Prospects of probing quintessence with HI 21-cm intensity mapping survey

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ABSTRACT

We investigate the prospect of constraining scalar field dark energy models using HI 21-cm intensity mapping surveys. We consider a wide class of coupled scalar field dark energy models whose predictions about the background cosmological evolution are different from the ΛCDM predictions by a few percent. We find that these models can be statistically distinguished from ΛCDM through their imprint on the 21-cm angular power spectrum. At the fiducial $z = 1.5$ corresponding to a radio interferometric observation of the post-reionization HI 21 cm observation at frequency $568\text{MHz}$, these models can in fact be distinguished from the ΛCDM model at $\text{SNR} > 3$σ level using a 10,000 hr radio observation distributed over 40 pointings of a SKA1-mid like radio-telescope. We also show that tracker models are more likely to be ruled out in comparison with ΛCDM than the thawer models. Future radio observations can be instrumental in obtaining tighter constraints on the parameter space of dark energy models and supplement the bounds obtained from background studies.

Key words: cosmology: theory – large-scale structure of Universe - cosmology: diffuse radiation – cosmology: Dark energy

1 INTRODUCTION

The latest observational data give compelling evidence about the presence of an unknown dark component with negative pressure in the universe (Betoule et al. 2014; Planck Collaboration et al. 2014; Sánchez 2012). The contribution of this unknown component, commonly termed as dark energy (Sahni & Starobinsky 2000; Peebles & Ratra 2003; Padmanabhan 2003; Copeland et al. 2006; Sahni 2002), is around 70% of the total energy budget of the universe. The presence of such a large unknown component in the universe whose origin and nature is still unexplained, is a major embarrassment for cosmologist. Understandably all the future cosmological observations have a common goal: to know the nature of dark energy.

Cosmological constant (with an equation of state $w = -1$) as proposed by Einstein himself to obtain a static universe, is the simplest explanation for the mysterious dark energy, given the fact that a flat ΛCDM universe agrees exceptionally well to all the observational data till date (See also (Delubac et al. 2015; Sahni et al. 2014; Trøst Nielsen et al. 2015; Di Valentino et al. 2016) for some recent contradiction). However, the problem of extreme fine tuning for the value of cosmological constant as well as the cosmic coincidence problem, have inspired researchers to explore beyond the cosmological constant and study models where dark energy evolves with cosmological evolution.

The natural alternative to cosmological constant is the quintessence scenario (Ratra & Peebles 1988; Caldwell et al. 1998; Liddle & Scherrer 1999; Steinhardt et al. 1999; Scherrer & Sen 2008) where a minimally coupled scalar field with canonical kinetic term rolling over a sufficiently flat potential around present time, can mimic a time varying cosmological constant. Although, one still needs to do the required fine tuning, one can at least evade the cosmic coincidence problem in such a scenario. Various alternatives of quintessence models such as k-essence (Chiba et al. 2000; Armendariz-Picon et al. 2000, 2001; Chiba 2002; Chimento & Feinstein 2004; Scherrer 2004; Sahni & Sen 2015; Li & Scherrer 2016), tachyons (Bagla et al. 2003; Sen 2006; Chimento 2004; Ali et al. 2009), non-minimally coupled scalar fields (Bertolami & Martins 2000; Torres 2002; Sen & Sen 2001; Sen et al. 2009), and chameleon fields (Khoury & Weltman 2004; Wei & Cai

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Coupled quintessence models where the scalar field is only coupled to DM have been studied in different contexts starting from background evolution to linear and nonlinear structure formation (Amendola 2000; Koivisto 2005; Lee et al. 2006; Saracco et al. 2010; Amendolia et al. 2014). Due to the absence of coupling to the baryonic sector, one can avoid the stringent constraints from local physics. In most coupled quintessence scenario, the potentials for scalar field were phenomenological and tracker type. For PST model we have a thawing scalar field (similar to inflaton) with a linear potential that is not phenomenological but arises out of the construction of the model itself. The avoidance of coupling with the baryonic sector also happens naturally in this set up. The only phenomenological aspect in this scenario is the form of the coupling due to our lack of complete understanding about the origin of dark matter. In recent past, coupled quintessence model in the PST scenario has been confronted with the latest observational data by Kumar et al (Kumar et al. 2013). It has been shown that with the current precision of various observations, a large class of coupled quintessence behaviour is still indistinguishable from the concordance $\Lambda$CDM model.

