Meeting della Commissione Nazionale II

7 Apr 2025, 08:00 → 9 Apr 2025, 16:00 Europe/Rome

Palazzo Loredan - Istituto Veneto (Venezia)

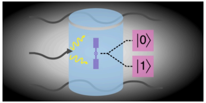
Sensori quantistici per la ricerca di materia oscura

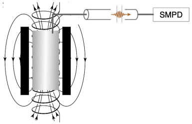
Caterina Braggio

INFN sezione di Padova

Dip. Fisica e Astronomia, UniPD

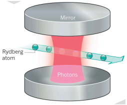
- detection of signals corresponding to ∼few microwave photons/s

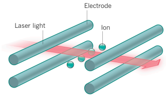


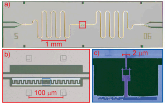


- physics cases:
  demonstrated in haloscopes (axions and dark photons), and for spin fluorescence detection
  ideas to leverage collective excitations in condensed matter systems for DM scattering

- quantum sensing with Rydberg atoms and with artificial atoms



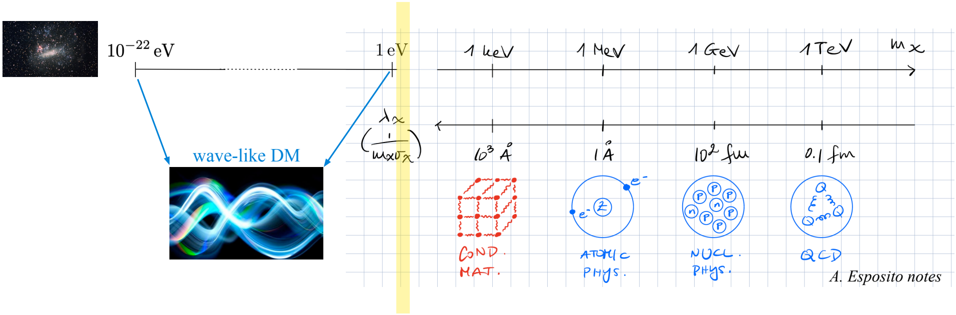




  particle physics is adopting metrological methods from QIS

- **operational experience** of a haloscope experiment equipped with photon counter

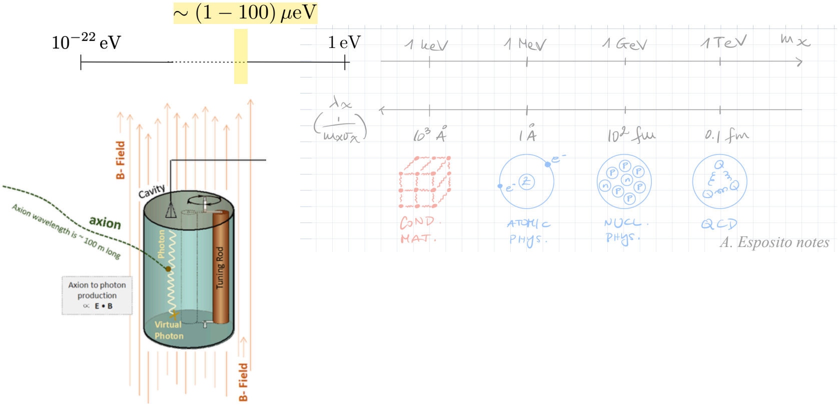
OBSERVABLES IN DM SEARCH: COHERENT CLASSICAL FIELDS



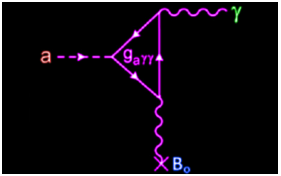
- particle → wave transition of DM below $\sim 10\,\mathrm{eV}$
- persistent, effective field oscillating at the Compton frequency $\quad 10\,\mathrm{GHz} = 41.36\,\mu\mathrm{eV}$
- which remains **coherent** for $\sim 10^6$ periods

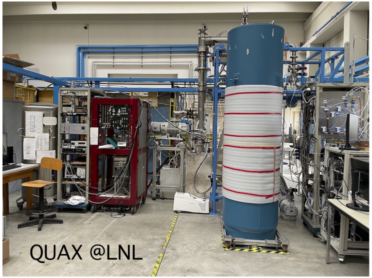
OBSERVABLES IN DM SEARCH

as the DM field is **coherent** for $\sim 10^6$ periods $\Longrightarrow$ **resonant enhancement** in microwave cavities



