ULTRALIGHT PARTICLE DARK MATTER

A. RINGWALD

Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85,
D-22607 Hamburg, Germany

We review the physics case for very weakly coupled ultralight particles beyond the Standard Model, in particular for axions and axion-like particles (ALPs): (i) the axionic solution of the strong CP problem and its embedding in well motivated extensions of the Standard Model; (ii) the possibility that the cold dark matter in the Universe is comprised of axions and ALPs; (iii) the ALP explanation of the anomalous transparency of the Universe for TeV photons; and (iv) the axion or ALP explanation of the anomalous energy loss of white dwarfs. Moreover, we present an overview of ongoing and near-future laboratory experiments searching for axions and ALPs: haloscopes, helioscopes, and light-shining-through-a-wall experiments.

1 Introduction

There are plenty of particle candidates for the cold dark matter in the Universe, spanning a huge parameter range in masses and strengths of couplings to the particles of the Standard Model. Among them, two particular classes stand out because of their convincing physics case and the variety of possible experimental and observational opportunities to search for them: Weakly Interacting Massive Particles (WIMPs), such as the neutralinos in supersymmetric extensions of the Standard Model, and very Weakly Interacting Slim (in the sense of ultralight) Particles (WISPs), such as axions in Peccei-Quinn extensions of the Standard Model. In this contribution to the conference, we will concentrate on WISPs. In particular, we will review the physics case for axions and axion-like particles and present ongoing and near-future laboratory experiments hunting for them. For more details and a review of other WISP candidates, see Refs. [1,2,3].

2 Physics Case for Axions and Axion-like Particles

2.1 The Axionic Solution of the Strong CP Problem

The axion is predicted in an elegant solution of the so-called strong CP problem. It is the prime example of a WISP.

Shortly after the emergence of Quantum Chromo-Dynamics (QCD) as the fundamental theory of strong interactions it was realized that its fundamental parameters are not only the strong fine structure constant α_s and the quark masses m_u, m_d, ..., but also the angular parameter $\overline{\theta} = \theta + \arg \det \mathcal{M}_q$, a sum of the arg det of the quark mass matrix $\mathcal{M}_q$ and the QCD vacuum angle θ, appearing in the theta term in the QCD Lagrangian,

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \theta \, G^a_{\mu\nu} \tilde{G}^{a,\mu\nu}, \tag{1}$$

where $G^a_{\mu\nu}$ is the gluon field strength and $\tilde{G}^{a,\mu\nu}$ its dual. This term $\propto G^a_{\mu\nu}\tilde{G}^{a,\mu\nu} \propto \mathbf{E}^a \cdot \mathbf{B}^a$, violates T and P, and thus CP.

Experimentally, the most sensitive probe of T and P violation in flavor conserving interactions is the electric dipole moment (EDM) of the neutron, which turns out to be tiny [4], $|d_n| < 2.9 \times 10^{-26} \, e \, \text{cm}$, implying an exponentially small value of the theta parameter, $|\bar{\theta}| \lesssim 10^{-9}$, obtained from comparing the QCD prediction,

$$d_n(\bar{\theta}) \sim \frac{e m_u m_d \bar{\theta}}{(m_u + m_d) m_n^2} \sim 6 \times 10^{-17} \, \bar{\theta} \, e \, \text{cm}, \tag{2}$$

with the experimental value. This tremendous fine-tuning of the angular theta parameter – the latter being expected to be naturally of order unity – constitutes the strong CP problem.

The Peccei-Quinn (PQ) solution[5] of the strong CP problem is based on the observation that the vacuum energy in QCD,

$$V(\bar{\theta}) = \frac{m_\pi^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \bar{\theta}^2 + \mathcal{O}(\bar{\theta}^4), \tag{3}$$

where m_π and f_π are the mass and the decay constant of the pion, respectively, has a localized minimum at vanishing theta parameter. Therefore, if theta were a dynamical field, its vacuum expectation value (vev) would be zero.

