IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
This keynote presentation Th-KEY-01 was given at ISEC 2017.

Toward Robust Hybrid Quantum Bits

Quantum Information Processing:

secure communications

quantum computing

a potential game-changer in HPC…that faces roadblocks

Major players already in:

IBM intel Google Microsoft

Atos Bull

National and Eu QT Flagship initiatives

Daniel ESTEVE

QUANTUM ELECTRONICS GROUP

cea

SPEC

2015

QUANTUM ELECTRONICS GROUP

Whole Quantronics group and collaborators

Audrey Bienfait
Pierre Jamoneau
Camille Janvier
Kristinn Juliusson

Landry Bretheau (MIT)
Cécile Grèzes (Stanford)
Agustin Palacios (CEA)
Vivien Schmitt (UNSW)

Philipe Campagne
Sebastian Probst
Patrice Bertet
Daniel Esteve
Marcelo Goffman
Philippe Joyez
Hélène le Sueur
Hugues Pothier
Cristian Urbina
Denis Vion
Pief Orfila Pascal Sénat

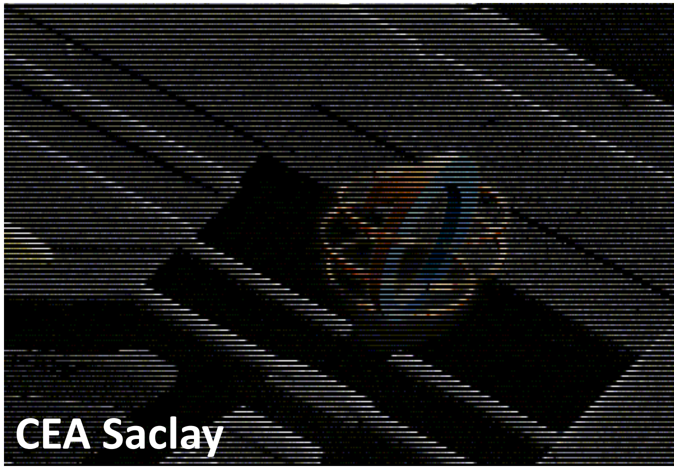
Yuimaru Kubo (OIST)
Michaël Stern (Bar Ilan)
Xin Zhou (Neel)

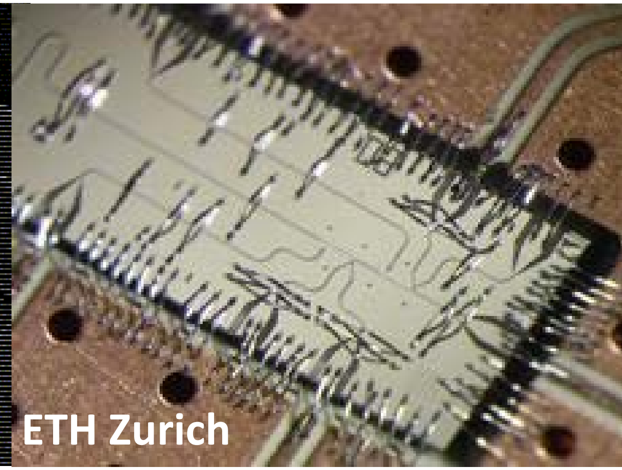
Coll.:
J. Morton (UCL)
Jarryd Pla (UNSW)
Brian Julsgaard (Aarhus)
Klaus Moelmer (Aarhus)

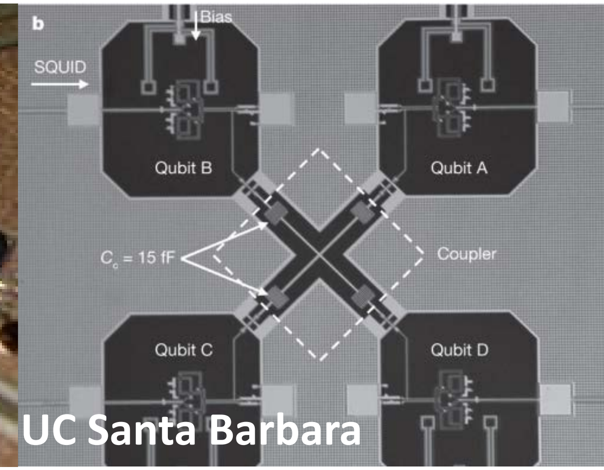
CG
YK

P. Bertet

Superconducting Josephson quantum bit circuits







1. Quantum behavior of Josephson junctions demonstrated in the 1980s
2. Since 1999 qubits with increasing coherence times.
3. **Potentially   scalable**

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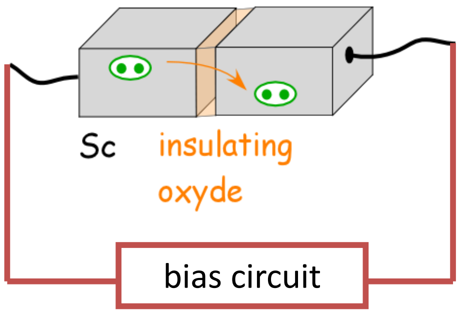
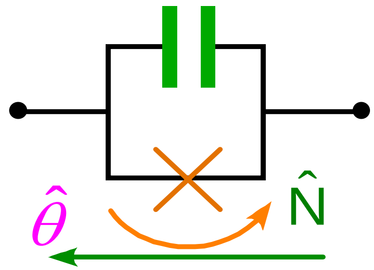
A quantum electrical component : the Josephson junction

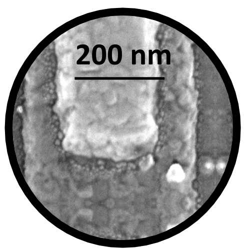




1 single degree of freedom:

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

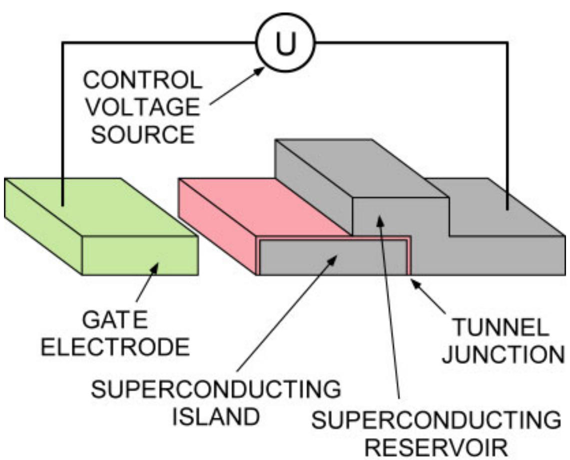
θ and N conjugated variables

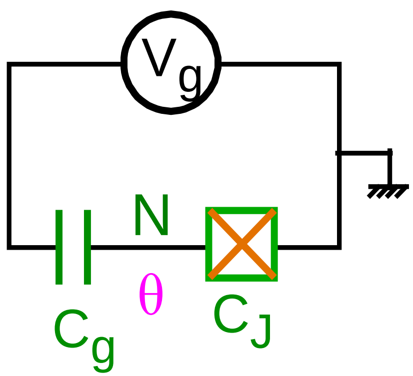


Al/AlOx/Al
tunnel junction

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

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)

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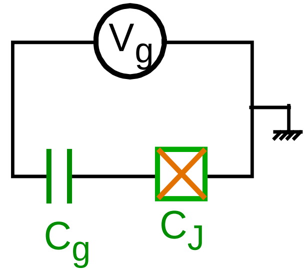
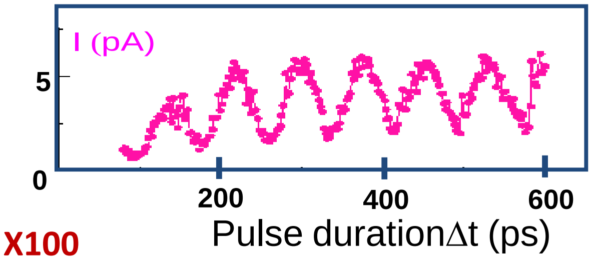
The Cooper Pair Box, 1999-2011 : from charge to phase

first electrical qubit : Cooper pair box
Nakamura, Pashkin &Tsai (NEC, 1999)

$$E_J \ll E_C = \frac{(2e)^2}{2C_\Sigma}$$

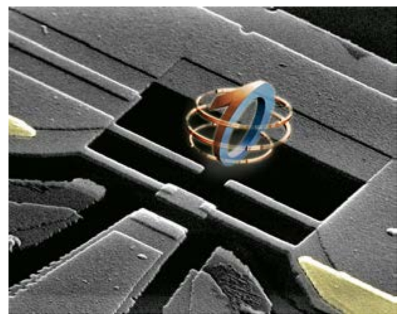


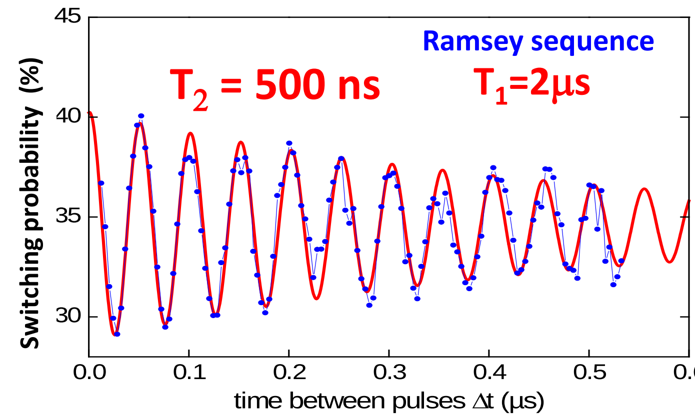


X100

First operational qubit : quantronium, single-shot readout, protected against dephasing
Vion et al., (Quantronics, 2002)

$$E_J \approx E_C = \frac{(2e)^2}{2C_\Sigma}$$



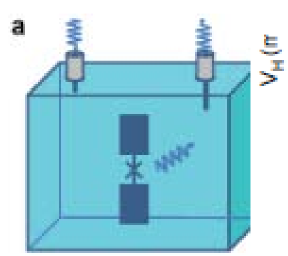


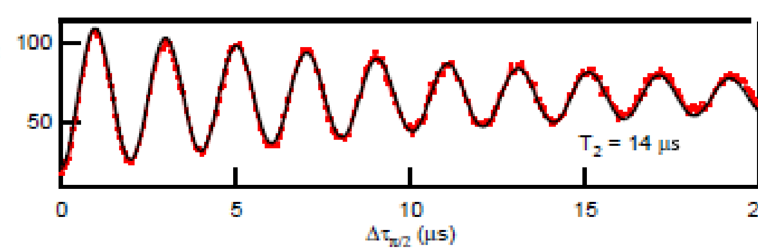
The modern version of the Cooper pair box: **circuit QED**

