Search for axion dark matter with a transmon-based photon counter

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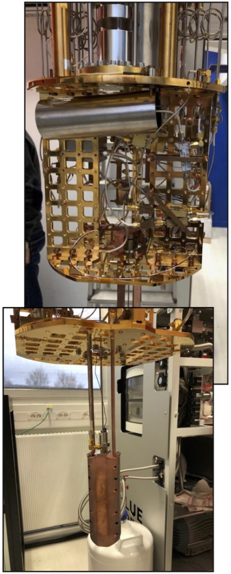
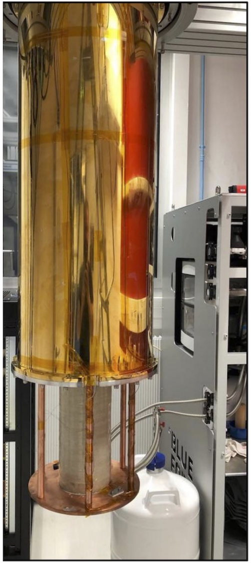
EXP SETUP

- ⊙ a **transmon-based** single microwave photon detector (SMPD) is used to readout the cavity mode
- ⊙ 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]

https://arxiv.org/abs/2403.02321

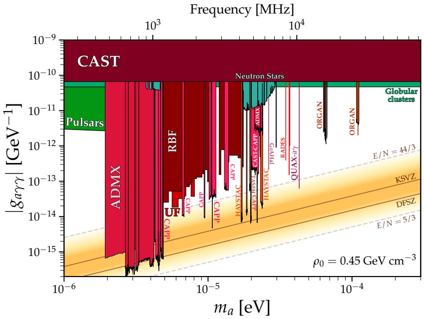


SMPD (top) and cavity



SC magnet

Heavier & Harder



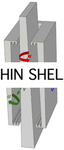
- heavier axions are well motivated,
  BUT
  the *scan rate df/dt scales unfavourably with f*

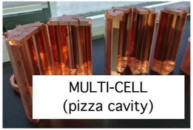
$$\frac{df}{dt} \propto \frac{g_{a\gamma\gamma}^4 B^4 V_{\text{eff}}^2 Q_L}{T_{sys}^2} \propto f^{-4}$$

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

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


DIELECTRIC CAVITY
(higher order modes)


THIN SHELL


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 → gain by 10^3

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

REAL DETECTOR WITH DARK COUNTS Γ_{dc}

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

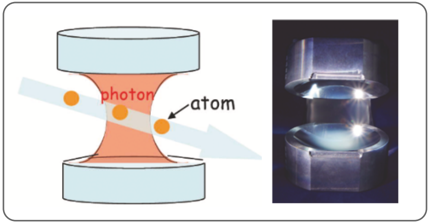
Γ_{dc} dark counts

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

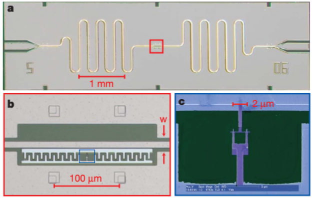
https://arxiv.org/abs/2403.02321

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)



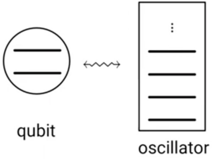
Nature **445**, 515–518 (2007)

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

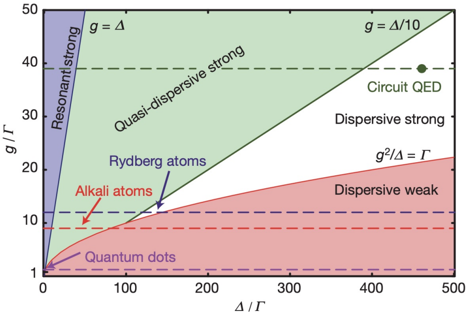
Jaynes-Cummings model

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 $\quad g/\Delta \ll 1$

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

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

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

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

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

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

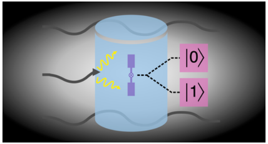
→ **qubit frequency** is a function of the **cavity photon number**

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

itinerant vs *cavity* photon detector in axion experiments

transmon-based detectors do not tolerate intense B fields

CAVITY PHOTONS



Phys. Rev. Lett. 126, 141302 (2021)

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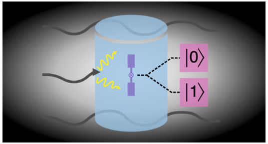

