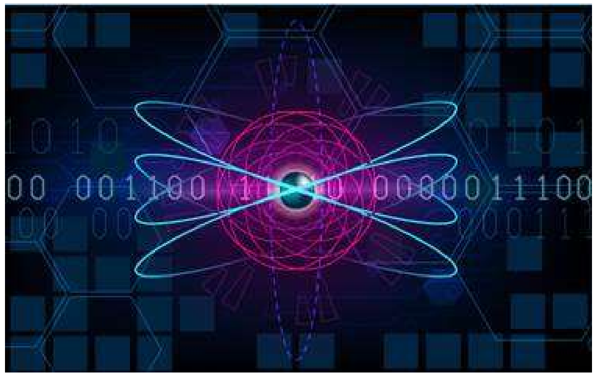
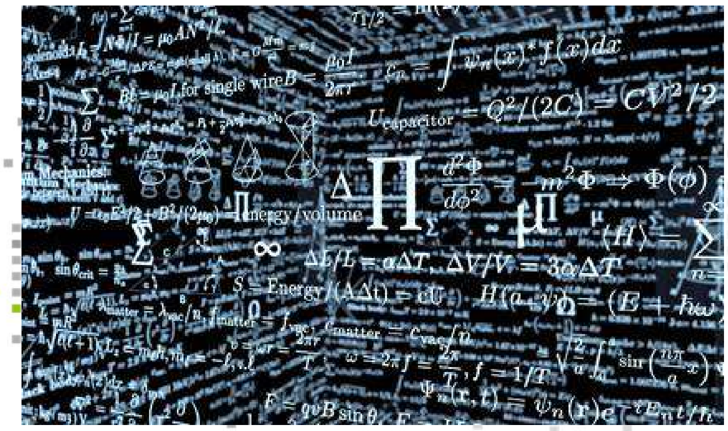
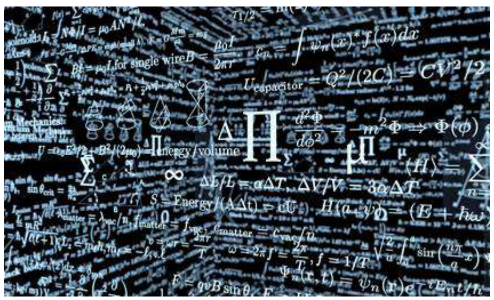




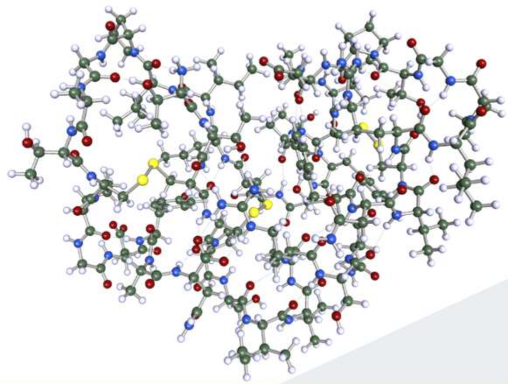
# QUANTUM COMPUTING ON SILICON

Leti Devices Workshop | Maud Vinet| Dec 2nd, 2018, Nikko Hotel, San Francisco

# QUANTUM COMPUTATION PROMISES



**Quantum supremacy**
50 logical computationnal qubits/ 50 physical qubits for sampling

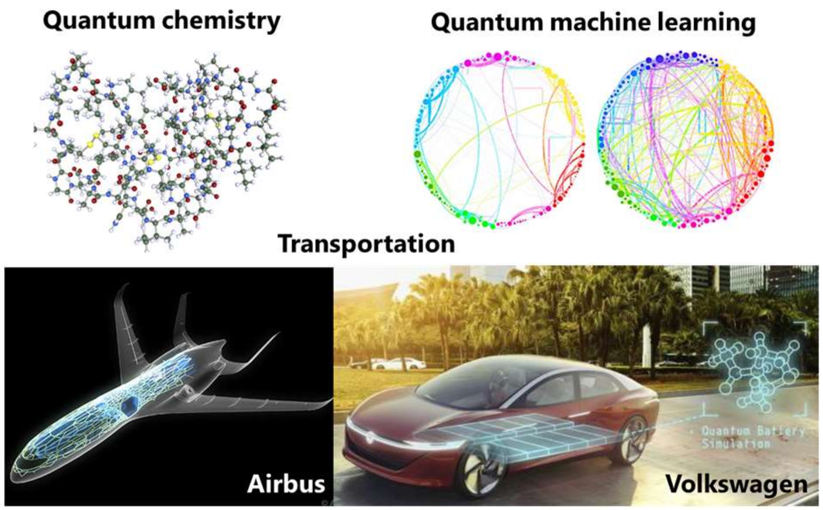


Quantum chemistry for **medicine** and **material developments**
**200 logical qubits**


