

New constraints on primordial minihalo abundance using cosmic microwave background observations

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It was proposed that the massive compact halo objects (MCHOs) would be produced during an earlier epoch of cosmology if the density perturbations are between 3×10^{-4} and 0.3. Then these objects can accrete dark matter particles onto them due to their high density. If the dark matter is in the form of the weakly interacting massive particles, the MCHOs can have a significant effect on the evolution of cosmology due to the dark matter annihilation within them. Using the WMAP-7 years data, we investigated the constraints on the current abundance of MCHOs (f_{MCHOs}) formed during the e^+e^- annihilation phase transition. We have found that the 2σ constraint is $f_{\text{MCHOs}} \lesssim 10^{-4}$ for dark matter masses in the range between 1 GeV and 1 TeV.

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I. INTRODUCTION

In order to form the present structure of cosmology, the initial density perturbations must satisfy the condition $\delta \sim 10^{-5}$. On the other hand, according to theory [1], if the density perturbations are larger than 0.3, primordial black holes (PBHs) can be formed during the radiation dominated era, and these objects are still in existence at present if the mass is large enough [2]. However, what about the result when it lies between these two cases? In paper [3], the authors argued that if the density perturbations are between 3×10^{-4} and 0.3, the nonbaryonic ultracompact minihalos named massive compact halo objects (MCHOs) can be formed during earlier times. Although within the conventional cases the density perturbations are not larger enough to form these objects, they could be enhanced through the inflation potential or during the phase transitions in the early Universe [4]. Because of their high density, these objects can accrete dark matter particles onto them.

Although the presence of dark matter in the Universe has been shown by many astrophysical observations, its nature still remains unknown. Among many models, the weakly interacting massive particles (WIMPs) model has been researched frequently [5–7]. According to theory, WIMPs can annihilate into the standard particles such as electrons, positrons, protons, antiprotons, or photons. The authors of [8] calculated the gamma rays from these MCHOs which have been formed during three phase transitions: electro-weak symmetry breaking, QCD confinement, and e^+e^- annihilation. And in the last case, they found that the integrated intensity of gamma-ray flux within the 100 pc has exceeded the threshold of EGRET and Fermi-LAT. In [9], using the Fermi gamma-ray observations, the authors

investigated the constraints on the current abundance of MCHOs. They found that for the mass of MCHOs $\sim 10^3 M_\odot$, the fraction is $\sim 10^{-7}$.

As discussed in papers [10], the dark matter annihilation has a significant effect on the evolution of cosmology especially when the structure formation process is included. The structure formation starts in the lower redshift ~ 100 , while the MCHOs can be formed and accrete the dark matter particles in the higher redshift ~ 3000 . So the dark matter annihilation within them has an effect on the ionization and recombination before the structure formation begins. In this paper, we consider this effect and try to give the constraints on the current abundance of MCHOs using the CMB observations.

One point to be noticed is that the PBHs can also accrete the dark matter particles to form similar objects and moreover the PBHs themselves can emit photons, electrons, and so on. So all of these objects can have effects on the evolution of cosmology [11]. However, in this paper, these effects will not be considered.

This paper is organized as follows: We give equations and discuss how MCHOs affect the cosmological evolution in Sec. II. In Sec. III, we give our results of constraints on the current abundance of MCHOs using the WMAP data. We conclude in Sec. IV.

II. THE EFFECTS OF MCHOS ON COSMOLOGICAL EVOLUTION

Massive compact halos would be produced during the radiation domination epoch if the δ satisfies the condition: $3 \times 10^{-4} < \delta < 0.3$. These objects can accrete dark matter particles by radial infall and then the mass of MCHOs evolves as [8]

$$M_{\text{MCHOs}}(z) = \delta m \left(\frac{1 + z_{\text{eq}}}{1 + z} \right), \quad (1)$$

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where the δm is the mass contained within a perturbation at the redshift of matter-radiation equality z_{eq} . Following [8], we adopt $\delta m = 5.4 \times 10^{-10} M_{\odot}$, $8.4 \times 10^{-4} M_{\odot}$, and $390 M_{\odot}$ for three phase transitions: electroweak symmetry breaking (EW), QCD confinement, and $e^+ e^-$ annihilation.

