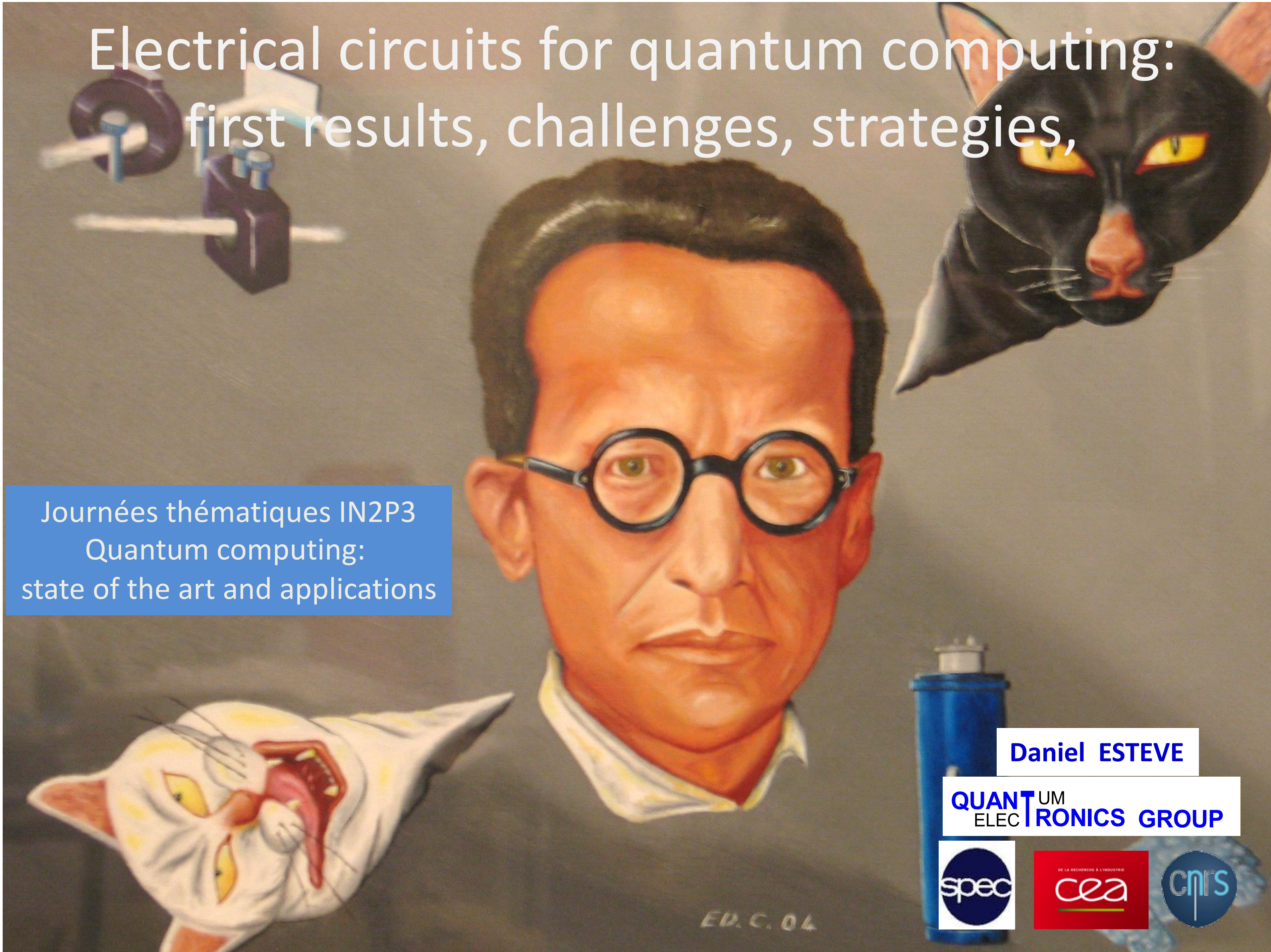
Electrical circuits for quantum computing: first results, challenges, strategies,

Journées thématiques IN2P3
Quantum computing:
state of the art and applications

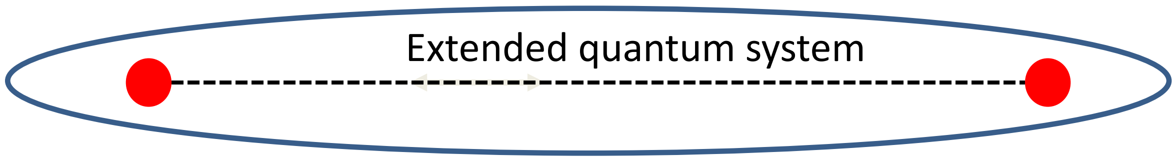


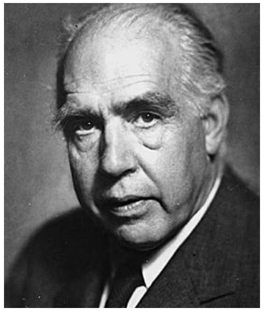
Daniel ESTEVE

QUANTUM ELECTRONICS GROUP

From quantum weirdness to quantum resources

1935… The EPR paradox and the Bohr-Einstein controversy

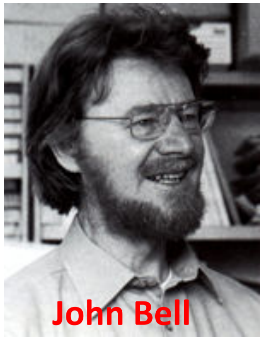




This cannot be described by a quantum state
Formalism is incomplete!

This is it !

1964: This debate can be addressed — done in 1982

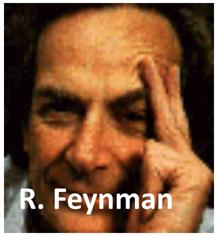


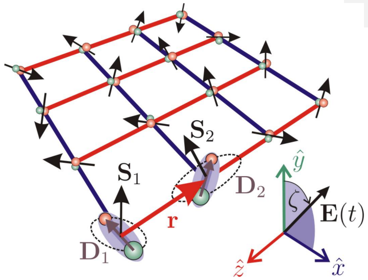
$$|left+, right-\rangle + |left-, right+\rangle$$

(non factorisable) entangled state $|left\rangle \otimes |right\rangle$

Non-local correlations in agreement with quantum predictions

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



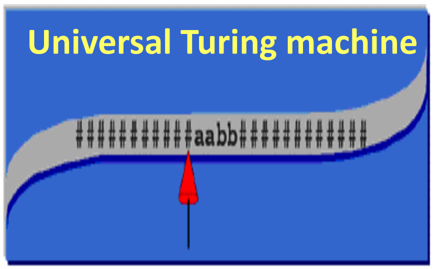


1984 quantum cryptography protocol
1985 an unexpected breakthrough

Quantum mechanics provides computational resources

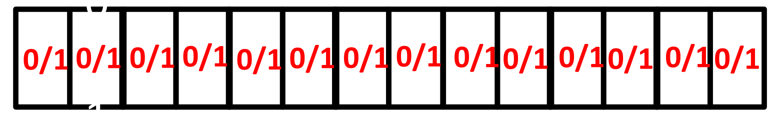
Quantum computing in an nut

Classical computing:



Turing machine not universal !
complexity classes scrambled
for quantum hardware

N (0,1) bits evolving
among **2^N states**



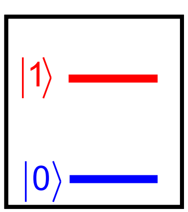
$$R = (i_1, i_2, i_3 \ldots i_{2^N}) \qquad i_k = 0,1$$

Quantum computing:

evolution of a N qubit quantum register using quantum gates
among **superpositions of 2^N basis states**

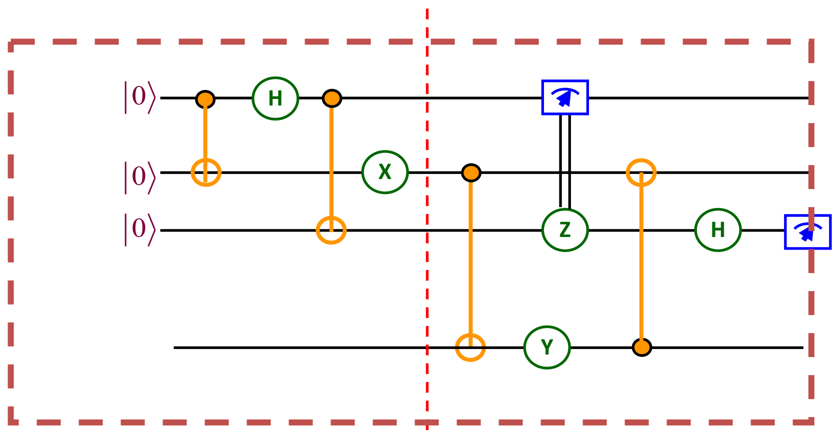
qubit

2 level system



N = 2^n computational basis states

$$\overbrace{|010001\ldots1\rangle}^{n} = |p\rangle$$



Readout

returns 0 or 1
for each qubit :
a basis state

non factorizable entangled state: $\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_{4\ldots} i_{2^N}} |i_1, i_2, i_3 \ldots i_{2^N}\rangle$

entanglement delivers computing power

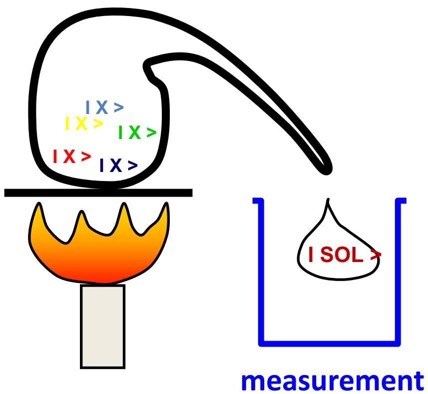
The art of QC

QM linearity provides massive parallelism

$|X\rangle + |X\rangle + |X\rangle + \dots \rightarrow \boxed{U} \rightarrow U|X\rangle + U|X\rangle + U|X\rangle + \dots$

But readout only returns a basis state & N bits

The method:



Difficult

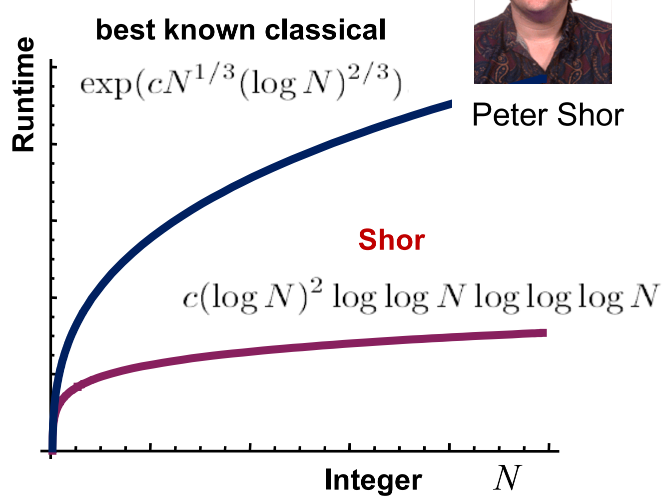
not so many different quantum algorithms

How many qubits for overcoming a classical computer ?

A 50-100 ideal qubit qu. computer could overcome classical computers (for some tasks)

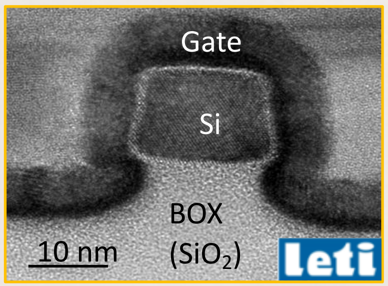
Factorization algorithm (1994)

Peter Shor



The hpc context:
massive integration reaches physical limits

Semiconducting circuits reach physics limits
+ increasing needs



Ultimate CMOS

(Soon ?)

3D stacking
ultra low power

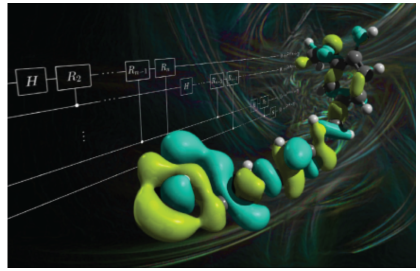
Alternative technologies for HPC ?

Quantum Computing now envisioned

QC: A potential breakthrough in HPC (?)

Use-cases

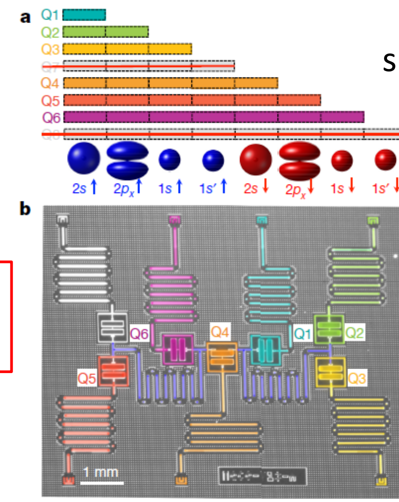
Many-body physics:
  quantum chemistry, materials
nuclear physics ...

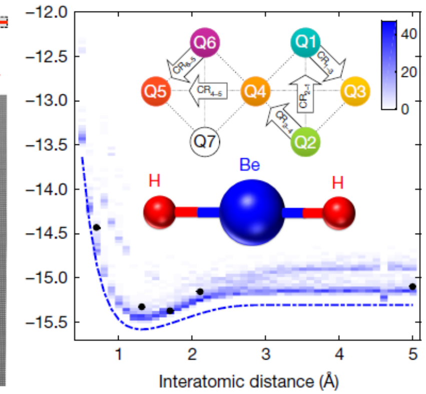


Fermionized Hamiltoniens map well on qubits

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 !

