Quantum sensing in axion dark matter search

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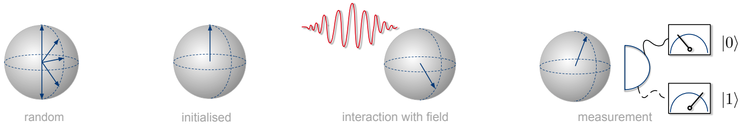
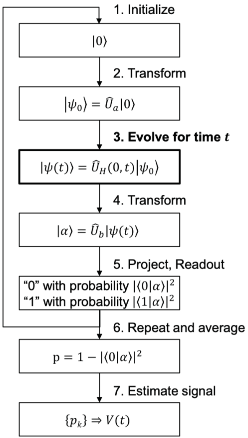
About QUANTUM SENSING: not just plain detection of quanta

"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



its **operational degrees of freedom** are intrinsically quantum mechanical


1. Initialize

$|0\rangle$

2. Transform

$|\psi_0\rangle = \hat{U}_a|0\rangle$

3. Evolve for time *t*

$|\psi(t)\rangle = \hat{U}_H(0,t)|\psi_0\rangle$

4. Transform

$|\alpha\rangle = \hat{U}_b|\psi(t)\rangle$

5. Project, Readout

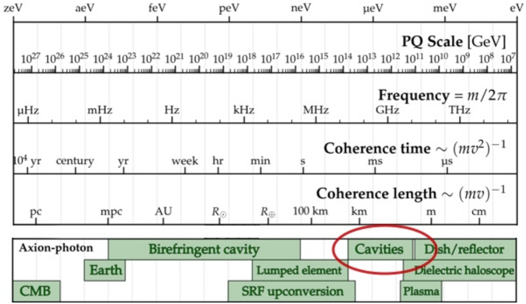
"0" with probability $|\langle 0|\alpha\rangle|^2$
"1" with probability $|\langle 1|\alpha\rangle|^2$

6. Repeat and average

$\mathrm{p} = 1 - |\langle 0|\alpha\rangle|^2$

7. Estimate signal

$\{p_k\} \Rightarrow V(t)$



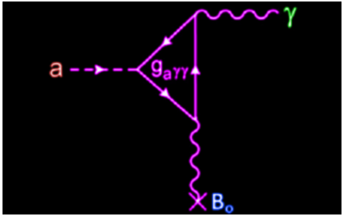
- below 1 eV, we look for a **persistent, oscillating field** with **frequency set by the particle mass** $\Longleftrightarrow$ wave-like DM
- resonant cavities (μeV - .1 meV): this is most sensitive method, we can probe QCD axions, not just ALPs
- open problem: this is an endless, time-consuming search due to the **poor S/N ratio**, with N set by QM when linear amplifiers are employed
- quantum sensors can **speed up the search** significantly

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

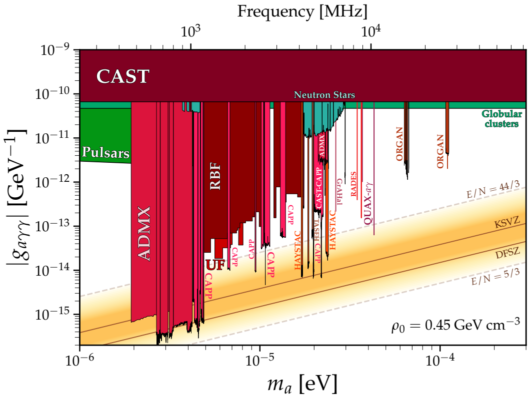
2. with **tunable frequency** to match the axion mass
   ($\delta\nu_c \sim$ MHz, target 100 MHz range at KSVZ)

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

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



OPEN CHALLENGES for advanced detectors

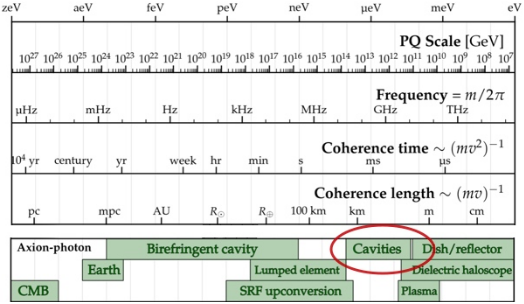


$P_a \propto B^2 V_{\rm eff} Q_L$ signal power in W ($\sim 10^{-22}$)

