Constraints on scalar coupling to electromagnetism

Ioannis Antoniou\textsuperscript{1,}\textsuperscript{*}

\textsuperscript{1}Department of Physics, University of Ioannina, GR-45110, Ioannina, Greece

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We review a possible non-minimal coupling (dilatonic) of a scalar field (axion like particle) to electromagnetism, through experimental and observational constraints. Such a coupling is motivated from recent quasar spectrum observations that indicate a possible spatial and/or temporal variation of the fine-structure constant. We consider a dilatonic coupling of the form

$$B_F(\phi) = 1 + g\phi$$

The strongest bound on the coupling parameter $g$ is derived from weak equivalence principle tests, which impose $g < 1.6 \times 10^{-17} \text{GeV}^{-1}$. This constraint is strong enough to rule out this class of models as a cause for an observable cosmological variation of the fine structure constant unless a chameleon mechanism is implemented. Also, we argue that a similar coupling occurs in chameleon cosmology, another candidate dark mater particle and we estimate the cosmological consequences by both effects. It should be clarified that this class of models is not necessarily ruled out in the presence of a chameleon mechanism which can freeze the dynamics of the scalar field in high density laboratory regions.

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I. INTRODUCTION

There are recent observational indications that the fine structure constant may be varying spatially and/or temporally [1–7] on cosmological scales. Such a variation could be due to a scalar field non-minimally coupled to electromagnetism. This field could also play the role of quintessence inducing the observed accelerating expansion of the universe [8–11]. The possible spatial variation of the fine structure constant would require a corresponding spatial variation of the scalar field which could be supported by non-trivial topological properties of the field configuration [12–15]. The variation of the fine structure constant is given by the relation

$$\frac{\Delta \alpha}{\alpha} = \frac{\alpha - \alpha_0}{\alpha_0}$$

for a spatial variation.

We focus on cases where scalar particles or chameleons are subject to coupling with the electromagnetic tensor [17]. We consider an Lagrangian interaction term of the form:

$$L_{\text{coupling}} = -\frac{1}{4} B_F(\phi) F_{\mu\nu} F^{\mu\nu}$$

where:

$$B_F(\phi) = 1 + g\phi$$

is the gauge kinetic function, $\phi$ is a scalar field such as axion-like particle (ALP), chameleon, quintessence, etc and $g$ is the coupling constant, which must be constrained.

Axions are particles, whose existence helps to solve the strong CP problem. Also, they are dark matter candidate particles because they interact mostly gravitational and can induce the required dark matter density of the universe. Their mass and their coupling to electromagnetism is constrained by laboratory, cosmological and astrophysical bounds [18].

ALPs are dark matter candidates [19, 20] (section 2). For consistency with the observed accelerating expansion rate, the required magnitude of the coupling $g$ of the scalar field is described for example in Ref. [21, 22]. It is therefore interesting to inquire if such values of the coupling are consistent with local experiments and astrophysical observations. This is the goal of the present analysis.

In the next section we present experimental bounds from the photon-ALP coupling and a brief discussion about these experiments while in section III we present corresponding bounds for chameleon scalar fields. In section IV we discuss astrophysical and cosmological constraints on $g$ and in section V, we conclude and summarize.

II. CONSTRAINTS FROM PHOTON-AXION LIKE SCALAR COUPLING

We focus on the class of experiments designed to constrain or detect the interaction between scalar ALPs and photons. Generally, a positive signal can determine mass, parity and coupling of the hypothetical scalar particle. This coupling, if ALPs are scalar, is described by the Lagrangian term [23]:

$$L_{\text{scalar}} = -\frac{g}{4} \phi F_{\mu\nu} F^{\mu\nu}$$

where:

$$F_{\mu\nu} F^{\mu\nu} = 2(B^2 - E^2)$$
If we compare the relations (1.1), (1.2) and (2.1), it is easy to show that:

\[ L_{\text{coupling}} = L_{\text{scalar}} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu} \]  
(2.3)

If ALPs are pseudoscalar, the corresponding Lagrangian term is:

\[ L_{\text{pseudoscalar}} = -g \phi F_{\mu\nu} F^{\mu\nu} \]  
(2.4)

where:

\[ F_{\mu\nu} F^{\mu\nu} = -2 E \cdot B \]  
(2.5)

The quantity \( F^{\mu\nu} \) is the dual electromagnetic tensor which violates parity and time reversal invariance. It conserves charge conjugation invariance, so it violates CP symmetry. In both cases, the expression for the coupling between ALPs and photons is given as [24]:

\[ g \equiv \frac{1}{M} \approx \frac{\alpha}{2\pi f_a} \]  
(2.6)

where \( \alpha \approx 1/137 \) is the fine structure constant, \( m \) the mass of the scalar or pseudoscalar particle and \( f_a \) the symmetry breaking scale (or decay constant). As the decay constant increases, the coupling \( g \) decreases. However, it can not be greater than \( f_a \sim 10^{-16} \text{GeV} \) [25], because this would lead to closed universe.

