Two-component millicharged dark matter and the EDGES 21cm signal

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Abstract:
We propose a two-component dark matter explanation to the EDGES 21 cm anomalous signal. The heavier dark matter component is long-lived whose decay is primarily responsible for the relic abundance of the lighter dark matter which is millicharged. To evade the constraints from CMB, underground dark matter direct detection, and XQC experiments, the lifetime of the heavier dark matter has to be larger than $0.1 \tau_U$, where $\tau_U$ is the age of the universe. Our model provides a viable realization of the millicharged dark matter model to explain the EDGES 21 cm, since the minimal model in which the relic density is generated via thermal freeze-out is ruled out by various constraints.
1 Introduction

The hyperfine transition of the cosmic hydrogen atom, which is known as the 21 cm signal, provides a powerful probe to the physics in the early universe; for reviews, see e.g., [1] [2] [3]. Recently, the Experiment to Detect the Global Epoch of Reionization Signature (EDGES) has reported a new measurement on the sky-averaged radio spectrum centered at $\nu = 78$ MHz, which corresponds to the 21 cm absorption signal of the primordial hydrogen gas at redshift $z \simeq 17$ [4]. The differential brightness temperature $T_{21}$ measured by the EDGES experiment at redshift $z \simeq 17$ is [4]

$$T_{21} = -500^{+200}_{-500} \text{ mK}, \quad (1.1)$$

which is about a factor of two larger than the value expected in the standard cosmology [4, 5]. This hints that either the cosmic microwave background (CMB) could be hotter than expected [6–9], or the hydrogen gas could be colder than expected [10–23].

If the EDGES measurement is interpreted as caused by a colder gas, the question is how to cool the hydrogen gas? One simple solution is that if there exits some sort of particle interactions between dark matter (DM) and hydrogen atom, the primordial hydrogen gas can be cooled by DM, which is colder than gas. However, there exist very
strong constraints from the CMB measurements as well as from other early universe measurements on DM interactions to standard model particles. Millicharged DM is one of the leading DM candidates to explain the EDGES anomaly because its interaction with baryons is proportional to $v^{-4}$, where $v$ is the relative velocity, and thus leads to a much smaller interaction cross section in the early universe than that needed at $z \simeq 17$ for the EDGES interpretation so that the early universe constraints can be significantly alleviated. Millicharged DM have been extensively investigated for the interpretation of the EDGES anomaly [10–15, 19–22]. The parameter space of the millicharged DM is constrained by various experiments, including accelerator experiments [24], the CMB anisotropy [25] [26] [27] [19] [20], the SN1987A [28], and the Big Bang Nucleosynthesis (BBN) [29] [12] [30]; the allowed parameter space is that the millicharged DM mass is $0.1 \text{ MeV} \lesssim m_\chi \lesssim 10 \text{ MeV}$, the millicharge is $10^{-6} \lesssim Q/e \lesssim 10^{-4}$, and the mass fraction of the millicharged DM is $0.0115\% \lesssim f \lesssim 0.4\%$. However, as pointed out by Ref. [21], such a parameter space is ruled out by the $N_{\text{eff}}$ limit with the Planck 2018 data if the relic abundance of the millicharged DM is set by thermal freeze-out. Recently, Ref. [22] proposed a new millicharged DM model in which the sub-component millicharged DM has a sizable interaction cross section with the other DM components so that the millicharged DM can be cooled by the other DM components; this reopens the parameter space that was previously excluded by various experimental constraints.

In this paper we propose a new DM model that consists of two DM components: the lighter DM component is the millicharged DM, and the heavier DM component is unstable, which decays into the lighter DM component. In our model, the millicharged DM are primarily produced after the recombination so that the stringent constraints from CMB can be alleviated. We show that such a model can explain the 21 cm anomaly observed by EDGES and satisfy various experimental constraints. The rest of the paper is organized as follows. We present our model in section 2. We compute the number density of the two DM components as a function of redshift in section 3. The temperature change due to the heavier DM decays is derived in section 4. We provide the time evolution equations for four different physics quantities in section 5. The results of our numerical analysis is given in section 6. We summarize our findings in section 7.

2 The model

We extend the standard model (SM) by introducing a hidden sector that consists of three $U(1)$ gauge bosons, $X^i_\mu$ ($i = 1, 2, 3$), and one Dirac fermion $\chi$ that is charged under both $X^2_\mu$ and $X^3_\mu$ gauge bosons. We use the Stueckelberg mechanism [31–36] to provide mass to the three $U(1)$ gauge bosons; the new Lagrangian is given by

$$
\Delta \mathcal{L} = - \sum_{i=1,2,3} \frac{1}{4} X_{i\mu\nu} X^i_{\mu\nu} + \bar{\chi} (i\gamma^\mu \partial_\mu - m_\chi) \chi + g_2^3 X^2_\mu \bar{\chi} \gamma^\mu \chi + g_3^3 X^3_\mu \bar{\chi} \gamma^\mu \chi

- \frac{1}{2} (\partial_\mu \sigma_1 + m_1 X^1_\mu)^2 - \frac{1}{2} (\partial_\mu \sigma_2 + m_1 X^1_\mu + m_2 X^2_\mu)^2

- \frac{1}{2} (\partial_\mu \sigma_3 + m_3 X^3_\mu + m_4 B_\mu)^2,
$$

(2.1)
where \( \sigma_1, \sigma_2, \) and \( \sigma_3 \) are the axion fields in the Stueckelberg mechanism, \( B_\mu \) is the SM hypercharge boson, \( m_\chi \) is the dark fermion mass, \( g_2^\gamma \) and \( g_Y^3 \) are the gauge couplings, and \( m_1', m_1, m_2, m_3, \) and \( m_4 \) are the Stueckelberg mass terms.

