Towards a medium-scale axion helioscope and haloscope

Towards a medium-scale axion helioscope and haloscope

V. Anastassopoulos,[a] F. Avignone,[b] A. Bykov,[c] G. Cantatore,[d] S.A. Cetin,[e] A. Derbin,[f] I. Drachnev,[f] R. Djilkibaev,[g] V. Eremin,[c] H. Fischer,[h] A. Gangapshev,[i] A. Gardikiotis,[a] S. Gninenko,[g] N. Golubev,[g] D.H.H. Hoffmann,[j] M. Karuza,[k] L. Kravchuk,[g] M. Libanov,[g] A. Lutovinov,[l] M. Maroudas,[a] V. Matveev,[g,m] S. Molkov,[l] V. Muratova,[f] V. Pantuev,[g] M. Pavlinsky,[l] K. Ptitsyna,[g] G. Rubtsov,[g] D. Semenov,[f] P. Sikivie,[n] A. Spiridonov,[o] P. Tinyakov,[p] I. Tkachev,[g] S. Troitsky,[g] E. Unzhakov[f] and K. Zioutas[a]

[a] *Patras University, Patras, Greece*
[b] *University of South Carolina, Columbia, U.S.A.*
[c] *Ioffe Institute RAS, St. Petersburg, Russia*
[d] *University of Trieste, Trieste, Italy*
[e] *High Energy Physics Research Center, Bilgi University, Istanbul, Turkey*
[f] *Petersburg Nuclear Physics Institute, St. Petersburg, Russia*
[g] *Institute for Nuclear Research RAS, Moscow, Russia*
[h] *Albert-Ludwigs-Universitaet, Freiburg, Germany*
[i] *Baksan Neutrino Observatory, INR RAS, Neutrino, Russia*
[j] *Institut für Kernphysik/Technische Universität, Darmstadt, Germany*
[k] *University Rijeka, Rijeka, Croatia*
[l] *Space Research Institute RAS, Moscow, Russia*
[m] *Joint Institute for Nuclear Research, Dubna, Russia*
[n] *University of Florida, Gainesville, U.S.A.*
[o] *Physics Department, Moscow State University, Moscow, Russia*
[p] *Université Libre de Bruxelles, Brussels, Belgium*

E-mail: `st@ms2.inr.ac.ru`

Abstraat: We discuss the physics case for and the concept of a medium-scale axion helioscope with sensitivities in the axion-photon coupling a few times better than CERN Axion Solar Telescope (CAST). Search for an axion-like particle with these couplings is motivated by several persistent astrophysical anomalies. We present early conceptual design, existing infrastructure, projected sensitivity and timeline of such a helioscope (Troitsk Axion Solar Telescope Experiment, TASTE) to be constructed in the Institute for Nuclear Research, Troitsk, Russia. The proposed instrument may be also used for the search of dark-matter halo axions.

Keywords: Dark Matter detectors (WIMPs, axions, etc.); Large detector systems for particle and astroparticle physics; X-ray detectors

1 Introduction and motivation

1.1 Axions and axion-like particles

The Standard Model of particle physics cannot explain the mechanism behind the charge-parity (CP) symmetry conservation in strong interactions and does not possess a viable candidate for a dark-matter particle (see e.g. ref. [1] for a brief review of these major problems and further references).

Long ago, attempts to attack the first problem led to the concept of the *axion*, a pseudoscalar particle which appears as a necessary ingredient of the Peccei-Quinn solution [2–4] to the strong CP problem, which remains the most successful and popular approach to the puzzle. Subsequently, it has been understood that the axion is a prospective candidate for a dark-matter particle [5–7]. Recent results of the Large Hadron Collider (LHC), which exclude a large number of other popular dark-matter candidates, make the axion dark matter even more plausible and revive theoretical and experimental interest to light pseudoscalars.

A characteristic property of the axion, which opens a number of possibilities to its laboratory and astrophysical searches, is its two-photon coupling in the Lagrangean,

$$-\frac{1}{4} g_{a\gamma\gamma} \phi F_{\mu\nu} \tilde{F}^{\mu\nu}, \tag{1.1}$$

where ϕ is the pseudoscalar field, $F_{\mu\nu}$ is the electromagnetic field stress tensor and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\lambda}F_{\rho\lambda}$ is its dual tensor. In most axion models related to Quantum Chromodynamics (QCD), the coupling (1.1) arises from the axion mixing with the π meson and is related to the axion mass m_a as [8, 9]

$$g_{a\gamma\gamma} = 10^{-10}\ \text{GeV}^{-1}\, C_\gamma \frac{m_a}{0.5\ \text{eV}}, \tag{1.2}$$

where the model-dependent coefficient $C_\gamma \sim 1$ (see, however, refs. [10–12]). At the same time, pseudoscalars with a similar interaction (1.1) arise in numerous extensions of the Standard Model of particle physics, see e.g. ref. [13] for a review. Depending on the model, they may or may not respect eq. (1.2) and may or may not solve the strong CP problem. For some values of couplings they also may be dark-matter candidates (see ref. [14] for the parameter space relevant for the case when no other interactions beyond eq. (1.1) are present). In any case, however, thanks to the interaction (1.1), these *axion-like particles* (ALPs) should manifest themselves in hot dense plasmas where thermonuclear reactions take place as well as in numerous other laboratory and astrophysical environments.

1.2 Astrophysical constraints and indications

Recent progress in astrophysics makes it possible to use observational data to search for axions and ALPs, or to constrain their parameters. Detailed studies of stellar energy losses constrain $g_{a\gamma\gamma} \lesssim 6.6 \times 10^{-11}\ \text{GeV}^{-1}$ at the 95% confidence level [15], at the same time giving a weak indication in favour of the presence of an axion or ALP with $g_{a\gamma\gamma} \sim (2.9 \pm 1.8) \times 10^{-11}\ \text{GeV}^{-1}$ at the 68% confidence level, see ref. [16] for a wider discussion. However, a much stronger evidence for the existence of an ALP with the photon coupling in this domain comes from the gamma-ray astronomy (for a brief review, see ref. [17]).

Indeed, the Universe is filled with background radiation, on which energetic gamma rays produce electron-positron pairs [18]. This process limits the mean free path of energetic photons to a small fraction of the Universe, strongly dependent on the photon energy. While a comparison of gamma-ray spectra of blazars observed at various distances with FERMI-LAT shows the presence of a certain distance-dependent flux suppresion [19], analyses of ensembles of gamma-ray sources at distances corresponding to large optical depths indicate [20, 21] that the suppression is much weaker than expected. The statistical significance of this anomaly, 12.4 standard deviations [21], makes it a strong argument in favour of existence of unaccounted processes related to the gamma-ray propagation. Interestingly, all the studies which indicate the anomaly have been based on minimal models of the extragalactic background light (EBL), e.g. [22, 23], on the level of the sum of the light from observed galaxies [24], while the very recent dedicated observations making use of two different approaches [25, 26], indicate the EBL intensity twice higher. Proved to be true, these EBL values would make the gamma-ray propagation anomaly even more dramatic.

Potential astrophysical explanations in terms of secondary particles [27, 28] have troubles explaining the effect for most distant sources and, more importantly, are at odds with the observations of strong variability of gamma-ray sources at large optical depths, e.g. [29]. One is forced to invoke new physics for the solution to the anomaly. The pair-production probability might be modified in the presence of a weak Lorentz-invariance violation; however, this violation would also result in non-observation of any TeV photons by Cerenkov atmospheric telescopes because the development of photon-induced air showers would also be suppressed, and is therefore excluded [30, 31].

The remaining viable explanation points to ALPs. Thanks to the interaction (1.1), photon and ALP mix in external magnetic fields [32, 33], while the ALP does not produce e^+e^- pairs. Depending on the parameters, this may result either in axion-photon oscillations in intergalactic magnetic fields, which would enlarge the mean free path of photons from distant sources [34, 35], or in a conversion of a part of emitted photons to ALPs in the magnetic field in the source or in its close environment, subsequent propagation of these ALPs through the Universe and reconversion back to photons in the Milky Way or its surroundings [36, 37]. Present upper limits on extragalactic magnetic fields together with constraints on ALP parameters from non-observation of gamma radiation from supernova SN1987A, persistence of the gamma-ray propagation anomaly up to high redshifts and some hints on the Galactic anisotropy in the anomaly manifestation make the second scenario more favourable [38], though the first one is not yet excluded. The second, Galactic-conversion, scenario may be realized for $g_{a\gamma\gamma} \sim \left(10^{-11} - 10^{-10}\right)\,\mathrm{GeV}^{-1}$ and $m_a \sim \left(10^{-9} - 10^{-7}\right)\,\mathrm{eV}$. Experimental searches for a particle with parameters in this range is therefore strongly motivated.

1.3 Landscape of experimental projects

There are three general approaches to the experimental searches of axions and ALPs.

1.3.1 Purely laboratory experiments

An interesting class of experiments is called “Light Shining through Walls”. In experiments of this kind (see e.g. ref. [39] for a review), a laboratory produced laser beam passes through the magnetic field, where a small fraction of photons convert to axions or ALPs. These particles penetrate freely through a nontransparent wall. Another region of the magnetic field provides for conditions for the reconversion of photons from ALPs. These photons, if any, are registered by a very sensitive detector. In the laboratory conditions, the probability of conversion for one pass of the photon through the installation is negligible, therefore an optical cavity is installed in the conversion magnet. This increases the probability of conversion proportionally to the cavity finesse. The most precise experiments of this kind were ALPS and OSQAR [40, 41]. It has been shown theoretically [42], that a second cavity, if installed in the reconversion magnet and locked with the first one, gives a further increase in the overall detection rate. This approach, called resonant regeneration, has never been realized in practice, but is planned to be implemented in ALPS-II experiment [43]. Another purely laboratory approach to the axion/ALP searches is based on polarization measurements, in which the vacuum birefringence in the external magnetic field is searched for. The most precise experiments of this kind was PVLAS [44].

1.3.2 Axion dark matter searches

Axions constituting the Milky Way dark matter halo resonantly convert into (almost) monochromatic microwave signal $\omega = m_a$ in a high-Q microwave cavity permeated by a strong magnetic field [32]. Such axion search experiments are called *haloscopes*. The Axion Dark Matter eXperiment (ADMX) has been pursuing this technique since 1996 and ruled out a range of axion models with 1.9 μeV $< m_a <$ 3.69 μeV [45]. Recently ADMX-HF [46] has put strong limits $g_{a\gamma\gamma} < 2 \times 10^{-14}$ GeV^{-1} over the mass range 23.55 μeV $< m_a <$ 24.0 μeV. These experiments are probing parameter ranges predicted by realistic axion models where axions can constitute a sizeable fraction of dark matter in the Universe. Corresponding limits (together with early experimental results) are shown in figure 1 by green shaded areas.

Technologies enabling dark matter detection at higher axion masses are urgently needed, in particular, probing the interesting and phenomenologically reach class of models, where the Peccei-Quinn phase transition occurs after inflation. Such experiments have been proposed recently [47–49] for the search of dark matter axions in the mass range (40–400) μeV. They use novel detector architecture which can be referred to as Open Cavity Resonators. The experiment [47, 48], called MADMAX, will consist of 80 semi-transparent parallel disks with area ~1 m^2 made from material with high dielectric constant and placed in a strong magnetic field of 10 Tesla. Separations of the discs can be adjusted which would allow to probe the emission of axion induced electromagnetic waves in the 10-100 GHz domain, with the frequency given by the axion mass. It is planned that as a first step a smaller prototype with disc diameters of ~30 cm will be designed and produced in the next 2-3 years.

The experiment [49], called Orpheus, will use open Fabry-Perot resonator and a series of current-carrying wire planes. Orpheus design assumes smaller magnetic field, 3 or 6 Tesla, depending upon targeted axion mass range.

The axion dark matter mass window will be probed in the upcoming decade also by other axion dark matter direct detection experiments as well. In addition to MADMAX and Orpheus, the projects include CULTASK [50], HAYSTAC [51], CASPEr [52], for a recent reviews see [53, 54]. Some concepts of direct axion dark matter searches can be implemented in helioscopes, as it was done recently in CAST [55]. Most interesting for us is the MADMAX concept (or dish antenna [56]) since it is relatively broadband and allows for searches of amplified rare signals from streaming dark matter [57, 58], see section 7.2.1.

