

QUAX Ferromagnetic haloscope read out by a Single Microwave Photon Detector

Giosuè Sardo Infirri

on behalf of the QUAX collaboration

Department of Physics and Astronomy, University of Padova
INFN Sezione di Padova

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Outline

Axions and Dark Matter

Axion detection and haloscopes

Single Microwave Photon Detector (SMPD)

Ferromagnetic haloscopes and SMPD

Conclusions

Axions

The **axion** is a light pseudoscalar boson introduced in 1977 to solve the strong CP problem

[Peccei and Quinn, 1977]

$$m_a = 5.70(6)(4) \mu\text{eV} \left(\frac{10^{12} \text{GHz}}{f_a} \right)$$

where f_a is the axion decay constant, related to the spontaneous PQ symmetry breaking scale

Axion coupling to ordinary matter is related to the model implementing the PQ symmetry. Two main models:

KSVZ - [Kim 1979], [Shifman-Vainshtein-Zakharov 1980]

DFSZ - [Dine-Fischler-Srednicki 1981], [Zhitnitsky 1980]

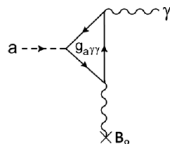
axion - photon interaction:

$$\begin{aligned} \mathcal{L}_{a\gamma\gamma} &= -\frac{\alpha g_\gamma}{\pi f_a} a \vec{E} \cdot \vec{B} \\ &= -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \end{aligned}$$

$g_{a\gamma\gamma}$ is the axion-photon coupling constant

$$* \quad g_\gamma^{\text{DFSZ}} = 0.36$$

$$* \quad g_\gamma^{\text{KSVZ}} = -0.97$$



axion - electron interaction:

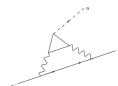
$$\mathcal{L}_{ae} = -i g_{ae} a \bar{\psi}_e \gamma^5 \psi_e$$

$$\mathcal{L}_{ae} \simeq 2\mu_B \vec{\sigma} \cdot \vec{B}$$

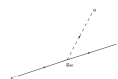
g_e is the axion-electron coupling constant

$$* \quad g_{ae}^{\text{DFSZ}} \sim 4 \cdot 10^{-11} m_a$$

$$* \quad g_{ae}^{\text{KSVZ}} \sim 0$$



(a) DFSZ



(b) KSVZ

Dark Matter Axion

Axions could have been produced by non-thermal processes in the early-universe (vacuum realignment mechanism and the decay of topological defects), making them a **cold Dark Matter (DM)** candidate

The expected cosmic mass density depends on whether the **PQ symmetry breaking happens before or after the inflation**

In the post-inflationary scenario, one could **predict the value of m_a** based on observed DM density (super challenging)

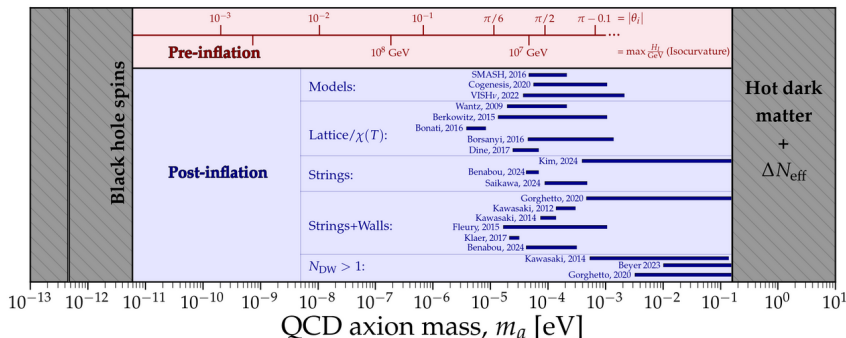


Figure: Axion mass predictions [1] updated up to mid-2025

Axion Assumptions

Assumptions for the axion detection from now on:

- ▶ **Existence** of DM halo
- ▶ Axions are **dominant component** of the DM halo
- ▶ Local DM density $\rho_{\text{DM}} \sim 0.3 - 0.45 \text{ GeV}/\text{cm}^3$
- ▶ Cold DM is **thermalized** and has a Maxwell-Boltzmann distribution with velocity dispersion $\sigma_v \sim 270 \text{ km/s}$

Under these assumptions, **axions**:

- ▶ have high occupation number
- ▶ can be treated as a **classical field** with frequency

$$\frac{\omega_a}{2\pi} = 2.42 \left(\frac{m_a}{10^{-6} \text{ eV}} \right) \text{ GHz}$$

