MPG HLL Inauguration Ceremony and Semiconductor Symposium

7–8 Oct 2024
Science Congress Center Munich

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

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quantum science technologies (QST) in particle physics

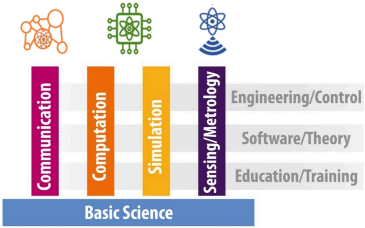
$\Longrightarrow$ the role of quantum science and technology in **fundamental physics**

$\Longrightarrow$ **beyond standard model (BSM)** physics

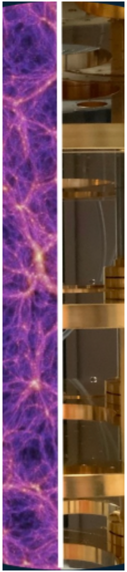
- ⊙ matter-antimatter asymmetry
- ⊙ dark matter
- ⊙ CP violation in QCD
- ⊙ …

$\Longrightarrow$ **feeble interactions** with SM particles (or none at all)

$\Longrightarrow$ sensing is the most consolidated QST,
with enormous potential to **increase the sensitivity** of our experiments



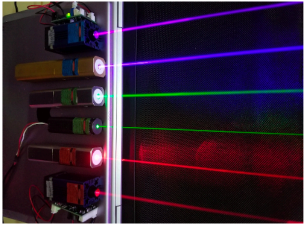
Quantum Technologies's primary areas of work. © UE

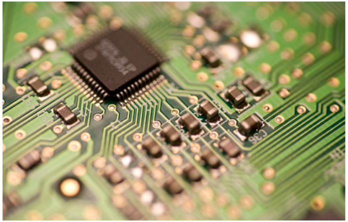


QUANTUM SENSING: a definition

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

S. M. Girvin, *Les Houches Circuit QED lectures*





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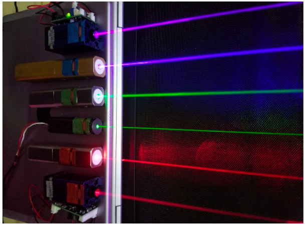
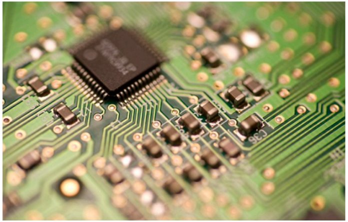




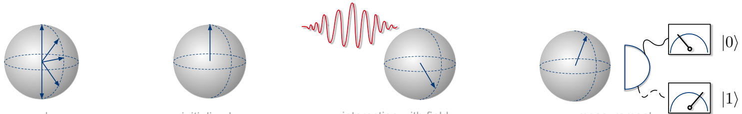
→ Examples of **classical machines**, because their **operational degrees of freedom are purely classical**

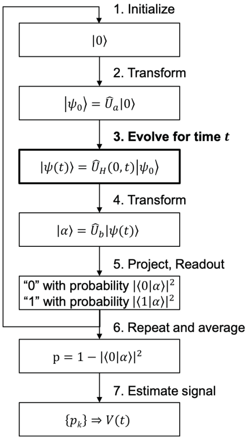
QUANTUM 1.0 vs QUANTUM 2.0

QUANTUM 2.0

"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)

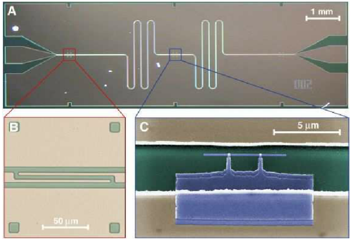
"A device whose measurement (sensing) capability is enabled by our ability to **manipulate and readout its quantum states**."
M. Safranova and D. Budker



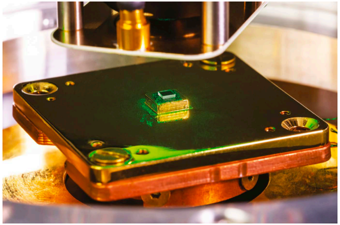


Quantum 2.0

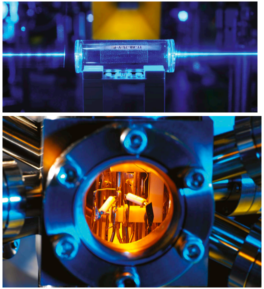
Quantum sensors have been realised in **multiple physical systems with very different operating principles**.