1.3.3 Search for solar axions

Like other stars, our Sun contains a huge thermonuclear reactor in its center, and axions or ALPs, if exist, should be produced there. They can be detected on the Earth with an axion helioscope [32], a tube pointing to the Sun and filled with magnetic field allowing for ALP-photon conversion and subsequent photon detection. Since the helioscope is the concept we choose for our proposal, we discuss it in more detail in section 2, 3. The CERN Axion Solar Telescope (CAST) is, up to day, the most powerful helioscope which has recently delivered the world-best upper limit on $g_{a\gamma\gamma}$ [59]. Amusingly, a weak excess of events was found in some runs, but it is not statistically significant. CAST has now finished its solar axion runs. An ambitious new project, the International Axion

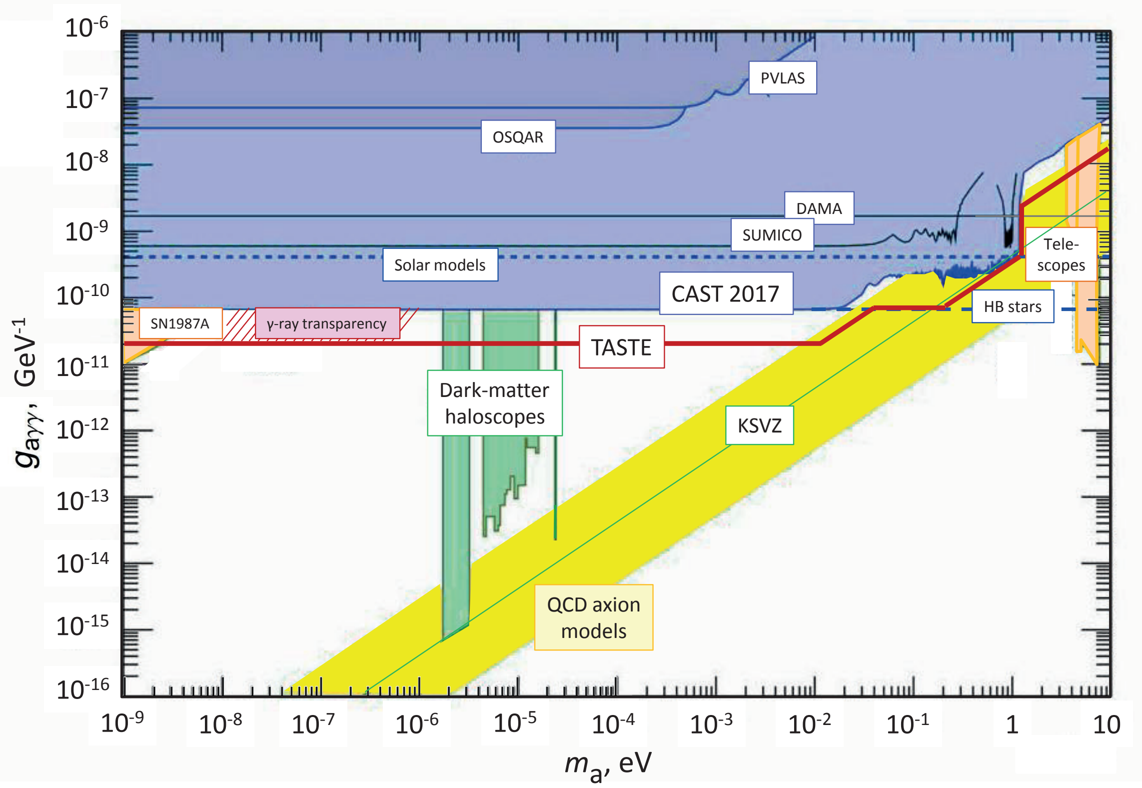

Figure 1. The axion/ALP parameter space ($m_a, g_{a\gamma\gamma}$). Shaded areas are excluded by light-shining-through-walls experiment OSQAR [41], polarization experiment PVLAS [64], solar axion searches by helioscopes Sumico [65] and CAST [59], as well as by the DAMA experiment [66], by telescope non-observation of cosmic axion decay lines [67–69] and by non-observation of gamma radiation from supernova 1987A [70]. The haloscope excluded areas [45, 46, 71, 72] assume that axions constitute the galactic dark matter. Horizontal dashed lines give astrophysical upper limits on $g_{a\gamma\gamma}$ from solar data [73] and from energy losses of horizontal-branch (HB) stars [15]. The yellow band indicates the parameter range favoured by QCD axion models, with the green KSVZ line corresponding to a benchmark example [74, 75].

Observatory (IAXO), has been proposed a few years ago [60, 61] and is now at the research and design stage. Another possibility to search for solar axions on the Earth is to explore their hadronic couplings, see e.g. refs. [62, 63].

1.3.4 Limits and sensitivities

Presently, none of the experiments has demonstrated an evidence for an axion or ALP. Astrophysical and experimental limits on the ($m_a, g_{a\gamma\gamma}$) parameter space are shown in figure 1, where we also indicate by hatching the range of parameters favoured by the Galactic photon/ALP mixing explanation of the gamma-ray absorption anomaly. While the best limits on $g_{a\gamma\gamma}$ in the relevant mass range, $g_{a\gamma\gamma} < 6.6 \times 10^{-11}$ GeV^{-1} (95% CL), is provided by the CAST final results, one can see that the astrophysically motivated range of couplings is just a few times lower. Still, we will see in section 3 that to reach this level of sensitivity, one needs an instrument with the signal-to-noise

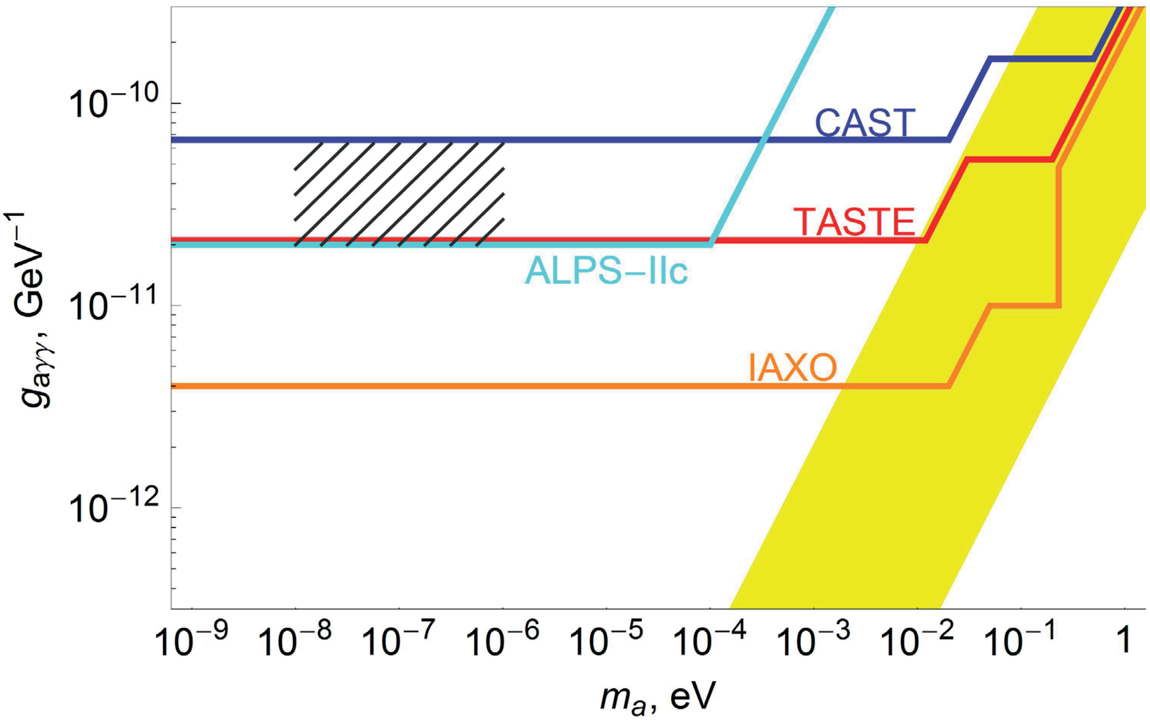

Figure 2. A sketch of comparison of sensitivities of proposed experiments to ALP parameters with the CAST limits. The yellow band is favoured by QCD axion models, the hatched area is favoured by the Galactic ALP conversion scenario explaining the anomalous transparency of the Universe.

ratio ∼ 100 times better than CAST. In this paper, we propose to build a new helioscope with the sensitivity down to $g_{a\gamma\gamma} \approx 2 \times 10^{-11}\,\text{GeV}^{-1}$ for a wide range of m_a, covering the region of the parameter space motivated by astrophysics, with the possibility to be used as an axion dark-matter haloscope at the same time.

In figure 2, we compare the projected sensitivity of our helioscope (Troitsk Axion Solar Telescope Experiment, TASTE) with those of two other projects aimed to explore the axion-photon coupling beyond the CAST limits, IAXO and ALPS-IIc. Both projected experiments plan to cover the range of the parameter space motivated by the gamma-ray transparency of the Universe. However, there are significant differences with our proposal, which make all three projects complementary.

Indeed, ALPS-IIc, a light-shining-through-wall experiment, will be based on the resonant-regeneration technique, which has not been demonstrated at work yet. If it works as planned, the first scientific runs are expected in 2020. Compared to helioscopes, this experiment will not cover the region of higher-mass ALPs and therefore will not explore the standard QCD axion scenario.

IAXO is a huge next-generation axion helioscopes with expected sensitivity superceding other projects. Given its scale and cost, the start of the full-scale experiment is planned beyond 2022. TASTE may be considered as the first step towards IAXO, aimed to scan physically interesting ALP and axion parameter space at much shorter timescale and at much lower cost.

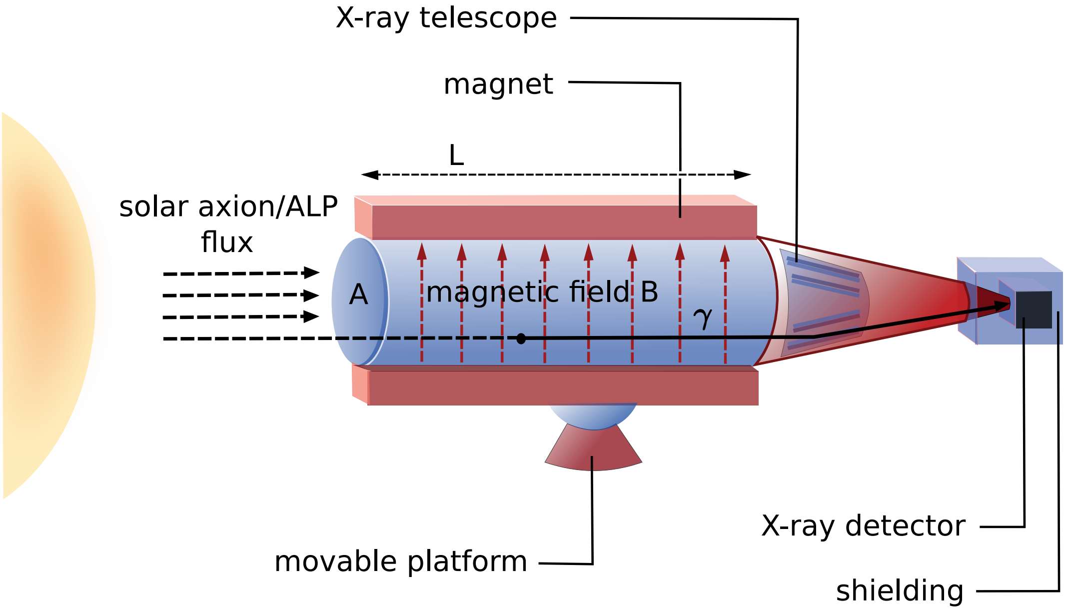

Figure 3. The sketch of the helioscope concept.

2 The helioscope concept

In this section, we briefly review the concept which we plan to apply to searches for axions and ALPs, first proposed in ref. [32]. The sketch of the approach is presented in figure 3. Axions and other light particles can be produced in hot and dense plasma in the Sun's core; unlike photons, they can penetrate freely through its outer parts and reach subsequently the terrestrial laboratory, entering the magnet tube shielded from any light. A tiny fraction of the solar axions is converted to photons in the field of the magnet and may be registered by a sensitive detector. To reduce the background, these photons may be focused into a small spot. Since the mean energy of the ALPs produced in the Sun are determined by the solar core temperature (keVs), a modern helioscope should include an X-ray telescope and a low-background detector of single X-ray photons.