The density profile of MCHOs is [8]

$$\rho_{\text{MCHOs}}(r, z) = \frac{3f_{\chi} M_{\text{MCHOs}}(z)}{16\pi R_{\text{MCHOs}}(z)^{3/4} r^{9/4}}, \quad (2)$$

where

$$R_{\text{MCHOs}}(z) = 0.019 \left(\frac{1000}{z+1} \right) \left(\frac{M_{\text{MCHOs}}(z)}{M_{\odot}} \right)^{1/3} \text{ pc}$$

and f_{χ} is the dark matter fraction. We also accept the assumption that MCHOs stop growing at $z \approx 10$, because the structure formation process prevents further accretion after the redshift.

In this paper, we assumed that the MCHOs have a monochromatic mass function, which means all of the MCHOs have the same mass, similar to the PBHs case [12]. We suppose that the abundance of MCHOs is the same everywhere and they do not merger with others. We neglect the energy loss of the dark matter annihilation production within MCHOs [13]. Based on these assumptions, we can get the annihilation rate of MCHOs:

$$\begin{aligned} \Gamma &= N_{\text{MCHOs}} \Gamma' = N_{\text{MCHOs}} \frac{\langle \sigma v \rangle}{m_{\chi}^2} \int 4\pi r^2 \rho^2(r, z) dr \\ &= \frac{\rho_{0, \text{MCHOs}}}{M_{\text{MCHOs}}(z=0)} (1+z)^3 \frac{\langle \sigma v \rangle}{m_{\chi}^2} \int 4\pi r^2 \rho^2(r, z) dr \\ &= \frac{f_{\text{MCHOs}} \rho_{0, \text{critical}}}{M_{\text{MCHOs}}(z=0)} (1+z)^3 \frac{\langle \sigma v \rangle}{m_{\chi}^2} \int 4\pi r^2 \rho^2(r, z) dr, \quad (3) \end{aligned}$$

where Γ' is the annihilation rate within one of the MCHOs and Γ is the annihilation rate per unit volume of the MCHOs. N_{MCHOs} is the number density of MCHOs, $f_{\text{MCHOs}} = \rho_{\text{MCHOs}} / \rho_{\text{critical}}$ and this definition is different from [9]. The limitation of the integral is from r_{cut} to R_{MCHOs} . The r_{cut} is [8,9,14]

$$\rho(r_{\text{cut}}) = \frac{m_{\chi}}{\langle \sigma v \rangle (t_0 - t_i)}, \quad (4)$$

where $t_0 \approx 13.7$ Gyr [8,9] is the age of the Universe, t_i is the time of the MCHOs formation, and we choose $t_i(z_{\text{eq}}) \approx 77$ kyr also used by [9].

Besides the MCHOs, we consider the dark matter halos in this paper. Their contribution can be treated as the ‘‘clumping factor’’ $C(z)$ relative to the smooth case [15]:

$$\begin{aligned} C(z) &= 1 + \frac{\Gamma_{\text{halo}}(z)}{\Gamma_{\text{smooth}}(z)} \\ &= 1 + \frac{(1+z)^3}{\bar{\rho}_{\text{DM}}^2(z)} \int dM \frac{dn}{dM}(M, z) \int \rho^2(r) 4\pi r^2 dr, \quad (5) \end{aligned}$$

where Γ stands for the dark matter annihilation rate. dn/dM is the halos mass function and we use the Press-Schechters formalism [16] to do our calculations. On the other hand, through the simulation, it was found that there are many substructures in dark matter halos [17]. These subhalos can also enhance the dark matter annihilation rate. In our paper, we include these subhalos, neglect the contributions from the sub-sub-, and use the smallest mass of them $\sim 10^{-6} M_{\odot}$ [17,18]. We consider $\sim 10\%$ halos mass within the subhalos, use the power law form of mass function $\sim M^{-\beta}$, and adopt $\beta = 1.95$ [17]. So the total clumping factor of dark matter halos and subhalos can be written as [15]

$$C_{\text{total}} = 1 + (C_{\text{halos}} - 1) + (C_{\text{subhalos}} - 1). \quad (6)$$