The three dimensional tomographic mapping of the neutral hydrogen (HI) distribution is a powerful probe to understand large scale structure formation in the post reionization era (Bharadwaj et al. 2001; Wyithe & Loeb 2009). The epoch of reionization was completed by redshift $z \sim 6$ (Becker et al. 2001; Fan et al. 2002). After this, most of the remnant neutral gas is contained in the self shielded Damped Ly-$\alpha$ (DLA) systems (Wolfe et al. 2005). These are supposedly the primary cosmological source of HI 21-cm signal (Furlanetto et al. 2006). The detection of the individual DLA clouds is technically very challenging due to their small size and weakness of the signal ($< 10 \mu$Jy). But the collective diffuse HI 21-cm radiation from all the clouds without resolving the individual DLAs is expected to form a background in radio observations at frequencies $< 1420$MHz. Intensity mapping of this background radiation can yield enormous cosmological information regarding the background evolution of the Universe as well as the structure formation in the post-reionization epoch (Wyithe & Loeb 2007; Visbal et al. 2009; Wyithe et al. 2008; Chang et al. 2008; Bharadwaj et al. 2009; Mao et al. 2008; Wyithe 2008; Bull et al. 2015; Guha Sarkar & Datta 2015). The upcoming Square Kilometer Array (SKA) in various phases has a dominant science goal of mapping out the large scale distribution of neutral hydrogen over a wide range of redshifts. Imaging of the Universe using the redshifted 21-cm signal from redshifts $z \lesssim 6$ (Wyithe & Loeb 2007; Bharadwaj et al. 2001; Wyithe & Loeb 2009) will open new avenues towards our understanding of cosmology (Loeb & Wyithe 2008; Wyithe & Loeb 2008; Visbal et al. 2009; Wyithe et al. 2008; Chang et al. 2008; Bharadwaj et al. 2009). The large scale clustering of the HI in the post-reionization epoch shall directly probe the nature of dark energy through the imprints of a given model on the background evolution and growth of structures. As a direct probe of cosmological structure formation, 21-cm intensity mapping may allow us to distinguish between dark energy models which are otherwise degenerate at the level of their prediction of background evolution.

In this paper, we study the prospects of probing coupled quintessence models using the HI intensity mapping in the context of forthcoming SKA observations. In addition to the PST model described above, we also consider other phenomenological potentials that have been considered in the literature. This gives a detail analysis on future constraints on coupled quintessence models in the context of observations from HI 21-cm intensity mapping. We concentrate on the thawing class of scalar field models (recent discussions argued that these are more favored than the tracking ones (Linder 2015)). But to make the investigation complete, we also consider one particular parametrization (called GCG parametrization) (Thakur et al. 2012) that broadly described both the thawing and tracker models and study the prospects of distinguishing these two behaviours using the HI intensity mapping survey by SKA. We also study the clustering on superhorizon scales where we can no longer ignore the scalar field fluctuations.
Amendola (2000, 2004) models. Here we also follow the same formalism. The relevant equations are given below:

\[ \ddot{\phi} + \frac{dV}{d\phi} + 3H\dot{\phi} = C(\phi)\rho_d \]

\[ \dot{\rho}_d + 3H(\rho_d) = -C(\phi)\rho_d\dot{\phi} \]

\[ \dot{\rho}_b + 3H(\rho_b) = 0 \]

\[ H^2 = \frac{\kappa^2}{3}(\rho_b + \rho_d + \rho_\phi). \]

This is complemented by the flatness condition

\[ 1 = \frac{\kappa^2\rho_b}{3H^2} + \frac{\kappa^2\rho_d}{3H^2} + \frac{\kappa^2\dot{\phi}^2}{6H^2} + \frac{\kappa^2V(\phi)}{3H^2} \]

