A Limit on the Warm Dark Matter Particle Mass from the Redshifted 21 cm Absorption Line

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Abstract

The recent Experiment to Detect the Global Epoch of Reionization Signature (EDGES; Bowman & Rogers 2010) collaboration detected a global absorption signal at a central frequency of $\nu = 78 \pm 1$ MHz points to the presence of a significant Ly$\alpha$ background by a redshift of $z = 18$. The timing of this signal constrains the dark matter particle mass ($m_\chi$) in the warm dark matter (WDM) cosmological model. WDM delays the formation of small-scale structures, and therefore a stringent lower limit can be placed on $m_\chi$ based on the presence of a sufficiently strong Ly$\alpha$ background due to star formation at $z = 18$. Our results show that coupling the spin temperature to the gas through Ly$\alpha$ pumping requires a minimum mass of $m_\chi > 3$ keV if atomic cooling halos dominate the star formation rate at $z = 18$, and $m_\chi > 2$ keV if H$_2$ cooling halos also form stars efficiently at this redshift. These limits match or exceed the most stringent limits cited to date in the literature, even in the face of the many uncertainties regarding star formation at high redshift.

Key words: dark ages, reionization, first stars -- dark matter -- diffuse radiation

1. Introduction

Recently, the Experiment to Detect the Global Epoch of Reionization Signature (EDGES; Bowman & Rogers 2010) collaboration detected a global absorption signal at a central frequency of $\nu = 78 \pm 1$ MHz, with a brightness temperature $T = -500 \pm 50$ mK and a signal-to-noise ratio of $\approx 37$ (Bowman et al. 2018). This points to the indirect coupling of the spin temperature ($T_s$) to the gas temperature ($T_g$) through the Wouthuysen–Field (WF) effect (Wouthuysen 1952; Field 1957) by a background of Ly$\alpha$ photons at a redshift of $z = 17.2$, which corresponds to $\approx 180$ million years after the Big Bang.

The spin temperature of H I is related to the gas ($T_g$), cosmic microwave background ($T_\gamma$), and Ly$\alpha$ background ($T_\alpha$) temperatures by

$$T_s^{-1} = T_\gamma^{-1} + x_c T_g^{-1} + x_a T_\alpha^{-1} \left(1 + x_c + x_a \right) ,$$

where $x_c$ is the collisional coupling constant and $x_a$ is the coupling coefficient to Ly$\alpha$ photons (Chen & Miralda Escude 2004; Hirata 2006) given by

$$x_a = \frac{8 \pi \chi^2 3 \nu_0 \gamma T_\alpha}{9 A_{i0} T_\gamma} , S_{\alpha} J_{\alpha} = 1.81 \times 10^{11} J_{\alpha} S_{\alpha} \left(1 + z \right) ,$$

where $\gamma = 50$ MHz is the half width at half-maximum of the Ly$\alpha$ resonance, $T_\alpha = h \nu / k_B = 68.2$ mK with $\nu_0 = 1.42$ GHz, $A_{i0} = 2.87 \times 10^{-15}$ s$^{-1}$ is the spontaneous emission coefficient of the 21 cm line, $J_{\alpha}$ is the background Ly$\alpha$ intensity (in units of cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$), and $S_{\alpha}$ is a factor that accounts for spectral distortions, which is less than 1 when the spin and gas temperature are similar (Hirata 2006).

As $x_a$ increases, the spin temperature shifts from the microwave background temperature to $T_\alpha$, providing information about the temperature of the high-redshift intergalactic medium. Interestingly, the best fit value of this temperature is lower than expected, potentially suggesting a subcomponent of dark matter particles with masses in the MeV range and charges that are a fraction of that of the electron (Dvorkin et al. 2014; Barkana 2018; Barkana et al. 2018; Muñoz & Loeb 2018).