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

- ⊙ target: QCD axions in the **yellow band**
- ⊙ to go from KSVZ to DFSZ is a long journey
  $(df/dt)_{DFSZ} \sim$ **50** $(df/dt)_{KSVZ}$
- ⊙ the “sweet spot”
- ⊙ heavier axions are better motivated,
  BUT
  (i) the *scan rate df/dt scales unfavorably with f*
  (ii) **quantum noise in linear amplifiers linearly increases with** f

→ **hundreds of years** are projected to probe the 1-10 GHz decade with current technology (i.e. cavities, magnets and SC amplifiers)



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SIGNAL READOUT

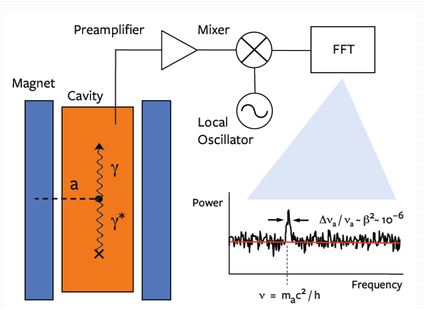
$$df/dt \propto V_{\text{eff}}^2 \; Q_L \; T_{sys}^{-2}$$

Even though the experiment is **cooled to the lowest temperatures in the Universe** ($\sim 10\,\text{mK}$), and Josephson Parametric Amplifiers (JPA) are employed to **minimize added noise**, they introduce fundamental noise (**SQL, Standard Quantum Limit noise**)

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

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T_c} - 1} + \frac{1}{2} + N_A \right)$$

$N_A \gtrsim 0.5$
S. K. Lamoreaux *et al.*, Phys Rev D **88** 035020 (2013)



SIGNAL READOUT

$$df/dt \propto V_{\mathrm{eff}}^2 \; Q_L \; T_{sys}^{-2}$$

weak interactions with SM particles $\implies 10^{-23}$ W signal power
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

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T_c} - 1} + \frac{1}{2} + N_A \right)$$

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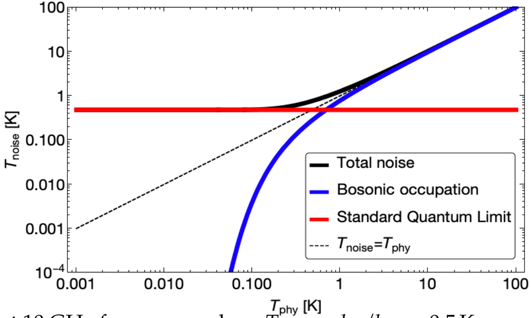


at 10 GHz frequency, where $T_{\mathrm{SQL}} = h\nu/k_B \to 0.5\,\mathrm{K}$

linear amplification vs photon counting

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:

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

Unlimited (exponential) gain in the haloscope scan rate R compared to linear amplification at SQL:

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

Ex. at 7 GHz, 40 mK

$\Longrightarrow 10^3$ faster than SQL linear amplifier readout with an ideal SMPD (dark count free, unitary efficiency)

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

beyond the SQL **with a “microwave phototube”** $\Longleftrightarrow$ **detection of quantum microwaves**

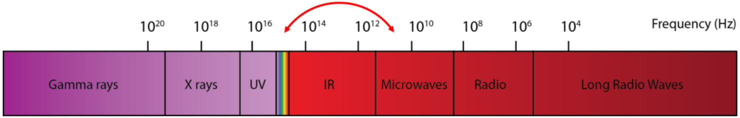
	B [T]	$P_{\rm sig}^{\rm KSVZ}$ [yW(ph/s)]	$P_{\rm sig}^{\rm DFSZ}$ [yW(ph/s)]
$\nu_c = 7.37\,\rm GHz$	2	0.84(0.17)	0.11(0.026)
	12	30.4(6.2)	6.3(0.86)
$\nu_c = 10\,\rm GHz$	12	22.39(3.38)	3.11(0.47)

signal power and photon rate for benchmark QCD axion models in yoctowatt (yW$= 10^{-24}$ W)

Using quantum-limited **linear amplifiers** (Josephson parametric amplifiers) the **noise set by quantum mechanics** exceeds the **signal** in the high frequency range, whereas **photon counting** has no intrinsic limitations

