Circuits mésoscopiques quantiques:

La voie des qubits robustes vers le calcul quantique

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QUANTUM ELECTRONICS GROUP

AEIS, Institut Curie, Oct. **2021**

The (first) quantum revolution

1900-1930

a revolutionary formalism:

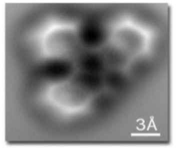
-Superposition principle:
The **superposition of physical sta**tes is still a possible physical state

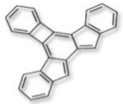
The superposition defines the quantum state and the possible outcomes of a measurement

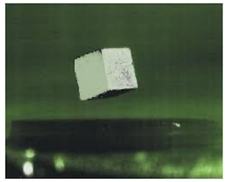
-Evolution rules of quantum state among all possible superpositions

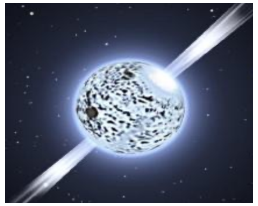
1930s → Quantum formalism applied to all areas of physics and at all scales

Particles nuclei atoms molecules condensed matter neutron stars ...

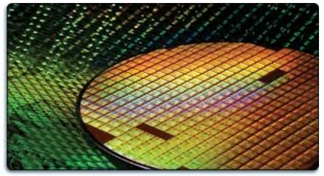








The basis of many technologies based on advanced materials (lasers, semiconductor electronics,...)



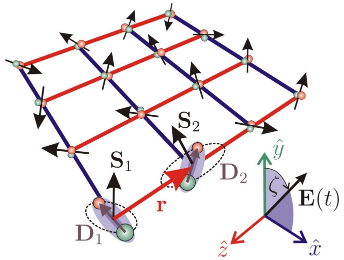
But does QM apply to all degrees of freedom ?

Second quantum revolution of quantum machines ?

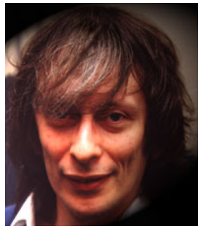
Quantum machines for Quantum Computing

1982: Solving quantum systems too difficult
quantum simulation needed!

R. Feynman



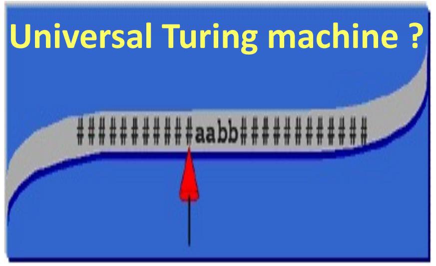
1985: unexpected breakthrough



D. Deutsch,
and others

Quantum mechanics provides computational resources

Classical computing:



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

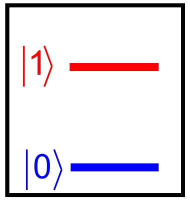
0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1	0/1

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

Quantum computing:

qubit

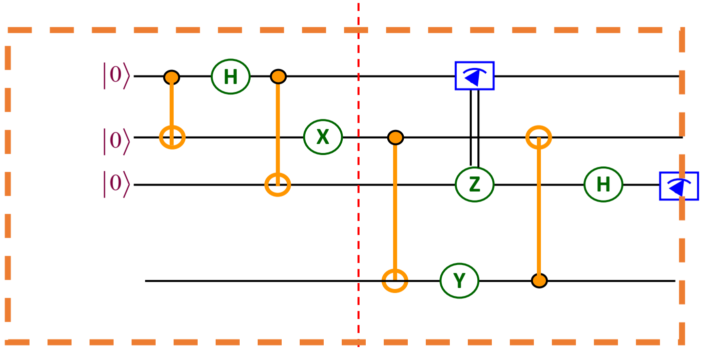
2 level system



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

N = 2^n computational
basis states

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



Readout

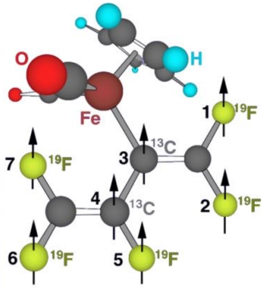
returns 0 or 1
for each qubit :
a basis state

$$\sum_{i_k=0,1} a_{i_1 i_2 i_3 i_4 \ldots i_{2^N}} |i_1, i_2, i_3 \ldots i_{2^N}\rangle$$

(entangled state)

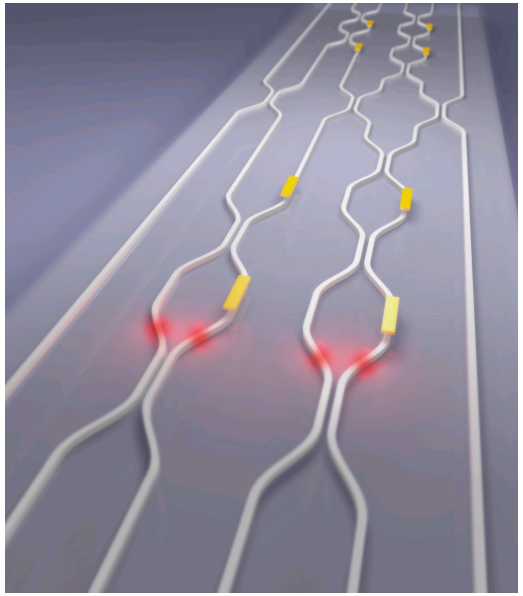
A disruptive technology ?   Physical implementations ?

NMR



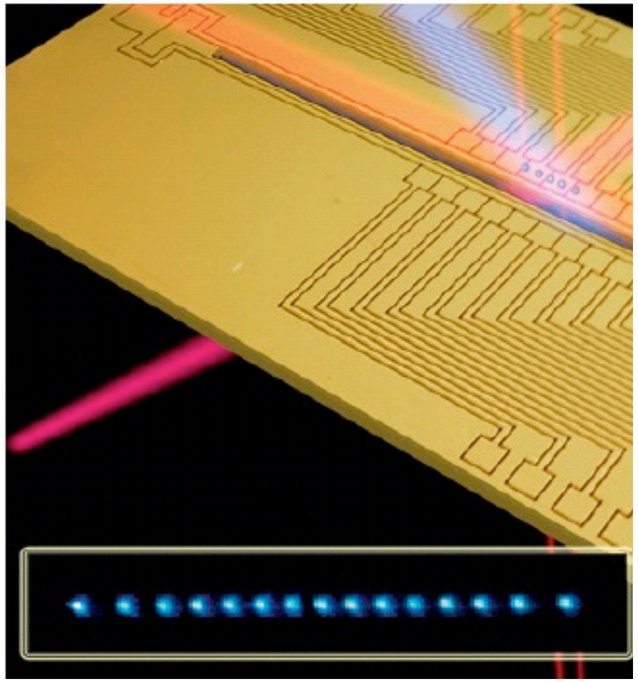
not scalable

Photons



Photons weakly interact
->measurement based QC
efficiency ?

Trapped ions
(or atoms)