Here \( C(\phi) \) represents coupling parameter between the scalar field and dark matter. Subscript “d” represents the DM sector and subscript “b” represents the baryonic sector. The details of the physics for the interaction between the dark energy and the dark matter is largely unknown. In view of this, we assume phenomenologically \( C(\phi) \) to be a constant in our subsequent calculations. This is similar to the earlier work by Amendola (Amendola 2000, 2004) and collaborators on coupled quintessence. For \( C = 0 \) we recover the uncoupled case, hence the system allows us to study both coupled and uncoupled cases.

Next, we construct the following dimensionless variables:

\[ x = \frac{\dot{\phi}}{\sqrt{3H}} \]

\[ y = \frac{\sqrt{V(\phi)}}{\sqrt{3H}} \]

\[ s = \frac{\kappa\sqrt{\rho_b}}{\sqrt{3H}} \]

\[ \lambda = -1 \frac{dV}{d\phi} \Gamma = \frac{V\sqrt{dV}}{(dV/d\phi)^2} \]

Note that the parameter \( \Gamma \) is related to the form of the potentials in our model. For the PST model described in the introduction, the potential is linear, hence \( \Gamma \) vanishes. For completeness, we also consider other power-law potentials of the form \( V(\phi) \propto \phi^n \) where \( \Gamma = (n-1)/n \).

The density parameter \( \Omega_\phi \) and the equation of state for the scalar field \( w_\phi \) can be written in terms of \( x \) and \( y \) as:

\[ \Omega_\phi = x^2 + y^2 \]

\[ \gamma = 1 + w_\phi = \frac{2x^2}{x^2 + y^2} \]

With this, one can form an autonomous system of equations:

\[ \Omega_\phi' = W\sqrt{3\gamma\Omega_\phi(1 - \Omega_\phi - s^2)} + 3\Omega_\phi(1 - \Omega_\phi)(1 - \gamma) \]

\[ \gamma' = W\sqrt{\frac{3\gamma}{\Omega_\phi}(1 - \Omega_\phi - s^2)(2 - \gamma) + \lambda\sqrt{3\gamma\Omega_\phi(2 - \gamma)}} \]

\[ -3\gamma(2 - \gamma) \]

\[ s' = -\frac{3}{2}s\Omega_\phi(1 - \gamma) \]

\[ \lambda' = \sqrt{3\gamma\Omega_\phi}\lambda^2(1 - \Gamma), \]

where \( W = \frac{\Gamma}{\kappa} \). We evolve the above system of equations from the decoupling era \((a = 10^{-3})\) to the present day \((a = 1)\). We need to fix the initial conditions for \( \gamma, \Omega_\phi \) and \( \lambda \) to solve the system of equations. For thawing models, scalar field is initially frozen due to large Hubble damping, and this fixes the initial condition \( \gamma_i \approx 0 \). The initial value \( \lambda_i \) is a model parameter; for smaller \( \lambda_i \), the equation of state \( w_\phi \) for the scalar field always remain close to cosmological constant \( w = -1 \) whereas for larger values of \( \lambda_i \), \( w_\phi \) increases from \( -1 \) as the universe evolves. The contribution of scalar field to the total energy density is negligibly small in the early universe (except for early dark energy models that we are not considering in this study). But we need to fine tune it initially in order to obtain a correct value of \( \Omega_\phi \) at present. This fixes the initial condition for \( \Omega_\phi \). Similarly, we need to fix the initial value of \( s \) (which is related to the density parameter for baryons) to get right value of the \( \Omega_b \) at the present epoch. In our subsequent calculations we fix \( \Omega_b \) = 0.05.

