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ULTRA LIGHT BOSONIC DARK MATTER AND CMB

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Abstract

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 noted the mass-to-temperature ratio necessary for being still a Dark Matter candidate. It is also needed a non-zero optical depth of Reionization.
Subject headings: Cosmology: cosmic microwave background, dark matter and theory.

1. INTRODUCTION

One of the most precise cosmological observations is the measurement of the anisotropies in the cosmic microwave background (CMB). This experimental data are useful to probe theoretical models of the dynamics and the whole content of matter in the Universe. Nowadays, the most successful model describing the observed profiles of CMB anisotropies is the so called, cold dark matter with a cosmological constant (ΛCDM). Nevertheless, the cold dark matter (CDM) model has some inconsistencies with the observations on galactic and sub-galactic scales. For instance, CDM predicts cusp central density profiles of dark halos in low surface brightness (LSB) galaxies, meanwhile the measurements indicate a smooth distribution of matter. Also, CDM has some discrepancies between the number of predicted satellite galaxies in high-resolution N-body simulations and observations. In this frame, the possibility of alternative hypothesis for dark matter nature is open.

In the last years, it has been argued that a real scalar field Φ, minimally coupled to gravity, could be a plausible candidate to dark matter (DM), this alternative proposal (or similar ideas) is called scalar field dark matter (SFDM) (Hu, Barkana & Gruzinov 2000; Matos & Guzmán 2000a; Matos, Guzmán, & Ureña-Lopez 2000b; Sahni & Wang 2000; Matos & Ureña 2001; Garcia & Matos 2009).

The SFDM paradigm has also been tested at galactic scales and shown interesting results. For instance, Bernal, Matos & Núñez (2008) showed that the density profiles for SFDM halos are non cuspy profiles, in accordance with the observations of LSB galaxies (see also Böhmer & Harko 2007, Matos et al. 2009). Moreover, it is noticeable that in the relativistic regime scalar fields can form gravitationally bounded structures. These are called boson stars for complex scalar fields (Ruffini 1969; Lee & Kho 1996; Guzmán 2006) and oscillatons for real scalar fields (Seidel & Suen 1991; Ureña-López 2002; Alcubierre et al. 2003). There are also scalar field stable gravitational structures described by the Schrödinger-Poisson system (Guzmán & Ureña-López 2003, 2006; Bernal, & Guzmán 2006).

A scalar field can be considered as a system of individual bosonic particles with zero spin. In the SFDM model, the mass of each bosonic particle is constrained by cosmological observations to an extremely low mass ($\sim 10^{-23}$ eV). If these particles are in thermal equilibrium, they must obey the Bose-Einstein statistics. In this sense, an ultra light bosonic dark matter (ULBDM) particle seems to keep some similitudes with the neutrino. In fact, neutrinos constitute a subdominant component of the DM in the Universe (see an excellent review. in Dodelson 2003).

An important intrinsic part of the nature of the neutrino is that it is a fermion and then its density has an upper bound. Thus, the content of neutrinos Ω_ν is entirely parameterized by its mass, i.e., $\Omega_\nu \approx m_\nu/51.01$ eV (see Kolb 1990). On the other hand, ULBDM can have an arbitrarily high number density and if we do not know its energy scale of interactions, its temperature T_B can be taken as a free parameter.

In the present work, inspired by the neutrino cosmology and the SFDM model, we assume that the Universe contains two components of DM. One component is ULBDM and the other component is the standard CDM. We are interested in the different contributions of these two types of dark matter on the CMB spectrum. We stress that in this approach, CDM is treated as a fluid while ULBDM has a phase-space description. As a first approach, we treat all the ULBDM particles in a non condensate state.

In the following, we consider a flat, homogenous and isotropic Universe. We assume that the temperature of the CMB photons today is $T_{CMB} = 2.726$ K, the current Hubble's parameter $H_0 = 75.0\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the current baryon density parameter $\Omega_{bar} = 0.04$. Also, we assume, just for simplicity, that the dark energy in the Universe is a cosmological constant Λ with a current density parameter $\Omega_\Lambda = 0.74$. We choose units in which $c = \hbar = k_B = 1$, then, 1K

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$\equiv 8.617 \times 10^{-5}$ eV.

This paper is organized as follows. Section 2 reviews some basic concepts of large scale structure formation on CMB. **??** is concerned to provide the key equations of this calculation. The physical implications of ULBDM in the CMB anisotropies spectrum are discussed in section 3. Concluding remarks are given in section 4.