At the same time, warm dark matter (WDM) candidates with masses in the keV range have been proposed to account for several tensions between observations and theoretical predictions. In particular, (i) cold dark matter (CDM) cosmological simulations predict cuspy halo profiles, while observations point to more core-like centers (Bullock et al. 2001; Gentile et al. 2004); (ii) CDM simulations predict larger stellar velocity dispersions than observed in Milky Way’s satellite galaxies (Boylan-Kolchin et al. 2012); and (iii) the number of subhalos predicted in the CDM simulations far exceeds the observed number of luminous Milky Way satellites (Klypin et al. 1999; Moore et al. 1999).

While it remains a matter of debate whether the resolution of these tensions can be achieved by improving models of baryonic physics, WDM particles could also address these issues by suppressing the formation of small-scale structure. These particles, such as sterile neutrinos (Dodelson & Widrow 1994; Abazajian et al. 2001) and gravitinos (Gorbunov et al. 2008), remain relativistic for a longer time in the universe. This leads to non-negligible velocity dispersions that cause them to free stream out of small-scale perturbations, attenuating the matter power spectrum above a characteristic comoving wavenumber ($k_{FS}$; Bode et al. 2001; Viel et al. 2005) of

$$k_{FS} = 15.6 \frac{h}{\text{Mpc}} \left( \frac{m_\chi}{1 \text{ keV}} \right)^{1/3} \left( \frac{0.12}{\Omega_{DM} h^2} \right)^{1/3} ,$$

which leads to less pronounced cusps and fewer and smaller-mass Milky Way satellites.

Various approaches have been adopted to provide lower bounds on $m_\chi$, which in turn place lower limits on $k_{FS}$. Based on the abundance of $z = 6$ galaxies in the Hubble Frontier Fields, Menci et al. (2016) arrived at $m_\chi > 2.4$ keV (2$\sigma$) and Corasaniti et al. (2017) arrived at $m_\chi > 1.5$ keV (2$\sigma$) based on...
the galaxy luminosity function at \( z \approx 6-8 \). Similarly, Pacucci et al. (2013) concluded that lensing surveys such as the Cluster Lensing and Supernova Survey with Hubble (CLASH) provide \( m_\chi > 0.9 \text{ keV} (2\sigma) \) lower bounds. The current best lower limit of \( m_\chi > 3.3 \text{ keV} (2\sigma) \) is based on the high-redshift Ly\( \alpha \) forest data (Viel et al. 2013).

The detection of the redshifted 21 cm background is also able to provide a limit on \( m_\chi \). based on the simple fact that enough small-scale structures must collapse at high redshift to lead to a Ly\( \alpha \) background strong enough to couple \( T_S \) to \( T_\alpha \) at the high end of the absorption trough, just beyond \( z = 18 \). The greater the suppression of small dark matter halos, the more difficult it is for Ly\( \alpha \) to couple the spin and the gas temperatures by the WF effect, and thus by calculating the maximum Ly\( \alpha \) intensity allowed as a function of the rate of dark matter collapse, we are able derive a minimum allowed value for the WDM particle. Although the idea of inferring the WDM particle mass from redshifted 21 cm absorption line has been proposed before (Yoshida et al. 2003; Sitwell et al. 2014), we have applied the idea to the EDGES signal in this Letter.

The structure of this Letter is as follows. In Section 2 we show how the high-redshift halo mass function (HMF) depends on \( m_\chi \), and relate this mass function to the Ly\( \alpha \) background. In Section 3 we show how the delayed formation of halos would place lower limits on \( m_\chi \), depending on whether atomic or \( \mathrm{H}_2 \) cooling halos dominate the star formation at \( z = 18 \).