Superconducting circuits



Solid-state spins

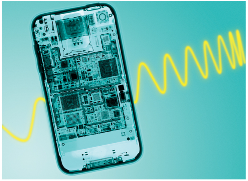


Atomic ensembles

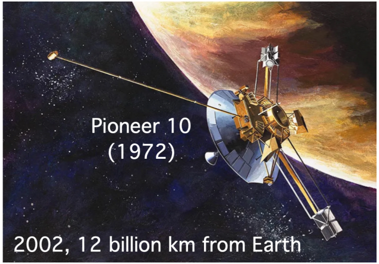
It might take some more time to adapt them in real-world settings, but **they are already in use in the lab**.
Applied to problems in which **significant** gain (up to 1000s) compared to conventional detectors is required.

QUANTUM MICROWAVES in DM search

kW

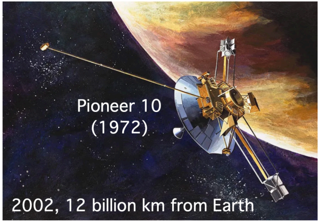


(0.1-2) W



2.5×10^{-21} W

quantum microwaves in DARK MATTER search



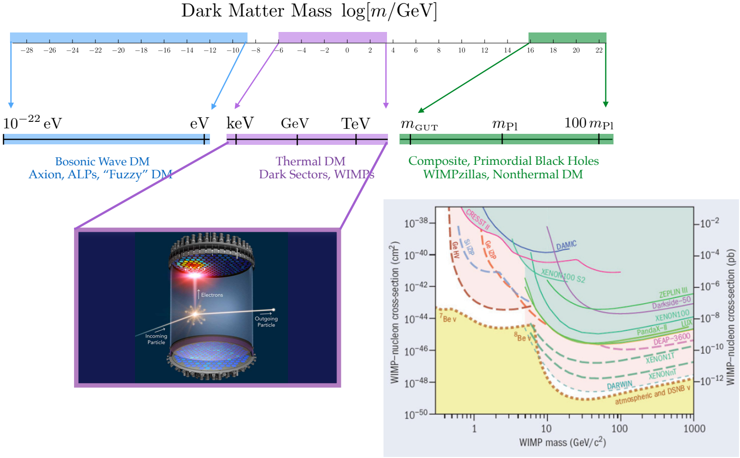
2.5×10^{-21} W

$< 10^{-23}$ W

Unknown frequency (particle mass)

< few photons/s ⇒ QUANTUM 2.0

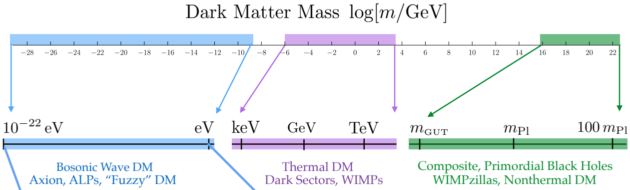
"wave-like" DM

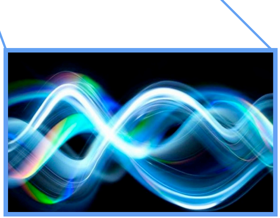


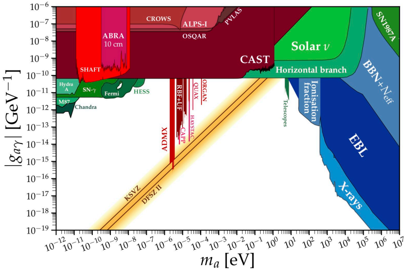
$m \gtrsim 10\,\mathrm{eV}$

individual particles scattering off a detector

“wave-like” DM







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

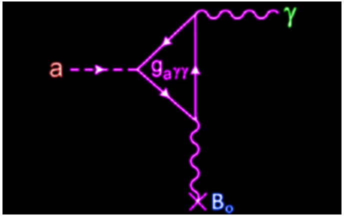
classical field oscillating at the Compton frequency 10^{-6} coherence