After the spontaneous symmetry breaking in the SM, the mass matrix of the neutral gauge bosons in the basis \((X_1, X_2, X_3, B, A^3)\), where \( A^3 \) is the third component of the \( SU(2)_L \) gauge bosons in the SM, is given by

\[
M^2 = \begin{pmatrix}
m_1'^2 + m_1^2 & m_1 m_2 & 0 & 0 & 0 \\
m_1 m_2 & m_2^2 & 0 & 0 & 0 \\
0 & 0 & m_3^2 & m_3 m_4 & 0 \\
0 & 0 & m_3 m_4 & m_4^2 + g_2^\gamma v^2/4 - g_Y g_2 v^2/4 & 0 \\
0 & 0 & 0 & -g_Y g_2 v^2/4 & g_Y^2 v^2/4
\end{pmatrix}, \tag{2.2}
\]

where \( v \) is the vacuum expectation value of the SM Higgs, and \( g_2 \) and \( g_Y \) are the \( SU(2)_L \) and \( U(1)_Y \) gauge couplings in the SM respectively. The mass matrix has a vanishing determinant such that there exists a massless mode to be identified as the SM photon. Because the mass matrix is block-diagonal, one can diagonalize the first two gauge bosons and the last three gauge bosons separately.

The mass matrix of the first two gauge bosons (the upper-left two by two block matrix in Eq. (2.2)) can be diagonalized via a rotation matrix \( \mathcal{R} \) which is parameterized by a single angle \( \theta \)

\[
\mathcal{R} = \begin{pmatrix}
\cos \theta & -\sin \theta \\
\sin \theta & \cos \theta
\end{pmatrix}. \tag{2.3}
\]

The mass eigenstates, \( Z_1 \) and \( Z_2 \), are related to the gauge states via \( Z_i = \mathcal{R}_{ij} X_j \). The rotation matrix \( \mathcal{R} \) leads to an interaction between \( \chi \) and \( Z_1 \) such that \( \mathcal{L}_{\text{int}} = \sin \theta g_2^\chi Z_1^\mu \chi \gamma^\mu \chi \equiv v_\chi^2 Z_1^\mu \chi \gamma^\mu \chi \). We are interested in the parameter space where \( \theta \ll 1 \) so that \( Z_1 \sim X_1 \) and \( Z_2 \sim X_2 \). In our analysis, we take \( m_1' \sim 2m_\chi, m_2 < m_\chi, \) and \( m_1 < m_2 \) so that the two mass eigenstates have masses \( m_{Z_1} \simeq m_1' \) and \( m_{Z_2} \simeq m_2, \) and the mixing angle \( \theta \) is given by \( \theta \simeq m_1 m_2/(m_1'^2 - m_2^2) \).

The mass matrix of the last three gauge bosons (the bottom-right three by three block matrix in Eq. (2.2)) can be diagonalized by an orthogonal matrix \( \mathcal{O} \) such that \( E_i = \mathcal{O}_{ji} G_j \), where \( G_j = (X_3, B, A^3) \) are the gauge states, and \( E_i = (Z', Z, \gamma) \) are the mass eigenstates. Here \( \gamma \) is the photon, \( Z \) is the neutral gauge boson in the weak interaction, and \( Z' \) is the new massive vector boson. Thus we have \( \mathcal{O}^T M_{3 \times 3}^2 \mathcal{O} = \text{diag}(m_{Z'}^2, m_Z^2, 0) \), where \( M_{3 \times 3}^2 \) is the bottom-right three by three block matrix in Eq. (2.2). Such a matrix diagonalization also leads to interactions between matter fields (both hidden sector fermion \( \chi \) and SM fermions \( f \)) and the three mass eigenstates \( (\gamma, Z, Z') \). The interaction Lagrangian can be parameterized as follows

\[
f \gamma_\mu (v_\mu f - \gamma_5 a_\mu^f) f E_\mu^i + v_\mu^\chi \gamma_\mu \chi E_\mu^i, \tag{2.4}
\]
where the vector and axial-vector couplings are given by

\[ v_i^f = (g_2 o_{3i} - g_Y o_{2i}) T_f^3/2 + g_Y o_{2i} Q_f, \]
\[ a_i^f = (g_2 o_{3i} - g_Y o_{2i}) T_f^3/2, \]
\[ v_i^\chi = g_\chi o_{1i}. \]

Here \( Q_f \) is the electric charge of the SM fermion, and \( T_f^3 \) is the quantum number of the left-hand chiral component under SU(2)\(_L\).

Thus, the hidden sector fermion \( \chi \) has a vector current interaction with the SM photon,

\[ v_3^\chi A_\mu \bar{\chi} \gamma^\mu \chi \equiv \epsilon e A_\mu \bar{\chi} \gamma^\mu \chi, \]

where we have defined an electric charge \( \epsilon \) for the \( \chi \) particle. In our analysis, we adopt the following model parameters: \( m_3 = 100 \text{ TeV} \), and \( m_4/m_3 \ll 1 \). In this case, the electric charge \( \epsilon \) is given by \( \epsilon \approx -(m_4/m_3) \cos \theta_W (g_2^3/\epsilon) \), where \( \theta_W \) is the weak rotation angle in the SM. Since \( m_4/m_3 \ll 1 \) in our analysis, we have \( \epsilon \ll 1 \), which is often referred to as millicharge. \( \chi \) is then the millicharged particle.