The idea is then to introduce a field $a(x)$, respecting a non-linearly realized $U(1)_{\text{PQ}}$ symmetry, i.e. a shift symmetry, $a(x) \to a(x) + \text{const.}$, broken only by the coupling to $G\tilde{G}$,

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \left(\bar{\theta} + \frac{a}{f_a} \right) G_{\mu\nu}^a \tilde{G}^{a,\mu\nu}, \tag{4}$$

where the Peccei-Quinn (PQ) scale f_a is a parameter with dimension of mass. The pseudo-scalar field $a(x)$ thus plays effectively the role of a dynamical theta parameter. In fact, exploiting the shift symmetry one can eliminate $\bar{\theta}$ in Eq. (4). QCD dynamics, cf. Eq. (3), leads then to a vanishing vev for the shifted field, i.e. T, P, and CP are conserved.

Inevitably, this mechanism predicts the existence of a particle excitation corresponding to the quantum field fluctuations around the vev: the "axion" [6,7]. The axion is a pseudo-Nambu-Goldstone boson rather than a proper, i.e. massless, Nambu-Goldstone boson: because of mixing with the neutral pion, described by the chiral QCD Lagrangian, the shift symmetry is broken and the axion acquires a mass, which can be read off from the quadratic part in the potential (3),

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 0.6 \, \text{meV} \times \left(\frac{10^{10} \, \text{GeV}}{f_a} \right). \tag{5}$$

The interactions of the axion with the Standard Model particles are suppressed by inverse powers of the PQ scale, as follows from the shift symmetry and behooves for a Nambu-Goldstone boson. From its mixing with the pion it inherits a universal coupling to hadrons and to photons,

$$\mathcal{L} \supset -\frac{1}{4} g_{a\gamma} a \, F_{\mu\nu} \tilde{F}^{\mu\nu} = g_{a\gamma} a \, \mathbf{E} \cdot \mathbf{B}, \tag{6}$$

with

$$g_{a\gamma} = \frac{\alpha}{2\pi f_a} \left(C_{a\gamma} - \frac{2}{3} \frac{m_u + 4 m_d}{m_u + m_d} \right) \sim (C_{a\gamma} - 1.92) \times 10^{-13} \, \text{GeV}^{-1} \left(\frac{10^{10} \, \text{GeV}}{f_a} \right), \tag{7}$$

where $C_{a\gamma}$ is a model dependent dimensionless factor. This model dependence is illustrated by the width of the red band in Fig. 1 (taken from Ref. [8]), which displays the expected axion coupling to the photon as a function of its mass $g_{a\gamma} \propto 1/f_a \propto m_a$.

The phenomenology of the axion is therefore largely determined by the value of the PQ scale. Currently, the most stringent lower bounds on it arise from astrophysical considerations and are summarized in Fig. 2 which has been adapted and updated from Ref. [9]. In particular, the observed duration of the neutrino signal from supernova SN 1987A pose the most stringent model independent limit, $f_a > 4 \times 10^8 \, \text{GeV} \Rightarrow m_a < 16 \, \text{meV}$. Thus, the axion is a prime paradigm of a WISP: it is indeed ultralight and very weakly coupled to the Standard Model.
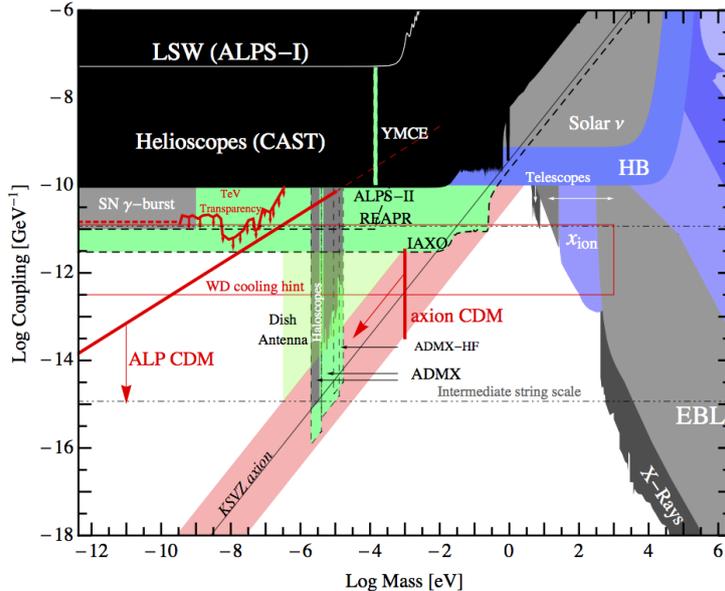
Figure 1: Exclusion regions in axion and ALP coupling to the photon vs. mass as described in the text.