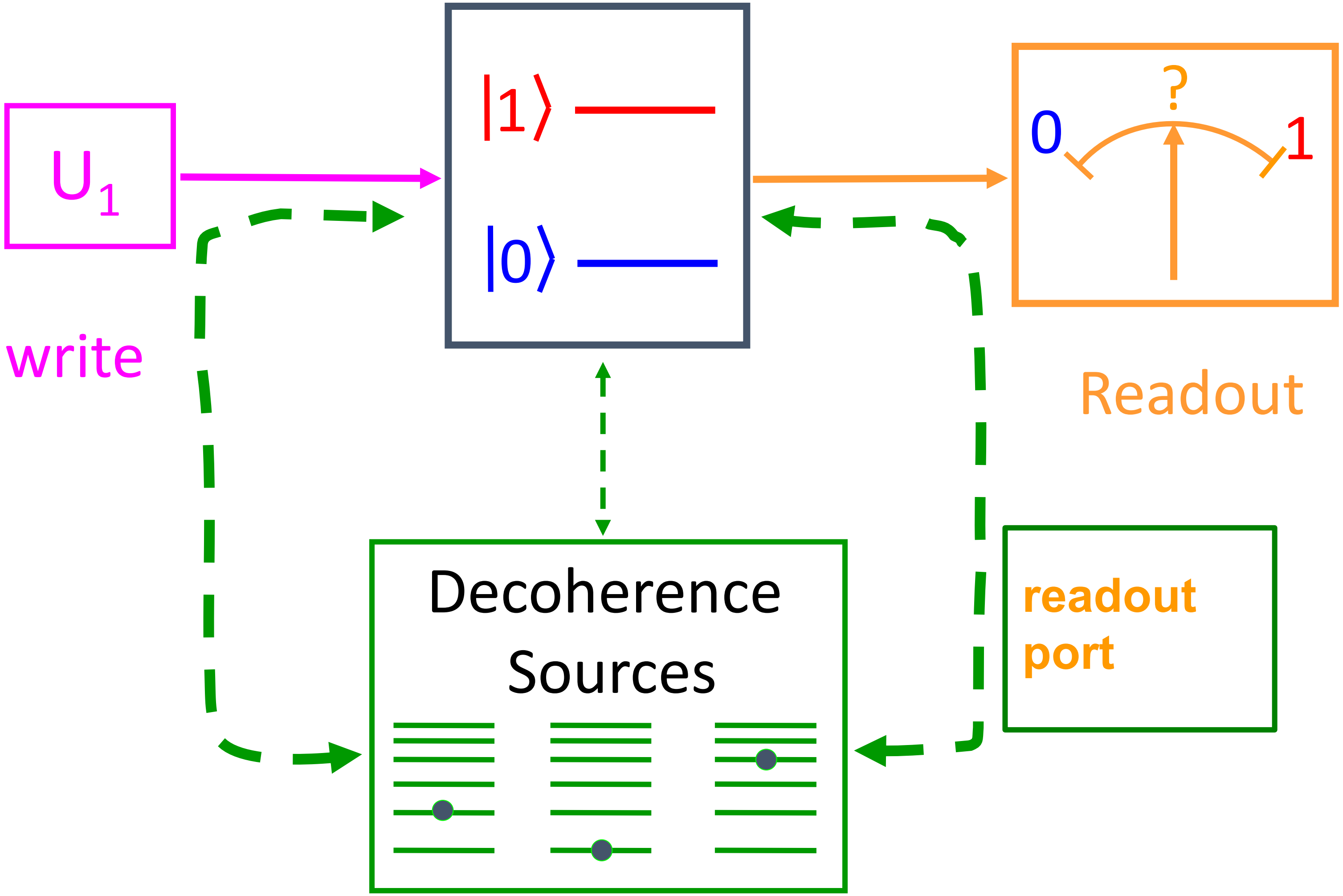


An advanced platform

Electrical circuits ?

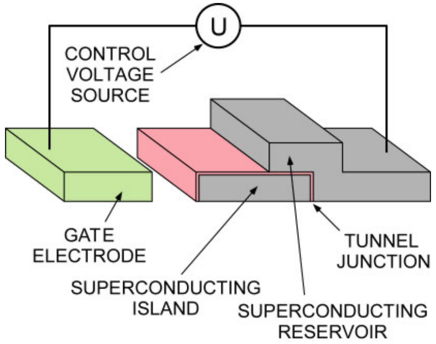
usually not quantum !
superconducting qubits
semiconduting qubits (less advanced, scalable fab.)

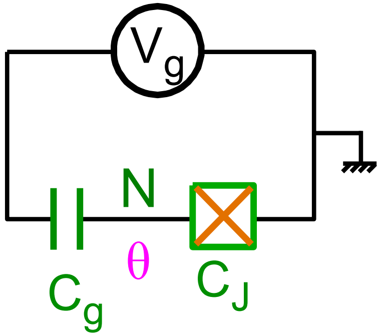
A major issue: coupling to the environment yields decoherence



An electrical quantum bit : the Cooper pair box

Quantronics
1997

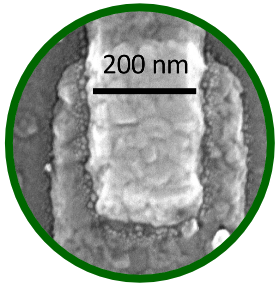




solvable quantum circuit

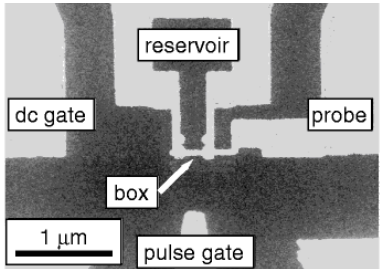
$$\hat{H} = E_C(\hat{N}-N_g)^2 - E_J\cos\hat{\theta}$$

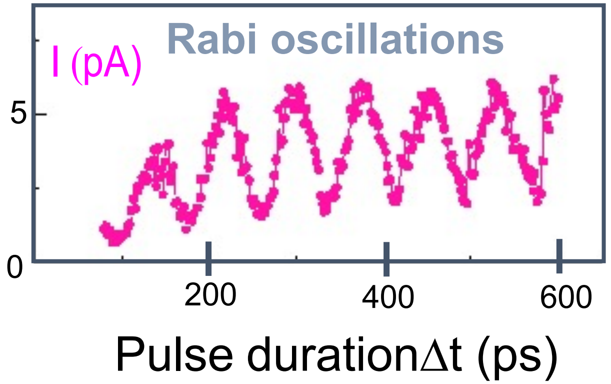
Ng=CgU/2e



1 degree of freedom
{ **N**, θ }

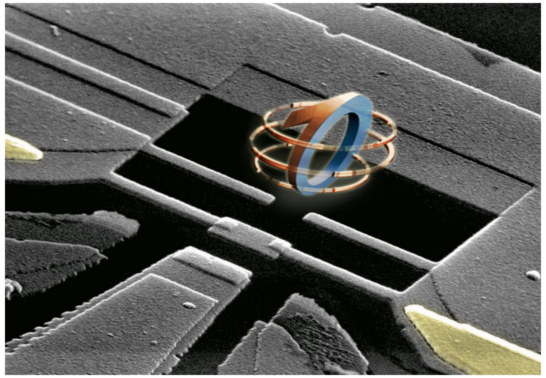
quantum coherence btw 2 states
(Nakamura, Pashkin & Tsai, 1999)
in the Cooper pair box circuit

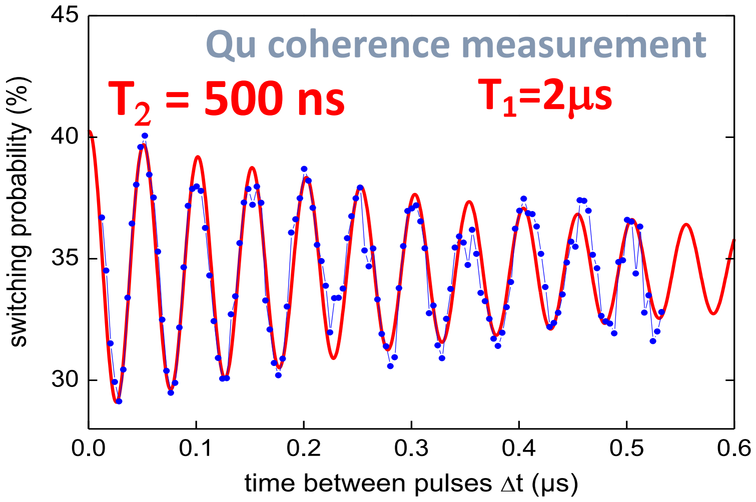




A true artificial atom :
Quantronium circuit
(Vion et al., 2002)

control,
single shot readout
&
coherence



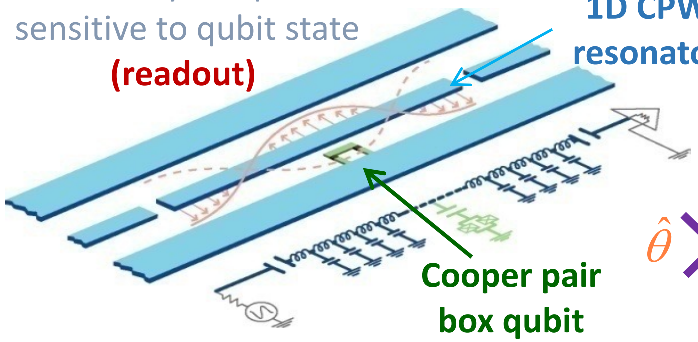


Superconducting qubits : state of the art

Transmon

Cooper pair box in
microwave cavity
(Yale, 2007)

cavity freq.
sensitive to qubit state
(readout)

