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The cosmological ultra-low frequency radio background: a solution to the Hubble tension and the 21-cm excess trough

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Abstract Recent observations of the Cosmic Microwave Background and the Hubble Space Telescope obtain two different values of the Hubble constant with a discrepancy of at least 4.4σ, which is now known as the Hubble tension. On the other hand, observations of 21-cm signal from the EDGES experiment reveal an unexpected excess absorption trough. These results give a big challenge to the standard cosmological model – the ΛCDM model. In this article, we propose that the existence of a cosmological ultra-low frequency radio background (ULFRB) can simultaneously reconcile both discrepancies. The best-fit amounts of the energy density of this additional radio component based on the two problems give an excellent agreement with each other. The extra radio component could be arisen from the simulated decay of axions in the early universe.

1 Introduction

Following the standard cosmological model (the ΛCDM model), precise measurements of the Cosmic Microwave Background (CMB) radiation from the Planck mission have obtained a set of cosmological parameters [1]. In particular, the best-fit value of the Hubble constant is $H_0 = 67.4 \pm 0.5$ km/s/Mpc, which is different from the one obtained by the SH0ES Team using the Hubble Space Telescope (HST): $H_0 = 74.03 \pm 1.42$ km/s/Mpc in 2018 [2] and $H_0 = 73.30 \pm 1.04$ km/s/Mpc in 2022 [3]. The discrepancy is more than 4.4σ and the problem is now known as the Hubble tension. A more recent analysis from Pantheon+ got $H_0 = 73.5 \pm 1.1$ km/s/Mpc [4], which is consistent with an over 5σ tension with the Planck result. Another recent study from 'The Tip of the Red Giant Branch (TRGB)' also gives similar result $H_0 = 72.94 \pm 1.98$ km/s/Mpc [5]. These recent measurements make the Hubble tension problem much more severe than before. Many solutions have been proposed to reconcile the Hubble tension, such as adding extra radiation due to neutrinos [6–8], self-interacting neutrino models [9], specific dark energy models [10,11], presence of primordial magnetic field [12], warm decaying dark matter models [13], and proposing interaction between dark energy and dark matter [14].

On the other hand, observations of 21-cm signal from the EDGES experiment have revealed some cosmological information in the cosmic dawn era (redshift $z \approx 16-19$) [15]. In this era, the ultra-violet radiation from the first stars couples the spin temperature back to the baryonic gas. The absorption strength (trough) can be quantitatively characterized by the redshifted brightness temperature T_{21} [16]. Intriguingly, the magnitude of T_{21} is much larger than the one predicted by the ΛCDM model, with a discrepancy of 3.8σ [15]. Various solutions have been proposed to account for the excess absorption trough, including the scattering between dark matter and baryons [17,18], excess radio background [19], millicharged dark matter [18], decaying relic neutrinos [20], dark matter vacuum energy interaction [21] and the absence of cosmological dark matter [22].

In this article, we propose the existence of a large radiation component of ultra-low frequency radio background (ULFRB) produced in the early universe. The extra radiation component can come from dark matter decay, such as axion dark matter decay. The axion dark matter might be created at the very early epoch [23–25]. Many past studies have already suggested QCD axion with mass $\sim 10^{-5}$ eV can decay to give ultra-low frequency photons via the weak axion-photon coupling [24]. Although the spontaneous decay rate is very slow (the coupling is extremely weak), it can be enhanced almost exponentially in a photon background via stimulated emission mechanism [26–28]. Since there was a high energy density of photons at the beginning stage of our universe, the existence of a large radiation component (ULFRB) due to the

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stimulated axion decay is quite likely (see Sect. 4). The extra radio background can somewhat alter the Hubble function in the radiation-dominated era to reconcile the Hubble tension. It can also provide extra scatterings between matter and photons such that lowering of the matter temperature would be resulted in the cosmic dawn era. We show that the required energy density of the ULFRB to solve the respective problem gives an excellent agreement with each other. One may argue that the additional radio component would have unphysical impact of the CMB or other observable consequences. Nevertheless, the extra radio component has a very low frequency (probably lower than 10 GHz at the epoch of recombination), which does not have any interaction with the baryons and CMB during recombination epoch. The frequency of the radio background for this extra component present may be lower than kHz, which is extremely difficult for us to detect unless we can block the noise from Earth (e.g. detect from the far side of the moon).