1. **3D** microwave **resonator** for resonant amplification
   -think of an HO driven by an external force-
2. the **resonator** is within the bore of a **SC magnet** $\rightarrow$ **B_0**
   multi-tesla field
3. it is readout with a **low noise receiver**





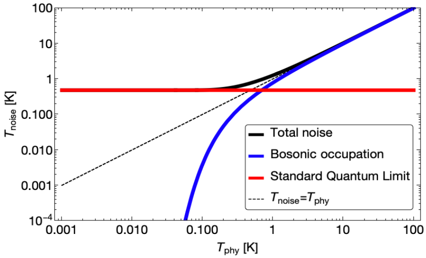
S/N ratio: signal **S** set by B_0 and 3D cavity at specified $g_{a\gamma\gamma}$, the noise **N** is set by the receiver

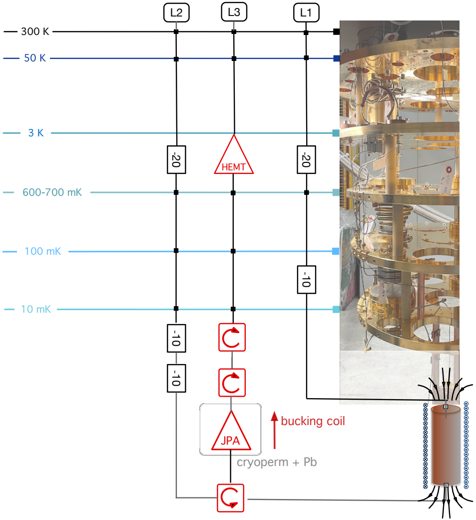
low noise receiver

quantum-limited readout with linear amplifiers (JPA, TWPA)

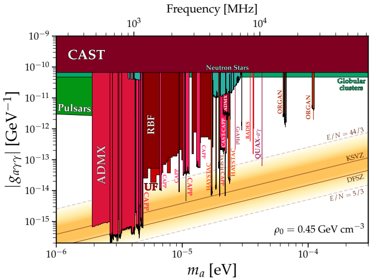
$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right), \; N_a \geqslant 0.5$$

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





Heavier (axions) & Harder (life)



- heavier axions are well motivated,
  BUT
  the *scan rate df/dt scales unfavourably with f*

$$\frac{df}{dt} \propto \frac{g_{a\gamma\gamma}^4 B^4 V_{\mathrm{eff}}^2 Q_L}{T_{sys}^2} \propto f^{-4}$$

  (best scenario asm. **SQL**, SC cavities, relax r/L)

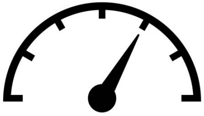
- $(df/dt)_{DFSZ} \sim$ **50** $(df/dt)_{KSVZ}$

PROBLEM: WAY TOO SMALL SEARCH SPEED

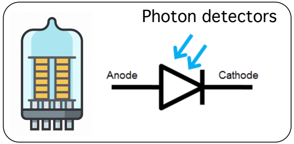
A haloscope optimized at best goes at:

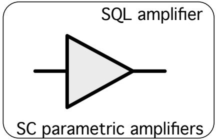
$$\left(\frac{df}{dt}\right)_{\mathrm{KSVZ}} \sim 100\,\mathrm{MHz/year} \qquad \left(\frac{df}{dt}\right)_{\mathrm{DFSZ}} \sim 2\,\mathrm{MHz/year}$$

To probe the mass range (1-10) GHz at relevant (DFSZ) sensitivity would require $\gtrsim 100$ years with current technology



photon counting vs parametric amplification at standard quantum limit (**SQL**)





IDEAL PHOTON DETECTOR

$$\frac{(df/dt)_{\text{counter}}}{(df/dt)_{\text{SQL}}} \approx \frac{Q_L}{Q_a} e^{\frac{h\nu}{k_B T}}$$

Ex. at 7 GHz, 40 mK $\rightarrow$ gain by 10^3

S. K. Lamoreaux *et al.*, Phys Rev D **88** 035020 (2013)

REAL DETECTOR WITH DARK COUNTS Γ_{dc}

$$\frac{(df/dt)_{\text{counter}}}{(df/dt)_{\text{SQL}}} \approx \eta^2 \frac{\Delta\nu_a}{\Gamma_{dc}}$$

Γ_{dc} dark counts

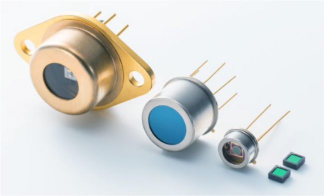
η photon counter efficiency
$\Delta\nu_a$ axion linewidth