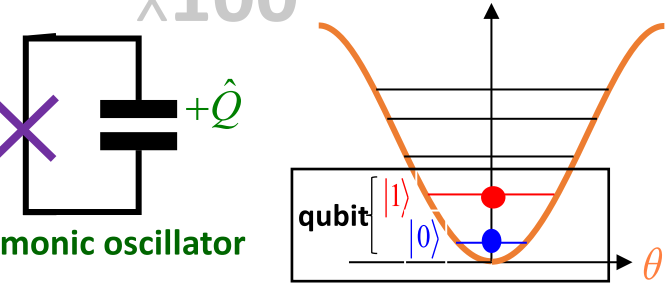


1D CPW resonator

Cooper pair box qubit

Coherence time up to ~**100 µs**

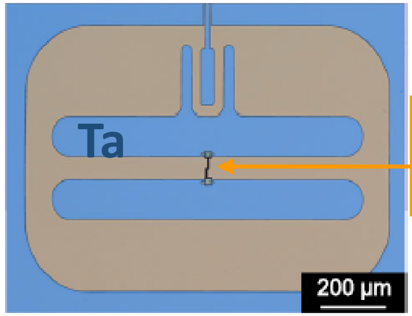
x**100**



anharmonic oscillator

Recent progress:

Reducing
material losses (Ta)
improves quantum
coherence
(Princeton 2020)



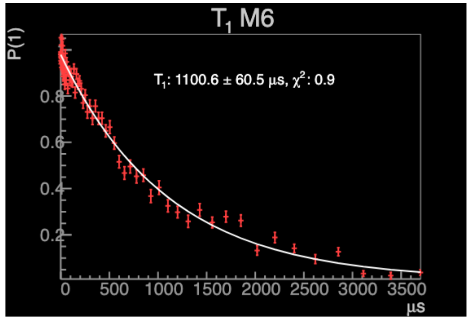
Al /AlOx/Al Josephson junction

x**3**

Coherence time: 250 µs

process tested
IBM, China
Quantronics, …

Best result from IBM
(unpublished)

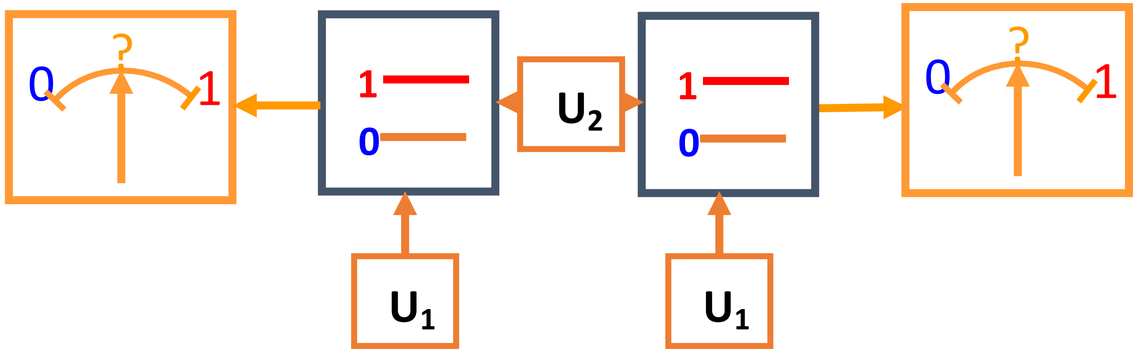


x**4**

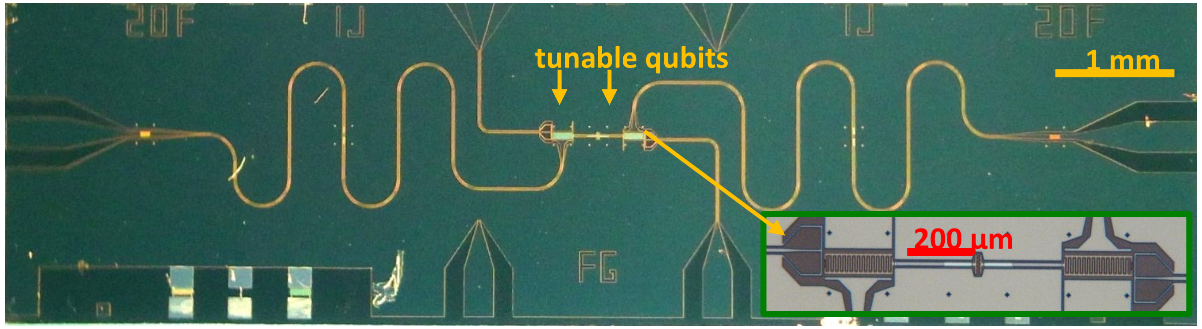
T_1, T_2 in ms range

But **processors** not yet there….

Quantum processors ?



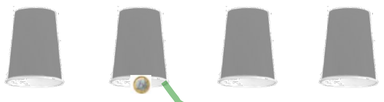
Proof of concept of
an **elementary**
two qubit processor

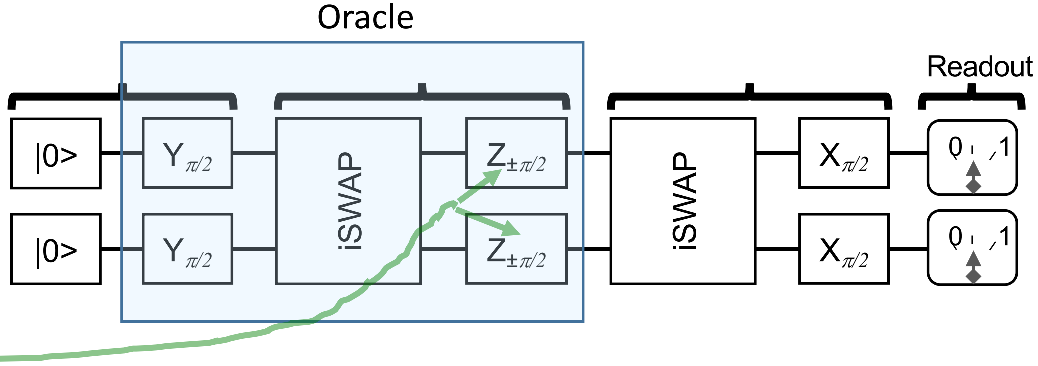


Quantronics, 2012

Dewes et al., PRL & PRB 2012

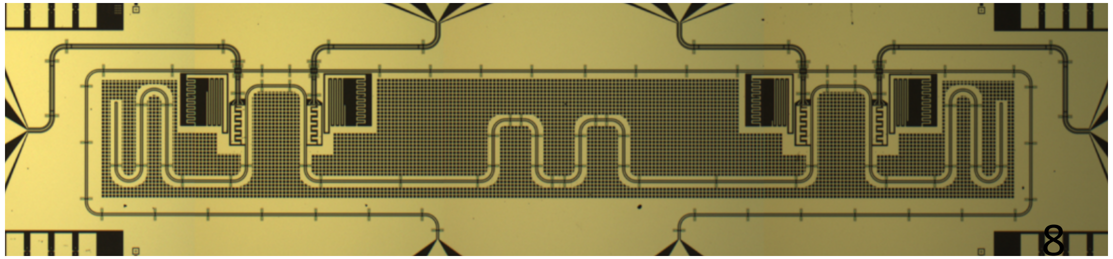
demonstration of the **Grover search quantum algorithm**
(here: find 1 state out of 4
in a single identification call)





Proof of principle of quantum acceleration

4 qubit processor with
multiplexed readout



The scalability challenge

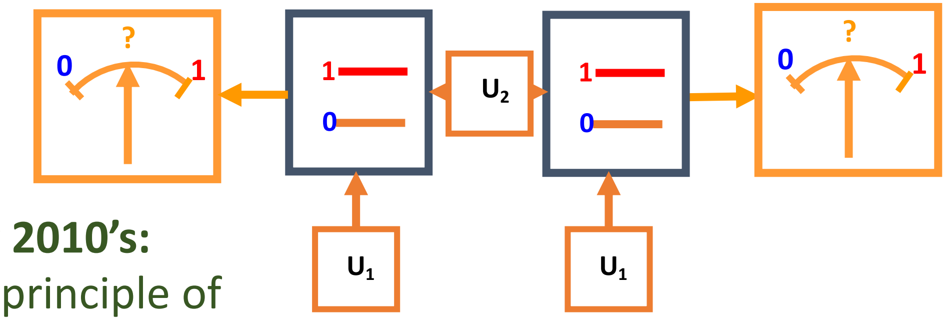
Use-cases for gate-based quantum computing needs >100 logical qubits

Quantum systems:
quantum chemistry,
materials,
nuclear physics, …

Linear algebra:
quantum inversion of
sparse matrices

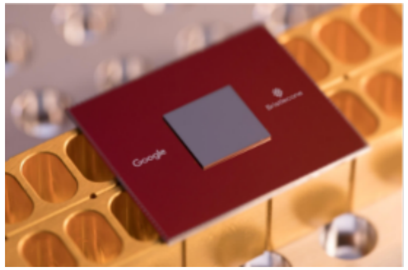
Classification :
Optimization
Machine learning

