INSTITUT POLYTECHNIQUE DE PARIS

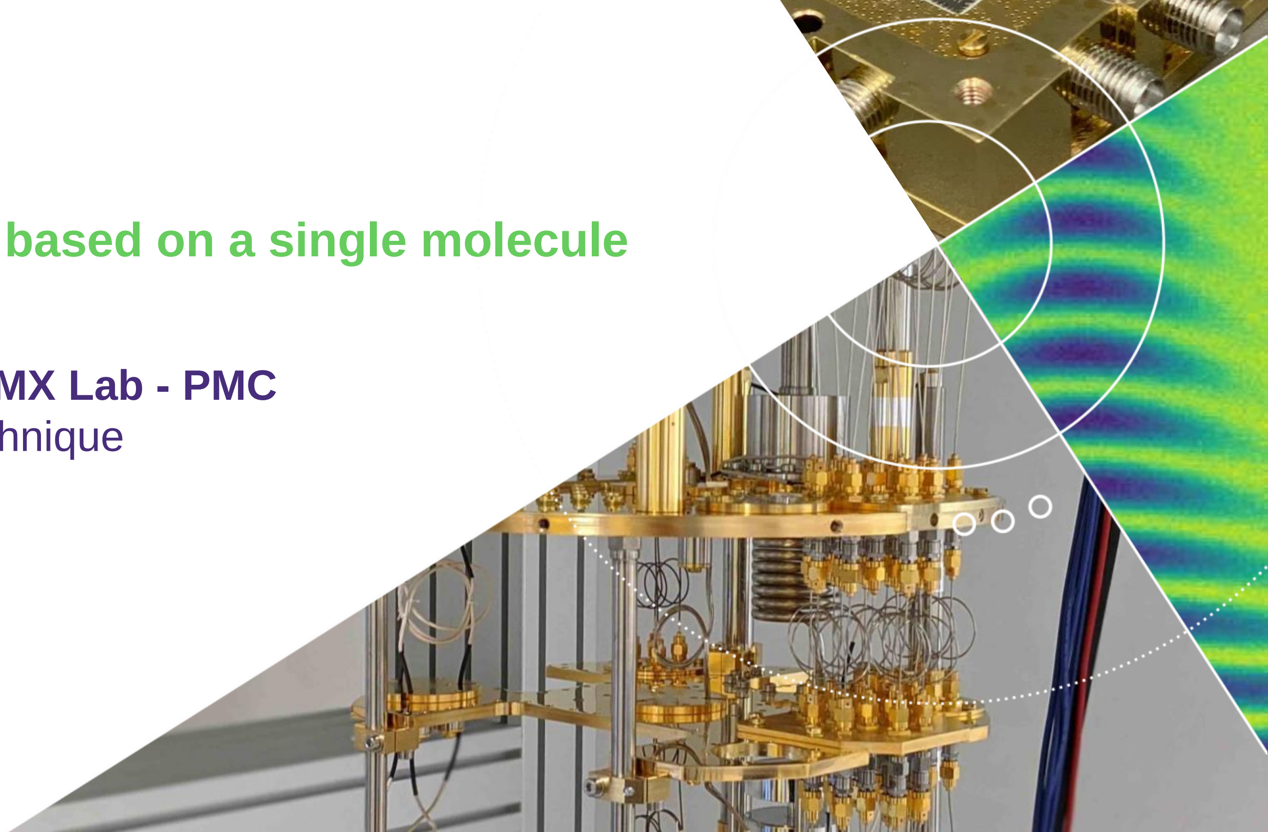
ÉCOLE POLYTECHNIQUE

LABORATOIRE PMC

cnrs

Superconducting qubit based on a single molecule
The nanotube gatemon

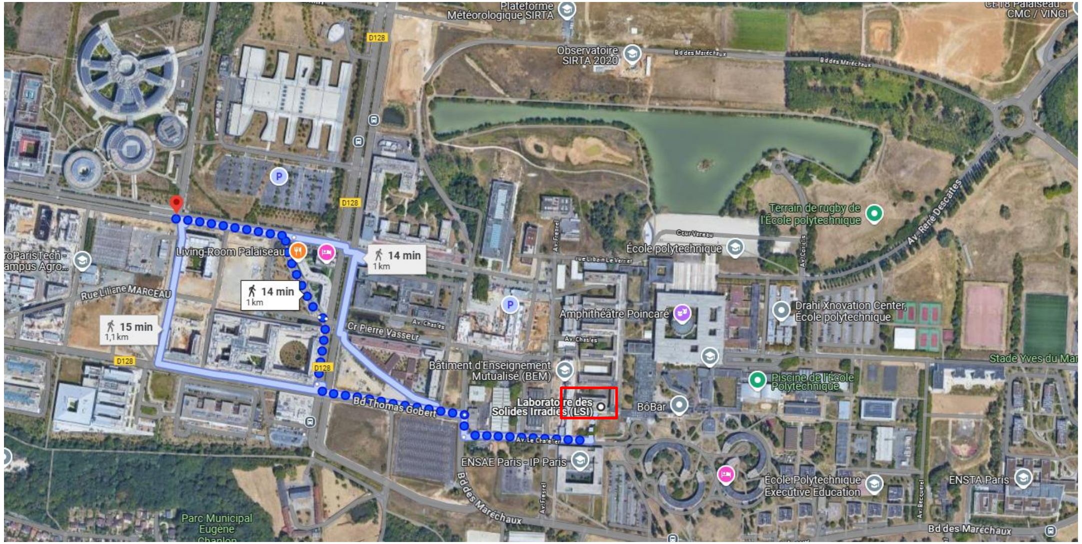
Jean-Damien PILLET - QCMX Lab - PMC
Professeur à l’Ecole Polytechnique



RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

ip-paris.fr

Where we are



QCMX Lab
PMC, X

Bâtiment 83

1er étage

83-20-20

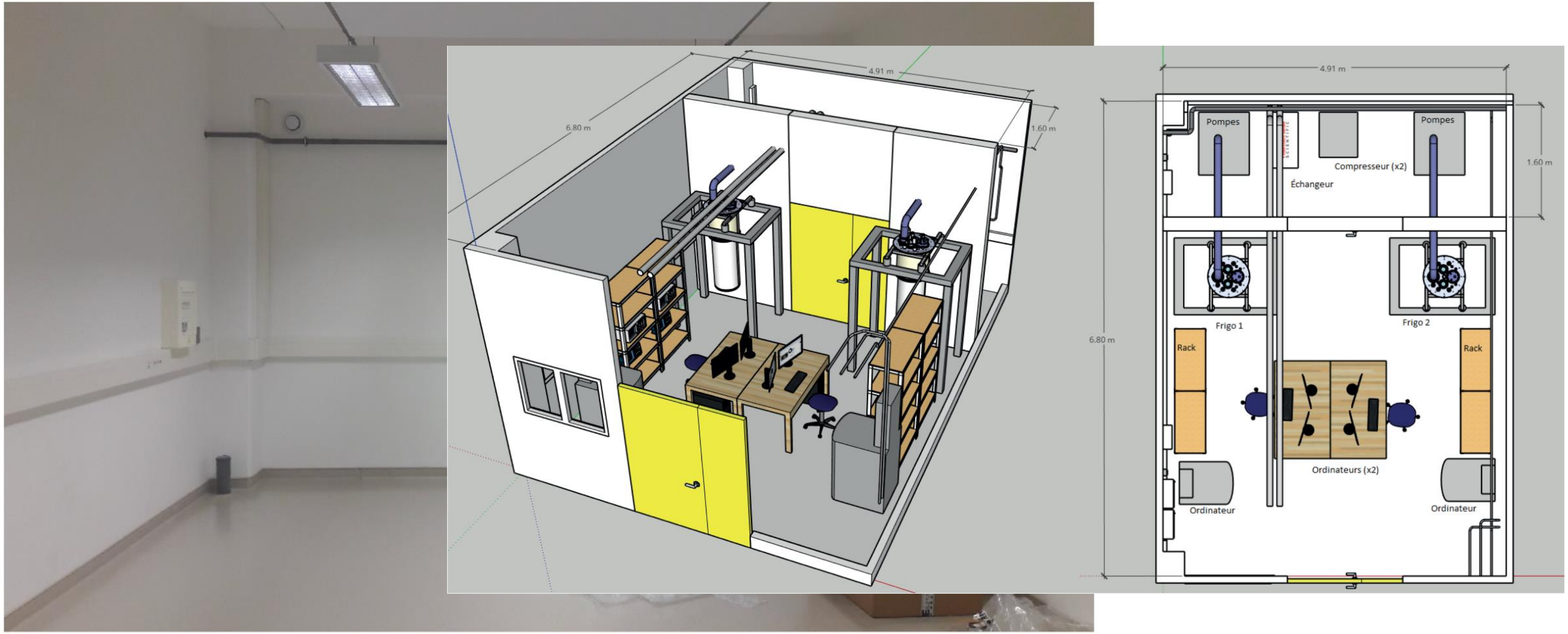
The QCMX Lab (2017)

J.-D. Pillet

L. Bretheau

At the beginning, there was… two empty rooms and two physicists.

