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The search of Axion Dark Matter with a dielectric haloscope: MADMAX

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Abstract. The strong CP problem is one of the most fundamental unresolved questions in the standard model of particle physics. The axion, emerging due to the maybe most elegant solution to the strong CP problem, could also solve the long standing dark matter problem. A short introduction to the strong CP problem is given. The axion as a dark matter candidate is discussed. The detection technology via inverse Primakoff effect using a dielectric haloscope is described. The MADMAX project is introduced and the status on the road towards its realization is given.

1 Introduction: The strong CP problem and the axion

The theory of Quantum Chromodynamics is based on the SU(3) group, which is non-Abelian, i.e. non commutative. This has the effect that there is an infinite amount of gauge inequivalent degenerate zero energy states $|n\rangle$, separated by a potential barrier. Quantum mechanical tunnelling between zero energy states (Instantons) lead to the lowest energy vacuum state $|\theta\rangle$ being a superposition of all possible states $|n\rangle$ such that $|\theta\rangle = \Sigma_n e^{in\theta}|n\rangle$ with θ an arbitrary phase that the vacuum acquires. Additionally, the strong vacuum acquires a complex phase from Yukawa coupling in the weak sector. This should lead to an observable non vanishing phase of QCD: $\overline{\theta} = \theta - argdetM_q$, where M_q corresponds to the quark mass matrix. This in turns adds the CP violating term θ to the QCD Lagrangian:

$$\theta \frac{\alpha_s}{8\pi} G_{\mu\nu a} \tilde{G}_a^{\mu\nu}, \tag{1}$$

α_s being the strong coupling constant, $G_{\mu\nu a}$ and $\tilde{G}_a^{\mu\nu}$ the gluon field and its dual, respectively.

Such a non vanishing physical QCD phase should induce a measurable dipole moment of the neutron of $d_n \sim \overline{\theta} \cdot 10^{-16}\, e\,\mathrm{cm}$, where e is the unit charge. In experiments no such neutron electric dipole moment could be found [1]. The best upper limit presently is $d_n < 2 \cdot 10^{-26}\, e\,\mathrm{cm}$, which leads to an upper limit for the CP violating phase of $\overline{\theta} < 10^{-10}$. This implies that the two seemingly unrelated CP violating phases in QCD are cancelling each other to 1 in 10^{10}. This can be considered unnatural fine-tuning, as even anthropic arguments do not seem to resolve the issue. This is called the strong CP problem.

The arguably most elegant solution to this problem is to make $\overline{\theta}$ dynamical by introduction of a chiral U(1) Peccei Quinn (PQ) symmetry, spontaneously broken by the vacuum expectation value of a complex scalar field at an energy scale f_a, also called the axion decay

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constant [2]. Here, $\overline{\theta}$ is the phase of the scalar field. After spontaneous symmetry breaking the vacuum obtains an arbitrary phase θ_i. During and after the QCD phase transition the PQ symmetry is also explicitly broken by the topological susceptibility of the QCD vacuum. Like this, the phase $\overline{\theta}$ obtains a non vanishing potential, with its minimum around zero, which is CP conserving. Hence, after the QCD phase transition $\overline{\theta}$ can start oscillating around the minimum. The higher θ_i, the more energy will be stored in the oscillation of the axion field. The oscillation is damped by the expansion rate of the universe during the phase transition, hence being dynamically driven to a value very close but different from zero. The oscillation of $\overline{\theta}$ is the axion [3]. The axion mass m$_a$ mass is inversely proportional to f_a and can be calculated in QCD as