Classification,
Optimization
Machine learning

Big players attracted, strong partnerships developed

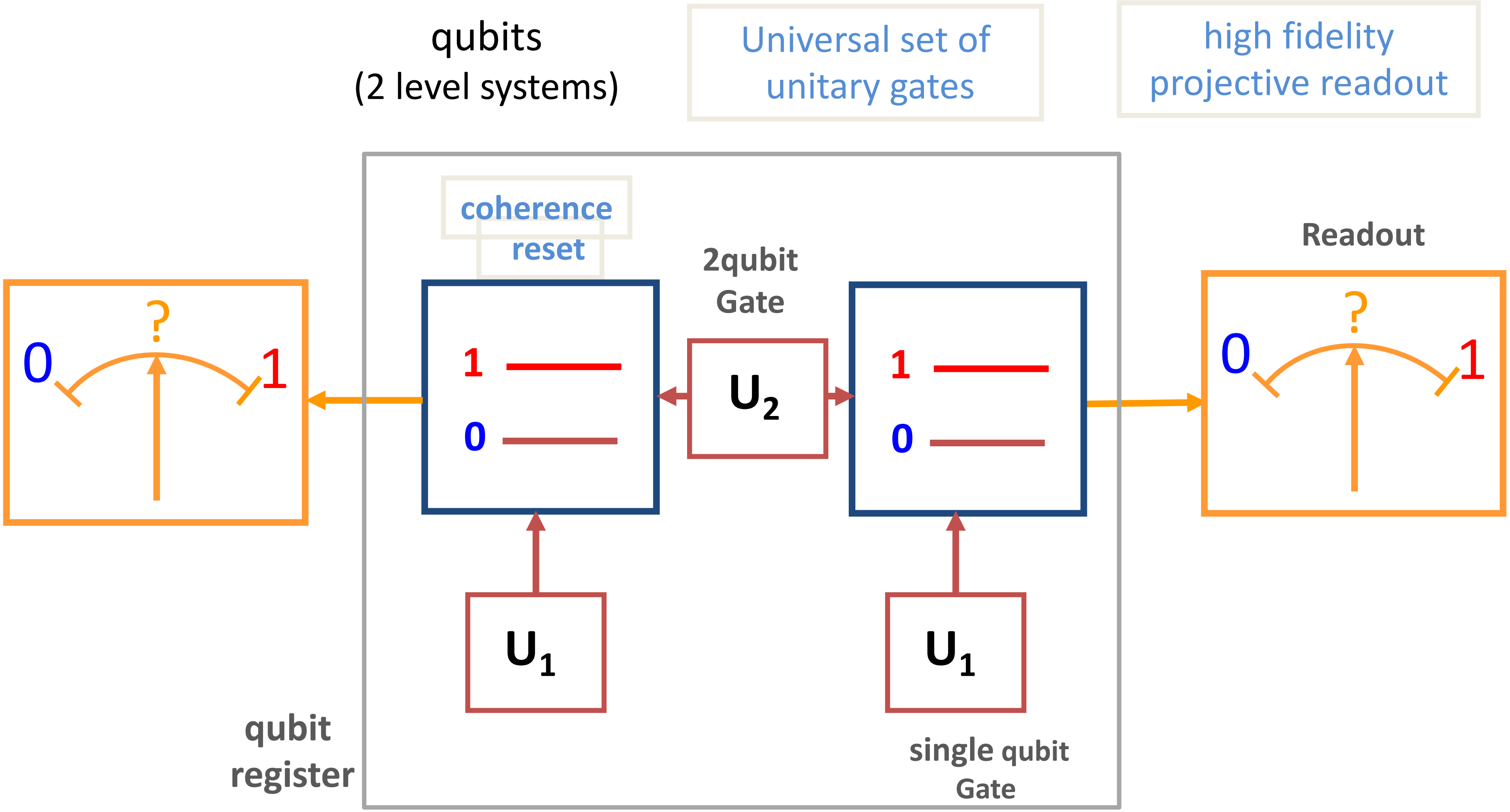
IBM intel Google Microsoft

Eu:

Atos

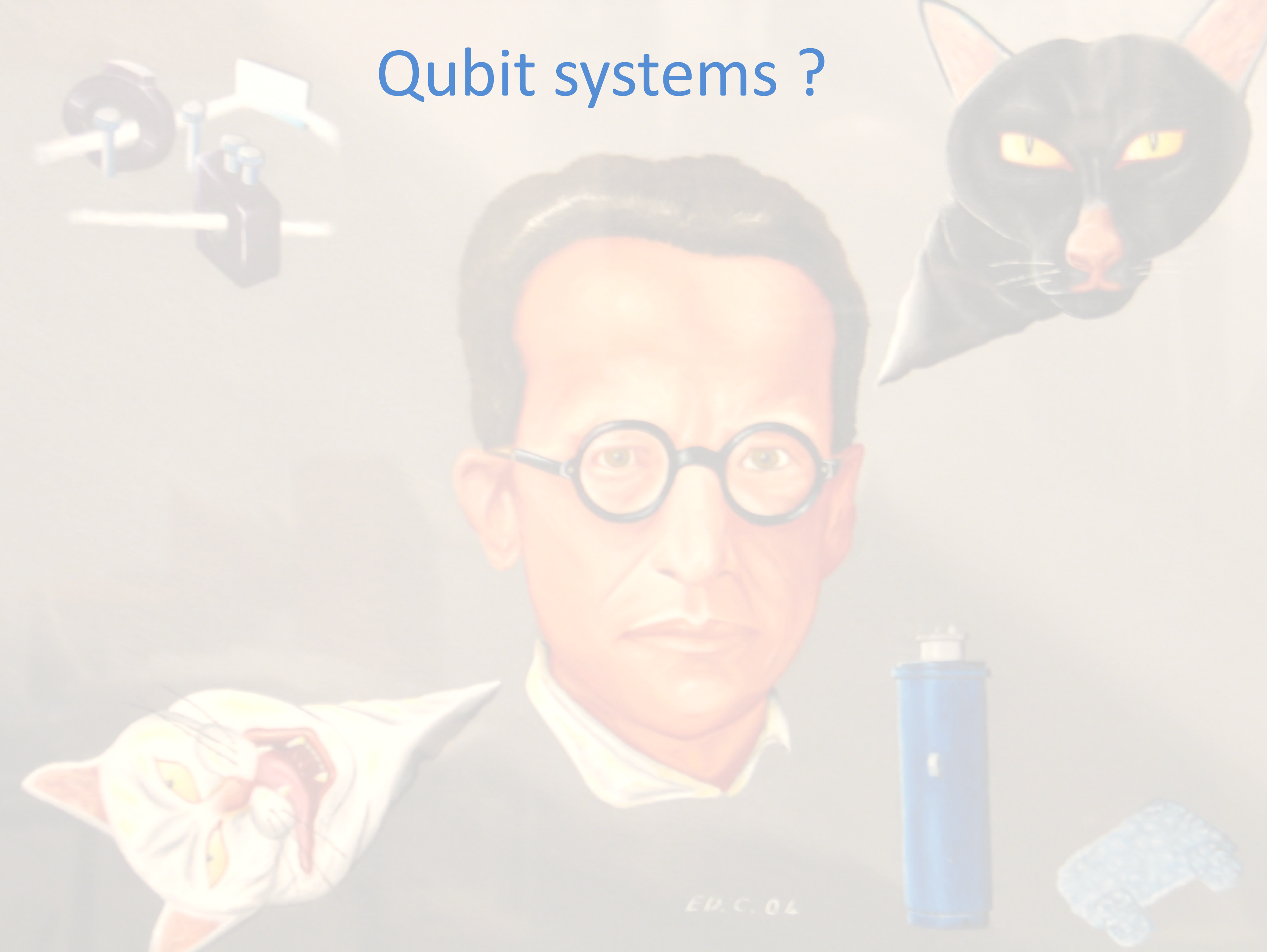
"*Strong* " Eu flagship initiative

blueprint of a quantum processor (based on quantum gates)



"DiVincenzo criteria"

Qubit systems ?



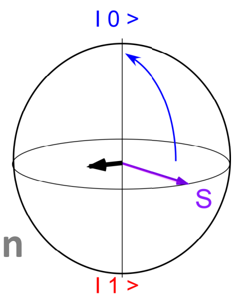
Why is any quantum system not a quantum bit ?

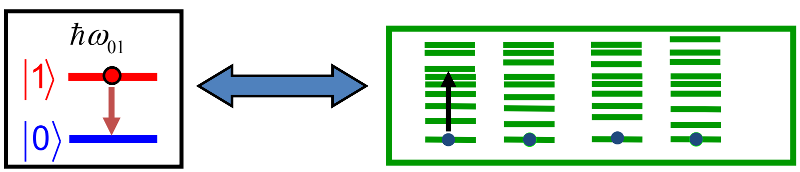
coupling to environment yields **decoherence**

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

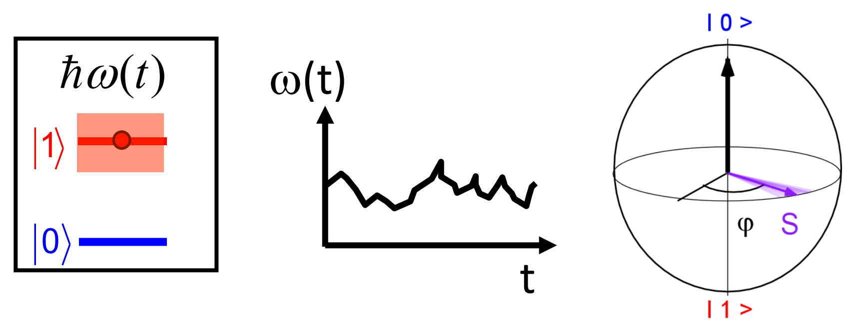
Relaxation (Spontaneous emission)

Bloch sphere representation





dephasing from fluctuating energy



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

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

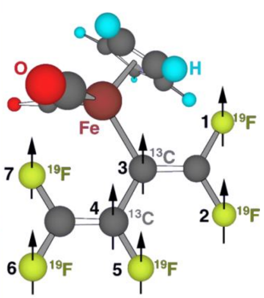
Microscopic systems
weakly coupled to their environment
quantum regime easy
not easily addressable

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

solutions ?

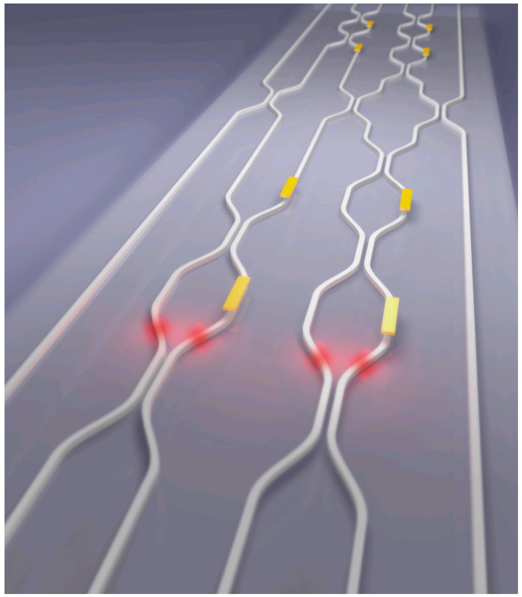
Physical implementations ?

NMR



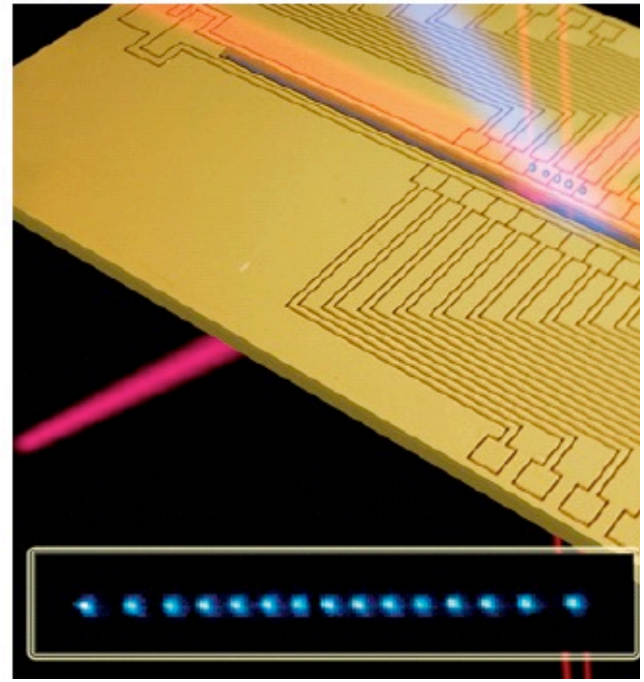
not scalable:
code=molecules

Photons



Measurement based QC:
not efficient

Trapped ions
(or atoms)

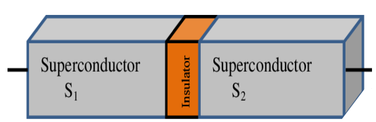


The most advanced platform

Electrical circuits ?

usually not quantum !

