First QUAX galactic axion search with a superconducting cavity

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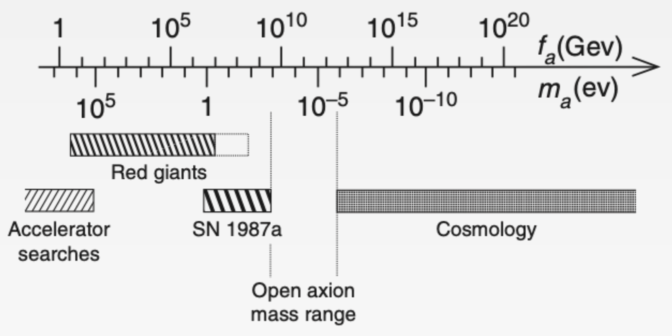
1. Abstract

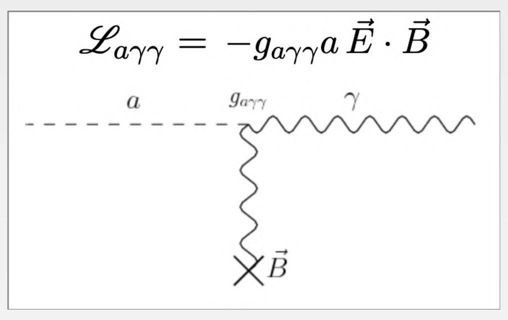
To account for the **Dark Matter** content in our Universe, post-inflationary scenarios predict for the QCD axion a mass in the range $(10-10^3)$ μeV. Searches with haloscope experiments in this mass range require the monitoring of resonant cavity modes with frequency above 5 GHz, where several experimental limitations occur due to linear amplifiers, small volumes, and low quality factors of Cu resonant cavities.

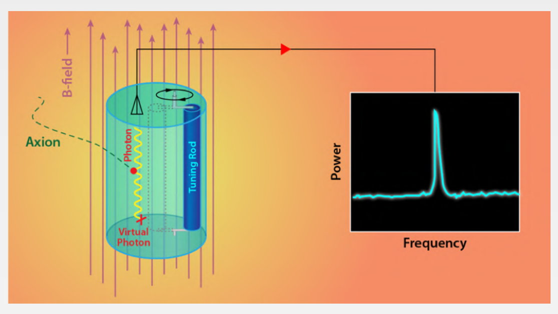


In this work we deal with the last issue, presenting the result of a search for **galactic axions** in the QUAX experiment, using a haloscope based on a 35 cm^3 NbTi **superconducting** cavity [1]. The cavity worked at $T = 4$ K in a 2 T magnetic field and exhibited a quality factor $Q_0 = 4.5 \times 10^5$ for the TM010 mode at 9 GHz. With such values of Q the axion signal is significantly increased with respect to Cu cavity haloscopes. Operating this setup we set the limit $\mathbf{g_{a\gamma\gamma} < 1.03 \times 10^{-12}\ GeV^{-1}}$ on the axion photon coupling for a mass of about 37 μeV. Results of a study of the NbTi cavity at different magnetic fields is also presented.

2. The QUAX experiment

► Primakoff haloscope





The **axion-photon coupling** allows their detection by means of a static magnetic field applied in a resonant cavity. The photon outcoming from the interaction vertex is stored in a resonant cavity and then extracted and read by electronics.

The **power** stored in the cavity due to the axion field is:

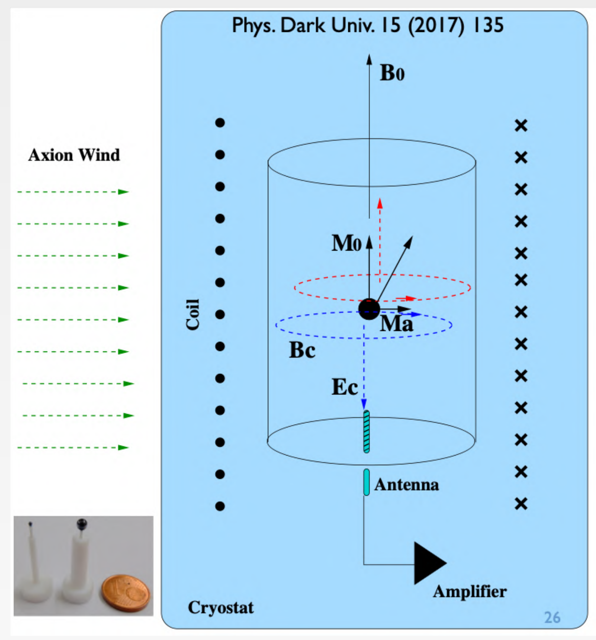
$$P_a = 1.85 \times 10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2 \times$$
$$\times\left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV\,cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

The resonant frequency has to be tuned to the axion mass:

$$E_a \simeq m_a c^2 = h\nu_c$$

► Ferromagnetic haloscope

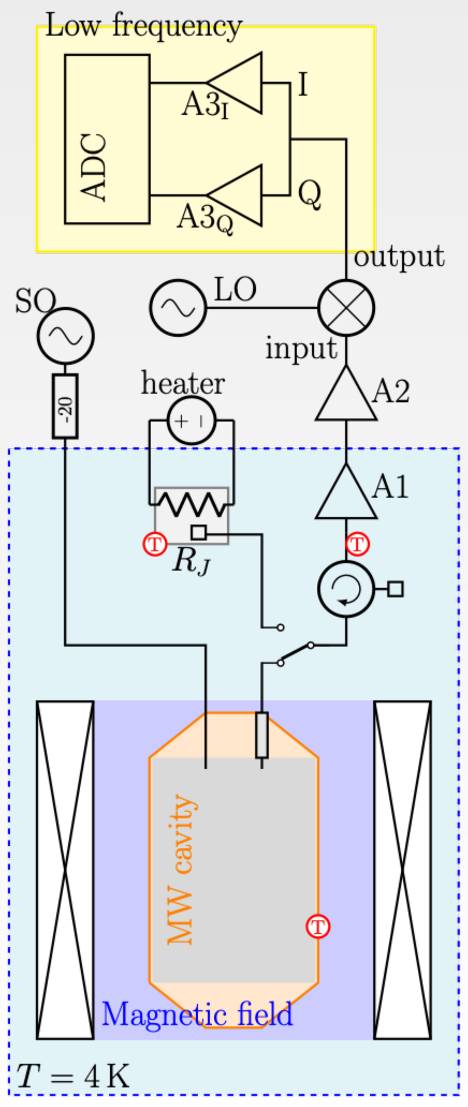
QUAX$-ae$ uses **magnetized materials** to detect axions via their interaction with electron spins ([2], [3]).
In fact in the non-relativistic limit the interaction of axions with the spin of electrons has the same form as a magnetic interaction, with the magnetic field given by $\mathbf{B_a} = \left(\frac{g_{aee}}{2e}\right)\nabla a$.



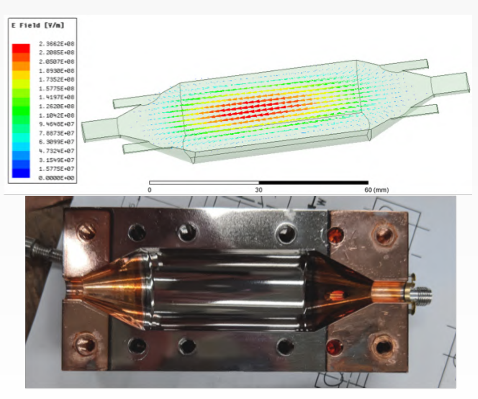
The axion wind can then transfer power to the cavity, with $P_{\rm sig}$ being:

$$P_{\rm sig} = 3.8 \times 10^{-26}\,\mathrm{W}\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right)^3\left(\frac{V_s}{100\,\mathrm{cm^3}}\right)\times$$
$$\times\left(\frac{n_s}{2\cdot 10^{28}/\mathrm{m^3}}\right)\left(\frac{\tau_{\rm min}}{2\,\mu s}\right)$$

3. Set-up & Measurements

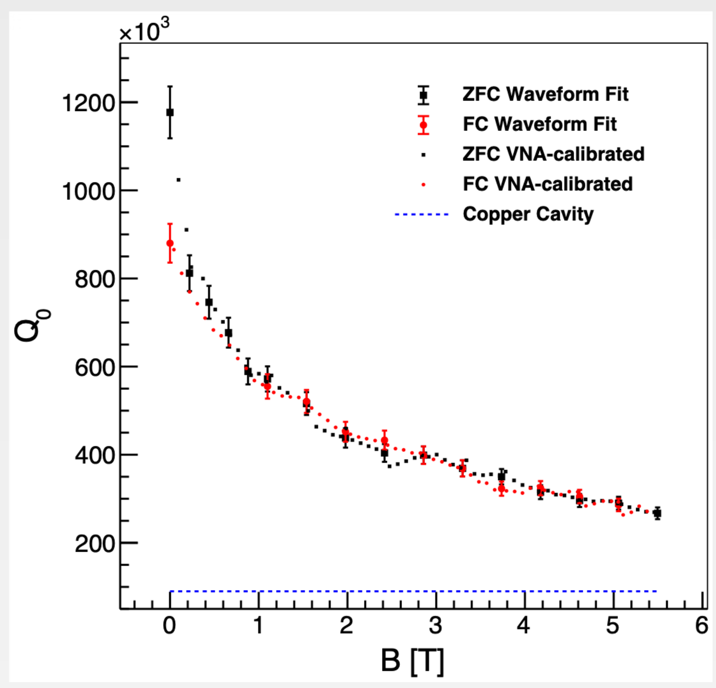


- The cavity is made of **Niobium-Titanium**, a type-II superconductor. Height: 5 cm, diameter: 2.6 cm. It is stored in a cryostat at $\mathbf{T = 4\,K}$ and immersed in a **2 T** magnetic field.
- Power is read by a critically coupled antenna. The signal is down-converted to low frequencies and acquired by an ADC. The amplification chain yields a gain of $G \simeq 2 \cdot 10^{12}$
- The system temperature is $T_{\rm sys} = T_{\rm cav} + T_{\rm n} = 15.3\,\mathrm{K}$, and the std dev of the output power is $\sigma_P = 6.19 \times 10^{-22}\,\mathrm{W}$



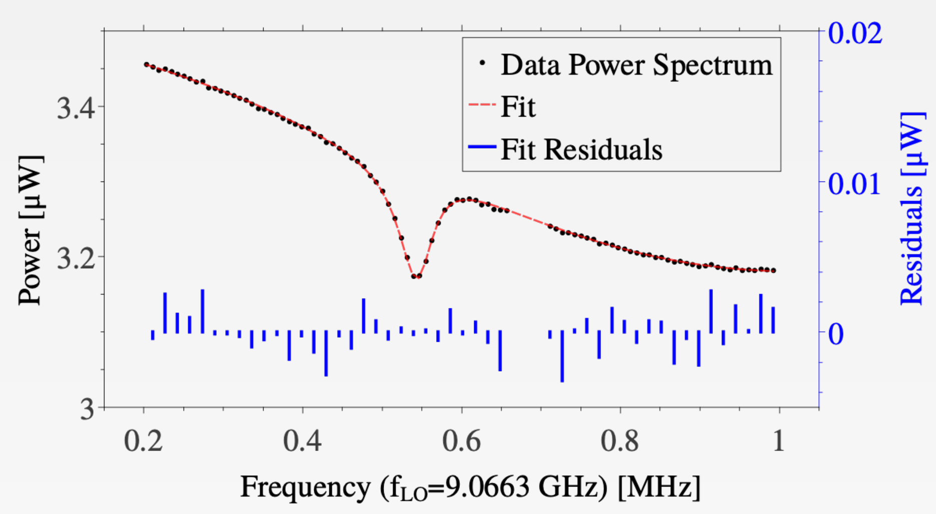
Top: electric field of 9.08 GHz TM010 mode in arbitrary amplitude units. *Bottom*: one half of the superconducting NbTi cavity. The NbTi is a thin film deposited on Cu bulk.

4. Results & $g_{a\gamma\gamma}$ exclusion plot



NbTi cavity characterization

Quality factor as a function of B. At 2 T the Q_0 of NbTi is $\sim \mathbf{4 \times 10^5}$, a factor of 5 better than copper cavities. At 5 T NbTi is a factor of 3.3 better than copper, and this would be equivalent to work at 9 T with Cu cavities. The working frequency is well below the depinning frequency (44 GHz) of this thin film [4].



Measured power spectrum

Power spectrum of the signal after the down-conversion and the amplification chain. The residuals follow a **gaussian** distribution and have std dev of

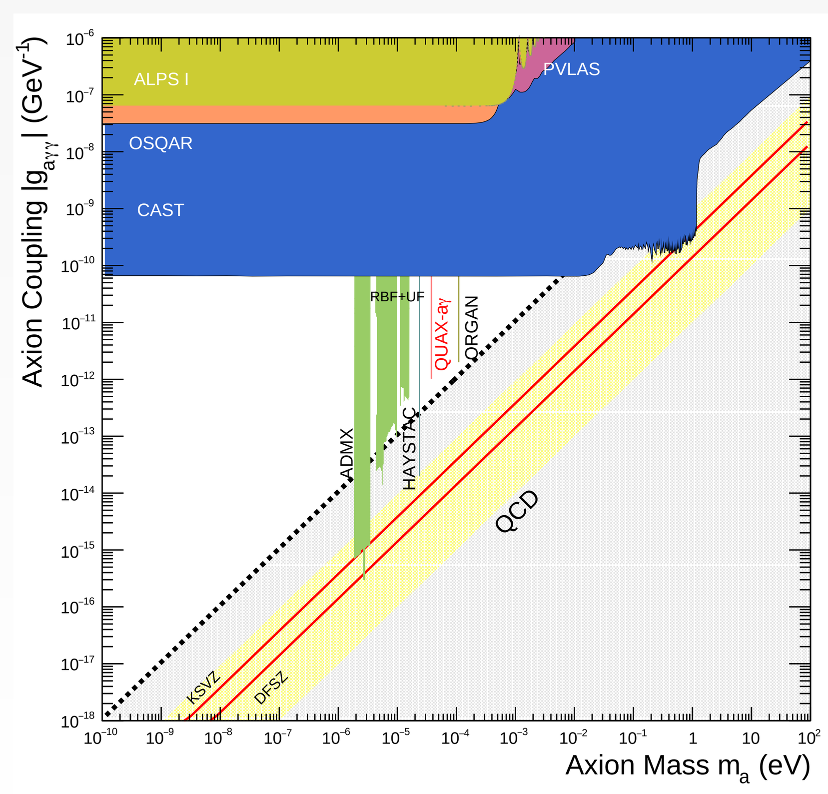
$$\sigma_{\mathbf{P}} = \mathbf{6.19 \times 10^{-22}\,W}.$$

► Axion-photon coupling

Exclusion plot of $|g_{a\gamma\gamma}|$ as a function of the axion mass. The diagonal red lines are theoretical predictions for KSVZ and DFSZ axion models. With our measurement we set a **95% CL** upper limit of

$$|\mathbf{g_{a\gamma\gamma}}| < \mathbf{1.03 \times 10^{-12}\,GeV^{-1}}$$

in a mass range of 0.2 neV around the mass value $m_a \simeq 37.5\,\mu$eV (see the red vertical QUAX-$a\gamma$ line).



5. Outlook

- Operate at **lower temperatures** $(20-50$ mK) with a dilution refrigerator. This reduces the Johnson noise.
- Use of **amplifiers** based on SC technology, like Josephson Parametric Amplifiers, to reach the Standard Quantum Limit.
- Increase the **magnetic field** (5 T) to directly increase the signal power.
- Make **longer cavities** (20 cm of height instead of 5 cm) to directly increase the signal power.

With this setup we would have a system temperature of $T_{\rm sys} = 400$ mK and a better quality factor wrt Cu ($Q_0 \simeq 3.5 \times 10^5$ at 5 T). With these improvements the expected 95% exclusion limit would be $\mathbf{g_{a\gamma\gamma} = 4 \times 10^{-14}\ GeV^{-1}}$ for $m_a \simeq 37.5\,\mu$eV, a value that touches the region expected for KSVZ axions.

Authors of the paper: D. Alesini, C. Braggio, G. Carugno, N. Crescini, D. D' Agostino, D. Di Gioacchino, R. Di Vora, P. Falferi, S. Gallo, U. Gambardella, C. Gatti, G. Iannone, G. Lamanna, C. Ligi, A. Lombardi, R. Mezzena, A. Ortolan, R. Pengo, N. Pompeo, A. Rettaroli, G. Ruoso, E. Silva, C. C. Speake, L. Taffarello, S. Tocci

References

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