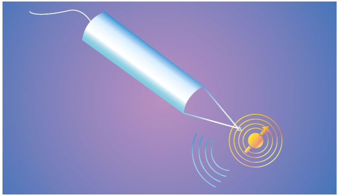
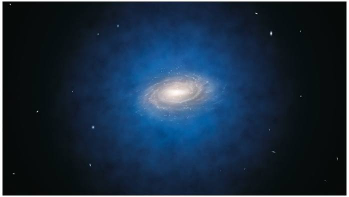




Quantum sensing in wave-like dark matter search

Caterina Braggio

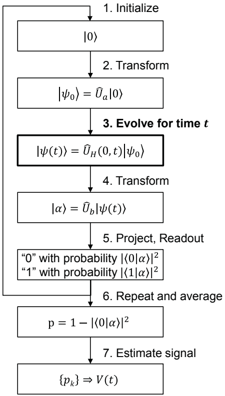
INFN Workshop for future detectors

17-19 October 2022, Bari

QUANTUM SENSING: a definition

"Quantum sensing" describes the use of a quantum system, quantum properties or quantum phenomena to perform a measurement of a physical quantity
Rev. Mod. Phys. 89, 035002 (2017)

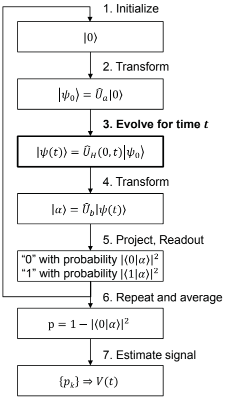
1. Use of a **quantum object** to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels, i.e. electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.
2. Use of **quantum coherence** (i.e., wave-like spatial or temporal superposition states) to measure a physical quantity
3. Use of **quantum entanglement** to improve the sensitivity or precision of a measurement, beyond what is possible classically.



BASIC PROTOCOL

quantum sensing experiments typically follow a generic sequence of processes known as:

1. sensor initialization into a known basis state
2. interaction with the signal
3. sensor readout
4. signal estimation



quantum sensors are **extremely sensitive** to disturbances

$\Longrightarrow$ they have the potential to become extraordinary **measuring instruments** in specific application areas quantum sensors are **extremely sensitive** to disturbances

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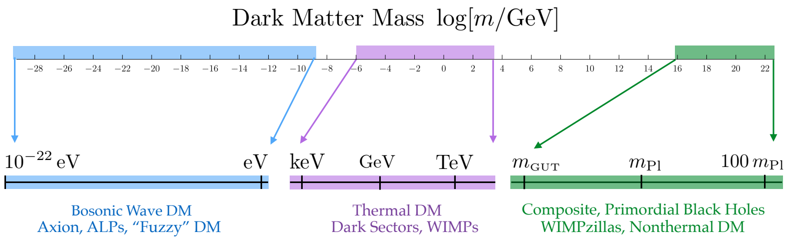
what about particle physics?



– $\simeq$ 10 eV is considered a fundamental watershed
– **quantum sensing** $\rightarrow$ significant opportunities for **wave-like DM** and in the 10 keV-1MeV range

Experimental methods

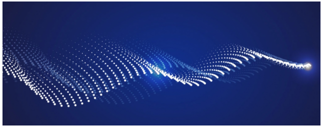
– axion/dark photon **haloscopes** $\rightarrow$ *well established field*
– **collective excitations** in solid state materials (magnons, phonons) $\rightarrow$ *only recently proposed, very promising*

Dark Matter waves

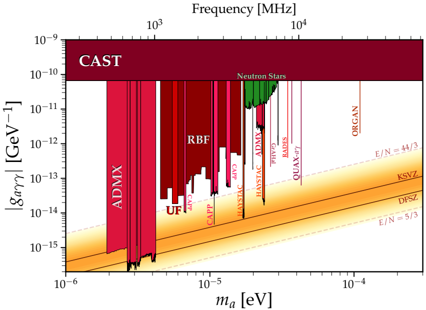
particle $\Leftrightarrow$ wave

$$\lambda = \frac{h}{mv}, \qquad h\nu = E = mc^2 + \frac{1}{2}mv^2$$

For **light** and **massless** particles the wavelength can be large.



