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Astrophysical constraints on a light spinless particle coupled to photons

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Abstract

We examine further astrophysical constraints on a light spinless particle coupled only to photons and proposed by Massó and Toldra. We consider constraints coming from measurements of extragalactic background and from ionization of III clouds.

1 Introduction

The possibility of a light pseudoscalar coupling mainly to two photons became popular with axion models [1]. Almost all experiments searching for axions, make use of the coupling of this particle with two photons [2]

$$L = \frac{1}{8} g_{a\gamma\gamma} \epsilon_{\mu\nu\alpha\beta} F^{\mu\nu} F^{\alpha\beta} a \quad (1)$$

As we know, the axion coupling with two photons is proportional to the axion mass m_a

$$g_{a\gamma\gamma} \approx \frac{\alpha}{2\pi} \frac{m_a}{1 \text{ eV}} 10^{-7} \text{ GeV}^{-1} \quad (2)$$

An interesting point addressed recently by Massó and Toldra [3] is : can we have another pseudoscalar particle ϕ coupled to photons in the same way as axions ? This particle, with a strong enough coupling g would induce a positive signal in some of axion searches.

Motivated by this arguments, in Ref.[3] it was considered the consequences of a light pseudoscalar particle ϕ coupled only to two photons through Eq.(1) and which could also be a dark matter candidate.

In what follows, we consider only this type of interaction for ϕ . We want to emphasize that the pseudoscalar ϕ is not an axion generalization, since the axion couples to leptons, quarks and nucleons and ϕ does not. So the coupling g and the mass m_ϕ of the ϕ particle are not related, as they are for the axion, see Eq.(2). The ϕ mass is in principle arbitrary, but in this work we will concentrate on the case that ϕ is a non-relativistic particle, $m_\phi > O(10^{-4} \text{ eV})$ and for ϕ being a dark matter candidate we should have also $m_\phi < 10 \text{ KeV}$ [3]. In Ref.[3] it was shown that for ϕ being a dark matter candidate would be classified as hot dark matter. However the formation of large structures in the Universe seems to require a large proportion of cold dark matter [4]. So the pseudoscalar ϕ would not have the main role in the structure formation, but we still assume as in Ref.[3] that most of the dark matter could be given by the ϕ particles.

In this work, we study the contribution of the process $\phi \rightarrow \gamma\gamma$ to the extragalactic background light [5]. We suppose that the pseudoscalars ϕ are bound up exclusively in Galactic halos [3], and these ϕ halos will comprise our sources of background radiation. In this case the telescope experiments looking for axions could also give a signal for the ϕ particle. Making comparison with observation we establish a region for m and g , where ϕ could be the Galactic dark matter.

The decaying photons of ϕ , considered as a cosmological dark matter candidate may be also responsible for the ionization of III clouds and therefore can also be limited by the degree of ionization of these clouds, which will be studied in section three. Our conclusions are summarized in section four.

2 Pseudoscalar ϕ in Galactic Halos

The extragalactic background light is the cosmological radiation field produced by galaxies. The intensity of this background at present epoch is low and is believed to be determined mainly by two factors : the finite lifetime of the galaxies that restricts the number of photons that have been emitted into intergalactic space, and the expansion of the universe that lowers the number density of photons by increasing the volume and also lowers their

energy via the redshift.

We will calculate background intensities with the method of Wesson, Valle and Stabel [6] and Wesson [5]. They showed that for a given dark matter candidate, emitting photons through some specific process the total intensity can be given as a function of the : number density $n(t)$ of radiating sources, and the energy distribution function $F(\lambda, t)$. Each source emits energy in the waveband λ to $\lambda + d\lambda$ at the rate $F(\lambda, t)d\lambda \text{ erg s}^{-1}$.

Assuming a standard Friedmann-Robertson-Walker metric, the total spectral intensity of all the sources in space can be shown to be [6]

$$I(\lambda_0) = c \int_{t_f}^{t_0} n(t) \mathcal{R}^5(t) F(\mathcal{R}\lambda_0, t) dt \quad (3)$$

where c is the speed of light, t is time, t_0 is the present time, t_f is the epoch of formation of the sources and the factor $\mathcal{R}(t) = R(t) / R_0$, where $R(t)$ is the cosmological scale factor and $R_0 = R(t_0)$. This spectral intensity is the combined intensity of many sources, whose photons are emitted at various wavelengths λ and redshifted by various amounts, but which reach us in a waveband centered on $\lambda_0 = \lambda / \mathcal{R}(t)$.