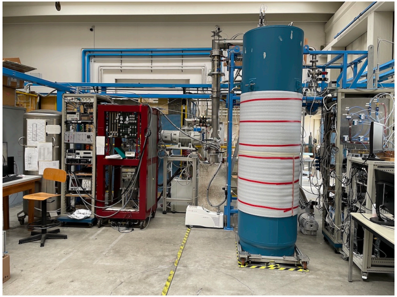
1. 3D microwave **resonator** for resonant amplification
   -think of an HO driven by an external force-

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

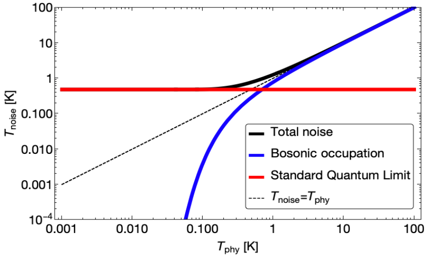


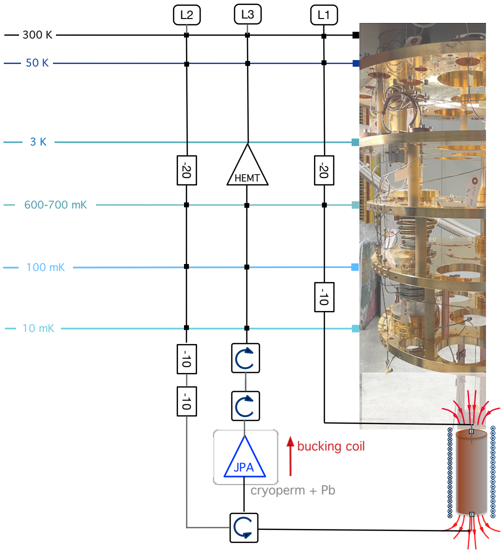


quantum-limited readout

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

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



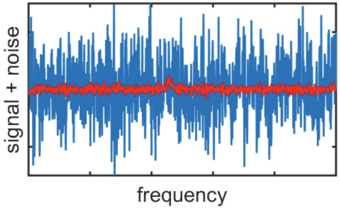


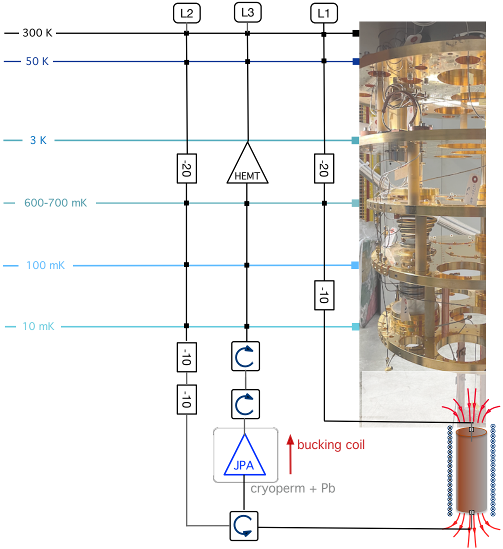
a poor S/N ratio

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

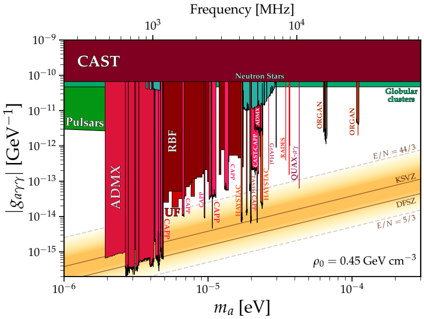
$$P_n = k_B T \Delta\nu \gg P_s \;\propto\; B^2\, V_{\mathrm{eff}}\, Q_L \sim 10^{-23}\,\mathrm{W}$$

