First QUAX galactic axions search with a SC resonant cavity

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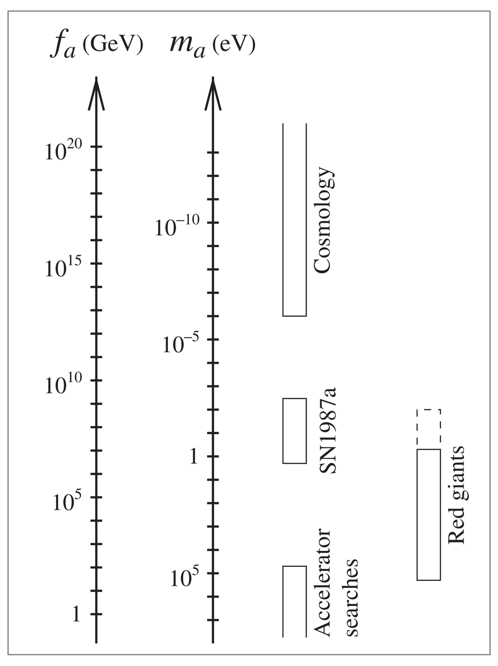
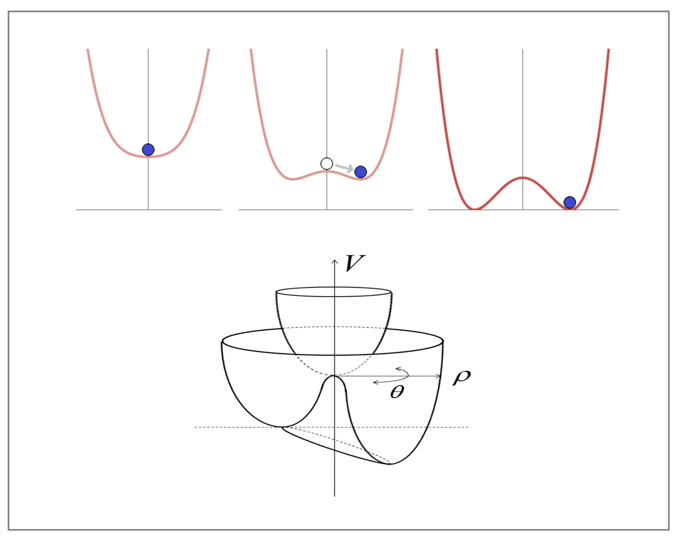
Intro - Axions

The axion is a pseudoscalar particle predicted by S.Weinberg and F.Wilczek in 1977 as a consequence of the mechanism introduced by R.D.Peccei and H.Quinn to solve the **strong CP problem**.

A global axial $U(1)$ symmetry is added in the SM, and the axion is the pseudo-Goldstone boson associated to the spontaneous symmetry breaking.



Cosmological production:

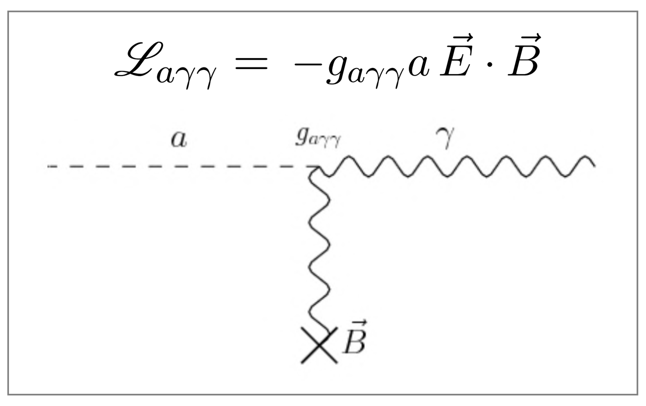


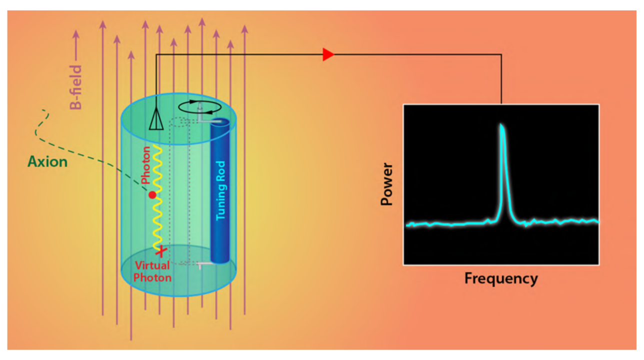
- When $T \sim f_a \gg \Lambda_{QCD}$ the PQ phase transitions generates the axion field.
- When $T \sim \Lambda_{QCD} \approx 200\,\mathrm{MeV}$ the QCD phase transition tilts the potential and axions acquire a mass.

