PROCEEDINGS OF SCIENCE

Updating constraints on the decaying dark matter scenario

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Decades after the first evidence of non-luminous matter component, the nature of dark matter is still controversial at best. In this work we shine *light* on the mysterious nature of *dark* matter by probing the stability of the dark matter particle. We constraint the decay rate of the Cold Dark Matter (CDM) using latest Planck CMB and lensing measurement together with Baryonic Acoustic Oscillations (BAO) measurement from SDSS DR7, BOSS DR12, eBOSS DR16, and 6dFGS. In our baseline model all CDM is unstable and decays into radiation-like, dark products. We then explore how changing the fraction of unstable to stable CDM affects the constraints on the decay rate. We find the most stringent constraints on dark matter decay rate for our baseline model of $\Gamma_{\mathrm{DCDM}} < 0.129 \times 10^{-18}\,\mathrm{s}^{-1}$ (or, equivalently, the dark matter lifetime τDCDM > 246 Gyr) at 95% C.L. with the combination of CMB, lensing and BAO measurements. We further conclude that the cosmological tension in the estimated values of H_0 and σ_8 persist in a universe with decaying dark matter.

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1. Introduction and background

Cold dark matter (CDM)is an essential component of our understanding of the universe and its gravitational influence on baryonic matter is the key to understanding the CMB spectra and galaxy distribution in the Universe. In the standard cosmological scenario dark matter is assumed to have absolute stability. In this work we relax the ad-hoc assumption of stability and put bounds on the decay rate of dark matter. We refer the reader to the paper of the talk for comprehensive literature survey and discussion on decaying dark matter (DCDM) [1].

We consider the scenario in which CDM decays exclusively into radiation-like dark products. We use Planck measurements of CMB and lensing along with Baryonic Acoustic Oscillations (BAO) measurement from SDSS DR7, BOSS DR12, eBOSS DR16, and 6dFGS to constraint the upper-limit on the decay rate of dark matter; see Section 3.1 for details of our dataset. In our baseline model, we make the assumption that all of dark matter is unstable (ΛDDM). Later we relax this assumption and explore the case when the DCDM makes up a smaller fraction of the total dark matter in the universe.

2. Effects of DCDM

Our baseline ΛDDM model is completely specified by the decay rate and the initial matter density of DCDM, in addition to the standard ΛCDM parameters: the baryon density parameter ω_b, the angular size of the sound horizon at recombination θ_s, the logarithmic amplitude $\log(A_s)$ at pivot scale $k_{\rm pivot} = 0.05\ {\rm Mpc}^{-1}$, the spectral index n_s of the primordial scalar perturbations, and the optical depth to reionization τreio. Furthermore, we impose spatial flatness, assume adiabatic initial conditions, and two massless and one massive neutrino of 0.06 eV with a standard contribution to the effective number of relativistic degrees of freedom of 3.046. In this paper, as a proxy of the DCDM energy density at early times, we use $\omega_{\rm ini}^{\rm DCDM}$:

$$\omega_{\rm ini}^{\rm DCDM} \equiv \Omega_{\rm DCDM} h^2 \exp(\Gamma_{\rm DCDM} t_0) = \frac{(\rho_{\rm DCDM} a^3)_{t \ll \tau_{\rm DCDM}}}{\rho_{c,0}} h^2 \,. \tag{1}$$

In this parametrization $\lim_{\tau_{\rm DCDM}\to\infty} \omega_{\rm ini}^{\rm DCDM} = \omega_{\rm CDM}$. We further parametrize the decay rate in terms of $\Gamma_{18} = \Gamma_{\rm DCDM}/10^{-18}\,{\rm s}^{-1}$, namely the decay rate in units of $10^{-18}\,{\rm s}^{-1}$.

