A dark matter telescope probing the 6 to 60 GHz band

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Abstract. In this article we present the Dark-photons\&Axion-Like particles Interferometer (DALI), a novel experiment designed for the detection of photon-mixing cold dark matter in the microwave band between 6 and 60 GHz. DALI is a haloscope for the simultaneous search for axions, ALPs and dark photons, with a number of novelties that make it unique. First, it is a dark matter telescope, with a capacity for pointing, tracking and rastering objects and areas in the sky. This potentially allows one to detect relativistic dark matter particles, substructures and flows, without compromising the simultaneous scanning for dark matter relic particles present in the laboratory. Second, it has been designed using commercial technology. This will allow feasible manufacture at a reasonable cost, thereby mitigating the need for R\&D and facilitating maintenance. Finally, it benefits from a high sensitivity over a broad band of frequencies with only minimal reconfiguration.

Keywords: dark matter detectors, dark matter experiments, axions
1 Introduction

The DALI Experiment is designed to investigate axion and dark photon (DP) cold dark matter (CDM) candidates through their interaction with photons within a range determined by theoretical considerations described in this article. The experiment will be feasible using commercial state-of-the-art technology and will present a high sensitivity and ultra-wide band operation. The detector is directional and able to track objects in the sky, with sensitivity to both virialized and rapid CDM particles simultaneously, within the limit of de Broglie (DB) coherence. DALI has the potential to test theoretical foundations and the existence of dark matter (DM) substructures, flares and flows, as well as the DM halo modulation.

The article is structured as follows. Section 1 is devoted to a brief summary of the scientific context and motivation of this experiment. Readers experienced in axion and DP experiments may directly advance to section 2 without lack of rigor. Section 2 presents the experimental background for this article and describes the experiment set-up in detail. A sensitivity projection is included. Section 3 discusses the scientific motivation and feasibility of the directional search for non-virialized DM particles. Finally, section 4 presents a discussion of the most relevant issues treated in the manuscript, noting the most important conclusions.

1.1 Background

One of the most important challenges of modern physics is to unveil the exact nature and properties of DM. One of the leading hypotheses is that DM is composed of a new type of scalar particle, generically referred as the axion. The axion is a hypothetical pseudo-scalar Goldstone boson theorized by Weinberg and Wilczek ([1], [2]) as consequence of the dynamic solution to the strong CP symmetry problem\(^1\) proposed by Peccei and Quinn (PQ) [3] and is predicted in multiple extensions of the Standard Model (SM) of Particle Physics.

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\(^1\)Charge and Parity or Charge-conjugation Parity symmetry, i.e., charge conjugation symmetry (C) and parity symmetry (P).
A fundamental parameter of the SM, the $\theta$ term, governs the value of the electric dipole moment of the neutron, and its absolute upper limit has been measured showing that $\theta$ is extremely fine tuned ($|\theta| < 10^{-11}$), against theoretical expectations. In the PQ solution, $\theta$ is not a parameter but a dynamic field (the QCD axion$^2$), whose potential has a minimum to which it evolves once the Universe cools sufficiently. The axion has a light mass, induced by its interactions with SM particles and scales inversely to a typical energy called the PQ scale, $f_a$. On the other hand, many extensions of the SM and String theory predict a set of particles similar to axion, the so-called axion-like particles or ALPs. A set of observational and laboratory experiments constrain the range of values in which the axion and ALPs mass can exist (e.g., [4], [5], [6]). For $f_a$ scales of the order of $10^{12}$ GeV, or masses of the order of the $\mu$eV, the axion and ALPs are well-grounded candidates for CDM. The exclusion regions of axion mass are represented in Fig. 1. These are briefly described in this section following the work carried out by [7], [8] and [9]$^3$ in order to examine the axion mass range and experiment layout chosen in our experiment.

![Exclusion graph of axion mass](image)

**Figure 1.** Exclusion graph of axion mass. Laboratory experiments are shaded in gray. Bluish exclusion regions are established using stellar and helioscopic hints. Zones shaded in green correspond to astronomical observations, cosmology and haloscopes. Reprinted with permission from [8].

The gray zones in Fig. 1 correspond to laboratory results. *Light shining through walls* (LSTW) experiments are based on the production and reversion of axion-two-photon vertex conversion from the Primakoff effect [10] within a controlled (laboratory) area [11]. A different laboratory search is based on the measurement of dichroism and birefringence caused by the axion field on a light beam. Vacuum magnetic birefringence (VMB) is also predicted in

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$^2$QCD stands for Quantum Chromodynamics.

$^3$These references are used repeatedly throughout this section, but will no longer be cited, except where extremely necessary, to avoid excessive repetition.
high-order quantum electrodynamics (QED) [12]. Fifth force experiments explore the long-range forces that could mediate pseudoscalar boson interactions, searching for new mass-spin coupling. The more relevant limits have been stated taking into account both fifth-force and stellar cooling considerations [13]. The bluish colors in Fig. 1 correspond to helioscopes or bounds depending on stellar physics. Helioscopes are solar haloscopes scanning the Sun. The experimental principle consists in reverting the Primakoff process within a magnet’s bore measuring the photon flux at keV energies ([14], [15], [16]). On the other hand, stellar considerations are based on interactions of the axion to fermions and photons in the plasma of stars, producing extra cooling ([17], [18]). The accelerated consumption of helium reduces the stellar lifetime. Stars on the horizontal branch (HB) present accelerated burning rates that can be compared with the expected Primakoff axion loss rate. Red giants (RGs), weakly affected by the Primakoff effect, act as a calibrator in global cluster observations. However, RGs particularly suffer from axion coupling to electrons in several radiative processes, such as atomic axio-recombination or deexcitation, axion bremsstrahlung and Compton scattering interactions [19]. White dwarfs (WDs), where the Primakoff and Compton processes are suppressed by the plasma frequency, are nevertheless sensitive to bremsstrahlung. Photometry compared with WD luminosity function models could reveal additional cooling due to axion losses [20]. Observations of the neutrino flux duration from supernova (SN) SN1987A compared to numerical simulations with state-of-the-art SN models can provide bounds ([21], [22]). A different stellar hint is related to observations of the neutron star (NS) in the SN remnant Cassiopeia A, which reveals an abnormally fast cooling rate. This extra cooling could be explained by the axion-neutron bremsstrahlung mechanism ([23], [24]). ALPs coupling to both electrons and photons would simultaneously be able to explain HB, RG branch stars and WD extra cooling, in concordance with SN1987A hints [25]. Finally, if the ALP Compton wavelength is of the order of a rotating black hole (BH) size, axions and ALPs field could induce superradiance because of the formation of gravitationally bound states [26]. The greenish regions in Fig. 1 represent exclusion zones from haloscopes and cosmological arguments. Resonant-cavity haloscopes ADMX and UF [27], RBF ([28], [29]), HAYSTAC [30] and ORGAN [31] had already scanned a relatively narrow bandwidth in the region preferred by pre-inflationary axions. Cosmology on cosmic microwave background (CMB), X and γ rays, Big Bang nucleosynthesis (BBN), cosmological extragalactic background light (EBL) and χ ion considerations can be consulted in detail in [9]. Regarding the lower limit for axion mass, several authors suggest that ultra-light axions should not exist below \( m_a \sim 10^{-21} - 10^{-22} \) eV (e.g., [32], [33]).

The coupling rate of the QCD axion contains a factor derived from the model-dependent ratio of electromagnetic (EM) and color anomalies (\( \mathcal{E}/\mathcal{C} \)) given by \( C_{a\gamma} = 1.92(4) - \mathcal{E}/\mathcal{C} \).\(^5\) This factor is related to the fundamental parameter of the axion through \( C_{a\gamma} = -\frac{\alpha}{2\pi} \epsilon a f_a \).\(^6\) The color anomaly is an integer, and is also referred to in cosmology as the domain wall number (i.e., \( \mathcal{C} = N_{DW} \)). In order to avoid topological defects, this parameter must, in principle, be \( N_{DW} = 1 \) [34]. The ratio \( \mathcal{E}/N_{DW} \) differs depending on the high-energy details of the axion model. In the case of the KSVZ (Kim–Shifman–Vainshtein–Zakharov) model ([35], [36]) \( \mathcal{E}/N_{DW} = 0 \) and \( N_{DW} = 1 \) are adopted. Topological defects could have catastrophic

\(^4\)Keep in mind that resonant cavity haloscopes are limited to light masses or low frequencies. We will extend this discussion in section 2.

\(^5\)Giving the number in brackets account on the uncertainty.

\(^6\)Where \( \alpha = e^2/4\pi \) is the dimensionless fine structure constant, \( e \) being the elementary charge.
cosmological effects if stable, so the KSVZ model is consistent. The DFSZ (Dine–Fischler–Srednicki–Zhitnitsky) model ([37], [38]) sets \( E/N_{DW} \) equal to 8/3 or 2/3 and \( N_{DW} \) equal to 6 or 3. Alternative mechanisms to solve these issues with topology defects have been proposed (e.g., [39]). KSVZ and DFSZ are the most generic axion models, although others exist (e.g., see [8] and [40] for a brief summary).

The *PQ-phase transition* is the moment in the history of the early universe in which the axion angular field acquires propagating degrees of freedom. Depending on inflation, two different cases are possible. This determines the scale \( f_a \). In the first case the PQ-phase transition occurs before inflation. Thus, a unique patch in the early Universe, with a misalignment angle \( \theta = \theta_i \in (-\pi, \pi) \) expands to become larger than the observable Universe, and so the initial misalignment angle \( \theta_i \) is stable, but unknown. This pre-inflationary scenario prefers an axion mass of the order of \( m_a \lesssim 20 \mu eV \). In the post-inflationary scenario, the PQ-phase transition occurs after inflation, and so different inflated patches can have different \( \theta_i \). These patches would remain causally disconnected and could give rise to the existence of DM substructures. This scenario undergoes the formation of cosmic strings and domain walls, solved when \( N_{DW} = 1 \), as was mentioned above. Assuming that all (or a significant part of) the DM in the Universe has an axionic nature, and a conservative DM halo density of the order of \( \rho_{DM} \sim 300 \text{ MeV cm}^{-3} \) [41], which will be adopted throughout the text, the value of the axion mass in this scenario is constrained in the range \( 26 \mu eV \lesssim m_a \lesssim 1 \text{ meV} \).