Axions are also well motivated **Dark Matter** candidates with expected mass laying in a broad range from peV to few meV. Post-inflationary scenarios restrict this range to $(10 - 10^3)\ \mu eV$.

QUAX experiment

QUAX-$a\gamma$ Haloscope





This lagrangian term describes the conversion of an axion into a photon when a static magnetic field is applied.

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 the cavity and then extracted and read by electronics.

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

$$P_a = 1.85\times10^{-25}\,\mathrm{W}\left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2\left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeVcm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$

QUAX-ae Ferromagnetic Haloscope

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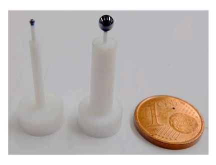
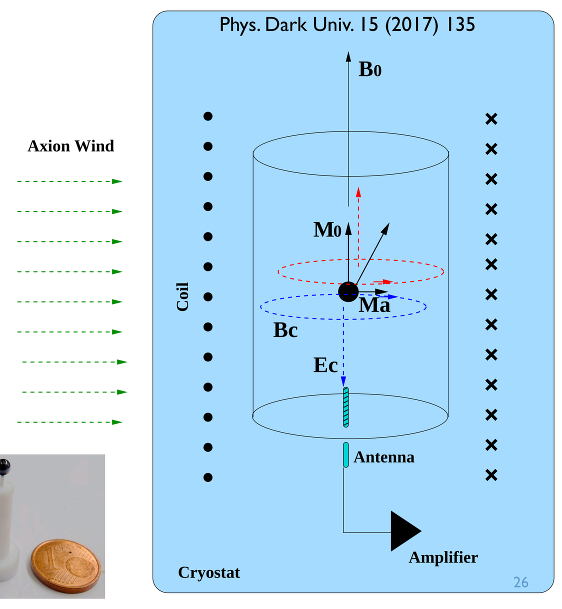
In the non-relativistic limit the interaction of axions with the spin of electrons has the same form as a magnetic interaction, with the magnetic field given by $\boldsymbol{B_a} = \left(\frac{g_{aee}}{2e}\right)\nabla a$. The power transferred is:

$$P_{\rm sig} = 3.8\cdot10^{-26}\left(\frac{m_a}{200\,\mu\mathrm{eV}}\right)^3\left(\frac{V_s}{100\,\mathrm{cm^3}}\right)\cdot\left(\frac{n_s}{2\cdot10^{28}/\mathrm{m^3}}\right)\left(\frac{\tau_{\min}}{2\,\mu s}\right)\,\mathrm{W}$$

QUAX-ae uses magnetized materials to detect axions via their interaction with spins.





QUAX-$a\gamma$ operation in the Primakoff configuration

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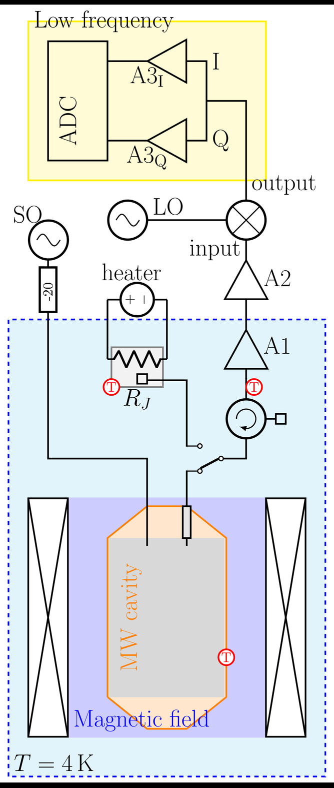
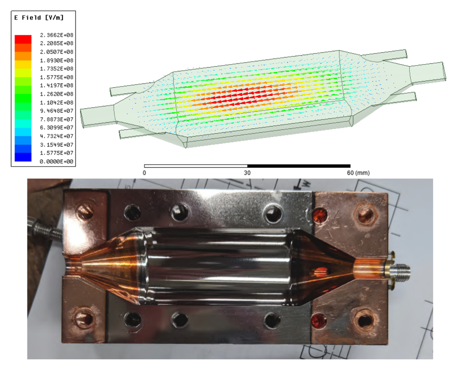
Operating haloscopes above 5 GHz has some limitations: linear amplifiers, small volumes, and low quality factors of Cu resonant cavities. In the paper we deal with the last one. We present the result of a search for galactic axions using a haloscope based on a NbTi SC cavity, working at $T = 4K$ in a 2 T magnetic field and exhibiting a quality factor $Q_0 = 4.5\times10^5$ for the TM010 mode at 9 GHz. With such values of Q the axion signal is increased with respect to Cu cavity haloscopes. We set the limit $g_{a\gamma\gamma} < 1.03\times10^{-12}GeV^{-1}$ on the axion-photon coupling for a mass of about 37 μeV. A study of the NbTi cavity at different magnetic fields, temperatures, and frequencies has also been performed.