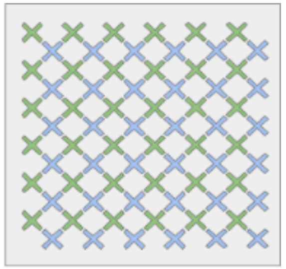
Gate-based quantum processor:
quantum coherent qubits, universal set of gates, readout, reset

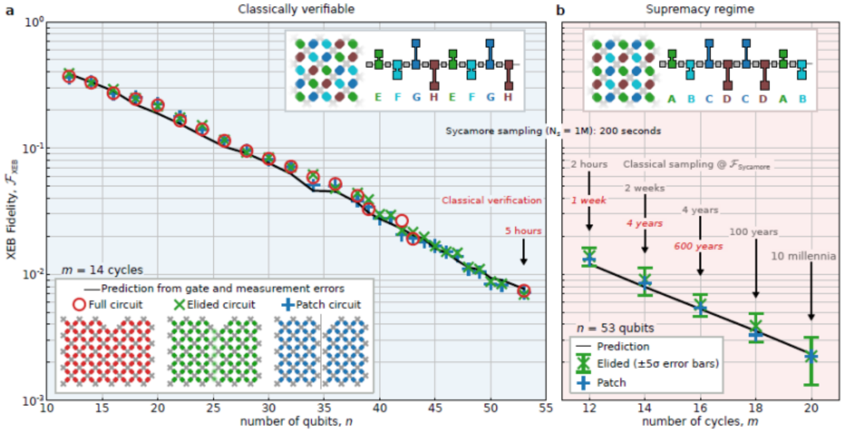


Early 2010's:
proof of principle of
small quantum
processors

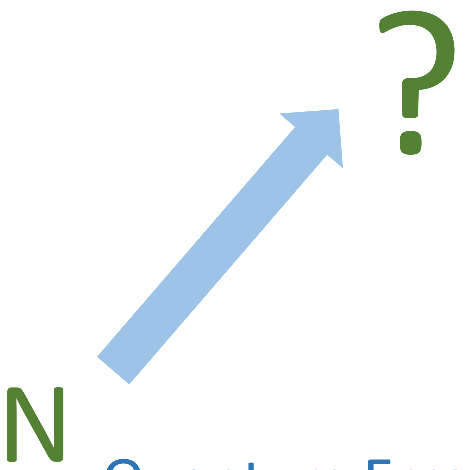
2019:
Google Sicamore 53 qubit processor







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



Quantum Error correction issue:

copy forbidden

Strategies for addressing the quantum error correction challenge

Fault-tolerant architecture based on the Surface Code

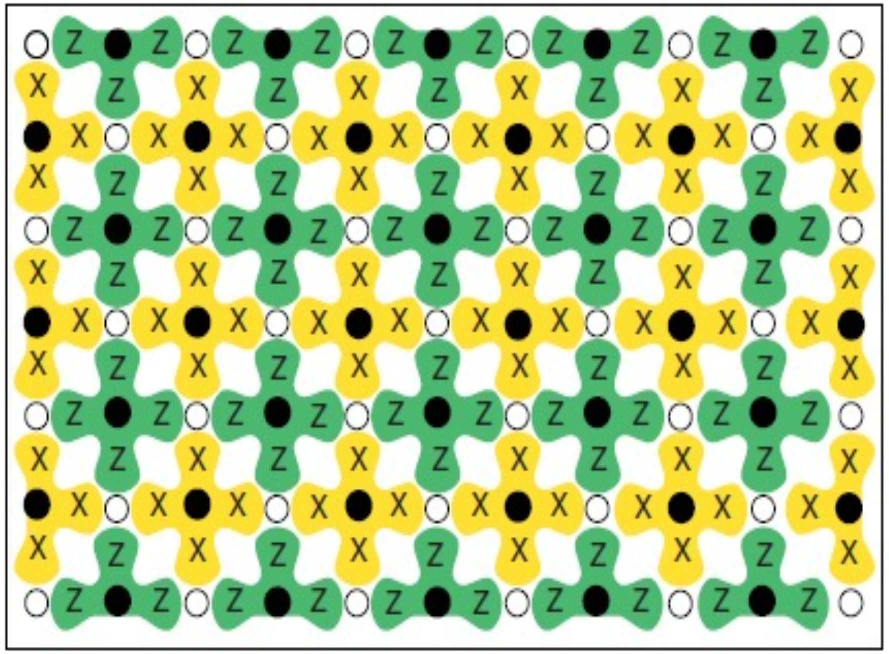
Method: detect & identify error
correct, or keep record

(Fowler et al, PRA 86 , 2012)

○ **Data**

● **measurement**

(a)



pro : <1 % error threshold enough

con : **huge resource overhead**

1 logical qubit >>10^3 physical qubits

ONLY POSSIBLE WITH SCALABLE FAB

adapted to semiconducting qubit
LSI circuits

QuantumSilicon
Grenoble

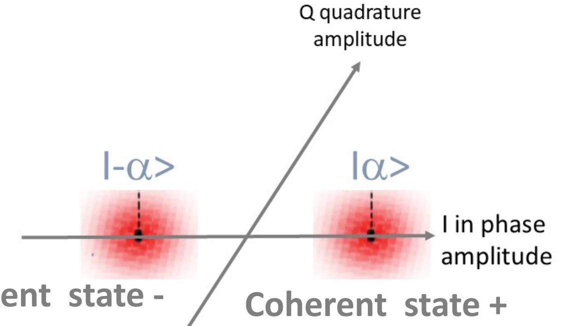
Other routes ?

Robust qubits with more coherence and less overhead

Cat-state qubits

Qubit states built from
high Q resonator coherent states

qubit states $\left|\alpha\right\rangle \pm \left|-\alpha\right\rangle$



Full protection: in progress Lescanne et al., Nat Phys 2020

1D code of cat-qubits (est x50 overhead)

fault-tolerant architecture

Guillaud-Mirrahimi PRX 2019

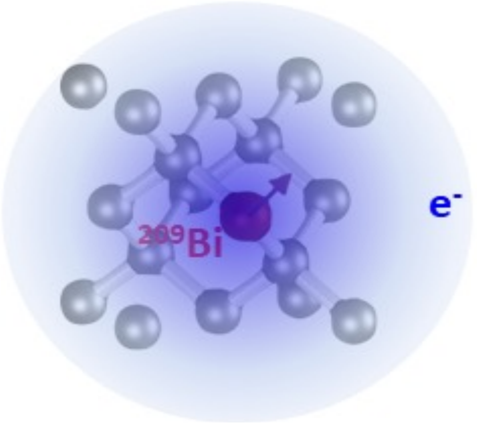
Quantic team (ENS, INRIA, Mines)
Alice&Bob , Yale

ALICE & BOB

(Amazon)

impurity spin qubits

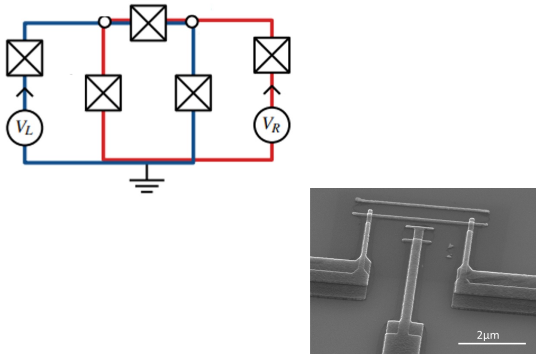
electro-nuclear levels with
superior quantum coherence



Coherence times
up to **seconds**

but microscopic objects
hard to control

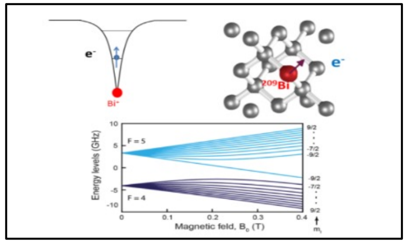
topologically protected qubits



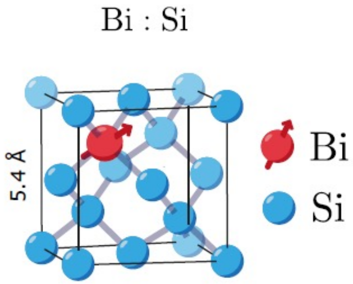
Suppressing
decoherence channels
by circuit design

