High quality factor photonic cavity for dark matter axion searches

D. Alesini,1 C. Braggio,2,3 G. Carugno,2,3 N. Crescini,3,4 D. D’Agostino,5 D. Di Gioacchino,1 R. Di Vora,2,6 P. Falferi,7 U. Gambardella,5 C. Gatti,1 G. Iannone,5 C. Ligi,1 A. Lombardi,4 G. Maccarrone,1 A. Ortolan,4 R. Pengo,4 C. Pira,4 A. Rettaroli,1,8 G. Ruoso,1 L. Taffarello,2 and S. Tocci1

(QUAX Collaboration)

1) INFN, Laboratori Nazionali di Frascati, Frascati (Roma) Italy
2) INFN, Sezione di Padova, Padova, Italy
3) Dip. di Fisica e Astronomia, Padova, Italy
4) INFN, Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
5) Dip. di Fisica E.R. Caianiello, Fisciano (SA), Italy and INFN, Sez. di Napoli, Napoli, Italy
6) Dip. di Fisica, Siena, Italy
7) Istituto di Fotonica e Nanotecnologie, CNR, INFN - TIFPA and FBK, Povo, Trento, Italy
8) Dip. di Matematica e Fisica Università di Roma 3, Roma, Italy

(Dated: 6 February 2020)

Searches for dark matter axion involve the use of microwave resonant cavities operating in a strong magnetic field. Detector sensitivity is directly related to the cavity quality factor, which is limited, however, by the presence of the external magnetic field. In this paper we present a cavity of novel design whose quality factor is not affected by a magnetic field. It is based on a photonic structure by the use of sapphire rods. The quality factor at cryogenic temperature is in excess of $5 \times 10^5$ for a selected mode.

I. INTRODUCTION

A remarkable result of modern cosmology is that a major fraction of the mass content of the universe is composed of dark matter (DM), i.e. particles not interacting significantly with electromagnetic radiation, ordinary matter, not even self-interacting (cold dark matter) [11]. A class of particles generically indicated as Weakly Interacting Sub-eV Particles (WISP) recently came into attention as possible candidates as main DM component. WISPs are very light bosons characterized by sub-eV masses and large occupation numbers, such as axions, axion-like particles (ALP) and hidden photons. The axion is a pseudoscalar field, following the detection scheme proposed by P. Sikivie in 1983 called axion haloscope, which is based on the inverse Primakoff effect [12]. After the pioneering work of the Rochester-Brookhaven-Fermilab collaboration [13,14] and of the group located at the University of Florida [15], the Axion Dark Matter eXperiment (ADMX) collaboration operated for over two decades the most advanced detector of this type. In particular, the ADMX experiment reached the cosmologically relevant sensitivity to exclude the axion mass range $2.66 < m_A < 3.31 \text{ meV}$ for DFSZ models and $1.91 < m_A < 3.69 \text{ meV}$ for KSVZ model [15,16]. Very recently many other haloscopes came into play and some of them are already running and taking data: among them HAYSTAC [20], ORGAN [21], CAPT [22,23], KLAST [24,22], RADES [25] and QUAX-ax [26].

While all these are bases on the Sikivie’s scheme, new techniques have also been proposed, like for example the dielectric haloscopes of MADMAX [28] and BRAS [28].

In a standard haloscope the detector is composed by a large factor $Q$ resonant cavity immersed in a static magnetic field $B_0$. When the resonant frequency of the cavity $\nu_c$ is tuned to the corresponding axion mass $m_A^2/\hbar$, the expected power deposited by DM axions is given by [20,33]

$$P_a = \left(\frac{\alpha^2}{\pi^2} \frac{\hbar^3 c^3 \rho_a}{\Lambda^4}\right) \times \left(\frac{\beta}{1 + \beta^2}\right) \frac{\omega_c}{\mu_0} \frac{B_0^2 V_{\text{cav}}}{C_{\text{mfl}} Q_0},$$

