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Strategic Search Plan for Axions and Axion-like-particles

Support Note for Dark Matter and Dark Sector

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Abstract

Axions are one of the most promising candidates to constitute the Dark Matter in our universe. The benchmark QCD axion covers a narrow parameter space, but many well-motivated extensions of the Standard Model predict Axion-like-Particles in wide parameter regions. In this support note we detail on searches covering the extended axion-like particle parameter space proposed to the European strategy

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1 Introduction

This note provides some supplementary information in addition to what was given in the briefing book. In a similar spirit to the briefing book it draws strongly from the relevant submissions to the European Strategy Process, in particular the numbers (27, 31, 42, 60, 69, 112, 113, 161), as well as the reports of the Physics Beyond Colliders Working group [1–3]. Moreover, we are very grateful for detailed textual input from the relevant experimental collaborations (mostly in sections 2 and 3) as provided by the persons listed in the Acknowledgements.

1.1 Standard QCD Axion

In this section we will not provide a review of axions. Instead we refer the reader to the briefing book for a very short intro and for more details to reviews, as, e.g. [4–7]. Here we just briefly provide some additional comments on its interactions.

The original QCD axion [8–11] with breaking of the U(1) PQ at the electroweak scale was soon ruled out. It was succeeded by "invisible" axion models that still solve the strong CP problem of QCD but where the breaking of the U(1) PQ occurs at a new independent scale f_a [12–15]. All interactions are then suppressed by this new scale f_a. If this scale is chosen suitably high, the interactions become very weak and the axion is invisible. Nevertheless new methods for the detection of even this invisible axion were soon devised. These famously include the axion helioscope and the axion haloscope [16] as well as the light-shining-through-walls setup that form the basis of the most important searches described in the main part of the briefing book.

Here, let us just comment on one aspect only briefly touched upon in the main part. Most experiments, in particular most promising ones described in the main text (and below) still focus on the experimentally best accessible coupling to photons. While this is still the most promising strategy for discovery, there are two aspects worth mentioning that support efforts to also search for other couplings featured by axions: 1) The axion-photon coupling is somewhat model-dependent. Thereby making it hard to conclusively test the axion. 2) Measuring more than one coupling gives information on the underlying model and thereby access to details of very deep UV physics.

1.2 Extension of the QCD Axion Parameter Space

Axion cosmology and phenomenology depend on a few details of the UV completion. For viable models, this UV completion is at high scales, $> 10^9$ GeV. Likewise, the cosmological history of axions is set up by the details of inflation and reheating, and then by the details of the QCD phase transition. On one hand this is an interesting feature since axions then give us a handle on physics at these high scales. At the same time, this physics is beyond our current direct experimental reach, so this leaves some uncertainty in predictions for axion experiments.

In this section we briefly review some of the key ways in which these assumptions can dramatically alter axion phenomenology. In the simplest models, the axion mass and couplings are all but fixed by its decay constant f_a. The coupling to photon which is of great phenomenological interest depends further on the quantum numbers of heavy particles. In the simplest models this factor is around 1. The abundance of axions under mild assumptions about cosmology leaves a preferred narrow range of f_a. This is a prime target for axion searches.

Given the uncertainty in the very early and very high energy physics, it is worth keeping in mind that the target space for viable axion models can be much larger.

The mass prediction of the QCD axion with a certain decay constant is thought to be model independent, arising from QCD dynamics. Any other contribution to the axion potential can shift the minimum, which would then be in contradiction to the non-observation of CP violation in the strong sector (such as EDM of neutrons). However, in extended models the QCD axion can receive new mass contributions which are aligned with the QCD contribution. This could be as a result of new Z_2 symmetries [17] or aligned UV instanton contributions [18]. Such heavier axions may be relevant for accelerator and even collider experiments.

The couplings of the axion to photons is one of the key ways to search for the axion. With simple model assumptions, this coupling is of the order of $\alpha/(4\pi f_a)$. Having larger representations can enhance this coupling only mildly. However, the clockwork mechanism can enhance this coupling by an exponential amount [19–22], such that for any mass of the axion the coupling to photons can be as large as that allowed by astrophysical constraints. This has far reaching implications for experiment – this shows that experiments that have sensitivity better than current astrophysical bounds over the entire axion mass range are sensitive to these kinds of QCD axion models.

Finally, light axions (corresponding to larger values of f_a close to the GUT scale) are theoretically motivated in string theory. These models typically have an overabundance of dark matter unless the initial value of the field is tuned to be close to the would-be minimum. In extended cosmological mechanisms, the overabundance of axions can be diluted to yield the correct relic abundance [23–25]. Experimental strategies for lighter axions are significantly different, and hence these extended cosmological mechanisms again further motivate searches in this extended region of parameter space.

These ideas serve to illustrate the fact that while the minimal axion models predict a narrow target for axion dark matter models, simple extensions can enlarge this parameter space significantly. The success of the search for axions may crucially depend on search broadly in this extended parameter space.

1.3 Hints from Astrophysics

Interesting hints for searching in the coupling range $g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ explored by the experiments in the main text arises from astrophysical observations.

Here, let us just list the main observations and their relation to axions and ALPs. An overview and details are provided, e.g. in [26] whom we follow closely. We also provide some exemplary references for further details (a more complete list can be found in [26])

- Anomalous transparency of the Universe in the γ-ray regime [27–29].
  This hint is directly pointing at a non-vanishing axion-photon coupling in the $g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ range for masses $m_a \lesssim 10^{-9}$ eV.
- Cooling of stars in late stages of their evolution [30, 31].
  This hint suggests a non-vanishing axion electron coupling in the g_{aee}. A region for the axion-photon coupling arises indirectly by translating the axion electron coupling $g_{aee} \sim m_e/f_a$ via f_a into an axion-photon coupling $g_{a\gamma\gamma} \sim \alpha/(4\pi f_a)$. Combined fits with the white dwarf cooling indicate also small preference also for a directly non-vanishing axion-photon coupling of the discussed magnitude. The mass range extends to masses $m_a \lesssim \text{few} \times \text{keV}$.
- Cooling of white dwarfs [31–34].
  As for the star hint discussed above.

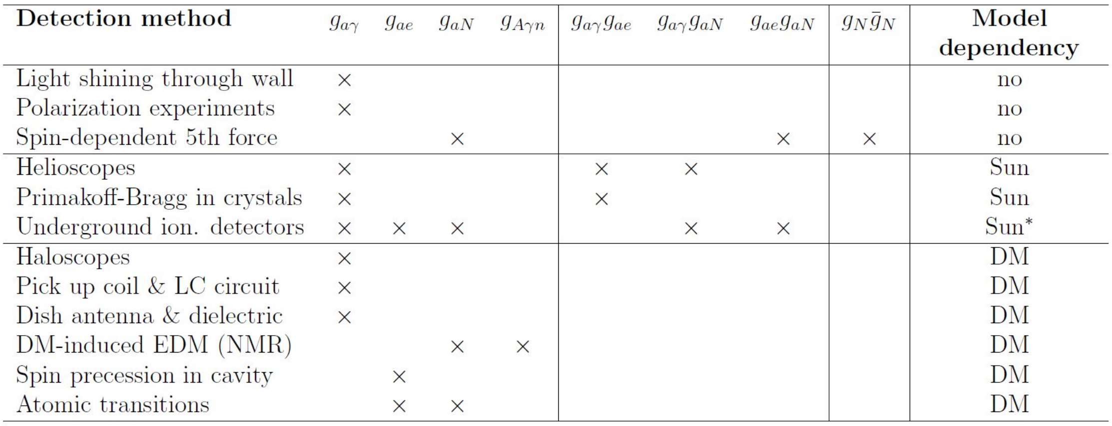
- Cooling of neutron stars [35].
  Also neutron stars seem to have a cooling anomaly. This would suggest a non-vanishing axion-neutron coupling. The ALP mass should then be $\lesssim \mathrm{few} \times 10\,\mathrm{keV}$.
- Soft X-ray excess and dark radiation [36, 37].
  Satellites have observed an excess X-ray emission from galaxy clusters. This could be explained by Axions/ALPs present as dark radiation being converted in the magnetic fields in the clusters. This again requires a direct axion-photon coupling in the $g_{a\gamma\gamma} \sim 10^{-11}\mathrm{GeV}^{-1}$ range but with even smaller masses $m_a \lesssim 10^{-12}\,\mathrm{eV}$.