ETH Zurich, Bristol, Usherbrooke, Google…

Factorizing prime numbers for **security, AI, data mining**
2000 logical qubits

# QUANTUM COMPUTATION NUMBERS




>>

Still improving

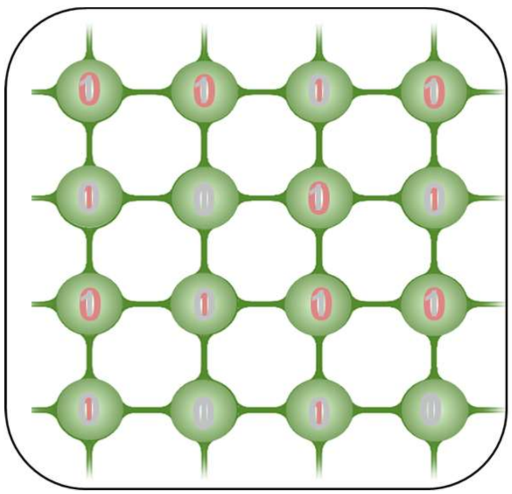
## Hundreds of qubits

## Millions of errorless quantum operations

## 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**

## SINGLE QUBIT SCALE FIGURES OF MERIT

**SPEED**

Competitive run-time quantum calculation

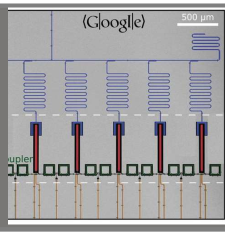
**FIDELITY**

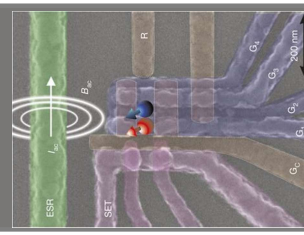
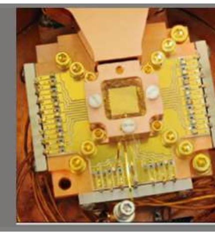
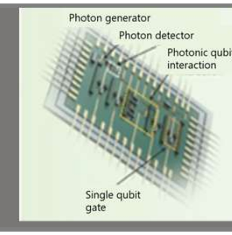
Logical qubits better than physical qubits

**SIZE**

Manageable dimensions of the quantum circuit

# BENCHMARK AND PLAYERS




| | Superconductors | Silicon spins | Trapped ions | Photons |
|---|---|---|---|---|
| Size | $(100\mu m)^2$ | $(100nm)^2$ | $(1mm)^2$ | 1 mm2 |
| Fidelity | ~99.9% | >98% | 99.99% | 50% (measurement and generation)<br>98% (one and two-qubit gate) |
| Speed | 200 ns | 5 µs | 100 µs | 1 ms |
| Number of entangled qubits | 17 (claimed 72) | 2 | 20 | 18 |

| | | | | |
|---|---|---|---|---|
| Companies | IBM, Google, Intel, Dwave, Rigetti, QCI… | Intel, HRL, Silicon Quantum Computing | IonQ | Xanadu, Quandela, HP, Tundra systems, PsiQuantum |
| Leading academic teams | UCSB, Yale, IBM Zurich, CEA, Berkeley, TU Delft, MIT | UNSW, CEA-CNRS Grenoble, Tokyo University, TU Delft, Princeton, Sandia, Uwisconsin, NTT | Innsbruck, Oxford, NIST, UMaryland, Sussex, MIT | Oxford University |

