



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

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

⇒ they have the potential to become extraordinary **measuring instruments** in specific application areas

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what about particle physics?



- $\simeq 10 \text{ eV}$ 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) → *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.



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



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

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

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
- \Rightarrow observable: scattering of individual particles



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



HALOSCOPE - resonant search for axion DM in the Galactic halo



- 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** $(10 50) \, \text{mK}$



weak interactions with SM particles $\implies 10^{-22}$ W signal power $\longleftrightarrow \leq$ 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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100 10 $T_{sys} = T_c + T_A$ T_c cavity physical temperature لا 0.100 کا ل T_A effective noise temperature of the amplifier Total noise 0.010 Bosonic occupation $k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a\right)$ Standard Quantum Limit 0.001 $---- T_{noise} = T_{phy}$ 10-4 0.001 0.010 0.100 10 100 T_{phy} [K]

at 10 GHz frequency

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STANDARD QUANTUM LIMIT IN LINEAR AMPLIFICATION

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

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

 X_1 and X_2 signal quadratures $a, a^* \rightarrow$ 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 $[X_1, X_2] = \frac{i}{2}$:

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

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

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*.

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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:

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

at 7 GHz, 40 mK \Longrightarrow 10³ faster than SQL linear amplifier readout



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

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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.



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





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SUPERCONDUCTING CIRCUITS





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Applied Physics Reviews

ve provide a review of how single- and two-qubit bically implemented in superconducing circuits, by ion of local magnetic flux control and microwave -qubit gates arising introduce several Wenne chieve high-fidelity ion processing that h-fidelity two-qubit research area. For 127 that a reader may s the pros and cons 17 ion for the types of -the-art supercon-Delete 107 engineering associly used to measure position processors. After a z, we give an intro-

duction to design of Purcell filters and the development of quantumlimited parametric amplifiers (PAs).

$$\begin{split} E_{01} &= E_1 - E_0 = \frac{h_{\rm ENCINEERING QUANTUM CIPCUITS}{h_{\rm MT}} his section, We will demonstrate flow quantum systems based \\ \rightarrow \text{good two-level atom.approximation.approximation provide a section with the section of the se$$

A. From quantum harmonic oscillator to the transmon qubit

A quantum machanical system is governed by the time



FIG. 1, (a) Circuit for a parallel LC-scillator (quantum harmonic scillator, CHO₂) with inductance t in parallel with expaciatone, C. The superconducting phase on the island is denoted as ϕ_i referencing the ground as zero. (b) Energy potential for the CHO, where energy levels are equidisatintly spaced $\hbar n_o$ part. (c) Josephson qubit circuit, where the nonlinear inductance L_i (represented by the Josephsonsubtrault in the dashed orange box) is shunded by a capacitance, C_e . (d) The Josephson inductance reshapes the quadratic energy potential (dashed red) into issubcial (able), which yields nonequidistant energy levels. This allows us to isolate the two lowest energy levels [0] and [1], forming a computational subspace with an energy separation $\hbar n_{02}$.

electrical energy in the capacitor C and magnetic energy in the inductor L. In the following, we will arbitrarily associate the electrical energy with the "kinetic energy" and the magnetic energy with the "potential energy" of the oscillator. The instantaneous, time-dependent energy in each element is derived from its current and voltage $\langle \Box \rangle \models \langle \Box \rangle \Rightarrow \langle \overline{\Box} \rangle$

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ARTIFICIAL ATOMS: the TRANSMON QUBIT





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) $\omega_{01} = 1/\sqrt{LC} \sim 10 \text{ GHz} \sim 0.5 \text{ K}$ $\rightarrow \text{ simple LC circuit is not a good$ **two-level atom**approximation

$$\begin{split} I_{J} &= I_{c} \sin \phi \qquad V = \frac{\phi_{0}}{2\pi} \frac{\partial \phi}{\partial t} \\ V &= \frac{\phi_{0}}{2\pi} \frac{1}{I_{c} \cos \phi} \frac{\partial I_{J}}{\partial t} = L_{J} \frac{\partial I_{J}}{\partial t} \\ L_{J} &= \frac{\phi_{0}}{2\pi} \frac{1}{I_{c} \cos \phi} \qquad \text{NL Josephson inductance} \end{split}$$

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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.





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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-Saclau, France

transmon-based SMPD





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



- 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
- $\odot~$ right cylinder resonator, TM₀₁₀ mode $\nu_c \sim 7.3~{\rm GHz}$ to match the new generation SMPD bandwidth (7.280 7.380) GHz
- \odot **system of sapphire triplets** to tune the cavity frequency ~ 10 MHz tuning without impacting *Q*
- nanopositioner to change the sapphire rods position



the dark count is a inhomogeneous Poisson process



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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

$$\Sigma = \frac{\eta \Gamma_{sig} \tau}{\sqrt{\Gamma_{dc} \tau}} = \eta \Gamma_{sig} \sqrt{\frac{\tau}{\Gamma_{dc}}} \qquad \text{the dark count contribution to the fluctuations dominates}$$
$$R_{\text{counter}} = \frac{\Delta \nu_c}{\tau} = \frac{\Delta \nu_c \eta^2 P_{a\gamma\gamma}^2}{h^2 \nu^2 \Sigma^2 \Gamma_{dc}} \qquad R_{\text{lin}} = \frac{Q_a}{Q_c} \left(\frac{P_{a\gamma\gamma}}{\Sigma k_B T}\right)^2 \qquad \text{scan rates lin. amp. and counter}$$
$$\frac{R_{\text{counter}}}{R_{\text{lin}}} = \left(\frac{k_B T_{sys}}{h\nu}\right)^2 \frac{\eta^2 \Delta \nu_a}{\Gamma_{dc}}$$

quantum advantage can be demonstrated even with high dark count rates Γ_{dc} $\eta \approx 0.4$, $\Gamma_{dc} \approx 100 \text{ Hz} \implies$ 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:

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

A haloscope optimized at best goes at:

$$\left(\frac{df}{dt}\right)_{\rm KSVZ} \sim {
m GHz/year}$$
 $\left(\frac{df}{dt}\right)_{
m DFSZ} \sim 20 \,{
m MHz/year} \quad \odot \odot$

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