Quantum devices

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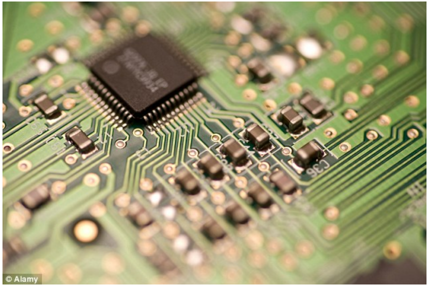
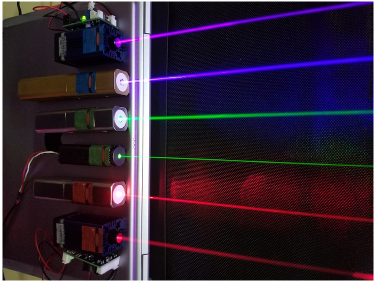
24/10/23

QUANTUM DEVICES: a definition

A quantum machine is a device whose **degrees of freedom** are **intrinsically quantum mechanical**



TRANSISTOR → electronic bandgap



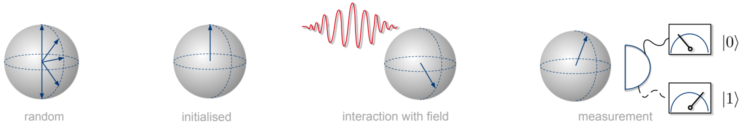
LASER→ 3/4-levels system

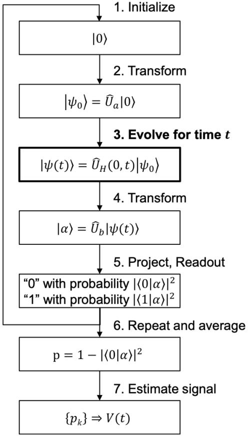
Every machine is made of atoms and its microscopic degrees of freedom (the electrons and nuclei) are intrinsically quantum. Nevertheless, both the laser and the transistor are **classical machines**, because their **operational degrees of freedom are purely classical**

WHAT IS A QUANTUM SENSOR?

“Quantum sensors are individual systems or ensembles of systems that use **quantum coherence**, **interference** and **entanglement** to determine physical quantities of interest.”
Rev. Mod. Phys. 89, 035002 (2017)

“A device whose measurement (sensing) capability is enabled by our ability to **manipulate and readout its quantum states**.”
M. Safranova and D. Budker





1. Initialize

$|0\rangle$

2. Transform

$|\psi_0\rangle = \hat{U}_a|0\rangle$

3. Evolve for time *t*

$|\psi(t)\rangle = \hat{U}_H(0,t)|\psi_0\rangle$

4. Transform

$|\alpha\rangle = \hat{U}_b|\psi(t)\rangle$

5. Project, Readout

“0” with probability $|\langle 0|\alpha\rangle|^2$
“1” with probability $|\langle 1|\alpha\rangle|^2$

6. Repeat and average

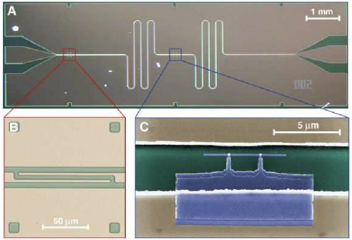
$p = 1 - |\langle 0|\alpha\rangle|^2$

7. Estimate signal

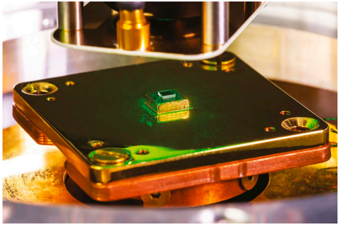
$\{p_k\} \Rightarrow V(t)$

WHAT IS A QUANTUM SENSOR?

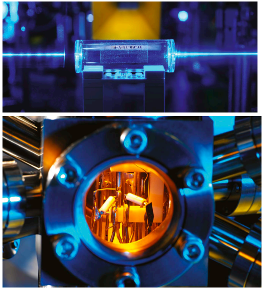
Quantum sensors have been realised in **multiple physical systems with very different operating principles**.