Considering the dark matter annihilation, the evolution of ionization fraction x_e can be written as [10,19]

$$(1+z) \frac{dx_e}{dz} = \frac{1}{H(z)} [R_s(z) - I_s(z) - I_{\chi}(z)], \quad (7)$$

where R_s is the standard recombination rate, I_s is the ionization rate by standard sources, and I_{χ} is the ionization rate sourced by dark matter which is given as [10]

$$I_{\chi} = \chi_i f \frac{2m_{\chi} c^2}{n_b E_b} \Gamma_{\text{total}}, \quad (8)$$

where n_b is the baryon number density and the $E_b = 13.6$ eV is the ionization energy. Γ_{total} is the total dark matter annihilation rate including the MCHOs and halos. f that depends on the redshift and the production of dark matter annihilation [20] is the released energy fraction depositing in the baryonic gas during the annihilation. In this paper, we assume that the total energy released by the annihilation is deposited, which means $f = 1$. χ_i is the energy fraction which ionizes the baryonic gas and we accept the form given by [19]

$$\chi_i = (1 - x_e)/3, \quad (9)$$

where x_e is the fraction of free electrons.

Following the method in papers [10,19], we modified the public code CAMB [21] in order to include the contributions from MCHOs and dark matter halos.

In Fig. 1, we show the evolution of x_e as a function of redshift z for the MCHOs formed during the $e^+ e^-$ annihilation phase transition. For the cosmological parameters, we use the WMAP7 results [22]. We can see that the larger the fraction of MCHOs, the more obvious change of the ionization fraction can be made. We also notice that the

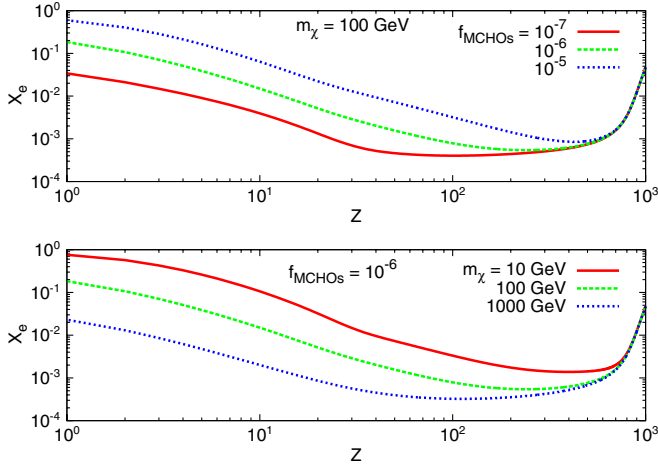


FIG. 1 (color online). The change of the ionization fraction x_e as a function of the redshift z . Upper panel: We fixed the mass of dark matter $m_\chi = 100$ GeV and changed the current fraction of MCHOs $f_{\text{MCHOs}} = 10^{-7}$, 10^{-6} , and 10^{-5} , from top to bottom. Lower panel: We fixed the current fraction of MCHOs $f_{\text{MCHOs}} = 10^{-6}$ and changed the dark matter mass $m_\chi = 10$, 100, and 1000 from top to bottom. Here we fixed the value $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$.

influence of dark matter annihilation within MCHOs on the cosmological ionization fraction is similar to the cases of dark matter decay [19] or the PBHs [2] for $M_{\text{PBH}} > 10^{14} \text{ kg}$.

For the other MCHOs formed during the EW and QCD phase transitions, the contribution on the cosmological evolution is much weaker due to their much smaller mass. For this property, it can be seen from the paper [8] where the integrated gamma-ray flux above 100 MeV for EW and QCD cases are ~ 12 and 6 orders lower than the e^+e^- case, respectively. So in this paper, we do not consider these two cases.

III. CONSTRAINTS FROM WMAP DATA

In this paper, we have modified the public COSMOMC code [23] and used the 7-year WMAP results, both the temperature and polarization data, to get the constraints of related parameters. We consider 6 cosmological parameters: $\Omega_b h^2$, $\Omega_d h^2$, θ , τ , n_s , and A_s , where $\Omega_b h^2$ and $\Omega_d h^2$ are the density of baryon and dark matter, θ is the ratio of the sound horizon at recombination to its angular diameter distance multiplied by 100, τ is the optical depth, and n_s and A_s are the spectral index and amplitude of the primordial density perturbation power spectrum. We fix the value $\langle\sigma v\rangle = 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$ and treat m_χ and f_{MCHOs} as free parameters. For recent observations [24–26], the preferred dark matter mass spreads from several GeV to TeV. So in our paper, we set the change range of dark matter mass from 1 GeV to 1 TeV and the prior of the $f_{\text{MCHOs}}: [0, 10^{-2}]$. For the convergence diagnostic of

TABLE I. Posterior constraints on the fractions of MCHOs, the mass of dark matter, and the related cosmological parameters.

