IFD 2025 - INFN Workshop on Future Detectors

17–19 Mar 2025

Europe/Rome timezone

Superconducting circuits in axion dark matter search: microwave photon counting with transmon qubits

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Physical Review X

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

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QUAX @INFN LNL

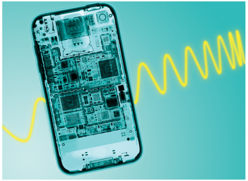
Istituto Nazionale di Fisica Nucleare

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

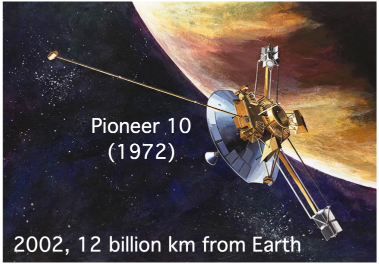
SMPD design, fabrication and tests

QUANTUM MICROWAVES in DM search

kW

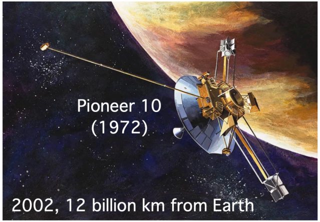


(0.1-2) W



2.5×10^{-21} W

quantum microwaves in DARK MATTER search



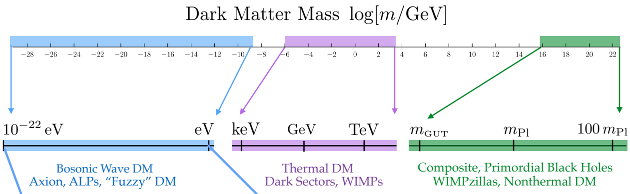
2.5×10^{-21} W

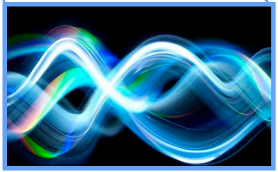
$< 10^{-23}$ W

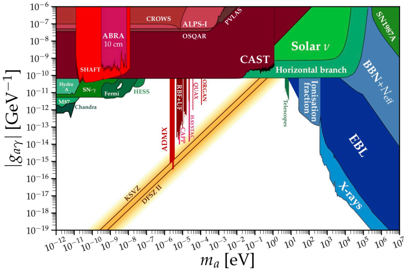
Unknown frequency (particle mass)

$<$ few photons/s ⇒ QUANTUM 2.0

“wave-like” DM







$m \lesssim 10\,\mathrm{eV}$

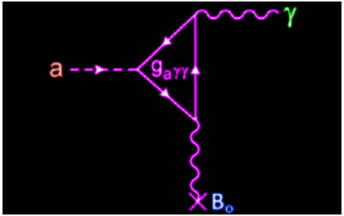
classical field oscillating at the Compton frequency 10^{-6} coherence

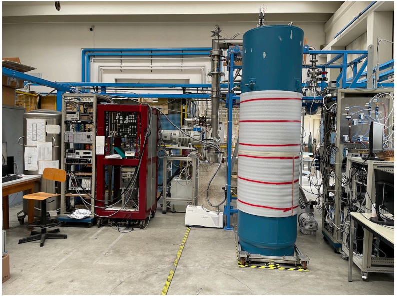
1. **3D** microwave **resonator** for resonant amplification
   -think of an HO driven by an external force-

2. with **tunable frequency** to match the axion mass
   ($\delta\nu_c \sim$ MHz, target 100 MHz range at KSVZ)

3. the **resonator** is within the bore of a **SC magnet** $\rightarrow$ $\mathbf{B}_0$
   multi-tesla field

4. it is readout with a **low noise receiver**
   delfridge operation at mK temperatures



