

Can an axion be the dark energy particle?

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Abstract

Following a phenomenological analysis done by the late Martin Perl for the detection of the dark energy, we show that an axion of energy $1.5 \times 10^{-3} eV/c^2$ can be a viable candidate for the dark energy particle. In particular, we obtain the characteristic length and frequency of the axion as a quantum particle. Then, employing a relation that connects the energy density with the frequency of a particle, i.e., $\rho \sim f^4$, we show that the energy density of axions, with the aforesaid value of mass, as obtained from our theoretical analysis is proportional to the dark energy density computed on observational data, i.e., $\rho_a/\rho_{DE} \sim \mathcal{O}(1)$.

Keywords: Axion, axion-like particles, dark energy, dark energy particle

1. Introduction

One of the most important and still unsolved problem in contemporary physics is related to the energy content of the universe. According to the recent results of the 2015 Planck mission (Ade *et al.*, 2016), the universe roughly consists of 69.11% dark energy, 26.03% dark matter, and 4.86% baryonic (ordinary) matter. Therefore, the energy content of the dark sector of our universe is 95% of the total energy. Actually, we do not know anything about its nature as well as which are, if any, the dark energy and matter particles. Consequently, we have not directly detected or observed dark energy and dark matter.

2. Still no detection of the dark energy?

Perl (2009) stated that it almost comes as a surprise that dark energy has not been directly detected yet, since we have detected energy densities, which are much smaller. In particular, critical energy density reads

$$\rho_c = \frac{3H_0^2}{8\pi G} = 7.76 \times 10^{-10} J/m^3 \quad (1)$$

where, the Hubble constant H_0 is $(67.74 \pm 0.46) km s^{-1} Mpc^{-1}$ (Ade *et al.*, 2016), and the Newton's constant G is $6.674 \times 10^{-11} N m^2 kg^{-2}$. Thus the dark energy density becomes

$$\rho_{DE} = 5.36 \times 10^{-10} J/m^3 \quad (2)$$

The corresponding mass density of the dark energy will be $0.60 \times 10^{-26} kg/m^3$, which is equivalently to almost 4 protons/ m^3 . On the other hand, one can do an experiment in a lab with an electric field of magnitude

$E = 1 V/m$ and measure the energy density of the electric field. The result will be

$$\rho_E = \frac{1}{2}\epsilon_0 E^2 = 4.4 \times 10^{-12} J/m^3 \quad (3)$$

Therefore, though the energy density of the electric field, i.e., ρ_E , can be detected and measured, the dark energy density, i.e., ρ_{DE} , which is much larger has not been detected yet. Of course, one has to avoid to make an experiment for the detection and measurement of the dark energy near the surface of the Earth, or the Sun, or the planets, since the energy density of the gravitational field on Earth's surface is

$$\rho_G = \frac{1}{8\pi G} g^2 = 5.7 \times 10^{+10} J/m^3 \quad (4)$$

where g is the gravitational acceleration¹. It is evident that the energy density of the gravitational field is much larger than the dark energy density. Thus, as already mentioned above, any attempt at detecting and measuring dark energy has to be performed far from the regions of space in which the gravitational field of massive bodies is quite strong.

3. Properties of a hypothetical dark energy particle

As already stated, we do not know the nature of the dark energy and we also do not know which is, if any, the dark energy particle. Making the assumption that such a particle exists, one can proceed with phenomenological arguments in order to obtain some properties of this would-be dark energy particle. The starting point will be the quantum mechanical relation between the mass and length of a particle²

$$m \times L = \frac{\hbar}{c} \quad (5)$$

Of course, we are not aware of the mass of the hypothetical dark energy particle, but we have calculated the dark energy density,

¹ The factor in the RHS of equation (4) is obtained by comparing the gravitational field on the surface of the Earth, i.e., $g = GM/R^2$ with the electric field of a charged conducting sphere on its surface, i.e., $E = (1/4\pi\epsilon_0)Q/R^2$.

² As expected, this is an equation satisfied by the Planck mass, i.e., $m_p = \sqrt{\frac{\hbar c}{G}} = 2.18 \times 10^{-8} kg$ and the Planck length, i.e., $\ell_p = \sqrt{\frac{\hbar G}{c^3}} = 1.62 \times 10^{-35} m$, respectively.