3 Two DM components

There are two DM particles in the hidden sector, the \( Z_1 \) boson and the hidden Dirac fermion \( \chi \). In the very early universe, \( Z_1 \) is the dominant DM component, which is assumed to be nonthermally produced. The \( Z_1 \) DM component is long-lived and decays into \( \bar{\chi} \chi \). The decay width of the \( Z_1 \) boson is given by

\[ \Gamma(Z_1 \rightarrow \bar{\chi} \chi) = \frac{m_{Z_1}}{12\pi} \sqrt{1 - \frac{4m_{\chi}^2}{m_{Z_1}^2}} \left( 1 + 2 \frac{m_{\chi}^2}{m_{Z_1}^2} \right) \left( v_{Z_1}^\chi \right)^2 \approx \frac{m_{Z_1} \Delta m}{4\sqrt{2} \pi} (g_2^3 \theta)^2, \]

where \( v_{Z_1}^\chi = g_2^3 \sin \theta \approx g_2^3 \theta, \Delta m \equiv m_{Z_1} - 2m_{\chi} \), and we have assumed \( \Delta m \ll m_{Z_1} \). In our analysis we have \( \theta \ll 1 \) and \( \Delta m \ll m_{Z_1} \), so that \( Z_1 \) is long-lived with a lifetime

\[ \tau(Z_1) \sim \sqrt{\frac{\text{MeV}}{m_{Z_1}}} \sqrt{\frac{\text{meV}}{\Delta m}} \left( \frac{2.3 \times 10^{-16}}{g_2^3 \theta} \right)^2 \tau_{17}, \]

where \( \tau_{17} \sim 7 \times 10^{15} \text{ second} \) is the time between the early universe and \( z = 17 \).

The value of \( \Delta m \) cannot be very large, otherwise the DM \( \chi \) is significantly heated by the decay process \( Z_1 \rightarrow \bar{\chi} \chi \) so that \( \chi \) is unable to cool the baryons. The velocity of the \( \chi \) particle is \( v_{\chi} \approx \sqrt{\Delta m/m_\chi} \) in the rest frame of \( Z_1 \), under the assumption of \( \Delta m \ll m_\chi \). For the case where \( m_\chi \sim 100 \text{ MeV} \) and \( \Delta m \sim O(\text{meV}) \), one has \( v_{\chi} \sim 3.2 \times 10^{-6} \). Thus, in our analysis, we assume a sufficiently small mass difference, \( \Delta m \sim O(\text{meV}) \), such that the \( Z_1 \) decay does not heat the \( \chi \) DM significantly.

The \( \chi \) DM component is mainly produced via the decay process \( Z_1 \rightarrow \bar{\chi} \chi \) in the universe. We assume that the initial number density of \( \chi \) is negligible. The relic density of \( \chi \) can also be produced via thermal freeze-out. There are two processes that contribute to the \( \chi \) DM annihilation cross section: \( \bar{\chi} \chi \rightarrow \gamma \rightarrow ff \) and \( \bar{\chi} \chi \rightarrow Z_2 Z_2 \). In our analysis,
The critical density \( \rho_{\text{cr}} \) in our analysis, we use the contribution to the relic density of DM (e.g. Ref. [21]) are not directly applicable to our model.

The total number of \( Z_1 \) particles in a comoving volume at time \( t \) is given by

\[
N_{Z_1}(t) = N_{Z_1}(0)e^{-t/\tau},
\]

where \( \tau \) is the lifetime of the \( Z_1 \) particle, and \( N_{Z_1}(0) \) is the total number of \( Z_1 \) particles at time \( t = 0 \). In our analysis, we set \( t = 0 \) at redshift \( z_0 = 10^6 \). The number of \( \chi \) particles at time \( t \) in a comoving volume is \( \chi(t) = 2N_{Z_1}(0) - 2N_{Z_1}(t) \). Thus, the number density of \( \chi \) is related to the number density of \( Z_1 \) via

\[
n_{\chi}(z) = 2(e^{t/\tau} - 1)N_{Z_1}.
\]

where \( n_{Z_1} (n_{\chi}) \) is the number density of the \( Z_1 \) (\( \chi \)) particle. In our analysis \( m_{Z_1} \approx 2m_{\chi} \), so the mass fraction of the millicharged DM \( \chi \) at redshift \( z \) in the total DM is given by

\[
f_{\chi}(z) \approx (1 - e^{-t(z)/\tau}),
\]

where \( t(z) \) is the time between early universe (which we take to be \( z_0 = 10^6 \)) and redshift \( z \). CMB observations provide strong constraints on millicharged DM; only 0.4% DM can be millicharged unless the millicharge is negligible [27] [19] [20]. This leads to an lower bound on the \( \tau \), which is \( \approx 3.6 \times 10^{15} \) s.

Because \( \Delta m \ll m_{\chi} \), the total DM density \( \rho_{Z_1} + \rho_{\chi} \) at redshift \( z \) is given by \( \rho_{Z_1} + \rho_{\chi} = \rho_{\text{DM},0} (1 + z)^3 \). Thus the number density of \( \chi \) particles at redshift \( z \) is given by

\[
n_{\chi}(z) = \frac{\rho_{\text{DM},0}}{m_{\chi}} (1 + z)^3 f_{\chi}(z) \approx \frac{\rho_{\text{DM},0}}{m_{\chi}} (1 + z)^3 (1 - e^{-t(z)/\tau}),
\]

where \( \rho_{\text{DM},0} = \Omega_{\text{DM}} \rho_{\text{cr},0} \) is the current DM density where \( \rho_{\text{cr},0} = 1.054h^2 \times 10^4 \) eV cm\(^{-3} \) is the critical density [38]. In our analysis, we use \( \Omega_{\text{DM}}h^2 = 0.1186 [39] \).