The QCMX Lab (2017)



The QCMX Lab (2018)

Construction work (masonry, plumbing, electricity)

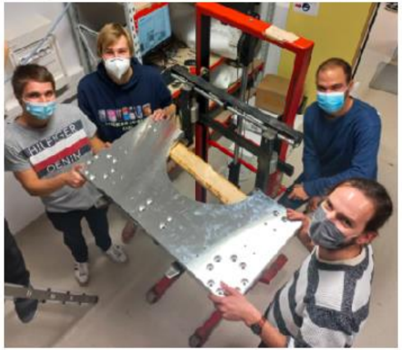
Help of P.-E. Coulon ,
B. Konate & DPI

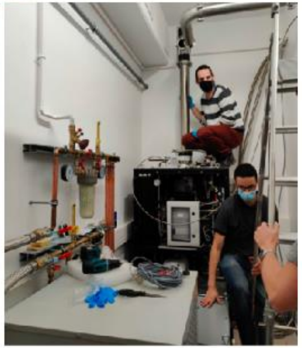
The QCMX Lab (2019)

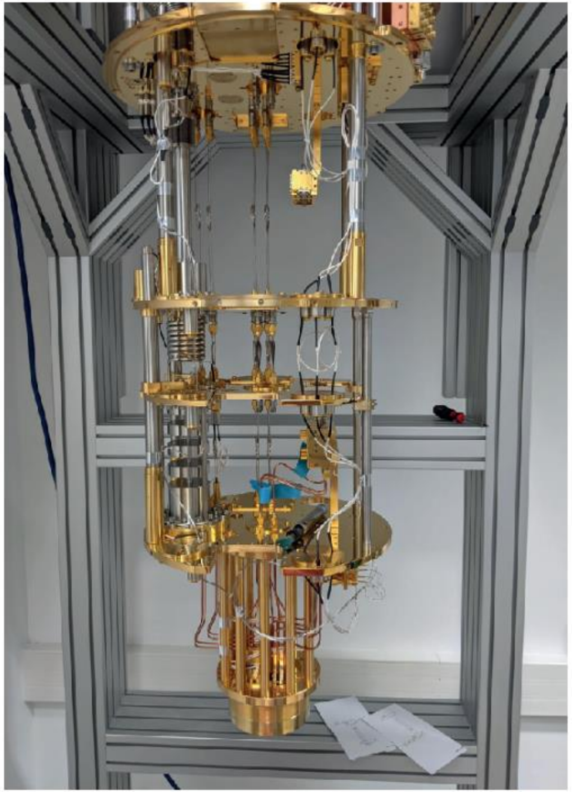
Cryogen-free dilution refrigerator (7 mK) + **Electronics instruments**

The QCMX Lab (2021)

2nd Cryostat (10 mK, 1T / 1T / 3T, bottom loader)







Preparation room

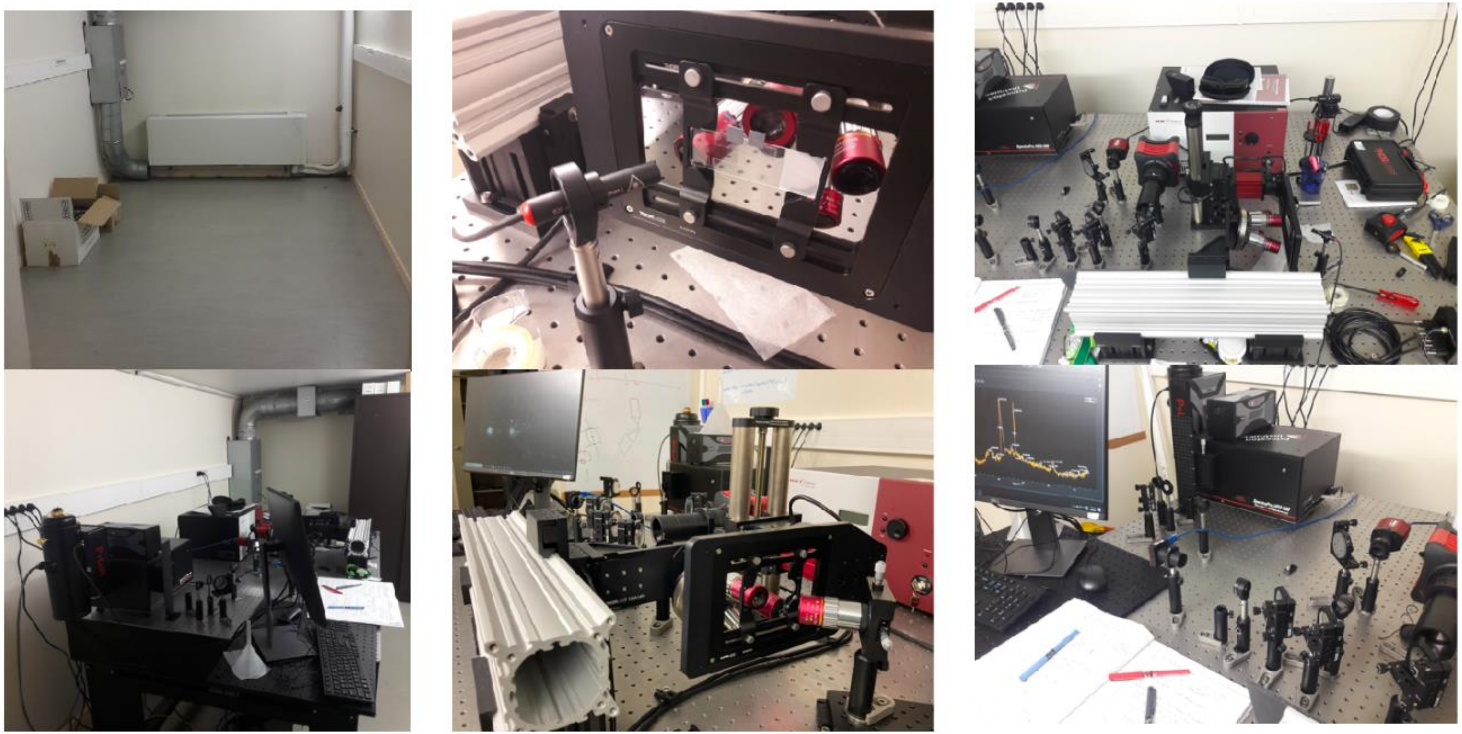
Wirebonding machine + fume hood

Microscope + workshop + soldering

Furnace & gaz handling system

Carbon Nanotube Platform: Optical Characterization + Transfer

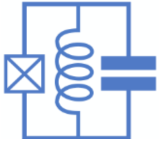
Supercontinuum laser, spectrometer, transfer station



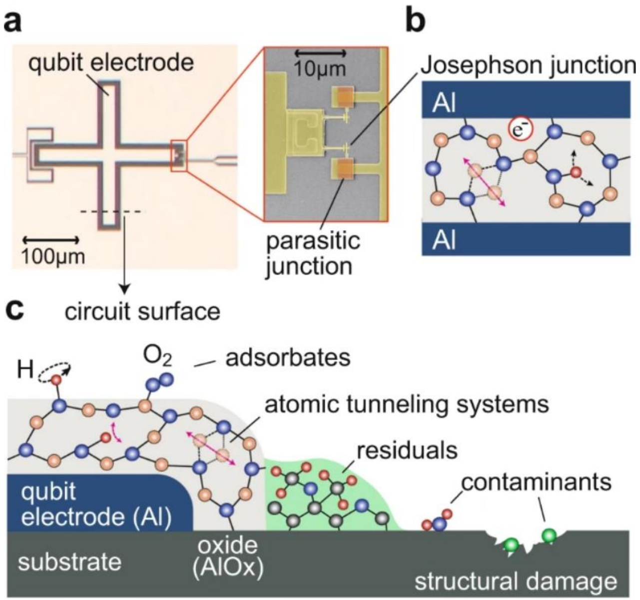
Everton Arrighi
Maxime Hantute
Landry Bretheau
Hannes Riechert
Joël Griesmar
Samy Annabi
Jean-Damien Pillet
Hadrien Duprez

Crédit: J. Barande

Qubit limitations related to materials and nanofabrication

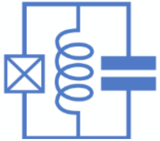


Superconducting qubits
Benjamin Huard's talk



[Lisenfeld et al. (KIT), npj QI 2019]

Qubit limitations related to materials and nanofabrication



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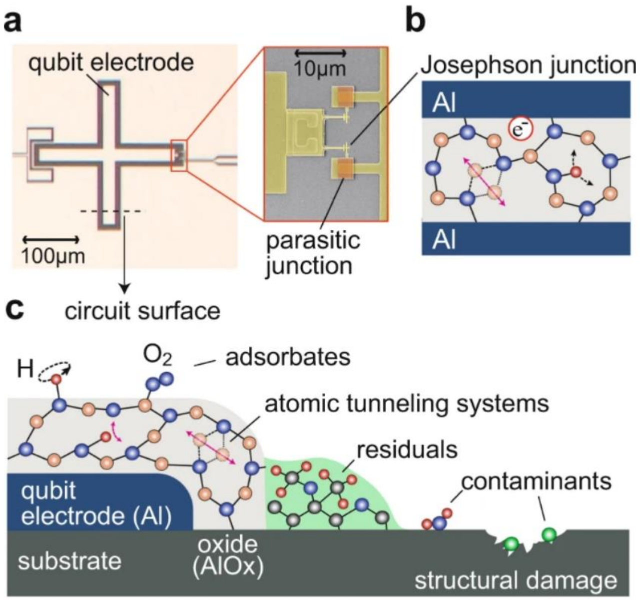
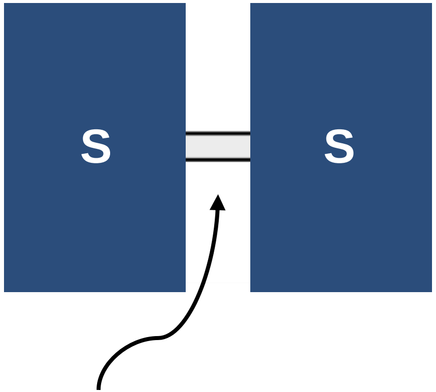
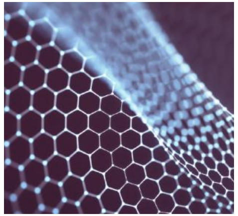
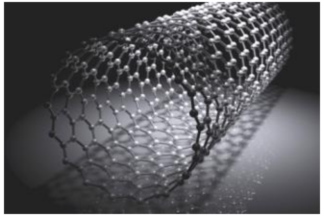
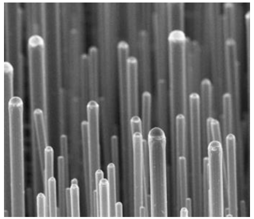