### 3 Growth of Matter Fluctuations in the Linear Regime

We next study the growth of matter fluctuations in the linear regime. Here matter consists of both dark matter and baryons; but in the late universe (which is the time period we are interested in), the dark matter perturbation is dominant and baryons follow the dark matter perturbation. Hence we ignore the baryonic contribution in our calculations. We should stress that even if we include the baryon contribution (which is very straightforward to do), our results do not change. We work in the longitudinal gauge:

\[ ds^2 = a^2 [-(1 + 2\Phi)dr^2 + (1 - 2\Psi)dx^idx_i], \]
where \( \tau \) is the conformal time and \( \Phi \) and \( \Psi \) are the two gravitational potentials. In the absence of any anisotropic stress \( \Phi = \Psi \). We follow the prescription by Amendola (Amendola 2000, 2004) and write the equations for the perturbations in dark matter density in the Newtonian limit. This is valid assumption for sub horizon scales. In these scales, one can safely ignore the clustering in the scalar field. Under these assumptions, the linearized equations governing the growth of fluctuations in dark matter is given by:

\[
\delta_d'' + \left( 1 + \frac{H'}{H} - 2\beta_d x \right) \delta_d' - \frac{3}{2}(\gamma_{dd} + \delta_d \Omega_d) = 0.
\]  

(9)

The prime denotes differentiation w.r.t to \( \log a \), \( x \) is given by equation (4). Here \( \beta_d = W, \gamma_{dd} = 1 + 2\beta_3^3 \). \( H \) is the conformal Hubble parameter \( H = aH \) and \( \delta_d \) is the linear density contrast for the DM. We solve the equation with the initial conditions \( \delta_d \sim a \) and \( \delta_d'_{ini} = 1 \) at decoupling \( a \sim 10^{-3} \). This is valid since the universe is matter-dominated at the epoch of decoupling. We take the Fourier transform of the above equation and define the linear growth function \( D_d \) and the linear growth rate \( f_d \) as

\[
\delta_{d, \text{ini}}(a) \equiv D_d(a)\delta_{d, \text{ini}}^{ini} \quad \quad f_d = \frac{d \ln D_d}{d \ln a}.
\]

(10)

(11)

The linear dark matter power spectrum defined as

\[
P(k, z) = A_0 k^{n_s} T^2(k) D^2_{\text{lin}}(z).
\]

(12)

Here \( A_0 \) is the normalization constant fixed by \( \sigma_8 \) normalization, \( n_s \) is spectral index for the primordial density fluctuations generated through inflation, \( D_{\text{lin}}(z) \) is growth function normalized such as it is equal to unity at \( z = 0 \) i.e. \( D_{\text{lin}}(z) = D_{\text{lin}0}(\Omega_m) \) and \( T(k) \) is the transfer function as prescribed by Eisenstein and Hu (Eisenstein & Hu 1999).

### 4 THE REDSHIFTED 21 CM SIGNAL FROM THE POST-REIONIZATION EPOCH

The neutral hydrogen (HI) distribution in post-reionization epoch is modeled by a mean neutral fraction \( \bar{x}_{H I} \) which remains constant over a wide redshift range \( z \leq 6 \) (Storrie-Lombardi et al. 1996; P'ecroux et al. 2003) and a linear bias parameter \( b_r \) which relates the HI fluctuations to the underling dark matter distributions (Bagla et al. 2010; Guha Sarkar et al. 2012). The quantity of interest is the fluctuation of the excess HI 21 cm brightness temperature \( \delta T_{H I} \). Denoting the comoving distance to the redshift \( z \) by \( r \) we have \( \delta T_{H I} \) given by a fluctuation field on the sky corresponding to radial and angular coordinates \( (z, r, \hat{n}) \) as \( \delta T_{H I} = \bar{T}(z) \times \eta_{H I}(r, \hat{n}) \) (Bharadwaj & Ali 2004) where

\[
\eta_{H I}(r, \hat{n}, z) = \bar{x}_{H I}(z) \left[ \delta_{H I}(z, \hat{n}) - \frac{1 + z}{H(z)} \right],
\]

(13)

and

\[
\bar{T}(z) = 4.0 \text{mK}(1 + z)^2 \left( \frac{\Omega_m h^2}{0.02} \right) \left( \frac{0.7}{H_0} \right) \left( \frac{H_0}{H(z)} \right)
\]

(14)