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





Heavier (axions) & Harder (life)



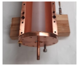
- heavier axions are well motivated,
  BUT
  the *scan rate df/dt scales unfavourably with f*

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

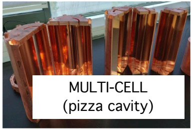
(asm. quantum noise, SC cavities, relax r/L)

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

DIELECTRIC CAVITY
(higher order modes)



THIN SHELL



→ 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 → gain by 10^3

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

REAL DETECTOR WITH DARK COUNTS Γ_{dc}

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

Γ_{dc} dark counts

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

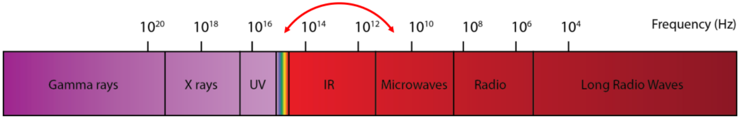
→ (×100s) gain [$\Gamma_{dc} \sim$ 10s count/s, $\eta^2 \sim 70\%$]

- 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 $\nu = 5$ GHz

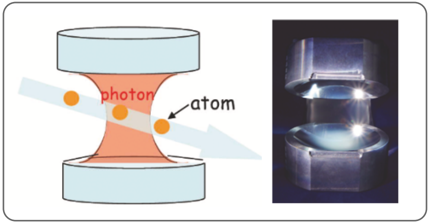


Requirements for dark matter search:

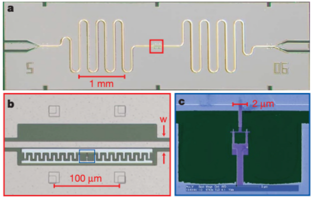
- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100$ Hz
- $\gtrsim 40 - 50\,\%$ efficiency
- large "dynamic" bandwidth $\sim$ cavity tunability

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)

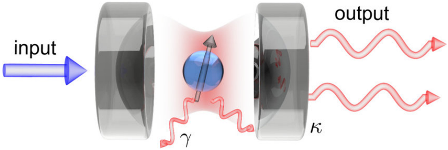
In both cases **two-level atoms** interact directly with a **microwave field mode** in the cavity

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
to modes $\neq$ from the mode of interest

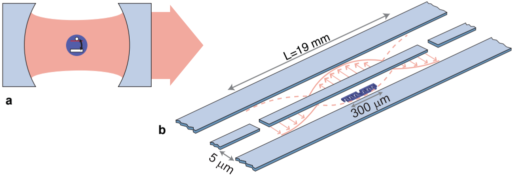
$g \gg \kappa, \gamma \iff$ regime of strong coupling
coherent exchange of a field quantum between the atom (matter) and the cavity (field)

from cavity-QED to circuit-QED

g is significantly increased compared to Rydberg atoms:

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

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



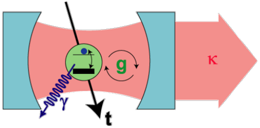
(a) $(g/2\pi)_{\text{cavity}} \sim 50\,\text{kHz}$

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

10^4 larger coupling than in atomic systems

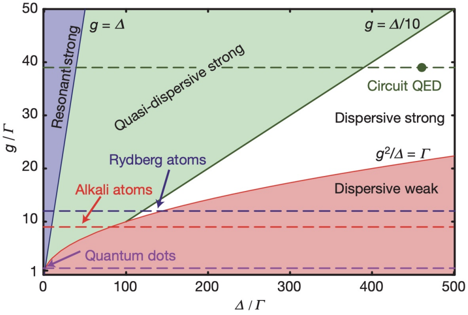
Jaynes-Cummings model

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 $\quad g/\Delta \ll 1$

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

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

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

2χ

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

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

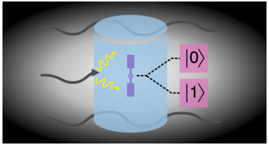
$\rightarrow 2\chi a^\dagger a$ number splitting

