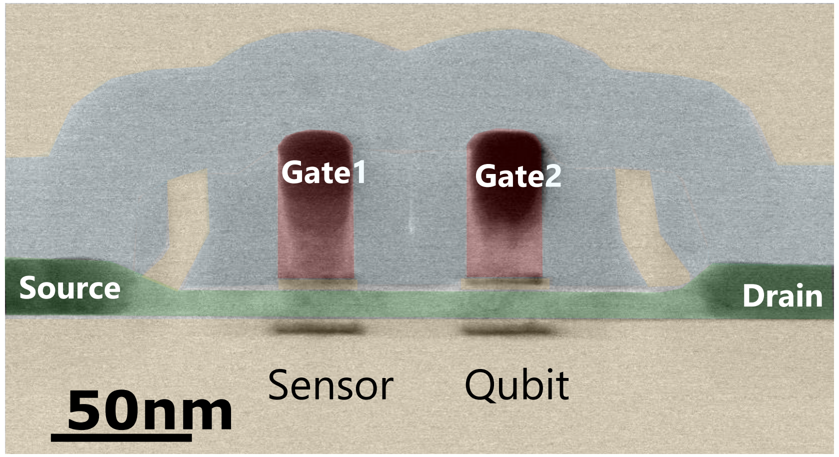
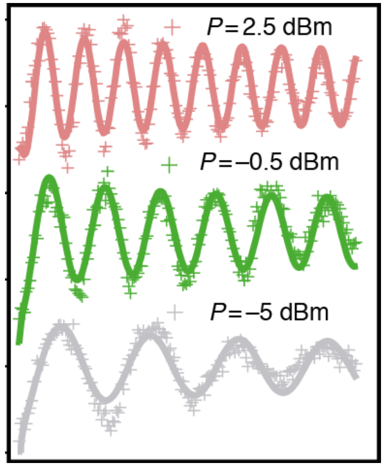
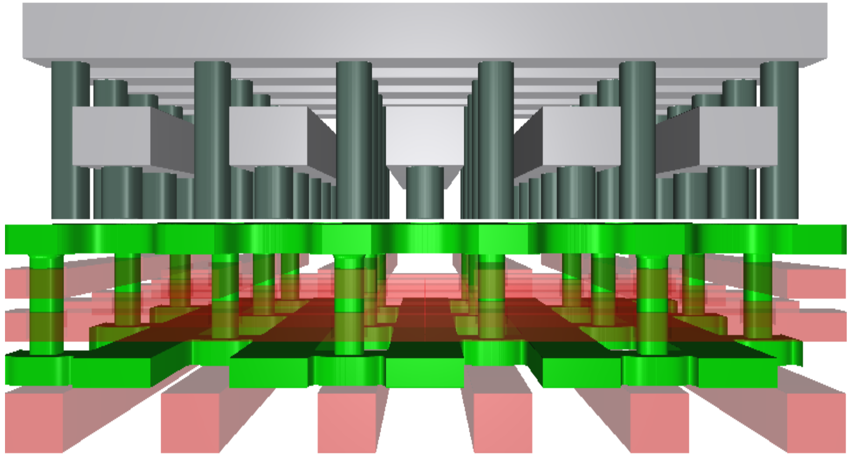
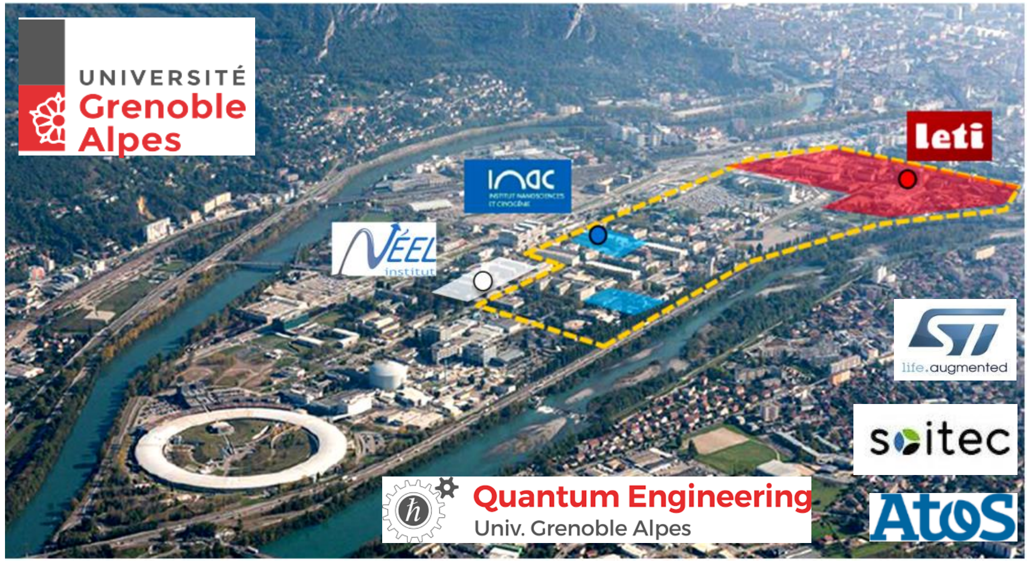
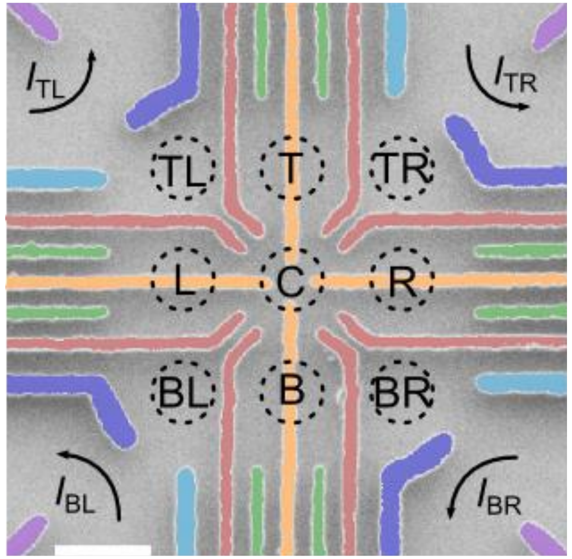
Towards a practical realization of spin based quantum nanoprocessors

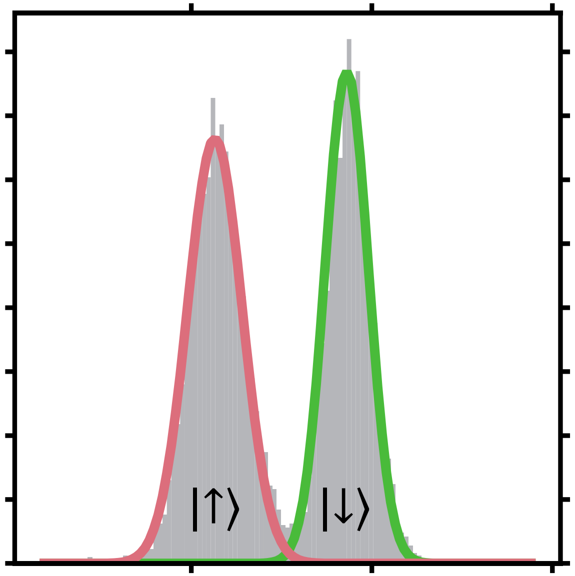






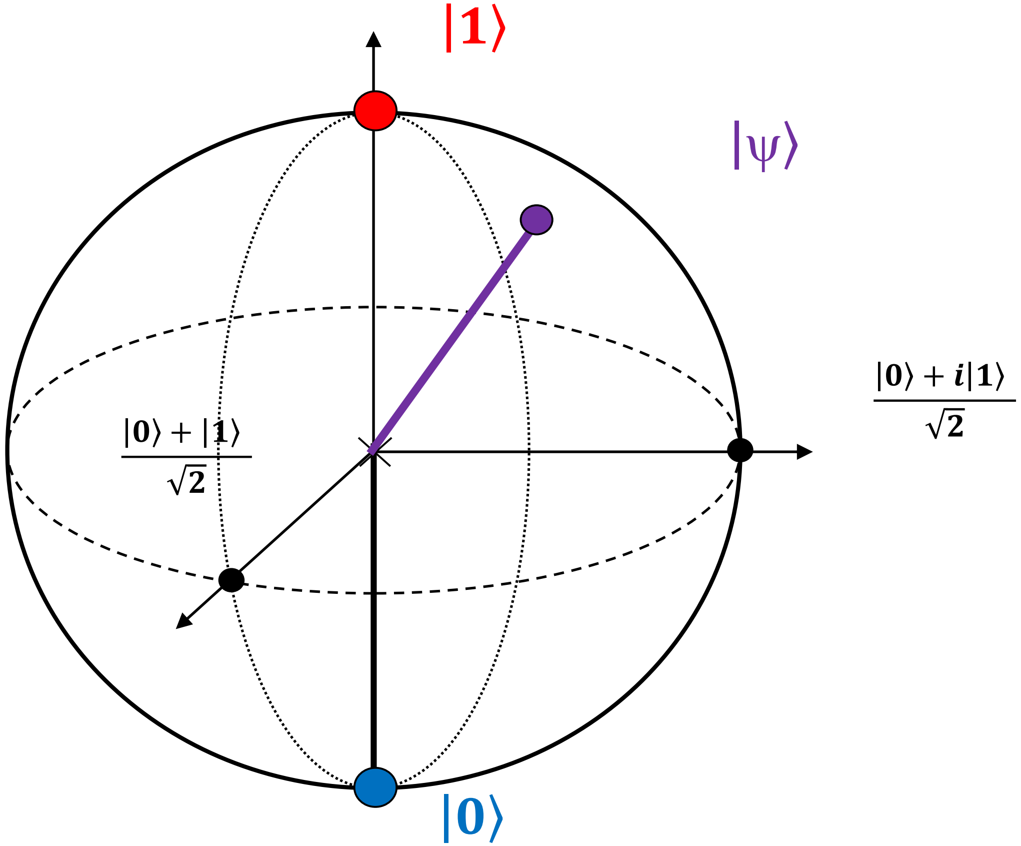




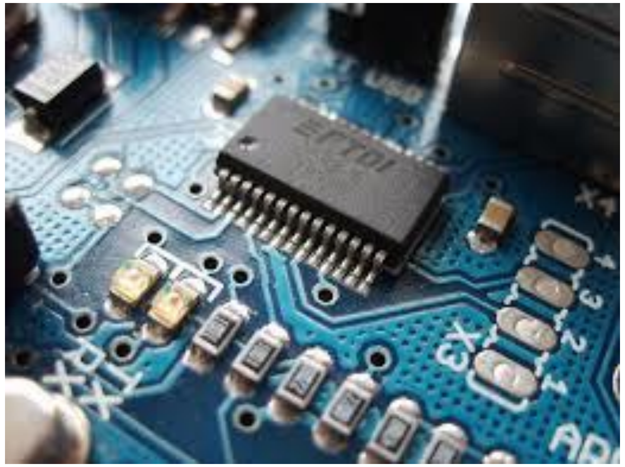


Quantum superposition

$$|\psi\rangle = cos\frac{\theta}{2}|0\rangle + e^{i\varphi} sin\frac{\theta}{2}|1\rangle$$