4 DM temperature increase generated by decays

The DM \( \chi \) is heated by the \( Z_1 \to \chi \bar{\chi} \) decay process because of the difference between the \( Z_1 \) mass and twice of the \( \chi \) mass. To compute this effect, consider the kinetic energy \( \Delta q \) that goes into the \( \chi \bar{\chi} \) final state for the decay process \( Z_1 \to \chi \chi \)

\[
\Delta q = \Delta m + \frac{3}{2}k_B T_{Z_1},
\]

\(^1\)The formulas to compute \( t(z) \) are given in Appendix A.
Figure 1. Mass fraction of $\chi$ in the total DM as a function of the redshift $z$. $\tau_U \approx 4.3 \times 10^{17}$ s is the age of the universe.

where $3k_B T_{Z_1}/2$ is the averaged kinetic energy of $Z_1$ with $T_{Z_1}$ being the temperature of the $Z_1$ particle and $k_B$ being the Boltzmann constant. Here we have assumed that $Z_1$ is non-relativistic and $\Delta m$ is sufficiently small such that $\chi$ is also non-relativistic. The change of the particle numbers in the comoving volume per unit time due to decay are given by $\dot{N}_{Z_1} = -\Gamma_{Z_1} N_{Z_1}$ and $\dot{N}_\chi = -2 \dot{N}_{Z_1}$, where the dot denotes the derivative with respect to time, $N_\chi$ ($N_{Z_1}$) is the particle number of $\chi$ ($Z_1$), and $\Gamma_{Z_1}$ is the decay width for the process $Z_1 \rightarrow \chi\chi$. The total kinetic energy transfer to the $\chi$ particles per unit time from $Z_1$ decays is given by $\Delta q|\dot{N}_{Z_1}|$, which is equal to the change of the kinetic energy of the $\chi$ particles per unit time.

\[
\Delta q|\dot{N}_{Z_1}| = \frac{d}{dt} \left( \frac{3}{2} k_B T_\chi N_\chi \right) = \frac{3}{2} k_B (T_\chi \dot{N}_\chi + N_\chi \dot{T}_\chi).
\] (4.2)

Thus, the $\chi$ temperature change per unit time due to $Z_1$ decays is given by

\[
\dot{T}_\chi = \frac{n_{Z_1}}{n_\chi} \left[ \frac{2}{3k_B} \Delta m + T_{Z_1} - 2T_\chi \right] \Gamma_{Z_1}.
\] (4.3)

5 Time evolution equations

To compute the baryon temperature at redshift $z = 17$, we numerically solve the temperature evolutions for various quantities.

The time evolution equation of the baryon temperature $T_b$ is given by (see e.g. [10, 40])

\[
\frac{dT_b}{dt} = -2HT_b + \frac{2}{3} \frac{dQ_b}{dt} + \Gamma_C (T_\gamma - T_b),
\] (5.1)

where $H$ is the Hubble parameter,$^2$ $T_\gamma$ is the CMB temperature, $Q_b$ is the energy transfer term due to DM-baryon scatterings, and $\Gamma_C$ is the Compton scattering rate which describes the effects due to CMB-baryon interactions. The Compton scattering rate is given by [10]

\[
\Gamma_C = \frac{8\sigma_{T,x_e}}{3(1 + f_{He})m_e} U
\] (5.2)

$^2$See Appendix A for the calculation of $H$. 

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where $\sigma_T$ is the Thomson cross section, $f_{\text{He}}$ is the Helium fraction, and $U$ is the energy density. In our analysis, we use $\sigma_T = 6.65 \times 10^{-25}$ cm$^2$ [38], $f_{\text{He}} = 0.08$ [10], and $U = (\pi^2/15) T_\gamma^4 = 0.26(1 + z)^4$ eV/cm$^3$ [41] [42].

The time evolution equation of the temperature $T_\chi$ of the lighter DM component $\chi$ is given by

$$\frac{dT_\chi}{dt} = -2HT_\chi + \frac{2}{3} \frac{dQ_\chi}{dt} + \frac{n_{Z_1}}{n_\chi} \left[ \frac{2}{3k_B} \Delta m + T_{Z_1} - 2T_\chi \right] \Gamma_{Z_1}, \quad (5.3)$$

where $Q_\chi$ is the energy transfer term due the interaction between DM $\chi$ and baryons. The first two terms on the right-hand side of Eq. (5.3) represent the effects due to universe expansion and the DM-baryon scattering respectively, which are similar to the first two terms in Eq. (5.1). The third term on the right-hand side of Eq. (5.3) is new and is due to the decay of the $Z_1$ particle in our model, as discussed in section 4.

In addition, we also solve the time evolution equation of the relative bulk velocity between baryon and DM, $V_{\chi b} = |\vec{V}_{\chi b}|$ where $\vec{V}_{\chi b} \equiv \vec{V}_\chi - \vec{V}_b$ [40],

$$\frac{dV_{\chi b}}{dt} = -HV_{\chi b} - D(V_{\chi b}), \quad (5.4)$$

and the time evolution equation of the ionization fraction $x_e \equiv n_e/n_H$ [43]

$$\frac{dx_e}{dt} = -C \left[ n_H \alpha B x_e^2 - 4(1 - x_e) \beta_B \exp \left( \frac{3E_0}{4T_\gamma} \right) \right]. \quad (5.5)$$

We follow Ref. [43] to obtain the various coefficients in Eq. (5.5). The formulas of $Q_b$, $Q_\chi$, and $D(V_{\chi b})$ for millicharged DM used in our analysis are given in Appendix B.

