The Abundance of New Kind of Dark Matter Structures

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Abstract. A new kind of dark matter structures, ultracompact minihalos (UCMHs) was proposed recently. They would be formed during the radiation dominated epoch if the large density perturbations are existent. Moreover, if the dark matter is made up of weakly interacting massive particles, the UCMHs can have effect on cosmological evolution because of the high density and dark matter annihilation within them. In this paper, one new parameter is introduced to consider the contributions of UCMHs due to the dark matter annihilation to the evolution of cosmology, and we use the current and future CMB observations to obtain the constraint on the new parameter and then the abundance of UCMHs. The final results are applicable for a wider range of dark matter parameters.

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1 Introduction

It is well known that the present structures of Universe originate from the density perturbations ($\delta \rho / \rho \sim 10^{-5}$). Theoretically, primordial black halos (PBHs) can be formed if the density perturbations are larger than 0.3 \cite{1}. Recently, it was proposed that a new kind of dark matter structures, ultracompact minihalos (UCMHs), can be formed during earlier epoch if the density perturbations are between $3 \times 10^{-4}$ and 0.3 \cite{2}. These large density perturbations can be obtained through the phase transitions in the early Universe \cite{3}.

Although the presence of dark matter has been shown by many observations, its nature still remains unknown. At present there are many dark matter models and the weakly interacting massive particles (WIMPs) model is a frequently studied one \cite{4,5}. These dark matter particles can annihilate into standard particles such as electrons, positrons, protons, antiprotons, or photons. Therefore, the evolution of the cosmos can be influenced by the dark matter annihilation process due to the interaction between the particles \cite{6}. On the other hand, since the dark matter annihilation rate is proportional to the square of the number density, the UCMHs would have effects on the cosmological evolution and can be regarded as the $\gamma$-ray sources due to the higher density within them. This might be a way for the indirect search of dark matter \cite{7,8,9,10}. In Ref. \cite{11}, the authors calculated the $\gamma$-ray flux from the nearby UCMHs which have been formed during three phase transitions: electroweak symmetry breaking (EW), QCD confinement (QCD), and $e^+e^-$ annihilation ($e^+e^-$). They found that after considering the sensitivity of EGRET or Fermi, these objects should be detectable. In Ref. \cite{12} the authors investigated the constraint on the current abundance of UCMHs. They found that the tightest bound is $f_{\text{UCMHs}} \leq 10^{-5}$ for $M_{\text{UCMHs}} \sim 10^5 M_\odot$ if no gamma-ray emission is detected from UCMHs.

In Ref. \cite{13}, the authors obtained the current abundance of UCMHs using the WMAP-7 years data, where the contributions from halos and subhalos are also included. Therefore, in addition to the parameter which describes the current abundance of UCMHs, another one which considers the nature of dark matter must be added. In this paper, we only consider the UCMHs effect simply. Its advantage is that besides the cosmological parameters only one free parameter is needed. Although we do not get the accurate results due to the rejection of the annihilation effect from the classical dark matter halos, we found that the comparable results can also be obtained, and they can be applied for wider range of dark matter parameters. In order to get the constraint on the abundance of UCMHs we use the WMAP-7 years data. Moreover, we also want to discuss the constraint for the future CMB observation of Planck. In this paper, we use the WMAP-7 years results as the fiducial model and produce the mock data for the future Planck-3 years observations, and then use these data to get the results.

This paper is organized as follows. In Sec. II we give the relevant equations which describe the UCMHs and their contributions to the cosmological evolution. In Sec. III, we give our results of the constraint on the current abundance of UCMHs using the current CMB data and
2 The constraint on the abundance of UCMHs from the current and future CMB observations

2.1 The relevant equations

After the formation of UCMHs, dark matter particles can be accreted by radial infall and the mass of UCMHs evolves according to \[ \frac{dm}{dt} = \delta m \left( \frac{1 + z_{eq}}{1 + z} \right), \]

where \( \delta m \) is the mass contained within a perturbation at the redshift of matter-radiation equality \( z_{eq} \). As in Ref. [11] (also followed by Ref. [13]), in this paper we adopt \( \delta m = 5.6 \times 10^{-10}, 1.1 \times 10^{-9}, 0.33 \) \( M_\odot \) for the three phase transitions: electroweak symmetry breaking, QCD confinement and \( e^+e^- \) annihilation.