2 Strategic searches for axions (Larger scale experiments)

Experiments looking for axions, axion-like particles (ALPs) or other weakly interacting slim particles (WISPs) with masses below the eV range typically have cost and time scales significantly below those of accelerator based experiments. With the evolving physics case a diverse landscape is forming worldwide with new experiments taking relevant data and lots of different R&D activities or concrete preparations for future setups. Frequently these activities benefit strongly from the advancement of technologies (for example quantum sensing), but also from research infrastructure at CERN and other European and national laboratories (for example magnets). Experiments try to detect axions, ALPs and more general WISPs originating from different sources.

- Laboratory experiments aim for producing and detecting axions/ALPs/WISPs in one setup.
- Helioscopes look with Earth bound experiments for axions/ALPs/WISPs emitted by the sun.
- Haloscopes are designed to "directly detect" axions/ALPs/WISPs that are a part of the local dark matter halo.

In general haloscopes offer the highest sensitivities due to the huge number density of dark matter axions/ALPs/WISPs, but are quite model dependent. On the contrary, purely laboratory experiments fully control the production and sensing scheme of axions/ALPs/WISPs, thus providing often nearly model independent results. An overview on the different experimental approaches is given in Figure 1 on the example for axion and ALP searches.



Detection method	$g_{a\gamma}$	g_{ae}	g_{aN}	$g_{A\gamma n}$	$g_{a\gamma}g_{ae}$	$g_{a\gamma}g_{aN}$	$g_{ae}g_{aN}$	$g_N\bar{g}_N$	**Model dependency**
Light shining through wall	×								no
Polarization experiments	×								no
Spin-dependent 5th force			×				×	×	no
Helioscopes	×				×	×			Sun
Primakoff-Bragg in crystals	×				×				Sun
Underground ion. detectors	×	×	×			×	×		Sun*
Haloscopes	×								DM
Pick up coil & LC circuit	×								DM
Dish antenna & dielectric	×								DM
DM-induced EDM (NMR)			×	×					DM
Spin precession in cavity		×							DM
Atomic transitions		×	×						DM

Fig. 1: Summary of different approaches axion and ALPS search experiments with g denoting the different couplings and $\bar{g}$ a CP-violating coupling (taken from I.G. Irastorza and J. Redondo [38].)

2.1 Strategic approach to the axion intersecting parameter space

In the following we will focus on experiments exploiting the axion/ALP couplings to photons. All approaches rely on the conversion of such particles into photons enabled by a background magnetic field. Here, purely laboratory experiments (light-shining-through-walls, LSW) and helioscopes deal with ultra-relativistic axions and ALPs, while haloscopes search for cold dark matter constituents that are non-relativistic. Consequently, LSW-experiments and helioscopes provide sensitivities for axions and ALPs independent of their mass up to an upper limit, while haloscopes typically require tuning of the experiments to the axion mass to be probed. Depending on cosmological and theoretical assumptions, a dark matter axion or ALP might have a mass in a parameter region spanning about 20 orders of magnitude. Therefore many different approaches are being investigated to tackle this enormous challenge.

It is not possible to review the landscape of axion/ALP experiments in the scope of this document. Instead, we will mention below in some detail larger scale and more costly initiatives as they might require some embedding in a future European strategy on elementary particle physics. However, the authors stress unambiguously that this selection does not come with a ranking of the different physics cases. On the contrary, we feel that a continuing or even increasing support of smaller scale experimental axion/ALP activities will be crucial for elementary particle physics as most experiments have the potential for game-changing breakthrough results.

2.2 LSW in the laboratory

In the first section of a light-shining-through-a-wall experiment, laser light is shone through a strong magnetic field. Here ALPs might be generated by interactions of optical photons with the magnetic field. The second section of the experiment is separated from the first one by a light-tight wall which can only be surpassed by ALPs and other WISPs . These particles would stream through a strong magnetic field behind the wall allowing for a re-conversion into photons. This effect will give the impression of light-shining-through-a-wall (LSW). Such pure laboratory experiment do not rely on astrophysical or cosmological assumptions.

The ALPS II experiment at DESY follows this approach. ALPS II strives to surpass the CAST sensitivity on the ALP-photon coupling by a factor of 3 for ALP masses below 0.1 meV. The improvement relative to existing LSW limits will be more than three orders of magnitude, which corresponds to an increase in signal-to-noise ratio by 10^{12}. Figure 2 sketches the concept of ALPS II.

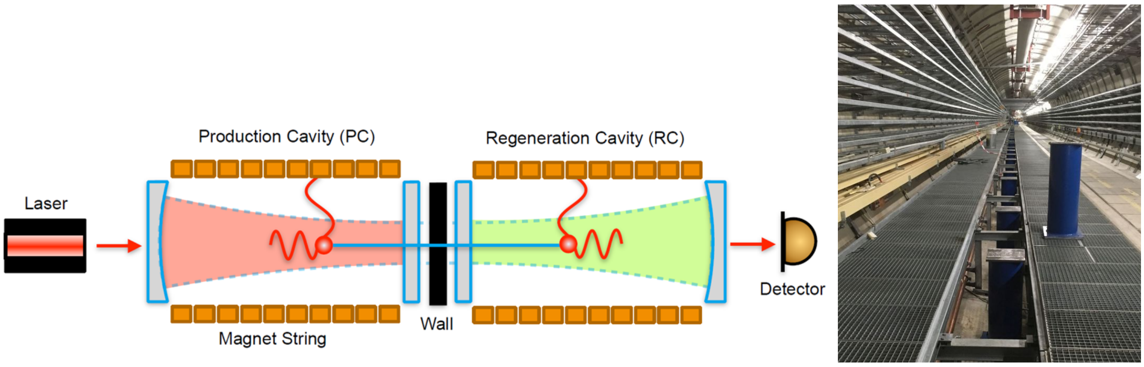


Fig. 2: Sketch of ALPS II (left) and the empty HERA tunnel (right) ready for the installation of the first magnets as of September 2019 (courtesy of the ALPS collaboration).

ALPS II is mainly motivated by probing a parameter region hinted at by astrophysical anomalies (stellar evolution, photon propagation in the universe) in a model-independent fashion.

ALPS II will achieve this goal by combining strings of straightened superconducting magnet from the HERA proton accelerator with mode-matched high finesse optical resonators before and behind the wall. Two different detection techniques, one based on a heterodyne approach and a second on a superconducting transition edge sensor, with sensitivities around 10^{-5} photons/second, are being developed for the signal search.

At the time of writing this text (August 2019), the basic performances of the optical system as well as the detection concepts have been demonstrated. 22 out of the 24 required straightened superconducting magnets have been modified and successfully tested. The site of ALPS II in a straight section of the HERA tunnel has been prepared and the installation of the first components is about to start. ALPS II will be ready for "first light" by the end of the year 2020. At present it is foreseen to take data for about two years.