2.2 Ultraviolet Completions of the Standard Model Predicting Axions and Axion-Like Particles

In purely field theoretic high-energy extensions of the Standard Model in four dimensions, the axion can be obtained as a Nambu-Goldstone boson from the breaking of a global $U(1)_{\rm PQ}$ symmetry. One introduces a complex Standard Model singlet scalar field σ whose vev $\langle\sigma\rangle = v_{\rm PQ}/\sqrt{2}$ breaks $U(1)_{\rm PQ}$ and whose phase, cf. $\sigma(x) = \frac{1}{\sqrt{2}}\big[v_{\rm PQ} + \rho(x)\big]e^{ia(x)/v_{\rm PQ}}$, is the axion field. The PQ scale f_a is then essentially the $U(1)_{\rm PQ}$ symmetry breaking scale, $f_a = v_{\rm PQ}/C_{ag}$, where C_{ag} is a model dependent factor of order unity which depends on the $U(1)_{\rm PQ}$ charge assignments of the fermions in the theory which have to be such that the mixed $U(1)_{\rm PQ} \times SU(3)_C \times SU(3)_C$ axial anomaly is non-vanishing. Very well known field theoretic PQ extensions of the Standard Model are the so-called KSVZ[10,11] and DFSZ[12,13] models. The PQ breaking scale in these models is however still ad-hoc. Interestingly, there are a number of well-motivated models which extend the Standard Model even more, thereby tying the PQ scale with other supposedly fundamental scales. Particularly intriguing are models in which additionally right-handed singlet Majorana neutrinos are introduced which carry also PQ charges and get their mass by PQ symmetry breaking, such that the PQ scale can in fact be identified with the seesaw scale. The masses of the active neutrinos, $m_\nu \propto v^2/v_{\rm PQ}$, where $v = 246\,{\rm GeV}$ is the electroweak breaking scale, are then naturally of order the observed mass splittings, $\sim 0.01\,{\rm eV}$, for an intermediate scale $v_{\rm PQ} \sim 10^{10 \div 12}\,{\rm GeV}$ [14]. These models, which can be embedded in certain Grand Unified Theories (GUTs) [15,16,17], therefore indeed prefer a PQ scale in the allowed parameter range, cf. Fig. 2.

Still, in these field theoretic PQ extensions one has to introduce the complex scalar singlets and the global $U(1)_{\rm PQ}$ by hand. This is different in low energy effective field theories emerging from string theory. In fact, they contain automatically candidates for the axion, often even an "axiverse" containing additional axion-like particles (ALPs), the latter being characterized by the fact that they do not couple to $G\tilde{G}$. One class, the so-called closed string axions and ALPs, arise as Kaluza-Klein zero modes of antisymmetric tensor fields living in ten dimensions and inherit their shift symmetry from gauge invariance in ten dimensions. Their number depends on the topology of the compactified six-dimensional space. Their predicted PQ scales $f_{a/{\rm ALP}}$ are typically of order of the string scale [18,19,20]. The latter is close to the Planck scale, $\sim 10^{18}\,{\rm GeV}$, in compactifications of the heterotic string, or the intermediate scale, $\sim 10^{10 \div 12}\,{\rm GeV}$, in LARGE volume compactifications of type II string theory realising brane world scenarios [21]. Further axions and ALPs appear automatically as pseudo Nambu-Goldstone bosons from the breaking of
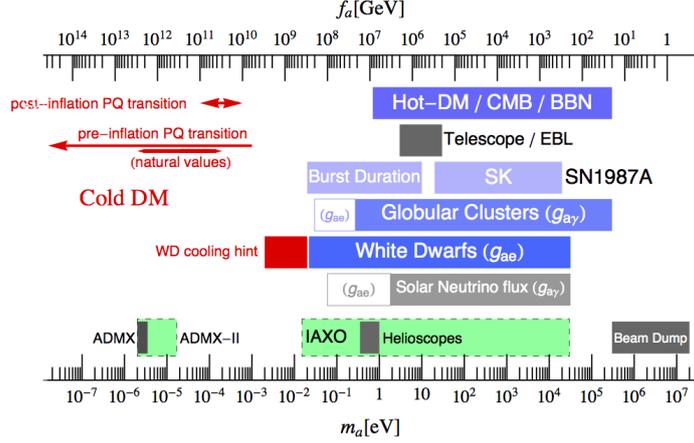
Figure 2: Exclusion regions in Peccei-Quinn scale f_a and axion mass m_a as described in the text.

accidental $U(1)_{\mathrm{PQ}}$ symmetries that appear as low energy remnants of exact discrete symmetries occuring in compactifications of the heterotic string [22,23,24]. In this case, it is possible to disconnect the PQ scales $f_{a/\mathrm{ALP}}$ from the string scale and chose them, e.g., in the phenomenologically interesting intermediate scale region.

