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

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I. INTRODUCTION

Because of its overwhelming dominance over other elements in its abundance, 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 cosmic Dark Ages and Epoch of Reionization – a period spanning between 375,000 years and 1 billion years after the big bang [4]. Conveniently, hydrogen occasionally emits photons of wavelength 21cm, resulting in the aptly named field of 21cm cosmology.

The 21cm signal is of such importance that numerous simulations have been written to predict its signal. One such simulation, named `21cmSPACE`[1] [2], has been developed by the Cambridge Cosmic Dawn group and uses a semi-numerical approach to achieve balance between accuracy and efficiency. At the basic level, `21cmSPACE` takes a set of initial conditions and evolves them through time to provide the present-day predicted 21cm global signal and 21cm power spectrum. This signal depends on many factors, both local and non-local, which are all into account by employing the following [3]:

1. A spatial volume is divided into cubical voxels of a specific side length.
2. Large-scale fields are initialized at the first time step from pre-specified initial conditions, or computed from values at the previous time step.
3. These large-scale fields are used by sub-grid model functions within each voxel to calculate local properties.
4. The local properties are then used to inform the large-scale fields, propagated by non-local processes.
5. Steps 2-4 are iterated until the simulation is complete.

Temporally, `21cmSPACE` operates in redshift space, with hard-coded endpoints beginning at $z = 50$ and ending at $z = 6$. At $z = 50$, the Universe is described by linear perturbation theory with negligible halo and star formation, permitting the use of the `CAMB` and `Recfast` codes for the creation of initial conditions [3].

Spatially, the total size of `21cmSPACE` can be set to one of 384^3 cMpc, 768^3 cMpc, and 1536^3 cMpc by changing the number of 3 cMpc side-length voxels to 128^3, 256^3, and 512^3 respectively [1]. This allows `21cmSPACE` to be potentially useful in the forecasting for the SKA, whose beam covers a large enough square-angle at high redshifts to require this increased box size. The voxel side-length itself, however, is currently hard-coded, which is disadvantageous since a single execution of `21cmSPACE` at 512^3 voxels costs upwards of 23000 CPU hours. On Cambridge's Wilkes3 HPC cluster, this costs almost £400 and takes approximately 2 weeks to complete [1]. Therefore, although the use of `21cmSPACE` for SKA forecasting is possible in principle, the large number of simulations needed combined with the high cost of each simulation renders the package nonviable in practice.

Additionally, the initial conditions are currently calculated from fixed parameters. In particular, `21cmSPACE` assumes the Planck 2013 best-fit ΛCDM model as a fixed cosmology [3]. The initial overdensity field δm and baryon-dark matter relative velocity v_{bc} are computed 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 2013.

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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.

The goals of this research project are twofold: 1. to allow the variation of voxel size in the spatial division of the simulation box, as well as 2. to allow implementation of cosmologies other than Planck 2013 in the initialization of starting values. Success in the first objective will enable `21cmSPACE` to simulate large spatial volumes with fewer voxels, which will drastically decrease runtime and enable `21cmSPACE` to be used for SKA forecasting. Of course, changing the voxel size will inevitably alter the final result of the simulation; this will therefore need to be rigorously tested as part of the project. 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.

II. PROJECT PROGRESS

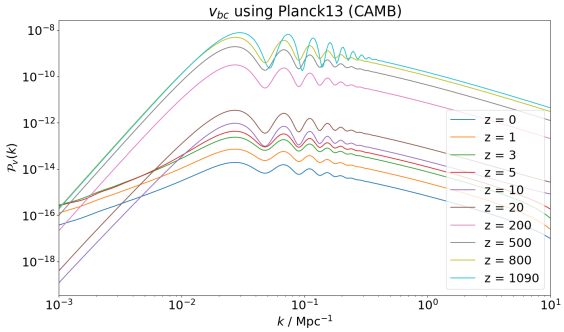
Progress has primarily been focused on achieving the second objective. The initial conditions of `21cmSPACE` at $z = 50$ are derived from four quantities: the matter power spectrum and velocity power spectrum as generated by `CAMB`, and the hydrogen ionization history and matter temperature history as generated by `Recfast`.

As of now, code has been developed to alter the cosmological inputs to `CAMB` and `Recfast`, resulting in the possibility of conveniently recalculating the functions specifying the four quantities required for computing 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, as shown below:

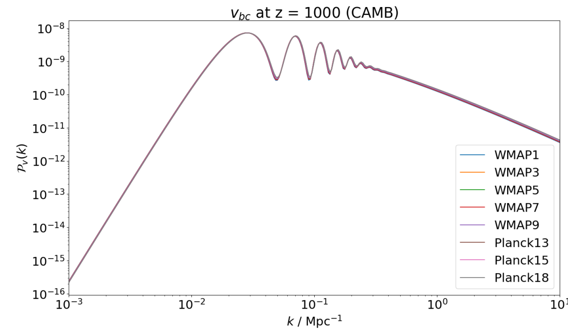
```
from astropy.cosmology import Planck13

default_cosmology = Planck13

class cosmology:
    def __init__(self,
                 name=default_cosmology.name,
                 h=default_cosmology.h,
                 H0=default_cosmology.H0,
                 Ob0=default_cosmology.Ob0,
                 Odm0=default_cosmology.Odm0,
                 Ok0=default_cosmology.Ok0,
                 Tcmb0=default_cosmology.Tcmb0.value):

        self.name = name
        self.h = h
        self.H0 = H0
        self.Ob0 = Odm0
        self.Ok0 = Ok0
        self.Tcmb0 = Tcmb0 # must be dictionary type.
                           # key is unimportant but
                           # astropy defaults to 'temperature'
```

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 $10^{-1}\mathrm{Mpc}^{-1}$ 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.

