Contributions of dark matter annihilation within ultracompact minihalos to the 21cm background signal

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In the dark age of the universe, any exotic sources, e.g., the dark matter annihilation, which inject the energy into the intergalactic medium (IGM) will left some imprint on the 21cm background signal. Recently, one new kind of dark matter structure named ultracompact dark matter minihalo (UCMHs) was proposed. Near the inner part UCMHs, the distribution of dark matter particles are steeper than that of the general dark matter halos, $\rho_{\text{UCMH}}(r) \sim r^{-2.25}$, and the formation time of UCMHs is earlier, $z_c \sim 1000$. Therefore, it is expected that the dark matter annihilation within UCMHs can effect the 21cm background signal. In this paper, we investigated the contributions of the dark matter annihilation within UCMHs to the 21cm background signal.

I. INTRODUCTION

In the earlier epoch, the Universe was in the fully ionized phase. With the expansion of the Universe, the temperature of IGM decreased and protons combined with electrons to form hydrogens. This process is named recombination and occurs at the redshift $z \sim 1100$. After the recombination, the Universe went into the epoch named "dark age". The most exciting way of detecting the "dark age" is to observe the 21cm background signal. The 21cm signal is caused by the transition of hyperfine split ($n = 1$) of the hydrogen. It is the result of the competition among the temperature of baryonic gas ($T_b$), radiation ($T_r$) and spin ($T_s$). Therefore, the energy injection during the dark age will affect $T_b$ and $T_s$, and left imprint on the 21cm background signal \cite{1, 2}.

As a kind of extra source, dark matter annihilation can also affect the 21cm signal. The basic idea is that the dark matter annihilation productions, e.g. photons ($\gamma$), electrons ($e^-$) and positrons ($e^+$), have interactions with the particles which are present in the Universe causing the heating, ionization and excitation of IGM \cite{3, 4}. Therefore, the temperature $T_b$ and $T_s$ will be affected and changed. Due to the factor that dark matter annihilation rate is proportional to the number density square of particles, the influence of dark matter annihilation on IGM can be studied using the 21cm background signal \cite{3, 4}. Recently, a new kind of dark matter structure named ultracompact dark matter minihalos (UCMHs) was proposed \cite{5}. They can be formed in the early Universe via the collapse of large density perturbations, $0.001 \lesssim \delta \rho/\rho \lesssim 0.3$. Compared with the general dark matter halos, the density profile of UCMHs is steeper, $\rho(r) \sim r^{-2.25}$, and the formation time is earlier, $z_c \sim 1000$. Therefore, it is expected that the dark matter annihilation rate is large within UCMHs.

Several works have discussed the gamma-ray flux and neutrino flux from UCMHs due to the dark matter annihilation or decay \cite{9, 10, 11}. Due to the large annihilation rate of dark matter within UCMHs, the gamma-ray or neutrino flux from UCMHs can exceed the threshold of some detectors or the atmosphere neutrino background. In Refs. \cite{15, 16, 17}, the authors investigated the effects of UCMHs on the anisotropy of cosmic microwave background and the structure formation due to the dark matter annihilation. In this paper, we will focus on the contributions of UCMHs to the 21cm background signal.

Dark matter as an essential component of the Universe has been confirmed while its nature is still unknown. At present, the mostly researched model is the weakly interactive massive particles (WIMPs). The typical mass of WIMPs is $m_\chi \sim 100$ GeV $- 10$ TeV, and the thermally averaged cross section is $\langle \sigma v \rangle \sim 3 \times 10^{-26}$ cm$^3$s$^{-1}$ \cite{18, 19}. However, in order to explain the gamma-ray excess of the Milky Way center the dark matter particle mass would be $m_\chi \sim 10$ GeV, e.g. Ref. \cite{20}. The observations on the positrons and electrons of the cosmic ray imply that the dark matter particle mass is $m_\chi \sim 1$ TeV and the thermally averaged cross section is $\langle \sigma v \rangle \sim 10^{-23}$ cm$^3$s$^{-1}$, e.g. see the review \cite{21}.

