

Mass-varying dark matter and its cosmological signature

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Nontrivial dark sector physics continues to be an interesting avenue in our quest to the nature of dark matter. In this paper, we study the cosmological signatures of mass-varying dark matter where its mass changes from zero to a nonzero value in the early Universe. We compute the changes in various observables, such as, the linear matter power spectrum and the cosmic microwave background anisotropy power spectrum. We explain the origin of the effects and point out a qualitative similarity between this model and a warm dark matter cosmology with no sudden mass transition. Finally, we do a simple analytical study to estimate the constraint on the parameters of this model from the Lyman- α forest data.

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I. INTRODUCTION

Though the presence of dark matter has been confirmed through its gravitational effect, the particle nature of dark matter (DM) remains a complete mystery. Combined with a cosmological constant (Λ), the simple hypothesis of a cold, collisionless dark matter (CDM) that may or may not interact with ordinary Standard Model (SM) particles is consistent with all cosmological observations to date, on scales ranging from individual galaxies [1], to galaxy clusters [2,3], to cosmological scales as probed by large scale structure [4,5], and cosmic microwave background (CMB) measurements [6–8].

During the course of the last several decades, myriad laboratory experiments have been performed to look for any nongravitational interaction of DM. However, none of them so far have yielded any conclusive evidence for its presence. Together they have put stringent limits on the conventional DM theories [9], and have compelled us to theorize novel DM models with nontrivial particle physics phenomena in the dark sector. Such effort have also led us to venture beyond the *vanilla* DM models and design experiments that are better optimized to look for observable signatures such models [10–13]. On the observation frontier, multiple galactic scale astrophysical anomalies, such as the *diversity problem* [14], *too big to fail problem* [15], and the *Hubble discrepancy* [16,17] have raised questions about the simple Λ CDM model of cosmology, and drawn attention to particle physics models beyond this paradigm.

In this paper we explore one such avenue of nonstandard dark matter physics. We ask the question—can the mass of dark matter particle be dynamical with cosmic time? In particular, we explore the scenario where DM species was made of massless and hence relativistic particles in the early Universe, but after a gradual phase transition at a certain redshift, its constituents acquire mass—eventually forming the CDM population in the Universe. Such a scenario can also be seen as a generalization of two popular cosmological models, namely, the ordinary warm dark matter (WDM) model and the dark radiation model. The former being the limit when the transition happens at a much earlier time, and the latter is when the transition is very late. A myriad of works have studied the nonstandard effects of these cosmological models [18–20]. However, this work broadens the theory space of the cosmological models in a straightforward but interesting way. We also note that a variety of related cosmological models have been studied before such as, late-forming DM [21], ballistic DM [22], etc.

The particle physics aspect of mass-varying DM (MVDM) has been explored before in a few works [23–30]. One example is when the dark matter mass is directly proportional to the vacuum expectation value of a scalar field. The DM mass becomes time varying when the scalar rolls over a potential [24]. In this model, the scalar vacuum expectation value is inversely related to the DM particle number density, leading to an increase in the DM mass as the Universe expands. A similar scenario (though in different particle physics context) was introduced for mass-varying neutrino models, where a fermionic particle can have a dynamical mass due to its interaction with a scalar field which may also play the role of the dark energy [25,26]

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(also see [27]). Adopting the same mechanism, a mass varying dark matter model was recently introduced in Ref. [29]. A fast transition from radiation to matter was discussed in [31]. In this case, a phase transition in a very light scalar field sector is responsible for such fast change in equation of state. After the transition, the scalar starts oscillating coherently around a minimum of a quadratic potential and starts behaving like dark matter. In the above studies, the particle phenomenology was discussed, but any detailed study on its cosmological implication was missing. Recently, phase space constraint on MVDM were discussed in Ref. [32].