All the analysis was done using the public code CMBFAST Seljak & Zaldarriaga (1996). The calculated curves were compared to the five years WMAP satellite data (Hinshaw et al. 2008). (It is available at http://lambda.gsfc.nasa.gov/product/map/current.)

2. CMB GENERALITIES

In the theory of cosmic microwave background (CMB) there are two main observables. The first is the anisotropies of the CMB which are usually measured by means of the two-point correlation function

$$\left\langle \frac{\delta T}{\bar{T}}(\hat{n})\frac{\delta T}{\bar{T}}(\hat{n}')\right\rangle = \sum_{l=0}^{\infty}\frac{(2l+1)}{4\pi}C_l P_l(\hat{n}\cdot\hat{n}').$$

Hence, for gaussian fluctuations all the information is contained in the multipoles C_l, which probe the correlations on angular scales $\theta = \pi/l$. The shape of the CMB spectrum is related mainly to the physical evolution before recombination. The second main observable is the matter power spectrum (MPS), which probes the structure of the universe to large scale. It is defined as the two-point correlation function of the non relativistic matter fluctuations in the Fourier space

$$P(k,z) = \left\langle |\delta_m(k,z)|^2 \right\rangle.$$

Precise measurements of the acoustic peaks yield precise determinations of four fundamental parameters of the working cosmological model: $\Omega_b h^2$, $\Omega_m h^2$, D_*, n. Here D_* is the distance light can travel between recombination and the present, it defines the *last scatering surface*.

The standard cosmological model is the so called, cold dark matter with a cosmological constant (ΛCDM). This model in a flat global geometry without neutrinos can be described by six parameters: the cosmological constant fraction ω_λ, the total non-relativistic matter density $\omega_m = \Omega_m h^2$, the baryon density $\omega_b = \Omega_b h^2$, the primordial spectrum amplitude A and tilt n_s, the optical depth to reionization τ_r. They are controled by the physical phenomena which determines the shape of the observable power spectra. Some of these phenomena are now stated.

The time of Matter / Radiation equality is fixed by the parameter ω_m. If ω_m is small, equality happens later. The time of equality is parameterized by $(a_{eq}/a_0) = \rho_r^0/\rho_m^0$, where ρ_r^0 is fixed by the CMB temperature. $\delta_m = \delta\rho_m/\rho_m$ grows more efficiently during matter domination (MD) than during radiation dominaon (RD) [1]. The effect of later time of equality induces higher CMB peaks, especially for the first one.

The time of Matter / *Lambda* equality. If Λ is larger, then the time of equality betwen matter and Λ is earlier. When the Universe enters to Λ domination δ_m grows more slowly. For this reason, the normalization of $P(k)$ is suppressed and the low l-multipoles are enhanced in the CMB.

The physical scale of the sound horizon at equality and the angular scale of the sound horizon at recombination, both depend on h, Ω_Λ and on the time of equality (ω_m). Let us here to abound more in the concept of sound horizon and free-streaming horizon.

Consider a physical process starting at a time t_i, propagating with the sound speed of the medium ($c_s^2 = \delta p/\delta\rho$), along radial geodesics, i.e., $c_s dt = a(t)dx$. Such a process can only affect wavelengths smaller than

$$d_s(t_i,t) = a(t)\int_{t_i}^{t}\frac{c_s dt'}{a(t')}.$$

This is the maximal physical distance in which the signal can travel across the medium in an interval $[t_i,t]$. It is defined as the *sound horizon*.

For t_i and t being in the matter or radiation era, with the condition $t \gg t_i$, and in the limit of c_s constant in a comovil volume, the *Jeans length* is defined as

$$\lambda_J(t) = 2\pi\sqrt{\frac{2}{3}}\frac{c_s(t)}{H(t)} = 2\pi\frac{a(t)}{K_J},$$

A stable Jeans mode is said to happen if the horizon of the acoustic perturbation is greatter than the scale of the space-time perturbation ($K_J < k$). The acoustic modes oscilate with a frequency $\omega_s = kc_s$ due to the competition betwen the gas pressure and the gravitational compression. On the other hand, Jeans instability ($K_J > k$) happens if the acoustic horizon is smaller than the space-time perturbation. The pressure can not causally support the gravitational compression and then the density perturbation grows monotolically.