X100

A Cooper pair box in the phase regime embedded in a microwave cavity (2D, 3D)
Schoelkopf lab., Yale
Wallraff et al., Nature 2004
Koch et al., PRB 2007
Paik et al., *PRL* **107**,

$$E_J \gg E_C = \frac{(2e)^2}{2C_\Sigma}$$





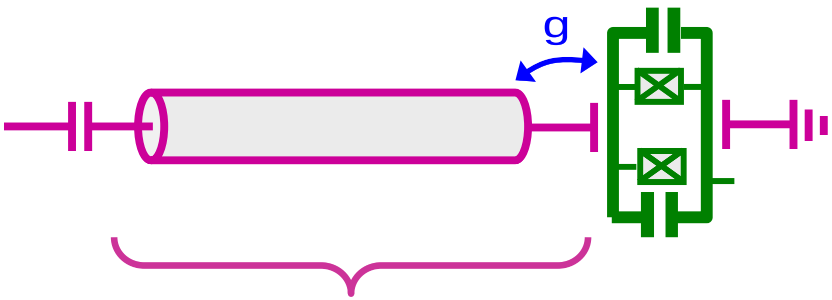
Energy levels insensitive to charge noise
Microwave readout

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

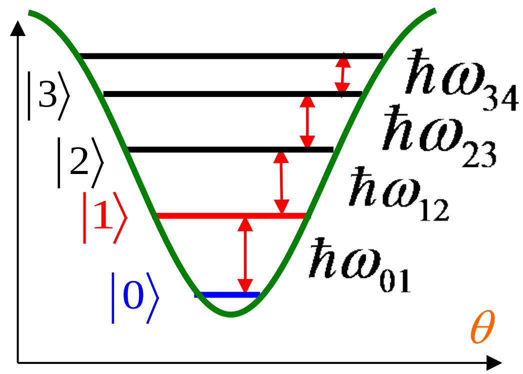
The basics of circuit QED

Cooper pair box
in the phase regime

$E_C \ll E_J$



λ/2 resonator
bare resonance frequency $= \nu_r^0$

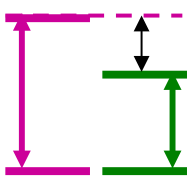


a non linear resonator
at the **single** photon level

$$H = H_{HO} + K\hat{n}^2$$

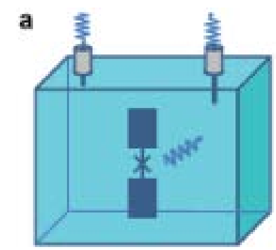
Kerr constant

The dispersive regime of circuit QED

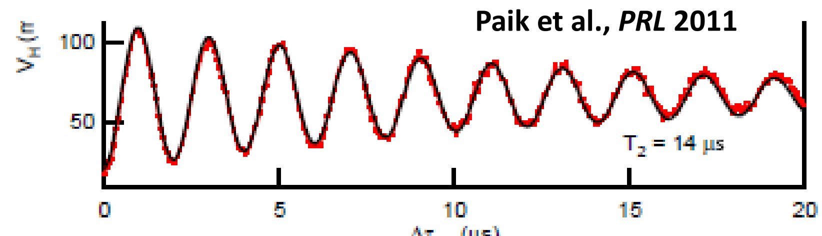


$$\hat{H}_{eff} = -\frac{\hbar}{2}(\omega_{01} + \chi)\hat{\sigma}_z + \hbar(\omega_r^0 - \chi\hat{\sigma}_z)\hat{a}^+\hat{a}$$

Qubit controlled cavity pull
& Stark shift



Paik et al., *PRL* 2011



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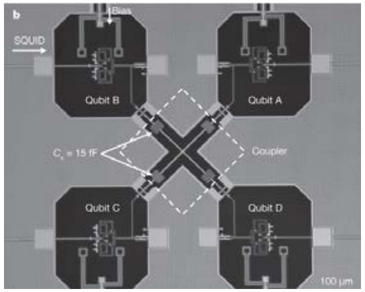
Running quantum algorithms on elementary processors

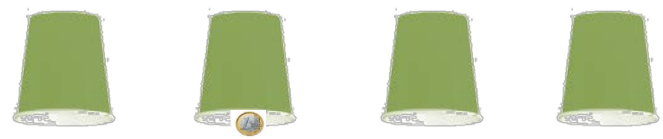
Martinis Lab, UC Santa Barbara
Yamamoto et.al. , PRB 82 2010 , Nat Phys 2012

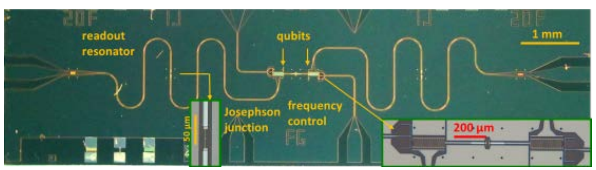


Shor factorization algorithm (of 15)

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

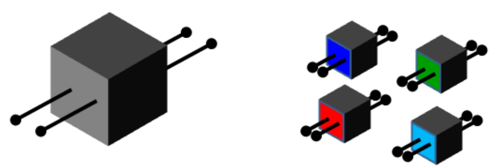
the Grover search algorithm



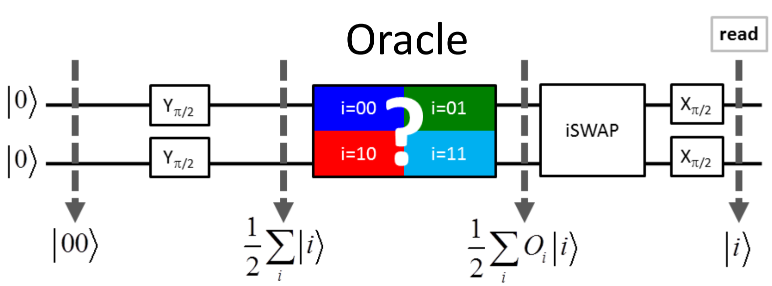


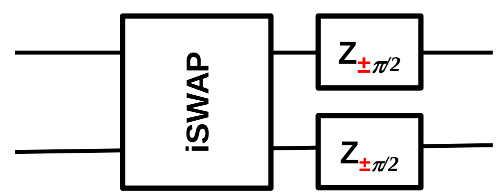
Classical search: O(N) steps Quantum search : O(√N) steps

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



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





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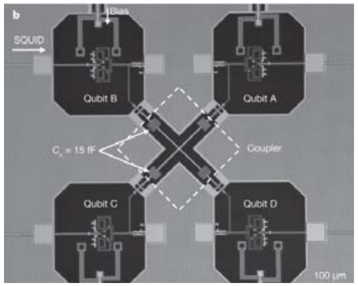

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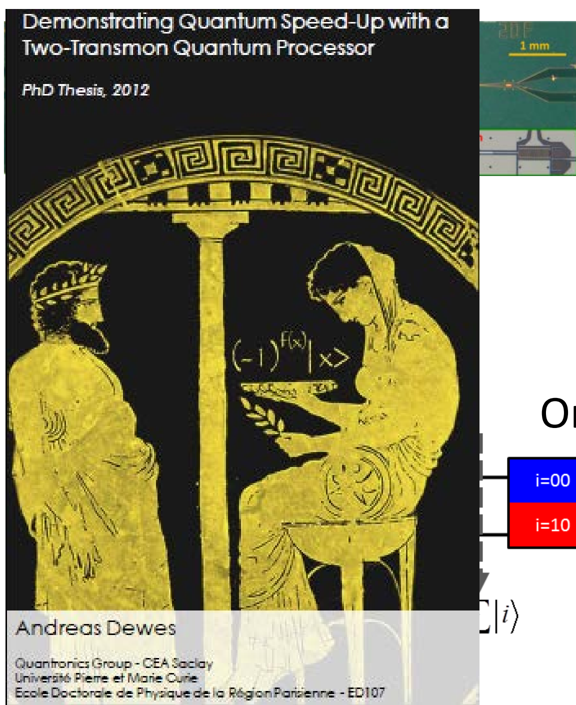

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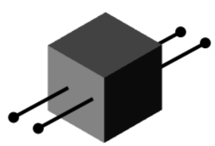

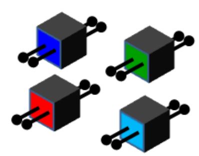

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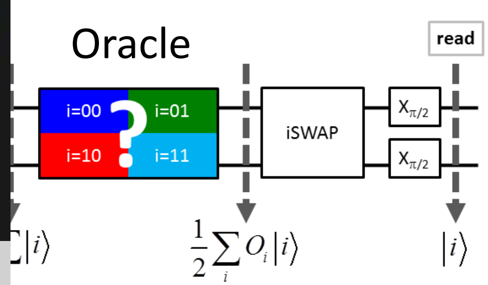

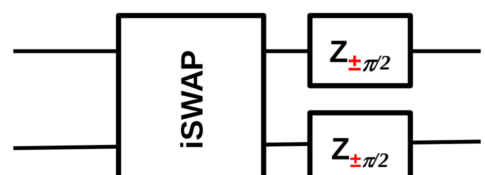

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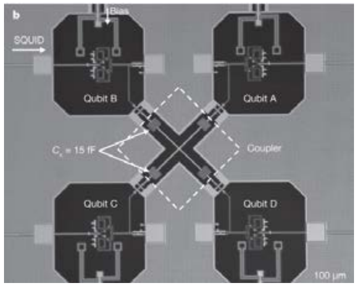

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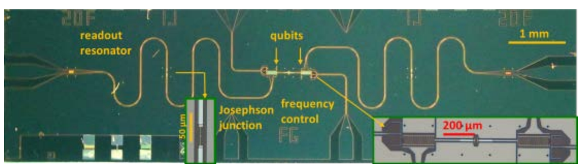

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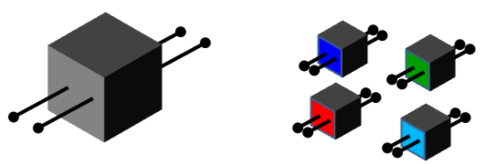
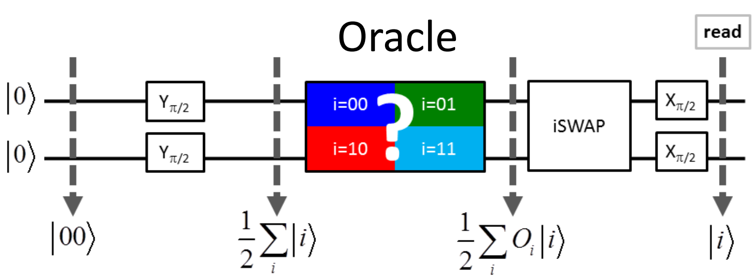
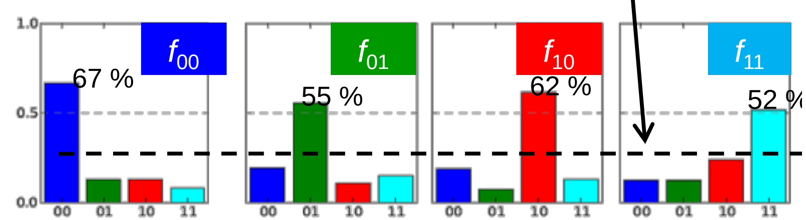