Superconducting circuits

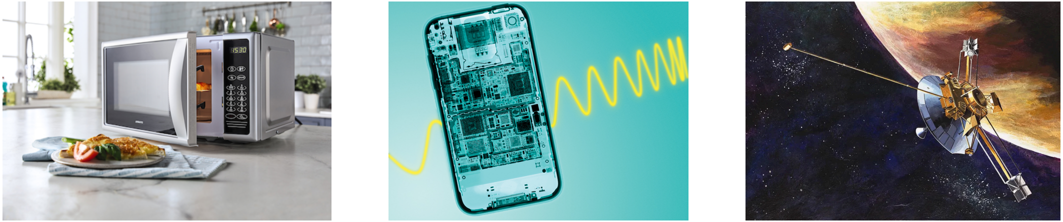


Solid-state spins

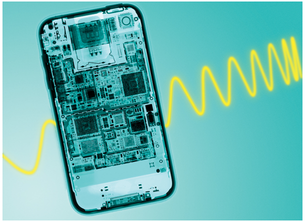


Atomic ensembles

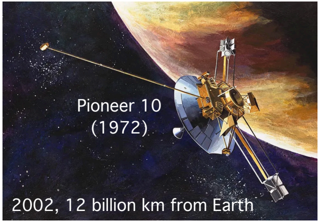
It might take some more time to adapt them in real-world settings, but **they are already in use in the lab**. Applied to problems in which **significant** gain (up to 1000s) compared to conventional detectors is required.



kW

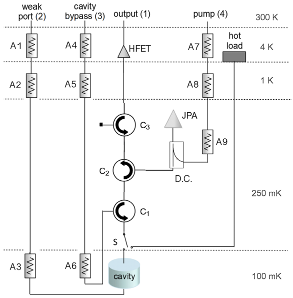


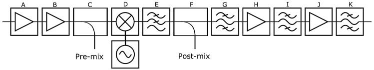
(0.1-2) W

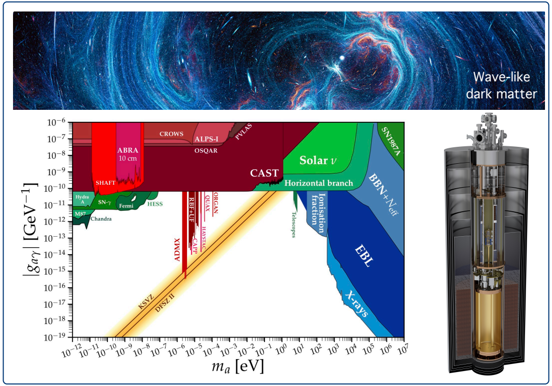


2.5×10^{-21} W

quantum microwaves in DARK MATTER search







Dilution refrigerator (mK temperature)
Quantum-limited amplifiers
Heterodyne microwave receiver

$< 10^{-23}$ W

Unknown frequency (particle mass)

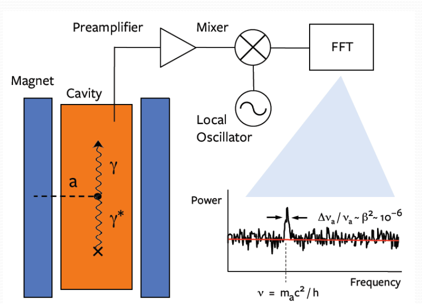
Thousands of years are required to probe the open parameter space with the conventional hetherodyne detector

Why 1000s-years? $df/dt \propto T_{sys}^{-2}$

Even though the experiment is **cooled to the lowest temperatures in the Universe** ($\sim 10\,\mathrm{mK}$), and Josephson Parametric Amplifiers (JPA) are employed to **minimize added noise**, they introduce fundamental noise (**SQL, Standard Quantum Limit noise**)

$T_{sys} = T_c + T_A$
T_c cavity physical temperature
T_A effective noise temperature of the amplifier

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right)$$



at 10 GHz frequency

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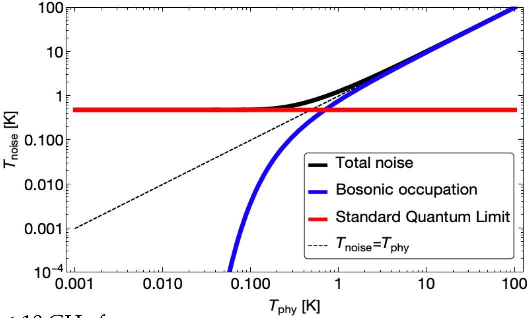
$N_a > 1$



at 10 GHz frequency

beyond the SQL **with a "microwave phototube"** $\Longleftrightarrow$ **detection of quantum microwaves**

