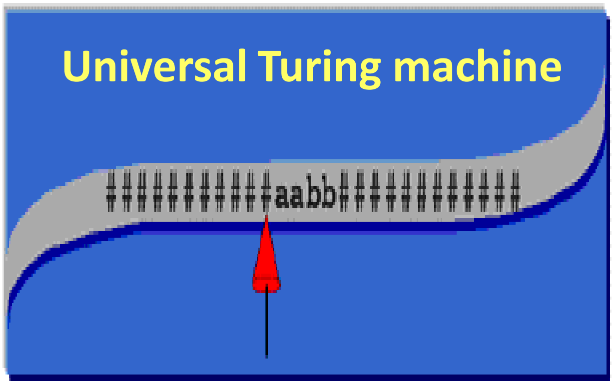
QUANTUM ELECTRONICS GROUP

spec cea cnrs

Quantum computing: the origin

Classical computing



Computer:

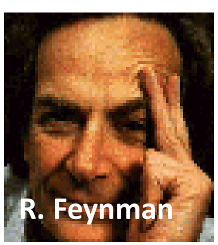
n (0,1) bits evolve among **2^n states**

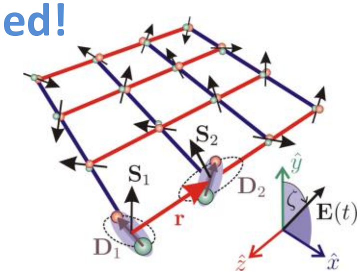
0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1

$$R = (i_1, i_2, i_3 \ldots i_{2^N}) \quad i_k = 0,1$$

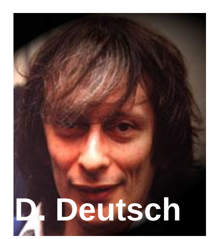
But is a universal Turing machine
truly universal ?

1982: Quantum systems too hard to crack, quantum simulation needed!





1985 the breakthrough:

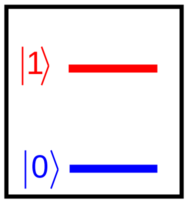


Quantum mechanics provides computational resources !

The art of Quantum computing

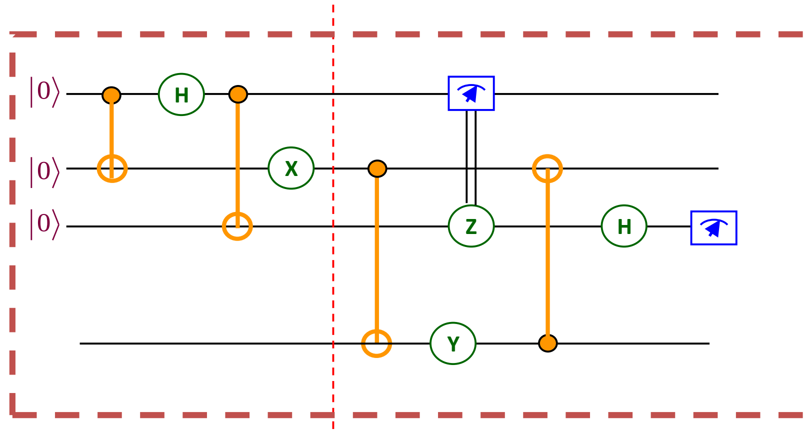
Unitary evolution of a n quantum bit register

qubit



2^n computational basis states

$$\overbrace{|010001...1\rangle}^{n} = |p\rangle$$



ideal projective readout at the end

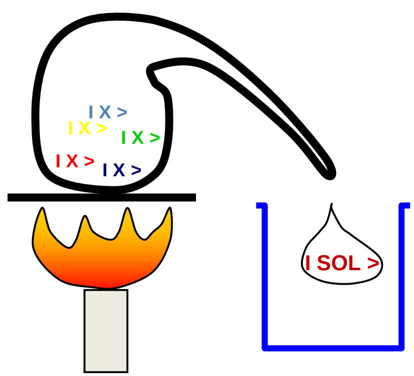
$$\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_{4....} i_{2^N}} |i_1, i_2, i_3 ... i_{2^N}\rangle$$ (entangled state)

QM being linear the evolution can be massively parallel

| X > + | X > + | X> + … → U → U | X > + U | X > + U | X> + …

But readout only delivers a N bit answer

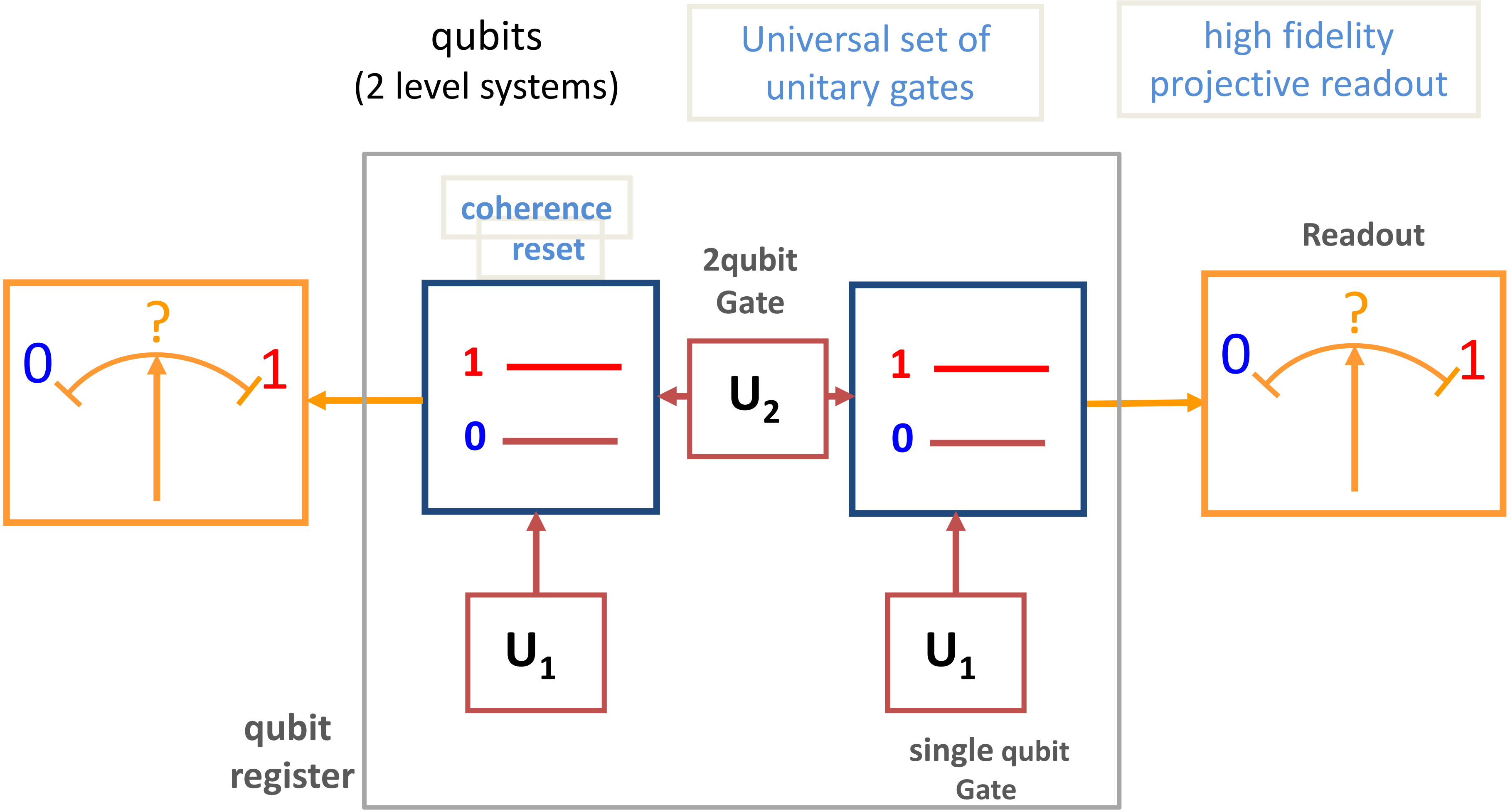
QC: the art of obtaining a useful answer at measurement time



measurement

A 50-100 **ideal qubit** quantum computer would overcome classical computers (for some already interesting tasks)

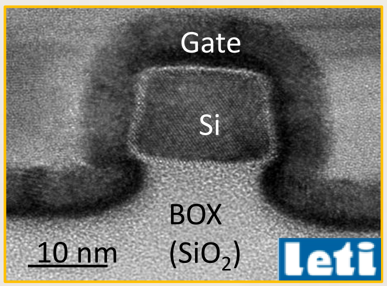
blueprint of a quantum processor (based on quantum gates)



"DiVincenzo criteria"

The hpc context: massive integration progresses at a slower pace

Semiconducting circuits reach physics limits
+ increasing needs



Ultimate CMOS

(Soon ?)

3D stacking
ultra low power

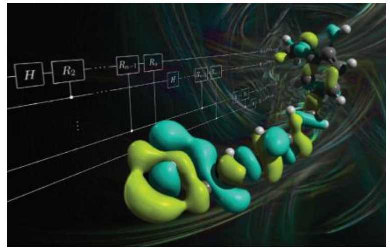
Alternative technologies for HPC ?

Quantum computing now envisioned

QC: A potential breakthrough in HPC (?)

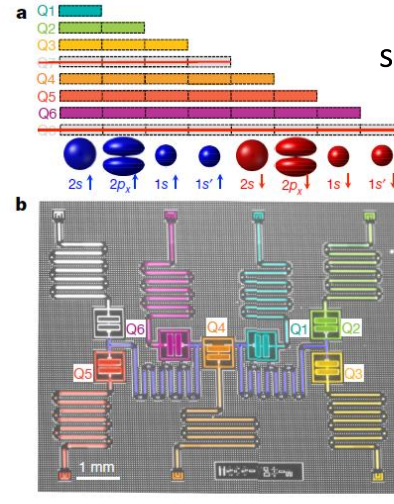
Use-cases

Many-body physics:
quantum chemistry, materials
nuclear physics …

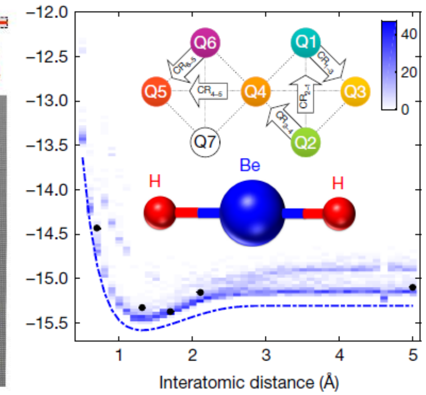


Fermionized Hamiltoniens
map well on qubits

needs: >100 qubits



small scale demos:



variational quantum eigensolver :
IBM Kandala et al., Nature 549, 242 (2017)

Linear algebra:
quantum inversion of
sparse matrices

HHL algorithm

Harrow, Hassidim, Lloyd, PRL 103, 150502 (2009)

quantum RAM needed !

Quantum machine learning

Gao, Zhang, Duan arXiv:1711.02038

quantum RAM needed !

Big players attracted, strong partnerships developed

IBM intel Google Microsoft

Eu:

AtoS

"*Strong* " Eu flagship initiative

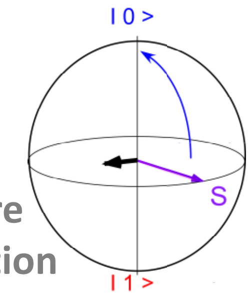
Qubit systems ?

Can any quantum system be a quantum bit ?