In Ref. \cite{22}, after the analysis of $\gamma$-ray data of the Milky Way dSphs from the Fermi-LAT the authors excluded the thermally averaged cross section $\langle \sigma v \rangle \sim 2.2 \times 10^{-26}$ cm$^3$s$^{-1}$ for the dark matter particle mass $m_\chi < 100$ GeV. The observational results of H.E.S.S towards the Galactic center for the very high energy $\gamma$-ray flux show that there is no

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a residual $\gamma$-ray flux in the energy range between 300 GeV and 30 TeV \cite{23}, and the thermally averaged cross section which is larger than $3 \times 10^{-23}\text{cm}^3\text{s}^{-1}$ is excluded for the Einasto density profile.

In this paper, we will focus on the general case, $m_\chi \sim 100$ GeV with $\langle \sigma v \rangle \sim 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$, and our results can be applied for the other cases. For the cosmological parameters, we used the results given by the Planck collaboration \cite{24}.

This paper is organized as follows: In Sec. II, we briefly show the general picture of the 21cm background and UCMHs. In Sec. III, we calculate the impact of dark matter annihilation within UCMHs on the 21cm background. The main conclusions and discussions are given in Sec. IV.

II. THE GENERAL PICTURE OF 21CM BACKGROUND AND UCMHS

A. The 21cm background from the dark age

The ground state of hydrogen ($n = 1$) can split into triplet and singlet states, which is named hyperfine structure. The energy change of these two levels is $E = 5.9 \times 10^{-6}$ eV which corresponds to the wavelength of photon $\lambda = 21$ cm. The transition between two states is usually expressed in the form of spin temperature, $T_s$, which is defined as

$$\frac{n_1}{n_0} = 3\exp\left(-\frac{T_s}{T_s}\right),$$  \hspace{1cm} (1)

where $n_1$ and $n_0$ are the number density of hydrogens in triplet and singlet states, $T_s = 0.068$ K is the equivalent temperature corresponding to the transition energy. During the evolution of the universe, there are mainly three processes which have influence on the spin temperature (i) the background photons, e.g. cosmic microwave background (CMB), which can be absorbed by hydrogen atoms; (ii) the collisions of the hydrogen atoms with other particles, such as hydrogen atoms, electrons and protons; (iii) The resonant scattering of Ly$\alpha$ photons which is named the Wouthuysen-Field effect. Including these effects, the spin temperature can be written as

$$T_s = \frac{T_{\text{CMB}} + (y_\alpha + y_e)T_k}{1 + y_\alpha + y_e},$$  \hspace{1cm} (2)

where $y_\alpha$ corresponds to the Wouthuysen-Field effect, and in this work we use the form as \cite{25}

$$y_\alpha = \frac{P_{10}T_s}{A_{10}T_k}e^{-0.3\times(1+z)^{0.5}T_k^{-2/3}(1+\frac{4K}{T})^{-1}},$$  \hspace{1cm} (3)

where $A_{10} = 2.85 \times 10^{-15}\text{s}^{-1}$ is the Einstein coefficient of the hyperfine spontaneous transition. $P_{10}$ is the de-excitation rate of the hyperfine triplet state due to Ly$\alpha$ scattering, here we use the form $P_{10} = 1.3 \times 10^9J_\alpha$, $J_\alpha$ is the intensity of Ly$\alpha$ radiation \cite{26}

$$J_\alpha(z) = \frac{n_H^2h\sigma_T}{4\pi H(z)}\left[x_e x_p \alpha_{2P}^{\text{eff}} + x_e x_{\text{HI}} \gamma_{\text{eH}} + \frac{\chi_\alpha E_{\text{UCMHs}}}{n_H h\nu_\alpha}\right],$$  \hspace{1cm} (4)

where $x_e$ is the fraction of the free electrons defined as $x_e = \frac{n_e}{n_e + n_H}$, $x_p = x_e$ and $x_{\text{HI}} = 1 - x_e$ are the fraction of protons and hydrogens respectively. $\alpha_{2P}^{\text{eff}}$ is the effective recombination coefficient to the $2P$ level and we adopt the form as \cite{27}

$$\alpha_{2P}^{\text{eff}} = 1.67 \times 10^{-13} \left(\frac{T}{10^4\text{K}}\right)^{-0.91-\frac{\log_2\frac{T}{10^4\text{K}}}{1.0}} \text{[cm}^3\text{s}^{-1}] ,$$  \hspace{1cm} (5)

