Cosmological constraints on mass-varying dark matter

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As one of the fundamental unknowns of our Universe, the mass of dark matter remains to be a topic of great interest. We consider the possibility of a time-variation of the dark matter mass. We study the cosmological constraints on a model where the dark matter mass transitions from zero to a finite value in the early Universe. In this model, the matter power spectrum exhibits power suppression below a certain scale that depends on the epoch of transition, and the angular power spectrum of the cosmic microwave background shows a distinctive phase shift and power suppression at small scales. We use the latest cosmic microwave background data and the S_8 priors from weak lensing data to place a lower limit on the transition redshift. We also find that the data from the Atacama Cosmology Telescope (ACT) show a mild preference for the mass-varying dark matter model over Λ Cold Dark Matter (Λ CDM).

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I. INTRODUCTION

Planck satellite observations of the cosmic microwave background (CMB) tell us that dark matter (DM) forms the dominant share of all matter in the Universe [1]. The most successful theory to explain the observations at different scales, ranging from galaxies and galaxy clusters to the horizon, is the ACDM model, which includes a cold, collisionless form of dark matter (CDM). All of these observations are, however, based on the gravitational effects of DM on the visible Universe, and hence, its exact particle nature remains elusive to date.

Numerous laboratory and space-based experiments have been conducted over the past few decades to shed light on the elusive particle nature of DM. However, despite these efforts, no conclusive evidence of nongravitational interactions with standard model particles has been found yet. In particular, the nondetection of weakly interacting massive particles (WIMPs), arguably considered one of the most promising candidates for DM over the last two decades, has raised concerns [2]. This has resulted in a wider search program in the DM model space. It also underscores the importance of a more careful study of the gravitational signatures of DM in cosmology. Additionally, problems related to the structure formation of the universe at a small scale, collectively known as the diversity problem, have further motivated the exploration of beyond-cold dark matter (CDM) models. While some of these issues have been addressed through baryonic feedback, it is still worthwhile to investigate alternative scenarios beyond CDM for cosmological purposes.

Warm dark matter (WDM) and mixed dark matter, which is a combination of hot dark matter (HDM) and WDM or CDM, have been proposed as alternatives to CDM to solve small-scale problems due to their free-streaming properties, which result in less structure formation at small scales [3–6]. It reduces the number of satellite galaxies in halos and suppresses the halo mass function. However, in addition to these small-scale problems, the standard Λ CDM model has been challenged by cosmological tensions such as the Hubble tension and the S₈ tension [7].

The clumpiness of the matter distribution in our Universe is parametrized by $S_8 = \sigma_8 (\Omega_m/0.3)^{0.5}$, where σ_8 is the root mean square of matter fluctuations on an 8 h^{-1} Mpc scale, and Ω_m is the total matter abundance. In ACDM, Planck observation yields $S_8 = 0.832 \pm 0.013$ [1]. The observation of weak lensing of galaxies from the CFHTLenS collaboration initially pointed to a higher $S_8 = 0.799 \pm$ 0.015 at the 2σ level [8,9] in the framework of ACDM. However, a reanalysis with the combination of DES data [10] and KiDS/Viking [11,12] established the tension at the 3σ level with the value $S_8 = 0.755^{+0.019}_{-0.021}$ [12]. The tension arises due to a lower matter clustering at scales $k \approx 0.1-1 h$ Mpc⁻¹, and a reduction in the amplitude

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of matter fluctuations on those scales can effectively resolve it.

Despite numerous attempts, alternative CDM scenarios such as WDM or mixed dark matter models have failed to resolve the S_8 tension. Adding massive thermal neutrinos, one of the proposed solutions does not alleviate the tension. This is because an increase in ΔN_{eff} can raise σ_8 and lower Ω_{m} , which exacerbates the tension [1,13]. Various approaches have been explored, such as decaying dark matter [14–21] and nonthermal dark matter models [13,22–26], to address this issue.

In this paper, we investigate the cosmological signatures of a novel scenario of mass-varying DM (MVDM) that is a natural generalization of the extra radiation N_{eff} and the WDM models. The realization of an MVDM scenario has been previously suggested in many particle physics models [27–30]. However, in this work, we refrain from assuming any particular model and assume a phenomenological relation proposed in [31].

Previously, cosmological effects of late formation of massive DM were studied in Refs. [31–34]. Similar phenomenon can also occur in models with late primordial black hole formation [35,36]. Particularly in Ref. [31], some of the authors showed in a model-independent approach that the Lyman- α data from small scale places strong constraint on the transition redshift z_t . Here, we follow a similar phenomenological approach to model the time-variation of DM mass from zero to a finite value.