In this work, we compute the effects of MVDM in cosmological observables, such as, the linear matter power spectrum and the CMB anisotropy power spectra. We find that the massless phase of MVDM before the transition creates a *suppression* in the linear matter power spectrum that is also reflected in the CMB power spectra. We explain the origin of the effects and point out a qualitative similarity between this model and a warm dark matter cosmology with no sudden mass transition. As our model deviates from the standard Λ CDM scenario at small length scales, we constrain our model using an analytical method with the Lyman- α data from HIRES/MIKE [33,34]. We show that this data already constrains a significant part of the new parameter space. It is important to note that we do not adopt a specific particle physics model but rather focus on a phenomenological model of time variation of the dark matter mass. Our aim is to utilize the known gravitational portal between the dark and the visible sectors of a nonstandard cosmological model without committing to a specific particle physics model. Depending on the specific model however, there might be additional signatures of nonstandard dark sector phenomena which will require dedicated studies.

The outline of the paper is as follows. We describe the background evolution of MVDM and compute the new effects in the background level observable in Sec. II. In Sec. III, we solve the Boltzmann equations of the perturbation quantities and compute the changes in the matter and CMB power spectra, followed by statistical comparison of our results with the SDSS Lyman- α data. Finally, We conclude in Sec. V.

II. BACKGROUND EVOLUTION

We will assume MVDM to be a fermionic thermal species with a temperature T to keep the model as generic as possible. In this case, the evolution of its background quantities, like energy density, are controlled by its time-varying mass $m(z)$. For the time variation of the mass, we consider a phenomenological model of formation of cold DM of mass M from a massless radiation-like species at a redshift z_t . Specifically, we take the following form of $m(z)$ to make the transition between the two epochs smooth,

$$m(z) = \frac{M}{2} \left[1 - \tanh\left(\frac{z - z_t}{\Delta z}\right) \right]. \quad (1)$$

Here, M is the final mass of MVDM, and Δz is the duration of the transition in redshift space. The exact nature and the duration of the transition depend on the underlying particle physics model [29,30]. In this work, we will only consider fast transition, i.e. $\Delta z \ll z_t$. The slow transition scenario $\Delta z \ll z_t$ is qualitatively similar to a WDM model. The actual form of the function $m(z)$ depend on the details of the model too. The form chosen in Eq. (1) is purely phenomenological with a minimal number of extra parameters.

The phase space distribution $f(q)$ of MVDM is given by a Fermi-Dirac distribution with a temperature T . For our work, we choose q to be the comoving momenta of the particle. We also define $\epsilon = \sqrt{q^2 + m(a)^2 a^2}$ to be the energy of the particle; $a = 1/(1+z)$ is the scale factor of the Universe. (For choice of momenta and energy see e.g. [35]). As $m(z)$ is zero before the redshift of transition, z_t , MVDM behaves as radiation. After z_t , it could behave as radiation or matter depending on its final mass and temperature at that time. It is relativistic if $m(z)/T \ll 3$ during the transition, eventually becoming matterlike, or nonrelativistic if $m(z)/T \gtrsim 3$. The total energy density of MVDM is given by an energy integral over the phase-space distribution,

$$\rho_{\text{MVDM}} = a^{-4} \int dq d\Omega q^2 f(q/T) \epsilon. \quad (2)$$

The energy density at the current epoch is matched to the best-fit energy density of the CDM particle by Planck. As the particle is nonrelativistic at the current epoch, $\rho_{\text{MVDM}} \propto T^3 M$. The final energy density of MVDM depends only this combination of mass and temperature and, as discussed later, the evolution of perturbations depends on only $m(z)/T$. This allows us to express our results in terms of the ratio M/T . In Fig. 1, we show the evolution of the energy density for two different values of z_t that are not excluded by the data. The jumps in $\rho_{\text{MVDM}}(z)$ are given by the quantity $\rho_{\text{MVDM}}^{\text{NR}}(z \rightarrow z_t^+) / \rho_{\text{MVDM}}^{\text{R}}(z \rightarrow z_t^-) = M/T_t$ in the respective cases where T_t is the temperature of MVDM at $z = z_t$.¹ These two values of z_t are chosen to show the difference from WDM in the evolution of ρ_{MVDM} . In the rest of the paper, we will fix MVDM temperature to $T = T_\gamma/10$ as a representative value. However, the results are qualitatively same for other lower values of the temperature. The extra period of time MVDM evolves as radiation between the gray vertical band in Fig. 1 and z_t is the reason behind the

¹Note that ρ_{MVDM} is a continuous function by the construction of $m(z)$ as shown in Eq. (1); only the transition happens very quickly.