[Lisenfeld et al. (KIT), npj QI 2019]

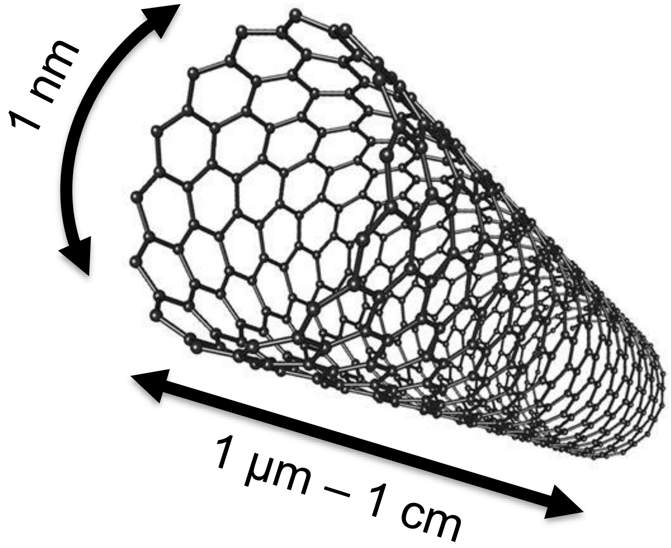
Hybrid Josephson junctions



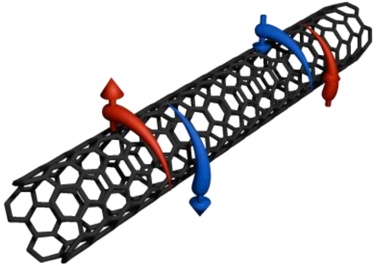
Perfectly crystalline quantum conductor
(graphene, carbon nanotube, nanowires…)

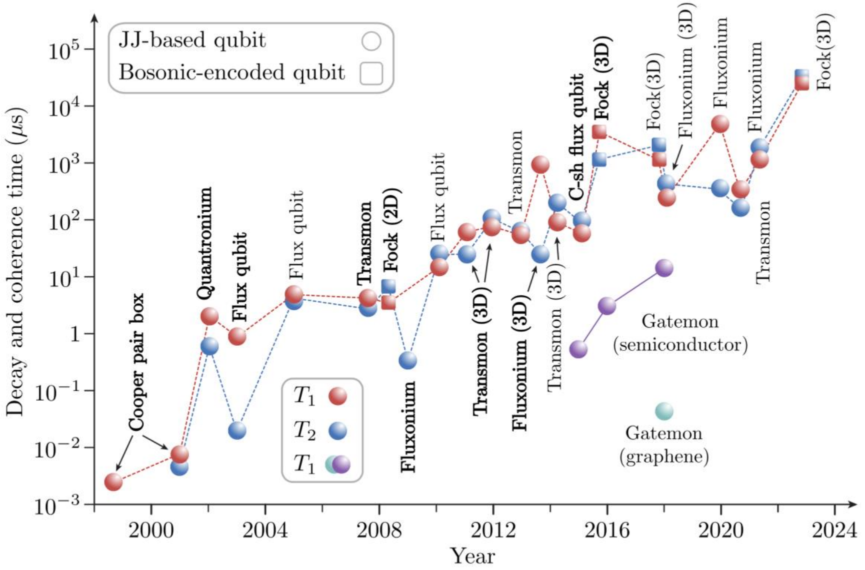
Hexagonal lattice of carbon atoms

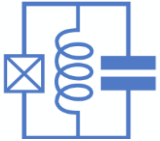


- Perfect crystalline coumpound
- Very few degrees of freedom
- Good electrical conductor
- Fundamentally interesting



Carbon Nanotube: a promising component for quantum bits ?

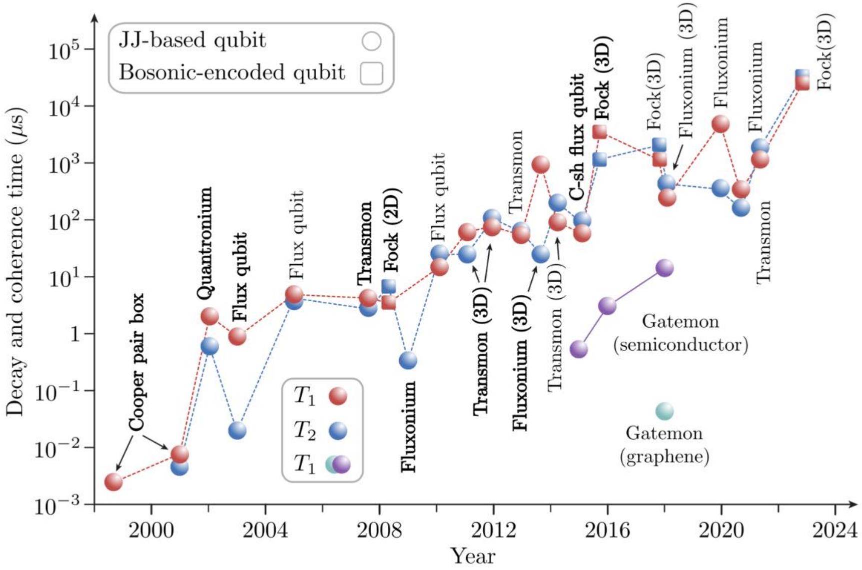


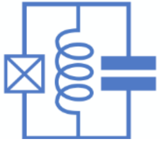


Superconducting qubits

Benjamin Huard's talk

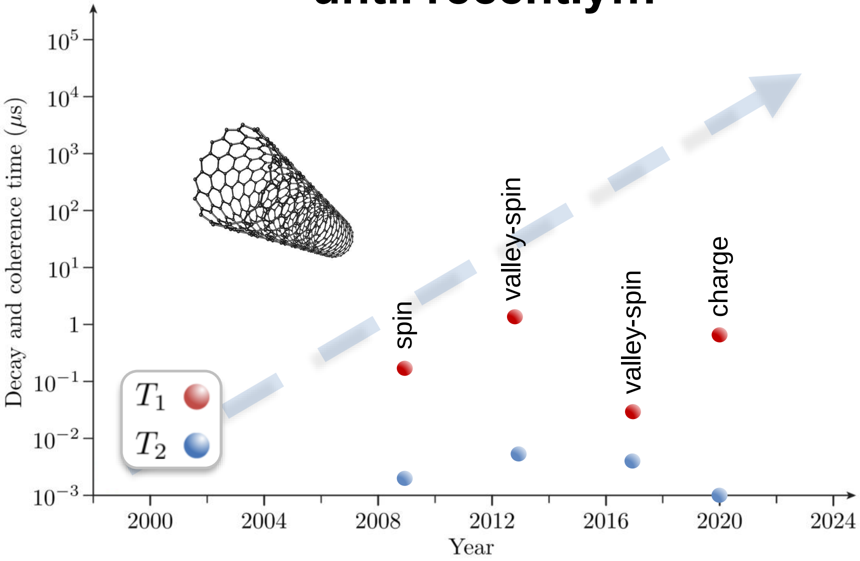
Carbon Nanotube: a promising component for quantum bits ?





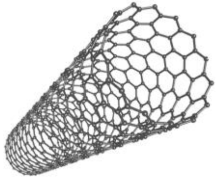
Superconducting qubits
Benjamin Huard's talk