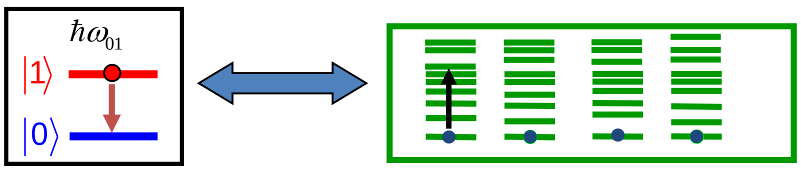
The issue: coupling to environment yields **decoherence**

cf Ithier et al., PRB 72, 134519, 2005

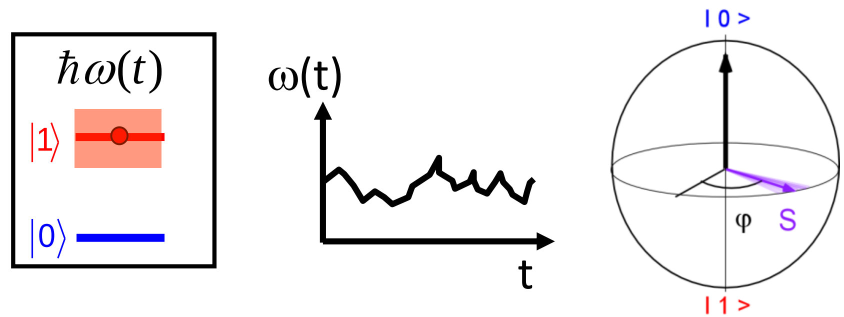
Relaxation
(spontaneous emission in or excitation by environment)



Bloch sphere representation



dephasing from fluctuating energy



$$\alpha|0\rangle + \beta e^{i\varphi(t)}|1\rangle$$

$$\left\langle e^{i\varphi(t)} \right\rangle \approx e^{-\Gamma_2 t}$$

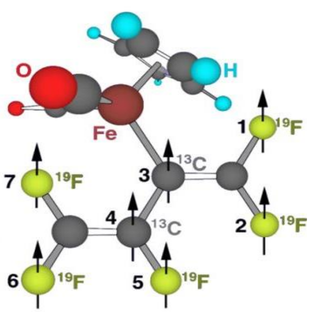
Microscopic systems
weakly coupled to their environment
quantum regime easy
not easily addressable

Macroscopic systems
strongly coupled to their environment
quantum regime difficult
easily addressable

solutions ?

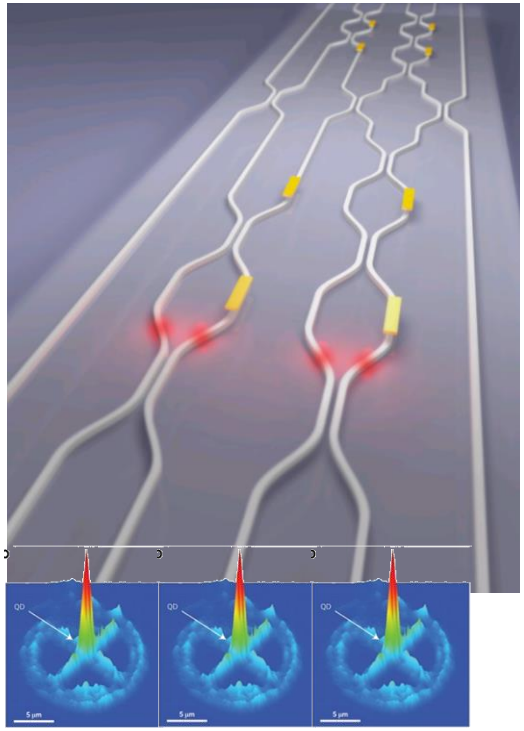
Physical implementations

NMR



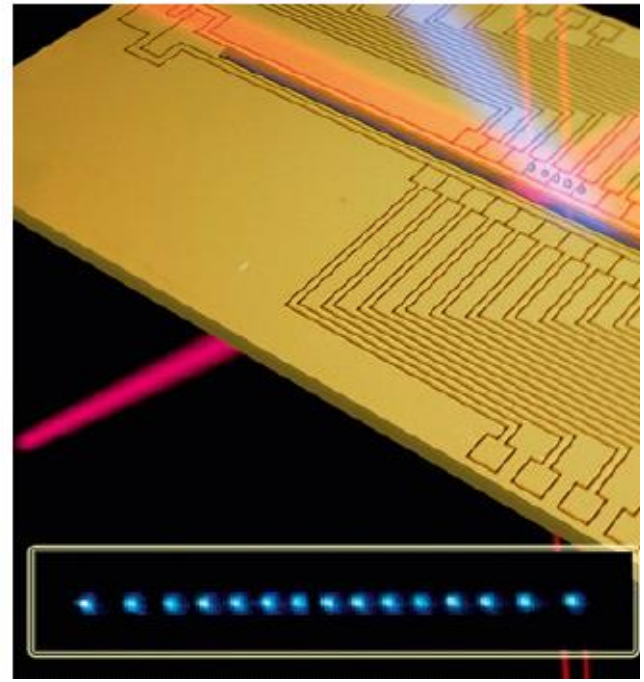
code=molecules
not scalable

Photons



gates yet not achieved
Other strategy:
measurement based Qcomp
with **cluster states** made
using identical photons

Trapped ion 1D-2D arrays



The most advanced platform

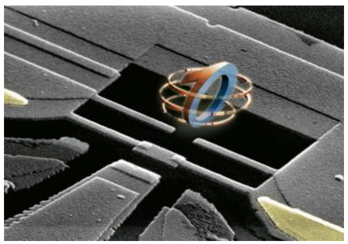
scalability problematic

… Electrical circuits ?

Electrical qubit circuits (non exhaustive)

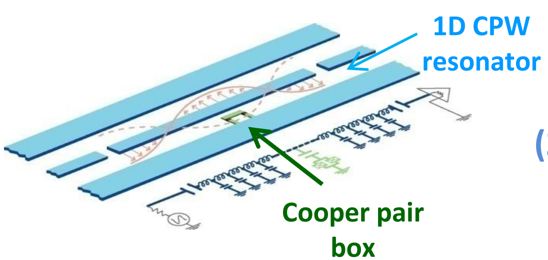
quantum states
of superconducting circuits

Superconducting qubits based on the
Single Cooper Pair Box circuit



functional SC qubit
(CEA 2002)

Now: Transmon type Cooper Pair Box circuit

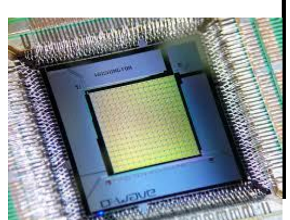


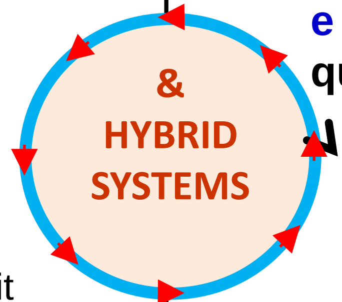
Yale
(2004-2006-2010)

Different computing strategy
quantum annealing

difficult problems solved
quantum speed-up not
demonstrated

DWAVE

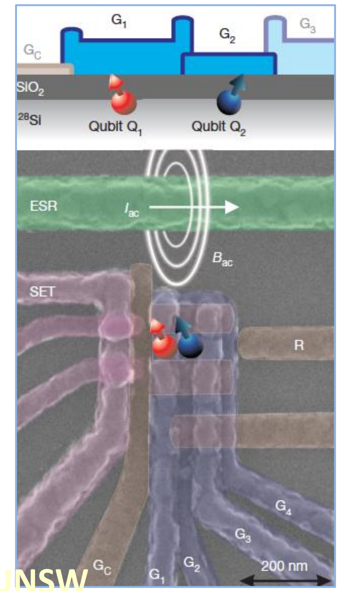




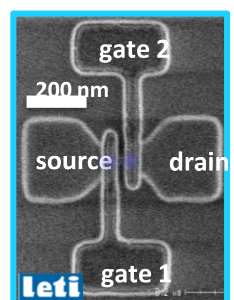
Electron spin states
in semiconductor structures

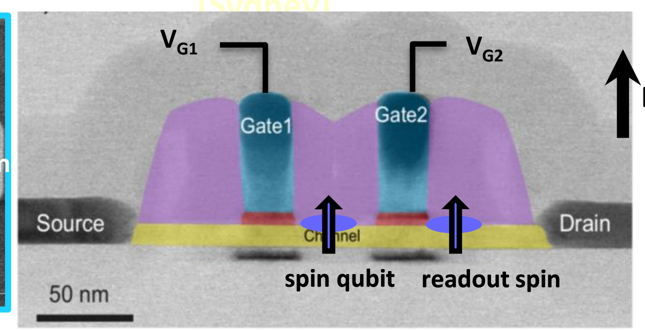
e spins in
quantum dots

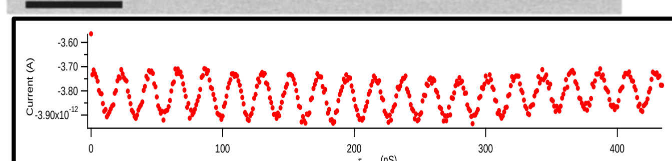
UNSW, TUDelft,
Harvard,
CEA (INAC-LETI)



a qubit from
on an industrial
fab line at CEA

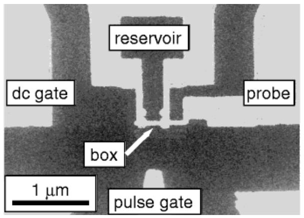


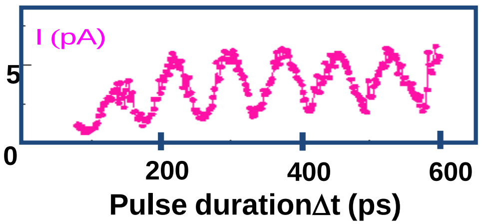




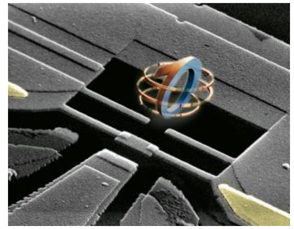
The Cooper Pair Box quantum bit: a brief survey

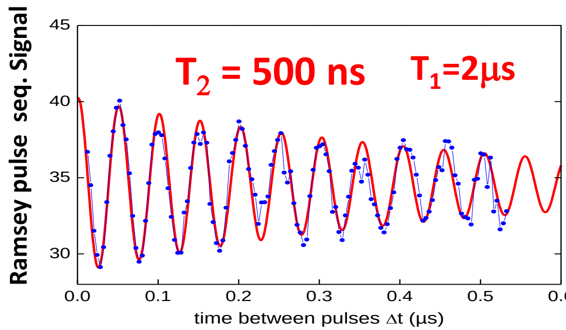
first Cooper Pair Box qubit
Nakamura, Pashkin &Tsai (NEC, 1999)



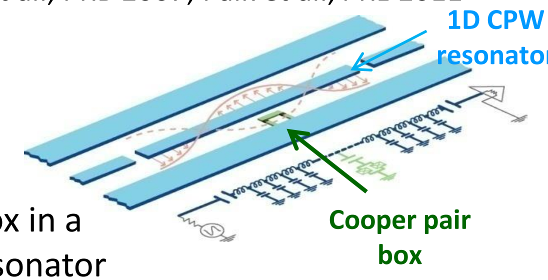


First operational qubit
Vion et al., (Quantronics, 2002)

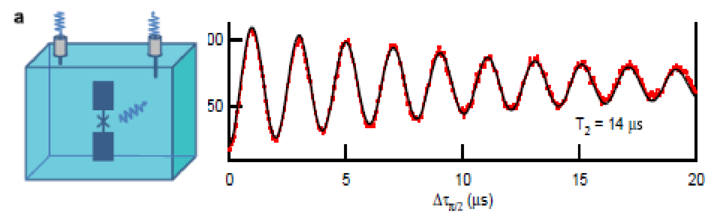




Circuit QED: transmon Cooper pair box in a microwave cavity (2D, 3D)
Schoelkopf lab., Yale ; Wallraff et al., Nature 2004
-Koch et al., PRB 2007; Paik et al., *PRL* 2011