$$m_a \simeq h\nu_a \qquad 1\,\mu\text{eV} \leftrightarrow 0.25\,\text{GHz}$$

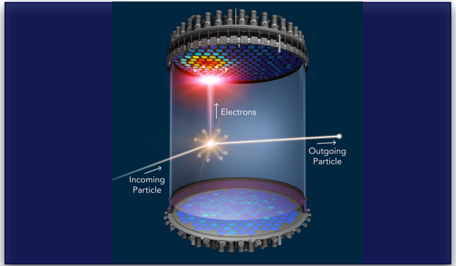


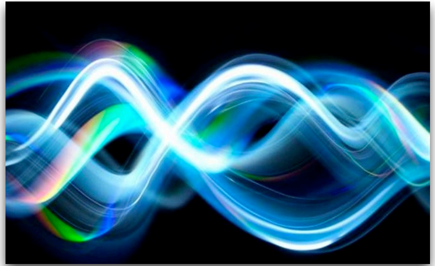
If these particles are also **bosons**, many particles **can occupy the same state**

$$\rho_{\text{DM}} = 0.3 - 0.4\,\text{GeV}\,\text{cm}^{-3} \qquad \Longrightarrow \qquad n_a \sim 3 \times 10^{12}(10^{-4}\text{eV}/m_a)\ \text{axions/cm}^3$$

it's a **macroscopic wave-like** behavior

AXION VS WIMP DETECTION





WIMP [1-100 GeV]
— number density is small
— tiny wavelength
— no detector-scale coherence

$\Longrightarrow$ observable: **scattering** of individual particles

AXION [$m_A \ll$ eV]
— number density is large (bosons)
— long wavelength
— coherence within detector

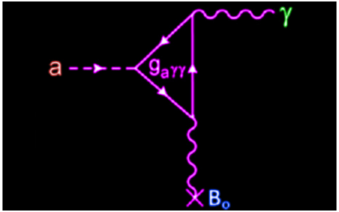
$\Longrightarrow$ observable: classical, oscillating, **background field**

HALOSCOPE - resonant search for axion DM in the Galactic halo

– original proposal by P. Sikivie (1983)

– search for axions as cold dark matter constituent: SHM from Λ_{CDM}, local DM density ρ
  $\rightarrow$ signal is a **line** with 10^{-6} relative width in the energy($\rightarrow$ frequency) spectrum

– an **axion** may interact with a **strong $\vec{B}$ field** to produce a **photon** of a specific frequency ($\rightarrow m_a$)



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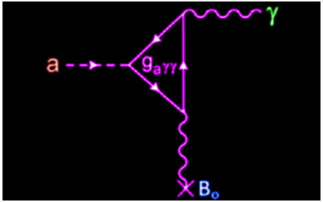


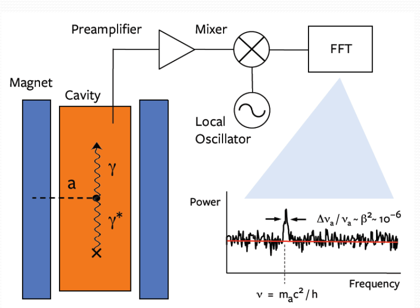
1. microwave cavity for resonant amplification
   -think of an HO driven by an external force-
2. with **tuneable frequency** to match the axion mass
3. the cavity is within the bore of a **SC magnet**
4. cavity signal is readout with a **low noise receiver**
5. cavity and receiver preamplifier are kept at base temperature of a **dilution refrigerator** $(10 - 50)$ mK

weak interactions with SM particles $\Longrightarrow 10^{-22}$ W signal power $\longleftrightarrow \lesssim$Hz signal rate at 10 GHz

Josephson Parametric Amplifiers (JPAs) introduce the lowest level of noise, set by the laws of quantum mechanics (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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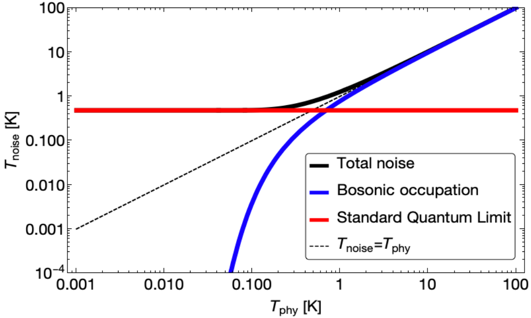


at 10 GHz frequency

Standard Quantum limit in linear amplification

Any narrow bandwidth signal $\Delta\nu_c \ll \nu_c$ can be written as:

$$\begin{aligned} V(t) &= V_0[X_1\cos(2\pi\nu_c t) + X_2\sin(2\pi\nu_c t)] \\ &= V_0/2[a(t)\exp(-2\pi i\nu_c t) + a^*(t)\exp(+2\pi i\nu_c t)] \end{aligned}$$