A quantum component
The Josephson junction



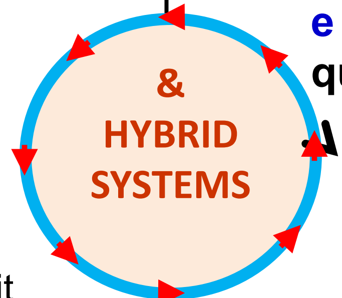
Quantum Mechanics of a Macroscopic Variable:
The Phase Difference of a **Josephson Junction**

Clarke, Cleland, Devoret, Esteve and Martinis, Science 239, 992, 1988

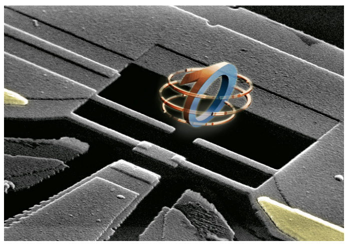
Electrical qubit circuits (in a nut)

quantum states
of superconducting circuits

Electron spin states
in semiconductor structures

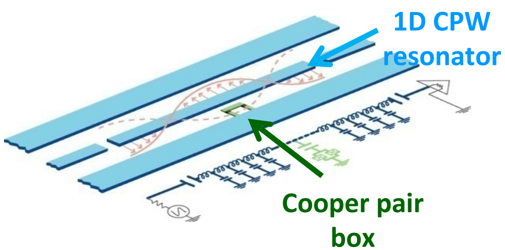


Superconducting qubits based on the
Single Cooper Pair Box circuit



functional SC qubit
(CEA 2002)

Now: Transmon type Cooper Pair Box circuit

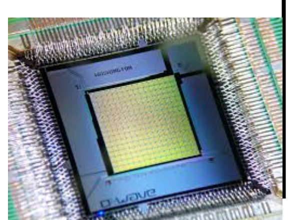


Yale
(2004-2006-2010)

Different computing strategy
quantum annealing

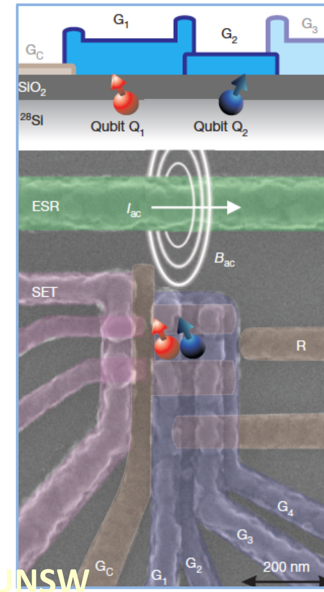
difficult problems solved
quantum speed-up not
demonstrated

DWAVE



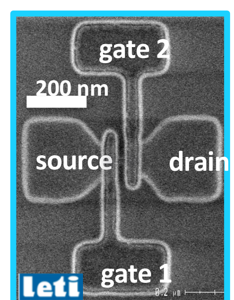
**e spins in
quantum dots**

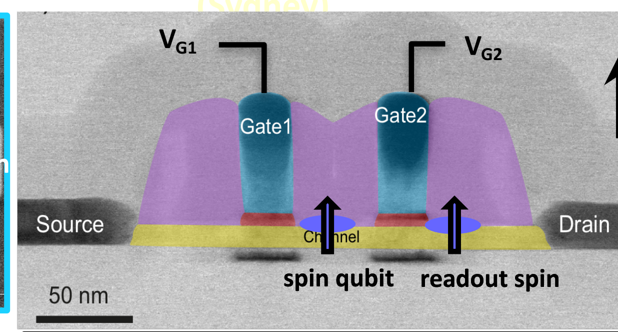
**UNSW, TUDelft,
Harvard,
CEA (INAC-LETI)**

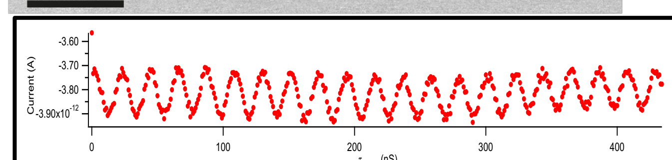


UNSW
(Sydney)

**First qubit from
on an industrial
fab line at CEA**



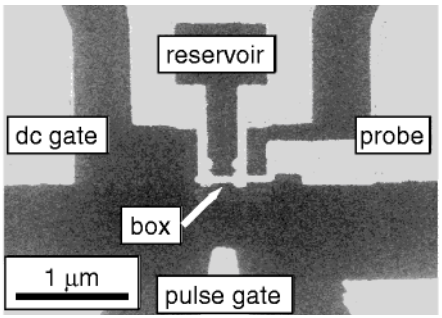


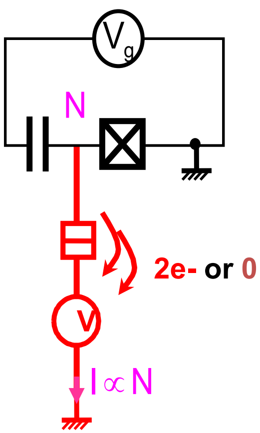


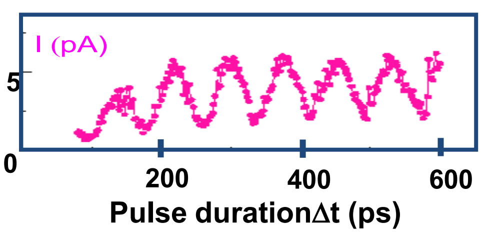
The Cooper Pair Box quantum bit: a brief survey

first Cooper Pair Box qubit

Nakamura, Pashkin &Tsai (NEC, 1999)



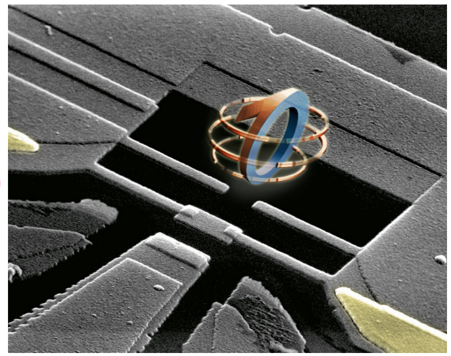


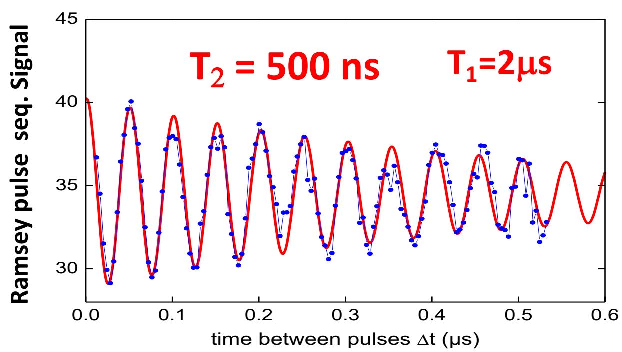


x100

First operational qubit

Vion et al., (Quantronics, 2002)



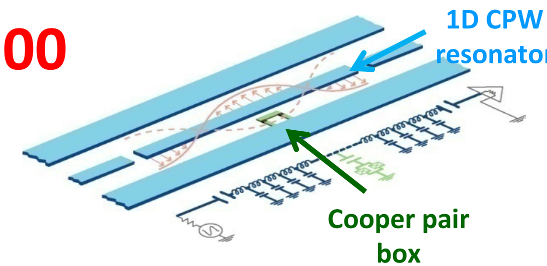


x100

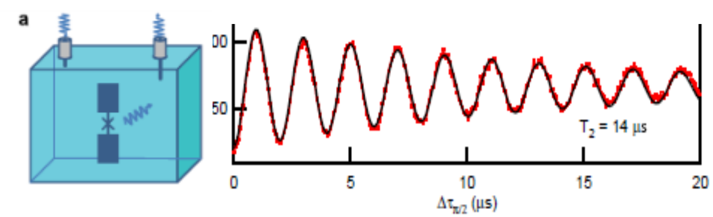
Circuit QED: transmon Cooper pair box in a microwave cavity (2D, 3D)

Schoelkopf lab., Yale ; Wallraff et al., Nature 2004

-Koch et al., PRB 2007; Paik et al., *PRL* 2011

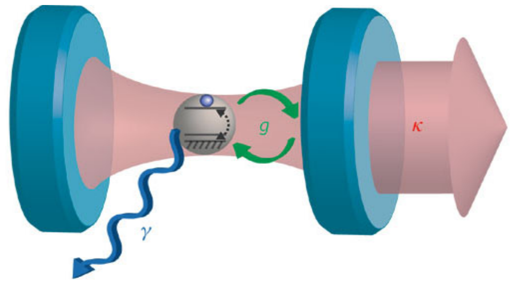


CPBox in a 3D resonator



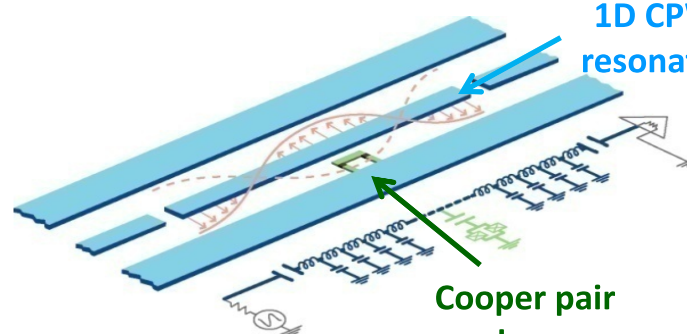
The modern Cooper pair box: Circuit QED

Inspired from cavity QED



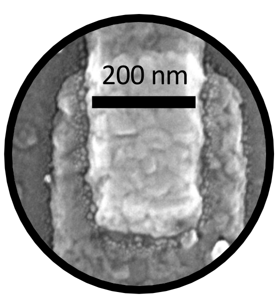
S. Haroche, JM Raimond, M. Brune
LKB- ENS Paris

Cooper Pair Box 'atom' in resonator
(Schoelkopf group , Yale, 2004)

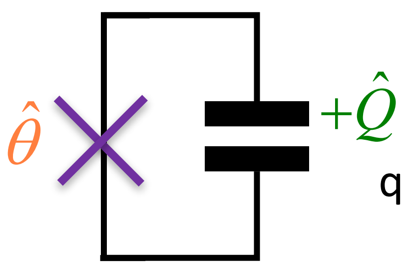


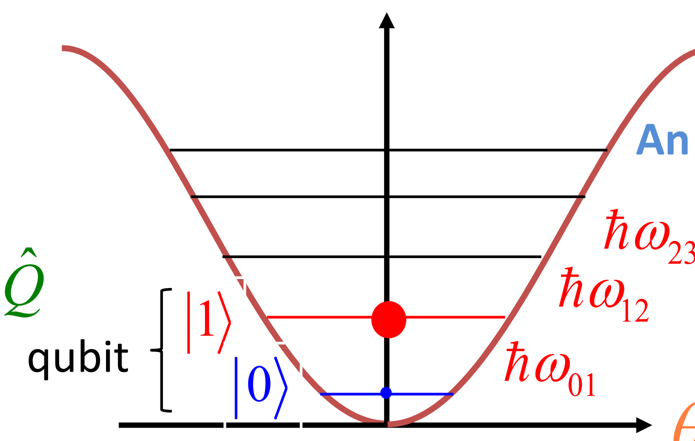
Transmon Cooper pair box insensitive to charge noise
Koch et al., Yale, 2007

The transmon



$Al/Al_2O_3/Al$





An artificial atom based on an anharmonic oscillator

$$E_J \gg E_C$$

embedded in a microwave resonator

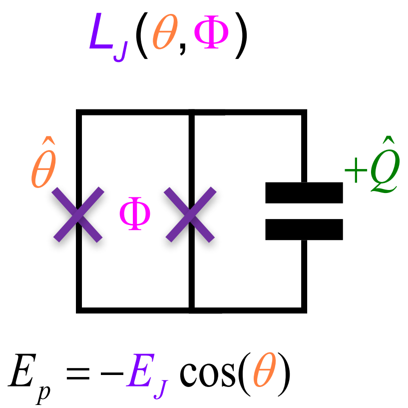
$$\hat{H} = -E_J \cos(\theta) + E_C (\hat{Q}/2e)^2$$

$$E_C = (2e)^2 / 2C$$

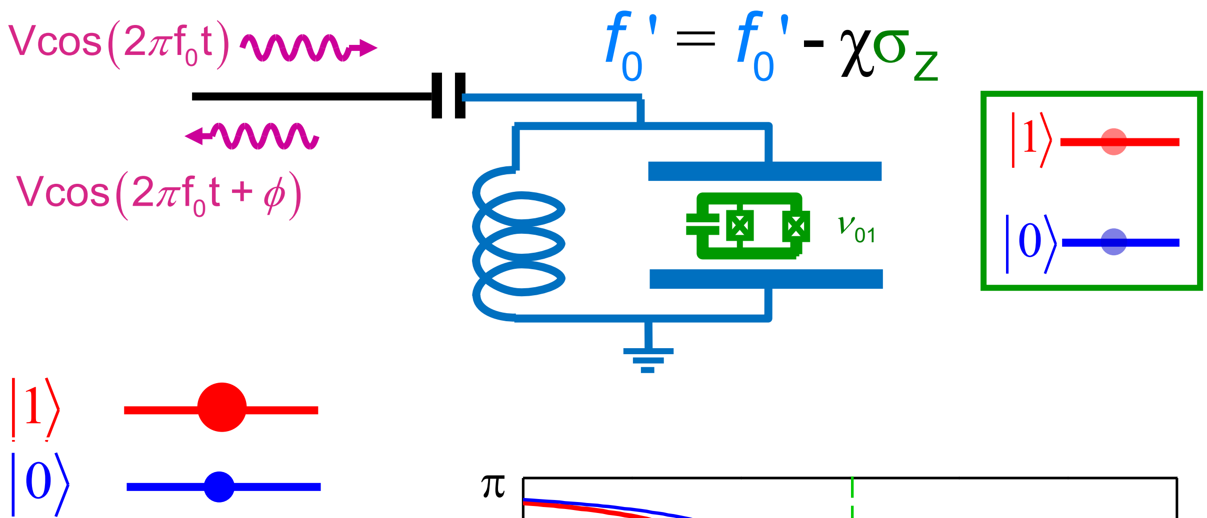
Bonus: insensitive to charge noise

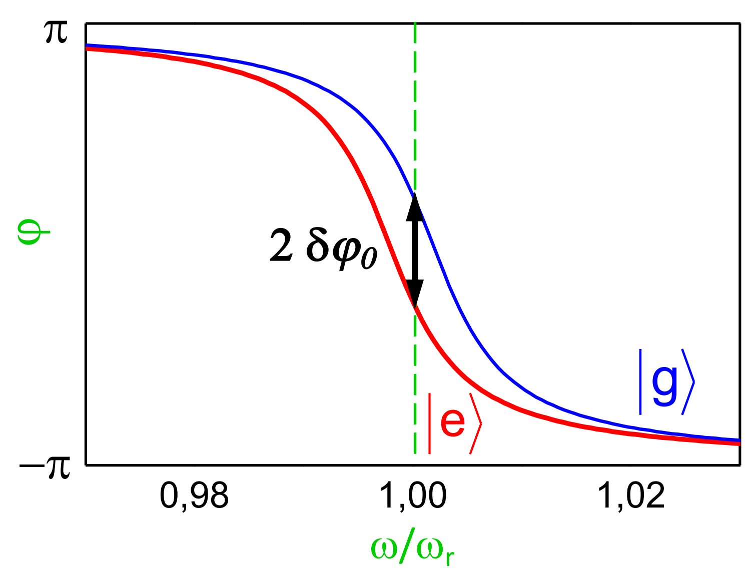
Circuit-QED architecture to readout a Josephson qubit