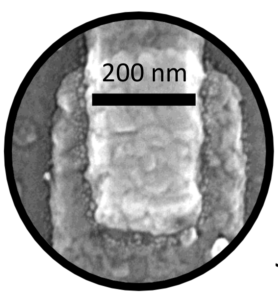


CPBox in a 3D resonator

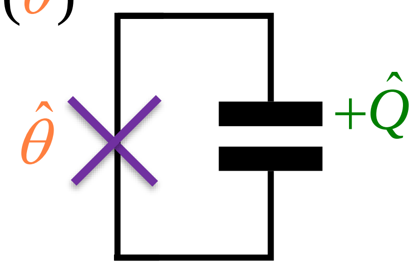


The transmon

$$E_p = -E_J \cos(\theta)$$

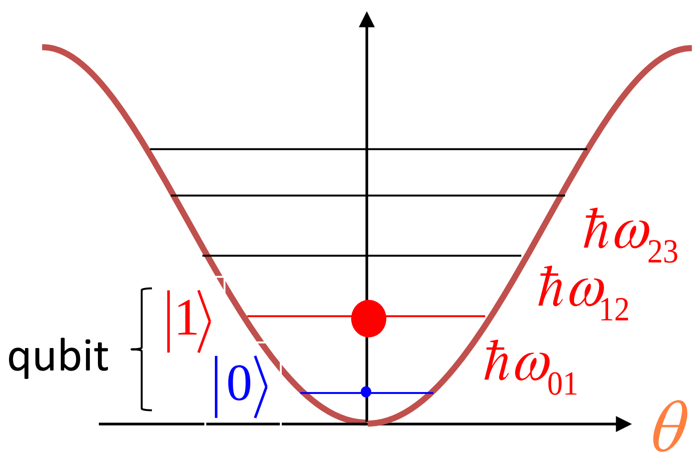


Al/Al$_2$O$_3$/Al



Josephson junction Phase : Flux across junction

$$\hat{\Phi} = \left(\frac{\hbar}{2e}\right)\hat{\theta}$$



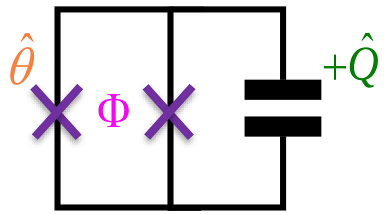
anharmonic oscillator

$$\hat{H} = -E_J \cos(\theta) + \frac{\hat{Q}^2}{2C}$$

Circuit-QED architecture to readout a Josephson qubit

flux tunable qubit

$L_J(\theta,\Phi)$

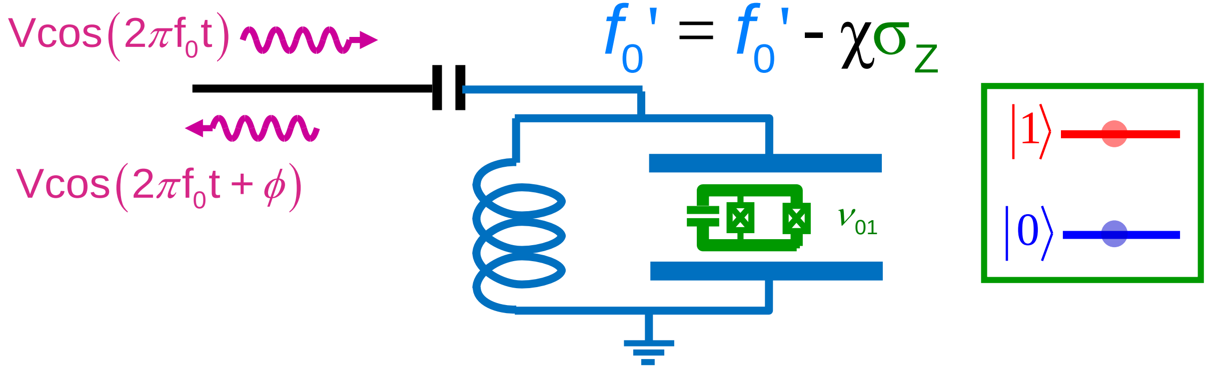


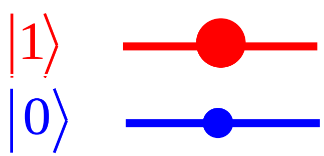
$$E_p = -E_J \cos(\theta)$$

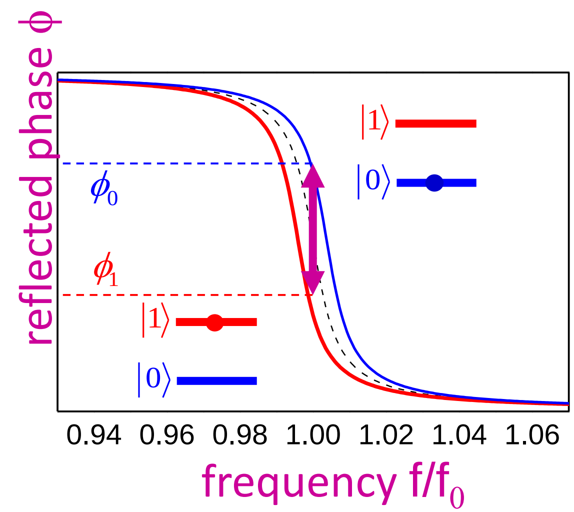
$$\hat{H} = -\hbar\omega_{01}(\Phi)\hat{\sigma}_z / 2$$

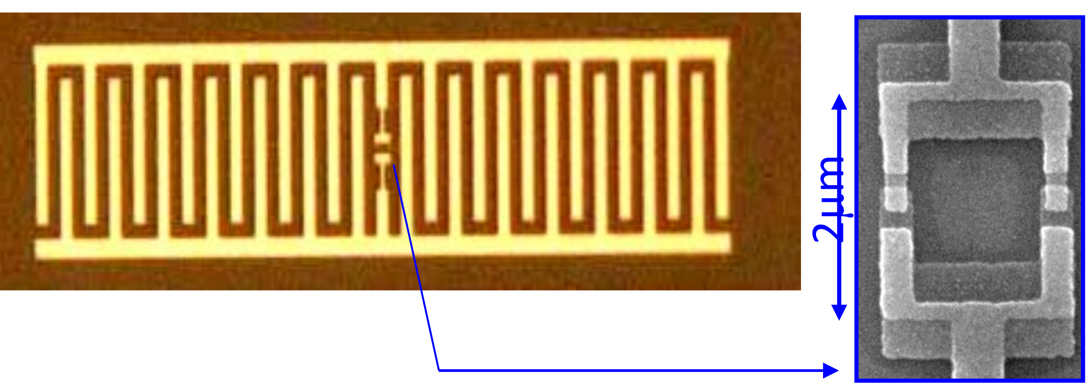
Dispersive readout with a resonator :

