Effects of variable resolution and cosmological parameters on the hydrogen 21cm cosmic dawn signal

Supervised by Prof. Anastasia Fialkov and Jiten Dhandha

Kyle Wong[1]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK*

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I. INTRODUCTION

As the most abundant element in the Universe, mapping the distribution of atomic hydrogen has the ability to inform the processes of structure formation, as well as shed light on the processes and events which occurred during the period spanning between 375,000 years and 1 billion years after the big bang [6]. Conveniently, hydrogen occasionally interacts with photons of wavelength 21cm, allowing 21cm cosmologists to measure its density.

The 21cm signal is of such importance that numerous simulations have been written to predict its signal. One such simulation, `21cmSPACE`[1], has been developed by the Cambridge Cosmic Dawn group [2][7]. At the basic level, `21cmSPACE` takes initial conditions and evolves them through time to provide the present-day predicted 21cm global signal and 21cm power spectrum, among other astrophysical observables. This is calculated through the following method [4]:

1. A spatial volume is divided into cubical voxels of a specific side length.
2. Large-scale fields such as the Lyman-Werner field are initialized at the first time step from initial conditions, or computed from the previous time step.
3. These large-scale fields are used by sub-grid models within each voxel to calculate local properties, such as star formation prescription.
4. The local properties are then used to inform the large-scale fields, propagated by non-local processes such as radiative transfer.
5. Steps 2-4 are iterated until termination.

Temporally, `21cmSPACE` operates in redshift space with hard-coded endpoints, evolving from $z = 50$ to $z = 6$. Across these redshifts, the Universe is described by linear perturbation theory. At $z = 50$, there is also negligible halo and star formation, permitting the use of the `CAMB`[2] and `Recfast`[3] codes for the creation of initial conditions [4].

Spatially, the total size of `21cmSPACE` can be set to one of 384^3 cMpc^3, 768^3 cMpc^3, and 1536^3 cMpc^3 by changing the number of 3 cMpc side-length voxels to 128^3, 256^3, and 512^3 respectively [1]. This largest simulation size of 1536^3 cMpc^3 allows `21cmSPACE` to be useful in the forecasting for the SKA [4], whose beam covers a large enough square-angle at high redshifts to require this volume. The voxel side-length itself, however, is currently hard-coded, which is disadvantageous since requiring 512^3 voxels to simulate a 1536^3 cMpc^3 box causes a single execution to cost upwards of 23000 CPU hours. Therefore, although it is possible to use `21cmSPACE` to forecast for experiments such as the SKA, the large number of simulations needed to adequately explore the parameter space of initial conditions renders the package nonviable in practice.

Additionally, the initial conditions are currently calculated from fixed parameters. In particular, `21cmSPACE` assumes the Planck 2015 best-fit ΛCDM model as a fixed cosmology [5]. The initial overdensity

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[1] This name, which stands for 21-cm Semi-numerical Predictions Across Cosmic Epochs, was not given until mid-2023; older papers referring to this code do not include this name.
[2] The Code for Anisotropies in the Microwave Background is a code for calculating various cosmological quantities, including power spectra and transfer functions.
[3] Recfast provides fast approximations for calculations of observables resulting from processes during the Epoch of Recombination, the era immediately preceding the period informed by 21cm astronomy.
[4] The Square Kilometre Array (SKA) experiment is a next generation 21cm project which expects to detect first light in 2027.

field δ_m and baryon-dark matter relative velocity v_{bc} are computed [3] from the matter power spectrum and velocity power spectrum as output from `CAMB`, and the initial gas temperature and ionization fraction are calculated from the outputs provided by `Recfast`, both assuming Planck 2015.

II. PROJECT OBJECTIVES

The goals of this research project are twofold: 1. to allow the variation of voxel size in the spatial division of the simulation, as well as 2. to allow implementation of cosmologies other than Planck 2015 in the initialization of starting values.

Success in the first objective will enable `21cmSPACE` to simulate large spatial volumes with fewer voxels,drastically decreasing runtime and enabling `21cmSPACE` to be used for SKA forecasting. Of course, changing the voxel size can alter the final result of the simulation; this will therefore need to be rigorously tested as part of the project to ensure that accuracy in the observables is unaffected.

Achieving the second objective will create a pipeline from a given cosmology to a predicted 21cm signal. Hence, if the predicted signal does not fall within the errors for current experimental data, the cosmology can be rejected. In other words, by making possible the variation of cosmology, `21cmSPACE` can be used to verify or reject theories.