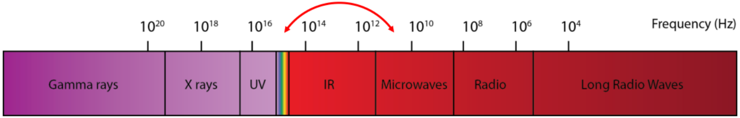
	B [T]	$P_{\mathrm{sig}}^{\mathrm{KSVZ}}$ [yW(ph/s)]	$P_{\mathrm{sig}}^{\mathrm{DFSZ}}$ [yW(ph/s)]
$\nu_c = 7.37\,\mathrm{GHz}$	2	0.84(0.17)	0.11(0.026)
	12	30.4(6.2)	6.3(0.86)
$\nu_c = 10\,\mathrm{GHz}$	12	22.39(3.38)	3.11(0.47)

signal power and photon rate for benchmark QCD axion models in yoctowatt (yW$= 10^{-24}$ W)

Using quantum-limited **linear amplifiers** (Josephson parametric amplifiers) the **noise set by quantum mechanics** exceeds the **signal** in the high frequency range, whereas **photon counting** has no intrinsic limitations

SMPDs in the microwave range

Detection of individual microwave photons is a challenging task because of their **low energy** e.g. $h\nu = 2.1 \times 10^{-5}\,\mathrm{eV}$ for $\nu = 5\,\mathrm{GHz}$

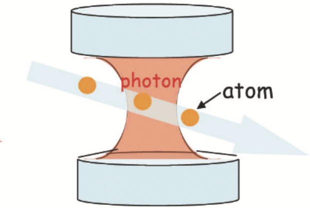


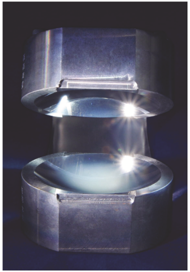
Requirements for dark matter search:

- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100\,\mathrm{Hz}$
- $\gtrsim 40 - 50\,\%$ efficiency
- large “dynamic” bandwidth $\sim$ cavity tunability

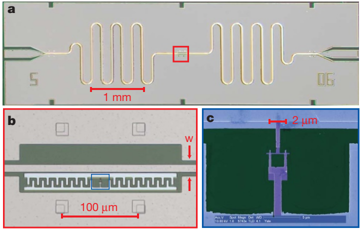
DETECTION OF QUANTUM MICROWAVES

The detection of individual **microwave photons** has been pioneered by **atomic cavity quantum electrodynamics experiments** and later on transposed to **circuit QED experiments**





Nature **400**, 239–242 (1999)



Nature **445**, 515–518 (2007)

In both cases **two-level atoms** interact directly with a **microwave field mode*** in the cavity

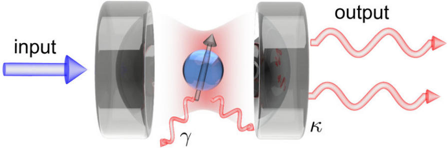
* a quantum oscillator whose quanta are photons

Cavity-QED for photon counting

Can the field of a single photon have a large effect on the atom (TLS)?

Interaction: $H = -\vec{d} \cdot \vec{E}$, $E(t) = E_0 \cos \omega_q t$

It's a matter of increasing the **coupling strength** g between the atom and the field $g = \vec{E} \cdot \vec{d}$:



→ work with **large atoms**

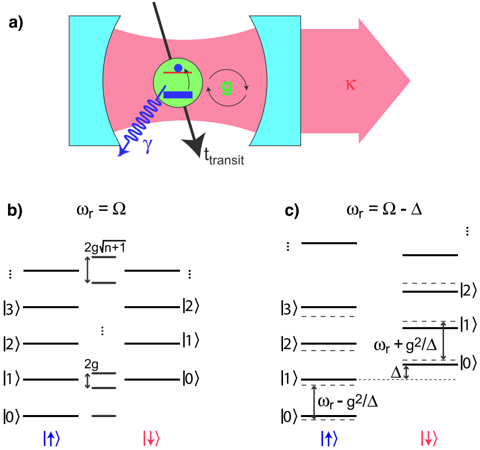
→ **confine the field** in a cavity

$$\vec{E} \propto \frac{1}{\sqrt{V}}, \; V \;\text{ volume}$$

κ rate of cavity photon decay
γ rate at which the qubit loses its excitation
to modes $\neq$ from the mode of interest