$$f_0' = f_0' - \chi\sigma_Z$$

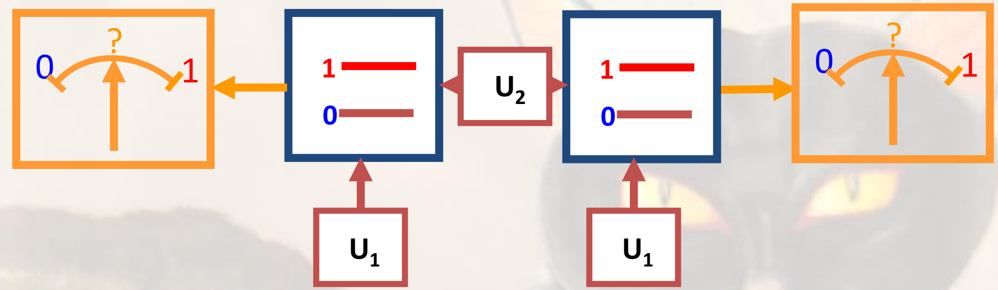




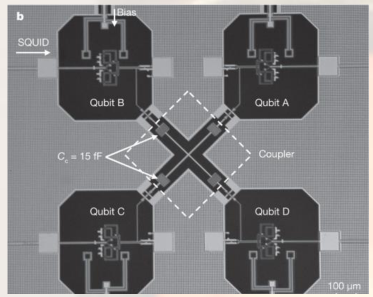




Running quantum algorithms on elementary processors

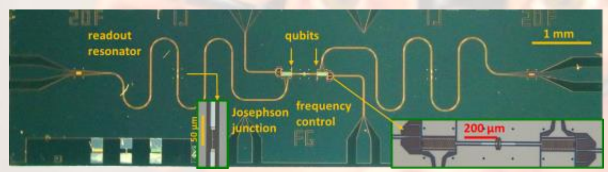


Martinis Lab, UC Santa Barbara
Yamamoto et.al. ,
PRB 82 2010 , Nat Phys 2012



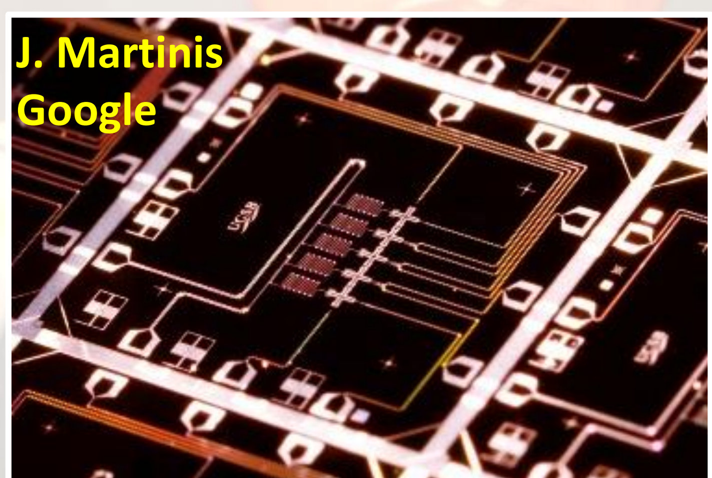
Shor factorization algorithm

Quantronics, CEA
Dewes et. al., PRL & PRB 2012



Grover search algorithm

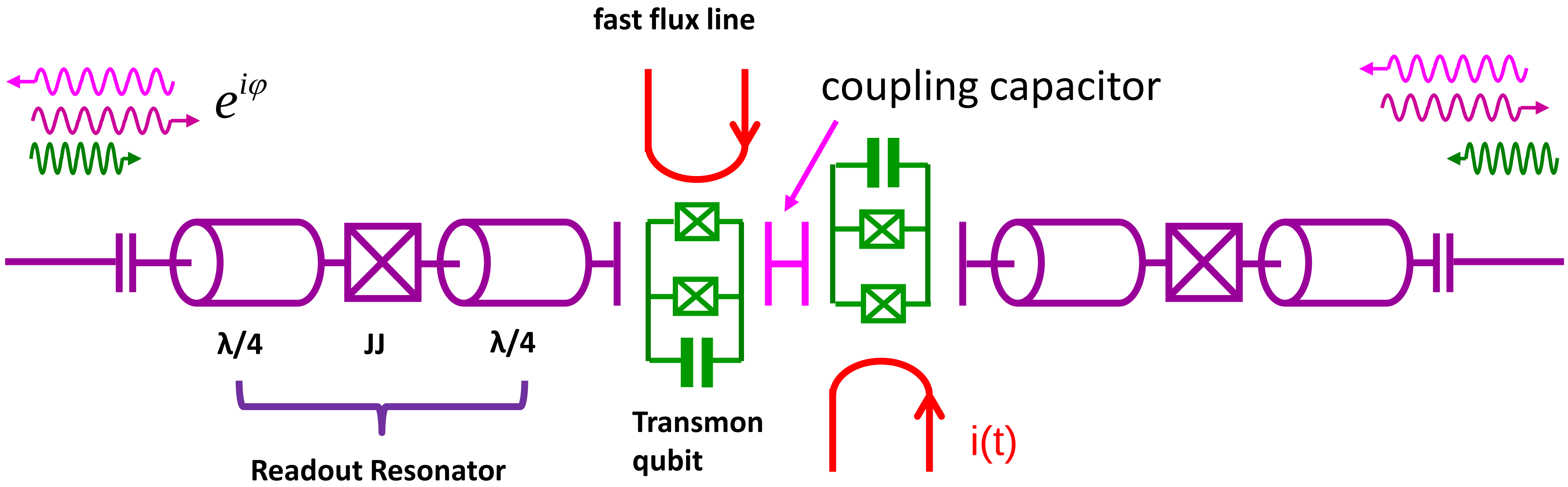
Martinis lab, Google 2015…
IBM, TUD

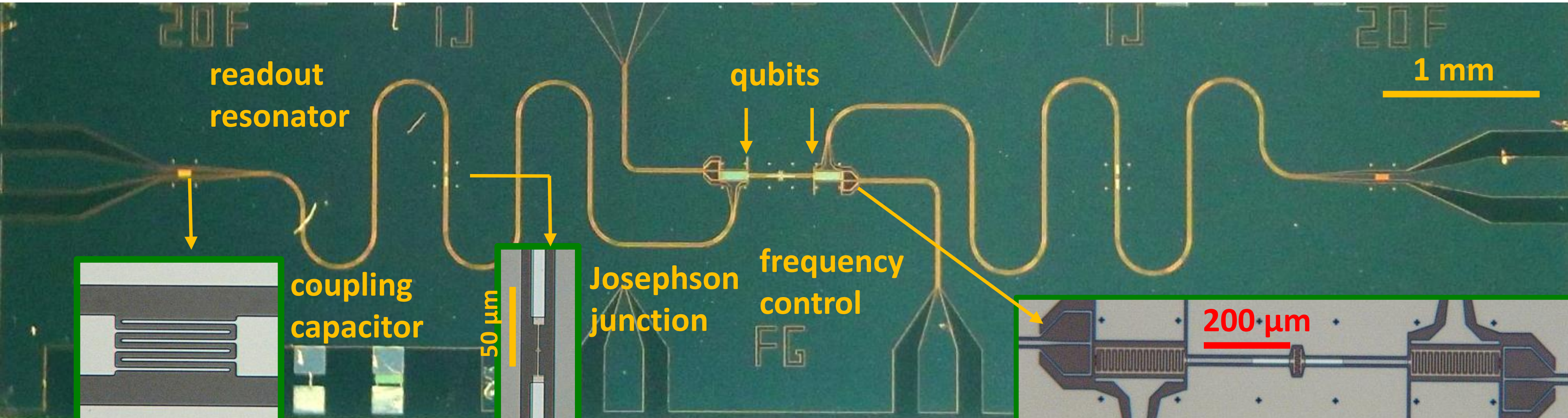


correcting some errors

The simplest case: a two-transmon processor

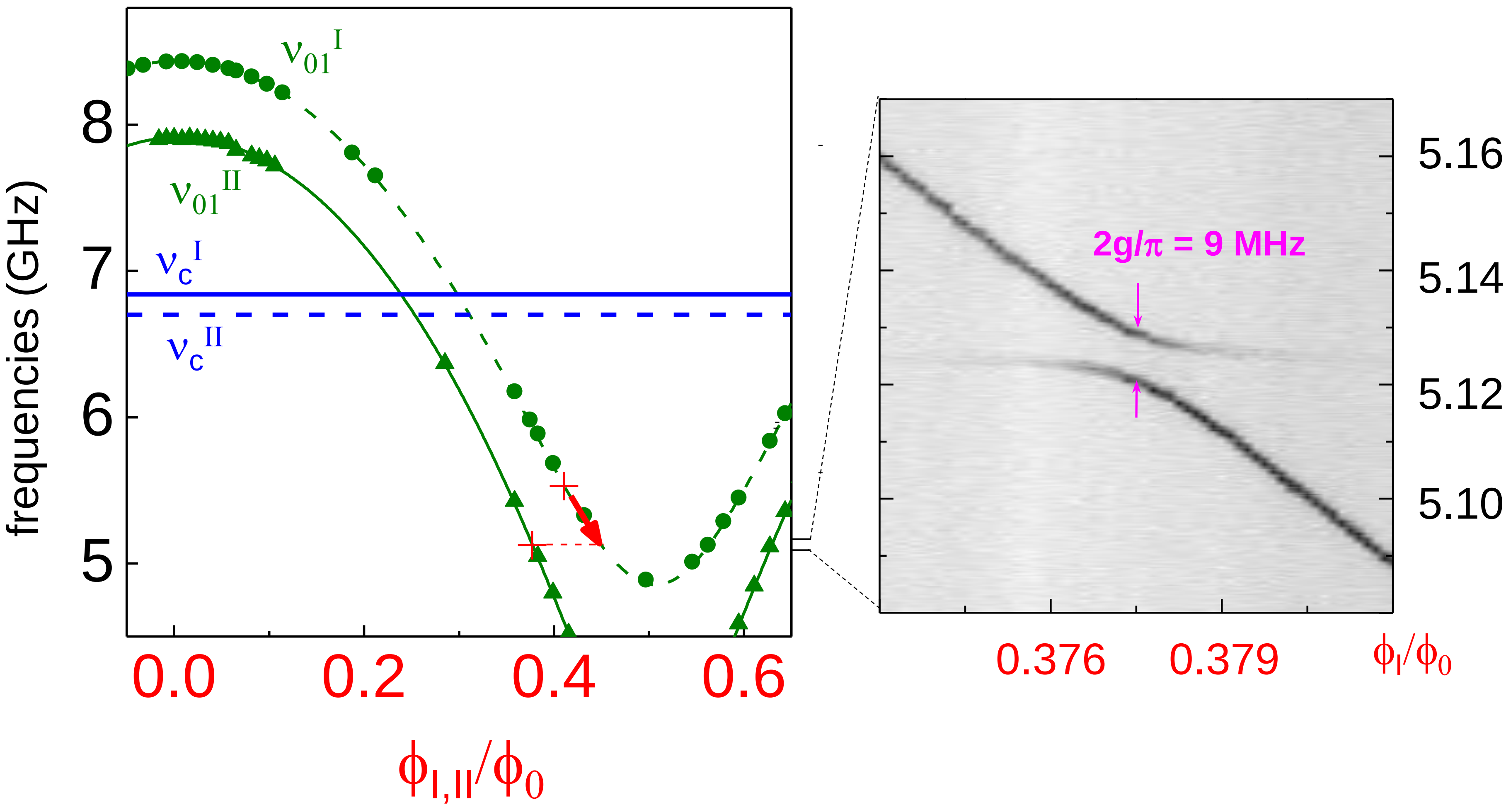
Dewes et al., Phys. Rev. Lett. 108, 057002 (2012)



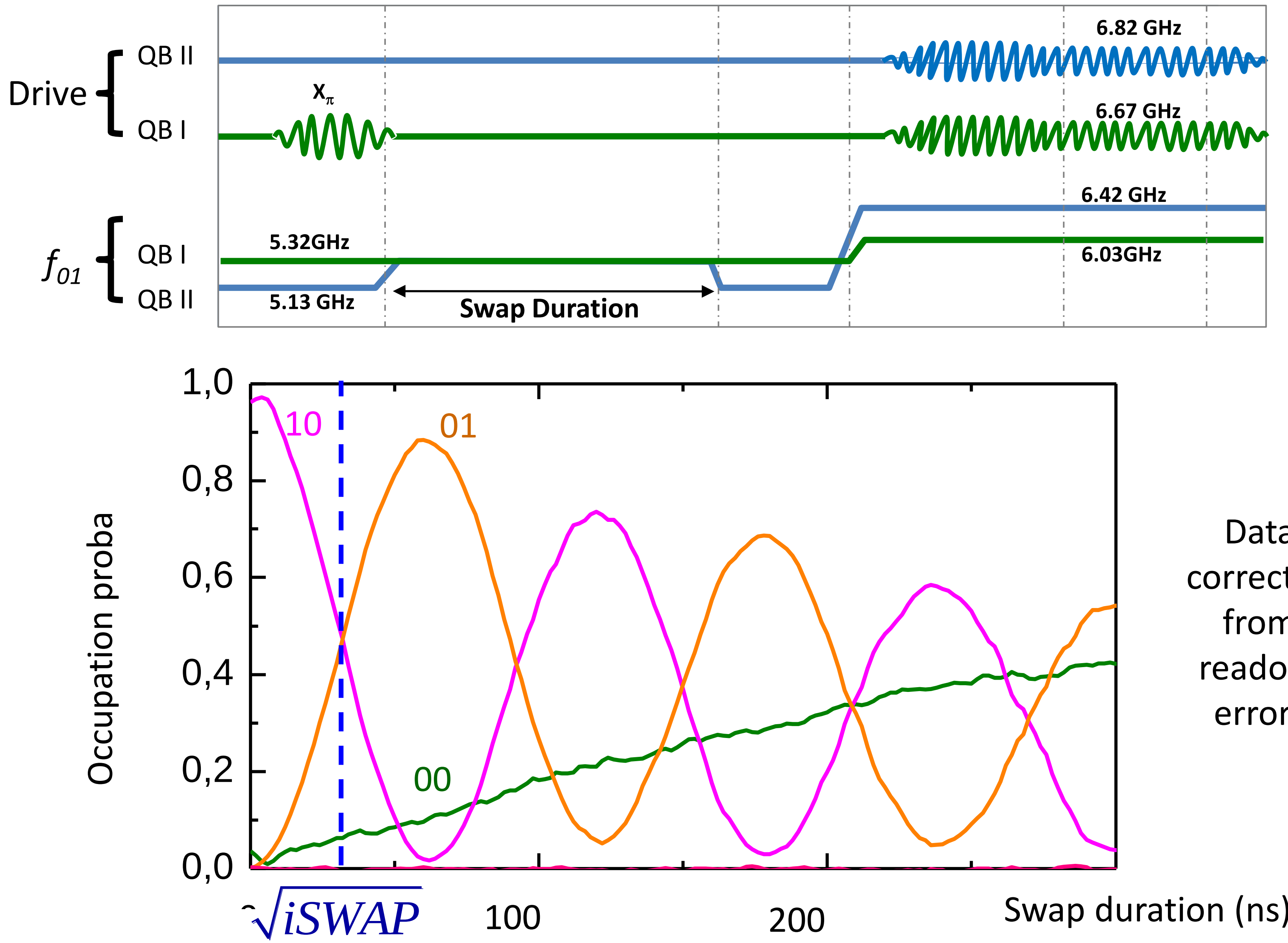


5. Simple example of the iSWAP$^{1/2}$ two-qubit gate

A. Dewes et al., PRL (2011)



4. Simple example of the iSWAP$^{1/2}$ two-qubit gate



Data corrected from readout errors

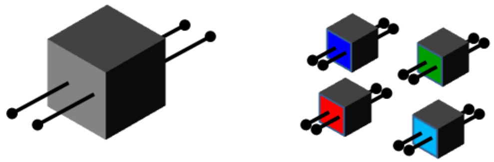
The Grover search algorithm on 4 objects

the search problem

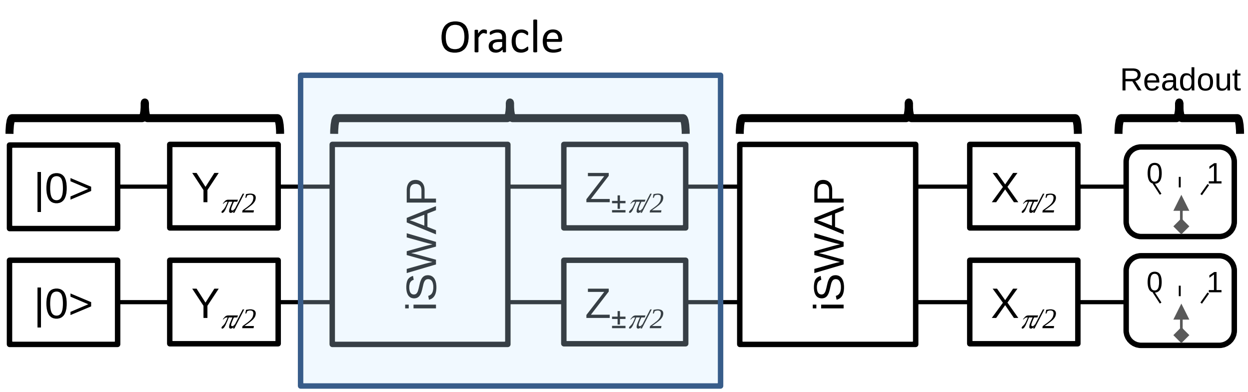
Classical search: O(N) steps   Quantum search : O(√N) steps

4 object benchmark case: **1 try** enough !