**Figure 2.** Exclusion graph for dark photon mass. Exclusion regions for the Sun and HB are limited by excessive luminosity in the Sun and HB stars in global clusters. The intergalactic diffuse photon background (IDPB) is limited by the dark photon production rate. Big Bang nucleosynthesis (BBN) is also considered. The "stable" region is permitted. Reprinted with permission from [44].

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\(^7\)See DFSZI and DFSZII models.
On the other hand, DPs, also called hidden photons or paraphotons ([42], [43]), arise in many extensions of the SM as candidate CMD components whose interaction with ordinary SM particles is commonly expressed through its dimensionless kinetic mixing parameter $\chi$. DPs can also be candidates for dark matter in the range $\chi \lesssim 10^{-11} - 10^{-10}$. The exclusion regions for DP are shown in Fig. 2.

Dark photons present Standard Model of Cosmology (SMC) concordance when $\Omega_{\gamma} h^2 \simeq 0.1$, where $\Omega_{\gamma}$ is a term related to the ratio of DP density to entropy density and thermal bath resonant temperature, while $h$ is the Hubble constant (e.g., see [44]). The region above this bound in Fig. 2 is excluded due to overproduction of DM. The black dashed line represents the limit in which DP interaction is sufficiently strong to reach thermal equilibrium. The exclusion regions representing the Sun and HB are the limit for excessive DP luminosity in the Sun and HB stars in global clusters. Above the limit of intergalactic diffuse photon background (IDPB), the DP photon production is exceeded. If $\chi$-independent mechanisms of production of photons are considered, the theory enters the yellow region. Cosmological considerations on pre-, post- and BBN epochs are also shown in gray in Fig. 2. Some of these and other arguments have been presented in Fig. 1 for the case of axions and ALPs.

In Fig. 1 it is remarkable that the region in the KVSZ range $10^{-5} < m_a < 10^{-1}$ [eV] remains poorly explored. In Fig. 2 is shown an unexplored window for the detection of DPs. Both candidates can be scanned simultaneously with this experiment within these sectors.

### 1.2 Experiment foundation

The fundamentals of both QCD axions and ALPs have been adequately reviewed by several authors and the bibliography is very extensive (e.g., [7], [34]). Throughout this section, we focus only on those aspects which are relevant for the understanding of the experiment, starting with the mechanism of interaction between axions and DPs with ordinary photons.

The axion-to-photon coupling Lagrangian density is

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2 - \frac{g_{a\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a - J^\mu A_\mu, \quad (1.1)$$

where $F_{\mu\nu}$ is the field strength tensor and $\tilde{F}$ is the dual field strength, $g_{a\gamma}$ is the axion-to-photon coupling constant, $a$ the axion field, $m_a$ the axion mass, $J$ is density of current and the SM photon field is $A_\mu$.

The specific case of a dielectric interface surrounded by a vacuum within an external magnetic field is treated now. A modification of Maxwell’s equations can be derived arising from a light, pseudo-stable QCD axion [48]. From a classical approach, the axion mix with photons within an EM field with a Lagrangian density

$$\mathcal{L}_{a\gamma} = g_{a\gamma} a E \cdot B, \quad (1.2)$$

where $E$ and $B$ are the electric and magnetic field, respectively. Within the classic limit, the axion field can be approximated by $a = \theta_0 \cos(m_a t) f_a$, where $t$ is time and $\theta_0 \simeq 4 \times 10^{-19}$ [49].

Owing to the action of the magnetic field, a density current enters on the right-hand side of Ampere’s law in the interface between the vacuum and dielectric

$$J = -g_{a\gamma} f_a B \dot{\theta}, \quad (1.3)$$

where $\theta = \theta_0 \cos(m_a t)$. This generates an electric field ($E$) in the interface.
The application of continuity conditions to parallel boundaries in the interface between both media in Eq. 1.4 ($E_1 = E_2$ & $B_1 = B_2$) shows that EM waves are generated to compensate for the discontinuity in electric permittivity ($\varepsilon_1 \neq \varepsilon_2$). Near the zero velocity limit of axions, the momentum parallel to the interface is conserved, whereas the perpendicular momentum is determined by the dispersion relations, forcing the EM waves to be emitted perpendicularly to the interface [50] with a frequency $\nu_a = m_a/2\pi$ [51].

A quantum-field theoretical derivation has been treated more recently for the same case of a planar dielectric interface surrounded by a vacuum, obtaining a similar result to that the used throughout this work [52].

The relation between $f_a$ and $m_a$ is

$$m_a = 5.70(6)(4) \mu\text{eV} \frac{10^{12} \text{GeV}}{f_a},$$

where the numbers in brackets account for the uncertainty.

The wavelength of EM radiation emitted from the surface is given by the axion oscillation pulse $\omega \sim m_a$. Thus

$$\lambda_a \simeq \frac{2\pi}{m_a} (\text{eV})(1.97 \times 10^{-7} \text{ m}).$$

Dark photons arise in many extensions of the SM of particle physics. The basic model involves a new broken U(1) gauge symmetry and kinetic mixing. In the Lagrangian in Eq. 1.7 we denote by $\tilde{X}^{\mu\nu}$ the field strength tensor of the DP field ($\tilde{X}^\mu$), and $F^{\mu\nu}$ the field strength tensor of the ordinary SM photon field ($A^\mu$) of the SM [51].

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} - \frac{1}{4} \tilde{X}_{\mu\nu} \tilde{X}^{\mu\nu} - \frac{\chi}{2} F_{\mu\nu} \tilde{X}^{\mu\nu} + \frac{1}{2} m_{\gamma'}^2 \tilde{X}_\mu \tilde{X}^\mu + J^{\mu} A_\mu,$$

where $\chi$ is the kinetic mixing strength, $m_{\gamma'}$ the DP mass and $J^{\mu}$ the EM current density. Some of these terms have been defined earlier in this article.

The calculation of the wavelength and mass relation of DPs is analogous to Eq. 1.6. DPs do not need an external magnetic field to mix with photons. Radiometry allows the simultaneous exploration of axion, ALPs and DP regions during the scanning.

2 Experiment set-up

DALI was thought to operate in three different modes: haloscope mode, in which the instrument is static, and which focuses on the detection of relic axions forming part of the galactic halo and hence already present in the laboratory; tracking mode, which benefits from the adding of an altazimuthal platform that gives the detector the capacity of pointing and tracking DM sources on the sky; and raster mode, in which regions of the sky are covered with

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Footnote 8: Natural units are used throughout the text.
an algorithm that permits the scanning of wide areas or extended objects (and structures) searching for DM sources. Tracking and raster modes are telescope mode.

This section presents the experimental approach and the experiment layout. A sensitivity projection is also included.

2.1 Experimental approach

Several apparatus for axion and DP detection have been suggested. We highlight the dish-antenna ([51], [53]), resonant cavity haloscope [48] and Fabry–Pérot (FP) haloscope ([54], [55], [56]).9 Experiments based on LC resonant circuits deserve our attention as well, although they are generally shorter in bandwidth, limited to low frequencies and relatively weak in sensitivity (e.g., see [57] for a state-of-the-art proposal facing these limitations).

We have established the exclusion regions for axion, ALP and DP detection in Figs. 1 and 2, respectively. These graphics shown significant unexplored regions in both mass range and coupling strength. These regions are preferably accessible by haloscopes. The origins of haloscopes are based on the need for power enhancement of the signal generated by axions and ALPs mixing with photons [48]. That is, the EM output produced by the physical mechanisms explained before in this manuscript is too weak owing to the limited magnetic inductance in real experiments (or low mixing strength) and must be enhanced before making possible a direct detection.10 In the pre-inflationary scenario, resonant cavity haloscopes are adequate. However, the dimensions of a resonant cavity scale with the Compton wavelength, and resonant cavity haloscopes lose DB coherence when $m_a > 40 \mu\text{eV}$ [58], or they are too large in the radio-wave domain, where different set-ups are used (e.g., [59]). The post-inflationary mass range is accessible using FP haloscopes, and it is the aim of our experiment to explore this concept.11

Here we present a modern experiment focused on the direct detection of post-inflationary axions, ALPs and DPs in the frequency range 6–60 GHz. DALI is an FP (interferometer) haloscope with some novelties that will be explained in this article.

In general, the principle of an FP interferometer is based on an interference between incoming and reflected waves within a resonator, forming a standing wave. Constructive interference occurs when incident and reflected waves are in phase. The output is spectrally modified compared to the input beam, allowing power enhancement in relatively narrow frequency bands centered at the resonant frequency. The classic FP resonator consists of a pair of mirrors surrounded by vacuum, or a medium with a known refractive index ($n = \sqrt{\varepsilon_r}$). FP interferometers and etalons have been used frequently in astronomy and are a very well established technology for infrared observations, where the mechanical requirements are relaxed compared to the optical range [60].

The classical theory on FP resonators has already been applied to the case of a dielectric (FP) haloscope ([49], [61]), where the internal resonance enhancement factor of the classic FP interferometer plays a role in the so-called boost factor ($\beta$). Throughout this work we follow this nomenclature. The boost factor is a figure of merit expressing the signal enhancement referred to a single magnetized mirror.12 The power boost factor scales with the number of

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9Resonant cavity haloscopes are ongoing experiments.
10Of the order of $10^{-27}\text{W/m}^2$ considering axions forming the galactic halo in the Solar System position [48] to be increased to around $10^{-23}\text{W/m}^2$.
11In the limit between pre- and post-inflationary scenarios, both resonant cavity and HP haloscopes can be used.
12Of area equal to the area of a plate, or equivalently the area of the mirror.
stacked plates ($N$) and its electric permittivity, $\beta^2(\nu, N, \varepsilon_r)$. In the proof-of-concept experiments, a narrow fake axion signal is injected in a continuum, and then detected with $\sim 5\sigma$ significance using high-electron-mobility transistor (HEMT) radiometry ([62], [63]).

Since DPs do not need the action of an external magnetic field to mix with SM photons, the observation of DPs maintains polarization coherence. In contrast, polarization in axion searching is degraded by the effects of the external magnetic field in haloscopes and helioscopes.