$i \in \{00 \quad 01 \quad 10 \quad 11\}$

classical query & check

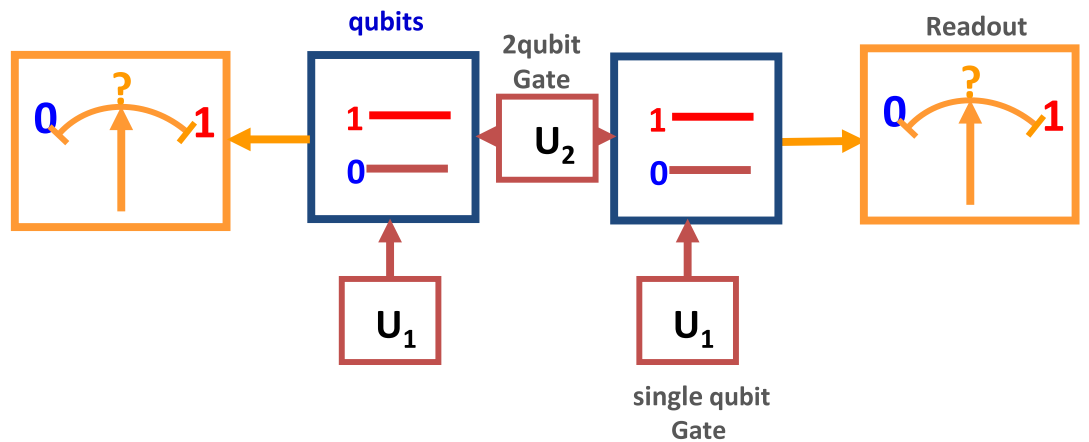




Dewes et al., rapid comm PRB 85, 2012

'quantum speed-up'

Scalability challenges



Daunting scalability challenges:

- Qubit coherence in a complex architecture
- Gate accuracy, cross-talk,…
- Readout : multiplexing, fidelity, QND character
- **Quantum Error Correction** **(beware: no-copy !)**

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The overall lanscape of SC quantum processors, the scalability challenge

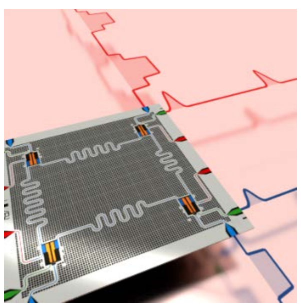
GATE BASED PROCESSORS

Elementary processors

Better coherence:
T_2: 10-30 μs

Not much progress on algorithms,

Protocols :
teleportation,
quantum feedback
Digital simulation



ETHZ Salathé et al. PRX 5, 2015

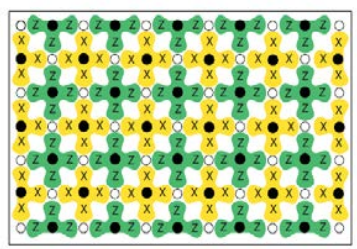
Quantum 'supremacy' with 50 qubits within reach ? (Google, IBM, …)

Quantum Error problem addressed

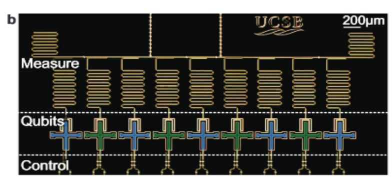
fault-tolerant architectures

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

Data ○ ● **measurement**



Keep track of errors
Huge resource overhead
1 logical qubit : >> 1000 physical qubits!



1D test circuits
for quantum error correction :
UCSB-Google Kelly et al., PRA94

more robust qubits

Dissipation engineering

Yale, INRIA-ENS
Mirrahimi et al. NJP 16, 2014

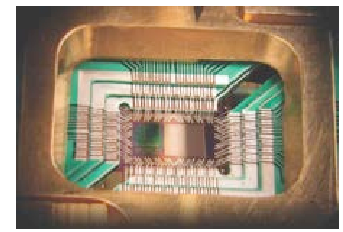
Schrödinger cat states in high Q resonators pumped and connected to low Q

Nuclear spins

better coherence

QUANTUM ASSISTED ANNEALING

The D-Wave route
The Quantum Computing Company™



D-Wave machines solve non-trivial problems

BUT

full QC power not expected

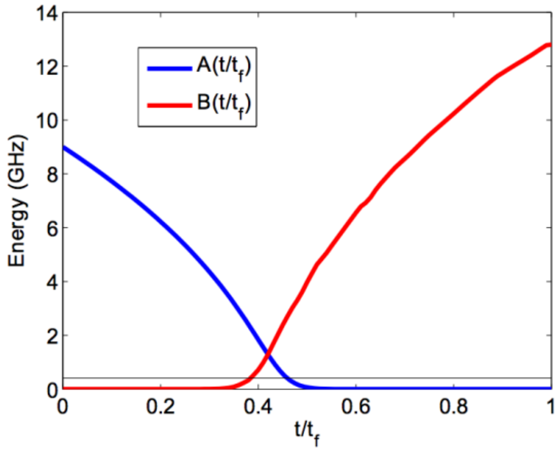
(debated issue)

Q C by finding the ground state of a complex Hamiltonian

Ising spin-glass Hamiltonian $$H^z(t) = \sum_{ij} -J_{ij}\sigma_i^z \sigma_j^z$$

Find ground state starting from aligned spins

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



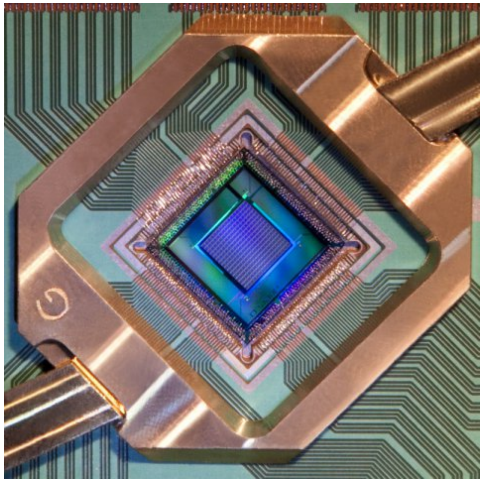
Pros and cons:

Evolution simple
Suited to optimization
Problem encoding not easy

role of decoherence and
Thermal excitation not understood

overcoming standard computers:

N= 4000-8000 qubits

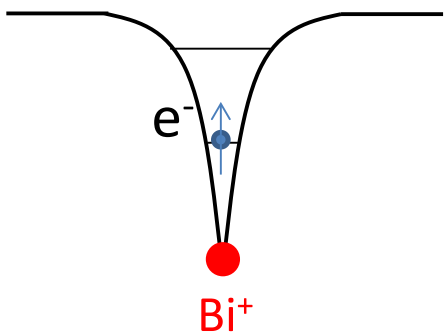


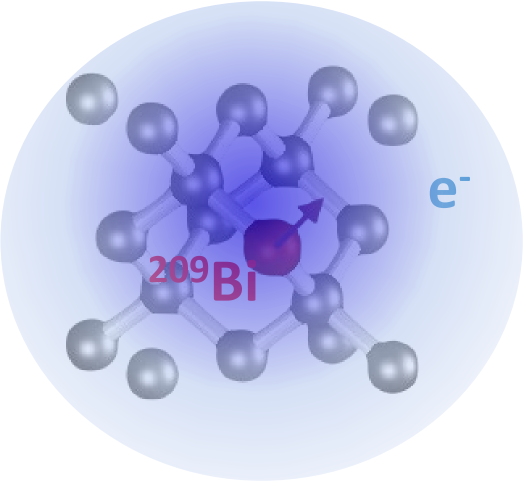
State of the art (D-Wave machine):

N=2000

The Spins: bismuth donors in silicon

Impurity
spins in solids





An electro-nuclear spin system

$$\frac{H}{\hbar} = A\boldsymbol{I}\cdot\boldsymbol{S} + \boldsymbol{B}_0\cdot(-\gamma_e\boldsymbol{S} - \gamma_n\boldsymbol{I})$$

HYPERFINE **ZEEMAN EFFECT**

- Electronic spin = 1/2
- Nuclear spin I=9/2

20 electro-nuclear states

- Large hyperfine coupling $\frac{A}{2\pi} = 1.4754\text{GHz}$

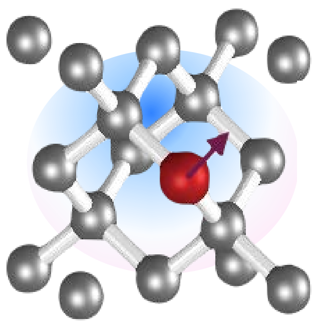
The nuclear spin route

A chain of coupled quantum systems

Nuclear spins Electronic spins low mode volume high Q resonators Gates,...

hyperfine coupling

Si : Bi



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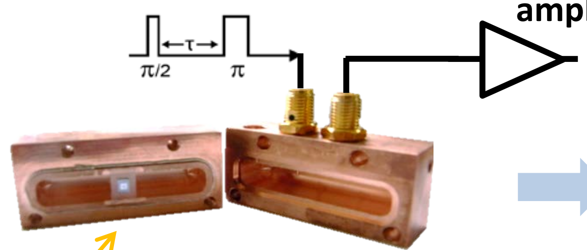
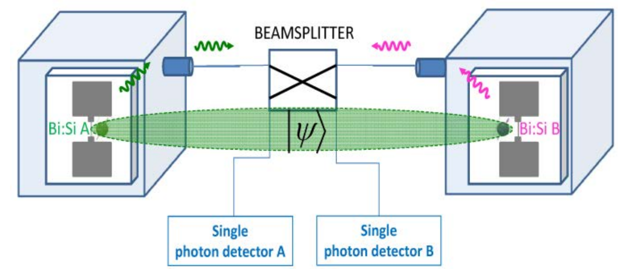


Quantum limited amplifier

nanoresonator



Intrication par la mesure

Highly coherent quantum system

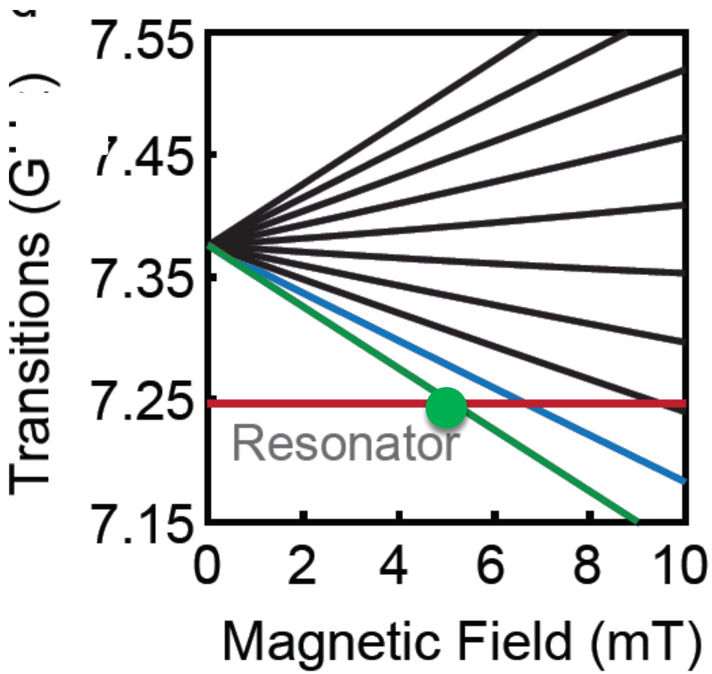
T_2 el-nucl: **-> 3 s**

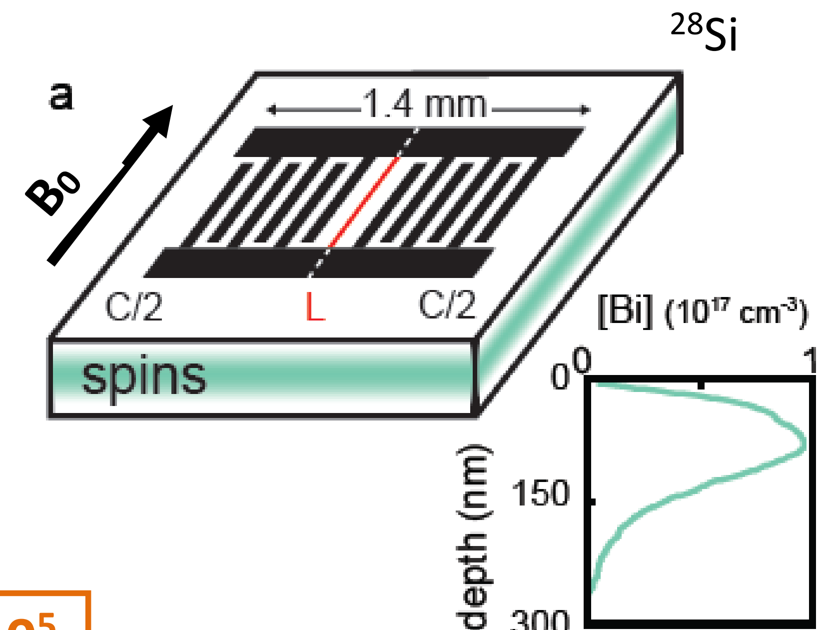
T_2 nucléaire **-> 6 h** (rare earth)

Preliminary results ?