We perform a comprehensive Bayesian analysis of this model using the latest cosmic microwave background (CMB) data from Planck and ACT. Our study reveals a lower bound on the transition redshift z_t ($\log_{10} z_t > 4.55$) and a mild preference for a DM mass of 41.7 eV when the Planck [1] and KIDS1000 + BOSS + 2dfLenS weak lensing data [37] are taken into account. The results indicate that the weak lensing data favors this model. Moreover, the inclusion of weak lensing data significantly reduces the S_8 tension as compared to the case when only Planck data is considered.

The plan of the paper is as follows. In Sec. II, we describe the model and the framework of MVDM and discuss its cosmological signatures. In Sec. III, we present the method of our Markov Chain Monte Carlo (MCMC) analysis with different datasets and discuss the results in Sec. IV. Finally, we conclude in Sec. V.

II. BACKGROUND DENSITY EVOLUTION AND PERTURBATIONS

In this study, we consider MVDM to be a fermionic particle with a temperature T. We do not commit to a particular particle physics model for the mass variation of DM. Instead, we adopt the phenomenological relation proposed in Ref. [31]. The essential concept is that DM was massless and relativistic in the early time, and at a transition redshift of z_t , it underwent an instantaneous transition to



FIG. 1. Evolution of background energy density with redshifts is plotted for mass M = 100 eV for a transitional redshift $z_t = 10^5$.

become nonrelativistic. The form of m(z) considered in this analysis is as follows

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

Here, *M* denotes the final mass of MVDM, whereas the redshift duration of the transition is represented by Δz . We note that, due to our assumption of the instantaneous nature of the transition, the value of Δz is considerably smaller than that of z_t ($\Delta z \ll z_t$). Consequently, the DM instantaneously loses its relativistic nature, necessitating the ratio of the final mass (*M*) to the transition temperature (T_t) to be significantly greater than unity, i.e., $M/T_t \gg 1$.

We take the phase space distribution of MVDM to be Fermi-Dirac, which enables us to calculate the energy density and other higher moments of the distribution. Due to the rapid transition, the energy density exhibits a jump during its evolution at z_t , which can be expressed as the quantity $\rho_{\text{MVDM}}^{\text{NR}}(z \rightarrow z_t^+ / \rho_{\text{MVDM}}^R(z \rightarrow z_t^-) = M/T_t$. This phenomenon is accurately depicted in Fig. 1 for a particular value of z_t . For the remainder of this paper, we have set the MVDM temperature to $T = T_{\gamma}/10$ in the relativistic phase as a representative value. The mass of a light, fermionic dark matter particle can be constrained by Tremaine-Gunn bound [38]. This bound can be cast in terms of the value of the initial (fine-grained) phase space distribution function [Ref. [38], Eq. (18.64)]. The constraint depends on the ratio M/T, which means the bounds need to be scaled by the corresponding factor for our choice of temperature, T.



FIG. 2. The relative change in the CMB TT and EE power spectra with respect to Λ CDM is plotted for mass M = 25, 50, and 100 eV for a transitional redshift $z_t = 10^5$.

We note that the parameter space studied in the paper is consistent with this bound.

Because of its relativistic nature before z_t , MVDM will contribute to the total radiation energy density, thereby affecting the evolution of the universe and leaving an imprint on observables such as the CMB and the matter power spectra. This contribution can be quantified as an additional relativistic degree of freedom, ΔN_{eff} , given by [31],

$$\Delta N_{\rm eff} \approx \frac{\rho_{\rm MVDM}(z=0)}{\rho_{\nu}^{\rm th}(z=0)} \frac{T_t}{M} \frac{1}{1+z_t}$$
(2)

This model shows observable effects at the perturbation level as well. The transition of DM from relativistic to nonrelativistic phase introduces a cutoff scale, denoted by k_t , in our model, which corresponds to the fluctuations that entered the horizon at the transition redshift z_t . Prior to the transition redshift, DM was relativistic and free streaming, prohibiting the growth of structure for the modes that entered before z_t . This results in a suppression of power for $k > k_t$ in the matter power spectra shown in Fig. 3. For lower transition redshift, the suppression moves to larger scales, implying the structure is washed away at lower k modes. Furthermore, the free streaming length is directly proportional to the thermal velocity of DM particles, i.e., $v_{th} = \frac{\langle p \rangle}{m}$. Therefore, the cutoff scale k_t , which is determined from the free-streaming length during the transition, is also dependent on the final mass of the DM [39–42]. Consequently, we obtain smaller k_t

values for DM with lighter mass. This suppression of power is also reflected in the CMB temperature and polarization anisotropy power spectrum at higher ℓ , as shown in Fig. 2.

The presence of free-streaming dark matter (DM) particles during their relativistic phase causes a small



FIG. 3. Relative change in matter power spectra with respect to Λ CDM is plotted for mass M = 25, 50, and 100 eV for a transitional redshift $z_t = 10^5$.

but nonzero $\Delta N_{\rm eff}$, which exerts an additional drag on the metric perturbation via gravity during the radiation-dominated era. This results in an extra phase shift in the acoustic oscillation of the photon-baryon plasma that can be detected in both the cosmic microwave background (CMB) and the matter power spectrum as small wiggles, which can be seen in both Figs. 2 and 3.