Quantum control of nanotube qubit until recently…



Very low coherence time…
Limited by charge noise
⇒ Sample quality is too low

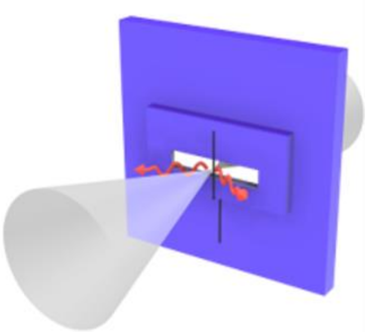
QCMX CNT-platform

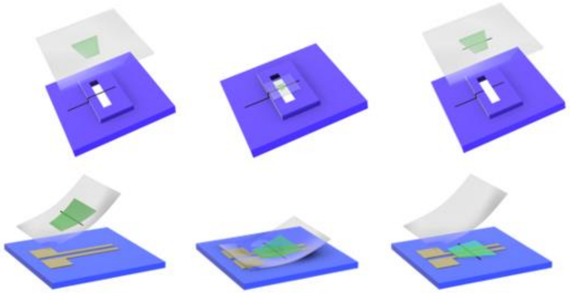


Growth

Characterization

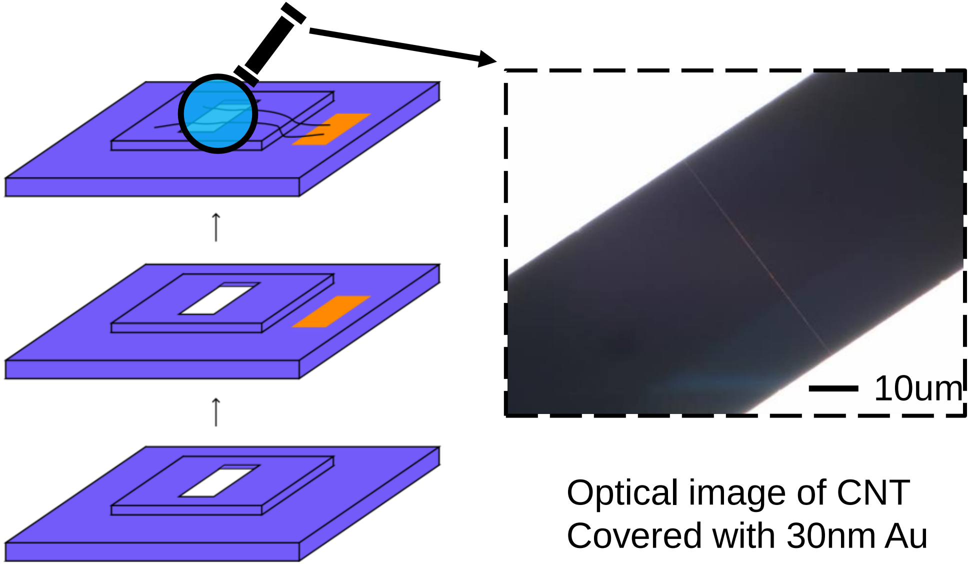
Integration by transfer





Growth of suspended carbon nanotubes

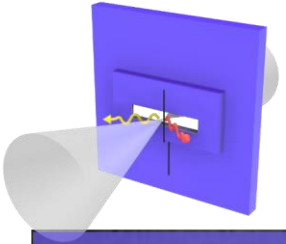
Furnace (~1000 °C) + Ar / H_2 / CH_4 flow

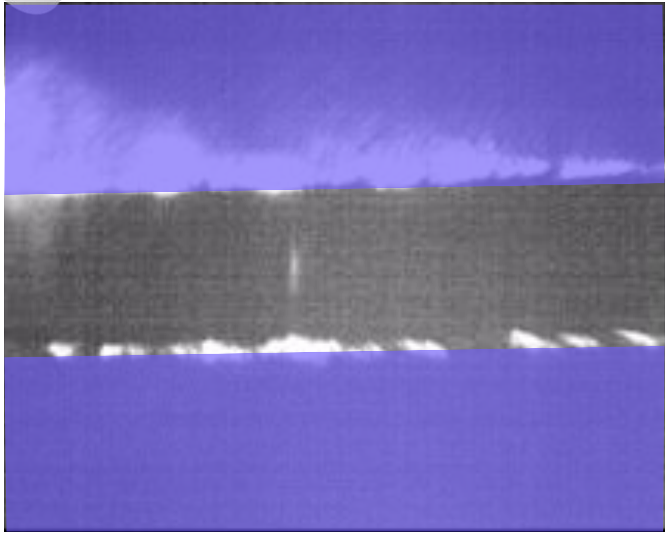


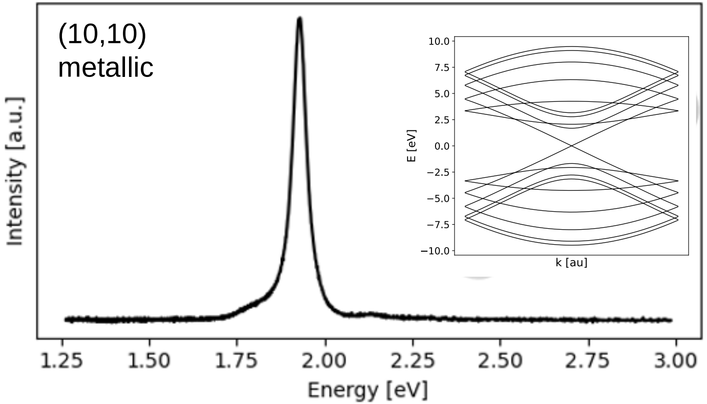
Optical image of CNT
Covered with 30nm Au

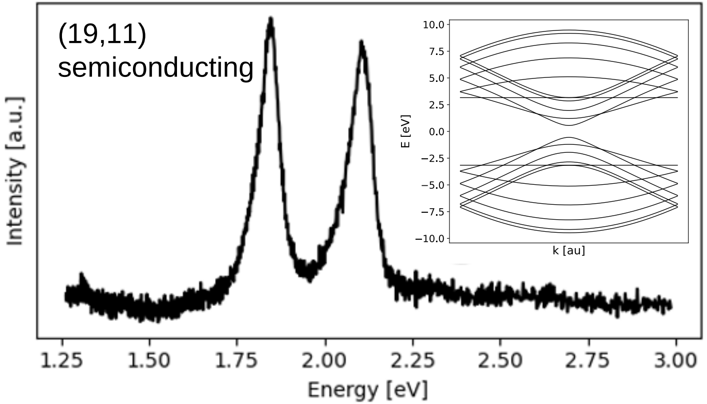
Optical characterization

Real time and real space imaging

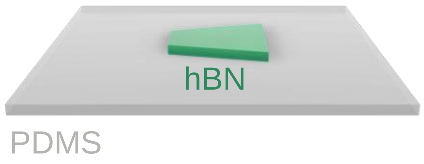


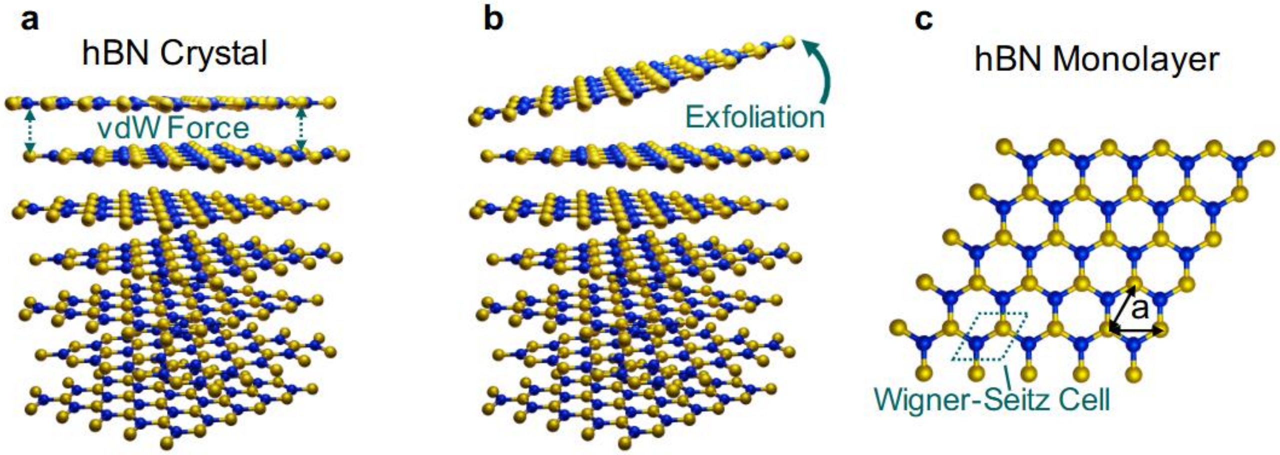






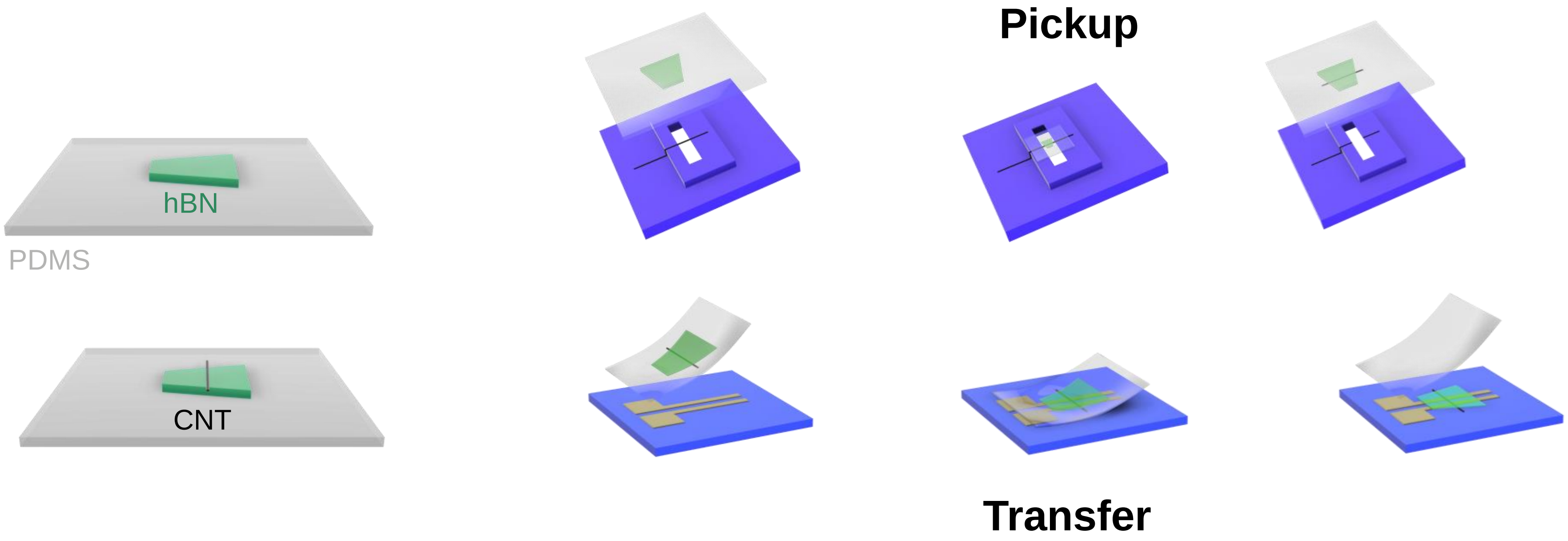
Using hexagonal Boron Nitride (hBN) as a perfectly crystalline substrate