$\rightarrow$ ($\times$100s) gain [$\Gamma_{dc} \sim$ 10s count/s, $\eta^2 \sim 70\%$]

- can probe in a day the same range a linear amplifier at SQL would take more than 3 months-

PHOTON DETECTION

Light* is typically detected **by destroying it**

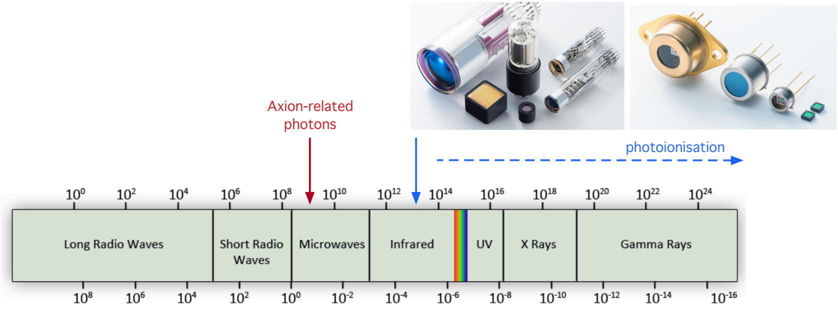


observable: generation of an electrical pulse when it absorbs (and so destroys) a photon

* holds for photons more energetic than IR

MICROWAVE PHOTON DETECTION

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



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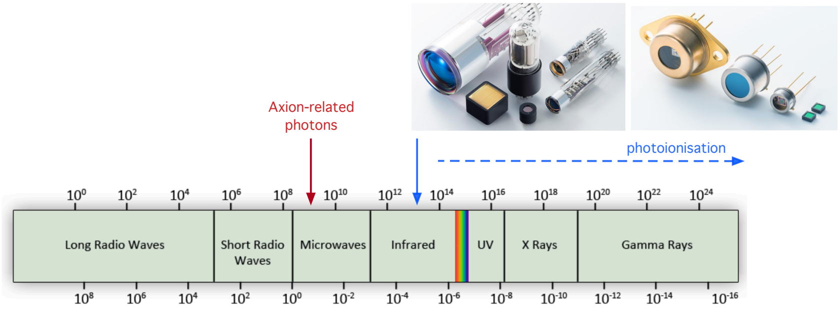


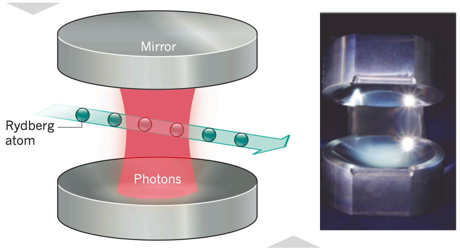
Requirements for dark matter search:

- detection of *itinerant photons* due to involved intense $\mathbf{B}$ fields
- lowest dark count rate $\Gamma < 100\,\mathrm{Hz}$ and $\gtrsim 40 - 50\,\%$ 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 446, 297-300 (2007)



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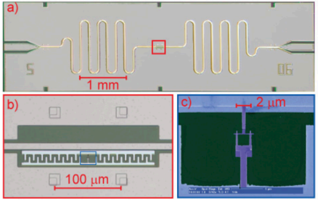

(a) photon resonator = coplanar waveguide
(b) artificial atom = transmon or CPB
(c) Josephson Junctions

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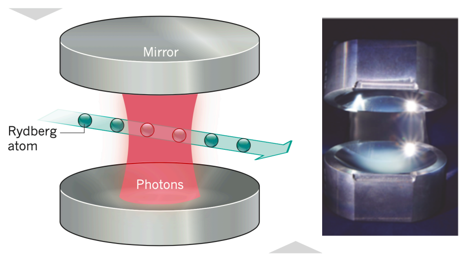

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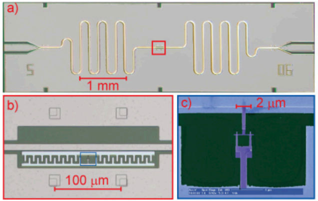


(a) photon resonator = coplanar waveguide
(b) artificial atom = transmon or CPB
(c) Josephson Junctions

$\Longrightarrow$ the detector is an atom with transitions in the microwave range: the Rydberg atom

$\Longrightarrow$ as it flies through the cavity, its energies are shifted by the trapped light (/cavity photons)

$\Longrightarrow$ cavity photon is detected **without destroying it**

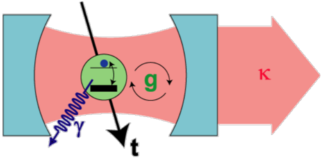
$\Longrightarrow$ in both cases **two-level atoms** interact directly with a **microwave field mode** in the cavity

Cavity-QED for photon counting

Can the field of a single photon have a large effect on the artificial atom?