Quantum computing machines



3 bits

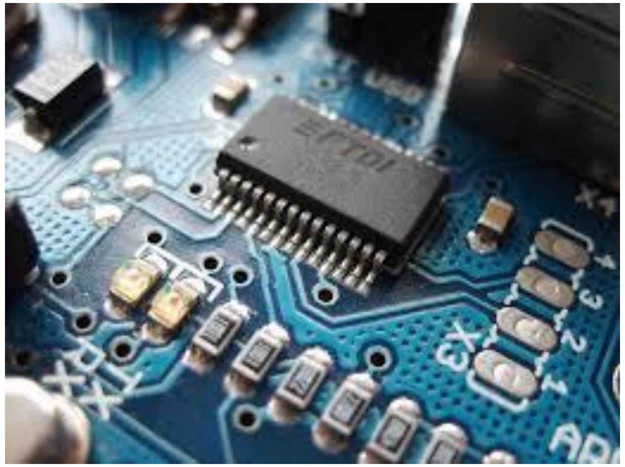
000
001
010
100
101
110
011
111

3 quantum bits

|000>
-|001>
+|010>
-|100>
+|101>
+|110>
-|011>
+|111>

Quantum parallelism

Quantum computing machines



3 bits

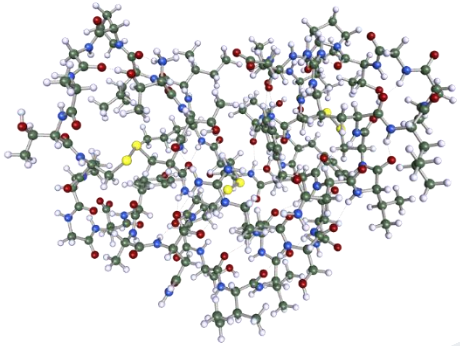
000
001
010
100
101
110
011
111

3 quantum bits

$+e^{i\pi/4}|000>$
$-e^{-i\pi/4}|001>$
$+e^{i\pi/4}|010>$
$-e^{i\pi/4}|100>$
$+e^{-i\pi/4}|101>$
$+e^{i\pi/4}|110>$
$-e^{-i\pi/4}|011>$
$+e^{-i\pi/4}|111>$

Quantum parallelism

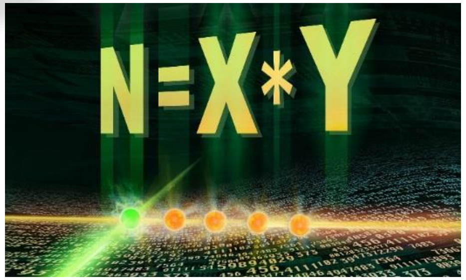
How many qubits do we need?



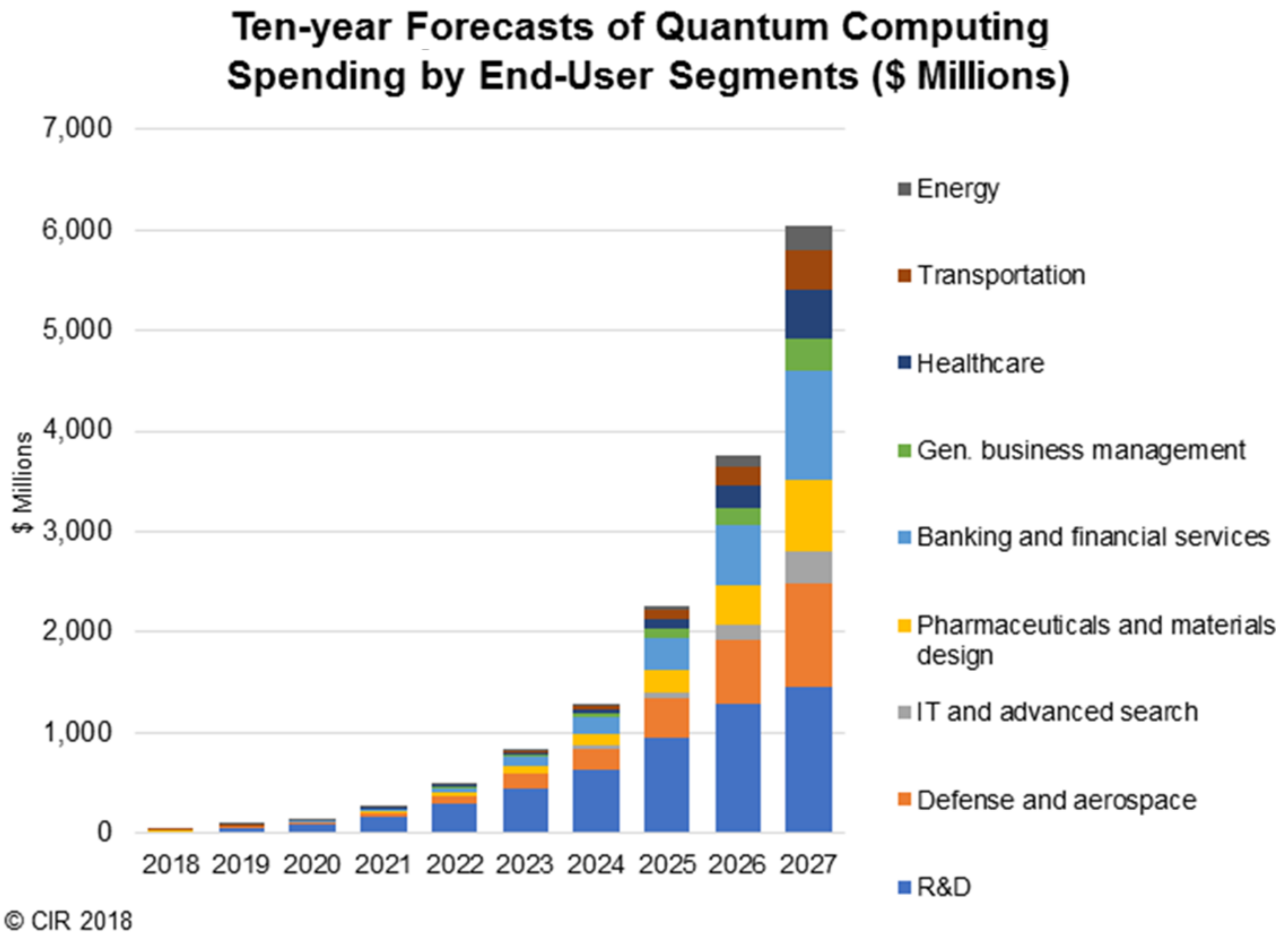
Quantum supremacy in **simulation**:
>56 logical qubits

Quantum chemistry for **medicine** and **material development:**
>200 logical qubits

Prime factorization of large numbers for **security**:
>2000 logical qubits



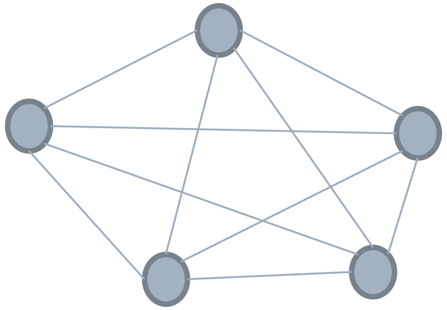
Applications in major industries

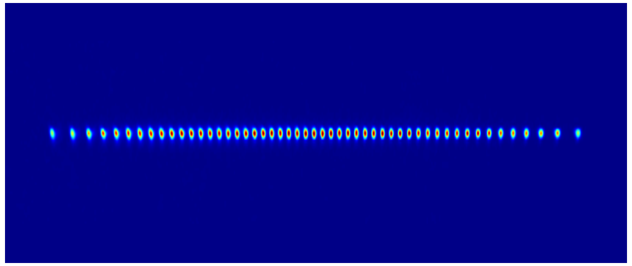


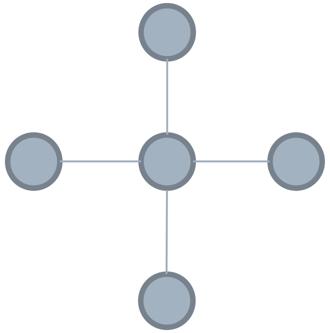
Connectivity

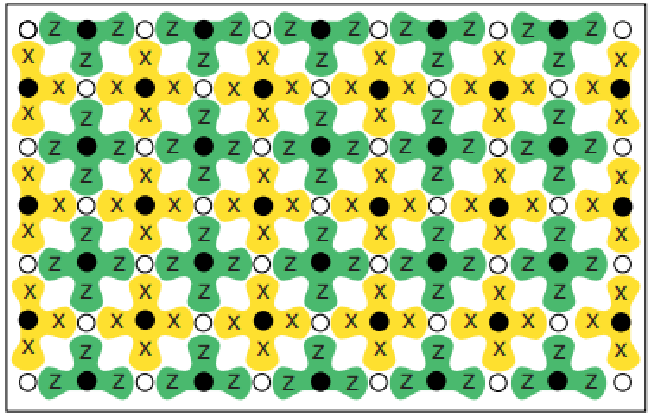
- Full connectivity between qubits
- N individual control + N(N-1) two-body control
- Correcting codes implemented in ion trap

- nearest neighbor interaction
- 4 N control parameters (refinement with architectures)



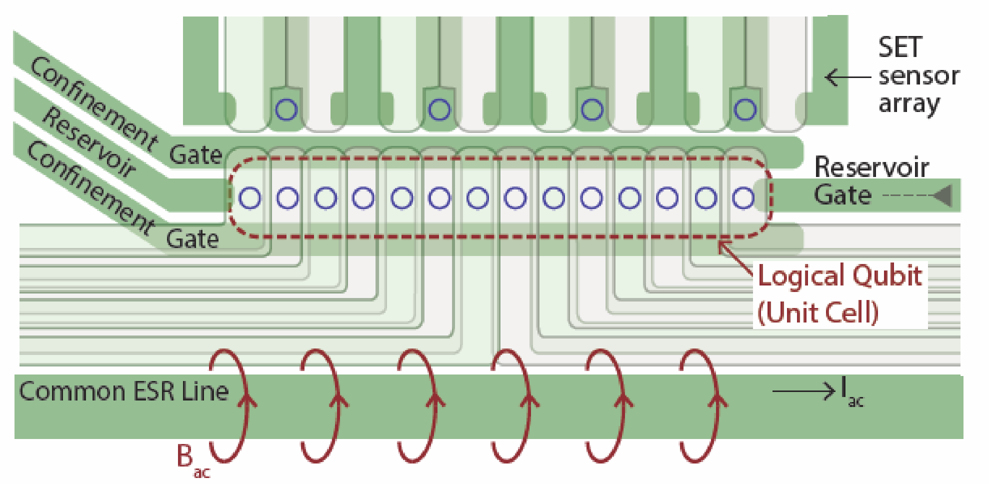






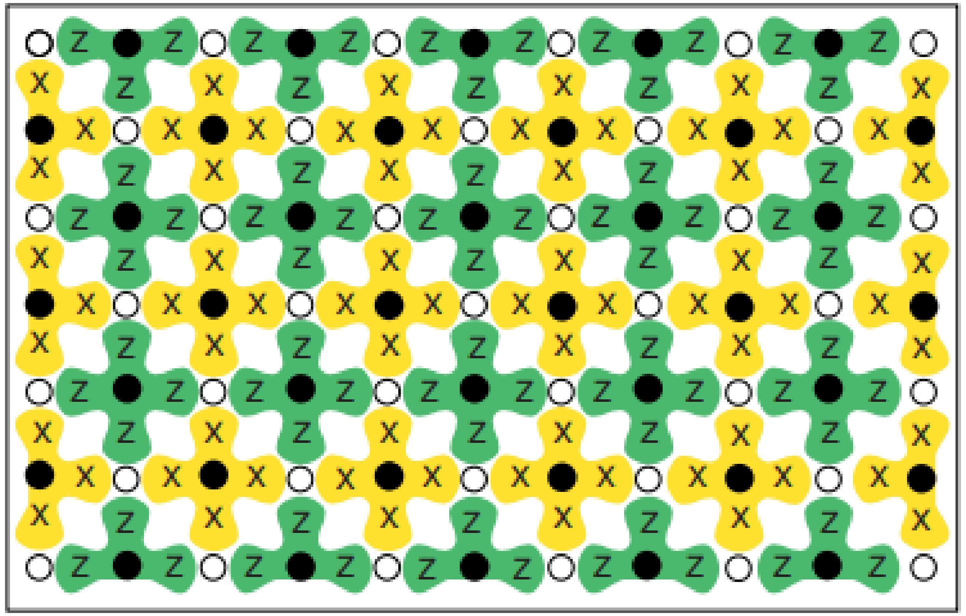
Nearest neighbor interaction

1D, 2D, 3D ?



