Ultra light bosonic dark matter and CMB

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In this work we report the cosmological effects that a species of Ultra Light Bosonic Dark Matter imprints in the Acoustic Peaks of the CMB, and some of its thermic features. We show that the effect of the Bose-Einstein statistics is small albeit perceptible, and is equivalent to an increase of non-relativistic matter. It is also noted the mass-to-temperature ratio necessary for being still a Dark Matter candidate. And it is needed a non-zero optical depth of Reionization.

I. INTRODUCTION

It has been argued that a Scalar Field may be a candidate to form the main component of the total Dark Matter in the universe [1, 2, 3, 4, 5], this alternative is called the **SFDM** model. The mass of this Scalar Field is assumed ultra light ($\sim 10^{-22}\ eV$), and obey an equation of state $p = \omega\rho$, with $-1 \leq \omega \leq 1$. It is also interesting that this type of matter can form astrophysical objects called **Boson Stars** [6, 7]. The SFDM model has been tested on galactic scales [8, 9, 10]. On the other hand, at cosmological scales, the most powerful observable to rule out theoretical models is the Cosmic Microwave Background (CMB) spectrum. In [11] it is studied the modification of the spectrum assuming an interaction with the baryonic sector. In the present treatment we analyze how the values of different parameters change the amplitudes of the acousitic peaks with no interaction at all.

There is a fermionic particle which shares some similitudes with this hypothetical bosonic species, that is, the neutrino. In fact, its study as a candidate for Dark Matter can serve as an antecedent for our goal. The neutrino was the first promising particle candidate to be the whole Dark Matter of the universe. That is because of their low interacting rate with baryons and the evidence of the flavour oscillations which strongly suggest a non-zero neutrino mass. Even though, there are some unavoidables problems that indicate that the neutrinos can not be the whole Dark Matter of the universe [12].

Very early in the universe, neutrinos were in thermal equilibrium with the primeval fireball. Due to its low mass compared with its temperature in this epoch, they behave exactly as radiation. After decoupling, they relax only with the expansion of the universe as $T_\nu \propto a^{-1}$, and eventually its temperature falls below its mass. It is known as the *non-relativistic transition* (NRT). Besides, once decoupled, its temperature remain well determined in terms of the temperature photons $T_\nu = (4/11)^{1/3} T_\gamma$, which fixes the neutrino number density today to $n_\nu^{(0)} \sim 100 cm^{-3}$. An important intrinsic part of its nature is that they are fermions and then their density has an upper bound. Thus the content of neutrinos Ω_ν is entirely parameterized by its mass, i.e., $m_\nu \approx \Omega_\nu 51.013\ eV$ [13].

Between the times of decoupling and the non-relativistic transition, neutrinos just *free-stream* due to the negligible interaction with the rest of the matter. Thus, the combined effect of free-streaming and radiation behavior clears off the fluctuations of $\delta_\nu \equiv \delta\rho_\nu/\rho_\nu$. This means that there is no contribution to the *acoustic oscillations* in the CMB due to massless (or relativistic) neutrions.

On the other hand, after the non-relativistic transition, the neutrinos behave closely as Cold Dark Matter. The fluctuations begin to grow quickly until they reach the Cold Dark Matter rate, that is $\delta_\nu \propto a$. Thus, the structure formation has a contribution in the neutrino gravitational fluctuations after the NRT. However, in most standard models, this transition takes place well after the matter dominated epoch and the neutrino contribution becomes subdominant. The effect of the neutrinos in the CMB is not negligible, although, it is too low to be considered as the whole component of Dark Matter [14].

In the following, we assume the value of the temperature of the CMB photons today $T_{CMB} = 2.726\ K$, the Hubble's constant $H_0 = 75.0 km\ s^{-1}\ Mpc^{-1}$, and a flat geometry with a Cosmological Constant Λ, just for simplicity. It is choosed units in which $c = k_B = 1$, then, $1\ K \propto 10^{-5}\ eV$. This paper is organized as follows. Section 2 is concerned to state the key equations of this calculation. Section 3 discusses the results, and the conclusions are enclosed in section 4.