2.3 Axions and ALPs as Cold Dark Matter

A few years after the proposal of the Peccei-Quinn solution of the strong CP problem it was realized that, for $f_a \gtrsim 10^{10}\,\mathrm{GeV}$, the axion is not as invisible as previously thought. In fact, for such large values of the PQ scale, it is produced mainly non-thermally in the early Universe and may comprise the dominant part of cold dark matter (for a review, see Ref. [25]).

The most generic non-thermal production in the early Universe proceeds via the so-called vacuum-realignment mechanism [26,27,28]. When the temperature in the early universe drops below the PQ scale, the spatially homogeneous mode of the axion field is frozen at a random initial value, $\theta_i = a(t_i)/f_a$, in each different causally connected region. Later, at the epoch of chiral symmetry breaking, the axion potential (3) rises and the axion acquires its mass m_a. Then, the axion field relaxes to its CP conserving minimum, around which it oscillates. These oscillations represent a population of non-relativistic axions.

If the reheating temperature after inflation is above the PQ scale, the initial misalignment angles $\theta_i = a(t_i)/f_a$ are randomly distributed in different causally connected parts of the Universe, leading to a prediction of

$$\Omega_a h^2 \approx 0.3 \times \left(\frac{f_a}{10^{12}\,\mathrm{GeV}} \right)^{7/6} \tag{8}$$

for the cosmic mass fraction in axions. Therefore, in this case, $m_a \sim 10^{-5}$ eV axions, corresponding to a PQ scale of order $f_a \sim 10^{11}\,\mathrm{GeV}$, can provide dark matter, but smaller masses (higher PQ scales) are excluded (in the absence of a dilution mechanism by late decays of particles beyond the Standard Model). Apart from the vacuum-realignment mechanism, the decay of cosmic strings and domain walls may provide additional sources for non-thermally produced axions [25]. These extend the region where axions may provide the whole of cold dark matter in the Universe to $10^{10}\,\mathrm{GeV} \lesssim f_a \lesssim 10^{11}\,\mathrm{GeV}$ [29,30,31], cf. the red region labelled "post-inflation PQ transition" in Fig. 2.

On the other hand, if the reheating temperature after inflation is below the PQ scale, then the axion field is homogenized by inflation, the inital misalignment angle thus being unique in all the observable Universe. Furthermore, topological defects are diluted away by inflation. Correspondingly, only the vacuum-realignment mechanism will contribute to the expected cosmic

mass fraction in axions, which is obtained as

$$\Omega_a h^2 \approx 0.71 \times \left(\frac{f_a}{10^{12} \text{ GeV}}\right)^{7/6} \left(\frac{\theta_i}{\pi}\right)^2 , \tag{9}$$

if there is no dilution by, e.g., late decays of particles beyond the Standard Model. Therefore, the axion can be the dominant part of cold dark matter if its decay constant exceeds $f_a \gtrsim 10^{11}$ GeV, corresponding to a mass $m_a < 10^{-5}$ eV. An axion with a GUT scale decay constant, $f_a \sim 10^{16}$ GeV, on the other hand, would overclose the universe, unless the initial misaligment angle is very small, $\theta_i \sim 10^{-3}$ ("anthropic axion window"[32]), or there is a late dilution.

Similar to axions, also ALPs would be produced in the early Universe via the vacuum-realignment mechanism, leading to an expected cosmic mass fraction[33]

$$\Omega_{a_i} h^2 \approx 0.16 \times \left(\frac{m_{\text{ALP}}}{\text{eV}}\right)^{1/2} \left(\frac{f_{\text{ALP}}}{10^{11} \text{ GeV}}\right)^2 \left(\frac{\theta_i}{\pi}\right)^2 , \tag{10}$$

if the reheating temperature after inflation is below f_{ALP}. This enlarges the search space for ultralight particle dark matter considerably, cf. Fig. 1.