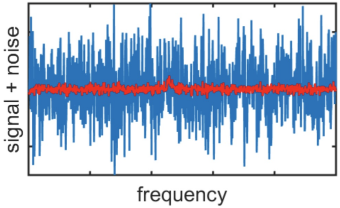


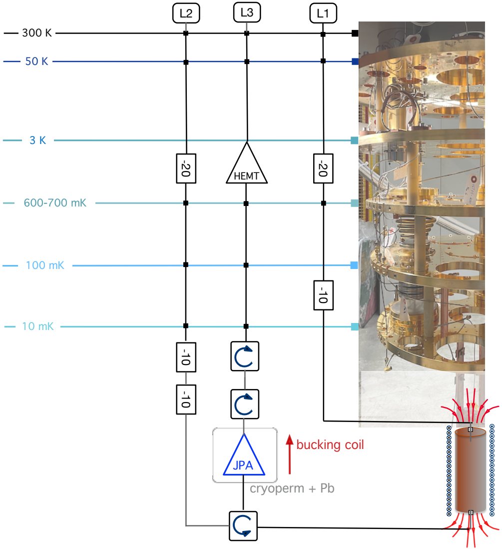
a poor S/N ratio

In these searches, **the signal is much smaller than noise**

$$P_n = k_B T \Delta\nu \gg P_s \;\; \propto B^2 \, V_{\text{eff}} \, Q_L \sim 10^{-23}\,\text{W}$$

To increase sensitivity we rely on **averaging several spectra** recorded at the same cavity frequency **over a certain integration time**.

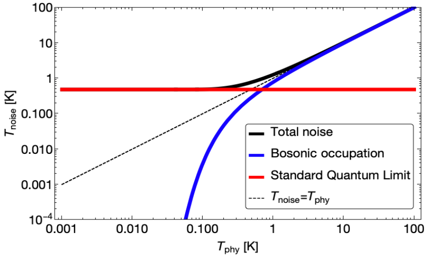


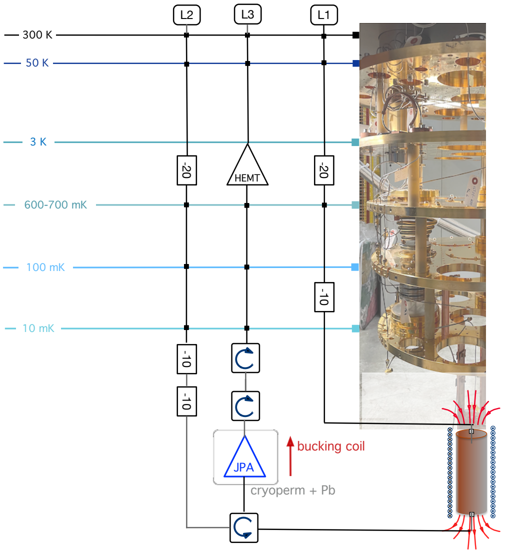


quantum-limited readout

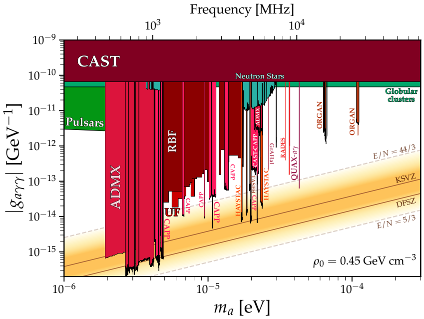
$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T} - 1} + \frac{1}{2} + N_a \right), \; N_a \geqslant 0.5$$

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





Heavier (axions) & Harder (life)



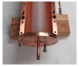
- heavier axions are well motivated,
  BUT
  the *scan rate df/dt scales unfavourably with f*

$$\frac{df}{dt} \propto \frac{g^4_{a\gamma\gamma} B^4 V^2_{\text{eff}} Q_L}{T^2_{sys}} \propto f^{-4}$$

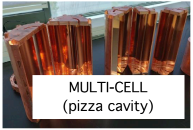
  (asm. quantum noise, SC cavities, relax r/L)

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

DIELECTRIC CAVITY
(higher order modes)



THIN SHELL



MULTI-CELL
(pizza cavity)

→ new cavities with larger V_{eff} compared to a pill-box cavity

→ QIS technologies and methods to **reduce the noise** (parametric amplifiers, photon counters)