where $\rho_a = 0.45 \text{ GeV/cm}^3$ is the local DM density, $\alpha$ is the fine-structure constant, $\Lambda = 78 \text{ MeV}$ is a scale parameter related to hadronic physics, and $\omega_c$ is a model dependent parameter equal to $-0.97 (0.36)$ in the KSVZ (DFSZ) axion model [27,28]. It is related to the coupling appearing in the Lagrangian $g_{a\gamma\gamma} = (g_a/\alpha/\pi \Lambda^2) m_a$. The second parentheses contains the vacuum permeability $\mu_0$, the magnetic field strength $B_0$, the cavity volume $V$, its angular frequency $\omega_c = 2\pi \nu_c$, the coupling between cavity and receiver $\beta$ and the unloaded quality factor $Q_0$. $C_{\text{mfl}} \simeq O(1)$ is a geometrical factor, depending on the cavity mode, defined as the overlap between the

---

[1] Corresponding author Giuseppe.Ruoso@lnl.infn.it
microwave electric field $\mathbf{E}_{mnl}$ and the static magnetic field $\mathbf{B}$

$$
C_{mnl} = \left[ \frac{\int_V dV \mathbf{E}_{mnl} \cdot \mathbf{B}}{VB^2 \int_V dV |\mathbf{E}_{mnl}|^2} \right]^2 \tag{2}
$$

A typical cavity geometry is of cylindrical type, which easily fits inside a superconducting solenoid providing a strong magnetic field. The cavity mode TM010 exhibits the largest coupling $C_{010} = 0.69$. This mode corresponds to a field distribution with maximum value of the electric field along the cavity axis.

The axion mass range studied by haloscopes up to now is limited to few $\mu$eV. Exploring larger ranges at higher values requires the excitation of modes with frequency above a few GHz where several experimental limitations occur: (i) the available linear amplifiers limit the sensitivity; (ii) conversion volumes are smaller since the normal modes resonant frequencies are inversely proportional to the cavity radius; and (iii) the anomalous skin effect reduces the quality factor of copper cavities at high frequencies. Solutions to the first two issues are proposed for instance in $\text{39,40}$ and $\text{41}$, respectively.

The optimum value of quality factor for haloscopes is $\sim 10^6$, as estimated by the coherence time of DM axions $\text{42}$. A 10 GHz copper cavity, cooled at cryogenic temperature, barely reaches $Q \lesssim 10^5$, a value that rapidly decreases with increasing frequency. In the first phase of the experiment QUAX-a$\gamma$ $\text{29}$, a solution to this problem has already been studied: a special type of hybrid superconducting cavity has been realized capable of operating inside a magnetic field with $Q_0$ in excess of $10^5$ for frequencies about 10 GHz. In this paper we show that another viable possibility is the use of dielectric resonators, i.e. cavities in which a low-loss material with high dielectric coefficient is inserted to shape and concentrate the mode, reducing the dissipation on the cavity walls and consequently increasing the quality factor. These type of cavities are normally referred to as photonic cavities. This work as been conducted within the experiment QUAX-a$\gamma$.

II. DESIGN AND REALIZATION

Inspired by previous works $\text{29,41}$ we designed a novel type of distributed Bragg reflector resonator working on the TM010-like mode at about 13.5 GHz. The choice of the frequency was mainly given by the possibility of incorporating the resonator in the detection chain developed for the QUAX experiment to search for dark matter axions $\text{42}$. The main idea was to design a pseudo-cylindrical cavity realizing an interference pattern to confine the TM010 through long dielectric rods placed parallel to the cavity axis. These types of cavities are also known as photonic band gap cavities $\text{43,44}$. The dielectrics, commercially available, were in the form of long sapphire cylinders of 2 mm diameter. Sapphire was chosen for its very low loss-tangent, going from about $10^{-5}$, at room temperature, down to a fraction of $10^{-7}$ at cryogenic temperature $\text{45}$.