Our problem is to obtain the energy spectrum $F(\lambda, t)$ and a number density $n(t)$ for the pseudoscalar ϕ . Substitution into equation (3) will yield the spectral intensity of their total expected contribution to the extragalactic background light. This can be compared to experimental observations to place constraints in the mass and the coupling constant of ϕ .

We assume that the pseudoscalars ϕ are concentrated in galactic halos [3]. These halos will constitute our photon sources. The number density of sources will be the mean galactic number density n_0 , normalized by three powers of the scale factor to account for expansion [6].

$$n(t) = n_0 \mathcal{R}^{-3}(t) \quad (4)$$

with $n_0 = 0.02 \text{ galaxies Mpc}^{-3}$. We neglect any time evolution in number density of galaxies apart from that due to expansion, and as we are interested only in the averaged background flux of radiation, we can also neglect any space dependence in galactic number density. The Eq.(4) is reasonable throughout the matter dominated era, and in particular throughout the lifetime of the galaxies.

Substituting Eq.(4) into Eq.(3) and writing everything in terms of redshift z defined as $R(t) / R_0 = (1 + z)^{-1}$ and considering the Einstein-DeSitter universe we have

$$I(\lambda_0) = \frac{c n_0}{H_0} \int_0^{z_f} F\left(\frac{\lambda_0}{1+z}, t\right) (1+z)^{-9/2} dz \quad (5)$$

where H_0 is the current value of Hubble's parameter, and z_f is the redshift value at the time of halo formation.

Each ϕ particle of rest energy E_ϕ decay into two photons of energy $E_\phi / 2$. Therefore, following Ref [7] we assume that decay photons wavelengths will be distributed normally about a peak wavelength:

$$\lambda_\gamma = \frac{2hc}{E_\phi}$$

$$F(\lambda) = \sqrt{\frac{2}{\pi}} \frac{L_{h\phi}}{\sigma} \exp\left[-\frac{1}{2} \left(\frac{\lambda - \lambda_\gamma}{\sigma}\right)^2\right] \quad (6)$$

where $L_{h\phi}$ is the luminosity of the ϕ halos and σ is the standard deviation of the normal distribution. To obtain σ we assume the ϕ halo to rotate giving rise to a velocity dispersion β among the bound ϕ 's, and hence a nonzero decay line width (in our galaxy $\beta = 10^{-3}$). So one can show [7] that $\sigma = 2\beta\lambda_\gamma$ and

$$F(\lambda) = \frac{L_{h\phi}}{\sqrt{2\pi} 2\beta\lambda_\gamma} \exp\left[-\frac{1}{8\beta^2} \left(\frac{\lambda}{\lambda_\gamma} - 1\right)^2\right] \quad (7)$$

We need to determine the luminosity $L_{h\phi}$ of the ϕ halo. This luminosity is the ratio of the number N_ϕ of ϕ particles to their decay lifetime τ_ϕ , multiplied by the energy E_ϕ of the decay process into two photons

$$L_{h\phi} = \frac{E_\phi N_\phi}{\tau_\phi} \quad (8)$$

where

$$\tau_\phi = \frac{64\pi}{g^2 m_\phi^3} \quad (9)$$

If each pseudoscalar has a rest mass given by E_ϕ/c^2 the halo mass in terms of ϕ particles will be $M_{h\phi} = \frac{E_\phi}{c^2} N_\phi$, so

$$L_{h\phi} = \frac{M_{h\phi} c^2}{\tau_\phi} \quad (10)$$

We suppose that ϕ is a non-relativistic particle $m > O(10^{-4} \text{ eV})$, then we can assume that the ratio of $M_{h\phi}$ to the mass M_{hbar} of baryonic matter in the halo is the same as the cosmological ratio of ϕ matter to baryonic matter, that is

$$\frac{M_{h\phi}}{M_{hbar}} = \frac{\Omega_\phi h^2}{\Omega_{bar} h^2} \quad (11)$$

where $0.5 \leq h \leq 1.0$, Ω_ϕ and Ω_{bar} are the cosmological mass density of ϕ matter and baryonic matter in units of the critical closure density.