C. Jones et al, Arxiv 2016

- Nearest neighbors
- Need for interconnection between distant qubits
- 1D requires multiple swapping



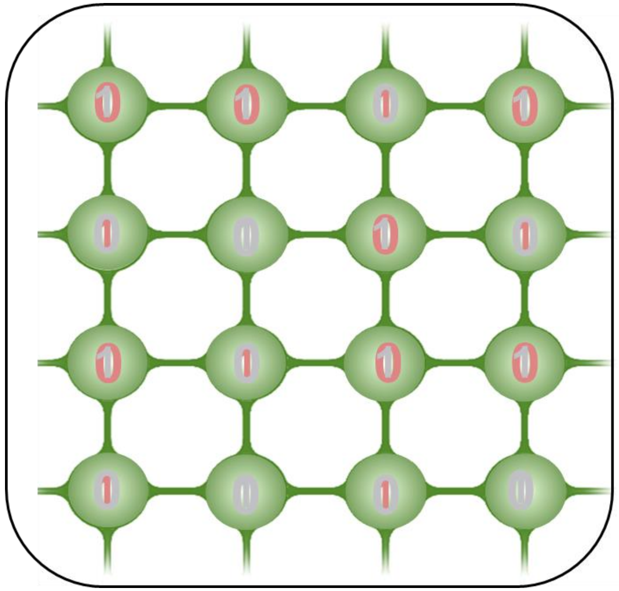
- ☐ Nearest neighbors
- ☐ No need for interconnection between distant qubits
- ☐ Compatible with reported fidelities

2D arrangement and 4 neighbors

Living with errors

Millions of errorless quantum operations

Quantum Error Correction
protocols

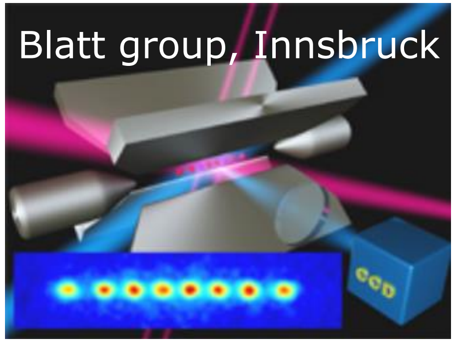


1 errorless logical qubit
> 1000 physical qubits

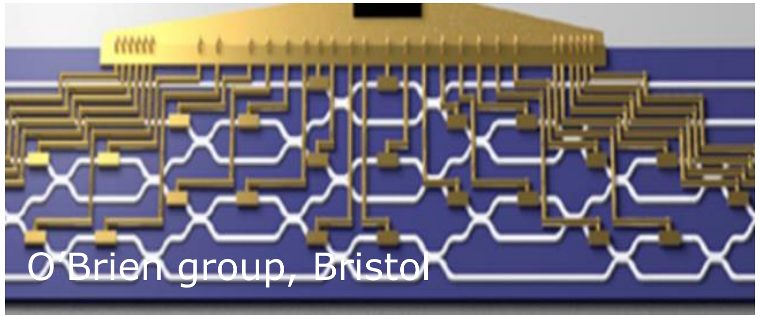
millions of physical qubits in a 2D array

Physical platforms for quantum computing

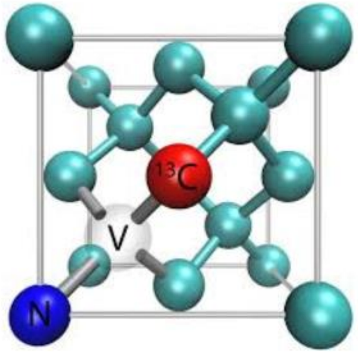
Ion Traps



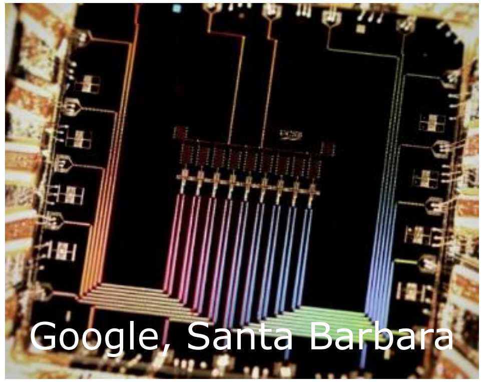
Photonic chips



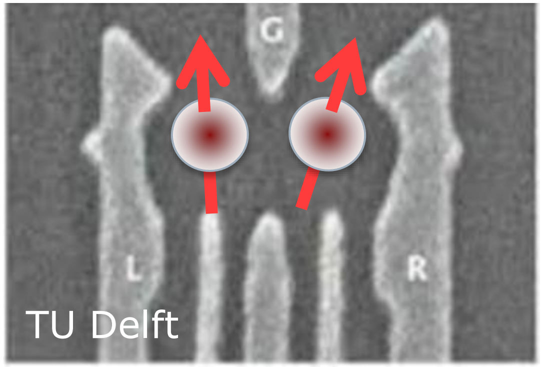
Defects in solids (NV,SiC)



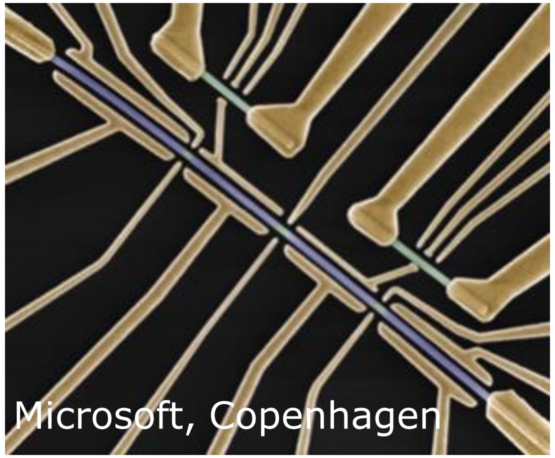
Superconducting Qubits



semiconductor spin qubits



Topological qubits



Qubit figures of merit

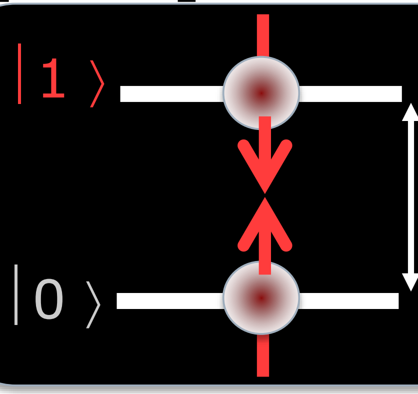
Speed, competitive run-time quantum calculation

Fidelity, logical qubits better than physical qubits

Size, manageable dimensions of the quantum circuit

Semiconductor spin qubits

Quantum information encoded in a spin degree of freedom

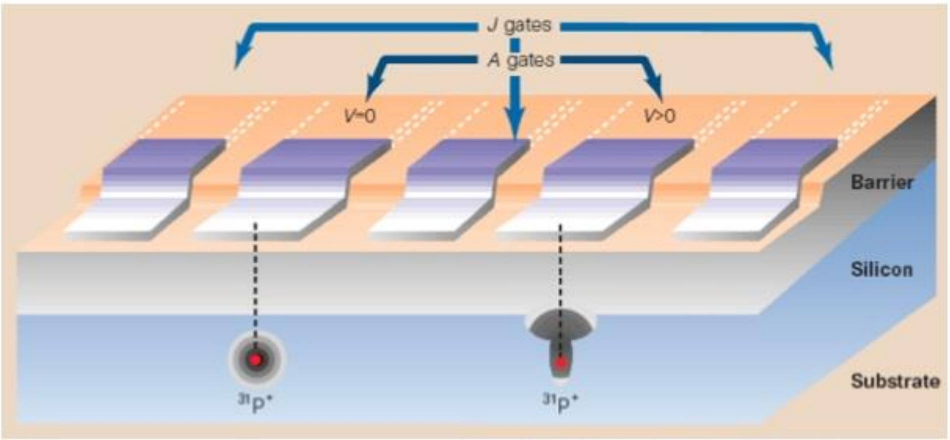


$\delta = |g\,\mu_B\,B|$

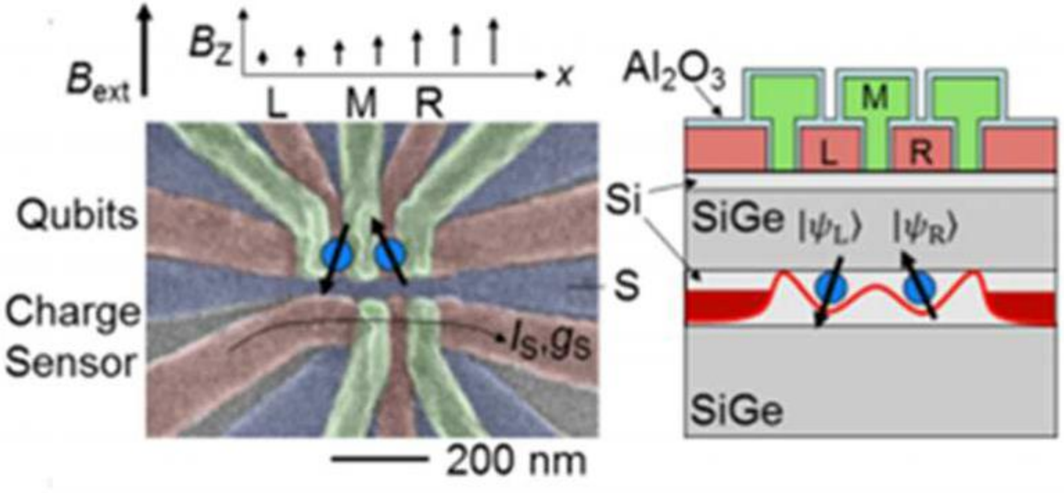
Spin qubit state:

$|s\rangle = a|0\rangle + b|1\rangle$

- Many possible physical realizations
- First demonstrations using electron spins in GaAs quantum dots (2005)
- Efforts now shifting to silicon