$\gamma_{\text{eH}}$ is the excitation rate of hydrogen due to the collisions of electrons \cite{27},

$$\gamma_{\text{eH}} = 2.2 \times 10^{-8}e^{-118400K/T_k} \text{[cm}^3\text{s}^{-1}] ,$$  \hspace{1cm} (6)

The third term of Eq. (4) is the effect of dark matter annihilation within UCMHs. $\chi_\alpha = (1 - x_e)/6$ and $E_{\text{UCMHs}}$ is the energy injection rate of dark matter annihilation, and it will be given in the next section.
In the Eq. (2), \( y_c \) corresponds to the collision effect between hydrogen, electrons and protons, it can be written as (see e.g. the Ref. [28])

\[
y_c = \frac{(C_{HH} + C_{eH} + C_{pH}) T^*}{A_{10} T_K},
\]

where \( C_{HH,eH,pH} \) are the de-excitation rate, and we use the form as [6, 28, 29]

\[
C_{HH} = 3.1 \times 10^{-11} T_k^{0.357} e^{-32K/T_k} \times n_{HI} \text{[cm}^3\text{s}^{-1}] (8)
\]

\[
C_{eH} = 10^{-9.607 + 0.5 \log(T_k) e^{-(\log(T_k))/4.5}} \times n_e \text{[cm}^3\text{s}^{-1}] (9)
\]

Following the previous discussions (see e.g. the Ref. [6]), the term of \( C_{pH} \) can be neglected safely due to the slight effect.

For the observations of 21cm background, the mostly used quantity is the brightness temperature, \( \delta T_b \), which is defined as the differences between the spin temperature and the CMB temperature [6, 30],

\[
\delta T_b \simeq 26 \times (1 - x_e) \left( \frac{\Omega_b h}{0.02} \right) \left[ \frac{1 + z}{10} \times \frac{0.3}{\Omega_m} \right]^{1/2} \left( 1 - \frac{T_{CMB}}{T_s} \right) \text{mK}. (10)
\]

In the section, we reviewed the basic quantity of the 21cm background simply, and for more detail discussions one can see e.g. the review [31, 32].

B. The basic character of UCMHs

It is well known that in the early Universe the density perturbations with the amplitude \( \delta \rho/\rho \sim 10^{-5} \) are the seeds of the present cosmological structures. If the density perturbations are larger than \( \sim 0.3 \) the primordial black holes can be formed. Recently, the authors of [8] proposed that a new kind of dark matter structures named ultracompact minihalos can be formed if the amplitude of density perturbations lie between the above mentioned values. The density profile of UCMHs can be obtained from via simulation,

\[
\rho_{UCMHs}(r, z) = \frac{3f_{\chi} M_{UCMHs}(z)}{16\pi R_{UCMHs}(z) (0.73)^{2.25}}, (11)
\]

where \( f_{\chi} = \Omega_{DM}/(\Omega_b + \Omega_{DM}) = 0.83 \) [6]. \( R_{UCMHs}(z) \) is 0.019 \( (1000 (1+z) (M_{UCMHs}(z)/M_{\odot})^{1/3}) \) pc is the radius of UCMHs at the redshift \( z \). \( M_{UCMHs}(z) \) is the mass of UCMHs at the redshift \( z \), and it is related with the initial mass \( M_i \) contained within the perturbation scale as they entering the horizon [6],

\[
M_{UCMHs}(z) = M_i \left( \frac{1 + z_{eq}}{1 + z} \right), (12)
\]

where \( z_{eq} \simeq 3160 \) is the redshift at which the energy density of radiation and matter are equal.