III. PROJECT PROGRESS

Progress has primarily been focused on achieving the second objective. As of now, code has been developed to alter the cosmological inputs to `CAMB` and `Recfast`, making it convenient to recalculate initial conditions. The interactions between functions are properly object-oriented such that new cosmologies can be defined simply by creating an instance of the `cosmology` class, which takes the following parameters at their present-day values as as initialization variables:

- Hubble parameter H_0
- baryonic matter density $\Omega_{\rm b,0}$
- dark matter density $\Omega_{\rm dm,0}$
- effective curvature density $\Omega_{\rm k,0}$
- CMB temperature $T_{\rm cmb,0}$.

This class is primarily organizational, written with both the intention of emulating a subset of the attributes attached to `Astropy` pre-defined cosmologies of datatype `FlatLambdaCDM` class, as well as being compatible with code written for changing `CAMB` and `Recfast` parameters. Changing these cosmologies results in altered initial conditions for `CAMB` outputs, as shown in Fig. 1. In particular, voxel side-lengths of 3 cMpc correspond to k of order 10^{-1}Mpc^{-1} with larger side-lengths, as is one aim of this project, corresponding to smaller k values where the differences induced by varied cosmologies are even more significant. On the other hand, varied cosmology has no effect on the ionization fraction nor the matter temperature, as shown in Fig. 2.

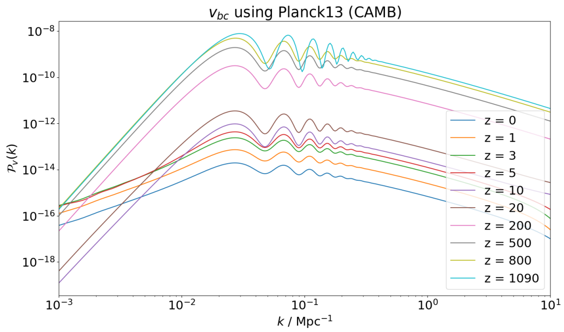
Taking the `CAMB` power spectra, `21cmSPACE` can be used to generate the Gaussian random fields for initialization. Taking slices of the 3D boxes allows visualization of these fields as in Fig. 3.

IV. UPCOMING WORK

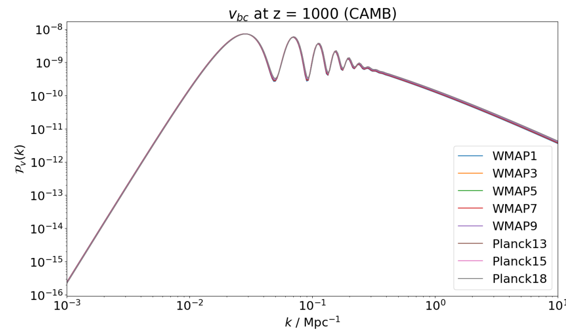
Having invested time learning the usage of `CAMB` and `Recfast` for generating initial conditions, actual implementation of the initial conditions into the `21cmSPACE` MATLAB code by making `CAMB` and `Recfast` outputs compatible with `21cmSPACE` inputs may now follow naturally. The code will also have to be carefully examined to ensure that the effects of variable cosmology are correctly propagated, such as in the calculations of halo abundance. This will ideally be completed by early Lent term.

As well as this, implementation of variable voxel size will be the next step, followed by rigorous testing of the effects these changes have on the predicted signal. Ideally, this will be completed about halfway through Lent term, leaving ample time for writing up.

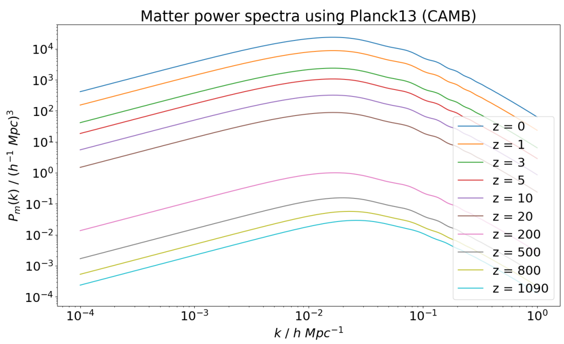
Finally, if time permits, the viability of upscaling these lower-resolution simulations through diffusion models can be explored, possibly recovering the same detail in the final signal at a fraction of the computational cost.