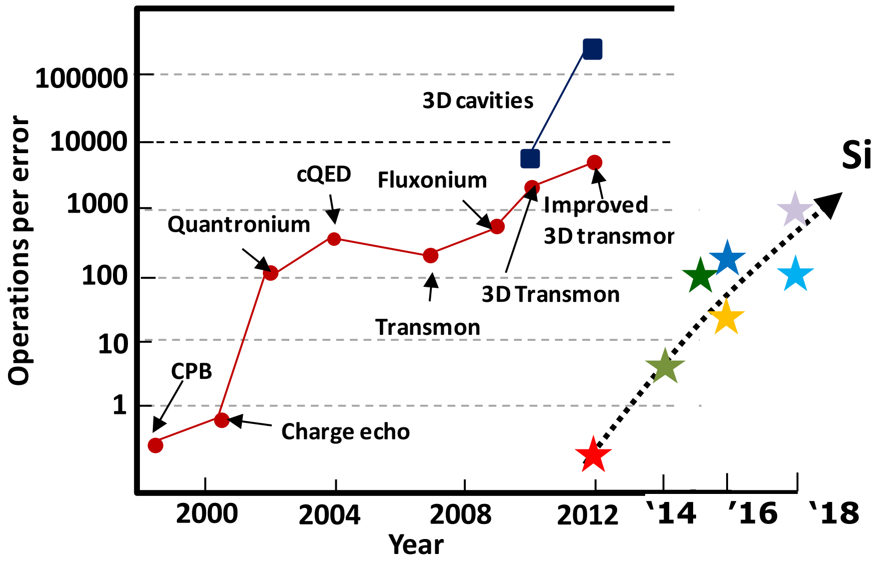


B.E. Kane, Nature 393, 133, 1998
D.P. DiVincenzo, Nature 393, 113, 1998



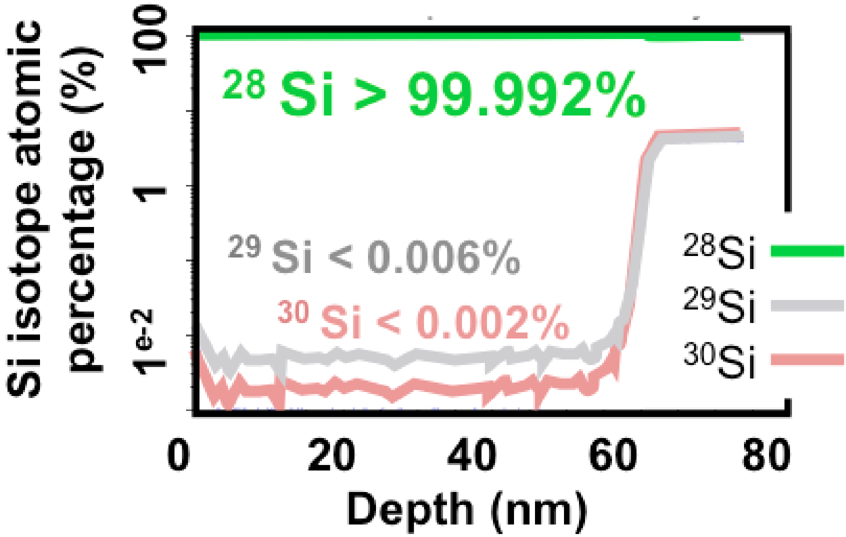
Silicon spin qubits

BENCHMARKING AGAINST SUPERCONDUCTING QUBITS



Adapted from M. H. Devoret, R. J. Schoelkopf, *Science* 2014

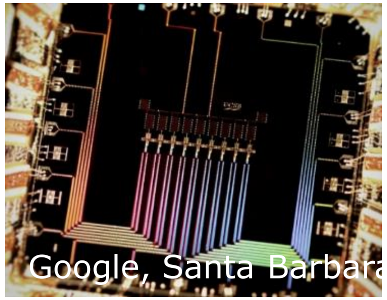
- Yoneda *et al.* (RIKEN), *Nature Nano 2018*: Quantum dot electron spin qubit in ^{28}Si/SiGe
- Takeda *et al.* (RIKEN), *Science Adv. 2016*: Quantum dot electron spin qubit in ^{nat}Si/SiGe
- Zajac *et al.* (Princeton), *Science 2018*: Quantum dot electron spin qubit in ^{28}Si/SiGe
- Veldhorst *et al.* (UNSW), *Nature 2015*: Quantum dot electron spin qubit in ^{28}Si
- Maurand *et al.* (CEA), *Nature Comm. 2016*: CMOS hole spin qubit in natural Si
- Kawakami *et al.* (TUDelft), *Nature Nano 2014*:
- Pla *et al.* (UNSW), *Nature 2012*: Single-donor electron-spin qubit in natural Si

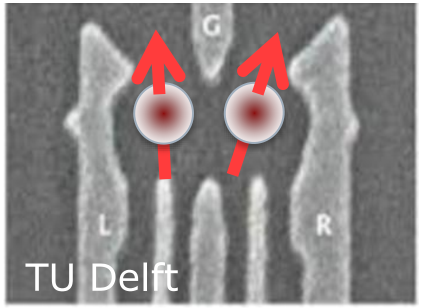


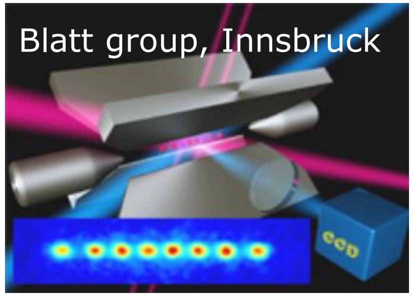
Mazzocchi et al., J of Crystal Growth (2018)

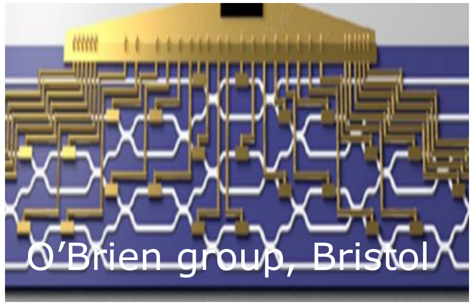
Isotopic purification => suppressed dephasing from ^{29}Si nuclear spins

^{28}Si	(92.2%)	S=0
^{29}Si	(4.7%)	S=1/2
^{30}Si	(3.1%)	S=0







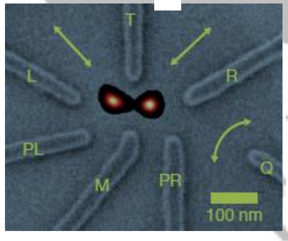


	Superconductors	Silicon	Trapped ions	Photon
Nb of entangled qubits	20	2	20	10
Size	$(100\mu m)^2$	$(100nm)^2$	$(1mm)^2$	$(1mm)^2$
Fidelity	~99.9%	~98%	99.99%	50% (measurement /generation) 98% (one, two-qubit gate)
Speed	100 ns	1 µs	100 µs	1 ms

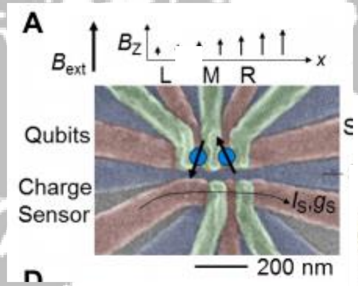
Silicon qubits offer a compelling platform

Silicon qubits worldwide

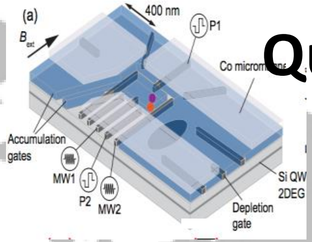
UMadison
UC Berkeley
Sandia



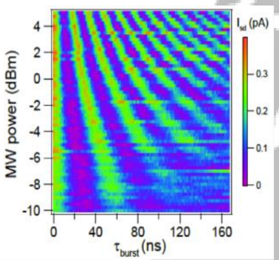
HRL, Malibu



Princeton

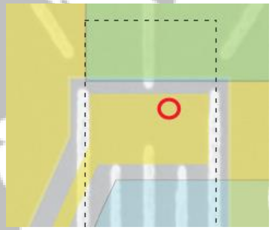


QuTech/Intel
(Delft)