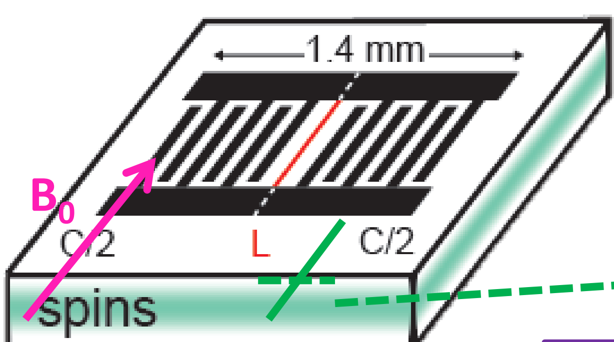
Coupling spins to a low mode volume resonator

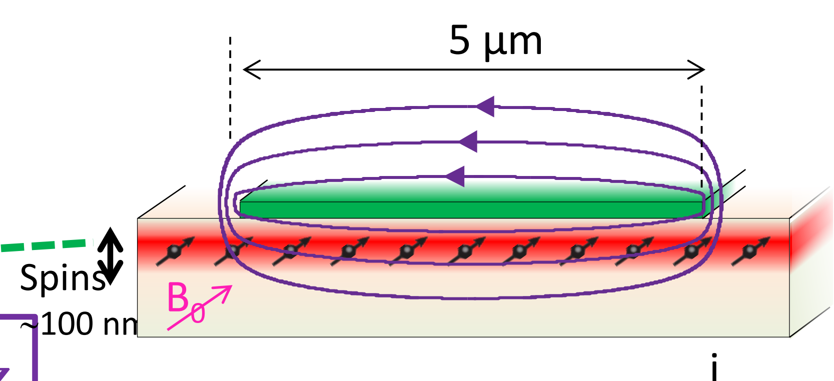
10 allowed ESR-like transitions @ low B_0





$Q = 3\ 10^5$

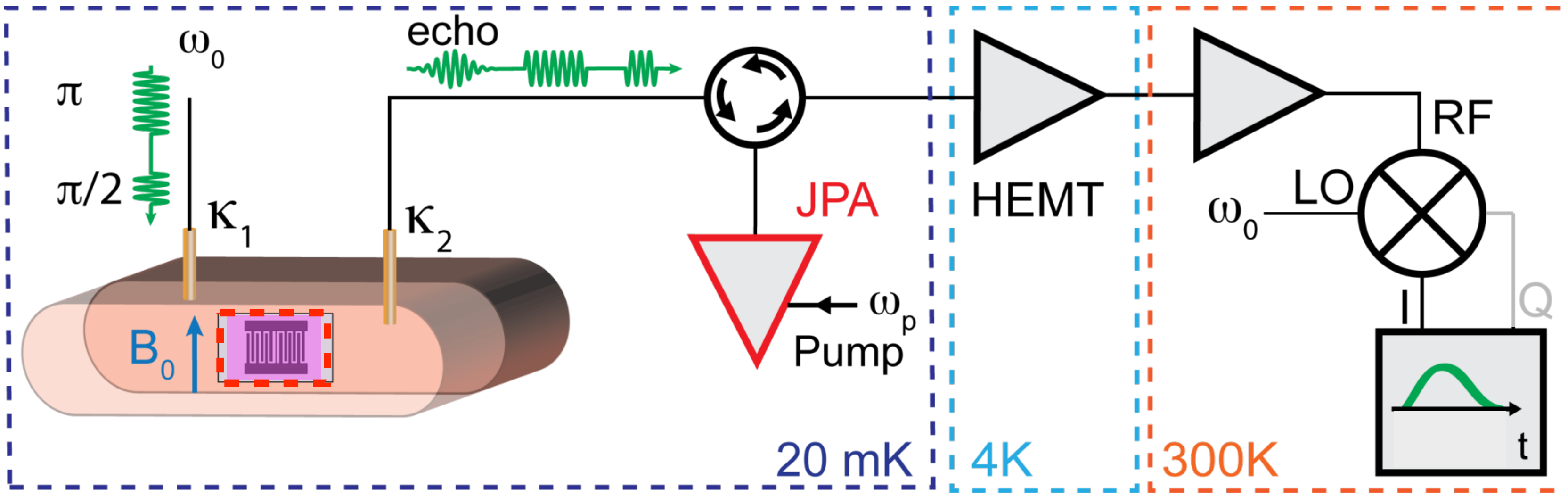


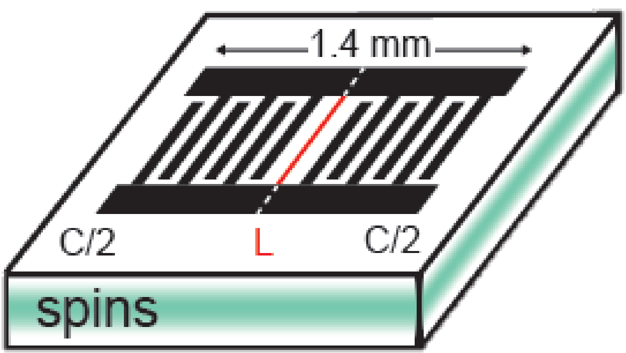


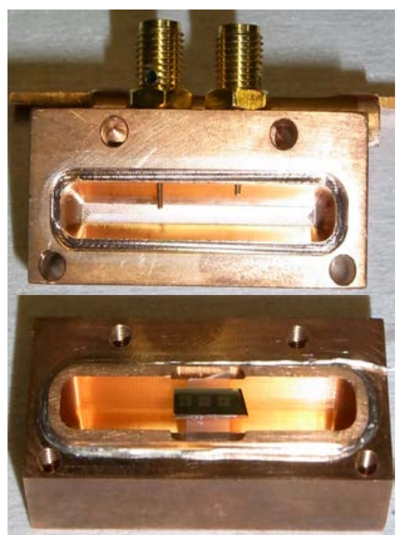
Spin-resonator coupling

$$\frac{g}{2\pi} = 55Hz$$

Detecting spins at the quantum limit



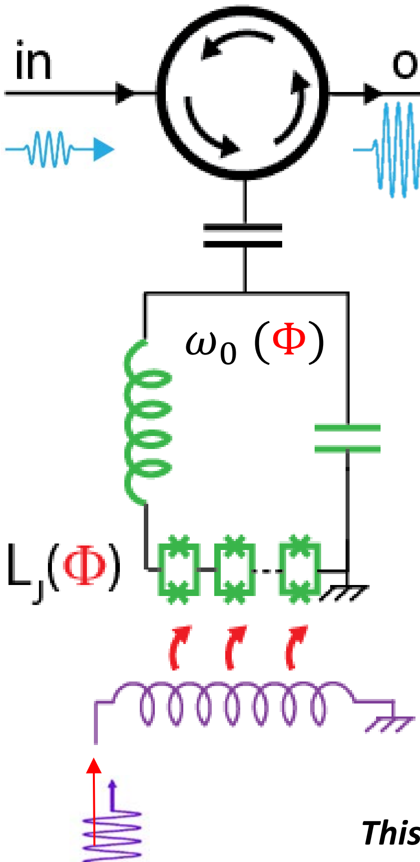




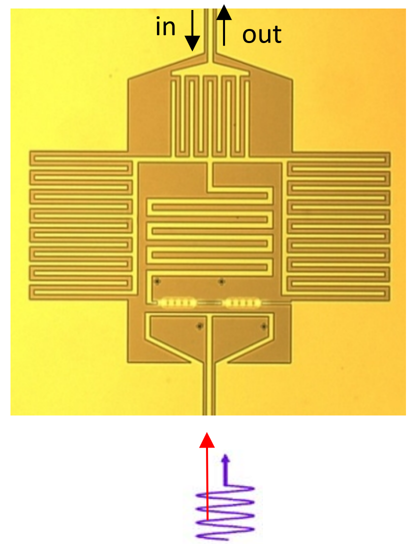
2D lumped element
Superconducting Al
resonator

$\omega_0/2\pi$ = 7.24 GHz, Q = 3 10^5

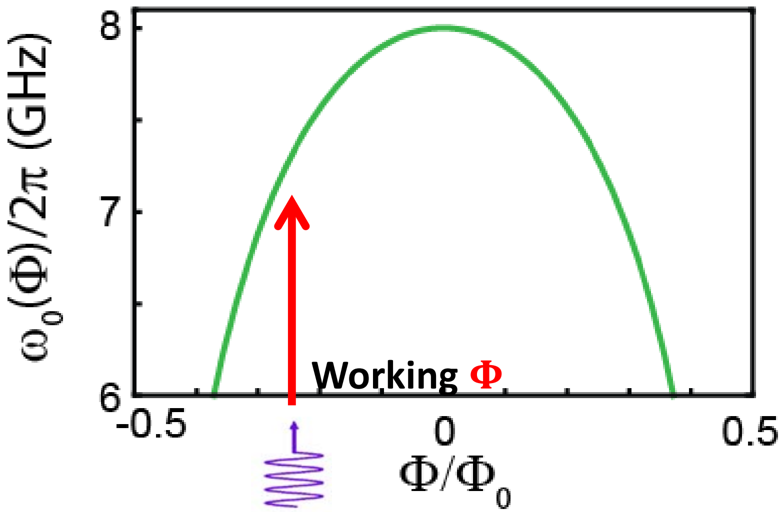
Josephson Parametric Amplifier (non degenerate mode)