$g \gg \kappa, \gamma \iff$ regime of strong coupling
coherent exchange of a field quantum between the atom (matter) and the cavity (field)

CAVITY QED SYSTEM



A simple theoretical model (Jaynes-Cummings) describes atoms as two-level, **spin-like systems** interacting with a quantum oscillator

$$H = \hbar\omega_{\mathrm{r}}\left(a^\dagger a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^z + \hbar g(a^\dagger\sigma^- + a\sigma^+)$$

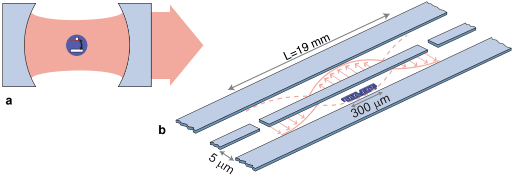
- ω_r cavity resonance frequency
- Ω atomic transition frequency
- g strength of the atom-photon coupling

from cavity-QED to circuit-QED

g is significantly increased compared to Rydberg atoms:

$\rightarrow$ artificial atoms are large ($\sim 300\,\mu$m)
$\Longrightarrow$ large dipole moment

$\rightarrow$ $\vec{E}$ can be tightly confined
$\vec{E} \propto \sqrt{1/\lambda^3}$
$\omega^2\lambda \approx 10^{-6}\,\mathrm{cm}^3$ (1D) versus $\lambda^3 \approx 1\,\mathrm{cm}^3$ (3D)
$\Longrightarrow 10^6$ larger energy density

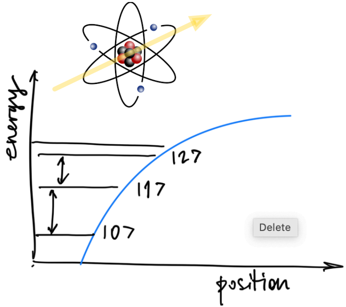


(a) $(g/2\pi)_{\text{cavity}} \sim 50\,\text{kHz}$

(b) $(g/2\pi)_{\text{circuit}} \sim 100\,\text{MHz}$ (typical)

10^4 larger coupling than in atomic systems

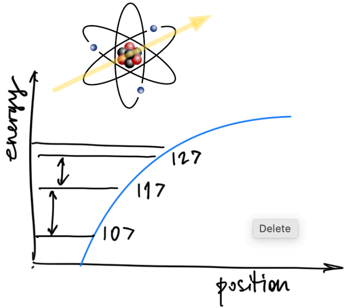
“Atoms”: (almost) natural qubits



$E_{01} = E_1 - E_0 = \hbar\omega_{01} \neq E_{02} = E_2 - E_1 = \hbar\omega_{21}$
→ good **two-level atom** approximation

control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos \omega_{01} t$

qubits from “**artificial atoms**”: LC circuit



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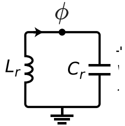
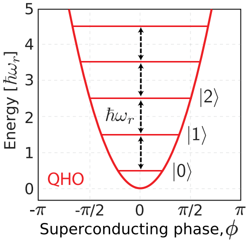
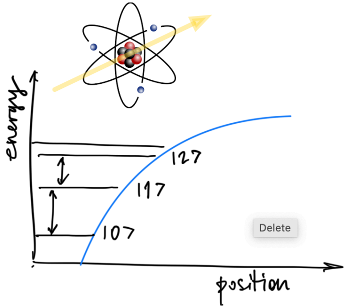




toolkit: capacitor, inductor, wire (all SC)
$\omega_{01} = 1/\sqrt{LC} \sim 10\,\text{GHz} \sim 0.5\,\text{K}$

→ simple LC circuit is not a good **two-level atom** approximation

qubits from “**artificial atoms**”: LC circuit **with NL inductance** of the Josephson Junction