2.2 Telescope description

The experimental set-up is shown in Figs. 3 to 5. A multicoil superconducting magnet ("1") houses the FP interferometer and microwave receivers. Multicoil magnets are commonly used in magnetic resonance imaging (MRI), industry and research. They reach typical magnetic inductances of 3, 5, 7 and 9 T, and eventually higher. The bore size is typically around 0.5 m with magnetic-field lines parallel to the cylinder axis. In a regular model, the length of the coil winding part is around 1.5 m, while the magnet total length is around 2 m. Field homogeneity is typically 1% over a sphere of 100 mm diameter within the magnet bore and field stability is around 3 ppm/h. The superconducting magnet uses an independent helium free cooling system ("2").

The experiment cryostat ("3") is contained within the magnet’s bore, but is independent. The cryostat is fabricated in non-magnetic material (Al). In order to achieve high thermal stability and homogeneity, the cryostat is mounted symmetrically and equipped with twin cold-heads. The primary mirror is composed of a group of stacked dielectric parallel plates ("4"). These plates form the FP interferometer. A polished mirror is attached at the bottom ("5"). The dielectric plates are composed of a grid made of a union of commercial wafers. A higher electrical permittivity results in a higher signal power. Standard dielectric wafers dimensions are 100 x 100 mm size of 0.25, 0.5, 0.75, 1 and 1.25 mm thicknesses. The polished surface roughness is around 0.02 $\mu$m. In the structure of the interferometer a combination of dielectric materials is used. Stacking wafers allows one to benefit from combining and intermediate thicknesses. This allows us to set a different plate thickness in every sub-band (or group of sub-bands) over the 6–60 GHz band, keeping $\beta^2$ not far from ideality. In order to benefit from maximum boost power, two thicknesses must be adjusted with precision: the thickness between consecutive plates or between the bottom plate and the mirror ($d_\vartheta$); and the thickness of the dielectric plates ($d_\varepsilon$). Both $d_\vartheta$ and $d_\varepsilon$ scale with wavelength. The ideal thickness of the dielectric plate $d_\varepsilon$ varies from around 2.5 mm at 6 GHz (or $m_a \simeq 25 \mu$eV) to 0.25 mm at 60 GHz (or $m_a \simeq 250 \mu$eV). The vacuum thickness $d_\vartheta$ varies from around 25 mm at 6 GHz to 2 mm around 60 GHz. These have a remarkable consequence: since the dimensions of the magnet’s bore are fixed, more dielectric plates can be stacked at high frequency. This increases the collecting area and the boost power. Thus, the instrument is more sensitive at higher frequencies in the band. To achieve a high boost factor, the sub-bands must be narrower at lower frequencies. The $\beta^2$ feature is narrow band because $P\Delta \nu_\beta$ is roughly constant. The plan is to scan in sub-bands of the order of 100 MHz wide, where $\beta^2 \sim 10^4$ is achievable in practice [55]. Since the sub-bands are determined before starting observations, the positions of the FP plates can be calculated in advance using finite-element-method (FEM) 3D simulation.

13-Ti and fiberglass are also non-magnetic materials commonly used in cryogenics.
14-We plan to use zirconia ($ZrO_2$), a commercial material with dielectric constant $\varepsilon_r \simeq 29$.
15-Zirconia and G-10&11 is a reliable option.
Figure 3. Experiment set-up. General view. DALI consist on a Fabry–Pérot interferometer within a 4 K cryostat. This cryostat is housed within a multicoil superconducting magnet (*1*). Approximate dimensions are 1.5x\(\varphi\)1 m for the magnet and 2x\(\varphi\)0.5 m of the experiment cryostat (*3*).

Figure 4. Experiment set-up. Lateral view. Symmetrical design allows better thermal stability of the experiment cryostat (*3*). The apparatus rests on an altazimuthal mount (*7*), which permits pointing and tracking with high speed rotation. Some objects has been removed for simplicity.

For plate positioning, both piezoelectric motors and cryogenic mechanisms are used. Non-magnetic piezoelectrics have been already probed in axion magnetized experiments ([97], [98]). They present an uncertainty in the positioning of the order of \(\pm 2 \mu m\). This uncertainty is within the experiment’s tolerance, of the order of a few \(\mu m\) at 60 GHz or tens of \(\mu m\) at 6 GHz.\(^\text{16}\) Static deflections should be considered as well. However, part of the loss due to mechanical deviation would be absorbed by FP reconfiguration based on 3D-FEM EM simulations. The same idea is applicable to edge spurious effects and permittivity discontinuities in the dielectric grid, based on the results in ([99], [100]). The output power is received by an antenna array placed at the top of the cryostat (*6*). The signal is amplified in independent pixels using HEMTs\(^\text{17}\) and processed in a cold front-end module. The signal is then transferred to a room-temperature back-end module, not shown in the schema for simplicity. The data acquisition system (DAS) is based on field-programmable gate array (FPGA) structure. The signal maintains phase coherence. The radiometer uses a cross-correlation schema. Hence, the mitigation of low frequency gain fluctuations caused by thermal and 1/f noise contributions is possible. The power from each pixel can be combined. Twin receivers at opposite ends of the cryostat can be pointed to reference cold-loads to calibrate the signal and obtain the power-offset generated by noise contribution during scanning. This would facilitate the directional observation of relativistic axions, where the line width of the axion\(^\text{18}\) (or DP) may be considerably wide, approaching \(\Delta \nu_a/\nu \simeq 0.5\) in some cases. This scheme (eg, see [110]) is not shown in the figure for simplicity.

\(^{16}\)For 90% efficiency.

\(^{17}\)We discuss an alternative option in section 2.3.

\(^{18}\)\(\Delta \nu_a/\nu = \sigma_{\nu_a}^2/2\).
Figure 5. Experiment set-up. Section. Detail of resonator and antennas. The grid is resizable so that it can be adjusted to the de Broglie wavelength of the axion, acquiring coherence. Here a grid size for maximal sensitivity to virialized DM particles and accelerated particles up to velocities of the order of a few percent speed of light is shown.

An altazimuthal mount ("7") equipped with a rotating joint [101] transmits sufficient torque for fast rotation of the approximately 3 mT weight of the instrument, making pointing and tracking feasible. 19

The experiment’s laboratory must be isolated from spurious microwave backgrounds. A standard Faraday cage provides around 100–120 dB attenuation over 10 MHz and up to frequencies of tens of GHz. 20 This is equivalent to a room placed approximately 20 m below the surface and is sufficient to mitigate background noise from terrestrial sources [56].

Since DM is weakly interactive, the telescope is bidirectional and some uncertainty in the pointing model is present. However, FP haloscopes are theoretically sensitive to the side of the plate in which the axion momentum is transferred through phase information [91]. The line of sight (l.o.s.) of the instrument, perpendicular to the dielectric plates, bifurcates in l.o.s+ and l.o.s− passing through the Earth. This allows simultaneous observation in both hemispheres.

2.3 Sensitivity projection

In this section we estimate the sensitivity projection of DALI operating in haloscope mode. Axions, ALPs and DPs are scanned simultaneously with the same set-up for each frequency (or equivalently, mass).

The sensitivity projection to relic axions of DALI equipped with a 7.5 T multicoil superconducting magnet operating in haloscope mode over the entire 25 to 250 µeV range is shown in Figure 6. In Eqs. 2.1 to 2.3 $A$ is the collecting area, $B$ the external field, $k_B$ the Boltzmann constant, $T_{sys}$ the system temperature, $\Delta \nu_a = 10^{-6} \nu$ the bandwidth referred to axion line width and $t$ is integration time. The axion–photon coupling factor is given by

$$g_{a\gamma} = 2.04 \times 10^{-16} \, C_{a\gamma} \, \frac{m_a}{\mu \text{eV}}.$$ (2.1)

The axion-induced electric field generates an energy flux density

19 The design shown in Fig. 3 is adapted from [102] and could undergo modifications.
20 http://www.hollandshielding.com
\[ P_{\alpha \gamma} = 2.2 \times 10^{-27} \beta^2 \left( \frac{B}{10 \text{T}} \right)^2 C_{\alpha \gamma}^2, \quad (2.2) \]

while the received power can be estimated using the well known \textit{ideal radiometer equation} \cite{103} in the form

\[ \frac{S}{N} = \frac{P}{k_B T} \sqrt{t \Delta \nu_a}. \quad (2.3) \]

The sensitivity projection is shown in Fig. 6 for the specific configuration of interferometer presented in Fig. 5. Here we consider three different cases: temperature \( T_{\text{sys}} \sim 8 \text{K} \) and 2-stage 4 K closed cycle refrigerators for HEMT radiometers, and double stage \(^3\text{He} - ^4\text{He} \) sorption cooler working at sub-K temperature and \( T_{\text{sys}} \sim 2 \text{ K} \) for HEMT based detectors or \( T_{\text{sys}} \sim 100 \text{ mK} \) replacing HEMTs with microstrip superconducting quantum interference device (SQUID) amplifiers (MSA) \cite{104}, \cite{105}, \cite{106}, \cite{107}, \cite{108}). In order to benefit from a dense power boost factor over the entire band, the sub-bands must be narrower at low frequency, where the space available for plate-stacking is smaller. In contrast, at higher frequencies, where \( d_\phi \) is short and so more plate levels can be stacked within the magnet’s bore enhancing \( \beta^2 \), the system suffers hardened mechanical tolerance and less efficient resonance.

\textbf{Figure 6.} Sensitivity projection to relic axions (upper) and dark photons (lower) in the 6–60 GHz band. Parameters are \( B=7.5 \text{ T} \), 15 day integration time, \( \beta^2 = 5 \times 10^4 \), \( \rho_{\text{DM}} = 300 \text{ MeVcm}^{-3} \), \( \alpha \) corresponds to random velocity dispersion, \( 3 \sigma \) significance and \( T_{\text{sys}} \) present three different cases: 2-stage close cycle with \( T_{\text{sys1}} \sim 8 \text{ K} \) and a \(^3\text{He} - ^4\text{He} \) sorption cooler down to \( T_{\text{sys2}} \sim 2 \text{ K} \) using HEMTs; and \( T_{\text{sys3}} \sim 100 \text{ mK} \) with microstrip SQUID Amplifiers (MSA). Sensitivities are compared to KSVZ and DFSZ models over the entire 25–250 \( \mu \text{eV} \) range. Exclusions regions in the vicinity are represented in light color for horizontal branch (HB) (blue) and haloscope (\cite{30}) (green). The Tokyo limit is shown in light yellow \cite{109}. 
Therefore, a compromise power boost factor $\beta^2 \sim 10^4$ is considered throughout the entire experimental range [55]. The sub-bands are scanned sequentially. The sensitivities are compared to theoretical predictions of reference axion models.