ALPs can have odd (pseudoscalar) or even (scalar particles) parity and can couple to two photons. There are four classes of experiments attempting to detect such particles. The first is based on the so-called haloscope [26]. In this experiment, ALPs from galactic halo, converts to photons in a cavity with a powerful magnetic field. The second category comes from the so-called helioscope [27], which corresponds to weakly interacting slim particles (WISPs) emitted by the Sun. The third class involves searching for ALPs which couple to photos and induce in a laser beam, which propagates in a magnetic field, optical dichroism and birefringence [28]. The fourth class includes photon regeneration experiments [29], such as GammeV [23], BFRT [30], OSCAR [31] and others described bellow. A possible signal currently exists from the third class of experiments (PVLAS). For a brief but not complete review, see Ref. [32].

Most of these experiments are based on fundamental optical properties of the materials affecting their interaction with polarized light, such as [33, 34]:

- **optical rotation** (**activity**): is the turning of the plane of linearly polarized light about the direction of motion as the light travels through materials. It is due to a selective attenuation of one polarization component [28].

- **birefringence**: is the optical property of a material having a refractive index that depends on the polarization and direction of light propagation [35]. The birefringence is often quantified as the maximum difference between refractive indices exhibited by the material.

- **dichroism**: there are two related but distinct meanings [36]. Dichroism is the phenomenon where light rays, having different polarizations, are absorbed by different amounts, or where a visible light can be split up into distinct beams of different wavelengths [37, 38].

- **ellipticity**: is the phenomenon where the polarization of electromagnetic radiation, such that the tip of the electric field vector, describes an ellipse in any fixed plane intersecting the direction of propagation [39]. It is due to selective retardation of one polarization component. In that case the direction of the rotation, and thus the specified polarization, may be either clockwise or counter clockwise.

### II.1. PVLAS experiment

The PVLAS experiment takes place at the INFN Legnaro National Laboratory, near Padua in Italy. In 2006 they reported a positive signal for a zero-spin particle [28]. This experiment is based on the fact that vacuum, in the presence of the scalar field, becomes birefringent and dichroic [40] when applying an external magnetic field [41]. So, when a linear polarized beam propagates in a Fabry-Perot cavity with strong magnetic field, the plane of polarization is rotated by an angle \( \alpha \).

The polarized laser beam has wavelength \( \lambda = 1064 \text{nm} \) or \( \lambda = 532 \text{nm} \) and enters in a high transverse magnetic field of order \( 5T \), in a cavity. It passed 44000 times through a 1m long magnet. The components of the laser polarization had a slight weakening. This effect is observed at varying levels if the polarization is transverse or parallel to the external magnetic field. The rotation angle was found to be:

\[ \alpha = (3.9 \pm 0.5) \times 10^{-12} \text{rad/pass} \]  
(2.7)

The signal was associated to a neutral, light boson produced by a two-photon vertex. The amplitude of the dichroism, which depends on the coupling constant \( g \), was estimated as [23]:

\[ g \sim 2.5 \times 10^{-6} \text{GeV}^{-1} \]  
(2.8)

The mass of the particle was estimated as \( m_\phi \sim 1.2 \text{meV} \) but its parity was undetermined, although the sign of the phase shift hints towards even parity (scalar).

This signal could also be explained by assuming the existence of millicharged particles [42]. They are light particles with electric charge \( q \ll e \), where \( e \) is the elementary (electron/proton) charge and appear in field theories, but they aren’t part of the Standard Model [43]. The PVLAS experiment was repeated without detection of any signal [44]. Thus, its results are currently under question.
II.2. GammeV experiment

The GammeV experiment [23] takes place at Fermilab and consists of two similar experiments. They are ‘light shining through a wall’ experiments based on the Primakoff effect, where two photons with high energy interact and produce ALP. One photon is real from the laser field and the other one is virtual from an external magnetic field.

The Primakoff effect is the production of bosons, when high energy photons interact with an atomic nucleus. Also, include the rotation of the plane of polarization, when a linearly polarized beam passes through a magnetic field. The beam has many directions of polarization. The Primakoff effect reduces the parallel component of polarised light to the magnetic field and leaves the perpendicular component to the magnetic field unchanged. This phenomenon can occur in a reverse manner (a particle can decay into two photons).

The GammeV experiment is a gamma (γ) to milli-eV ALP search. The mass of this particle is expected to be of order meV. A scalar particle couples to photons with a polarization orthogonal to the magnetic field [29], [45]. The photon beam is blocked by the wall, but the ALPs hardly interact with the wall and passes through the wall. The particles convert again to photons in the magnetic field and the regenerated photons are counted with an appropriate detector. The primary and the regenerated photons have the same properties. The photon regeneration experiment is based on different effects of light, compared to the optical rotation experiment. In the first, the appearance of light beyond the wall is detected, while in the second, perturbations of the initial beam are detected.