We did the electromagnetic calculations using the code ANSYS Electronics $\text{46}$. Because of cylindrical symmetry we simulated only one quarter of the structure with perfect magnetic boundary conditions. The final designed cavity with relevant dimensions is given in Figure 1. In the cavity 36 sapphire rods of 2 mm diameter are positioned with the pattern shown in figure while the distance between the rods was chosen to have the resonant frequency of the confined mode TM010 at around 13.5 GHz. The number of rods was chosen to have enough attenuation of the electromagnetic field toward the cavity outer wall. Since the sapphire dielectric constant varies in a wide range depending on the crystal orientations, impurities and temperature, in the simulations we have considered a sapphire dielectric constant equal to 11.1 and a loss tangent at cryogenic temperature of $10^{-7}$ (See $\text{47}$). The copper surface resistance was set to about 5.5 m$\Omega$ as expected in the anomalous regime at this frequency $\text{42}$. The two conical end plates were designed in order to reduce their loss contribution to a negligible level. In particular, as already implemented and illustrated in ref $\text{29,41}$ the length of the conical shapes is such as to permit a sufficient attenuation of the electromagnetic field at the end plates. To excite and detect the resonant modes, two coaxial antennas were inserted at the end of the cones.

The magnitude of the electric field of the first two TM resonant modes, TM010 and TM011, is given in Figure 2. The first mode is expected to have a quality factor of about $3 \times 10^5$ at liquid helium temperature, essentially limited by the losses on the cavity walls and endplates. Figure 3 shows the simulated transmission coefficient between the two coupled antennas whose peaks correspond to the resonant modes TM010 and TM011, respectively. In the plot is also visible one spurious peak corresponding to a mode configuration weakly coupled to the coaxial antennas.
FIG. 2. Magnitude of the electric field of the first two TM resonant modes: TM010 (a) and TM011 (b).

By using the simulations it is easy to calculate the effective volume of the system, essential to deduce the axion signal. We got \( C_{mnl} \times V = 0.024 \times 9.5 \times 10^{-4} = V_{\text{eff}} = 2.3 \times 10^{-5} \text{ m}^3 \).

FIG. 3. Simulated transmission coefficient between the two coupled antennas. The peaks correspond to the resonant modes TM010 and TM011.

To realize the cavity two pieces of oxygen free high purity copper were machined to form two separate identical halves of the cavity. The inner surfaces were electro polished to reduce surface roughness. The two parts can then be joined together to form a closed cylinder, tightness is guaranteed by twelve M4 steel bolts. Bolts have been chosen of non magnetic iron (AISI 304). Before closing the cavity, the 36 sapphire rods are mounted. For each of them a 2.1 mm diameter hole is present on each ends of the two cavity halves. Excluding the two most central ones, all sapphire rods are kept in place by teflon screws provided with copper berillium springs at their ends. The use of the springs is necessary to avoid breaking of the rods when cooling the system to cryogenic temperatures and, at the same time, keeping a constant force on the rods to avoid unwanted displacements. Figure 4 shows the two halves of the cavity, complete of sapphire rods and teflon screws.

FIG. 4. Photograph of the cavity opened in two halves.

III. MEASUREMENTS

The first measurement of the cavity is the identification of the principal modes. This has been performed, at room temperature, by using the standard bead pulling method, where a small dissipative sphere is moved along the cavity axis while the quality factor and frequency of selected modes are monitored. These parameters are obtained by measuring the S12 power transmission spectrum using a Vector Network Analyser (VNA), connected to input/output ports on the cavity. Since the standard antennas are located on the cavity axis, two other holes were drilled just slightly off axis to be used as input/output ports, while the standard antenna holes where used as passages for a thin wire holding the bead. In figure 5 the results of these measurements are shown. The TM010 mode is identified with a single maximum for both quality factor and frequency shift with respect to a scan of the entire cavity length with the bead. The TM011 shows two maxima. The measured frequency for the two modes were also compatible with the calculated ones, thus permitting a clear identification of the modes. During this measurements care was taken to have both I/O ports with small coupling, so that no correction has to be taken into account due to the antennas.