2.1 Axion production in the Sun

Axions and other light particles are produced in hot plasmas in the regions where thermonuclear reactions take place, in particular in the central parts of the Sun. For a general ALP, the guaranteed production channel is the conversion of thermal photons to pseudoscalars due to the interaction (1.1) on the external field of the medium nuclei and electrons.[1] If the ALP has other interactions besides eq. (1.1), other channels may dominate, in particular those related to the tree-level electron coupling.

---

[1] This conversion is often called the Primakoff process, but, as suggested by one of us (KZ), a more proper name is the Sikivie [32] process: the Primakoff effect involves π mesons and it was proposed [76] in 1951, decades before axions have been introduced in physics.

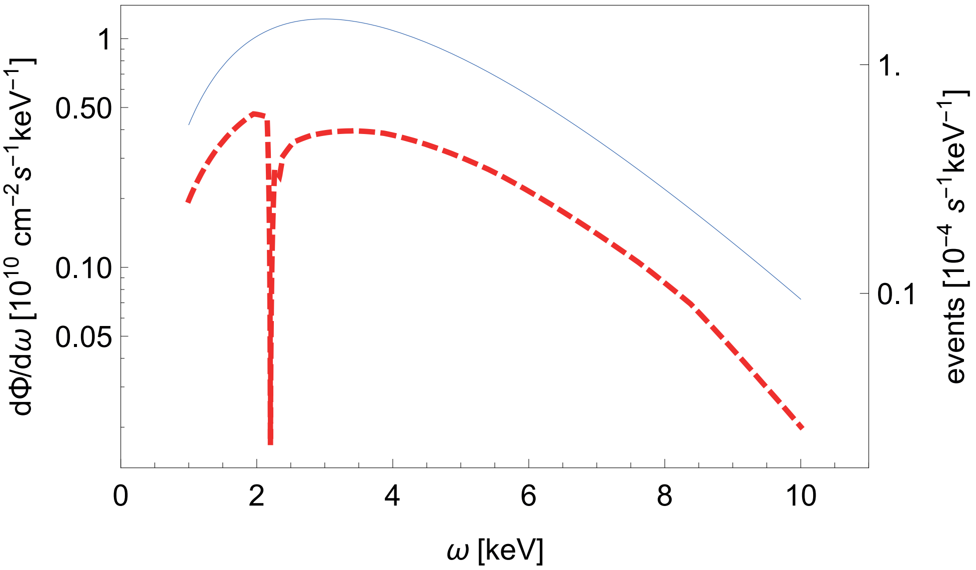

Figure 4. Full line: the flux at the Earth of solar axions or ALPs emitted due to the Sikivie process [77] for $g_{a\gamma\gamma} = 4 \times 10^{-11}\,\text{GeV}^{-1}$ and $m_a \lesssim 0.01\,\text{eV}$. The right-hand-side scale gives the number of converted photons in TASTE per second, assuming $B = 3.5$ T, $L = 12$ m and the tube diameter of 60 cm. Note that the flux scales as $g^2_{a\gamma\gamma}$ but the number of converted photons scales as $g^4_{a\gamma\gamma}$. The dashed line assumes SODART energy-dependent efficiency, see section 5.1, and gives the number of photons collected by the telescope.

Since these production channels are less general, we postpone their discussion to section 7.2.2 and concentrate on the $g_{a\gamma\gamma}$-related flux here.

The flux of ALPs produced in the solar interior by means of the interaction (1.1) has been calculated e.g. in ref. [77] and is presented, for typical values of parameters, in figure 4. A convenient parametrization, valid for ALP energies $1\,\text{keV} \lesssim \omega \lesssim 11\,\text{keV}$, is given [77] by

$$\frac{d\Phi}{d\omega} = \mathcal{N} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\text{GeV}^{-1}} \right)^2 \left(\frac{\omega}{\omega_0} \right)^\beta \exp\left(-(\beta+1)\frac{\omega}{\omega_0} \right), \tag{2.1}$$

where the normalization constant is $\mathcal{N} = 2.11 \times 10^{12}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{keV}^{-1}$, the mean energy is $\omega_0 = 4.195\,\text{keV}$ and the parameter $\beta = 2.481$. For a broad range of ALP parameters, the flux scales as $g^2_{a\gamma\gamma}$ and does not depend on m_a.

2.2 Conversion in the helioscope

Suppose that the helioscope magnetic field, transverse to the direction to the Sun, is B, constant over the vacuum conversion zone of length L. Then the probability to create a photon from an axion/ALP is [32, 33]

$$P_{a\to\gamma} = 4.6 \times 10^{-18} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\text{GeV}^{-1}} \right)^2 \left(\frac{B}{3.5\,\text{T}} \right)^2 \left(\frac{L}{12\,\text{m}} \right)^2 \frac{\sin^2(qL/2)}{(qL/2)^2}, \tag{2.2}$$

where in the vacuum case, $q = m_a^2/(2\omega)$. The last multiplier, sometimes called the form factor, is due to the nonzero m_a and describes the loss of coherence between the photon and ALP wave functions; it is almost constant (coherent conversion) provided

$$m_a \lesssim 0.012\ \text{eV} \left(\frac{\omega}{\omega_0}\right)^{1/2} \left(\frac{L}{12\ \text{m}}\right)^{-1/2}. \qquad (2.3)$$

If the conversion zone is filled with a buffer gas, m_a^2 in eqs. (2.2), (2.3) should be replaced with $(m_a^2 - m_\gamma^2)$, where m_γ is the effective photon mass. The latter is, under the conditions we discuss, equal to the plasma frequency, $m_\gamma = \omega_{\text{pl}} = \sqrt{4\pi\alpha n_e/m_e}$, where n_e is the electron concentration and m_e is the electron mass, α is the fine-structure constant. Therefore, matching $m_a \approx m_\gamma$ helps to restore coherence at larger m_a with the same L. In our project, we will preview the possibility to fill the conversion zone with gas, which would allow to extend the sensitivity deeper into the parameter region favoured by the QCD axion models.

2.3 Comparison to other approaches

Helioscopes, compared to other instruments, test a very wide range of ALP masses with the same observation. The result relies on robust assumptions about physical conditions in the solar interior. Axion dark-matter experiments may reach better sensitivity in $g_{a\gamma\gamma}$ but only for a very narrow range of m_a; what is more important, they rely theoretically on particular assumptions about the axion interactions and on the very early Universe. Modern light-shining-through-walls experiments, though having a benefit of a pure laboratory approach, are considerably less sensitive, while more involved and more sensitive future implementations are based on yet unexplored techniques. The helioscope concept has been succesfully tested, since the first realization in 1992 in Brookhaven [78], with the Tokyo helioscope (SUMICO) [65] and the CERN axion solar telescope (CAST) [59, 77, 79]. The novelty of our project is mostly in its scale (e.g. a factor of 100 enhancement of the collecting area with respect to CAST) and in the potential use of new dedicated low-background X-ray detectors.

3 Figures of merit and technical requirements

A useful set of figures of merit, allowing to compare sensitivities of axion helioscopes, has been discussed in ref. [60]. In this section, we use the figures of merit to determine basic technical requirements for a helioscope sensitive to the astrophysically motivated range of $g_{a\gamma\gamma}$. Clearly, this approach does not capture many important details like the energy and directional dependence of the signal, efficiency and background; a more detailed simulation of the TASTE sensitivity will be performed upon fixing its design.

In the regime when the statistics of background counts is high enough, the instrument's sensitivity is roughly driven by the ratio $s/\sqrt{b}$, where s and b are the numbers of signal and background events, respectively. The number of signal photons produced in the conversion zone per second is given by a product of the flux (2.1) and the conversion probability (2.2). The total number of signal events in the detector is given by the time integral of this rate multiplied by the detector efficiency. Overall, we have

$$s \propto g_{a\gamma\gamma}^4 B^2 L^2 A \cdot \epsilon_t t \cdot \epsilon_o \cdot \epsilon_d,$$

where A is the conversion-zone cross section area, ϵ_t is the fraction of time the helioscope tracks the Sun (determined, in particular, by the moving abilities of the mount), t is the total operation time, ϵ_o and ϵ_d are the efficiencies of X-ray optics and detector, respectively.

The number of background events is assumed to scale with the area a of the spot to which the X-ray telescope phocuses the photons,

$$b = \bar{b}a \cdot \epsilon_t t,$$

where $\bar{b}$ is the background count rate per unit area of the detector. The overall sensitivity is therefore

$$\frac{s}{\sqrt{b}} \propto g_{a\gamma\gamma}^4 F,$$

where the figure of merit F is determined as

$$F = B^2 L^2 A \cdot \frac{\epsilon_o \epsilon_d}{\sqrt{a\,\bar{b}}} \cdot \sqrt{\epsilon_t t}, \tag{3.1}$$

where the three multipliers correspond to the magnet, the X-ray part and the tracking time, respectively.

Since the incoming solar-ALP flux is the same for all devices, it is customary to determine the sensitivity of a new helioscope to $g_{a\gamma\gamma}$ through the CAST sensitivity,

$$\frac{g_{a\gamma\gamma}}{g_{\text{CAST}}} \simeq \left(\frac{F}{F_{\text{CAST}}}\right)^{1/4},$$

where $g_{\text{CAST}} = 6.6 \times 10^{-11}$ GeV^{-1} is the CAST limit and F_{CAST} is the figure of merit (3.1) calculated for the CAST parameters (note that these estimates are valid for the coherent-conversion case, $m_a \lesssim 0.01$ eV). This is a simplified approximation because the CAST result comes from a combined analysis of different runs performed under different conditions; however, this approach fits the overall level of precision of our approximate estimates. The relevant CAST parameters are given in table 1. Our goal is to have $F/F_{\text{CAST}} \sim 3^4$, and this determines technical requirements for the experiment.

The principal benefit of the new device with respect to CAST will be in the cross section of the conversion zone. Indeed, CAST used a decommissioned magnet from the Large Hadron Collider (LHC) with $A_{\text{CAST}} \simeq 3 \times 10^{-3}$ m^2 (in two bores). For TASTE, we will construct a dedicated magnet so we are free to enlarge the cross-section area. However, the limitation comes from the X-ray telescope: the largest available ones have the diameter of ~ 60 cm. We therefore keep this diameter fixed in our proposal. On the other hand, as will be discussed in section 4, we plan to use available superconducting cable, whose parameters and amount determine the working magnetic field value $B \sim 3.5$ T and the magnet length $L \sim 12$ m. Our goal is to have the tracking time fraction $\epsilon_t \sim 0.5$ (going beyond that is not only technically unfeasible but also poorly motivated, since we need a sufficient amount of off-Sun time to measure the background). For the X-ray optics, we use parameters of the SODART telescope, see section 5, that is the collection efficiency ~ 0.36. The area of the image in the focal plane $a = 0.5$ cm^2 is determined from eq. (3.8) of ref. [61]. For the detector parameters ϵ_d and $\bar{b}$, we take the best available presently values. These parameters, summarized also in table 1, result in the figure of merit improvement $F/F_{\text{CAST}} \sim 3^4$, which implies the expected sensitivity 3 times better than CAST, that is down to $g_{a\gamma\gamma} \sim 2 \times 10^{-11}$ GeV^{-1}, see figures 1, 2. More details on feasibility of these values are given below.

Table 1. Parameters of TASTE versus CAST and their contributions to the figure of merit.

parameter	CAST value (2017)	TASTE value (projected)	F/F_{CAST} contribution
B, T	9	3.5	0.15
L, m	9.26	12	1.68
A, m^2	0.003	0.28	94.2
in total (magnet)			23.9
ϵ_o	0.27	0.36	1.33
ϵ_d	0.7	0.7	1
$\bar{b}$, cm^{-2}s^{-1}keV^{-1}	10^{-6}	5×10^{-7}	1.41
a, cm^2	0.15	0.5	0.55
in total (X-ray)			1.03
ϵ_t	0.12	0.5	2.04
t, years	1.08	3	1.67
in total (tracking)			3.4
F/F_{CAST}			83.9

4 Magnet and cryogenics

Two principal complications drive the preliminary magnet design which we present here. Firstly, the magnetic field should be perpendicular to the tube axis. Secondly, the entire system should be installed on a moving mount and hence its weight should be minimized. We therefore select a dipole-like magnet with active (iron-free) shielding, inspired in particular by some of proposals for the detector magnets of the Future Circular Collider (FCC), see e.g. ref. [80]. Active shielding implies the use of additional external coils to close magnetic flux lines and to suppress stray fields. For large magnets, this approach is advantageous compared to the conventional iron-yoke design [81].