2. Method

2.1. The HMF

Throughout this Letter, we adopt the Planck 2015 cosmological parameters (Planck Collaboration et al. 2016a), where \( \Omega_M = 0.308, \Omega_\Lambda = 0.692, \Omega_b = 0.048 \) are total matter, vacuum, and baryonic densities in units of the critical density \( \rho_c \), \( h = 0.678 \) is the Hubble constant in units of 100 km s\(^{-1}\) Mpc\(^{-1}\), \( \sigma_8 = 0.82 \) is the variance of linear fluctuations on the 8 h\(^{-1}\) Mpc scale, \( n_s = 0.968 \) is the tilt of the primordial power spectrum, and \( Y_{\mathrm{He}} = 0.24 \) is the primordial helium fraction. We compute the power spectrum for CDM and modify it according to the following formula to be appropriate for different WDM scenarios with different particle masses:

\[
P_J(k) = T^2(k) P_{\text{CDM}}(k),
\]

where \( P(k) \) denotes the power spectrum as a function of comoving wavenumber \( k \). The power spectrum is taken from CAMB (Lewis et al. 2000), and we adopt the fitting formula for \( T(k) \) given by Bode et al. (2001):

\[
T(k) = [1 + (\alpha \nu)^{2}]^{-5/2},
\]

where \( \mu = 1.12 \) and the parameter \( \alpha \) determines the cutoff position in the power spectrum as

\[
\alpha = \frac{0.05}{h \text{ Mpc}^{-3}} \left( \frac{m_\chi}{1 \text{ keV}} \right)^{-1.15} \left( \frac{\Omega_{\text{WDM}}}{0.4} \right)^{0.15} \times \left( \frac{h}{0.65} \right)^{13} \left( \frac{\delta_{\text{WDM}}}{1.5} \right)^{-0.29},
\]

where \( \Omega_{\text{WDM}} \) is the WDM contribution to the density parameter, and we set the number of degrees of freedom to \( \delta_{\text{WDM}} = 1.5 \). Figure 1 shows the power spectrum for the CDM model as compared to WDM model for \( m_\chi = 1, 3, \) and 10 keV.

We compute the HMF as (Press & Schechter 1974):

\[
\frac{dn}{d \ln M} = \frac{\bar{\rho}}{M} f(\nu) \frac{d\nu}{d \ln M},
\]

where \( n \) is the number density of halos, \( M \) is the halo mass, \( \nu \) is the peak height of perturbations, \( \bar{\rho} \) is the average density of the universe, and the first crossing distribution \( f(\nu) \) (Bond et al. 1991) is obtained from the ellipsoidal collapse model leads as

\[
f(\nu) = A \sqrt{\frac{2\pi}{\nu}} \left[ 1 + (\nu a)^{-p} \right] e^{-\nu^2/2},
\]

with \( A = 0.322, p = 0.3, \) and \( a = 0.75 \) (Sheth & Tormen 2002, hereafter ST02). Here, the peak height \( \nu \) is defined as \( \nu = \delta_c 0 \sigma_8 (r, z)^{-2} \), with \( \delta_c 0 = 1.686 \). The variance is \( \sigma^2(\nu) = \delta^2(\nu, M, 0) D(z)^2 \), with

\[
\sigma^2(\nu, M, 0) = \sigma^2(\nu, R, 0) = \int_0^\infty \frac{dk}{2\pi^2} k^2 P_J(k) \omega^2(kR),
\]

where \( M = 4\pi R^3 \Omega_M \rho_c / 3 \), \( \omega(kR) = 3j_k(kR)/(kR) \), with \( j_k \) is \( (\sin x - x \cos x)/x^2 \), and \( D(z) \) is the linear growth factor

\[
D(z) = \frac{H(z)}{H(0)} \int_0^\infty \frac{dz (1 + z')}{H^2(z')} \left[ \int_0^\infty \frac{dz' (1 + z')}{H^2(z')} \right]^{-1}.
\]

While the adoption of a spherical top-hat window filter is not perfect for a truncated power spectrum (Benson et al. 2013), it is a conservative choice in that it gives a weaker lower bound on \( m_\chi \) than other window functions in the literature. Figure 2 shows the redshift evolution of the HMF compared to the Bolshoi–Planck \( N \)-body simulations from \( z = 0 \) to 9 (Rodriguez-Puebla et al. 2016) and the Trac et al. (2015; Trac15) simulations at \( z = 6, 8, \) and 10. Our formula provides a good match to all these
and 30 keV, respectively.