flux tunable qubit



Dispersive readout with a resonator :





qubit controlled

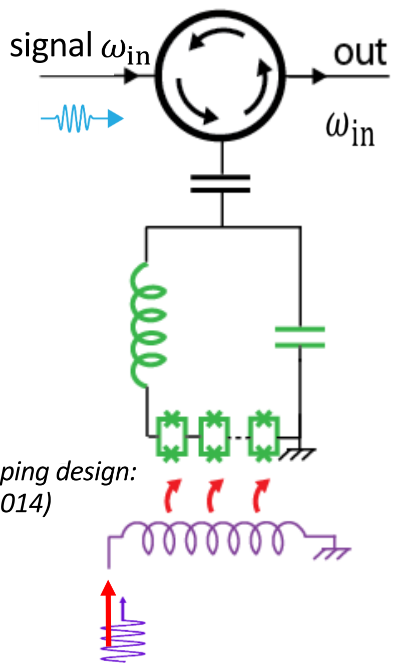
Cavity pull

used for qubit readout

A key element for low power measurements: the Josephson Parametric Amplifier

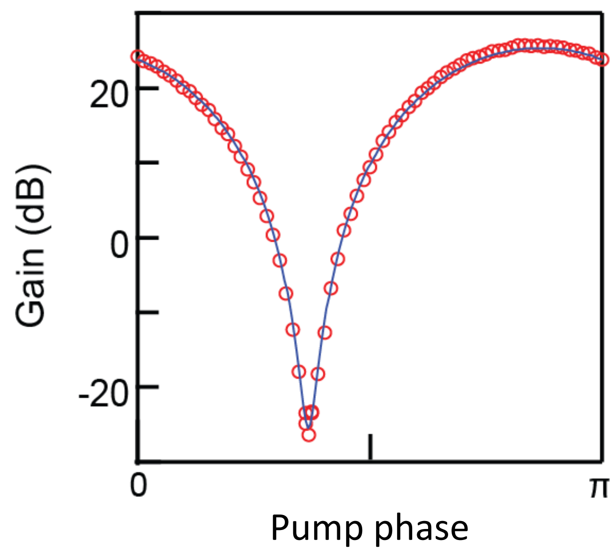
M. Castellanos-Beltran et al., APL (2007)….*TWPA (wide band): Macklin et al. Science 2015*

JPA in degenerate mode



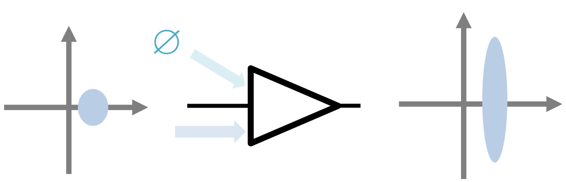
Flux parametric pumping design:
X. Zhou et al., PRB (2014)