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

IDEAL PHOTON DETECTOR

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

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}

$$\frac{R_{\text{counter}}}{R_{\text{SQL}}} \approx \eta^2 \frac{\Delta\nu_a}{\Gamma_{dc}} \qquad \Gamma_{dc} \text{ dark counts}$$

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

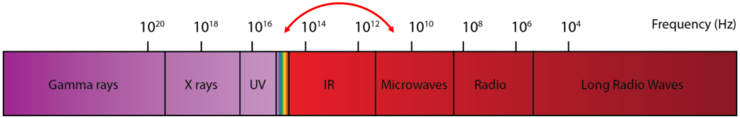
$\rightarrow$ ($\times$100s) gain [$\Gamma_{dc} \sim$ 10s count/s, $\eta^2 \sim 70\%$]

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

https://arxiv.org/abs/2403.02321

SMPDs in the microwave range

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

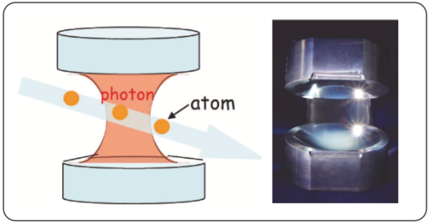


Requirements for dark matter search:

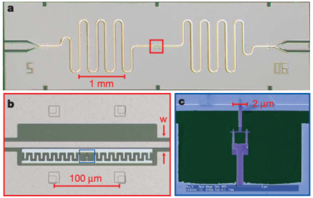
- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100\,\mathrm{Hz}$
- $\gtrsim 40 - 50\,\%$ efficiency
- large "dynamic" bandwidth $\sim$ cavity tunability

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)

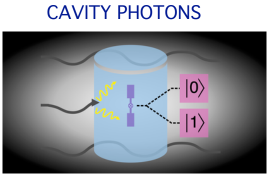


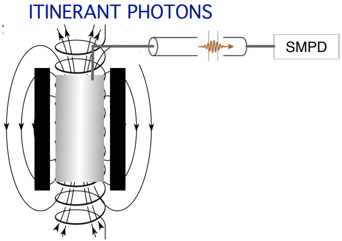
Nature **445**, 515–518 (2007)

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

itinerant vs *cavity* photon detector in axion experiments

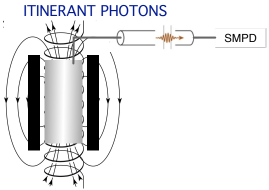
transmon-based detectors do not tolerate intense B fields

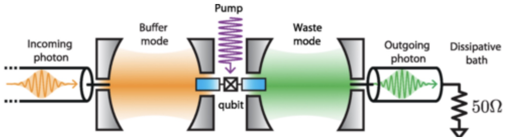




→ in axion detection, itinerant photon detection is preferred, as the SMPD is located in a region **where it can be screened by the B field** (but anyway at the MC stage)

TRAVELING QUANTUM MICROWAVES

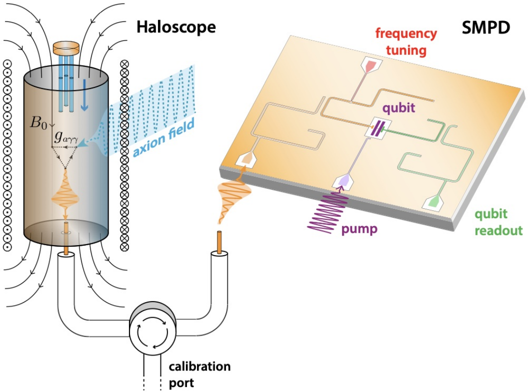




Phys. Rev. X 10, 021038 (2020) ← 1.3 counts/ms
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip
Phys. Rev. Appl. 21, 014043 (2024) ← 85 counts/s