From Eq. (11) it can be seen that for \( r \rightarrow 0 \) the density \( \rho \rightarrow \infty \). In order to avoid this divergence we truncate the density profile at the radius \( r_{min} \) and it satisfies the condition as [6, 32]

\[
\rho_{UCMHs}(r_{min}) = \frac{m_{\chi}}{4\pi(\sigma v)(t - t_i)}, (13)
\]

where \( t_i \) is the formation time of UCMHs. This relation is the result of considering the dark matter annihilation with the halos. For smaller radius \( r < r_{min} \), we set the density is constant, \( \rho_{UCMHs}(r < r_{min}) = \rho_{UCMHs}(r_{min}) \).
III. THE IMPRINT OF DARK MATTER ANNIHILATION WITHIN UCMHS ON THE 21CM BACKGROUND

The influences of dark matter annihilation on the evolution of the Universe have been researched by many works. The main effects are on the evolution of the ionization degree and the temperature of IGM. Including the dark matter annihilation, the change of the ionization degree \((x_e)\) and the temperature of IGM \((T_b)\) with the time can be written as \([3, 4]\)

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

\[
(1 + z) \frac{dT_b}{dz} = \frac{8\sigma_T a_T T^4_{\text{cmb}}}{3m_e c H(z)} \frac{x_e}{1 + f_{\text{He}} + x_e} (T_b - T_{\text{cmb}}) - \frac{2}{3k_B H(z)} \frac{K_\chi}{1 + f_{\text{He}} + x_e} + T_b,
\]

where \(R_s(z)\) and \(I_s(z)\) are the standard recombination rate and ionization rate caused by the standard sources, respectively. \(I_\chi\) and \(K_\chi\) are the ionization rate and heating rate associated with the dark matter annihilation,

\[
I_\chi = \chi_i f \frac{2m_\chi c^2}{n_b E_b} \Gamma_{\text{DM}}
\]

\[
K_\chi = \chi_h f \frac{2m_\chi c^2}{n_b E_b} \Gamma_{\text{DM}}
\]

where \(f\) is the energy fraction which is injected into the IGM from dark matter annihilation. It depends on the redshift and the annihilation channel. In fact, for the dark matter annihilation, \(f\) depends on the redshift slightly \([26]\). In this paper, we adopted \(f = 1\) for our calculations and very detailed discussions will be presented in the future work. \(\chi_i\) and \(\chi_h\) are the ionizing and heating fractions of energy which deposit into the IGM. There are several parameterizations of this form. In this paper, we adopted the widely used forms proposed by the authors of \([3]\), \(\chi_i = (1 - x_e)/3\) and \(\chi_h = (1 + 2x_e)/3\). In this work, we considered the dark matter annihilation within UCMHs, so the annihilation rate \(\Gamma_{\text{DM}}\) in Eqs. \(16\) and \(17\) can be written as \(15\).

\[
\Gamma_{\text{UCMHs}} = f_{\text{UCMHs}} \frac{\rho_{0,c}}{M_{0,\text{UCMHs}}} (1 + z)^3 \chi \frac{(\sigma v)}{m_\chi^2} \int 4\pi r^2 \rho_{\text{UCMHs}}(r, z) dr
\]

where \(f_{\text{UCMHs}} = \rho_{\text{UCMHs}}/\rho_{0,c}, \rho_{0,c}\) is the current critical density of the universe. Be similar to the PBHs case, here, we have assumed that the mass of UCMHs is the same when they are formed, and this assumption means that the mass function of UCMHs is in the delta form \([9, 15]\), \(dn/dM \sim \delta(M - M_{\text{UCMHs}})\). We also assume that there are no mergers between of them. Now, we can write the energy injection rate in Eq.\(11\) as

\[
E_{\text{UCMHs}} = 2m_\chi \frac{\Gamma_{\text{UCMHs}}}{n_{b,0}}
\]

where \(n_{b,0}\) is current number density of baryon. We modified the public code \textsc{RecFast} in the \textsc{Camb} \(1\) to include the effect of dark matter annihilation within UCMHs, and the evolution of \(x_e\) and \(T_{\text{IGM}}\) can be obtained using the modified code. In this section, we will not consider the contributions of general dark matter halos, however, the relative discussions will be given in the next section.