Once the modes were identified, antennas have been mounted in the standard central holes along the cavity axis. The length of the dipole antennas has been chosen in such a way to have minimum coupling, but still measurable with the VNA, so that the quality factor directly measured by the VNA practically coincides with the cavity unloaded \( Q_0 \).

The cavity has been placed inside a vacuum chamber designed to allow operation inside cryogenic dewars. The vacuum chamber is equipped with two rf feedthroughs and a thermometer measures the temperature of the cavity.

Measurements have been performed at room temperature, liquid nitrogen and liquid helium temperature. Before cooling, the vacuum chamber is filled with about 10 mbar of helium to speed up the cooling process of the cavity. Low temperature rf measurements have been performed when the cavity temperature have reached a stationary value.

The starting point, with the cavity at room temperature, is as follows: mode TM010: both antennas coupled
at -0.04 dB, resonance frequency $f_{TM010} = 13\,468\,\text{MHz}$, linewidth $\Delta f_{TM010} = 76\,\text{kHz}$, unloaded quality factor $Q_{0,\,TM010} = 173\,000$.

During the cooling phase, due to the changes in the dimensions of the cavity, the cavity modes change their frequency accordingly. Moreover, probably due to changes in the relative positions of the sapphire rods, new modes show up and interfere with the main modes, thus making the identification of the modes at low temperature difficult. For this reason, during the cooling the drift of the principal modes was constantly followed by taking continuous S12 spectra.

![Figure 5](image1.png)

**FIG. 5.** Bead pulling results (see text).

![Figure 6](image2.png)

**FIG. 6.** S12 Spectra at room (red curve) and cryogenic (black curve) temperature ($T = 5.5\,\text{K}$).

Figure 6 show the S12 spectra for room temperature and liquid helium temperature measurements. On the spectra the identified modes have been labelled. It has to be noted that the number and position of the unwanted modes are different for different cooling process. We are now working to make this phenomena reproducible.

To get a correct value of the quality factor, a zoomed spectra of the TM010 mode has been measured. This is then fitted with a Lorentzian line shape. Results are showed in figure 7. It can be seen that this mode is not anymore clear but another mode is interfering with it, thus reducing the quality factor to a lower value than the one expected from simulations.

![Figure 7](image3.png)

**FIG. 7.** Measured S12 spectra (black dots) of the TM010 mode at liquid Helium temperature, superimposed with a fit (blue line) made with a Lorentzian function.

Table I summarizes the main results obtained.

| System     | Cavity Temperature | $Q_0$ TM010 | $Q_0$ TM011 |
|------------|-------------------|-------------|-------------|
| Room T     | 298 K             | 173 000     | 94 000      |
| Liquid He  | 5.5 K             | 290 000     | 520 000     |

### IV. CONCLUSIONS

In this paper we have presented a novel type of cavity suitable to be operated in a strong magnetic field. These cavities are ideal devices in the search for dark matter axions, where normal conducting ones are normally used. With the photonic cavity, an order of magnitude improvement of the quality factor is expected, while keeping the same detection volume. In fact, a cylindrical cavity working at the same frequency would have a cross section of about 17 mm diameter, corresponding to an area of $2.3 \times 10^{-4}\,\text{m}^2$. Taking the same length of our photonic cavity, the effective volume is $V_{\text{eff}}^{\text{Cu}} = C_{mn} V = 0.69 \times 3.4 \times 10^{-5} = 2.5 \times 10^{-5}\,\text{m}^3$, to be compared with the value $V_{\text{eff}}^{\text{Sa}} = 2.3 \times 10^{-5}\,\text{m}^3$ given in Section II. This shows that the two cavities are equivalent for the purpose of axion searches. It is then possible...
to calculate what is the output power expected by using a set-up with, for example, an 8 T magnetic field. We use this number since in our laboratory tests have been already performed with a recently available superconducting magnet.