→ **qubit frequency** is a function of the **cavity photon number**

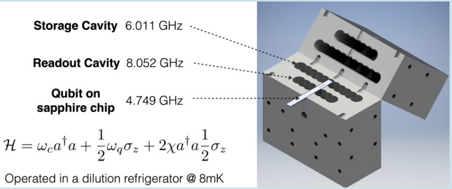
→ measuring the **qubit frequency** is equivalent to measuring the **number of photons** in the cavity

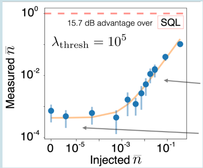
cavity photon detector

CAVITY PHOTONS



SMPD - qubit coupled to 3D resonators





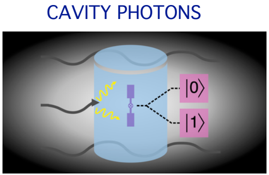
potential **X 1300** scan rate

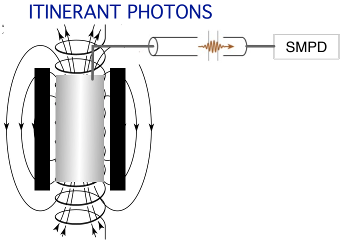
exclusion limit for dark photons at fixed freq. (6 GHz)

A. Dixit *et al.*, Phys. Rev. Lett. **126**, 141302 (2021)

itinerant vs *cavity* photon detector in axion experiments

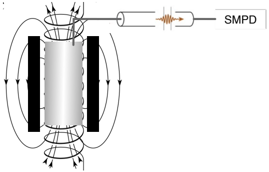
transmon-based detectors do not tolerate intense B fields

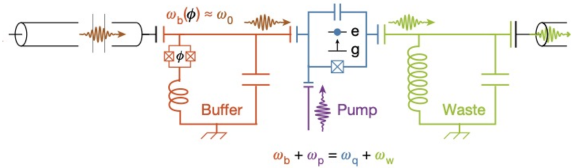




→ in axion detection, itinerant photon detection is preferred, as the SMPD is located in a region **where it can be screened by the B field** (but anyway at the MC stage)

TRAVELING QUANTUM MICROWAVES

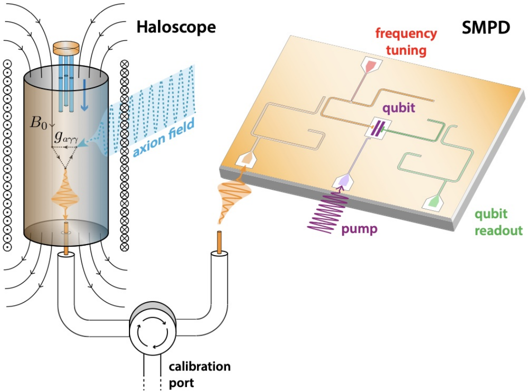




- wave mixing (4WM) process: the incoming photon is converted into an excitation of the qubit
- readout of the qubit state with quantum information science (QIS) methods
- efficiency $\eta \sim 0.5$, dark counts $\Gamma_d \sim 85\,\mathrm{s}^{-1}$
- $\sim 100\,\mathrm{MHz}$ tuning range
- on/off resonance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