- 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

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



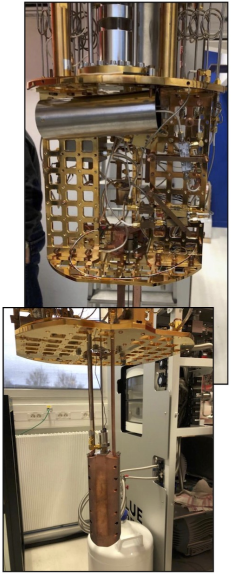
Qubit	
$\omega_q/2\pi$	6.222 GHz
T_1	17 – 20 μs
T_2^*	28 μs
$\chi_{qq}/2\pi$	240 MHz
$\chi_{qb}/2\pi$	3.4 MHz
$\chi_{qw}/2\pi$	15 MHz
Waste mode	
$\omega_w/2\pi$	7.9925 GHz
$\kappa_{\text{ext}}/2\pi$	1.0 MHz
$\kappa_{\text{int}}/2\pi$	$<$ 100 kHz
Buffer mode	
$\omega_b/2\pi$	7.3693 GHz
$\kappa_{\text{ext}}/2\pi$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

https://arxiv.org/abs/2403.02321

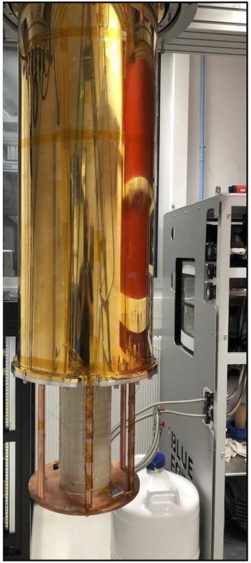
EXP SETUP

- 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)

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



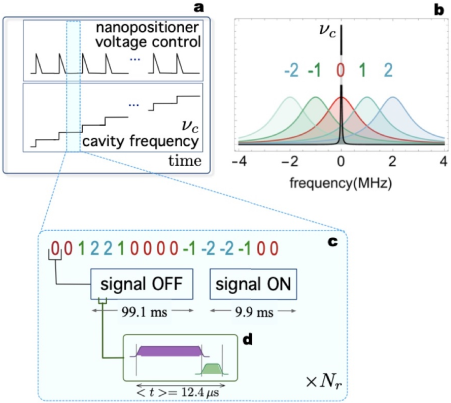
SMPD (top) and cavity



SC magnet

https://arxiv.org/abs/2403.02321

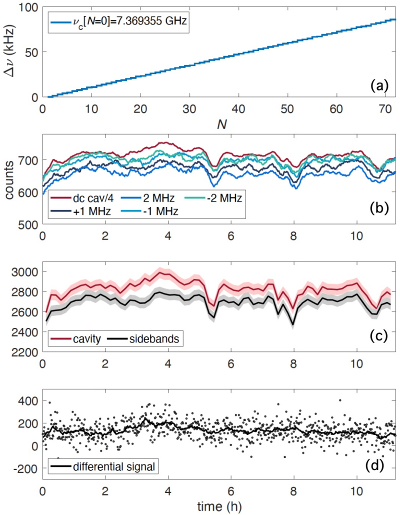
readout protocol: the SMPD is operated through **nested cycles**



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

- $\rightarrow$ basic block (d) is detection + qubit readout $\sim (10+2)\,\mu s$
- $\rightarrow$ measure SMPD efficiency and cavity parameters
- $\rightarrow$ control the nanopositioner for cavity frequency tuning
- $\rightarrow$ monitor dark counts under different conditions: at resonance $\omega_b = \omega_c$ and at 4 sidebands $\omega_b = \omega_c \pm 1\,\text{MHz}$, $\omega_b = \omega_c \pm 2\,\text{MHz}$

How long can we integrate to improve S/N?