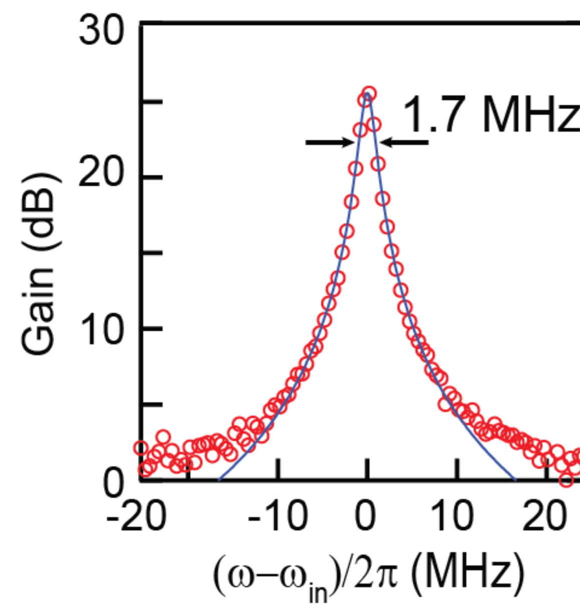


DC bias
AC pump tone
$\omega_p \approx 2\omega_0$



X. Zhou et al., PRB (2014)

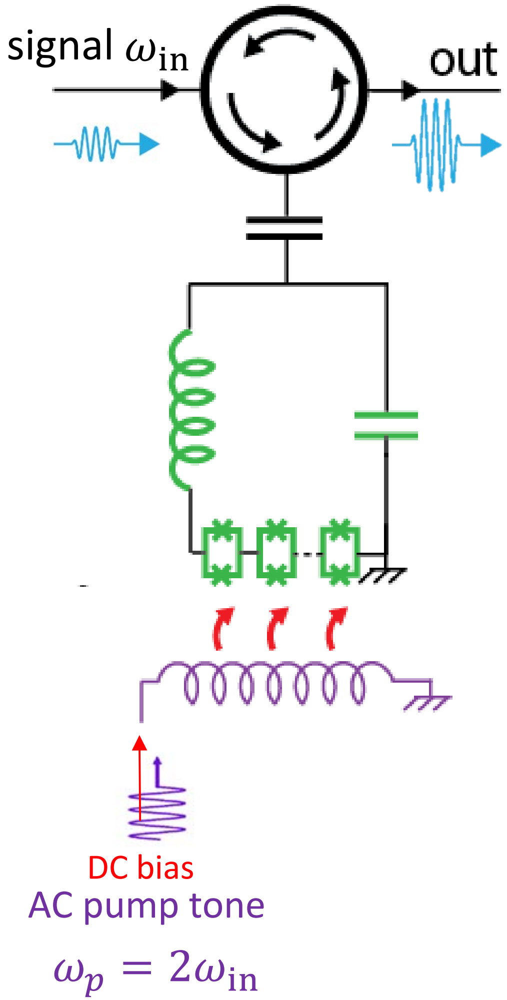


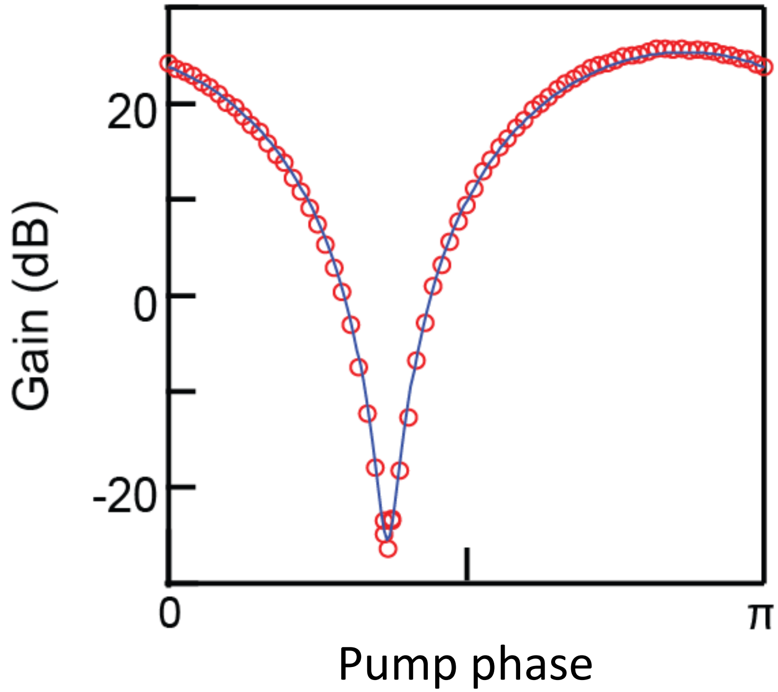


This work: X. Zhou et al., PRB (2014)
M. Castellanos-Beltran et al., APL (2007)
C. Eichler et al., PRL (2010)
N. Bergeal et al., Nature (2010)

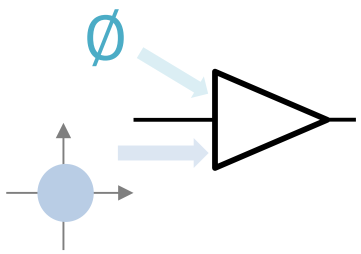
Wideband TWPA nowadays !
Macklin et al., Science 350, 307 (2015)