The sensitivity to slow DPs of the experiment is shown in Fig. 6 (lower). In Eq. 2.4 $\rho_{DM}$ is DM halo density, $A$ the detection area and $\alpha$ is a factor determining the incidence angle of the DP ($\alpha = \sqrt{2/3}$ represents random case) [51]. $P$ can be obtained from Eq. 2.3 and $\Delta\nu_{DP} = 10^{-6}\nu$.

$$\chi = 4.5 \times 10^{-14} \left( \frac{P}{10^{-23} W} \frac{0.3 \text{ GeV cm}^{-3} \text{ m}^2}{\rho_{DM}} \frac{1}{A} \beta^2 \right)^{1/2} \frac{\sqrt{2/3}}{\alpha} ,$$  \hspace{1cm} (2.4)

Fig. 6 reveals a high sensitivity within the stable DP region over the entire 25 to 250 $\mu$eV range.

### 3 The aim for directional observation

The mathematical formalism and first approximations to establish a calculation of sensitivities for the case of low-velocity axions in directional haloscopes have been elegantly carried out already in ([50], [91]). Ongoing static low-frequency experiments incorporated some of these uncertainties some time ago, anticipating the possibility of receiving microwave photons from random axion discrete flows and streams ([92], [93], [94], [95]). Helioscopes can be reconfigured in order to be sensitive to streaming CDM axions and miniclusters [96].

In this section, we discuss dynamic coherence in relativistic particle scanning and the scientific motivation for directional search for axions and DPs.

#### 3.1 Detectability of rapid particles

The DB coherence must be maintained in order to make the axion detectable because of cross-section considerations.\(^{21}\) This allows the axion field to be measured including phase information. Therefore, the DB wavelength of the axion or ALP ($\lambda_{DB} = 2\pi \gamma/m_a v_a$)\(^{22}\) must be larger than the collector or primary mirror scale length ($\ell$). Given this, the detector is coherent when the following condition is fulfilled

$$v_a \ell \lesssim 2\pi \gamma m_a \ell (\text{eV})(1.97 \times 10^{-7} \text{ m}) .$$  \hspace{1cm} (3.1)

The expression in Eq. 3.1 is represented in Fig. 7 left and establishes a limit to the velocity of non-virialized axions that is possible to receive with a telescope characterized by the scale length of its detector ($v_a$). In Fig. 7 left, the horizontal dashed gray line represents the virial velocity of the DM halo around $10^{-3}$ as reference. Axion velocities up to around 50% of the velocity of light in vacuo are accessible in the case of the basic unit of around 10 cm in length.\(^{23}\) At these energies, Lorentz relativistic correction to the axion rest mass below 15% ($\gamma < 1.15$) remain moderate, specially considering the limited spectral resolution of FP haloscopes, of the order of the 100 MHz or equivalently around 0.4 $\mu$eV. Thus, the left

\(^{21}\)See [64] pp. 86–87 for an intuitive review of this fundamental issue.

\(^{22}\)\(\gamma = 1/\sqrt{1 - v^2/c^2}\) is the Lorentz factor.

\(^{23}\)Several basic units that cover the entire longitudinal section of the bore can be placed if they are sufficiently separated in order not to interfere.
Figure 7. Study of de Broglie (DB) coherence in the frequency range 6–60 GHz. Left: Non-relativistic case. Limiting velocity ($v_a$) over mass of detectable axions. The region above the line loses DB coherence and is hidden. Axions with velocities up to around 0.5$c$ are detectable with the more basic unit of grid of 10 cm length ($\ell = 0.1$). The horizontal gray dashed line at the bottom represents the virial velocity of the relic axions, around $10^{-3}c$, as reference. Right: Relativistic analysis. DB wavelength over rest mass. Lines corresponding to relativistic velocities from 0.5$c$ to 0.99$c$ are represented. Light ultrarelativistic axions are shifted from the radio domain to the experiment band. The gray horizontal line represents the limiting DB wavelength, which is coherent with a basic unit with $\ell \sim 0.1$ m. The gray dashed line represents the diffraction limit ($\lambda_a \sim \ell$). The limit of relativism around 0.5$c$ is arbitrary.

The observation of non-virialized particles is preferably directional. Note that from the dot product in Eq. 1.2 it follows that the interaction is maximal when the axion incidence angle to a dielectric plane is perpendicular to the magnetic field, transmitting maximum mo-
menta. The velocity dispersion from the zero velocity limit up to the virial velocity around $10^{-3}$ through its effects on $\beta^2$ has been studied in a similar haloscope concept [50]. The instrument becomes sensitive to velocity dispersion when the haloscope size is of the order of 15–20% of the axion DB wavelength. Below this limit, $\beta^2$ can in principle be considered velocity independent and so the instrument presents low or null sensitivity to velocity dispersion and incoming direction of the axion. When the DB wavelength of the axion is of the order of the size of the haloscope, directional sensitivity is $\mathcal{O}(1)$. This gives a strong directionality to the axioscope. Virialized axion search is weakly sensitive to directionality up to around 250 $\mu$eV. Directional and non-directional observations can be carried out simultaneously.

3.2 Scientific motivation

Directional search for non-virialized DM particles does not compromise the classical (haloscopic) exploration for relic axions and DPs. Both necessarily take place simultaneously during scanning. Particles of diverse origin could mix. An extra population of particles with similar dynamic mass would only result in a signal enhancement and hence an enhanced probability of detection, so long as the de Broglie coherence is maintained. This would allow the detector to access sensitivity sectors that were previously prohibited.

The existence and detectability of DM substructures is an interesting hypothesis arising from anomalous large-scale observations. Axion streams density would vary between 0.3–30% of local DM density ($\rho_{DM}$). Thus, they would be potentially detectable. Furthermore, streams would present a $10^6$ flux enhancement factor compared to the local DM density (i.e., $\rho_a \sim 10^6 \rho_{DM}$) once aligned in the Sun-Earth l.o.s. focusing low velocity axions at the Earth’s position [115]. Moreover, streams may be enhanced by microlensing. Gravitational microlens caused by planets in the direction planet-Earth may provide $\rho_a \sim 10^6 \rho_{DM}$, or around $\rho_a \sim 10^4 \rho_{DM}$ in the case of the Moon. Only once data are stacked during month-year periods planetary effects underlying streams would be revealed in broad band observations with shortened integration time. A different case of interest is the Galactic-center-Sun-Earth alignment, repeated annually. This effect would be enhanced every 8–9 years, when the Moon is aligned in the same l.o.s. Streaming dark matter could explain why both the terrestrial atmospheric ionisation and solar activity show dependence on the longitudinal position of the planets or lunar phase [118]. Referring now to small-scale substructures such as miniclusters, they could be disrupted forming tidal streams with flux density $\rho_a \sim 10 \rho_{DM}$. Stream-crossing events may occur around 1 every 20 years with a few-day duration, so the probability of entering or leaving a DM minicluster during a measurement is (almost) negligible. However, miniclusters trapped by the Solar System during its formation [114], with $\rho_a \sim 10^5 \rho_{DM}$ and few-day events duration annually have been suggested. Such trapped substructures are within the observational bounds [116]. Refer to [65], [66], [67], [68], [69], [70], [71], [72], [74] and [73] for a general view on the status of dark universe research. The same concept on DM substructures and flows explained here for the case of axions and ALPs can be extended to the search for DPs.

Recently, the ANITA experiment, dedicated to measuring isolated impulsive radio signals originating from cosmic ray showers reflected in the Antarctica ice, reported the detection of two anomalous events, which are not explainable by cosmic rays ([75], [76]). An explanation strictly within the SM conflicts with other experiments and theory. Different arguments over the years depend on further investigations and/or tend to be in conflict with data (e.g. [77], [78], [79], [80], [81]). The possibility of instrumental artifacts must not be discarded either. However, authors have recently suggested that these events could be explained in

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terms of resonance in the ionosphere by the axion–photon conversion mechanism. Although the analysis is in principle consistent with $m_a \lesssim 0.1 \, \mu eV$ and is thus below the haloscope region, we consider the uncertainties in the calculations to be important enough to give our attention to this case. Furthermore, QCD axions and ALPs from SM and string theory extensions and DPs could coexist in a variety of masses [82].

With reference to stellar physics, solar axions produced by the Primakoff effect are ultrarelativistic, emitted with keV-level energies and so are invisible for our experiment [15]. However, axion quark nugget (AQN) theory [84] suggests a mechanism for creating a significant population of axions in the solar corona released with velocities of 10–90% of the speed of light [85]. The mass relativistic corrections are moderate, so photons created by AQN mechanisms may be received in the microwave regime. The AQN prediction is based on two observations. Firstly, conventional solar physics currently fails to explain extreme ultraviolet (EUV) radiation from the solar corona ([86], [87]). The extra flux that would be produced in the Sun through the AQN mechanism matches the observed EUV soft X-ray intensity, around $10^{27} \, \text{erg s}^{-1}$ ([88], [89]). Secondly, the AQN model could explain the unusual solar flares and EUV radiation observed in the solar atmosphere ([87], [90]). AQN-induced axions would mix with relic axions [113]. AQN-induced axions present flux density $\rho_a \sim 10^{-5} \rho_{DM}$ and typical velocity around 0.6c. Linearity in velocity enhances the flux density of AQN-induced axions up to $\rho_a \sim 10^{-2} \rho_{DM}$ [119]. Benefit from microlensing or the halo modulation amplification time dependent factor $(A(t))$ would be helpful in finding these DM particles. The preferred mass for AQN-induced axions is $m_a \sim 100 \, \mu eV$ corresponding to around 24–30 GHz [112]. Low velocity gravitationally trapped axions produced by AQN mechanism have been also suggested [111].

The daily modulation of dark matter distribution can be studied by implementing directionality. The daily modulation of a non-directional experiment is of the order of 0.2%, but it is increased up to around 1% in the case of a directional detector. Other authors suggest an annual modulation of the axion line width of 10% [83]. See [117] for a recent review.