In perfect fluids the sound waves propagate in scales smaller than the sound horizon and with speed c_s. On the other hand, non-collisional fluids (e.g. dark matter and decoupled photons) can not propagate sound waves. However, the free particles can free-stream with a characteristic average *thermal velocity* v_{th}. Thus, the *Free-streaming horizon* is definded as the typical distance in which the particles can travel betwen t_i and t (as before, $t \gg t_i$ in the era of radiation or matter)

$$\lambda_{FS}(t) = 2\pi\sqrt{\frac{2}{3}}\frac{v_{th}(t)}{H(t)} = 2\pi\frac{a(t)}{K_{FS}}$$

As long as some species of HDM is still relativistic, it spreads out at the speed of light and λ_{FS} at that time is just the Hubble radius. On the other hand, when it becomes non relativistic, its thermal velocity falls as

$$v_{th} \equiv \frac{\langle p\rangle}{m} \approx \frac{3T_\nu}{m}.$$

This time of transition depends on the mass and is defined when $v_{th} \approx 1$. After the time of non relativistic transition (NRT) and during matter domination, λ_{FS} is still growing but at the rate $1/aH \propto t^{1/3}$. It means that λ_{FS} grows in that epoch but it does slower than the scale factor $a \propto t^{2/3}$.

This means that the NRT epoch fixes a maximum free-streaming legth. The modes with $k < K_{nr}$ are scales bigger than the free-streaming scale, in which the HDM velocity can be considered effectively vanishing. Hence for this scales and after NRT, the HDM perturbations behaves near CDM does.

In small scales ($k \gg K_{nr}$), the free-streaming damps the fluctuations of HDM density. This is because HDM can not be confined inside regions smaller than the free-streaming length. (For more details see Lesgourgues & Pastor 2006).

[1] In ΛCDM the structure forms first on the smallest scales, and they form the bigger objects by means of galaxy mergers.

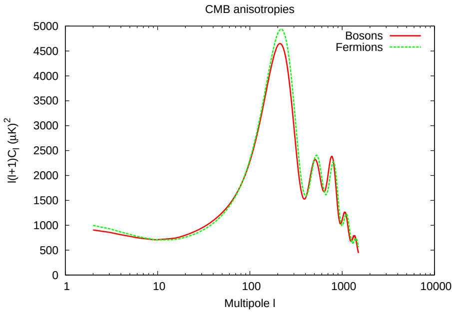

FIG. 1.— CMB spectrums for $\Omega_F = \Omega_B = 0.2$, $x_F = x_B = 63109$, $\tau = 0.13$. All the parameters are the same for both curves. The continuous line corresponds to bosons and the dashed line to fermions.

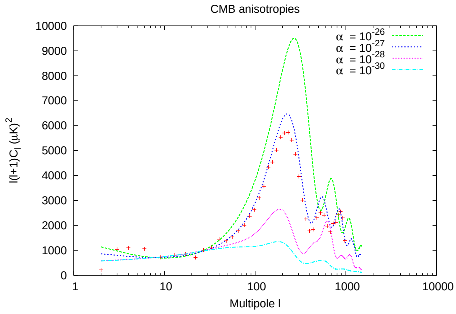

FIG. 2.— CMB spectrums for α in the interval $(10^{-26}, 10^{-30})$. With $\Omega_B = 0.2$, $\Omega_{CDM} = 0.02$, and no reionization.

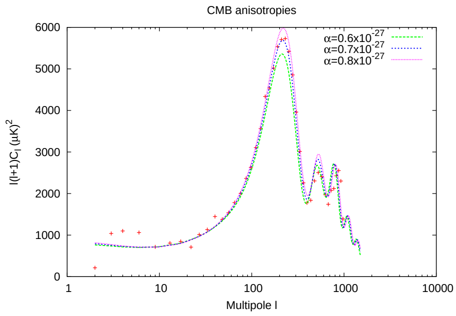

FIG. 3.— Response of the CMB spectrum to the change in the mass-to-temperature ratio of the SFDM. For the three curves $\Omega_B = 0.2$, $\Omega_{CDM} = 0.02$, $\alpha \propto 10^{-27}$.

3. TESTING WITH THE CMB

Here we explore the hypothesis of the existence of a kind of DM in the Universe composed by particles with an extremely tiny mass and zero spin, that is, the ULBDM. We assume that ULBDM was in thermal equilibrium with the primeval fireball at least in some very early stage of the Universe. Accordingly, it can be defined a temperature T_B of the ULBDM and the dynamics of these particles may be described by the Bose-Einstein statistics. It is natural then to assume that the mass-to-temperature ratio was very small at the moment of its decoupling, then the ULBDM falls in the classification of hot dark matter (HDM). It means that the ULBDM behaves as radiation at its decoupling epoch with an equation of state $\omega = 1/3$.