The expected axion power would be:

\[ P_{\text{ax}} = 3.3 \cdot 10^{-24} W \left( \frac{V_{\text{eff}}^2}{2.3 \times 10^{-5} \text{ m}^4} \right) \left( \frac{B}{8 \text{ T}} \right)^2 \times \left( \frac{g_\gamma}{-0.97} \right)^2 \left( \frac{\rho_a}{0.45 \text{ GeV cm}^{-3}} \right) \left( \frac{f}{13.5 \text{ GHz}} \right) \left( \frac{Q_L}{145,000} \right) \]

that could be reached with an almost quantum limited detection system integrating for a time span

\[ t_m = \frac{k_B^2 T_n^2 f}{P_{\text{ax}}} \approx 2.4 \cdot 10^5 \text{ s} \left( \frac{T_n}{1 \text{ K}} \right)^2 \times \left( \frac{3.3 \cdot 10^{-24} W}{P_{\text{ax}}} \right)^2 \left( \frac{13.5 \text{ GHz}}{f} \right) \left( \frac{10^6}{Q_a} \right). \]

where \( k_B = 1.38 \cdot 10^{-23} \text{ J K}^{-1} \) is the Boltzmann constant, \( T_n \) is the system noise temperature and \( Q_a \) the axion linewidth. A stable operation of a Josephson Parametric Amplifier with a system noise temperature around 1 K has been already obtained at a slight different frequency in our laboratory at the Laboratori Nazionali di Legnaro of INFN[23].

We are thus currently working to implement this new cavity type in our haloscope, and meanwhile we are also studying other sapphire geometries that could boost the quality factor to even higher values.

**ACKNOWLEDGEMENTS**

We are very grateful for the work of M. Zago that realized the technical drawings of the cavity. E. Berto, A. Benato and M. Rebeschini executed the mechanical work, while F. Calao and M. Tessaro helped with the electronics and cryogenics, and F. Stivanello helped with the chemical works. We acknowledge the work of the Cryogenic Service of the Laboratori Nazionali di Legnaro, providing us with large quantities of Liquid Helium on demand.

1. F. Zwicky, “Die Rotverschiebung von extragalaktischen Nebeln,” Helvetica Physica Acta 6, 110–127 (1933).

2. V. C. Rubin, N. Thonnard, and W. K. Ford, Jr., “Extended rotation curves of high-luminosity spiral galaxies. IV - Systematic dynamical properties, SA through SC,” *Astrophysical Journal* **225**, L107–L111 (1978).

3. V. C. Rubin, W. K. Ford, Jr., and N. Thonnard, “Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 / R = 4kpc/ to UGC 2885 / R = 122 kpc/,” *Astrophysical Journal* **238**, 471–487 (1980).

4. R. D. Peccei and H. R. Quinn, “CP conservation in the presence of pseudoparticles,” *Phys. Rev. Lett.* **38**, 1440–1443 (1977).

5. S. Weinberg, “A new light boson?” *Physical Review Letters* **40**, 223 (1978).

6. P. Wilczek, “Problem of strong p and t invariance in the presence of instantons,” *Physical Review Letters* **40**, 279 (1978).

7. J. E. Kim, “Weak-interaction singlet and strong CP invariance,” *Phys. Rev. Lett.* **43**, 103–107 (1979).

8. M. Shifman, A. Vainshtein, and Y. Zakharov, “Can confinement ensure natural cp invariance of strong interactions?” *Nuclear Physics B* **166**, 493–506 (1980).

9. M. Dine, W. Fischler, and M. Srednicki, “A simple solution to the strong cp problem with a harmless axion,” *Physics Letters B* **104**, 199–202 (1981).

10. A. R. Zhitnitsky, “On Possible Suppression of the Axion Hadron Interactions. (In Russian.),” Sov. J. Nucl. Phys. **31**, 260 (1980), [Yad. Fiz.31,497(1980)].

11. G. I. Inestrosa and J. Redondo, “New experimental approaches in the search for axion-like particles,” *Prog. Part. Nucl. Phys.* **102**, 89–159 (2018), [arXiv:1801.08127 [hep-ph]].