Oracle marking a state

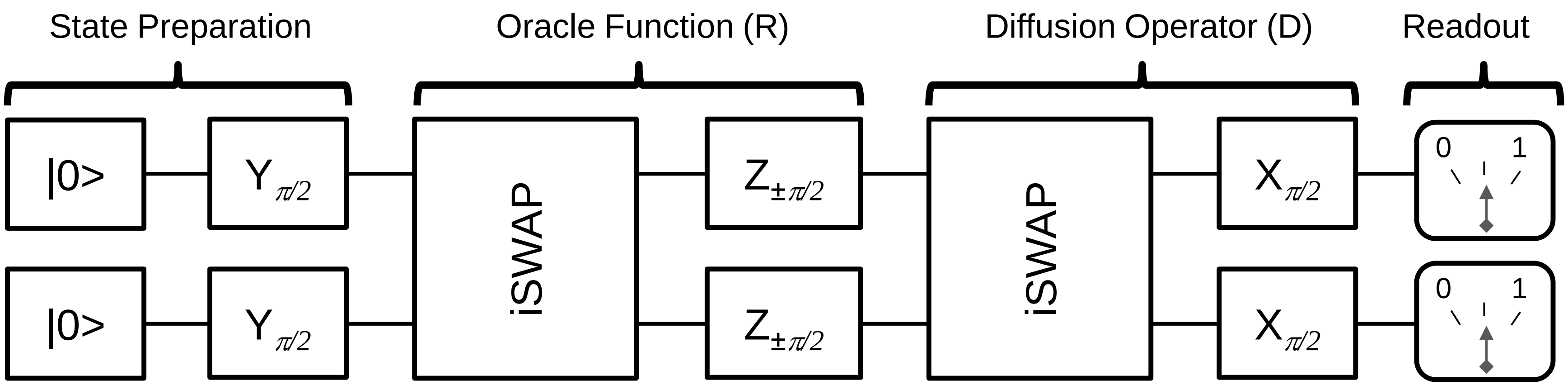


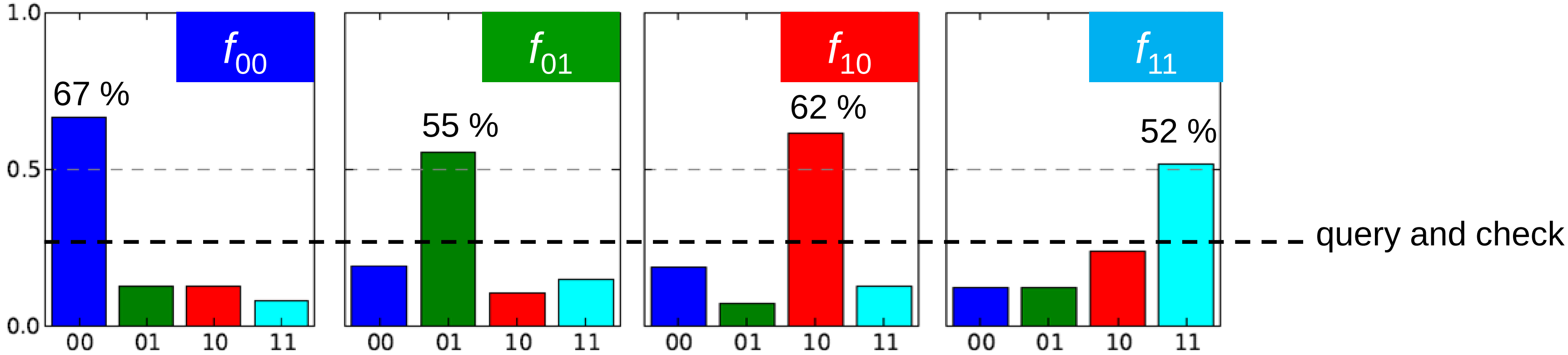
$i \in \{00 \quad 01 \quad 10 \quad 11\}$



Quantronics, CEA
Dewes et. al., PRL & PRB 2012

The Grover search algorithm: success probability





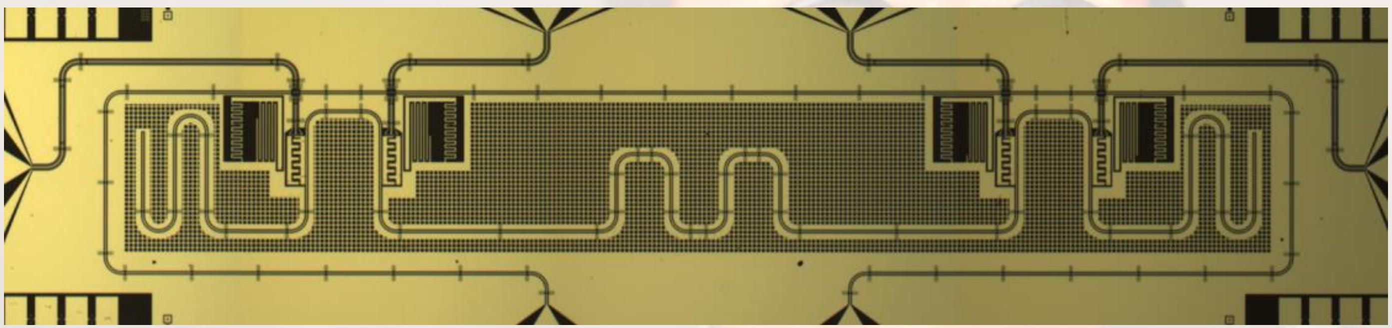
$F_i > 25\ \% \rightarrow$ Quantum speed-up achieved!

Dewes et. al., PRB Rapid Comm **85** (2012)

Scaling up ?

4 qubit processor (2015) :

multiplexed readout
2 qubit gates through common bus
& did not work well



Issue:

A route that does not solve the scalability challenge

The scalability challenge

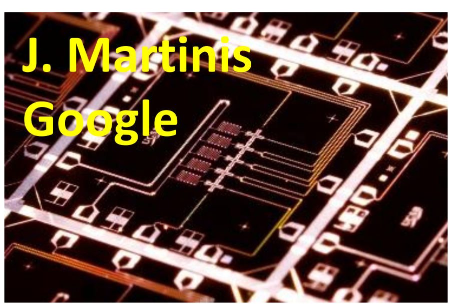
GATE BASED PROCESSORS

Elementary processors

Better coherence:
T_2: 10-30 μs

Protocols :
teleportation,
quantum feedback
Digital simulation

The NISQ era



Quantum advantage within reach ?

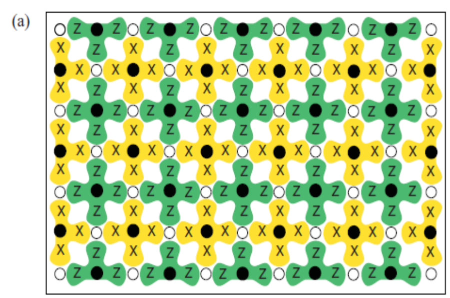
Addressing Quantum Error Correction

Beware: copying forbidden!

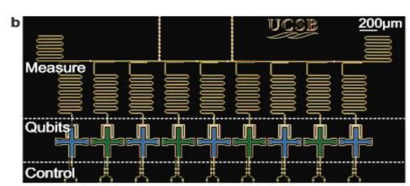
fault-tolerant architectures

surface code fabric
(see Fowler et al, PRA 86 (2012)

○ **Data** ● **measurement**



Huge resource overhead
1 logical qubit>>1000 physical qubits

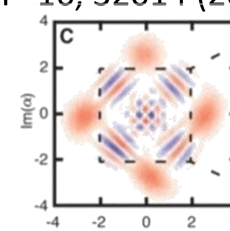


test circuits
for quantum error correction

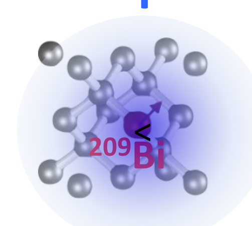
robust qubits

Dissipation engineering

Yale Quantlab,
INRIA- LPA (ENS)
ENS Lyon (B. Huard)
Schrödinger cat states in high Q resonators
Mirrahimi et al.
NJP 16, 32014 (2014)



hybrids: spins in circuits



better coherence

A few pictures from Ted White (Google AI) at SQ20th (Tsukuba, May 2019)

Quantum Supremacy

QUANTUM COMPUTING AND THE ENTANGLEMENT FRONTIER

JOHN PRESKILL

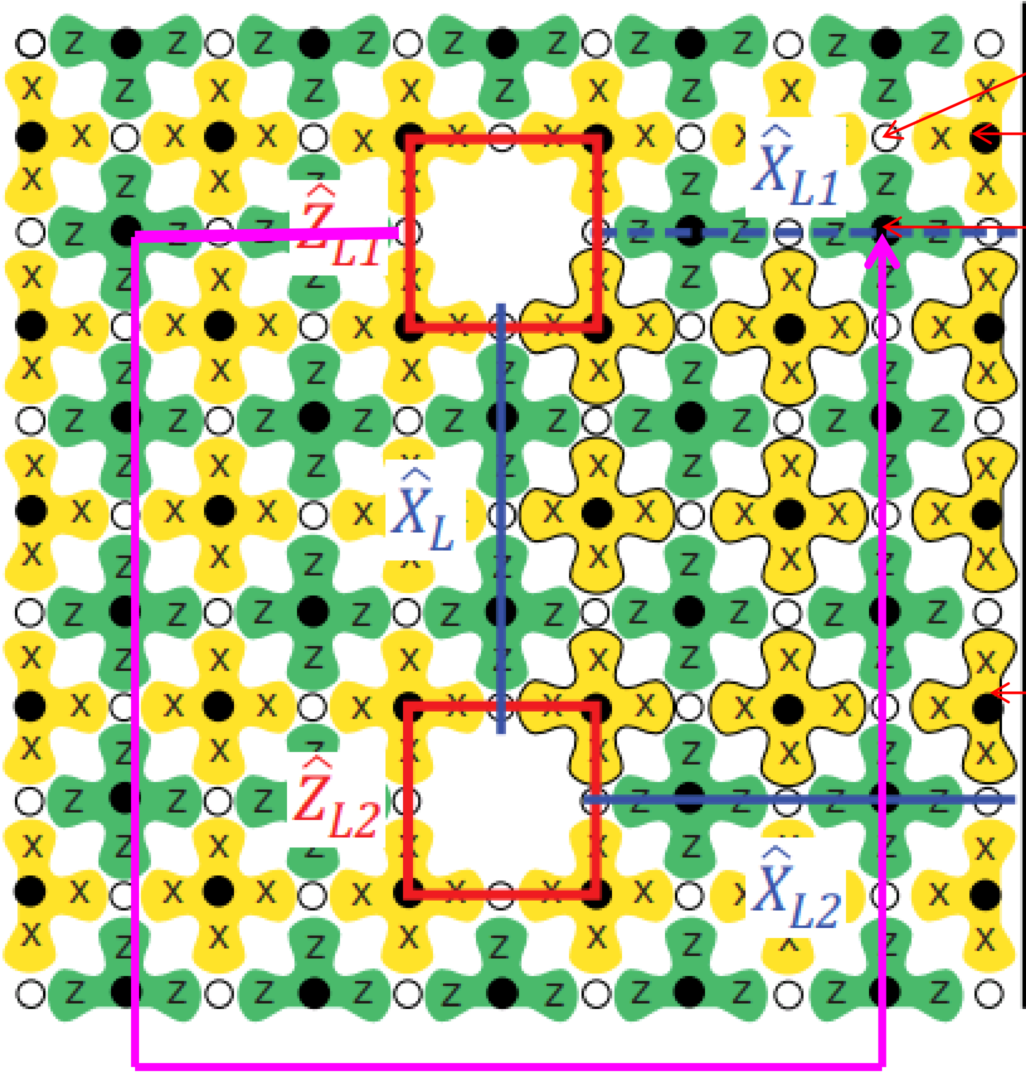
Quantum advantage ?