2.4 ALP Explanation of Anomalous Transpareny of the Universe for TeV Photons

Intriguingly, the existence of at least one ALP could help to solve a puzzle in gamma ray astronomy, namely the non-observation of absorption features in very high energy (VHE) photon spectra from distant active galactic nuclei (AGN) which are expected due to e^+e^- pair production off the extragalactic background light[34]. This may be explained by photon $\leftrightarrow$ ALP oscillations: the conversion of gamma rays into ALPs in the magnetic fields around the AGNs or in the intergalactic medium, followed by their unimpeded travel towards our galaxy and the consequent reconversion into photons in the galactic/intergalactic magnetic fields[35,36,37], requiring a very light ALP, which couples to two photons with strength[38] $g_{\text{ALP}\gamma} \gtrsim 10^{-12}$ GeV^{-1} $\Rightarrow$ $f_{\text{ALP}}/C_{\text{ALP}\gamma} \lesssim 10^9$ GeV, for $m_{\text{ALP}} \lesssim 10^{-7}$ eV. Note, that this particle must be an ALP, rather than the axion. In fact, an axion with $m_a \lesssim 10^{-7}$ eV would have a photon coupling $g_{a\gamma} \lesssim 10^{-16}$ GeV^{-1}.

2.5 Axion or ALP Explanation of Anomalous Energy Loss of White Dwarfs

Bremsstrahlung of axions or ALPs, if they couple directly to electrons, may also explain another puzzle in astrophysics. In fact, the white dwarf (WD) luminosity function seems to require a new energy loss channel that can be interpreted in terms of axion or ALP losses corresponding to a PQ scale $f_{a/\text{ALP}}/C_{a/\text{ALP}\,e} \simeq (0.7 \div 2.6) \times 10^9$ GeV, where $C_{a/\text{ALP}\,e}$ is a model-dependent dimensionless constant[39]. Moreover, the observations of the period decrease of the pulsating WDs G117-B15A and R548 imply additional cooling that can be interpreted in terms of similar axion/ALP losses[40,41]. The corresponding region in axion parameter space is shown as a red box labelled as "WD cooling hint" in Fig. 2. The red parameter region labelled "WD cooling hint" in Fig. 1 indicates the extrapolation to the two-photon coupling, if one allows for a reasonable uncertainty in the ratio $C_{a/\text{ALP}\,\gamma}/C_{a/\text{ALP}\,e}$.

3 Laboratory Searches for Axions and ALPs

Fortunately, there appear to be a number of opportunities for laboratory searches for axions and ALPs if their photon couplings are indeed in the range 10^{-16} GeV$^{-1} \lesssim g_{a/\text{ALP}\gamma} \lesssim 10^{-11}$ GeV^{-1}, corresponding to intermediate scale PQ scales, $f_{a/\text{ALP}} \sim 10^{9 \div 12}$ GeV, which we will review in the next few subsections. A common feature of these experiments is that they exploit the conversion of axions and ALPs into photons (or the reverse processes) in strong, laboratory made magnetic fields.

3.1 Haloscope Searches

These searches aim for the direct detection of dark matter axions or ALPs in the laboratory.

The currently most sensitive haloscopes consist of a high-Q microwave cavity placed in a superconducting solenoidal magnet [42], trying to detect the electromagnetic power arising from the conversion of dark matter axions or ALPs into real photons, with frequency $\nu = m_{a/\text{ALP}}/(2\pi) = 0.24$ GHz $\times (m_{a/\text{ALP}}/\mu\text{eV})$. The best sensitivity is reached on resonance, the power output then being proportional to the quality factor of the cavity. A number of experiments of this type have already been done and the limits obtained to date, scanning the mass range by tuning the cavities, are shown as a grey region labelled "Haloscopes" in Fig. 1. The Axion Dark Matter eXperiment (ADMX) has indeed reached the sensitivity to probe proper axion dark matter [43] (see also Fig. 2). The ongoing experiments ADMX-II and ADMX-High Frequency (HF) aim to explore the correspondingly labelled green regions in the same figures and will thus probe a significant part of the natural parameter region in scenarios where the PQ transition happens before inflation. Further haloscope opportunities in complementary mass ranges may arise from recycling available microwave cavities and magnets at accelerator laboratories [44]. One example is the WISPDMX proposal in Hamburg, which plans to use a high-Q HERA accelerator cavity and a superconducting solenoid from the H1 experiment [45].