The density profile of UCMHs is \[ \rho_{\text{UCMHs}}(r, z) = \frac{3f_\chi M_{\text{UCMHs}}(z)}{16\pi R_{\text{UCMHs}}(z)^2 r^4}, \]

where \( R_{\text{NACHOs}}(z) = 0.019 \left( \frac{1000}{z+1} \right) \left( \frac{\text{M}_{\text{UCMHs}}(z)}{\text{M}_\odot} \right)^{1/3} \) pc and \( f_\chi \) is the dark matter fraction. We follow the assumption that UCMHs stop growing at \( z \approx 10 \) because the structure formation process prevents further accretion after the redshift.

Similar to the case of the black hole [15], and following Ref. [13], we assume that the UCMHs have a monoenergetic mass function, and the abundance of UCMHs is the same everywhere and they do not merger with others [7]. We neglect the energy loss of the dark matter annihilation production within UCMHs [16]. We also neglect the effect of adiabatic contraction on the density profile of UCMHs. This is because it has remarkable effect only around the edge of baryonic core, and the density profile of the centre is not changed significantly [17]. Following Ref. [13], based on these assumptions, we can get the annihilation rate of UCMHs

\[ \Gamma = \frac{f_{\text{UCMHs}} \rho_{0,\text{critical}}}{N_{\text{UCMHs}}(z = 0)} (1 + z)^3 \frac{\langle \sigma v \rangle}{m_\chi^2} \int 4\pi r^2 \rho^2(r, z) dr, \]

where \( \Gamma \) is the annihilation rate per unit volume of UCMHs. \( N_{\text{UCMHs}} \) is the number density of UCMHs, \( f_{\text{UCMHs}} = \rho_0 \rho_{\text{UCMHs}}(z = \rho_{0,\text{critical}}) \) is the current abundance of UCMHs. The upper limit of the integral is \( R_{\text{UCMHs}} \). However, there is a cut radius \( r_{\text{cut}} \) due to the dark matter annihilation.

\( r_{\text{cut}} \) can be estimated as follows. According to Ref. [13], the evolution equation of the dark matter number density can be written as

\[ \frac{dn_\chi}{dt} = -\langle \sigma v \rangle n_\chi^2, \]

then at any time \( t \), the number density is

\[ n_\chi(r, t) = n_\chi(r, t_i) \frac{1 + n_\chi(r, t_i)}{1 + n_\chi(r, t_i)(\sigma v)(t - t_i)}, \]

we can get the maximal density \( \sim m_\chi/(\sigma v)(t - t_i) \). We define \( r_{\text{cut}} \) at present time \( t_0 \) which satisfies the equation

\[ \rho(r_{\text{cut}}) = \frac{m_\chi}{(\sigma v)(t_0 - t_i)}, \]

where \( t_0 \approx 13.7 \text{ Gyr} \) [11,12] is the age of the universe, \( t_i \) is the time of UCMHs formation and as in Ref. [12], we choose \( t_i(z_{eq}) = 77 \text{ Gyr} \). Following Ref. [11,12], we assume that the density is constant within \( r_{\text{cut}}, \rho(r_{\text{cut}}) = \rho(r_{\text{cut}}) \).

Considering the dark matter annihilation, the evolution of ionization fraction \( x_i \) is [7]

\[ (1 + z) \frac{dx_i}{dz} = \frac{1}{H(z)} [R_\chi(z) - I_\chi(z) - I_{\text{ion}}(z)], \]

where \( R_\chi \) is the standard recombination rate, which is the ionization rate by standard sources, and \( I_\chi \) is the ionization rate sourced by dark matter. \( I_\chi \) is given as [7]

\[ I_\chi = \chi_\iota f_\chi \frac{2m_\chi c^2}{\pi E_b} \Gamma, \]

where \( n_b \) is the baryon number density, \( E_b = 13.6 \text{ eV} \) is the ionization energy, \( m_\chi \) is the dark matter mass, and \( f_\chi \) is the released energy fraction deposited in the baryonic gas during the annihilation. Following Ref. [13], we set \( f_\chi = 1 \). \( \chi_\iota \) is the energy fraction which ionizes the baryonic gas and we accept the form given in Ref. [17], followed by Refs. [7,13]

\[ \chi_\iota = (1 - x_e)/3, \]

where \( x_e \) is the fraction of free electrons.