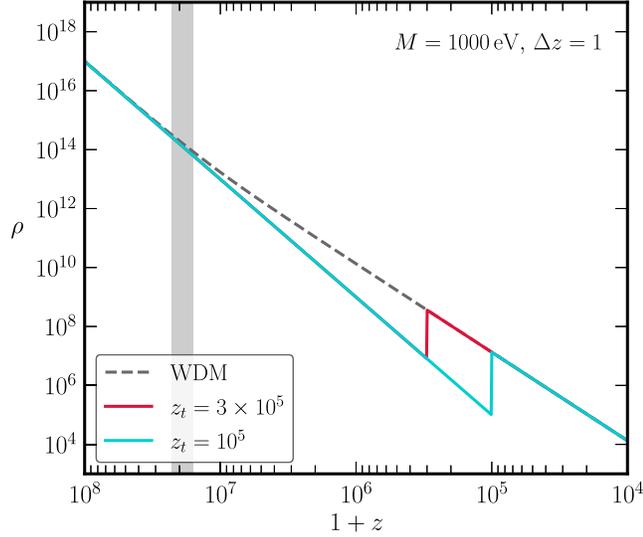


FIG. 1. The background density as a function of redshift for mass $M = 1$ keV, temperature $T = T_\gamma/10$, and two different transition redshifts $z_t = 3 \times 10^5$ and 10^5 (red and cyan, respectively). The jumps in the density evolution at z_t are given by $M/T(z_t) = 142$ and 426 in the respective cases. The density evolution of WDM of the same mass is also shown as a dashed line for comparison. The vertical light gray-shaded band shows the time when the WDM particles become nonrelativistic.

new effects on the matter and CMB power spectra as we will see below.

In this work, we will only consider the scenario $M/T_t \gg 1$ which implies that the DM becomes instantly nonrelativistic when its mass turns nonzero at z_t . As discussed before, this choice bridges the gap between WDM and dark radiation models. In passing, we want to compare the present scenario with the ballistic dark matter model considered in Ref. [22] which also had a relativistic to nonrelativistic phase transition in the dark sector. However, in that case, the particles were tightly coupled and behaved like a fluid in the relativistic phase that can sustain acoustic waves. Hence, it has characteristic features that are distinct from the present noninteracting model.

A. Extra relativistic degrees of freedom

In the early Universe before z_t , the MVDM acts as radiation and would add to the total relativistic energy density in addition to the photons and neutrinos. This can be quantified as the extra relativistic degrees of freedom ΔN_{eff} defined as

$$\Delta N_{\text{eff}} = \frac{\rho_{\text{MVDM}}}{\rho_\nu^{\text{th}}}, \quad (3)$$

where ρ_ν^{th} is the thermal energy density of a single neutrino species. Because the Universe was radiation dominated before $z \simeq 3400$, any extra relativistic energy would have changed the rate of expansion of the Universe. This would have affected the production of light elements during the

epoch of big bang nucleosynthesis (BBN) and could also affect the angular power spectra of the fluctuations in the CMB coming from the epoch of recombination. Very precise observational data from these two eras helps us constrain ΔN_{eff} . The fit to the data of the light element abundance in the Universe yields $N_{\text{eff}} = 2.85 \pm 0.3$ [36]. The CMB data from Planck 2018 gives $N_{\text{eff}} = 2.89^{+0.36}_{-0.38}$ for the TTTEEE + lensing analysis [37].

The energy density ρ_{MVDM} evolves as $\sim(1+z)^3$ after z_t , and as $\sim(1+z)^4$ before z_t . For a fast transition, we can ignore the duration of the transition. Then the energy density changes by a factor of M/T_t . Hence, $\rho_{\text{MVDM}}(z)$ prior to z_t can be written as

$$\rho_{\text{MVDM}}(z) \approx \rho_{\text{MVDM}}(z=0) \frac{T_t (1+z)^4}{M (1+z_t)}. \quad (4)$$