III. METHOD

We use the Boltzmann hierarchy for the MVDM model implemented in CLASS in Ref. [31] to compute the CMB anisotropy power spectra and the matter power spectrum [43].

We perform a comprehensive Markov Chain Monte Carlo (MCMC) analysis of the MVDM model using the following combinations of cosmological datasets:

- (i) Planck 2018 measurements of the low-ℓ CMB TT, EE, and high-ℓ TT, TE, EE power spectra [1].
- (ii) The BAO measurements from 6dFGS [44] and SDSS DR7 MGS [45] for low redshift z < 0.2 comprises the likelihood for "Bao-smallz-2014." In addition to this we also use BOSS DR12 at z = 0.38, 0.51 and 0.61 [46].
- (iii) We use the S_8 -prior from the KIDS1000 + BOSS + 2dfLenS weak lensing data with $S_8 = 0.766^{+0.02}_{-0.014}$ [37]. In this work, we use the S_8 value obtained as a prior for our MCMC analysis. In order to gain



FIG. 4. Reconstructed 2D and 1D marginalized posterior distributions of $\log_{10} z_t$, M(eV), Ω_m , S_8 with 68% and 95% confidence level. The weak lensing measurement of S_8 is shown as gray bands (68% and 95%). Here we considered Pantheon + dataset for "SN-Ia."

an understanding of the effect of prior, we also consider different S_8 prior values obtained from different weak lensing measurements. We use a higher S_8 prior i.e. $S_8^+ = 0.772^{+0.018}_{-0.017}$ obtained from shear-shear analysis from DES Y3 survey [47] as well as a lower prior $S_8^- = 0.759^{+0.024}_{-0.021}$ obtained from KIDS1000-cosmic shear analysis [48].

- (iv) ACT data from ACT Collaboration, which includes the DR4 data release [49]. We use actpollite dr4 likelihood code which contains TT measurements ($600 < \ell < 4126$) and TE and EE measurements ($350 < \ell < 4126$). Since it does not have large-scale data, constraining reionization optical depth τ_{reio} is not possible. So a Gaussian prior is also added, centered at $\tau_{reio} = 0.06 \pm 0.01$ while analyzing ACT data alone [50].
- (v) Type-Ia supernova (SN-Ia) catalog Pantheon + spanning in redshift 0.001 < z < 2.26. [51].

In this study, we adopt the standard ACDM model as our base framework, which comprises of the six parameters: $\omega_b, \omega_{cdm}, 100\theta_s, \ln 10^{10}A_s, n_s, \tau_{reio}$. To incorporate our MVDM model, we introduce two additional parameters $\log_{10} z_t$, M in conjunction with the six aforementioned parameters.

The MCMCs are executed using the MontePython-v3 [52] code with the Metropolis-Hasting algorithm. We utilize our modified CLASS version to interface with the MCMCs. We obtain all the reported χ^2_{min} values using the Python package iMinuit [53]. We use a Choleski decomposition to handle various nuisance parameters [54] better

and consider chains to be converged when the Gelman-Rubin convergence criterium $R - 1 \lesssim 0.01$ [55].

IV. RESULTS

For the Planck-only analysis with the MVDM cosmology, shown in Fig. 4 and in Table I, we were able to obtain a bound on the mass M > 23 eV and $\log_{10} z_t > 4.72$ (obtained at half of the peak posterior value of the respective parameter). Our analysis yields $S_8(\text{MVDM}) = 0.822^{+0.0236}_{-0.0179}$, which is to be compared with $S_8(\text{ACDM}) = 0.831^{+0.0164}_{-0.0165}$.MVDM shifts S_8 downward almost by ~0.5 σ , thus effectively reducing the level of S_8 tension from ~2.7 σ to ~2.2 σ . So, MVDM prefers a slightly lower value of S_8 , and the minimum χ^2 shows a slight improvement compared to the standard ACDM model i.e. $\Delta \chi^2_{\min} = \chi^2_{\min}(\text{MVDM}) - \chi^2_{\min}(\text{ACDM}) = -1.23$. The inclusion of the S_8 prior in our analysis yields

The inclusion of the S_8 prior in our analysis yields significant changes in the results. Specifically, we observe a mild preference for dark matter final mass M = $41.7^{+7.81}_{-27.5}$ eV and a tighter constraint on $\log_{10} z_t > 4.67$ in the MVDM model. We get $S_8(\text{MVDM}) = 0.79^{+0.0209}_{-0.0167}$ in this likelihood combination, which can be compared with our baseline $S_8(\Lambda\text{CDM}) = 0.805^{+0.0126}_{-0.0129}$. Consequently, the χ^2_{min} in the combined analysis decreases for the MVDM case, with $\Delta\chi^2_{\text{min}} = \chi^2_{\text{min}}(\text{MVDM}) - \chi^2_{\text{min}}(\Lambda\text{CDM}) = -3.81$. Further, we note that the overall χ^2_{min} is less impacted by the inclusion of the S_8 prior in the MVDM case (+3.78) as compared to that in the ΛCDM case (+6.36). This finding

TABLE I. The mean (best-fit) $\pm 1\sigma$ error of the cosmological parameters in the Λ CDM and MVDM model obtained from the analysis of Planck [1] and Planck + S_8 [37] data. Lower limits are obtained at half of the peak posterior value of the respective parameter.