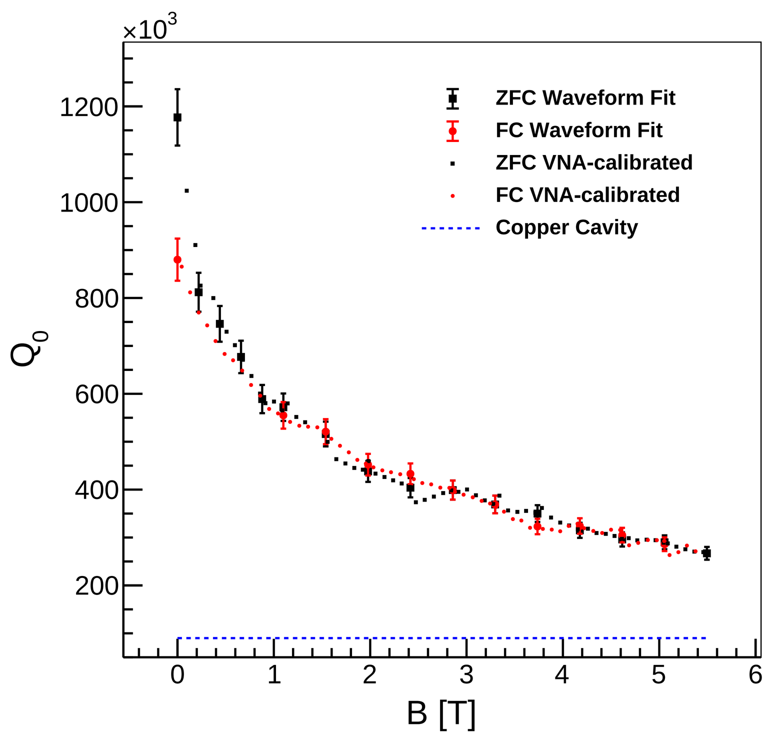
Setup & Measurements

- The cavity is made of type-II superconductor. Height: 5 cm, diameter: 2.6 cm. It is stored in a cryostat at $T = 4K$ 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 $G \simeq 2\times10^{12}$.
- The system temperature is $T_{sys} = T_{cav} + T_n = 15.3\,K$, and the std dev of the output power is $\sigma_P = 6.19\times10^{-22}\,W$.



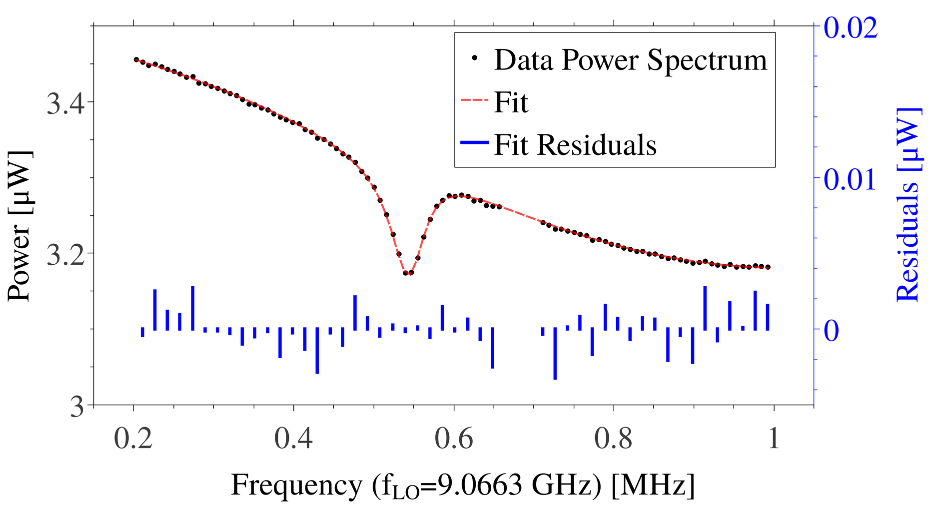
Top: electric field of 9.08 GHz TM010 mode in arbitary amplitude units. *Bottom*: one half of the superconducting NbTi cavity. The NbTi is a thin film deposited on Cu bulk.