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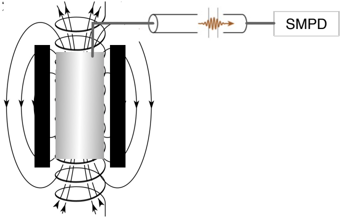
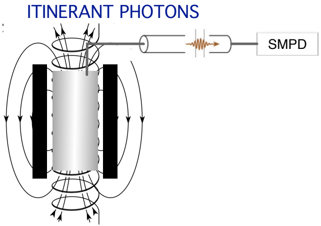
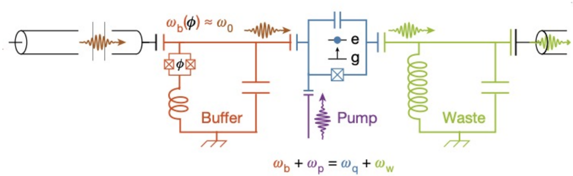
ITINERANT PHOTONS



→ 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)

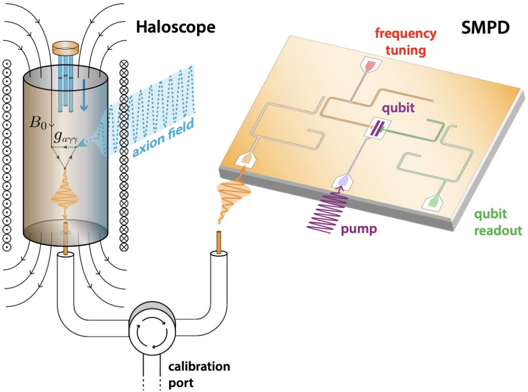




Phys. Rev. X 10, 021038 (2020) ← 1.3 counts/ms
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip
Phys. Rev. Appl. 21, 014043 (2024) ← 85 counts/s

- 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 $\Gamma_d \sim 85\,\mathrm{s}^{-1}$
- $\sim 100\,$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

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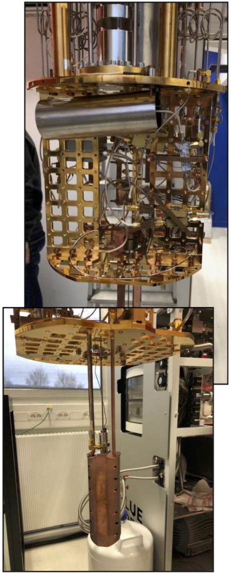
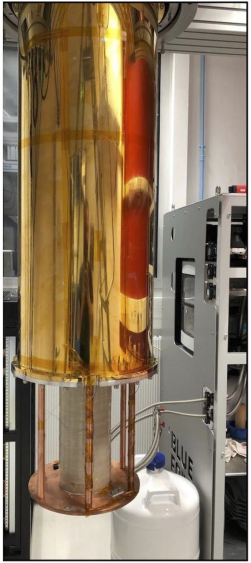


SMPD (top) and cavity



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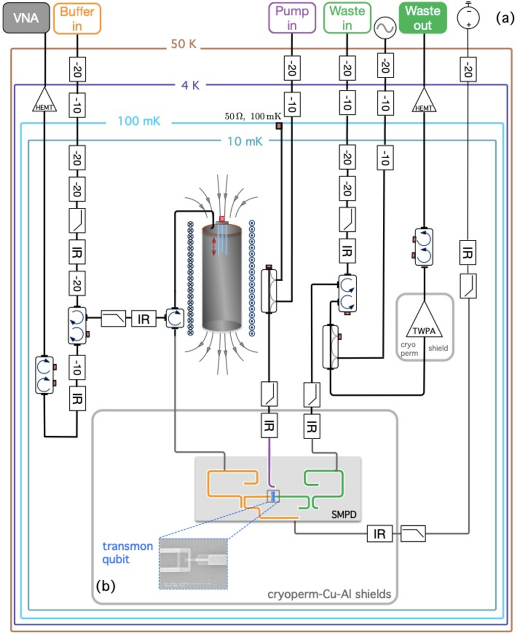
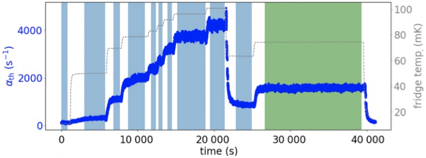


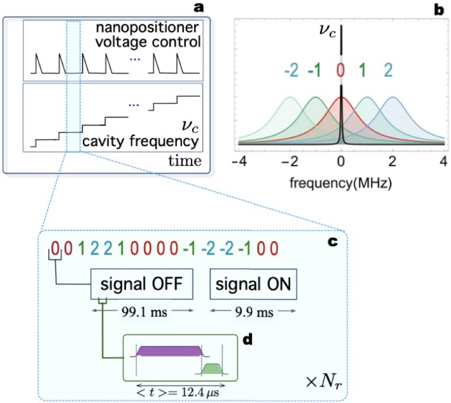
→ 2 RF lines more than plain JPA/TWPA cavity readout