II. ULTRA LIGHT BOSONS AS DARK MATTER

We consider a Bosonic Ultra Light species of matter. We just know that (*i*) it is a boson, (*ii*) with a mass $m_B \sim 10^{-22}\ eV$. (*iii*) It should be ultra-relativistic when decoupled, behaving thus, as radiation. Note that in this approach the Dark Matter is not treated as a Scalar Field, but as a bosonic particle. The equation of state at the moment of decoupling is assumed to be $\omega = 1/3$, corresponding to radiation. We want to investigate if the Ultra Light Bosonic Dark Matter (**ULBDM**) can form the main component of Dark Matter and reproduce the observed CMB spectrum.

The geometry of this universe is described by the Friedmann-Lemaître (FL) metric, perturbed to first order and we take the conformal newtonian gauge

$$ds^2 = a^2 \left\{ -(1+2\psi)d\tau^2 + (1-2\phi)dx^i dx_i \right\}. \tag{1}$$

Where τ is the proper time. In this gauge the tensor and vector degrees of freedom are eliminated from the begining and it just appear the scalar modes (ψ and ϕ) of the perturbation.

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Following the same formalism developed for the fermionic sector [15], it is useful to define the *corrected proper momentum* $q_i \equiv a p_i$, $q_j = q n_j$, where n_j is its direction unit vector and a is the scale factor. The proper momentum p_i was defined in terms of the canonical conjugate momentum $P_i = a(1-\psi)p_i$ of the the comoving coordinate x^i. The comovil proper energy is $\varepsilon \equiv a(p^2+m^2)^{1/2}$. We also know that the linear metric perturbations induce linear statistical perturbations in the distribution function.

$$f(x^i, P_j, \tau) = f_0(q)\left[1+\Psi(x^i, q, \hat{n}_j, \tau)\right], \tag{2}$$

where f_0 is the phase-space distribution function in an homogeneus background universe

$$f_0(q) = \frac{1}{e^{q/T_B}-1} \tag{3}$$

and Ψ is related to the perturbation of the bosons temperature

$$\Psi(x^i, q, \hat{n}_j, \tau) = -\frac{\partial \ln f_0}{\partial \ln q}(q)\frac{\delta T_B}{T_B}(x^i, q, \hat{n}_j, \tau). \tag{4}$$

The evolution of the ULBDM is described by the collisionless Boltzmann (or Vlasov) equation, which in Fourier space reads

$$\dot{\Psi} - i\frac{q}{\varepsilon}\Psi = -\left((\vec{k}\cdot\hat{n})\psi + i\frac{\varepsilon}{q}(\vec{k}\cdot\hat{n})\phi\right)\frac{\partial \ln f_0}{\partial \ln q}. \tag{5}$$

This equation gives the response of the phase-space distribution function to the metric perturbations.

III. TESTING WITH THE CMB

The first interrogative is whether the CMB is effectively sensitive to the nature of the statistics of the SFDM. We denote the mass-to-temperature ratio of some species of fermions as x_F, and a species of bosons as x_B, evaluated today. We compute the CMB spectrums for fermions and bosons separetely. It is important to mantain all the parameters fixed in order to observe only the effect of the change of the statistics. In figure 1 one can see that for bosons, the amplitudes of the first and second peaks are reduced, albeit the third peak is increased respect to the corresponding of fermions. This is an effect similar to that due to an icrease in the ratio between the non-relativistic Matter and the Radiation. Thus, it could be interpreted as an additional effective attractive potential.

Here, the main problem is that the temperature of the ULBDM is entirely unknown. This fact is due to the unknown way of colliding with the rest of the matter. Moreover, if the interaction rate was always zero, thus there is no reason to believe that this species was in thermal equilibrium with the primeval fireball. Without any interactions between the particles, there is no even a physical meaning for the temperature. However, we suppose that there was some primordial decay which generated the ULBDM. It also decoupled very early (maybe near the *Big Bang*). Once the species is decoupled from the rest of matter, its phase-space distribution function