DC bias
AC pump tone
$\omega_p = 2\omega_{in}$

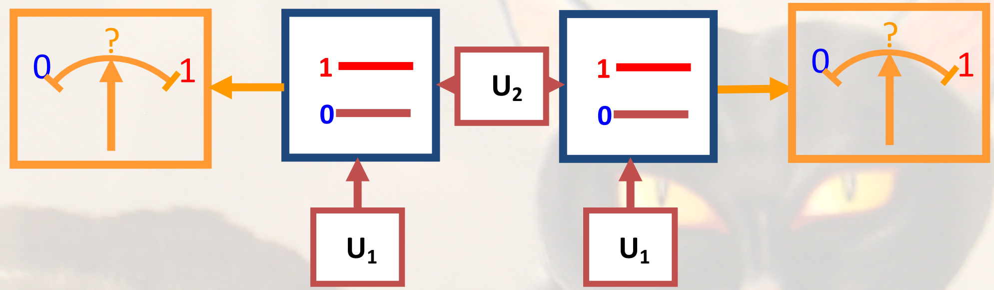


Noiseless amplifier

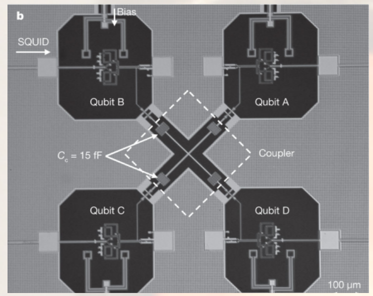
Unitary transformation of input signal



Running quantum algorithms on elementary processors

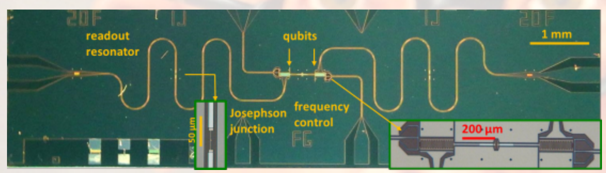


Martinis Lab, UC Santa Barbara
Yamamoto et.al. ,
PRB 82 2010 , Nat Phys 2012



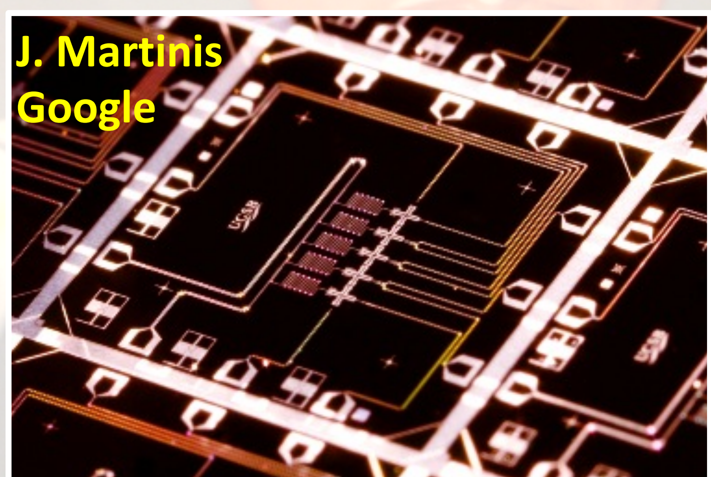
Shor factorization algorithm

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



Grover search algorithm

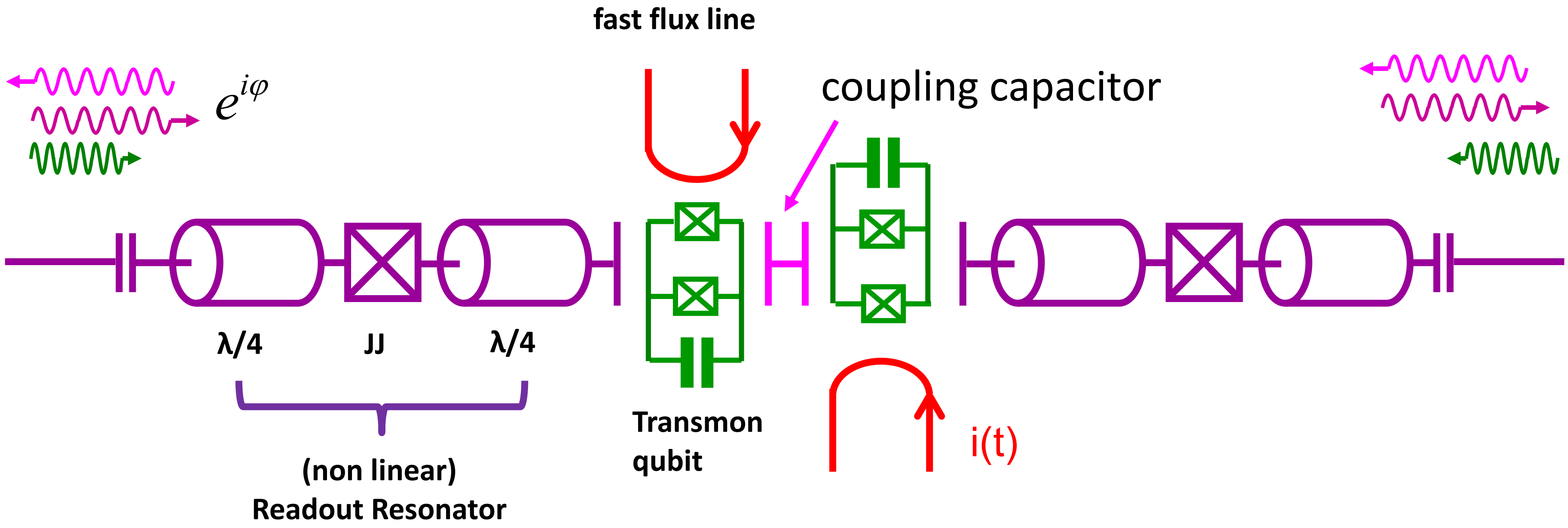
Martinis lab, Google 2015…
IBM, TUD

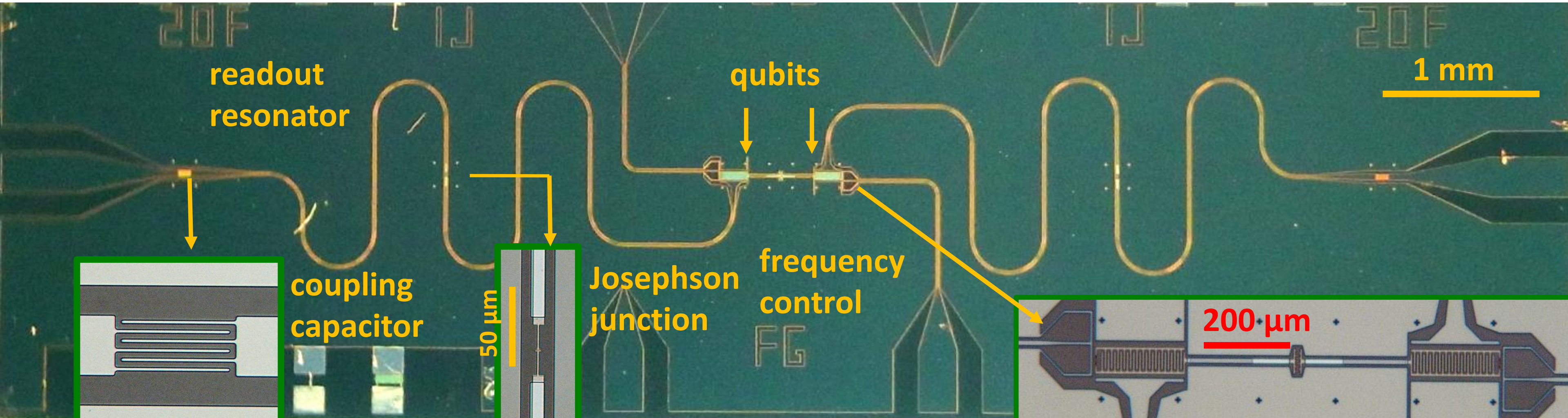


correcting some errors

The simplest case: a two-transmon processor

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





Capacitive coupling yields iSWAP Gate

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

« Natural » universal gate : $\sqrt{iSWAP}$

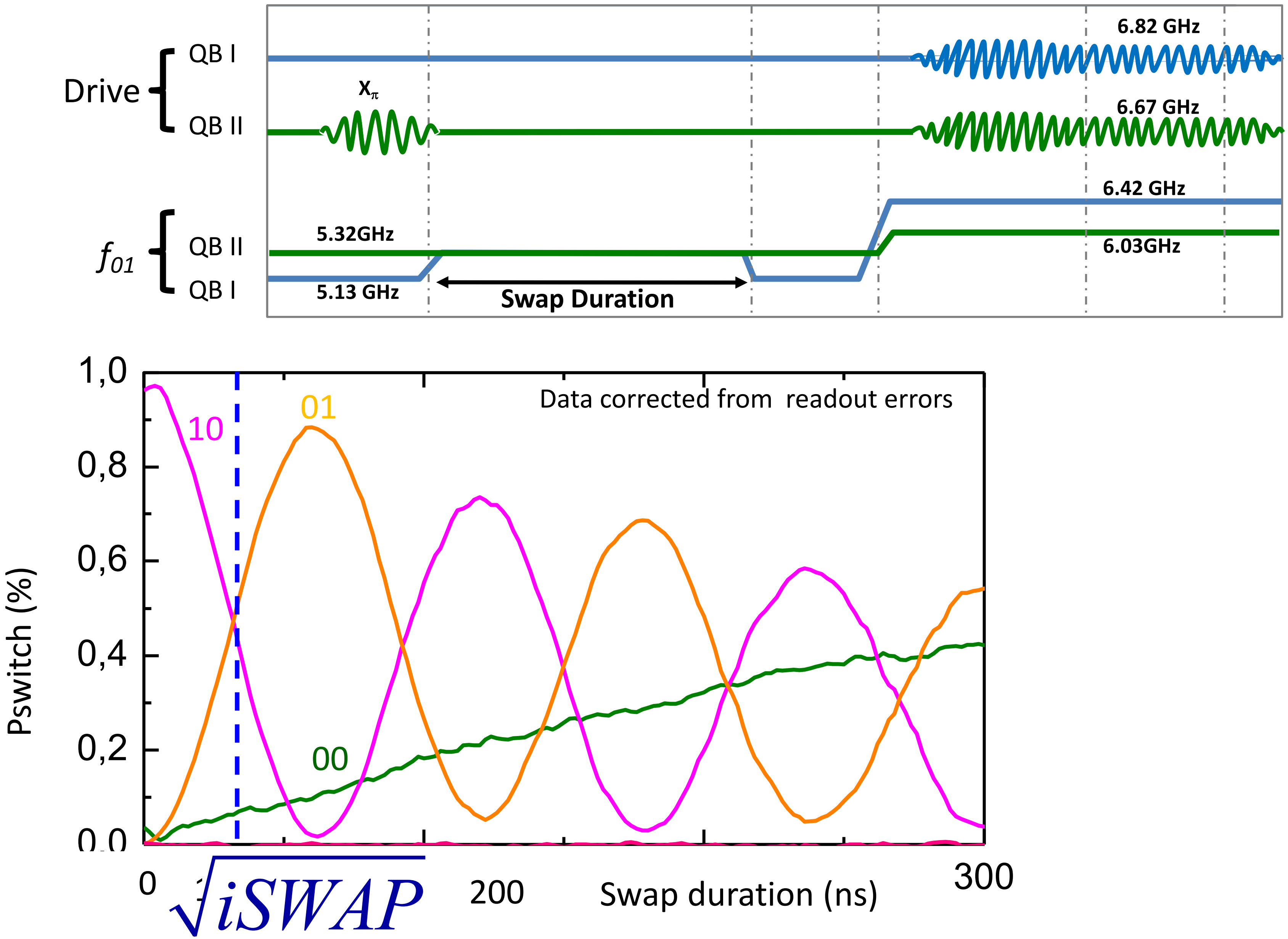
On resonance, $(\omega_{01}^{I} = \omega_{01}^{II})$

$$\begin{array}{cccc} \mathbf{00} & \mathbf{10} & \mathbf{01} & \mathbf{11} \end{array}$$

$$U_{\text{int}}(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(gt) & -i\sin(gt) & 0 \\ 0 & -i\sin(gt) & \cos(gt) & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

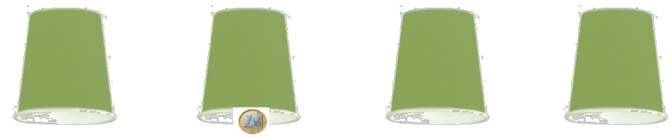
$$U_{\text{int}}\left(\frac{\pi}{2g}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1/\sqrt{2} & -i/\sqrt{2} & 0 \\ 0 & -i/\sqrt{2} & 1/\sqrt{2} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \sqrt{i\text{SWAP}}$$

SWAP between two transmon qubits



The Grover search algorithm on 4 objects

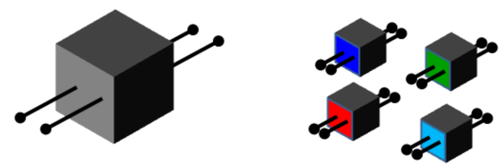
the search problem



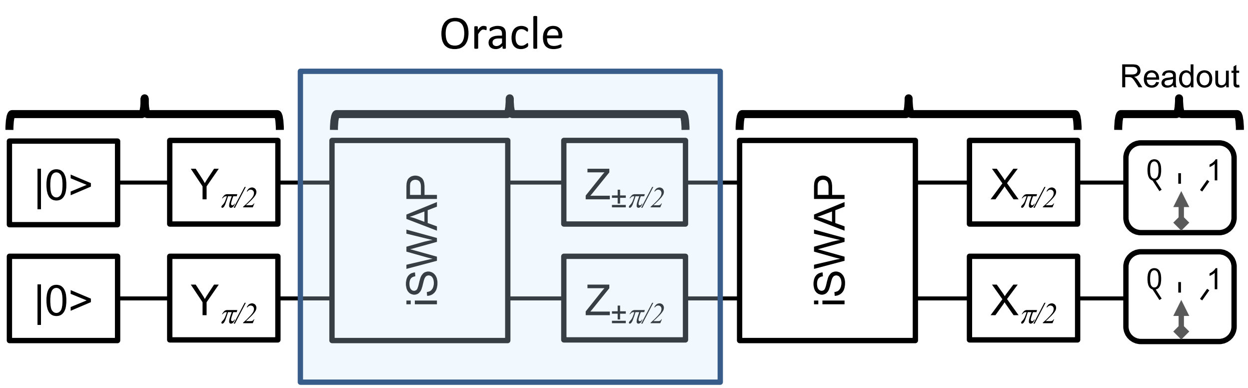
Classical search: O(N) steps Quantum search : O(√N) steps

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

Oracle marking a state

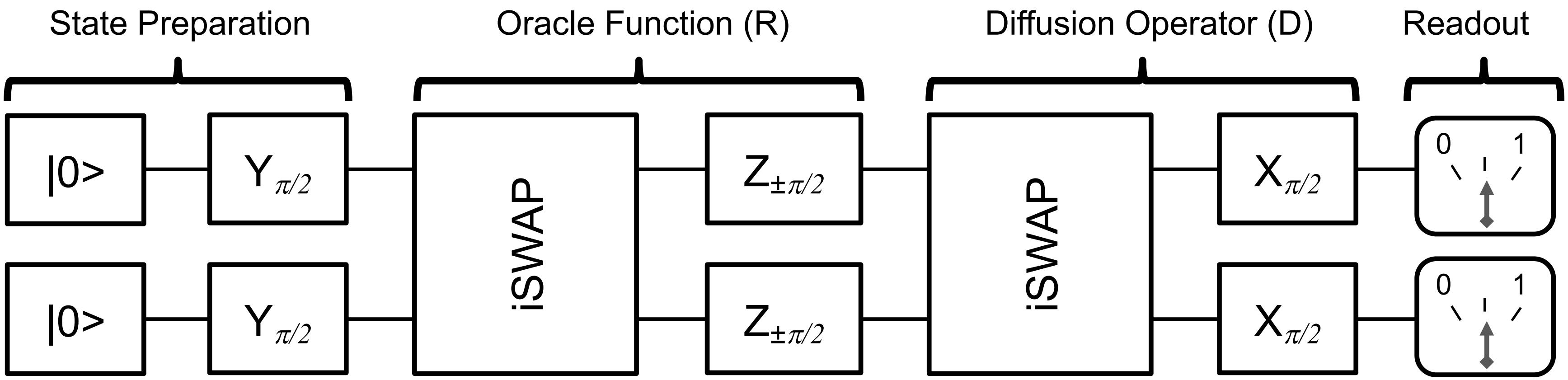


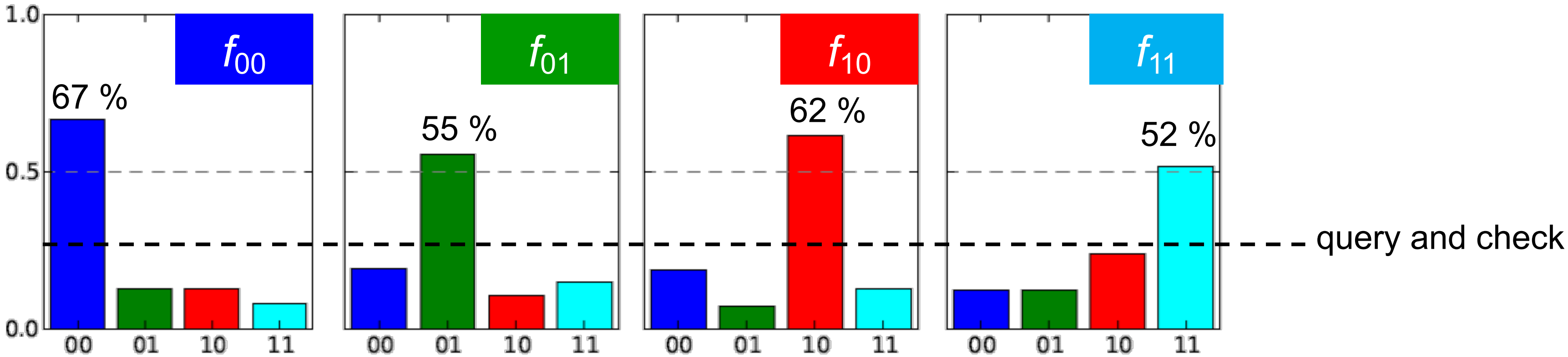
$i \in \{00 \quad 01 \quad 10 \quad 11\}$



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

The Grover search algorithm: success probability



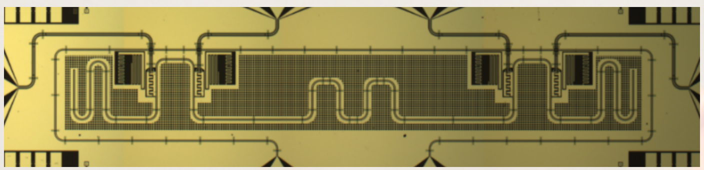


F_i > 25 % → Quantum speed-up

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

Scaling up ?

4 qubit processor (2014) :



multiplexed readout
2 qubit gates through common bus

& did not work well

Scalability challenge ahead

Challenge:
interesting tasks need 100 perfect qubits (at least) !

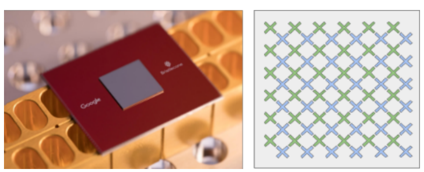
A quantum computing perspective: the scalability challenge
from toys to devices (?)

ELECTRICAL GATE BASED PROCESSORS

Larger superconducting processors

The Noisy Intermediate-Scale Quantum (NISQ) technology era

Google, IBM, Rigetti



Processors ?
~50 qubits,
benchmarking

Google 's sicamore

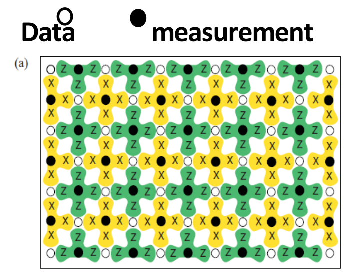
No quantum advantage yet ,
But quantum « supremacy »

Addressing Quantum Error Correction

fault-tolerant architectures

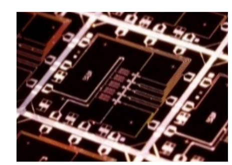
reminder:
copying forbidden!

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



Pb: huge resource overhead
1 logical qubit>>1000 physical qubits

Google,IBM,TUD, ... test circuits
for quantum error correction



Preliminary results since 2015

Quantum Supremacy

QUANTUM COMPUTING AND THE ENTANGLEMENT FRONTIER

JOHN PRESKILL

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****?*

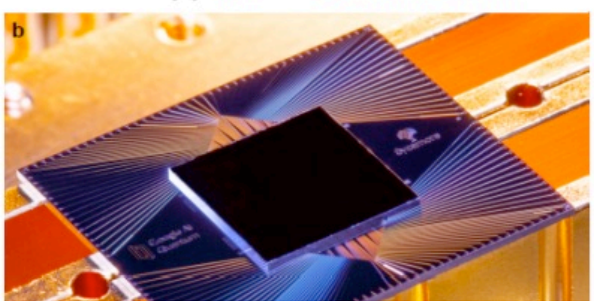
Google's achievment towards NISQ machines