Here we have normalized the energy density by fixing its today's value $\rho_{\text{MVDM}}(z=0)$ to the observed CDM density $\Omega_c h^2 = 0.12$ [37]. For this rough estimate we neglect the current Λ -dominated epoch because, as we will see later, the ΔN_{eff} does not yield the strongest bound on this model. Using Eq. (4) in (3) then gives

$$\Delta N_{\text{eff}} \approx \frac{\rho_{\text{MVDM}}(z=0) T_t}{\rho_\nu^{\text{th}}(z=0) M (1+z_t)}, \quad (5)$$

during BBN. At present time, neutrino energy density is miniscule relative to DM. In fact, $\rho_{\text{MVDM}}(z=0)/\rho_\nu(z=0) \simeq 10^5$, and, as will be shown shortly, we will mostly consider $z_t \gtrsim 10^5$. Therefore, for MVDM that are nonrelativistic at z_t (i.e. $T_t/M \ll 1$) will have $\Delta N_{\text{eff}} \lesssim 0.01$ and will not contribute significantly to the extra relativistic degrees of freedom in the early Universe during BBN. Moreover, as we are interested in transition epochs much earlier than the recombination and the MVDM density is fixed to the CDM density today, the ΔN_{eff} by definition vanishes during recombination. Hence, the CMB bound on ΔN_{eff} does not constrain this model.

III. MATTER AND CMB POWER SPECTRA

The radiation phase of MVDM will also affect the evolution of the density fluctuations in the Universe before z_t . Below, we discuss these effects using the Boltzmann equations in the linear approximation of the perturbations.

The perturbation evolution equations can be obtained from the Boltzmann hierarchy [35],

$$\begin{aligned} \dot{\Psi}_0 &= -\frac{qk}{\epsilon} \Psi_1 - \dot{\phi} \frac{d \ln f_0}{d \ln q}, \\ \dot{\Psi}_1 &= \frac{qk}{3\epsilon} (\Psi_0 - 2\Psi_2) - \frac{ek}{3q} \psi \frac{d \ln f_0}{d \ln q}, \\ \dot{\Psi}_\ell &= \frac{qk}{(2\ell+1)\epsilon} [\ell \Psi_{\ell-1} - (\ell+1) \Psi_{\ell+1}], \quad \ell \geq 2. \end{aligned} \quad (6)$$

Here, Ψ_ℓ are the ℓ -th multipole of the perturbations to the phase space distribution, ϕ and ψ are the metric perturbations, f_0 is the unperturbed Fermi-Dirac distribution, and $\epsilon = \sqrt{q^2 + a^2 m(a)^2}$ as mentioned earlier. Macroscopic variables such as density contrast, bulk velocity, and anisotropic stress can be constructed by integrating Eq. (6) over comoving momenta. The non-vanishing mass prohibits us from performing the phase space integral (over comoving momentum q) analytically. Another variable in our study is the unperturbed temperature, T , in the Fermi-Dirac distribution function. From Eq. (6) it can be shown that the relevant variables are q/T and ϵ/T or, at late times when the particles are non-relativistic, the evolution of the system of equations is determined by $m(z)/T$. We modify the Boltzmann solver code CLASS to add a new species with time-varying mass $m(z)$, and compute the linear matter power spectrum and the CMB anisotropy power spectra [38].

In the left panel of Fig. 2, we show the ratio of the matter power spectra to that in Λ CDM $P/P_{\Lambda\text{CDM}}$ for two values of z_t with $\Delta z = 1$ and $M = 1000$ eV, and the right panel shows the same ratio for two values of M . The main feature in the new power spectrum is the suppression of power at small scale. The *cutoff scale* k_t , above which this happens, is the scale that entered the horizon at redshift z_t . For a mode $k > k_t$, MVDM was still relativistic when it entered the horizon and was free streaming. This inhibits the growth of structures at those scales resulting in a power suppression. Note that this is qualitatively similar to the analogous feature observed in warm dark matter power spectrum [39–42].

This suppression can also be understood from the Boltzmann hierarchy [Eq. (6)], which is an expansion in

q/ϵ . As the particle enters the nonrelativistic phase, $q \simeq ma$ and $q \ll ma$ at later epochs. This allows us to truncate the hierarchy in Eq. (6) and obtain the corresponding fluid equations (e.g. see Refs. [35,40,43]). The free-streaming scale at the time of this transition determines the cutoff scale k_t above which the perturbations are wiped out. The free-streaming length is inversely proportional to the thermal velocity of particles. The thermal velocity is close to the speed of light at the transition and decreases slowly as $1/a$ at later epochs. The comoving free streaming wave number k_{fs} reaches a minimum at the epoch of transition but continue to be important for much later epochs for perturbations at small scales. In this paper we consider $\Delta z/z_t \ll 1$ or fast transition from a massless to a massive particle. The models with slow transition could differ significantly from the case we study because of the expected behavior of free-streaming scale. Unlike the WDM model, for which this transition occurs with the onset of the nonrelativistic era, and hence its perturbations are driven solely by the mass of the particle, z_t is responsible for the start of this phase in our case. This is an important distinction between the two models.