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

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



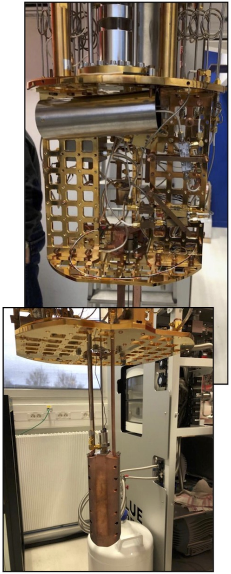
Qubit	
$\omega_q/2\pi$	6.222 GHz
T_1	17 – 20 μs
T_2^*	28 μs
$\chi_{qq}/2\pi$	240 MHz
$\chi_{qb}/2\pi$	3.4 MHz
$\chi_{qw}/2\pi$	15 MHz
Waste mode	
$\omega_w/2\pi$	7.9925 GHz
$\kappa_{ext}/2\pi$	1.0 MHz
$\kappa_{int}/2\pi$	< 100 kHz
Buffer mode	
$\omega_b/2\pi$	7.3693 GHz
$\kappa_{ext}/2\pi$	0.48 MHz
$\kappa_{int}/2\pi$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

https://arxiv.org/abs/2403.02321

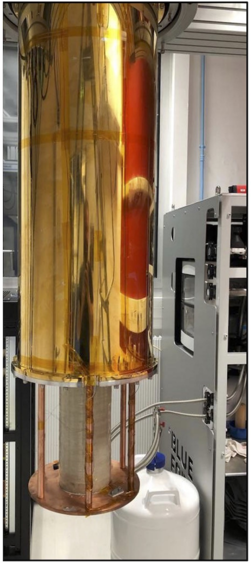
EXP SETUP

- 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]

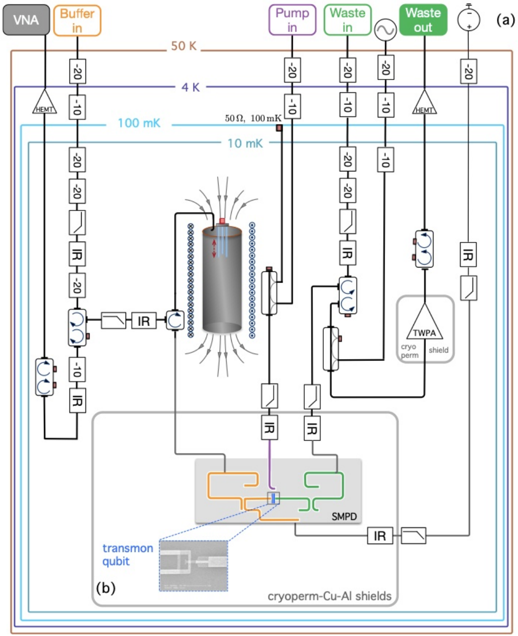


SMPD (top) and cavity



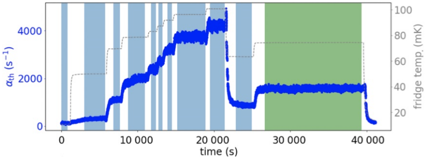
SC magnet

https://arxiv.org/abs/2403.02321



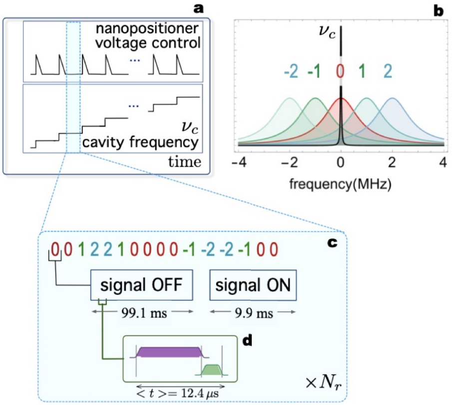
→ 2 RF lines more than plain JPA/TWPA cavity readout

→ 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.

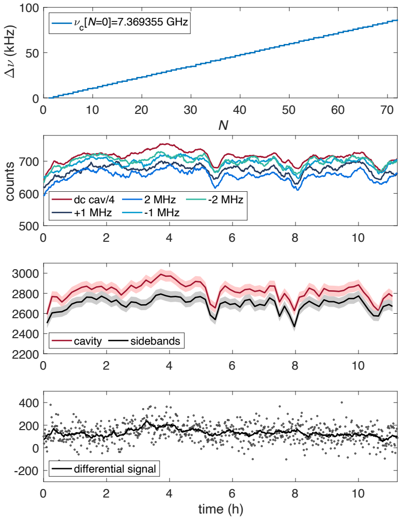
readout protocol: the SMPD is operated through **nested cycles**



$\Longrightarrow$ 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?