We therefore hope to hasten the onset of the era of ~~*quantum supremacy*~~, when we will be able to perform tasks with controlled quantum systems going beyond what can be achieved with ordinary digital computers. To realize that dream, we must overcome the formidable enemy of *decoherence*, which makes typical large quantum systems behave classically. So another question looms over the subject:

> *Is controlling large-scale quantum systems merely **really, really hard**, or is it **ridiculously hard**?*

Google AI
Quantum

The surface (stabilizer) code architecture



data qubit

X measure qubit

Z measure qubit

- Repeat measurements of all X,Z
- Memorize errors
- don't need to correct
- Define plaquette logical qubit
- Define logical qubits by holes
- Single qubit gate X_{L1}= product X
- Two qubit gates by braiding

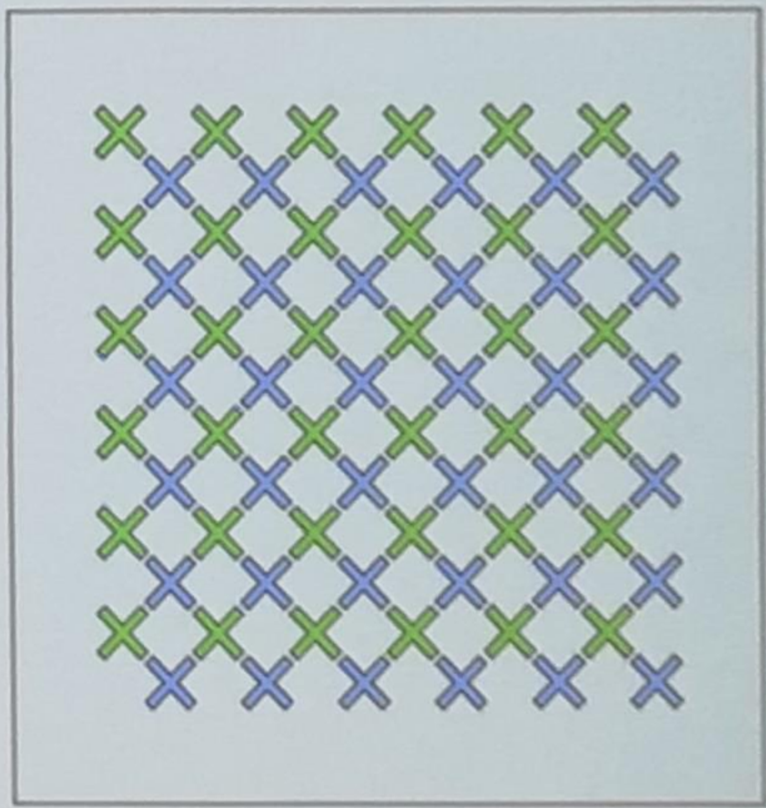
But … huge overhead: >3600 qubit/logical qubit @ 0.1% error/gate !

Scalable fabrication mandatory!

"Bristlecone" a true 2-D grid

- 12 unit cells of 6 qubits = 72
- Flux tunable transmon qubits
- Fixed capacitive coupling
- Enough for "Quantum Supremacy"
- Enough for 1st, 2nd order Surface Code
- Starting point for near-term algorithms

Bristlecone



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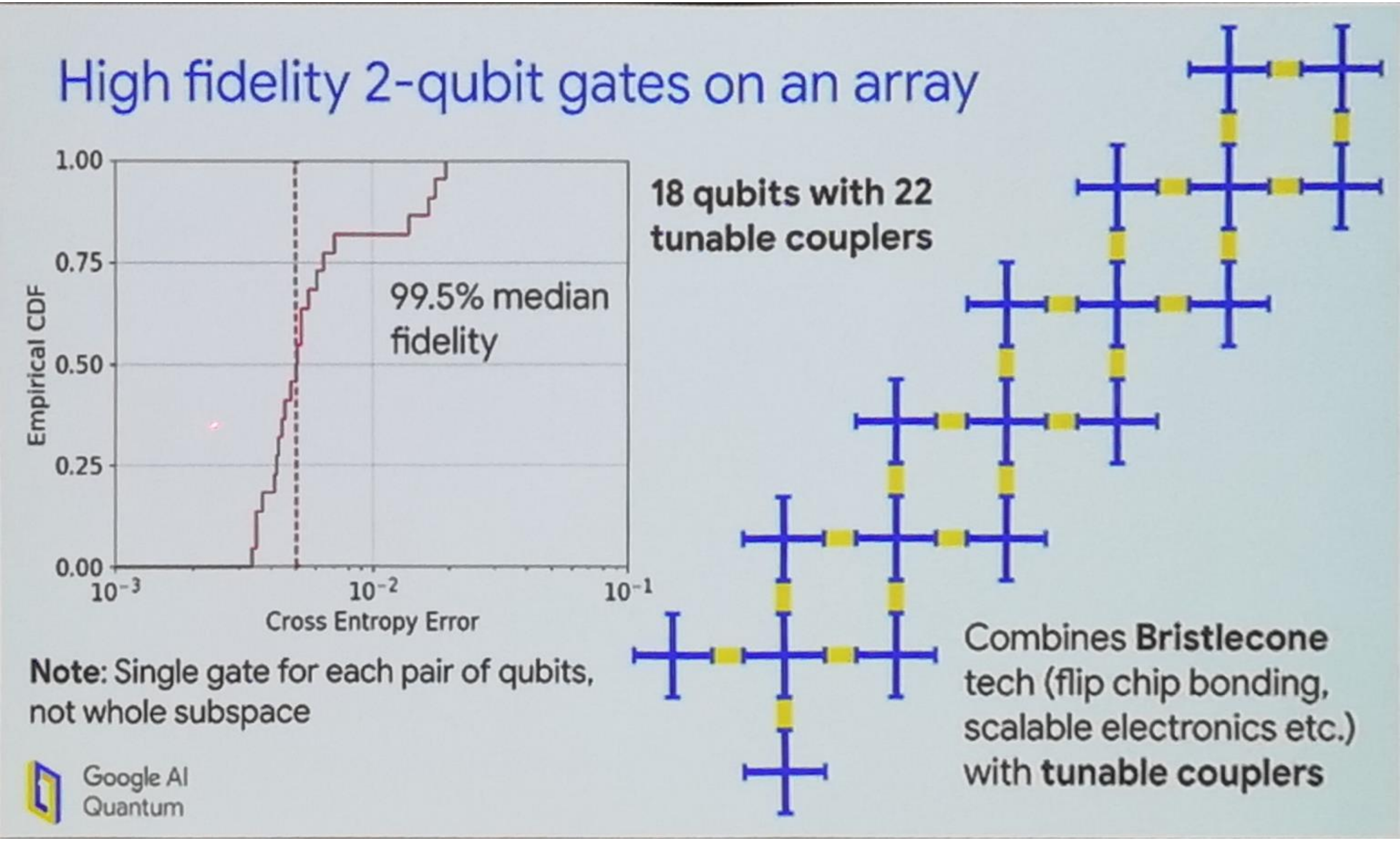
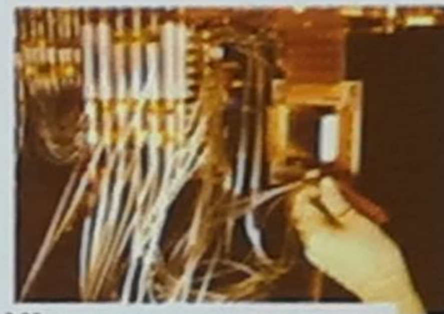
does not work well, but…

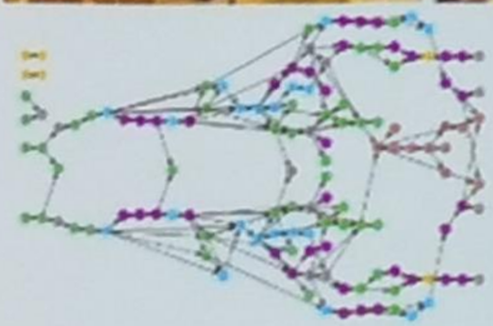
Significant progress achieved using tunable couplers

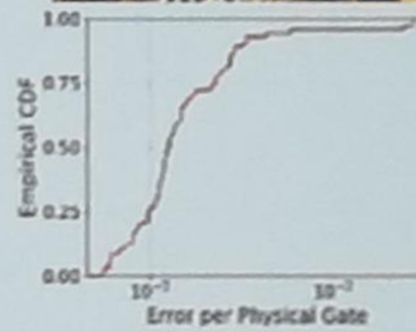


Device targets for quantum supremacy



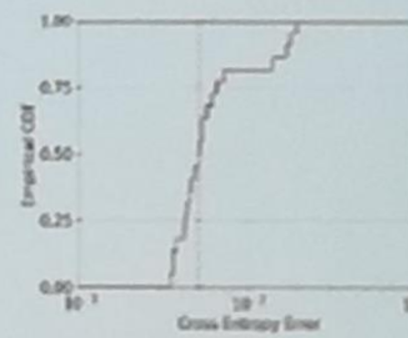
50+ qubits





99.9% single qubit gates

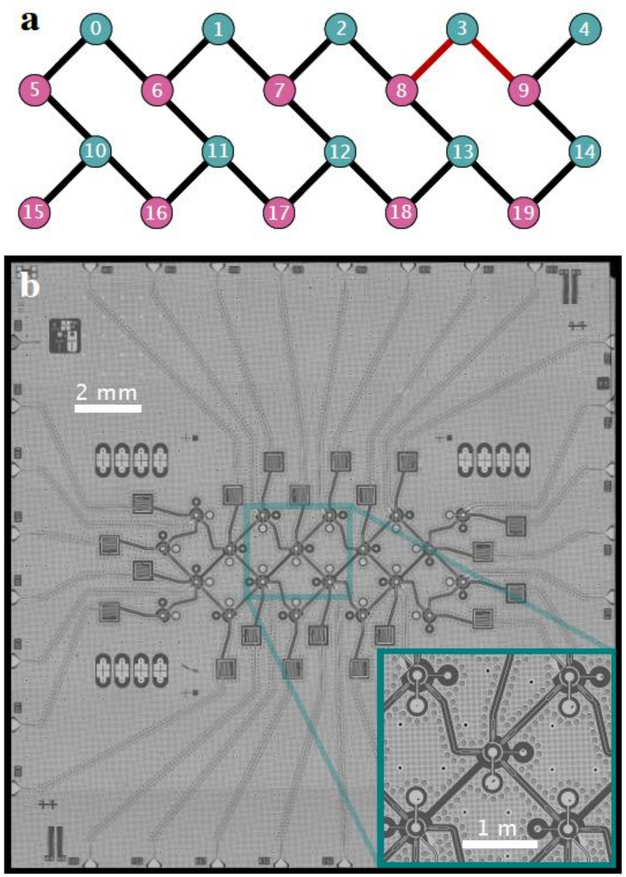
99.5% two qubit gates



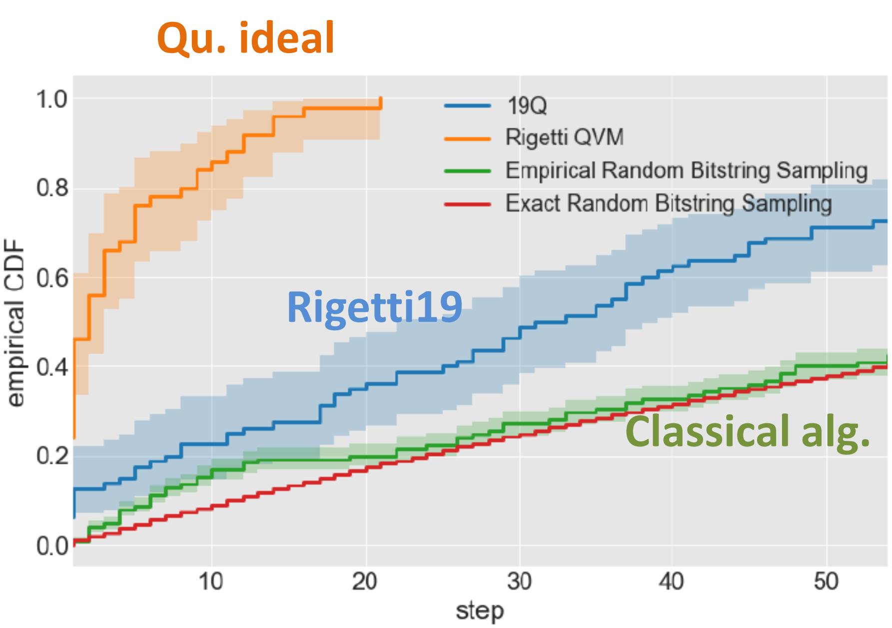
Google AI
Quantum

A hot subject:
quantum machine learning

Rigetti19 qubit circuit (2017)



Otterbach et al.,
PRL 2018 & **arXiv:1712.05771**



The scalability challenge

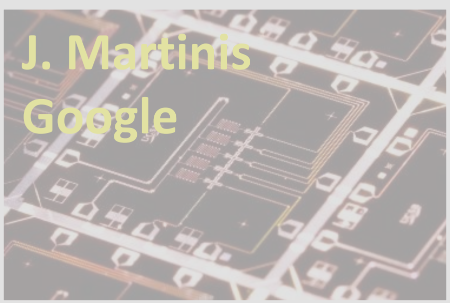
GATE BASED PROCESSORS

Elementary processors

Better coherence:
T_2: 10-30 μs

Protocols :
teleportation,
quantum feedback
Digital simulation

The NISQ era



Quantum advantage within reach ?