Model	ΛCD	М	MVDM			
Parameter	Planck	$Planck + S_8$	Planck	$Planck + S_8$		
$100\omega_b$	$2.24(2.2334)^{+0.0154}_{-0.0155}$	$2.25(2.2528)^{+0.0145}_{-0.0146}$	$2.24(2.239)^{+0.0153}_{-0.0157}$	$2.25(2.245)^{+0.0152}_{-0.0156}$		
$\omega_{ m dm}{}^{ m a}$	$0.12(0.1199)^{+0.00141}_{-0.0014}$	$0.118(0.1178)^{+0.00114}_{-0.00118}$	$0.12(0.1208)^{+0.00141}_{0.00143}$	$0.119(0.12)^{+0.00134}_{-0.00158}$		
$100 \times \theta_s$	$1.04(1.04184)^{+0.000304}_{-0.0003}$	$1.04(1.04215)^{+0.000301}_{-0.000294}$	$1.04(1.042)^{+0.000322}_{-0.000353}$	$1.04(1.0419)^{+0.000317}_{-0.000362}$		
n_s	$0.965(0.96754)\pm0.00453$	$0.969(0.972)^{+0.00421}_{-0.00422}$	$0.968(0.9655)^{+0.00466}_{-0.00503}$	$0.97(0.965)^{+0.00493}_{-0.00511}$		
$\ln 10^{10} A_s$	$3.04(3.0391)^{+0.0156}_{-0.0162}$	$3.04(3.021)^{+0.0159}_{-0.0158}$	$3.05(3.0442)^{+0.0162}_{-0.0173}$	$3.04(3.042)^{+0.0158}_{-0.0171}$		
$ au_{ m reio}$	$0.0541 (0.0517)^{+0.00763}_{-0.00786}$	$0.0521(0.0507)^{+0.00799}_{-0.00785}$	$0.0546(0.0547)^{+0.00786}_{-0.00847}$	$0.0538(0.05198)^{+0.00758}_{-0.00826}$		
$\log_{10} z_t$	••••		> 4.72	> 4.67		
M[eV]			> 23	$41.7(23.87)^{+7.81}_{-27.5}$		
S_8	$0.831(0.827)^{+0.0164}_{-0.0165}$	$0.805(0.8114)^{+0.0126}_{-0.0129}$	$0.822(0.821)^{+0.0236}_{-0.0179}$	$0.79(0.776)^{+0.0209}_{-0.0167}$		
Ω_{m}	$0.315(0.3138)^{+0.00852}_{-0.00867}$	$0.303(0.3064)^{+0.00672}_{-0.00712}$	$0.309(0.301)^{+0.00823}_{-0.00884}$	$0.302(0.311)^{+0.00759}_{-0.0095}$		
$H_0[\text{Km/s/Mpc}]$	$67.3(67.35)^{+0.602}_{-0.643}$	$68.2(67.88)^{+0.528}_{-0.527}$	$67.9(67.52)^{+0.638}_{-0.636}$	$68.4(67.96)^{+0.695}_{-0.606}$		
$\chi^2_{ m min}$	2771.78	2778.14	2770.55	2774.33		

^aFor ACDM model, the dm subscript means the cold dark matter (CDM), and for the MVDM model, it means the mass varying dark matter considered in this paper.

indicates that the MVDM model is better suited to explain both CMB and weak lensing data compared to ACDM. We also report the individual contribution from each dataset in each run for both of the models, which are reported in Table VI in the Appendix.

The analysis of Planck data reveals comparatively higher values of S_8 , indicating an increased amplitude of matter fluctuations at the 8 h^{-1} Mpc scale. In contrast, the MVDM model exhibits a suppression of fluctuations at smaller length scales, resulting in a reduced amplitude of matter fluctuations. Consequently, the incorporation of S_8 priors significantly affects the posterior distributions, demonstrating a mild preference for detecting the mass of dark matter, an aspect that the Planck data alone does not exhibit. Given the substantial impact on the result of MCMC analysis, we performed an additional set of analyses utilizing different S_8 priors derived from various weak lensing measurements, as elaborated in Sec. III. The outcomes of this analysis are illustrated in Fig. 5 and Table V. Notably, the posterior distributions indicate that variations in the priors do not lead to significant changes in the results, which is why the minimum χ^2 has not been computed.