53 Qubit Sicamore processor operated at sub 1% error /gate

Al. and J. Martinis,
Nature 574, 461, 2019

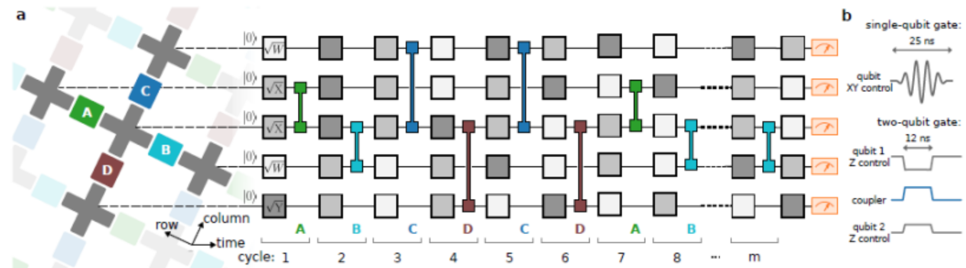
Pauli and measurement errors

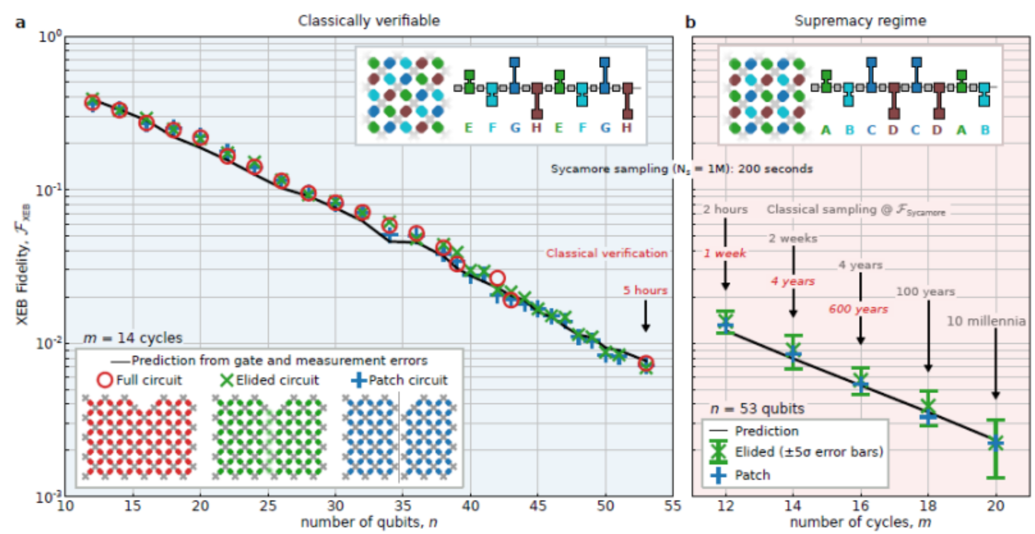
Average error	Isolated	Simultaneous
Single-qubit (e_1)	0.15%	0.16%
Two-qubit (e_2)	0.36%	0.62%
Two-qubit, cycle (e_{2c})	0.65%	0.93%
Readout (e_r)	3.1%	3.8%



Application of ~random complex gate sequences for fidelity tests

(hard task for classical computers)



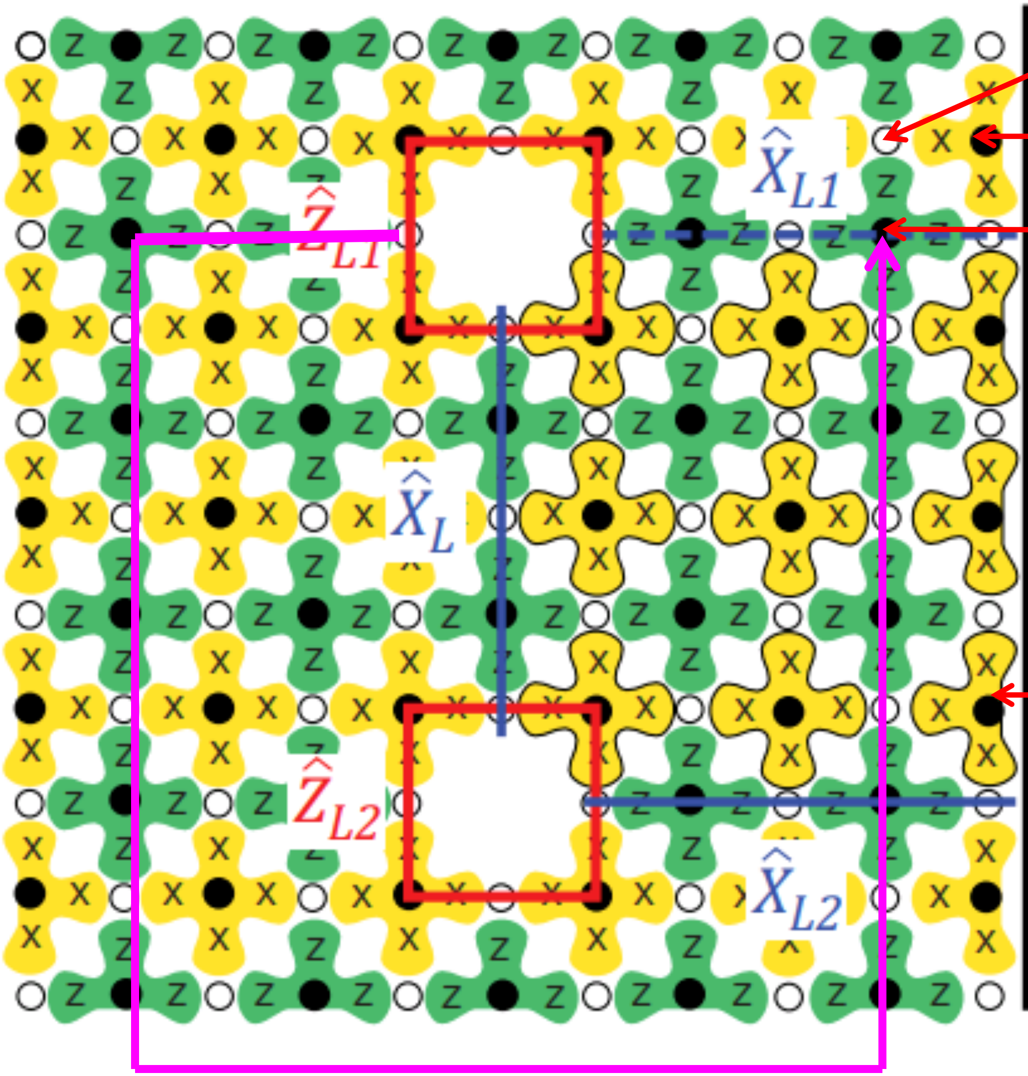


$$F \sim (0.995..)^{N(\#gates/step, \#depth)} \rightarrow 0 \text{ too quickly for being useful}$$

Quantum advantage still far away ?

More nines and more scalable fab. needed!

The surface (stabilizer) code architecture (just a flavor)



data qubit

X measure qubit

Z measure qubit

- Repeat measurements of all X,Z

- Define logical qubits by holes

- Single qubit gate X_{L1}= product X

- Two qubit gates by braiding

Scalable fabrication mandatory!

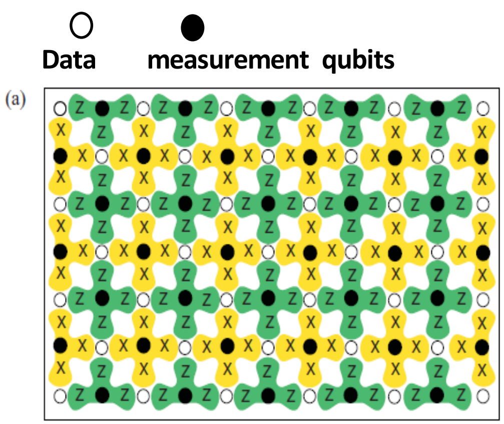
But … huge overhead: >3600 qubit/logical qubit @ 0.1% error/gate !

Strategies for addressing the scalability challenge

fault-tolerant architectures

surface code fabric

(see Fowler et al, PRA 86 (2012)



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

Better qubits requesting easier quantun error correction

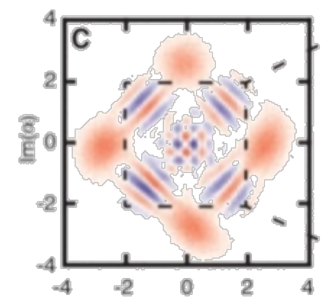
Dissipation engineering

Yale Quantlab,
INRIA- ENS Paris, ENS Lyon

Schrödinger cat states in high Q resonators

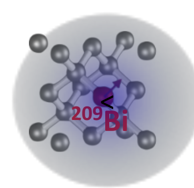
Autonomous qubits

Mirrahimi et al.
NJP 16, 32014 (2014)

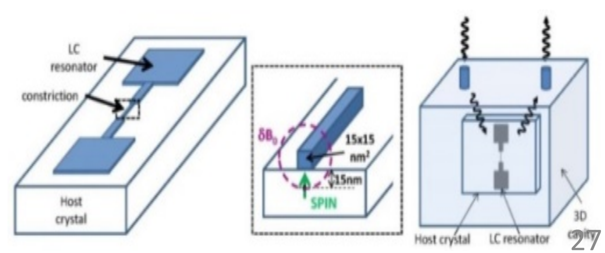


Hybrid structures

spins and quantum circuits, and others



quantum coherence, control issue

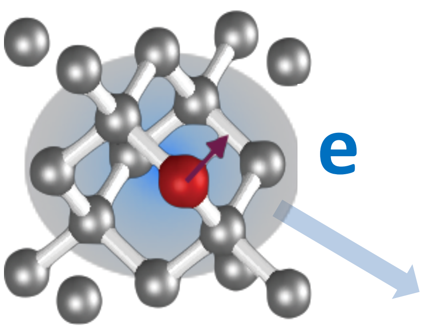


A new hybrid route : spins coupled to superconducting circuits

Nuclear spins **Electronic spins**

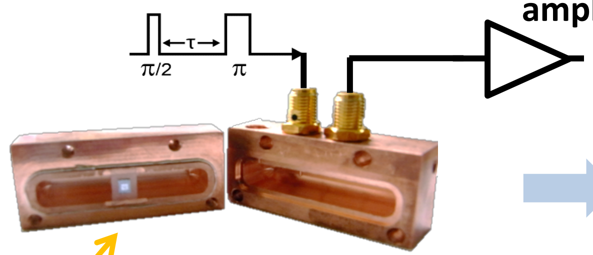
hyperfine coupling

Si : Bi



low mode volume high Q resonators

Quantum limited amplifier



nanoresonator

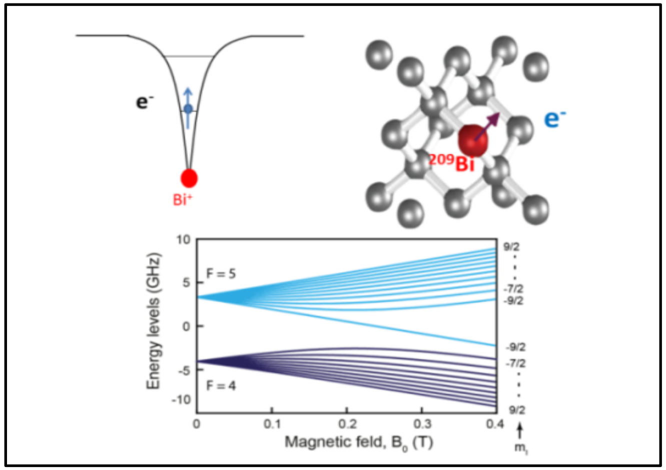
hybrid architecture ?

Highly coherent quantum system

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

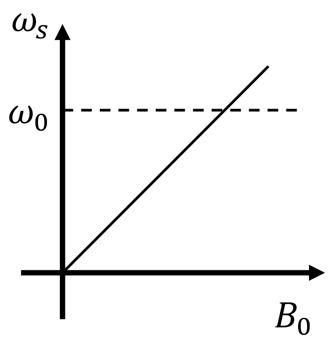
$$\frac{H}{\hbar} = A\boldsymbol{I}\cdot\boldsymbol{S} + \boldsymbol{B_0}\cdot(-\gamma_e\boldsymbol{S} - \gamma_n\boldsymbol{I})$$

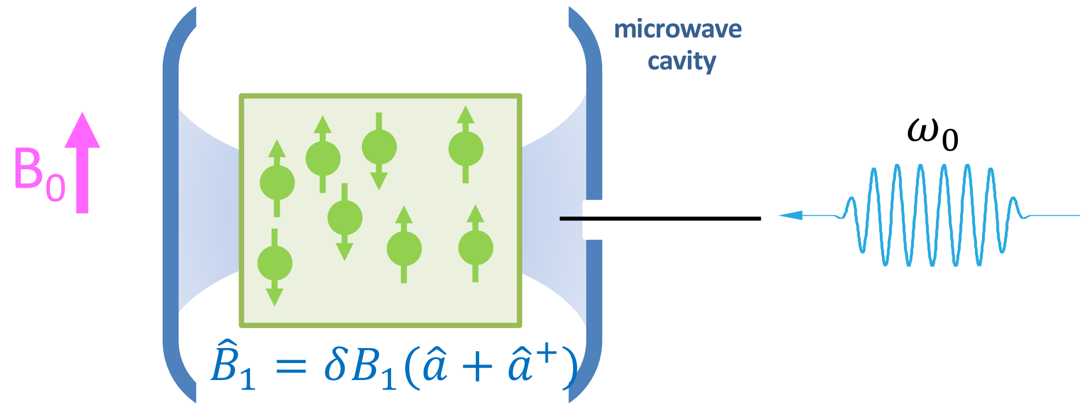
20 electro-nuclear states for making qubits



Preliminary ESR work

Magnetic resonance in a quantum microwave field



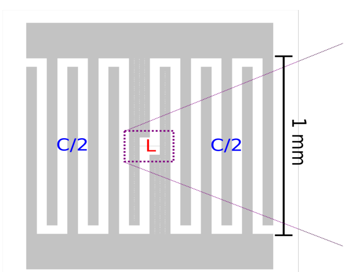


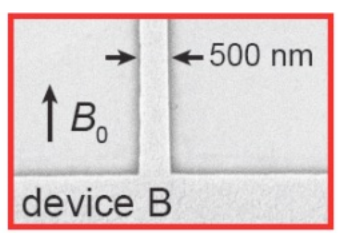
$$\hat{H} = -\sum \hat{M}_j \cdot \hat{B}_1 = \sum g_j (\hat{\sigma}_j^{+} \hat{a} + \hat{\sigma}_j^{-} \hat{a}^{+})$$