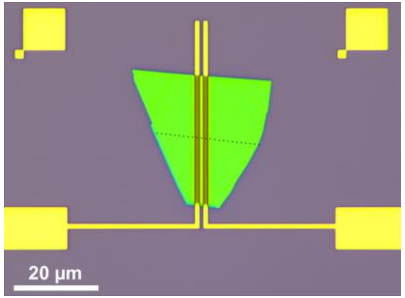
From Andreas Paul Gottscholl PhD thesis

Carbon nanotube integration



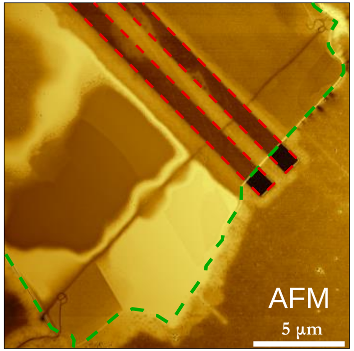
Help from: F. Cadiz, S. Park (LPMC), R. Ribeiro (C2N), A. Vecchiola (CNRS-THALES), *AdN SPEC (CEA Saclay), Watanabe & Taniguchi*

Ultraclean CNT-based superconducting devices



Substrate — hBN — Electrodes — CNT

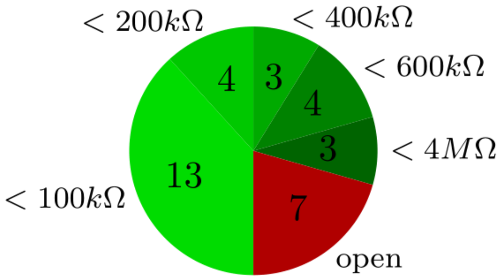
Superconducting (Nb)

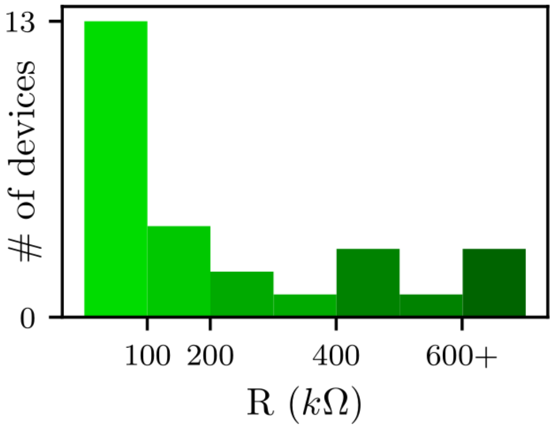


Electrodes

hBN

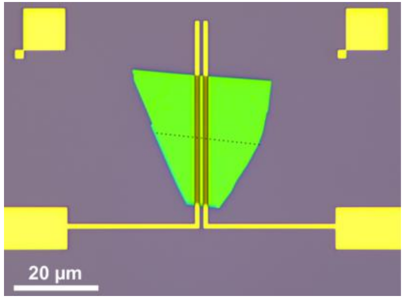
Succesful devices (40%)



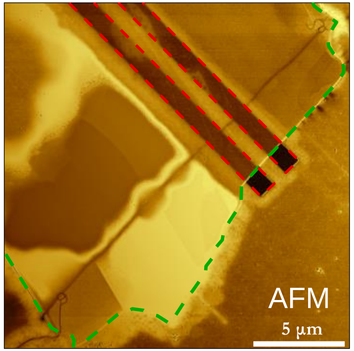


(pessimistic estimation)

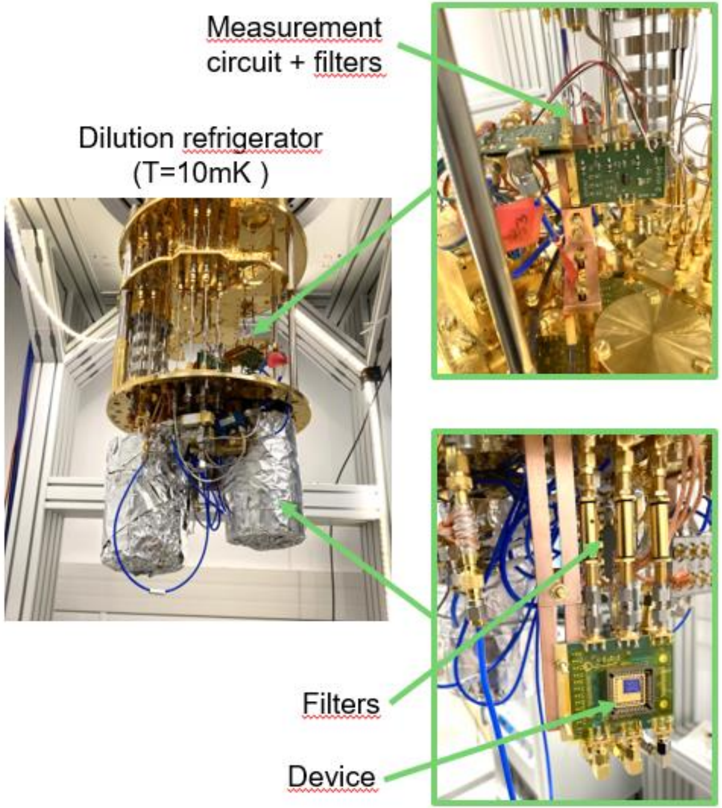
Ultraclean CNT-based superconducting devices



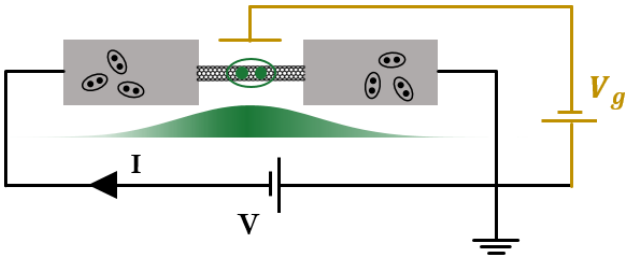
Substrate
hBN
Electrodes
CNT
Superconducting (Nb)

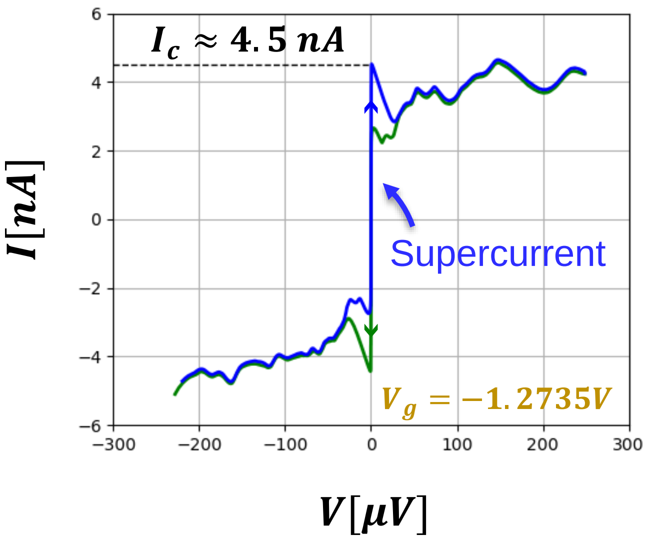


Electrodes
hBN

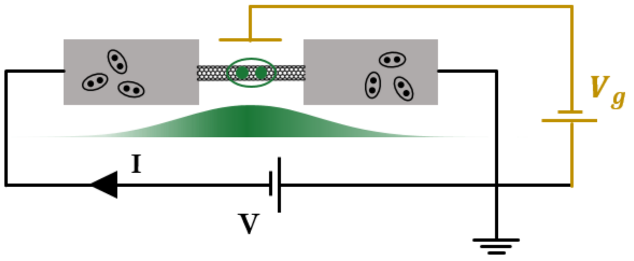


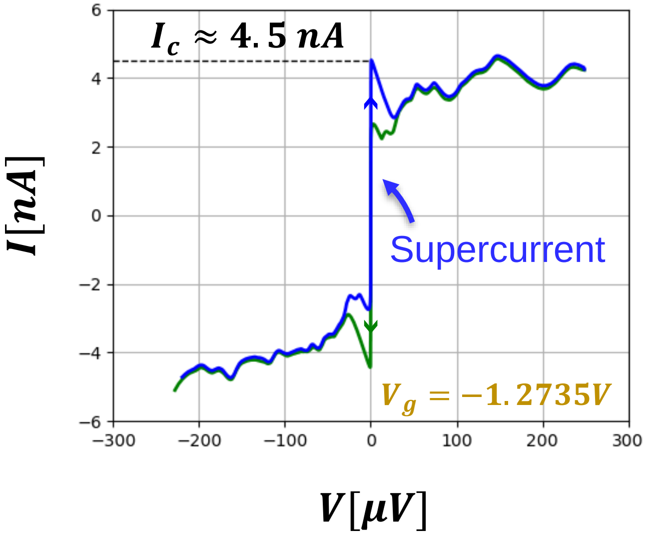
Superconducting single-electron transistor