The magnet, in our preliminary conceptual design, consists of three identical sections, each of ~ 4 m length. The bore diameter is 60 cm, as dictated by the X-ray telescope part. The bore will be kept cold in order to possibly host equipment for dark-matter axion searches at certain stages of the project, see section 7.2.1. The coil configuration and the magnetic-field map for one section are presented in figures 5 and 6, respectively.

Our plan is to construct one section first and to test it without the moving mount and the X-ray telescope; we call this stage of the experiment “LabTASTE” because the 4-meter magnet with a cold bore may be used as a laboratory to test various approaches to axion searches. It will be sufficient to perform all dark-matter experiments described in section 7.2.1. In parallel, depending on the availability of funds, two other magnet sections will be manufactured and RnD works for the X-ray part, as well as to the technical design of the moving platform, will be finalized.

To make the magnet, we plan to use ~ 35 km of superconducting cable available at INR. It has been manufactured in 1990s for the MELC experiment [82] proposed to search for $\mu - e$ conversion

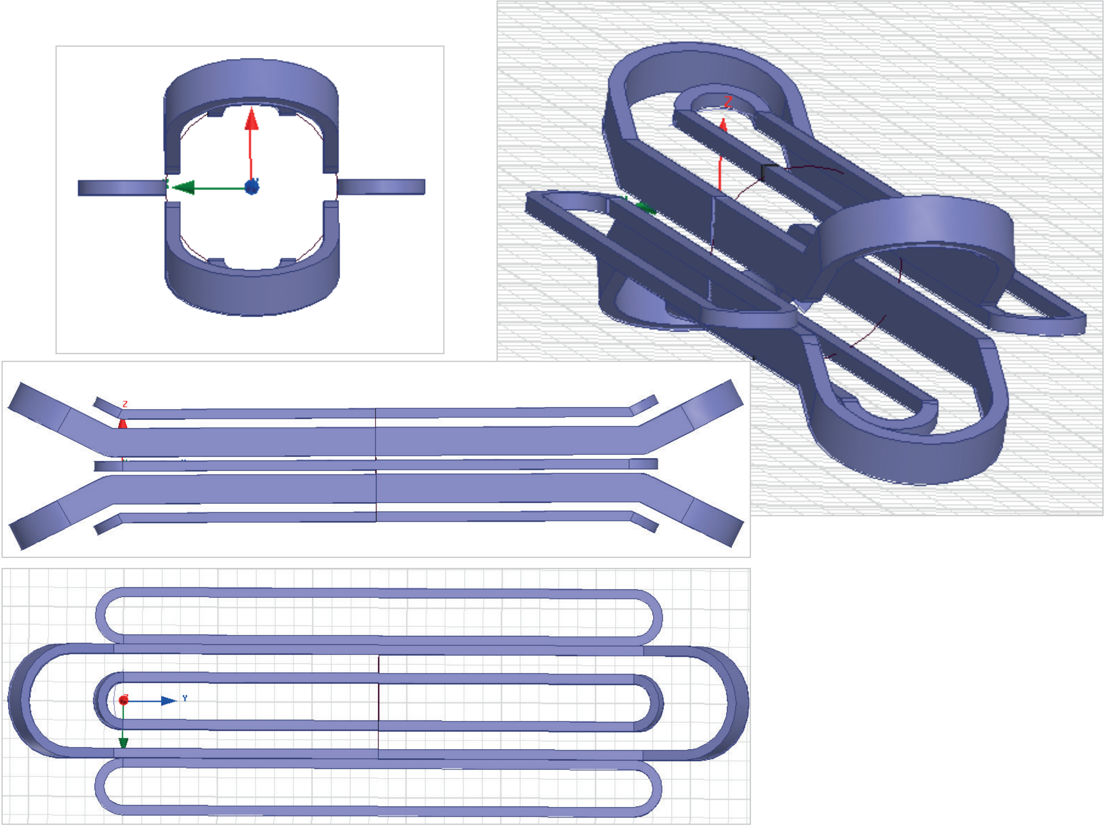

Figure 5. Preliminary design of one section of the TASTE magnet: overview of the coils and three projections.

in INR, Troitsk. This experiment has never been launched but the conductor (figure 7) is still kept in INR. The cable consists of 8 twisted veins of the PSNT-0.85 NiTi superconducting wire soldered in the aluminium-copper matrix with the cross section of 4×9 mm^2. The high-purity aluminium (99.995%) is placed into the copper matrix (the thickness of the copper layer is ≈ 0.1 mm). The critical current at 4.2 K was measured in the outer magnetic field of 3 T to be $\approx (6.5 - 7.0)$ kA. Measurements at different values of the field and theoretical estimates suggest that the conductor can be safely used in magnetic fields of ~ 5 T at the current of ~ 3.5 kA, which is implied by our design. We note that the magnet design presented here is very preliminary; parameters of the magnet should be optimized at the technical-design stage.

In our proposal, we aim at the maximal usage of available resources and plan to benefit from the cryogenic equipment of the Troitsk-nu-mass experiment [83] in INR. It includes a LINDE TCF-50 helium plant with 60 l/h capability equipped with cryogenic transport and quench protection systems, see photos in figure 8. At the first stage of the project, LabTASTE, the system will be used in turns with Troitsk-nu-mass, figure 9. When the full TASTE magnet is available, the cryogenic system may be rearranged for the full-time use in TASTE.

After the main data taking program with vacuum bores, the stage of the experiment with gas filling is anticipated to improve the sensitivity at higher axion masses m_a, see section 2.2. We plan

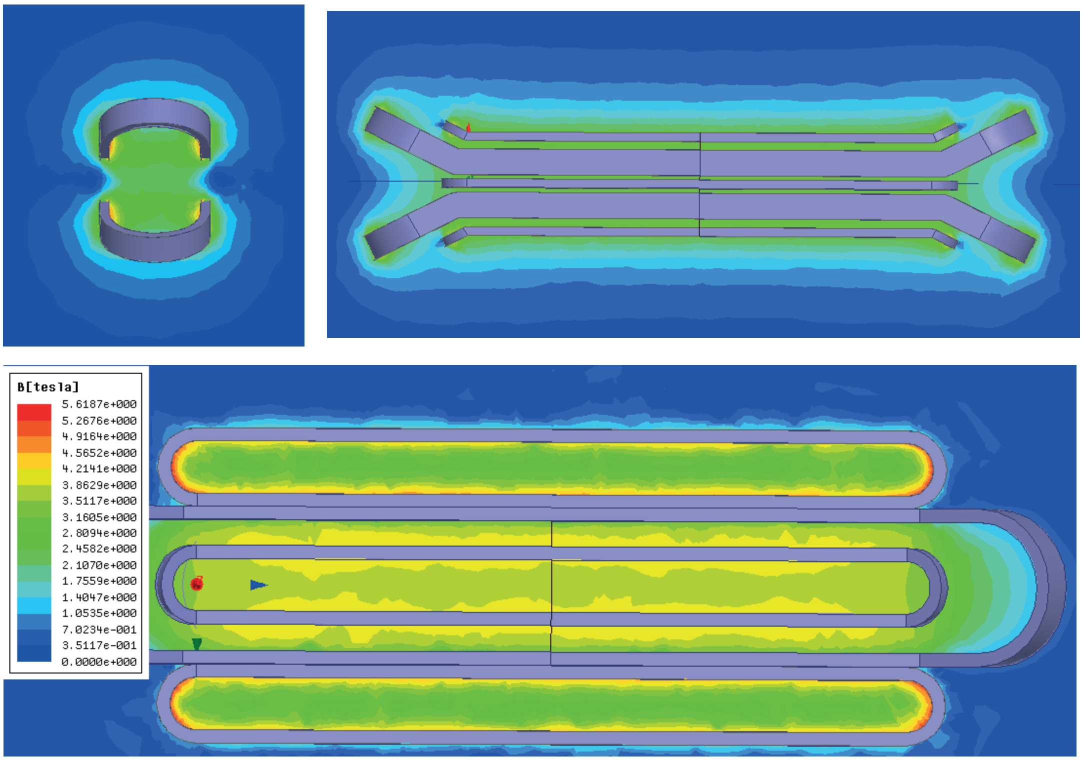

Figure 6. Magnetic-field strength map for the design presented in figure 5.

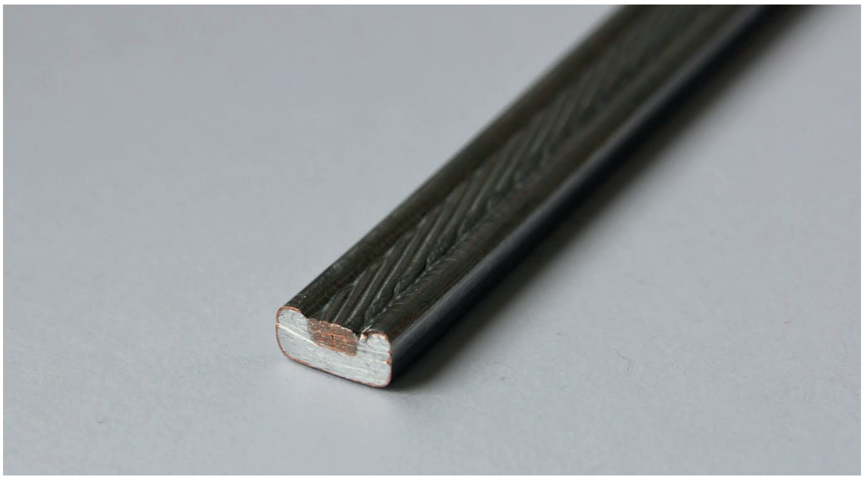

Figure 7. The superconducting cable of the MELC experiment, planned to be used in TASTE.

Figure 8. The cryogenic system of the Troitsk-nu-mass experiment, planned to be used in TASTE.

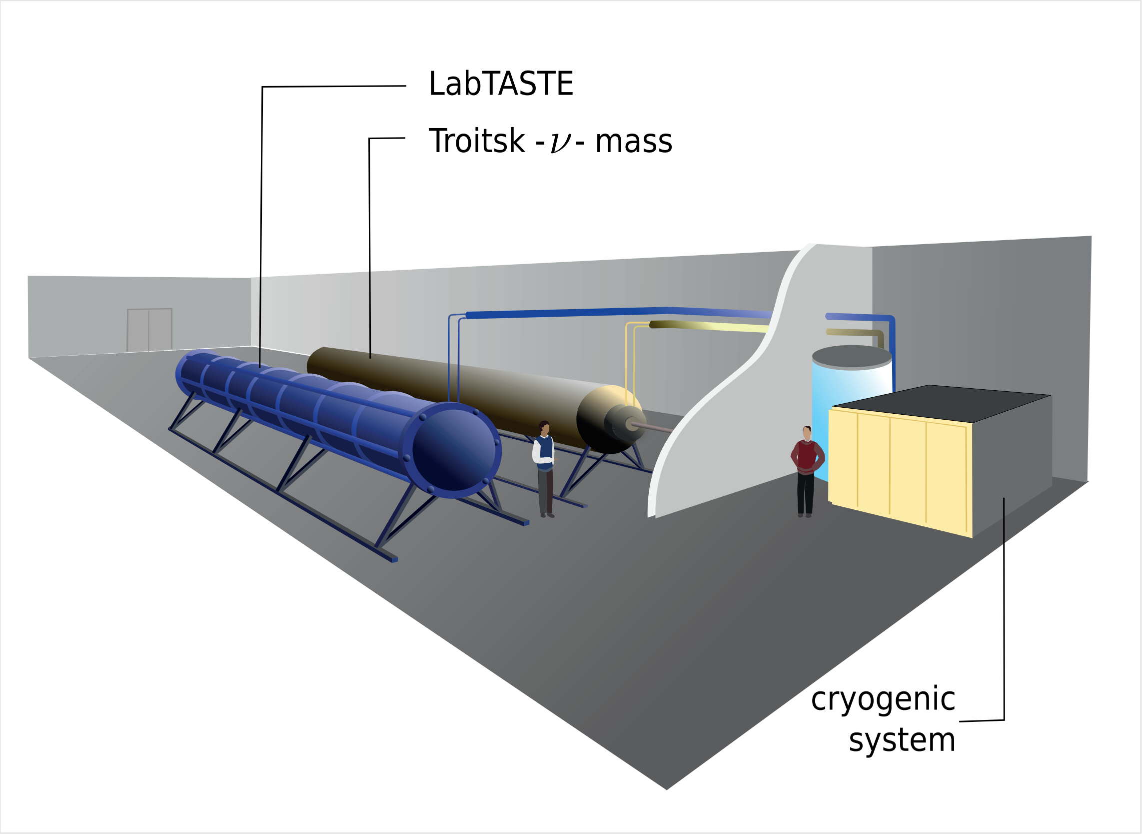

Figure 9. The artist's view of LabTASTE in the Troitsk-nu-mass experimental hall.