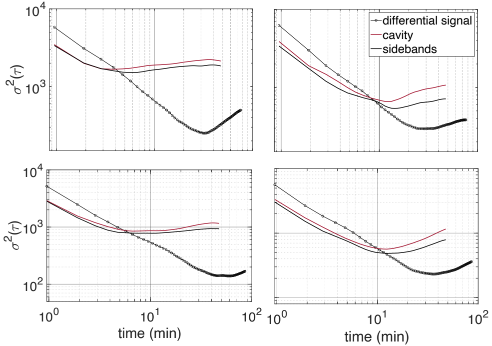


- counts at $\omega_b = \omega_c$ registered in a time interval of 28.6 s (set by readout protocol structure) $\Longleftrightarrow$ **average** ~ 90 **Hz dark count rate**
- both the counts at resonance and on sidebands $\omega_b = \omega_c \pm 1, 2$ MHz vary **beyond statistical uncertainty** expected 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



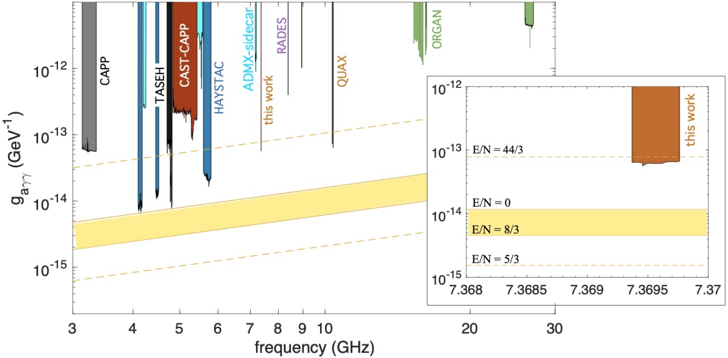
→ counts fluctuations decrease as $1/\tau$, up to a maximum observation time τ_m of about 10 min

→ 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 $g_{a\gamma\gamma}$

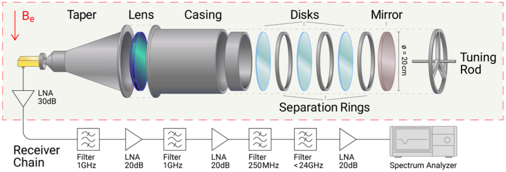


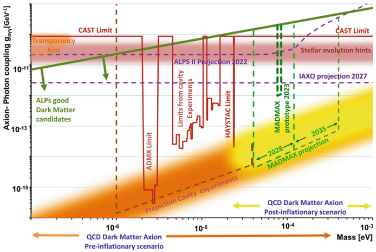
→ data analysed in 420 kHz $\simeq 14\Delta\nu_c$ range

→ 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

beyond cavity haloscopes: DIELECTRIC HALOSCOPES





arXiv:2409.11777v1 [hep-ex] 18 Sep 2024

→ extend TWPAs and microwave photon counting technologies to frequencies **above 10 GHz**

WRAP UP

- lab-scale, tabletop vs conventional “scaling up” approach
- importing metrological methods from QIS in particle physics
  → J(TW)PA, SMPD *to increase the sensitivity of our experiments*
- there is room for further improvement:
  → *circuit design and fabrication, extension to higher frequencies*
- new instruments are new fundamental physics probes

QUAX @INFN LNL

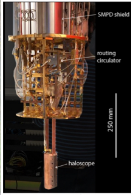
INFN
Istituto Nazionale di Fisica Nucleare

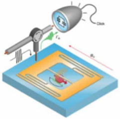
SQMS

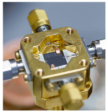
Quantronics Group

Research Group in Quantum Electronics, CEA-Saclay, France

SMPD design, fabrication and tests







NÉEL institut

N. Roch group in Grenoble (TWPAs)

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:

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

X_1 and X_2 signal quadratures

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