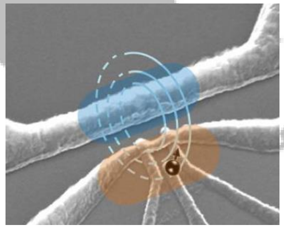


Grenoble

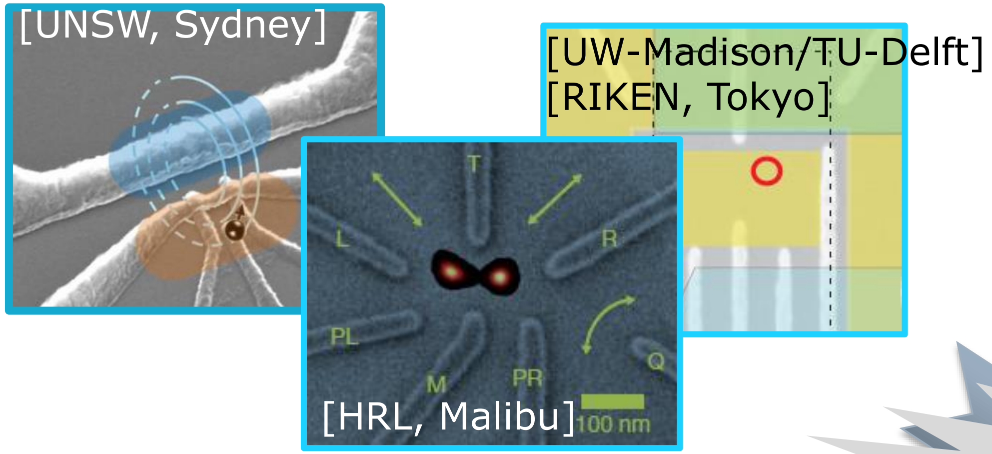
RIKEN & University of Tokyo



UNSW (Sydney)
Start up: SQC



Next: large-scale integration

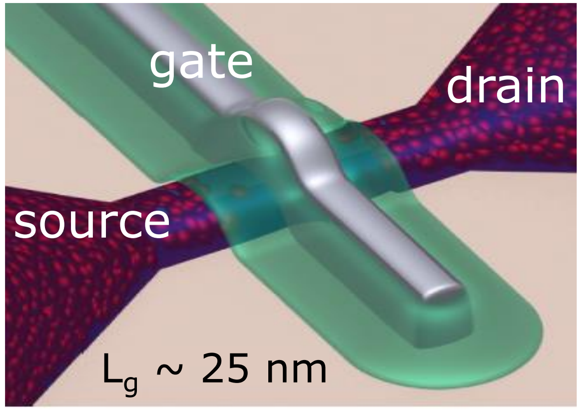


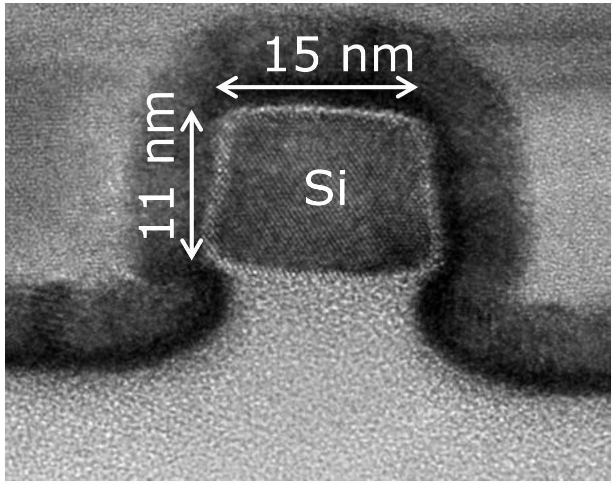
few silicon qubits

Challenges:
- Variability
- Large-scale control

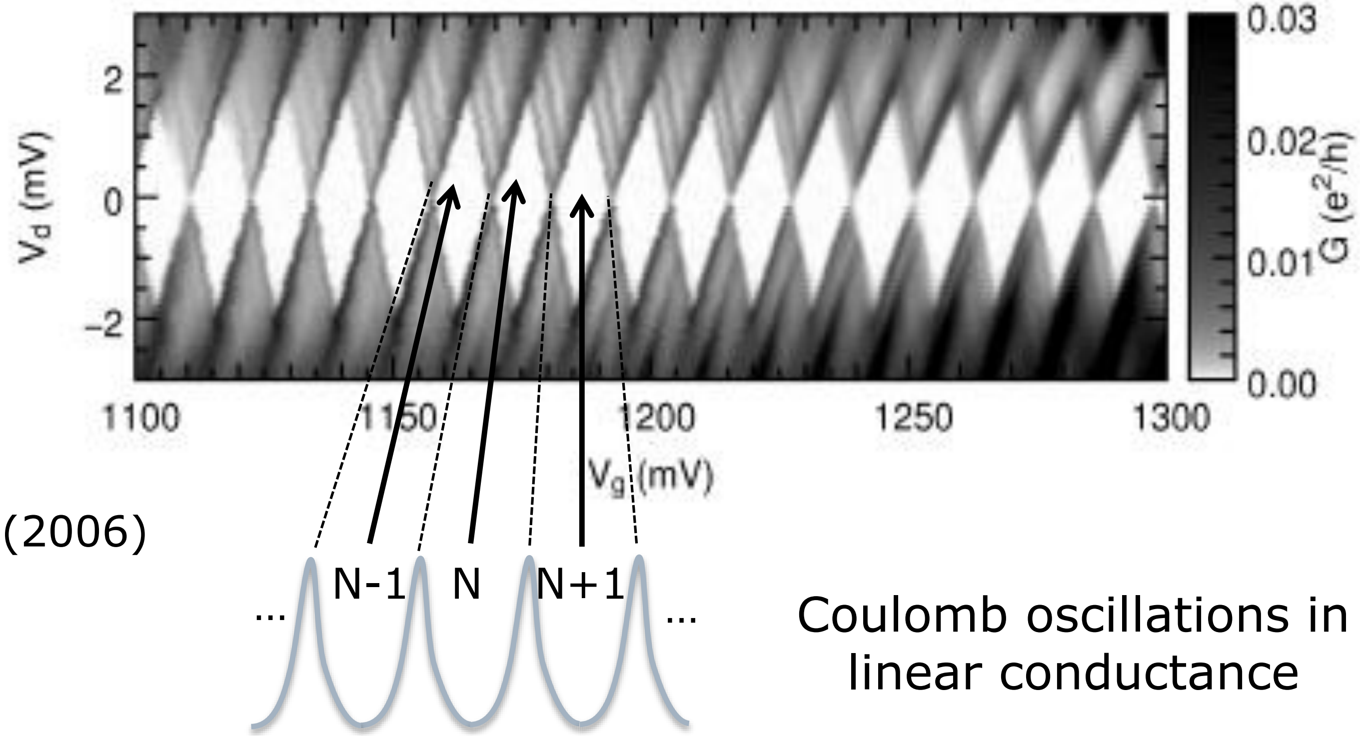
scalable (fault-tolerant) quantum processor

CMOS quantum dot





Silicon single-electron transistors



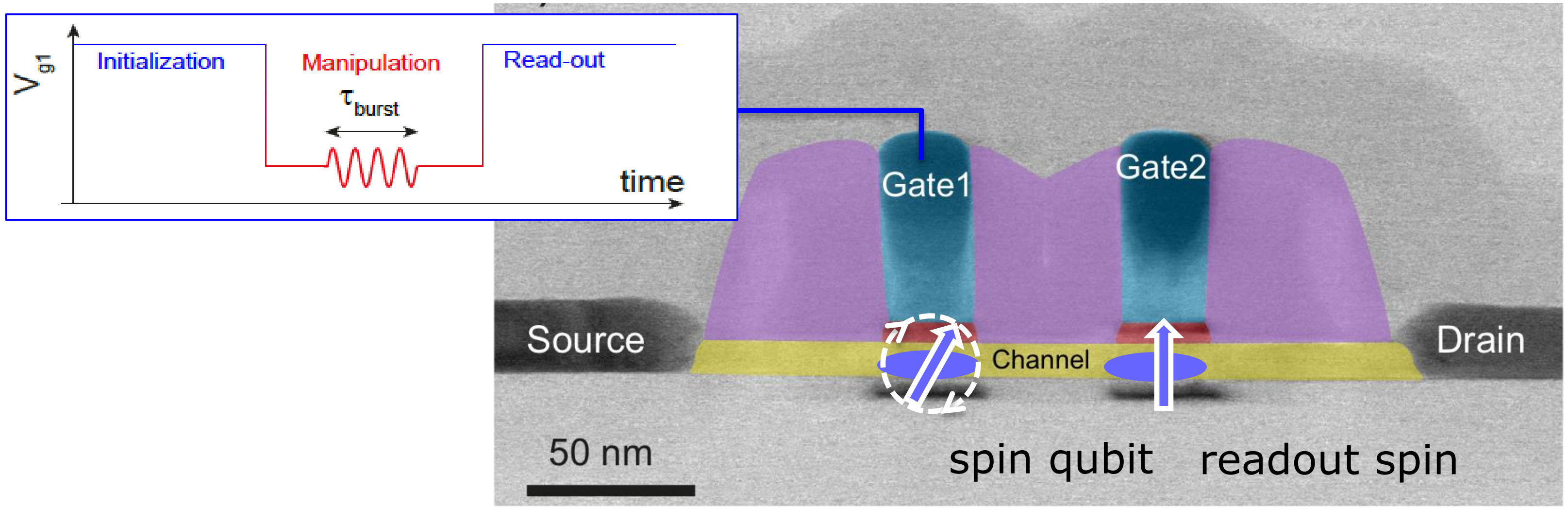
(2006)

Coulomb oscillations in linear conductance

Large number of confined electrons (N > 10^2)

M Hofheinz et al., APL (2007)

First CMOS spin qubits



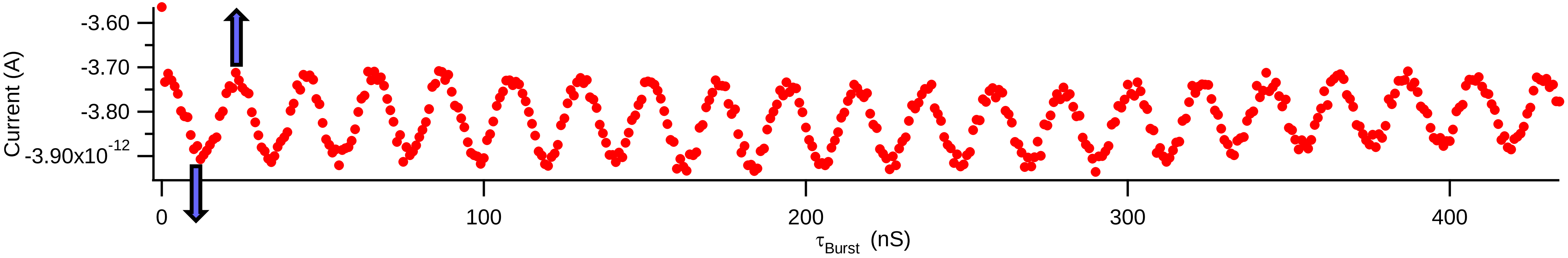
Hole spin qubits:

Maurand et al., Nat. Comm. 2016

Crippa et al., Phys. Rev. Lett. 2018

Venitucci et al., arXiv:1807.09185

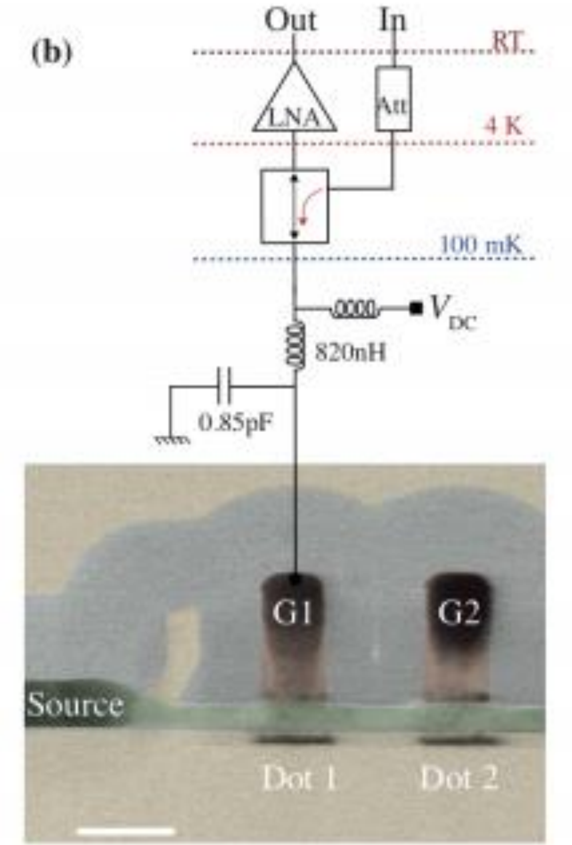
Hutin et al., ESSDERC 2018

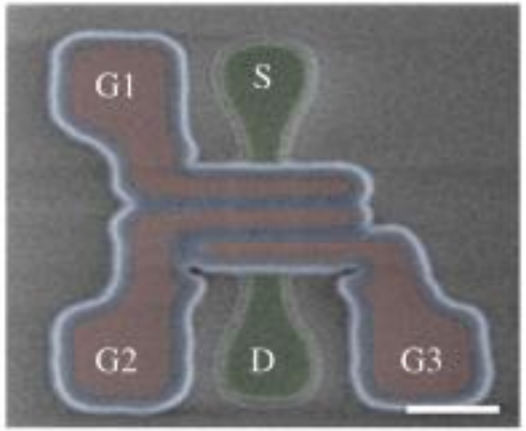


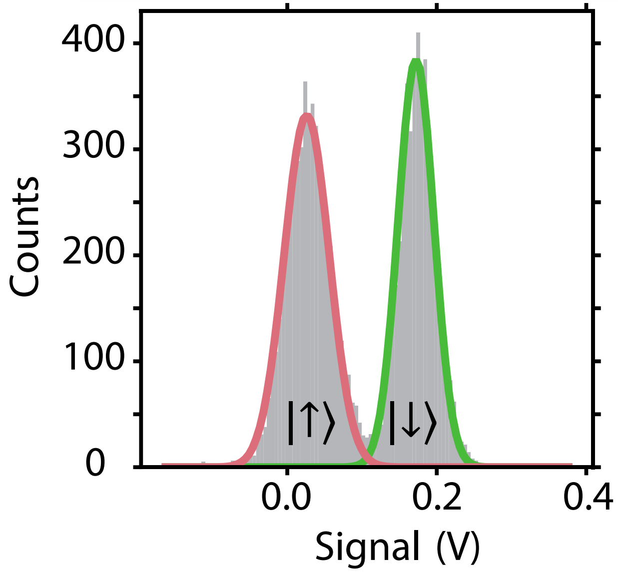
Electric-field driven electron-spin manipulation