X_1 and X_2 signal quadratures
$a, a^* \to$ to operators $a, a^\dagger$ with $[a, a^\dagger] = 1$ and $N = aa^\dagger$
Hamiltonian of the cavity mode is that of the HO:

$$\mathcal{H} = h\nu_c\left(N + \frac{1}{2}\right)$$

Alternatively, with $[X_1, X_2] = \frac{i}{2}$:

$$\mathcal{H} = \frac{h\nu_c}{2}(X_1^2 + X_2^2)$$

$$kT_{\text{sys}} = h\nu_c N_{sys} = \left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} + N_A\right)$$

Caves' Theorem: $N_A > 1/2$

The quantum noise is a consequence of the base that we want to use to measure the content of the cavity.
A **linear amplifier** measures the amplitudes in phase and in quadrature, while a **photon counter** measures N.

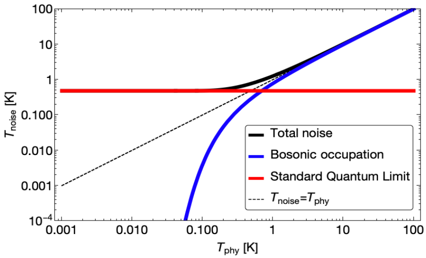
Beyond SQL: photon counting

- **Photon counting** is a game changer at high frequency and low temperatures: in the **energy eigenbasis** there is no intrinsic limit (SQL)

- unlimited (exponential) gain in the haloscope scan rate compared to linear amplification at SQL:

$$\frac{R_{\text{counter}}}{R_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$

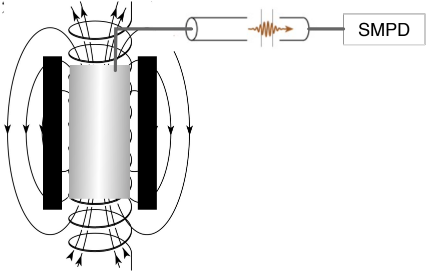
at 7 GHz, 40 mK $\Longrightarrow 10^3$ faster than SQL linear amplifier readout



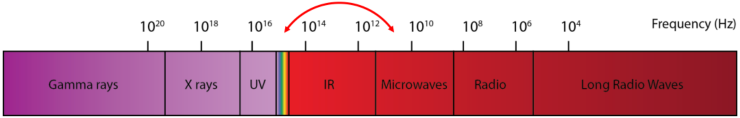
plot example at 10 GHz, where $T_{\text{SQL}} = h\nu/k_B \rightarrow 0.5\,\text{K}$

SMPDs FOR ITINERANT PHOTONS

A Single Photon Microwave Counter (SMPD) architecture is significantly different whether it is meant for **cavity photons** or **itinerant (traveling) photons**.
We are interested in the itinerant version due to the magnetic fields involved.

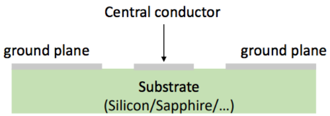


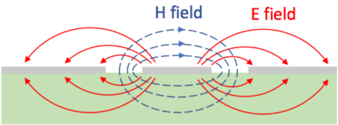
- detection of individual microwave photons is a challenging task because of their**low energy** $\sim 10^{-5}$ eV
- a solution: use "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ∼GHz range
- or: rely on a single **current-biased Josephson junction**



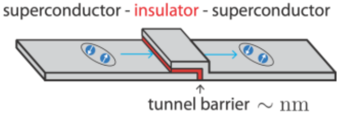
SUPERCONDUCTING CIRCUITS and the JOSEPHSON JUNCTION

SC circuits are solid state electrical circuits fabricated using techniques borrowed from conventional integrated circuits.