Complementary to these narrow-band microwave cavity based searches, dish antennas have also been proposed as haloscopes [46]. In fact, monochromatic photons generated by the conversion of dark matter axions/ALPs will be emitted perpendicular to the surface of a spherical dish antenna, if it is placed in a background magnetic field. The photons can be focused in the centre of the dish onto a broad-band detector. The projected sensitvity of such an haloscope is shown in Fig. 1 as a green region labelled as "Dish Antenna".

Another possibility to search directly for axion/ALP cold dark matter may be based on the fact that the oscillating galactic dark matter axion/ALP fields will induce oscillating nuclear electric dipole moments in the laboratory. Conceivably, these could be detected by precision magnetometry, most sensitive in the sub-MHz band, corresponding to $m_{a/\text{ALP}} \lesssim$ neV, which means trans-GUT scale, $f_a \gtrsim 10^{16}$ GeV, for the axion [47,48].

3.2 Helioscope Searches

These searches aim to detect solar axions and ALPs by their conversion into photons inside of a strong magnet pointing towards the Sun [42]. In fact, up to 10% of the solar photon luminosity could be radiated in axions of ALPs without being in conflict with helioseismological and solar neutrino data. The currently best sensitivity has been obtained by the CERN Axion Solar Telescope (CAST), employing an LHC dipole test magnet. As can be seen in Fig. 1, the CAST limits (labelled "Helioscopes (CAST)") have already surpassed, at low masses, the bounds from Horizontal Branch (HB) stars [49]. At larger masses, CAST has started to probe the predictions for axions [50,51]. A proposed next-generation axion helioscope [52], dubbed the International Axion Observatory (IAXO), envisions a dedicated superconducting toroidal magnet with much bigger aperture than CAST, a detection system consisting of large X-ray telescopes coupled to ultra-low background X-ray detectors, and a large, robust tracking system [53]. IAXO would enable the search for solar axions and ALPs in a broad mass range, as shown by the green region labelled "IAXO" in Fig. 1, allowing to probe a part of axion parameter space, corresponding to $f_a \sim 10^{9 \div 10}$ GeV, which will not be covered by the haloscope searches. The projected sensitivity of IAXO nicely overlaps with the ALP parameter region required to explain the puzzles from astrophysics, such as the anomalous transparency of the universe for VHE photons, see Fig. 1.

3.3 Light-Shining-through-a-Wall (LSW) Searches

These searches aim for the production and detection of axions or ALPs in the laboratory. In these experiments, laser photons are sent along a strong magnetic field, allowing for their conversion

into axions or ALPs, which may then reconvert in the strong magnetic field behind a blocking wall into photons, susceptible to detection [54,55,56]. The currently best sensitivity has been reached by the Any Light Particle Search (ALPS-I) experiment at DESY [57], which used a superconducting HERA dipole magnet, with the first half of the magnet, the production region, being enclosed in an optical resonator and the second half being used as the regeneration region. The end of the latter was connected to a light-tight box in which signal photons were redirected to a CCD camera. The bound established by ALPS-I for ALPs is labelled "LSW (ALPS-I)" in Fig. 1. Recently, the first stages of the successor experiment ALPS-II have been approved by the DESY directorate [58,59]. ALPS-II proposes to use 10+10 straightened HERA magnets [60], a high-power laser system, a superconducting low-background detector and the pioneering realization of an optical regeneration cavity [61]. The Resonantly Enhanced Axion-Photon Regeneration Experiment (REAPR) at Fermilab is a quite similar proposal which differs from ALPS-II in the scheme to lock the optical cavities [62]. This generation of LSW experiments aims at surpassing the current helioscope bounds from CAST and tackle some of the ALP parameter space favored by astrophysical observations, cf. the light-green region in Fig. 1 labelled by "ALPS-II, REAPR".

4 Summary and Conclusions

There is a strong physics case for very weakly coupled ultralight particles beyond the Standard Model. The elegant solution of the strong CP problem proposed by Peccei and Quinn gives a particularly strong motivation for the axion. In many theoretically appealing ultraviolet completions of the Standard Model, in particular in completions arising from strings, there occur axions and axion-like particles (ALPs) automatically. Moreover, axions and ALPs are natural cold dark matter candidates. They can explain the anomalous transparency of the Universe for VHE gamma rays and the anomalous cooling of white dwarfs. Fortunately, a significant portion of axion and ALP parameter space will be tackled in this decade by a number of experiments of haloscope, helioscope, and light-shining-through-a-wall type. Stay tuned!