We want to investigate if the NRT for ULBDM occurs at enough early times in order to build the structure observed. We investigate this hypothesis computing the CMB spectrum of anisotropies of a Universe with ULBDM and CMD and compare with the observational data of the last five years of the WMAP experiment. Of course, the predicted CMB spectrum is expected to depend on the contents of ULBDM and CDM.

The first interrogative is whether the CMB is effectively sensitive to the nature of the statistics of the ULBDM. 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 we 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 one for 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.

It is important to say that the temperature of the ULBDM is unknown *a priori*, this is the main difficulty of the present treatment. It is due to the ignorance of the way in which the DM particles collide 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 and it also decoupled quite early (maybe close to the big bang). Once the DM particle is decoupled from the rest of matter, its phase-space distribution function is freezed-out and its temperature can only relax with the expansion of the universe $T_B \sim a^{-1}$. Then, after photon decoupling, in a manner quite similar to neutrinos, the temperature of the ULBDM just can be

$$T_B = \alpha T_\gamma, \qquad (1)$$

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

$$x_B \equiv \frac{m_B}{T_B^{(0)}} \qquad (2)$$

would be effectively zero, which means that the particle should be still ultra-relativistic 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. For all 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. In all the 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.

In figure 2 we also show 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 on the acoustic oscillations, because of an increase in the gravitational potential wells. At the bottom of the same figure also appears the curve for $\alpha = 10^{-30}$, in which the same effect is enhanced.

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 we plot how the CMB power spectrum is sensitive to little changes of α. The range shown here is from $\alpha = 0.3x10^{-27}$ to $\alpha = 1.1x10^{-27}$ (from $x_B = 73,367$ to $x_B = 40,759$). It is noted that the first and second peaks are enhanced if the ULBDM is more relativistic.

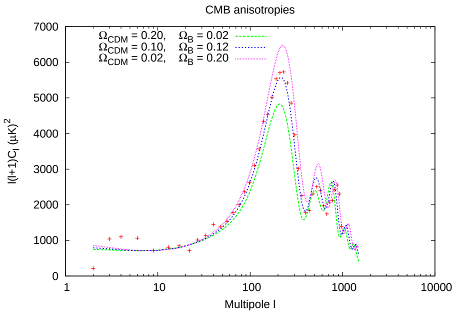

FIG. 4.— CMB power spectrums for diferent contents of ULBDM and CDM. For the three curves shown $\alpha \propto 10^{-27}$, no reionization.

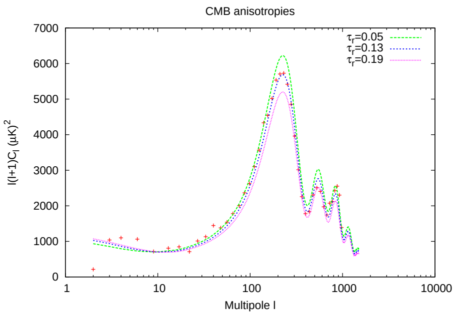

FIG. 5.— CMB power spectrums for diferent optical depths of reionization. The range shown is from $\tau_r = 0.05$ to $\tau_r = 0.19$. $\Omega_{Bos} = 0.2$, $\Omega_{CDM} = 0.02$, $\alpha \propto 10^{-27}$.

Once the necessary mass-to-temperature ratio is estimated, we now investigate the content of ULBDM against the content of CDM. Figure 4 shows how the increase in CDM 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 consider the effect of the fraction of reionized baryonic matter too. We fix all the parameters and now vary the optical depth in figure 5. We show that a universe ULBDM-dominated ($\Omega_B = 0.2$) could be allowed for $x_B \propto 10^5$ and τ_r between 0.05 and 0.19.

We now want to say something about the number density of the ULBDM. First, we must keep in mind that in this approach, all the particles are treated in a non-condensate state. Next, if we assume that nowadays the ULBDM particles behave as non-relativistic, thus we can use the relationship

$$m_B n_B = \Omega_B \rho_c. \tag{3}$$

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 future work.

4. CONCLUSIONS

A universe dominated by Ultra Light Bosonic DM in a non-condensate state could be possible only if these particles fulfill the condition that its mass-to-temperature ratio is close to 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 explain such a low temperature unless it can be given a mechanism of interaction with the rest of the matter.

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 $\tau_r \gtrsim 0.07$.

The most promising and physically interesting feature of the ULBDM and SFDM resides on its condensate state, as said by Woo & Chiueh (2008); Ureña-López (2002); Ureña (2009). We have shown that the change in the type of statistics in the distribution function has non negligible effects on the CMB. It remains to include explicitly the information of a Bose-Einstein condensate in the dynamical equations. The number density of the ULBDM, if it dominated the DM 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 by a condensate state.

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