The photon to scalar particle conversion probability (and the reverse process), is given by the relation:

\[
P_{\gamma \leftrightarrow s} = \frac{1}{4u}(gB\sin \theta)^2 \left( \frac{2}{qL} \sin \frac{qL}{2} \right)^2
\]

where the transverse magnetic field B has length L, and θ is the angle between the laser polarization and the magnetic field. It is clear that, the direction of polarization must be perpendicular to magnetic field for optimum conversion. For pseudoscalar particles it must be parallel to magnetic field, because the probability contains the term \(\cos \theta\) instead of \(\sin \theta\). Here, \(g\) is the coupling constant, \(u\) the velocity of the scalar particle and \(q\) the momentum transfer. The probability becomes maximum when \(q \cdot L \rightarrow 0\), i.e when the particle has very little mass compared to its energy \((m \ll \omega)\). In order to increase the convention probability, we must use strong, long range magnetic fields. The momentum transfer is proportional to the square mass of the particle:

\[
q = \sqrt{\omega^2 - m^2} \approx \frac{1}{2} \frac{m^2}{\omega}
\]

We can split the above probability (2.9) in two phases. The first one is the probability in the production region:

\[
P_{\gamma \rightarrow s} = \frac{(2gB\sin \theta)^2}{m^4}(\sin \frac{Lm^2}{2\omega})^2
\]

(where the photons convert to scalar particles [46]), which increases with the number of passes through the wall. The second, is the probability in the regeneration region:

\[
P_{s \rightarrow \gamma} = \frac{(2gB\sin \theta)^2}{m^4}(\sin \frac{Lm^2}{2\omega})^2
\]

(where the scalars reconvert to photons), which increases by using a resonant cavity in the regeneration region. The expected counting rate of photons in the detector is of the form:

\[
\frac{dN_\gamma}{dt} = P \eta (P_{\gamma \leftrightarrow s})^2
\]

where \(\eta\) is the detector efficiency and \(P\) is the optical power.

Short laser pulses of \(\lambda = 532\) nm were used in the experiment and the external magnetic field was 5T [23]. The weakly-interacting ALP interpretation of the PVLAS data was excluded at more than 5σ by the GammeV data for scalar particles. No events were found above the background and thus a bound was set for the coupling [23]:

\[
g \leq 3.1 \times 10^{-7} GeV^{-1}
\]

This limit is the mean value of two configurations for the magnetic field and it is valid for small values of the mass \(m_s\) (bellow meV). Generally, the coupling depends on the mass of the scalar particle, but when the mass is small (bellow few meV), the coupling is almost unchanged.

II.3. Fifth force experiments

The coupling between scalar particle and two photons \(\phi \gamma\) [47], which can be described with the Lagrangian term (2.1), leads to the existence of long-range non-Newtonian forces (fifth force). They are bounded by Eötvös type experiments and they don’t violate the Equivalence Principle. The relative difference between inertial and gravity mass is less than \(10^{-12}\) [48] and drives to constrains on the coupling constant.

The Lagrangian contains an interaction term of the form:

\[
L_{interaction} = -\frac{g\phi}{4} F_{\mu\nu} F^{\mu\nu} - L_2
\]

The above term of the Lagrangian density induces radiatively a coupling to charged particles, such as electrons or protons. The additional term in Lagrangian density is \(L_2 = g\phi \nabla \nabla \Psi\) where \(y\) is the Yukawa coupling and \(\Psi\) is the
field of the charged particle. The authors of [47] used existing experimental limits to constrain the coupling constant \( g \) as a function of the mass of the scalar field \( m_\phi \). These limits emerge from a micromechanical resonator which measures the Casimir force between parallel plates [49, 50] (two mirrors in a vacuum will be attracted to each other) placed a few nanometers apart, from experiments with torsion pendulum and a rotating attractor [51] and from experiments which use torsion-balance [52]. Using the last class of experiments, the authors [47] reached very stringent results when the field satisfies the condition \( \Lambda \gg m_p \) (\( \Lambda \) is the cosmological constant and \( m_p \) the proton-mass). When \( m_\phi \sim meV \), they found that [52]:

\[
g < 1.6 \times 10^{-17}GeV^{-1} \tag{2.16}
\]

It is a stringent limit and the terrestrial experiments don’t have until now, the sensitivity to detect some event.

Scalar particles with almost zero mass can lead not only to long-range forces (in the same manner as quintessence), but also to variation of fundamental constants [53]. Bekenstein type models with a scalar field \( \phi \), that affects the electromagnetic permeability, lead to variations of the effective fine structure constant up to very high red-shifts. The coupling between scalar field and electromagnetic tensor of the form:

\[
\beta_{\mu\nu}(\phi/M)F_{\mu\nu}F^{\mu\nu} \equiv \frac{g}{4}\phi F_{\mu\nu}F^{\mu\nu} \tag{2.17}
\]

can lead to a time variation [54] of the fine structure constant, due to the time variation of the scalar field. The scalar field \( \phi \) is expected to have a variation at the present time (in cosmological timescales) of order \( M_{Pl} \) and there are several observations to bound such variation. From the Oklo natural reactor in Gabon [55], the researchers analyzed the isotope ratios of \(^{149}\text{Sm} / ^{147}\text{Sm} \) in the natural uranium fission reactor (mine) that operated 1.8 billion years ago. The isotopic abundances lead to \(|\dot{\alpha}/\alpha| < 10^{-15}yr^{-1}\) over the last 1.8 billion years and constrains the coupling as:

\[
g \leq 4 \times 10^{-6}\left(\frac{H_0}{\langle \dot{\phi} \rangle}\right) \tag{2.18}
\]

where \( H_0 \sim 10^{-33}eV \) and \( \langle \dot{\phi} \rangle \) is the mean rate of change of \( \phi \) in the above time range.