Corna et al. Nat. Quantum Inf. 2018
Bourdet & Niquet, Phys. Rev B 2018

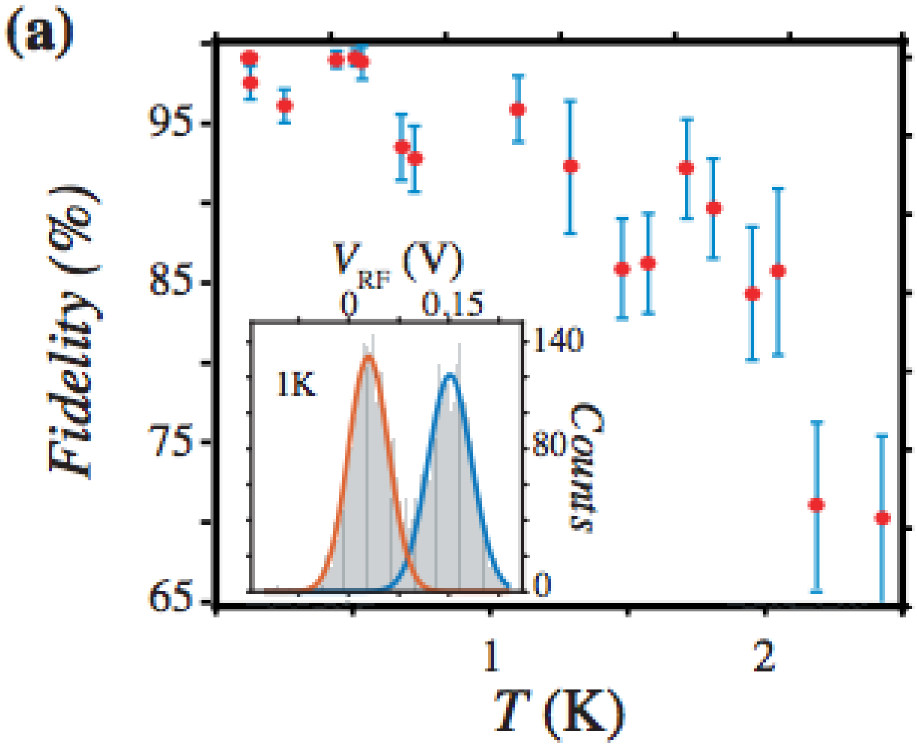
High-fidelity electron-spin readout via rf gate reflectometry





