innovative integrated instrumentation for nanoscience

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High Resolution Electronic Measurements in Nano-Bio Science

Solid-State Qubits

Devices and Measurements

Giorgio Ferrari

Milano, June 2025

Outline

- Brief recap of quantum computer principles
- Qubit technologies
  - Spin qubit
    - single-spin detection using room temperature instrumentation
  - Superconducting qubit
    - principle and readout
- Conclusions

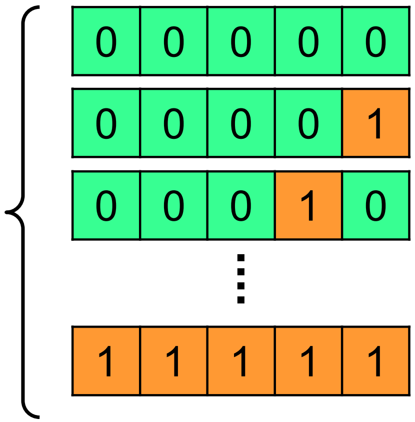
Quantum computer

Classical computer

bit: 0 **"or"** **1**

N bits

2^N discrete states



one N-bit state

change a bit: new calculation

deterministic result

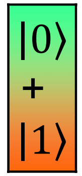
Quantum computer

Two-level system: $|0\rangle$ $|1\rangle$

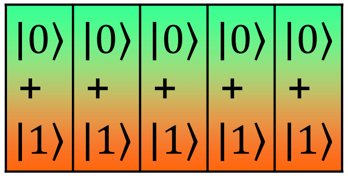
e.g. single electron spin

Qubit: superposition of $|0\rangle$ **"and"** $|1\rangle$

$$|\psi\rangle = \alpha_0|0\rangle + \alpha_1|1\rangle$$



N qubits: superposition and entanglement



2^N components in **one** state

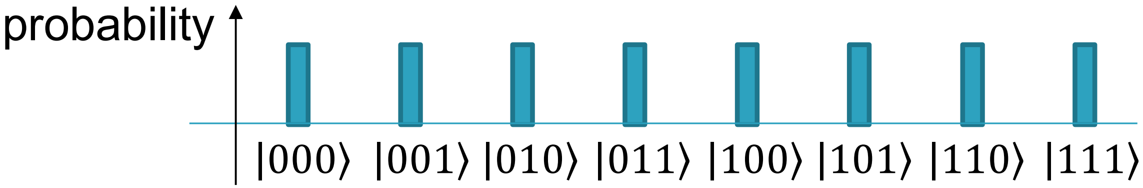
quantum parallelism & interference:

one operation operates on entire 2^N components

the output is one of the 2^N discrete states

probabilistic result!

Input state:

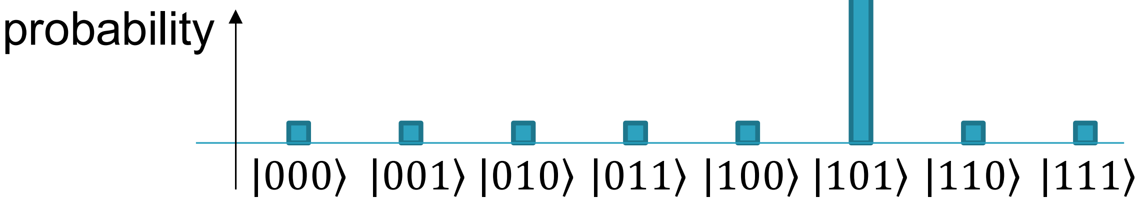


superposition

3 qubit: a single state where a measurement produces one of the 2^3 results with a given probability

Operations on qubits following *very smart* algorithms

Output state:



qubit read-out:
0 or 1 (digital output)

71 quantum algorithms are known [https://quantumalgorithmzoo.org/]

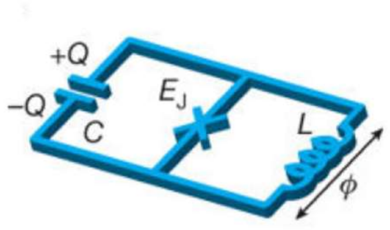
DiVincenzo criteria

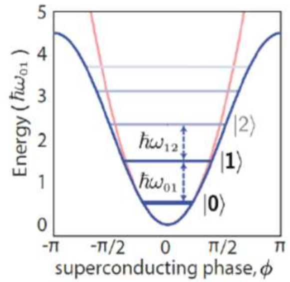
Minimum requirements for the physical implementation of a quantum computer

- Robust, reproducible, and scalable qubit technology
- Qubit initialization
- Universal set of gates (single-qubit operations and two-qubit operations)
- Long-coherence time (figure of merit: number of gates before the state is lost for the environmental disruptions)
- Qubit measurement

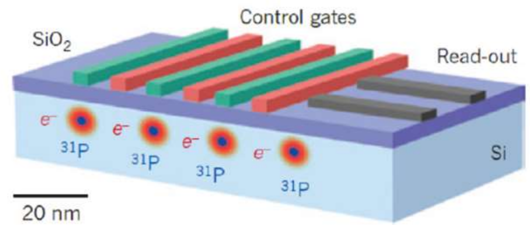
[DiVincenzo 2000]

Qubit: examples of physical implementations

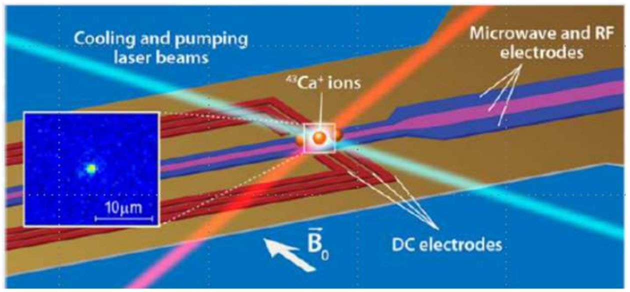




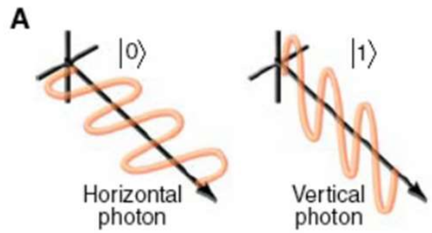
superconducting qubits
(Google, IBM, Amazon, Rigetti,…)
quantum annealing (D-Wave)



electron spin
(Intel, Quantum Motion, SpinQ…)



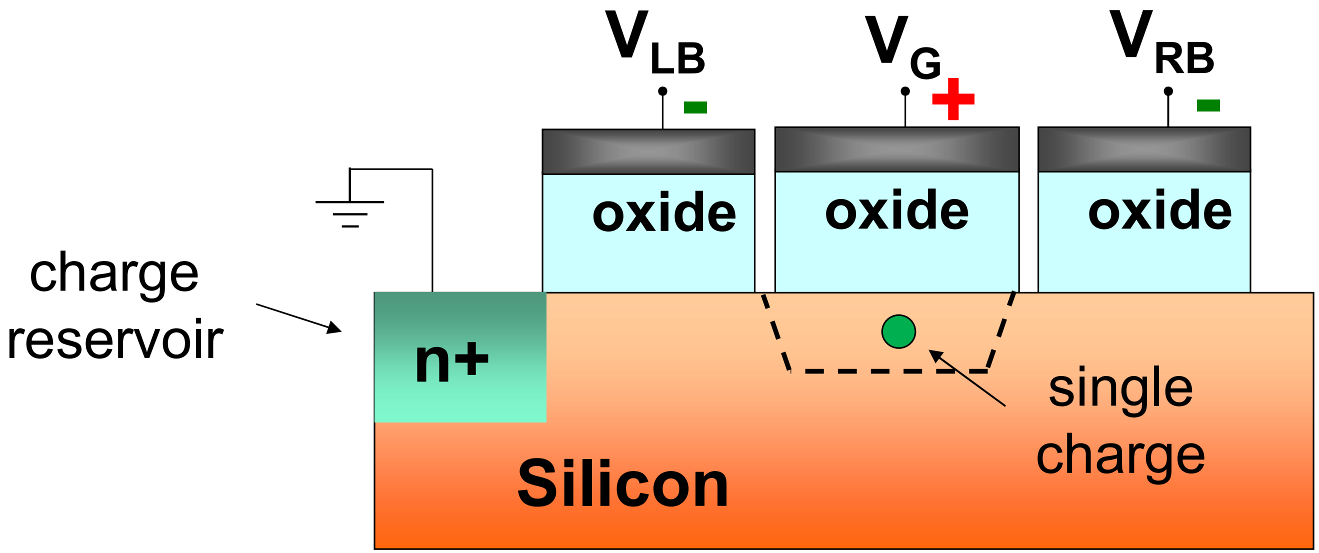
Trapped ions (Honeywell, Ion-Q,…)
Neutral atoms (Pasqal, QuEra,…)



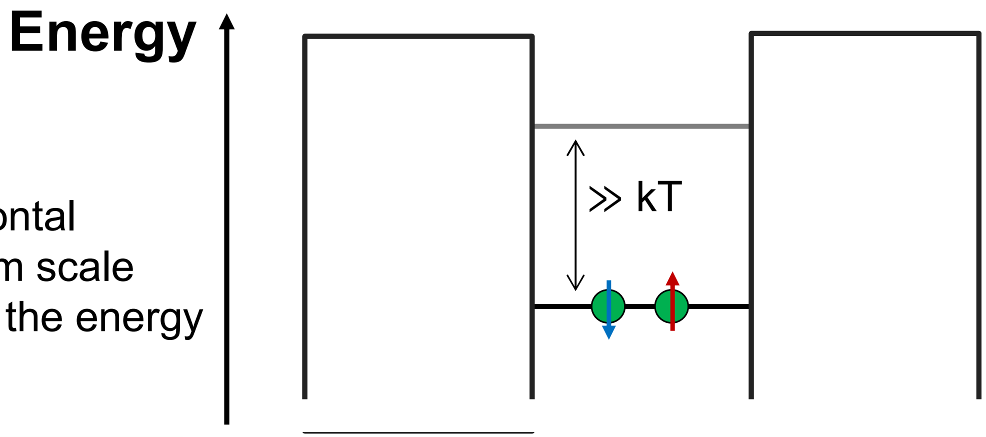
Photons
(PsiQuantum, Xanadu, Quix,…)

"Useful" applications require **≈10^6** of physical qubits → scalability issue

Gate-defined quantum dot



- multi-gate device on CMOS technology (300mm wafer, Zwerver 2022)
- appropriate voltages to trap a single electron

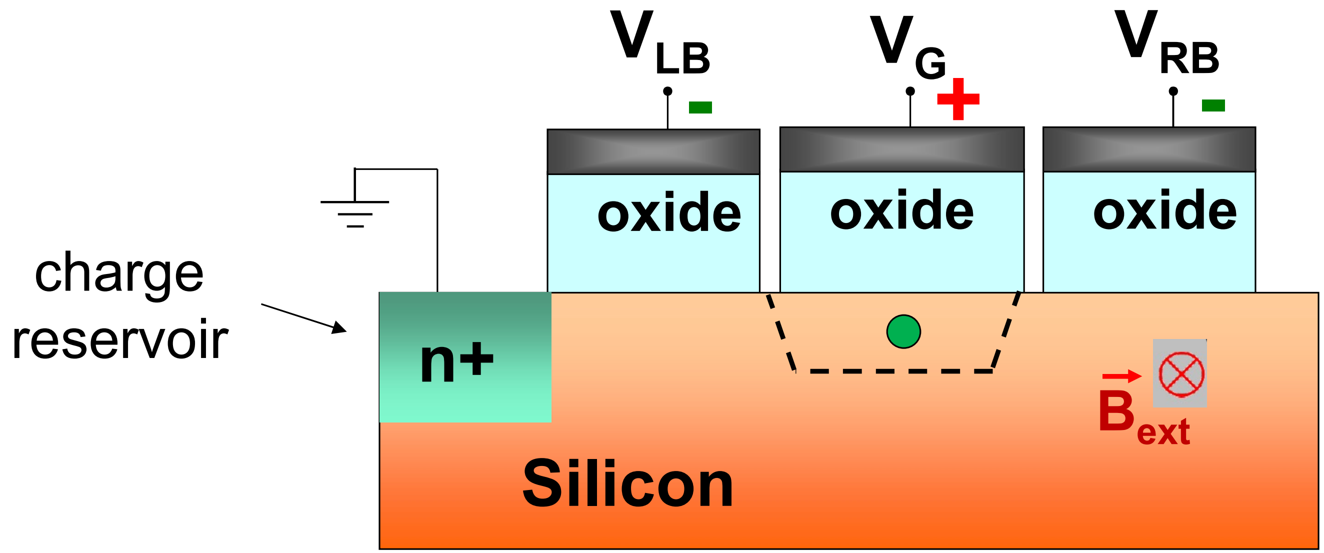


vertical and horizontal confinement on nm scale → quantization of the energy levels

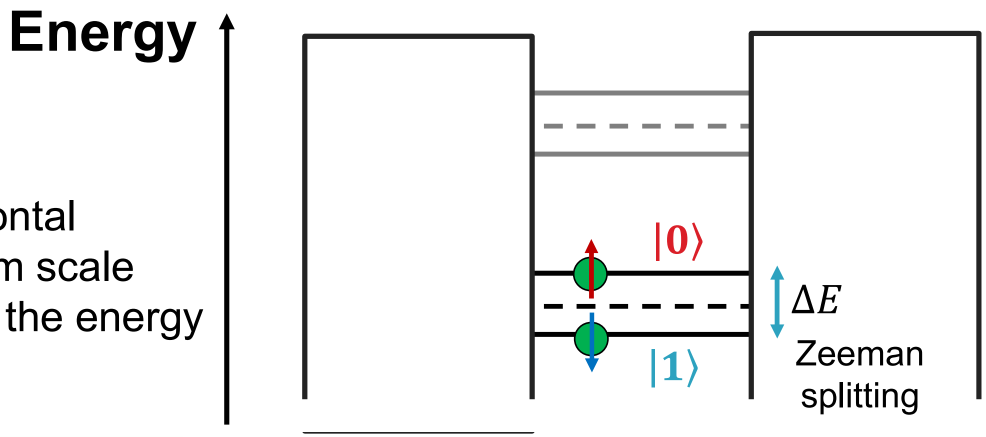
Still ***not*** a qubit: degenerate energy levels (spin up and spin down)

To operate the qubit, we need a system with two different energy levels

Spin qubit based on quantum dot



- multi-gate device on CMOS technology (300mm wafer, Zwerver 2022)
- appropriate voltages to trap a single electron
- magnetic field splits spin up/down
- $kT < \Delta E \rightarrow T <\approx 1K$
- additional gates to couple multiple qubits

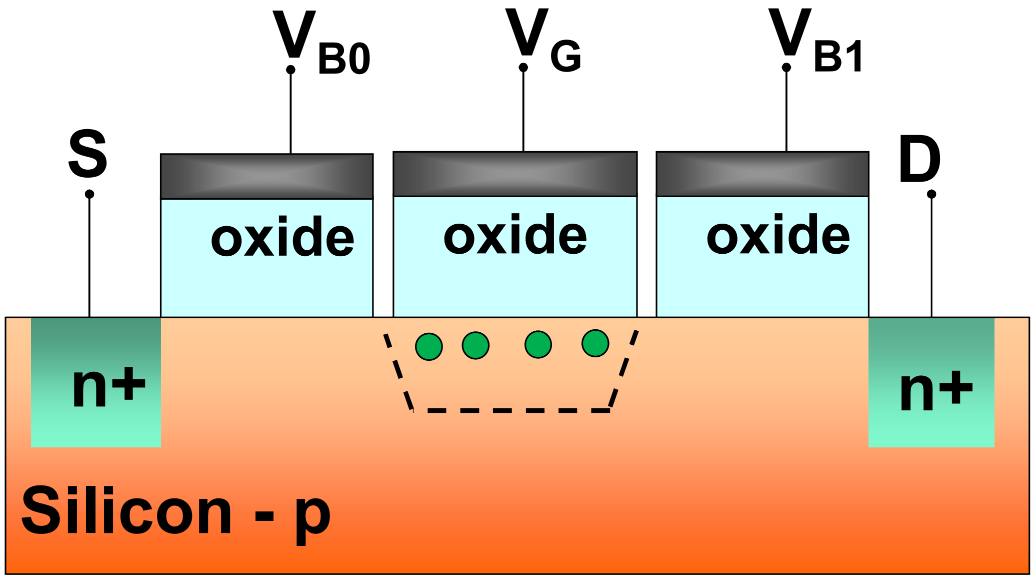


vertical and horizontal confinement on nm scale → quantization of the energy levels

How do you detect the spin of a single electron?