SMPDs in the microwave range

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

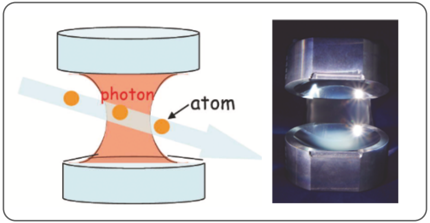


Requirements for dark matter search:

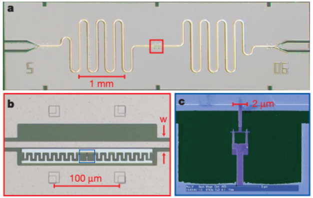
- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate $\Gamma < 100\,\mathrm{Hz}$
- $\gtrsim 40 - 50\,\%$ efficiency
- large “dynamic” bandwidth $\sim$ cavity tunability

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)

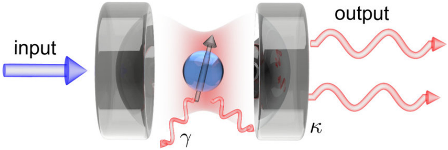
In both cases **two-level atoms** interact directly with a **microwave field mode*** in the cavity

Cavity-QED for photon counting

Can the field of a single photon have a large effect on the atom (TLS)?

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**

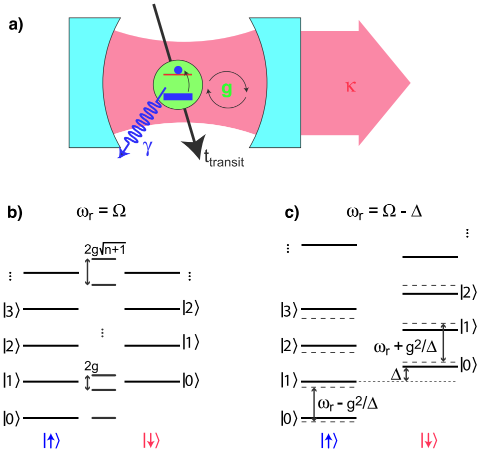
→ **confine the field** in a cavity

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

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)

CAVITY QED SYSTEM

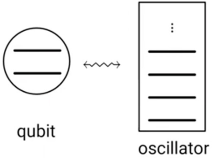


A simple theoretical model (Jaynes-Cummings) describes atoms as two-level, **spin-like systems** interacting with a quantum oscillator

$$H = \hbar\omega_{\mathrm{r}}\left(a^{\dagger}a + \frac{1}{2}\right) + \frac{\hbar\Omega}{2}\sigma^{z} + \hbar g(a^{\dagger}\sigma^{-} + a\sigma^{+})$$

- ω_r cavity resonance frequency
- Ω atomic transition frequency
- g strength of the atom-photon coupling

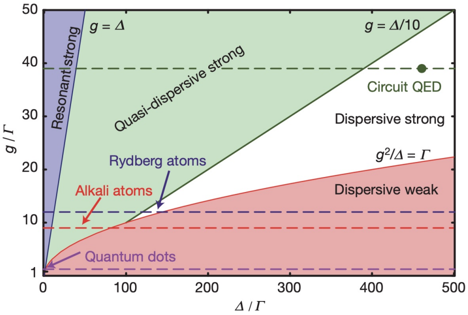
Jaynes-Cummings model



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 $g/\Delta \ll 1$

$$\begin{aligned}\hat{H}^{\text{eff}}_{\text{JC}} &= \hbar\omega_r \hat{a}^\dagger\hat{a} + \frac{\hbar\omega'_q}{2}\hat{\sigma}_z + \hbar\chi\hat{a}^\dagger\hat{a}\hat{\sigma}_z \\ &= (\hbar\omega_r + \hbar\chi\hat{\sigma}_z)\hat{a}^\dagger\hat{a} + \frac{\hbar\omega'_q}{2}\hat{\sigma}_z \\ &= \hbar\omega_r\hat{a}^\dagger\hat{a} + \frac{\hbar}{2}(\omega'_q + \underset{2\chi}{\cancel{\omega_r}}\hat{a}^\dagger\hat{a})\hat{\sigma}_z\end{aligned}$$

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

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

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

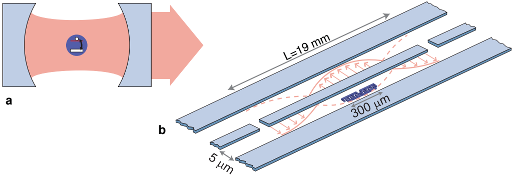
→ **qubit frequency** is a function of the **cavity photon number**

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

from cavity-QED to circuit-QED

In circuit QED the atom-photon interaction is implemented using **artificial atoms**, capacitively coupled to **transmission line resonators**.