To gain a deeper understanding of the results obtained from the MCMC analysis, we present residual plots in Fig. 7 for the CMB TT, EE power spectra, and the matter power spectra with respect to Λ CDM in the best-fit massvarying dark matter (MVDM) model obtained when Planck, Planck + S_8 , and Planck+BAO+Pantheon+ datasets are considered. Notably, the suppression of power at small length scales (i.e., large k modes and large ℓ 's) is a crucial factor in mitigating the tension.



FIG. 5. The 2D and 1D marginalized posterior distributions of $\log_{10} z_t$, M, Ω_m , S_8 with 68% and 95% confidence level for three different S_8 priors as mentioned in Sec. III.

Model	ΛС	DM	MV	ЪМ
Parameter	ACT	$ACT + S_8$	ACT	$ACT + S_8$
$100\omega_b$	$2.15(2.1471)^{+0.0308}_{-0.0318}$	$2.16(2.1561)^{+0.0307}_{-0.0314}$	$2.16(2.166)\pm 0.0317$	$2.17(2.1698)^{+0.0304}_{-0.0323}$
$\omega_{ m dm}{}^{ m a}$	$0.118(0.1171)^{+0.00373}_{-0.00384}$	$0.114(0.11401)^{+0.00162}_{-0.00177}$	$0.118(0.11839)^{+0.00379}_{-0.00385}$	$0.115(0.1168)^{+0.00179}_{-0.00266}$
$100 \times \theta_s$	$1.04(1.0433)^{+0.000728}_{-0.000708}$	$1.04(1.04385)^{+0.000666}_{-0.000686}$	$1.04(1.0436)^{+0.000723}_{-0.000727}$	$1.04(1.0436)^{+0.000691}_{-0.000698}$
n_s	$1.01(1.0092)^{+0.0156}_{-0.0159}$	$1.02(1.0177)^{+0.0142}_{-0.0144}$	$1.01(1.00945)^{+0.0154}_{-0.0164}$	$1.02(1.0131)^{+0.0147}_{-0.0149}$
$\ln 10^{10} A_s$	$3.04(3.04165)^{+0.0224}_{-0.0238}$	$3.03(3.0332)^{+0.0209}_{-0.0223}$	$3.04(3.0421)^{+0.0225}_{-0.0239}$	$3.03(3.029)^{+0.0209}_{-0.0232}$
$ au_{ m reio}$	$0.0604(0.06058)^{+0.00927}_{-0.01}$	$0.0601(0.06145)^{+0.00897}_{-0.0102}$	$0.0606(0.05936)^{+0.00922}_{-0.0103}$	$0.0604(0.05645)^{+0.00914}_{-0.0102}$
$\log_{10} z_t$	••••	••••	> 5.1	> 5.2
M[eV]			> 27	$51.2(25.31)^{+16}_{-33.5}$
S_8	$0.826(0.8169)^{+0.0419}_{-0.044}$	$0.777(0.78)^{+0.016}_{-0.0183}$	$0.817(0.8159)^{+0.0452}_{-0.046}$	$0.777(0.7711)^{+0.0159}_{-0.0183}$
$\Omega_{\rm m}$	$0.303(0.2986)^{+0.0202}_{-0.023}$	$0.279(0.2822)^{+0.00842}_{-0.00955}$	$0.3(0.2998)^{+0.0203}_{-0.0226}$	$0.283(0.2913)^{+0.00916}_{-0.0143}$
$H_0[\mathrm{Km/s/Mpc}]$	$67.9(68.11)^{+1.51}_{-1.55}$	$69.6(69.384)^{+0.736}_{-0.699}$	$68.4(68.339)^{+1.51}_{-1.58}$	$69.6(68.95)^{+1.06}_{-0.768}$
$\chi^2_{\rm min}$	280.0495	281.8939	275.7832	276.7859

TABLE II. The mean (best-fit) $\pm 1\sigma$ error of the cosmological parameters in the Λ CDM and MVDM model obtained from the analysis of ACT [49,50] and ACT + S₈ [37] data. Lower limits are obtained at half of the peak posterior value of the respective parameter.

^aFor ACDM model, the dm subscript means the cold dark matter (CDM), and for the MVDM model, it means the mass varying dark matter considered in this paper.