# MATURITY OF VLSI TECHNOLOGY

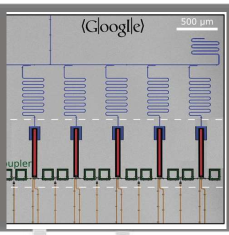
Integration

Better control of interfaces

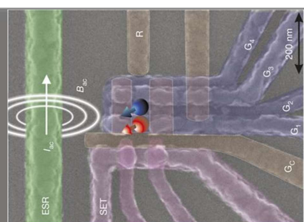
Better control of thicknesses

Better control of chemical composition

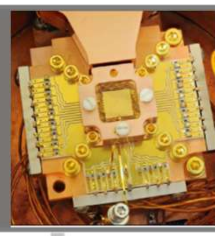
Better control of critical dimensions



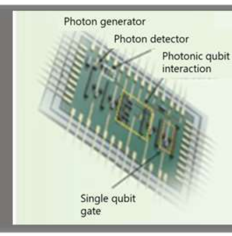

**Superconductors**



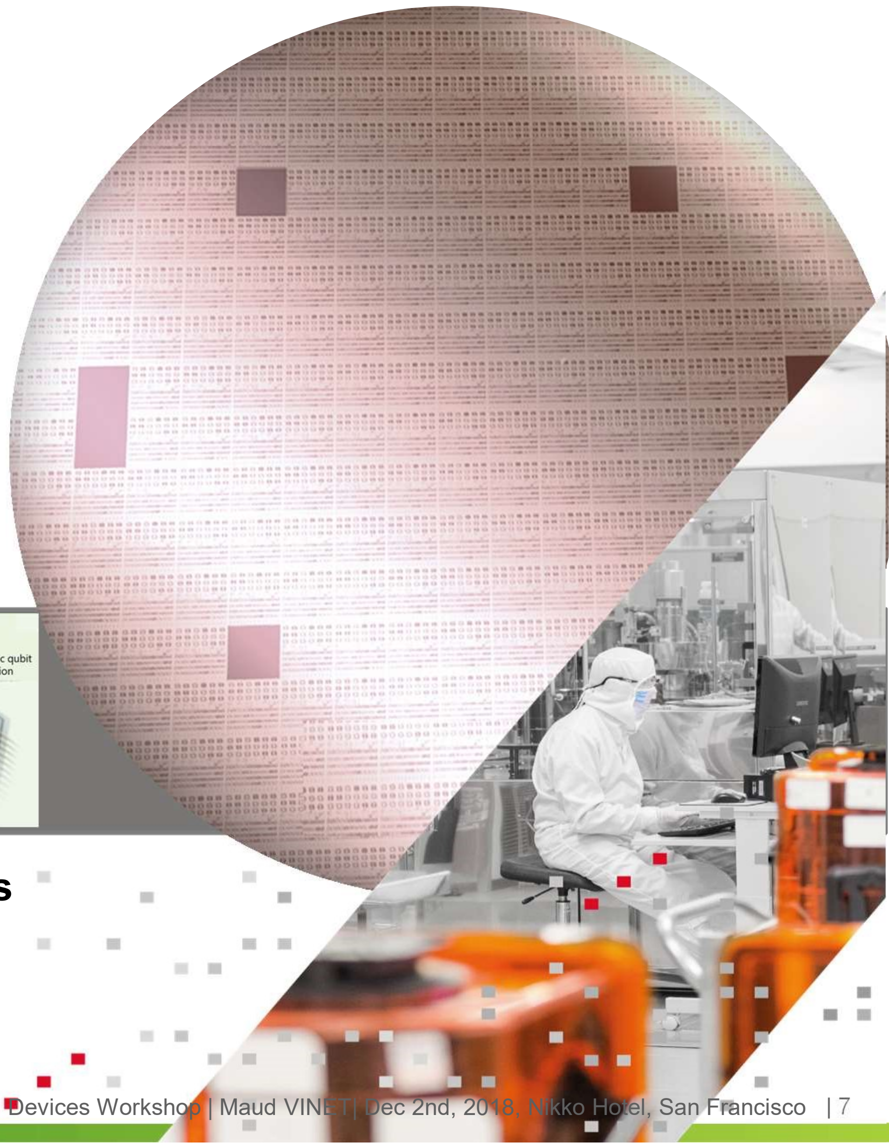

**Semiconductors**



**Trapped ions**



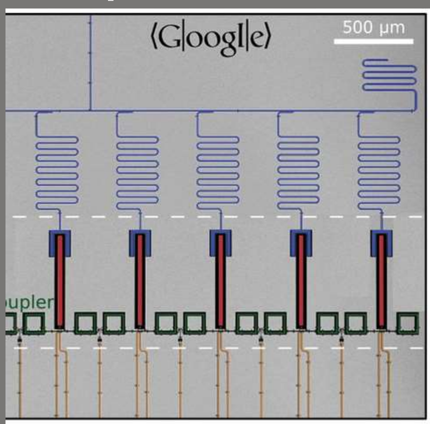

**Photons**



# REQUIRED FOR ALL TECHNOLOGICAL PLATFORMS

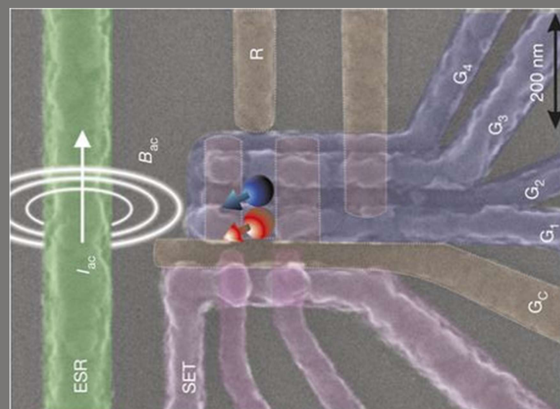
| Superconductors | Silicon spins | Trapped ions | Photons |
|---|---|---|---|