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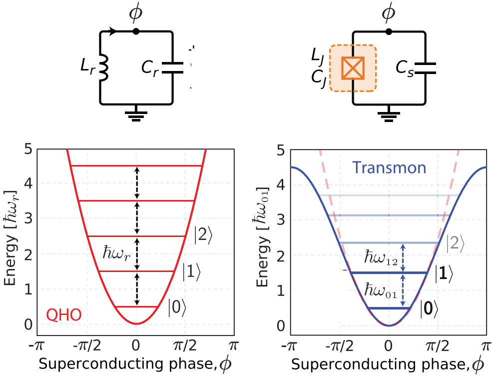


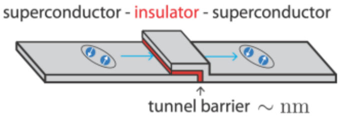
toolkit: capacitor, inductor, wire (all SC) + **JJ**

JJ is a **nonlinear** and dissipationless element

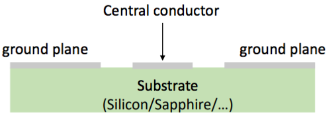
$$L_J = \frac{\phi_0}{2\pi} \frac{1}{I_c \cos \phi}$$

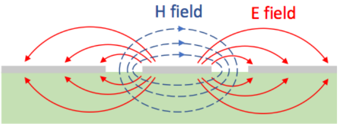
the Josephson Junction

the only circuit element that is both **dissipationless** and **nonlinear** (fundamental properties to make quantum hardware)



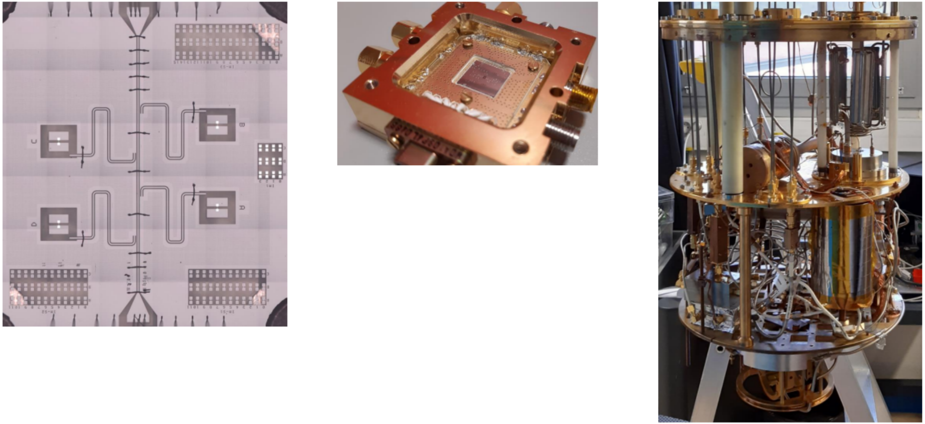
It's integrated in superconducting (SC) circuits, solid state electrical circuits fabricated using techniques borrowed from **conventional integrated circuits**.





$T = 10 - 20\,\mathrm{mK}$ in dilution refrigerators

$k_B T$ $\qquad$ $h\nu$

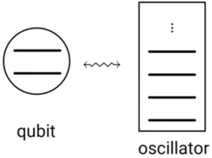


$\Longrightarrow$ low temperature physics

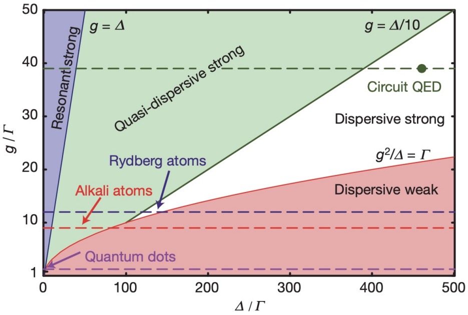
Jaynes-Cummings model

Interaction of a **two state system** with **quantized radiation in a cavity**

$$\mathcal{H}_{\mathrm{JC}} = \frac{1}{2}\hbar\omega_q\hat{\sigma}_z + \hbar\omega_r\hat{a}^\dagger\hat{a} + \hbar g(\hat{a}\hat{\sigma}_+ + \hat{a}^\dagger\hat{\sigma}_-)$$