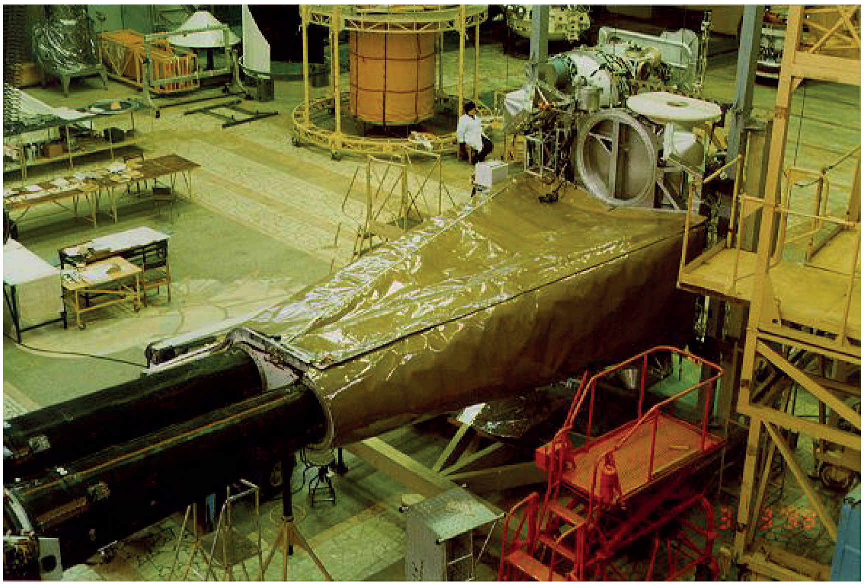

Figure 10. Covered part of the SODART optical block with two telescopes.

to use ^{4}He or ^{3}He for filling. The number of pressure steps necessary for scanning the required mass range may be estimated based on the CAST experience and discussion in ref. [84], see eqs. (9)–(12) there. For $L = 12$ m and $m_a \lesssim 0.1$ eV, the relative width of the mass range at the resonance is $\Delta m_a/m_a \sim 3\%$, which transforms into $\sim 6\%$ variation in density. We will need ~ 30 density settings, each of one day data taking, to cover $m_a \lesssim 0.1$ eV. Moving to higher masses is more tricky, and our estimate is to have ~ 300 density settings to reach $m_a \sim 0.5$ eV at the resonant sensitivity. More details of the gas phase will be determined at the stage of the technical design of the magnet.

5 X-ray photon collection

5.1 X-ray optics

Though focusing of energetic X-ray photons is not an easy task, numerous X-ray telescopes have been developed for space-based astronomical instruments (a brief overview of their relevant parameters is given e.g. in ref. [60]). In 1990s, the Soviet-Danish Roentgen Telescope (SODART) [85] has been developed and manufactured for the Spectrum-Roentgen-Gamma (SRG) space observatory which, however, has never been launched. The modern version of the SRG satellite, being considered for launch in 2018, will carry other scientific instruments. We propose to use one of two SODART X-ray mirrors, figure 10, in the TASTE project.

The SODART mirror [85] consists of 143 nested aluminium foil shells divided into quadrant and forming the cone which approximates the Wolter I geometry. The thickness of the shells is 0.4 mm, the length of each one is 20 cm. The reflecting surface was prepared with a lacquer coating technique. The telescope's diameter is 60 cm, the focal length is 8 m and the mass of the mirror is ~ 100 kg. The working energy range of the instrument is $\sim (0.2 - 20)$ keV. The telescope has been tested extensively in laboratory conditions [86, 87] and its performance has been simulated [88–90]. Figure 11 presents the energy dependence of the on-axis effective area in the units of the ideal

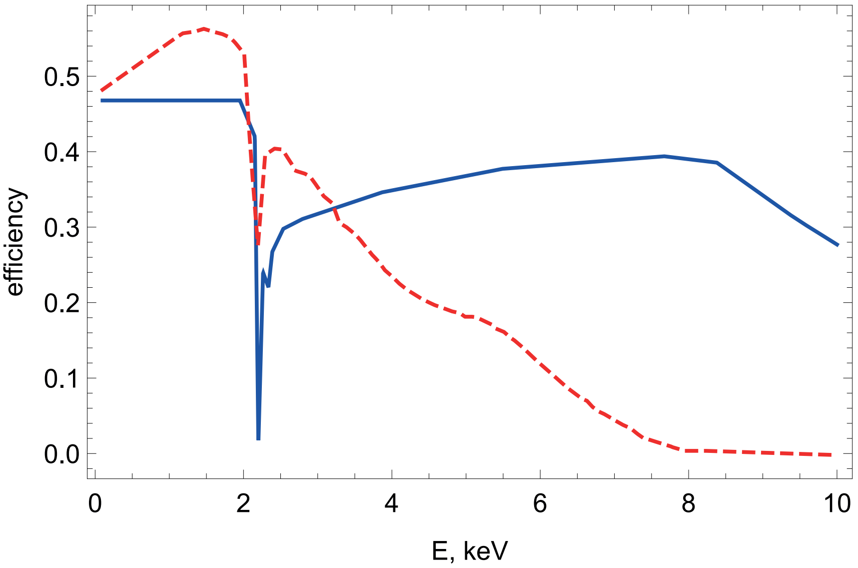

Figure 11. The energy dependence of the X-ray optics efficiency for SODART (full line, ref. [90]) and CAST (dashed line, ref. [91]).

geometric one [90]. For comparison, we plot also the similar quantity for CAST [91]. Weighted by the effective sectrum of the Sikivie solar axions and integrated over energy, this gives the values of the optics efficiency ϵ_0, given in table 1. Note that preliminary simulations indicated [89] flat efficiency within (0.1–1) keV which may be important for searches of solar axions interacting with electrons.

These SODART values are used in our baseline design; if the telescope is not available, other options will be considered; if it is, more detailed simulations and measurements will be performed.

5.2 X-ray photon detector

For the TASTE experiment, we plan to select the appropriate X-ray detector through additional RnD studies. Options to be considered include several solid-state detectors under development for astrophysics, high-energy physics and axion searches. The approaches followed by various groups participating in TASTE are described e.g. in refs. [62, 92, 93].

One of the most challenging parameters of the detector is its low background. While present-day background rate values for astrophysical detectors are too high for our purposes, they are dominated by cosmic-ray contamination, which will be reduced by a combination of the passive shielding and a dedicated veto system. The detectors themselves will be tested and the shielding will be designed in the Low-background Measurement Laboratory in Baksan Neutrino Observatory of INR. Several approaches will be combined in the X-ray detecting unit to fulfill the condition of extremely low dark counting rate, including:

- reduction of the detector electronic noise by the detector cooling;
- reduction of the front-end electronics noise by its cooling;
- increase of the signal amplitude via avalanche multiplication in the detector;
- unification of the detector response and the use of its features for rejection of noise signals.

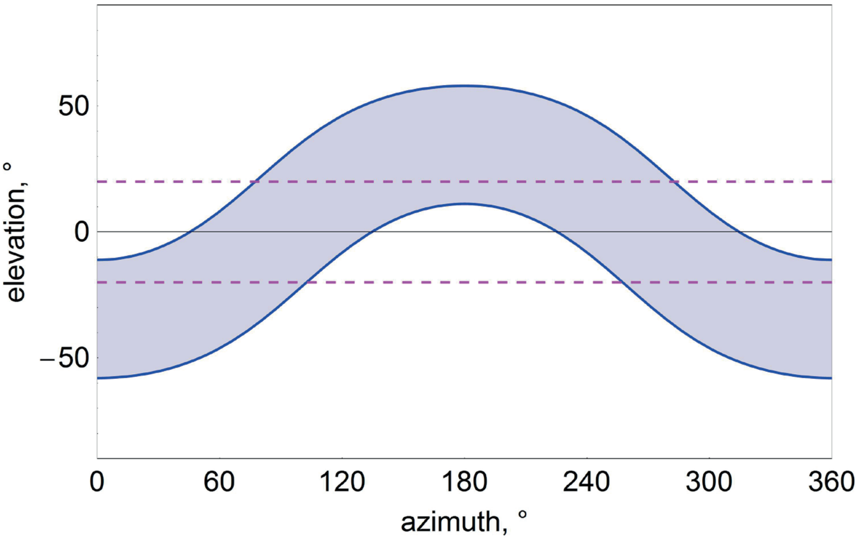

Figure 12. Part of the sky spanned by the Sun throughout the year, in horizontal coordinates (azimuth and elevation) for the latitude of Troitsk. Dashed horizontal lines bound the range ±20° corresponding to $\epsilon_t \approx 0.5$.

To realize the approaches, a new construction of a silicon detector will be developed and implemented in the DAQ system with digital processing of the signals. Details of the detector design will be discussed elsewhere.

6 Tracking and infrastructure

As we discussed above, our goal is to track the Sun for $\epsilon_t = 0.5$ fraction of the time throughout the year. This determines certain requirements for the movable mount of the helioscope.

In figure 12, we present the part of the sky spanned by the Sun throughout a year, for the geographical latitude of Troitsk, 55.5° North. A straightforward calculation demonstrates that $\epsilon_t = 0.5$ is reached if the helioscope can move by ±20° above and below the horizon, while rotating by 360° in the horizontal plane. It is not beneficial to constrain the azimuthal movement at the price of increased inclination range.

We estimate the total mass of the helioscope tube as $\sim$ 12 tons. This number demonstrates a serious advantage of the iron-free magnet design: for comparison, the CAST magnet (having $\sim$ 100 times smaller aperture area) weights 27.5 tons. In addition, we estimate the mass of the X-ray telescope support as $\sim$ 1 ton (the telescope itself, designed for launching in space, weights less than 0.1 ton), and another $\sim$ 1 ton for the detector shielding. For the total mass of $\sim$ 14 tons for the moving part of the installation, it is a nontrivial task to find or construct the mount; however, solutions exist in industry, gamma-ray and radio astronomy. We will determine the exact design of the moving mount at subsequent stages of the project realization.

An important part of the helioscope is the vacuum vessel which hosts the magnet and the cryostat. For the one-section magnet, LabTASTE, we plan to use the vessel of the decommissionned old Troitsk-nu-mass spectrometer, which is 7 m long and has a diameter of 1.2 m.

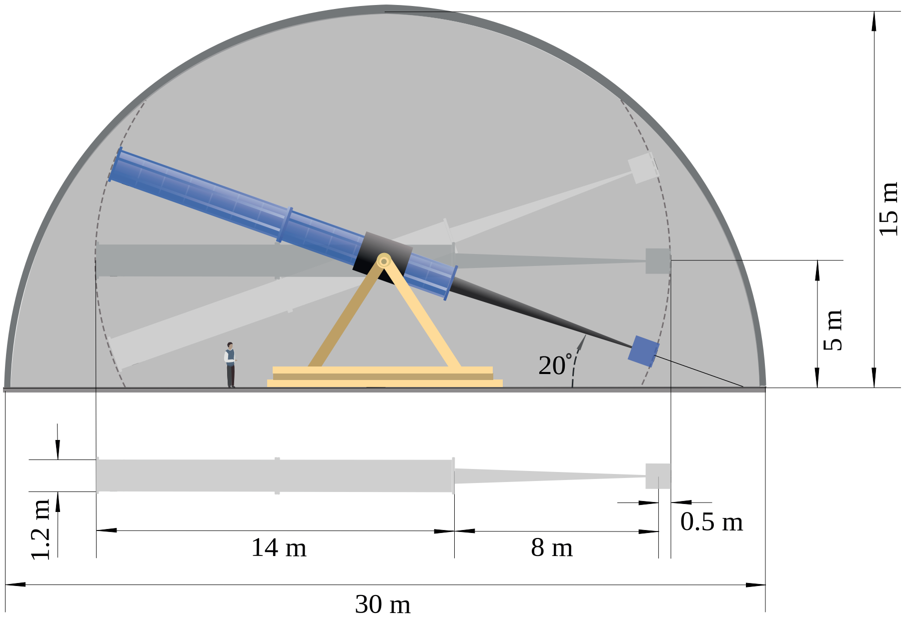

Figure 13. Geometry of the TASTE helioscope in a half-cylinder warm hangar.