A new hybrid route : spins coupled to superconducting circuits

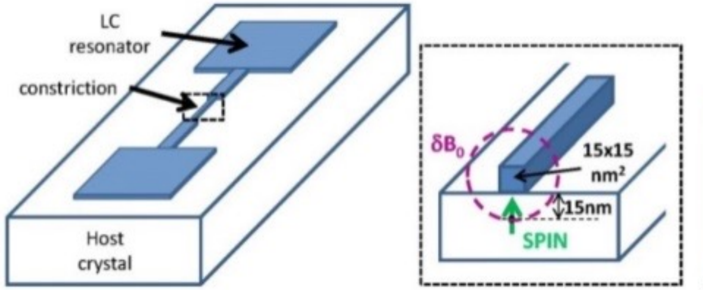
Highly coherent
electro-nuclear
spin states



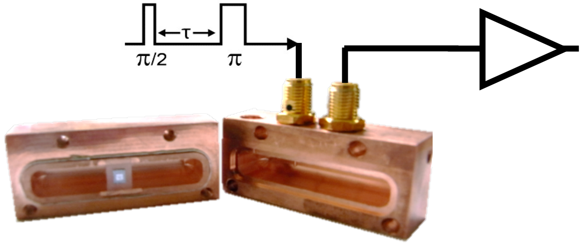
Coherence times:
electronic spins: ms, s
nuclear spins: s, h



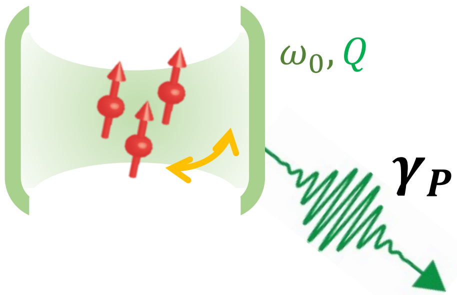
g = 2

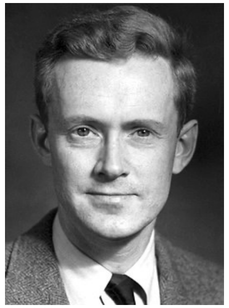


controlled
coupling to
environment



Strong coupling:
radiative relaxation
channel dominant
(**Purcell regime**)



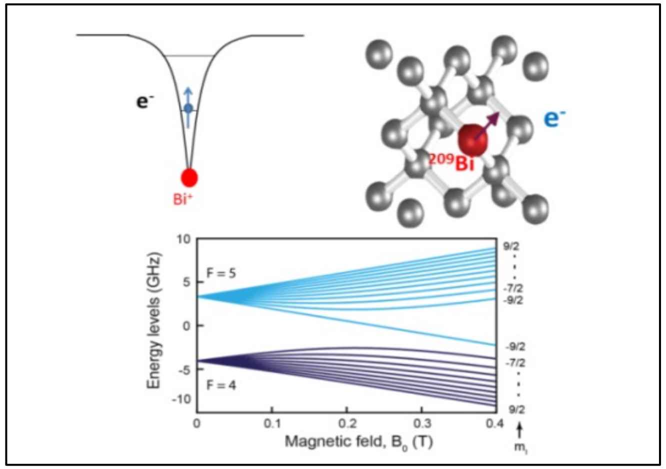


1946
E. Purcell

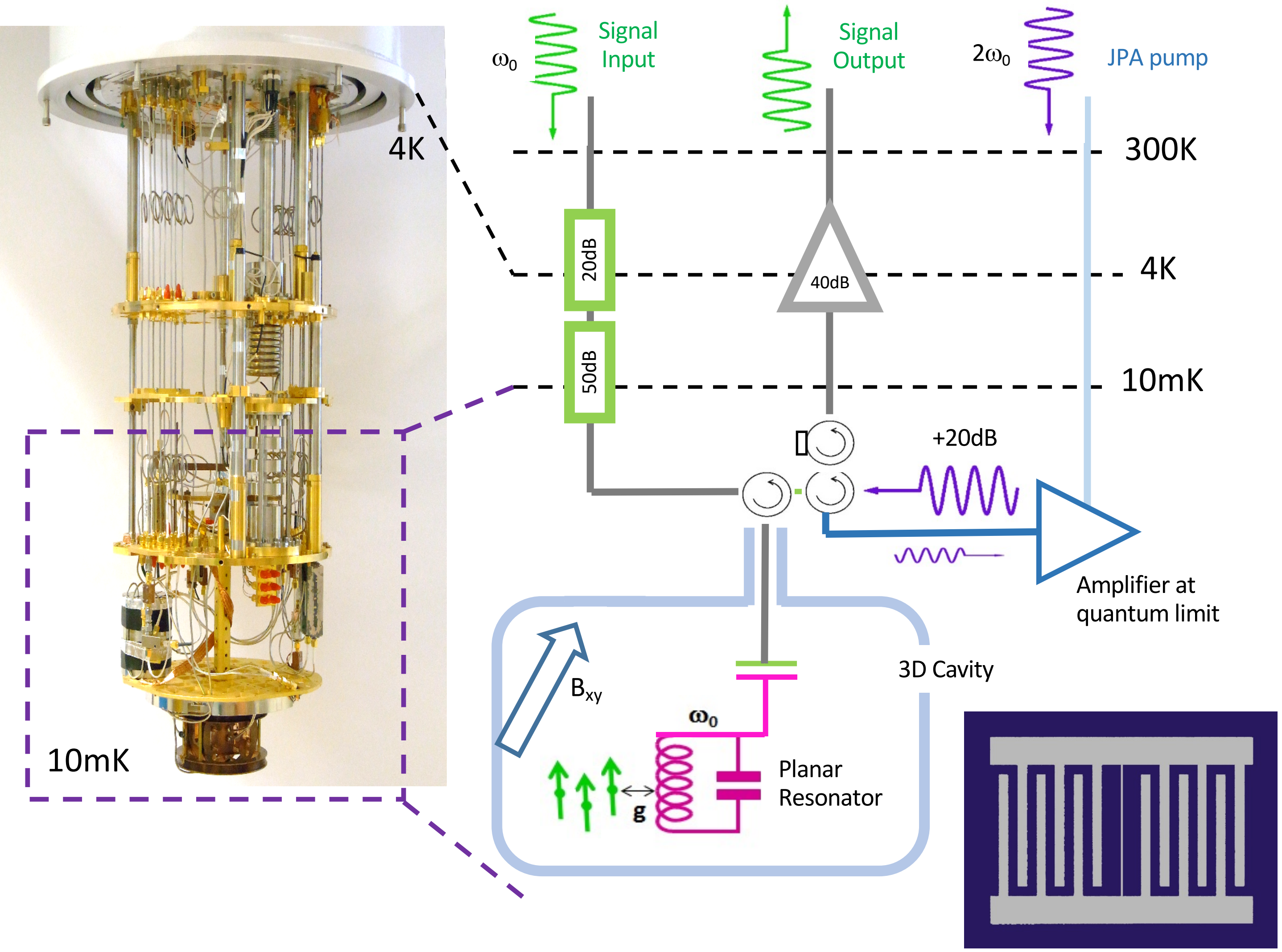
- Electronic spin = 1/2
- Nuclear spin I=9/2
- Large hyperfine coupling $\frac{A}{2\pi} = 1.4754\text{GHz}$

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

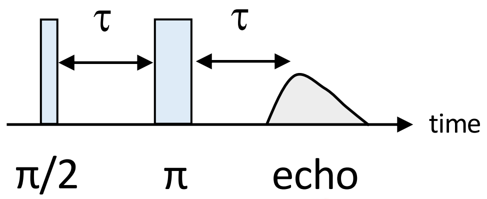
20 electro-nuclear states
for making qubits