Finally, the velocity distribution of the galactic DM halo cannot be ideally isotropic, so directionality could be relevant even at this basic level.

4 Summary and conclusions

The experimental search for axions is extraordinarily motivated. Several fundamental problems in modern physics can be explained with a single pseudo-scalar particle. ALPs are particles similar to axion arising from Standard Model and String theory extensions. Simultaneously with the search for axions, another interesting dark matter candidate can be explored, the so-called dark photon. These particles interact with ordinary photons and so can be detected.

Given the fruitless searches of other DM candidates [45] and the discovery in July 2012 of a Higgs-like boson ([46], [47]), the first fundamental particle of a scalar nature, there is a renewed effort in the scientific community to characterize experimentally and find the axion in the parameter space in which this can simultaneously solve the mystery of DM and the problem of CP symmetry of the strong interaction. This energy space is weak and requires ultra sensitive detectors. In order to face this challenge, the haloscope was proposed [48].

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24 It is in the mass range of [59].
25 Notice that axion is a pseudo-scalar particle.
In this article, we have presented a haloscope of high sensitivity and remarkable simplicity able to probe the 25–250 µeV mass range. The proposed set-up has the advantage of simultaneously exploring axion, ALPs and dark photon sectors during scanning.

A highlighted novelty of this experiment is the possibility of directional scanning. The apparatus is sensitive from low-velocity up to ultrarelativistic particles. The relevance on directionality and the exploration of rapid particles (astroparticles) is remarkable. The haloscope is the most sensitive instrument to date for the detection of relic axions, ALPs and dark photons. However, in the case that cold dark matter is distributed in the form of substructures (miniclusters, minihalos, etc.), and that Earth is placed within a low density region ($\rho_{\text{DM}} << 300 \text{ MeV cm}^{-3}$), haloscopes present a weakness since they depend on halo density. In this case, DM astroparticle scanning (assuming a significant particles flux) using DM telescopes and helioscopes, or laboratory experiments in which the axion pump is artificially generated, could be the only direct detection strategy. Note that DM populations of varied origin are additive if they have a similar dynamic mass, resulting in an improved signal to noise ratio. On the other hand, the telescope mode of DALI would allow one to obtain data from a variety of sources, mechanisms, etc. Axioastronomy could probe several theories and hypotheses.26

Another advantage of DALI is that it has been designed using only state-of-the-art (commercial) technology.27 There lack of the need for R&D reduces the cost in hardware and benefits from faster manufacturing and easier maintenance. We estimate that the cost of the experiment compared to similar proposals is reduced by an order of magnitude, even considering that DALI adds an altazimutal platform. Extending the discussion, the dielectric plates should not be monolithic if we aim for low cost and easy fabrication. The size of the plates is too big for this type of manufacturing and there is currently no reliable technique to fabricate such thin and long plates at a reasonable price without consuming resources in R&D, as far as the author is aware. The solution using a grid formed of commercial wafers reduces the price of the experiment at the cost of introducing uncertainties in the Fabry–Pérot resonator with respect to ideality. However, some of the mechanical uncertainties (which could affect the power boost factor) would be mitigated by 3D-FEM simulations of a parsimonious model.28 The grid based Fabry–Pérot interferometer allows us to establish a compromise between boost power (sensitivity to particles density) and de Broglie coherence (sensitivity to particle velocity and mass) for each specific scientific case, with minimal reconfiguration. On the other hand, the decision to use an (MRI) commercial multi-coil magnet, although this limits the size and the magnetic inductance that is possible to incorporate into the experiment, results in economy and reduced (global) fabrication time.

We plan to scan the entire 6–60 GHz band sequentially, in sub-bands of the order of 100 MHz wide, each taking a few days/weeks of time for scanning. In case of marginal detection, more time will be spent scanning the sub-band of interest. The reconfiguration needed for scanning the 6–60 GHz band is small and consists in grid resizement and the replacement of the microwave receivers.29 Thus, the completion of the experiment will take several years, during which slight adjustments will be made. Regarding the timeline, we aim to be able to start science before 2025.

26See section 3 for an extended discussion.
27With the exception of the MSA-based radiometers presented in case 3 in Fig. 6. Although used in magnetized experiments, this technology is feasible but challenging.
28Simplified, scaled, etc. whose results are transferable to the case of study.
29Standard radiometers have a typical bandwidth factor 1.4:1.
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References

[1] S. Weinberg, *A new light boson?*, Phys. Rev. Lett. 40 (1978) 223–226. doi:10.1103/PhysRevLett.40.223.

[2] F. Wilczek, *Problem of strong p and t invariance in the presence of instantons*, Phys. Rev. Lett. 40 (1978) 279–282. doi:10.1103/PhysRevLett.40.279.

[3] R. D. Peccei, H. R. Quinn, *CP conservation in the presence of pseudoparticles*, Phys. Rev. Lett. 38 (1977) 1440–1443. doi:10.1103/PhysRevLett.38.1440.

[4] L. Abbott, P. Sikivie, *A cosmological bound on the invisible axion*, Physics Letters B 120 (1) (1983) 133 – 136. doi:https://doi.org/10.1016/0370-2693(83)90639-X.

[5] M. Dine, W. Fischler, *The not-so-harmless axion*, Physics Letters B 120 (1) (1983) 137 – 141. doi:https://doi.org/10.1016/0370-2693(83)90637-8.

[6] J. Preskill, M. B. Wise, F. Wilczek, *Cosmology of the invisible axion*, Physics Letters B 120 (1) (1983) 127 – 132. doi:https://doi.org/10.1016/0370-2693(83)90638-X.

[7] M. Tanabashi, K. Hagiwara, K. Hikasa, K. Nakamura, Y. Sumino, F. Takahashi, J. Tanaka, K. Agashe, G. Aielli, C. Ansler, M. Antonelli, D. M. Asner, H. Baer, S. Banerjee, R. M. Barnett, T. Basaglia, C. W. Bauer, J. J. Beatty, V. I. Belousov, J. Beringer, S. Bethke, A. Bettini, H. Bichsel, O. Biebel, K. M. Black, E. Blucher, O. Buchmüller, V. Burkert, M. A. Bychkov, R. N. Cahn, M. Carena, A. Cecchini, A. Cerri, D. Chakraborty, R. M.-C. Chen, R. S. Chivukula, G. Cowan, O. Dahl, G. D’Ambrosio, T. Damour, D. de Florian, A. de Gouvêa, T. DeGrand, P. de Jong, G. Dissertori, B. A. Dobrescu, M. D’Onofrio, M. Doser, M. Dreess, H. K. Dreiner, D. A. Dwyer, P. Eerola, S. Eidelman, J. Ellis, J. Erler, V. V. Ezhelea, W. Fetscher, B. D. Fields, R. Firestone, B. Foster, A. Freitas, H. Gallacher, L. Garren, H.-J. Haber, C. Hanhart, S. Hashimoto, G. Hayato, K. G. Hayes, A. Hebecker, S. Heinemeyer, B. Helsley, J. J. Hernández-Rey, J. Hisano, A. Höcker, J. Holder, A. Holtkamp, T. Hyodo, K. K. Iwaki, K. F. Johnson, M. Kado, M. Karlins, U. F. Katz, S. R. Klein, E. Klempt, R. V. Kowalewski, F. Krauss, M. Kreps, B. Krusche, Y. V. Kuyanov, Y. Kwon, O. Lahav, J. Laiho, J. Lesgourgues, A. Liddle, Z. Ligeti, C.-J. Lin, C. Lippmann, T. M. Liss, L. Littenberg, K. S. Lvovskyy, S. B. Luvsy, A. Lusiani, Y. Makida, F. Maltoni, T. Mannel, A. V. Manohar, W. J. Marciano, A. D. Martin, A. Masoni, J. Matthews, U.-G. Meißen, D. Milstead, R. E. Mitchell, K. Möüig, P. Molaro, F. Moortgat, M. Mosovic, H. Murayama, M. Nair, P. Nason, S. Navas, M. Neubert, P. Nevski, Y. Niy, K. A. Olive, S. Pagani Griso, J. Parsons, C. Patrignani, J. A. Peacock, M. Pennington, S. T. Petcov, V. A. Petrov, E. Pianori, A. Piepke, A. Pomarol, A. Quadtt, J. Rademacker, G. Raffelt, B. N. Ratcliff, P. Richardson, A. Ringwald, S. Roesler, S. Rolli, A. Romaniouk, L. J. Rosenberg, J. L. Rosner, G. Rybak, R. A. Ryutin, C. T. Sachrajda, Y. Sakai, G. P. Salam, S. Sarkar, F. Sauli, O. Schneiders, K. Scholberg, A. J. Schwartz, D. Scott, V. Sharma, S. R. Sharpe, T. Shutt, M. Silari, T. Sjöstrand, P. Skands, T. Skwarnicki, J. G. Smith, G. F. Smoot, S. Spanier, H. Spieler, C. Spiering, A. Stahl, S. L. Stone, T. Sumiyoshi, M. J. Syphers, K. Terashi, J. Terning, U. Thoma, R. S. Thorne, L. Tiator, M. Titov, N. P. Tkachenko, N. A. Törnqvist, D. R. Tovey, G. Valencia, R. Van de Water, N. Varelas, G. Venanzoni, L. Verde, M. G. Vincenzo, P. Vogel, A. Vogt, S. P. Wakely, W. Walkowiak, C. W. Walter, D. Wands, D. R. Ward, M. O. Wascko, G. Weiglein, D. H.
Weinberg, E. J. Weinberg, M. White, L. R. Wienecke, C. G. Wohl, J. Womersley, C. L. Woody, R. L. Workman, W.-M. Yao, G. P. Zeller, O. V. Zenin, R.-Y. Zhu, S.-L. Zhu, F. Zimmermann, P. A. Zyla, J. Anderson, L. Fuller, V. S. Lugovsky, P. Schaffner, Review of particle physics, Phys. Rev. D 98 (2018) 030001. doi:10.1103/PhysRevD.98.030001.

[8] I. G. Irastorza, J. Redondo, New experimental approaches in the search for axion-like particles, Progress in Particle and Nuclear Physics 102 (2018) 89 – 159. doi:https://doi.org/10.1016/j.ppnp.2018.05.003.