## 6 Results

We solve simultaneously the four time evolution equations for $T_b$, $T_\chi$, $V_{\chi b}$ and $x_e$ from redshift $z = 1010$ to $z = 10$. The baryon temperature $T_b$ at $z = 1010$ is assumed to be equal to the CMB temperature $T_\gamma = T_0 (1 + z)$ where $T_0 = 2.7$ K, since these two components are tightly coupled in the early universe. The temperatures for both DM components are assumed to be negligible in the early universe, so we set $T_{Z_1} = 0$ and $T_\chi = 0$ at $z = 1010$. This is due to the fact that in our model $Z_1$ does not interact with the SM particles and $\Delta m \ll m_\chi$. We also set $x_e = 0.05$ [44] and $V_{\chi b} = 29$ km/s [10] at redshift $z = 1010$.

| Model | $m_1$ | $m_2$ | $m_3$ | $m_4$ | $m_\chi$ | $\Delta m$ | $\theta$ | $\epsilon$ | $\tau_{Z_1}(s)$ |
|-------|-------|-------|-------|-------|-------|--------|--------|--------|---------------|
| A     | $160$ | $1.55$ | $10^8$ | $2.76 \times 10^3$ | $\sim 80$ | $10^{-9}$ | $6.1 \times 10^{-18}$ | $8 \times 10^{-5}$ | $8 \times 10^{17}$ |
| B     | $400$ | $10^{-8}$ | $1.25 \times 10^{-4}$ | $10^8$ | $3.45 \times 10^3$ | $\sim 200$ | $10^{-9}$ | $7.8 \times 10^{-18}$ | $1 \times 10^{-4}$ | $3 \times 10^{17}$ |

Table 1. Benchmark model points. All the masses are in unit of MeV. We take $g_2^X = g_3^X = 1$ in our analysis.

We scan the parameter space spanned by $\epsilon$ and $m_\chi$ for three different decay lifetimes of $Z_1$: $\tau = 2 \times 10^{16}$ s, $3 \times 10^{17}$ s, and $8 \times 10^{17}$ s. In our analysis, we fix $\Delta m = 1$ meV. In order
Figure 2. Parameter space spanned by the millicharge $\epsilon$ and the DM mass $m_\chi$. Model points in which $T_b = 5$ K at $z = 17$ correspond to three different lifetimes: $\tau = 2 \times 10^{16}$ s (blue dot-dashed), $\tau = 3 \times 10^{17}$ s (purple dashed), and $\tau = 8 \times 10^{17}$ s (red solid), with the mass fraction of the millicharged DM component being 0.06%, 0.004%, and 0.001% at $z = 1100$, and 100%, 77%, and 42% today respectively. The green shaded region is excluded by various accelerator experiments, including SLAC electron beam dump [24], CMS [45], MiniBooNE and LSND [46], ArgoNeuT [47], milliQan demonstrator [48], and others [49] [50]. The gray shaded region indicates the parameter region excluded by the dark matter direct detection (DMDD) experiments; above the DMDD region, millicharged DM is absorbed by the rocks on top of underground labs [51] [22]. The magenta region is ruled out by the rocket experiment XQC for mass fractions: $f = 100\%$ (solid) [52], $f = 1\%$ (solid) [52], and $f = 0.4\%$ (solid) [51]. The brown shaded region is excluded by the SN1987A data [53]. The black dashed vertical line indicates the upper bound on DM mass due to $\Delta N_{\text{eff}}$ from CMB [29] [12]. The black dotted line indicates the parameter space of the minimal millicharged DM model with a mass fraction of 0.4% to explain EDGES data [22].

to explain the EDGES data, the baryon temperature $T_b$ has to at least 5.1 K at $z = 17$ [22]. Fig. (2) shows the parameter space where the baryon temperature can be cooled to be $T_b = 5.1$ K at $z = 17$ for three different lifetimes of $Z_1$: $2 \times 10^{16}$ s (blue dot-dashed), $3 \times 10^{17}$ s (purple dashed), and $8 \times 10^{17}$ s (red solid). The mass fractions of the $\chi$ DM at $z = 1100$ are about 0.06%, 0.004%, and 0.001% for the lifetimes $\tau = 2 \times 10^{16}$ s, $\tau = 3 \times 10^{17}$ s, and $\tau = 8 \times 10^{17}$ s respectively, which are smaller than 0.4% required by the CMB data [27], [19], [20]. We find that the viable parameter in our model is much larger than the minimal millicharged DM model, which is indicated by the black dotted line with 0.4% millicharged DM [22]. Various experimental constraints are considered in Fig. (2). These

\(^3\)In the minimal millicharged DM model, the millicharge interaction is responsible for both DM thermal freeze-out and cooling of the cosmic hydrogen atoms.
include the underground dark matter direct detection (DMDD) experiments [51] [22], the XQC experiment [52] [51], SN1987A [53], and the accelerator experiments: SLAC electron beam dump [24], CMS [45], MiniBooNE [46], LSND [46], ArgoNeuT [47], and milliQan demonstrator [48]. Two benchmark model points that can explain the 21 cm anomaly while satisfying various constraints are presented in Table (1). The mass fractions of the $\chi$ DM at today are 100%, 77%, and 42% for the lifetimes $\tau = 2 \times 10^{16}$ s, $\tau = 3 \times 10^{17}$ s, and $\tau = 8 \times 10^{17}$ s respectively. We find that the $Z_1$ lifetime $2 \times 10^{16}$ s are nearly excluded by both the underground DMDD and the XQC constraints. In order to evade the XQC constraints, the $Z_1$ lifetime has to be $\geq 2 \times 10^{16}$ s.

7 Conclusions

We construct a new millicharged DM model to explain the recent 21 cm anomaly. In our model, the millicharged DM $\chi$ is a subcomponent in the early universe and is mainly produced via decays of the other DM component $Z_1$. The DM annihilation cross section $\bar{\chi}\chi \rightarrow Z_2Z_2$ is so strong that the relic abundance due to thermal freeze-out is negligible. We compute the heating term due to the decay process $Z_1 \rightarrow \bar{\chi}\chi$ and include it in our numerical calculations of the time evolution equation of the DM temperature. We find that the model can explain the EDGES 21 cm anomaly while satisfying various experimental constraints, including those from colliders, XQC, underground DMDD, and CMB.