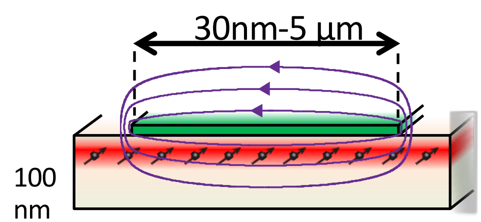
$$g_j = -\gamma \delta B_1(r_j) \langle \downarrow | S_{x,j} | \uparrow \rangle$$

coupling :
1 photon magnetic field at spin position

Small mode volume high Q resonators







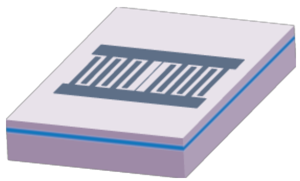
spins close to nanowire inductor

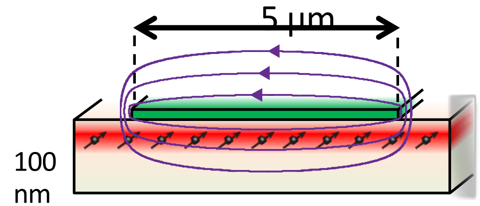
L=0.1mm
w=0.5µm
$V \simeq 200 fL$

$$\frac{g}{2\pi} \simeq 450\text{Hz}$$

Superconducting micro-resonator geometries

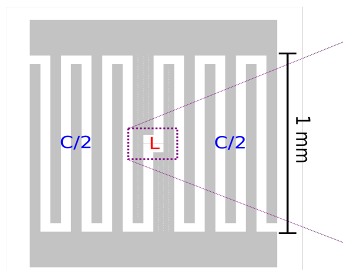
L=1mm
w=5µm
$V \simeq 20pL$

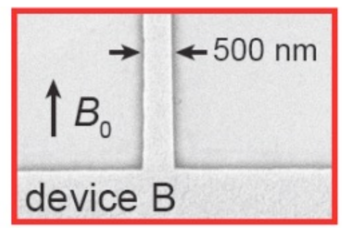




$$\frac{g}{2\pi} \simeq 60\text{Hz}$$

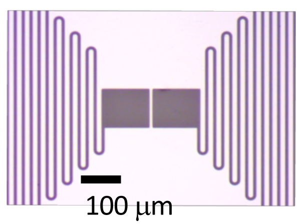
L=0.1mm
w=0.5µm
$V \simeq 200fL$

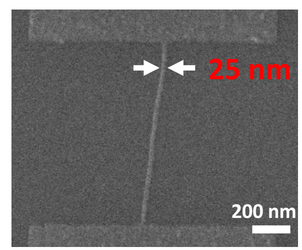




$$\frac{g}{2\pi} \simeq 450\text{Hz}$$

L=2µm
w ≃ 25 nm
$V \simeq 0.1\ fL$

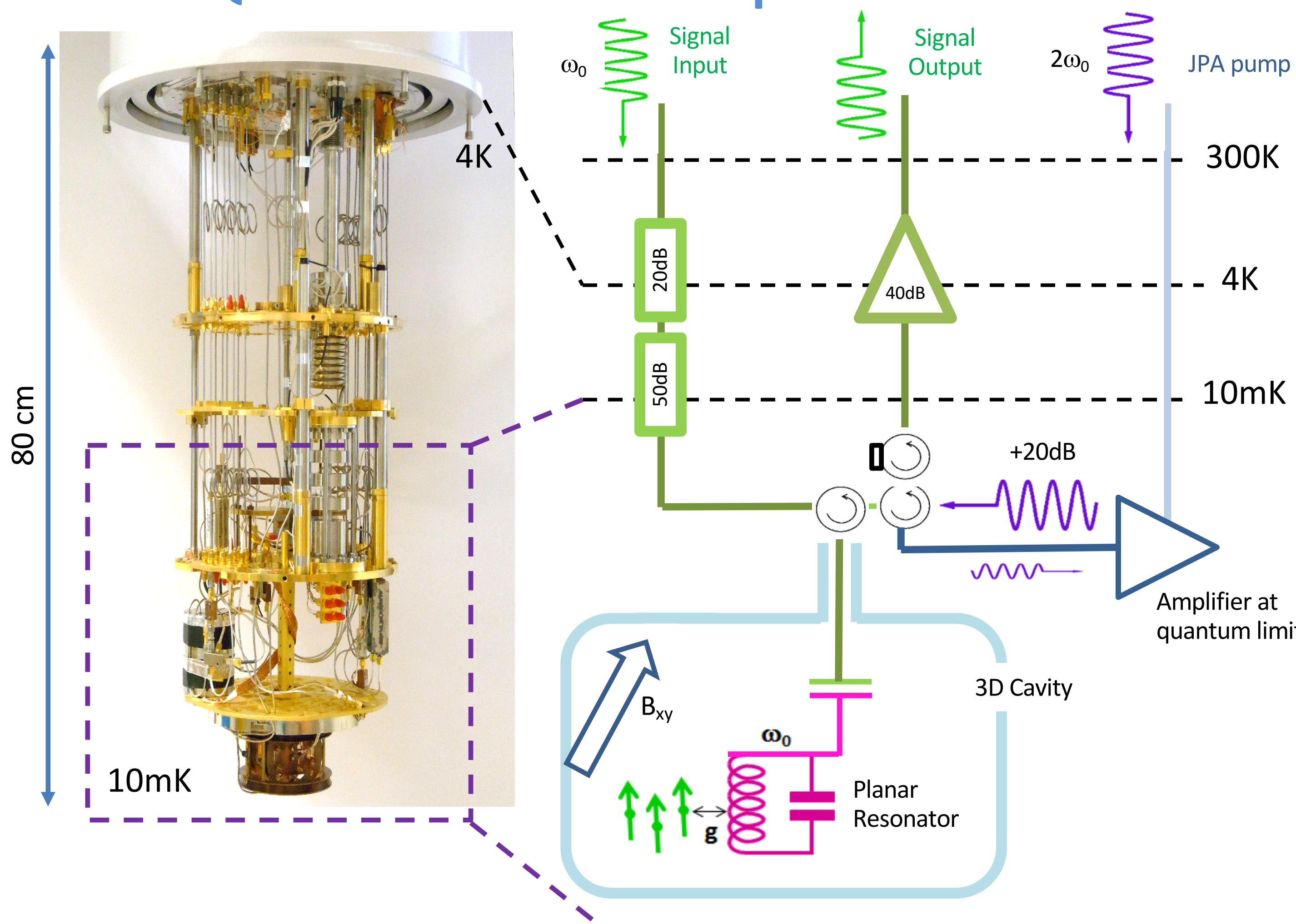




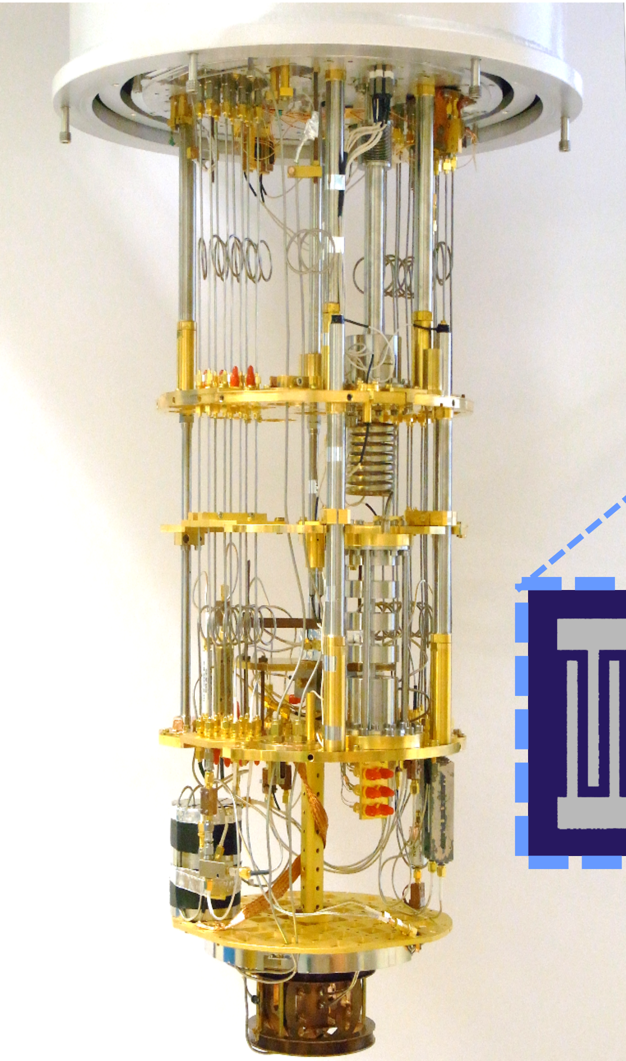
$$\frac{g}{2\pi} \simeq 2-8\text{ kHz}$$

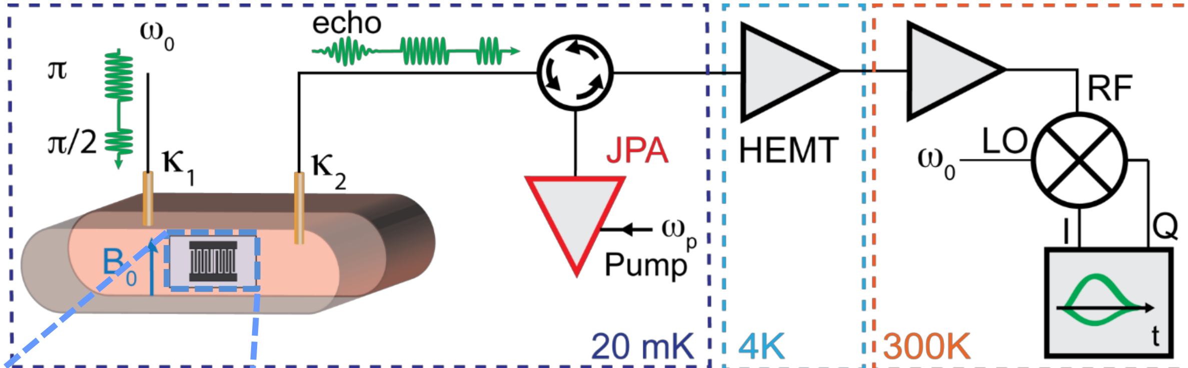
not yet probed

Quantum limited ESR spectrometer



Quantum limited ESR with Parametric Amplifier

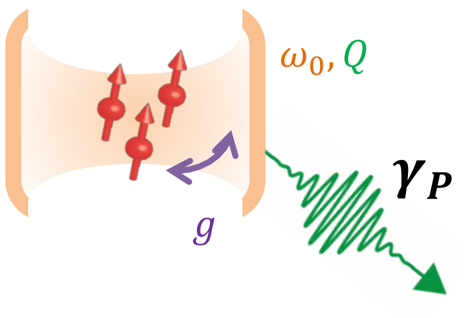




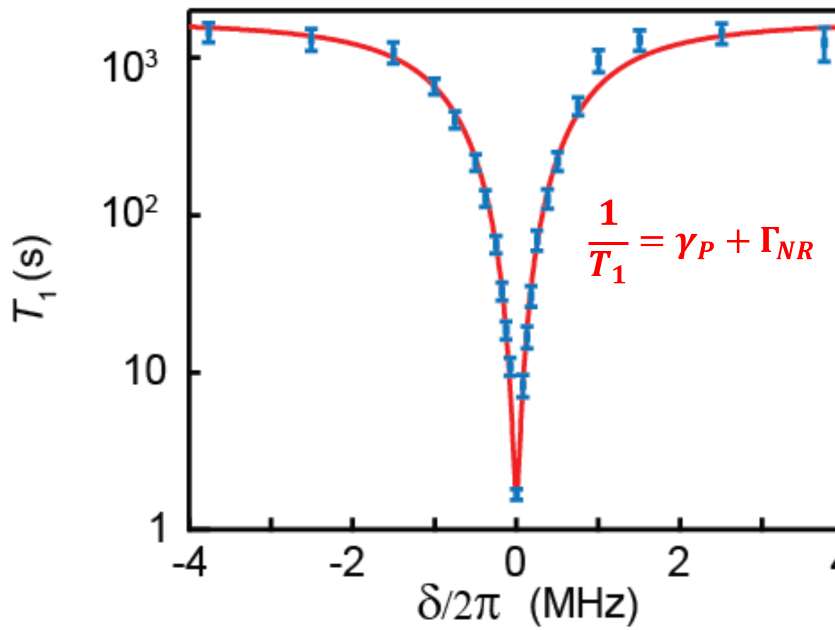
JPA: **J**osephson **P**arametric **A**mplifier
reaching the quantum limit

High Q low mode volume bonus: the Purcell effect

1946
E. Purcell



$$\gamma_P = \frac{4Qg^2}{\omega_0}\frac{1}{1+4Q^2\left[\frac{\omega_s-\omega_0}{\omega_0}\right]^2}$$



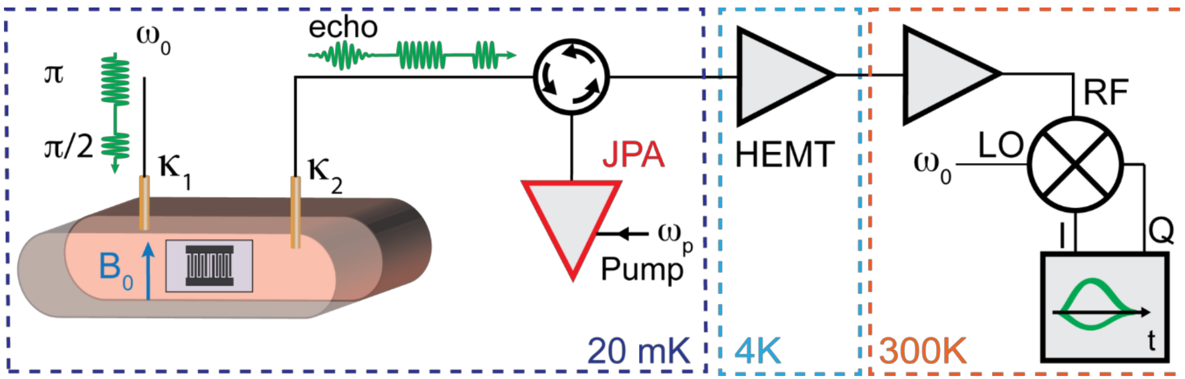
A. Bienfait et al., Nature 531, 74 (2016)