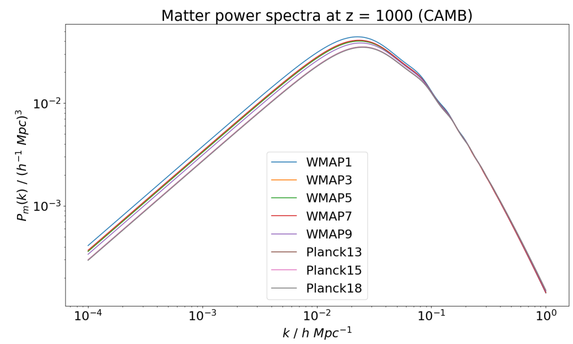
(a) v_{bc} for various redshifts assuming Planck 2015



(b) v_{bc} for various cosmologies at redshift $z = 1000$

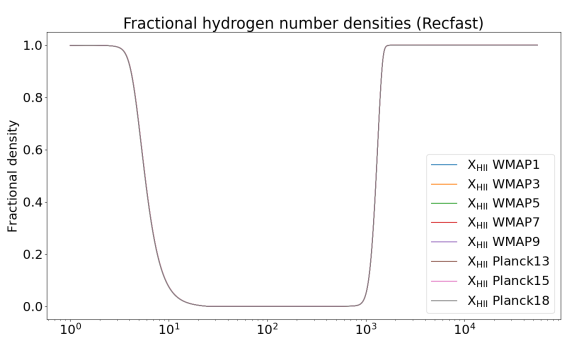


(c) Matter power spectrum for various redshifts assuming Planck 2015

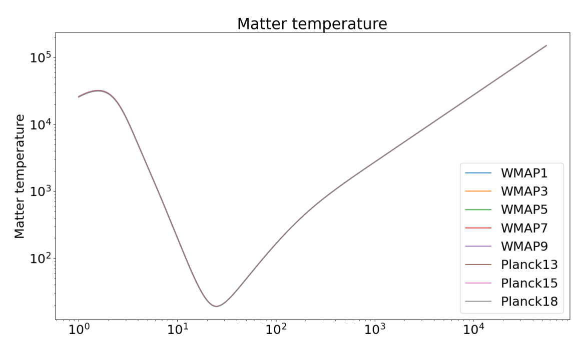


(d) Matter power spectrum for various cosmologies at redshift $z = 1000$

FIG. 1: Figure 1a shows the v_{bc} power spectrum for the Planck 2015 best fit model (the default cosmology in `21cmSPACE`) for various redshifts. Figure 1b shows the v_{bc} power spectrum for various cosmologies imported from `Astropy`. These figures are plotted outputs from `CAMB`.



(a) Ionization fraction history of H_{II} for various cosmologies



(b) Matter temperature history for various cosmologies

FIG. 2: Figure 2a shows the ionization history, and Figure 2b shows the matter temperature history, both for various cosmologies imported from `Astropy`. These figures are plotted outputs from `Recfast`.

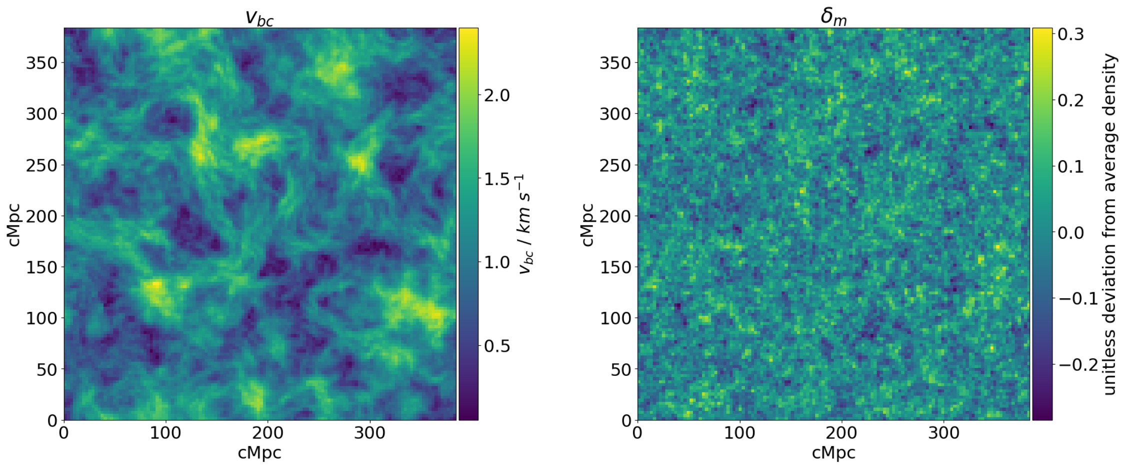


FIG. 3: Slices of the 3D initial condition grids as generated from the `CAMB` outputs. These specific boxes are generated using the default power spectra contained in `21cmSPACE`.

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