1. spin-to-charge conversion
2. single charge detection ⇦

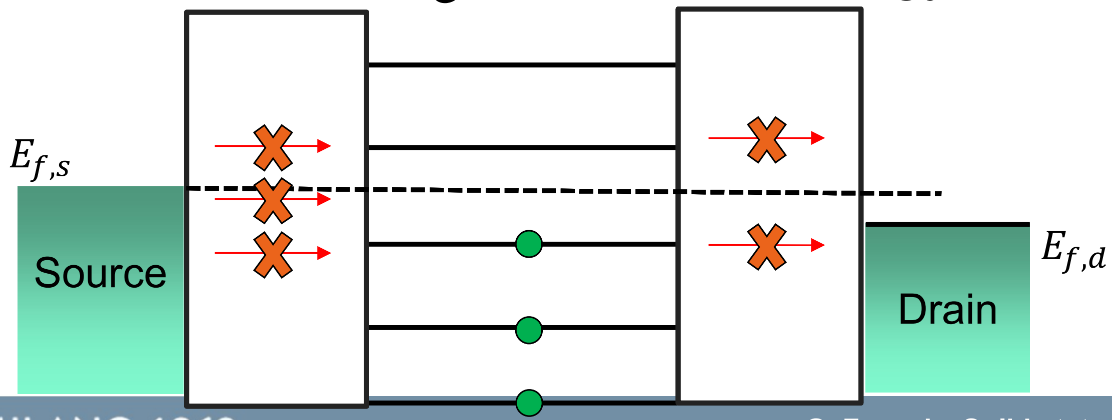
Single-Electron Transistor (SET)

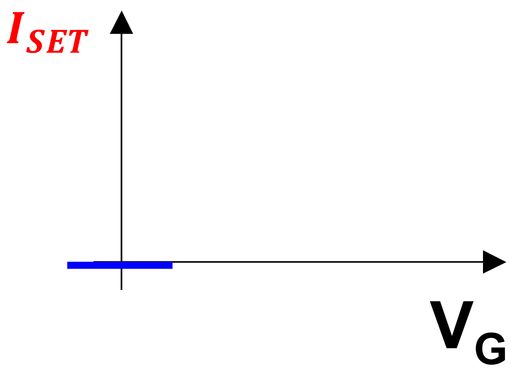


V_{B0}, V_{B1} biased to have an energy barrier for the electrons
The energy barriers are thin enough to allow tunneling

T < ≈10K

V_G controls the energy levels of the island





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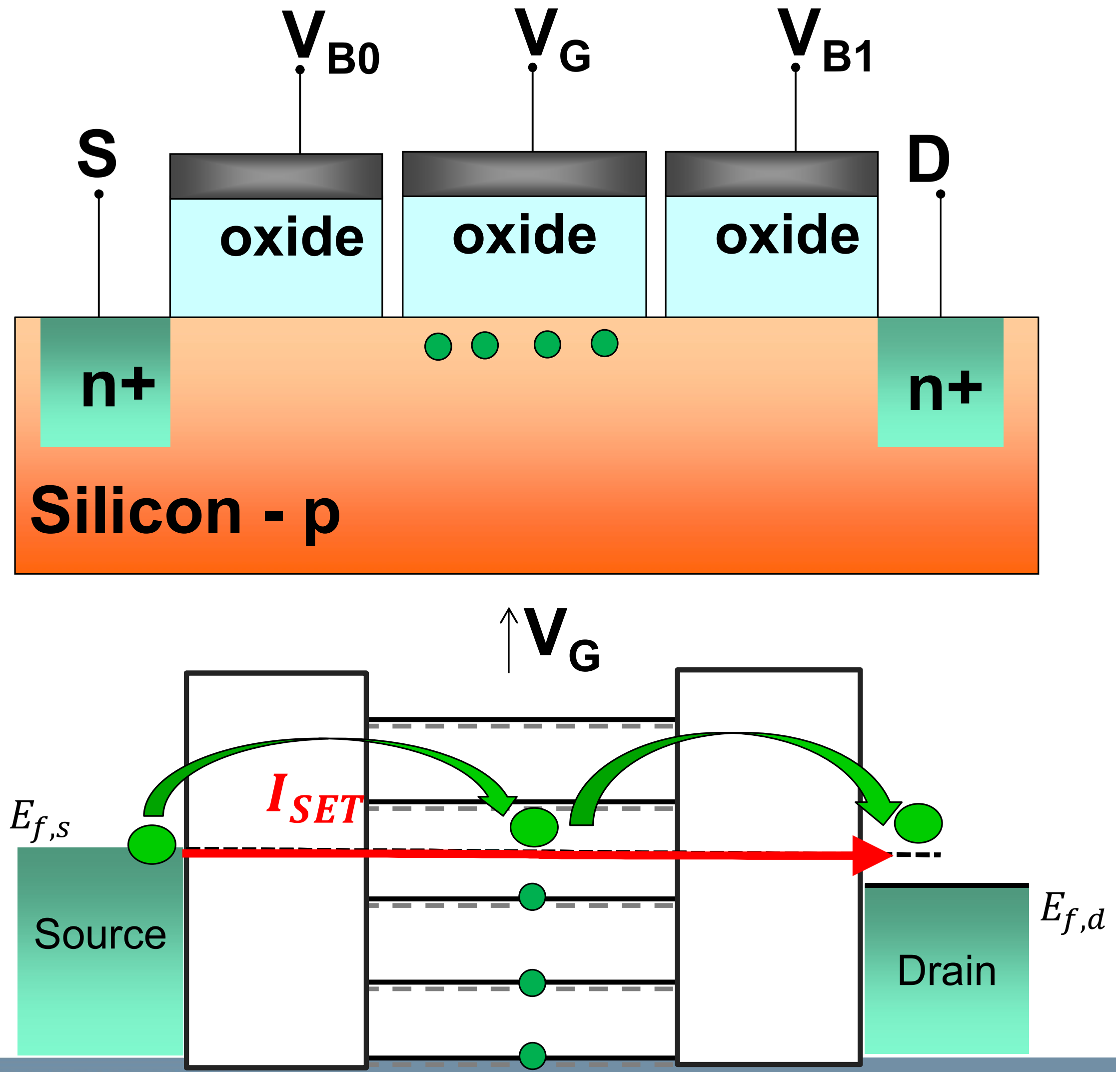
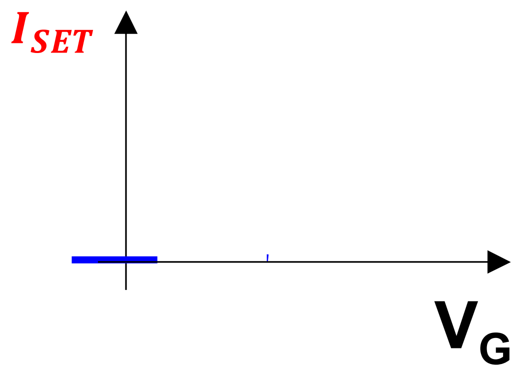


V_{B0}, V_{B1} biased to have an energy barrier for the electrons
The energy barriers are thin enough to allow tunneling

$T < \approx 10K$



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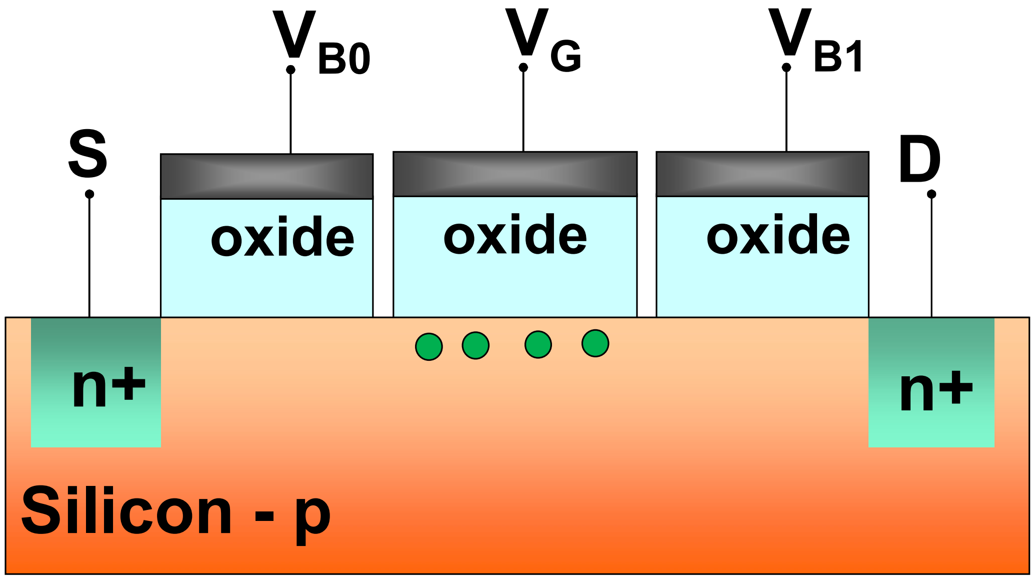

V_{B0}, V_{B1} biased to have an energy barrier for the electrons
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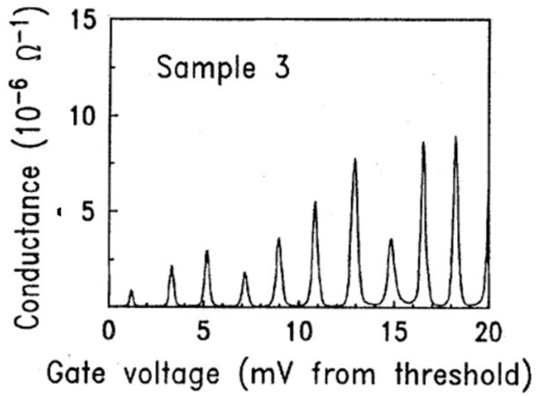
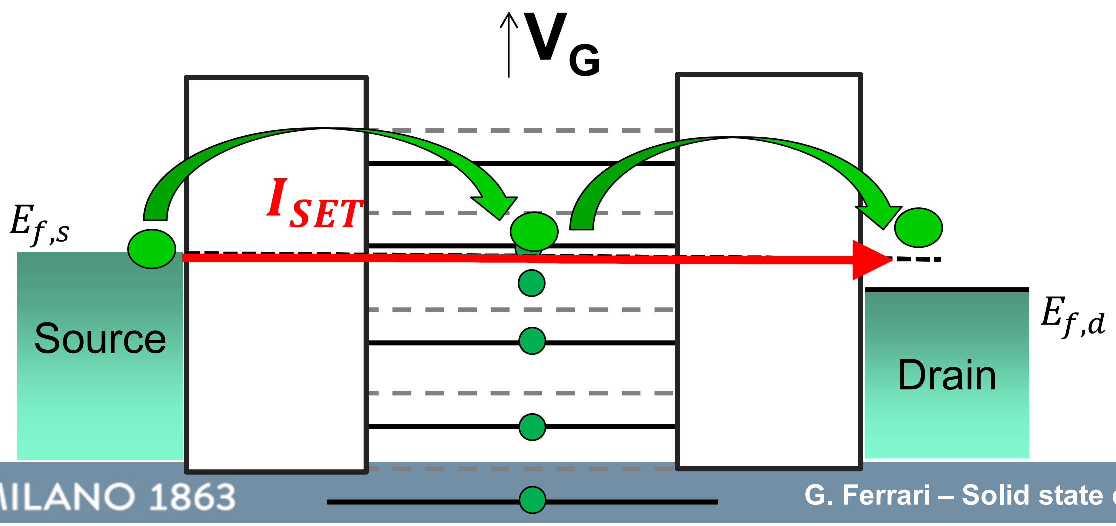
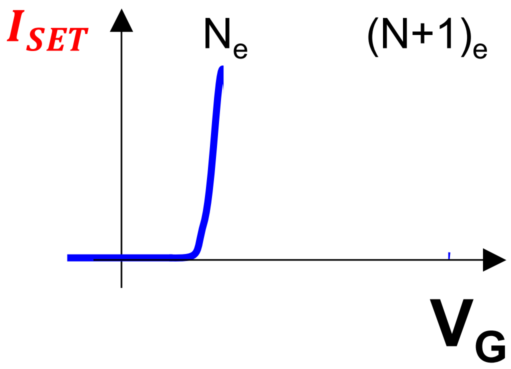


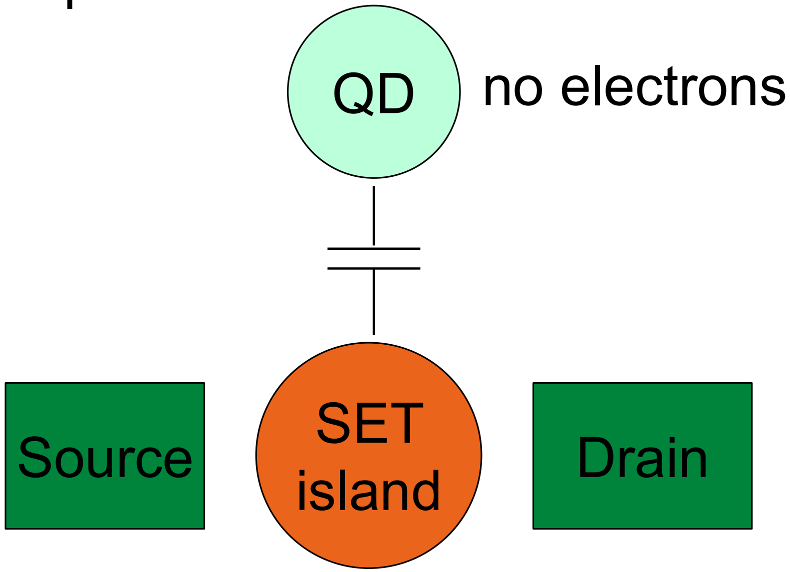
M.A. Kastner, Rev. Mod. Phys. (1992)