[9] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo, A. Ringwald, WISPy cold dark matter, Journal of Cosmology and Astroparticle Physics 2012 (06) (2012) 013–013. doi:10.1088/1475-7516/2012/06/013.

[10] H. Primakoff, Photo-production of neutral mesons in nuclear electric fields and the mean life of the neutral meson, Phys. Rev. 81 (1951) 899–899. doi:10.1103/PhysRev.81.899.

[11] R. Ballou, G. Deferne, M. Finger, M. Finger, L. Flekova, J. Hosok, S. Kunc, K. Macuchova, K. A. Meissner, P. Pugnat, M. Schott, A. Szczepaniak, M. Sulc, C. Weinheimer, J. Zicha, New exclusion limits on scalar and pseudoscalar axionlike particles from light shining through a wall, Phys. Rev. D 92 (2015) 092002. doi:10.1103/PhysRevD.92.092002.

[12] F. Della Valle, A. Ejlli, U. Gastaldi, G. Messineo, E. Milotti, R. Penco, G. Ruso, G. Zavattini, The PVLAS experiment: measuring vacuum magnetic birefringence and dichroism with a birefringent Fabry–Perot cavity, Eur. Phys. J. C76 (1) (2016) 24. arXiv:1510.08052, doi:10.1140/epjc/s10052-015-3869-8.

[13] G. Raffelt, Limits on a $cP$-violating scalar axion-nucleon interaction, Phys. Rev. D 86 (2012) 015001. doi:10.1103/PhysRevD.86.015001.

[14] D. M. Lazarus, G. C. Smith, R. Cameron, A. C. Melissinos, G. Ruso, Y. K. Semertzidis, F. A. Nezrick, Search for solar axions, Phys. Rev. Lett. 69 (1992) 2333–2336. doi:10.1103/PhysRevLett.69.2333.

[15] V. Anastassopoulos, et al., New CAST Limit on the Axion-Photon Interaction, Nature Phys. 13 (2017) 584–590. arXiv:1705.02290, doi:10.1038/nphys4109.

[16] D. S. Akerib, S. Alsum, C. Aquino, H. M. Araújo, X. Bai, A. J. Bailey, J. Balajthy, P. Beltrame, E. P. Bernard, A. Bernstein, T. P. Biesiadzinski, E. M. Boulton, P. Brás, D. Byram, S. B. Cahn, M. C. Carmona-Benítez, C. Chan, A. A. Chiller, C. Chiller, A. Currie, J. E. Cutter, T. J. R. Davison, A. Dobi, J. E. Y. Dobson, E. Druszkiewicz, B. N. Edwards, C. H. Faham, S. R. Fannon, S. Fiorucci, R. J. Gaiteskill, V. M. Gehman, C. Ghag, K. R. Gibson, M. G. D. Gilchriese, C. R. Hall, M. Hanhardt, S. J. Haselschwart, S. A. Hertel, D. P. Hogan, M. Horn, D. Q. Huang, C. M. Ignarra, R. G. Jacobsen, W. Ji, K. Kamdín, K. Kazkaz, D. Khaitan, R. Knoch, N. A. Larsen, C. Lee, B. G. Lenardo, K. T. Lesko, A. Lindote, M. I. Lopes, A. Manalaysay, R. L. Mannino, M. F. Marzonia, D. N. McKinsey, D.-M. Mei, J. Mock, M. Moongweluwan, J. A. Morad, A. S. J. Murphy, C. Nehrkor, H. N. Nelson, F. Neves, K. O’Sullivan, K. C. Oliver-Mallory, K. J. Palladino, E. K. Pease, L. Reichhart, C. Ryhne, S. Shaw, T. A. Shutt, C. Silva, M. Solmaz, V. N. Sołowoj, P. Sorensen, S. Stephenson, T. J. Sumner, M. Szydagis, D. J. Taylor, W. C. Taylor, B. P. Tennyson, P. A. Ternan, D. R. Tiedt, W. H. To, M. Tripathi, L. Tzirnikova, S. Uvarov, V. Velan, J. R. Verbus, R. C. Webb, J. T. White, T. J. Whitmis, M. S. Witherell, F. L. H. Wolfs, J. Xu, K. Yazdani, S. K. Young, C. Zhang, First searches for axions and axionlike particles with the lux experiment, Phys. Rev. Lett. 118 (2017) 261301. doi:10.1103/PhysRevLett.118.261301.

[17] G. G. Raffelt, Particle physics from stars, Annual Review of Nuclear and Particle Science 49 (1) (1999) 163–216. arXiv:https://doi.org/10.1146/annurev.nucl.49.1.163, doi:10.1146/annurev.nucl.49.1.163.

[18] N. Vinyoles, A. Serenelli, F. Villante, S. Basu, J. Redondo, J. Isern, New axion and hidden
photon constraints from a solar data global fit, Journal of Cosmology and Astroparticle Physics 2015 (10) (2015) 015–015. doi:10.1088/1475-7516/2015/10/015.

[19] N. Viaux, M. Catelan, P. B. Stetson, G. G. Raffelt, J. Redondo, A. A. R. Valcarce, A. Weiss, Neutrino and axion bounds from the globular cluster m5 (ngc 5904), Phys. Rev. Lett. 111 (2013) 231301. doi:10.1103/PhysRevLett.111.231301.

[20] M. M. Bertolami, B. Melendez, L. Althaus, J. Isern, Revisiting the axion bounds from the galactic white dwarf luminosity function, Journal of Cosmology and Astroparticle Physics 2014 (10) (2014) 069–069. doi:10.1088/1475-7516/2014/10/069.

[21] T. Fischer, S. Chakraborty, M. Giannotti, A. Mirizzi, A. Payez, A. Ringwald, Probing axions with the neutrino signal from the next galactic supernova, Phys. Rev. D 94 (2016) 085012. doi:10.1103/PhysRevD.94.085012.

[22] P. Carenza, T. Fischer, M. Giannotti, G. Guo, G. Martínez-Pinedo, A. Mirizzi, Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung, Journal of Cosmology and Astroparticle Physics 2019 (10) (2019) 016–016. doi:10.1088/1475-7516/2019/10/016.

[23] L. B. Leinson, Axion mass limit from observations of the neutron star in cassiopeia a, Journal of Cosmology and Astroparticle Physics 2014 (08) (2014) 031–031. doi:10.1088/1475-7516/2014/08/031.

[24] A. Arvanitaki, S. Dimopoulos, S. Dubovsky, N. Kaloper, J. March-Russell, String axiverse, Phys. Rev. D 81 (2010) 123530. doi:10.1103/PhysRevD.81.123530.

[25] W. U. Wuensch, S. De Panfilis-Wuensch, Y. K. Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, F. A. Nezrick, Limits on the abundance and coupling of cosmic axions at 4.5< m< 5.0 µev, Phys. Rev. Lett. 59 (1987) 839–842. doi:10.1103/PhysRevLett.59.839.

[26] S. DePanfilis, A. C. Melissinos, B. E. Moskowitz, J. T. Rogers, Y. K. Semertzidis, W. U. Wuensch, H. J. Halama, A. G. Prodell, W. B. Fowler, F. A. Nezrick, Results of a laboratory search for cosmic axions and other weakly coupled light particles, Phys. Rev. D 40 (1989) 3153–3167. doi:10.1103/PhysRevD.40.3153.

[27] L. Zhong, S. Al Kenany, K. M. Backes, B. M. Brubaker, S. B. Cahn, G. Carosi, Y. V. Gurevich, W. F. Kindel, S. K. Lamoreaux, K. W. Lehnert, S. M. Lewis, M. Malnou, R. H. Maruyama, D. A. Palken, N. M. Rapidis, J. R. Root, M. Simonovskaia, T. M. Shokair, D. H. Speller, I. Urdinaran, K. A. van Bibber, Results from phase 1 of the haystac microwave cavity axion experiment, Phys. Rev. D 97 (2018) 092001. doi:10.1103/PhysRevD.97.092001.

[28] B. T. McAllister, G. Flower, E. N. Ivanov, M. Goryachev, J. Bourhill, M. E. Tobar, The organ experiment: An axion haloscope above 15 ghz, Physics of the Dark Universe 18 (2017) 67 – 72. doi:https://doi.org/10.1016/j.dark.2017.09.010.

[29] B. Bozek, D. J. E. Marsh, J. Silk, R. F. G. Wyse, Galaxy UV-luminosity function and reionization constraints on axion dark matter, Monthly Notices of the Royal Astronomical
[33] D. J. E. Marsh, J. Silk, A model for halo formation with axion mixed dark matter, Monthly Notices of the Royal Astronomical Society 437 (3) (2013) 2652–2663. arXiv:https://academic.oup.com/mnras/article-pdf/437/3/2652/18465517/stt2079.pdf, doi:10.1093/mnras/stt2079.

[34] D. J. Marsh, Axion cosmology, Physics Reports 643 (2016) 1–79, axion cosmology. doi:https://doi.org/10.1016/j.physrep.2016.06.005.

[35] J. E. Kim, Weak-interaction singlet and strong CP invariance, Phys. Rev. Lett. 43 (1979) 103–107. doi:10.1103/PhysRevLett.43.103.

[36] M. Shifman, A. Vainshtein, V. Zakharov, Can confinement ensure natural cp invariance of strong interactions?, Nuclear Physics B 166 (3) (1980) 493 – 506. doi:https://doi.org/10.1016/0550-3213(80)90209-6.

[37] M. Dine, W. Fischler, M. Srednicki, A simple solution to the strong cp problem with a harmless axion, Physics Letters B 104 (3) (1981) 199 – 202. doi:https://doi.org/10.1016/0370-2693(81)90590-6.

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

[39] S. M. Barr, J. E. Kim, New confining force solution of the qcd axion domain-wall problem, Phys. Rev. Lett. 113 (2014) 241301. doi:10.1103/PhysRevLett.113.241301.

[40] L. Di Luzio, F. Mescia, E. Nardi, Redefining the axion window, Phys. Rev. Lett. 118 (2017) 031801. doi:10.1103/PhysRevLett.118.031801.

[41] E. I. Gates, G. Gyuk, M. S. Turner, The local halo density, The Astrophysical Journal 449 (2). doi:10.1086/309652.