$$m_a \sim 5.7\mu eV \frac{10^{12}GeV}{f_a}. \tag{2}$$

It turns out that the axion is also an ideal cold dark matter candidate. It is produced non thermally, hence should be non relativistic in the present universe. If it is assumed that axions make up the whole dark matter density of the universe $\rho_{DM} = 1.2\,\mathrm{keV/cm^3}$, some predictions can be made for the axion mass. For the case that PQ symmetry breaking happened before the inflationary epoch of the universe, today's observable universe was in casual contact during the PQ phase transition and relation can be given between $|\theta_i|$ and m_a. As $|\theta_i|$ is arbitrary, m_a in this case is predicted to range from ~ 1 neV for $|\theta_i| = 0.01$ to ~ 1 meV for $|\theta_i| = \pi$. If PQ symmetry breaking happened after the inflationary epoch, today's observable universe would consist of many patches non-causually connected during PQ symmetry breaking. Hence, the observed dark matter density ρ_{DM} needs to be related to the average $|\theta_i|$ from all patches causally disconnected during the phase transition. This, in principle could give an accurate prediction for m_a. However, in this case topological defects like strings and domain walls contain extra energy that later decays into an additional population of axions. The calculation of the additional amount of axions due to the topological defects brings in considerable uncertainties. The prediction for m_a in the post-inflationary scenarios is thus widened to a range between $\sim 25\,\mu$eV and ~ 100 meV.

Axions can couple to photons via mixing with neutral mesons, like the π^0. Hence, it can in principle decay to two photons. The coupling is, however, suppressed by f_a, leading to a half life many orders of magnitudes longer than the age of the universe for the relevant axion mass. The "inverse Primakoff effect" can be used to convert axions to photons: a B-field "supplies" a virtual photon to the axion, which can then be converted into a single photon. Hence, axion field oscillations inside a B-field induce tiny E-field fluctuations. Again, the conversion probability is suppressed by f_a. The amplitude of the induced E-field oscillation will be proportional to the B-field, hence the power of the radiation that converts from axion oscillations to E-field oscillations scales with B^2.

Any spontaneously and explicitly broken U(1) symmetry is actually leading to a massive Goldstone Boson. In fact, string theory predicts a plethora of such particles from compactification. This is sometimes also called the 'axiverse'. Here, no relation between mass of the axion like particle (ALP) and energy scale of spontaneous symmetry breaking can be given and prediction of the viable mass range is even more relaxed as for axions.

It should be noted here, that some astrophysical anomalies such as the anomalous cooling of stars [4] or the anomalous transparency of the intergalactic medium [5] could actually be explained by ALPs with $g_{a\gamma} \sim 10^{-10}\,\mathrm{GeV^{-1}}$.

2 Detection of axions and ALPs: cavity and dielectric haloscope

Axion or ALP induced E-field oscillations in a static magnetic field can be amplified if they happen inside a resonant cavity that is tuned to the frequency of the oscillations. This is uti-

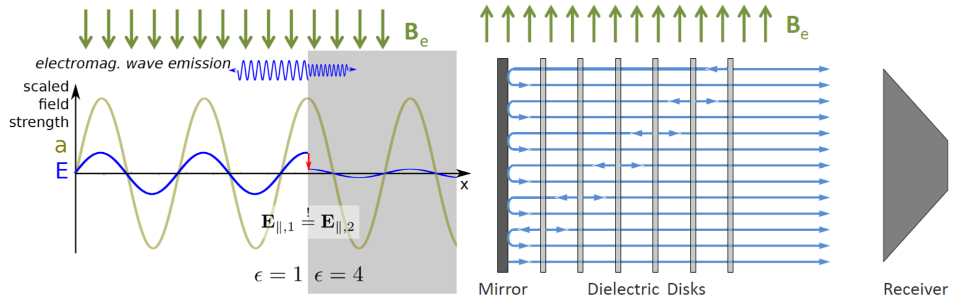

Figure 1. Left: Visualization of photon emission from surfaces with change of dielectric constant. Right: Sketch of the principle of a dielectric haloscope. For details see text.x

lized by the experiments presently leading the field, ADMX [6] and the CAPP [7] initiatives. These experiments use cavities with high quality factor. They utilize a low loss dielectric tuning rod inside the cavity, that changes the resonant frequency of the cavity when moved. This allows for scanning a wide mass range. These experiments have managed to reach a sensitivity covering a large fraction of the benchmark models compatible with theory predictions [8, 9]. They are sensitive in the mass range between ~ 1 and $\sim\ 40\,\mu$eV and have set limits in the $2\,\mu$eV mass range.