II.4. BFRT experiment

One of the first photon regeneration experiments took place in Brookhaven National Laboratory [30]. In this experiment the beam had wavelength \( \lambda = 514nm \) and the magnetic field was 3.7T. The search for scalar particles requires the laser polarization to be perpendicular to the magnetic field. The photons, produced during the regeneration, are detected by sensitive photocathode of a photomultiplier tube (PMT) [56]. For 220 minutes the laser was on and subsequently for 220 minutes the laser was off. They didn’t observe significant difference between laser on and laser off states. Thus [30], [57], in the absence of signal, the coupling constant was constrained as:

\[
g < 6.7 \times 10^{-7}GeV^{-1} \tag{2.19}
\]

at 90% confidence level. This limit is applicable when the scalar particle is very light with mass \( m < 10^{-3}eV \). The PVLAS signal and the BFRT constraint can be combined as [57]:

\[
1.7 \times 10^{-6}GeV^{-1} \leq g \leq 5 \times 10^{-6}GeV^{-1} \tag{2.20}
\]

assuming the mass of the scalar in the range \( 1meV \leq m_\phi \leq 1.5meV \).

II.5. OSCAR experiment

The OSCAR experiment takes place at LHC and it is a photon regeneration experiment which uses two LHC dipole magnets. The laser beam has wavelength \( \lambda = 514nm \) and the dipole superconducting magnets are cooled down to 1.9K [31]. The innovation in this experiment is that they use a buffer of neutral gas as a resonant amplifier medium. The conversion probability, divided by the refractive index \( n = \sqrt{\varepsilon} \), is:

\[
P_{\gamma_{\pm\gamma}} = \frac{1}{4\alpha\varepsilon(L)}(gL)^2\frac{2}{qL}\sin\frac{qL}{2} \tag{2.21}
\]

while the expected counting rate is given by equation (2.13). The device of the OSCAR experiment hasn’t recorded any signal and the coupling is constrained as [58]:

\[
g < 1.15 \times 10^{-7}GeV^{-1} \tag{2.22}
\]

An updated result [59], is currently the lowest limit from such experiments. In the case of massless scalar particle, the coupling constrained as:

\[
g < 5.76 \times 10^{-8}GeV^{-1} \tag{2.23}
\]

at 95% confidence limit.

II.6. ALPS experiment

The ALPS (Any Light Particle Search) is another one experiment, which based on the effect ”light shining through the wall”. The experiment takes place in Deutsches Electronen Synchrotron (DESY), in Germany [60, 61]. The researchers use a HERA superconducting dipole magnet where the magnetic field is 5T. The photons have wavelength \( \lambda = 1024nm \), or \( \lambda = 512nm \). They collect data in vacuum and in low pressure gas, inside a tube, but in the absence of any positive signal for photon
TABLE I. Constrains on coupling between photons and scalar particles from all known experiments. Each limit is valid for the corresponding range of the mass of the scalar particle, which is shown in the third column. In the fourth column we show the basic physical effect on which each experiment is based (LSW means light shining through a wall).

| experiment | $g(\times GeV^{-1})$ | $m_\phi$ (meV) | effect |
|------------|----------------------|----------------|--------|
| PVLAS [23] | $\sim 2.5 \times 10^{-6}$ | $\sim 1.2 meV$ | birefrigence |
| GammeV [23] | $\leq 3.1 \times 10^{-7}$ | $\leq 1 meV$ | LSW |
| Fifth force [52] | $< 1.6 \times 10^{-17}$ | $\sim meV$ | Casimir force |
| BFRT [57] | $< 6.7 \times 10^{-7}$ | $\leq 1 meV$ | LSW |
| OSCAR [59] | $< 5.76 \times 10^{-8}$ | massless | LSW |
| ALPS [62] | $< 7 \times 10^{-8}$ | massless | LSW |
| LIPSS [63] | $< 1 \times 10^{-6}$ | $\sim meV$ | LSW |

In the case of massless scalar particle in vacuum, they estimated [62] the coupling constant as:

$$g < 7 \times 10^{-8} GeV^{-1} \quad (2.24)$$

II.7. LIPSS experiment

The Light Pseudoscalar and Scalar Particle Search (LIPSS) collaboration [63] was another similar experiment, looked for photons coupled to light neutral particles. It took place in Jefferson Lab in the Spring of 2007 and was also based on the light shining through the wall effect. The magnetic field was 1.77T for both generation and regeneration regions. The wall was a mirror and the wavelength of the photons was $\lambda = 935 nm$. The innovation of this approach was that data were taken for longer time (almost 1 hour), than previous similar experiments. No signal was recorded above background and the constraint [63] on the coupling strength is:

$$g < 10^{-6} GeV^{-1} \quad (2.26)$$

assuming a mass of the scalar particle of order $meV$.

In table I we present the constrains on the coupling between scalar particles and photons, from all known experiments in order to compare them and identify the most stringent. For small masses of the scalar particle (bellow $meV$), the coupling $g$ is mass independent, because the oscillation length between ALPs and photons far exceeds the length of the magnet. As we see, the controversial result of PVLAS leads to a weak constraint. The other experiments give more stringent bounds, which in fact aren’t consistent with the PVLAS result.

Also, the data of table I are shown through a histogram in Figure 1. We have neglected the PVLAS experiment, because the Italian collaboration doesn’t defend it. Thus, the most stringent bound obtained from the fifth force experiments.