Here, \( \delta_{H I} \) denotes the HI fluctuations and \( \nu \) denotes the peculiar velocity of the gas. If \( \Delta(k, z) \) and \( \Delta_{H I}(k, z) \) denote dark matter overdensity \( \delta_d \) and \( \delta_{H I} \) respectively in Fourier space then they are related by a bias function \( b_r(k, z) \) as \( \Delta_{H I}(k, z) = b_r(k, z) \Delta(k, z) \). On large scales of our interest, the bias is found to be a constant in numerical simulations of the post-reionization HI signal (Guha Sarkar et al. 2012). We use a linear bias model in this analysis. If the peculiar velocities of the gas are sourced by dark matter over densities then the angular power spectrum of the brightness temperature in the flat sky limit is given by (Datta et al. 2007)

\[
C_{l} = \frac{T^2}{\pi f_r^2} \int_0^\infty dk \left( 1 + \beta_d^2 \right)^2 P(k, z)
\]

(15)

where \( P(k, z) \) is the dark matter power spectrum defined equation in (12), \( k = \sqrt{k^2 + \nabla^2}, \mu = \frac{k}{r} \) and \( \beta = \frac{f_d(z)}{b_r} \) with \( f_d(z) \) is the growth factor for dark matter defined in equation (11). We note that the redshift dependent quantities \( T \) and \( r \) are directly related to the background cosmology and \( \beta \) and \( P(k, z) \) imprint both background history and structure formation. We adopt the value of \( \Omega_{H I} = 10^{-3} \) at \( z < 3.5 \). This yields \( x_{H I} = 2.45 \times 10^{-3} \) (Storrie-Lombardi et al. 1996) which is assumed to be constant across the redshift range of our interest.

We consider a radio interferometric measurement of the power spectrum of the 21 cm brightness temperature. The directly measured ‘Visibility’ is a function of frequency \( \nu \) and baseline \( U = k \perp r/2\pi \) and allows us to compute the angular power spectrum \( C_l \) directly using Visibility-Visibility correlation (Bharadwaj & Ali 2005) with the association \( l = 2\pi U \).

The noise in the measurement of angular power spectrum comes from cosmic variance on small scales and instrument noise on small scales. We have

\[
\Delta C_l = \left[ \frac{2}{(2l + 1)\Delta f_{sky} N_p} \right] (C_l + N_l)
\]

(16)

where \( N_p \) denotes the number of pointings of the radio interferometer, \( f_{sky} \) is the fraction of sky observed in a single pointing, and \( \Delta l \) is the
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5 RESULTS

In figure 1 (left), we plot the evolution of Hubble parameter $H(z)$ with redshift for different combinations of $W$ and $\lambda_i$ and also for $\Lambda$CDM for the PST model with linear potential. Remember $W$ parameter determines the strength of the coupling and $\lambda_i$ determines the deviation from the cosmological constant. We choose the combinations (mentioned in figure 1) so that the deviation from $\Lambda$CDM is very small and in actual it is around $3 - 4\%$ or less up to a redshift $z = 1.5$. This is much smaller than the current error bar in the measurement of $H(z)$ at different redshift.

The fact that the models are statistically indistinguishable at the level of their predictions about background evolution, prompts us to investigate their signature in structure formation. The imprint of the dark energy model on the 21-cm angular power spectrum is not only in actual it is around $3 - 4\%$ or less up to a redshift $z = 1.5$. The same combinations of $(W, \lambda_i)$ as in left figure are used. The black line corresponds to the noise level with SKA1-mid like telescope assuming the fiducial $\Lambda$CDM value model.

width of the $l$ bin. The noise power spectrum $N_l$ is given by

$$N_l = \left( \frac{\lambda^2}{A_d} \right)^3 \frac{T^2_{sys}}{N_{pol} \Delta \nu t_0 n(U)}$$

(17)

where, $\lambda$ is the observed wavelength, $A_d$ is the effective antenna diameter, $T_{sys}$ is the system temperature, $t_0$ is the observation time, $N_{pol}$ denote the number of polarization states used, $\Delta \nu$ is the frequency band and $n(U)$ is the baseline distribution function normalized as

$$\int d^2U \ n(U) = \frac{N_{ant} (N_{ant} - 1)}{2}$$

(18)

where $N_{ant}$ denotes the number of antennae in the radio array.