Using the limits $0.011 \leq \Omega_{bar} h^2 \leq 0.020$ [10], taking for M_{hbar} the value $8 \times 10^{43} g$ [9] and selecting an intermediate value $\Omega_{bar} h^2 = 0.016$ we obtain for the luminosity of the halo

$$L_{h\phi} = \frac{5 \times 10^{45} c^2 \Omega_\phi h^2}{\tau_\phi} \quad (12)$$

Two possibilities are interesting: ϕ being the cosmological dark matter of a critical Universe or ϕ being the dark matter in galactic halos. So the interesting range to consider is $0.01 \leq \Omega_\phi h^2 \leq 1$. In our calculations we consider the two extremes of the range.

To compare with experimental data, we need a photon flux given by

$$F(E_{\gamma 0}) = \frac{I(E_{\gamma 0})}{4\pi E_{\gamma 0}} \quad (13)$$

where $E_{\gamma 0}$ is the photon energy at present time, and the flux units are $\text{cm}^{-2} \text{A}^{-1} \text{s}^{-1} \text{sr}^{-1}$.

With all this in mind, and using Eq.(5), we have

$$F(E_{\gamma 0}) = \frac{n_0}{4\pi\sqrt{2\pi}} \frac{5 \times 10^{45} c^2 \Omega_\phi h^2 E_\phi}{H_0 \tau_\phi 2\beta h c E_{\gamma 0}} \int_0^{z_f} dz (1+z)^{-9/2} \exp \left[\frac{-1}{8\beta^2} \left(\frac{E_\phi}{2E_{\gamma 0}(1+z)} - 1 \right)^2 \right] \quad (14)$$

This integral has to be evaluated numerically. For simplicity we let $z_f \rightarrow \infty$

To obtain constraints we need to use a photon flux observationally measured. This has been done by Martin and Bowyer [8], who obtained a flux

$$F = (16 - 52) \text{ photons } s^{-1} \text{cm}^{-2} \text{A}^{-1} \text{sr}^{-1}$$

throughout the region stretching from $\lambda_0 = 1350$ to $1900 \text{ \AA}$. To use this results we take an intermediate value in this interval. So in our calculations we assume:

$$F(7.8 \text{ eV}) = 39 \text{ photons } s^{-1} \text{cm}^{-2} \text{A}^{-1} \text{sr}^{-1} \quad (15)$$

We note that our numerical integration, with these values, was independent of ϕ mass, having the same value to the ϕ mass interval considered in this work.

We were able to find a relation between the coupling constant g , the pseudoscalar mass m_ϕ , and the parameter $\Omega_\phi h^2$. We consider the extremes for this parameter $\Omega_\phi h^2 = 0.01$ and $\Omega_\phi h^2 = 1$, and so we obtained curves relating the coupling constant g and m_ϕ represented in fig. 1. Note we should have $\Omega_\phi h^2 \geq 0.01$ and $\Omega_\phi h^2 \leq 1$ and this will give an allowed region between the two curves. We have also an inferior bound in the pseudoscalar mass m_ϕ so that the photons can have an energy of 7.8 eV. The smallest mass for ϕ will be 15.6 eV. The condition that ϕ has survived since the beginning of the Universe until the present time is obtained imposing $\tau_\phi > H_0^{-1}$, this will give a relation between g and m_ϕ represented by a dotted line in fig. 1. These conditions results in an allowed region in fig. 1, that relates g with m_ϕ so that ϕ is a galactic dark matter candidate.

3 Ionization of HI regions

In this section we assume that the observed ionization in III regions of the galaxy, which is difficult to explain in terms of known sources [11], is mainly due to photons emitted by the pseudoscalar ϕ .

From observational data on H_α emission from an intergalactic III cloud in Leo, Reynolds et al. [12] were able to put an upper limit on the flux of hydrogen-ionizing photons in intergalactic space at the present epoch. Reynolds et al. [11] obtained

$$F_i < 6 \times 10^5 \text{ photons } \text{cm}^{-2} \text{sec}^{-1} \quad (16)$$

where each photon has 13.6 eV and is responsible for one ionization only.