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A Time

The time $t(z)$ at redshift $z$ is given by

$$t(z) = \int_z^{z_0} \frac{dz'}{H(z')(1 + z')}, \quad (A.1)$$

where $H$ is the Hubble parameter. Here we use $z_0 = 10^6$. We compute the Hubble parameter at redshift $z$ via

$$H(z) = H_0 \sqrt{\Omega_R(1 + z)^4 + \Omega_m(1 + z)^3 + \Omega_\Lambda}, \quad (A.2)$$

where $H_0 \equiv 100h$ km s$^{-1}$ Mpc$^{-1}$ is the present Hubble parameter, $\Omega_R$, $\Omega_m$, and $\Omega_\Lambda$ are the density of radiation, matter, and dark energy respectively. In our analysis, we adopt the following values: $\Omega_R = 2.47 \times 10^{-5}/h^2$ [54], $\Omega_m = 0.308$, $\Omega_\Lambda = 0.692$, and $h = 0.678$ [39].
We provide the formulas of $\sigma_{0,t}$, $Q_b$, $Q_\chi$, and $D(V_{\chi b})$ for millicharged DM used in our analysis.

The scattering cross section between millicharged DM and baryons can be parameterized as $\sigma_t = \sigma_{0,t} v^{-4}$ where $v$ is the relative velocity between DM and baryons, and $\sigma_{0,t} = 2\pi\alpha^2\epsilon^2\xi/\mu_{\chi t}^2$ where $\alpha$ is the fine structure constant, $\epsilon$ is the millicharge, $\mu_{\chi t}$ is the reduced mass of DM $\chi$ and the target particle $t$, and $\xi$ is the Debye logarithm \cite{55} \cite{10} $\xi = \ln \left[ 9T_b^3/(4\pi\epsilon^2\alpha^3 x_e n_H) \right]$.

The baryon heating term due to interactions with millicharged DM is given by \cite{40} \cite{10} 

$$
\frac{dQ_b}{dt} = n_\chi x_e \sum_{t=e,p} \frac{m_t m_\chi}{(m_\chi + m_t)^2 u_{\text{th},t}^2} \sigma_{0,t} \sqrt{\frac{2}{\pi}} \frac{e^{-r_t^2/2}}{u_{\text{th},t}^2} \left( T_\chi - T_b \right) + m_\chi \frac{F(r_t)}{r_t}.
$$

(B.1)

where $u_{\text{th},t}^2 \equiv T_b/m_b + T_\chi/m_\chi$, $r \equiv V_{\chi b}/u_{\text{th}}$, and $F(r) = \text{erf} \left( r/\sqrt{2} \right) - \sqrt{2\pi} r e^{-r^2/2}$. Here we assume that electron and proton share a common temperature $T_b$ with the hydrogen atom.

The DM heating term due to interactions with baryons is given by 

$$
\frac{dQ_\chi}{dt} = n_\text{H} x_e \sum_{t=e,p} \frac{m_t m_\chi}{(m_\chi + m_t)^2 u_{\text{th},t}^2} \sigma_{0,t} \sqrt{\frac{2}{\pi}} \frac{e^{-r_t^2/2}}{u_{\text{th},t}^2} \left( T_b - T_\chi \right) + m_t \frac{F(r_t)}{r_t}.
$$

(B.2)

where $n_e = n_p = n_\text{H} x_e$ is assumed.

The $D$ term in Eq. (5.4) is given by \cite{40} 

$$
D(V_{\chi b}) = \frac{\rho_m \sigma_0}{m_\chi + m_b} \frac{F(r)}{V_{\chi b}^2},
$$

(B.3)

where we consider both electron and proton as the target baryons.

References

\cite{1} S. Furlanetto, S. P. Oh and F. Briggs, “Cosmology at Low Frequencies: The 21 cm Transition and the High-Redshift Universe,” Phys. Rept. 433, 181-301 (2006) [arXiv:astro-ph/0608032 [astro-ph]].

\cite{2} M. F. Morales and J. S. B. Wyithe, “Reionization and Cosmology with 21 cm Fluctuations,” Ann. Rev. Astron. Astrophys. 48, 127-171 (2010) [arXiv:0910.3010 [astro-ph.CO]].

\cite{3} J. R. Pritchard and A. Loeb, “21-cm cosmology,” Rept. Prog. Phys. 75, 086901 (2012) [arXiv:1109.6012 [astro-ph.CO]].

\cite{4} J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen and N. Mahesh, “An absorption profile centred at 78 megahertz in the sky-averaged spectrum,” Nature 555, no.7694, 67-70 (2018) [arXiv:1810.05912 [astro-ph.CO]].

\cite{5} A. Cohen, A. Fialkov, R. Barkana and M. Lotem, “Charting the Parameter Space of the Global 21-cm Signal,” Mon. Not. Roy. Astron. Soc. 472, no.2, 1915-1931 (2017) [arXiv:1609.02312 [astro-ph.CO]].

\cite{6} C. Feng and G. Holder, “Enhanced global signal of neutral hydrogen due to excess radiation at cosmic dawn,” Astrophys. J. Lett. 858, no.2, L17 (2018) [arXiv:1802.07432 [astro-ph.CO]].
[7] S. Fraser, A. Hektor, G. Hütsi, K. Kannike, C. Marzo, L. Marzola, C. Spethmann, A. Racioppi, M. Raidal and V. Vaskonen, et al. “The EDGES 21 cm Anomaly and Properties of Dark Matter,” Phys. Lett. B 785, 159-164 (2018) [arXiv:1803.03245 [hep-ph]].

[8] T. Moroi, K. Nakayama and Y. Tang, “Axion-photon conversion and effects on 21 cm observation,” Phys. Lett. B 783, 301-305 (2018) [arXiv:1804.10378 [hep-ph]].

[9] E. D. Kovetz, I. Cholis and D. E. Kaplan, “Bounds on ultralight hidden-photon dark matter from observation of the 21 cm signal at cosmic dawn,” Phys. Rev. D 99, no.12, 123511 (2019) [arXiv:1809.01139 [astro-ph.CO]].