JPA in degenerate mode





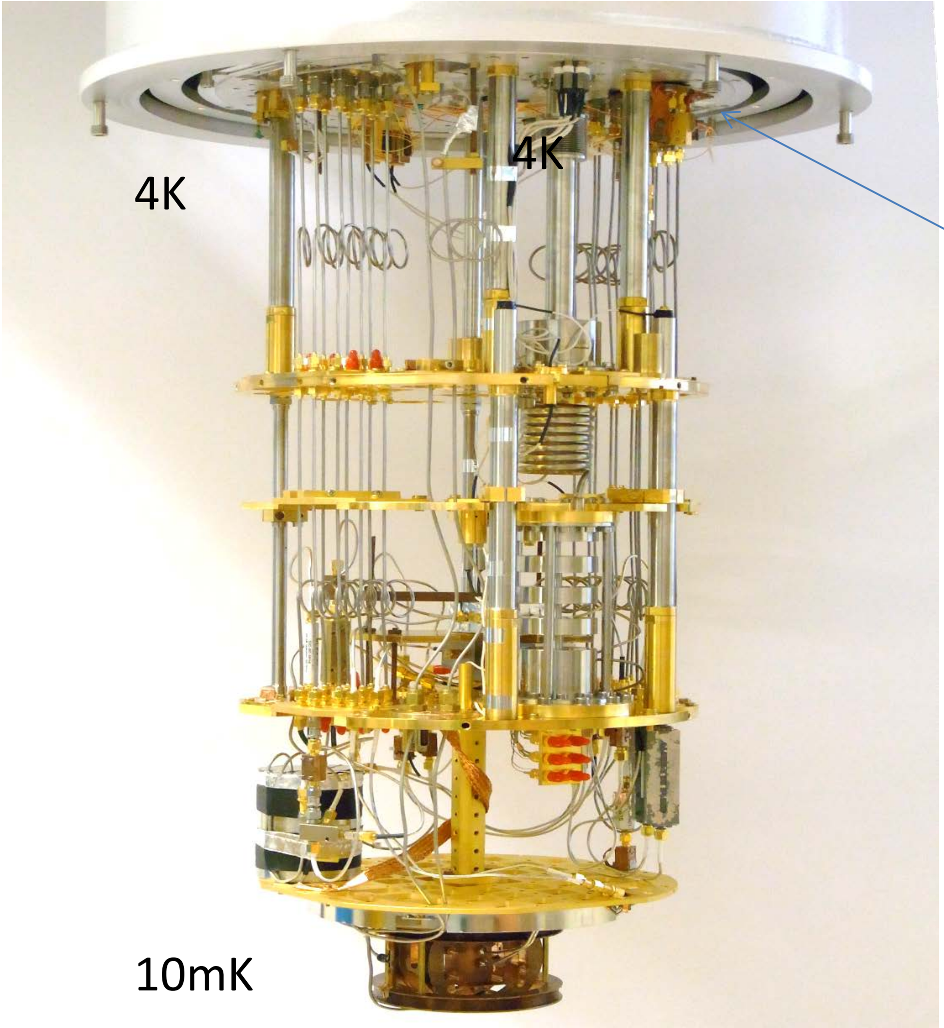
Noiseless amplifier



X. Zhou et al., PRB (2014)

Quantum limited ESR spectrometer

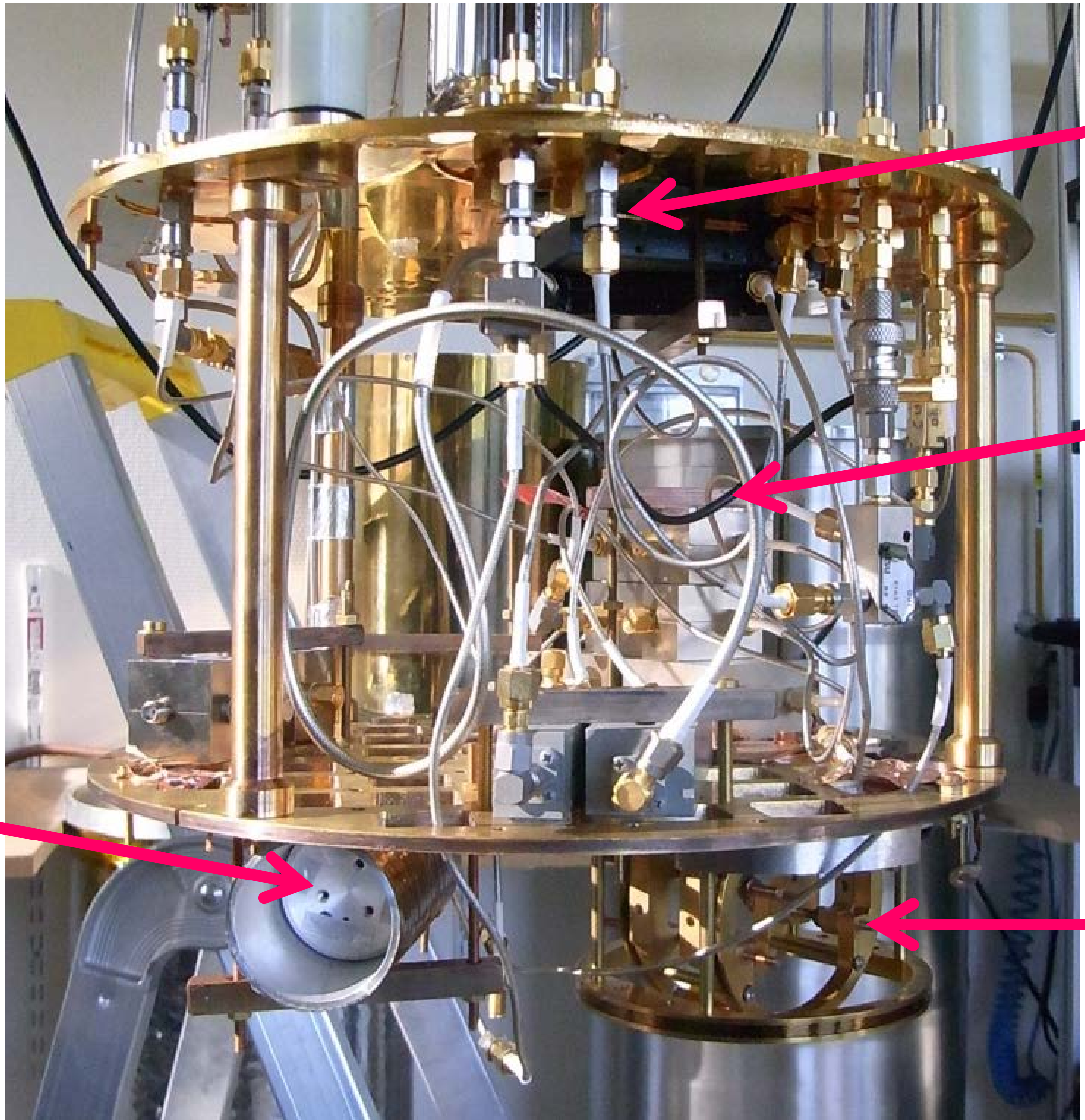
80 cm



4K HEMT amplifiers

Quantum limited ESR spectrometer

10mK plate



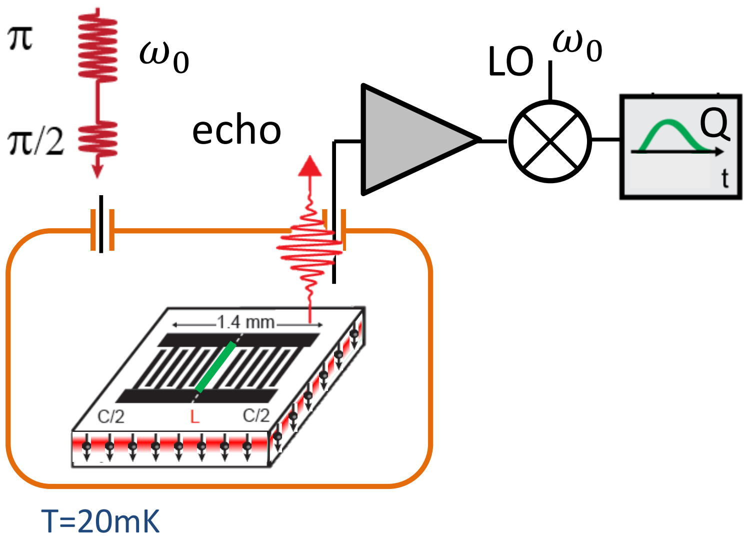
Attenuators

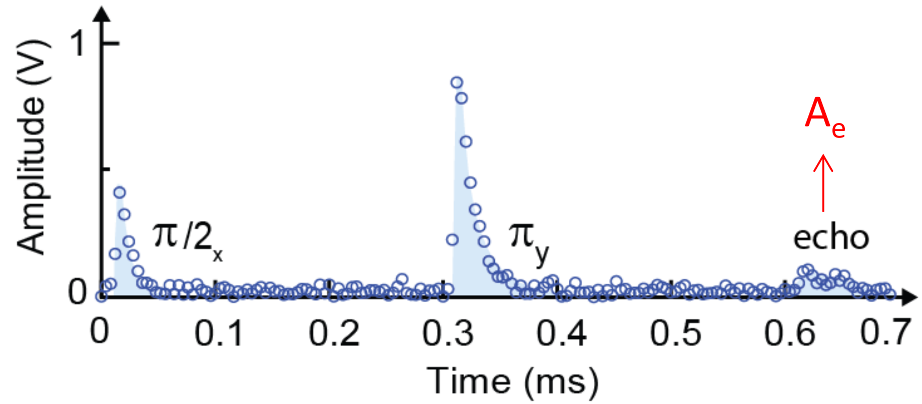
Circulators

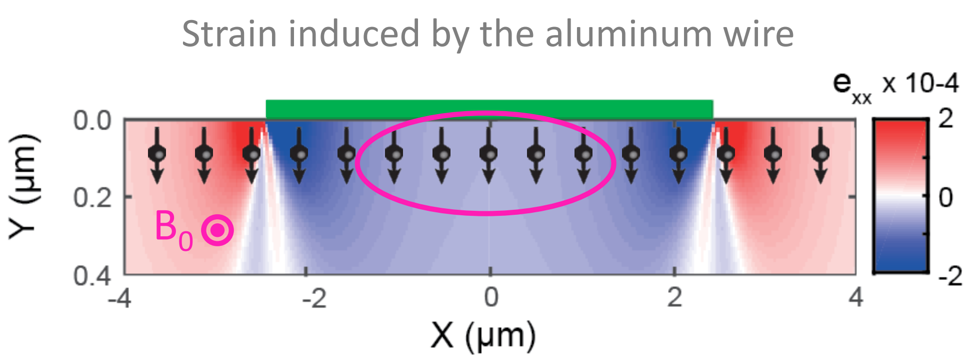
JPA

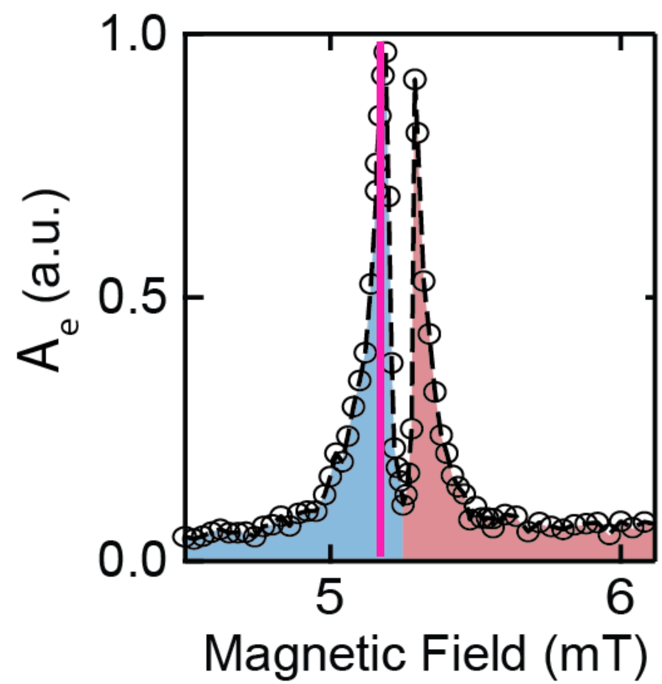
2-axis coil w. sample

Hahn-echo Detected ESR Spectroscopy



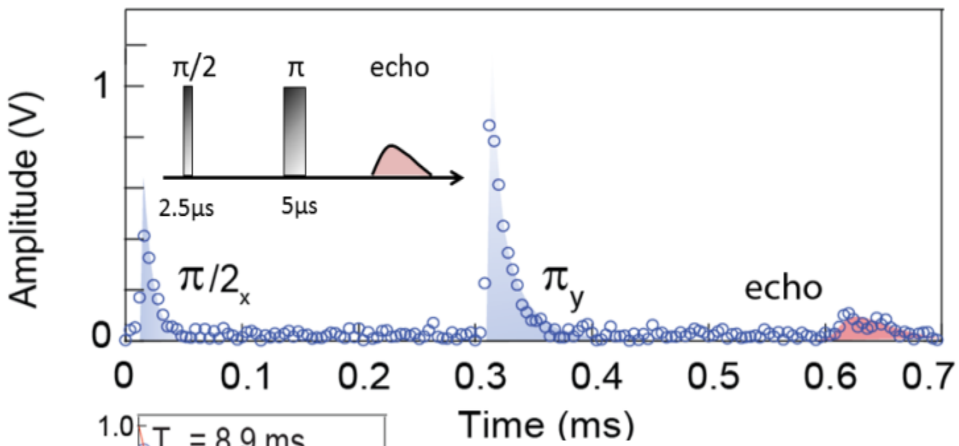


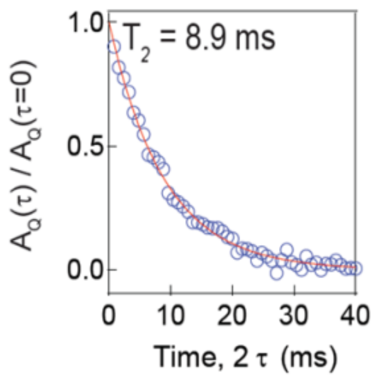




A. Bienfait et al., Nature Nanotechnology 11, 253–257 (2016)

Spectrometer single-shot sensitivity





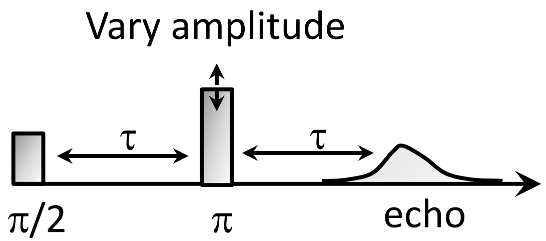
Estimated sensitivity per echo :