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

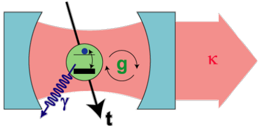
$$\vec{E} \propto \frac{1}{\sqrt{V}}, \; V \;\text{ volume}$$

κ rate of cavity photon decay
γ rate at which the qubit loses its excitation

Different regimes set by the parameters g, κ, γ and $\Delta = |\omega_r - \omega_q|$

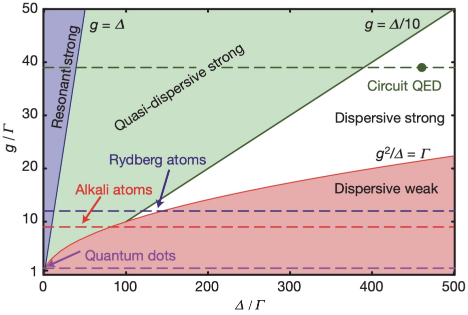
Jaynes-Cummings model

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



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

Parameter space diagram for cavity-QED



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

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

- $\omega_r \sim \omega_q$ *resonance* case:
  $g \gg \kappa, \gamma \iff$ strong coupling regime
  coherent exchange of a field quantum between the atom and the cavity field mode
  QUAX_{ae} magnon-photon
- $\Delta = |\omega_r - \omega_q| \gg g$ *dispersive limit* case
  non demolition field intensity measurements

Dispersive regime $\quad g/\Delta \ll 1$

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

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

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

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

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

$\rightarrow$ 2nd line: **cavity frequency** is a function of the **qubit state** (measuring the **cavity frequency** is equivalent to measuring the **qubit state**)

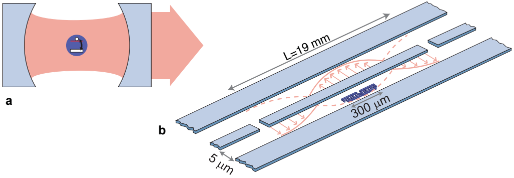
$\rightarrow$ 3rd line: and viceversa, this is the case of the Rydberg atoms experiment

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

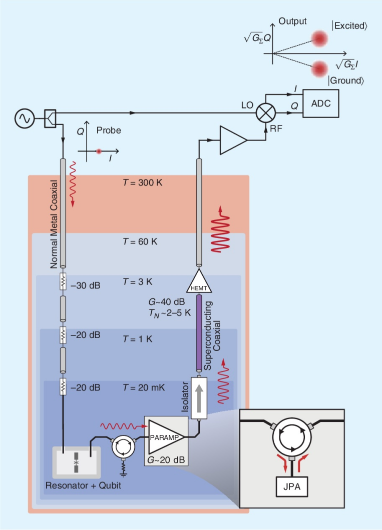


(a) $(g/2\pi)_{\text{cavity}} \sim 50\,\text{kHz}$

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

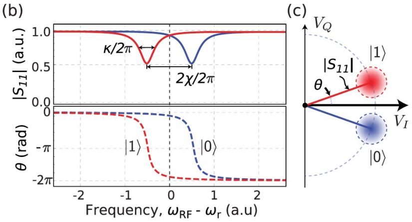
10^4 larger coupling than in atomic systems

dispersive qubit readout of qubits



$$H/\hbar = (\omega_r + \chi\sigma_z)\left(aa^\dagger + \frac{1}{2}\right) + \frac{\omega_q'}{2}\sigma_z$$

$\chi = \frac{g^2}{\Delta}$, qubit-state dependent frequency shift



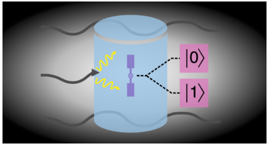
$\Longrightarrow$ **Amplitude readout**: the frequency of the microwave probe pulse is at either at $\omega_r + \chi$ or $\omega_r - \chi$. Depending on T($|S_{12}|$)/R$|S_{11}|$ power you know what the qubit state is

$\Longrightarrow$ **Phase readout**: the probe is at 0 (reflected power same for $|0\rangle$ and $|1\rangle$). All info is in the phase $\theta = \pm\arctan(\chi/\kappa)$