**Superconductors**



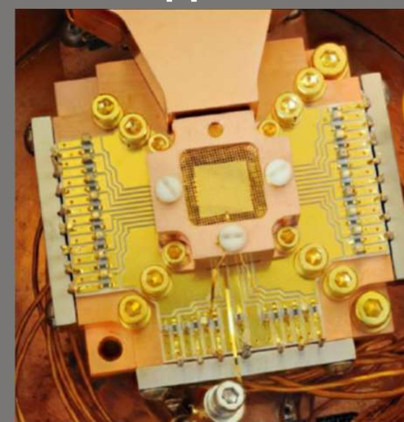

Yield and variability control

**Silicon spins**



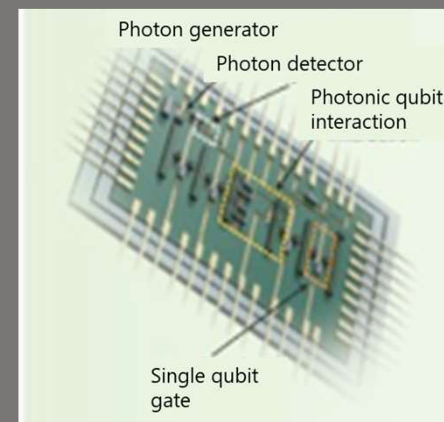

Yield and variability control

**Trapped ions**



Better interfaces

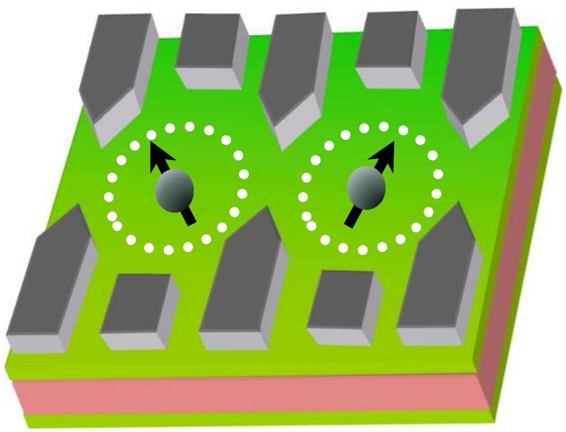
**Photons**




Integration of all components

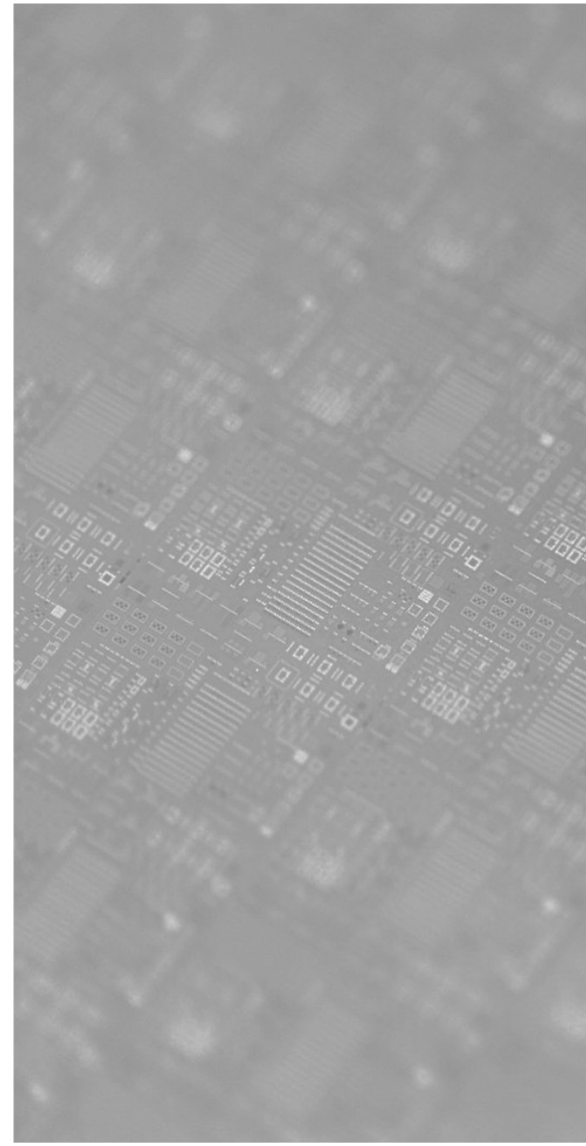
## SILICON QUBIT

# Spin degree of freedom of an electron



$$0 \rightarrow |\uparrow\rangle$$
$$1 \rightarrow |\downarrow\rangle$$

Gate defined quantum dots



## QUBIT FIGURES OF MERIT

- Speed ✓
- Fidelity ✓
- Size ✓

# Large ensemble of qubits


Variability

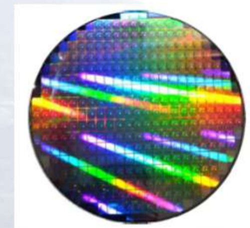
Large scale control

?

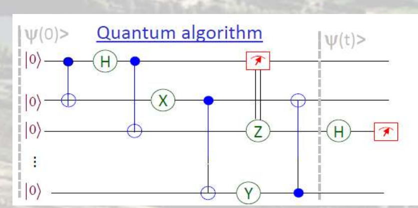
# GRENOBLE MULTIDISCIPLINARY SKILLS

### CMOS Device physics
Spin and charge properties of Si CMOS devices

### VLSI technology
Advanced CMOS integration
IC design and architecture

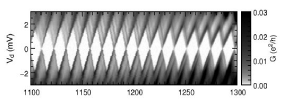


### Quantum engineering
Coherent control of electron spins in semiconductors

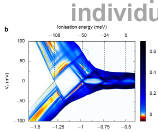


# GRENOBLE LONG STANDING EFFORTS TOWARDS SILICON QUANTUM COMPUTING

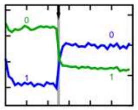
## Key dates



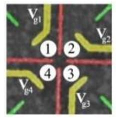
**2007**
Control of Si CMOS quantum devices



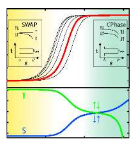
**2010**
Spectroscopy of individual dopants in si CMOS nanodevices



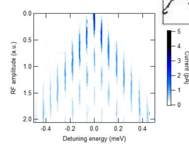
**2011**
Control displacement of individual electrons



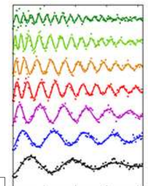
**2012**
2x2 array electron control



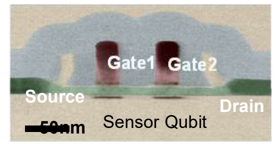
**2011**
Fast Cphase protocol for individual electron spins



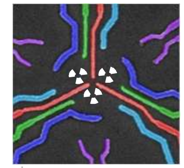
**2013**
Coherent control on two dopants



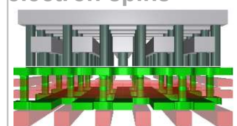
**2015**
Symmetric exchange of a spin between 2 electrons



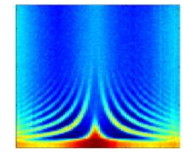

**2016**
First CMOS Qubit



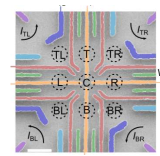
**2017**
Coherent shuttling of individual electron spins



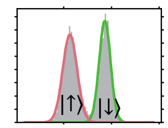
**2017**
3D integration for electron spin qubits patents



**2018**
Spin entanglement at distance in semiconductor quantum devices




Electrons filling in a 9 dot array

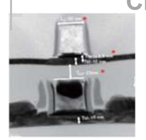


**2018**
High fidelity spin read-out in Si CMOS devices

90s | 00s | 10s

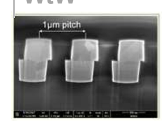
## Key technological assets

**2011**
Demonstration Lg = 50nm Si/Si CMOS

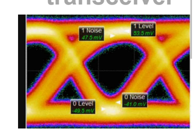


**2016**
First 300mm monolithic 3D integration

**2017**
Demonstration of 1µm pitch WtW




**2018**
10Gbit/s photonic transceiver



## Key fundings

**2007**
Poesi Electron pumps for metrology)

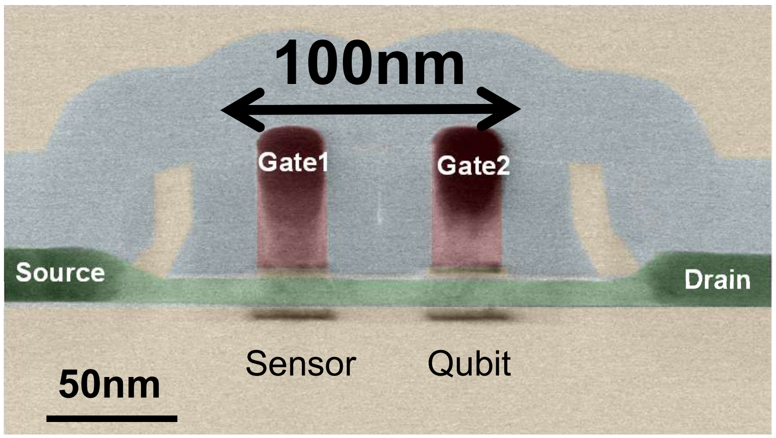
**2009**
AFSID Atomic functionalities in Si devices)