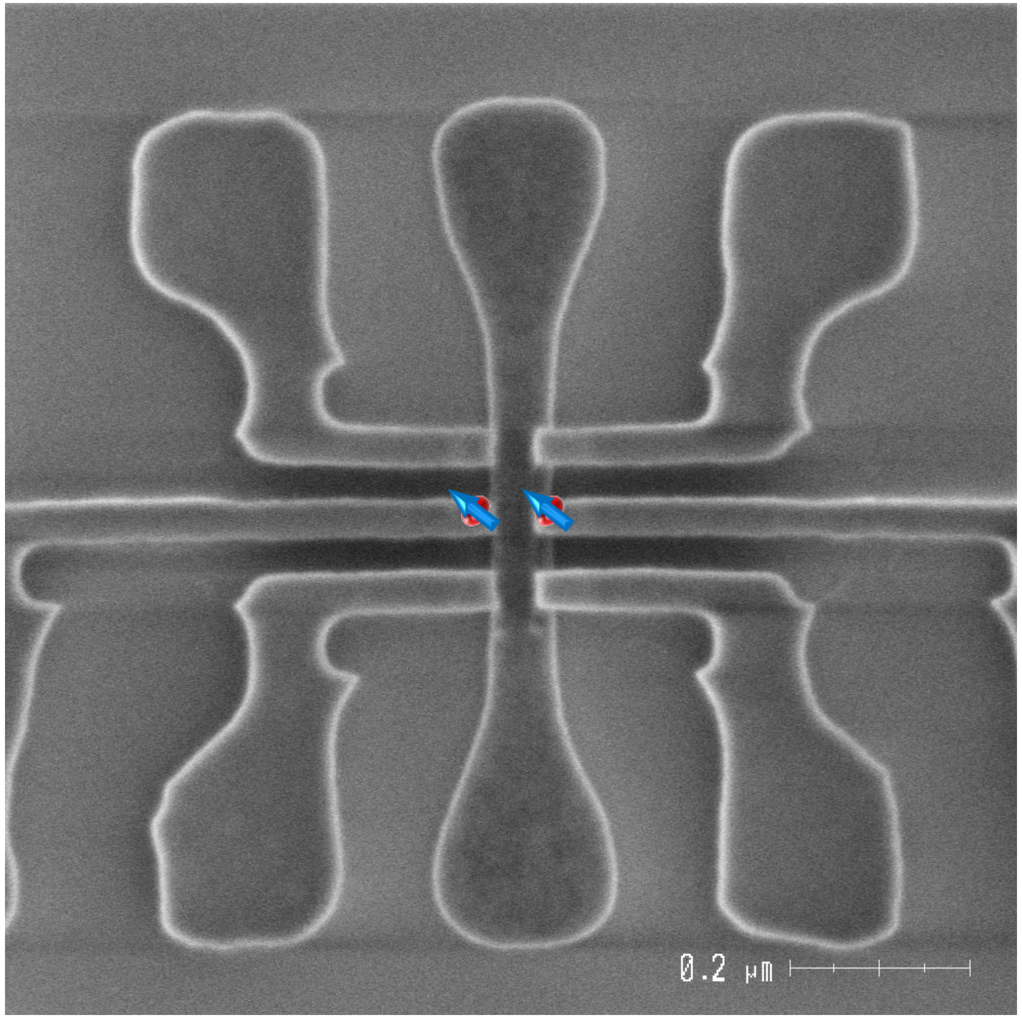


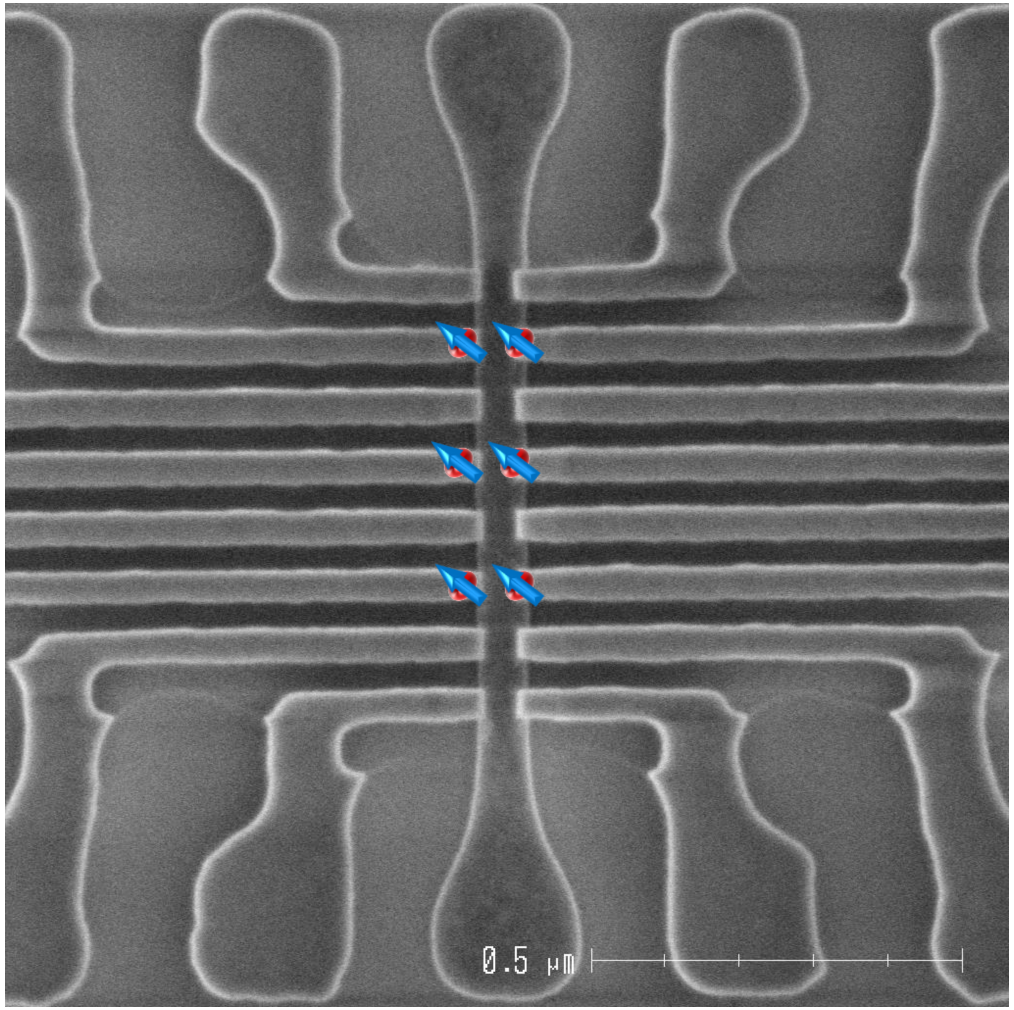
Fidelity > 99%



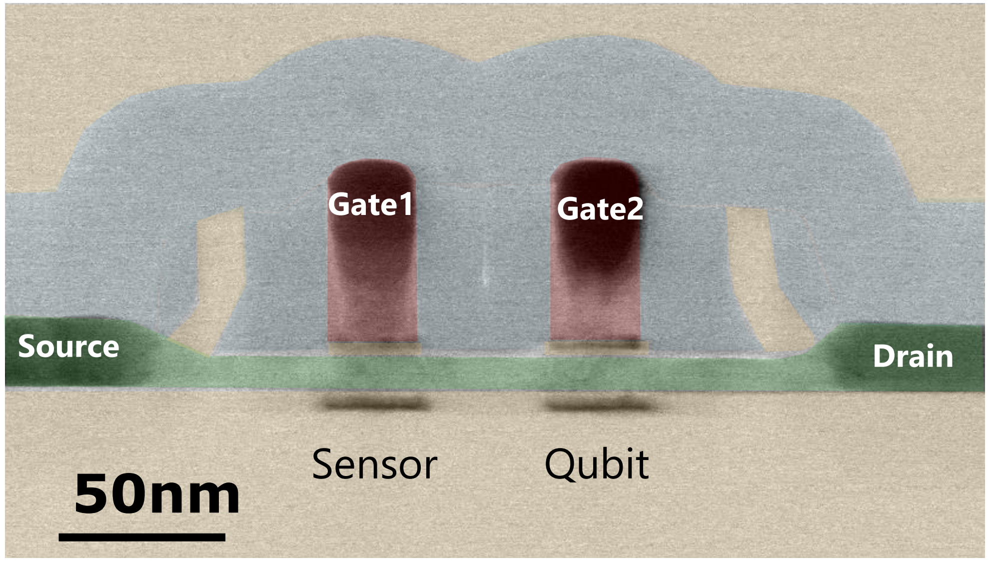
Urdampilleta et al.,
arXiv:1809.04584

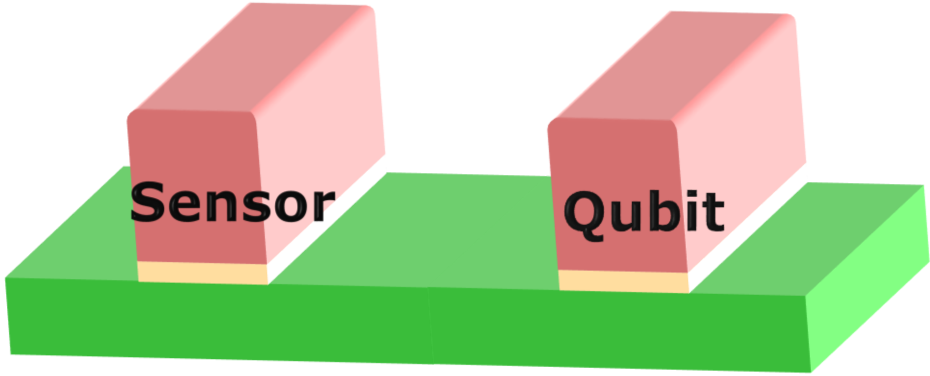
Towards multi-qubit operations

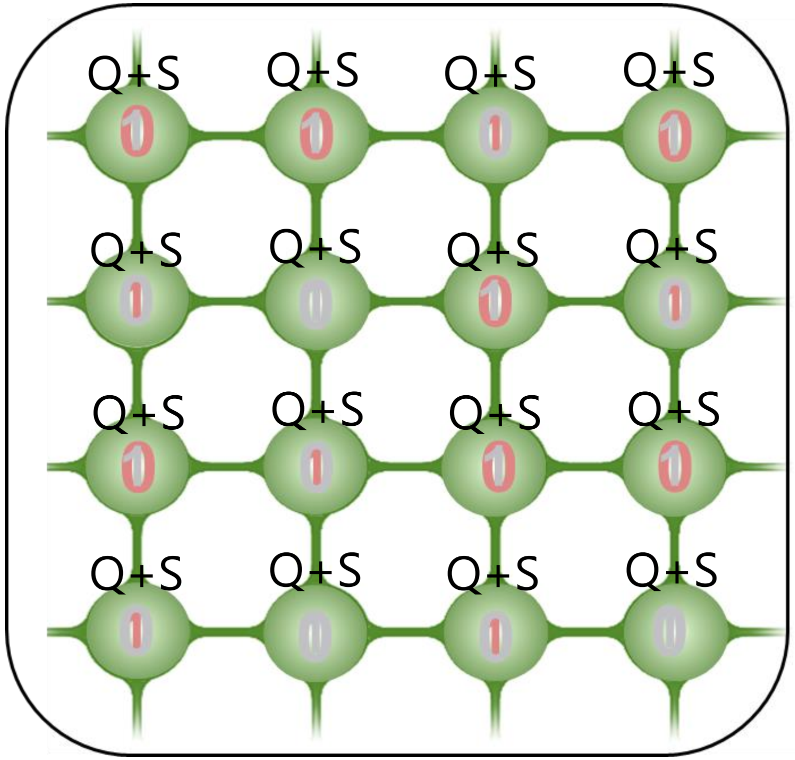




Next step: scalability?







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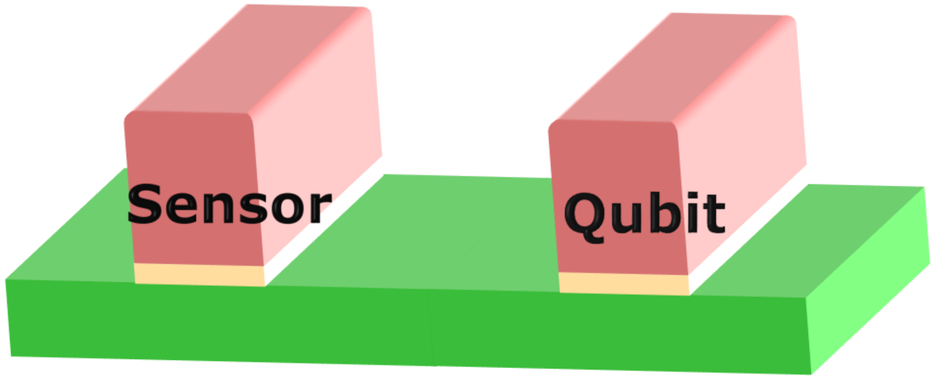
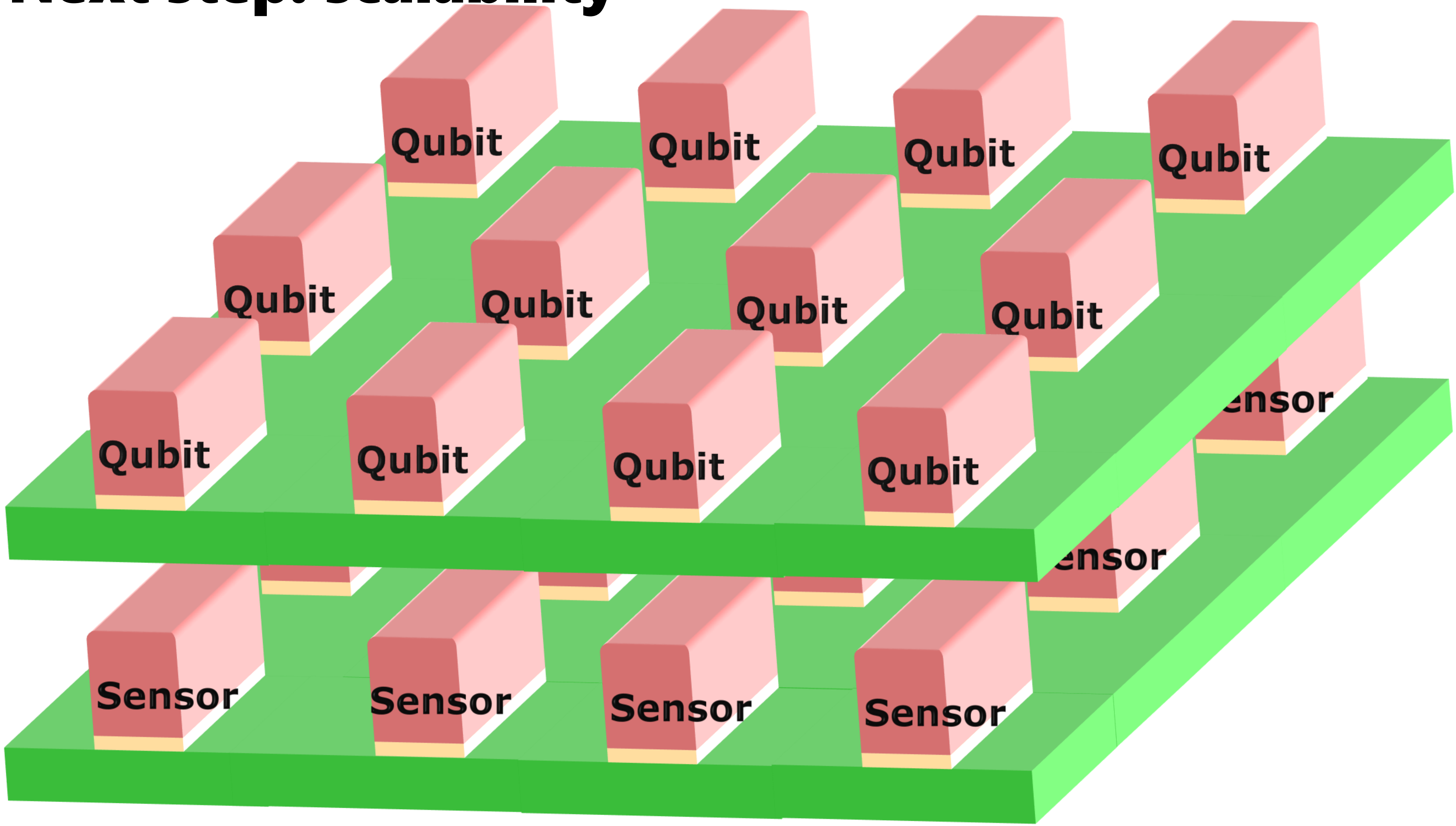
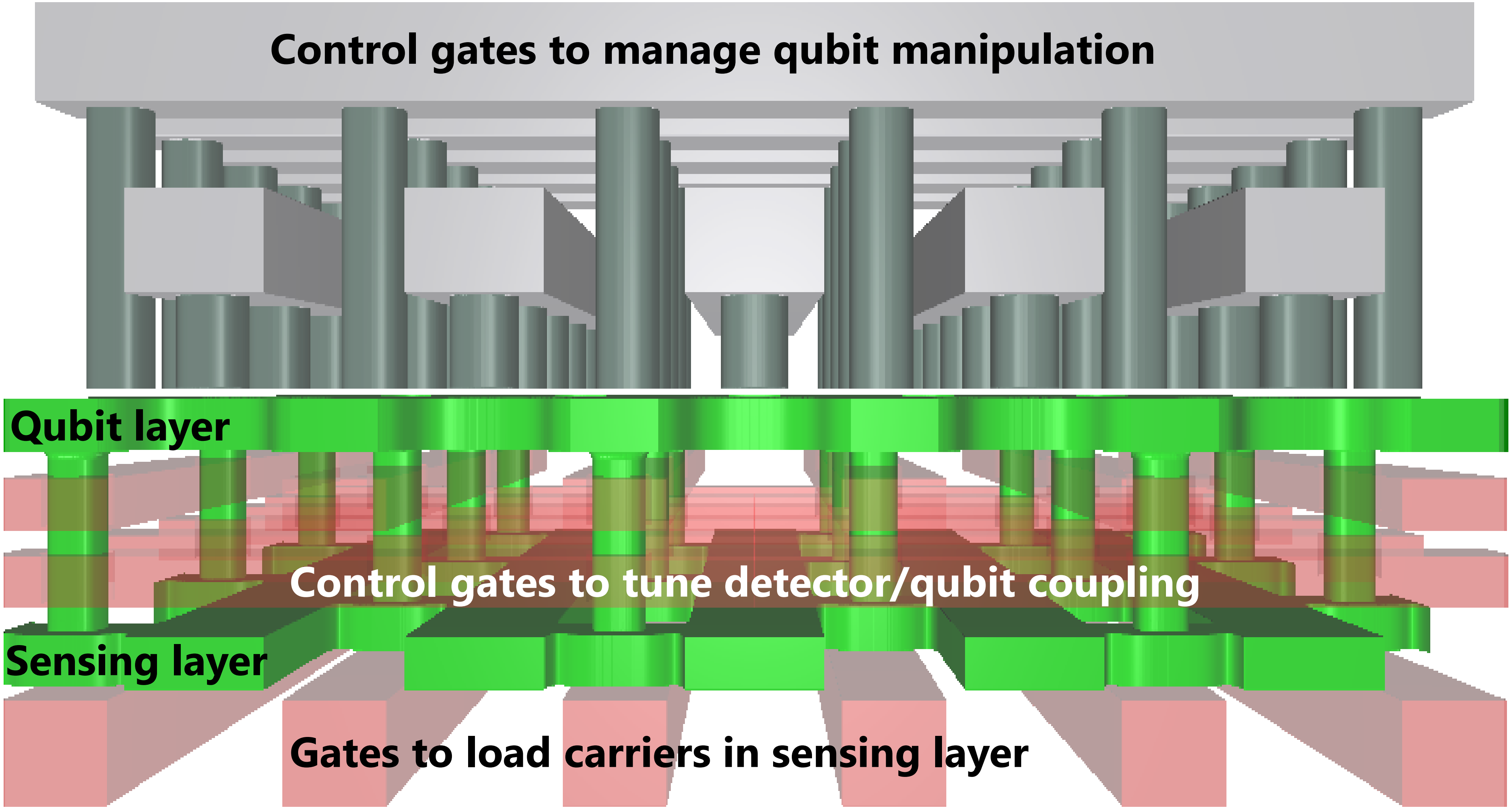