Later transition means the MVDM was relativistic for longer time, which in turn means they could wash out structures at larger length scales, i.e. smaller k modes. This is evident from the left panel of Fig. 2 as the model with $z_t = 10^5$ case has a smaller cutoff scale k_t relative to the WDM model with the same mass. Therefore, it shows that the mass of DM is not the only parameter that controls the cutoff scale, as opposed to the WDM cosmology. From the right panel of Fig. 2, one can see that the cutoff scale also depends on DM mass with smaller M having smaller k_t .

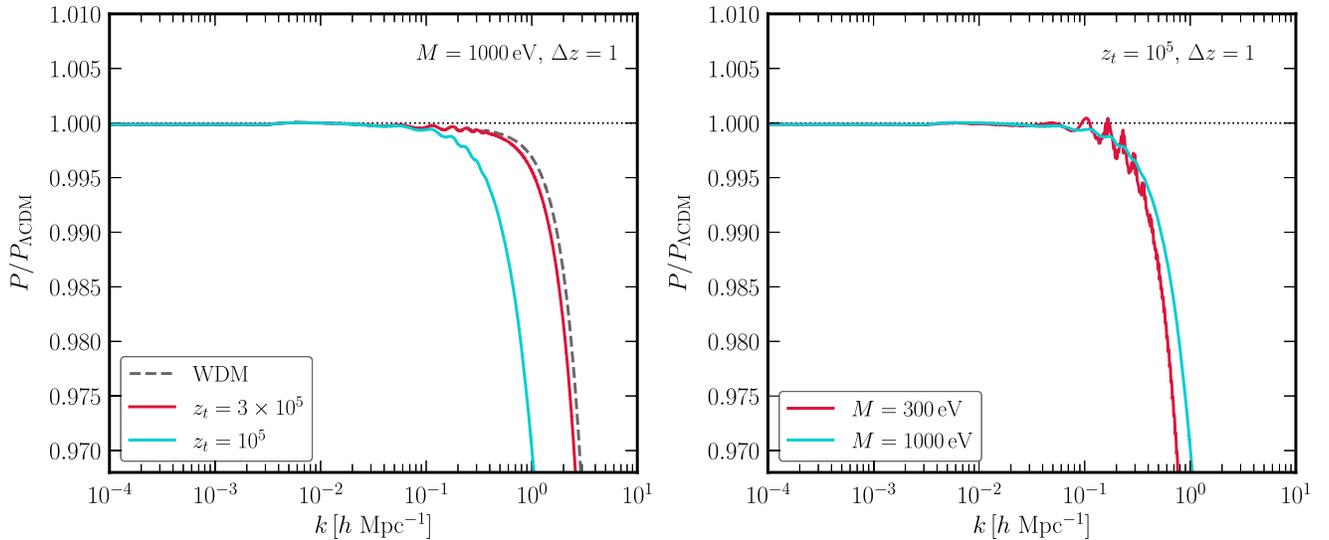


FIG. 2. Ratio of the linear matter power spectrum for MVDM to that of Λ CDM, $P(k)/P_{\Lambda\text{CDM}}(k)$ for different values of z_t with $M = 1000$ eV (Left), and different values of M with $z_t = 10^5$ (Right). See text for the explanation of different features, such as the power suppression at small scales and the wiggles near the cutoff scale. For comparison, we also show the ratio in WDM cosmology with same mass M on the left panel. The temperature is assumed to be $T = T_\gamma/10$ and $\Delta z = 1$.