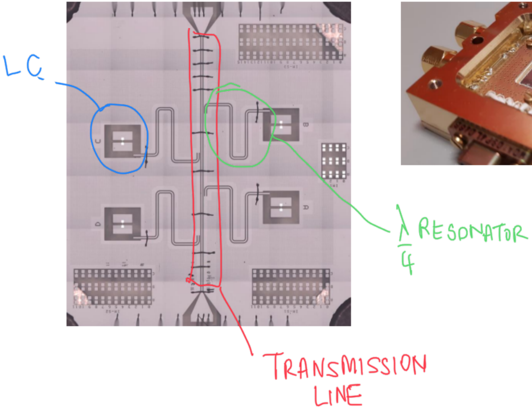


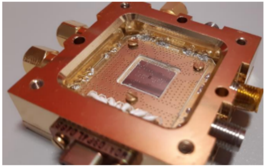


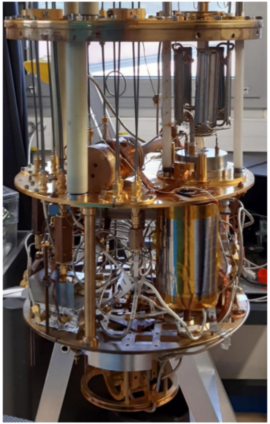
Devices useful for circuit QED are fabricated starting from a **non-dissipative, non-linear element**: the Josephson tunnel junction



SUPERCONDUCTING CIRCUITS

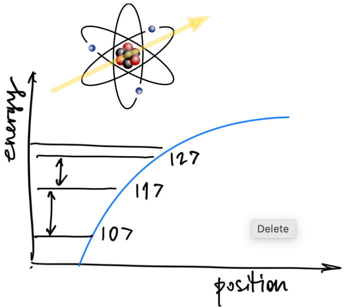






$\hbar\omega \gg kT$

ARTIFICIAL ATOMS: the TRANSMON QUBIT



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

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

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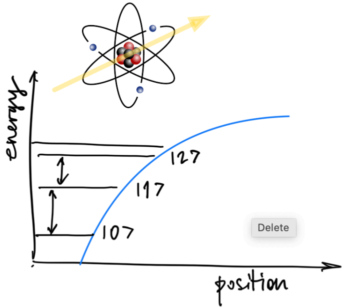

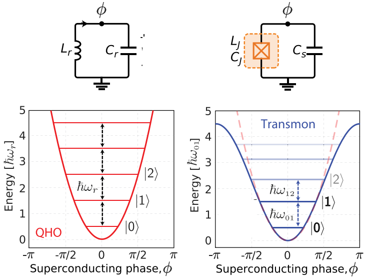

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control internal state by shining laser tuned at the transition frequency:
$H = -\vec{d} \cdot \vec{E}(t)$, with $E(t) = E_0 \cos\omega_{01} t$

toolkit: capacitor, inductor, wire (all SC)
$\omega_{01} = 1/\sqrt{LC} \sim 10\,\mathrm{GHz} \sim 0.5\,\mathrm{K}$
$\rightarrow$ simple LC circuit is not a good **two-level atom** approximation

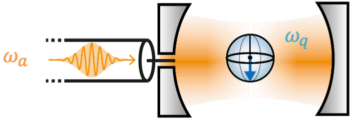
$I_J = I_c \sin\phi \qquad V = \frac{\phi_0}{2\pi}\frac{\partial\phi}{\partial t}$

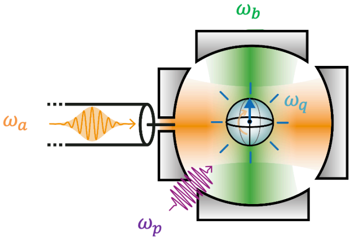
$V = \frac{\phi_0}{2\pi}\frac{1}{I_c\cos\phi}\frac{\partial I_J}{\partial t} = L_J\frac{\partial I_J}{\partial t}$

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

quantum engineers and **particle physicists** joining efforts

A practical transmon-based counter has been recently developed (Quantronics group CEA, Saclay) that we will apply to haloscope signal readout.



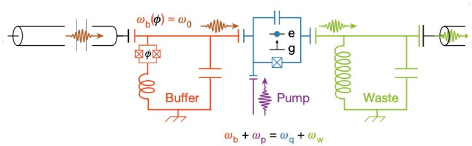


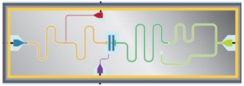
$$\omega_a + \omega_p = \omega_q + \omega_b$$

R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)
E. Albertinale *et al*, Nature 600, 434 (2021)