\(1\) http://camb.info/
In Fig. 1 the changes of $T_b$ and $T_s$ with redshift for different cases are shown. For comparison, we also plotted the case without dark matter. The thin red solid line represents the temperature of CMB, $T_{CMB}$. The parameters of dark matter particle are $m_\chi = 100$GeV, $\langle \sigma v \rangle = 3 \times 10^{-26}$cm$^3$s$^{-1}$. From the figure, it can be seen that the temperature of IGM becomes notably different compared with the no dark matter case. The $T_{IGM}$ is higher for the larger fraction of UCMHs. The spin temperature $T_s$ also show the similar variation trend. We also show the evolution of intensity of the Ly$\alpha$ due to dark matter annihilation within UCMHs in Fig. 2. In this figure, one can see that the UCMHs provide extra sources of Ly$\alpha$ during the early time. At the redshift $z \sim 300$, for $f_{UCMHs} = 10^{-5}$, the intensity of Ly$\alpha$ is $J_\alpha \sim 10^{18}$erg s$^{-1}$Hz$^{-1}$sr$^{-1}$. In Ref. [25], the authors showed the contributions from the first stars to the Ly$\alpha$ background (Fig.5 of that Ref.). These contributions increase dramatically only after $z \sim 30$, and the intensity of Ly$\alpha$ reach the peak value $J_\alpha \sim 10^{21}$erg s$^{-1}$Hz$^{-1}$sr$^{-1}$ at redshift $z \sim 10$.

Having obtained the evolution of spin temperature $T_s$, we can now calculate the differential brightness temperature $\delta T_b$ using Eq. 10. The results are shown in Fig. 3. In this plot, we also show the case of without UCMHs (red solid line) for comparison. For the smaller fraction of UCMHs, $f_{UCMHs} \lesssim 10^{-6}$, there are absorption features in $\delta T_b$. If the fraction of UCMHs is larger than $10^{-6}$, the emission feature appear. We also plotted the differences between the cases of with and without UCMHs, $\Delta \delta T_b = \delta T_{b} - \delta T_{b,0}$, in Fig. 1. As shown in this figure, the largest differences are $\Delta \delta T_b \sim 67$mk at redshift $z \sim 67$ for $f_{UCMHs} = 10^{-5}$, $\Delta \delta T_b \sim 28$mk at redshift $z \sim 80$ for $f_{UCMHs} = 10^{-6}$ and $\Delta \delta T_b \sim 8.7$mk at redshift $z \sim 100$ for $f_{UCMHs} = 10^{-7}$, respectively.

**IV. DISCUSSIONS**

We have investigated the effects of dark matter annihilation within UCMHs on the 21cm background signal. The formation time of UCMHs is early ($z \sim 1000$) and the density profile is steep ($\rho(r) \sim r^{-2.25}$). So the dark matter annihilation rate within UCMHs is higher than that of general dark matter halos, e.g. NFW models. Due to the extra energy injection from UCMHs, the evolution of the temperature of IGM and spin with the redshift will be changed. $T_{IGM}$ can be up to 1000K at the redshift $z \sim 10$ for $f_{UCMHs} = 10^{-5}$. The spin temperature is also changed obviously at the redshift $z \sim 200$ especially for large fraction of UCMHs. Moreover, UCMHs can also provide extra Ly$\alpha$ background during the early epoch. For the observation of the 21cm background signal the mostly used quantity is the differential brightness temperature $\delta T_b$. We found that for the small fraction of UCMHs, $f_{UCMHs} \lesssim 10^{-6}$, there is an f absorption feature, and the emission feature appears for large fraction of UCMHs. We also investigated the quantity $\Delta \delta T_b$ which is defined as $\Delta \delta T_b = \delta T_{b} - \delta T_{b,0}$. We found that the values of $\Delta \delta T_b$ are changed for different fraction of UCMHs. For the fraction of UCMHs $f_{UCMHs} = 10^{-5}$, $\Delta \delta T_b$ can be up to $\sim 67$mk at the redshift $z \sim 67$, and it becomes smaller with the decreasing of the fraction of UCMHs.