12. P. Sikivie, “Experimental tests of the ‘invisible’ axion,” *Phys. Rev. Lett.* **51**, 1415–1417 (1983).

13. S. De Panfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Y. K. Semertzidis, W. Wiensch, H. J. Halama, A. G. Proddell, W. B. Fowler, and F. A. Nezrick, “Limits on the Abundance and Coupling of Cosmic Axions at 4.5 < m_a < 5.0 μeV,” *Phys. Rev. Lett.* **59**, 839 (1987).

14. W. Wiensch, S. De Panfilis-Wiensch, Y. K. Semertzidis, J. T. Rogers, A. C. Melissinos, H. J. Halama, B. E. Moskowitz, A. G. Proddell, W. B. Fowler, and F. A. Nezrick, “Results of a Laboratory Search for Cosmic Axions and Other Weakly Coupled Light Particles,” *Phys. Rev. D* **40**, 3153 (1989).

15. C. Hagemann, P. Sikivie, N. S. Sullivan, and D. B. Tanner, “Results from a search for cosmic axions,” *Phys. Rev. D* **42**, 1297–1300 (1990).

16. W. Du, N. Force, R. Khatiwa, E. Lentz, R. Ottens, L. J. Rosenberg, G. Rybka, G. Carosi, N. Woollett, D. Bowring, A. S. Chou, A. Sonnenschein, W. Wester, C. Boutan, N. S. Oblath, R. Bradely, E. J. Daw, A. V. Dixit, J. Clarke, S. R. O’Kellely, N. Crisosto, J. R. Gleason, S. Jois, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, and C. G. Hilton (ADMX Collaboration), “Search for invisible axion dark matter with the axion dark matter experiment,” *Phys. Rev. Lett.* **120**, 151301 (2018).

17. T. Braine, R. Cervantes, N. Crisosto, N. Du, S. Kimes, L. J. Rosenberg, G. Rybka, J. Yang, D. Bowring, A. S. Chou, R. Khatiwa, A. Sonnenschein, W. Wester, G. Carosi, N. Woollett, L. D. Duffy, R. Bradely, C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, M. S. Taubman, J. Clarke, A. Dove, A. Eddins, S. R. O’Kellely, S. Nawaz, I. Siddiqi, N. Stevenson, A. Agrawal, A. V. Dixit, J. R. Gleason, S. Jois, P. Sikivie, N. S. Sullivan, D. B. Tanner, E. Lentz, E. J. Daw, J. H. Buckley, P. M. Harrington, E. A. Henriksen, and K. W. Murch, “Extended search for the invisible axion with the axion dark matter experiment,” (2019), [arXiv:1910.08638 [hep-ex]].

18. G. Asztalos, E. Daw, H. Peng, L. J. Rosenberg, C. Hagemann, D. Kinion, W. Stoefll, K. van Bibber, P. Sikivie, N. S. Sullivan, D. B. Tanner, F. Nezrick, M. S. Turner, D. M. Moltz, J. Powell, M.-O. André, J. Clarke, M. Mück, and R. F. Bradley, “Large-scale microwave cavity search for dark-matter axions,” *Phys. Rev. D* **64**, 092003 (2001).

19. S. J. Asztalos, G. Carosi, C. Hagemann, D. Kinion, K. van Bibber, M. Hotz, L. J. Rosenberg, G. Rybka, J. Hoikins, J. Hwang, P. Sikivie, D. B. Tanner, R. Bradely, and J. Clarke, “Squid-based microwave cavity search for dark-matter axions,” *Phys. Rev. Lett.* **104**, 041301 (2010).

20. B. M. Brubaker, L. Zhong, Y. V. Gurevich, S. B. Cahn, S. K. Lamoreaux, M. Simanovskaia, J. R. Root, S. M. Lewis, S. Al-Khann, K. M. Backes, I. Urdinaran, N. M. Rapidis, T. M. Shokair, K. A. van Bibber, D. A. Falken, M. Halmon, W. F. Kindel, M. A. Anil, K. W. Lehmert, and G. Carosi, “First results from a microwave cavity axion search at 24 μeV,” *Phys. Rev. Lett.* **118**, 061302 (2017), [arXiv:1610.02580 [astro-ph.CO]].