given by equation (2), of the dark energy, i.e., ρ_{DE} , based on observational data. Thus, it will be easy to compute the length scale of the dark energy particle, i.e., L_{DE} , and its corresponding frequency, i.e., f_{DE} . Therefore, assuming the dark energy particle is located in the volume L_{DE}^3 , equation (5) becomes

$$\rho_{DE} \times L_{DE}^4 = \hbar c \quad (6)$$

where the length of the dark energy particle reads

$$L_{DE} = \left(\frac{\hbar c}{\rho_{DE}} \right)^{1/4} = 88 \mu m , \quad (7)$$

and the corresponding frequency is equal to

$$f_{DE} = \frac{c}{L_{DE}} = 3.40 \times 10^{12} \text{ Hz} . \quad (8)$$

4. Is axion a candidate for a dark energy particle?

If one assumes that the vacuum provides its energy for the acceleration of the universe, this means that the vacuum energy density, i.e., ρ_{vac} , can run for the dark energy density. Now, one can theoretically compute the former using techniques of Quantum Field Theory, while the latter is computed using astronomical observations. From equation (2) we can obtain

$$\frac{\rho_{vac}}{\rho_{DE}} \sim 10^{120} . \quad (9)$$

This is the well-known "old" cosmological problem (Burgess, 2015). It is obvious that if one would like to suggest a candidate for the dark energy particle, this candidate particle, as a starting point, has to at least alleviate this "old" problem. At this point, one would like to investigate which are the options for a dark energy particle. As we will see it seems that axion can run for dark energy particle. Axion is a hypothetical elementary particle, which was suggested as a solution to the strong CP problem in QCD (Peccei & Quinn, 1977). From a theoretical point of view, it is known that the masses of axions in the context of QCD range from

$50 \mu eV/c^2$ to $1500 \mu eV/c^2$ (Borsanyi *et al.*, 2016). In addition, nowadays axions are also known as cold dark matter candidates with masses that range from $50 \mu eV/c^2$ to $200 \mu eV/c^2$ (Ringwald, 2016). It is clear that there is a range of masses, namely $0.2 \times 10^{-3} eV/c^2 < m < 1.5 \times 10^{-3} eV/c^2$, which is not "used" and it is worth looking into it. Therefore, we choose an axion with mass $1.5 \times 10^{-3} eV/c^2$ and we will investigate whether it can run for dark energy density. Utilizing equation (5), the length of the axion is

$$L_a = \frac{\hbar}{c m_a} = 1.32 \times 10^{-4} m , \quad (10)$$

while utilizing equation (8), the frequency of the axion reads

$$f_a = 2.27 \times 10^{12} \text{ Hz} . \quad (11)$$

At this point, one employs equation (6) to obtain a relation that connects the dark energy density with the frequency

$$\rho_{DE} = \frac{\hbar}{c^3} f_{DE}^4 . \quad (12)$$

It should be stressed that this equation is also satisfied by the energy density of axions, hence

$$\frac{\rho_a}{\rho_{DE}} \sim \left(\frac{f_a}{f_{DE}} \right)^4 \sim \mathcal{O}(1) . \quad (13)$$

This is really an acceptable and welcomed result.

5. Discussion

In this work we have employed a phenomenological analysis presented in (Perl, 2009) in order to show that an axion of mass 1.5 meV is a viable candidate for the dark energy particle. In particular, we derived the length that is characteristic for the axion as a quantum particle and then obtained its frequency. Since we produced a relation that connects the energy density with the frequency of a particle, i.e., $\rho \sim f^4$, we showed that the energy density of axions, with the specific value of mass, as obtained from our theoretical analysis is proportional to the dark energy density computed on observational data. At this point a couple of comments are in order. First, since our analysis here is completely phenomenological, it is evident that our acceptable result does not prove that the axion with mass $1.5 \times 10^{-3} eV/c^2$ is the dark energy particle. However, this analysis can serve as an easy and quick criterion to classify the viable candidates for dark energy particles. Second, until now there is no experimental evidence for an axion or an axion-like particle (ALP) (Anastassopoulos *et al.*, 2017). The experiment which is looking in the range of masses under consideration here, i.e., $m \geq 1 \text{ meV}$, is the PVLAS (Polarization of Vacuum LASer) experiment (Della Valle *et al.*, 2016).

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هل يمكن لأكسيون ما Axion أن يكون جسيم طاقة مظلمة؟

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الملخص

تتبعنا تحليل الظواهر الذي قام به الراحل مارتن بيرل للكشف عن الطاقة المظلمة، وأظهرنا أن أكسيون الطاقة $1.5 \times 10^{-3} \text{ eV} / c^2$ قد يكون أحد جسيمات الطاقة المظلمة. فقد حصلنا بوجه خاص على طول وتكرار مميز للأكسيون كجسيم كمي. ومن ثم، استخدمنا علاقة تربط كثافة الطاقة مع تردد الجسيم، أي: $\rho \sim f^4$ ، وأظهرنا أن كثافة طاقة الأكسيونات، بالتزامن مع قيمة الكتلة المذكورة، وفقاً لما تم الحصول عليه من تحليلاتنا النظرية، تتناسب مع كثافة الطاقة المظلمة المحسوبة على بيانات الرصد، أي: $\rho_{\text{ax}} / \rho_{\text{DE}} \sim O(1)$.