For DCDM decay rate which is not too high, the DCDM affects the evolution of the Universe at late time. We demonstrate the effects on the evolution of the Universe in Figures 1a and 1b for several values of Γ_{18} for a fixed reference cosmological model. When we change Γ_{18}, while keeping fixed the angular size of sound horizon, the dark energy density increases to counter the change in the angular diameter distance. This, in-turn, also changes the evolution of the Hubble parameter and the redshift of matter-Λ equality is shifted towards earlier time. The primary effect of the DCDM on the CMB temperature power spectra is to enhance the large scale late-ISW effect for higher decay rate. This effect is caused by, 1) the enhancement of dark energy density, and 2) the shifting of matter-Λ equality redshift compared to the ΛCDM universe. However, the large scale effects of the polarization spectra is negligible compared to the CMB temperature spectra. On the contrary, small scale lensing effect is more pronounced on the polarization spectra than the temperature spectra, indicating that small scale measurement effect on the polarization spectra is the key to improving constraints from CMB measurements. The small scale effects on the temperature and polarization spectra can be understood from the suppression in the power spectra of lensing potential: Higher value of decay rate diminishes the potential at late times thus reducing the smearing effect of lensing on the CMB speaks.

3. Dataset, Results and Discussion

3.1 Dataset

In our analysis, we consider the following data:

(i) CMB temperature and polarization measurements from Planck 2018 legacy release [2] (referred to as "Planck T&P"),

(ii) Planck 2018 CMB lensing reconstruction power spectrum from legacy release [3] (referred to as "lensing"),

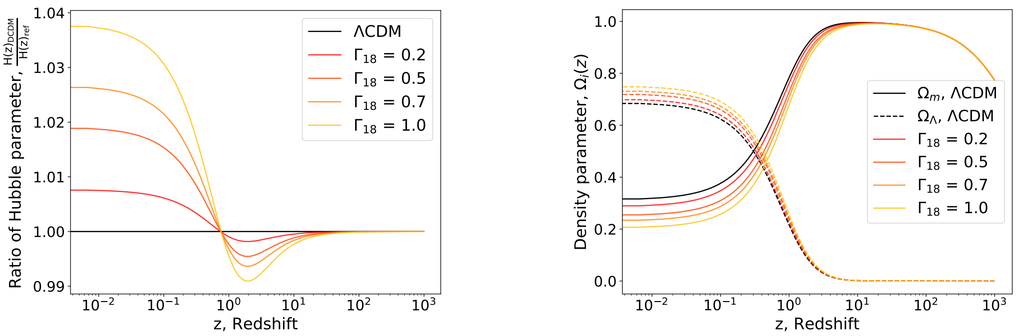
(iii) Baryon Acoustic Oscillations (BAO) measurements from: Six-degree Field Galaxy Survey (6dFGS $z = 0.106$) [4], the Sloan Digital Sky Survey (details of the individual measurement used in this work can be found in [5]).

3.2 Results for our baseline ΛDDM model

We summarize our results for our baseline case in Figure 3a. We note that Planck T&P alone puts stringent constraints (always quoted the 95% C.L.) on the DCDM decay rate ($\Gamma_{18} < 0.175$ and $\tau_{\rm DCDM} dm > 181$ Gyr). Further adding the lensing measurement improves the lower limit on DCDM lifetime by $\approx 22\%$ ($\Gamma_{18} < 0.136$ and $\tau_{\rm DCDM} > 234$ Gyr). Further adding the BAO data further improves the lower limit by $\approx 5\%$ ($\Gamma_{18} < 0.129$ and $\tau_{\rm DCDM} > 246$ Gyr). We further comment on the degeneracy between decay rate of Γ_{18} and two well-known controversial measurements in cosmology, namely H_0 and σ_8. The plot in Figure 3a shows that H_0 and σ_8 are very weakly degenerate with Γ_{18}. This degeneracy is further weakened when we add lensing and BAO measurement to Planck T&P measurement. This indicates that there is little possibility to solve the Hubble and σ_8 tension in a universe where dark matter decays in dark radiation.