**2013…2015**
SIAM
SISPIN
TOLOP

**2016**
MOSQUITO

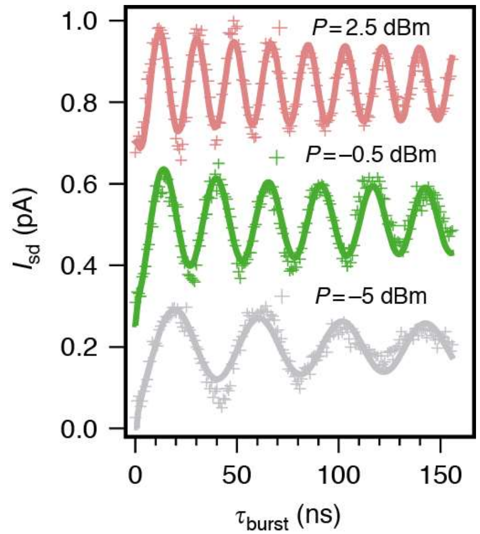
**2018**
ERC QuCube

# 1ST CMOS SPIN QUBITS (OUR WORK)




**Single qubit gate**

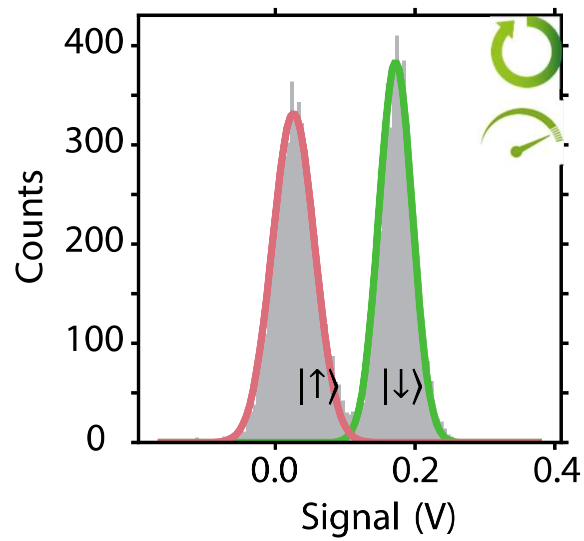
*Maurand, Nat. Comm. (2016)*
*Hutin, VLSI (2016)*




Manipulation time 20ns

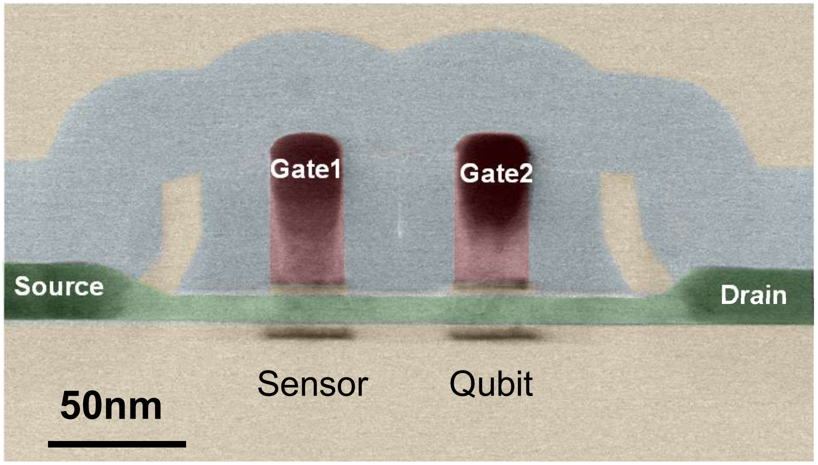
**High fidelity RF scalable spin read-out**