[42] L. Okun, The limits of electrodynamics - paraphotons, Zhurnal Eksperimental noi i Teoreticheskoi Fiziki 83 (1982) 892–898.

[43] A. Vilenkin, Particles and the universe, North Holland. G. Lazarides and Q. Shafi (eds.) Amsterdam (1986) p. 133.

[44] J. Redondo, M. Postma, Massive hidden photons as lukewarm dark matter, Journal of Cosmology and Astroparticle Physics 2009 (02) (2009) 005–005. doi:10.1088/1475-7516/2009/02/005.

[45] M. Schumann, Direct detection of WIMP dark matter: concepts and status, Journal of Physics G: Nuclear and Particle Physics 46 (10) (2019) 103003. doi:10.1088/1361-6471/ab2ea5.

[46] G. Aad, et al., Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC, Phys. Lett. B716 (2012) 1–29. arXiv:1207.7214, doi:10.1016/j.physletb.2012.08.020.

[47] S. Chatrchyan, et al., Observation of a New Boson at a Mass of 125 GeV with the CMS Experiment at the LHC, Phys. Lett. B716 (2012) 30–61. arXiv:1207.7235, doi:10.1016/j.physletb.2012.08.021.

[48] P. Sikivie, Experimental tests of the "invisible" axion, Phys. Rev. Lett. 51 (1983) 1415–1417. doi:10.1103/PhysRevLett.51.1415.

[49] A. J. Millar, G. G. Raffelt, J. Redondo, F. D. Steffen, Dielectric haloscopes to search for axion dark matter: theoretical foundations, Journal of Cosmology and Astroparticle Physics 2017 (01) (2017) 061–061. doi:10.1088/1475-7516/2017/01/061.
[50] A. J. Millar, J. Redondo, F. D. Steffen, Dielectric haloscopes: sensitivity to the axion dark matter velocity. Journal of Cosmology and Astroparticle Physics 2017 (10) (2017) 006–006. doi:10.1088/1475-7516/2017/10/006.

[51] D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo, A. Ringwald, Searching for WISPy cold dark matter with a dish antenna. Journal of Cosmology and Astroparticle Physics 2013 (04) (2013) 016–016. doi:10.1088/1475-7516/2013/04/016.

[52] A. N. Ioannisian, N. Kazarian, A. J. Millar, G. G. Raffelt, Axion-photon conversion caused by dielectric interfaces: quantum field calculation. Journal of Cosmology and Astroparticle Physics 2017 (09) (2017) 005–005. doi:10.1088/1475-7516/2017/09/005.

[53] J. Jaeckel, S. Knirck, Directional resolution of dish antenna experiments to search for wispy dark matter. Journal of Cosmology and Astroparticle Physics 2016. doi:10.1088/1475-7516/2016/01/005.

[54] G. Rybka, A. Wagner, K. Patel, R. Percival, K. Ramos, A. Brill, Search for dark matter axions with the orpheus experiment. Physical Review D 91. doi:10.1103/PhysRevD.91.011701.

[55] A. Caldwell, G. Dvali, B. Majorovits, A. Millar, G. Raffelt, J. Redondo, O. Reimann, F. Simon, F. Steffen, Dielectric haloscopes: A new way to detect axion dark matter. Phys. Rev. Lett. 118 (2017) 091801. doi:10.1103/PhysRevLett.118.091801.

[56] MADMAX Collaboration, P. Brun, A. Caldwell, L. Chevalier, G. Dvali, P. Freire, E. Garutti, S. Heyninck, J. Jochum, S. Knirck, M. Kramer, C. Krieger, T. Lasserre, C. Lee, X. Li, A. Lindner, B. Majorovits, S. Martens, M. Matysek, A. Millar, G. Raffelt, J. Redondo, O. Reimann, A. Ringwald, K. Sakawa, J. Schaffran, A. Schmidt, J. Schütte-Engel, F. Steffen, C. Strandhagen, G. Wieching, A new experimental approach to probe QCD axion dark matter in the mass range above 40 µeV. The European Physical Journal C 79 (3) (2019) 186. doi:10.1140/epjc/s10052-019-6683-x.

[57] A. Á. Melcón, S. A. Cuendis, C. Cogollos, A. Díaz-Morcillo, B. Dávirich, J. D. Gallego, B. Gimeno, I. G. Irastorza, A. J. Lozano-Guerrero, C. Malbrunot, P. Navarro, C. P. Garay, J. Redondo, T. Vafeiadis, W. Wuensch, Axion searches with microwave filters: the RADES project. Journal of Cosmology and Astroparticle Physics 2018 (05) (2018) 040–040. doi:10.1088/1475-7516/2018/05/040.

[58] I. G. Irastorza, J. A. García, Direct detection of dark matter axions with directional sensitivity. Journal of Cosmology and Astroparticle Physics 2012 (10) (2012) 022–022. doi:10.1088/1475-7516/2012/10/022.

[59] J. L. Ouellet, C. P. Salemi, J. W. Foster, R. Henning, Z. Bogorad, J. M. Conrad, J. A. Formaggio, Y. Kuhn, J. Minervini, A. Radovinsky, N. L. Rodd, B. R. Safdi, J. Thaler, D. Winklehner, L. Winslow, First results from abracadabra-10 cm: A search for sub-µeV axion dark matter. Phys. Rev. Lett. 122 (2019) 121802. doi:10.1103/PhysRevLett.122.121802.

[60] M. R. Islam, M. M. Ali, M. H. Lai, K.-S. Lim, H. Ahmad, Chronology of fabry-perot interferometer fiber-optic sensors and their applications: A review. Sensors (Basel, Switzerland) 14 (2014) 7451–88. doi:10.3390/s140407451.

[61] S. Knirck, Madmax: A new way of probing qcd axion dark matter with a dielectric haloscope – foundations. Journal of Physics: Conference Series 1342. doi:10.1088/1742-6596/1342/1/012097.

[62] B. Majorovits, J. Group, Madmax: A new dark matter axion search using a dielectric haloscope.

[63] J. Egge, S. Knirck, B. Majorovits, C. Moore, O. Reimann, A first proof of principle booster setup for the madmax dielectric haloscope (2020). arXiv:2001.04363.

[64] A. Larkoski, Elementary particle physics. An intuitive introduction. isbn:9781108496988, Cambridge University Press (2019) pp.86–87.
[65] P. Tinyakov, I. Tkachev, K. Zioutas, Tidal streams from axion miniclusters and direct axion searches, Journal of Cosmology and Astroparticle Physics 2016 (01) (2016) 035–035. doi:10.1088/1475-7516/2016/01/035.

[66] V. I. Dokuchaev, Y. N. Eroshenko, I. I. Tkachev, Destruction of axion miniclusters in the galaxy, Journal of Experimental and Theoretical Physics 125 (3) (2017) 434–442. doi:10.1134/S1063776117080039.

[67] V. Berezinsky, V. Dokuchaev, Y. Eroshenko, Formation and internal structure of superdense dark matter clumps and ultracompact minihaloes, Journal of Cosmology and Astroparticle Physics 2013 (11) (2013) 059–059. doi:10.1088/1475-7516/2013/11/059.

[68] S. Davidson, T. Schwetz, Rotating drops of axion dark matter, Phys. Rev. D 93 (2016) 123509. doi:10.1103/PhysRevD.93.123509.

[69] I. I. Tkachev, Fast radio bursts and axion miniclusters, JETP Letters 101 (1) (2015) 1–6. doi:10.1134/S0021364015010154.

[70] M. Fairbairn, D. J. E. Marsh, J. Quevillon, Searching for the qcd axion with gravitational microlensing, Phys. Rev. Lett. 119 (2017) 021101. doi:10.1103/PhysRevLett.119.021101.

[71] M. Fairbairn, D. J. E. Marsh, J. Quevillon, S. Rozier, Structure formation and microlensing with axion miniclusters, Phys. Rev. D 97 (2018) 083502. doi:10.1103/PhysRevD.97.083502.

[72] D. G. Levkov, A. G. Panin, I. I. Tkachev, Gravitational bose-einstein condensation in the kinetic regime, Phys. Rev. Lett. 121 (2018) 151301. doi:10.1103/PhysRevLett.121.151301.

[73] C. Hogan, M. Rees, Axion miniclusters, Physics Letters B 205 (2) (1988) 228 – 230. doi:https://doi.org/10.1016/0370-2693(88)91655-3.

[74] L. Visinelli, S. Baum, J. Redondo, K. Freese, F. Wilczek, Dilute and dense axion stars, Physics Letters B 777 (2018) 64 – 72. doi:https://doi.org/10.1016/j.physletb.2017.12.010.

[75] P. Gorham, et al., Observation of an unusual upward-going cosmic-ray-like event in the third flight of ANITA, Phys.Rev.Lett. 121 (16) (2018) 161102. arXiv:1803.05088, doi:10.1103/PhysRevLett.121.161102.

[76] M. Aartsen, et al., A search for ICECUBE events in the direction of ANITA neutrino candidates.arXiv:2001.01737.

[77] K. D. de Vries, S. Prohira, Coherent transition radiation from the geomagnetically induced current in cosmic-ray air showers: Implications for the anomalous events observed by ANITA, Phys. Rev. Lett. 123 (2019) 091102. doi:10.1103/PhysRevLett.123.091102.

[78] I. Shoemaker, A. Kusenko, P. Munneke, A. Romero-Wolf, D. Schroeder, M. Siegert, Reflections on the anomalous anita events: The antarctic subsurface as a possible explanation (05 2019).

[79] D. B. Fox, S. Sigurdsson, S. Shandera, P. MÁ¡száros, K. Murase, M. Mostafã±, S. Coutu, The ANITA anomalous events as signatures of a beyond standard model particle, and supporting observations from icecube (2018). arXiv:1809.09615.

[80] G.-y. Huang, Sterile neutrinos as a possible explanation for the upward air shower events at ANITA, Phys. Rev. D98 (4) (2018) 043019. arXiv:1804.05362, doi:10.1103/PhysRevD.98.043019.

[81] J. M. Cline, C. Gross, W. Xue, Can the ANITA anomalous events be due to new physics?, Phys. Rev. D 100 (2019) 015031. doi:10.1103/PhysRevD.100.015031.