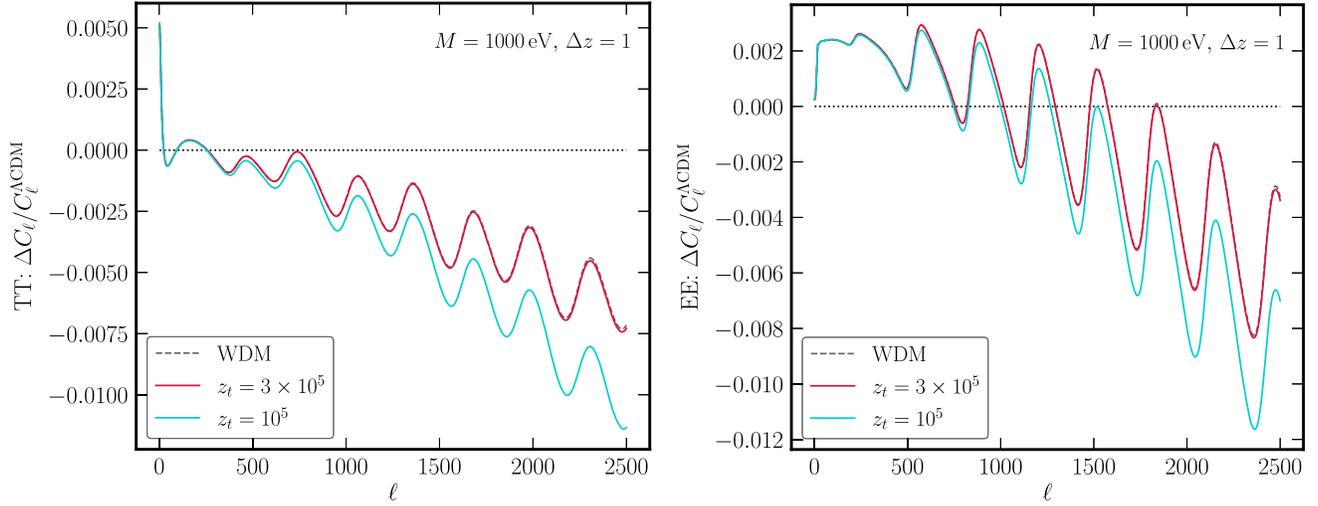


FIG. 3. The relative change $\Delta C_\ell/C_\ell^{\Lambda\text{CDM}}$ of the CMB TT (Left) and EE (Right) angular power spectra for two values of z_t and $M = 1000$ eV, $\Delta z = 1$. See text for the explanation of the oscillatory feature and the power suppression seen here. The corresponding spectrum for the same mass WDM is also shown for comparison. The MVDM spectrum deviates from WDM for lower transition redshift z_t .

Another feature of the ratio of power spectra in Fig. 2 is the oscillations around $k \gtrsim 0.1 h \text{ Mpc}^{-1}$. This is a result of a phase shift in the matter power spectrum relative to ΛCDM [44,45]. Any free streaming relativistic species travels at the speed of light that is greater than the sound speed in the photon-baryon bath before recombination. As a result, they drag the metric perturbations via gravity in a radiation-dominated Universe. This in turn creates a phase shift in the acoustic oscillations in the thermal bath manifesting itself in the observable density fluctuations in the Universe today. Such phase shifts have been observed in both CMB anisotropy power spectrum and the baryonic acoustic oscillation (BAO) in the matter power spectrum [45–47]. Its presence (or lack of it) has been used to look for other new physics scenarios, including neutrino self-interaction [48–56]. In the present scenario, the MVDM generates this phase shift during its relativistic phase prior to z_t due to its small but nonzero ΔN_{eff} . Because the ΛCDM matter power spectrum has the BAO oscillations in the range $0.1 \lesssim k \lesssim 1 h \text{ Mpc}^{-1}$, the phase shift manifests itself in that BAO oscillations [45]. As expected from Eq. (5), this oscillatory feature in the matter power spectrum becomes more pronounced (see the right panel of Fig. 2) for lighter mass because it increases ΔN_{eff} before z_t .