We will suppose that the pseudoscalar ϕ is a dark matter candidate, and that the decaying photons from $\phi \rightarrow \gamma\gamma$ are responsible for the ionization of this HI cloud. This idea was considered by Sciamma, in the case of a neutrino decaying theory[13].

To avoid the discrepancy between this flux Eq.(16) and a cosmological flux coming from pseudoscalars ϕ , we will have to suppose that the redshift associated with the expansion of the Universe reduces the photon energy to below the ionization potential 13.6 eV of hydrogen for decaying particles which are at distances much less than the radius of the Universe.

Consider the minimum mass of the decaying particle ϕ , if the photons are just able to ionize hydrogen. In the rest frame of ϕ we would have $\phi \rightarrow \gamma + \gamma$ and for the energy of the decay photon $E_\gamma = m_\phi / 2$, so we should have $E_\gamma \geq 13.6$ eV and $m_\phi \geq 27.2$ eV.

To derive a limit on the contribution of pseudoscalars to the density of Universe, we need to know their number density n_ϕ . This is given by [3]

$$n_\phi \simeq \frac{83 \text{ cm}^{-3}}{g_{\bullet F}(T_f) / 10} \quad (17)$$

where $g_{\bullet F}(T_f)$ are the effective degrees of freedom that contribute to the entropy of the Universe at the freeze-out temperature T_f . Using the bound obtained by Massó and Toldra [3], $g_{\bullet S}(T) > 17.4$, we will conservatively obtain $n_\phi \simeq 47 \text{ cm}^{-3}$.

We now consider the metagalactic flux F of hydrogen-ionizing photons. We have to suppose that E_γ exceeds its minimum value by only a small amount ϵ , so that the redshift rapidly cuts off the ionizing flux. Writing

$$E_\gamma = (13.6 + \epsilon)$$

with $\epsilon \ll 1$, we have[14]

$$F = \frac{n_\phi \text{ c } \epsilon}{2 \tau_\phi H_0 13.6} \quad (18)$$

Using Eq.(9) and the limit on F we obtain a relation between the coupling constant g and the ϕ mass

$$g < 10^9 \left(\frac{5.38 \times 10^{-36}}{m_\phi^3(m_\phi - 27.2)} \right)^{1/2} \quad (19)$$

where g is in GeV^{-1} and m_ϕ is in eV . This relation is represented in fig. 2. Note we have an inferior bound in the pseudoscalar mass m_ϕ of 27.2 eV, given by the minimal energy necessary to ionize hydrogen. We find our limit on the coupling constant g is approximately 10^{-11}GeV^{-1} , slightly varying with ϕ mass.

4 Conclusions

The experiments searching for axions are also sensitive to a pseudoscalar ϕ that couples only to two photons. Motivated by this we investigated to which extent ϕ can be the galactic dark matter responsible for the photons of the extragalactic background. We have obtained a small region in mass and coupling constant where ϕ could be the galactic dark matter (see fig. 1). Note that we are restricted to a ϕ mass interval $15.8 \text{ eV} \leq m_\phi \leq 1 \text{ KeV}$, and in this interval our coupling constant is approximately restricted to the interval $10^{-11} \text{GeV}^{-1} \leq g \leq 10^{-7} \text{GeV}^{-1}$.

Using the argument of ionizing photon flux responsible for the H_α emission in a HI cloud in Leo, and suposing these photons are emitted in the decaying $\phi \rightarrow \gamma\gamma$ only, we could obtain an upper bound relating the coupling constant g and the ϕ mass (see fig. 2). These bounds have not been discussed in Ref. [3], and are complementary to those presented there.

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FIGURE CAPTIONS

Figure 1: The solid parallel lines represent the extremes of the allowed region., they are obtained doing $\Omega_\phi h^2 = 0.01$ and $\Omega_\phi h^2 = 1$. The condition that ϕ has survived until the present time, $\tau_\phi > H_0^{-1}$, is represented by the dotted line. We have also an inferior bound in pseudoscalar mass of 15.6 eV, represented by the dotted vertical line. In dark is the allowed region for m_ϕ and g .

Figure 2: The constraint from ionization of III regions given by Eq.(19), is represented by the solid line, that relates g and m_ϕ . We have an inferior bound in pseudoscalar mass of 27.2 eV represented by the dotted vertical line.

FIG. 1

FIG. 2