References

1. J. Jaeckel and A. Ringwald, *Ann. Rev. Nucl. Part. Sci.* **60**, 405 (2010) [arXiv:1002.0329 [hep-ph]].
2. A. Ringwald, *Phys. Dark Univ.* **1**, 116 (2012) [arXiv:1210.5081 [hep-ph]].
3. J. Jaeckel, *Frascati Phys. Ser.* **56**, 172 (2013) [arXiv:1303.1821 [hep-ph]].
4. C. A. Baker *et al.*, *Phys. Rev. Lett.* **97**, 131801 (2006) [hep-ex/0602020].
5. R. D. Peccei and H. R. Quinn, *Phys. Rev. Lett.* **38**, 1440 (1977).
6. S. Weinberg, *Phys. Rev. Lett.* **40**, 223 (1978).
7. F. Wilczek, *Phys. Rev. Lett.* **40**, 279 (1978).
8. K. Baker *et al.*, *Annalen Phys.* **525**, A93 (2013) [arXiv:1306.2841 [hep-ph]].
9. J. L. Hewett *et al.*, arXiv:1205.2671 [hep-ex].
10. J. E. Kim, *Phys. Rev. Lett.* **43**, 103 (1979).
11. M. A. Shifman, A. I. Vainshtein, V. I. Zakharov, *Nucl. Phys.* B **166**, 493 (1980).
12. M. Dine, W. Fischler, M. Srednicki, *Phys. Lett.* B **104**, 199 (1981).
13. A. R. Zhitnitsky, *Sov. J. Nucl. Phys.* **31**, 199 (1980) [*Yad. Fiz.* **31**, 497 (1980)].
14. P. Langacker, R. D. Peccei and T. Yanagida, *Mod. Phys. Lett.* A **1**, 541 (1986).
15. R. N. Mohapatra and G. Senjanovic, *Z. Phys.* C **17**, 53 (1983).
16. A. G. Dias and V. Pleitez, *Phys. Rev.* D **70**, 055009 (2004) [hep-ph/0407074].
17. G. Altarelli and D. Meloni, *JHEP* **1308**, 021 (2013) [arXiv:1305.1001 [hep-ph]].
18. E. Witten, *Phys. Lett.* B **149**, 351 (1984).
19. A. Arvanitaki *et al.*, *Phys. Rev.* D **81**, 123530 (2010) [arXiv:0905.4720 [hep-th]].
20. B. S. Acharya, K. Bobkov, P. Kumar, *JHEP* **1011**, 105 (2010) [arXiv:1004.5138 [hep-th]].