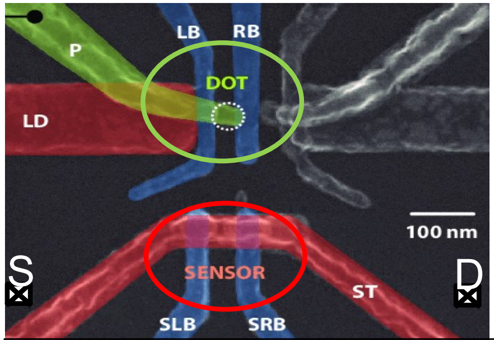




SET-based single-charge detector

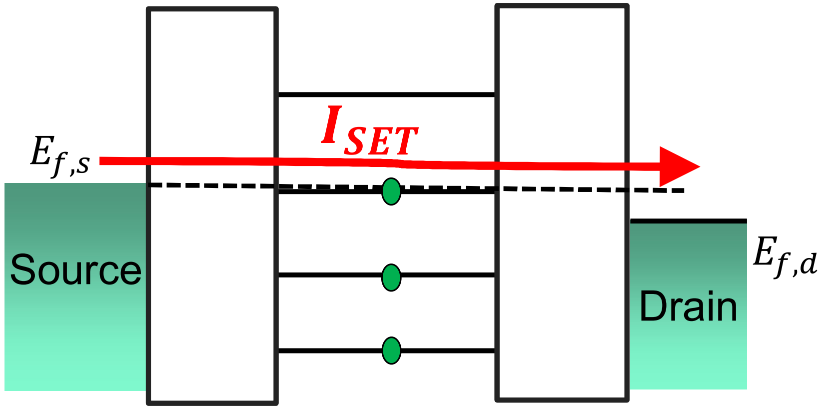
Top view:

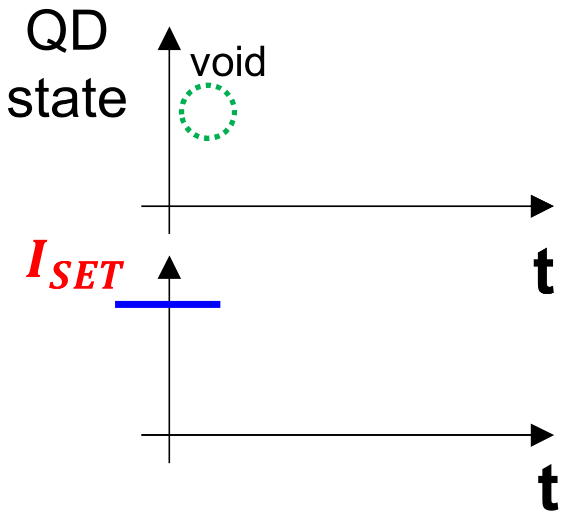




H. Yang et al., Physical review B, **86**, 2012

Energy levels:





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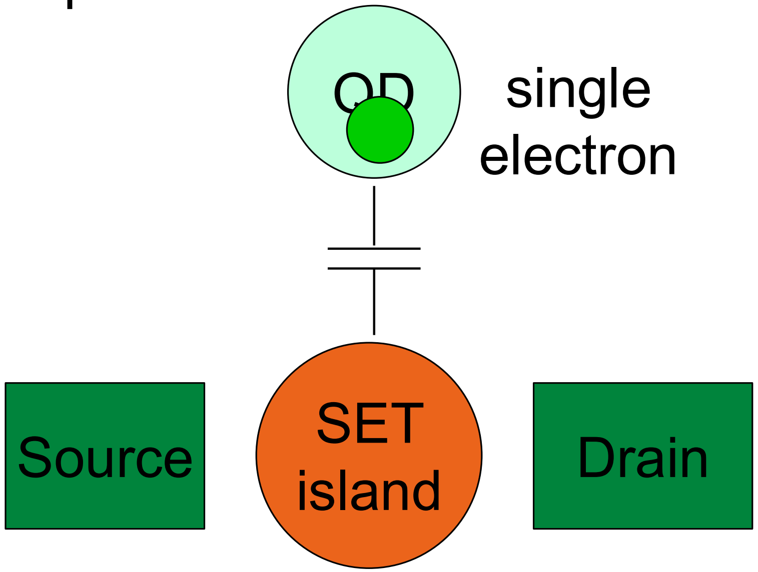

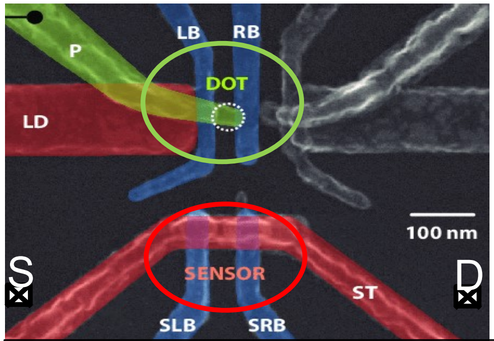

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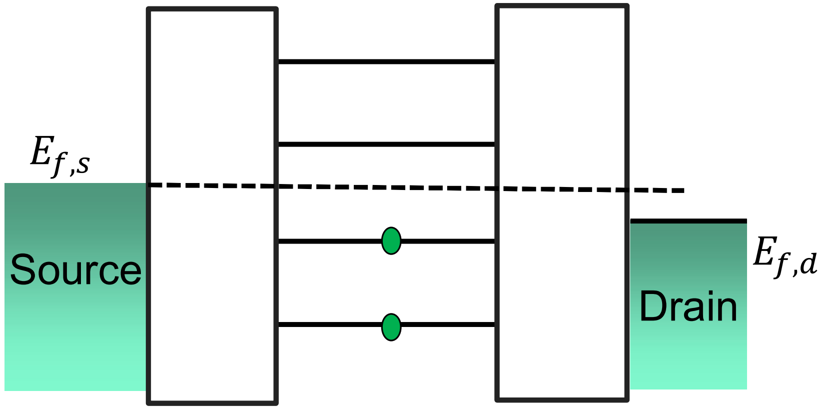
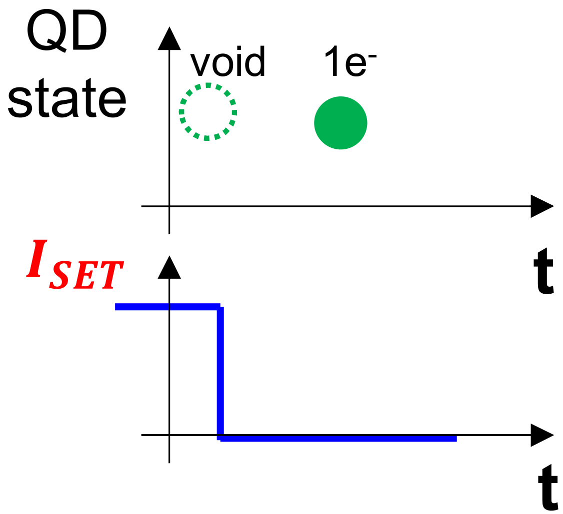
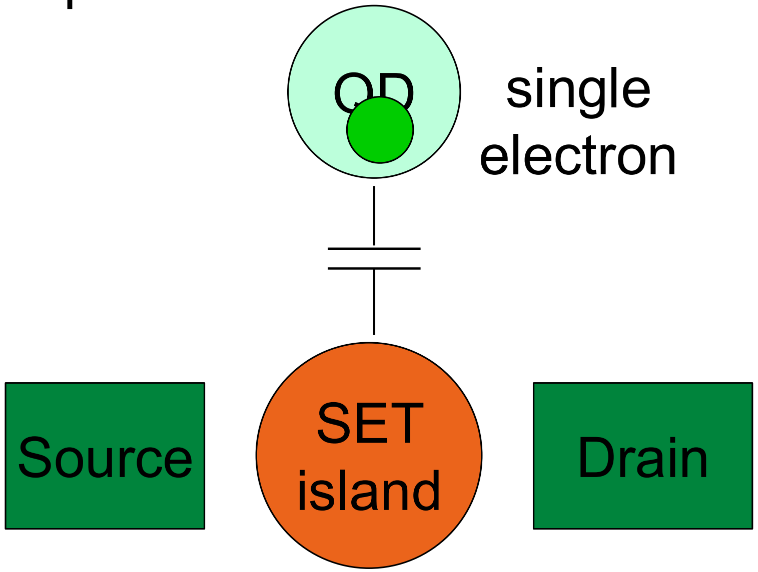


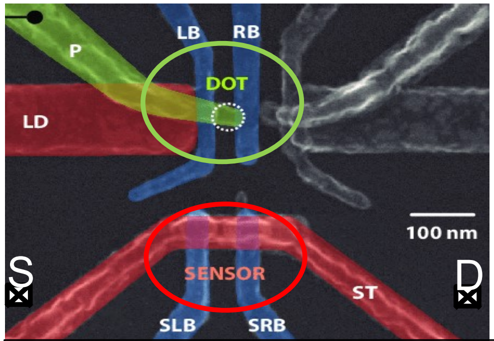


A single electron in the QD changes I_{SET}

SET-based single-charge detector

Top view:





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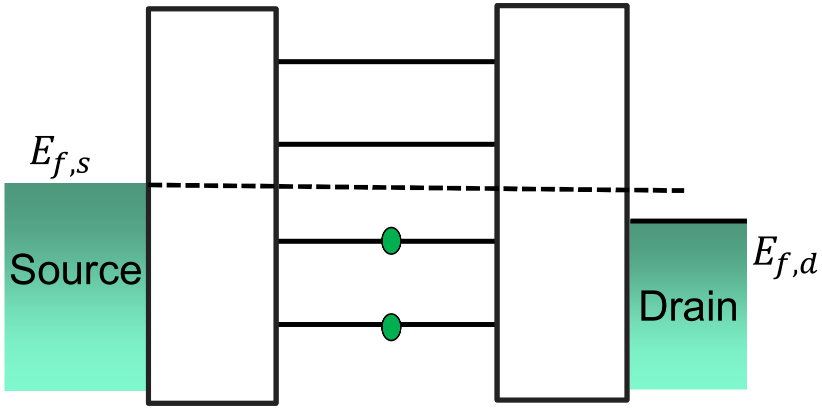
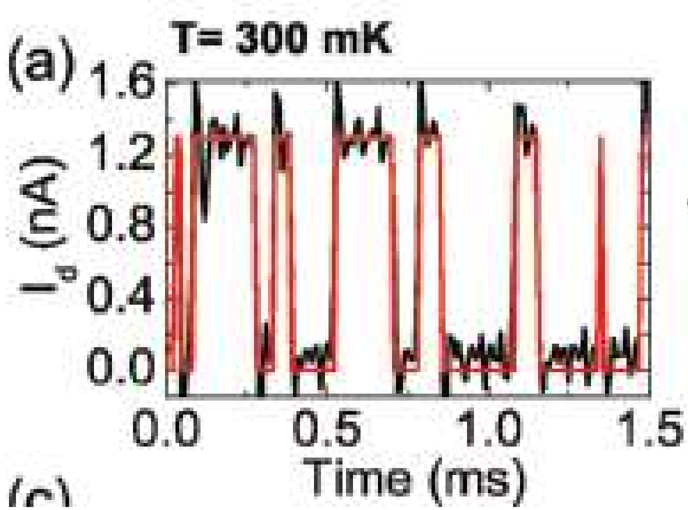
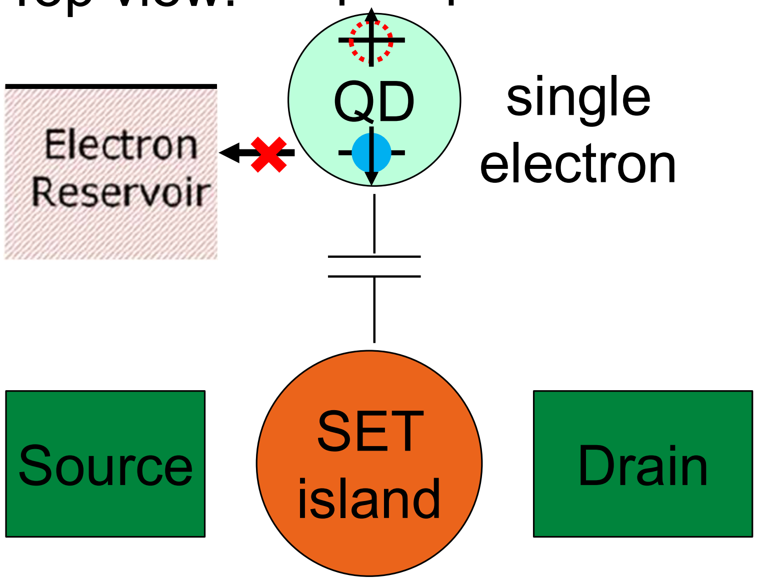




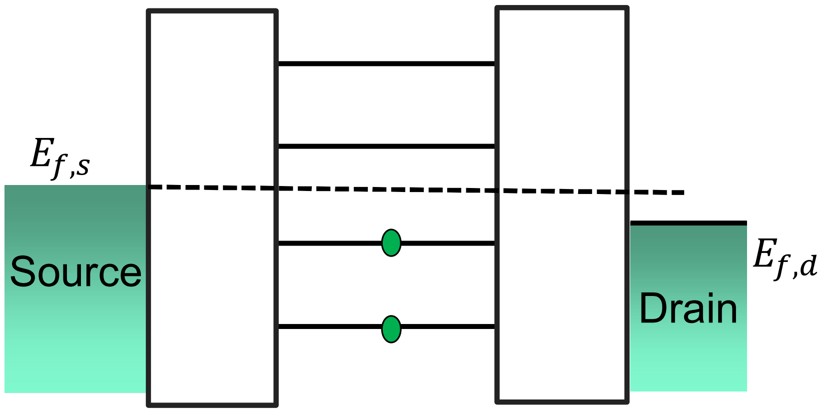
Mazzeo, Prati, Ferrari et al APL 2012

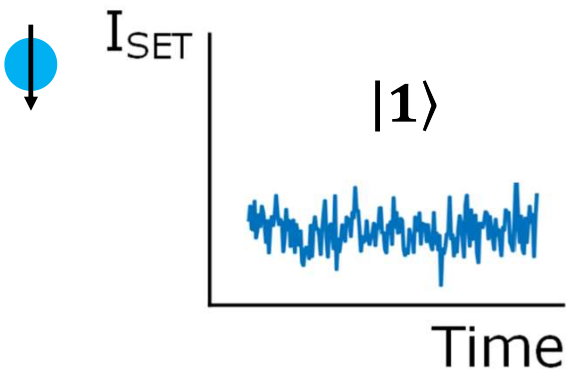
Spin state detection: spin-to-charge conversion + SET

Top view:



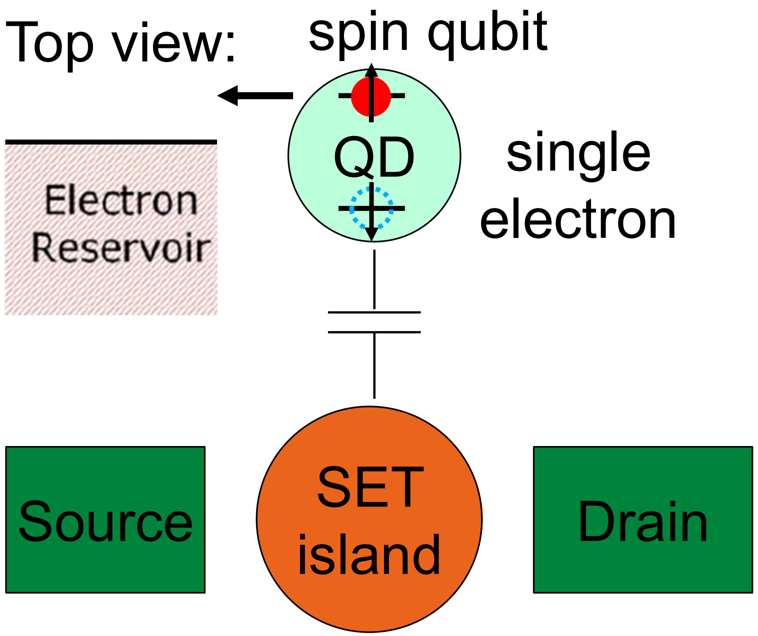
Energy levels:

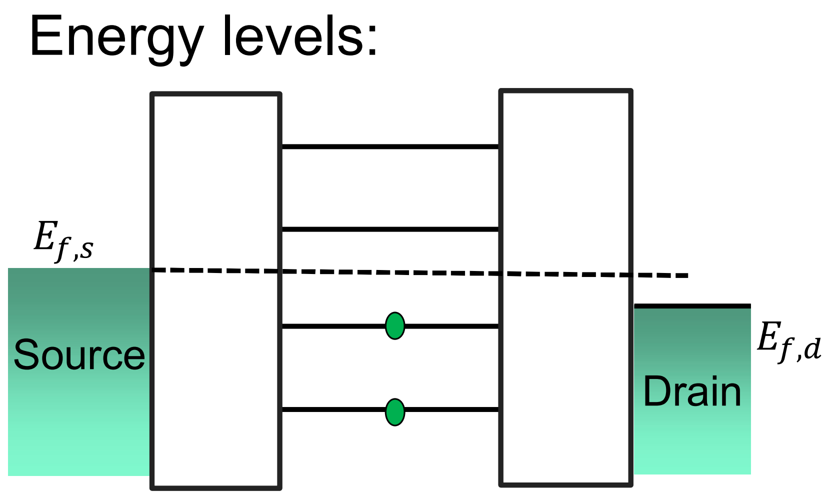


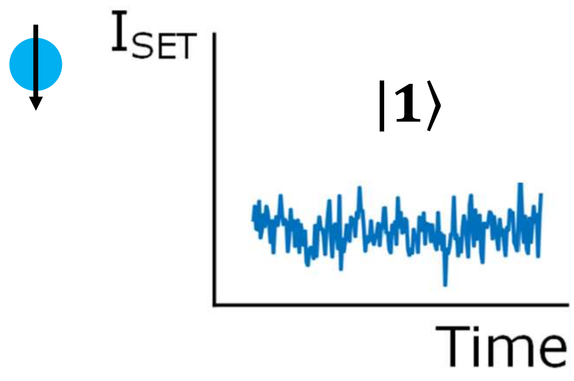


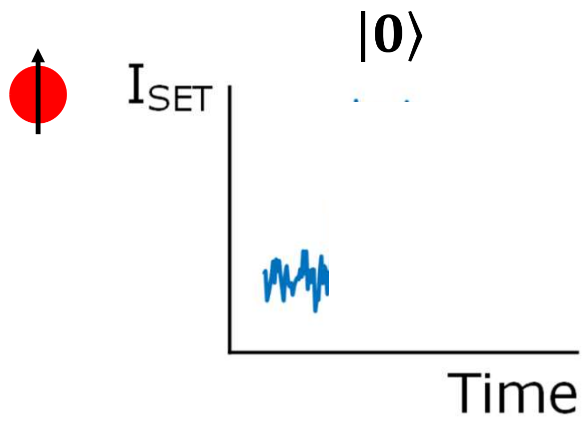
(Elzermann 2004; alternative method: two QDs + Pauli blockade)

Spin state detection: spin-to-charge conversion + SET



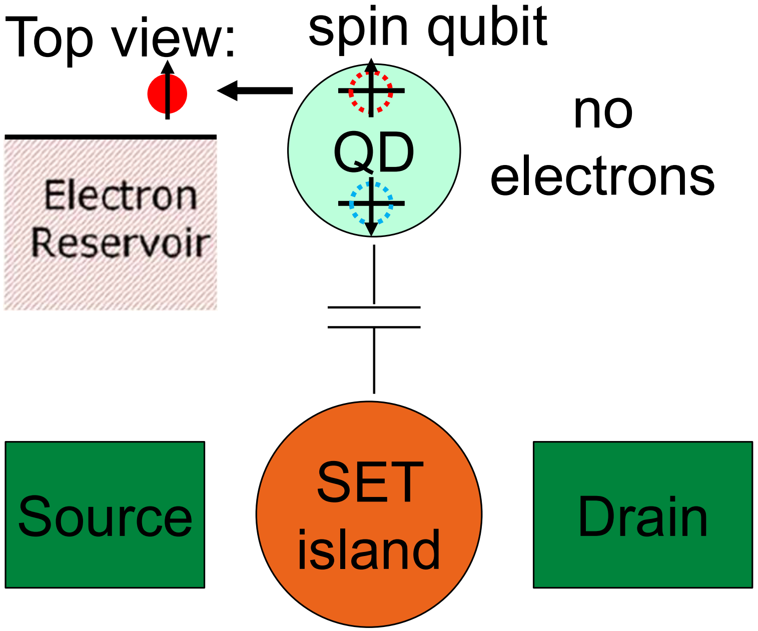




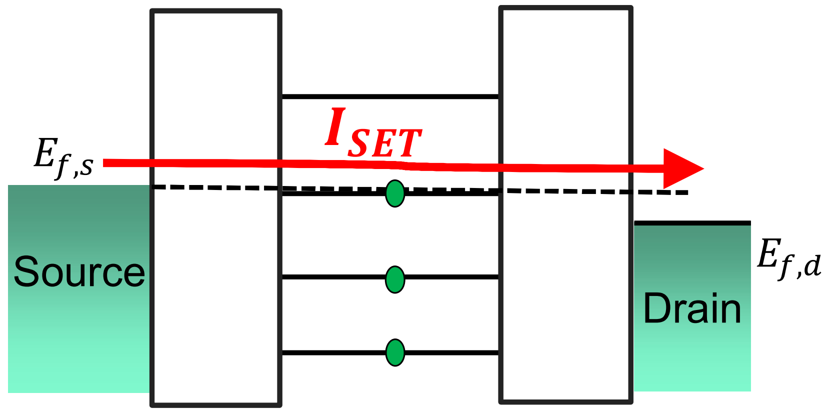


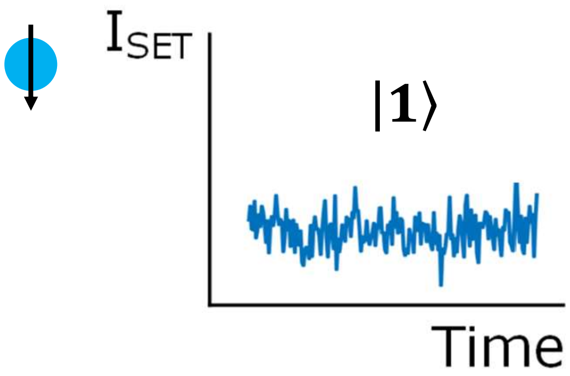
Spin state detection: spin-to-charge conversion + SET

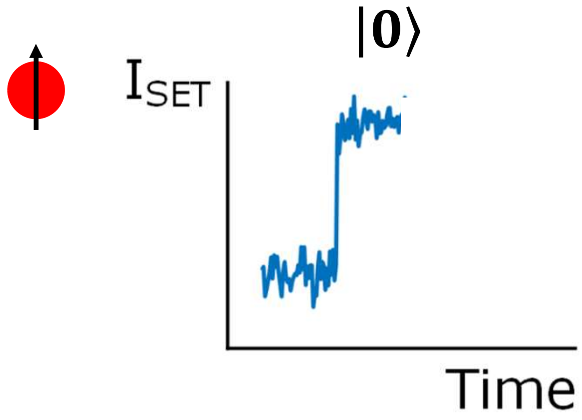
Top view:



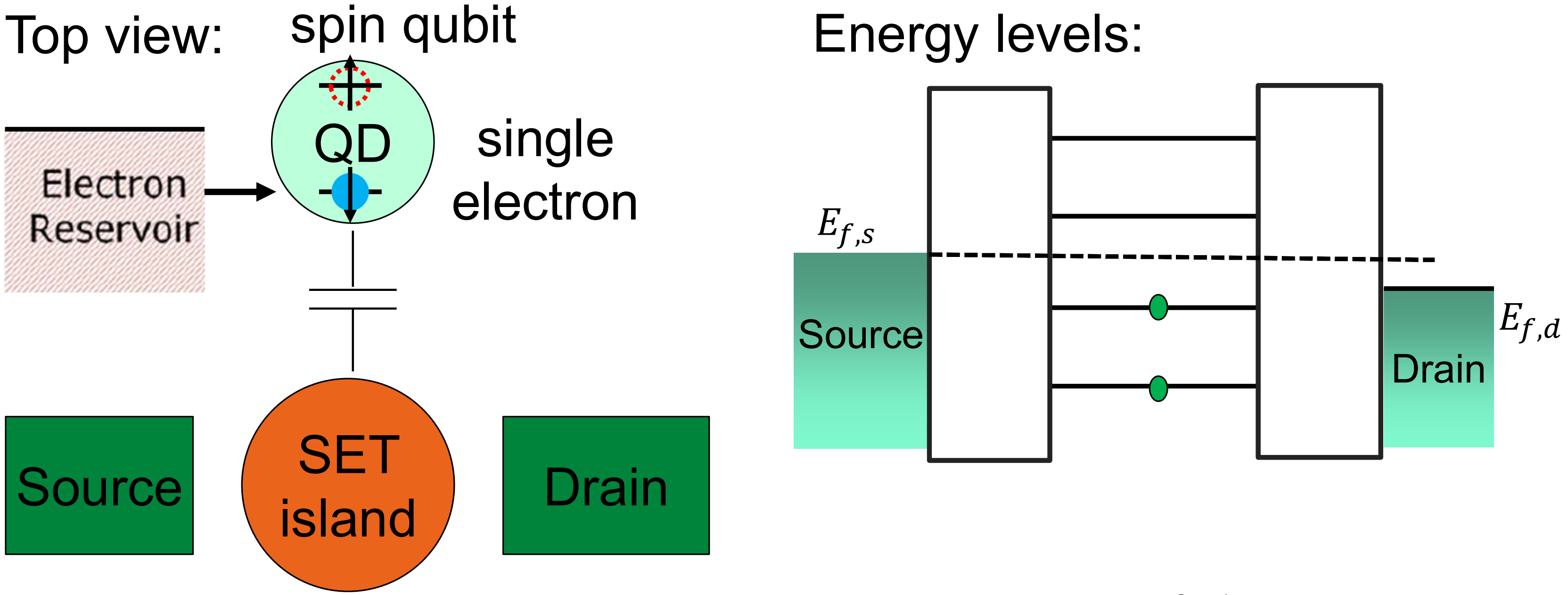
Energy levels:

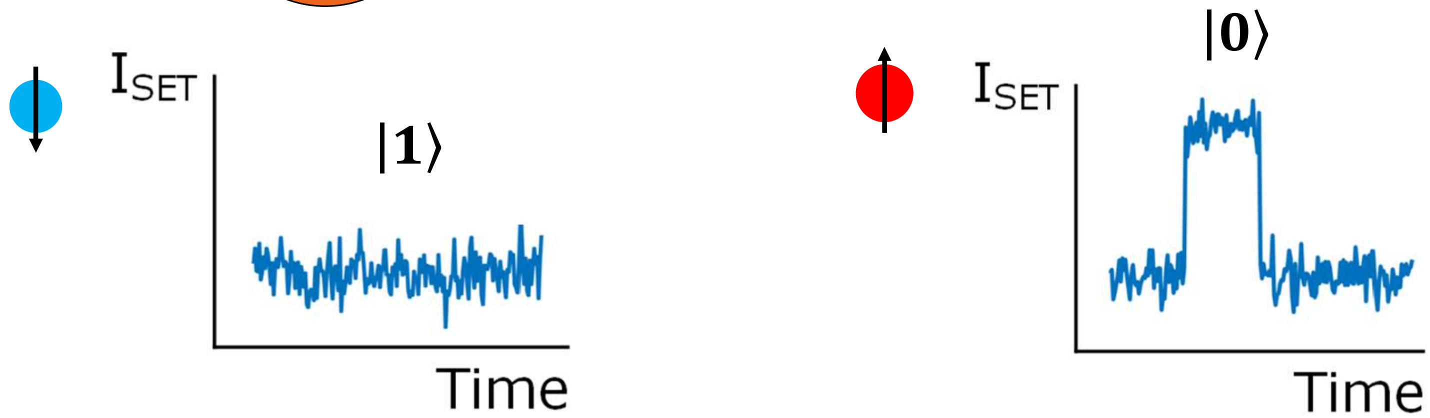






Spin state detection: spin-to-charge conversion + SET



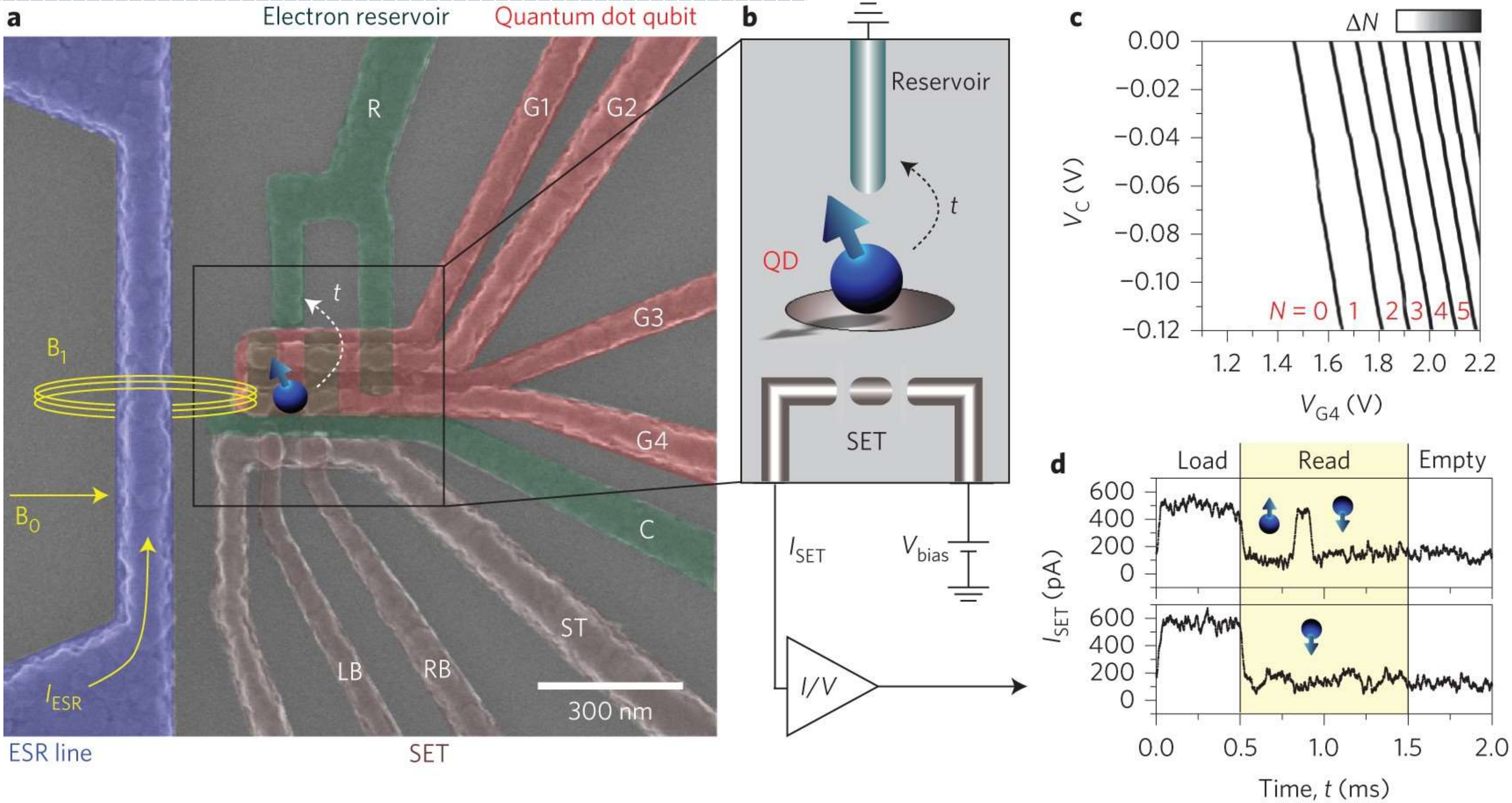


ΔI ≈ 100pA -1nA

time scale: μs

Example of spin qubit

M. Veldhorst, et al., Nature Nanotech. 9, 981 (2014)



$T \approx 50$ mK and a d.c. magnetic field of $B_0 = 1.4$ T.