III. CONSTRAINTS ON CHAMELEONS

The existence of chameleons [64–67] could support the accelerating expansion of the universe (as components of dark energy) and the time evolution of the fine structure constant. Chameleons are scalar particles [68, 69] whose effective mass is a function of its local environment. Just like a chameleon changes color in different environments, the magnitude of the mass of a cosmological chameleon particle depends on the location. In regions with high density, such as Earth, the mass is large in order to evade the fifth force searches, which excluded by experiments on a wide range of scales. In regions with low density, such as our solar system, the mass is lower and in cosmological scales is of order of the present Hubble value [70, 71]. In any case the effective mass is:

$$m_{eff} = \sqrt{\frac{\epsilon}{m^2}} \quad (3.1)$$

with

$$V_{eff}(\phi, \vec{x}) = V(\phi) + e^{\frac{\phi}{\rho_{\gamma}}} \rho_{\gamma}(\vec{x}) + e^{\frac{\phi}{\rho_{\gamma}}} \rho_{\gamma}(\vec{x}) \quad (3.2)$$

It is clear, that the effective mass depends on the electromagnetic fields and the local matter density [72]. A possible potential for chameleons is the Ratra-Peebles potential:

$$V(\phi) = M^4(\frac{\phi}{\gamma})^n \quad (3.3)$$

with $n$ is an integer and $M$ is model parameter (in the case of dark matter, $M \approx 3 meV$). When the local matter density is high, the chameleon becomes invisible due to mixing with the environment. For this reason experiments, which have the purpose to detect chameleons in laboratory, are performed in almost absolute vacuum.

Chameleons can couple to all forms of matter and can also couple to photons [73]. Coupling to matter leads to fifth force which act only on large scales and is very small.
on small scales. We do not see any fifth force or modification of gravity in the laboratory or in the Solar System. The chameleon mechanism has exactly the above properties, because it suppresses the fifth force mediated by the new degree of freedom without killing the modification on all scales. The environment dependent mass \((3.1)\) is enough to hide the fifth force in dense media such as the atmosphere. The chameleon force \([74,75]\) is only sourced by a thin shell near the surface of dense objects, which reduces its magnitude significantly.

Chameleon theories are intriguing and lead to new physics. Hints of such theories have been seen in active galactic nuclei’s (AGNs) and in the structure of starlight polarization. In conclusion, chameleon mechanism make this class of models cosmologically interesting despite of the strong laboratory constrains imposed by the fifth force experiments.

There are two classes of experiments for searching chameleons:

- experiments in empty, closed container or jar, such as GammeV and CHASE.
- experiments in microwave cavity, such as ADMX.

They are based on the coupling between photons and chameleons, where the coupling to electromagnetism is dominant. These experiments aren’t photon regeneration experiments \([76]\) because the mass of the chameleons depends on local density and thus they can’t pass through the wall. Inside the wall the density is high compared to the vacuum and the chameleons get reflected by the wall. These experiments are based on the afterglow effect \([77]\), which we describe below. In both cases the coupling to electromagnetism may be described by a dilatonic function:

\[
B_F(\phi) = e^{g\phi} \simeq 1 + g\phi
\]  

because \(g\) is very small \((g \ll 1)\). This coupling allows photon-chameleon oscillations in the presence of an external strong magnetic field. The scalar field \(\phi\) with mass \(m_\phi\) expected of order \(meV\). Such a mass could explain the dark energy density, which is \(\sim (meV)^4\).

III.1. GammeV experiment

The GammeV collaboration includes experiments for ALPs and experiments for chameleons \([76,78]\), which couple to photons. It constitutes the first test of dark energy models in laboratory. Chameleons produced inside a optical transparent jar from photon oscillations (Primakoff effect \([79]\)) and trapped there, if its total energy is less than its effective mass. Then, the chameleons reflected by the walls and they detected via their afterglow as they slowly converted to photons. The afterglow is possible if the mixing time between scalars and photons is larger than the travelling time of photons into the chamber. An afterglow photon can be observed by a photomultiplier tube (PMT) at the exit window, when the original photon source (laser) is tuned off. The pressure in the chamber is \(P \approx 10^{-7} Torr\) and the probability per photon to chameleon production is:

\[
P_{br} = \frac{4g^2B^2\omega^2}{m_{eff}^4} \sin^2 \left(\frac{m_{II}^2L}{4\omega}\right) \hat{k} \times (\hat{x} \times \hat{k})
\]  

proportional to the square of coupling \(g\).

The magnetic field is in the \(\hat{z}\) direction and \(\hat{k}\) is the direction of motion of the particle. It is clear that, if we want to have the maximum probability, the photons must propagate in a direction perpendicular to magnetic field. The photons have energy \(2.33eV\), production rate \(\sim 10^{13}\) photons per second and the magnetic field is \(5T\).

In this case, the action which describes the coupling between photons and chameleons is:

\[
S = \int d^4x( -\frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{e^{\phi/M_\gamma}}{4} F_{\mu\nu} F^{\mu\nu}
+ \mathcal{L}_m(e^{2\phi/M_\gamma} g_{\mu\nu}, \psi_m))
\]  

where \(V(\phi)\) is the chameleon potential and \(\mathcal{L}_m\) the Lagrangian density for the matter. The coupling to matter defined as \(\beta_m = M_{Pi}/M_m\) and the coupling to electromagnetism is the dimensionless parameter \(\beta_\gamma = M_{Pi}/M_\gamma \equiv g M_{Pi}\). Data were taken for one hour after the laser turned off, but there wasn’t detection of any significant signal in the highly sensitive PMT. Thus, the parameter \(g\) estimated as: \([76]\)

\[
2.1 \times 10^{-7} GeV^{-1} < g < 2.7 \times 10^{-6} GeV^{-1}
\]  

This limit valid for coherent oscillations and therefore the effective mass must be quite small \((m_{eff} \ll 0.98 meV)\).