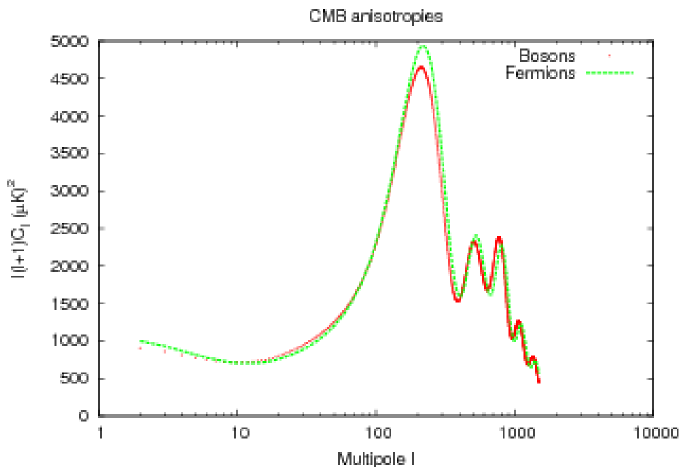

Figure 1: CMB spectrums for $\Omega_F = \Omega_B = 0.2$, $x_F = x_B = 63109$, $\tau = 0.13$. All the parameters are the same for both curves. The continuous line corresponds to bosons and the dashed line to fermions.

is "freezed-out" and its temperature can only relax with the expansion of the universe $T_B \sim a^{-1}$. Then, after photon decoupling, the temperature of the bosons just can be

$$T_B = \alpha T_\gamma, \tag{6}$$

where α is a constant free parameter to be determined. It is crucial to note that if $T_B \sim T_\gamma$, the quantity

$$x_B \equiv \frac{m_B}{T_B^{(0)}} \tag{7}$$

is effectively zero, which means that the particle is ultrarelativistic today ($x_B = m_B/\alpha T_{CMB}$). The addition of ULBDM to the total matter background with this value of x_B just moves the entire CMB spectrum to the right and upwards. The effect is shown in figure 2. In all the following figures: $\Omega = 1$, $\Omega_\Lambda = 0.74$, $\Omega_{bar} = 0.04$, and the crosses form the curve of the mean value of the observed CMB spectrum.

For all the values $\alpha \geqslant 10^{-25}$ it is noticed that the predicted power spectrum is not sensitive to the change of α unless it approaches to $\alpha = 10^{-26}$ ($x_B = 10^4$) or greater. The order of magnitude needed to fit the data is $\alpha \propto 10^{-27}$ ($x_B \propto 10^5$). The mass of the ULBDM must be five orders of magnitude greater than its temperature. In figure 3 it is plotted how the CMB power spectrum is sensitive to little changes of α. The range shown is from $\alpha = 0.3x10^{-27}$ to $\alpha = 1.1x10^{-27}$ (from $x_B = 73,367.57$ to $x_B = 40,759.76$). It is noted that, the more relativistic the species is, the more enhanced the first and second peaks are.

In figure 4 it is shown the prediction for $\alpha = 10^{-28}$ (second curve from bottom to top). In this case, the ULBDM become non-relativistic very early, causing a damping in the acoustic oscillations because of an increase in the gravitational potential wells. On the bottom of the same figure also appears the curve for $\alpha = 10^{-30}$, in which the same effect is enhanced.

Once the necessary mass-to-temperature ratio is estimated, we now investigate the content of bosons against the content

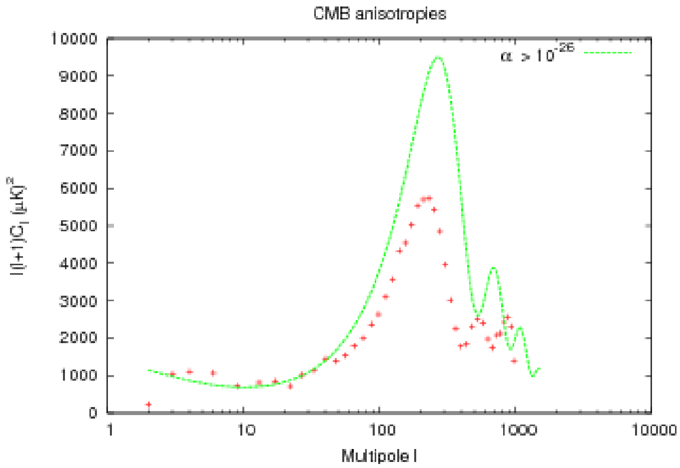

Figure 2: CMB spectrum for a Universe with $\Omega_B = 0.2$, $\Omega_{CDM} = 0.02$, $\alpha \geqslant 10^{-26}$.