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

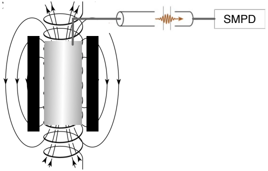
(b) $(g/2\pi)_{\text{circuit}} \sim 100\,\mathrm{MHz}$ (typical)

10^4 larger coupling than in atomic systems

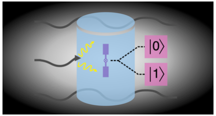
coupling qubits with 3D cavities

→ *itinerant* and *cavity* single microwave photon counter (SMPD)

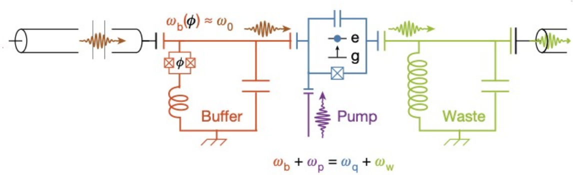
ITINERANT PHOTONS



CAVITY PHOTONS



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



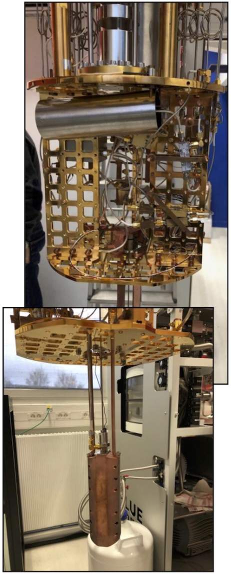
Nature **600**, 434–438 (2021) ← spin fluorescence detection
Nature **619**, 276–281 (2023) ← single spin flip

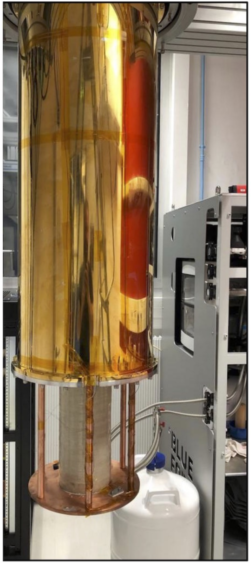
- 4WM process: the incoming photon is converted into an excitation of the qubit
- readout of the qubit state with QIS methods
- efficiency $\eta \sim 0.5$,
  dark counts $\Gamma_d \sim 90\,\mathrm{s}^{-1}$
- on/off resonance → monitor the dark counts, which set the background in these experiment

SMPD-HALOSCOPE prototype

- hybrid (normal-superconducting) cavity 7.37 GHz, tunable, $Q_0 = 9 \times 10^5$
- T=14 mK delfridge base temperature @ Quantronics lab (CEA, Saclay)
- 2 T-field
- triplet of rods controlled by a nanopositioner mounted at the MC stage to probe for different axion masses
- passive protection by the B-field for SMPD and TWPA

https://arxiv.org/abs/2403.02321


SMPD (top) and cavity

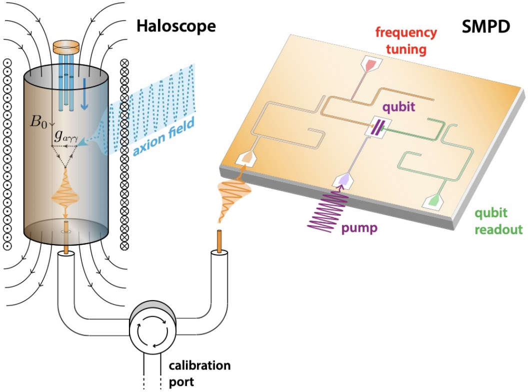


SC magnet

a four wave mixing process

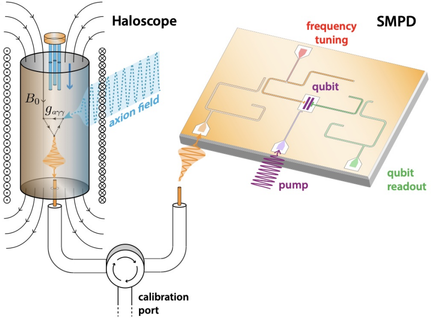
an atom coupled to a single mode is not good for single photon detection, as you want the conversion process to be optimized ($\eta \simeq 1$) $\Longrightarrow$ 4WM is implemented on the SC circuit