Lyα from Bolshoi simulation are:

Here is the comoving photon emissivity $P_n$ of the Lyman-α resonance line, $R_{\alpha,\beta}$ is the horizon beyond which photons redshift into another frequency $\nu$, and $\epsilon(\nu^\prime, z^\prime)$ is the photon emissivity (defined as the number of photons emitted per unit volume, time, and frequency) at a redshift $z^\prime$ and frequency $\nu^\prime$, where $n(M, t)$ is the comoving number density of halos per unit mass, $f_n(M)$ is the fraction of the mass that is turned into stars as a function of halo mass, and

$$\epsilon(\nu^\prime, z^\prime) = \epsilon(\nu_0) \times \left(\frac{\nu^\prime}{\nu_0}\right)^{\alpha_{\nu} - 1} \tau_{\alpha} \int_{M_{\text{max}}}^{\infty} n(M, t) f_n(M) M dM$$

is the comoving photon emissivity for Population III stars in the mass range of 50–500 $M_{\odot}$ with a top-heavy Salpeter initial mass function. This is by a factor of $\approx 3$ larger than the Lyα yields from Population III stars in the 1–500 $M_{\odot}$ mass range. To be on the conservative side, we adopt the largest possible Lyα yield of $L_{\alpha} = 3.37 \times 10^{21} \text{erg}^{-1} \text{Hz}^{-1} M_{\odot}^{-1}$ in this Letter.

The lower limit of the integral is set based on whether we assume atomic cooling halos dominate the star formation rate (SFR) or the H2 cooling halos. In the case of atomic cooling halos, the limit is $M_{\text{min}} = 4 \times 10^5 M_{\odot}$ at $z = 18$, where it corresponds to halos with virial temperature $T_{\text{vir}} > 10^4$ K.

The minimum halo mass in order for the gas to cool and condense to form stars due to both atomic and H2 cooling based on adaptive mesh refinement (AMR) simulations (Machacek et al. 2001; Wise & Abel 2007) is

$$M_{\text{crit}} = 2.5 \times 10^5 + 1.7 \times 10^6 (F_{\text{LW}}/10^{-2})^{0.47} M_{\odot},$$

where $F_{\text{LW}}$ is Lyman–Werner intensity integrated over solid angle in units of erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$. To be conservative, we consider all halos with $M > 2.5 \times 10^5 M_{\odot}$, ignoring the suppression of star formation due to $F_{\text{LW}}$.

Finally, $f_n$ is modeled as $f_e = \epsilon_e \times f_0$, where $f_0 = \Omega_m/\Omega_M$. For atomic cooling halos we adopt a conservative value for a star formation efficiency ($\text{SFE}$) of $\epsilon_e = 3\%$. This is a generous choice as it leads to an SFR density of $0.033 M_{\odot}$ yr$^{-1}$ cMpc$^{-3}$ at $z = 8$, which is a factor of 3 above the upper bounds of the observed SFR density of $\log \rho_\text{sfr} = -2.08 \pm 0.07$ M$_{\odot}$ yr$^{-1}$ cMpc$^{-3}$ at $z = 8$ (Madau & Dickinson 2014; Bouwens et al. 2015). The observed SFR density at $z = 8$ is obtained by integrating the observations down to a limiting magnitude of $M_{\text{AB}} = -17$ and correcting for dust obscuration (see Table 7 of Bouwens et al. 2015). We choose a value $3$ above the observed upper limit to ensure we take into account the faint population of galaxies that are not observed directly. Our high SFR density is consistent with the maximum extrapolated upper limits on SFR density based on SFE models of Sun & Furlanetto (2016). For H$_2$ cooling halos we similarly assume $\epsilon_e = 3\%$, even though this would require almost all of the cold gas found in AMR simulations of early star formation to be converted into stars (Machacek et al. 2001; Wise & Abel 2007).
3. Results