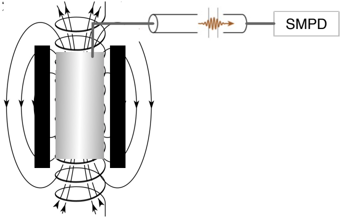
itinerant vs *cavity* photon detector in axion experiments

back to axion-related photons…

CAVITY PHOTONS

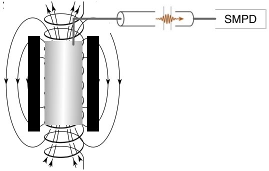


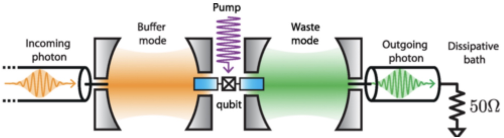
ITINERANT PHOTONS



→ in axion detection, itinerant photon detection is preferred, as the SMPD is located in a region **where it can be screened by the B field** (but anyway at the MC stage)

TRAVELING QUANTUM MICROWAVES





Phys. Rev. X 10, 021038 (2020) ← 1.3 counts/ms
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip
Phys. Rev. Appl. 21, 014043 (2024) ← 85 counts/s

- wave mixing (4WM) process: the incoming photon is converted into an excitation of the qubit
- readout of the qubit state with quantum information science (QIS) methods
- efficiency $\eta \sim 0.5$, dark counts $\Gamma_d \sim 85\,\mathrm{s}^{-1}$
- $\sim 100\,\mathrm{MHz}$ tuning range
- on/off resonance → monitor the dark counts, which set the background in these experiments

Physical Review X

Quantum-enhanced sensing of axion dark matter with a transmon-based single microwave photon counter

C. Braggio, L. Balembois, R. Di Vora, Z. Wang, J. Travesedo, L. Pallegoix, G. Carugno, A. Ortolan, G. Ruoso, U. Gambardella, D. D'Agostino, P. Bertet, and E. Flurin

Phys. Rev. X - **Accepted** 24 February, 2025

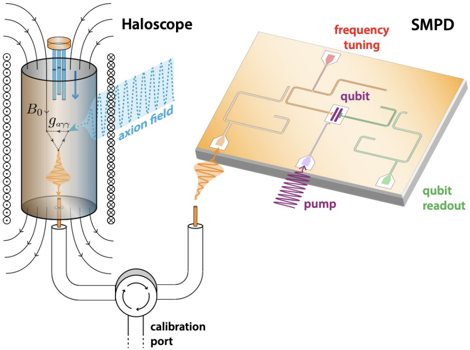
QUAX @INFN LNL

Istituto Nazionale di Fisica Nucleare

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

SMPD design, fabrication and tests

$\omega_b + \omega_p = \omega_q + \omega_w$



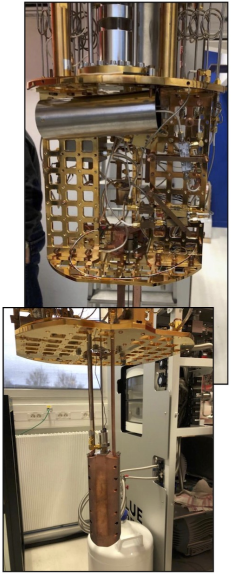
Qubit	
$\omega_q/2\pi$	6.222 GHz
T_1	$17-20\ \mu$s
T_2^*	28 μs
$\chi_{qq}/2\pi$	240 MHz
$\chi_{qb}/2\pi$	3.4 MHz
$\chi_{qw}/2\pi$	15 MHz
Waste mode	
$\omega_w/2\pi$	7.9925 GHz
$\kappa_{\text{ext}}/2\pi$	1.0 MHz
$\kappa_{\text{int}}/2\pi$	<100 kHz
Buffer mode	
$\omega_b/2\pi$	7.3693 GHz
$\kappa_{\text{ext}}/2\pi$	0.48 MHz
$\kappa_{\text{int}}/2\pi$	40 kHz

https://arxiv.org/abs/2403.02321

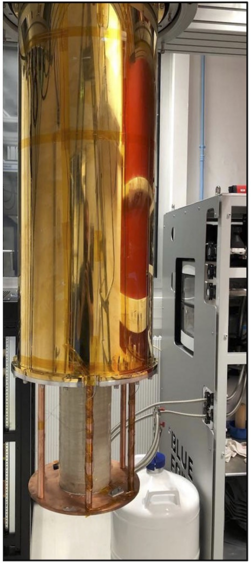
PATHFINDER

- a **transmon-based** single microwave photon detector (SMPD) is used to readout the cavity mode
- TWPA for dispersive readout of the qubit state
- hybrid (normal-superconducting) cavity TM_{010} at 7.37 GHz
  tunable by a triplet of rods
  $Q_0 = 9 \times 10^5$ at 2 T-field
- T=14 mK
  @ fridge Quantronics lab (CEA, Saclay)