The temperature and polarization anisotropy power spectra of the CMB are also modified by the new physics in MVDM. In Fig. 3, we show the relative changes to the TT and EE power spectra. For comparison, we also the spectrum for the WDM model with the same DM mass. The most prominent feature is the power suppression at smaller angular scales which is arises because of the same reason as in the matter power spectrum. This effect is similar to the WDM model. However, the spectrum deviates from the

WDM curve for lower z_t as expected because of the longer radiation phase. A phase shift is also present in the CMB spectrum because of the additional ΔN_{eff} in the MVDM model. It creates the wiggles seen in Fig. 3. The wiggles are more pronounced in the EE spectrum as the peaks are sharper compared to the TT spectrum.

IV. CONSTRAINTS FROM LYMAN- α FOREST DATA

The Lyman- α forest correspond to the absorption features on the redward side of the rest frame Lyman- α radiation from distant quasars by the intervening neutral hydrogen gas clouds. The density and amplitude of these features tell us about fluctuations in the neutral hydrogen density of the mostly ionized diffuse intergalactic medium (IGM) in the postreionization era in the redshift range $2.5 \leq z \leq 6$. This in turn tells us about the DM structure formation at those redshifts. Hydrodynamical simulations have shown that the observed fluctuations correspond to mildly nonlinear density contrast ($\delta < 10$) of the underlying density field (e.g. [33,57–63] and references therein). The Lyman- α data allows one to probe the fluctuations of the density field at scales as small as the Jeans' scale of the IGM ($k \simeq 5\text{--}7 \text{ Mpc}^{-1}$) in the redshift range $2.5 < z < 6$. The CMB and galaxy data probe much larger scales $k \lesssim 0.1 \text{ Mpc}^{-1}$.² Therefore, the Lyman- α data is particularly suited for our study as the our results deviate

²Planck measures the CMB angular power spectrum for $\ell \leq 2500$. The linear scale k , corresponding to the angular scale ℓ , can be computed approximately from $k\eta_0 \simeq \ell$. For the best-fit cosmological model, the conformal time at the current epoch, $\eta_0 \simeq 1400 \text{ Mpc}$.

significantly from the Λ CDM (and WDM) model at small scales (see Fig. 2).

In this section, we estimate the bounds on the parameters M and z_t using the Lyman- α forest data from HIRES/MIKE spectrographs [33,34]. We use a formalism prescribed in Refs. [64,65] to derive the bounds, exploiting the qualitative similarity between the power suppression effects of our model and a WDM model. We essentially compare the area under the 1D matter power spectrum curve with the Λ CDM model. We compute the 1D matter power spectrum as

$$P_{1D}(k) = \frac{1}{2\pi} \int_k^\infty dk' k' P(k'), \quad (7)$$

and define the ratio $r(k)$ of the 1D power spectrum with respect to that of the Λ CDM model,

$$r(k) = \frac{P_{1D}(k)}{P_{\Lambda\text{CDM}}(k)}. \quad (8)$$

Finally, we compare the area under $r(k)$ with a WDM model, that is excluded at 95% confidence level, to put limit in the $M/T_t - z_t$ plane,

$$A = \int_{k_{\min}}^{k_{\max}} dk r(k), \quad \Delta A \equiv 1 - \frac{A}{A_{\Lambda\text{CDM}}} < 0.38. \quad (9)$$

Here, $k_{\min} = 0.5h \text{ Mpc}^{-1}$ and $k_{\max} = 20h \text{ Mpc}^{-1}$ enclosing the scales that are probed by the Lyman- α data [34].

In Fig. 4 we show 2σ (95% confidence level) exclusion region in the plane of M/T_t and z_t as described above. In the limit of small M/T , the MVDM is still relativistic when $m(z)$ becomes nonzero. This scenario is identical to a WDM model (labeled by a gray shade in Fig. 4). The shape of the exclusion region follows from the discussion in the previous section. Generally for smaller M/T_t , the lightness of MVDM and large free-streaming length creates more power suppression at small scales than allowed by the data. Whereas, for larger M/T_t , the free-streaming length decreases, and the parameter space is allowed. We also show the ΔN_{eff} limit from BBN as a blue-shaded region. The CMB data from Planck 2018 yield a slightly weaker bound. We show only the space above $z_t = 4 \times 10^4$, below which the code CLASS runs into numerical trouble while solving the Boltzmann equations. We believe below this redshift the transition is so delayed that the radiation phase of MVDM before z_t would create large changes in the power spectrum drawing tight constraints from both CMB and Lyman- α data. We plan to investigate this part of the parameter space further in a future work.