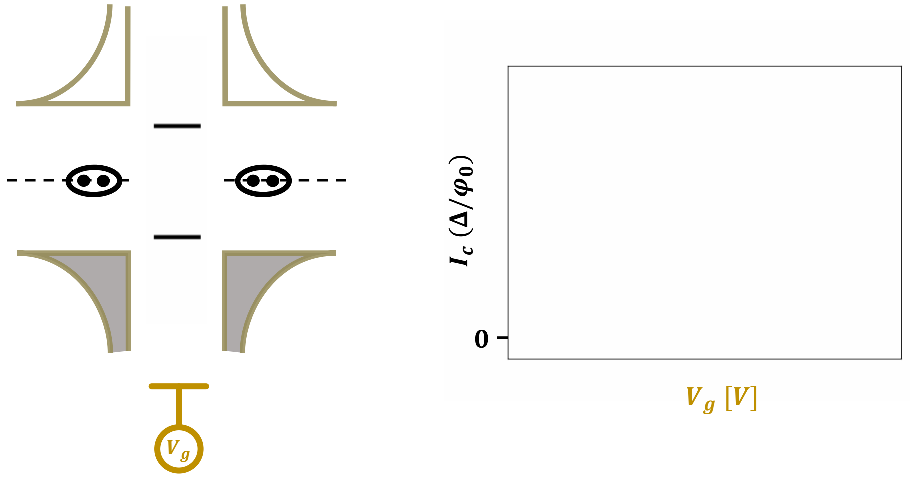


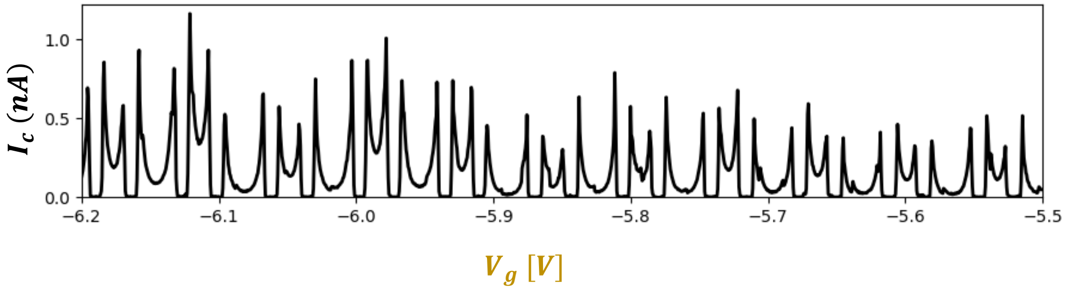
Superconducting single-electron transistor



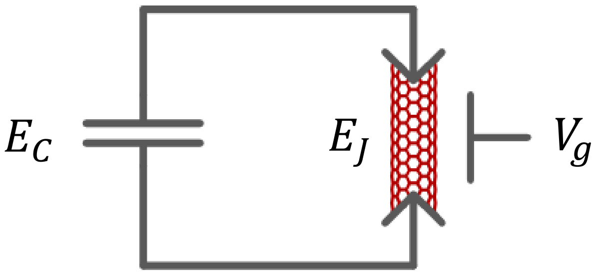


Gate tunable supercurrent



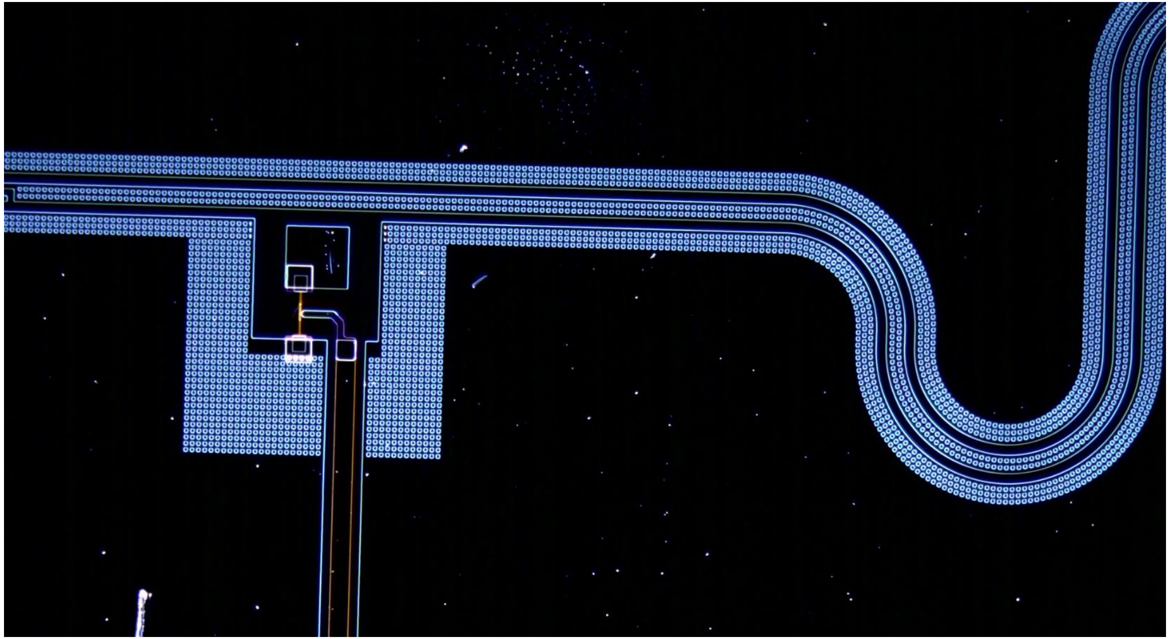


Nanotube gatemon
Gate tunable qubit



$$E_J \sim \varphi_0 I_c$$

$$\omega_q \approx \sqrt{8 E_C E_J}$$



Nanotube gatemon

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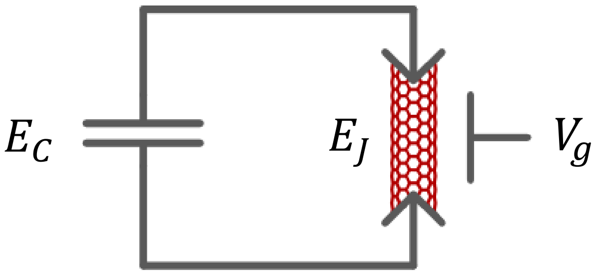
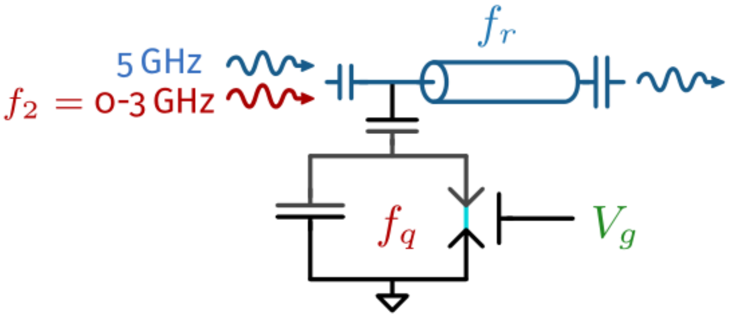