III.2. ADMX experiment

The Axion Dark Matter experiment has two parts. The first is the search for ALPs and the second, the search for chameleons. In both cases the particles interact with photons inside a cavity and estimated the range of the coupling. The advantage of the microwave cavity is, that the resonance is stronger than the case where laser is used. This effect increases the conversion probability and the expected counting rate of photons in the detector. A microwave receiver amplifies the excitation of the resonance. The mixing is maximum when photons and chameleons have the same energy \((\omega_{cham.} = \omega_\gamma)\). It is crucial to emphasize that if the coupling is very weak, the chameleons don’t have enough energy to be detected, while if the coupling is very strong the chameleons immediately decay.

As discussed in \([80]\), this experiment used a magnet \(7T\), while the cavity had volume \(220\ell\). It was hold under vacuum at 2 Kelvin. No significant signal was observed and the excluded region was estimated as \([80]\):

\[
3.75 \times 10^{-9} GeV^{-1} < g < 2.1 \times 10^{-4} GeV^{-1}
\]
TABLE II. Excluded regions on coupling between photons and chameleons from all known afterglow experiments. In third column, recorded the corresponding effective mass for the chameleons.

| Experiment  | $g(\times \text{GeV}^{-1})$ | $m_{\text{eff}}$ |
|-------------|-----------------------------|------------------|
| GammeV [76] | $(2.1 \times 10^{-3}, 2.7 \times 10^{-5})$ | $\ll 0.98 \text{meV}$ |
| ADMX [80]  | $(3.75 \times 10^{-9}, 2.1 \times 10^{-8})$ | $[1.9510 \mu \text{eV}, 1.9525 \mu \text{eV}]$ |
| CHASE [81]  | $(4 \times 10^{-6}, 1.3 \times 10^{-3})$ | $\lesssim 1 \text{meV}$ |

at 90% confidence level. This bound is valid for a very small range of the effective mass, between $1.9510 \mu \text{eV}$ and $1.9525 \mu \text{eV}$. The above limit overlaps with the limit (3.7).

III.3. CHASE experiment

The Chameleon Afterglow Search Experiment (CHASE) is a continuation of the GammeV experiment in the same laboratory [81]. The excluded region for the chameleon-photon coupling in this case, is significantly improved. Also, the results smooth out the differences between the two previous experiments [82].

The novelty of this experiment is twofold. First, it uses two glasses into the cavity. Thus, the magnetic field is divided in three parts with different ranges. The shorter part has sensitivity to chameleons with high mass. Second, in order to improve the sensitivity for large $g$, used several magnetic fields, with values lower than 5T. Finally, in order to improve the sensitivity for small $g$, a shutter (chopper) is used to modulate any possible signal from afterglow. The data didn’t show any signal of a photon-chameleon coupling and the excluded region for $m_{\text{eff}} \lesssim 1 \text{meV}$ is estimated as [81]:

$$4 \times 10^{-6} \text{GeV}^{-1} < g < 1.3 \times 10^{-3} \text{GeV}^{-1}$$

at 90% confidence level.

IV. COSMOLOGICAL AND ASTROPHysical effects

We can extend the Bekenstein theory when we introduce the dilatonic function $B_F(\phi) = e^{-2\phi}$ in formula (1.1). This function affects the scalar field and the cosmological evolution of a quintessence scalar field [83] and effects of multidimensional gravity [84]. We discuss these effects in some detail.

We want to investigate the cosmological evolution and the effect of the new coupling on the Big Crunch singularity [85–87] that is present in linear potentials. In Ref. [83] the authors introduced the Lagrangian density

$$L = \frac{R}{2} - \frac{\omega(\phi)}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} e^{-2\phi} F_{\mu\nu} F^{\mu\nu} + L_m$$

where the fine structure constant varies through the relation $\alpha = a_0 e^{-2\phi}$. We consider FRW flat spacetime, with $\omega(\phi) = 1$ and $V(\phi) = -s(\phi)$. We introduce the rescaling $H = H_0\bar{t}$, $t = \frac{1}{H_0}$, $V = V_0 \bar{t}^3$, $\rho_m = \bar{\rho}_m H_0^3$ and $\rho_r = \bar{\rho}_r H_0^2$, ($H_0$ is the present value of the Hubble constant) in the dynamic equations of Ref [83] and from now on we omit the bar. Thus, the scalar field equation of motion takes the form

$$\ddot{\phi} + 3H \dot{\phi} + V'(\phi) = -\frac{6\zeta_m \Omega_{0m} e^{-2\phi}}{a^4 (1 + |\zeta_m| e^{-2\phi}_0)}$$

(4.2)

where $\phi_0$ is the present value of the scalar field and $\zeta_m = L_{\text{em}} / \rho_m$. Here, $\rho_m$ is the energy density of non-relativistic matter. In a radiation epoch, variations in fine structure constant are driven only by the electromagnetic energy of non-relativistic matter, because $L_{\text{em}} = \frac{1}{3} (E^2 - B^2) = 0$.