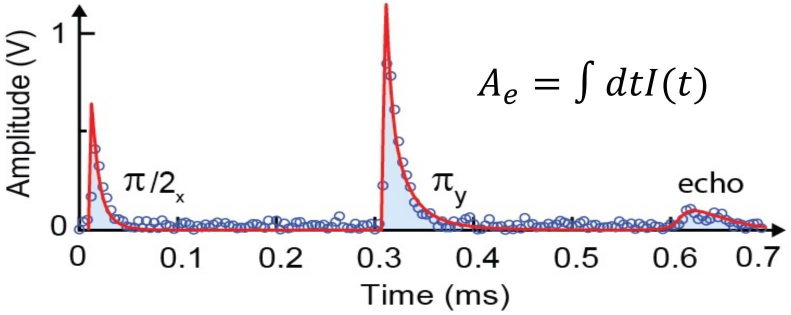


Quantum limited ESR spectrometry



inductance:
length=0.1mm
width=0.5µm
Mode vol≃ $200fL$



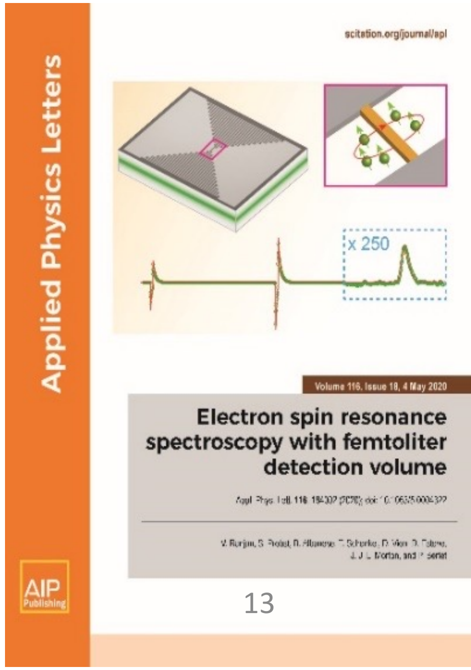


best achieved ESR detection sensitivity:

single echo : ~100 spins

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

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



Applied Physics Letters

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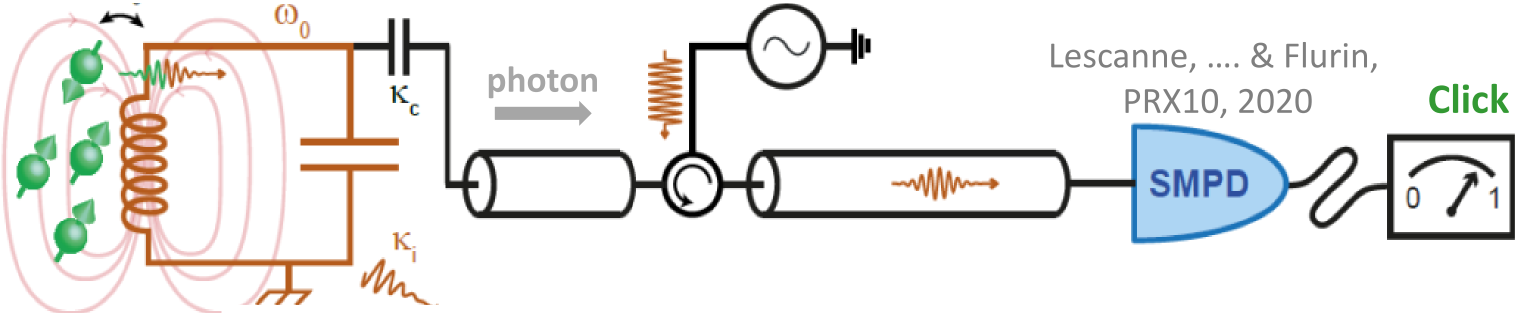
Electron spin resonance spectroscopy with femtoliter detection volume

A new detection strategy based on a single microwave photon counter

E. Albertinale…& **E. Flurin**
to appear in Nature
arXiv:2102.01415

spin fluorescence Bienfait et al., Nature 2016

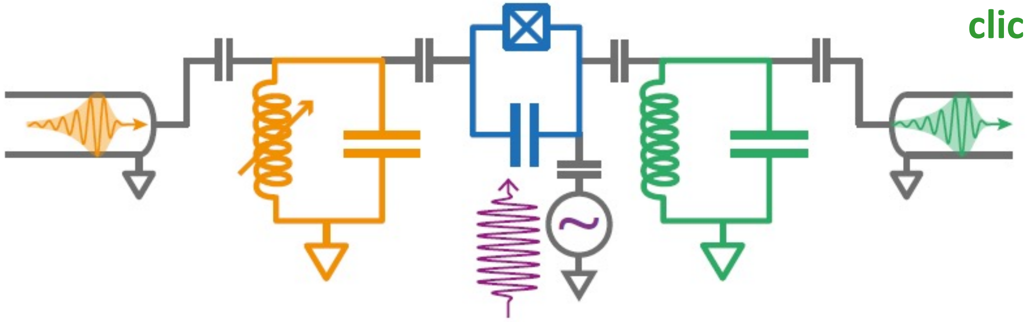


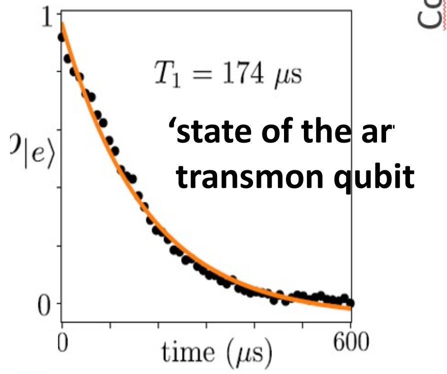
Lescanne, …. & Flurin, PRX10, 2020

Click !

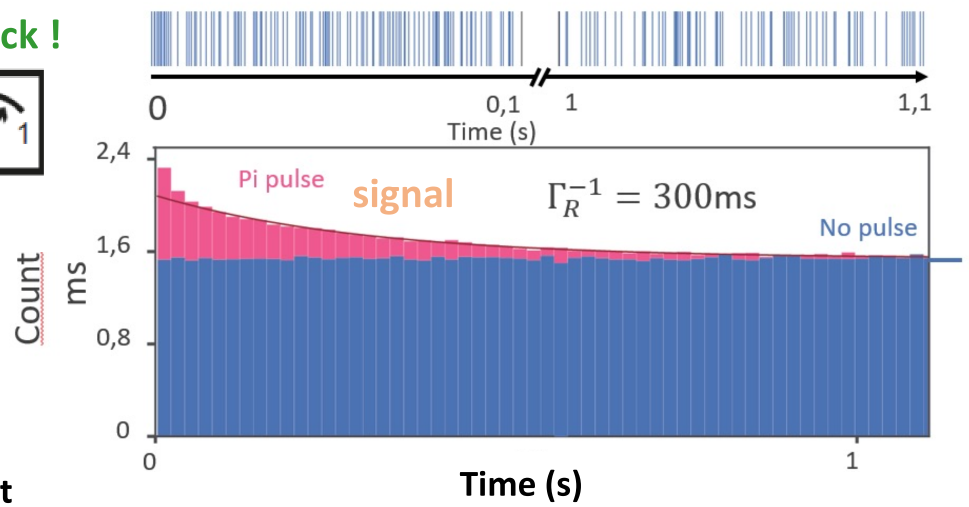
mixing with photon excites a transmon

qubit readout :
click !

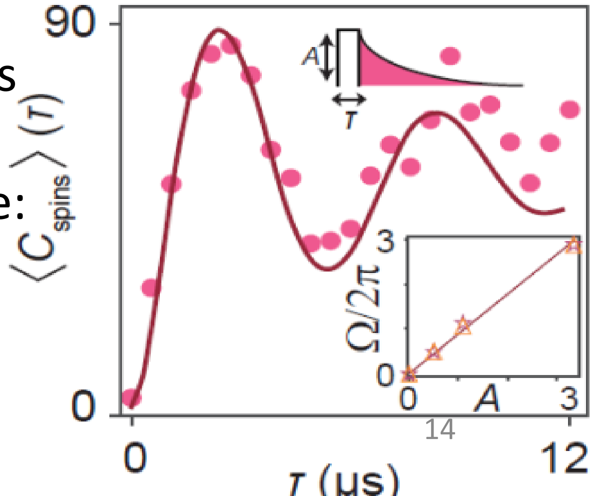


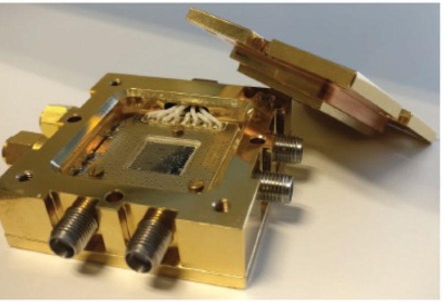


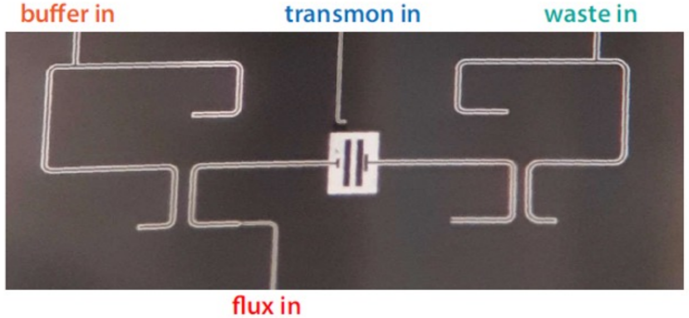
'state of the ar transmon qubit



Rabi oscillations detected by fluorescence:





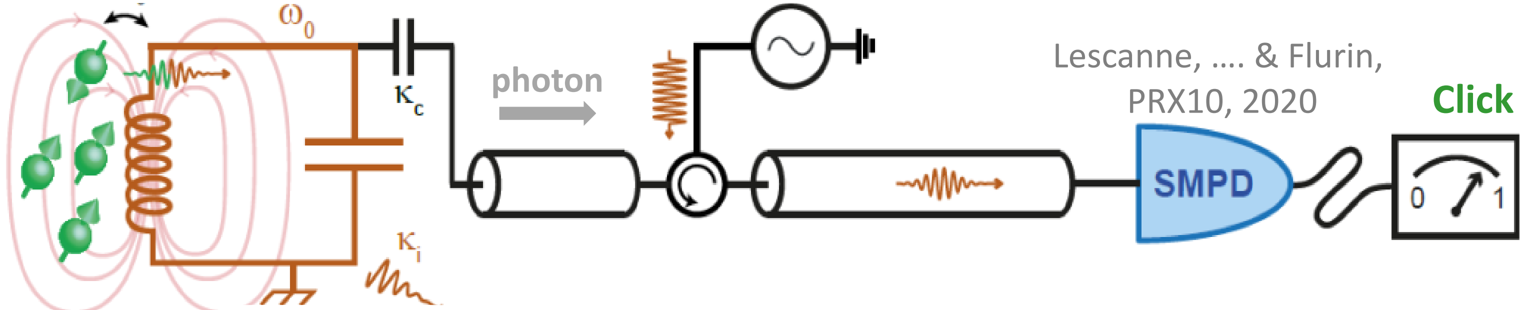


dark count rate:
70 counts/s
goal:
1 count/s

A new detection strategy based on a single microwave photon counter

E. Albertinale…& **E. Flurin**
to appear in Nature
arXiv:2102.01415

spin fluorescence Bienfait et al., Nature 2016

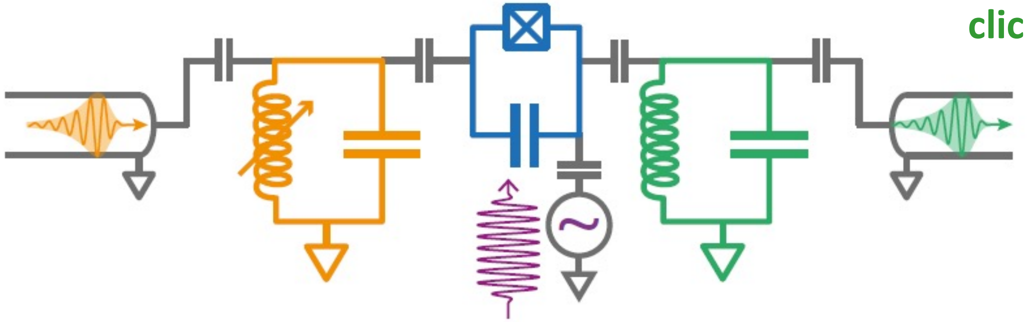


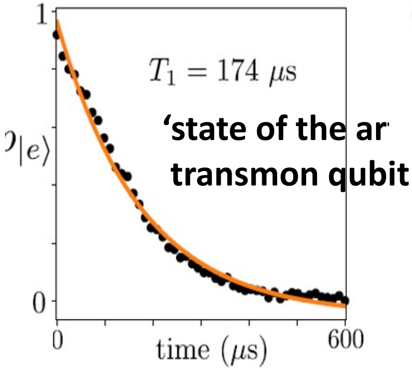
Lescanne, …. & Flurin, PRX10, 2020

Click !

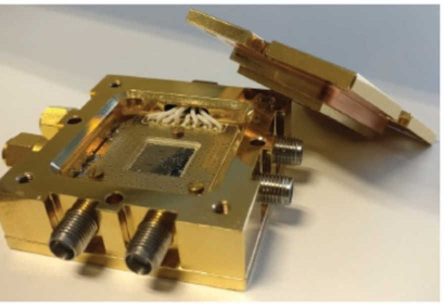
mixing with photon excites a transmon

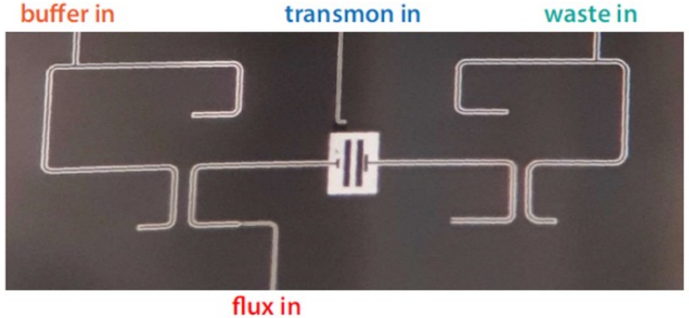
qubit readout : **click !**



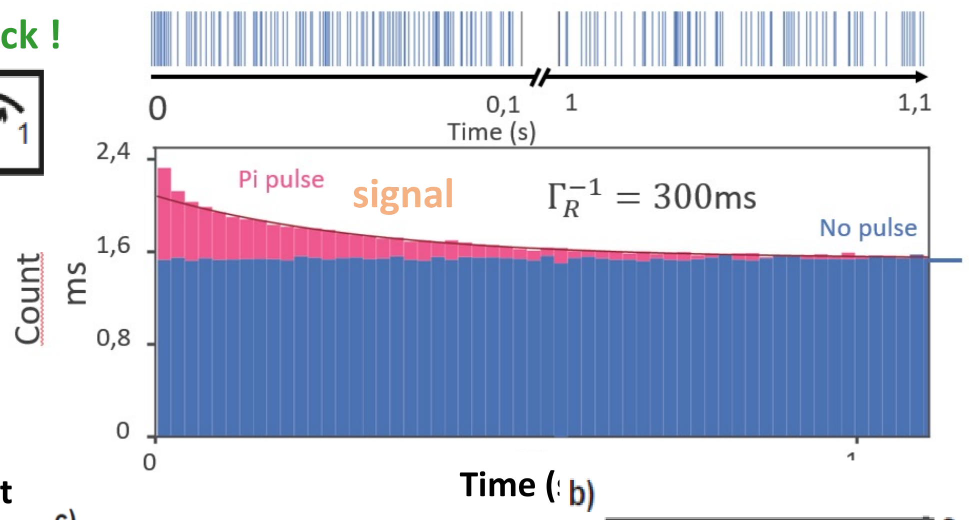


'state of the ar transmon qubit



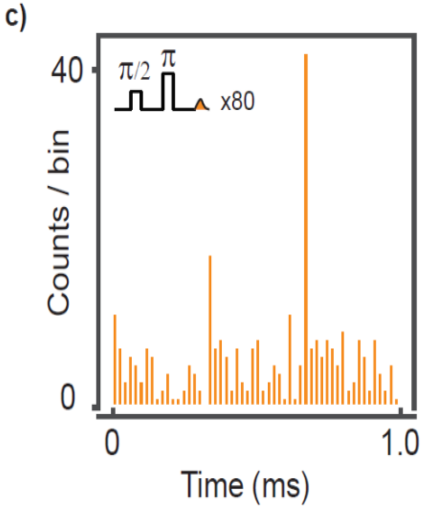


dark count rate:
70 counts/s
goal:
1 count/s

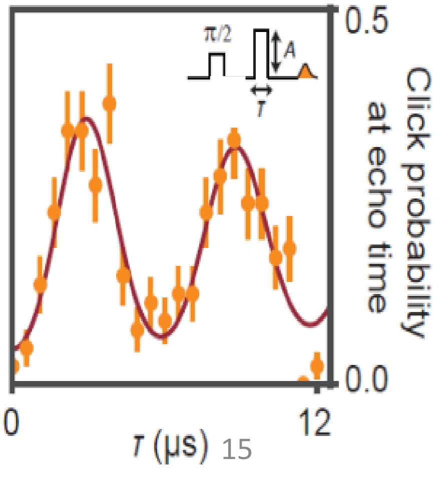


signal

$\Gamma_R^{-1} = 300\mathrm{ms}$

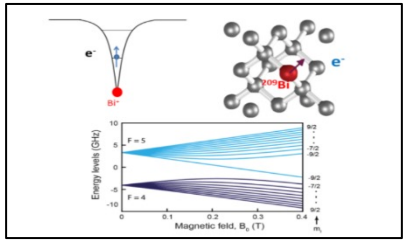


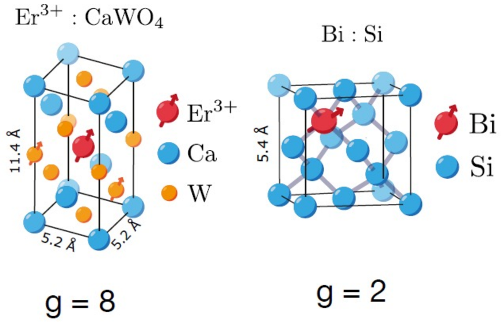
echo



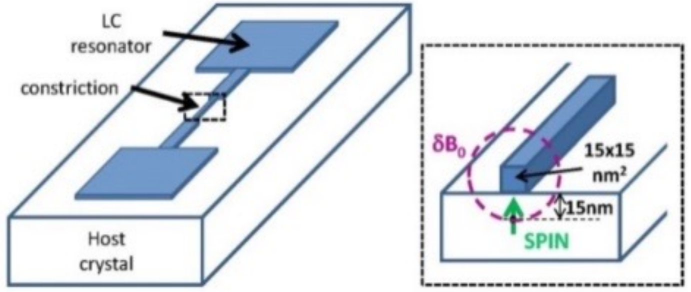
An hybrid route toward quantum information