Parameter	τ	z_{re}	$f_{\text{MCHOs}}(10^{-4})$	m_χ (GeV)
Mean	0.0753	9.59	0.48	682.0
2σ lower	0.0538	7.09	0.0	188.4
2σ upper	0.0983	11.95	1.52	999.3

MCMC, we use the default value of the Gelman and Rubin statistics in COSMOMC ([variance of chain means]/[mean of chain variances]): $R - 1 = 0.03$. The results are shown in Table I where some important parameters such as the optical depth (τ), the redshift of reionization (z_{re}), the current abundance of MCHOs (f_{MCHOs}), and the dark matter mass (m_χ) are given.

It can be seen that the 2σ limitation of the MCHOs fraction is $f_{\text{MCHOs}} \sim 10^{-4}$. As shown above, the larger the mass of dark matter, the smaller the contributions are. So the 2σ constraints on the dark matter mass approach our prior limitation. We also plot the 1D and 2D probability distributions in Figs. 2 and 3.

From Fig. 2, we see that f_{MCHOs} has the biggest probability at zero and decreases approximately to zero at $\sim 3 \times 10^{-4}$. For the dark matter mass, the constraints are weaker, which is much more obviously in the 2D probability distribution of parameters f_{MCHOs} and m_χ , where the dark matter mass spreads a larger range.

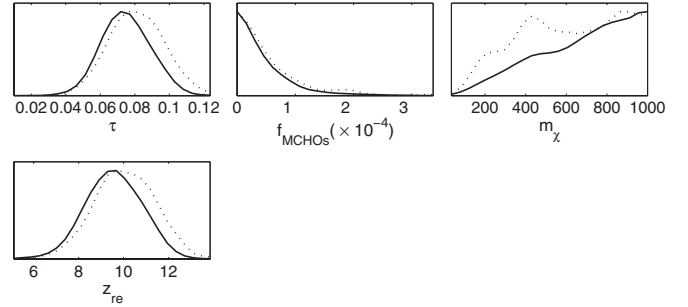


FIG. 2. The marginalized probability distribution function of parameters τ , f_{MCHOs} , m_χ , and z_{re} (solid curves) and the relative mean likelihood (dotted curves).

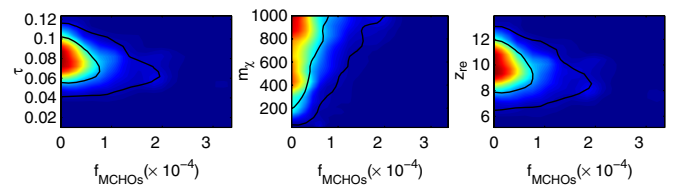


FIG. 3 (color online). The 2D contours of the distribution of f_{MCHOs} and the parameters τ , m_χ , and z_{re} .

IV. CONCLUSION

We have investigated the current abundance of MCHOs formed in an earlier epoch due to the large density perturbations ($3 \times 10^{-4} < \delta < 0.3$) using the WMAP-7 years data. We found that for the mass range 1 GeV–1 TeV, the current abundance of MCHOs which are produced during the e^+e^- annihilation phase transition is $f_{\text{MCHOs}} \sim 10^{-4}$ corresponding to the 2σ limitation. This is the first constraint using the WMAP data and it is comparable with the results in paper [9], where they used the Fermi gamma-ray observations.

The influences of MCHOs formed during the electro-weak breaking and QCD confinement phase transitions on the cosmological evolution are much weaker than the

e^+e^- annihilation case because of their much smaller mass, so the WMAP cannot give the significant constraints on their current abundance.

We also found that the effect on the cosmological ionization fraction of dark matter annihilation within MCHOs is similar to the cases of dark matter decay [19] or the PBHs for $M_{\text{PHB}} > 10^{14}$ kg [2].

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