The ALPS II experiment is facilitated by combining particle physics know-how and optics expertise from gravitational wave interferometry. The optical system of ALPS II fully profits from experiences at GEO600 and Advanced LIGO. To a very large extend the experiment reuses HERA infrastructure at DESY for a very cost-effective approach.

The collaboration consists of DESY, the Albert-Einstein-Institute and Leibniz University of Hanover, the Johannes Gutenberg University of Mainz, the University of Florida in Gainesville (FL), and Cardiff University.

Going significantly beyond the ALPS II sensitivity would require strings of magnet with higher field strengths and larger apertures to allow for longer optical resonators. A stepwise JURA (Joint Undertaking on Research for Axions) approach has been proposed along these lines, which could finally result in an LSW experiment surpassing even the IAXO sensitivity for very lightweight axion-like particles.

2.3 Helioscope[1]

The International Axion Observatory (IAXO) will be a next generation axion helioscope, aiming for a signal-to-noise ratio (SNR) a factor $> 10^4$ higher than CAST, and therefore with sensitivity to axion-photon coupling down to a few $10^{-12}\mathrm{GeV}^{-1}$. BabyIAXO is conceived as an intermediate stage in size, and will allow testing all subsystems (magnet, optics and detectors) at a relevant scale. BabyIAXO will enjoy a SNR $\sim$100 better than CAST, and therefore will produce relevant physics results in itself.

While the latest result from CAST has improved, for the first time for an axion helioscope, the best limits on $g_{a\gamma\gamma}$ from astrophysics, and has marginally entered into unexplored ALP and axion parameter space, BabyIAXO and IAXO will go beyond this point and venture deep into unexplored area. In particular, IAXO will probe a large fraction of QCD axion models in the meV to eV mass band. The axion/ALP region to be probed encompasses the values invoked to solve the Universe's transparency anomaly, and the ones solving the stellar cooling anomalies, as well as a number of other possible hints. It also includes some of the axion models that can account to the totality of dark matter.

Most of this region is only realistically within the reach of the helioscope technique, and therefore the BabyIAXO/IAXO program is unique in the wider landscape of experimental axion searches. The emission of axions by the Sun is a generic prediction of most axion models. Given that the potential of the experiment does not rely on assuming DM is made of axions, in case of a non-detection, robust limits on the axion parameters will be set. In the case of a positive detection, (Baby)IAXO will permit high-precision measurement campaigns to determine axion

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[1] We would like to thank Igor Irastorza for providing most of the text in this section.

parameters (e.g. its mass) and getting further insight on the underlying axion model. In any case, IAXO can play an important role in the future of axion and ALP research, with potential for a discovery, even already at the BabyIAXO stage.

The project is based on the 15-years long experience acquired in CAST, as well as on state-of-the-art technologies on superconducting magnets, x-ray optics and low background detectors. Despite the considerable scaling-up step with respect to CAST, the project design does not rely on untested solutions or pending R&D. BabyIAXO will further mitigate risks of the final IAXO. A design of BabyIAXO is shown in Figure 3.

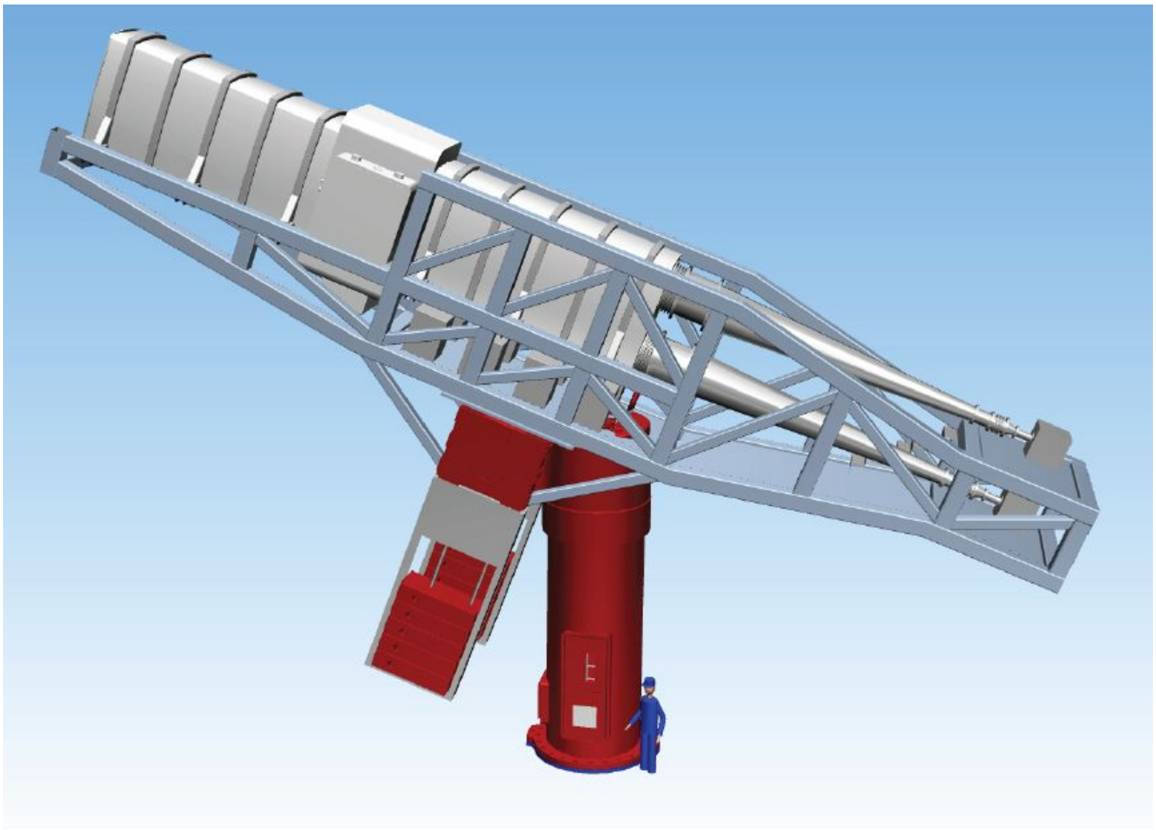

Fig. 3: Sketch of the preliminary baseline design of the BabyIAXO proposal (courtesy of the IAXO collaboration, taken from [39]).

The IAXO collaboration, the largest in the axion field with O(100) scientists, already encompasses the required expertise. In particular, the project relies on know-how from large institutions, like DESY and CERN. The former as host of the experiment, and the latter with its expertise on large superconducting magnets. The DESY physics review committee recently endorsed the realization of BabyIAXO, and the collaboration is taking the steps to start construction. It could lead to first data taking in about 3-4 years. IAXO could start construction as soon as BabyIAXO is built. Note that IAXO's feasibility does not rely on BabyIAXO results, but the experience in the construction and commissioning of BabyIAXO systems could lead to incremental improvements of the figure of merit of the final IAXO design. With an estimated cost of $\sim$50 MEur, IAXO is of strategic size and it requires the endorsement of the ESPP.

2.4 Haloscope

The MAgnetized Disks and Mirror Axion eXperiment (MADMAX) collaboration is developing a new approach to search for axionic dark matter in a mass region not accessible presently by other approaches. More specifically, it targets axion masses between 40 and 400 μeV as motivated by cosmological scenarios with a Peccei-Quinn symmetry breaking after an early inflation phase. The experiment strives for sensitivities down to the DFSZ benchmark model.