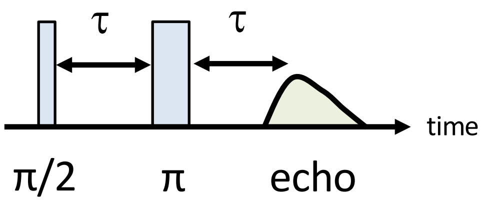
Bi spins & resonator
L=1mm
w=5µm
$V \simeq 20pL$

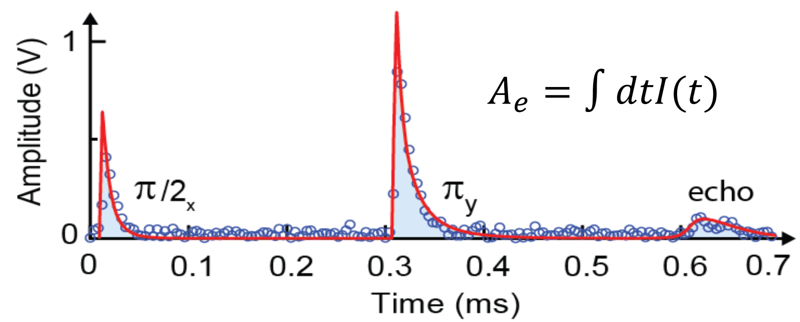
fit yields:
$\frac{g}{2\pi} = 60 \pm 10\text{Hz}$

Purcell relaxation allows to increase the repetion rate

Quantum limited ESR with Parametric Amplifier







$$A_e = \int dt I(t)$$

S. Probst et al., Appl. Phys. Lett. (2017)

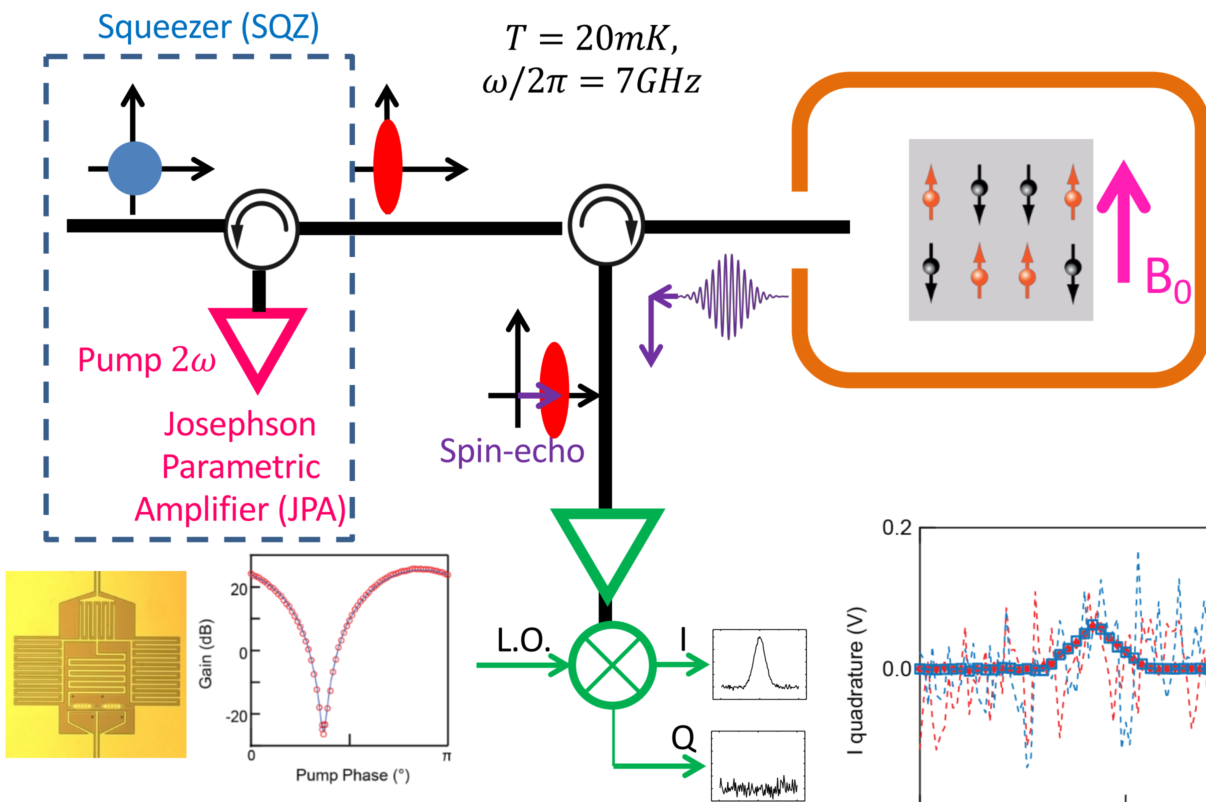
L=0.1mm
w=0.5μm
$V \simeq 200fL$

best achieved ESR detection sensitivity:

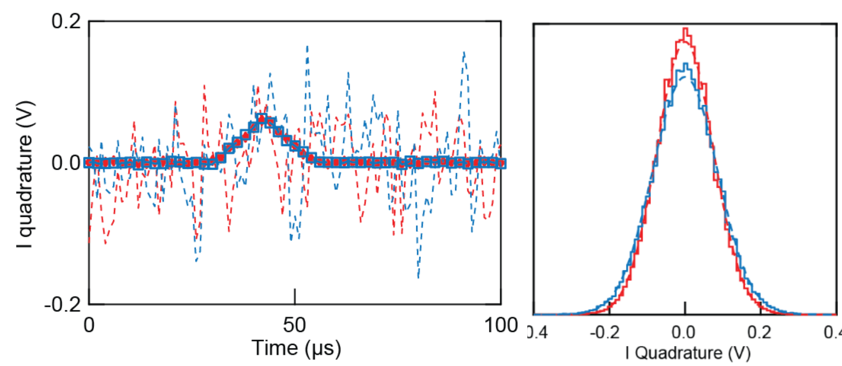
single echo : ~100 spins

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

Squeezing-enhanced magnetic resonance : principle



Small 12% SNR gain
limited by losses

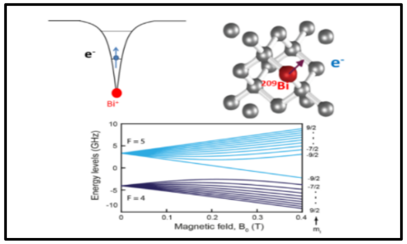


X. Zhou et al., PRB (2014)
M. Castellanos-Beltran et al., APL (2007)
C. Eichler et al., PRL (2010)
N. Bergeal et al., Nature (2010)

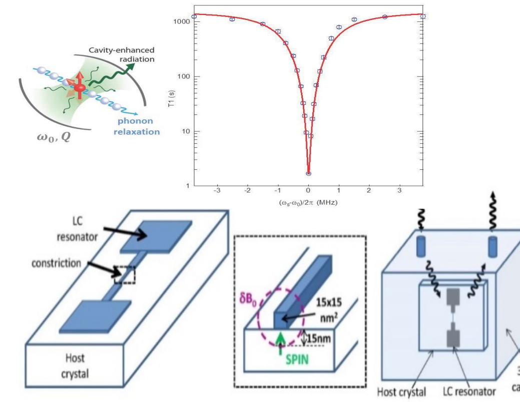
An hybrid route toward quantum information ?

Electro-nuclear spin system

with good quantum coherence

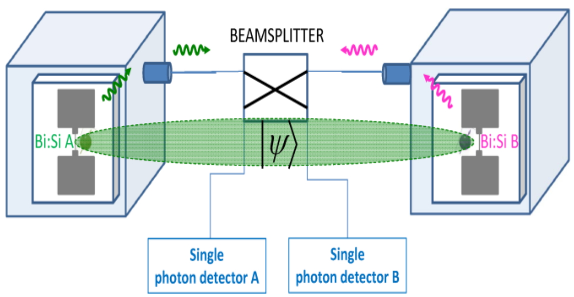


controlled coupling to environment



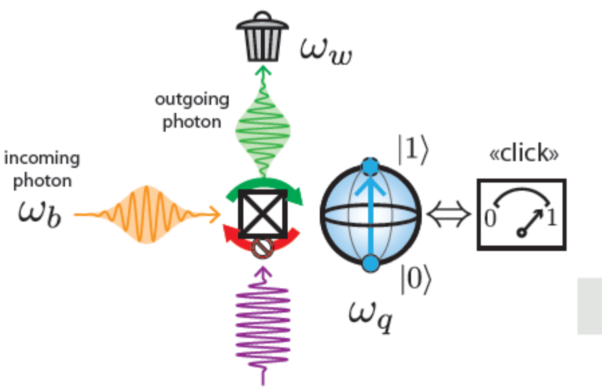
Quantum information perspective :

generating entanglement ?

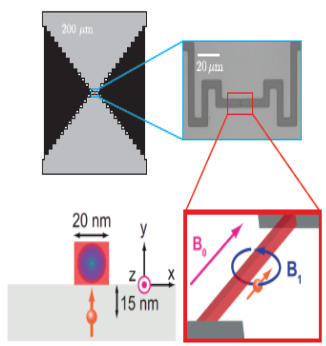


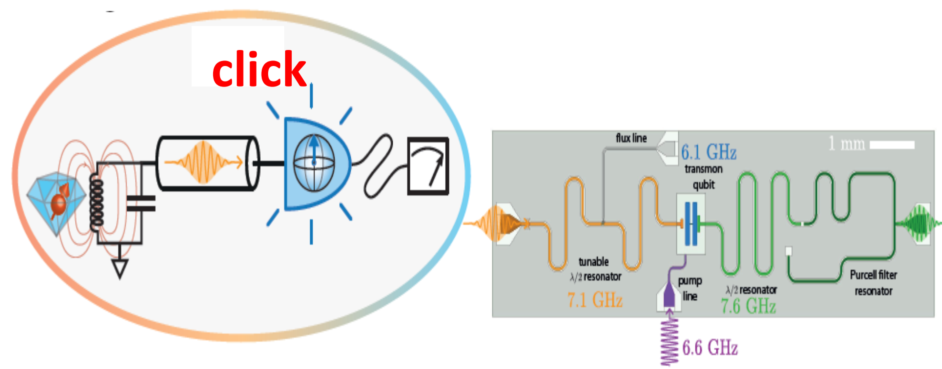
key element: photon detector

new quantum optics design (E. Flurin, 201



$$\omega_p = \omega_q + \omega_w - \omega_b$$





Work in progress...

Conclusions

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

IBM, Intel, Google, Microsoft, Atos

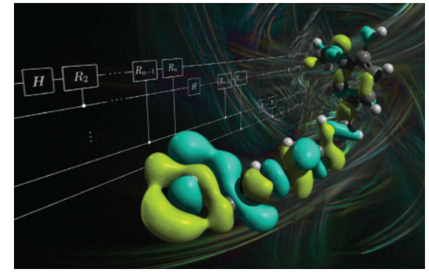
-Low depth processors at Google, IBM, Rigetti
targeting quantum advantage
-Sizeable progress on different platforms

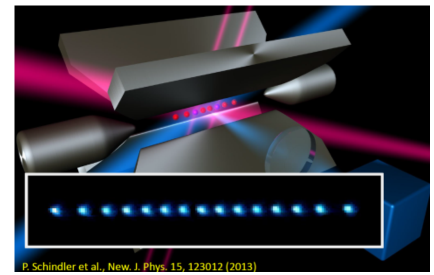
-gate-based processors with quantum error correction
very difficult.
Scalable fab. mandatory.

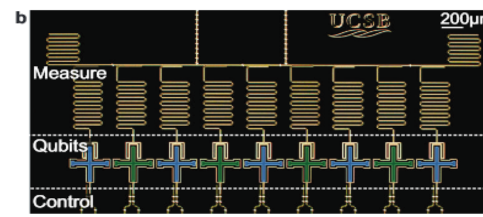
-Other route **more coherent qubits**
autonomous correction, Schröd. cat states, spins, …

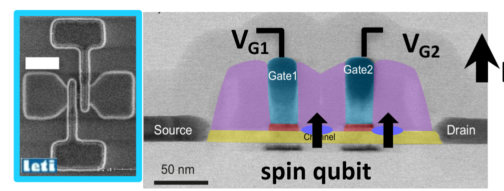
Appealing potential, but perspectives still unclear

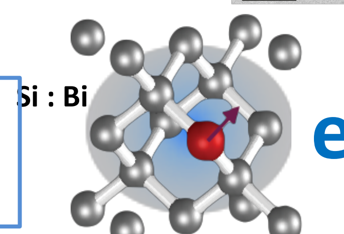
Rich quantum physics on the road





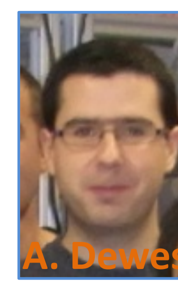






QUANTUM ELECTRONICS GROUP

and



& V. Ranjan, M. Rancic, M. Lee, F. Barbosa,
B. Albanese, E. Albertinale, M. le Dantec
& former members: A. Dewes, **X. Zhou, V. Schmitt,A. Bienfait, S. Probst**