Their sensitivity scales with the volume of the cavity, hence the range in mass is limited by the size of the cavity used. For resonant conditions the diameter of the cavity roughly has to match the half wavelength of the axion induced E-field oscillations. For higher frequencies, hence smaller cavities need to be used. Additionally, the Q-factor of cavities is deteriorating for higher frequencies due to the skin effect. This so far limits the axion mass range accessible by the cavity haloscope experiments.

The dielectric haloscope approach has been introduced to circumvent the high frequency limitations of the cavity approach [10]. It utilizes the effect that at boundaries between two media with different dielectric constant with a static B-field parallel to the surface, the axion induced E-field oscillation has a discontinuity, as shown in Fig. 1(left). To compensate for this, electromagnetic waves are emitted from the surface [11]. Assuming a local axion dark matter density of $\rho_{DM} = 0.3\,\mathrm{GeV/cm^3}$, for a perfect mirror ($\epsilon = \infty$) this leads to an emission of EM radiation with a power of

$$P \sim 2 \cdot 10^{-27} \left(\frac{B}{10\mathrm{T}}\right)^2 \left(\frac{A}{1\mathrm{m}^2}\right) C_{a\gamma}^2 \ \mathrm{W}\,, \tag{3}$$

with $C_{a\gamma} \sim \mathcal{O}(1)$ for axion benchmark models [8, 9].

In order to boost the emitted power, the dish antenna approach can be extended by putting discs from low loss dielectrics in front of a perfect mirror. Like this, there will be coherent emission from all surfaces of the discs and the mirror, additionally the coherent radiation from all surfaces can constructively (or destructively) interfere, as displayed in Fig. 1(right). With proper spacing between the individual discs and the mirror, a boost of the emitted power in a quasi broad frequency range can be obtained [12]. The frequency and the bandwidth of the boost factor depend on the disc and mirror configuration. With adjustable disc distances, hence the axion mass can be scanned. This concept can be used to access the so far unexplored axion mass range around $100\,\mu$eV. The discs and mirror configuration leading to the actual power boost of the signal is called "Booster" in the following.

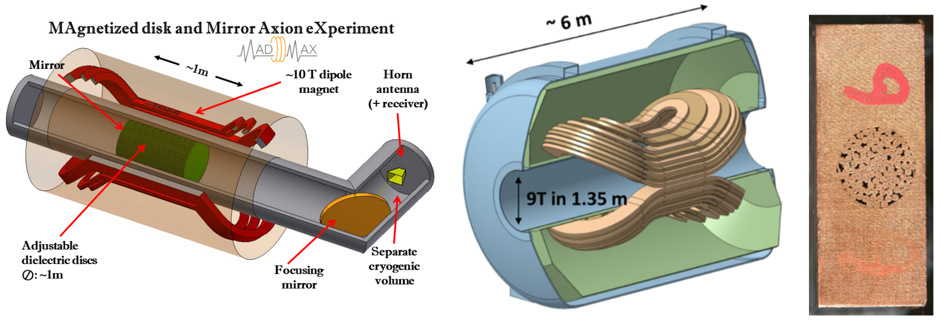

Figure 2. Left: Sketch of MADMAX baseline design. Center: Drawing of the planned MADMAX magnet configuration. Right: CICC supeconductor cross section after compaction.

3 MADMAX status of R&D

MADMAX is based on the dielectric haloscope concept. As baseline design it is envisioned to place a booster with many dielectric discs of area $\sim 1\,\text{m}^2$ inside a large warm bore dipole magnet with B-field $O(10\text{T})$. A signal power of a few $10^{-23}\,W$ is needed as this can be detected by state of the art detectors. For such a configuration a power boost factor of roughly 10^4 is needed. This could be obtained for example by a set of some tens of discs [13]. A sketch of the baseline design is shown in Fig. 2.