The proposed geometry of the helioscope is shown in figure 13. We plan to put it in a commercially available half-cylinder warm hangar with the square base of 30 m×30 m, attached to the INR building where Troitsk-nu-mass is located (see figure 14 for the artist's view). The INR campus in Troitsk possesses all required infrastructure, including high-power electric line built for the Moscow Meson Factory (a linear proton accelerator in INR), laboratory space and mechanical workshops.

7 Discussion and conclusions

7.1 Costs and timeline

As discussed above, we preview two stages of the experiment, LabTASTE and the full TASTE. Subject to available funds, these projects may be realized in parallel, and this is the scenario we imply in the timeline presented in figure 15. Our preliminary plan includes 3 years of data taking under the vacuum conditions, then installation of the gas filling system and two additional gas runs: 1 month to explore $m_a \lesssim 0.1$ eV and 1 year to reach $m_a \sim 0.5$ eV. A rough estimate of the budget is given in figure 16. This estimate, of course, does not include materials and equipment already available: the superconducting cable, the helium plant, the vacuum vessels and the X-ray telescope, as well as available infrastructure at the INR campus in Troitsk.

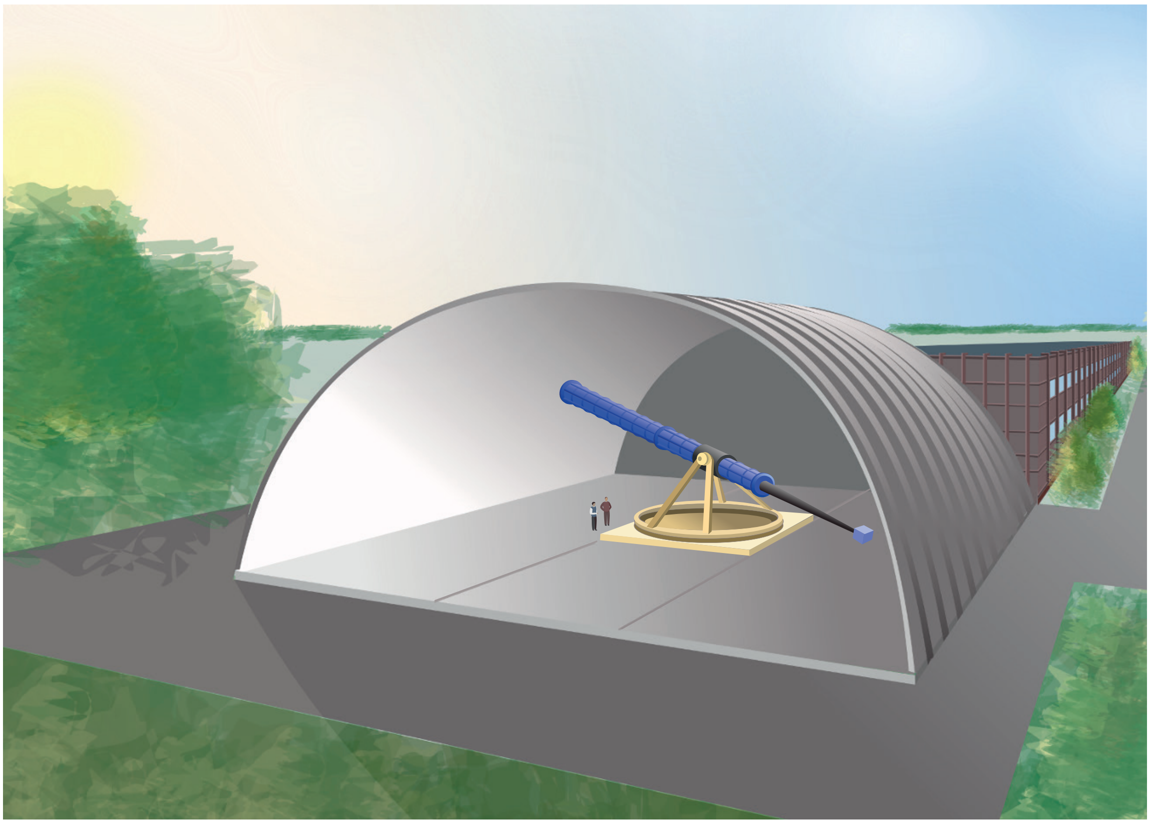

Figure 14. The artist's view of the TASTE experiment in a warm hangar attached to INR building 101 in Troitsk. The Troitsk-nu-mass cryogenic system is located in this building.

7.2 Scientific opportunities beyond solar $g_{a\gamma\gamma}$

7.2.1 Dark-matter axion searches

Dark matter axion searches can be conducted during LabTASTE stage and continued inside the full TASTE magnet. Rather large diameter, 60 cm, of TASTE magnet is beneficial here. First, it can be used for RnD studies for MADMAX, see section 1.3.2. TASTE bore area is 3.5 times smaller, and, additionally, magnetic field strength is a factor of 2.8 smaller than required by the MADMAX design. Therefore, TASTE will be a factor of 15 short for an average dark matter axion signal searches using that concept. However, TASTE can be used for high amplitude transient signals searches using broadband MADMAX-like design or even simply employing dish antenna strategy [56].

In models where Peccei-Quinn phase transition occurs after inflation, the axion dark matter is fragmented into miniclusters of large density [94]. During encounters with miniclustres the expected signal in axion detectors would increase by a factor of 10^8, however, such encounters are rare, they occure on average once in 10^5 years. On the other hand, small fraction of miniclusters is destroyed in gravitational collisions with stars. Density in resulting tidal streams is smaller, but a probability of a crossing is larger. As a result [57], signal increase by an order of magnitude may be expected every ~20 years due to crossings of a tidal stream (smaller/larger amplitudes are more often/rare). Large amplitude signals can also be caused by possible trapping of an axion minicluster in the Solar system and by gravitational lensing of dark matter streams [58]. In order not to miss the actually unpre-

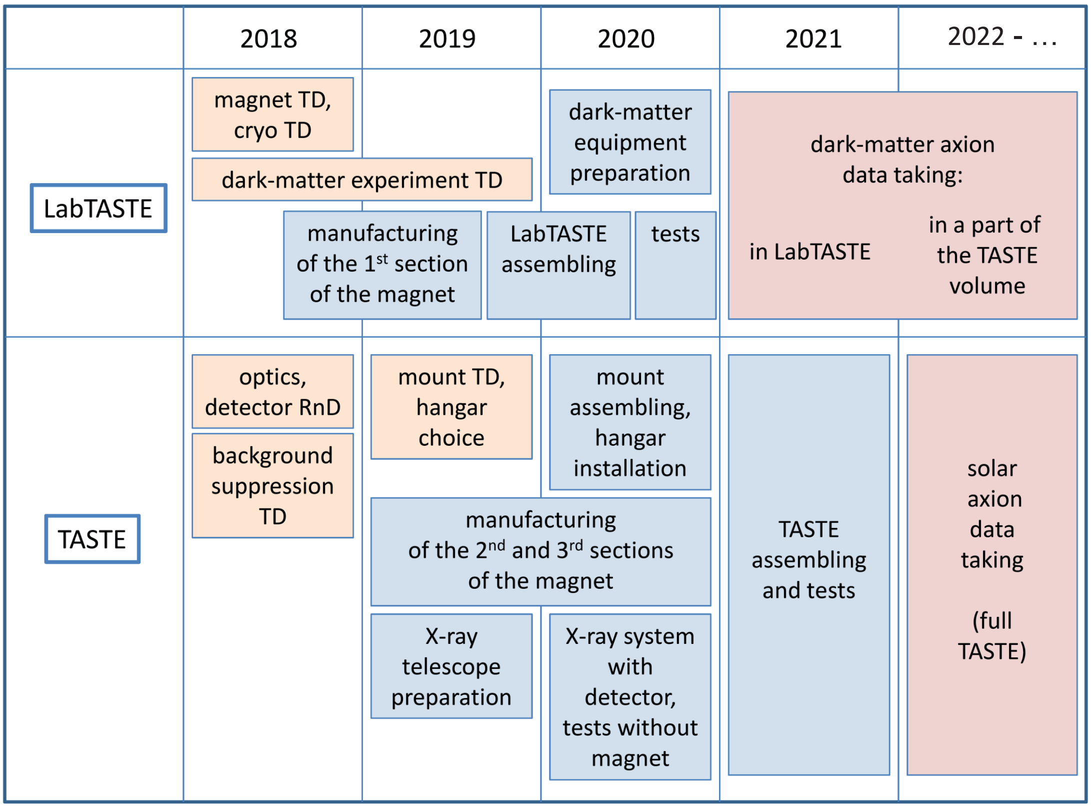

Figure 15. TASTE estimated timeline.

dictable timing of such short duration signals (few days for a tidal streams from miniclusres), a network of co-ordinated axion antennae is required, preferentially distributed world-wide, and TASTE can be part of such network. Prospects for TASTE here are even brighter for the ALP searches with increased coupling to photons, covering yet unexplored territories in their parameter space.

7.2.2 Solar axions with the electron coupling

In certain models, axions or ALPs interact with electrons by means of the Yukawa term in the Lagrangian,

$$-g_{ae}\, a\, \bar{e}\gamma_5 e,$$

where e is the electron spinor field, γ_5 is the chiral Dirac matrix and g_{ae} is the dimensionless Yukawa coupling. The solar axion flux due to this coupling has been calculated in ref. [95]; it peaks at energies $\sim$ 1 keV and is therefore detectable by a helioscope provided it has a sufficiently low detection energy threshold. While the emission rate is proportional to g_{ae}^2, the detection in a helioscope is still driven by $g_{a\gamma\gamma}^2$, and therefore this method constrains the product $g_{ae}g_{a\gamma\gamma}$ (unless the Sikivie flux dominates). The limits of this kind have been obtained by CAST [96]. They are however weaker than the present-day astrophysical limits from red-giant energy losses [97]. It is interesting to note that numerous studies of white-dwarf cooling, based either on the luminosity function, e.g. ref. [98], or on long-term observations of pulsating white dwarfs, e.g. refs. [99, 100], continue to favour a

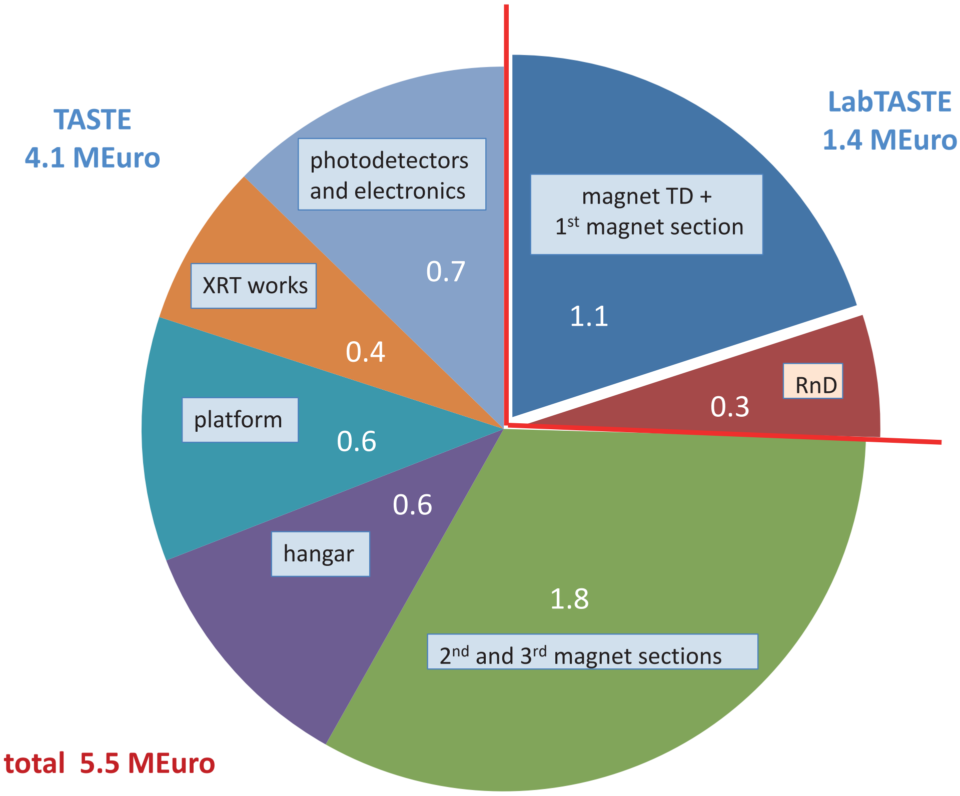

Figure 16. TASTE estimated costs.

nonzero value of $g_{ae} \sim 10^{-13}$ (see ref. [16] for a discussion). The helioscope sensitivity to $\sqrt{g_{ae}g_{a\gamma\gamma}}$ scales with the same figure of merit $F^{1/4}$, eq. (3.1); though TASTE will be hardly able to probe $g_{ae} \sim 10^{-13}$, the most interesting scenario where white-dwarf cooling and gamma-ray transparency are both explained by the effects of one and the same particle will be probed through $g_{a\gamma\gamma}$.