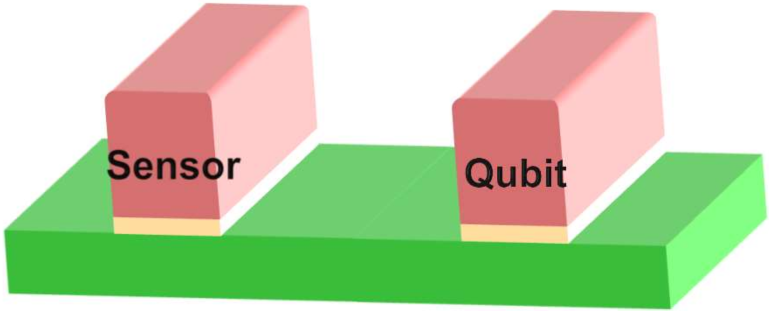
*Urdampilleta (to be published)*

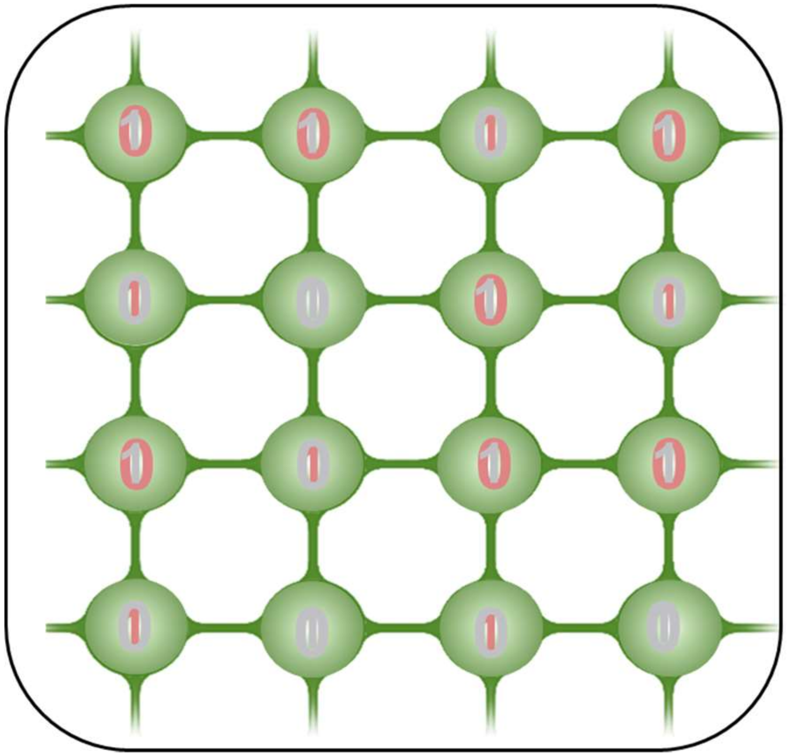



Fidelity > 99%

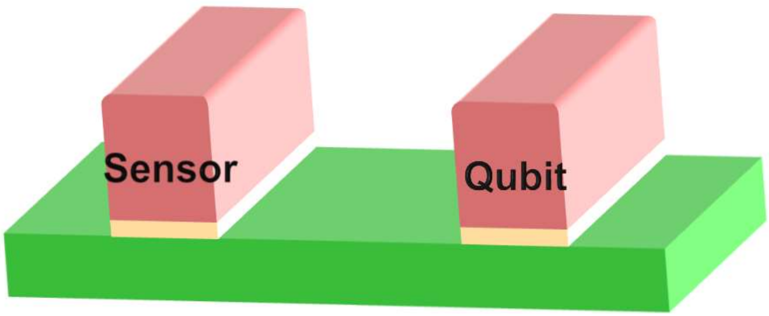
# NEXT STEP: SCALABILITY?