$1.7\ 10^3$ spins

Quantitative agreement with expected sensitivity

A. Bienfait et al., Nature Nanotechnology 11, 253–257 (2016)

Rabi oscillations : g calibration

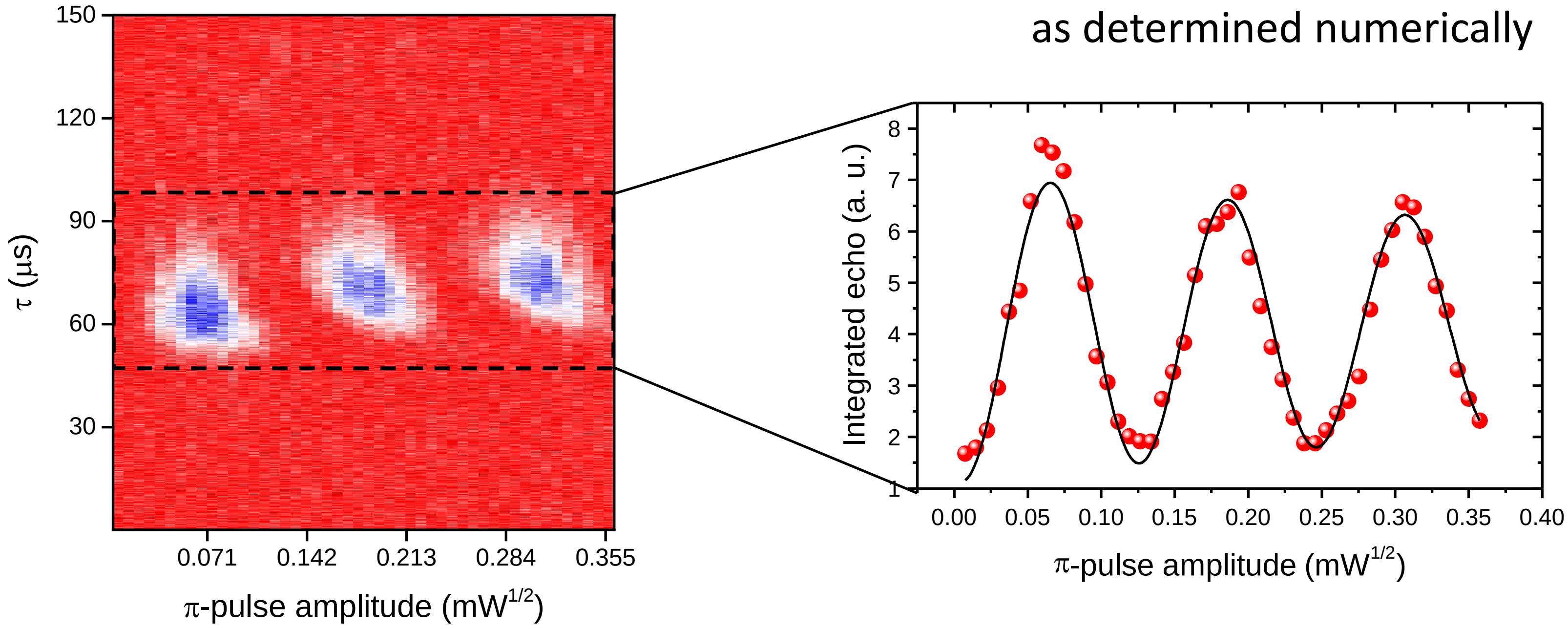


$$\Omega_R = 2\sqrt{\bar{n}}g$$

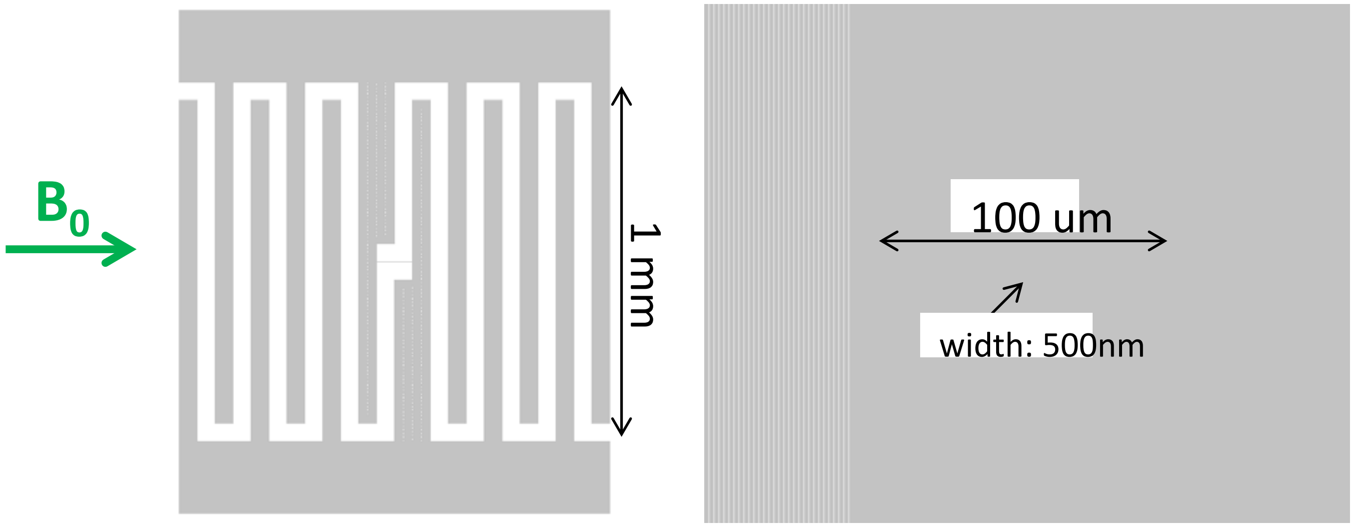
with $\bar{n} = 4\frac{\kappa_1}{\kappa^2}P_{in}$

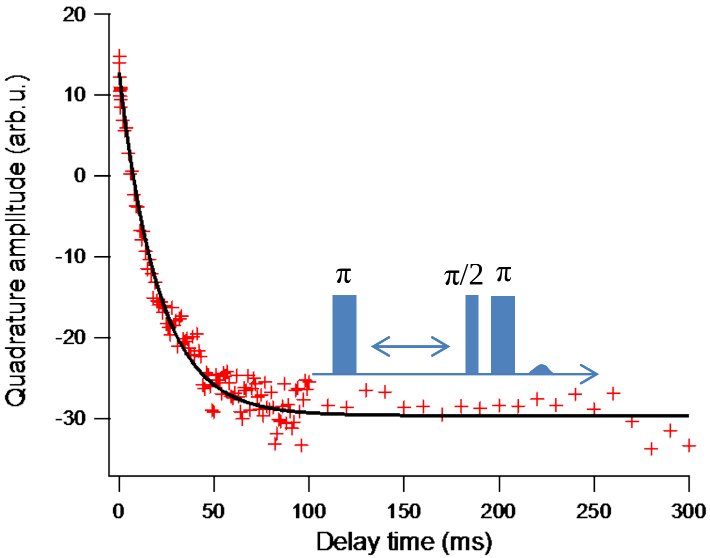
$$\frac{g}{2\pi} = 50 \pm 10\text{Hz}$$

as determined numerically



Increasing sensitivity with narrower wire





T_1 = 21 ms

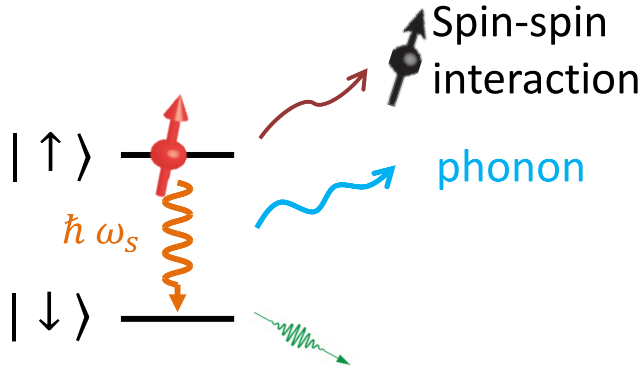
$g/2\pi$ = 440 Hz

N_{min} = 300 spins

Sensitivity : 65 spins $/\sqrt{Hz}$

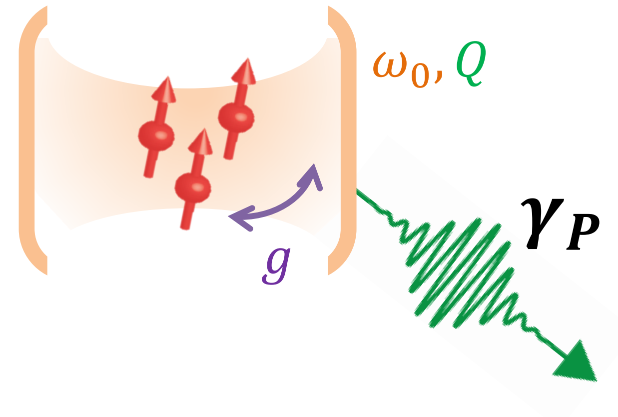
S. Probst et al., in preparation (2017)

Controlling relaxation: by spontaneous emission



Photon in free space
$\approx$ 10000 years !

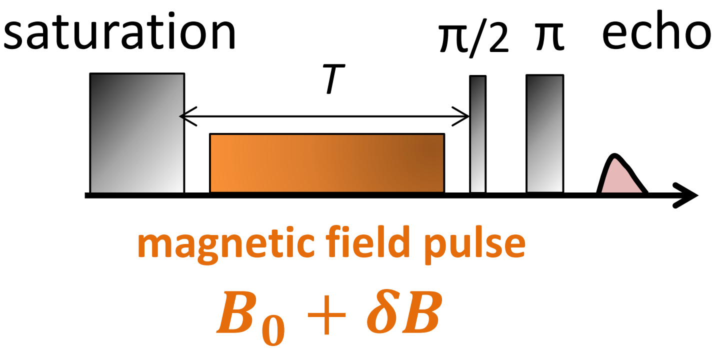
PURCELL
1946



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

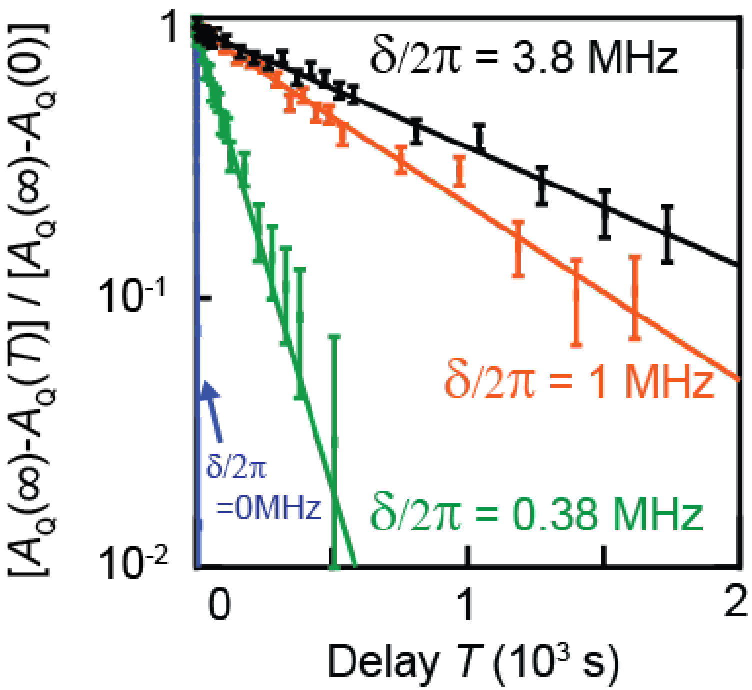
- For $T_1 \approx \gamma_P^{-1}$: need small mode volume, high Q cavity
- Allows to shorten T_1 on-demand : accelerate spin thermalization

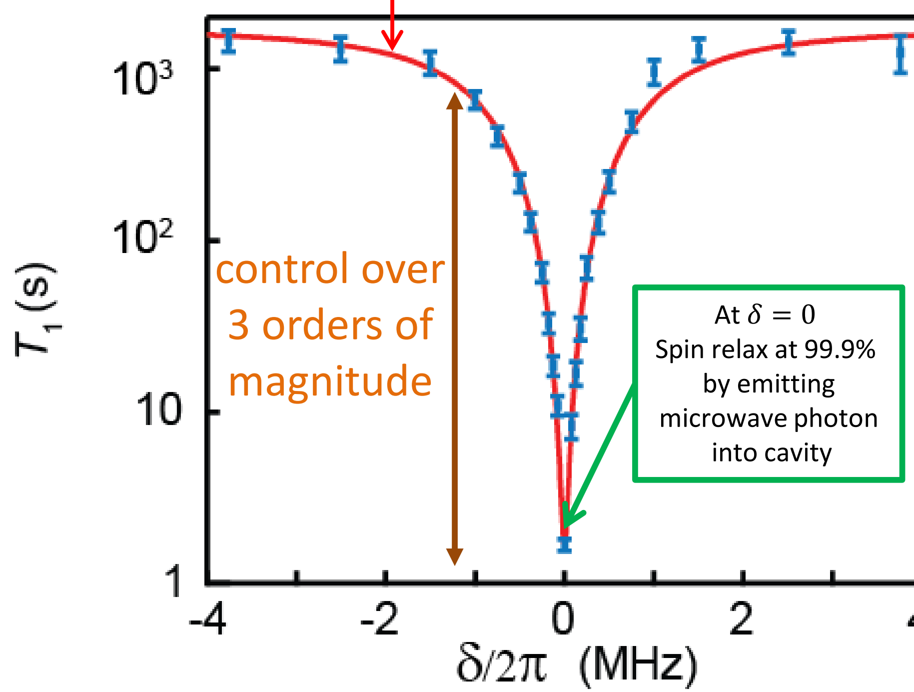
Spin relaxation control by δ-tuning



Spins detuned during T from cavity by $\delta = \delta B \left|\frac{\partial \omega_s}{\partial B}\right|$

$$\gamma_P = \frac{\gamma_P(\omega_s = \omega_0)}{1 + 4Q^2\left[\frac{\delta}{\omega_0}\right]^2}$$