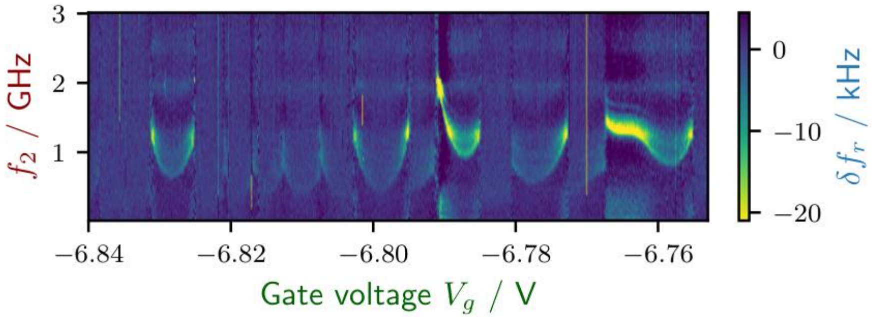
$$E_J \sim \varphi_0 \, I_c$$

$$\omega_q \approx \sqrt{8 E_C E_J}$$

cQED architecture



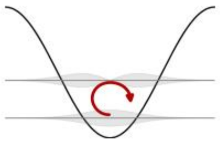
Qubit frequency

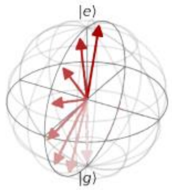


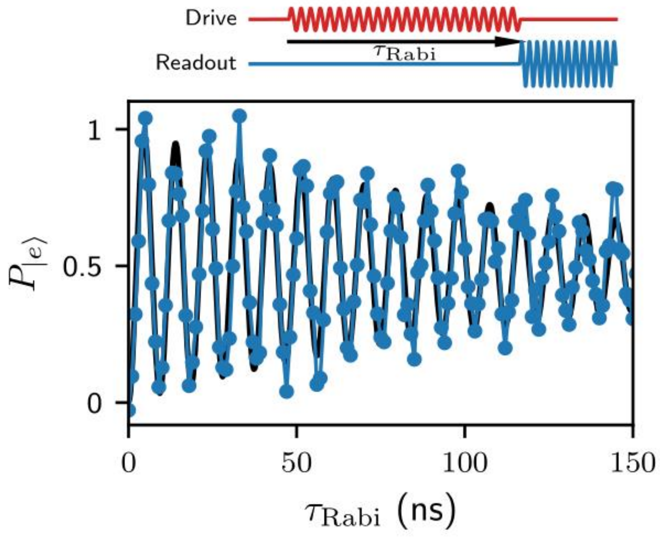
Coherent control

Rabi oscillations

Coherent oscillations between ground and excited state







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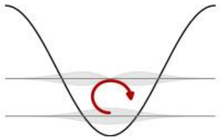
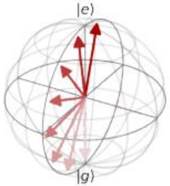
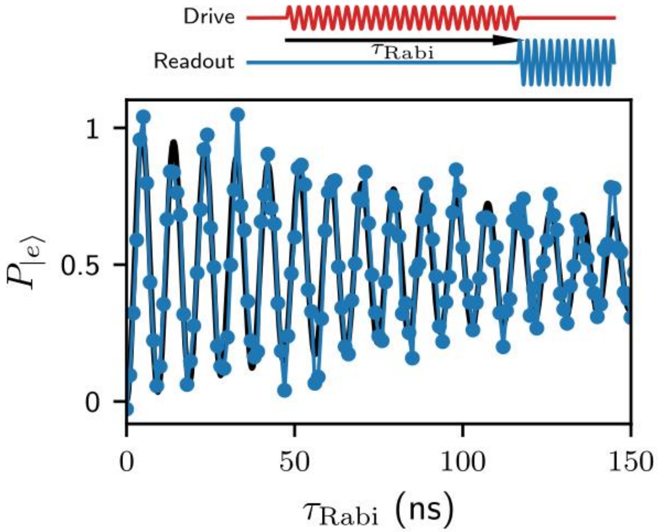
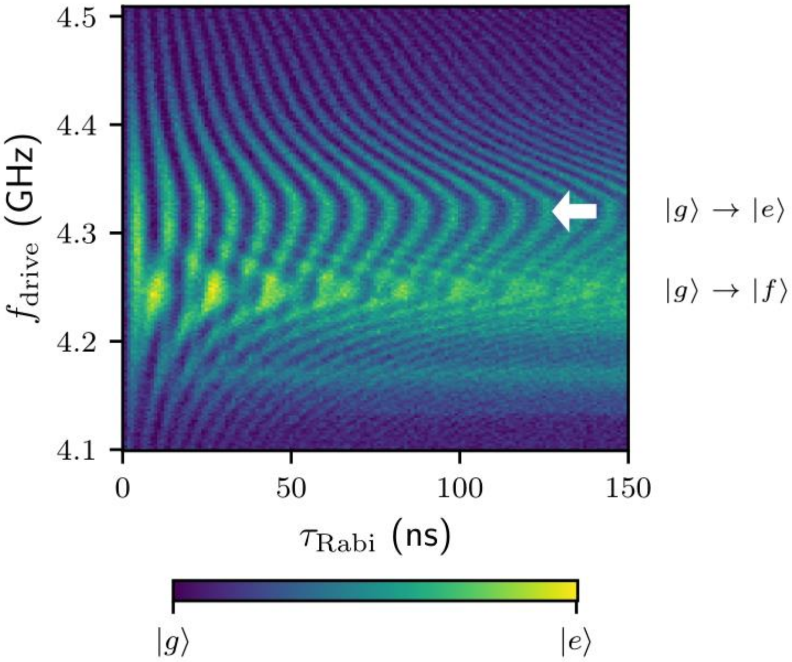
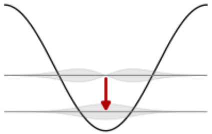




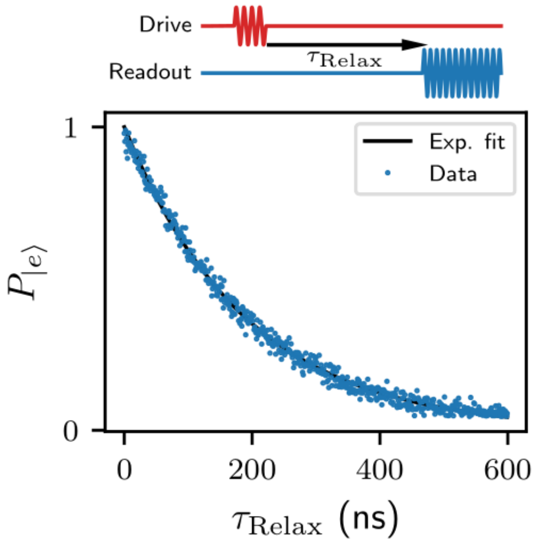






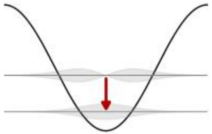
Relaxation

photon loss



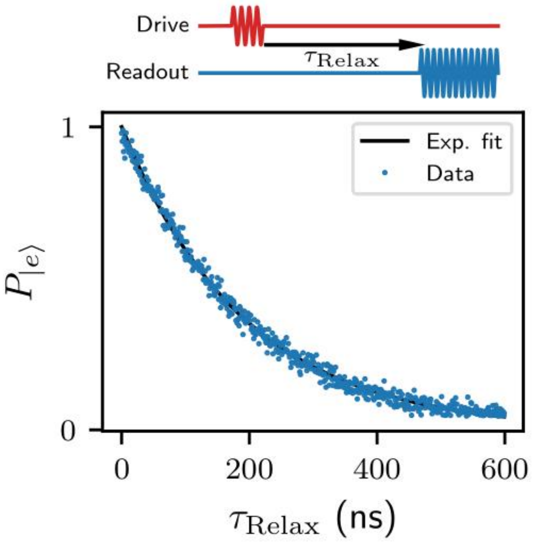
$$T_1 = (191 \pm 2)\,\mathrm{ns}$$

Coherent control



Relaxation

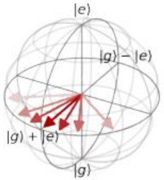
photon loss

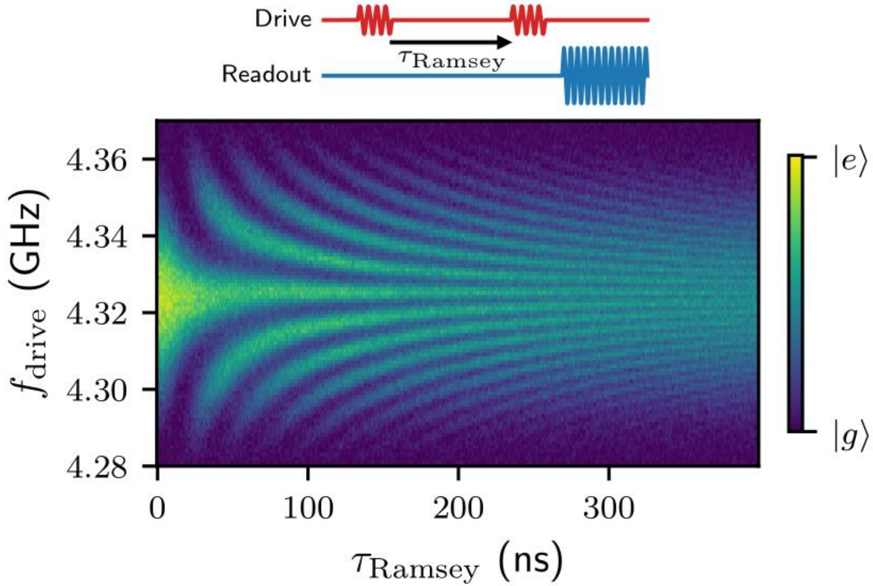


$T_1 = (191 \pm 2)\,\text{ns}$

Coherence time

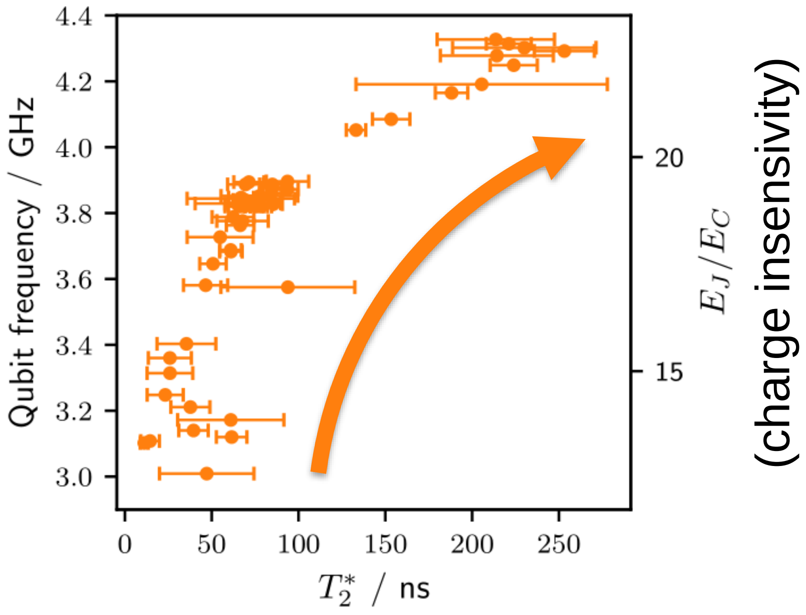
f_q fluctuations

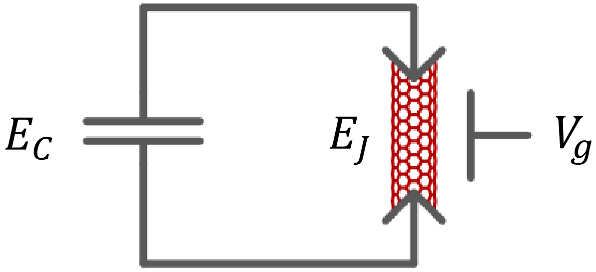




$T_2^* = (200 \pm 13)\,\text{ns}$

Increasing E_J/E_C
decreases charge sensitivity



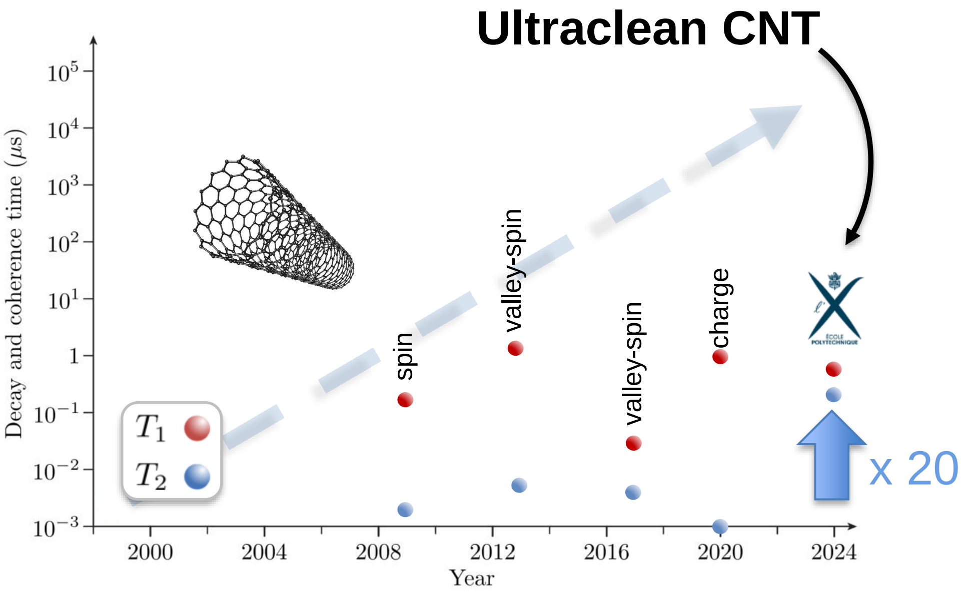


$$E_J \sim \varphi_0 \, I_c$$

$$\omega_q \approx \sqrt{8 E_C E_J}$$

There is no hard limit on E_J/E_C
⇒ We can increase T_2^* further !