21. B. T. McAllister, G. Flower, E. N. Ivanov, M. Goryachev, J. B. Bourhill, and M. E. Tobar, “The organ experiment: An axion
haloscope above 15 ghz,” *Physics of the Dark Universe* **18**, 67–72 (2017).

22W. Chung, “CULTASK, Axion Experiment at CAPP in Korea,” in *Proceedings, 13th Patras Workshop on Axions, WIMPs and WISPs, (PATRAS 2017): Thessaloniki, Greece, 15 May 2017*. 19–27 (2017). (2018) pp. 97–101.

25Y. K. Semertzidis, J. E. Kim, S. Youn, J. Choi, W. Chung, S. Hicianoregolu, D. Kim, J. Kim, B. Ko, O. Kwon, A. Matlashov, L. Miceli, H. Natori, S. Park, M. Lee, S. Lee, E. Sala, Y. Shin, T. Seong, S. Uchaykin, D. Ahn, S. Ahn, S. P. Chang, W. Cheong, H. Jeong, J. Joeng, D. O. Kim, J. Kim, O. Kim, Y. Kim, K. Kuthu, D. Lee, Z. Omarov, C.-K. Sung, B. Yeo, A. K. Yi, and M. Yildiz, “Axion dark matter search with its/capp,” (2019), arXiv:1910.11591 [physics.ins-det].

26S. Lee, J. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis, “Axion dark matter search around 6.7 µev,” (2020), arXiv:2001.05102 [hep-ex].

27D. Alessi, D. Babusci, D. Di Gioacchino, C. Gatti, G. Lamanna, and C. Ligi, “The KLASH Proposal,” (2017), arXiv:1707.06010 [physics.ins-det].

28C. Gatti, D. Alessi, D. Babusci, C. Braggio, G. Carugno, N. Crescini, D. Di Gioacchino, P. Falferi, G. Lamanna, C. Ligi, A. Ortolan, L. Pellegrino, A. Rettaroli, G. Russo, and S. Tocci, “The KLASH Proposal: Status and Perspectives,” in *14th Patras Workshop on Axions, WIMPs and WISPs (AXION-WIMP 2018)* (PATRAS 2018) Hamburg, Germany, June 18–22, 2018 (2018) arXiv:1811.06754 [physics.ins-det].

29D. Alessi, D. Babusci, P. B. S. J., F. Bjerkroth, F. Bossi, P. Ciambrone, G. D. Monache, D. Di Gioacchino, P. Falferi, A. Gallo, C. Gatti, A. Ghigo, M. Giannotti, G. Lamanna, C. Ligi, G. Maccarrone, A. Mirrizi, D. Montanino, D. Mortaccini, A. Mostacci, M. M. E. Nardi, F. Nguyen, L. Pellegrino, A. Rettaroli, R. Ricci, L. Sabbatini, S. Tocci, and L. Visinelli, “Klasch conceptual design report,” (2019), arXiv:1911.02427 [physics.ins-det].

30A. Á. Melcón, S. A. Cuendis, C. Cogollo, A. Díaz-Morillo, B. Doebisch, J. D. Gallego, B. Gimeno, I. G. Irastorza, A. J. Lozano-Guerrero, C. Malbrunot, P. Navarro, C. P. Garay, J. Rodríguez, T. Seong, S. Uchaykin, D. Ahn, S. Ahn, S. P. Chang, H. Jeong, J. Joeng, D. O. Kim, J. Kim, O. Kim, Y. Kim, K. Kuthu, D. Lee, Z. Omarov, C.-K. Sung, B. Yeo, A. K. Yi, and M. Yildiz, “Axion dark matter search with its/capp,” (2019), arXiv:1910.11591 [physics.ins-det].

31S. Lee, J. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis, “Axion dark matter search around 6.7 µev,” (2020), arXiv:2001.05102 [hep-ex].

32A. K. van Bibber, and L. Zhong, “Design and operational experience of a microwave cavity axion detector for the 20-100 µev range,” (2020), arXiv:2001.05102 [hep-ex].