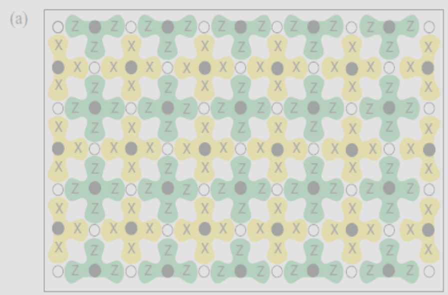
Addressing Quantum Error Correction

Beware: copying forbidden!

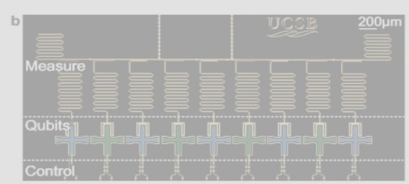
fault-tolerant architectures

surface code fabric
(see Fowler et al, PRA 86 (2012)

Data measurement



Huge resource overhead
1 logical qubit>>1000 physical qubits

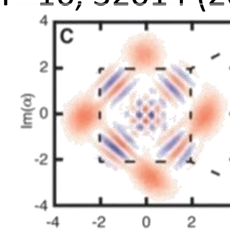


test circuits
for quantum error correction

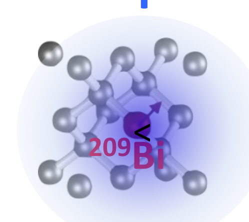
robust qubits

Autonomous qubits

Yale Quantlab, M. Devoret
INRIA- LPA (ENS)
ENS Lyon (B. Huard)
Schrödinger cat states in high Q resonators
Mirrahimi et al.
NJP 16, 32014 (2014)



hybrids: spins in circuits



better coherence

Borrowed from Mazyar Mirrahimi at SQ20th :

See: arXiv:1904.09474
Jérémie Guillaud, Mazyar Mirrahimi

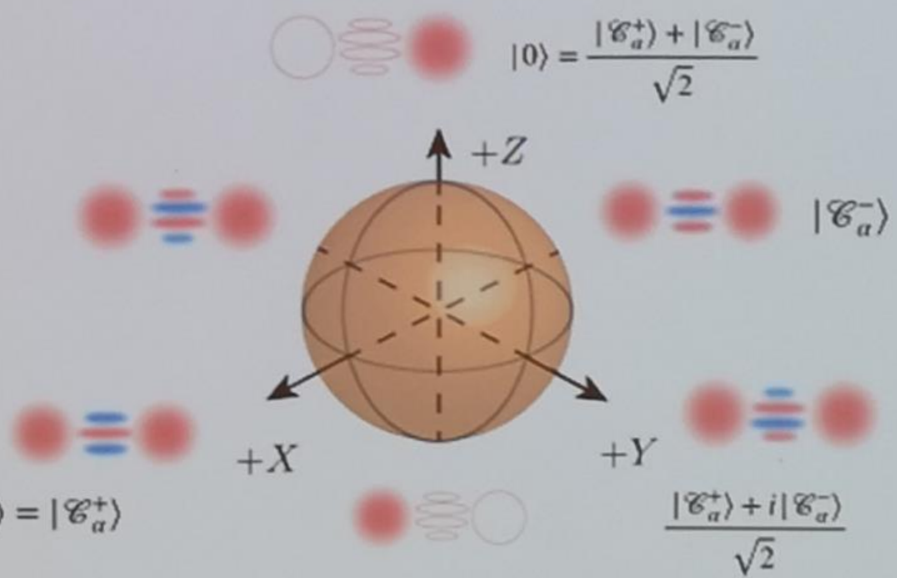
Cat-qubits: definition

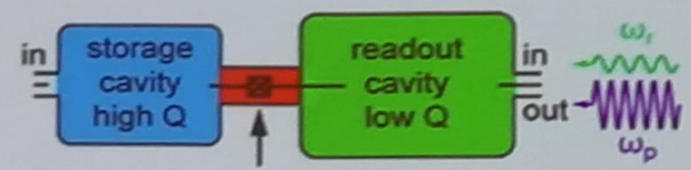
Cat qubits based on coherent states of a high Q harmonic oscillator maintained alive using dissipation engineering

$$\alpha = \pm\sqrt{\frac{2\epsilon^*_{2ph}}{\kappa_{2ph}}}$$

$$|+\rangle = |\mathscr{C}^+_\alpha\rangle \doteq \mathscr{N}_+(|\alpha\rangle + |-\alpha\rangle) = \sum c_{2n}|2n\rangle$$

$$|-\rangle = |\mathscr{C}^-_\alpha\rangle \doteq \mathscr{N}_-(|\alpha\rangle - |-\alpha\rangle) = \sum c_{2n+1}|2n+1\rangle$$





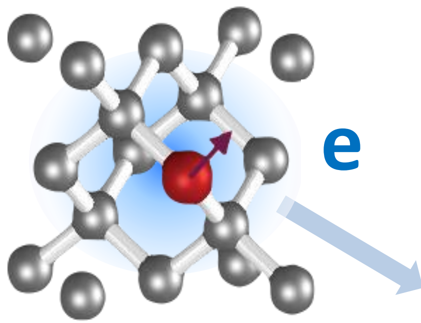
M. Mirrahimi et al., NJP 16, 2013

A new hybrid route : spins coupled to superconducting circuits

Nuclear spins **Electronic spins**

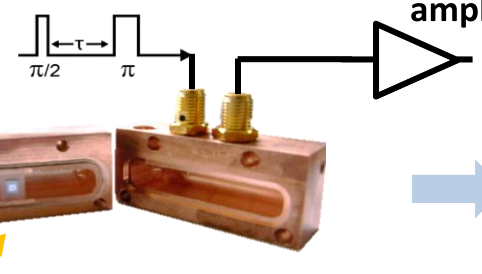
hyperfine coupling

Si : Bi



low mode volume high Q resonators

Quantum limited amplifier



nanoresonator

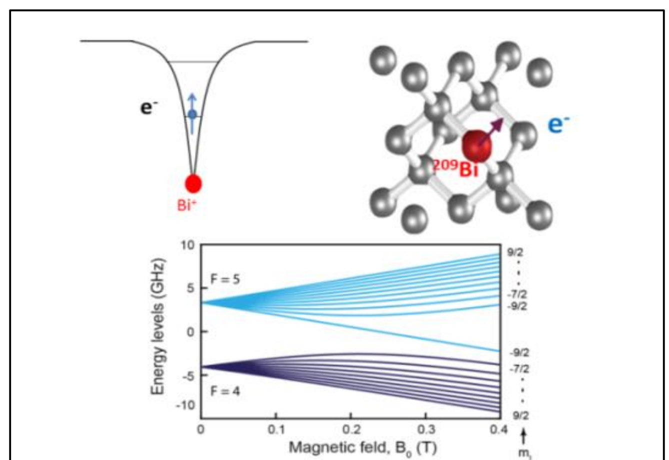
hybrid architecture ?

Highly coherent quantum system

- Electronic spin = 1/2
- Nuclear spin I=9/2
- Large hyperfine coupling $\frac{A}{2\pi} = 1.4754\text{GHz}$

$$\frac{H}{\hbar} = A\boldsymbol{I}\cdot\boldsymbol{S} + \boldsymbol{B_0}\cdot(-\gamma_e\boldsymbol{S} - \gamma_n\boldsymbol{I})$$

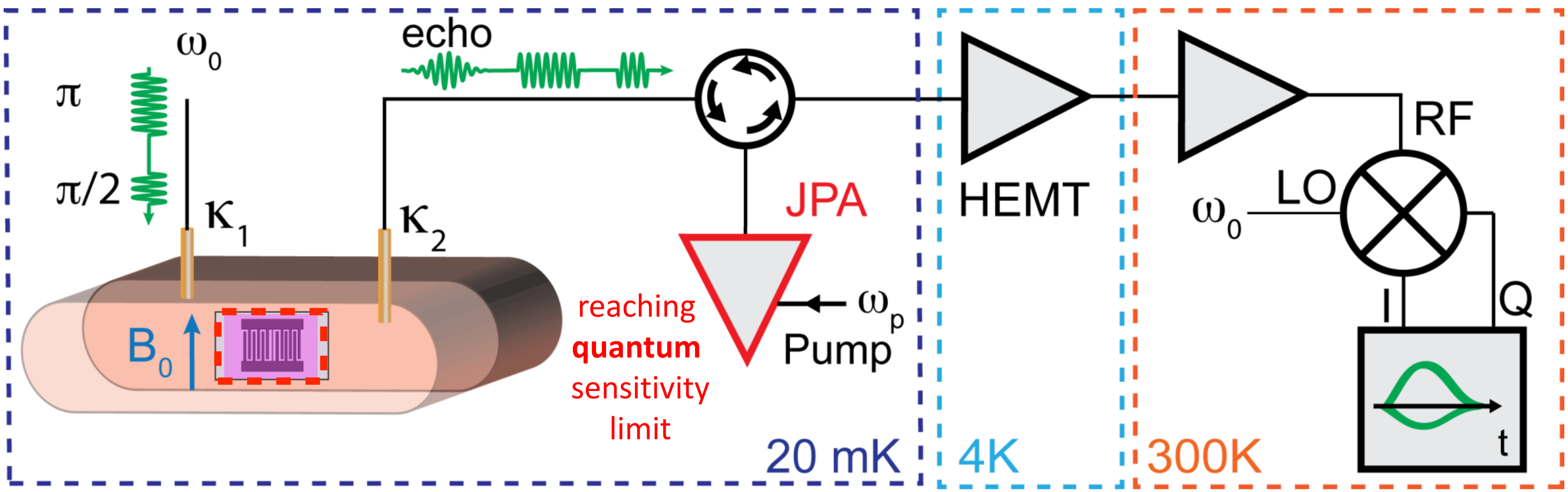
20 electro-nuclear states for making qubits

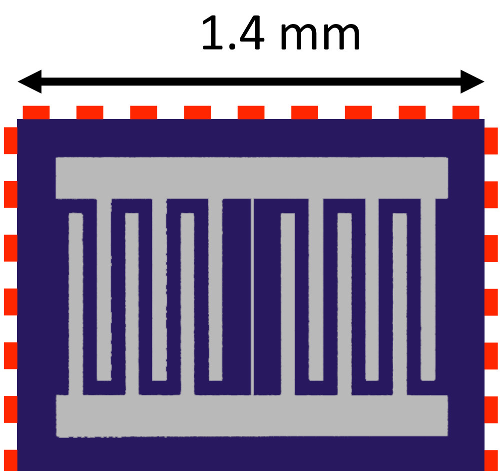


Preliminary work

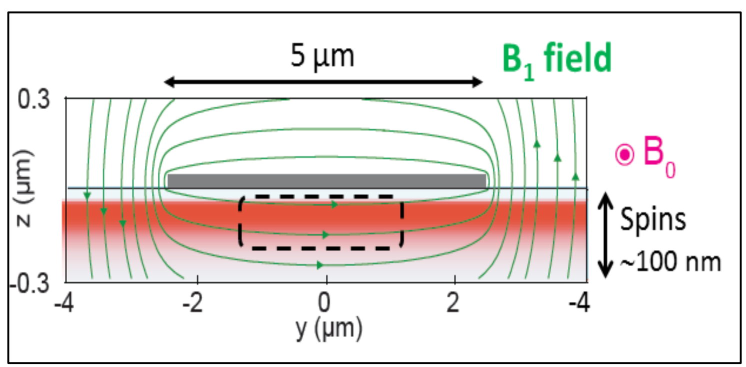
Ultra-sensitive ESR

Bienfait et al.,
Nature 2016, Nature Nano 2016,
PRA 2017, PRX 2017; Probst et al., APL 2017