MADMAX will be the first so-called dielectic haloscope [40] (see also [41, 42] for precursors of this concept). It will be based on a large aperture dipole magnet encompassing a "booster" system of up to 80 movable dielectric disks likely made out of $LaAlO_3$. The magnet's figure of merit (aperture times square of the magnetic field strength) is required to be around $100\,T^2m^3$. By changing the distance between the dielectric disks the resonance frequency of the booster as well as its bandwidth can be tuned allowing scanning the abovementioned mass region. With a bandwidth of 50 MHz a power boost factor of several 10^4 can be achieved increasing the microwave generation by dark matter DFSZ axions in MADMAX to a measurable level of 10^{-23} W. The MADMAX concept is sketched in Figure 4.

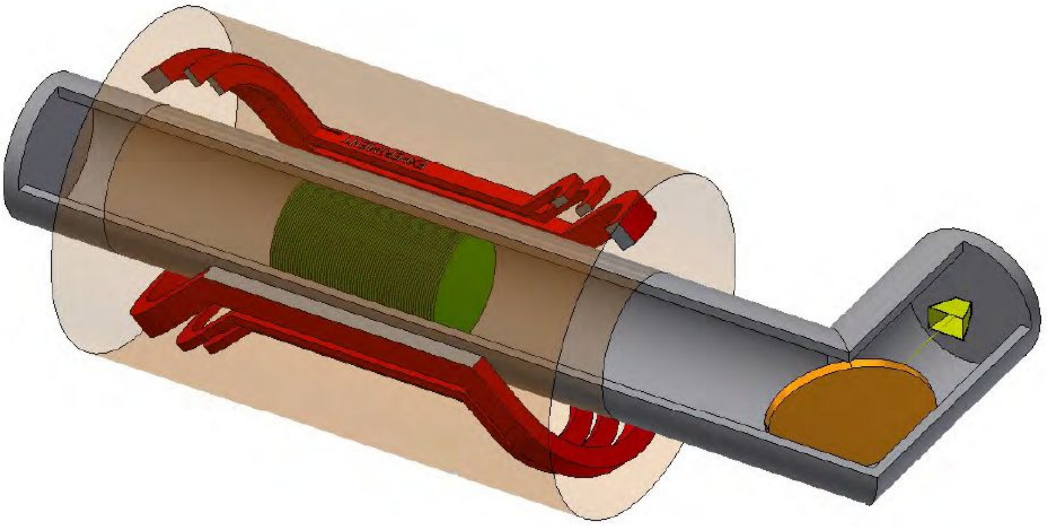

Fig. 4: Sketch of the preliminary baseline design of the MADMAX approach (not to scale). The experiment can be divided into these parts: magnet (red racetracks), booster consisting of the mirror (copper disk at the far left), the 80 dielectric disks (green) and the system to adjust disk spacing (not shown)), the receiver (consisting of the horn antenna (yellow) and the cold preamplifier inside a separated cryostat) (taken from [43]).

At the time of writing this text (July 2019), the design of the large magnet is entering a decisive second phase to be finished in early 2020. A demonstration booster system is being investigated and the design of a prototype system including the microwave detection concept is in full swing. The collaboration strives for first prototype tests at the "MORPURGO" magnet at CERN in the test beam shutdown periods 2021-2023. The final experiment with the newly developed dipole magnet will be installed in the iron yoke of the former H1 experiment at DESY in Hamburg ready for data taking in the year 2025.

The MADMAX collaboration is led by the Max Planck Institute for Physics (Germany) and consists of further eight European institutes and universities. It combines expertise in particle physics, radio astronomy and quantum sensing.

2.5 Summary

Experimental particle physics tackling very low mass axions, ALPs and other WISPs is making rapid progress. Next to a vibrant landscape of small to medium sized activities, European initiatives also include lager scale efforts related to LSW experiments, helioscopes and haloscopes:

ALPS II (and later JURA) as well as IAXO are leading experiments world-wide for axion and ALP searches not depending on the dark matter paradigm. Technologically they are ready to be built. The unique MADMAX approach enables to experimentally probe a dark matter mass region well motivated by cosmology, but inaccessible up to now. MADMAX still requires significant development before construction will start. Figure 5 shows the parameter space which could be probed by the experiments mentioned above and other activities world-wide.

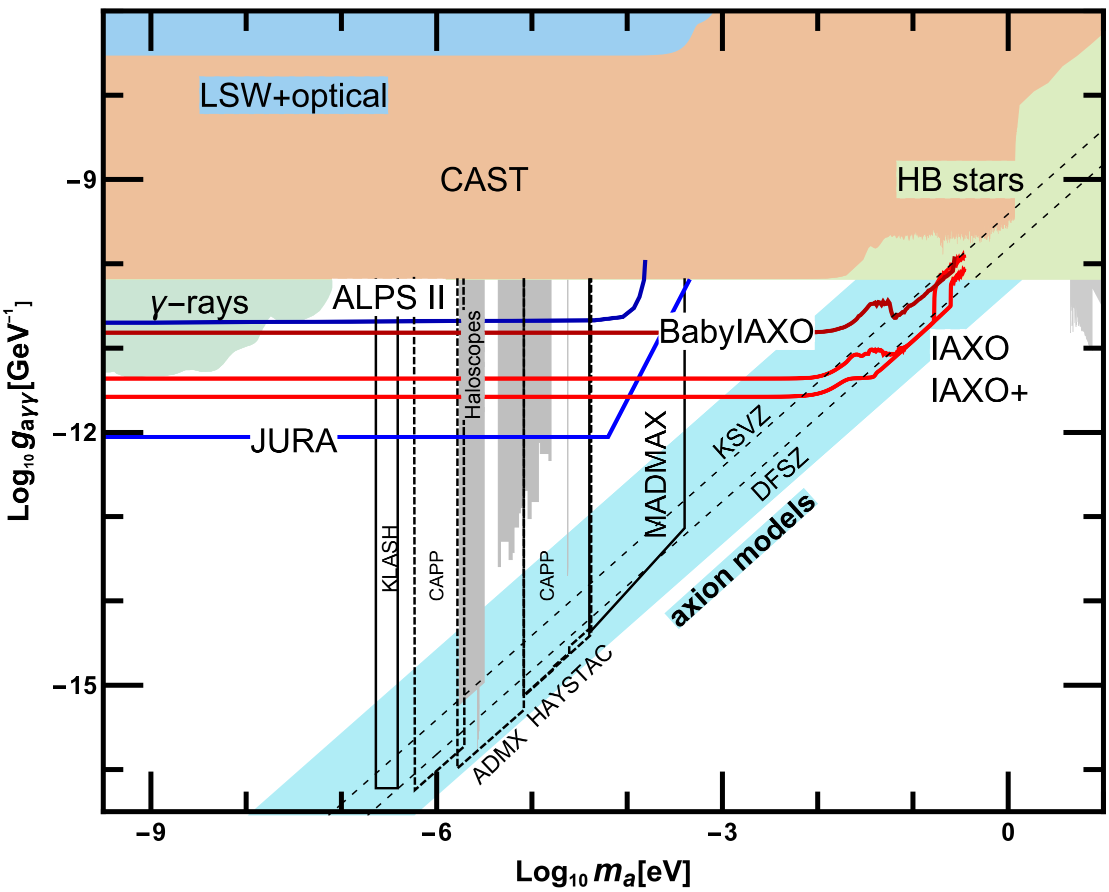

Fig. 5: Overview of the relevant ALP parameter space as well the experiments exploring it in the next about 10 to 15 years (adapted from the briefing book [44]; compilation based on [5, 38]).

It is worth mentioning that such progress could be achieved with rather modest costs compared to accelerator based experiments. Estimations for investment core costs range from about 3 MEuro (ALPS II) to about 58 MEuro (IAXO). JURA is not costed yet.