As mentioned in Sec. II and [31], this suppression is attributed to the fact that the MVDM stays relativistic until the transition redshift z_t , contributing to the relativistic energy density, which can be quantified through additional degrees of freedom in Eq. (2). This effect washes away all perturbations at very small length scales, as evidenced by the matter power spectra residual plot and CMB TT, EE residual plots in Fig. 7. Consequently, we observe a reduction in the S_8 value relative to Planck due to the reduction in fluctuation amplitude on scales $k \approx 0.1-1 h \text{ Mpc}^{-1}$ as discussed in the Introduction. The addition of S_8 prior yields a mild preference for the mass of MVDM at around 23.87 eV (best-fit value), as shown in Fig. 4. These results clearly demonstrate that the KIDS1000 + BOSS + 2dfLenS weak lensing data mildly prefers the MVDM model. It should be noted that the error bars in the angular power spectra from Planck are larger at higher ℓ owing to the Planck beam, which makes it difficult to put a stringent bound on the dark matter mass. This is because significant deviations from the standard Λ CDM paradigm occur only at small length scales, as is evident from the matter power spectra residual plot.



FIG. 6. Reconstructed 2D marginalized posterior distributions of $\Omega_{\rm m}$ and S_8 with 68% and 95% confidence levels.



FIG. 7. Residuals of the CMB TT, EE (top panel) and matter (bottom panel) power spectra with respect to Λ CDM in the best fit MVDM model for Planck, Planck + S_8 , ACT, ACT + S_8 and Planck+BAO+SN-Ia data set. Here we considered Pantheon + dataset for "SN-Ia."

TABLE III. The mean (best-fit) $\pm 1\sigma$ error of the cosmological parameters in the ACDM and MVDM model obtained from the analysis of combined Planck + BAO + Pantheon + dataset. Lower limits are obtained at half of the peak posterior value of the respective parameter.

Dataset	Planck + BAO + Pantheon+			
Parameter	ACDM	MVDM		
100\omega_b	$2.24(2.2403)^{+0.0136}_{-0.0138}$	$2.24(2.249)^{+0.0137}_{-0.0140}$		
$\omega_{ m dm}{}^{ m a}$	$0.12(0.1201)^{+0.000981}_{-0.000997}$	$0.121(0.1186)\substack{+0.000982\\-0.000964}$		
$100 \times \theta_s$	$1.04(1.0419)^{+0.000284}_{-0.000289}$	$1.04(1.0420)^{+0.000311}_{-0.000342}$		
n _s	$0.966(0.9645)^{+0.00376}_{-0.00387}$	$0.967(0.9618)^{+0.00387}_{-0.00427}$		
$\ln 10^{10} A_s$	$3.04(3.038)^{+0.0161}_{-0.0168}$	$3.05(3.045)^{+0.0157}_{-0.0166}$		
$ au_{ m reio}$	$0.0546(0.051609)^{+0.00756}_{-0.00809}$	$0.0547(0.05589)^{+0.00755}_{-0.00798}$		
$\log_{10} z_t$		> 4.75		
M[eV]		> 26		
S ₈	$0.826(0.828)^{+0.0127}_{-0.0128}$	$0.824(0.819)^{+0.0203}_{-0.0132}$		
Ω_{m}	$0.312(0.315)^{+0.00591}_{-0.00605}$	$0.309(0.301)^{+0.00579}_{-0.00588}$		
H_0 [Km/s/Mpc]	$67.5(67.408)^{+0.442}_{-0.441}$	$67.9(68.45)^{+0.427}_{-0.443}$		
$\chi^2_{\rm min}$	4189.92	4189.66		

^aFor ACDM model, the dm subscript means the cold dark matter (CDM), and for the MVDM model, it means the mass varying dark matter considered in this paper.

TABLE IV. Comparison of $\Delta \chi^2_{min}$ and ΔAIC per experiment for MVDM and ΛCDM models.

Dataset	MV	DM
	$\Delta \chi^2_{ m min}$	ΔAIC
Planck	-1.23	+2.77
$Planck + S_8$	-3.81	+0.19
ACT	-4.2663	-0.2663
$ACT + S_8$	-5.108	-1.108
Planck + BAO + SN-Ia	-0.26	+3.74

To address this issue, we have also done our MCMC analysis using ACT data, which has better angular resolution than Planck and has measured the CMB power spectra up to $\ell \simeq 4000$. The results are also included in Fig. 4 and in Table II, where it is clear that the ACT data does a slightly better job in constraining the mass of dark matter and lowering the S_8 value than Planck. ACT data provides a lower limit on the mass M > 27 eV and $\log_{10} z_t > 5.1$ (obtained at half of the peak posterior values of the respective parameters). Our analysis also shows $S_8(\text{MVDM}) = 0.817^{+0.0452}_{-0.046}$, compared to $S_8(\Lambda \text{CDM}) = 0.826^{+0.0419}_{-0.044}$ where MVDM lowers S_8 by 0.2σ . We also observe an improvement in minimum χ^2 over ΛCDM , i.e. $\Delta \chi^2_{\text{min}} = \chi^2_{\text{min}}(\text{MVDM}) - \chi^2_{\text{min}}(\Lambda \text{CDM}) = -4.2663$.