We consider a radio interferometer with parameters roughly following the specifications of SKA1-mid. The fiducial redshift $z = 1.5$ corresponds to an observing frequency of 568MHz which falls in the band of frequencies to be probed by SKA1-mid. We consider a frequency bandwidth of 32MHz around the central frequency. The array is assumed to be composed of 200 dishes each of diameter 15m. The antennae are distributed in a manner such that 75% of the dishes are within 2.5Km radius and the density of antennae are assumed to fall off radially as $r^{-2}$. We also use $T_{sys} = 180 (\frac{\nu}{180MHz})^{-2.6}$ K. in our error estimates. With this we calculate the error bar $\Delta C_l$ for SKA1-mid assuming a fiducial $\Lambda$CDM model with $\Omega_{\Lambda} = 0.7, \Omega_{m0} = 0.05, n_s = 1, h = 0.7$ and $\sigma_8 = 0.8$. We also fix the constant linear bias to be 1.0 at the fiducial redshift from numerical simulations of the 21cm signal (Guha Sarkar et al. 2012).
Figure 2. Same as figure 1 but for inverse power law potential \( V \sim \phi^{-2} \).

Figure 3. Same as in figure 1 but for square law potential \( V \sim \phi^2 \).

level or more. Note that we choose combinations of parameters \( W \) and \( \lambda \) for which the Hubble parameter deviates from \( \Lambda \)CDM value by 3 – 4% which is very conservative choice. Current data allows bigger deviations from \( \Lambda \)CDM value. In such cases, the deviation in \( C_l \) from \( \Lambda \)CDM predictions should be certainly distinguished with larger confidence level with future SKA1-mid data.

Also if we put \( W = 0 \) in all these cases, the fractional difference with \( \Lambda \)CDM will be much less than the error bar and can not be distinguished at all from \( \Lambda \)CDM with future survey like SKA1-mid.

6 THAWING VS TRACKER

In the previous sections, we consider scalar field models which are thawer in nature. In such models, the scalar field is initially frozen due to large hubble damping and the equation of state of the scalar field is very close to \(-1\). As the universe evolves, hubble damping decreases and the scalar field slowly thaws away from the frozen state and the equation of state of the scalar field slowly increase towards \( w > -1 \). There is another class of models, known as the tracker models where initially the scalar field fast rolls due to the steep nature of the potential and mimics the background matter density (\( w \sim 0 \)). In late times, the scalar field potential flattens up and the scalar field finally freezes to \( w \sim -1 \) behaviour. Although a variety of potentials can give rise to both thawer and tracker potentials, it may be useful to have simple parametrization for the equation of state of the scalar field that broadly describes these two behaviours. The generalized chaplygin gas (GCG) equation of state described by \( p = -\frac{A}{\rho}^{\alpha} \) where \( A \) and \( \alpha \) are two constant parameters, is useful for this purpose (Thakur et al. 2012). For such a parametrization the dark energy equation of state is given by

\[
 w_{de} = -\frac{A_s}{A_s + (1 - A_s)A^{3(1+\alpha)}}. \tag{19}
\]

where \( A_s = \rho_{de,0}/A^{1+n} \). It is straightforward to check that for \((1 + \alpha) < 0\), \( w_{de} \) behaves like thawer model while for \((1 + \alpha) > 0\), \( w_{de} \)
behaves like tracker model. The parameter $A_s$ is related to the current value of the equation of state for the dark energy, $A_s = -w_{de}$. In figure 4, we show these two behaviours.

With this, we investigate whether one can distinguish these two behaviours from $\Lambda$CDM using the future SKA data. We concentrate on the uncoupled case where the dark energy is not coupled with the dark matter and follow the same procedure as described in section 3 and 5. The result is shown in figure 5.

The result for the thawer model is consistent with our previous observation in section 5 that without interaction with DM ($W = 0$), the thawing model cannot be distinguished from $\Lambda$CDM with future SKA-mid. On the other hand, the tracker model can be distinguished from $\Lambda$CDM with very high confidence with future SKA observations even without the interaction with DM.

7 FLUCTUATIONS IN THE SUPER-HORIZON SCALES

In the previous sections, we study the dark matter density perturbation for quintessence models in the sub-horizon scales where we ignored the perturbations in the dark energy scalar field and concentrate in the Newtonian limit. We show that it will be possible to distinguish these scalar field models from $\Lambda$CDM specially for coupled scenario using the observations of angular power spectra from HI 21-cm mapping survey like SKA-mid. In this section, we study how these models deviate from $\Lambda$CDM at super-horizon scales. On such scales, we cannot ignore the perturbations in the scalar field for dark energy and also one has to do the full relativistic perturbation. Such study has been done by various authors in recent past. Here we specifically concentrate on the coupled quintessence of thawer class with linear potentials as constructed in the PST model. It can be straightforwardly generalized for any other scalar field potentials.

For this purpose we follow the set up as provided by Unnikrishnan et al (Unnikrishnan et al. 2008). We work in the longitudinal gauge as described by the metric in equation (8) with $\Phi = \Psi$ for vanishing anisotropic stress. The perturbed Einstein equations are given

$$\delta G_{\mu\nu} = \delta T_{\mu\nu},$$

where $\delta T_{\mu\nu}$ contains both the perturbations in the matter part as well as in the scalar field part. These are supplemented by
Also, \( \vec{\Phi}(x, t) = \hat{\Phi}(t) + \delta \phi(\vec{x}, t) \) and \( \delta \dot{\phi} = \delta \phi' = 0 \) (scalar field is homogeneous initially) and \( \delta_c \sim a \). In figure 6, we show the scale dependence of the gravitational potential \( \Phi(k) \) and the DM density contrast \( \delta_c(k) \). We fix the redshift at \( z = 1.5 \). It is evident that on large scales, there are large deviations from \( \Lambda \)CDM model in the coupled scenario as we take into account the perturbations of the scalar field. On smaller scales (increasing \( k \)), however, the effect of scalar field perturbation becomes negligible. One should note here, that observing large scale effect of the scalar field dark energy perturbation is difficult due to large cosmic variance. It is possible, in principle to detect the imprint of such large scale effects by considering a full sky 21-cm survey covering a large band in say \( 0.5 < z < 3 \) and collapsing all the multipoles in an experiment where instrumental noise is made to go below the cosmic variance level. Large survey volumes may in future allow us to detect the imprints of clustering dark energy using the maximally available tomographic 21-cm data.
8 DISCUSSIONS

The large scale clustering of the neutral hydrogen in the post reionization era contains a lot of information about our universe for both the background evolution as well as formation of large scale structures. Hence it is a natural probe for dark energy behaviour. In this paper we study the prospects of probing a large class of scalar field dark energy models using angular power spectra for the HI 21-cm intensity mapping from future SKA like instruments. Several observational challenges poses serious difficulties towards the detection of the cosmological redshifted 21-cm signal. Astrophysical foregrounds from galactic and extra galactic sources are several orders of magnitude larger than the signal (Ghosh et al. 2011) and significant amount of foreground subtraction is required for a statistical detection of the signal (Di Matteo et al. 2002; Santos et al. 2005; Gleser et al. 2008; Liu et al. 2009; Ghosh et al. 2011; Alonso et al. 2015). The cross correlation of the redshifted 21 cm signal with other cosmological probes like the Lyman-alpha forest and Lyman-Break galaxies, has been proposed (Guha Sarkar et al. 2011; Guha Sarkar & Datta 2015; Villaescusa-Navarro et al. 2015) to cope with the effect of foreground residuals. Further man made Radio frequency interferences and other systematic effects like calibration errors shall also have to be tackled before obtaining the pristine cosmological signal.