Hall north of the former HERA ring at DESY is the designated site of MADMAX. This comes with the advantage of being able to use the DESY infrastructure, for example for cryogenics. Also, MADMAX will reuse the yoke of the former H1 detector solenoid [14]. Its use ensures that the fringe field in the direct vicinity of the experiment is low enough and in parallel homogenises and even increases the B-field in the centre of the magnet.

The required magnet is presently being developed and designed by CEA Irfu in cooperation with Bilfinger NOELL in the framework of an innovation partnership (EU tendering tool). The design is based on 2 times 9 skateboard double pan cake coils. A sketch of the magnet design is shown in Fig. 2 (centre). The coils are made from a novel conductor in conduit cable (CICC) design, where the superconducting filament made from NbTi is guided inside a hole of a copper conduit. Cooling of the superconductor happens via superfluid helium at 1.8 K inside the hole of the conductor. By now it has been verified that the required components to build such a conductor can be purchased from industrial partners. Also, it has been demonstrated that the conductor can be produced in the required length with the needed compaction leading to the proper ratio of superconductor to void area inside the hole of the stabilizer. A cross section of the conductor after compaction is shown in Fig. 2 (right).

Another important question that needed to be answered was the possibility of quench detection, i.e. the propagation velocity of quenches inside the detector. For safe magnet operation, a possible quench needs to be detected within 0.1 s, which translates into a minimum quench propagation velocity of 1 m/s. To test this, a dedicated solenoid using a CICC cable according to MADMAX specifications has been designed and built by the two innovation partners. It has been extensively tested inside a test vacuum cryostat at CEA. The solenoid was equipped with proper sensors on top of the conductor, allowing to measure the velocity of quenches. Controlled quenches could be triggered using a heater. Like this it could be demonstrated that the MADMAX CICC superconductor has a quench velocity compatible with safe quench protection. Figure 3 (left) shows the measured quench velocity and the beginning of the quench as a function of the applied current to the coil. Clearly, even for an applied

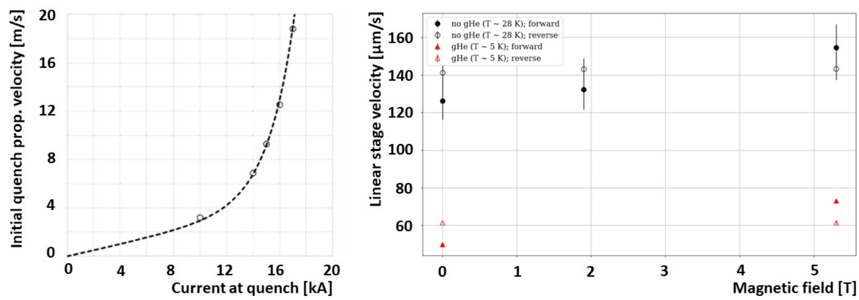

Figure 3. Left: Quench propagation velocity as function of applied voltage. Right: Speed of piezo motor carriage under different B-fields and helium gas pressure.

current as low as 10 kA (operational current at 21 kA), the minimum quench propagation velocity of 1 m/s is exceeded.

One of the most important questions is how to determine and calibrate the actual power boost factor. Reflection measurements of the setup give important information on the optical behaviour of a booster itself. However, they do not give direct information on the signal shape expected from coherent emission of all disc and mirror surfaces. Also, the influence of the first stage amplifier itself is not obtained. To overcome these shortcomings, additional noise measurements of the system are performed. These provide the interference between the amplifier and the booster system as well as the thermal noise from the booster system itself, which is emitted directly from the booster disc and mirror surfaces, similar as expected from axion induced radiation. A 1D noise model with input parameters taken from the reflectivity measurements can then be fitted to the actual noise measurement itself. Like this, information on the relevant parameters for determination of the power boost factor can be extracted. By varying the parameters within their uncertainties, the uncertainty of the power boost factor determination can be obtained.