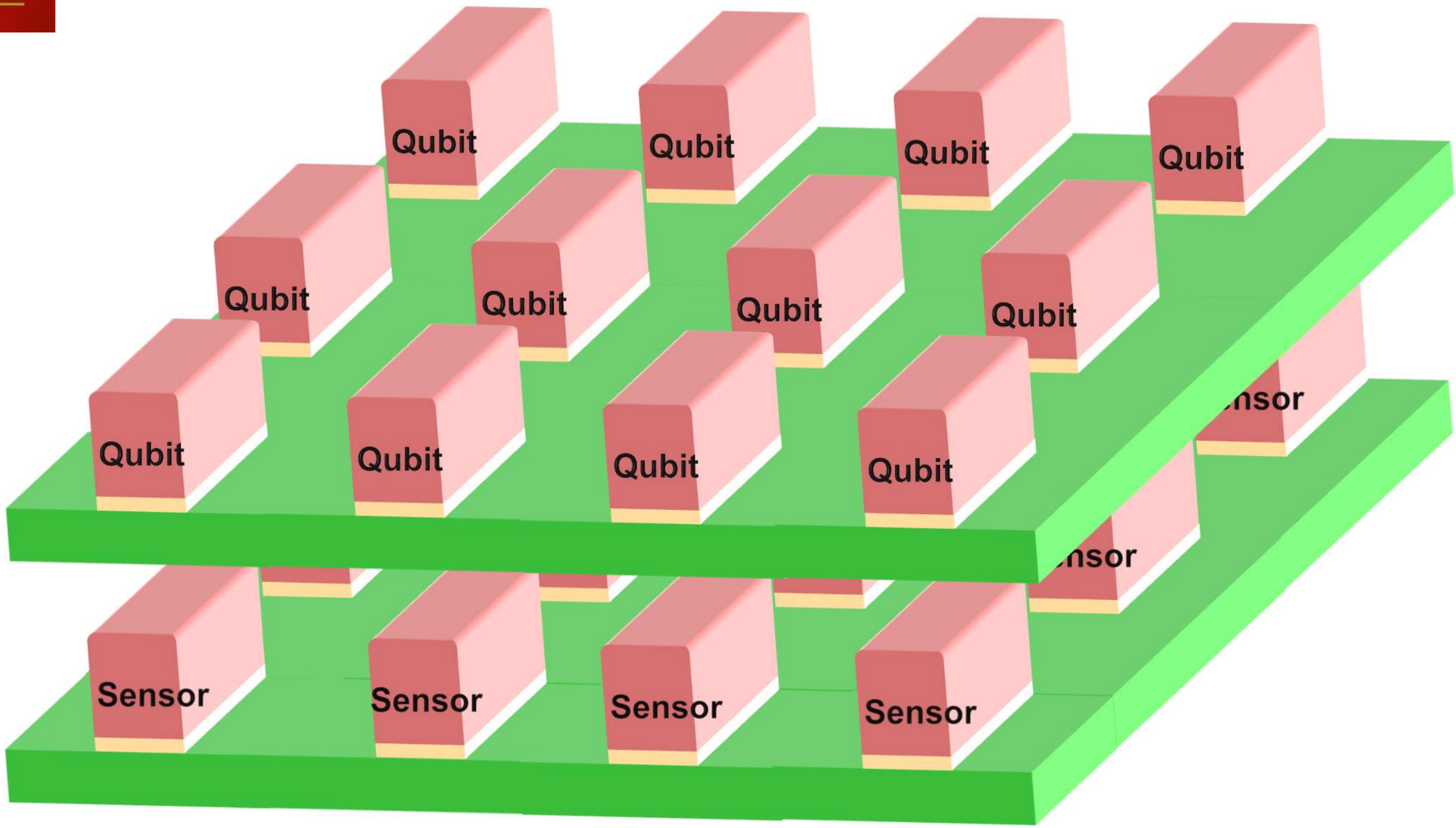



# NEXT STEP: SCALABILITY?

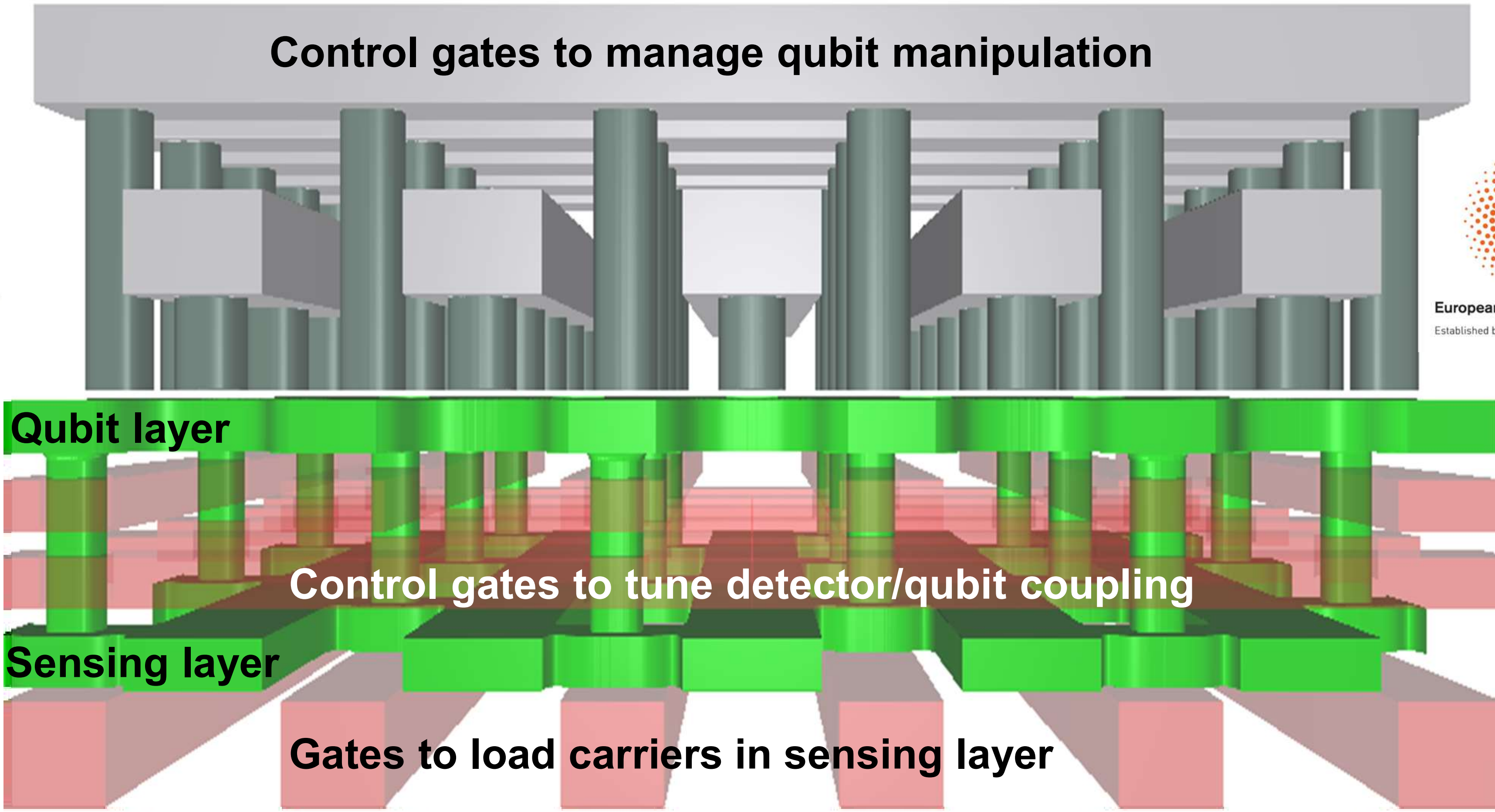


## NEXT STEP: SCALABILITY



# QUCUBE CONCEPT

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



# MORE TECHNICAL DETAILS DURING THE CONFERENCE

2:00 PM - 2:25 PM

**7.2 Breakthroughs in 3D Sequential Technology,** *L. Brunet, C. Fenouillet-Beranger, P. Batude, S. Beaurepaire, F. Ponthenier,2, N. Rambal,2, V. Mazzocchi, J-B. Pin**, P. Acosta-Alba, S. Kerdiles, P. Besson*, H. Fontaine, T. Lardin, F. Fournel, V. Larrey, F. Mazen, V. Balan, C. Morales, C. Guerin, V. Jousseaume, X. Federspiel*, D. Ney*, X. Garros, A. Roman,2, D. Scevola,2, P. Perreau, F. Kouemeni-Tchouake, L. Arnaud, C. Scibetta, S. Chevalliez, F. Aussenac, J. Aubin***, S. Reboh, F. Andrieu, S. Maitrejean, M. Vinet, CEA-LETI, *STMicroelectronics, **Applied Materials Inc., *** SCREEN LASSE*

3:40 PM - 4:05 PM

**6.5 Towards scalable silicon quantum computing (Invited),** *M. Vinet, L. Hutin, B. Bertrand, S. Barraud, J.-M. Hartmann, Y.-J. Kim, V. Mazzocchi, A. Amisse, H. Bohuslavskyi, L. Bourdet*, A. Crippa*, X. Jehl*, R. Maurand*, Y.-M. Niquet*, M. Sanquer*, B. Venitucci*, B. Jado**, E. Chanrion**,P.-A. Mortemousque**, C. Spence**, M. Urdampilleta**, S. De Franceschi* and T. Meunier**, Université Grenoble Alpes, *CEA, LETI, **CNRS*