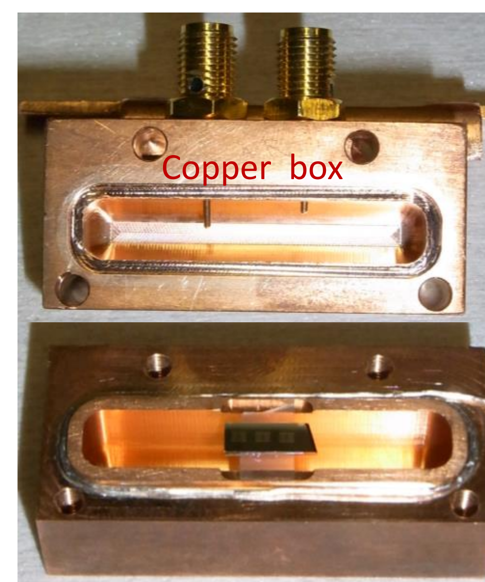




2D high Q superconducting Al resonator



spins in small mode volume



Ultra-sensitive ESR

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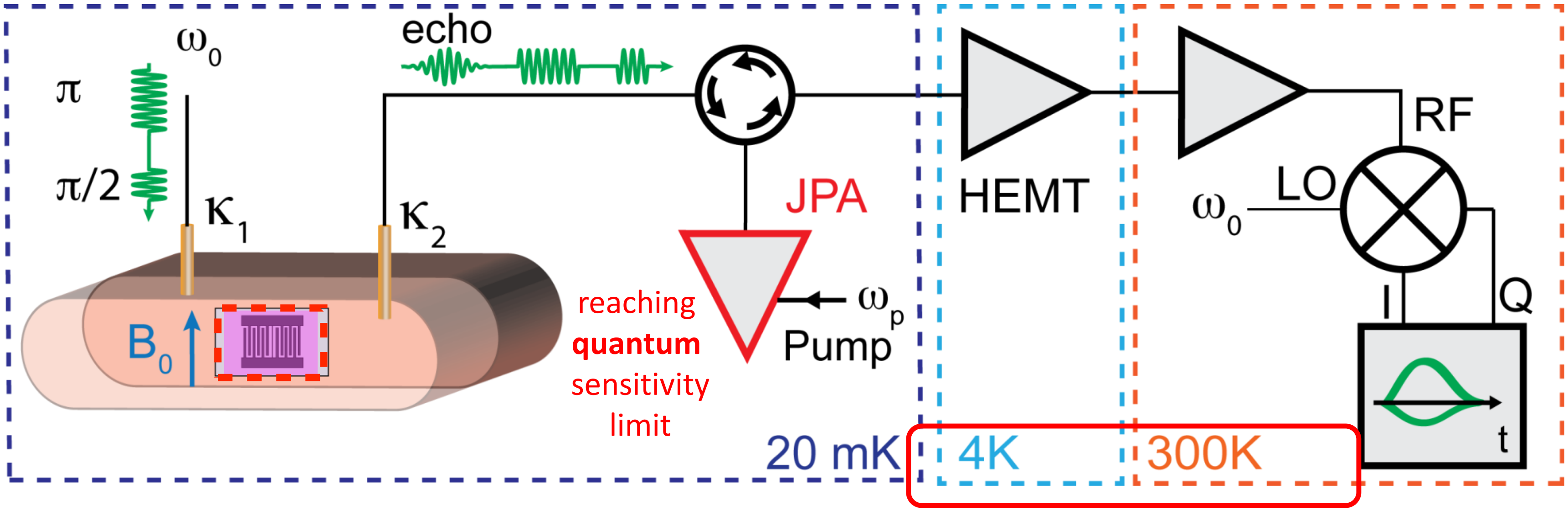
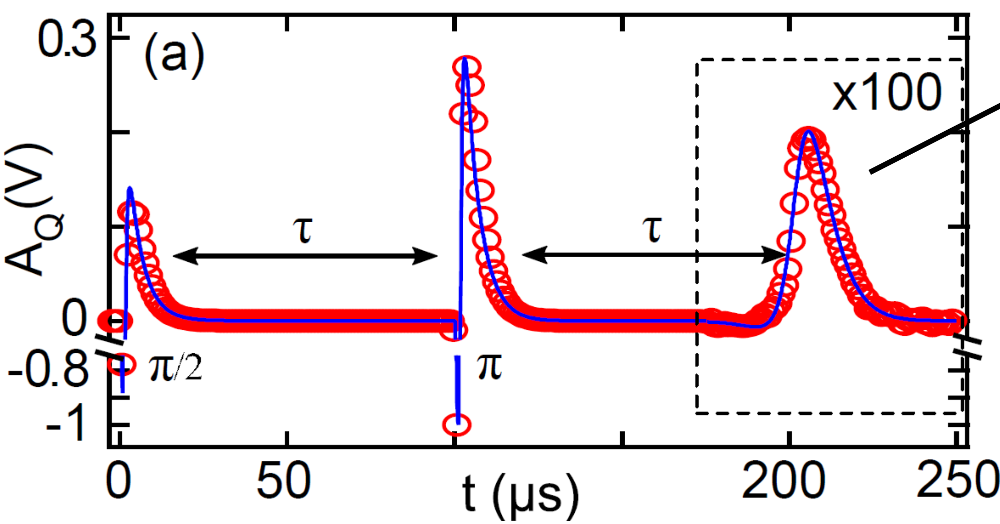




250 spins/echo @SNR 1

NOW:

Effective detection sensitivity:

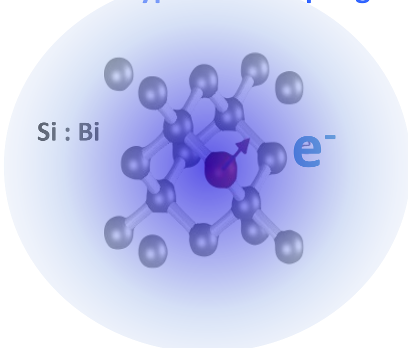
10 spins $/\sqrt{Hz}$ @ T_1 = 21 ms

Toward single spin ESR

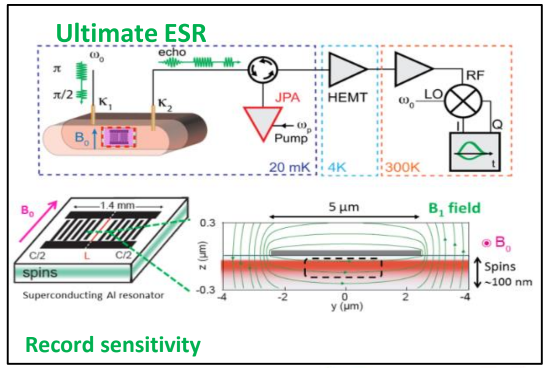
A new hybrid architecture based on nuclear spins

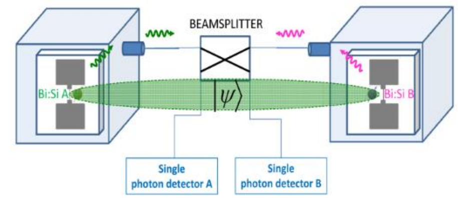
Nuclear spins | Electronic spins | Superconducting quantum circuits | Gate & readout schemes

Hyperfine coupling

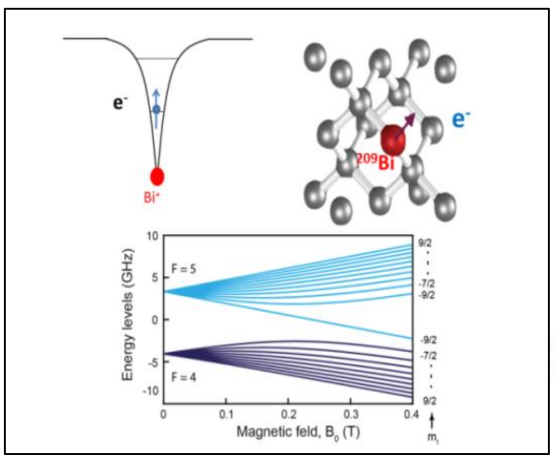


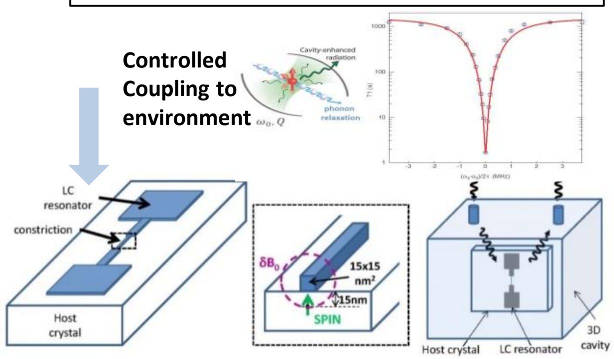
High Q low mode volume resonators, quantum amplifiers,...





e.g. measurement based entanglement





electronic spin-single microwave photon coupling

A route towards more robust quantum bits

QUANTUM ELECTRONICS GROUP

AGENCE NATIONALE DE LA RECHERCHE ANR

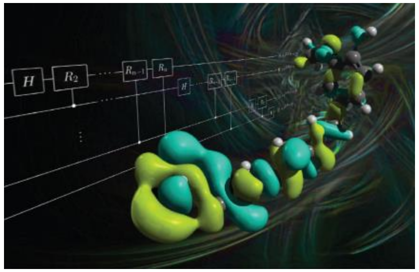
Atos

Chair

rich & coherent set of quantum levels

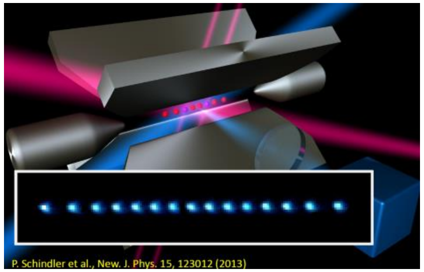
Conclusions

-Interesting use-cases identified
many-body problem, classification, ….
but >100 logical (error corrected) qubits needed …

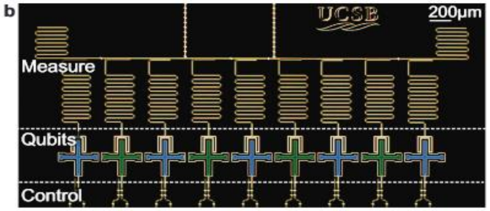


IBM intel Google Microsoft Atos

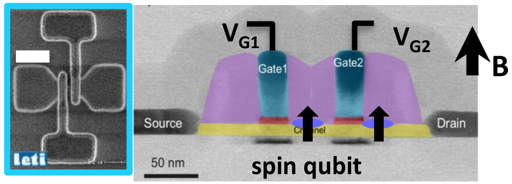
-Low depth processors at Google, IBM, Rigetti
targeting quantum advantage
-Sizeable progress on different platforms



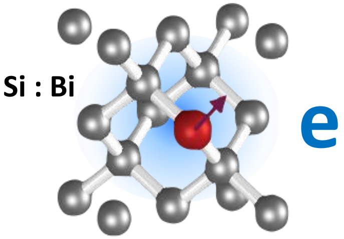
-gate-based processors with quantum error correction
very difficult.
Scalable fab. mandatory.



-Other route **more coherent qubits**
autonomous correction, Schröd. cat states, spins, …



Appealing potential,
but
perspectives still unclear



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+

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