Increasing coherence

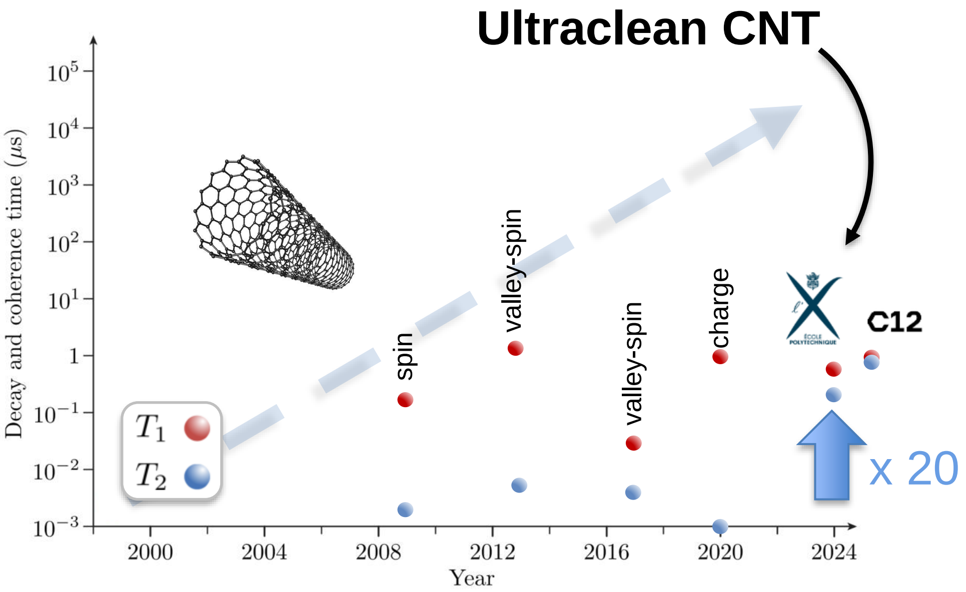


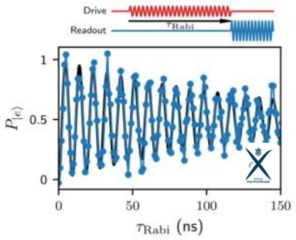
We gain **one order of magnitude on T_2^***

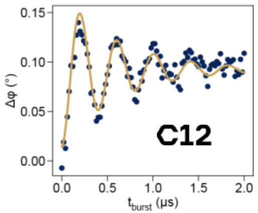
on the first attempt

Still limited by charge noise…

Increasing coherence





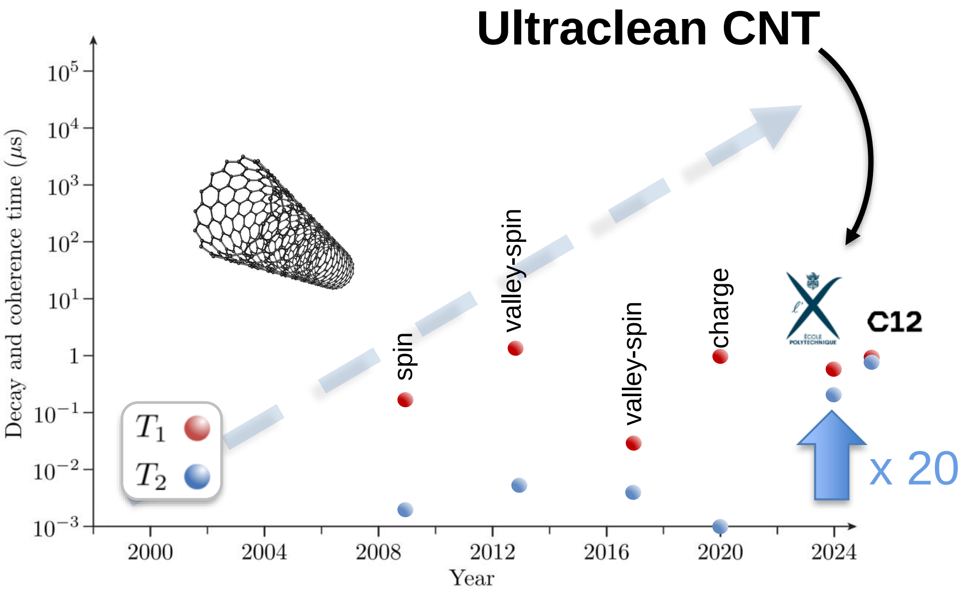


We gain **one order of magnitude on** T_2^*

on the first attempt

Still limited by charge noise…

Quentin Schaeverbeke's talk



We gain one order of magnitude on T_2^*
on the first attempt
Still limited by charge noise…

A lot of room for improvement

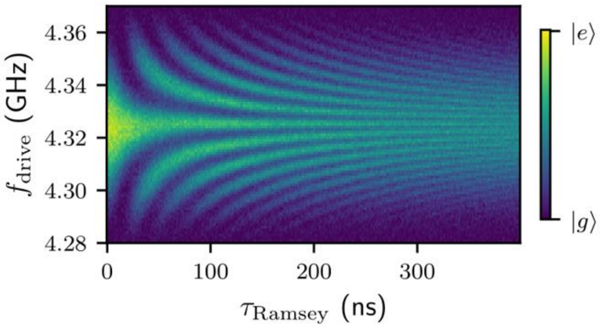
- Increase E_J/E_C
- Full hBN encapsulation
- Screen Si substrate with a bottom gate

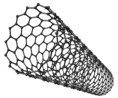
Dall-e's artist view of the CNT gatemon

⇒ Adjust design and nanofab

Conclusion and perspectives for CNT superconducting devices

Nanotube qubits with ultraclean nanotube





C12

Rydberg atoms
(Harvard, Pasqal)

Superconducting qubits
(IBM, Google)

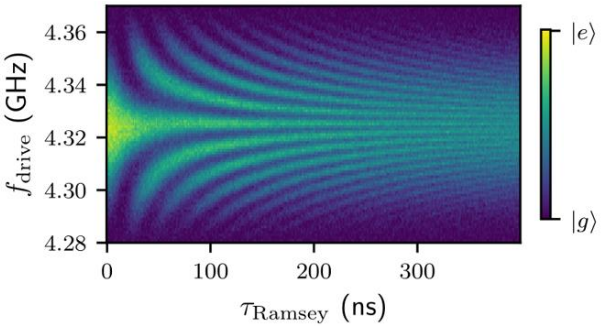
Cat qubits
(Alice and Bob)

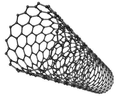
Spin qubits in silicon
(TU Delft)

Qubit → Quantum control → 2-qubits gate → Scaling up → Error Correction → **Quantum processor**

Conclusion and perspectives for CNT superconducting devices

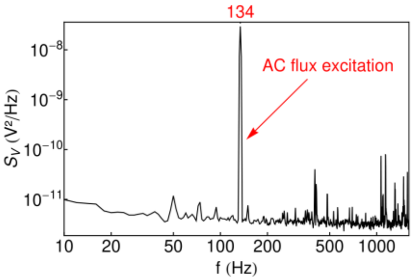
Nanotube qubits with ultraclean nanotube

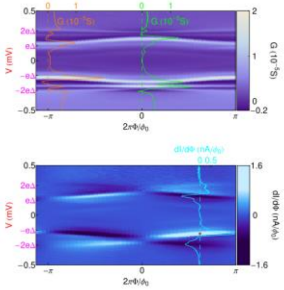




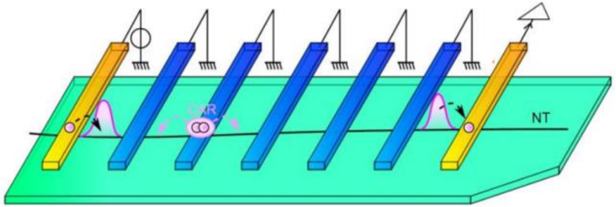
C12

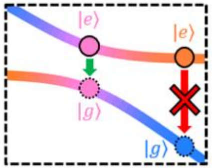
Quantum sensors

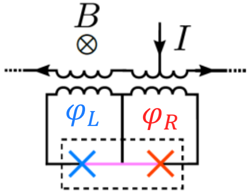




Quantum simulators and protected fermionic qubit







Qubit → Quantum control → 2-qubits gate → Scaling up → Error Correction → **Quantum processor**