3.3 Results for $f_{\rm DCDM} \neq 1$

We change the fraction of decaying dark matter to the total dark matter in the universe (referred as $f_{\rm DCDM}$). Changing fraction of the DCDM effects the constraint on the decay rate in the following way: When all of dark matter is considered unstable ($f_{\rm DCDM} = 1$), the decay rate of DCDM is tightly constrained as CDM has to fulfill its essential role in the structure formation, therefore high decay rate values are strongly disfavoured by data. As we reduce the fraction of DCDM, the strong constraints on the decay rate can be relaxed. When the DCDM fraction is small (less than $f_{\rm DCDM} \lessgtr 20\%$), the decay rate is largely unconstrained as it can be very large number without being in tension with the data, as long as the initial DCDM density is appropriately compensated to allow a small quantity of dark matter to decay before recombination. These results are summarized in Figure 3b.



(a) **(b)**

Figure 1: *Panel (a)*: Ratio of the Hubble parameter $H(z)$ with respect to ΛCDM model for various values of the decay rate. *Panel (b)*: Evolution of the matter (solid lines) and dark energy (dashed lines) density parameters. Note that for larger values of decay rate, the matter-Λ equality occurs at higher redshift than in a universe with stable dark matter.

4. Conclusions and future outlook

In this work we explore the constraints on the DCDM decay rate in the scenario where dark matter decays into radiation-like products. We use CMB, and lensing measurements from Planck complemented with BAO measurements from Sloan Digital Sky survey. In our baseline model we assume that all of dark matter is unstable and later we relax this assumption. We provide comparative constraints from CMB, lensing and BAO measurements and report that the tightest constraints on the decay rate, of $\Gamma_{\rm DCDM} < 0.129 \times 10^{-18}\,{\rm s}^{-1}$, come from our baseline model. We later relax the assumption of the fraction of DCDM in the total CDM and consider different, fixed, values of the fraction and assess the constraints. For a fraction of DCDM with small decay rate, the cosmological probes essentially constrain the combination $\Gamma_{\rm DCDM} f_{\rm DCDM}$. Furthermore, within a few percentage difference, our combined dataset always puts the tightest constraints on the decay rate.

In this work we have focused on constraints from linear scales and Planck CMB measurement limited to $\ell \approx 2000$. We note that future improvements in the constraints could be expected from future CMB measurements which will extend their analysis to smaller even scales, where the effect of gravitational lensing is pronounced. A wealth of information can further be unlocked from non-linear scales in galaxy surveys. We note that several efforts have been made to model the non-linear scales in ΛDDM model and with a more robust understanding of the physics of non-linear structure evolution (see our published paper for details [1]). We expect future large-scale-structure surveys (e.g. Euclid [6], DESI [7], and Rubin Observatory [8]) to further improve over current constraints on the decaying dark matter model discussed in this work.

References

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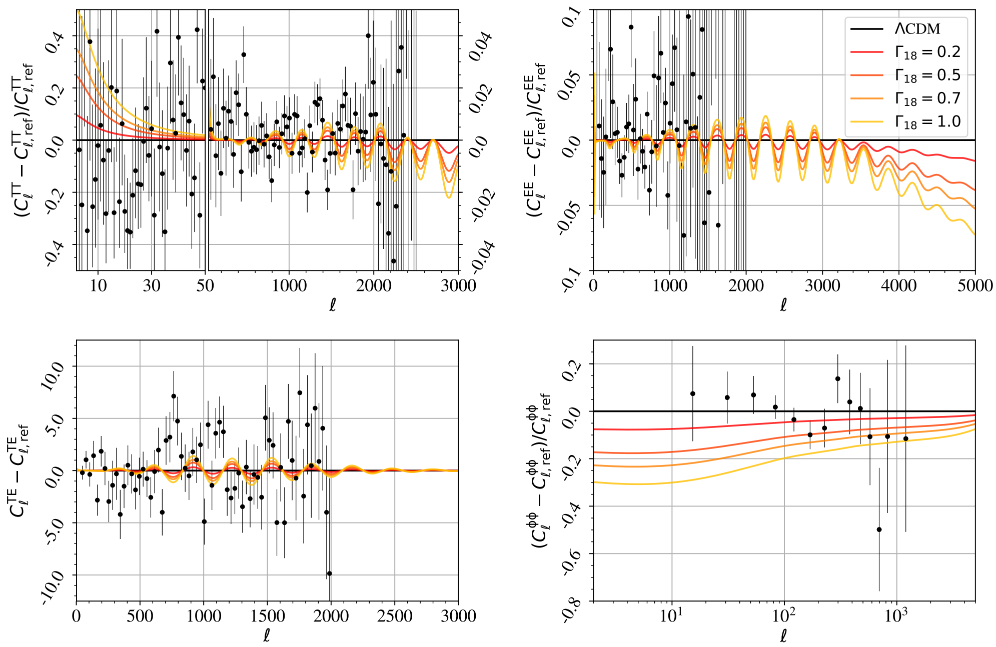