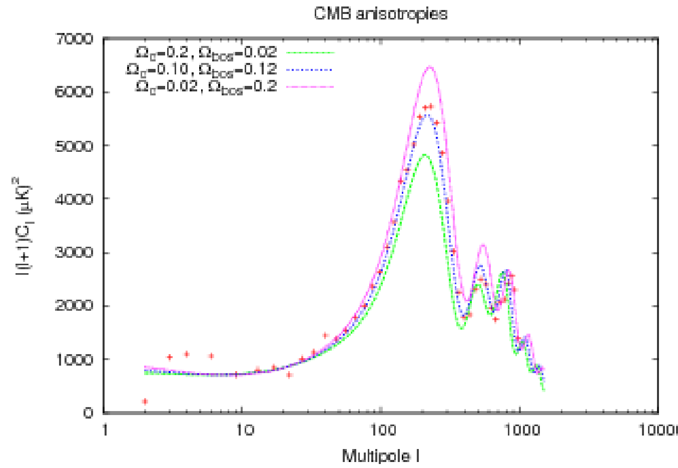

Figure 5: CMB power spectrums for diferent contents of ULBDM and CDM. For the three curves shown $\alpha \propto 10^{-27}$, no reionization.

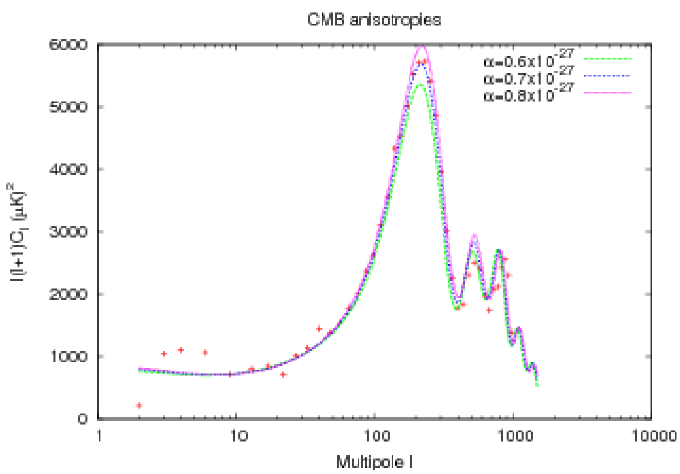

Figure 3: Response of the CMB spectrum to the change in the mass-to-temperature ratio of the SFDM. For the three curves $\Omega_B = 0.2$, $\Omega_{CDM} = 0.02$, $\alpha \propto 10^{-27}$.

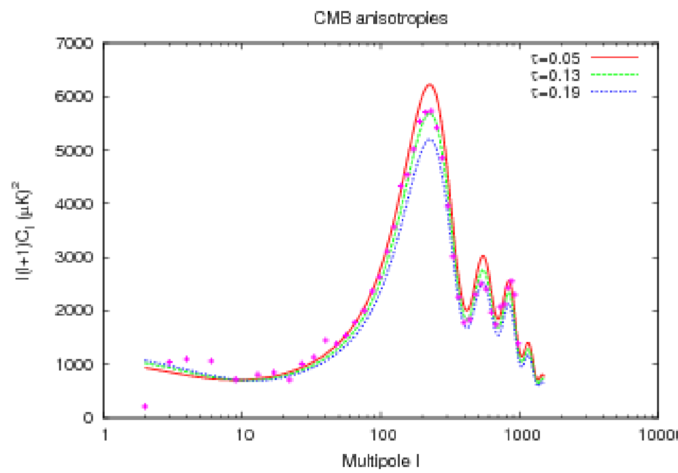

Figure 6: CMB power spectrums for diferent optical depths of reionization. The range shown is from $\tau = 0.05$ to $\tau = 0.19$. $\Omega_{Bos} = 0.2$, $\Omega_{CDM} = 0.02$, $\alpha \propto 10^{-27}$.