- ▶ have coherence time and length

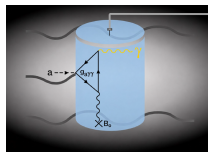
$$\lambda = 1400 \left(\frac{10^{-6} \text{ eV}}{m_a} \right) \text{ m}$$

$$t = 5 \left(\frac{10^{-6} \text{ eV}}{m_a} \right) \text{ ms}$$

Sikivie-type haloscope

Haloscopes aim to detect axions via inverse Primakoff effect: **axions are converted into photons in a magnetic field**

Because photons are *easy* to detect: these are **microwave photons**, since $\mu\text{eV} \leftrightarrow \text{GHz}$



Since axion velocity is $\beta_a \sim 10^{-3}$, axion mass determines the photon frequency as:

$$h\nu = m_a c^2 (1 + O(10^{-6}))$$

Haloscopes use **microwave cavities** to enhance the signal[3]

Given the unknown axion mass, **tuning is necessary!**

Expected signal from the experiment is with quality factor

$$Q_a = \frac{E}{\Delta E_x} \sim 10^6:$$

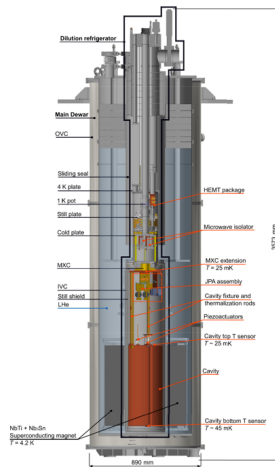
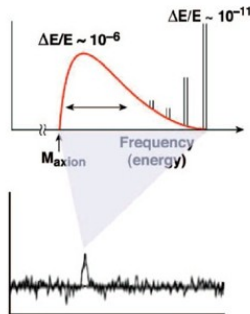


Figure: CAPP haloscope [4]

Single Microwave Photon Detector

Single Microwave Photon Detector (SMPD) is a superconducting device able to **detect a single photon in the microwave**

SMPD is comprised of:

- superconducting buffer resonator
- superconducting qubit
- superconducting waste resonator

The resonators are capacitively coupled to the qubit (non-linear inductance). Each element has an rf line connected to room temperature electronics

[Phys. Rev. X 10, 021038 (2020)]

[Nature 600, 434–438 (2021)]

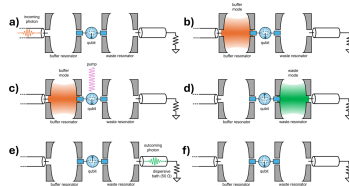
[Nature 619, 276–281 (2023)]

[Phys. Rev. Appl. 21, 014043 (2024)]

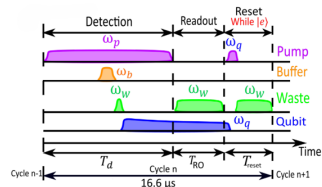
SMPD works as a photon counter thanks to **four wave mixing (4WM)** process activated by an incoming photon at ω_b in the buffer resonator

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

Protocol is realized **with FPGA** and at **10 mK** to suppress the thermal photons occupation number



To read out photons this protocol is cyclically iterated



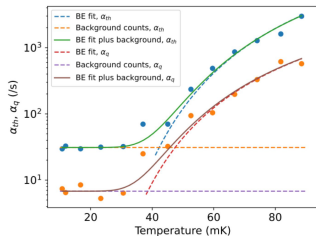
The device needs

- very careful calibration
- measure of ON/OFF ratio

More information on the CEA Saclay website

Tunable SMPD

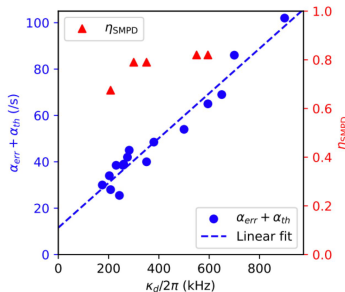
Fundamental background of the SMPD is due to **thermal photons**
 → **work at 10 mK** to suppress



Background photons due to protocol and poor thermalization of the SMA connector internal pin
 NB: Maybe other contributions

[<https://arxiv.org/pdf/2501.07354>]

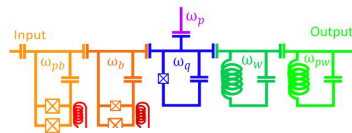
A **smaller buffer resonator linewidth** κ_d reduces the number of detected background photons