[10] J. B. Muñoz and A. Loeb, “A small amount of mini-charged dark matter could cool the baryons in the early Universe,” Nature 557, no.7707, 684 (2018) [arXiv:1802.10094 [astro-ph.CO]].

[11] A. Fialkov, R. Barkana and A. Cohen, “Constraining Baryon–Dark Matter Scattering with the Cosmic Dawn 21-cm Signal,” Phys. Rev. Lett. 121, 011101 (2018) [arXiv:1802.10577 [astro-ph.CO]].

[12] A. Berlin, D. Hooper, G. Krnjaic and S. D. McDermott, “Severely Constraining Dark Matter Interpretations of the 21-cm Anomaly,” Phys. Rev. Lett. 121, no.1, 011102 (2018) [arXiv:1803.02804 [hep-ph]].

[13] R. Barkana, N. J. Outmezguine, D. Redigolo and T. Volansky, “Strong constraints on light dark matter interpretation of the EDGES signal,” Phys. Rev. D 98, no.10, 103005 (2018) [arXiv:1803.03091 [hep-ph]].

[14] R. Barkana, “Possible interaction between baryons and dark-matter particles revealed by the first stars,” Nature 555, no.7694, 71-74 (2018) [arXiv:1803.06698 [astro-ph.CO]].

[15] T. R. Slatyer and C. Wu, “Early-Universe constraints on dark matter-baryon scattering and their implications for a global 21 cm signal,” Phys. Rev. D 98, no.2, 023013 (2018) [arXiv:1803.09734 [astro-ph.CO]].

[16] L. B. Jia, “Dark photon portal dark matter with the 21-cm anomaly,” Eur. Phys. J. C 79, no.1, 80 (2019) [arXiv:1804.07934 [hep-ph]].

[17] N. Houston, C. Li, T. Li, Q. Yang and X. Zhang, “Natural Explanation for 21 cm Absorption Signals via Axion-Induced Cooling,” Phys. Rev. Lett. 121, no.11, 111301 (2018) [arXiv:1805.04426 [hep-ph]].

[18] P. Sikivie, Phys. Dark Univ. 24, 100289 (2019) doi:10.1016/j.dark.2019.100289 [arXiv:1805.05577 [astro-ph.CO]].

[19] E. D. Kovetz, V. Poulin, V. Gluscevic, K. K. Boddy, R. Barkana and M. Kamionkowski, “Tighter limits on dark matter explanations of the anomalous EDGES 21 cm signal,” Phys. Rev. D 98, no.10, 103529 (2018) [arXiv:1807.11482 [astro-ph.CO]].

[20] K. K. Boddy, V. Gluscevic, V. Poulin, E. D. Kovetz, M. Kamionkowski and R. Barkana, “Critical assessment of CMB limits on dark matter-baryon scattering: New treatment of the relative bulk velocity,” Phys. Rev. D 98, no.12, 123506 (2018) [arXiv:1808.00001 [astro-ph.CO]].

[21] C. Creque-Sarbinowski, L. Ji, E. D. Kovetz and M. Kamionkowski, “Direct millicharged dark matter cannot explain the EDGES signal,” Phys. Rev. D 100, no.2, 023528 (2019) [arXiv:1903.09154 [astro-ph.CO]].
[22] H. Liu, N. J. Outmezguine, D. Redigolo and T. Volansky, “Reviving Millicharged Dark Matter for 21-cm Cosmology,” Phys. Rev. D 100, no.12, 123011 (2019) [arXiv:1908.06986 [hep-ph]].

[23] C. Li and Y. F. Cai, “Searching for the Dark Force with 21-cm Spectrum in Light of EDGES,” Phys. Lett. B 788, 70-75 (2019) [arXiv:1804.04816 [astro-ph.CO]].

[24] A. A. Prinz, R. Baggs, J. Ballam, S. Ecklund, C. Fertig, J. A. Jaros, K. Kase, A. Kulikov, W. G. J. Langeveld and R. Leonard, et al. “Search for millicharged particles at SLAC,” Phys. Rev. Lett. 81, 1175-1178 (1998) [arXiv:hep-ex/9804008 [hep-ex]].

[25] S. Dubovsky, D. Gorbunov and G. Rubtsov, “Narrowing the window for millicharged particles by CMB anisotropy,” JETP Lett. 79, 1-5 (2004) [arXiv:hep-ph/0311189 [hep-ph]].

[26] A. Dolgov, S. Dubovsky, G. Rubtsov and I. Tkachev, “Constraints on millicharged particles from Planck data,” Phys. Rev. D 88, no.11, 117701 (2013) [arXiv:1310.2376 [hep-ph]].

[27] R. de Putter, O. Doré, J. Gleyzes, D. Green and J. Meyers, “Dark Matter Interactions, Helium, and the Cosmic Microwave Background,” Phys. Rev. Lett. 122, no.4, 041301 (2019) [arXiv:1805.11616 [astro-ph.CO]].

[28] J. H. Chang, R. Essig and S. D. McDermott, “Supernova 1987A Constraints on Sub-GeV Dark Sectors, Millicharged Particles, the QCD Axion, and an Axion-like Particle,” JHEP 09, 051 (2018) [arXiv:1803.00993 [hep-ph]].

[29] C. Boehm, M. J. Dolan and C. McCabe, “A Lower Bound on the Mass of Cold Thermal Dark Matter from Planck,” JCAP 08, 041 (2013) [arXiv:1303.6270 [hep-ph]].

[30] P. F. Depta, M. Hufnagel, K. Schmidt-Hoberg and S. Wild, “BBN constraints on the annihilation of MeV-scale dark matter,” JCAP 04, 029 (2019) [arXiv:1901.06944 [hep-ph]].