To verify this method that allows for a reliable boost factor determination, a reduced booster with fixed disc and mirror positions with well defined boundary conditions was designed and built. Three sapphire discs with 100 mm diameter were put in front of a copper mirror inside a tight metallic cylinder. A schematic of the setup in explosion is shown in Fig. 4 (left). The simulated RF response of the system in the frequency regime between 18 and 20 GHz did well reproduce the measurements. Also the established noise model could well describe the actual noise measurements. The shape of the power boost factor with maxiumum at 750 obtained from a corresponding 1D model is shown in Fig. 5 (right) as overlay to a background measurement.

A further challenge of the Madmax design concept is the actuation over macroscopic distances (up to a few cm) of the many discs with the necessary precision (around μm) in the cryogenic environment at high B-field. From the beginning piezo motors had been identified as the most promising technology. An R&D project had been started together with JPE [1]. The design foresees three motor carriages per disc which are actuated by a piezo crystal via stick

[1] https://www.jpe-innovations.com/

& slip. Controlling of the positions and tilts of the discs is done using laser interferometry, measuring the distances for each disc between the referenced copper mirror and the three points on the individual disc rings.

As a first step, a motor carriage equipped with a piezo crystal was designed and produced. It is running on a high precision cryo compatible ceramic rail. The system was tested at cryogenic temperature (~ 5 K) in vacuum, as well as in a test magnet with a B-field of 5.3 T applied. Latter tests were also performed at a temperature of 5 K in an exchange gas helium surrounding (10^{-2} mbar). The motor was reliably operated and the obtainable speed was measured to be around 100 μm/s. Figure 3 shows the measured velocities in the forward and backward directions for different settings (no gHe: vacuum, < 10^{-4} mbar, gHe: helium exchange gas at ~ 10^{-2} mbar) and with different B-field applied. These tests show that piezo motors are suitable for use in the MADMAX setup.

To show the feasibility of building the MADMAX booster with the needed precision, a mechanical mock up with a mirror and one disc was built. The diameter of mirror and disc were 200 mm. The mock up - called project 200 - does include all mechanical parts that are necessary to build the MADMAX booster according to its baseline design. Most importantly, the interplay between piezo motors, the disc and the interferometer system can be tested in different surroundings, i.e. at cryogenic temperatures and inside a B-field. After precision assembly and commissioning at room temperature the setup has been tested inside a vacuum cryostat at CERN. In both surroundings, the discs could be reliably moved and the disc positions controlled to the needed precision of better ~ 1 μm. Also, the setup was reliably and reproducibly operated inside the 1.6 T B-field of the MORPURGO magnet at CERN [15].

A Receiver DAQ system has been developed earlier to measure the power output of the CB100 system in the relevant frequency regime. It is based on a low noise first stage amplifier coupled to a heterodyne mixing scheme with three intermediate frequencies and four samplers with on board FPGAs that are recording the fast Fourier Transforms with a dead time of < 2%. The setup with CB100 attached has been tested inside the 1.6 T B-field of the MORPURGO magnet at CERN in the north area. It could be shown that the highly sensitive receiver system could be operated in the direct surrounding of the magnet. Radio frequency interference measurements have revealed that no spurious lines appeared and that the system has a sensitivity as expected from earlier investigations. Figure 5 (left) shows the whole