Parameter space diagram for cavity-QED

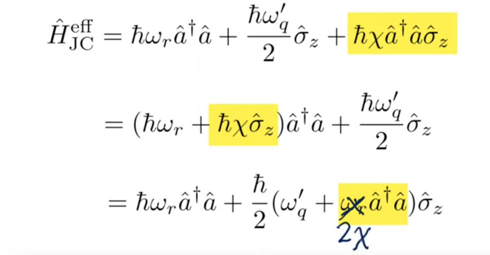


$$\Delta = |\omega_r - \omega_q|$$

$$\Gamma = \min\{\gamma,\ \kappa,\ 1/T\}$$

- $\omega_r \sim \omega_q$ *resonance* case
- $\Delta = |\omega_r - \omega_q| \gg g$ *dispersive limit* case

Dispersive regime of detuning $g/\Delta \ll 1$



$$\hat{H}_{\mathrm{JC}}^{\mathrm{eff}} = \hbar\omega_r \hat{a}^\dagger \hat{a} + \frac{\hbar\omega_q'}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z$$

$$= (\hbar\omega_r + \hbar\chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\hbar\omega_q'}{2}\hat{\sigma}_z$$

$$= \hbar\omega_r\hat{a}^\dagger\hat{a} + \frac{\hbar}{2}(\omega_q' + \underset{2\chi}{\cancel{\omega_r}}\hat{a}^\dagger\hat{a})\hat{\sigma}_z$$

$$\chi = \frac{g^2}{\delta}$$

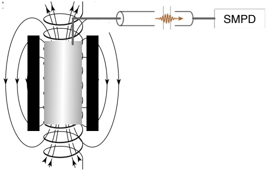
$\rightarrow \hbar\chi\hat{\sigma}_z$ dispersive qubit readout

$\rightarrow 2\chi a^\dagger a$ number splitting

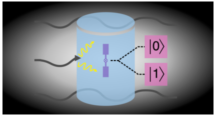
a real (B field, tunable) DM search with a QIS device

→ *itinerant* vs *cavity* single microwave photon counter (SMPD)

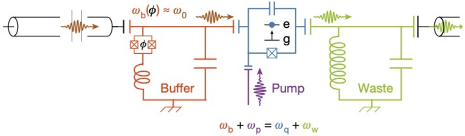
ITINERANT PHOTONS



CAVITY PHOTONS



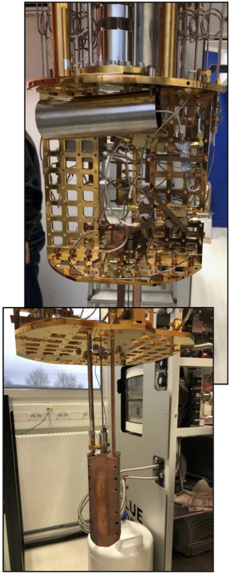
Phys. Rev. Lett. 126, 141302 (2021)



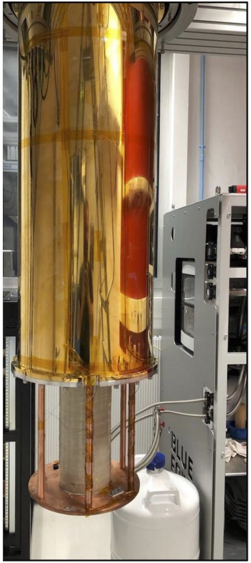
- ⊙ low dark counts $\Longrightarrow$ sensitivity
- ⊙ tunability
  static ($\simeq 100\,\mathrm{kHz}$), dynamical ($\simeq 100\,\mathrm{MHz}$)
  + Josephson mixer
- ⊙ metrological methods from QIS field
- ⊙ on/off resonance studies

SMPD-HALOSCOPE experiment

- hybrid (normal-superconducting) cavity
  7.37 GHz, tunable, $Q_0 = 9 \times 10^5$
  (at 14 mK, under 2 T)
- T=14 mK delfridge base temperature
  @ Quantronics lab (CEA, Saclay)
- a thousandfold acceleration of the search
- spin-off company in 2024 (FR)
- come to visit the lab
  Progetto di Eccellenza, DFA



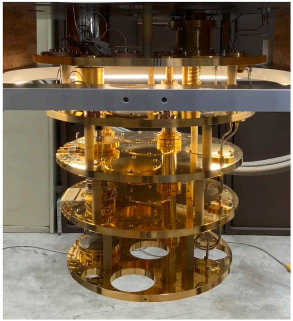
SMPD (top) and cavity



SC magnet

building a SMPD-HALOSCOPE experiment in Padova

Progetto di Eccellenza, DFA



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SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER