Chapter 1

Introduction

Dark energy and dark matter remains the two major mysterious aspects in the modern cosmological paradigm. A large number of observations in recent times have indicated that the expansion of the Universe is accelerating [1]. The underlying cause of the cosmic acceleration is, however, largely unknown. In the standard paradigm of cosmology accelerated expansion is possible when $\rho + 3P < 0$. One therefore assumes a dark energy component with an equation of state (EoS) $P/\rho = w < -1/3$. Precision cosmological measurements indicate that the Universe contains approximately $\sim 70\%$ of the energy density in the form of dark energy [2, 3] and the remaining $\sim 30\%$ in the form of non-relativistic matter (both baryonic matter and dark matter). A natural candidate for constant dark energy is the cosmological constant. This model with $w = -1$ is well tested by many observations. While there are theoretical difficulties pertaining to the cosmological constant (like the 'fine tuning' problem), recent results from low redshift measurements of H_0 also contradict the the Planck-2015 predictions for flat LCDM model (Cosmological constant Λ as dark energy + Cold dark matter CDM) [4]. Further, there are observational indications that a varying dark energy model maybe preferable over the concordance LCDM model [5] at a high level of statistical significance. Our understanding of the cosmic acceleration is still highly uncertain.

Out of the total matter budget, baryonic matter is only $\sim 5\%$. The bulk of the type of matter present in the universe is non-baryonic and manifests only through their gravitational interaction. This matter is known as dark matter. Although the physics of the baryons can be understood by using standard model of particle physics, the dark matter and dark energy sector are not known to us. Presence of dark matter has been established from Galaxy rotation curve [6, 7] but other information about their mass and velocities of the dark matter particles has a lot of uncertainty. Dark matter particles can be classified according to their velocities. These particles are relic particles from the very early universe and expected to have decoupled in the early universe when the interaction rate of the dark matter particles fell below the expansion rate of the Universe.

The mass of the dark matter particle and the temperature of the universe at the time of decoupling determines whether the dark matter particles are relativistic or non-relativistic. If the mass of the particle is greater than the temperature of the universe their motion has to be relativistic. Particles with relativistic velocities are known as hot dark matter (HDM). While dark matter particles having non relativistic velocities known as cold dark matter. Dark Matter species with velocities which falls between HDM and CDM known as Warm dark matter (WDM). CDM model has been very successful in explaining the large scale structure of the universe. The CDM model assumes the dark matter particles are collisionless, dissipationless with a lifetime comparable to the age of the Universe. These particles constitute a perfect fluid on large scales. Despite of the several success there are some potentially serious problems on the scales of individual dark halos. The observed discrepancy in the number of small mass halos requires a modification of the CDM model. It is believed that tiny fluctuations generated at the time of inflation grew under gravitational instability to form the cosmic web that we see today. The nature of dark matter plays an important role in structure formation. The WDM model has been suggested as an alternative to CDM model. If WDM particles are in thermal equilibrium in early universe then the mass of the particle should be ~ 1 keV. Inflation generated matter power spectrum has a unique scale independent power law form [$P(k) \propto k^{n_s - 1}$ where $n_s \sim 1$]. The fluctuations can either grow or decay with time depending upon the Jeans length. Jeans length can be found by balancing the fluid pressure with gravity in an expanding Universe and is given by $\lambda_J = C_s\sqrt{\frac{\pi}{G\rho}}$.where C_s and ρ denote the speed of sound and the density of the fluid respectively. Particles cannot be clustered into regions smaller than the Jeans length or free-streaming length, because their velocity is greater than the escape velocity from gravitational potential wells on those scales. On scales very much larger than the free-streaming scale, the particle velocity can be effectively considered as vanishing after the non-relativistic transition (due to expansion of the universe) allows perturbations to grow and contribute to structure formation. Depending on the free streaming length the dark matter perturbations can either grow or decay with time. CDM perturbations can grow on every scale due to negligible velocities whereas presence of WDM would prevent gravitational clustering on small scales. This could potentially lower the densities in the centres of dark halos and reduce the number of subhalos, thereby resolving the problems faced by CDM model. Therefore the power spectrum below the Jeans length scale will changed. The free streaming length of the WDM particle is comparable to the Galaxy length scales ($\sim$ Mpc).

In particle physics there exists many WDM candidates. The most important example is gravitino, supersymmetric partner of the graviton. The gravitino mass is of the order of Λ_{susy}/h_p. If $\Lambda_{susy} \leq 10^{-6}$ GeV then the gravitino has a wide range of possible masses varies from 10^{-6} eV up to the keV region. Gravitino in this mass range decouples much earlier than at neutrino decoupling when it is still relativistic. The effective gravitino temperature is therefore always smaller than the neutrino temperature, and such light gravitinos may play the role of WDM.

Neutrino oscillations shows that neutrinos are massive particles. It is known that neutrinos have three species at least two of the three species of neutrinos are non-relativistic today. Neutrinos also plays almost the same role as of HDM/WDM in affecting the growth of structures. Neutrinos moves in relativistic speeds as a result they have much larger Jeans length(λ_J^ν) larger then CDM. Length scale larger then (λ_J^ν) have contributions from matter(λ CDM+ baryons) but in smaller scales have only contributions from matter.The free streaming behaviour wipe out the fluctuations on scales smaller than the horizon scale, causes a suppression in matter power spectrum directly related to the fractional neutrino density.

Neutrino oscillations measure the mass square difference between three species is $\Delta m_{21}^2 \equiv m_2^2 - m_1^2 = 7.59_{-0.21}^{+0.19} \times 10^{-5}\text{eV}^2$ [8] and $\Delta m_{32}^2 \equiv m_3^2 - m_2^2 = 2.43_{-0.13}^{+0.13} \times 10^{-3}\text{eV}^2$. However, absolute values and their hierarchical structure (normal or inverted) have not been obtained yet and more information on them is necessary to build "beyond standard model" particle physics theories.

Non-zero neutrino masses affect cosmological evolution significantly through a suppression of the growth of density fluctuation because relativistic neutrinos have large thermal velocity and erase the density fluctuations up to horizon scales due to their free streaming behaviour.This has been studied in [9–11] where they provide a fitting formula for the suppression. Recent work [12] studied these fitting formulae with using numerical simulation which uses wide range of simulation box size and neutrino masses($\sum m_\nu \sim 0.05 - 1.9$ eV) in the present epoch.The overall suppression is found to be $\frac{\Delta P}{P} \sim -10 f_\nu$, (where f_ν is the fractional neutrino budget of the universe) for $\sum m_\nu \leq 0.5$eV. By measuring the power spectrum of cosmological 21 cm line radiation fluctuation, we will be able to obtain useful information on the total neutrino masses and the effective number of neutrino species N_ν.

In this thesis we probe the imprint of such free streaming effects on the cosmological matter power spectrum. We consider the post-reionization intergalactic medium where the redshifted 21-cm signal and the Lyman-alpha forest are studied as a probe of the power spectrum.

The flux through the Lyman-alpha forest and the redshifted 21 cm signal from the post-reionization epoch are modelled as biased tracers of the underlying dark matter distribution. Hence the Universe can be probed using the 21cm line and Ly-Alpha forest from neutral hydrogen allows us to probe universe in the post reionization epoch ($z < 6$).

The 21 cm line arises from the transition between hyperfine levels of the ground state of Hydrogen atom. The states ($1S_{3/2}, 1S_{1/2}$) between which this transition takes place correspond to the electron and proton spins being parallel and anti-parallel. The parallel state has little higher energy then the anti-parallel state. The energy difference between these two states is 5.9×10^{-6} eV which corresponds to a wavelength 21 cm or a frequency 1420.40 MHz. This transition for a single hydrogen atom in excited state shall take $3.5 \times 10^{15} s$ to complete but large number of hydrogen atoms in the astronomical context make this possible.

Ly-alpha arises transition from n=2 to n=1 energy level of neutral Hydrogen atom. This transition has wavelength of 1216 A^0 in the rest frame. The optical depth of Ly-α at a given frequency is given by

$$\tau_{Ly\alpha} = \frac{4.14 \times 10^{12} n_H}{H(z)} \tag{1.1}$$

$n_H$is the number density of neutral hydrogen atoms in the scattering region. The flux is reduced by the factor $e^{-\tau_{Ly\alpha}}$. The expected number density of intergalactic hydrogen is

$$n_H = 2.5 \times 10^{-8}(1+z)^3 \tag{1.2}$$

Our work shall focus on the post-reionization epoch. The astrophysical processes that ionize most of the neutral IGM gets over by redshift $z \sim 6$. The post-reionization IGM presents us with two astrophysical systems. The bulk of the gas is contained in self shielded damped Lyman-alpha systems which source the 21-cm signal seen in emission. Then there is the diffuse gas which produces distinct absorption features in the spectrum of background Quasars when in an expanding Universe, the redshifted frequency matches with the Lyman-alpha frequency in the rest frame of the gas. This forms a dense series of absorption lines known as the Lyman-alpha forest.

The 21 cm signal from IGM is very weak compared to the other foregrounds [13–18], removal of those foregrounds undergo inextricable technical challenges. The cross correlation of the 21 cm signal with other cosmological probes like the Lyman-alpha forest has been proposed as a viable way to mitigate the effect of foregrounds [19–21] (in the work we use this cross-correlation to predict parameters).These two signals are expected to be correlated [22–25]. The cross-correlation signal is a direct probe of the matter power spectrum over a large redshift range in the post reionization epoch. Nevertheless the detection of that signal requires dedicated observations even with the best possible telescopes in the world. We consider a future radio interferometric observation of the 21 cm using a telescope like SKA1-mid [1] and a BOSS [2] like Lyman-alpha forest survey for obtaining predictions for bounds on the parameters.

Quasar surveys like the BOSS, SDSS have given high resolution spectra of the Lyman-alpha forest. Several radio telescopes like the Square Kilometre Array (SKA) are also aimed towards the detection of the 21-cm signal. This allows for the possibility of cross-correlating the signals in future and thus allow us to gain valuable insights about the nature of dark matter and dark energy.

1.1 Outline Of the Thesis

This theis is organized as follows.

In the *second chapter* an overview of cosmological 21 cm signal is presented. This gives a review of the use of the redshifted 21 cm line of neutral hydrogen as a cosmological probe of the dark ages, reionization and post reionization era. The observational aspects of 21 cm line will also be discussed.

In the *third chapter* the formalism of cross correlation and its uses in cosmology is presented. We focus on the post-reionization HI 21-cm signal and investigate the of cross correlating the 21 cm signal with other tracers of the large scale structure. The cross-correlation of the post-reionization 21 cm signal with the Lyman-forest will be discussed separately and feasibility of detecting the 21 signal will be studied.

The neutral intergalactic medium in the post reionization epoch allows us to study cosmological structure formation through the observation of the redshifted

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[1] https://www.skatelescope.org/

[2] https://www.sdss3.org/surveys/boss.php

21 cm signal and the Lyman-alpha forest. In the *fourth chapter* the possibility of measuring the total neutrino mass through the suppression of power in the matter power spectrum will be investigated. The possibility of measuring the neutrino mass through its imprint on the cross-correlation power spectrum of the 21-cm signal and the Lyman-alpha forest will be studied by using a radio interferometric measurement of the 21 cm signal with a SKA1-mid like radio telescope and a BOSS like Lyman-alpha forest survey.

In the *fifth chapter*, the prospects for measuring the cross Warm Dark Matter power spectrum of the redshifted HI 21-cm signal and the Lyman-forest is discussed. The possibility of constraining WDM mass using observations with upcoming radio-interferometers - the Ooty Wide Field Array and SKA1-mid, and a spectroscopic survey of the quasars is taken up. It is shown that it is possible to have a measurement of the suppression of power from the Cold Dark Matter power spectrum at a confidence level of $\sim 7.2 - \sigma$ and $\sim 2.7 - \sigma$ in two different k-bins over the k-range $0.1 \leq k \leq 3.13\ Mpc^{-1}$ for $m_{WDM} = 0.15$ keV. Considering the analysis with SKA1-mid, we find that for a fiducial $m_{WDM} = 0.25$ keV, the suppression in the cross power spectrum can be measured at $\sim 10 - \sigma$ around $k \sim 0.2 Mpc^{-1}$ for a total observing time of 20000 hrs distributed uniformly over 50 independent pointings where the available k-range is binned as $k = k/5$.

The *sixth chapter* is concerned with dark energy. We consider model independent parametrizations of dynamic dark energy with an equation of state parameter w(z) varying with redshift. The CPL and BA parametrization involving two parameters (w_0, w_a) are constrained using the imprint of baryon acoustic oscillation (BAO) on the cross-correlation of the 21-cm signal and the Lyman-forest. We make error projections on (w_0, w_a) implicitly from the predicted errors on H(z) and $D_A(z)$ from the BAO signature on the cross-power spectrum.

In the last chapter we conclude with some of the directions in which the work done in the thesis can be continued further.