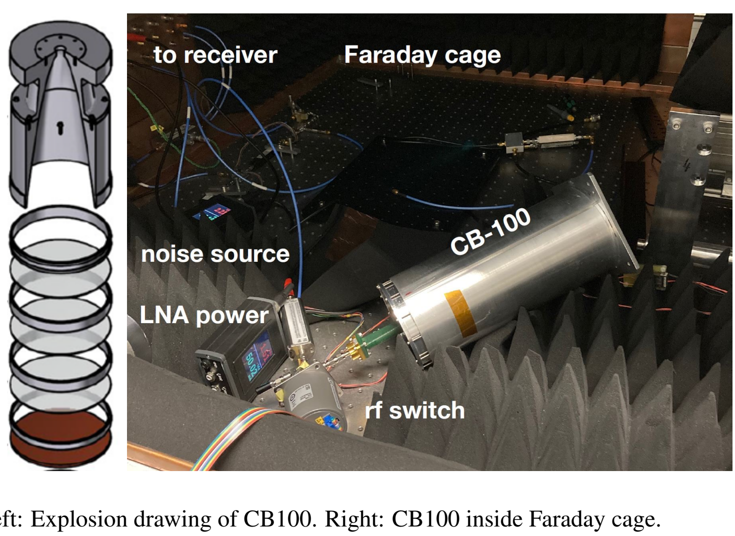

Figure 4. Left: Explosion drawing of CB100. Right: CB100 inside Faraday cage.

setup at the MORPURGO magnet. Figure 5 (right) displays the 10 hour data set taken with CB100 inside the MORPURGO magnet with the B-field at 1.6 T. Overlayed is the boost factor of CB100, indicating at which frequency the sensitivity is the highest due to the potential signal receiving a power boost proportional to the black curve. The center frequency is at roughly 19.65 GHz, corresponding to $\sim 78.6\,\mu$eV. With the obtained sensitivity at the center frequency, ALP photon couplings $g_{a\gamma} > 10^{-10}\,\mathrm{GeV}^{-1}$ can be excluded.

4 Conclusion and Outlook

Axions have been proposed to explain the strong CP problem. They are also an excellent candidate to solve the dark matter problem. The dielectric haloscope concept has the potential to detect dark matter axions in the mass range compatible with the post inflationary PQ symmetry breaking scenario around $100\,\mu$eV. The MADMAX project is developing the dielectric haloscope concept with the goal to achieve the required sensitivity. Significant milestones have lately been reached. A method to determine the power boost factor of the axion induced E-field including its uncertainty has been shown to work on a closed booster system. Piezo motors have been verified to work in strong B-field and at cryogenic temperatures. The conductor for the required magnet has been shown to be suitable for safe operation in terms of fast enough quench protection. Industrial suppliers have been identified that can deliver the required conductor and conduit with required tolerances. First measurements of a booster setup have been performed at CERN inside the MORPURGO magnet. The measurements show that radio frequency interference is not deteriorating the sensitivity of the setup.

The projection of the sensitivity of MADMAX as a dielectric haloscope is shown in Fig. 6 together with existing limits from cavity experiments as well as from the CAST solar axion experiment. Note that the haloscope limits and projections are based on the assumption that axions explain all of the dark matter density. Also shown in the plot are projections for future solar experiments and the ALPS II light shining through the wall experiment. Furthermore, the regions compatible with the astrophysical hints are indicated. QCD axions are predicted to lie on the diagonal line according to the most familiar KSVZ and DFSZ benchmark models. MADMAX could cover a significant fraction of the parameter space predicted for the model in which Peccei Quinn symmetry is broken after cosmic inflation.

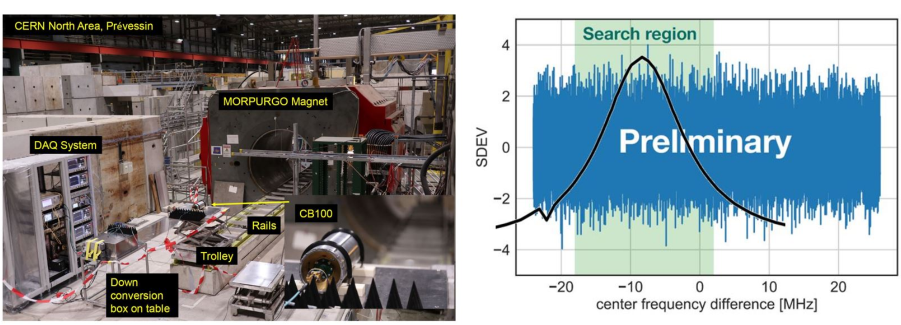

Figure 5. Left: CB100 setup including receiver and DAQ at CERN in front of the MORPURGO magnet before insertion. Right: Background measurement with the receiver and DAQ system with CB100 connected and B-field on. The measured power is normalized to the noise level in terms of standard deviation. The black curve gives the shape of the power boost factor of CB100. The shaded area indicates the frequency range where the setup is sensitive due to the power boost.