21. M. Cicoli, M. Goodsell, A. Ringwald, *JHEP* **1210**, 146 (2012) [arXiv:1206.0819 [hep-th]].
22. G. Lazarides, C. Panagiotakopoulos and Q. Shafi, *Phys. Rev. Lett.* **56**, 432 (1986).
23. K. -S. Choi *et al.*, *Phys. Lett.* B **675**, 381 (2009) [arXiv:0902.3070 [hep-th]].
24. A. G. Dias, A. C. Machado, C. C. Nishi, A. Ringwald, P. K. S. Vaudrevange, in preparation.
25. P. Sikivie, *Lect. Notes Phys.* **741**, 19 (2008) [astro-ph/0610440].
26. J. Preskill, M. B. Wise and F. Wilczek, *Phys. Lett.* B **120**, 127 (1983).
27. L. F. Abbott and P. Sikivie, *Phys. Lett.* B **120**, 133 (1983).
28. M. Dine and W. Fischler, *Phys. Lett.* B **120**, 137 (1983).
29. O. Wantz and E. P. S. Shellard, *Phys. Rev.* D **82**, 123508 (2010) [arXiv:0910.1066 [astro-ph.CO]].
30. T. Hiramatsu *et al.*, *Phys. Rev.* D **83**, 123531 (2011) [arXiv:1012.5502 [hep-ph]].
31. T. Hiramatsu *et al.*, *Phys. Rev.* D **85**, 105020 (2012) [Erratum-ibid. D **86**, 089902 (2012)] [arXiv:1202.5851 [hep-ph]].
32. M. Tegmark *et al.*, *Phys. Rev.* D **73**, 023505 (2006) [astro-ph/0511774].
33. P. Arias *et al.*, *JCAP* **1206**, 013 (2012) [arXiv:1201.5902 [hep-ph]].
34. D. Horns, M. Meyer, *JCAP* **1202**, 033 (2012) [arXiv:1201.4711 [astro-ph.CO]].
35. A. De Angelis *et al.*, *Phys. Rev.* D **76**, 121301 (2007) [arXiv:0707.4312 [astro-ph]].
36. M. Simet *et al.*, *Phys. Rev.* D **77**, 063001 (2008) [arXiv:0712.2825 [astro-ph]].
37. M. A. Sanchez-Conde *et al.*, *Phys. Rev.* D **79**, 123511 (2009) [arXiv:0905.3270 [astro-ph.CO]].
38. M. Meyer *et al.*, *Phys. Rev.* D **87**, 035027 (2013) [arXiv:1302.1208 [astro-ph.HE]].
39. J. Isern *et al.*, *Astrophys. J.* **682**, L109 (2008) [arXiv:0806.2807 [astro-ph]].
40. J. Isern *et al.*, *Astron. Astrophys.* **512**, A86 (2010) [arXiv:1001.5248 [astro-ph.SR]].
41. A. H. Corsico *et al.*, *JCAP* **1212**, 010 (2012) [arXiv:1211.3389 [astro-ph.SR]].
42. P. Sikivie, *Phys. Rev. Lett.* **51**, 1415 (1983) [Erratum-ibid. **52**, 695 (1984)].
43. S. J. Asztalos *et al.* [The ADMX Collaboration], *Phys. Rev. Lett.* **104**, 041301 (2010) [arXiv:0910.5914 [astro-ph.CO]].
44. O. K. Baker *et al.*, *Phys. Rev.* D **85**, 035018 (2012) [arXiv:1110.2180 [physics.ins-det]].
45. D. Horns, A. Lindner, A. Lobanov and A. Ringwald, arXiv:1309.4170 [physics.ins-det].
46. D. Horns *et al.*, *JCAP* **1304**, 016 (2013) [arXiv:1212.2970].
47. P. W. Graham and S. Rajendran, *Phys. Rev.* D **88**, 035023 (2013) [arXiv:1306.6088 [hep-ph]].
48. D. Budker *et al.*, arXiv:1306.6089 [hep-ph].
49. S. Andriamonje *et al.* [CAST Collaboration], *JCAP* **0704**, 010 (2007) [hep-ex/0702006].
50. S. Aune *et al.* [CAST Collaboration], *Phys. Rev. Lett.* **107**, 261302 (2011) [arXiv:1106.3919 [hep-ex]].
51. M. Arik *et al.* [CAST Collaboration], arXiv:1307.1985 [hep-ex].
52. I. G. Irastorza *et al.*, *JCAP* **1106**, 013 (2011) [arXiv:1103.5334 [hep-ex]].
53. J. K. Vogel *et al.* [IAXO Collaboration], arXiv:1302.3273 [physics.ins-det].
54. A. A. Anselm, *Yad. Fiz.* **42**, 1480 (1985).
55. K. Van Bibber *et al.*, *Phys. Rev. Lett.* **59**, 759 (1987).
56. J. Redondo, A. Ringwald, *Contemp. Phys.* **52**, 211 (2011) [arXiv:1011.3741 [hep-ph]].
57. K. Ehret *et al.* [ALPS Collaboration],, *Phys. Lett.* B **689**, 149 (2010) [arXiv:1004.1313 [hep-ex]].
58. R. Bähre *et al.* [ALPS-II Collaboration], *JINST* **8**, T09001 (2013) [arXiv:1302.5647 [physics.ins-det]].
59. B. Döbrich *for the* [ALPS-II Collaboration], arXiv:1309.3965 [physics.ins-det].
60. A. Ringwald, *Phys. Lett.* B **569**, 51 (2003) [hep-ph/0306106].
61. F. Hoogeveen, T. Ziegenhagen, *Nucl. Phys.* B **358**, 3 (1991).
62. G. Mueller *et al.*, *Phys. Rev.* D **80**, 072004 (2009) [arXiv:0907.5387 [hep-ph]].