In fact, some previous studies have considered the proposal of the existence of background radio excess to explain the EDGES signal [19]. They have considered the existence of a very small component of astrophysical radio background with frequency ∼ 1 GHz, which can change the spin temperature coupling between matter and radiation to account for the EDGES results. Nevertheless, the study in [29] has shown that this proposal is quite unlikely to explain the EDGES signal. Our proposal of the ULFRB is a large radiation component with a very low frequency ($\ll 1$ MHz at present), which is different from the previous proposal suggested in [19].

2 Solving the Hubble tension

The Hubble constant can be calculated based on the acoustic peaks appeared in the CMB anisotropy spectra and the galaxy power spectra. For the peaks in the galaxy power spectra (also known as the Baryonic Acoustic Oscillation (BAO) peaks), their features can be characterized by the sound horizon $r_s(z)$ at the cosmic drag epoch (redshift $z_d \approx 1060$), which is given by [6]

$$r_s(z) = \int_z^\infty \frac{c_s}{H(z')} dz', \tag{1}$$

where

$$c_s = c\left[3 + \frac{9\Omega_{b0}}{4\Omega_{\gamma 0}}(1+z)^{-1}\right]^{-1/2} \tag{2}$$

and $H(z) = H_0[\Omega_{m0}(1+z)^3 + \Omega_{R0}(1+z)^4]^{1/2}$ is the Hubble function in the early epoch. Here, Ω_{b0}, Ω_{m0}, $\Omega_{\gamma 0}$ and Ω_{R0} are the present cosmological density parameters of baryons, matter, photons and radiation (including active neutrinos) respectively. Theoretically, we can see that $r_s(z_d)$ depends on the Hubble function so that it is cosmological model-dependent.

On the other hand, the value of $r_s(z_d)$ could be found by the BAO measurements such as the extended Baryon Oscillation Spectroscopic Survey (eBOSS) [30]. The observed value is somewhat model-independent, but it is inversely proportional to the Hubble parameter h, where $H_0 = 100h$ km/s/Mpc. Recent observations give $r_s(z_d) = (101.2 \pm 2.3)h^{-1}$ Mpc [31].

Suppose we add an additional cosmic radio background component, the ULFRB, with the cosmological density parameter $\Omega_{\rm ULFRB}$ so that we have $\Omega_{\gamma 0} = \Omega_{\rm CMB} + \Omega_{\rm ULFRB}$ and $\Omega_{R0} = \Omega_{\rm CMB}[1+0.68(N_{\rm eff}/3)]+\Omega_{\rm ULFRB}$, where $N_{\rm eff}$ is the effective number of neutrino species. Therefore, putting this additional ULFRB component would alter the Hubble function $H(z)$ as well as $r_s(z_d)$ in the early epoch. Then, we can calculate the revised Hubble parameter h by comparing the new calculated $r_s(z_d)$ with the observed value.

Putting the corresponding parameters fitted in the CMB spectrum $\Omega_{m0}h^2 = 0.14$, $\Omega_{\rm CMB}h^2 = 2.47 \times 10^{-5}$ and $N = 3.046$ [1], and writing $\Omega_{\rm ULFRB} = \varepsilon\Omega_{\rm CMB}$, we can get the value of ε as a function of h (see Fig. 1). The values of h for different ε could be best fitted by the expression $h \approx 0.0040\varepsilon^2 + 0.046\varepsilon + 0.67$. For the standard ΛCDM model, we have $\varepsilon = 0$ and get $h = 0.67$. To match the value obtained by the local measurement $h = 0.7403 \pm 0.0142$ [2], from the χ^2 plot in Fig. 2, we find the best-fit $\varepsilon = 1.25 \pm 0.25$ (68% C.L.). Here, we have used a more conservative Hubble parameter obtained from [2] rather than the more recent one from Pantheon+ [4].