Figure 2: From the top left going clockwise, CMB temperature (TT), polarization (EE), temperature-polarization (TE) and lensing potential (ΦΦ) power spectra for ΛDDM and ΛCDM model. In a ΛDDM universe: late-ISW effect is enhanced; gravitational lensing is suppressed (reducing the smoothing and increased damping of the high-ℓ region of the CMB primary anisotropies spectra).

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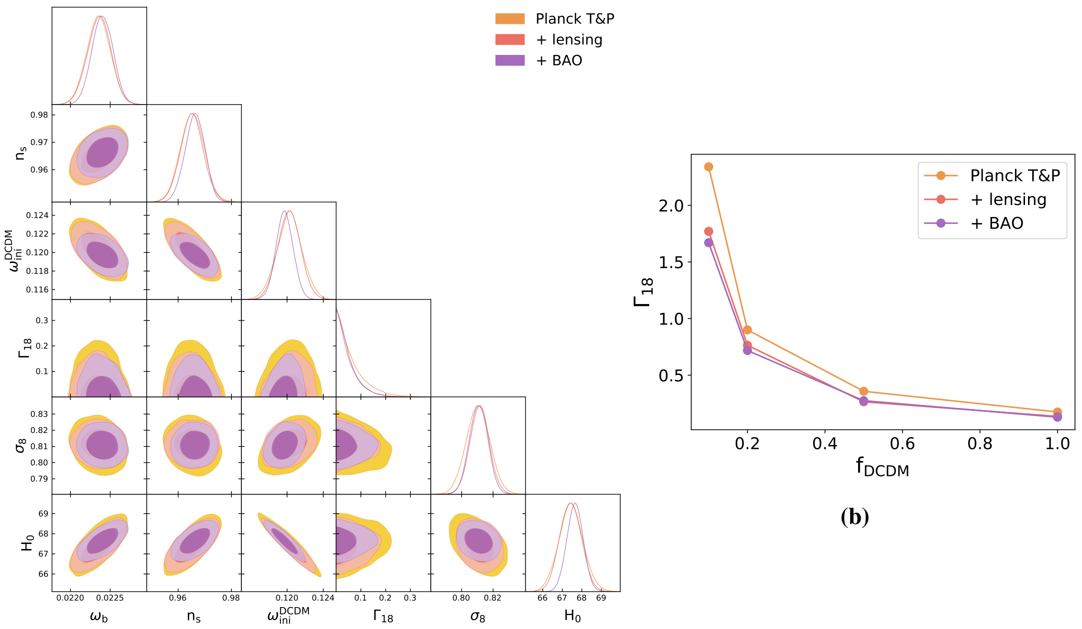

(a) **(b)**

Figure 3: *Panel (a)*: The figure shows the 68% (darker) and 95% (lighter) C.L. bounds on dark matter decay rate Γ_{18} and lifetime $\tau_{\rm DCDM}$ for various datasets considered in this work: Planck 2018 CMB temperature and polarization spectra alone, with the Planck 2018 CMB lensing power spectrum, and additionally with BAO measurements from eBOSS DR16 and earlier dataset (see Section 3.1 for more details). In the accompanying table we report the 95% C.L. bounds. *Panel (b)*: The 95% C.L. upper limit of decay rate for various fixed values of DCDM fraction for the various datasets considered in this work. As explained, for larger values of fraction, the upper limit on the decay rate is constrained to smaller values while for smaller values of the fraction, the limit is relaxed and DCDM can be allowed to decay quickly, even depleting before matter-radiation equality.