[82] A. Ringwald, Searching for axions and ALPs from string theory, Journal of Physics: Conference Series 485 (2014) 012013. doi:10.1088/1742-6596/485/1/012013.

[83] J. Vergados, Y. Semertzidis, Axionic dark matter signatures in various halo models, Nuclear Physics B 915 (2017) 10 – 18. doi:https://doi.org/10.1016/j.nuclphysb.2016.12.002.
[84] A. R. Zhitnitsky, *Nonbaryonic dark matter as baryonic colour superconductor*, Journal of Cosmology and Astroparticle Physics 2003 (10) (2003) 010–010. doi:10.1088/1475-7516/2003/10/010.

[85] H. Fischer, X. Liang, A. Zhitnitsky, Y. Semertzidis, K. Zioutas, *New mechanism producing axions in the aqn model and how the cast can discover them*, Phys. Rev. D 98 (2018) 043013. doi:10.1103/PhysRevD.98.043013.

[86] J. A. Klimchuk, *On solving the coronal heating problem*, Solar Physics 234 (1) (2006) 41–77. doi:10.1007/s11207-006-0055-z.

[87] L. DiLella, K. Zioutas, *Observational evidence for gravitationally trapped massive axion(-like) particles*, Astroparticle Physics 19 (1) (2003) 145 – 170. doi:https://doi.org/10.1016/S0927-6505(02)00186-X.

[88] A. Zhitnitsky, *Solar extreme EUV radiation and quark nugget dark matter model*, Journal of Cosmology and Astroparticle Physics 2017 (10) (2017) 050–050. doi:10.1088/1475-7516/2017/10/050.

[89] N. Raza, L. Van Waerbeke, A. Zhitnitsky, *Solar corona heating by axion quark nugget dark matter*, Phys. Rev. D 98 (2018) 103527. doi:10.1103/PhysRevD.98.103527.

[90] L. Duffy, *High Resolution Search for Dark Matter Axions in Milky Way Halo Substructure*, Ph.D. thesis, Florida U. (2006).

[91] S. Bertolucci, K. Zioutas, S. Hofmann, M. Maroudas, *The sun and its planets as detectors for invisible matter*, Physics of the Dark Universe 17 (2017) 13 – 21. doi:https://doi.org/10.1016/j.dark.2017.06.001.

[92] K. Choi, J. E. Kim, D. Son, *Proceedings on 11th International Symposium on Particles, Strings and Cosmology (PASCOS 2005)*, AIP Conf. Proc. 805 (2005) pp.1–486.

[93] J. Hoskins, N. Crisosto, J. Gleason, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, C. Boutan, M. Hotz, R. Khatiwada, D. Lyapustin, A. Malagon, R. Ottens, L. J. Rosenberg, G. Rybka, J. Sloan, A. Wagner, D. Will, G. Carosi, D. Carter, L. D. Duffy, R. Bradley, J. Clarke, S. O’Kelley, K. van Bibber, E. J. Daw, *Modulation sensitive search for nonvirialized dark-matter axions*, Phys. Rev. D 94 (2016) 082001. doi:10.1103/PhysRevD.94.082001.

[94] K. Zioutas, V. Anastassopoulos, S. Bertolucci, G. Cantatore, S. A. Cetin, H. Fischer, W. Funk, A. Gardikiotis, D. H. H. Hoffmann, S. Hofmann, M. Karuza, M. Maroudas, Y. K. Semertzidis, I. Tkatchev, *Search for axions in streaming dark matter*, arXiv e-prints (2017) arXiv:1703.01436arXiv:1703.01436.

[95] C. Boutan, M. Jones, B. H. LaRoque, N. S. Oblath, R. Cervantes, N. Du, N. Force, S. Kimes, R. Ottens, L. J. Rosenberg, G. Rybka, J. Yang, G. Carosi, N. Woollett, D. Bowring, A. S. Chou, R. Khatiwada, A. Sonnenschein, W. Wester, R. Bradley, E. J. Daw, A. Agrawal, A. V. Dixit, J. Clarke, S. R. O’Kelley, N. Crisosto, J. R. Gleason, S. Jois, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, P. M. Harrington, E. Lentz, *Piezoelectrically tuned multimode cavity search for axion dark matter*, Phys. Rev. Lett. 121 (2018) 261302.

[96] L. Zhong, B. M. Brubaker, S. B. Cahn, S. K. Lamoreaux, *Recent technical improvements to the haystack experiment* (2017). arXiv:1706.03676.

[97] J. SchAjtte-Engel, *Simulation studies for the madmax axion direct detection experiment* (2018). arXiv:1811.00493.
[100] S. Knirck, J. SchÃijtte-Engel, A. Millar, J. Redondo, O. Reimann, A. Ringwald, F. Steffen, A first look on 3d effects in open axion haloscopes, Journal of Cosmology and Astroparticle Physics 2019 (08) (2019) 026–026. doi:10.1088/1475-7516/2019/08/026.

[101] O. Tajima, J. Choi, M. Hazumi, H. Ishitsuka, M. Kawai, M. Yoshida, GroundBIRD: an experiment for CMB polarization measurements at a large angular scale from the ground, in: Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI, Vol. 8452 of Proceedings of SPIE, 2012, p. 84521M. doi:10.1117/12.925816.

[102] J. A. RubiÃśño Martín, R. Rebolo, M. Tucci, R. Génova-Santos, S. R. Hildebrandt, R. Hoyland, J. Herreros, F. GAñnez-ReAñasco, C. López-Caraballo, E. Martínez-Gonzalez, P. Vielva, D. Herranz, F. Casas, E. Artal, B. Aja, L. de la Fuente, J. Cano, E. Villa, A. Mediavilla, B. Etxeita, The Quijote CMB Experiment (2010) 127–135 doi:$10.1007/978-3-642-11250-8_12$.

[103] R. H. Dicke, The measurement of thermal radiation at microwave frequencies, Sci. Inst. 17 (1946) 268–275.

[104] J. Clarke, D. Kinion, The Microstrip SQUID Amplifier: Upgrading the Axion Dark Matter Experiment (ADMX), in: APS California Section Meeting Abstracts, APS Meeting Abstracts, 2011, p. F2.007.

[105] S. Asztalos, G. Carosi, C. Hagmann, D. Kinion, K. van Bibber, M. Hotz, L. J. Rosenberg, G. Rybka, A. Wagner, J. Hoskins, C. Martin, N. Sullivan, D. Tanner, R. Bradley, J. Clarke, Design and performance of the ADMX squid-based microwave receiver, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 656 (1) (2011) 39 – 44. doi:https://doi.org/10.1016/j.nima.2011.07.019.

[106] S. O’Kelley, G. Hilton, J. Clarke, ADMX Collaboration, Tunable microstrip SQUID amplifiers for the Gen 2 Axion Dark Matter eXperiment (ADMX), in: APS April Meeting Abstracts, Vol. 2016 of APS Meeting Abstracts, 2016, p. K16.004.

[107] S. Uchaikin, A. Matlashov, D. Lee, W. Chung, S. J. Oh, Y. Semertzidis, V. Zakosarenko, C. Kuthu, A. van Loo, Y. Urade, S. Kono, M. Schmelz, R. Stolz, Y. Nakamura, Development of squid amplifiers for axion search experiments, in: 2019 IEEE International Superconductive Electronics Conference (ISEC), 2019, pp. 1–3. doi:10.1109/ISEC46533.2019.8990953.

[108] A. Matlashov, M. Schmelz, V. Zakosarenko, R. Stolz, Y. K. Semertzidis, Squid amplifiers for axion search experiments, Cryogenics 91 (2018) 125 – 127. doi:https://doi.org/10.1016/j.cryogenics.2018.03.003.

[109] J. Suzuki, Y. Inoue, T. Horie, M. Minowa, Hidden photon CDM search at Tokyo (2015). arXiv:1509.00785.

[110] De Miguel-Hernandez, Javier and Hoyland, Roger J. and Renasco, Maria F. and Gomez and Rubino-Martín, J. and Albert and Viera-Curbelo, Teodora A., A High Sensitivity Fourier Transform Spectrometer for Cosmic Microwave Background Observations, IEEE Transactions on Instrumentation and Measurement (2019). https://arxiv.org/abs/1910.10415

[111] K. Lawson, X. Liang, A. Mead, M. S. R. Siddiqui, L. Van Waerbeke and A. Zhitnitsky, Gravitationally trapped axions on the Earth, Phys. Rev. D 100 (2019) no.4, 043531 doi:10.1103/PhysRevD.100.043531 [arXiv:1905.00022 [astro-ph.CO]].

[112] D. Budker, V. V. Flambaum, X. Liang and A. Zhitnitsky, Axion Quark Nuggets and how a Global Network can discover them, Phys. Rev. D 101 (2020) no.4, 043012 doi:10.1103/PhysRevD.101.043012 [arXiv:1909.09475 [hep-ph]].

[113] X. Liang and A. Zhitnitsky, Gravitationally bound axions and how one can discover them, Phys. Rev. D 99 (2019) no.2, 023015 doi:10.1103/PhysRevD.99.023015 [arXiv:1810.00673 [hep-ph]].
[114] K. Zioutas et al., *Search for axions in streaming dark matter*, arXiv:1703.01436 [physics.ins-det].

[115] B.J. Patla, NIST, private communication (2017).

[116] J.-M. Frere, F. S. Ling and G. Vertongen, *Bound on the Dark Matter Density in the Solar System from Planetary Motions*, Phys. Rev. D 77 (2008) 083005 doi:10.1103/PhysRevD.77.083005 [astro-ph/0701542].

[117] F. Froborg and A. R. Duffy, *Annual Modulation in Direct Dark Matter Searches*, arXiv:2003.04545 [astro-ph.CO].

[118] Sergio Bertolucci, Konstantin Zioutas, Sebastian Hofmann, Marios Maroudas, *The Sun and its Planets as detectors for invisible matter*, Physics of the Dark Universe, Volume 17, 2017, Pages 13-21, ISSN 2212-6864.

[119] P. W. Graham and S. Rajendran, *New Observables for Direct Detection of Axion Dark Matter*, Phys. Rev. D 88 (2013) 035023 doi:10.1103/PhysRevD.88.035023 [arXiv:1306.6088 [hep-ph]].