Note that the SH0ES result has been automatically satisfied in the above analysis, though we have used the BAO data, because we have adopted the local Hubble parameter $h = 0.7403 \pm 0.0142$. Also, in principle we can generate a new set of cosmological parameters through a Markov chain Monte Carlo (MCMC) approach after adding this extra radio background component. However, we need to specify the formation time of this extra component, its frequency spectrum, etc. If the radio background originates from particle decay, the time of the decaying epoch and the duration can affect the fittings significantly. Therefore, the actual details are highly model-dependent. The scope of this study is to discuss a possible new direction to solve the Hubble tension problem. Thus, without the actual details of the radio background or particle decaying mechanism, the parameter ε has set to be a free parameter in the analysis by fixing the cosmological parameters fitted with the ΛCDM model for illustration.

Moreover, from a theoretical perspective, the CMB spectrum is sensitive to the cosmological parameters. However, the additional ULFRB appears at the very low frequency regime, which does not affect the CMB spectral fits from observational data (the uncertainties of the ultra-low frequency CMB data are very large). Here, the additional

Fig. 1 The graph of the Hubble parameter h against ε. The red dotted lines indicate the CMB bound of h measured by the Planck mission following the ΛCDM model [1]. The blue dashed lines indicate the local bound of h measured by the SH0ES Team [2]

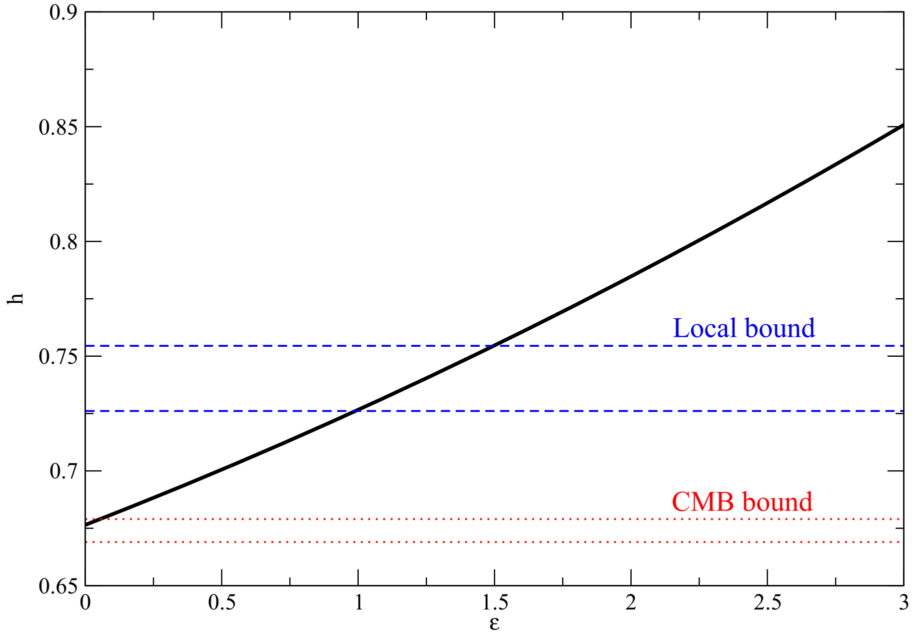
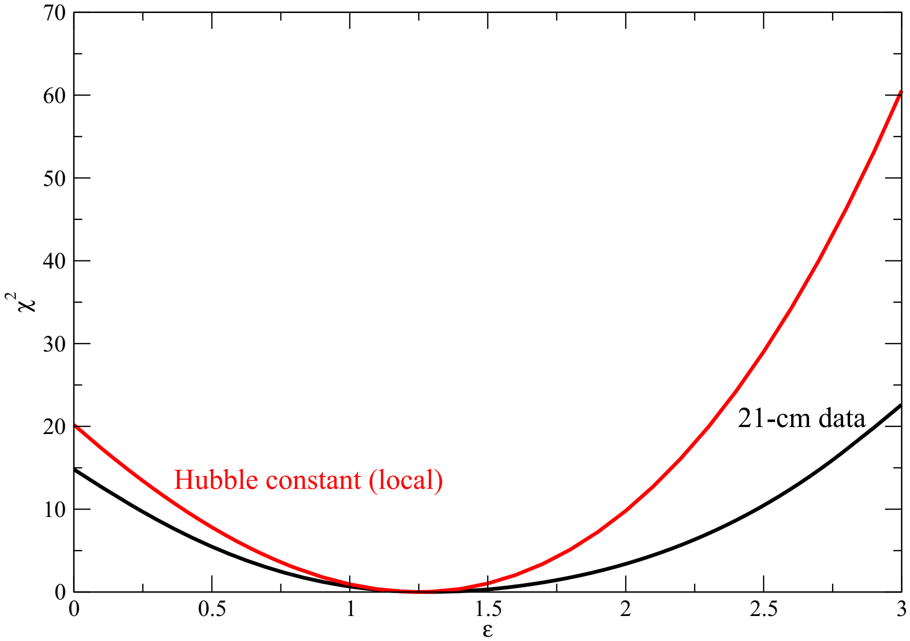