In addition to the S_8 value, we find a tighter lower bound on $\log_{10} z_t > 5.2$. It also tightens the constraint on the dark matter mass $M = 51.2(25.31)^{+16}_{-33.5}$ eV, compared to previous ACT analysis, but this constraint is much weaker than

that of Planck + S_8 . We find S_8 (MVDM) = $0.777^{+0.0159}_{-0.0183}$ in comparison with $S_8(\Lambda \text{CDM}) = 0.777^{+0.016}_{-0.0183}$, showing no significant change in the S_8 values in either of the models except for their best-fit values, as given in Table II. However, the addition of prior reduces the S_8 tension significantly compared to all the previous analyses considered in this work. For example, $\chi^2_{\rm min}$ in the combined analysis decreases for the MVDM case, with $\Delta \chi^2_{\rm min} =$ $\chi^2_{\min}(\text{MVDM}) - \chi^2_{\min}(\Lambda \text{CDM}) = -5.108$. The individual contribution from each dataset in each run for both models is reported in Table VII in the Appendix. We show the posteriors of S_8 and Ω_m for each dataset in Fig. 6, which provides a comparison between MVDM and ACDM models across various datasets. Additionally, we have included the residual plots for both the ACT and ACT + S_8 datasets along with the other datasets previously mentioned in Fig. 7.

We have also performed a comprehensive analysis by integrating the Planck, BAO, and Pantheon + datasets. The mean and best-fit values of the cosmological parameters derived from this combined analysis are presented in Table III. The results show no significant changes compared to the Planck-only analysis, both in terms of the posterior distributions and the estimated values of the cosmological parameters, as shown in Fig. 4.

We found the lowest lower limit on the transition redshift $\log_{10} z_t > 4.55$ among all combinations of datasets. It is worth noting that the lower bound must be higher than the redshift of recombination to avoid significant impacts on the CMB power spectra. We have also performed an MCMC analysis by considering all of the datasets into

TABLE V. The mean (best-fit) $\pm 1\sigma$ error of the cosmological parameters in the MVDM model obtained from the analysis of Planck + S_8^+ [47], Planck + S_8 [37] and Planck + S_8^- [48] data. Lower limits are obtained at half of the peak posterior value of the respective parameter.

Model		MVDM	
Parameter	Planck + S_8^+	$Planck + S_8$	Planck + S_8^-
$100\omega_b$	$2.25(2.2527)^{+0.0156}_{-0.0153}$	$2.25(2.245)^{+0.0152}_{-0.0156}$	$2.25(2.247)^{+0.0153}_{-0.0154}$
$\omega_{ m dm}{}^{ m a}$	$0.119(0.1189)^{+0.00132}_{-0.00158}$	$0.119(0.12)^{+0.00134}_{-0.00158}$	$0.119(0.1194)^{+0.00133}_{0.00153}$
$100 \times \theta_s$	$1.04(1.0422)^{+0.000329}_{-0.000359}$	$1.04(1.0419)^{+0.000317}_{-0.000362}$	$1.04(1.0418)^{+0.000323}_{-0.000344}$
n _s	$0.97(0.97133)^{+0.00503}_{-0.00513}$	$0.97(0.965)^{+0.00493}_{-0.00511}$	$0.97(0.9722)^{+0.00484}_{-0.00503}$
$\ln 10^{10} A_s$	$3.04(3.0499)^{+0.0159}_{-0.0168}$	$3.04(3.042)^{+0.0158}_{-0.0171}$	$3.04(3.0568)^{+0.0161}_{-0.0166}$
$ au_{ m reio}$	$0.0535(0.0564)^{+0.00773}_{-0.00811}$	$0.0538 (0.05198)^{+0.00758}_{-0.00826}$	$0.0536(0.0595)^{+0.00777}_{-0.008}$
$\log_{10} z_t$	> 4.72	> 4.67	> 4.75
M[eV]	$41.6(26.59)^{+7.26}_{-26.9}$	$41.7(23.87)^{+7.81}_{-27.5}$	$41.6(23.5)^{+8.51}_{-28.4}$
<i>S</i> ₈	$0.791(0.787)^{+0.0191}_{-0.0155}$	$0.79(0.776)^{+0.0209}_{-0.0167}$	$0.79(0.782)^{+0.0248}_{-0.0178}$
Ω_{m}	$0.302(0.3018)^{+0.00763}_{-0.00935}$	$0.302(0.311)^{+0.00759}_{-0.0095}$	$0.303(0.305)^{+0.00783}_{-0.00906}$
$H_0[\mathrm{Km/s/Mpc}]$	$68.4(68.46)^{+0.685}_{-0.603}$	$68.4(67.96)^{+0.695}_{-0.606}$	$68.4(68.12)^{+0.664}_{-0.614}$

^aFor ACDM model, the "dm" subscript means the cold dark matter (CDM), and for the MVDM model, it means the mass varying dark matter considered in this paper.