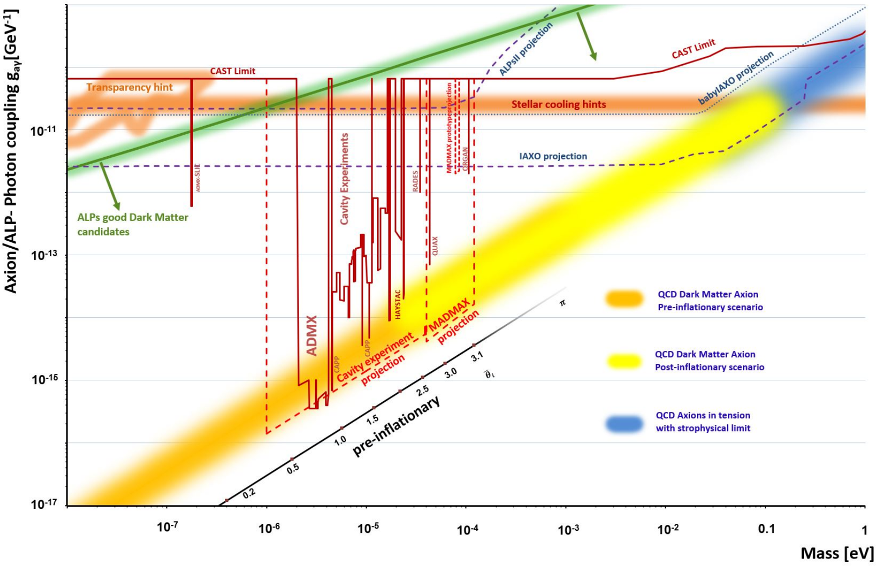

Figure 6. Plot of the axion/ALP to photon coupling vs. mass. Limits are indicated as solid lines, projections as dashed lines. Astrophysical limits are also shown as shaded areas in orange. The diagonal gives the range compatible with KSVZ and DFSZ axions.

References

[1] C. Abel et al., Phys. Rev. Lett. **124** 081803 (2020)

[2] R.D. Peccei and H. Quinn, Phys. Rev. Lett. **38** 1440 (1977) and Phys. Rev. D **16** 1791 (1977)

[3] S. Weinberg, Phys. Rev. Lett. **40** 223 (1978) and F. Wilczek, Phys. Rev. Lett., **40** 279 (1978)

[4] M. Giannotti et al., JCAP **1605** 057 (2016) and M. Giannotti et al., JCAP **1710** 010 (2017)

[5] D. Horns and M. Meyer, JCAP **1202** 033 (2012) and P. Brun, J. Phys. Conf. Series **460** 012015 (2013)

[6] ADMX collaboration, C. Bartram et al., Phys. Rev. Lett. **127** 261803 (2021)

[7] A.K. Yi et al., arxiv:[2210.10961] and J. Kim et al. arxiv:[2207.13597]

[8] J.E. Kim, Phys. Rev. Lett. **43** 103 (1979) and M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, Nucl. Phys. B **166** 493 (1980)

[9] M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104** 199 (1981) and A.R. Zhitnitsky, Sov. J. Nucl. Phys. **31** 260 (1980)

[10] MADMAX interest group, A. Caldwell et al., Phys. Rev. Lett. **118** 091801 (2017)

[11] D. Horns et al., JCAP **1304** 016 (2013)

[12] J. Jaeckel and J. Redondo, Phys. Rev. D **88** 11502 (2013)

[13] MADMAX collaboration, P. Brun et al., Eur. Phys. J. C **79** 186 (2019)

[14] H1 collaboration, I. Abt et al., Nucl. Inst. Meth. A **386** 310 (1997)

[15] M. Morpurgo, Cryogenics **19** 411 (1979)