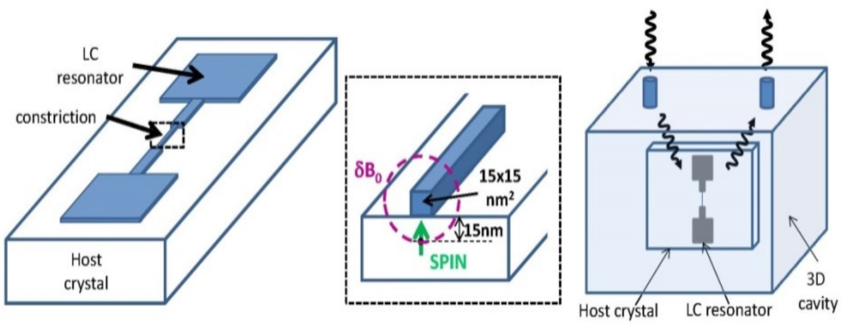




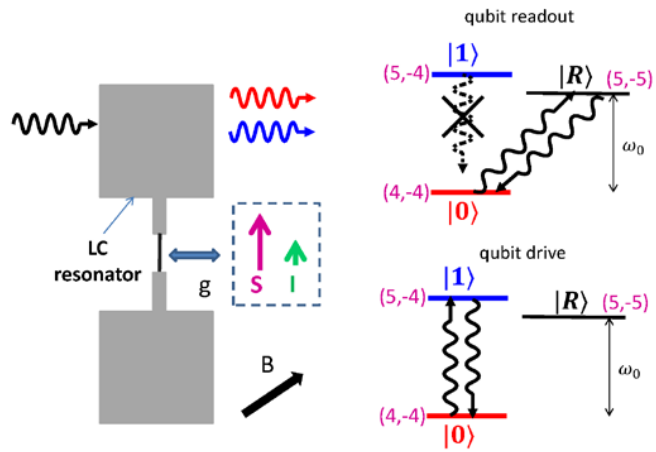
A. Bienfait et al., Nature 531, 74 (2016)

The nuclear spin route : next elements

Increasing the spin-resonator coupling

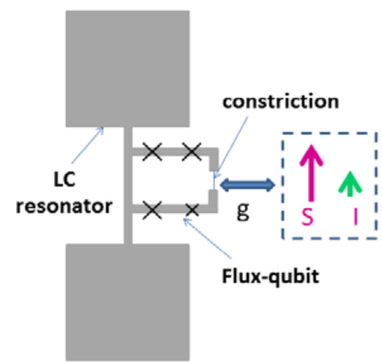


Nuclear spin readout

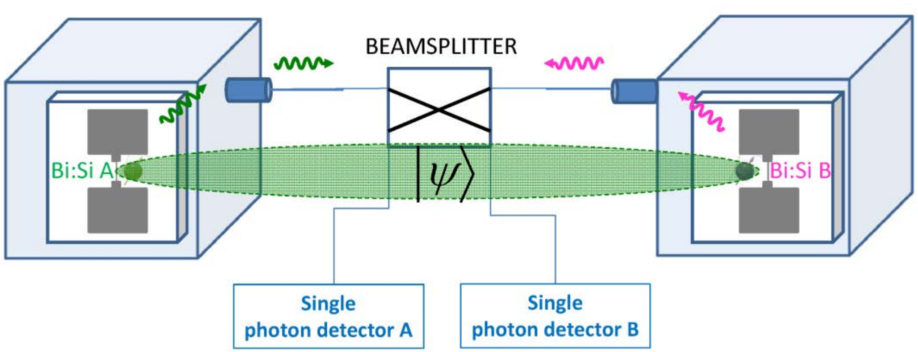


Achieving
strong coupling

Coupling scales as zero-point current fluctuations



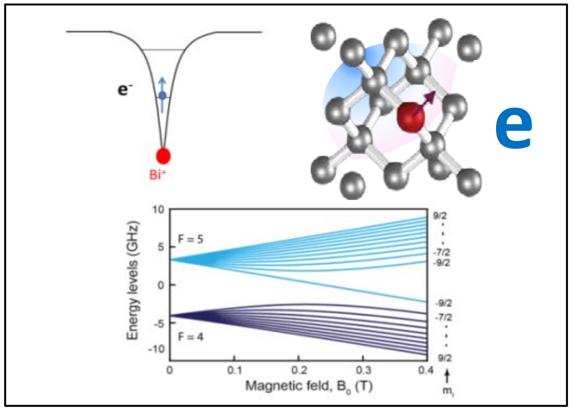
Entangling qubits for making a two qubit gate

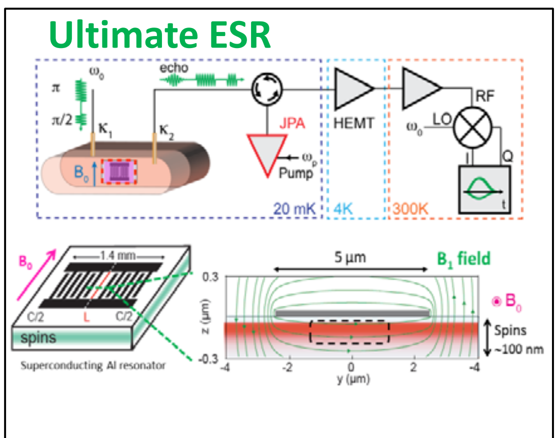


IEEE/CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 41, July 2017.
This keynote presentation Th-KEY-01 was given at ISEC 2017.

QIP research based on spins

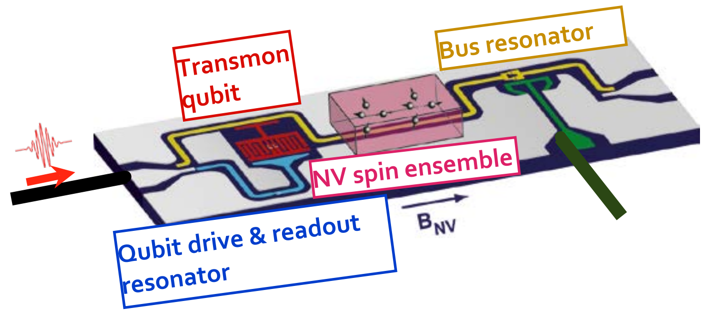
Spin project

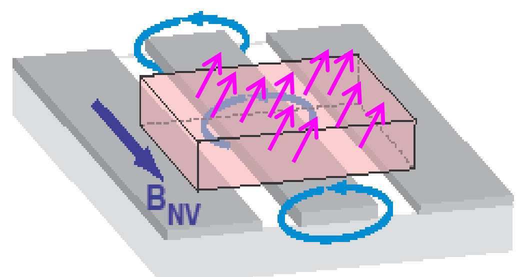




Huge sensitivity gain:
Bienfait et al., Nature Nano 11, 253 (2016)
Single spin sensitivity within reach

A multimode hybrid memory for sc qubits



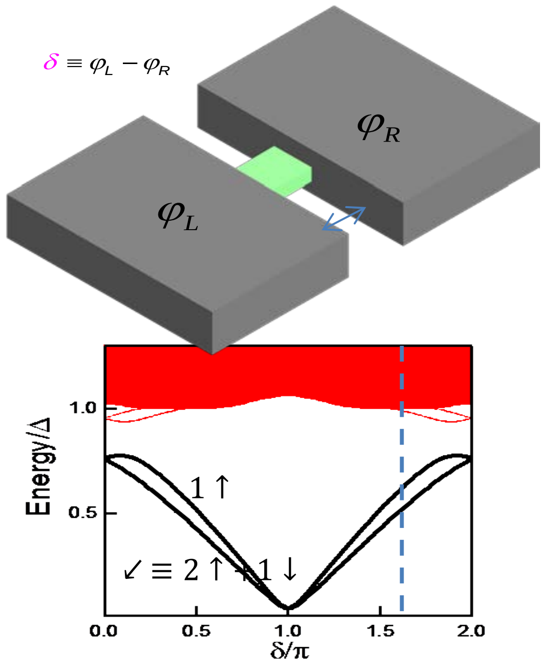


Proof of principle demonstrated

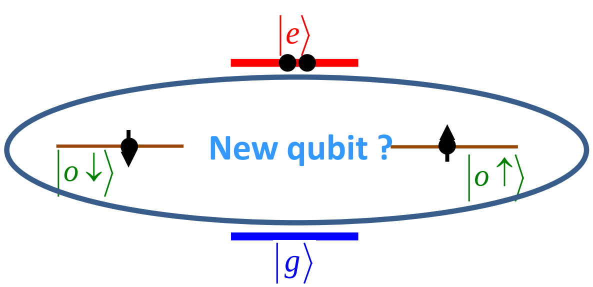
Kubo et al., PRL 107, 220501 (2011)
Julsgaard et al., PRL 110, 047001 (2013)
Grèzes et al., PRX 4, 021049 (2014)
Grèzes et al., CRAS 167, 693 (2017)

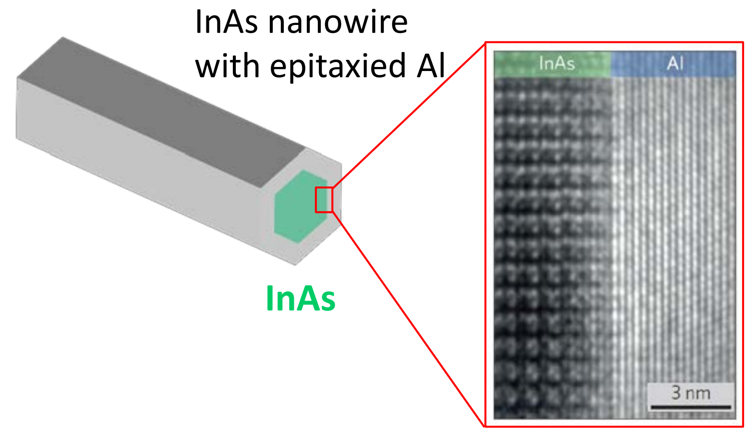
SC challengers : spin qubits in proximitized InAs wires ?

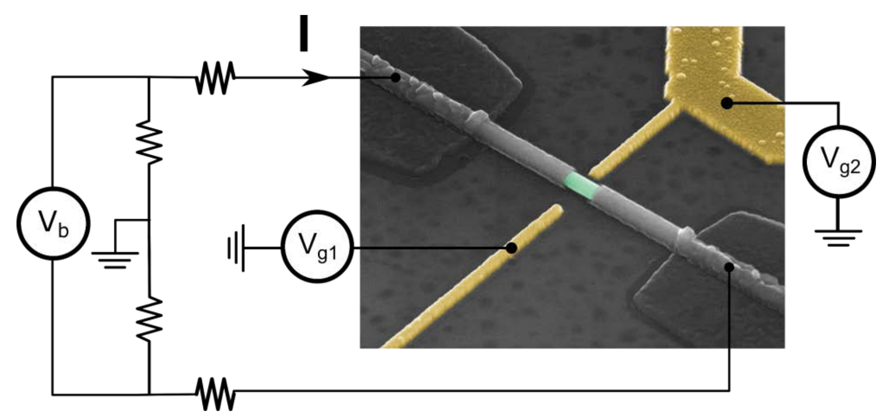
Rashba spin-orbit coupling weak link



Tight-binding calculation







Goffman et al., arXiv 1706.09150 to appear in NJP.