We computed the Akaike information criterion (AIC) to investigate any preference of the data for the MVDM model over ACDM. It is a statistical tool for evaluating the relative quality of different models when applied to a specific dataset. The difference in AIC between two models is given by

$$\Delta \text{AIC} = \chi^2_{\text{min,Model}} - \chi^2_{\text{min,ACDM}} + 2(N_{\text{Model}} - N_{\text{ACDM}}).$$
(3)

The $\Delta \chi^2_{min}$ and ΔAIC for each dataset combination are given in Table IV. We see that the ACT data exhibits a mild preference for MVDM over ΛCDM , which is not the case for Planck. This result can also be attributed to the smaller error bars of ACT at high- ℓ compared to Planck, as the changes in the power spectrum for MVDM come from the small scales.

V. CONCLUSIONS

In this study, we explored the model of a mass-varying dark matter (MVDM), where it transitions from a relativistic to a nonrelativistic phase in the early Universe, and derived constraints using cosmological observation data. We assumed a phenomenological relation of dark matter mass as a function of redshift without invoking any specific particle physics model. We focused only on fast transitions in this work. The large free streaming velocity in the relativistic phase of DM at early time washes out the structures at small scales and manifests its effect in easing the tension between the amplitude of matter fluctuations (S_8) determined from local [8–12,37] and high redshift probes [1], as depicted in Fig. 4. Our Bayesian analysis with the MVDM model reveals a slight reduction in S_8 when only Planck CMB data is used, and the result does not change significantly when BAO and supernova datasets are included. However, the inclusion of S_8 prior, obtained from KIDS1000 + BOSS + 2dfLenS weak lensing measurements, significantly reduces the value of S_8 . Furthermore, the model puts a lower bound on the transition redshift and shows a mild preference for the mass of the dark matter to be 23.87 eV. Similar ~ eV order warm dark matter mass has also been predicted in other models [56].

The MVDM model shows new features at high multipoles of the CMB anisotropic power spectra. Because of its relatively larger error bars at high multipoles, Planck-only analysis yields poorer constraints on the DM mass. Since ACT data provides those measurements at higher multipoles with comparatively better precision, our MCMC analysis showed better constraining of mass *M* compared to Planck. This is also reflected in the Δ AIC calculations. Including prior from KIDS1000 + BOSS + 2dfLenS weak lensing data even further reduces the *S*₈ as expected.

Future experiments, such as CMB-S4 [57,58], are expected to achieve higher precision measurements at high multipoles, specifically for goals related to delensing the inflationary B-modes, constraining N_{eff} and Σm_{ν} , among others. Such experiments are expected to provide insight into the detailed small-scale physics of the CMB data, which could aid in the detection and proper constraint of the DM mass *M* of our model. In this regard, a Fisher forecast can also be conducted in the future. Another way to probe such a model is through CMB spectral distortion as shown in [59], which might also be detected in future experiments.

As previously mentioned, we did not invoke any specific particle physics model to explain the mass variation of dark matter. However, considering a particular particle physics model could potentially introduce additional model-dependent effects beyond those reported in this work. The residual plots of CMB power spectra and matter power spectra, as shown in Fig. 7 and referenced in [31], exhibit oscillatory structures resulting from the additional drag force exerted by the relativistic DM, leading to a phase shift in the baryon acoustic oscillation. A similar phenomenon could occur in the dark sector, too. This model could also be employed to constraint the dark acoustic oscillation [60,61]. Additionally, the present model could be tested by the small-scale Lyman- α forest data in line with recent works [24,62–68].

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APPENDIX: χ^2_{min} **PER EXPERIMENT**

Experiment		ЛCDM			MVDM	
Planck high- ℓ TT, TE, EE Planck low- ℓ EE Planck low- ℓ TT	2353.36 395.75 22.67	2354.37 395.85 22.70	2358.06 395.8 21.9	2350.87 396.15 23	2352.13 396.82 23.35	2353.6 395.84 23.6
KiDS/BOSS/2dFGS			2.38			1.29
BAO-boss-dr12 BAO-smallz-2014 Pantheon+	 	4.10 1.31 1411.59	···· ···	···· ···	4.09 1.32 1411.95	···· ···
Total	2771.78	4189.92	2778.14	2770.55	4189.66	2774.33

TABLE VI. Best-fit χ^2_{min} per experiment (and total) for both the model.

TABLE VII.	Best-fit $\chi^2_{\rm min}$	per experii	ment (and	total)) for	both	the	model.
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Experiment	ΛC	DM	MV	DM
ACTPol lite DR4	280.0462	281.1964	275.7791	276.5869
$\tau_{\rm reio}$ prior	0.0033	395.8	0.0041	0.1261
KiDS/BOSS/2dFGS		0.6766		0.0729
Total	280.0495	281.8939	275.7832	276.7859

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