Fig. 2 The χ^2 values as a function of ε for matching the local Hubble constant measured by the SH0ES Team (red) and the 21-cm observations by EDGES (black)



ULFRB only changes the sound horizon (the early epoch in the Friedmann equation). Even if we use the MCMC approach to find the ranges of the cosmological parameters based on the sound horizon fits, we also need to fit those ranges with the CMB spectrum. Nevertheless, to satisfy the CMB spectral constraints, the allowed cosmological parameters should not be different from the standard ranges too much, since the proposed additional ULFRB in the present study does not affect the CMB spectral fits. Therefore, the cosmological parameters are severely constrained by the CMB spectrum rather than the sound horizon. Ultimately, the fit of the sound horizon or Friedmann equation can provide a meaningful constraint of ε only. Our choice of using the standard cosmological parameters fitted in previous CMB studies would be justified. The uncertainty of the only free parameter $\varepsilon = 1.25 \pm 0.25$ can almost reflect the actual uncertainty in our proposal.

3 Solving the 21-cm excess trough

During the cosmic dawn era, the first sources of radiation produce a large amount of Lyman-α photons which couple the spin temperature to the color temperature of the Lyman-

α photons. Due to the multiple scattering of the Lyman-α photons with hydrogen atoms, the spin temperature T_S is strongly coupled to the matter kinetic temperature T_K (see the review of the 21-cm cosmology in [16]). The observed brightness temperature relative to the CMB is given by [16]

$$T_{21} \approx 27(1-x)\left(\frac{1-Y_P}{0.76}\right)\left(\frac{\Omega_{b0}h^2}{0.023}\right)\sqrt{\frac{0.15(1+z)}{10\Omega_{m0}h^2}} \times \left(1-\frac{T_{\mathrm{CMB}}}{T_S}\right)\ \mathrm{mK}, \tag{3}$$

where x is the ionization fraction and $Y_P \approx 0.245$ is the helium abundance. In the cosmic dawn era, the Wouthuysen-Field effect dominates the scattering between the Lyman-α photons and hydrogen atoms so that the spin temperature would be very close to the matter kinetic temperature (i.e. $T_S \approx T_K$). However, the accurate relation between T_S and T_K depends on the uncertain radiation flux in the cosmic dawn era [32]. In the followings, we simply assume $T_S = T_K$ and this is a very good approximation when the Lyman-α scattering is vigorous.