$\rightarrow$ investigated the background,
and set a limit to $g_{a\gamma\gamma}$ [0.5 MHz band]



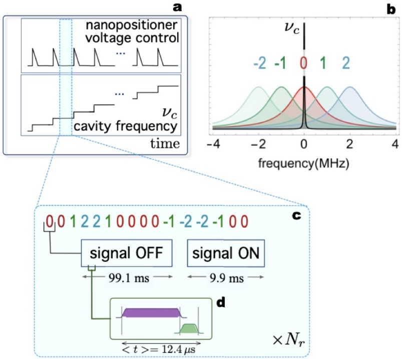
SMPD (top) and cavity



SC magnet

readout protocol: the SMPD is operated through **nested cycles**

multi-core pulse processing unit (OPX+): classical calculation and quantum control pulses in real time

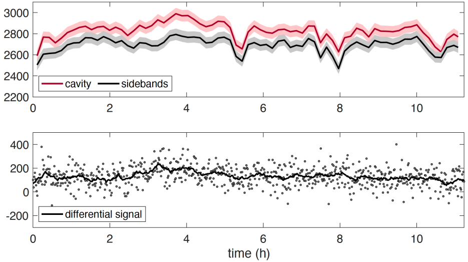


→ basic block (d) is detection + qubit readout $\sim (10 + 2)\ \mu s$

→ measure SMPD efficiency and cavity parameters

→ noise assessment at resonance $\omega_b = \omega_c$ and at 4 sidebands $\omega_b = \omega_c \pm 1\,\text{MHz}$, $\omega_b = \omega_c \pm 2\,\text{MHz}$

SMPD diagnostics for axion detection: dark counts are non stationary



- counts at $\omega_b = \omega_c$ registered in 28.6 s (set by readout protocol structure) $\Longleftrightarrow$ **average** $\sim$ 90 **Hz dark count rate** Γ_d

$$\Gamma_d = \Gamma_{\text{qubit}} + \Gamma_{\text{4WM}} + \Gamma_{th}$$

  dominated by thermal photons in the input line

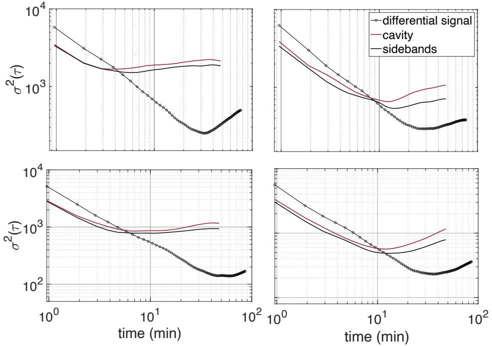
- both the counts at resonance and on sidebands $\omega_b = \omega_c \pm 1.2\,\text{MHz}$ vary **beyond statistical uncertainty** expected for poissonian counts

- **correlation** between the two channels

- systematic **excess** at cavity frequency $\rightarrow$ the cavity sits at a slightly higher T ($\sim$ 0.5 mK)

Long-term stability: how long can we integrate to improve S/N?

We compute the Allan variance to assess the long term stability of the detector



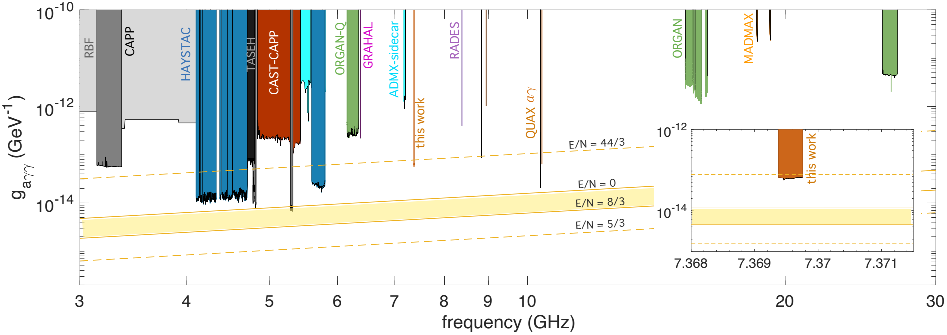
→ counts fluctuations decrease as $1/\tau$, up to a maximum observation time τ_m of about 10 min