Except for UCMHs the general dark matter halos have also contributions to the 21cm background signal. The effects
of general dark matter halos can be treated as a ‘clumping factor’ \( C(z) \) relative to the smooth case \( \mathcal{C} \). According to the simulation, there are many subhalos and sub-sub halos. In this paper, we considered the subhalos while neglecting the sub-subhalos. We adopted the smallest mass of halos as \( \sim 10^{-6} M_\odot \) \[34\]. The halos mass within subhalos is about \( \sim 10\% \), and we used the power law form of mass function \( \sim M^{-\beta} \) with \( \beta = 1.95 \) \[33\]. We used the NFW dark matter halo model for our calculations. For different fraction of UCMHs, \( f_{\text{UCMHs}} = 10^{-7}, 10^{-6} \) and \( 10^{-5} \), \( \Delta \delta T_b \) are shown in Fig. 5. The obvious differences between the contributions of UCMHs and general dark matter halos to the 21cm background signal appear at the redshift \( z \sim 40 \) for the small fraction of UCMHs, \( f_{\text{UCMHs}} < 10^{-5} \). For large fraction of UCMHs, \( f_{\text{UCMHs}} \gtrsim 10^{-5} \), the main contributions are from UCMHs. For the observations of 21cm background signals, as shown in Fig. 4 the values of \( \Delta \delta T_b \) can reach \( \sim 27 \text{mK} \) at redshift \( z \sim 30 \). Therefore, in order to find the impacts of UCMHs on IGM due to the dark matter annihilation the systematics of experiments e.g. EDGES(Experiment for Detecting the Global EOR Signature) \[36\] should be below 27mK at least.

As mentioned above, the \( \gamma \)-ray flux due to the dark matter annihilation provide a way to detect the minihalos, such

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**FIG. 2:** The Ly\( \alpha \) intensity from UCMHs due to the dark matter annihilation. The solid red line and the dashed green line correspond to the \( f_{\text{UCMHs}} = 10^{-7}, 10^{-6} \) and \( 10^{-5} \), respectively. The other parameters are the same as in Fig. 1.

**FIG. 3:** The evolution of the differential brightness temperature \( \delta T_b \). The solid red line is the case without UCMHs. The long green dashed and the short blue dashed lines correspond to the \( f_{\text{UCMHs}} = 10^{-7}, 10^{-6} \) and \( 10^{-5} \) from bottom to up, respectively.
as UCMHs. In Ref. [37], the authors used the null detection of γ-ray flux from UCMHs to constrain the fraction of UCMHs, and they found the strongest limits are $f_{\text{UCMHs}} < 10^{-7}$. Besides the contributions on the local γ-ray flux, UCMHs can also provide an extra contribution on the extragalactic γ-ray background. Using the data of extragalactic γ-ray background from the Fermi-LAT, the authors of [11] found the strongest limits on the fraction of UCMHs are $f_{\text{UCMHs}} < 10^{-5}$, and these limits are stronger than that obtained using the CMB data [11, 10]. For the researches on UCMHs, one except to find them directly from the present observations. In Ref. [38], using the third Fermi-LAT sources catalog, the authors found that there are nearly 33% sources (about 34) which remains unassociated. The authors of [39] found that there are about 10 dark matter minihalos in the local space. Therefore, as a kind of potential high energy astrophysical objects, UCMHs would be present within these unassociated minihalos. Another very interesting way of finding UCMHs is to investigate the formation of baryonic structures within UCMHs. Due to the early formation time of UCMHs, it was pointed by the authors of [8] that the low-mass and low-metallicity Pop III.
stars could be formed in the early time within UCMHs and these stars might survive to the present day. Therefore, the surveys of low-metallicity stars would provide one important way of finding UCMHs indirectly \cite{40}. On the other hand, these Pop III stars can also provide extra photons to ionize the IGM and impact the 21cm background signals. It is excepted that in the near future the analysis of data from e.g. JWST\footnote{http://www.jwst.nasa.gov/}(James Webb Space Telescope), GMT\footnote{http://www.gmto.org/}(Giant Magellan Telescope)\footnote{http://www.tmt.org/} and TMT\footnote{http://www.tmt.org/}(The Thirty-meter Telescope) can provide a potential possible way of detecting UCMHs indirectly.

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