The evolution of the matter kinetic temperature and the ionization fraction can be given by [33]

$$(1+z)\frac{dT_K}{dz} = 2T_K + \frac{8x\sigma_T a_R T_{\mathrm{CMB}}^4 (T_K - T_{\mathrm{CMB}})}{3m_e c H(z)(1+f_{\mathrm{He}}+x)} \tag{4}$$

and

$$\frac{dx}{dz} = \frac{C}{H(z)(1+z)}\left[n_H x^2 \alpha_B - 4(1-x)\beta_B e^{-E_{21}/kT_{\mathrm{CMB}}}\right], \tag{5}$$

where σ_T is the Thomson cross section, f_{He} is the Helium fraction, n_H is the hydrogen number density, $T_{\mathrm{CMB}} = 2.725(1+z)$ K is the CMB temperature, C is the Peebles-C factor, α_B is the case-B recombination coefficient, β_B is the photoionization coefficient and $E_{21} = 10.2$ eV [34,35].

The standard ΛCDM model predicts $T_K \sim 6-7$ K and $x \sim 2 \times 10^{-4}$ [33] at $z = 17$, which give $T_{21} \approx -220$ mK. However, observations from EDGES has reported a much smaller trough $T_{21} \approx -500^{+200}_{-500}$ mK (99% C.L. intervals), which corresponds to a 3.8σ excess [15]. The observed T_{21} implies that the matter kinetic temperature should be as low as $T_K \approx 3.26^{+1.94}_{-1.58}$ K at $z = 17$ [18].

If there is an additional ULFRB as mentioned above, this would give an extra scattering between the baryonic matter and the ULFRB, which can affect both the evolutions of the matter kinetic temperature and the ionization fraction. Therefore, we revise Eq. (4) by adding an additional scattering term due to the ULFRB:

$$(1+z)\frac{dT_K}{dz} = 2T_K + \left(\frac{x}{1+f_{\mathrm{He}}+x}\right) \times \frac{8\sigma_T a_R T_{\mathrm{CMB}}^4 [(T_K - T_{\mathrm{CMB}}) + \varepsilon T_K]}{3m_e c H(z)}. \tag{6}$$

Here, similar to the energy density of the CMB, the energy density of the ULFRB is $u_{\mathrm{ULFRB}} \propto (1+z)^4$. Therefore, we have written $u_{\mathrm{ULFRB}} = \varepsilon a_R T_{CMB}^4$ in Eq. (6). Also, the effective temperature of the ULFRB is much less than T_K. Adding this extra scattering term would further enhance the cooling of matter. Since the evolution of the ionization fraction is also coupled with the matter kinetic temperature, lowering of the matter kinetic temperature would decrease the ionization fraction and suppress the Compton heating between the CMB and matter. We can calculate T_K and T_{21} at $z = 17$ as a function of ε (see Fig. 3). We also plot the revised matter kinetic temperature and the ionization fraction in Fig. 4, and compare with the predictions following the ΛCDM model. Based on the χ^2 plot in Fig. 2, the best-fit value of ε for solving the 21-cm excess trough is $\varepsilon \approx 1.28$ (1σ range: $\varepsilon \approx 0.9 - 1.7$), which surprisingly agrees with the one obtained in solving the Hubble tension. Note that the extra scattering term considered above is not ad hoc but follow from standard physics. The additional large quantity of radiation can come from dark matter decay (e.g. axion decay, see the next section). This gives a direct predictable consequence for the cosmological effect of the evolution of matter's temperature, like the recent proposal of the cosmic radio background originated from primordial black hole evaporation [36].

If the excess T_{21} signal observed by EDGES and the Hubble constant determined by the SH0ES Team (local measurement) are both correct, the predictions based on the ΛCDM model would have a combined 5.8σ tension with the observations. Nevertheless, in our scenario with $\varepsilon \approx 1.3$, the tension can be reconciled completely without adding many extra parameters and assumptions. Therefore, our simple scenario is a very good solution to both of the Hubble tension and the 21-cm excess trough problem.