The left panel of Figure 3 shows the Lyα coupling coefficient based on the estimated flux of Lyα photons in the WDM model as a function of $m_\chi$ for two cases: (i) only atomic cooling halos contributing to star formation at $z = 18$, and (ii) both H$_2$ cooling and atomic cooling halos contributing to $z = 18$ star formation. Here we conservatively adopt $S_{\alpha} = 1$. In the right panel we study the impact of changing the SFE for the atomic cooling halos. Requiring coupling of gas to spin temperature to have $x_\alpha > 0.5$ through Lyα pumping by Population III stars translates into a lower bound of $m_\chi > 2 (3) \text{ keV}$ if H$_2$ (atomic) cooling halos dominate the SFR density at $z = 18$, respectively.

Fitting for the EDGES signal and the ultraviolet luminosity function of galaxies out to $z \approx 10$, Mirocha & Furlanetto (2018) predicted an SFR density of $\approx 10^{-3}$ and $2 \times 10^{-2} \text{ M}_\odot \text{ yr}^{-1} \text{ cMpc}^{-3}$ at $z \approx 18$ and $z \approx 10$, respectively, when considering only atomic cooling halos (see their Figure 4, right panel). Adopting an SFE of 3%, we predict an SFR density of $\approx 2.1 \times 10^{-3}$ and $2.6 \times 10^{-2}$ at the same redshifts without including the H$_2$ cooling halos.

The various different sets of cosmological parameters reported by the Planck team show <2% fractional differences in $\Omega_{m0}^{2/3}$, a proxy for structure formation power (Planck Collaboration et al. 2016a, 2016c). We would have 4% less mass in collapsed halos had we adopted cosmological parameters from counting clusters (Planck Collaboration et al. 2016b; Salvati et al. 2017), and about 3% more collapsed mass had we adopted WMAP9 cosmological parameters (Hinshaw et al. 2012). We have verified that our results are not sensitive to such variations.

Of the various cosmological parameters, the one that impacts our calculations the most is $\sigma_8$. Over the past decade, the reported values of $\sigma_8$, from studies of galaxy clusters to the cosmic microwave background (CMB), vary from 0.75 to 0.88. In order to ascertain the sensitivity of our lower bound on $m_\chi$ to the adopted value of $\sigma_8$, we repeat the calculation for the two endpoint values of $\sigma_8$, while keeping the other cosmological parameters fixed to their fiducial values and requiring the same times the upper limits of the observed SFR density at $z = 8$. Only values of $\sigma_8$ higher than our fiducial value of 0.82 affect the outcome, with the lower bound dropping to 2 keV (for $\sigma_8 = 0.88$) in the case of only atomic cooling halos. However, values of $\sigma_8 > 0.88$ are ruled out at all redshifts (Behroozi et al. 2013), and one of the most stringent limits on $m_\chi$ if one maintains the same normalization of the SFE in the observed range. This is because the number density of halos in the atomic cooling range at $z = 18$ that could provide the Lyα photons would lead to a more stringent limit on $m_\chi$. Also, while we have assumed that the SFE does not change with redshift, we cannot rule out the possibility that it begins...
increasing beyond $z = 8$ in a way that is not seen in either numerical simulations or in lower redshift observations (see Sun & Furlanetto 2016, and references therein). Similarly, our choice of $S_\alpha = 1$ is motivated by the fact that lower values of $S_\alpha$ would push the lower bound on $m_s$ to larger values.

We note that we have not modeled the shape of the EDGES signal in this Letter, which implies that we have assumed the timing of the signal and its shape could be studied separately. If instead these two are related, we would not be able to make the arguments in the Letter without properly modeling the absorption signal.

These lower limits match or exceed the most stringent limits achieved so far in the literature (Viel et al. 2013), even in the face of the many uncertainties regarding star formation at high redshift. As observations and models of high-redshift galaxies continue to improve, along with detections of redshift 21 cm absorption line, comparisons of the type described here will continue to provide new insight and constraints on warm dark matter and its role in the history of structure formation.

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