3 Other approaches and experiments centered in Europe (small/middle size)

An overview of the experiments discussed below and references to their results and more details on their setup can be found in Tab. 1

3.1 STAX[2]

STAX LSW is a proposal that aims to optimize the idea of light-shining-through walls by utilizing THz photons instead of optical photons which are typically used (e.g. at ALPS-II). The reasoning is the high flux of THz photons achivable in principle, with fluxes up to 10^{28} photons/s. Thereby the ALP production rate can be increased by many orders of magnitude, see, e.g. [45, 46] A challenge is posed to efficiently detect single THz photons. STAX proposes to profit from Transition-Edge-Sensor (TES) detection at the sub-THz range. The STAX collaboration has recently submitted a paper with first R&D results to JLTP. [47]

STAX could, in principle, improve the present laboratory limits on g four orders of magnitude. The STAX facility proposes to rely on two strong dipole magnetic fields of intensity B $=$ 11 Tesla each, and a length L $=$ 150 cm. The suggested magnets to be used are two prototypes of the HL-HLC program. Further details and references can be found in the PBC technology strategy input [3].

3.2 Haloscope

Haloscopes are based on a resonant cavity approach, where axions are converted into photons via a magnetic field inside a radio-frequency cavity. Technology-wise these searches thus potentially profit from expertise of the accelerator community [3]. Existing Haloscopes, mostly US-led, have started scan the lower mass part of the parameter space for the QCD axion and have started to cross the 20 μeV mass in limited mass ranges. In Europe (see Table 1 and more details below), most efforts are concentrating on the high-mass reach above $\sim 30\mu$eV with the exception of KLASH at Frascati [48] that aims at axions below the μeV range using potentially the Finuda magnet. Higher masses are particularly motivated as for axion models where for the Peccei Quinn transition happens after inflation. In this case the axion mass is in principle calculable. Recent lattice calculations suggest a lower bound to the axion mass of $\gtrsim 28\mu$eV [49]. In this mass range novel concepts are needed. European efforts here are QUAX-aγ [50], relying on superconductive cavities, RADES and CAST-CAPP at CAST [51], relying on novel cavity geometries and BRASS, relying on an open haloscope resonator as well as MADMAX, based on dielectrics (discussed in greater detail in section 2.4).

3.2.1 RADES

One set-up aimed to search axions above the 30μeV scale, called RADES ('Relic Axion Dark Matter Exploratory Setup') has been recently developed and has taken data for some weeks in the CAST magnet at CERN.

The central idea of RADES is to develop cavity structures that can resonate at large frequencies (and thus test large axion masses) whilst not compromising on the effective volume of the cavity. Two considerations are central for this: Firstly, these cavities should be able to search

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[2] We would like to thank Paolo Spagnolo for input and feedback on this section.

for axions in dipole magnetic fields. The reason is that in the future, dipole magnets should provide a larger magnetic volume available for axion searches. For example, the IAXO magnet is expected to provide a $B^2V \gtrsim 300\mathrm{T}^2\mathrm{m}^3$. Secondly, as described in detail in [51], a long rectangular cavity, interconnected by a number N of irises, can indeed have resonant modes with a large geometric coupling to the axion G at a frequency scale that is mainly determined by the dimension of the individual irises.

At the time of writing, a RADES cavity with $\sim$ 1 m length is taking data in CAST and a tuneable RADES [52] cavity is being tested in CERN's cryolab.

3.2.2 CAST-CAPP

The CAST-CAPP/IBS Detector integrates the CAST dipole magnet (43 mm twin bore with 9 T) and four TE-mode rectangular cavities, developed in CAPP/IBS. The initial target on the mass range is (21–25) μeV, but the sensitivity could reach into the QCD axion parameter space in a wider, yet-unexplored, mass region. The integration study with one CAPP cavity started in 2016 and tuning of the cavity frequency at room temperature has almost finished. The phase-matching mechanism of all four long cavities at low temperature is now being developed, and electroplating of the cavities has been started in a CERN surface treatment laboratory. The first phase-matched operation of the four-cavity setup is planned to scan the mass around 23 μeV for 180 days, expected to give a coupling limit which is 2.9 times larger than the QCD model.

3.2.3 QUAX[3]

QUAX (QUest for AXion) is an INFN experiment, now in its R&D phase, performing two different searches for galactic axions exploiting both the couplings to electrons and to photons. In the first search, QUAX$-ae$ proposed in [53], dark-matter axions resonantly interact with electronic spins in a magnetized sample. Axion-induced magnetization changes can be detected by embedding the sample in a radiofrequency cavity in a static magnetic field. Results of the first operation of a *ferromagnetic haloscope* at T=4 K were published in [54]. With this search, QUAX set an upper limit on the coupling constant of DFSZ axions to electrons $g_{ae} < 4.9 \times 10^{-10}$ at 95% C.L. for a mass of 58 μeV (14 GHz). The second search, QUAX$-a\gamma$, is performed with a standard haloscope. The first limit, published in [50], was obtained using a NbTi cavity operating at 4 K in a uniform 2 T magnetic field. The cavity resonated at 9 GHz with a quality factor $Q_0^{2\,\mathrm{T}} = 4.5 \times 10^5$. With this search, QUAX set the upper limit $g_{a\gamma\gamma} < 1.03 \times 10^{-12}$ GeV^{-1} at 95% C.L. for a mass of $37.5\,\mu$eV. Both these measurements are limited by the total noise $T_{noise} \sim 15$ K.

The QUAX plan for the years 2020-2022 is to reach the sensitivity to KSVZ axions for $g_{a\gamma\gamma}$ in the mass range around $40\,\mu$eV and start the data-taking phase. The total noise has already been reduced below 1 K by operating a Josephson parametric amplifier in a dilution refrigerator at T$\sim$100 mK. A new 8 T magnet is under construction. With its 15 cm bore and 48 cm length it will be able to house larger-volume cavities. Operating a NbTi cavity at 5 T, QUAX will reach a sensitivity $g_{a\gamma\gamma} < 4 \times 10^{-14}$ GeV^{-1} while the KSVZ limit will be reached by operating photonic band gap cavities in a 8 T field. Further improvements are needed to reach the DSFZ limits such as stronger field magnets (20 T) and single microwave photon counters [55].

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[3] We would like to thank Claudio Gatti for providing most of the text in this section.

3.2.4 KLASH[4]

KLASH (KLoe magnet for Axion SearcH) is a proposal for a large-volume haloscope with sensitivity to galactic axions in the region (0.3-1) μeV [48, 56]. The haloscope is composed of a large resonant cavity (20 m^3) made of copper, inserted in a cryostat cooled down to 4.5 K. The cryostat is inserted inside the KLOE magnet at Laboratori Nazionali di Frascati (LNF), an iron shielded solenoid coil made from an aluminium-stabilised niobium titanium superconductor, providing an homogeneus axial field of 0.6 T. Two different resonant cavities are foreseen to investigate the axion mass region between 0.3 μeV and 1 μeV. They are cylindrical with length 2041 mm and radius 1860 mm and 900 mm. Frequency tuning is obtained by means of three metallic rods and fins and by replacement of the larger cavity with a smaller one. Fine frequency tuning, between rod rotations, is obtained by the insertion of a dielectric rod. A similar technique is used to avoid mode crossing. Three different phases are foreseen. In the first phase, the large cavity is tuned with three rods changing the frequency from 65 MHz to 115 MHz. In the second phase three fins are inserted to allow frequency tuning up to 150 MHz. Finally, the large cavity is replaced with a smaller one to allow frequency tuning from 140 MHz to 225 MHz. The resonant cavity must be build in oxygen-free high thermal conductivity copper (OFHC). This type of copper may show residual resistance ratios (RRR) that vary from 50 to 700. Assuming RRR=50, ANSYS-HFSS simulations show a quality factor of the TM010 mode ranging from 700,000 to 350,000 by varying the frequency from 65 MHz to 250 MHz. An optimal solution for the first amplification stage of the signal in terms of low noise, frequency band and gain is a Microstrip SQUID Amplifier. The KSVZ limit is reached in the whole mass between 0.3 and 1 μeV with an integration time of 5 minutes for a single measurement with the large cavity and 10 minutes for measurements with large cavity with fins and small cavity for a total integrated time of about 3.5 years. The construction of the haloscope inside the KLOE magnet is estimated to be between 2.5 and 3 million of euros. In June 2019 INFN decided to allocate the KLOE magnet to the DUNE experiment and the collaboration is now considering the possibility to replace it with a second large superconducting-magnet operated by the FINUDA experiment at LNF.