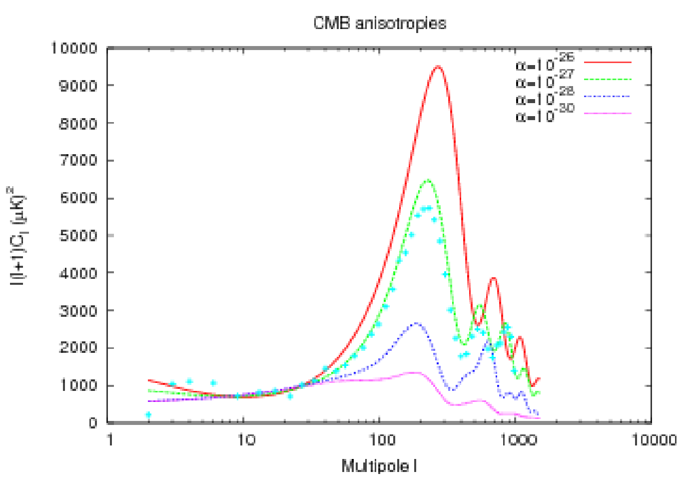

Figure 4: CMB spectrums for α in the interval $(10^{-26}, 10^{-30})$. With $\Omega_B = 0.2$, $\Omega_{CDM} = 0.02$, and no reionization.

of Cold Dark Matter. Figure 5 shows how the increase in Cold Dark Matter diminishes the amplitude of the oscillations. This is an effect of an enhancement of the gravitational potential wells. It also seems to suggest a universe with these two contents equilibrated. Nevertheless, we must measure the effect of the fraction of reionized baryonic matter too. We fix all the parameters and now vary the optical depth in figure 6. We show that a universe ULBDM-dominated ($\Omega_B = 0.2$) could be allowed for $x_B \propto 10^5$ and τ between 0.05 and 0.19.

Now we just want to say something about the number density of the SFDM. Firstly, we must keep in mind that in this scheme, there is no condensation explicitly taked into account yet. Next, if we must assume that nowadays the ULBDM particles behave as non-relativistic, so we can use

$$m_B n_B = \Omega_B \rho_c. \tag{8}$$

Then if one fixes the mass, the content of bosons in the universe Ω_B determines its number density. For $m_B \approx 10^{-22}$ and $\Omega_B = 0.2$ it follows that $n_B \approx 10^{25}\ cm^{-3}$. Such a big density must be accompanied by a Bose-Einstein condensate treatment of this matter. That is the aim of one following work to be presented.

IV. CONCLUSIONS

A universe dominated by Ultra Light Bosonic Dark Matter in a non-condensate state could be possible only if these particles fulfill the condition that its mass-to-temperature ratio must be close to $\sim 10^5$. For a mass $\sim 10^{-22}\ eV$, this is equivalent to a temperature of the order of $\sim 10^{-27}\ eV \sim 10^{-22}\ K$. Until now, there is no way to falsify such a low temperature unless it can be given a mechanism of interaction with the rest of the matter or a primeval decay which had could generate the ULBDM. The energy of interaction would reveal the temperature of decoupling. Then the temperature of the ULBDM would be determined and it could be predicted a set of allowed values of the parameter α. If this interaction can be parameterized by a *constant of interaction*, then the CMB data can serve to predict an allowed range of values for this constant. This range could be used to search this particles by other means.

We have shown that the effect of Reionzation is of crucial importance to understand the nature of this type of matter in the CMB. To get in concordance between the model and the observations, it is needed at least a value of $\tau \gtrsim 0.07$.

The most promising and physically interesting feature of the ULBDM or SFDM resides on its condensate state [16], [17], [18]. We have shown that the change in the type of statistics in the distribution function has non negligible effects in the CMB. It remains to include explicitly the information of a Bose-Einstein condensate in the dynamical equations. The number density of the ULBDM ($\sim 10^{-22}\ eV$), if it dominated the Dark Matter content, should be of the order of $\sim 10^{25}\ cm^{-3}$ today. It is necessary to investigate whether the condition $x_B \propto 10^5$ should be still satisfied in a condensate state, or not.

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All the analysis was done using the public code CMBFAST [19]. And all the calculated curves were compared to the obserbations of the WMAP satellite on its last five years. Available at http://lambda.gsfc.nasa.gov/product/map/current.

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