In this paper, we introduce one new parameter \( f_s \) which describes the nature of dark matter and the current abundance of UCMHs

\[ f_s = \left( \frac{\langle \sigma v \rangle}{10^{-26}\text{cm}^3\text{s}^{-1}} \right) \left( \frac{m_\chi}{1\text{GeV}} \right)^{-1} \left( \frac{f_{\text{UCMHs}}}{10^{-5}} \right). \]

This is different from Ref. [13] where \( f_{\text{UCMHs}} \) and one of \( \langle \sigma v \rangle \) and \( m_\chi \) must be treated as free parameters in order to include the contributions of halos. For example, they fix the value of \( \langle \sigma v \rangle \) and take the dark matter mass and current abundance of UCMHs as free parameters. We will see that the neglect of contributions from halos do not affect the final results significantly, and they can be used for wider range of dark matter parameters.
2.2 Constraint on the abundance of UCMHs

We have modified the public COSMOMC code \[18\] in order to include the new parameter \(f_s\). We use the WMAP-7 years data and the mock data of future 3-years observations of Planck \[19\] to get the constraint on the abundance of UCMHs. In order to produce the mock data, we use the WMAP-7 years results \[20\] as the fiducial model. We consider 6 cosmological parameters and the new parameter:

\[
\{\Omega_b h^2, \Omega_c h^2, \theta, n_s, A_s, f_s\},
\]

where \(\Omega_b h^2\) and \(\Omega_c h^2\) are the density of baryons and dark matter respectively, \(\theta\) is the ratio of the sound horizon at recombination to its angular diameter distance multiplied by 100, \(\tau\) is the optical depth, and \(n_s\) and \(A_s\) are the spectral index and amplitude of the primordial density perturbation power spectrum, respectively. Because the annihilation rate of UCMHs are almost the same for the three phase transitions, we only do the calculation for the \(e^+e^-\) case and the results are listed in Table 1.

In Tab. 1, the 2σ value of the parameters are shown. From this it can be seen that for the future 3-years observation of Planck the constraint is better than the WMAP-7 years data by about one order of magnitude.

For the WMAP-7 years data, the constraint on the current abundance of UCMHs is

\[
f \leq 1.85 \times 10^{-4} \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}}\right)^{-1} \left(\frac{m_\chi}{1 \text{GeV}}\right),
\]

while for the future 3-years observations of Planck (mock data), the constraint is

\[
f \leq 0.19 \times 10^{-4} \left(\frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}}\right)^{-1} \left(\frac{m_\chi}{1 \text{GeV}}\right).
\]

These constraints are comparable with the results in Ref. \[13\]. For this point, we think that the contributions of the conventional dark matter halos are smaller than those of the UCMHs, and the dominant effect is from UCMHs. This is also shown in Ref. \[21\] where the luminosity from UCMHs is dominant compared with the background. Moreover, we do not have to set the range of dark matter mass for the new parameter introduced by us, so the constraints in this paper are applicable for wider range of dark matter mass.

### 3 Conclusion

During an earlier epoch, if the density perturbations are between \(3 \times 10^{-4}\) and 0.3, a new kind of dark matter structure, ultracompact minihalos would be formed. If the dark matter is made up of weakly interacting massive particles, these objects would have effects on the cosmological evolution, especially the recombination and reionization. Therefore, the CMB observations can give constraints on their abundance. In this paper, we reinvestigate the current abundance of them using the WMAP-7 years data and the mock data for future 3-years observation of Planck. Our treatment is different form Ref. \[13\]. Although we do not include the halos’ contributions, we still find that the results are comparable. It is because the contributions from UCMHs to the evolution of cosmology are dominant. Moreover, because only one new parameter is introduced, so the final results are applicable for wider range of dark matter mass.

From these results we can see that for the typical value \(\langle \sigma v \rangle = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}\) and \(m_\chi = 100 \text{GeV}\), the current abundance of UCMHs are \(f \leq 6.2 \times 10^{-3}\) and \(6.3 \times 10^{-4}\) for the WMAP and Planck, respectively. On the other hand, because the parameter \(f_{UCMHs}\) is not fixed in this paper, so we can get the constraint on \(f_{UCMHs}\) for the abnormal value of \(\langle \sigma v \rangle\). For example, the recent observations of the cosmic ray, such as PAMELA \[22\] and ATIC \[23\], \(\langle \sigma v \rangle \sim 10^{-23} \text{cm}^3 \text{s}^{-1}\) and \(m_\chi \sim 1 \text{TeV}\), the current abundance of UCMHs are \(f \leq 1.85 \times 10^{-4}\) and \(1.9 \times 10^{-5}\) for the WMAP and Planck, respectively.

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