3.2.5 BRASS[5]

The BRASS (Broad-band Axion Search experimentS) is an experiment designed to search for axionic dark matter in a broad frequency range, covering the mass interval from 70 μeV up to 3.95 meV. The experiment consists of a parabolic reflector collecting the emission from a plane of $Nd_2Fe_{14}B$ permanent magnets arranged in a Hallbach configuration. The high resolution ($<$ 100 Hz) and broad-band spectra (16 GHz) are recorded using front- and backend receiver used for radio and sub-mm telescopes.

The current status of the installation includes a 6 m^2 parabolic reflector already installed and aligned within a shielded lab space. The conversion surface will consist of 24 individual panels with permanant magnets glued in a Hallbach configuration. The panels are under production and will be installed until end of 2019. The receiver for the 18 GHz–44 GHz band is under construction and will be integrated shortly after the alignment and characterization phase of the dish/converter surface are completed in the first half of 2020. Commissioning of BRASS-6 (6 m^2 surface) will conclude in 2020, followed by science-runs. Funding for this stage of the experiment is secured. All components (dish and conversion surface) can be re-used to extend

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[4] We are grateful to Claudio Gatti for the text in this section.

[5] We are indebted to Dieter Horns for most of the text in this section.

name	timing	mass target	location	reference
MADMAX	data-taking 2025	$> 50\mu$eV	DESY	[57]
QUAX a-gamma	data-taking now	$\sim 37\mu$eV	Frascati	[50]
BRASS	data-taking 2020	$> 50\mu$eV	Hamburg	website
RADES	data-taking now	$\sim 33\mu$eV	CERN	[51]
KLASH	CDR in 2019	$< \mu$eV	Frascati	[48]

Table 1: Overview of small and mid scale European centered experiments for direct Dark Matter Axion search.

the area to approximately 100 m^2.

4 Oversea activities

Various axion and ALP searches based on the European initiative have been summarized in the last two sections. This section reviews prominent oversea projects that cover different mass regions. For more detailed information on each experiment and the other activities which are not covered in this note, please refer to summaries such as [38,58–61]. Again the main experiments and relevant references for the specific experiments are summarized in Tab. 2.

4.1 Haloscope experiments

ADMX

The second generation of ADMX has improved its already world-leading sensitivity to ultralow signal power levels and probed the DFSZ couplings in (2.66–2.81) μeV (645–680) MHz in 2018. It operates a large-volume haloscope at sub-Kelvin temperatures, which reduce thermal noise as well as the excess noise from the ultra-low-noise SQUID amplifier used for the signal power readout. The mass range up to 3.3 μeV (800 MHz) is covered in the current scanning phase, and studies to probe higher frequencies up to about 2 GHz is in progress by testing a prototype of multicavity systems, which will be installed inside the current magnet. To probe a much larger range of masses up to 41 μeV (10 GHz) in the next 10 years with a similar sensitivity, 30T class HTSC magnets are designed in collaboration with NHMFL.

CULTASK

CAPP's flagship axion experiment, CULTASK, has been built on a low vibration facility at Munji campus of KAIST in Korea. Four dilution refrigerators have so far been installed with two 8 T superconducting magnets, which allow them to explore the axion mass range of (2–2.5) GHz and (1.35–1.6) GHz, respectively. A resonant cavity (10 cm outer diameter) with a sapphire tuning rod driven by piezoelectric actuator system has been cooled down below 30 mK and showed very high unloaded Q-factor ($\sim$120,000) even under 8 T magnetic field. RF receiver now employs 1 K HEMT amplifier out of the cavity, but the design is flexible enough to replace it with SQUID amplifier when R&D is completed in the near future. The very first data acquisition has been almost completed and many R&D projects on the development of superconducting cavities and SQUID amplifiers are currently in progress.

HAYSTAC

The HAYSTAC detector is designed to achieve sensitivity to cosmologically relevant couplings at higher masses above 20 μeV. The difficulty of reaching such mass region comes from the fact that the effective volume VC_{mnl} of the cavity in which axion coupling can occur falls off rapidly with increasing frequency. Despite the difficulty of working in this mass range, the total noise has been reduced to 2.3 times the standard quantum limit, and set an exclusion limit of $|g_\gamma| \gtrsim 2.7 \times |g_\gamma^{\mathrm{KSVZ}}|$ over the range 23.15 μeV $< m_a <$ 24.0 μeV in the first phase experiment in 2018 which utilizes a conventional copper cavity and a single JPA. The experiment is now being upgraded with a squeezed-vacuum state receiver to improve the sensitivity and scan speed of the search.

ORGAN

The ORGAN experiment covers the highest mass region that can be reached by using resonant cavities. The pathfinding run was completed in 2017 and gave constrains on the axion-photon coupling in a narrow span around 26.531 GHz, with the best limit reached $g_{a\gamma\gamma} > 2.02 \times 10^{-12}\text{eV}^{-1}$, which corresponds to ∼50 times KSVZ at this frequency. Developments of later stages of the experiment are underway to probe (60–200) μeV region by utilizing a 14 T magnet and a series of small resonators. The experiment has funding through the ARC Centre of Excellence for EQuS for seven years, and will develop quantum limited amplification. The first scanning stage of the experiment is planned to run for approximately one year, and after this, 6 further years of searching are planned.

Appendix 1: definition of acronyms

ADMX: Axion Dark Matter eXperiment
CAPP: Center for Axion and Precision Physics research
CAST: CERN Axion Solar Telescope
CULTASK: CAPP Ultra Low Temperature Axion Search in Korea
EQuS: Engineered Quantum Systems
KAIST: Korea Advanced Institute of Science and Technology
HTSC: High-Temperature Super-Conductor
IBS: Institute for Basic Science
HAYSTAC: Haloscope At Yale Sensitive To Axion Cold dark matter
HEMT: High Electron Mobility Transistor
JPA: Josephson Parametric Amplifier
NHMFL: National High Magnetic Field Laboratory
ORGAN: Oscillating Resonant Group AxioN
SQUID: SUperconducting Quantum Interference Device

Appendix 2: brief overview of oversea haloscope projects

Experiment	**Location (country)**	**RF frequency (GHz)**	**Axion mass (μeV)**	**Coupling $g_{a\gamma\gamma}$ (GeV^{-1})**	**Reference**
ADMX	Univ. of Washington	0.645–2 (10)	2.66–8.2 (41)	2×10^{-16}	[62, 63]
CULTASK	CAPP/IBM (Korea)	1.35–1.6, 2–2.5	5.4–6.4, 8–9	1×10^{-15}	[64]
CAST-CAPP	CERN (Switzerland)	5.25–6.25	21–25	1×10^{-14}	[65]
HAYSTAC	Yale Univ. (US)	5.6–5.8	22.4–23.2	1×10^{-14}	[66–68]
ORGAN	Univ. of Western Australia (Australia)	15–50	60–200	2×10^{-12}	[69]

Table 2: Oversea haloscope projects

5 Synergy

It is clear that experimental constrains on ALP couplings can have a significant impact on other fields of physics, in particular astrophysics and cosmology. For example, through their various kinds of couplings to photons, electrons, and nucleons, ALPs could solve some of the astrophysical and cosmological problems currently observed. This has been discussed in Sec. 1.3, and important outcomes expected from strategic ALP programs in the next 5–10 years have been briefly summarized there.