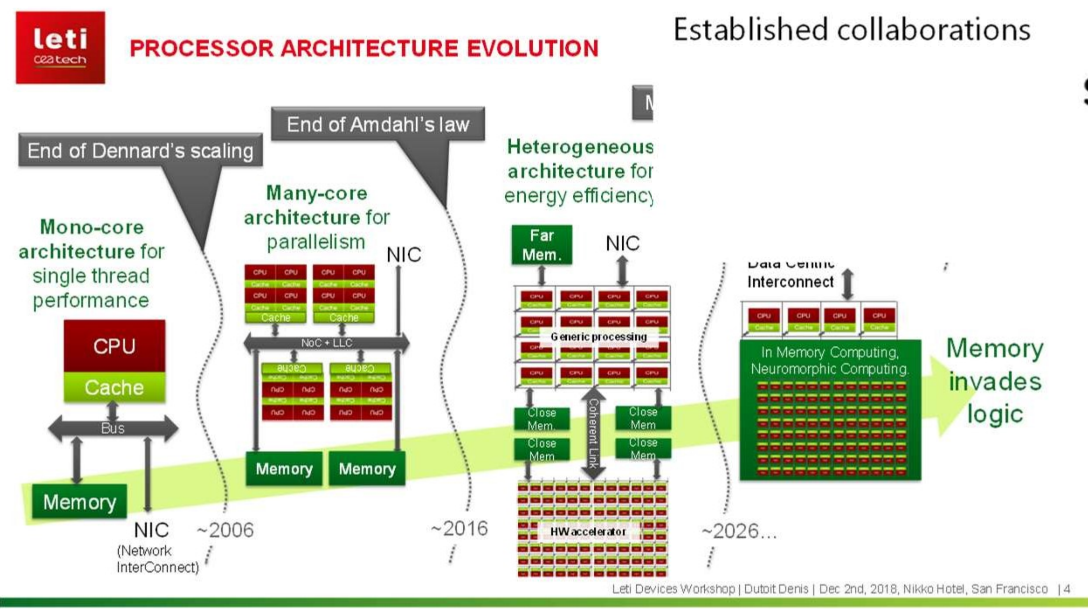
# CONCLUSION

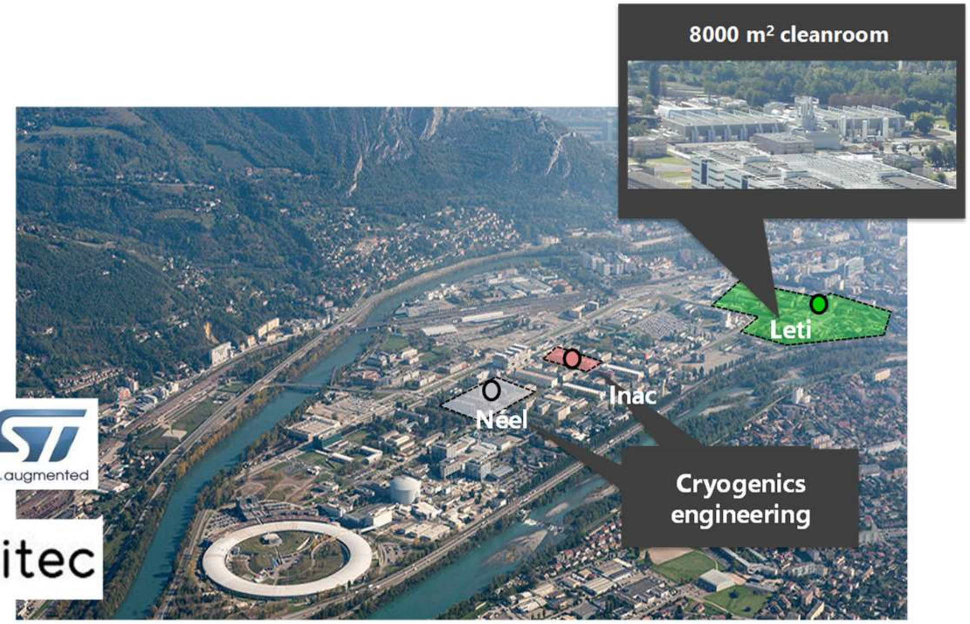
Geographic proximity

Exceptional co-location facilities

Unique ecosystem

Established collaborations

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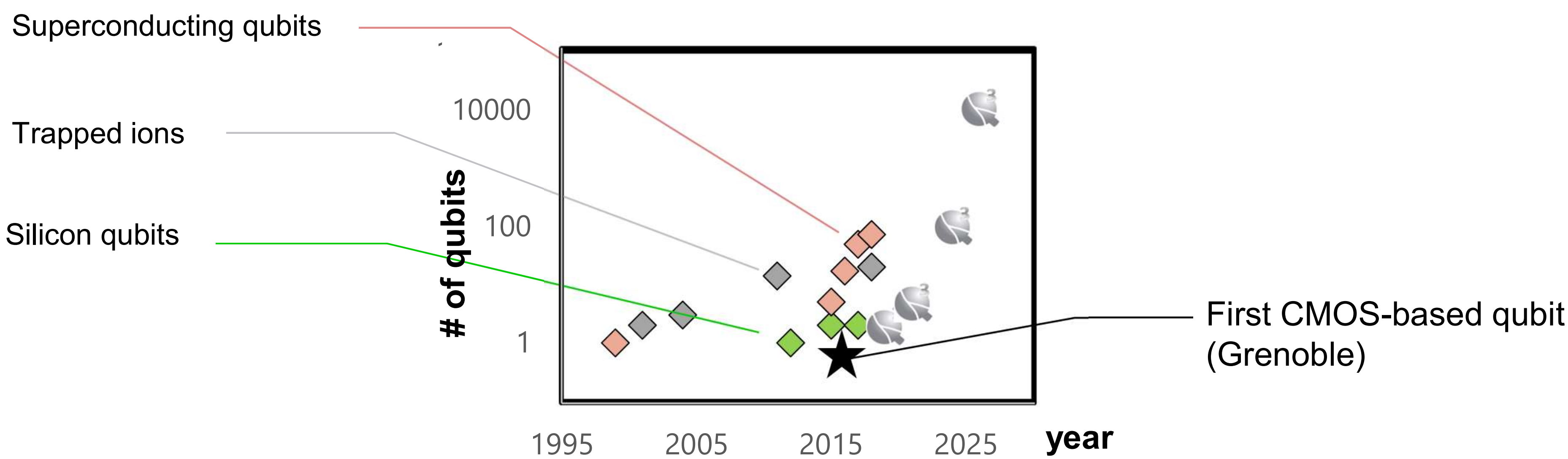
Quantum Engineering
Univ. Grenoble Alpes

## CONCLUSION

We are willing to open a viable path to large-scale qubit integration




Create vast opportunities for the industrial ecosystem

- Semiconductor industry
- Software industry

leti
cea tech

INAC
INSTITUT NANOSCIENCES
ET CRYOGÉNIE

NÉEL
institut

UNIVERSITÉ
Grenoble
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# Thank you!

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