[31] B. Kors and P. Nath, “Aspects of the Stueckelberg extension,” JHEP 07, 069 (2005) [arXiv:hep-ph/0503208 [hep-ph]].

[32] D. Feldman, Z. Liu and P. Nath, “Probing a very narrow Z-prime boson with CDF and D0 data,” Phys. Rev. Lett. 97, 021801 (2006) [arXiv:hep-ph/0603039 [hep-ph]].

[33] D. Feldman, Z. Liu and P. Nath, “The Stueckelberg Z Prime at the LHC: Discovery Potential, Signature Spaces and Model Discrimination,” JHEP 11, 007 (2006) [arXiv:hep-ph/0606294 [hep-ph]].

[34] D. Feldman, Z. Liu and P. Nath, “The Stueckelberg Z-prime Extension with Kinetic Mixing and Milli-Charged Dark Matter From the Hidden Sector,” Phys. Rev. D 75, 115001 (2007) [arXiv:hep-ph/0702123 [hep-ph]].

[35] D. Feldman, Z. Liu, P. Nath and B. D. Nelson, “Explaining PAMELA and WMAP data through Coannihilations in Extended SUGRA with Collider Implications,” Phys. Rev. D 80, 075001 (2009) [arXiv:0907.5392 [hep-ph]].

[36] M. Du, Z. Liu and V. Tran, “Enhanced Long-Lived Dark Photon Signals at the LHC,” JHEP 05, 055 (2020) [arXiv:1912.00422 [hep-ph]].

[37] J. M. Cline, G. Dupuis, Z. Liu and W. Xue, “The windows for kinetically mixed Z’-mediated dark matter and the galactic center gamma ray excess,” JHEP 08, 131 (2014) [arXiv:1405.7691 [hep-ph]].

[38] E. W. Kolb and M. S. Turner, “The Early Universe,” Front. Phys. 69, 1-547 (1990)
[39] P. Ade et al. [Planck], “Planck 2015 results. XIII. Cosmological parameters,” Astron. Astrophys. 594, A13 (2016) [arXiv:1502.01589 [astro-ph.CO]].

[40] J. B. Muñoz, E. D. Kovetz and Y. Ali-Haimoud, “Heating of Baryons due to Scattering with Dark Matter During the Dark Ages,” Phys. Rev. D 92, no.8, 083528 (2015) [arXiv:1509.00029 [astro-ph.CO]].

[41] S. Seager, D. D. Sasselov and D. Scott, “How exactly did the universe become neutral?,” Astrophys. J. Suppl. 128, 407-430 (2000) [arXiv:astro-ph/9912182 [astro-ph]].

[42] P. J. E. Peebles, “Principles of physical cosmology.”

[43] Y. Ali-Haimoud and C. M. Hirata, “HyRec: A fast and highly accurate primordial hydrogen and helium recombination code,” Phys. Rev. D 83, 043513 (2011) [arXiv:1011.3758 [astro-ph.CO]].

[44] S. S. McGaugh, “Predictions for the Sky-Averaged Depth of the 21 cm Absorption Signal at High Redshift in Cosmologies with and without Nonbaryonic Cold Dark Matter,” Phys. Rev. Lett. 121, no.8, 081305 (2018) [arXiv:1808.02532 [astro-ph.CO]].

[45] S. Chatrchyan et al. [CMS], “Search for Fractionally Charged Particles in pp Collisions at $\sqrt{s} = 7$ TeV,” Phys. Rev. D 87, no.9, 092008 (2013) [arXiv:1210.2311 [hep-ex]].

[46] G. Magill, R. Plestid, M. Pospelov and Y. D. Tsai, “Millicharged particles in neutrino experiments,” Phys. Rev. Lett. 122, no.7, 071801 (2019) [arXiv:1806.03310 [hep-ph]].

[47] R. Acciarri et al. [ArgoNeuT], “Improved Limits on Millicharged Particles Using the ArgoNeuT Experiment at Fermilab,” Phys. Rev. Lett. 124, no.13, 131801 (2020) [arXiv:1911.07996 [hep-ex]].

[48] A. Ball, G. Beauregard, J. Brooke, C. Campagnari, M. Carrigan, M. Citron, J. De La Haye, A. De Roeck, Y. Elskens and R. E. Franco, et al. “Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV,” Phys. Rev. D 102, no.3, 032002 (2020) [arXiv:2005.06518 [hep-ex]].

[49] S. Davidson, S. Hannestad and G. Raffelt, “Updated bounds on millicharged particles,” JHEP 05, 003 (2000) [arXiv:hep-ph/0001179 [hep-ph]].

[50] A. Badertscher, P. Crivelli, W. Fetscher, U. Gendotti, S. Gninenko, V. Postoev, A. Rubbia, V. Samoylenko and D. Sillou, “An Improved Limit on Invisible Decays of Positronium,” Phys. Rev. D 75, 032004 (2007) [arXiv:hep-ex/0609059 [hep-ex]].

[51] T. Emken, R. Essig, C. Kouvaris and M. Sholapurkar, “Direct Detection of Strongly Interacting Sub-GeV Dark Matter via Electron Recoils,” JCAP 09, 070 (2019) [arXiv:1905.06348 [hep-ph]].

[52] M. S. Mahdawi and G. R. Farrar, “Constraints on Dark Matter with a moderately large and velocity-dependent DM-nucleon cross-section,” JCAP 10, 007 (2018) [arXiv:1804.03073 [hep-ph]].

[53] M. Fabbrichesi, E. Gabrielli and G. Lanfranchi, “The Dark Photon,” [arXiv:2005.01515 [hep-ph]].

[54] S. Dodelson, “Modern Cosmology.”

[55] S. D. McDermott, H. Yu and K. M. Zurek, “Turning off the Lights: How Dark is Dark Matter?,” Phys. Rev. D 83, 063509 (2011) [arXiv:1011.2907 [hep-ph]].