In the following we focus on two aspects beyond these neighboring fields. The connection to non-linear QED as well as to technology based synergies.

The first part of this section highlights the synergistic aspect of ALP searches, with non-linear electrodynamics The existence of ALPs provides anomalous contribution to non-linear photon interactions, which are also induced by the QED box diagram. This results in vacuum magnetic birefringence (VMB). In either case, the VMB signals are expected to be the smallest birefringence ever detected, and both physics cases can be tested in the same measurement.

The rest of this section then deals with technical issues that one commonly faces when implementing the experiments mentioned in Section 2–4 and where synergies at the technological level become important. Practical aspects when implementing these mid- to large-scale projects are reviewed with respect to optics, cryogenics, high-field magnets, and RF cavities. Realizing these technology in each experiment is not efficient . Enormous expertise and experience in these directions has been accumulated at CERN as well as the national labs. A European initiative with a common platform where the experiments are carried out could therefore bring significant benefits.

5.1 Vacuum magnetic birefringence

Non-linear electrodynamic effects have been predicted since the formulation of the Euler effective Lagrangian in 1935 [70–73]. These include processes such as light-by-light scattering, Delbrück scattering, g-2 and VMB. This last effect appears at a macroscopic level for photons propagating in external magnetic fields. Although experimental efforts have begun at CERN in 1978 and have been active for about 40 years, a direct laboratory observation of VMB is still lacking due to the tiny size of the predicted birefringence $\Delta n = 4.0 \times 10^{-24}$ at 1 T.

Key ingredients of a polarimeter for detecting such a small birefringence are a long optical path within an intense magnetic field and a time dependent effect. Currently, three experiments are ongoing; PVLAS (Italy) [74], BMV (France) [75], and OVAL (Japan) [76], with similar high-finesse Fabry-Perot cavities to lengthen the optical path inside a magnet, but with different modulation schemes on their magnetic field. Recently, another scheme using a static field was presented [77, 78]. The scheme is based on inserting two co-rotating half-wave plates inside of the cavity, thus maintaining the polarization direction on the mirrors while it is rotating between the plates where a static magnetic field generates the desired modulation (Fig. 6a). Here the new scheme proposed at CERN is first reviewed and then, the progress in pulsed field experiments is presented.

5.1.1 *Static field experiments*

Physics goal

A proposed experiment, VMB@CERN [79], plans to apply the novel polarization modulation scheme and to operate an LHC dipole magnet, which generates static fields up to 9.5 T over a length of 14.3 m. Given that the sensitivity is limited by the shot noise of the detector current while rotating the wave plates faster than 1.5 Hz, the $\mathrm{SNR} = 1$ is expected in less than 1 day. Insertion of a quarter-wave plate after the cavity allows to detect the rotation of an incident linear polarization, induced by the dichroism (VMD) from ALP production. In this VMD measurement, the above sensitivity corresponds to $g_{a\gamma\gamma} \sim 1 \times 10^{-9}$ GeV^{-1} for $m_a < 2.5 \times 10^{-4}$ eV, and a similar sensitivity is obtained for a slightly higher masses around $m_a \sim 5 \times 10^{-4}$ eV in the VMB measurement, where a virtual-state ALP intermediates the non-linear photon interaction.

Technical challenges and timeline

The technical challenges arise from the possible increase of the noise level due to i) insertion of the wave plates in the cavity, ii) rotation-induced errors among the three axes; the rotation axis, the laser beam direction defined by the cavity, and the normal direction with respect to the wave-plate surface, and finally iii) a 10-m class long cavity.

The first tests in 2019 using two non-rotating wave plates inserted in a small cavity ($\sim$ 1 m) did not show a significant increase of the noise level (Fig. 6b, c). Tests of the rotation of the wave plates and their alignment system will be carried out in 2020. A 20-m test cavity will be mounted first without a magnet. If the test phase in the next few years is successful, the magnet will be implemented and the data taking will begin after the debugging.

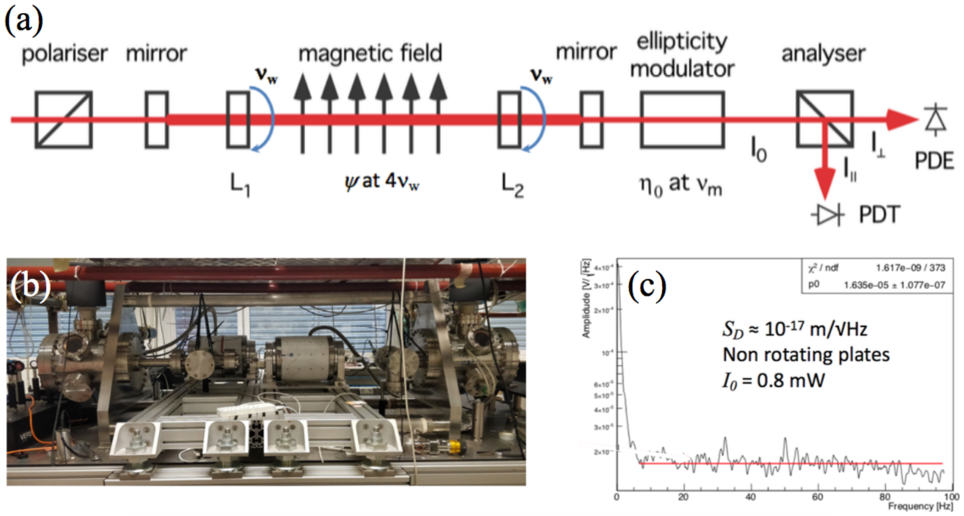

Fig. 6: (a) Proposed modulation scheme. $\mathrm{L}_{1,2}$: rotating half-wave-plates in the cavity mirrors. PDE: Extinction Photodiode; PDT: Transmission Photodiode (taken from [77, 80]). (b, c) First tests in 2019 using two non-rotating wave plates inserted in a small cavity ($\sim$ 1 m), which do not show a significant increase of the noise level (taken from [80], courtesy of the VMB@CERN collaboration).

5.1.2 Pulsed field experiments

Another type of field modulation, which is not caused by the mechanical rotation of magnets or wave plates, is to use pulsed magnets. Since the VMB signal depends on the applied field as B^2, a large amount of signal is expected by a single high-field pulse. The repetition rate of pulses is limited by the cooling time for the magnet down to the liquid nitrogen temperature (77 K). To enhance the interaction length of the laser field in the cavity, racetrack-shaped magnets are dedicatedly developed and applied in stead of conventional solenoids.

Two kinds of approaches are on going. The first is to pursue the highest fields obtained in high magnetic field facilities. Racetrack fields of 31.8 T are currently available in the BMV project at LNCMI-Toulouse and 32.3 T in Tokyo (Fig. 7) [75]. The other approach is to produce relatively lower fields∼10 T but with a higher repetition rate and a larger racetrack length∼1 m. To increase the total field length, simultaneous operation of multiple magnets can also be carried out.