Next step: scalability

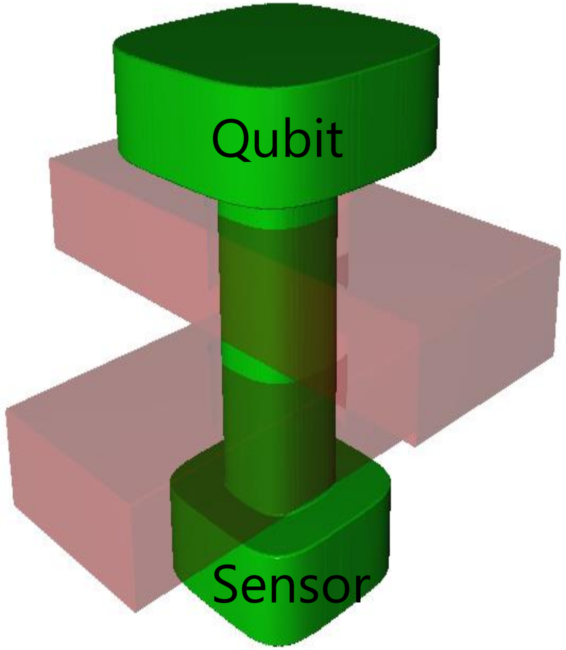


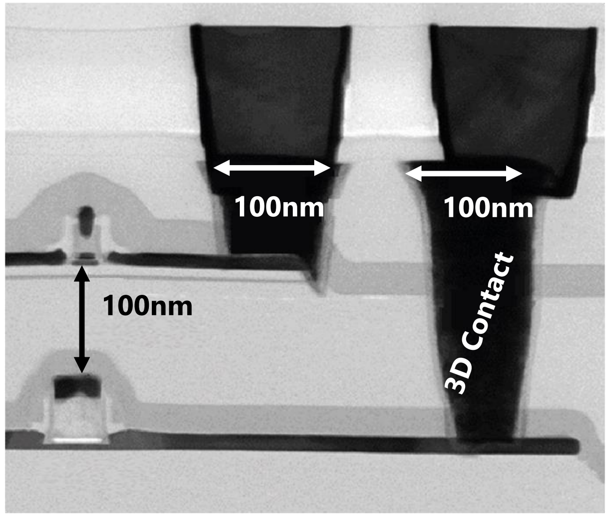
Array architecture

Patent Meunier, De Franceschi, Vinet, Hutin (2017)

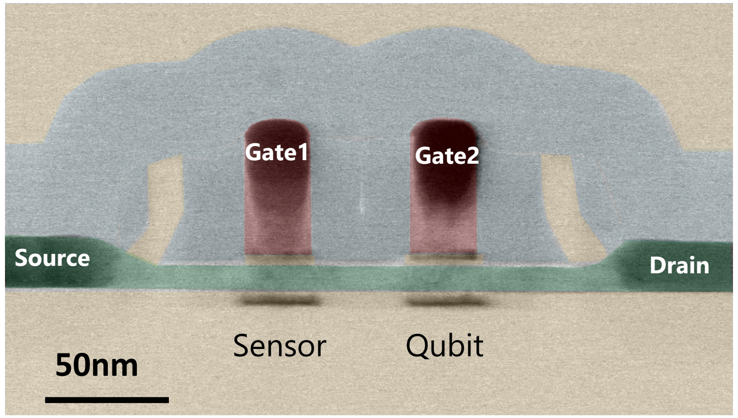


Coupling between sensor & qubit





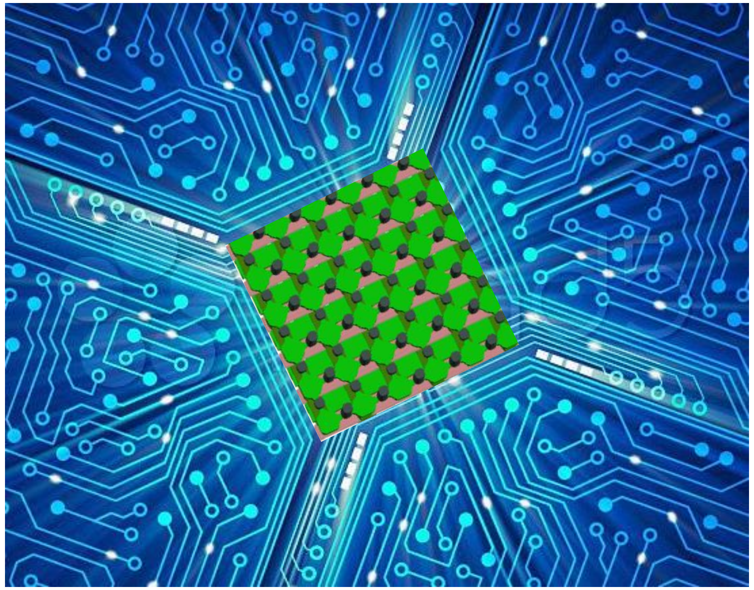
3D CMOS nanoscale integration
L. Brunet, VLSI (2017)



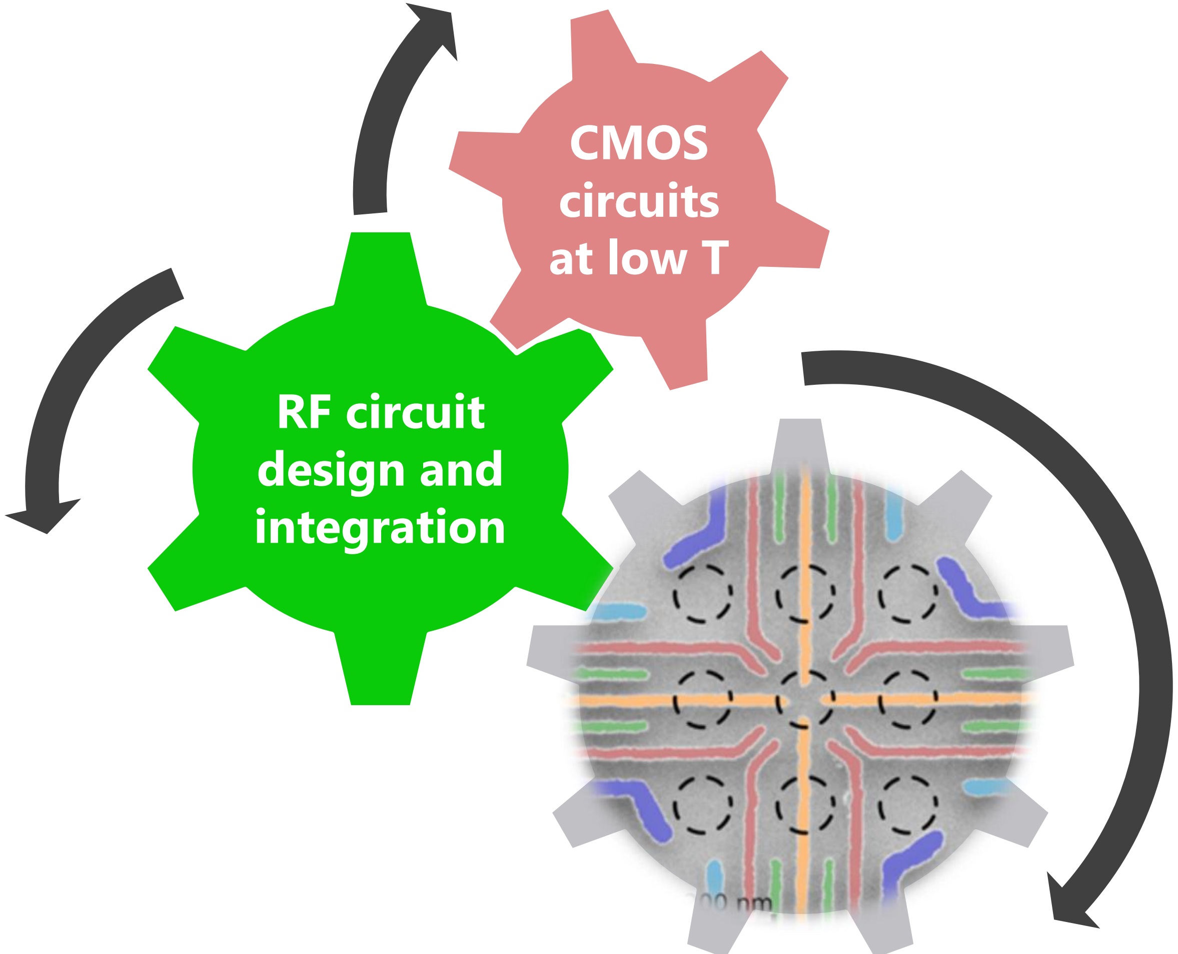
Lateral tunnel coupling (experiment & simulation)
S. De Franceschi, IEDM (2016)

Si vias to interconnect the layers

Large scale control



Scalable quantum/classical interface



Coherent control of 2D array

PA Mortemousque et al., Arxiv (2018)

Multiplexed read-out and control

Conclusion

Quantum information is powerful, but it is **very fragile**.
Each possible qubit: **stability/addressability trade-off**

Late-blooming Si spin qubits on the rise from an underdog's position

Quantum Error Correction is needed for useful universal computing, hence **large scale integration**.

$\Rightarrow$**Si spin qubits have strong potential for extensibility**, which entails numerous fundamental and engineering challenges

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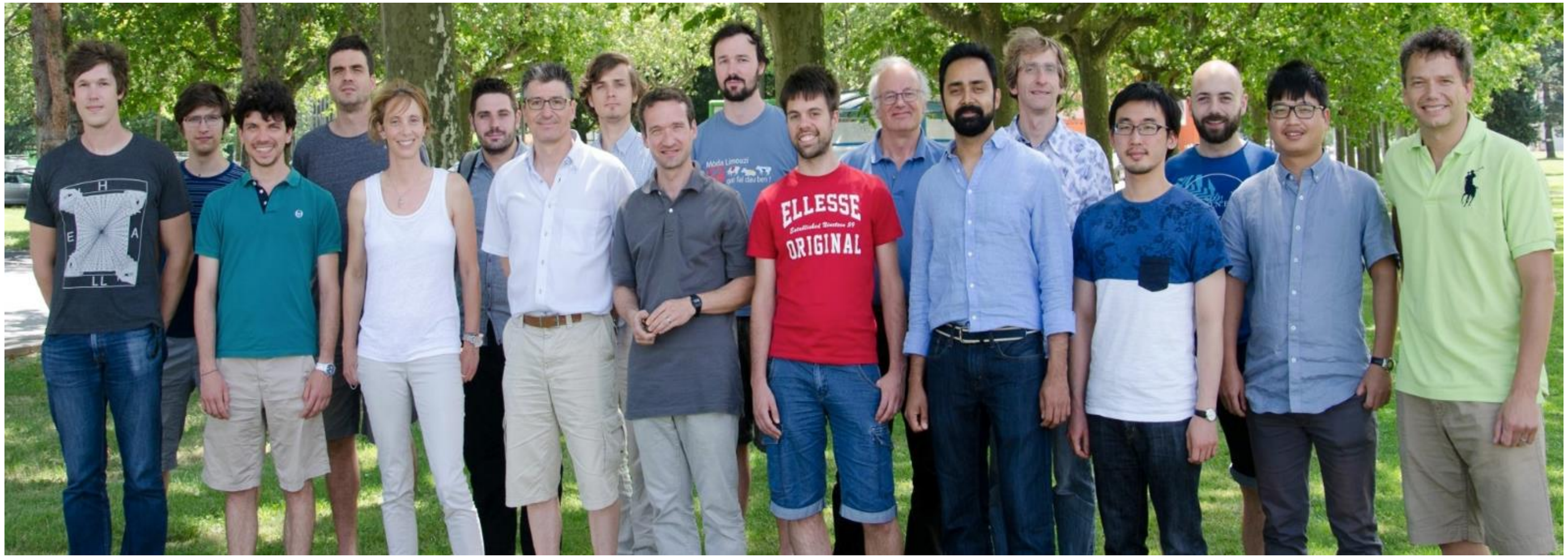






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Thank you!