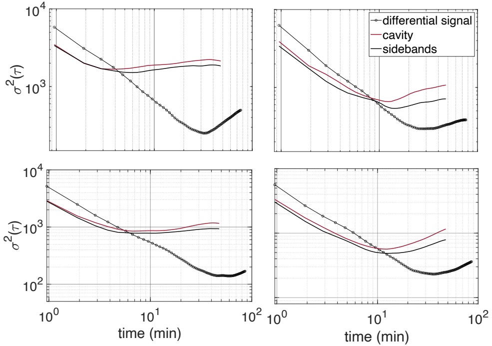


- counts at $\omega_b = \omega_c$ registered in a time interval of 28.6 s (set by readout protocol structure) $\Longleftrightarrow$ **average** ~ 90 **Hz dark count rate**
- both the counts at resonance and on sidebands $\omega_b = \omega_c \pm 1, 2\,\mathrm{MHz}$ vary **beyond statistical uncertainty** expected for poissonian counts
- notice a **correlation** between the two channels
- and a systematic **excess** at cavity frequency $\rightarrow$ the cavity sits at a higher T

https://arxiv.org/abs/2403.02321

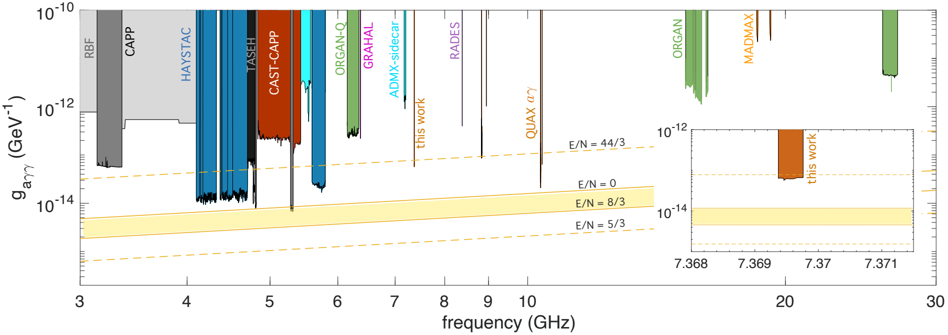
Long-term stability

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



- $\rightarrow$ counts fluctuations decrease as $1/\tau$, up to a maximum observation time τ_m of about 10 min
- $\rightarrow$ for $\tau > \tau_m$ the Allan variance increases $\rightarrow$ system drifts
- $\rightarrow$ the differential channel follows the $1/\tau$ trend up to a longer time interval $\tau \sim 30$ min $\rightarrow$ small correlation
- $\rightarrow$ no additional noise in the data recorded between successive step motion intervals compared to unperturbed cavity

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

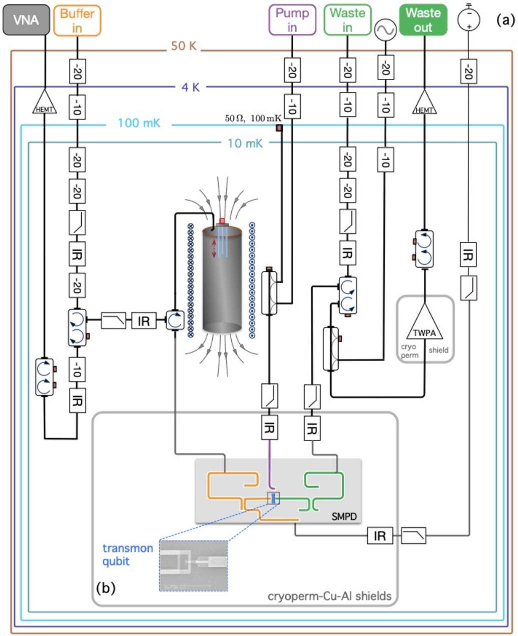


→ data analysed in 420 kHz $\simeq 14\Delta\nu_c$ range

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

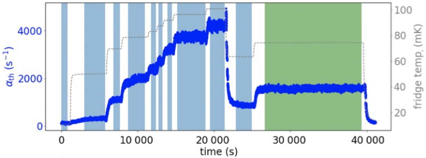
⊙⊙ **x20 gain [conservative]** in scan speed vs linear amplifiers https://arxiv.org/abs/2403.02321

BACKUP SLIDES



→ 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

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

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

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