The limit $\Delta A < 0.38$ used in Eq. (9) is approximate, and based on an earlier analysis corresponding to a WDM mass $m_{\text{WDM}} = 3.5 \text{ keV}$. More recent studies, using both

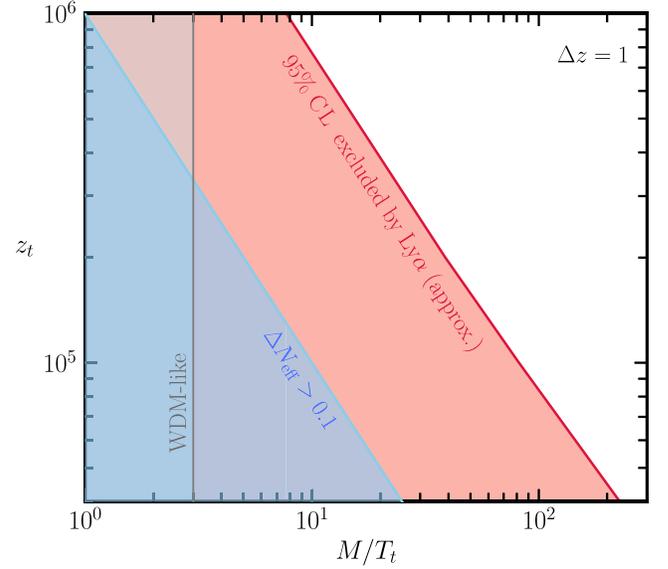


FIG. 4. The approximate 2σ (95% CL) exclusion region in the plane of M/T_t and z_t using the HIRES/MIKE Lyman- α data [34], following the analysis of Refs. [64,65]. A fast transition with $\Delta z = 1$ is assumed. The ΔN_{eff} limit from BBN is also shown as a blue-shaded region. The vertical gray-shaded region on the left is where MVDM is still relativistic when $m(z)$ becomes nonzero and the model is similar to a warm dark matter.

Lyman- α and other methods, have yielded different values for the lower limit [20,66–70] (including one with a weak preference for a nonzero WDM mass [70]). However, we note that the differences between these results are not large enough to drastically affect our results. Finally, we note that a more comprehensive comparison of our model with the Lyman- α data will require a statistical analysis which we leave for a future work.

V. CONCLUSION

We have studied the cosmological signatures of a mass-varying dark matter model where the mass $m(z)$ of the DM particle changes from zero to M at a redshift z_t . We consider scenarios in which the transition is fast, i.e. $\Delta z/z \ll 1$ and the MVDM is nonrelativistic when $m(z)$ becomes nonzero. We have computed the linear-matter power spectrum and the CMB angular power spectra in this model.

The main new effects on the matter and CMB power spectra are power suppression at small scales and a phase shift in the BAO and CMB peaks. These effects are qualitatively similar to that of a WDM model. In both cases, the free streaming of DM with large thermal velocity impedes structure formation at small scales resulting in matter power suppression. However, relative to a WDM of same mass, MVDM yields greater suppression and impact larger scales (or a smaller cutoff scale k_t). This is because the particle is massless before the transition redshift z_t .

Therefore, unlike the WDM model, both the mass M and transition redshift z_t determine the relevant scales at which the power is suppressed and the amount of suppression.

Similarly, the CMB temperature and polarization anisotropy power spectra receive changes in this model that are broadly similar to the WDM case but distinct from it. In addition to the suppression of power, there is a phase shift in the oscillations of the CMB spectra. This could constitute a tell-tale signature of any new radiation and/or secret interaction in the early Universe [44,46]. Near future CMB experiments, that plan to measure the polarization anisotropies more precisely, can attempt to detect such phase shift in the power spectra.

As the expected departure of our model from the standard cases is more prominent at small scales, we constrain this model using the Lyman- α data. In the current work, we do not attempt to pinpoint the unique features of our model. The degeneracy between M and z_t might make

this task difficult. For example, a small-scale power suppression might be explainable either by WDM or MVDM of larger mass but later z_t . Further work is needed to find any qualitative differences between the two models and quantify them. In a future work, we plan to statistically analyze this model in more detail, and quantify its differences from a WDM model.

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