Respectively, the acceleration equation for the scale factor becomes [83]

$$\frac{\ddot{a}}{a} = \frac{\Omega_{0m} (1 + |\zeta_m| e^{-2\phi}_0)}{2a^3 (1 + |\zeta_m| e^{-2\phi}_0)} - \frac{\Omega_r e^{-2(\phi - \phi_0)}}{a^4} - \frac{1}{3} [\dot{\phi}^2 - V(\phi)]$$

(4.3)

FIG. 2: The scalar field $\phi(t)$ as a function of time $t$ when $\zeta_m = 0$, $\zeta_m = 10^{-8}$, $\zeta_m = 10^{-7}$ and $\zeta_m = 10^{-6}$, when the potential is of the form $V(\phi) = -0.1\phi$. The present time $t_0$ is derived from the solution and must be almost equal to 1. As we see, the field after some time increases quickly, thus the effective force becomes attractive.

We have solved the system of the cosmological dynamical equations for the scalar field and for the scale factor (4.2) and (4.3). We assume $\Omega_{0r} = 10^{-4}$, $\Omega_{0m} = 0.3$ and initial conditions deep in the radiation era where the scalar field $\phi_i$ was almost constant ($\phi(t_i) = 0$). Due to rescaling, the acceptable solutions must satisfy the conditions $a(t_0) = 1$, $H(t_0) = 1$ and $\Omega_{0\phi} = 0.7$, where $t_0$ is the present time. In fig. 2 we present the scalar field as a function of time when $V(\phi) = -0.1\phi$, while in fig. 3 we have plot the logarithm of the scale factor $\ln(a(t))$.

It is clear that, when the scalar field increases rapidly, the effective force becomes attractive, the scale factor decreases also rapidly and the Universe leading to Big Crunch. When $\zeta_m$ increases, the effect occurs later.
and we have plot the results in fig. 3. The model corresponds to quintessence cosmology because $w > -1$ and as we see (magenta or green line), the dilatonic function induces small changes in the parameter $w(z)$, if we compare with the case $\zeta_m = 0$ (red line). Specifically, when the parameter $\zeta_m$ increases, the equation of state parameter $w(z)$ also increases in the context of quintessence cosmology. Also, in fig 5, we have plot the parameter $w$, as a function of time.

The dilatonic function $B_F(\phi) = e^{-2\phi}$ can also describe spatial variations of fine structure constant in nonlinear multidimensional theories of gravity [84, 88, 89]. This term arises naturally from the metric determinant, by taking into account spatial perturbations (of order of the cosmological horizon scale) of the scalar field and the metric, when the system reduces to four dimensions. The observational data of variations of $\alpha$ depend on the size of the extra factor space and define the model parameters. In this cosmological model, the values of fine structure constant changes slightly or remain almost constant in all cosmological epochs (radiation epoch, matter epoch or accelerating expansion epoch due to a cosmological constant). This process can be used for the research of variations and other fundamental constants, such as the gravitational constant $G$ [90].

Large scale inhomogeneity of the scalar field $\phi$ of multidimensional origin can induce spatial variations of $\alpha$. The variations of $\alpha$ are very small (of order $10^{-9}$), as we have mentioned in the introduction [1] and have been observed from Very Large Telescope (VLT) in Chile [91] and Keck telescope in Hawaii [92, 93]. The results obtained from spectra of distant quasars and shows a smaller value for fine structure constant when $z < 1.8$ from both telescopes. When $z > 1.8$, the Keck data shows that $\frac{\Delta\alpha}{\alpha} < 0$, but the VLT data drives to $\frac{\Delta\alpha}{\alpha} > 0$. The combined dataset fits a spatial dipole for the variation of $\alpha$, which is unlikely to be caused by systematic effects.

There are many cosmological and astrophysical observations, which could be explained by the existence of scalar ALPs or chameleons and their coupling with photons. One of them is the dark energy density of the uni-
verse [94–96], which is of order $\rho_A \sim (meV)^4$. If the scalar ALPs or chameleons exist and have masses of order of $meV$, the vacuum energy density has the cosmologically required value.

Scalar dark radiation with a sector $\phi$ of spin-0, can be tightly coupled to thermal plasma of hydrogen, $\alpha$ particles, baryons, photons and electrons. Such a particle can be scattered from the plasma. The full Lagrangian [97] in this case has the form:

$$L_{\text{total}} = L_{\text{visible}} + L_{\text{dark matter}} + L_{\text{interaction}} \quad (4.5)$$

where $L_{\text{int.}}$ contains the coupling between ALPs and plasma. This term includes Yukawa-type and dilaton-like operators and has the form [97]:

$$L_{\text{interaction}} = -\frac{g_B}{4} F_{\mu\nu} F^{\mu\nu} - \sum_i \frac{m_i}{\Lambda_i} \bar{\phi}\psi_i \psi_i \quad (4.6)$$

Astronomical observations [57], [98] from the duration of the red giant phase and the population of Helium Burning stars (helium burning generates enough energy to prevent further contraction of the star core) in globular clusters [99], require:

$$g < 6.25 \times 10^{-11} GeV^{-1} \quad (4.7)$$

This constraint isn’t as stringent as experimental constraints due to two uncertainty effects. First, the ALPs may be emitted with less energy than produced, due to stellar medium diffusion and second, there may be much less ALPs produced due to a possible stellar suppression mechanism. Scattering rate of scalar dark radiation near the above bound of $g$, will be too small to significantly distort the CMB blackbody spectrum. Stronger limits on $g$ can be extracted by considering the cosmological evolution of the vacuum expectation value of $\phi$.