→ for $\tau > \tau_m$ the Allan variance increases → system drifts

→ the differential channel follows the $1/\tau$ trend up to a longer time interval $\tau \sim 30$ min → small correlation

→ no additional noise in the data recorded between successive step motion intervals compared to unperturbed cavity

beyond SMPD diagnostics: UPDATING THE EXCLUSION PLOT FOR $g_{a\gamma\gamma}$



→ data analysed in 420 kHz $\simeq 14\Delta\nu_c$ range

→ reached the extended QCD axion band with a short integration time (10 min), in spite of the small B-field

☉☉ **x20 gain [conservative]** in scan speed vs linear amplifiers https://arxiv.org/abs/2403.02321

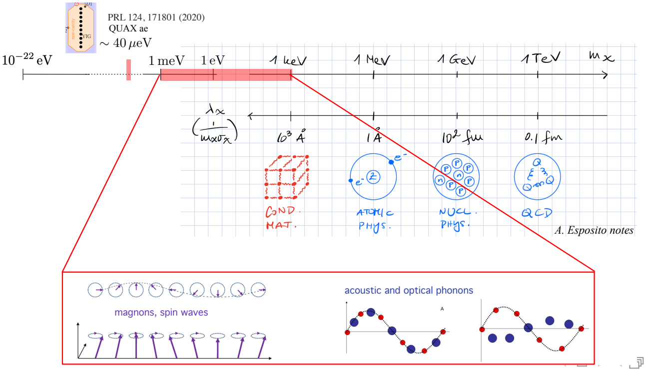
ONGOING ACTIVITY @LNL

→ we're reloading QUAX$_{ae}$ to probe the axion-electron spin interaction

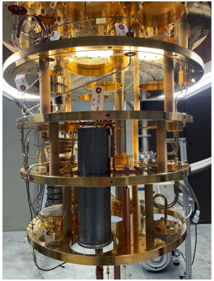
→ scaling up the pilot experiment to probe the axion-photon interaction (larger B field, better 3D resonator)

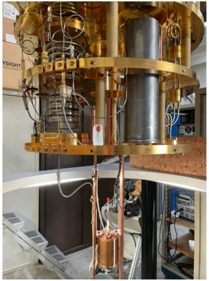
→ following efforts to expand the bandwidth of the current SMPD architecture

→ discussing with theorists new observables in DM search (collective excitations as **magnons**, **phonons** that might rise to photons)



ONGOING ACTIVITY @LNL





"Per quanto una situazione possa sembrare disperata, c'è sempre una possibilità di soluzione. Quando tutto attorno è buio non c'è altro da fare che aspettare tranquilli che gli occhi si abituino all'oscurità.
(H. Murakami)

BACKUP SLIDES

$$n_{\phi,0} = \frac{N}{a_0^3} = \frac{\rho_{DM}}{m_0}$$ high number density of particles

$$N_{occ.} \sim \frac{dN}{d^3x\, d^3p}(2\pi\hbar)^3 \sim \frac{(2\pi)^3}{4\pi/3}\frac{n_{\phi,0}}{m_0^3\,\delta v^3} \sim 10^{42}\left(\frac{m_1}{m_0}\right)^{3/2}\left(\frac{eV}{m_0}\right)^{5/2}$$

h

velocity distribution with a very narrow width today $\delta v(t) \ll 1$

huge occupation number, behaves like a classical field.

de Broglie wavelenght :

$$\lambda_{dB} = \frac{2\pi\hbar}{m_\phi v} \simeq 0.5\ \text{kpc}\left(\frac{10^{-22}\,eV}{m_\phi}\right)\left(\frac{250\ km/s}{v}\right)$$

size of dwarf galaxies

$$\simeq 1.5\ \text{km}\left(\frac{10^{-6}\,eV}{m_\phi}\right)\left(\frac{250\ km/s}{v}\right)$$