4 Possible source of the ULFRB

What is the possible source of the ULFRB? One possible origin is the photons coming from axion decay. It has been suggested that the cosmological dark matter could be made up of a kind of hypothetical particles called axions. The existence of axions can solve the CP-violation problem of the strong interaction [23,37]. Cosmological axions could be produced thermally [38] or non-thermally (e.g. misalignment mechanism) [23,24]. The possible range of cosmological axion mass could be $m_a \sim 10^{-9} - 10$ eV [24]. In particular, one of the recent benchmark cosmological axion models proposes $m_a \sim 10^{-5}$ eV, which could be produced in the very early universe [23–25].

Theoretically, axions can decay. The spontaneous decay of an axion particle gives two identical photons with frequency $\nu = m_a c^2/2\pi\hbar$. For $m_a \sim 10^{-5}$ eV, the frequency of the spontaneous decay is $\sim$ 1 GHz, which is in radio band.

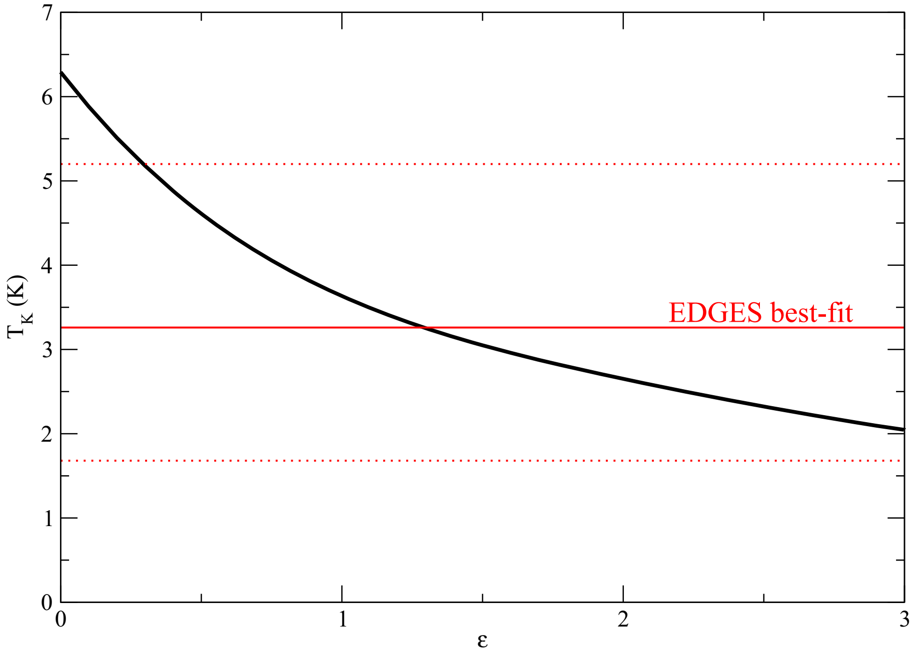


Fig. 3 The black solid line represents the matter kinetic temperature T_K against ε at redshift $z = 17$. The red solid line indicate the best-fit T_K at $z = 17$ based on the EDGES observations [15,18]. The red dotted lines indicate the 3σ upper and lower limits of the best-fit T_K observed by EDGES