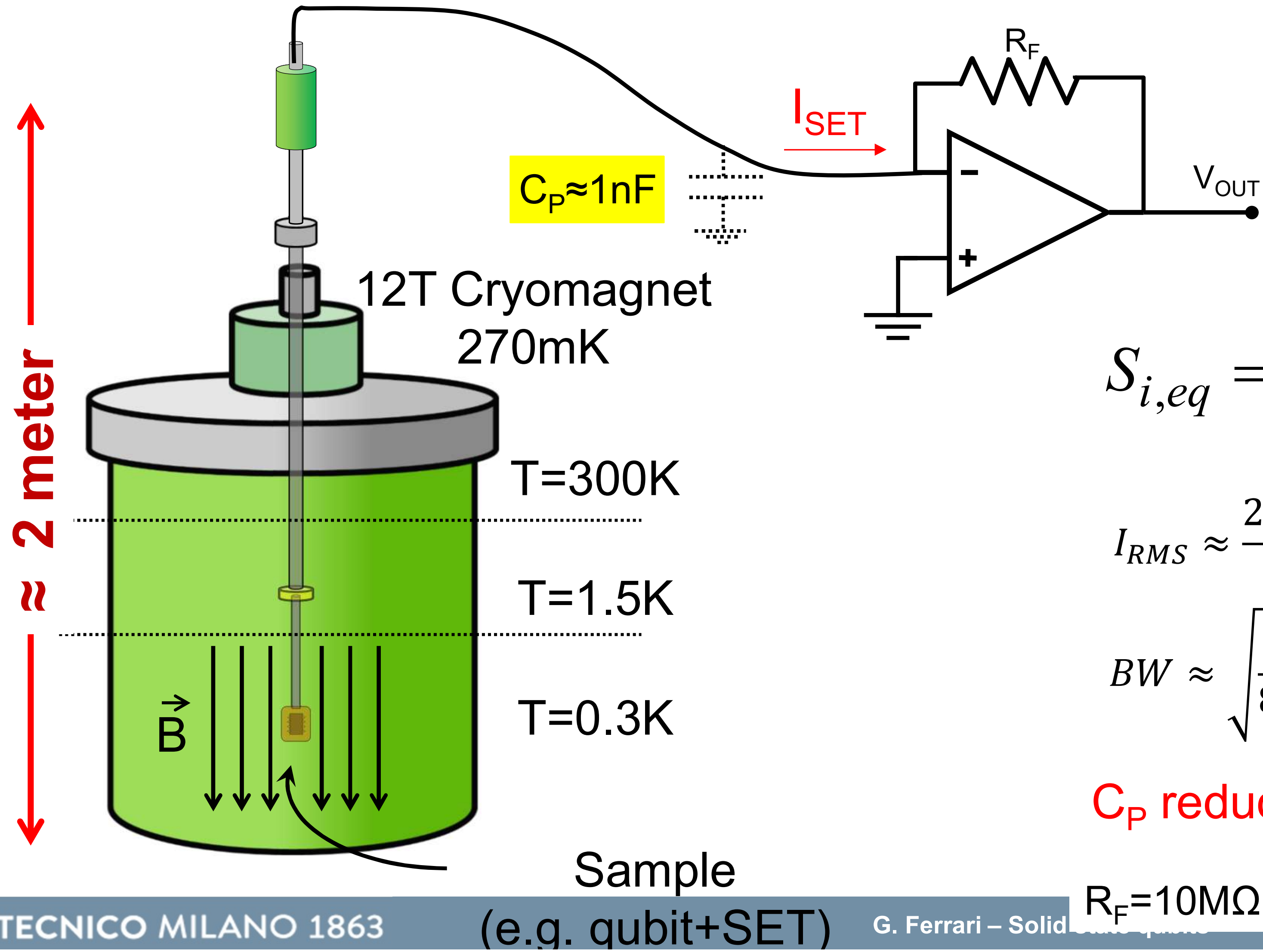
Experimental setup to operate many quantum computers

Quantum motion
(spin qubit)

Google
(superconducting qubit)

huge cryostats to keep the temperature below 1K

Experimental set-up to study quantum devices



$$S_{i,eq} = \frac{4kT}{R_F} + \overline{e_N^2}\omega^2 C_P^2$$

$$I_{RMS} \approx \frac{2\pi e_N C_P BW^{3/2}}{\sqrt{3}}$$

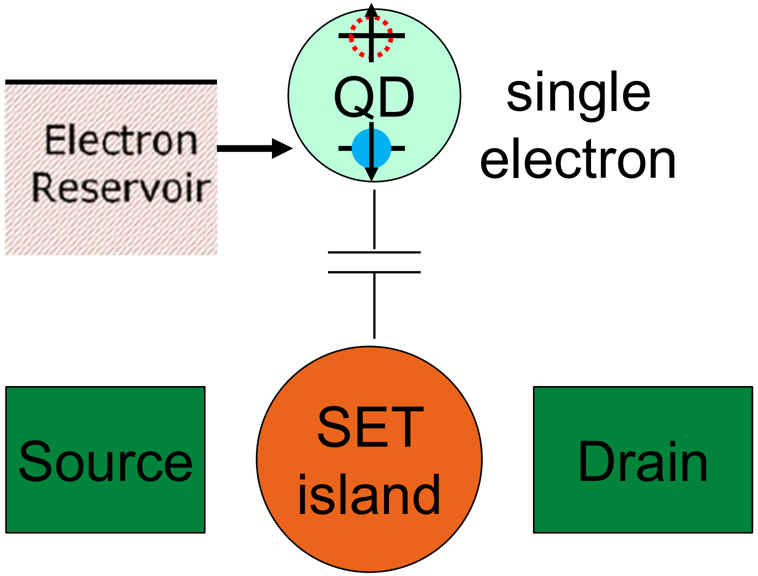
$$BW \approx \sqrt{\frac{GBWP}{8\pi R_f C_P}}$$

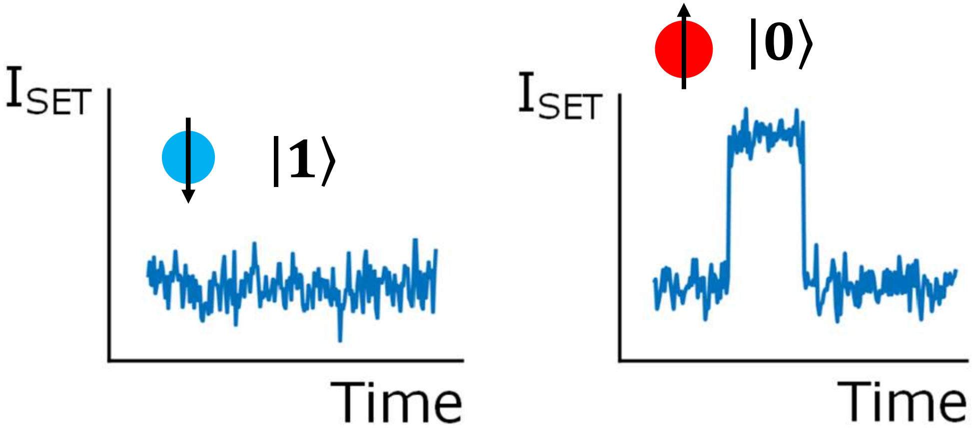
C_P reduces performances

R_F=10MΩ: BW=100kHz, 450pArms

How to avoid being penalized by a long cable?

<u>Note</u>:



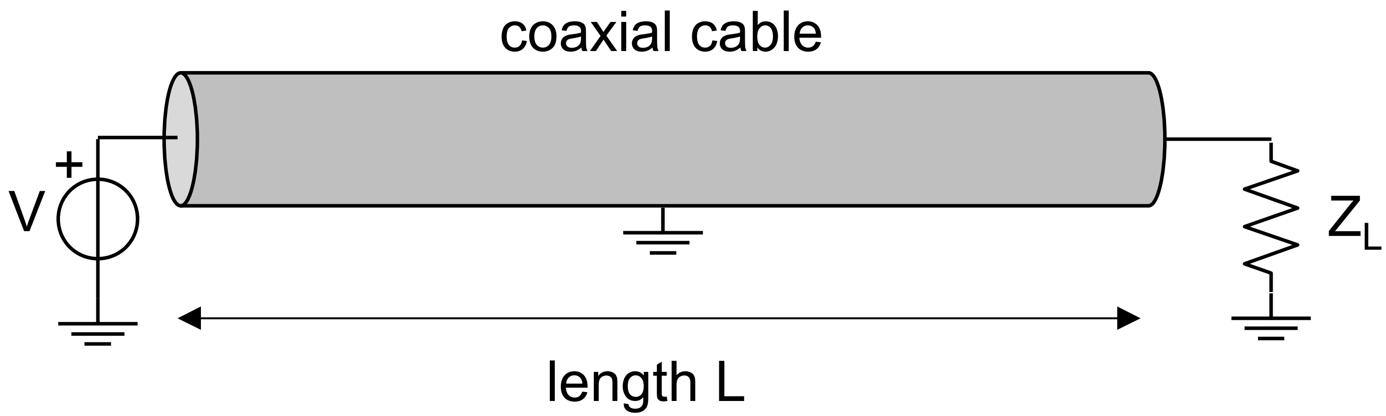


the ΔI is given by a *variation of the SET resistance* $(R_{SET} > \frac{h}{e^2} \cong 25k\Omega)$

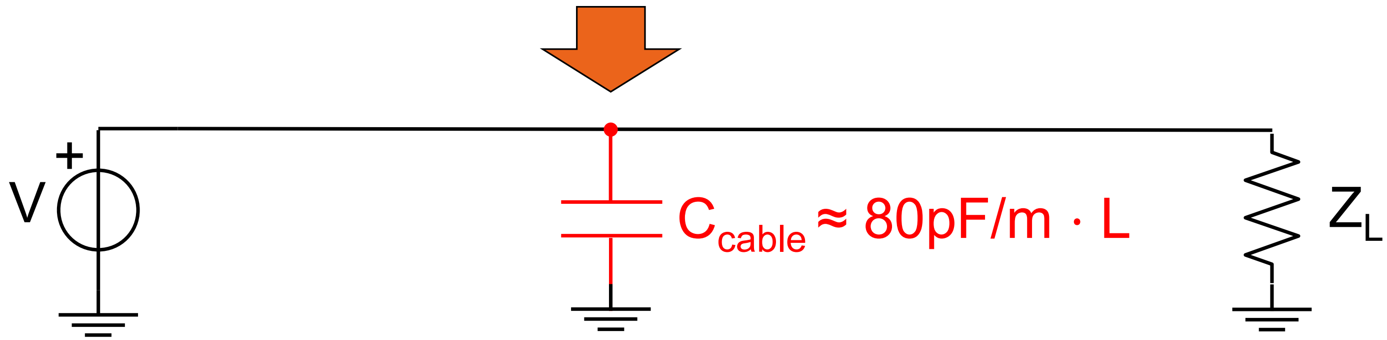
An impedance can be measured using a rf reflectometry technique

How to avoid being penalized by a long cable?

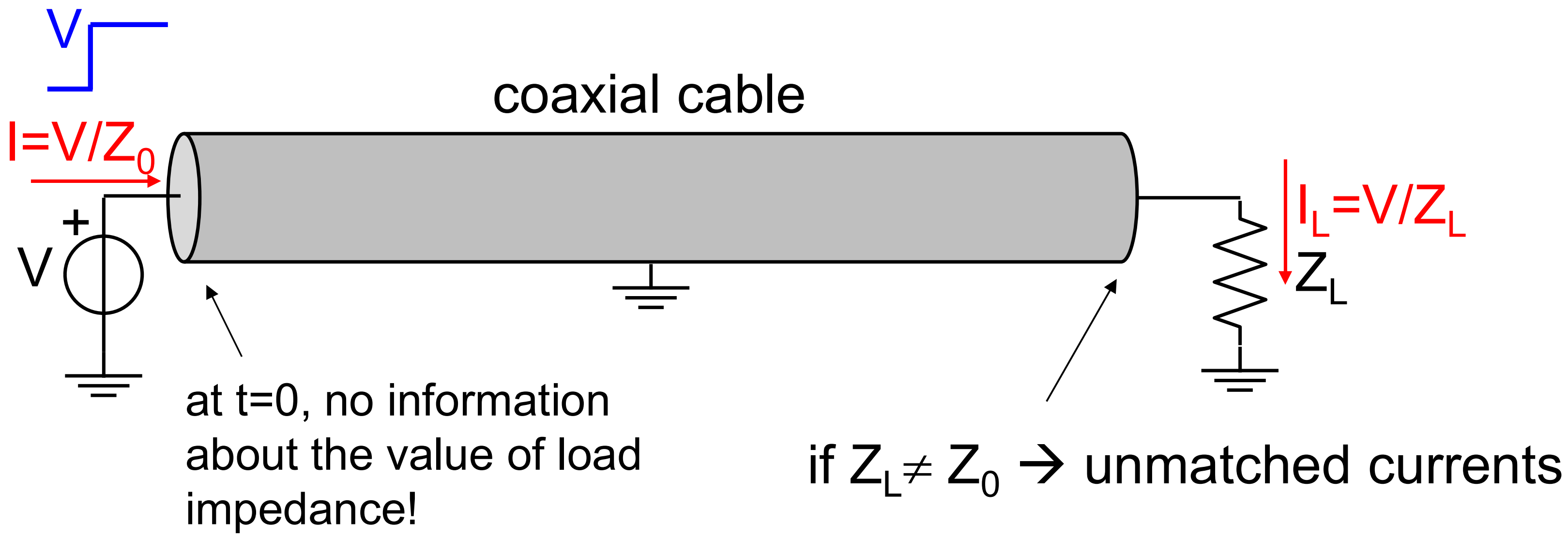
Measuring an impedance using the properties of the cable:



If V changes slowly compared to the transit time of the electromagnetic wave (t_t= L/v_{light}):



Transmission line

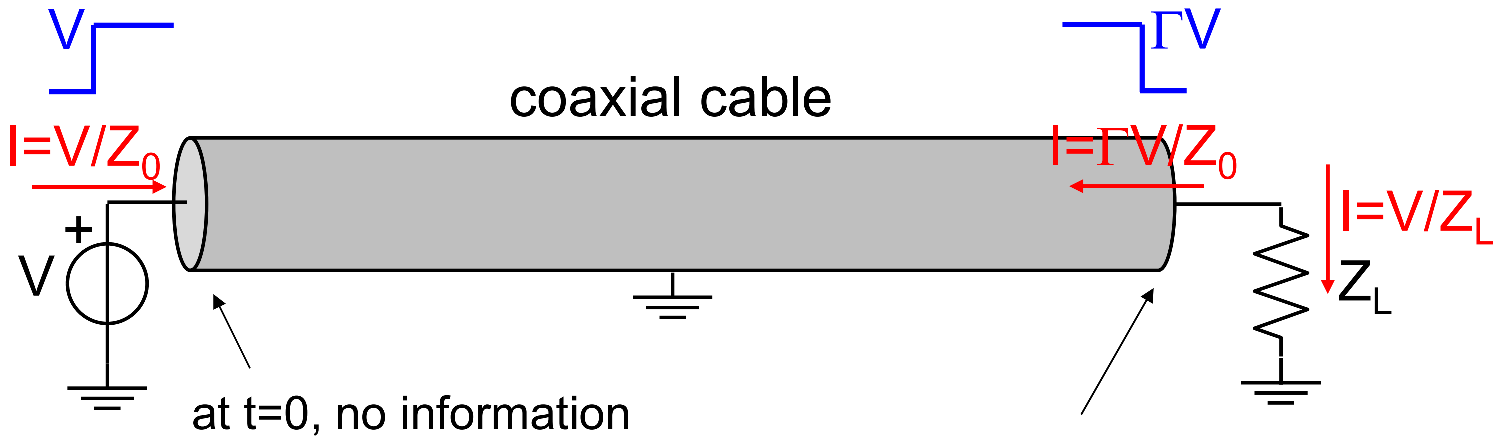


Z_0 = characteristic impedance of the cable, usually 50Ω

Example: cylindrical coaxial cable

$$Z_0 = \frac{1}{2\pi}\sqrt{\frac{\mu_r}{\epsilon_r}}\log\left(\frac{r_{outer}}{r_{inner}}\right)$$

Transmission line



if $Z_L \neq Z_0$ → unmatched currents

a reflected wave is created to force $I=I_L$!