In this work we have considered thawing class of coupled quintessence models with different potentials including that constructed in a string theory set up in the PST model. The equations are constructed in such a way that one can easily switch off the interaction term and study the uncoupled case as well. We show that models which deviate from the \( \Lambda \)CDM universe at \( 3 - 4\% \) level and can not be distinguished by current observations, can be easily ruled out in comparison with \( \Lambda \)CDM model in a multipole region \( l \sim 7000 \) with \( 3 - 5\sigma \) confidence level which is very encouraging. But with the anticipated error bar for SKA1-mid, it will still not be possible to distinguish the uncoupled models from \( \Lambda \)CDM. Large survey volumes in future however may allow a possible detection.

Although our analysis focuses primarily on the thawing class of scalar field models, tracker class of models is another possibility. To distinguish between these classes of models without considering individual potentials, we consider the GCG equation of state which broadly describe both the models for different parameter ranges. With this, we compare the thawing and tracking class of models for the uncoupled case and show that tracker models can be easily ruled with very high confidence level in comparison with both \( \Lambda \)CDM as well as thawing models. The same is true for coupled tracking model although we do not show it explicitly.

In the end, we have studied the deviations of the coupled quintessence model from \( \Lambda \)CDM on very large scales where one can no longer ignore the perturbations in the scalar field and one needs to consider the full relativistic calculations. We show that there is substantial deviation from \( \Lambda \)CDM on large scales for coupled quintessence. But limitation due to cosmic variance on large scales is a problem to probe these deviation. Future tomographic 21-cm data with large survey volume may be useful to probe dark energy on these scales.

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REFERENCES

Ali A., Sami M., Sen A. A., 2009, Phys. Rev. D , 79, 123501
Alonso D., Bull P., Ferreira P. G., Santos M. G., 2015, Mon. Not. Roy. Ast. Soc. , 447, 400
Amendola L., 2000, Phys. Rev. D , 62, 043511
Amendola L., 2004, Phys. Rev. D , 69, 103524
Amendola L., Barreiro T., Nunes N. J., 2014, Phys. Rev. D , 90, 083508
Armendariz-Picon C., Mukhanov V., Steinhardt P. J., 2000, Physical Review Letters, 85, 4438
Armendariz-Picon C., Mukhanov V., Steinhardt P. J., 2001, Phys. Rev. D , 63, 103510
Bagla J. S., Jassal H. K., Padmanabhan T., 2003, Phys. Rev. D , 67, 063504
Bagla J. S., Khandai N., Datta K. K., 2010, Mon. Not. Roy. Ast. Soc. , 407, 567
Becker R. H., Fan X., White R. L. e. a., 2001, Astron. J. , 122, 2850
Bertolami O., Martins P. J., 2000, Phys. Rev. D , 61, 064007
Betoule M., et al., 2014, A&A, 568, A22
Bharadwaj S., Ali S. S., 2004, Mon. Not. Roy. Ast. Soc. , 352, 142
Bharadwaj S., Ali S. S., 2005, Mon. Not. Roy. Ast. Soc. , 356, 1519
Bharadwaj S., Nath B. B., Sethi S. K., 2001, Journal of Astrophysics and Astronomy, 22, 21
Bharadwaj S., Sethi S. K., Sami T. D., 2009, Phys. Rev. D , 79, 083538
Bull P., Ferreira P. G., Patel P., Santos M. G., 2015, Astroph. J. , 803, 21
Caldwell R. R., Dave R., Steinhardt P. J., 1998, Physical Review Letters, 80, 1582
Chang T., Pen U., Peterson J. B., McDonald P., 2008, Physical Review Letters, 100, 091303
Chiba T., 2002, Phys. Rev. D , 66, 063514
Chiba T., Okabe T., Yamaguchi M., 2000, Phys. Rev. D , 62, 023511
Chimento L. P., 2004, Phys. Rev. D , 69, 123517
Chimento L. P., Feinstein A., 2004, Modern Physics Letters A, 19, 761
Copeland E. J., Sami M., Tsujikawa S., 2006, International Journal of Modern Physics D, 15, 1753

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