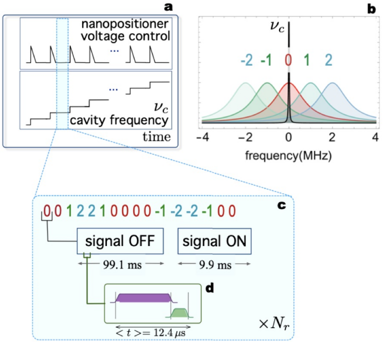
$$\omega_b + \omega_p = \omega_q + \omega_w$$



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

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





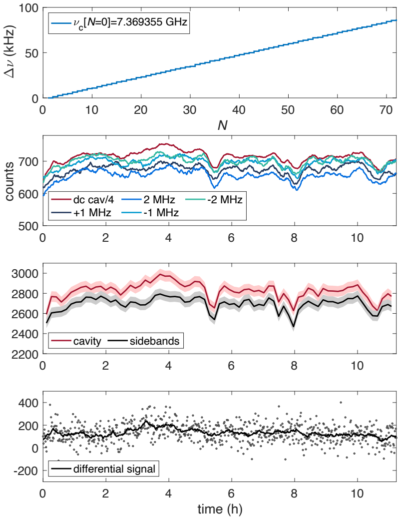
→ basic block (d) is detection + qubit readout (non deterministic)

→ 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 $\omega_b = \omega_c \pm 1\,\mathrm{MHz}$, $\omega_b = \omega_c \pm 2\,\mathrm{MHz}$

A background-limited search: dark counts

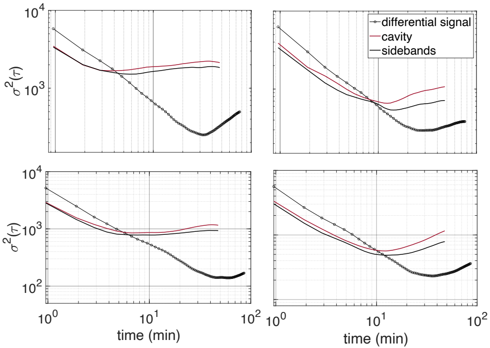


- counts at $\omega_b = \omega_c$ registered in a time interval of 28.6 s (set by readout protocol structure) $\Longleftrightarrow$ **average** $\sim$ 90 **Hz dark count rate**
- both the counts at resonance and on sidebands $\omega_b = \omega_c \pm 1, 2$ MHz vary **beyond statistical uncertainty** expected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

A background-limited search: dark counts

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



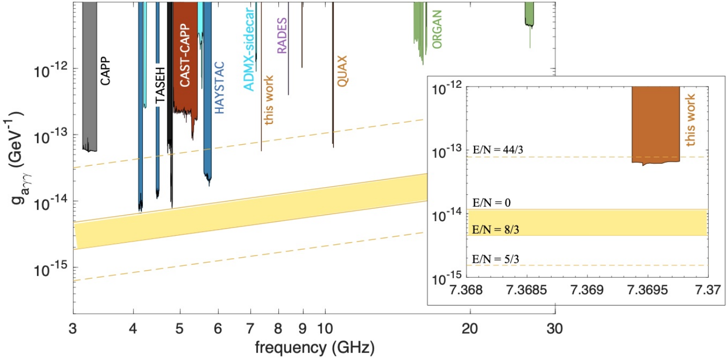
→ click number fluctuations decrease as $1/\tau$, up to a maximum observation time τ_m of about 10 min

→ for $\tau > \tau_m$ the Allan variance increases → random walk

→ 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

PERSPECTIVES

- what next: scaling up to observatory $\Longrightarrow$ increase the B field, and probe for axions in a much broader range
- this is **particle physics with lab-scale, tabletop experiments**
  → new windows at energy scales not accessible to collider experiments
  https://www.science.org/doi/10.1126/science.aal3003
  https://arxiv.org/pdf/2311.01930
- in line with the approach outlined in the **DRD5 proposal**
  (see the document prepared by the TSF5 co-conveners, guided by M. Doser and M. De Marteau)