7.2.3 Other light particles

Chameleons are hypothetical scalar particles proposed [101, 102] to explain the accelerated expansion of the Universe ("dark energy"). Their interactions with matter result in the appearence of the effective particle mass which depends on the ambient energy density. In certain cases, they possess the interaction (1.1) and represent, therefore, a subclass of ALPs. However, the density dependence of the mass makes their phenomenology quite different from the general ALP case. They can be created in magnetic fields inside the Sun and detected in a helioscope in a way similar to usual ALPs [103]. This has been used to constrain chameleon parameters with CAST [104]. These constraints may be improved with TASTE provided its detector is sensitive to sub-keV photons.

Paraphotons [105], or hidden photons, are hypothetical vector bosons of an additional U(1) gauge group not present in the Standard Model. Abelian gauge bosons mix in their kinetic terms [106, 107], and this makes the photon/paraphotons conversion possible. Helioscopes can be used to constrain parameters of these hypothetical vector bosons, see e.g. refs. [108–110]. Since the external magnetic field is not required for the conversion, switching off the magnet while continuing solar tracking might help to distinguish paraphotons from ALPs in the case of positive detection.

7.3 Brief conclusions

To summarize, we propose a multi-purpose discovery experiment to search for axions and other hypothetical light particles, predicted by extensions of the Standard Model of particle physics and motivated by recent astrophysical observations. Our projected device, with its total cost on the scale of ~ 5 MEuro, would test, on the timescale of less than 5 years, several models of the anomalous transparency of the Universe, dark matter and even dark energy, as well as a particular part of the parameter space relevant for the axion solution of the strong CP problem. The results of the project would shed light on the unexplored processes involving light particles in hot plasmas where thermonuclear reactions take place.

Acknowledgments

We thank our colleagues from the worldwide axion-searching community, notably Maurizio Giannotti, Igor Irastorza, Axel Lindner, Javier Redondo, Andreas Ringwald and Yannis Semertzidis, for numerous inspiring discussions; Valery Rubakov and the INR administration for encouragement and helpful interest in the project; Oleg Kazachenko, Vladimir Kekelidze, Vyacheslav Klyukhin, Sergey Kozub and Nikolay Mezentsev for helpful discussions related to the magnet; Alexander Blinov for consultations related to the moving platform.

References

[1] S. Troitsky, *Unsolved problems in particle physics*, *Phys. Usp.* **55** (2012) 72 [*Usp. Fiz. Nauk* **182** (2012) 77] [`arXiv:1112.4515`].

[2] R.D. Peccei and H.R. Quinn, *CP conservation in the presence of instantons*, *Phys. Rev. Lett.* **38** (1977) 1440.

[3] S. Weinberg, *A new light boson?*, *Phys. Rev. Lett.* **40** (1978) 223.

[4] F. Wilczek, *Problem of strong p and t invariance in the presence of instantons*, *Phys. Rev. Lett.* **40** (1978) 279.

[5] J. Preskill, M.B. Wise and F. Wilczek, *Cosmology of the invisible axion*, *Phys. Lett.* **B 120** (1983) 127.

[6] L.F. Abbott and P. Sikivie, *A cosmological bound on the invisible axion*, *Phys. Lett.* **B 120** (1983) 133.

[7] M. Dine and W. Fischler, *The not so harmless axion*, *Phys. Lett.* **B 120** (1983) 137.

[8] D.B. Kaplan, *Opening the axion window*, *Nucl. Phys.* **B 260** (1985) 215.

[9] M. Srednicki, *Axion couplings to matter* 1. *CP conserving parts*, *Nucl. Phys.* **B 260** (1985) 689.

[10] V.A. Rubakov, *Grand unification and heavy axion*, *JETP Lett.* **65** (1997) 621 [`hep-ph/9703409`].

[11] Z. Berezhiani, L. Gianfagna and M. Giannotti, *Strong CP problem and mirror world: the Weinberg-Wilczek axion revisited*, *Phys. Lett.* **B 500** (2001) 286 [`hep-ph/0009290`].

[12] L. Gianfagna, M. Giannotti and F. Nesti, *Mirror world, supersymmetric axion and gamma ray bursts*, *JHEP* **10** (2004) 044 [`hep-ph/0409185`].

[13] J. Jaeckel and A. Ringwald, *The low-energy frontier of particle physics*, *Ann. Rev. Nucl. Part. Sci.* **60** (2010) 405 [`arXiv:1002.0329`].

[14] P. Arias, D. Cadamuro, M. Goodsell, J. Jaeckel, J. Redondo and A. Ringwald, *WISPy cold dark matter*, *JCAP* **06** (2012) 013 [`arXiv:1201.5902`].

[15] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi and O. Straniero, *Revisiting the bound on axion-photon coupling from globular clusters*, *Phys. Rev. Lett.* **113** (2014) 191302 [`arXiv:1406.6053`].

[16] M. Giannotti, I. Irastorza, J. Redondo and A. Ringwald, *Cool WISPs for stellar cooling excesses*, *JCAP* **05** (2016) 057 [`arXiv:1512.08108`].

[17] S.V. Troitsky, *Axion-like particles and the propagation of gamma rays over astronomical distances*, *JETP Lett.* **105** (2017) 55 [`arXiv:1612.01864`].

[18] A.I. Nikishov, *Absorption of high-energy photons in the universe*, *Sov. Phys. JETP* **14** (1962) 393 [*Zh. Eksp. Teor. Fiz.* **41** (1962) 549].

[19] Fermi-LAT collaboration, M. Ackermann et al., *The imprint of the extragalactic background light in the gamma-ray spectra of blazars*, *Science* **338** (2012) 1190 [`arXiv:1211.1671`].

[20] D. Horns and M. Meyer, *Indications for a pair-production anomaly from the propagation of VHE gamma-rays*, *JCAP* **02** (2012) 033 [`arXiv:1201.4711`].

[21] G.I. Rubtsov and S.V. Troitsky, *Breaks in gamma-ray spectra of distant blazars and transparency of the universe*, *JETP Lett.* **100** (2014) 355 [*Pisma Zh. Eksp. Teor. Fiz.* **100** (2014) 397] [`arXiv:1406.0239`].

[22] R.C. Gilmore, R.S. Somerville, J.R. Primack and A. Domínguez, *Semi-analytic modeling of the EBL and consequences for extragalactic gamma-ray spectra*, *Mon. Not. Roy. Astron. Soc.* **422** (2012) 3189 [`arXiv:1104.0671`].

[23] A. Franceschini, G. Rodighiero and M. Vaccari, *The extragalactic optical-infrared background radiations, their time evolution and the cosmic photon-photon opacity*, *Astron. Astrophys.* **487** (2008) 837 [`arXiv:0805.1841`].

[24] R. Keenan, A.J. Barger, L.L. Cowie and W.-H. Wang, *The resolved NIR extragalactic background*, `PoS(CRF 2010)007` [`arXiv:1102.2428`].

[25] S. Matsuura et al., *New spectral evidence of an unaccounted component of the near-infrared extragalactic background light from the CIBER*, *Astrophys. J.* **839** (2017) 7 [`arXiv:1704.07166`].

[26] K. Mattila, P. Vaisanen, K. Lehtinen, G. von Appen-Schnur and Ch. Leinert, *Extragalactic background light: a measurement at* 400 *nm using dark cloud shadow II. Spectroscopic separation of dark cloud's light, and results*, *Mon. Not. Roy. Astron. Soc.* **470** (2017) 2152 [`arXiv:1705.10790`].

[27] W. Essey and A. Kusenko, *A new interpretation of the gamma-ray observations of active galactic nuclei*, *Astropart. Phys.* **33** (2010) 81 [`arXiv:0905.1162`].

[28] T.A. Dzhatdoev, E.V. Khalikov, A.P. Kircheva and A.A. Lyukshin, *Electromagnetic cascade masquerade: a way to mimic γ-axion-like particle mixing effects in blazar spectra*, *Astron. Astrophys.* **603** (2017) A59 [`arXiv:1609.01013`].

[29] H.E.S.S. collaboration, A. Abramowski et al., *The* 2012 *flare of PG* 1553 + 113 *seen with H.E.S.S. and Fermi-LAT*, *Astrophys. J.* **802** (2015) 65 [`arXiv:1501.05087`].

[30] G. Rubtsov, P. Satunin and S. Sibiryakov, *Prospective constraints on Lorentz violation from ultrahigh-energy photon detection*, *Phys. Rev.* **D 89** (2014) 123011 [`arXiv:1312.4368`].

[31] G. Rubtsov, P. Satunin and S. Sibiryakov, *Constraints on violation of Lorentz invariance from atmospheric showers initiated by multi-TeV photons*, *JCAP* **05** (2017) 049 [`arXiv:1611.10125`].

[32] P. Sikivie, *Experimental tests of the invisible axion*, *Phys. Rev. Lett.* **51** (1983) 1415 [*Erratum ibid.* **52** (1984) 695].

[33] G. Raffelt and L. Stodolsky, *Mixing of the photon with low mass particles*, *Phys. Rev.* **D 37** (1988) 1237.

[34] C. Csáki, N. Kaloper, M. Peloso and J. Terning, *Super GZK photons from photon axion mixing*, *JCAP* **05** (2003) 005 [`hep-ph/0302030`].

[35] A. De Angelis, M. Roncadelli and O. Mansutti, *Evidence for a new light spin-zero boson from cosmological gamma-ray propagation?*, *Phys. Rev.* **D 76** (2007) 121301 [`arXiv:0707.4312`].

[36] M. Simet, D. Hooper and P.D. Serpico, *The milky way as a kiloparsec-scale axionscope*, *Phys. Rev.* **D 77** (2008) 063001 [`arXiv:0712.2825`].

[37] M. Fairbairn, T. Rashba and S.V. Troitsky, *Photon-axion mixing and ultra-high-energy cosmic rays from BL Lac type objects — shining light through the universe*, *Phys. Rev.* **D 84** (2011) 125019 [`arXiv:0901.4085`].

[38] S. Troitsky, *Towards discrimination between galactic and intergalactic axion-photon mixing*, *Phys. Rev.* **D 93** (2016) 045014 [`arXiv:1507.08640`].

[39] J. Redondo and A. Ringwald, *Light shining through walls*, *Contemp. Phys.* **52** (2011) 211 [`arXiv:1011.3741`].

[40] K. Ehret et al., *New ALPS results on hidden-sector lightweights*, *Phys. Lett.* **B 689** (2010) 149 [`arXiv:1004.1313`].

[41] OSQAR collaboration, R. Ballou et al., *New exclusion limits on scalar and pseudoscalar axionlike particles from light shining through a wall*, *Phys. Rev.* **D 92** (2015) 092002 [`arXiv:1506.08082`].

[42] P. Sikivie, D.B. Tanner and K. van Bibber, *Resonantly enhanced axion-photon regeneration*, *Phys. Rev. Lett.* **98** (2007) 172002 [`hep-ph/0701198`].

[43] R. Bähre et al., *Any light particle search II — technical design report*, 2013 *JINST* **8** T09001 [`arXiv:1302.5647`].

[44] PVLAS collaboration, E. Zavattini et al., *New PVLAS results and limits on magnetically induced optical rotation and ellipticity in vacuum*, *Phys. Rev.* **D 77** (2008) 032006 [`arXiv:0706.3419`].

[45] ADMX collaboration, S.J. Asztalos et al., *A SQUID-based microwave cavity search for dark-matter axions*, *Phys. Rev. Lett.* **104** (2010) 041301 [`arXiv:0910.5914`].

[46] B.M. Brubaker et al., *First results from a microwave cavity axion search at* 24 *μeV*, *Phys. Rev. Lett.* **118** (2017) 061302 [`arXiv:1610.02580`].

[47] MADMAX WORKING GROUP collaboration, B. Majorovits and J. Redondo, *MADMAX: a new dark matter axion search using a dielectric haloscope*, `arXiv:1611.04549`.

[48] MADMAX INTEREST GROUP collaboration, P. Brun et al., *A new experimental approach to probe QCD axion dark matter in the mass range above* 40 *μeV*, https://www.mpp.mpg.de/fileadmin/user_upload/Forschung/MADMAX/madmax_white_paper.pdf.