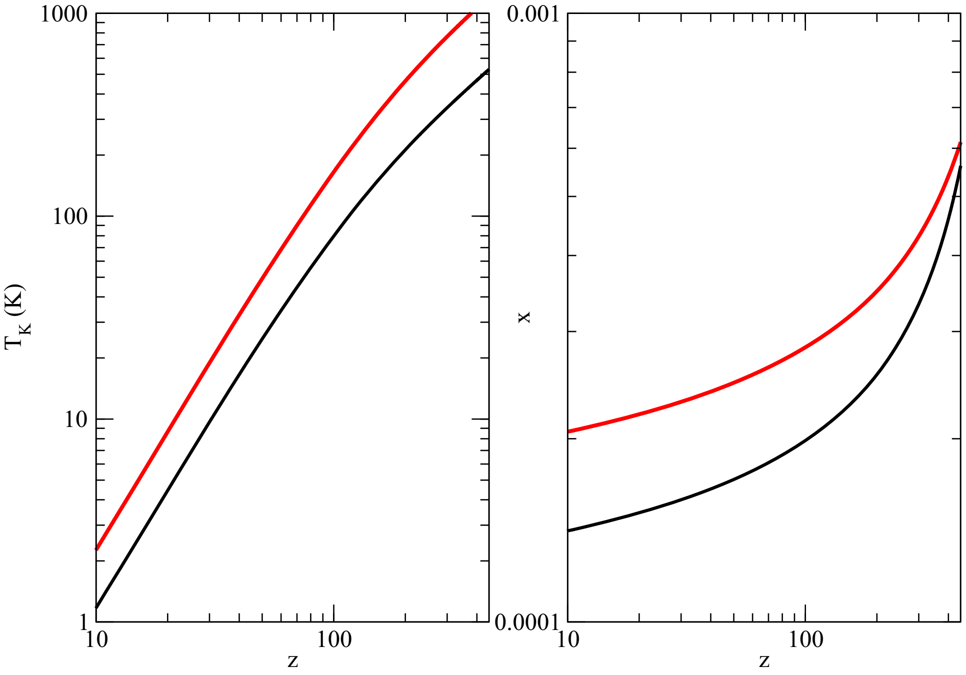


Fig. 4 The evolutions of the matter kinetic temperature T_K and the ionization fraction x for the standard ΛCDM model (red lines) and our model (black lines)

Nevertheless, due to the extremely small axion-photon coupling constant, the decay time can be as large as 10^{40} s [24], which is much longer than the age of our universe. Therefore, axions are massive and very stable so that they can be a good candidate of dark matter.

However, if there exists a photon background with the frequency same as that of the decaying photons, the photon background would stimulate the axion decay so that the decay rate would be greatly enhanced by a factor f, which is the photon occupation number for the background photons [26, 27,39]. The photon occupation number is given by

$$f = (e^{m_a c^2/2kT_{\rm CMB}} - 1)^{-1} \approx \frac{2kT_{\rm CMB}}{m_a c^2}. \tag{7}$$

In the early universe, the photon background has a very high temperature $T_{\rm CMB}$. For $T_{\rm CMB} \sim 10^{10}$ K and $m_a \sim 10^{-5}$ eV, f can be larger than 10^{10}. Furthermore, if the axion momentum spread is not too large and the gravitational potential well in which axions are bound is not too strong, some decaying photons would contribute to the photon occupation number responsible for stimulating the decay [40,41]. As a result, an exponential growth of photons would be achieved due to the stimulated decay of axions. This can greatly enhance the axion decay rate so that a significant portion of axions could decay. Nevertheless, when the CMB cools down due to cosmic expansion, the photon occupation number decreases and the axion decay would be suppressed. The remaining axions might finally become the stable cold dark matter component in our universe [28].

If our scenario is correct and the ULFRB is produced by axion decay, the best-fit value of $\varepsilon = 1.3$ would correspond to the decay of 0.02% of the cosmological axion dark matter. However, due to the cosmic expansion, the frequency of the ULFRB would decrease and nowadays it might be smaller than 1 kHz, which is quite difficult for us to detect. Since the frequency and the energy of these photons is too low, there is almost no observable effect for baryonic matter and dark matter. The actual cosmic radio background component would be easily hindered from the noise generated by Earth. If one can set up observations from the far side of the moon, the radio noise could be blocked significantly so that we can directly detect the cosmic radio background component. Moreover, as only 0.02% of the cosmological axion dark matter has been decayed, the impact for structure formation is nearly negligible. In this regard, there is no implication for the dark matter simulation study or galactic rotation curve analysis. Nevertheless, the additional ULFRB can somewhat change the cosmic expansion history in the early universe (e.g. radiation dominated era). Therefore, any observational data sensitive to the early cosmic expansion history can indirectly examine our proposal.