Quantronics Group
Research Group in Quantum Electronics, CEA-Saclay, France

transmon-based SMPD





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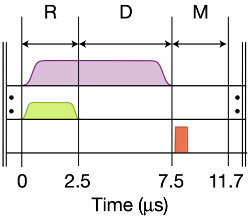
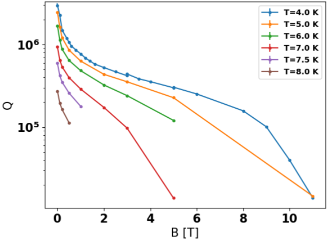


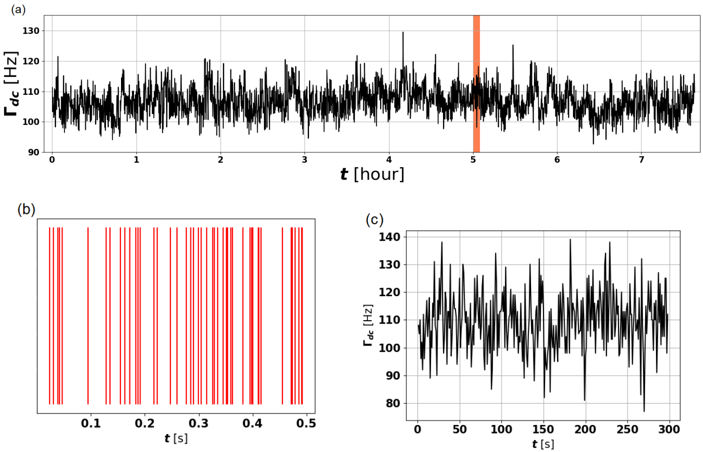
- a three-step process repeated several times
- qubit reset (R) performed by turning on the pump pulse + a weak resonant coherent pulse to the waste port
- detection (D) step with the pump pulse on
- measurement (M) step probes the dispersive shift of the buffer resonator to infer the qubit state

Pilot SMPD-haloscope experiment

- copper cavity **sputtered with NbTi**
  magnetron sputtering in INFN-LNL
- right cylinder resonator, TM_{010} mode
  $\nu_c \sim 7.3$ GHz to match the new generation SMPD bandwidth (7.280 - 7.380) GHz
- **system of sapphire triplets** to tune the cavity frequency
  $\sim$ 10 MHz tuning without impacting Q
- **nanopositioner** to change the sapphire rods position



the dark count is a **inhomogeneous Poisson process**



Real SMPDs have finite efficiency η and dark counts $\Gamma_{dc} > \Gamma_{sig}$

$\delta N_{dc} = \sqrt{\Gamma_{dc}\tau}$ uncertainty in the number of dark counts collected in an integration time τ

$\Sigma = \frac{\eta\Gamma_{sig}\tau}{\sqrt{\Gamma_{dc}\tau}} = \eta\Gamma_{sig}\sqrt{\frac{\tau}{\Gamma_{dc}}}$ the dark count contribution to the fluctuations dominates

$R_{\text{counter}} = \frac{\Delta\nu_c}{\tau} = \frac{\Delta\nu_c\eta^2 P^2_{a\gamma\gamma}}{h^2\nu^2\Sigma^2\Gamma_{dc}}$ $R_{\text{lin}} = \frac{Q_a}{Q_c}\left(\frac{P_{a\gamma\gamma}}{\Sigma\, k_B T}\right)^2$ scan rates lin. amp. and counter

$$\frac{R_{\text{counter}}}{R_{\text{lin}}} = \left(\frac{k_B T_{sys}}{h\nu}\right)^2 \frac{\eta^2\Delta\nu_a}{\Gamma_{dc}}$$

quantum advantage can be demonstrated even with high dark count rates Γ_{dc}
$\eta \approx 0.4$, $\Gamma_{dc} \approx 100\,\text{Hz} \Longrightarrow$ potential improvement of a factor 11 compared to SQL scan rate

Scan rate

For a target sensitivity $g_{a\gamma\gamma}$, the parameter space scan rate is given by:

$$\frac{df}{dt} \propto \frac{B^4 \, V_{\text{eff}}^2 \, Q_L}{T_{sys}}$$

A haloscope optimized at best goes at:

$$\left(\frac{df}{dt}\right)_{\text{KSVZ}} \sim \text{GHz/year}$$

$$\left(\frac{df}{dt}\right)_{\text{DFSZ}} \sim 20\,\text{MHz/year} \qquad \odot\,\odot$$

Take-home: to probe the mass range (1-10) GHz at DFSZ sensitivity would require $\gtrsim$ 100 years with 4-5 complementary haloscopes