Results

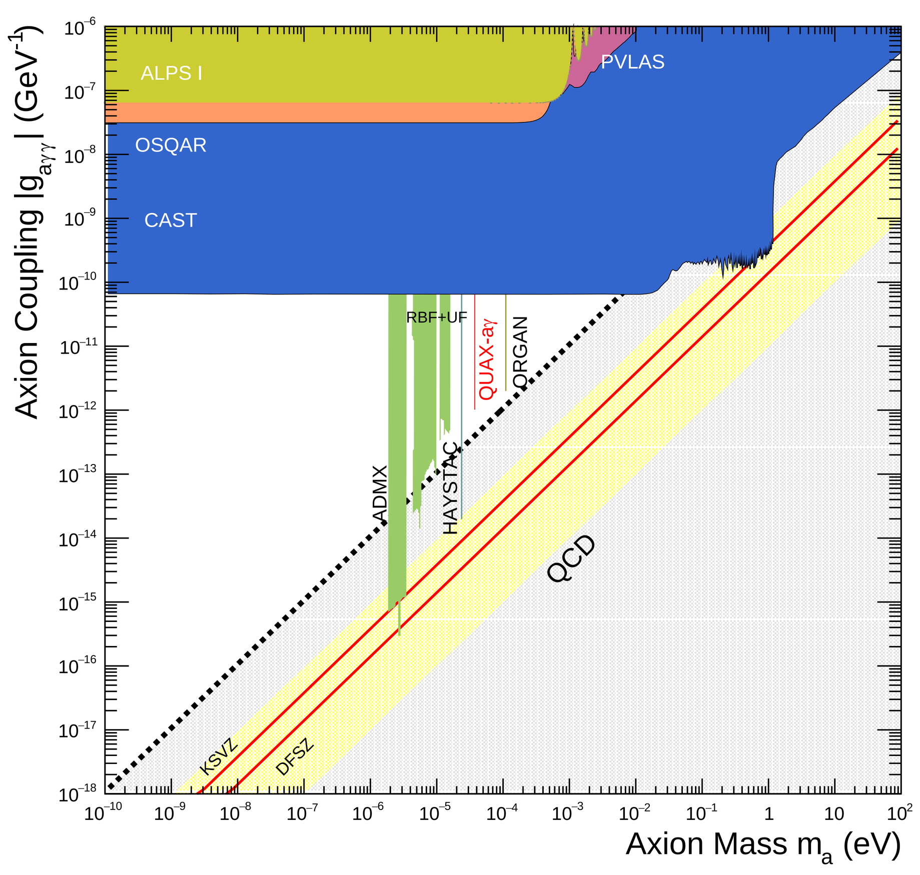


Quality factor as a function of B. At 2 T the Q_0 of NbTi is $\mathbf{4.02\times10^5}$, a factor of 5 better than copper cavities. At 5 T NbTi is a factor of 3.3 better than copper, and this would be equivalent to work at 9 T with copper cavities.
The working frequency is well below the depinning frequency (44 GHz) of this thin film.

Power spectrum of the signal after the down-conversion and the amplification chain. The residuals follow a gaussian distribution and have std dev of $\sigma_P = 6.19\times10^{-22}\,W$.



Exclusion plot for $|g_{a\gamma\gamma}|$ 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 on $|g_{a\gamma\gamma}|$ of $\boldsymbol{g_{a\gamma\gamma} < 1.03\times10^{-12}\ GeV^{-1}}$ in a mass range of $\sim 0.2\,neV$ around $m_a \simeq 37.5\,\mu eV$ (see red vertical QUAX-$a\gamma$ line).



Outlook

- Operate at lower temperatures (50 mK) with a diluition 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 $T_{sys} = 400\,mK$ and a better quality factor wrt Cu ($Q_0 \simeq 3.5\times10^5$ at 5 T). With these improvements the expected 95% exclusion limit would be $g_{a\gamma\gamma} < 4\times10^{-14}\ GeV^{-1}$ for $m_a \simeq 37.5\,\mu eV$, a value that touches the region expected for KSVZ axions.

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