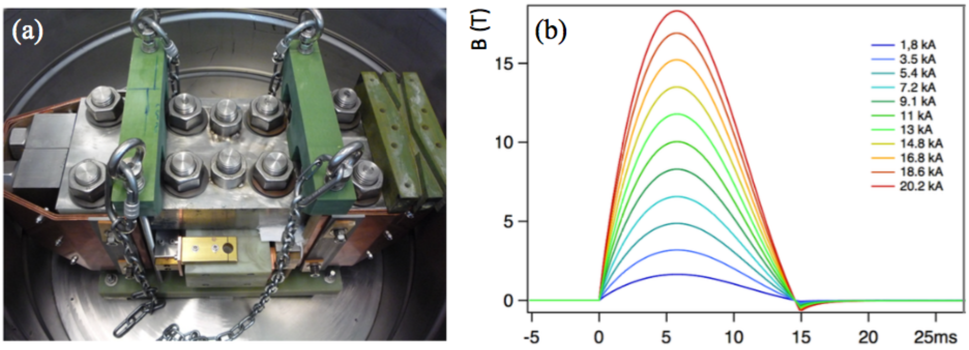

Fig. 7: (a) XXL-coil used in a high-field setup of the BMV project, producing the maximum field of 31.8 T over 32 cm. (b) Typical field shape of the magnet with 15-ms pulse duration (taken from [81]). (Both courtesy of the BMV collaboration).

5.2 Technological synergies

5.2.1 High-field, large-bore magnets

Most ALP searches rely on the ALP-photon couplings under external magnetic fields, and superconducting magnets play an essential role. In these experiments high-field, large-bore magnets are commonly used to obtain higher sensitivity to the ALP couplings. Various kinds of magnet structure are necessary and have been used in previous searches. Dipoles have been used in ALPS, OSQAR, and CAST experiments, while solenoids in ADMX.

In the next generation experiments such as ALPS II and JURA, a string of LHC-type dipole magnets are required as well as their supply of cryogenics and powering infrastructure. In MADMAX and IAXO, new types of large-scale magnet are currently designed, for example a toroidal structure for IAXO. In addition, many experiments such as VMB@CERN and LSW-STAX plan to use state-of-the-art dipole magnets.

In many cases, CERN is expected to provide engineering expertise on the design, construction, and operation of magnets along with significant financial contribution. This also benefits CERN by making it a technology center not only in the accelerator physics community. At the same time other big national labs such as DESY can provide important expertise as well as the the crucial infrastructure to host such small- and medium-scale experiments.

5.2.2 RF cavities

Radio-frequency (RF) cavities are commonly used in dark matter ALP searches to enhance the signal power under resonance. To probe a wide range of ALP mass, the RF range of (0.2–200) GHz must be covered in the frequency domain. The development of resonant cavities having various sizes and shapes with quality factor of 10^5–10^6 could profit from CERN's accumulation of know-how in RF technologies. Implementation of high-Q cavities as well as low-temperature amplifiers in a strong superconducting magnet is also a challenging part of the experiment, which requires engineering expertise in both fields.

To fully exploit the conversion volume permeated by the strong magnetic field, multiple cavity schemes could be implemented at high frequency. This implies the production of identical cavities and tuning all of them at the same frequency with dedicated phase matching.

To improve the RF detection chain, the development of state-of-the-art quantum amplifiers for the above frequency range is also of prime importance. In the microwave range, the best performances are obtained using cryogenic devices such as high electron mobility transistor amplifiers, SQUID-based amplifiers or parametric devices. To achieve the lowest possible noise temperature, Josephson parametric amplifiers (JPAs) have become the technology of choice for the sub-GHz range and could allow reaching the quantum limit as this was already demonstrated in various laboratory worldwide. RF filter structures are being explored and pursued at CERN within an emerging collaboration between RF specialists and physicists (RADES project). To reduce the thermal noise, all RF equipment including cavities and amplifiers, shall be cooled down below 4K, ideally 40 mK with dilution refrigeration, requiring dedicated cryogenic developments.

5.2.3 Optics and technology hub

Recent detection of gravitational waves clearly shows that light sensing technology, especially precision interferometry using Fabry-Perot cavities, provides a powerful tool to search for dark matter and dark energy. CERN already hosts many groups who routinely use optics-based techniques such as: interferometry, polarimetry, opto-mechanics, fiber scintillators and fiber optics, laser ranging, spectroscopy.

An "Optics Technology Hub" (OTH) has been proposed in the PBC technology working group to support and facilitate applications of advanced optics technologies to particle physics experiments under CERN initiative. Many experiments such as ALPS II, JURA, VMB@CERN, and BMV will benefit from OTH.

5.2.4 Cryogenics and vacuum systems

As in the previous sections, cryogenic environment is required for the operation of superconducting magnets and RF cavities by using liquid helium cryogenics. In addition, a sub-Kelvin environment is necessary to reach quantum-limited sensitivity in the RF detection chain in some of the dark matter searches. Most of them are installed in dedicated large-volume vacuum chambers with special coating or electroplating on the surface.

CERN can provide a wide range of operating temperature from 120 K to mK with various refrigeration capacities. It also can provide cryogenic test benches and many superconducting devices. Experimental initiatives in the ALP searches can take advantage from CERN's already existing cryogenic infrastructure, technological experience and long term reliable operation of such equipment.

Appendix 1: definition of acronyms

BMV: Biréfringence Magnétique du Vide
LNCMI: Laboratoire National des Champs Magnétiques Pulsés
OVAL: Observation of Vacuum Anisotropy using a Laser
PVLAS: Polarization of quantum Vacuum with LASers
SNR: Signal to Noise Ratio
VMB: Vacuum Magnetic Birefringence
VMD: Vacuum Magnetic Dichroism

6 Summary

ALPs are one of the most promising candidates to constitute the Dark Matter in our universe. Not only as the solution of the Dark Matter, but discovery of ALPs would also give us direct information about the physics model realised at very high energies, typically much higher than the energy using particle colliders. The search for ALPs is, therefore, an approach complementary to using colliders, and there is large beneficial synergy expected between ALP searches and physics using colliders.

Important key technologies to search for ALPs are, for example, strong magnets, vacuum technologies, precise optics, high sensitive particle-detection. These are common to collider technologies. Synergy in developing these technologies is also obtained in ALP searches.

Three central approaches to search for ALPs are summarized in the following table.

Methods	**advantage**	**disadvantage**
LSW	Model independent, broadband sensitivity in the mass m_a	signal suppressed by $g^4_{\gamma a}$ mass reach limited to $\lesssim \mathrm{meV}$
Helioscopes	Less model dependent, broadband mass coverage up to $m_a \sim 1\mathrm{eV}$	signal is suppressed by $g^4_{\gamma a}$ or $g^2_{\gamma e(N)} g^2_{\gamma a}$
Haloscopes	Highly sensitive search. Can confirm DM nature of axion/ALP	Needs Axion/ALP to be DM, Cover narrow m_a window

Table 3: Summary of methods

In particular three European major proposals (ALPSII, IAXO, and MADMAX; summarized in Chapter 2) cover these methods and are complementary to each other. The budget size of these experiments is about $O(10-50)$ MEuro, and data taking can be started within the period of European Strategy 2020. At the same time, new, innovative ideas are also proposed as shown in Chapter 3 and 5, and significant synergy of new technologies (for example, THz optics and highly sensitive optical detectors, etc) is expected. R&D will be encouraged in the European Strategy 2020.

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