There are many cosmological sources, such as quasars [100], X-rays from the Sun [101], cosmic rays with ultra high energy (of order $10^{18}eV$) [102], which produce photons. These photons can be converted to scalar particles due to magnetic fields, around their sources. They travel to Earth and reconvert back to photons due to magnetic fields from our galaxy, or due to intergalactic or intracluster magnetic fields (‘cosmic photon regeneration’). The photons can be detected through experiments on Earth. The required mass [103] for the ALPs situated in the range $m_a \ll (1peV - 1neV)$ and the required coupling is:

$$g \sim (10^{-12} - 10^{-11}) GeV^{-1} \quad (4.8)$$

Scalar particles can also be produced inside the stars [108] and their properties depend on the density of the environment [57]. They can be produced in stellar plasma, only if their mass is tuned to be resonant with the frequency of the plasma [109].

Also, scalar fields can change the energy of the bound states in atoms [108]. The nuclear electric field, in and around the atom, induce a perturbation to scalar field and the corresponding energy levels of hydrogenic atoms are shifted. Thus, the gap between the energy levels increases. These shifts (for example Lamb shift), can be used to constrain the parameter $g$. The energy gap between the levels $2S_{1/2}-2P_{1/2}$ requires $g \approx 10^{-5} GeV^{-1}$, so it is easier to detect scalar couplings in laboratory experiments from photon regeneration experiments than from atomic measurements [57].

ALPs maybe emitted by explosion of Supernovae. They could be produced by the Primakoff effect with energy $E \sim 100MeV$ and finally converted into high energy photos in the magnetic field of our Galaxy. For example, at a distance $50kpc$ of Milky Way is the remnant of SN1987A, in Large Magellanic Cloud. The authors of Ref. [110] used the current models for the Supernova magnetic field and the Milky Way magnetic field and they obtained a bound for the coupling between photons and ALPs. In the future, any supernova core-collapse could be used to detect this process.

The coupling between photons and chameleons can also be observed through effects in light from astrophysical sources [111]. This coupling can induce linear and circular polarization which can be detected on Earth. The intergalactic region has very low density [112], where the chameleons behave as ALPs. They must have mass $m_\phi \lesssim 10^{-11}eV$, the range of the chameleon force is $\lambda_\phi \gtrsim 20 Km$ and the required coupling is $g \lesssim 10^{-11} GeV^{-1}$.

The dilatonic function $B_F(\phi) = 1 + g(\phi - \phi_0)$ can describe variations of the fine structure constant [112]. The evolution of $\alpha$ is given by the relation [113] $\frac{d\alpha}{dt} = (B_F(\phi))^{-1} - 1$. Assuming that $\phi_0 = 0$, scalar particles or chameleons would change the value of this constant, when they interact with photons. If we determine the order of coupling $g$, then we would check if this value could support the observed variation of the fine structure constant.

V. CONCLUSIONS

The existence of scalar (or pseudoscalar) ALPs and chameleons can play the role of dark matter or can induce the accelerating expansion of the universe. The detection of these light particles (with masses in the sub-eV range) is a very difficult problem [114]. For this purpose, many experiments until today have been designed and executed. There are laboratory experiments and astrophysical or cosmological observations based on light shining through the wall effect, optical effects in laser polarization, etc [115] in order to detect the coupling between
scalar particles and photons through the effects, that induce in light. These experiments haven’t recorded any positive signal, because the coupling, as it seems from the results, is very weak.

We examined the case where the coupling, described by a dilatonic function, varies linearly with the scalar field $\phi$ (1.2). Due to the shift symmetry of scalar field, quadratic terms of $\phi$ are excluded. Experiments are being conducted, which try to detect optical effects from these particles in polarized laser beam, or photon regeneration inside a strong magnetic field. The detection sensitivity of these experiments is restricted by the technical features of each apparatus. In these experiments there isn’t currently any positive signal for the existence of ALPs, so we currently have an upper bound. The most stringent bound comes from the fifth force experiments where long range forces are induced by the scalar field (Casimir force).

An alternative way to explain the accelerating expansion of the universe is the chameleon scalar particles, a kind of particles whose mass depends on the local density. In dense environment, the chameleon becomes massive (mediate a short range force), but in sparse environment becomes very light (mediate a long range force) [116]. This feature makes chameleons consistent with local experiments but still effective on the cosmological dynamics beyond the cosmological constant. They are coupled to photons and this coupling can described with the same dilatonic function as scalar ALPs. The experiments are based on different effects because the chameleons get reflected by the wall, due to their mass, so they cannot induce photon regeneration.

In many astrophysical, astronomical and cosmological effects, light travel from one distant source, to our planet. It passes through several magnetic fields and it is possible to detect changes in light, when we observe it, in laboratory.

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