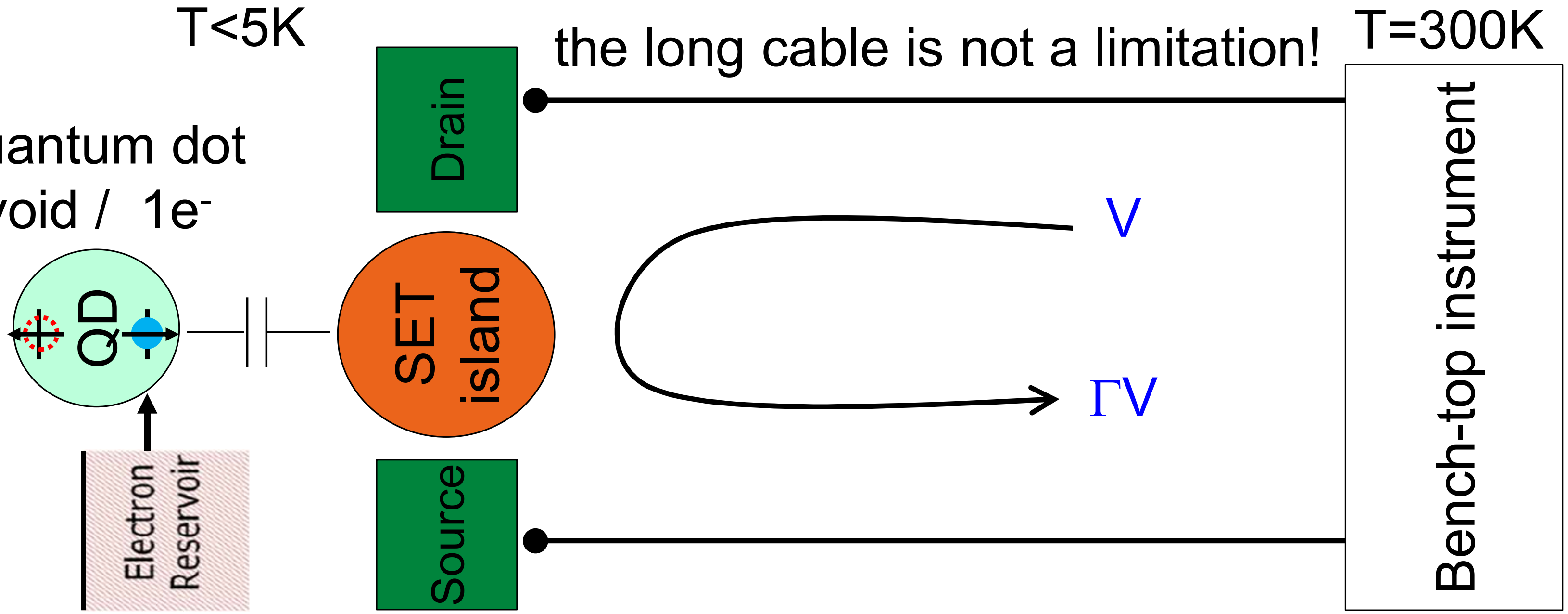
Z_0 = characteristic impedance of the cable, usually 50Ω

$$\Gamma = \frac{Z_L - Z_0}{Z_L + Z_0}$$

reflection coefficient

The reflected wave is related to the load impedance!

Radio-frequency spin readout

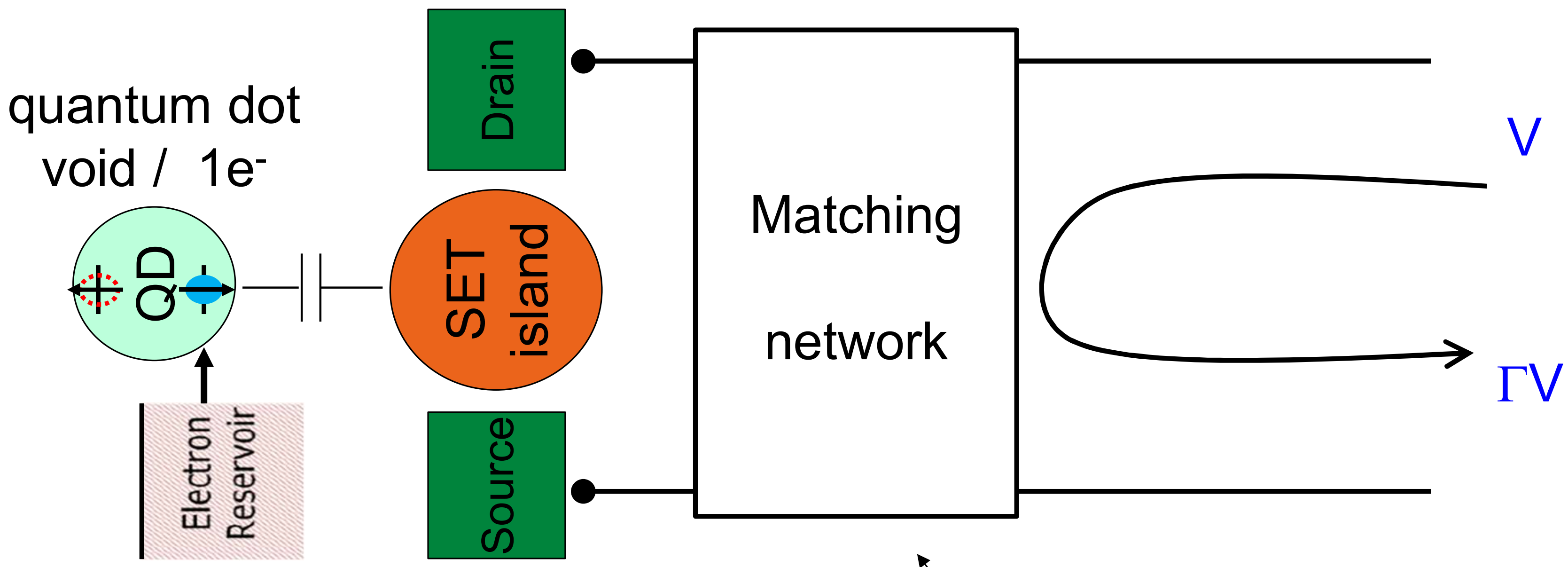


SET resistance depends on the Quantum Dot charge that, in turn, depends on the spin

$$\Gamma = \frac{R_{SET} - Z_0}{R_{SET} + Z_0}$$

However, R_{SET}>25kΩ, Z_0≈ 50Ω ➡ limited sensitivity

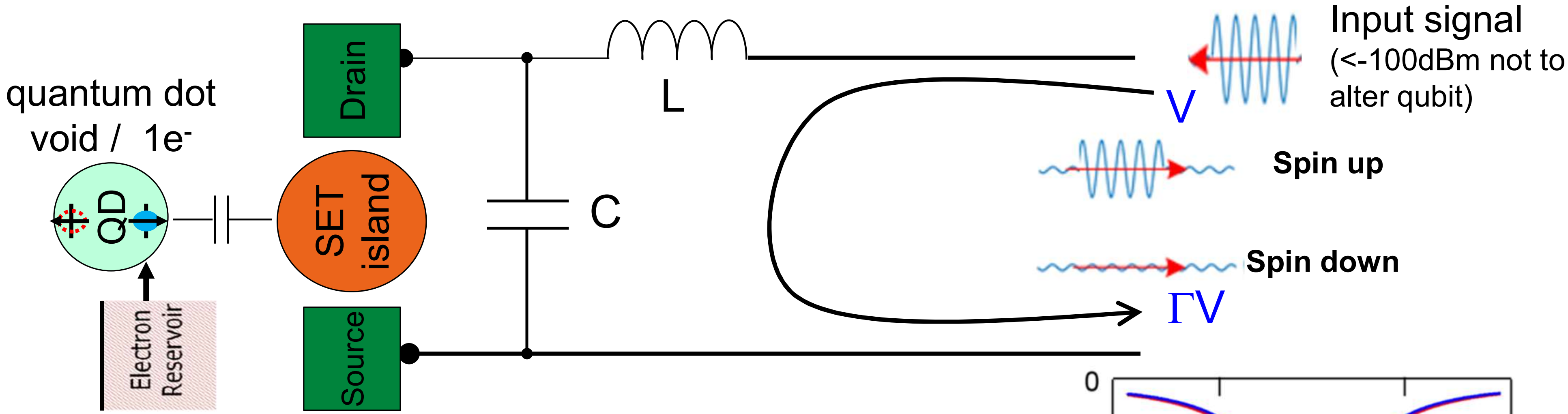
Matching network



SET resistance depends on the Quantum Dot charge that, in turn, depends on the spin

Passive network to match the high resistance of the SET to the Z_0=50Ω of the line

Matching network



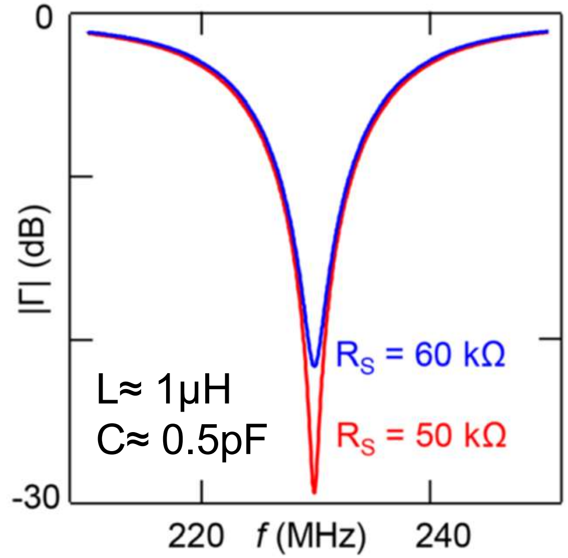
$$Z_L = R_{SET}\frac{1 + \frac{sL}{R_{SET}} + s^2LC}{1 + sCR_{SET}}$$

$$\omega_{res} = \frac{1}{\sqrt{LC}}$$

$$Z_L(\omega_{res}) = \frac{L}{CR_{SET}}$$

$$\Gamma(\omega_{res}) = \frac{Z_{eq}(\omega_{res}) - Z_0}{Z_{eq}(\omega_{res}) + Z_0}$$

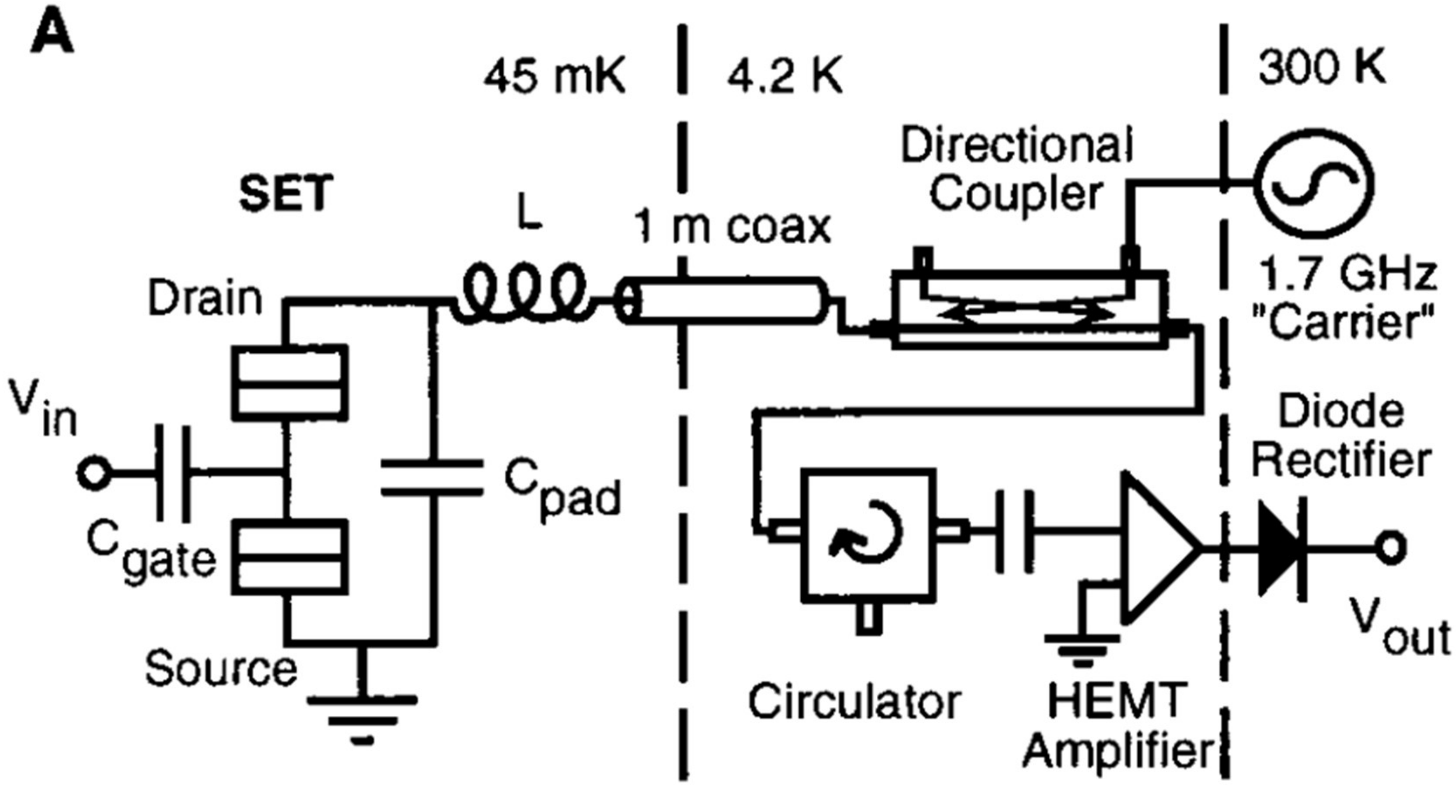
L,C selected to have
$Z_L(\omega_{res}) \approx Z_0$



F. Vigneau, et al. *Appl. Phys. Rev.* (2023), doi: 10.1063/5.0088229.

Readout based on RF reflectometry

R. Schoelkopf, et al. "The radio-frequency single-electron transistor (RF-SET): A fast and ultrasensitive electrometer," *Science*, vol. 280, no. 5367, pp. 1238–42, May 1998



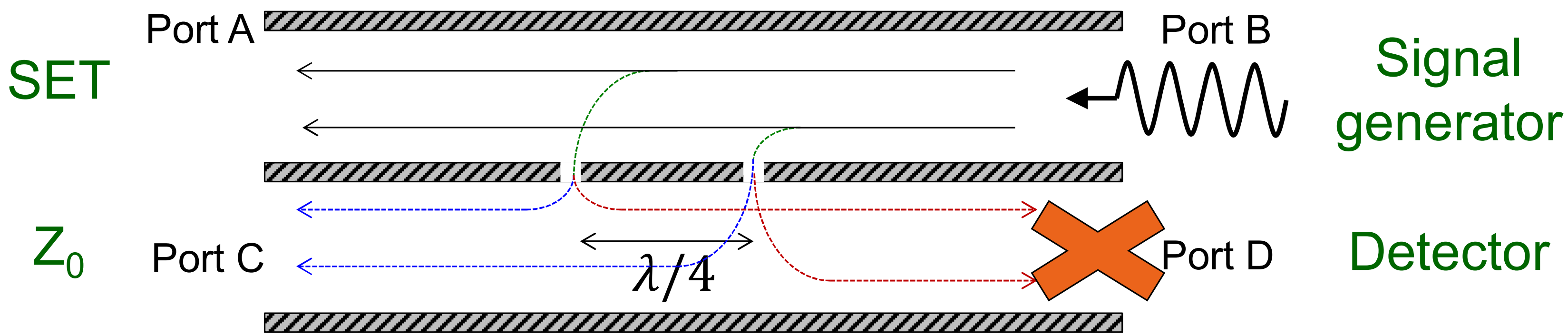
Reflectometry allows high-sensitivity impedance meas. despite long cables

(a similar technique can be applied to the gate of the QD, measuring a capacitance variation related to the charge)

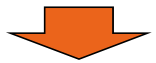
Review paper: F. Vigneau, et al. *Appl. Phys. Rev.* (2023), doi: 10.1063/5.0088229.