$v \simeq 10^{-3}c$ $\rightarrow$ velocity dispersion of DM in the galactic halo

From L. Di Luzio notes

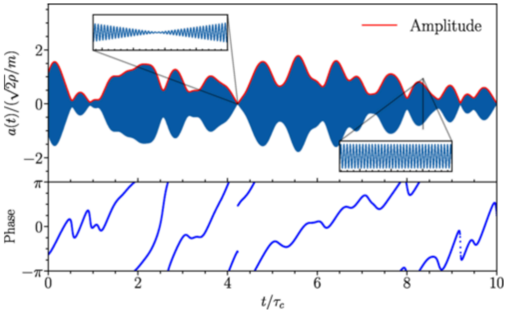
at a fixed spatial point:

$$\tau_{coh.} \sim \lambda_{dB}/v \sim \frac{1}{m v^2} \cdot \frac{c^2}{c^2}$$

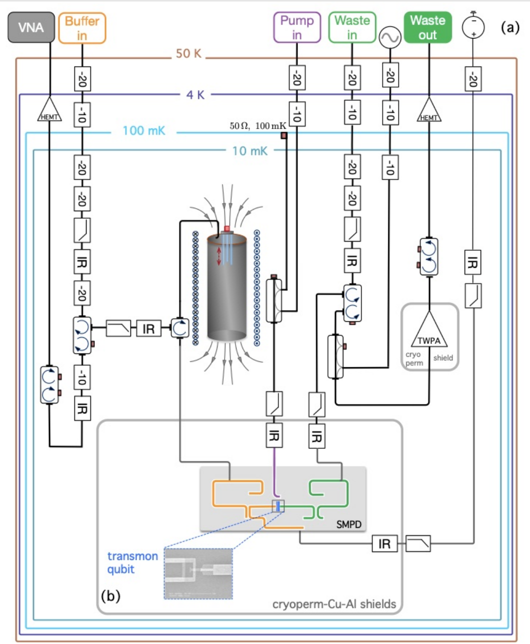
$v/c \simeq 10^{-3}$

$$\simeq 10^6 \, \tau_{Comp} \longrightarrow$$ oscillation frequency of DM field

$$\simeq \underbrace{10^6 \cdot \underbrace{10^{-9}\,\mathrm{sec}}_{GHz}}_{kHz} \left(\frac{10^{-6}\,eV}{m_\phi}\right)$$

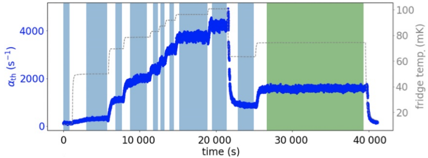


- amplitude and phase vary stochastically over the coherence time τ_{coh}
- Compton oscillation



→ 2 RF lines more than plain JPA/TWPA cavity readout

→ dilution refrigerator base temperature must not exceed $\sim 20\,\mathrm{mK}$



→ used only passive screening due to the relatively low field employed ($B = 2\,\mathrm{T}$).
Bucking coil necessary to run at higher fields.

SQL IN LINEAR AMPLIFICATION

The quantum noise is a consequence of the base that we want to use to measure the EM field in the cavity. A **linear amplifier** measures the amplitudes in phase and in quadrature.
Any narrow bandwidth signal $\Delta\nu_c \ll \nu_c$ can in fact be written as:

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

LINEAR AMPLIFIER READOUT

Alternatively, with $[X_1, X_2] = \frac{i}{2}$
the hamiltonian of the HO is written as:

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

PHOTON COUNTER: measuring N

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

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

Photon counting is a game changer (high frequency, low T): in the **energy eigenbasis** there is no intrinsic limit effective_temperature.nb

100%

Insert Cell...

In[18]:= $\hbar = 6.626\times10^{-34} \,/\, (1.60218 * 10^{-19}) \,/\, (2\,\mathrm{Pi})$; (* [eV*s] *)

$h = 6.626\times10^{-34}$; (* [J*s] *)

$k = 1.38\times10^{-23}$;

$\nu_c = 7 * 10^9$;

$\frac{h\,\nu_c}{k\,T}$ /. {$T \to 0.1$}

Out[22]= 3.36101

In[23]:= $\frac{1}{\left(\mathrm{Exp}\left[\frac{h\,\nu_c}{k\,T}\right] - 1\right)}$ /. {$T \to 0.1$}

Out[23]= 0.0359474

In[24]:= $\frac{\Gamma_{dc}}{\eta\,\Delta\nu_c}$ /. {$\Gamma_{dc} \to 100$, $\eta \to 0.47$, $\Delta\nu_c \to 30\,000$}

Out[24]= 0.0070922

In[25]:= $T_{eff} = \frac{h\,\nu_c}{k\,\mathrm{Log}\left[1 + \frac{\eta\,\Delta\nu_c}{\Gamma_{dc}}\right]}$ /. {$\Gamma_{dc} \to 100$, $\eta \to 0.47$, $\Delta\nu_c \to 480\,000$}

Out[25]= 0.0435264