Synopsis

The dark matter is the most dominating matter candidate and a key driving force for the structure formation in the universe. Despite decade-long searches, the precise nature and particle properties of dark matter are still unknown. The standard cold dark matter candidate, the Weakly Interacting Massive Particle(WIMP) can successfully describe the large-scale features of the universe. However, when it comes to the scales comparable to a galaxy or a group of galaxies, it fails to explain the observations. The nature of the small-scale anomalies suggests a lower amount of dark matter at the scales of interest and can be tackled with different strategies. The simulation suites, used to produce the small-scale universe theoretically, can be equipped with varieties of baryonic phenomena, leading to a better agreement with observation. Another way is to use some new dark matter candidate altogether that reduces the small-scale power. Many such alternative dark matter candidates have been suggested and explored in the literature. The aim of the work presented in this thesis is to study the effects of small-scale power reduction due to new dark matter physics on different cosmological observables.

In Chapter 2 of this thesis, we have discussed the particle physics properties of three dark matter candidates proposed as alternatives of the WIMP. The first one is the Late Forming Dark Matter(LFDM), where dark matter is created due to a phase transition in the massless neutrino sector [1] long after the Big Bang Nucleosynthesis(BBN). Another candidate is the Ultra Light Axion Dark Matter(ULADM), which is born due to spontaneous symmetry breaking in the early universe and is stuck to its initial condition because of the Hubble drag. When the mass of the particle exceed the Hubble parameter, it decouples from the drag and starts behaving like dark matter [2], with a free-streaming length that is dependent on its mass. The last candidate we consider is the Charged Decaying Dark Matter (CHDM), which is born in

the radiation dominated era, after an instantaneous decay of a massive charged particle [3]. All of these dark matter candidates suppress small-scale power, though because of different physical reasons. In the next three chapters, we have studied their effects on various cosmological observables. The methods of study, along with the data used to validate the theoretical predictions and results are discussed below.

Chapter 3:

This chapter is based on the work performed in [4]. In this chapter, we focus on the LFDM and study its effects on linear matter power spectra at both small and large scales.

Method of Study: The LFDM model is specified by two parameters: The effective massless neutrino degrees of freedom(DOF) $N_{\rm eff}$ and the redshift of formation z_f. We have generated a set of matter power spectra using publicly available code `CAMB` for different sets of $N_{\rm eff}$ and z_f, and performed a χ^2 analysis using matter power spectrum data to constrain the model parameters. We have also considered a scenario, where a fraction $f_{\rm lfdm}$ of the total dark matter is LFDM and repeated the exercise. We have computed multi-parameter contours and posterior probabilities by marginalization over redundant parameters that allow us to estimate the model parameters.

The Data: The two parameters—z_f and $N_{\rm eff}$—affect the linear power spectrum at different scales. The main impact of changing $N_{\rm eff}$ is to alter the MRE epoch, shifting the peak of the matter power spectrum, which is located at $k \simeq 0.01\,{\rm hMpc}^{-1}$ in the standard model of cosmology. We use the SDSS DR7 data [5] for our analysis. As the SDSS data on the galaxy power spectrum gives the power at scales: k=0.02–0.1 h/Mpc, this data is sensitive to the variation of $N_{\rm eff}$. On the other hand, the main effect of formation redshift z_f is to suppress the power at scales $k > 0.1\,{\rm h/Mpc}$. In this scales, we use the linear matter power spectrum, reconstructed from Lyman-α forest power spectrum in the range: $0.2 < k < 4.8\,{\rm h/Mpc}$ from [6,7]. We use 45 band-powers from the SDSS galaxy data and 12 points from the reconstructed linear power spectrum from the Lyman-α data.

Results: Our results can be summarized as follows. If all the presently observed CDM is late forming, then both the data sets lead to upper limits on the redshift of formation of LFDM, with Lyman-α data resulting in tighter bounds: $z_f < 3 \times 10^6$ at 99% confidence limit.

On the other hand, if we allow only a fraction of the CDM to form at late times, then we improve the quality of fit as compared to the standard ΛCDM model for the Lyman-α data. This is suggestive that the present data allows for a fraction 30% of the CDM to form at $z_f \simeq 10^5$. Therefore, our result underlines the importance of the Lyman-α data for studying the small-scale power spectrum in alternative dark matter regime.

Chapter 4:

This chapter is based on the work performed in [8]. Here, we have studied the effects of small-scale power suppression on the Epoch of Reionization(EoR) and the evolution of collapsed fraction of gas at high redshift. We have considered two of the alternative dark matter candidates discussed in Chapter-2 in this chapter: the LFDM and the ULADM.