Directional coupler

Basic idea using waveguides:



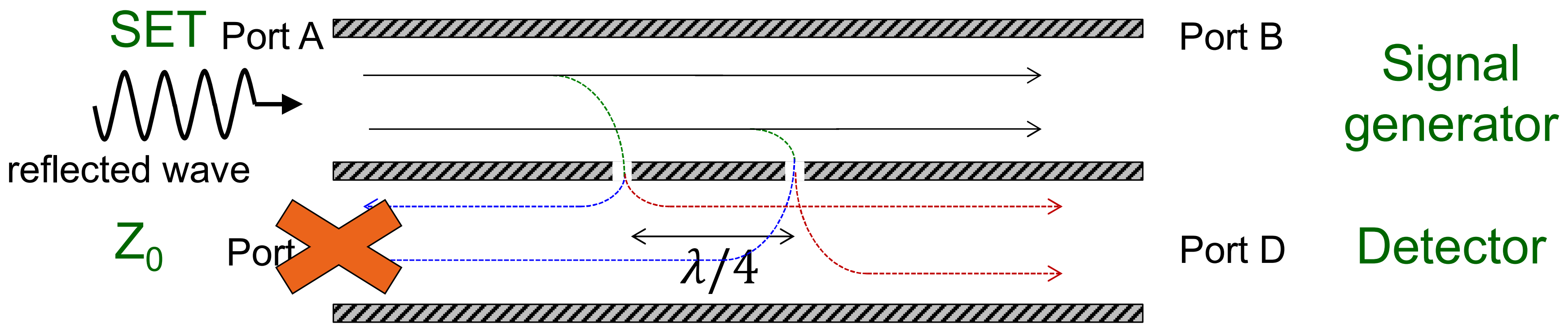
The contributions are added in-phase at port C.
However, since the paths differ in length by λ/2, they cancel at port D.



The detector does not measure the electromagnetic wave sent to the SET

Directional coupler

Basic idea using waveguides:



The only signal at port D is the reflected wave! (≪ voltage of the signal generator)

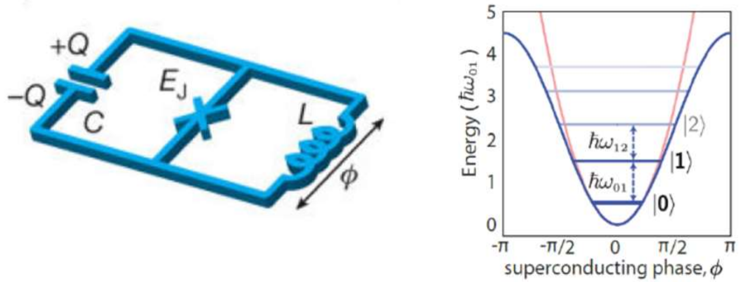
<u>Disadvantage</u>: size!

f=1GHz → λ ≈ 25cm

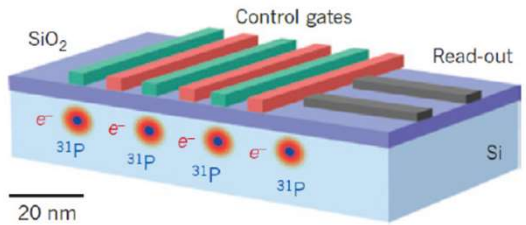
Spin qubits - summary

+ very small footprint (≈ 100nm) → scalability
+ compatible with microelectronic technology → scalability
+ can operate at relatively high temperatures (1K)
+ excellent readout method
    + spin-to-charge conversion + rf reflectometry
    - … but requires microwaves (inductor size ≈ 10k qubits!)
- no convincing proof of non-trivial cases (6 qubits in I. Fernández de Fuentes et al., preprint arXiv:2505.19200, May 2025)
- no qubit uniformity demonstrated

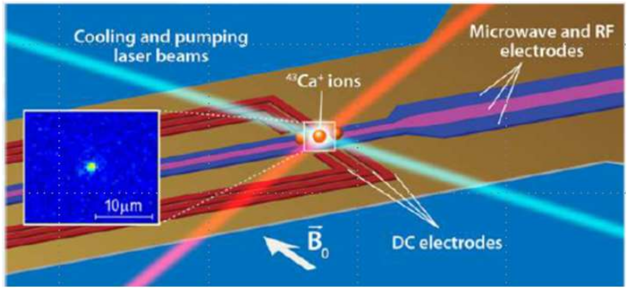
Qubit: examples of physical implementations



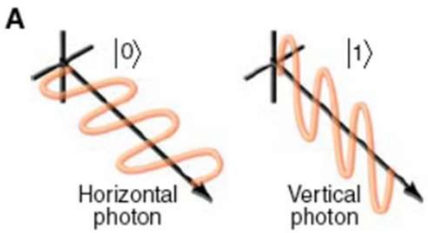
superconducting qubits
(Google, IBM, Amazon, Rigetti,…)
quantum annealing (D-Wave)



electron spin
(Intel, Quantum Motion, SpinQ…)



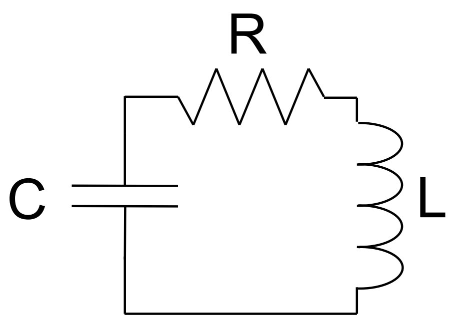
Trapped ions (Honeywell, Ion-Q,…)
Neutral atoms (Pasqal, QuEra,…)



Photons
(PsiQuantum, Xanadu, Quix,…)

"Useful" applications require **≈10^6** of physical qubits → scalability issue

LC resonator

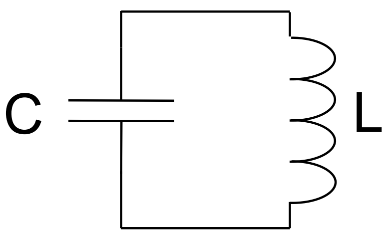


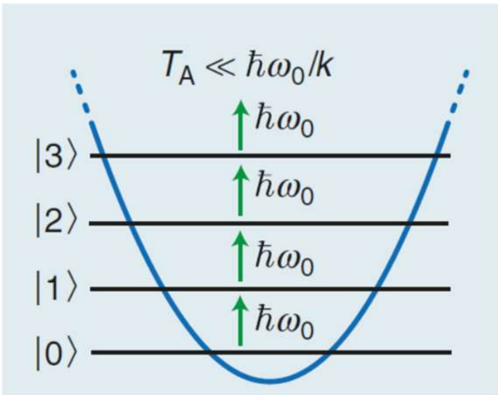
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

$$Q = \frac{1}{R}\sqrt{\frac{L}{C}}$$

The resistance introduces losses that limit the Q-factor, i.e., the coherence time

LC resonator using **superconductors** (R=0)





[J. Bardin et al, IEEE Microwave Magazine, 2020]

The LC oscillator can be viewed as a quantum harmonic oscillator

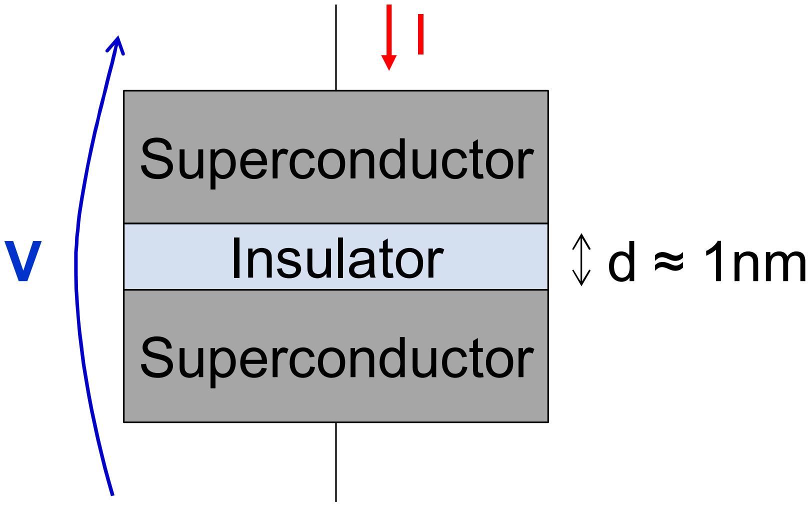
→ energy quantization (integer number of photons $\hbar\omega_0$)

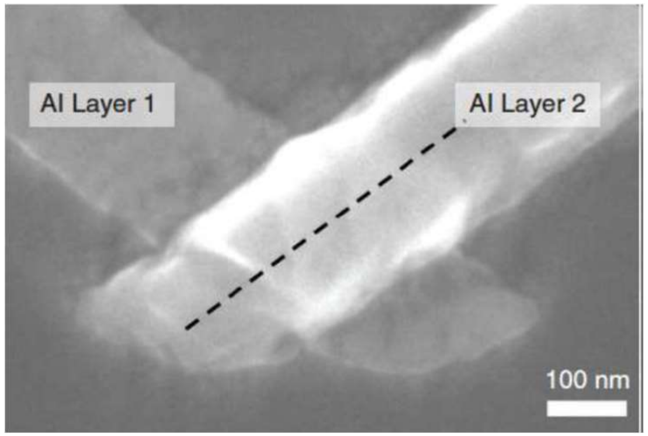
$$\hbar\omega_0 = 20\mu eV \ \ @\ 5GHz$$

$$\rightarrow \ \ T \ll 250mK$$

Still ***not*** a qubit: degeneracy of all the transition energies $\Delta E = E_n - E_{n-1} = \hbar\omega_0$

Josephson junction





Al_2O_3 insulator

Superconducting tunnel junction

zero DC resistance (V=0) if I < critical current I_0

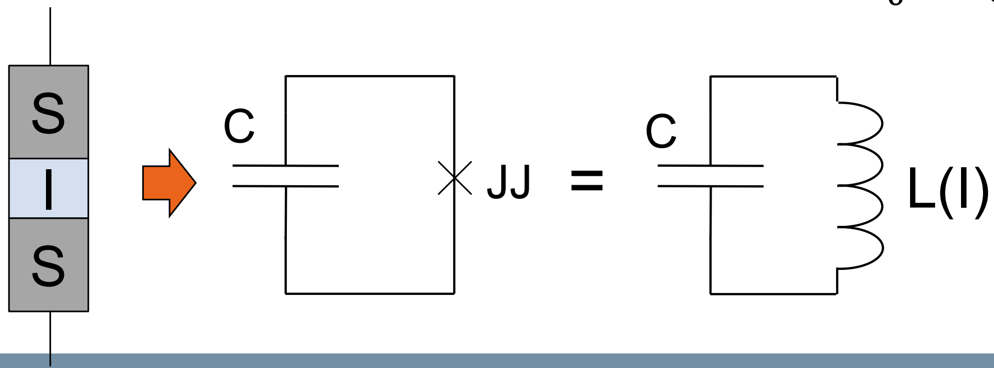
A phase difference $\phi = \phi_1 - \phi_2$ exists between the two superconducting layers

$$I = I_0 \sin(\phi)$$

$$V = \frac{\hbar}{2e}\frac{d\phi}{dt} = \frac{\hbar}{2e}\frac{1}{I_0\cos(\phi)}\frac{dI}{dt}$$

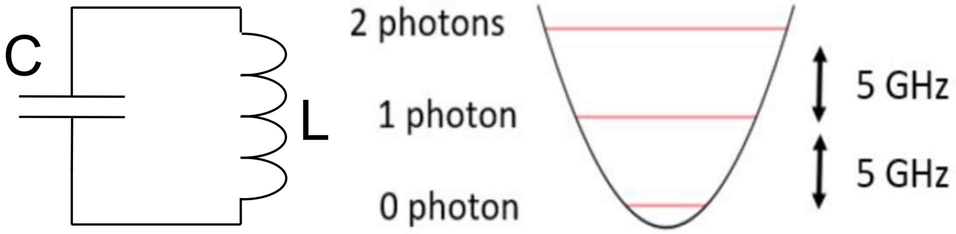
non-linear inductor:

$$L = \frac{\hbar}{2e\, I_0 \cos(\phi)} = L(I)$$

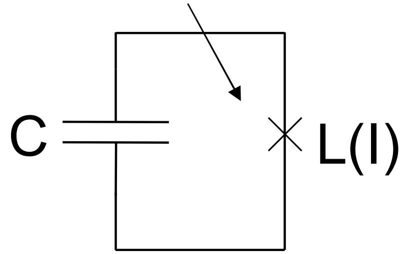


Superconducting qubit - transmon

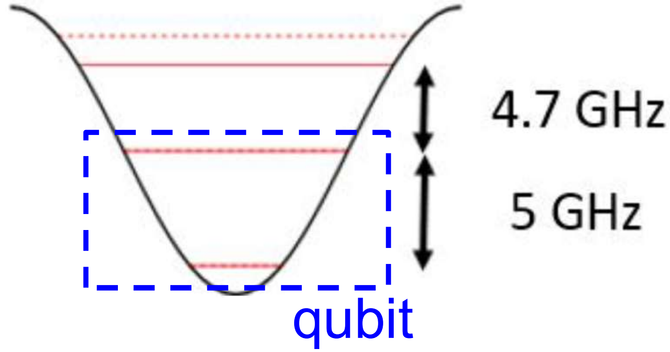
$$f_0 = 5GHz, kT \ll hf_0$$



non-linear inductor (Josephson junction)