→ dilution refrigerator base temperature must not exceed ∼ 20 mK



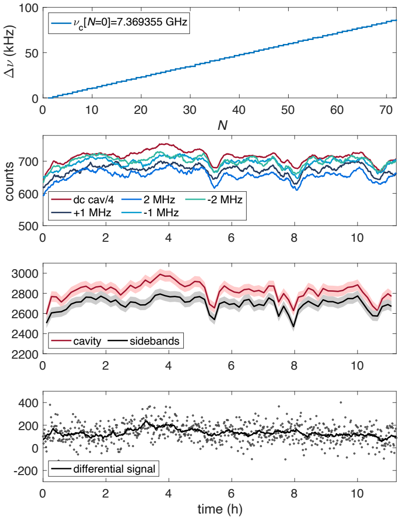
→ used only passive screening due to the relatively low field employed ($B = 2\,\mathrm{T}$).
Bucking coil necessary to run at higher fields.

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



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

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** $\sim 90\,$**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

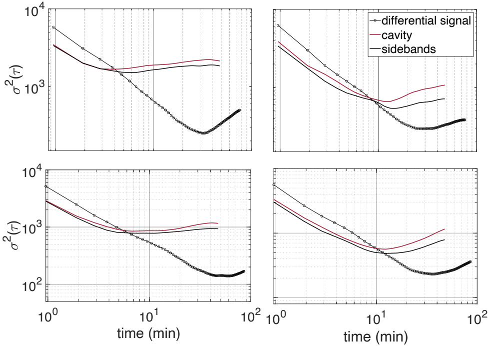
- notice a **correlation** between the two channels

- and a systematic **excess** at cavity frequency
  → the cavity sits at a higher T

https://arxiv.org/abs/2403.02321

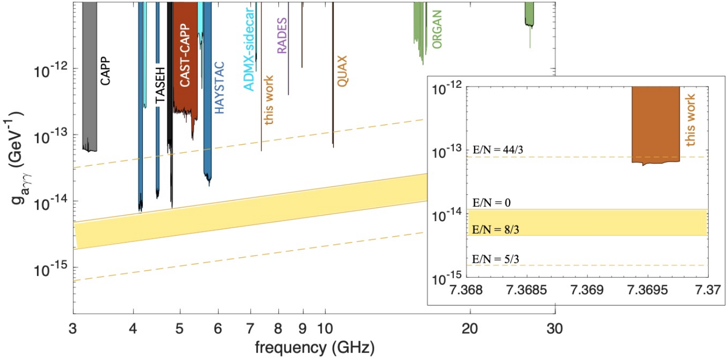
Long-term stability

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 $\tau \sim 30\,\text{min}$ → small correlation
- → no additional noise in the data recorded between successive step motion intervals compared to unperturbed cavity

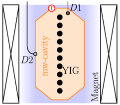
beyond SMPD diagnostics: UPDATING THE EXCLUSION PLOT FOR $g_{a\gamma\gamma}$

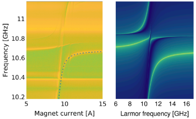


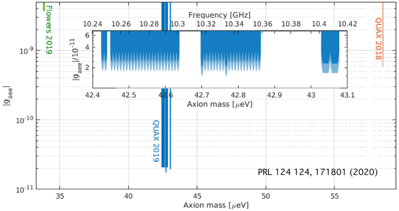
- → data analysed in 420 kHz $\simeq 14\Delta\nu_c$ range
- → reached the extended QCD axion band with a short integration time (10 min), in spite of the small B-field
- ⊙⊙ **x20 gain [conservative]** in scan speed vs linear amplifiers https://arxiv.org/abs/2403.02321

at the QUAX lab in Padova

- finally, photon counting in axion DM search!
- reloading our **ferrimagnetic haloscope**, this time equipped with the SMPD to probe g_{ae} in a range of 200 MHz with enhanced sensitivity (adv: low B field, tuning with B → no moving parts)







- while we complete the QUAXaγ search with the single **shell-dielectric cavity** readout by a **TWPA** ⋆⋆ **60 MHz** range with the **clamshell tuning mechanism** around 10 GHz at ∼ KSVZ sensitivity ⋆⋆

at the QUAX lab in Padova (CONT’D)

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$\Longrightarrow$ $\Longrightarrow$ see A. Rettaroli’s talk tomorrow (+LNF haloscope @Frascati, Rome)

→ ongoing collaboration with CAPP to develop tunable HTS cavities

→ we’re part of the SQMS center, the fridge with 9 T field (Fermilab) will host a similar experiment

→ projects to sell these devices via spin-off → contact Patrice or Manu at Quantronics group