Electro-nuclear spin systems

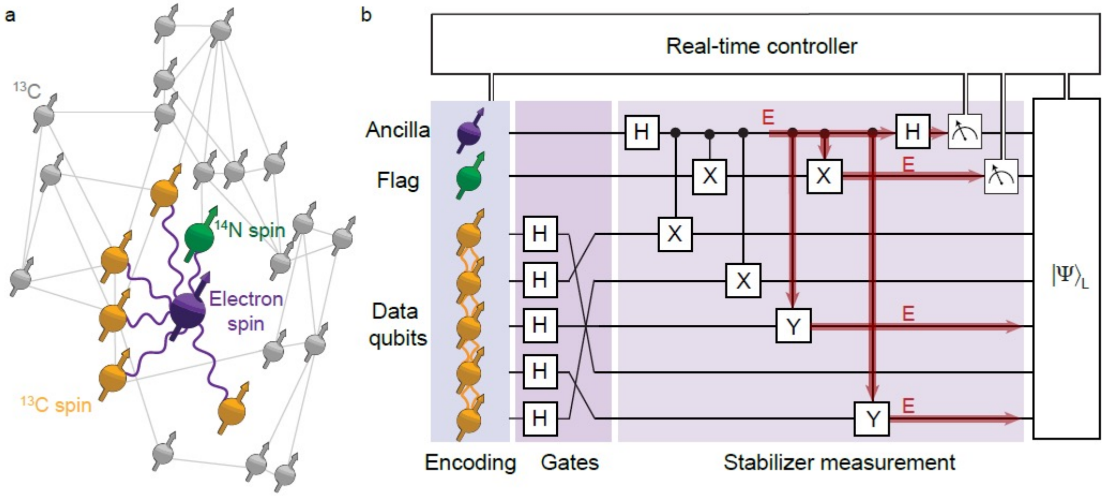




controlled coupling to environment



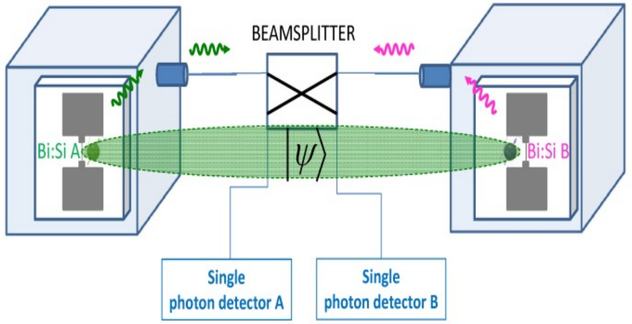
Proof of concept (TUD, 2021)



generating entanglement

↓

measurement based QC



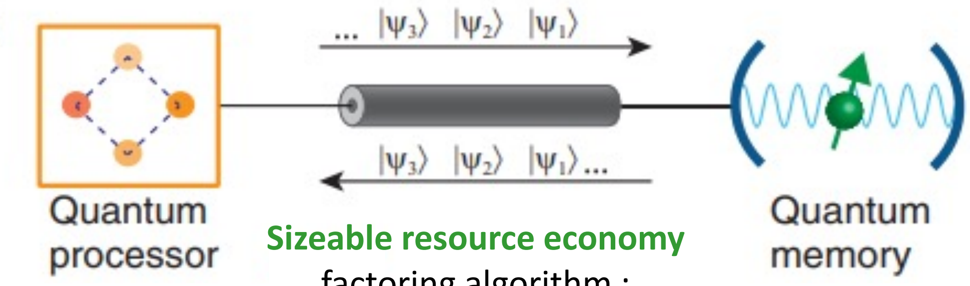
SMPDs

Work in progress

Another QC paradigm : a small processor coupled to a quantum memory

Architecture

small processor coupled to a **quantum memory**

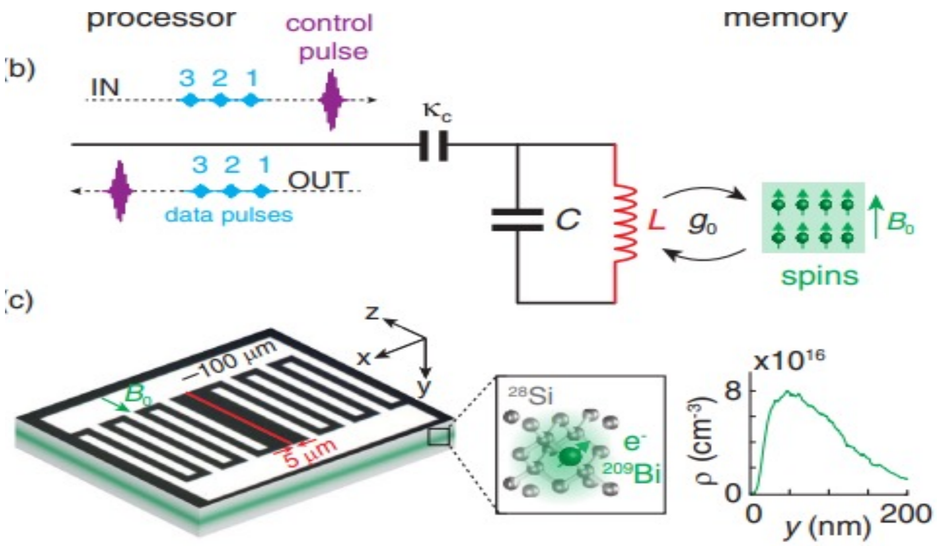


Sizeable resource economy

factoring algorithm :

E. Gouzien & N. Sangouard (IPhT) PRL 2021

Spin ensemble based quantum memories (Grèzes et al, PRL 2014)

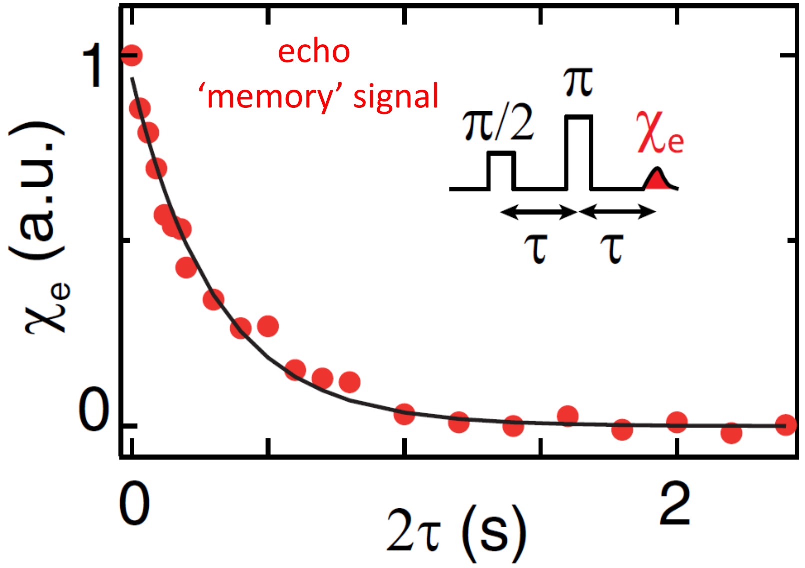


Bi spin ensemble coupled to inductor

Preliminary result : microwave pulse storage

Ranjan et al, PRL 125 (2020)

long 300ms memory time
but low efficiency



Ongoing memory work :

CEA-FZJ collaboration

QUANTUM ELECTRONICS GROUP

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