Method of Study: Our method of constructing the reionization fields consists of three steps: (i) Generating the dark matter distribution at the desired redshift, (ii) Identifying the location and mass of collapsed dark matter halos within the simulation box, (iii) Generating the neutral hydrogen map using an excursion set formalism. The assumption here is that the hydrogen exactly traces the dark matter field and the dark matter halos host the ionizing sources. Given the uncertainty of reionization history, we do not assume a particular model for reionization history $\bar{x}_{\rm HI}(z)$, where $\bar{x}_{\rm HI}$ is the fraction of neutral hydrogen in the universe. Instead, we fixed the redshift at $z = 8$ and the ionization fraction at $\bar{x}_{\rm HI} = 0.5$ and compared these models. We have produced HI power spectra, and photon brightness temperature fluctuation(δT_b) maps to compare the alternative models with the standard ΛCDM model. We discard the models where no halo is formed to host the ionizing sources, or an absurdly high number of ionizing photon is necessary to make $\bar{x}_{\rm HI} = 0.5$ at $z = 8$ successfully.

The collapsed fraction, defined as the fraction of collapsed mass in haloes with masses larger than a threshold mass M at a redshift z, is sensitive to the mass function of the haloes. As obtaining the mass function from N-body simulation is numerically expensive, we integrate the Sheth-Tormen mass function above the density threshold of collapse at a given redshift for computing the collapsed fraction in case of LFDM models. For computing the collapsed fraction for ULADM models, we integrate the halo mass functions derived by [9]. The collapsed fractions are calculated for two threshold halo masses, $10^{10} M_\odot$ and $5 \times 10^{10} M_\odot$ in the redshift range $2 < z < 5$ and compared to observational data. Models that are unable to produce the observed collapsed fractions at high redshifts are discarded.

The Data: From absorption studies of the Damped Lyman-α(DLA) clouds, the evolution of average mass density of HI in the universe can be inferred. Assuming that the collapsed fraction of baryons traces dark matter, this allows us to get an approximate measure of the minimum amount of collapsed fraction of the total matter in the redshift range $2 < z < 5$. We have used the data of density of gas trapped in DLAs (Ω_{HI}), at the mentioned redshift range from [10, 11] and converted them to collapsed fraction of gas. The re-constructed collapsed fractions are used to compare the theoretical predictions.

Results: Our method predicts an 'inside-out' reionization where the high-density regions are ionized first. We find that the HI power for LFDM and ULADM models is greater than the ΛCDM model over a large range of scales $0.1 < k < 4\,\mathrm{Mpc}^{-1}$. In the maps of δT_b, there are two main differences between ΛCDM and alternative models. The size of the ionized regions is larger in the LFDM (ULADM) models and the HI fields have stronger density contrast. Checking the facts that halos are actually formed to host stars and a realistic number of ionizing photons are produced to achieve the desired level of ionization, we put a rough limit on $z_f \sim 4 \times 10^5$ and $m_a \simeq 2.6 \times 10^{-23}$ eV as lower cut-offs. Comparing the estimated collapsed fraction with data we found weaker constraints on $z_f \lesssim 2 \times 10^5$ and $m_a \lesssim 10^{-23}$ eV. All these constraints are in good agreement with previous constraints.

Chapter 5:

This chapter is based on the work performed in [12]. The observable of interest here is the spectral distortion in the Cosmic Microwave Background(CMB).

Method of Study: The distortion on the CMB spectra can occur due to heating or cooling of the medium owing to several mechanisms at different times in the history of the universe. In this work, we consider heating due to the dissipation of acoustic waves, well-known as the Silk Damping. The fraction of energy injected into the photon bath is a function of the evolution of the fluctuation in gravitational potential Φ and the CMB dipole Θ_1. We have computed the evolution of Φ and Θ_1 for all the three dark matter candidates studied in Chapter 2, along with the WDM, using the publicly available code `CMBFAST` and `axionCAMB`. Using them, we estimate the evolution of the heating rate and integrate it to get the distortion parameters. The distortion parameters thus found are used to calculate the distorted CMB spectrum. The final output is the percentage change of the distortion parameters for the alternative dark matter models with respect to the ΛCDM model.

Results: The two earlier spectral distortions, namely the μ- and the i-distortion, are not found to be affected due to new dark matter physics. The y-distortion is the only one that carries the signatures of small-scale power suppression. We conclude that, unless the constraints on the model parameters found in previous studies are violated, the change in the y-distortion parameter is not more than $\sim 14\%$ compared to the standard model with identical spectral shapes. y-distortion occurring from later phenomena, i.e., structure formation and tSZ effects in the galaxy clusters have orders of magnitude higher distortion parameters than the Silk Damping, again with the same spectral shape. Thus, unless these foregrounds are understood and cleared correctly, distinguishing between dark matter candidates which reduce small-scale power is next to impossible.

Finally, our study shows that changing matter power at small scales can have noticeable impacts on other observables of the universe. However, to see the difference, the phenomena themselves are to be understood properly. The constraints found on the models using different probes are in good agreement with each other. In future, we will extend our research by investigating whether it is possible to accommodate an O(10 eV) particle as a dominating cold dark matter candidate, by exploring its effects on linear matter power spectrum and CMB spectral distortion.