[49] G. Rybka, A. Wagner, A. Brill, K. Ramos, R. Percival and K. Patel, *Search for dark matter axions with the Orpheus experiment*, *Phys. Rev.* **D 91** (2015) 011701 [`arXiv:1403.3121`].

[50] W. Chung, *Launching axion experiment at CAPP/IBS in Korea*, in *Proceedings of the* 12th *Patras AXION-WIMP workshop*, (2016).

[51] B.M. Brubaker, L. Zhong, S.K. Lamoreaux, K.W. Lehnert and K.A. van Bibber, *The HAYSTAC axion search analysis procedure*, `arXiv:1706.08388`.

[52] A. Garcon et al., *The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance*, `arXiv:1707.05312`.

[53] P.W. Graham, I.G. Irastorza, S.K. Lamoreaux, A. Lindner and K.A. van Bibber, *Experimental searches for the axion and axion-like particles*, *Ann. Rev. Nucl. Part. Sci.* **65** (2015) 485 [`arXiv:1602.00039`].

[54] E. Petrakou, *Haloscope searches for dark matter axions at the center for axion and precision physics research*, `arXiv:1702.03664`.

[55] L. Micelli, *The CAST-CAPP/IBS detector project: progress and challenges*, in *Proceedings of the* 12th *Patras AXION-WIMP workshop*, (2016).

[56] D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald, *Searching for WISPy cold dark matter with a dish antenna*, *JCAP* **04** (2013) 016 [`arXiv:1212.2970`].

[57] P. Tinyakov, I. Tkachev and K. Zioutas, *Tidal streams from axion miniclusters and direct axion searches*, *JCAP* **01** (2016) 035 [`arXiv:1512.02884`].

[58] K. Zioutas et al., *Search for axions in streaming dark matter*, `arXiv:1703.01436`.

[59] CAST collaboration, V. Anastassopoulos et al., *New CAST limit on the axion-photon interaction*, *Nature Phys.* **13** (2017) 584 [`arXiv:1705.02290`].

[60] I.G. Irastorza et al., *Towards a new generation axion helioscope*, *JCAP* **06** (2011) 013 [`arXiv:1103.5334`].

[61] E. Armengaud et al., *Conceptual design of the International Axion Observatory (IAXO)*, 2014 *JINST* **9** T05002 [`arXiv:1401.3233`].

[62] A.V. Derbin, I.S. Drachnev, A.S. Kayunov and V.N. Muratova, *Constraints on the axion-electron coupling constant for solar axions appearing owing to bremsstrahlung and the Compton process*, *JETP Lett.* **95** (2012) 339 [*Pisma Zh. Eksp. Teor. Fiz.* **95** (2012) 379] [`arXiv:1206.4142`].

[63] Yu.M. Gavrilyuk et al., *New experiment on search for the resonance absorption of solar axion emitted in the $M1$ transition of ^{83}Kr nuclei*, *JETP Lett.* **101** (2015) 664 [*Pisma Zh. Eksp. Teor. Fiz.* **101** (2015) 739].

[64] F. Della Valle et al., *The PVLAS experiment: measuring vacuum magnetic birefringence and dichroism with a birefringent Fabry-Perot cavity*, *Eur. Phys. J.* **C 76** (2016) 24 [`arXiv:1510.08052`].

[65] S. Moriyama, M. Minowa, T. Namba, Y. Inoue, Y. Takasu and A. Yamamoto, *Direct search for solar axions by using strong magnetic field and X-ray detectors*, *Phys. Lett.* **B 434** (1998) 147 [`hep-ex/9805026`].

[66] R. Bernabei et al., *Search for solar axions by Primakoff effect in NaI crystals*, *Phys. Lett.* **B 515** (2001) 6.

[67] M.A. Bershady, M.T. Ressell and M.S. Turner, *Telescope search for multi-eV axions*, *Phys. Rev. Lett.* **66** (1991) 1398.

[68] Yu. N. Gnedin, S.N. Dodonov, V.V. Vlasyuk, I.I. Spiridonova and A.V. Shakhverdov, *Astronomical searches for axions: observations at the SAO* 6 *m telescope*, *Mon. Not. Roy. Astron. Soc.* **306** (1999) 117.

[69] D. Grin, G. Covone, J.-P. Kneib, M. Kamionkowski, A. Blain and E. Jullo, *A telescope search for decaying relic axions*, *Phys. Rev.* **D 75** (2007) 105018 [`astro-ph/0611502`].

[70] A. Payez, C. Evoli, T. Fischer, M. Giannotti, A. Mirizzi and A. Ringwald, *Revisiting the SN*1987*A gamma-ray limit on ultralight axion-like particles*, *JCAP* **02** (2015) 006 [`arXiv:1410.3747`].

[71] W. Wuensch et al., *Results of a laboratory search for cosmic axions and other weakly coupled light particles*, *Phys. Rev.* **D 40** (1989) 3153.

[72] C. Hagmann, P. Sikivie, N.S. Sullivan and D.B. Tanner, *Results from a search for cosmic axions*, *Phys. Rev.* **D 42** (1990) 1297.

[73] N. Vinyoles, A. Serenelli, F.L. Villante, S. Basu, J. Redondo and J. Isern, *New axion and hidden photon constraints from a solar data global fit*, *JCAP* **10** (2015) 015 [`arXiv:1501.01639`].

[74] J.E. Kim, *Weak interaction singlet and strong CP invariance*, *Phys. Rev. Lett.* **43** (1979) 103.

[75] M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, *Can confinement ensure natural CP invariance of strong interactions?*, *Nucl. Phys.* **B 166** (1980) 493.

[76] H. Primakoff, *Photoproduction of neutral mesons in nuclear electric fields and the mean life of the neutral meson*, *Phys. Rev.* **81** (1951) 899.

[77] CAST collaboration, S. Andriamonje et al., *An improved limit on the axion-photon coupling from the CAST experiment*, *JCAP* **04** (2007) 010 [`hep-ex/0702006`].

[78] D.M. Lazarus et al., *A search for solar axions*, *Phys. Rev. Lett.* **69** (1992) 2333.

[79] K. Zioutas et al., *A decommissioned LHC model magnet as an axion telescope*, *Nucl. Instrum. Meth.* **A 425** (1999) 480 [`astro-ph/9801176`].

[80] M. Mentink et al., *Design of a* 56*-GJ twin solenoid and dipoles detector magnet system for the future circular collider*, *IEEE Trans. Appl. Supercond.* **26** (2016) 4003506.

[81] B. Gastineau, C. Pes and J.-E. Ducret, *Comparison between active and passive shielding designs for a large acceptance superconducting dipole magnet*, *IEEE Trans. Appl. Supercond.* **16** (2006) 485.

[82] R.M. Dzhilkibaev and V.M. Lobashev, *On the search for $\mu \to e$ conversion on nuclei*, *Sov. J. Nucl. Phys.* **49** (1989) 384 [*Yad. Fiz.* **49** (1989) 622].

[83] Troitsk collaboration, V.N. Aseev et al., *An upper limit on electron antineutrino mass from Troitsk experiment*, *Phys. Rev.* **D 84** (2011) 112003 [`arXiv:1108.5034`].

[84] K. Zioutas, M. Tsagri, Y. Semertzidis, T. Papaevangelou, T. Dafni and V. Anastassopoulos, *Axion searches with helioscopes and astrophysical signatures for axion(-like) particles*, *New J. Phys.* **11** (2009) 105020 [`arXiv:0903.1807`].

[85] J. Polny, N.J. Westergaard, F.E. Christensen, H.U. Noergaard-Nielsen and H.W. Schnopper, *Production, assembly, and alignment of the XSPECT mirror modules for the SODART x-ray telescope on the Spectrum Roentgen Gamma satellite*, *Proc. SPIE* **3113** (1997) 349.

[86] F.E. Christensen et al., *X-ray calibration of the SODART flight telescopes*, *Proc. SPIE* **3113** (1997) 294.

[87] B. Madsen, F.E. Cristensen, A. Hornstrup, P. Frederiksen, K. Pedersen and N.J. Westergaard, *Imaging capabilities of the SODART telescopes*, *Phys. Scr.* **T 77** (1988) 25.

[88] H.-J. Wiebicke, I. Halm and F.E. Christensen, *SODART-OXS experiment simulation*, *Proc. SPIE* **4140** (2000) 549.

[89] H.W. Schnopper, *X-ray spectroscopy with the SODART/XSPECT telescope*, *Lect. Notes Phys.* **385** (1991) 274.

[90] A. Kaniovsky and W. Borkous, *Simulations of cosmic X-ray background illumination of the SODART telescope focal plane*, preprint IKI Pr-1886, Space Research Institute RAS, Moscow Russia, (1994).

[91] F. Aznar et al., *A MicrOMEGAs-based low-background X-ray detector coupled to a slumped-glass telescope for axion research*, *JCAP* **12** (2015) 008 [`arXiv:1509.06190`].

[92] E. Verbitskaya et al., *Development of silicon detectors for beam loss monitoring at HL-LHC*, 2017 *JINST* **12** C03036.

[93] V. Levin et al., *Results of ground tests and calibration of X-ray focal plane detectors for ART-XC/SRG instrument*, *Proc. SPIE* **9905** (2016) 990551.

[94] E.W. Kolb and I.I. Tkachev, *Nonlinear axion dynamics and formation of cosmological pseudosolitons*, *Phys. Rev.* **D 49** (1994) 5040 [`astro-ph/9311037`].

[95] J. Redondo, *Solar axion flux from the axion-electron coupling*, *JCAP* **12** (2013) 008 [`arXiv:1310.0823`].

[96] K. Barth et al., *CAST constraints on the axion-electron coupling*, *JCAP* **05** (2013) 010 [`arXiv:1302.6283`].

[97] N. Viaux et al., *Neutrino and axion bounds from the globular cluster $M5$ (NGC 5904)*, *Phys. Rev. Lett.* **111** (2013) 231301 [`arXiv:1311.1669`].

[98] M.M. Miller Bertolami, B.E. Melendez, L.G. Althaus and J. Isern, *Revisiting the axion bounds from the galactic white dwarf luminosity function*, *JCAP* **10** (2014) 069 [`arXiv:1406.7712`].

[99] A.H. Córsico et al., *The rate of cooling of the pulsating white dwarf star $G117$-$B15A$: a new asteroseismological inference of the axion mass*, *Mon. Not. Roy. Astron. Soc.* **424** (2012) 2792 [`arXiv:1205.6180`].

[100] A.H. Córsico et al., *An asteroseismic constraint on the mass of the axion from the period drift of the pulsating DA white dwarf star $L19$-2*, *JCAP* **07** (2016) 036 [`arXiv:1605.06458`].

[101] J. Khoury and A. Weltman, *Chameleon fields: awaiting surprises for tests of gravity in space*, *Phys. Rev. Lett.* **93** (2004) 171104 [`astro-ph/0309300`].

[102] P. Brax, C. van de Bruck, A.-C. Davis, J. Khoury and A. Weltman, *Detecting dark energy in orbit — the cosmological chameleon*, *Phys. Rev.* **D 70** (2004) 123518 [`astro-ph/0408415`].

[103] P. Brax and K. Zioutas, *Solar chameleons*, *Phys. Rev.* **D 82** (2010) 043007 [`arXiv:1004.1846`].

[104] CAST collaboration, V. Anastassopoulos et al., *Search for chameleons with CAST*, *Phys. Lett.* **B 749** (2015) 172 [`arXiv:1503.04561`].

[105] L.B. Okun, *Limits of electrodynamics: paraphotons?*, *Sov. Phys. JETP* **56** (1982) 502 [*Zh. Eksp. Teor. Fiz.* **83** (1982) 892].

[106] B. Holdom, *Two* U(1)*'s and ϵ charge shifts*, *Phys. Lett.* **B 166** (1986) 196.

[107] K.R. Dienes, C.F. Kolda and J. March-Russell, *Kinetic mixing and the supersymmetric gauge hierarchy*, *Nucl. Phys.* **B 492** (1997) 104 [`hep-ph/9610479`].

[108] J. Redondo, *Helioscope bounds on hidden sector photons*, *JCAP* **07** (2008) 008 [`arXiv:0801.1527`].

[109] S. Troitsky, *Solar paraphotons*, `arXiv:1112.5276`.

[110] J. Redondo, *ATLAS of solar hidden photon emission*, *JCAP* **07** (2015) 024 [`arXiv:1501.07292`].