Dark Count (DC): number of detected photons in absence of an injected signal

Lower DC $\Rightarrow$ increased axion sensitivity

New generation of SMPD allows to tune buffer resonator **frequency** and **bandwidth** thanks to an additional **purcell resonator**
 → Purcell effect



Two DC lines tune ω_{pb} and ω_b

Tunability: ~ 200 MHz at ~ 7 GHz with quasi-constant **efficiency η**

SMPD as haloscope detector

For a haloscope the **scan rate** is the speed at which we are able to probe for axion frequencies. For Sikivie haloscope:

$$\frac{d\nu}{dt} \propto \frac{B_0^4 V_{\text{eff}}^2 Q}{T_{\text{noise}}^2}$$

- * B_0 (~ 8 T) is the external magnetic field
- * V_{eff} (~ 0.4 l) and Q ($\sim 4 \cdot 10^4$) are cavity volume and quality factor
- * T_{noise} (~ 0.36 K) is the equivalent noise temperature, in power $\sim 510^{-24}$ W

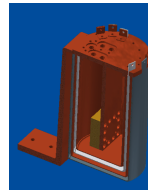
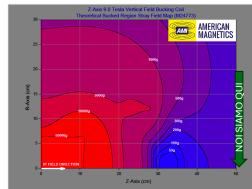
When using SMPD scan rate enhancement $\mathcal{R}$ with respect to SQL is related to the DC

$$\mathcal{R} = \eta^2 \frac{\Delta\nu_a}{\text{DC}}$$

[Braggio et al., Phys. Rev. X, 15, 021031 (2025)]

[Kuo et al., Phys. Rev. D, 111, 123018 (2025)]

SMPD cannot work under strong magnetic fields (Al-based)
→ **Multiple shields** required

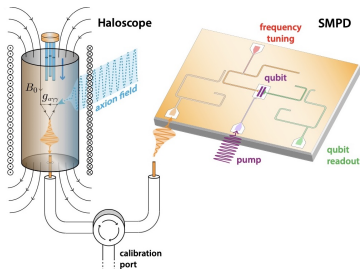


Shields (inner to outer): Cu + Al + μ -metal + Pb



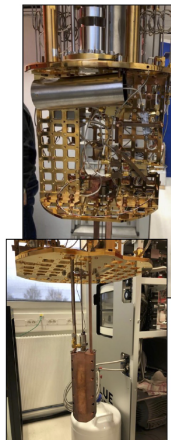
Pathfinder at CEA Saclay

Implementation:

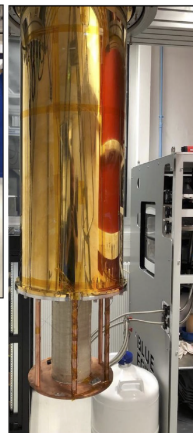


- ▶ hybrid (normal-superconducting) cavity with mode TM_{010} at 7.37 GHz tunable by a triplet of rods
- ▶ $Q_0 = 9 \cdot 10^5$ at 2 T-field
- ▶ $T = 14$ mK Quantronics Lab fridge (CEA, Saclay)

Scan rate enhancement: $\mathcal{R} \sim 20$



SMPD (top) and cavity



SC magnet

Ferromagnetic haloscope

Axion DM could act as an **effective RF field on the electron spin**, due to the motion of the solar system in the DM halo

The field excites a magnetic transition in a magnetized sample and produces a detectable signal

Experiment working principle:

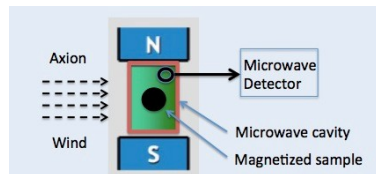
- ▶ magnetized material sit inside microwave cavity and are free-to-rotate
- ▶ Axion-electron coupling excites the **magnon** mode, collective excitation of electron spins in the magnetized material
- ▶ Strong coupling between magnon and cavity mode produces a detectable signal in cavity

Idea coming from multiple "old" papers:

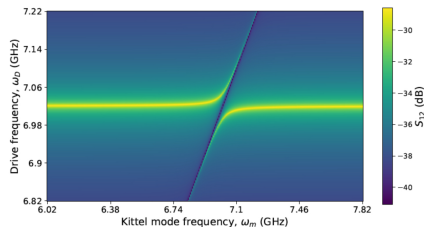
[L.M. Krauss, et al., HUTP-85/A006 (1985)]

[R. Barbieri et al., Phys. Lett. B 226, 357 (1989)]

[F. Caspers, Y. Semertzidis, World Scientific Pub. Co. (1990)]



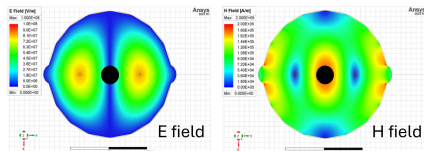
The system behaves as an ensemble of coupled harmonic oscillators, as proven by the **anticrossing curves**



Experimental Setup

The magnetic material is a set of 12 **Yttrium Iron Garnet (YIG)** spheres, which have spin density $n_s \sim 10^{28}/\text{m}^3$

Strong coupling is ensured by placing the YIG spheres in the high-H-field region of cavity mode



[Phys. Dark Universe 15, 135-141 (2017)]

[Phys Rev Lett 124, 171801 (2020)]

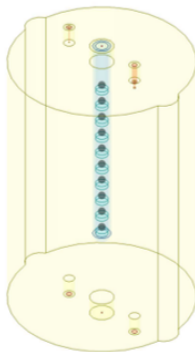
[Commun. Phys. 3, 164 (2020)]

[Phys Rev B 104, 064426 (2021)]

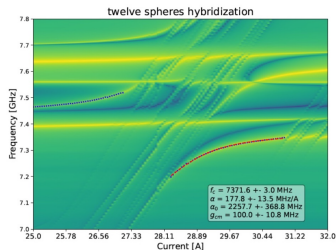
Total deposited power

$$P_a = \gamma_e \mu_B N_s \omega_a B_a^2 \tau_s$$

number of spins $N_s = n_s V_{\text{YIG}}$



Different axion masses can be probed by **changing the magnetic field amplitude** (and therefore Larmor frequency)



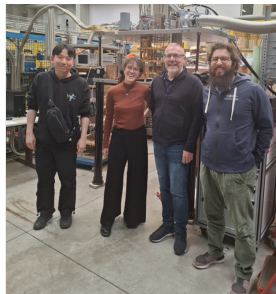
Limits of the sensitivity:

1. Linear amplifiers have a **Standard Quantum Limit (SQL)** due to vacuum fluctuations
2. YIG spheres **maximum diameter** reached is 2 mm with satisfying linewidth

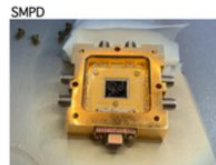
People



F. Calaan
G. Ruoso, R. Di Vora, E. Berto, G. Carugno, A. Lombardi
C. Braggio M. Tessaro



D. Ahn, D. Maiello, A. Ortolan
G. Sardo Infirri



P. Bertet, E. Flurin lab



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Conclusions

- ▶ Axion models require us to probe different couplings
- ▶ Axion searches with haloscopes (both Sikivie-type and ferromagnetic) are inherently time-consuming
→ need better readout strategies
- ▶ Quantum Sensors represent a new paradigm for detecting ultra-weak signals in DM experiments
- ▶ Available SMPD technology largely enhance sensitivity, as demonstrated in pathfinder
- ▶ First wide-tuning search using SMPD on ferromagnetic haloscope to demonstrate the scan rate enhancement w.r.t. existing results

Thank You

References I

- [1] Ciaran O'Hare. *cajohare/AxionLimits: AxionLimits*. <https://cajohare.github.io/AxionLimits/>. Version v1.0. July 2020. DOI: 10.5281/zenodo.3932430.
- [2] P. Sikivie. "Experimental Tests of the "Invisible" Axion". In: *Phys. Rev. Lett.* 51 (16 Oct. 1983), pp. 1415–1417. DOI: 10.1103/PhysRevLett.51.1415. URL: <https://link.aps.org/doi/10.1103/PhysRevLett.51.1415>.
- [3] G Sardo Infirri et al. "Search for Postinflationary QCD Axions with a Quantum-Limited Tunable Microwave Receiver". In: *Physical Review Letters* 135.21 (2025), p. 211002.
- [4] Saebyeok Ahn et al. "Extensive Search for Axion Dark Matter over 1 GHz with CAPP'S Main Axion Experiment". In: *Phys. Rev. X* 14 (3 Aug. 2024), p. 031023.
- [5] N Crescini et al. "Axion search with a quantum-limited ferromagnetic haloscope". In: *Physical Review Letters* 124.17 (2020), p. 171801.

Additional Material

Qubit calibration