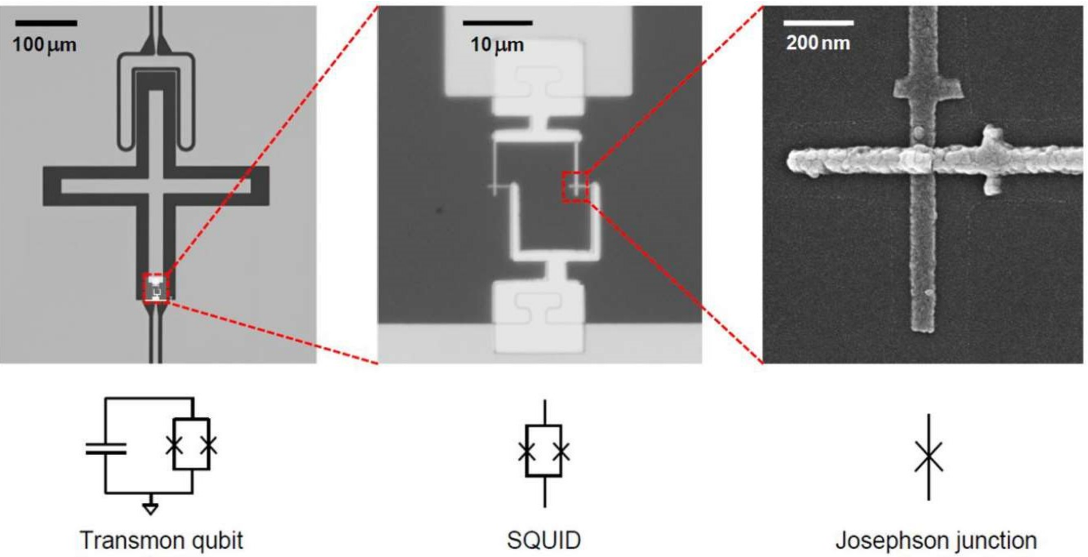
[T.E. Rothet al, IEEE Ant. Magazine, 2021]



<u>non-linear resonator</u>

→ nonuniform energy level spacing

Transmon qubit:

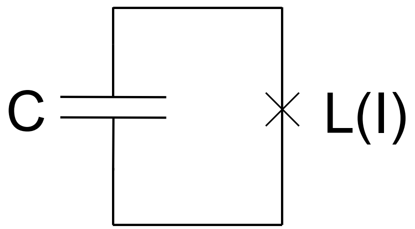


- large C to reduce charge noise
- magnetic flux tunes the resonance

Typical values:

$C \approx 70fF$
$I_0 \approx 20nA$
$L \approx 15nH$
$f_0 \approx 5GHz$
$Q > 10^7$
size ≈ 100µm

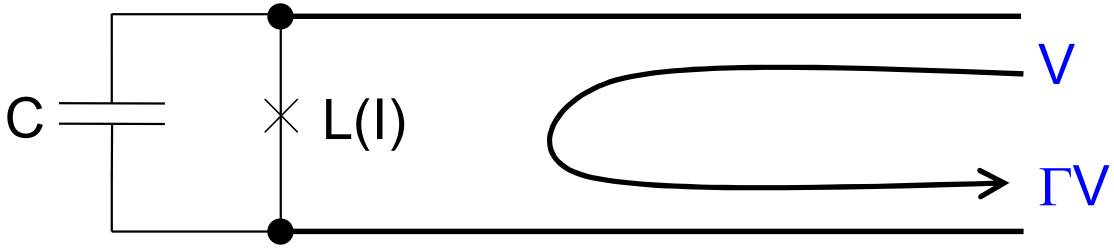
qubit:



|0> : 0 photon
|1> : 1 photon

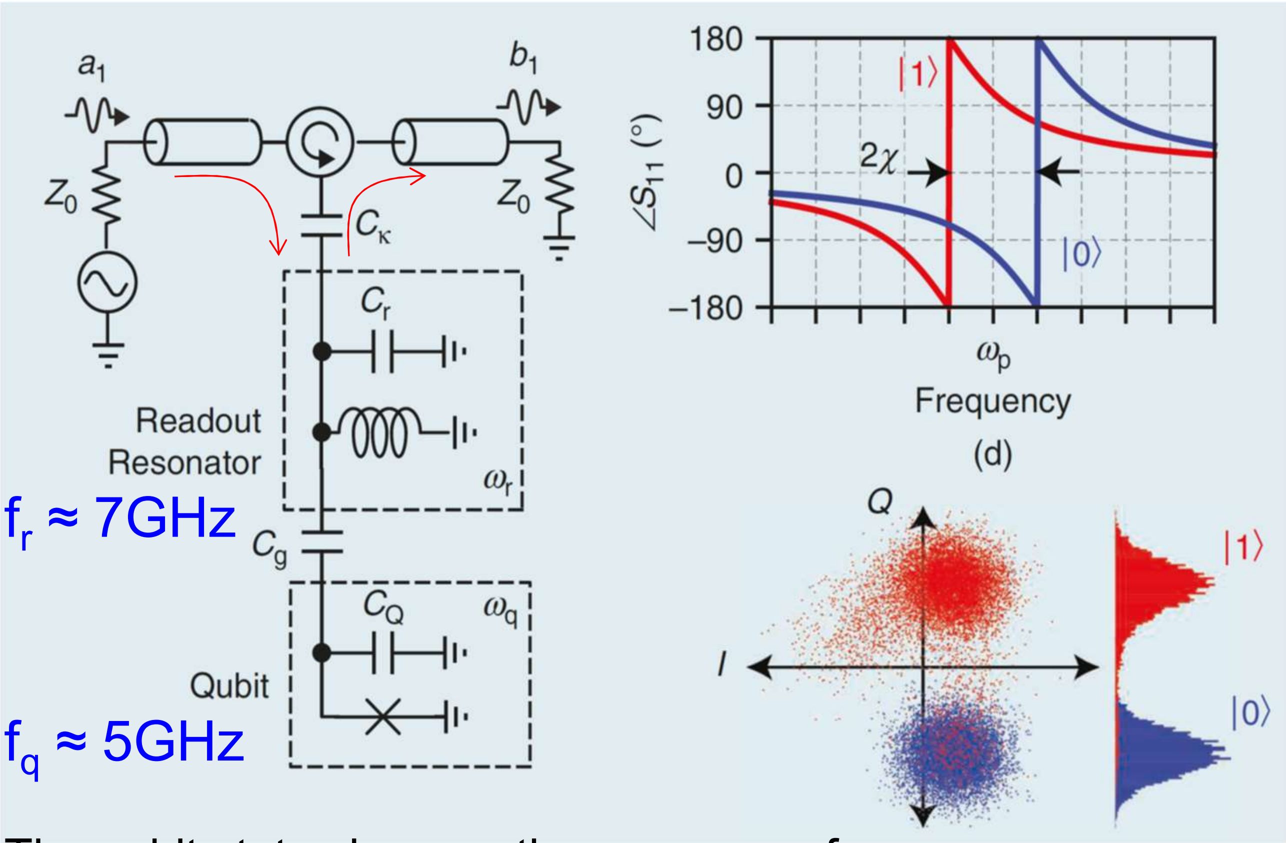
We should be able to detect a single photon with an energy of only ≈ 20μeV!

The Josephson junction is a non-linear inductor
→ **impedance depends on the oscillation amplitude, i.e., the qubit state**
→ we can use **rf reflectometry!**



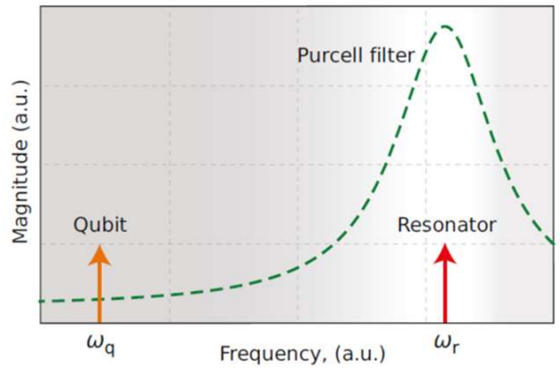
How to maximize the signal and minimize the perturbation on the qubit?

Superconducting qubits – dispersive readout



The qubit state changes the resonance frequency of the readout resonator

- The transmission line is not directly connected to the qubit but to a second resonator
- *dispersive readout* ($f_r \neq f_q$) and a small capacitor C_g (≈ 25aF) to limit the perturbation

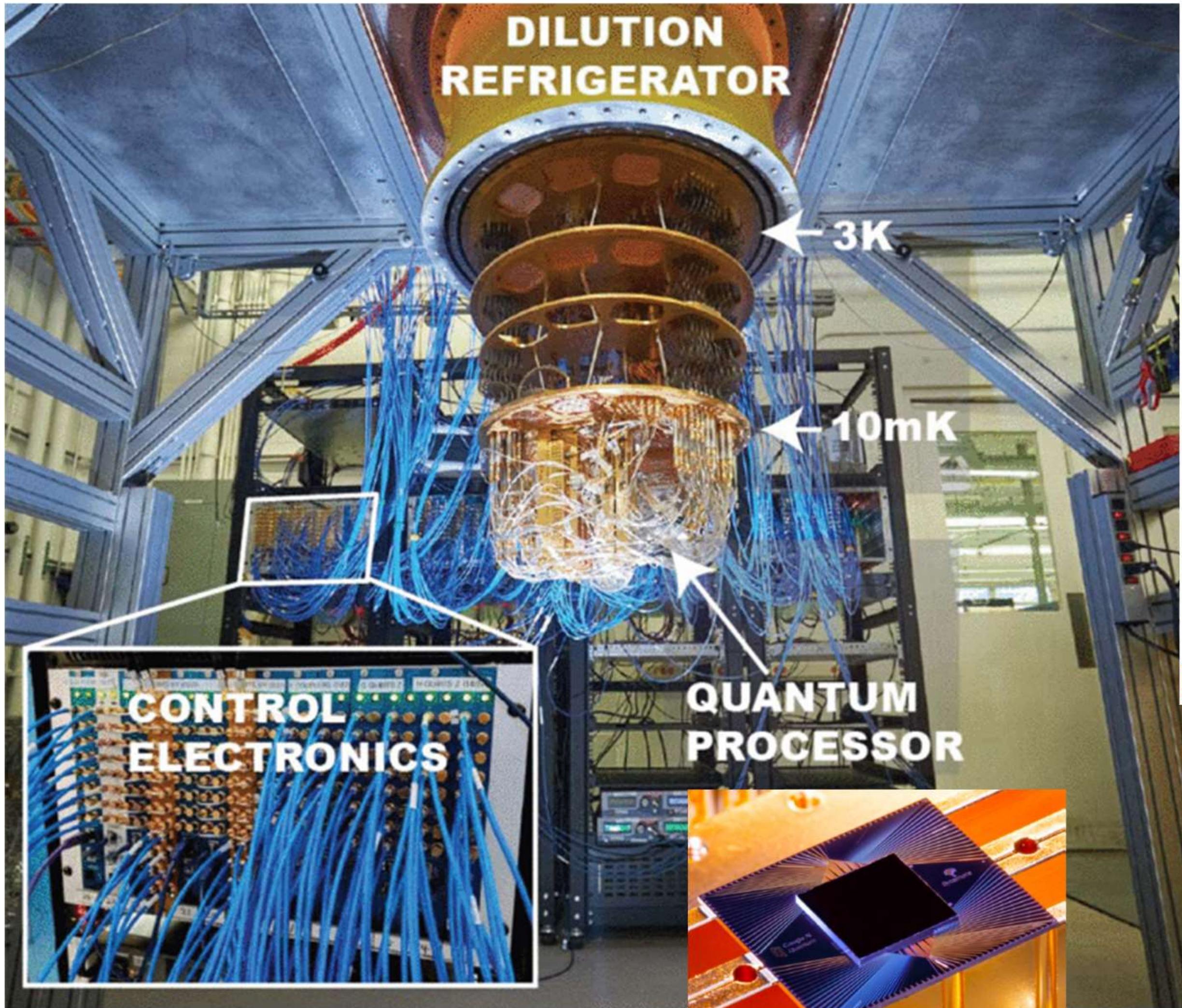


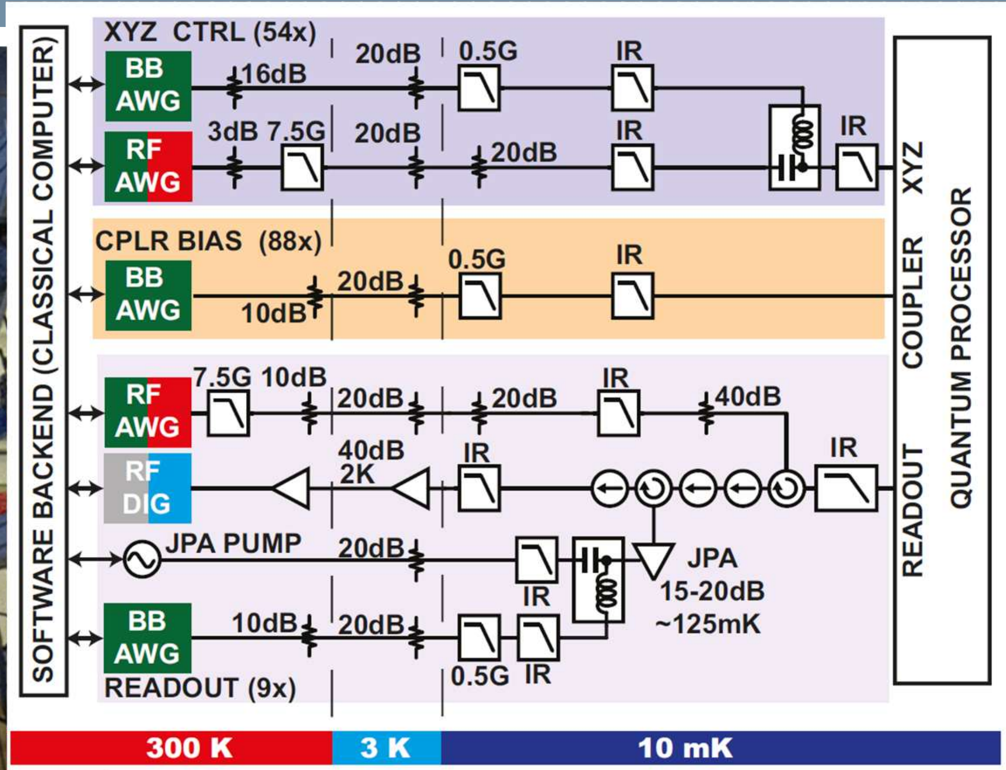
- small injected power (< -125dBm)
- Josephson Parametric Amplifier (T<100mK) with near-quantum-limited noise

[J. Bardin et al, IEEE Microwave Magazine, 2020]

[P. Krantz et al, Applied Physics Review, 2019]

Google quantum computer (sycamore)





[J. Bardin, ISSSCC 2022]

- 54 qubits (transmons)
- T=10mK
- 9 readout channels (<1μs, ≈ 10 photons of the readout resonator)
- new version (Dec. 2024): 105 qubits (Willow)

Superconducting qubits - summary

- \+ compatible with microelectronic technology
- \+ reproducible and reliable fabrication
- \+ control and readout using microwaves
- \+ most advanced quantum computers (Google, IBM) are based on this technology
- \- large footprint (≈ 100μm) + microwaves → scalability issue
- \- operates at tens of mK: limited cooling power, no active electronics → wiring bottleneck
- \- requires an extremely sensitive readout

Summary

- Scaling of quantum control and measurement systems is a major challenge without (yet) a winning qubit platform
- Measurement challenges:
  - detect a single quantum state
  - fast and with minimal perturbation
  - solid-state qubits are cryogenic devices in huge cryostats
- **rf reflectometry**: a powerful technique to detect an impedance variation, benefiting from long cables
  - drawback: inductors, directional couplers (gyrators) are large components
- Single-Electron transistors are excellent charge detectors at cryogenic temperatures
- Experimental results demonstrate successful qubit control and readout
- Research in this field is just beginning, with substantial work needed to determine the optimal electronics for a specific quantum processor architecture and technology