Another recent study has proposed that the evaporation of primordial black holes can provide a cosmic radio background to explain the EDGES trough [36]. Although the idea is different from the axion decay, the overall effect could be almost the same. Therefore, such a proposal is also a possible source of the radio background.

5 Discussion

In this article, we show that the existence of the ULFRB can simultaneously solve the Hubble tension and the 21-cm excess trough problem. The ULFRB could possibly originate from the decay of cosmological axion dark matter in the early universe. The best-fit energy density of the ULFRB is about 1.3 times of the CMB energy density. This is a simple scenario without invoking many unknown physics or any modified gravity. Combining the Hubble tension and the 21-cm excess trough problem, the statistical discrepancy encountered by the ΛCDM model is more than 5.8σ. Nevertheless, our proposed scenario with $\varepsilon \approx 1.3$ can fully reconcile the discrepancy.

In our proposal, the extra radiation added to the Hubble function might speed up the early expansion of the universe a bit so that it might violate other cosmological constraints. For example, the observed Helium fraction predicted by the Big Bang Nucleosynthesis (BBN) has constrained the amount of radiation in the very early universe [42]. Fortunately, if the axion decay takes time, most of the ULFRB photons would be produced after the BBN epoch. Therefore, our proposal can escape from this severe constraint.

On the other hand, the extra radiation added might alter the Hubble expansion rate during the recombination and change the recombination history. In fact, there are two popular strategies to solve the Hubble tension problem [43]. This first strategy is to vary the relativistic degrees of freedom $N_{\rm eff}$. In this strategy, the standard recombination history following the ΛCDM model is adopted. Some recent studies are using this strategy to solve the Hubble tension problem [7,44]. However, the CMB observations have constrained the value of $N_{\rm eff}$ to 3.04 ± 0.33 (95% C.L.) [45,46]. Therefore, this strategy seems not easy to tackle the Hubble tension problem. The second strategy is to modify the recombination history. In this strategy, the recombination history is free to vary so that an earlier recombination would be resulted [43]. This is allowed in the CMB model because the sound horizon and recombination redshift parameters could be free to change in the CMB spectral fits if we do not follow the standard recombination history and the ΛCDM model. Some recent studies are considering the change in the recombination history by allowing a time-varying electron mass [47] or a much higher CMB temperature [48] to solve the Hubble tension problem. In our proposal, we are following the second strategy to change the recombination history. A large amount of low-energy photons (ULFRB) produced would alter the recombination history (also the sound horizon) so that a new Hubble constant would be obtained. If the ULFRB is produced by decaying dark matter, the radiation density would increase while the matter density would decrease simultaneously. The change in matter density might compensate some of the effect on recombination rate due to the increase in radiation density. Therefore, the overall change in the Hubble expansion rate is not large. Since the matter density and radiation density are time-varying, we are not following the ΛCDM model and the standard recombination history. In present analysis, we only provide a background test for the idea of adding an ULFRB. Therefore, a more comprehensive analysis combining the data of CMB, BAO and BBN is definitely required. It is also important to examine the possible effects of our proposal on other cosmological constraints, such as the weak lensing constraints derived by the Dark Energy Survey (DES) [49] and the Kilo-Degree Survey (KiDS) [50], and the acoustic scale measurement derived by the CMB spectrum [1,51]. In view of this, further combined tests of our scenario involving all of the cosmological parameters might be required. However, it might depend on the exact details of the dark matter decay.

This proposal could also be potentially verified or falsified by direct observations. We predict that there exists an ULFRB with a specific frequency, unlike the blackbody CMB spectrum in our universe. Nevertheless, the frequency could be lower than 1 kHz, which makes the detection very difficult because of the radio noise generated by human activities. We may need to detect this ultra-low frequency signal far away from the Earth or on the far side of the Moon, in which the radio noise could be minimized.

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