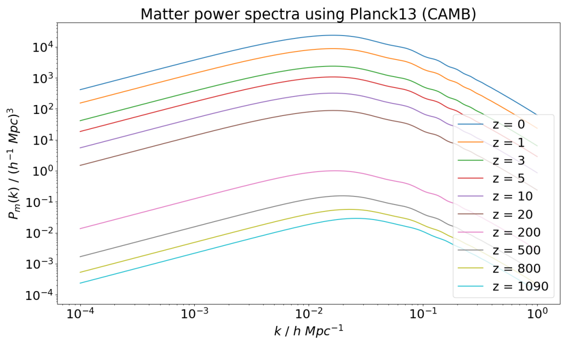
Taking the `CAMB` power spectra, `21cmSPACE` can be used to generate the initial Gaussian random fields for initialization. Taking slices of the 3D boxes allows visualization of these fields as in Fig. 3.



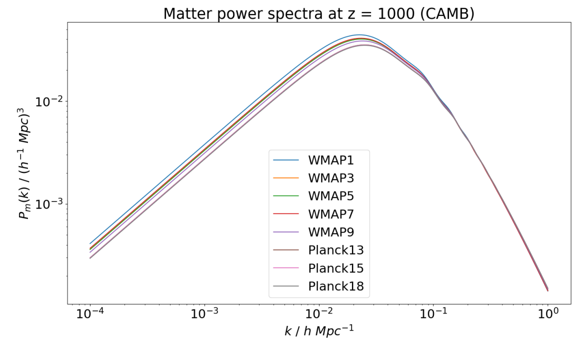
(a) v_{bc} for various redshifts assuming Planck 2013



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

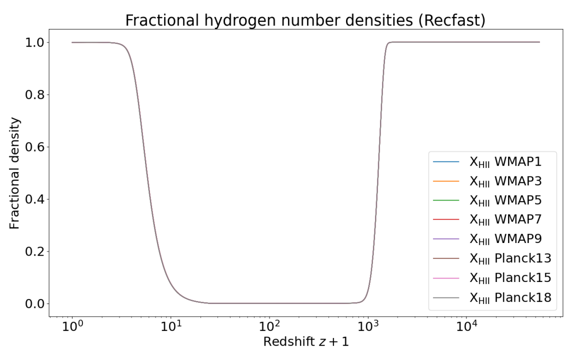


(c) Matter power spectrum for various redshifts assuming Planck 2013

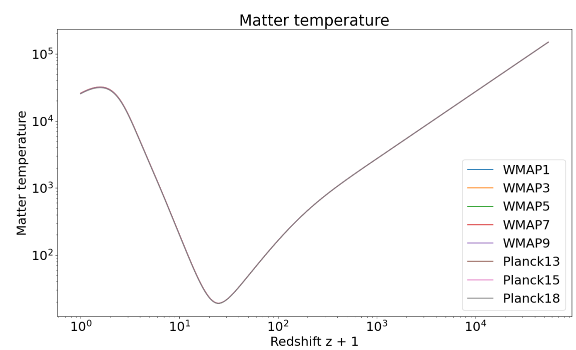


(d) Matter power spectrum for various cosmologies at redshift $z = 1000$

FIG. 1: Figure 1a shows the v_{bc} power spectrum for the Planck 2013 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`.

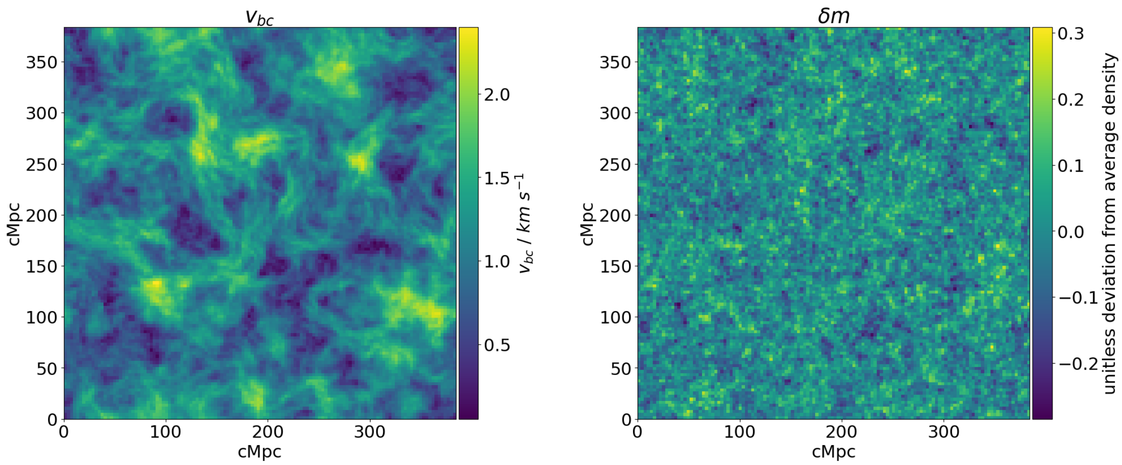


FIG. 3: Slices of the 3D initial condition grids as generated from the `CAMB` outputs. These specific boxes are generated using the default power spectra contained in `21cmSPACE`.

III. 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. As well as this, implementation of variable voxel size will be the next step, followed by rigorous testing of the effects of these changes on the predicted signal. 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.

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[4] Jonathan R Pritchard and Abraham Loeb. "21 cm cosmology in the 21st century". In: *Reports on Progress in Physics* 75.8 (July 2012), p. 086901. ISSN: 1361-6633. DOI: 10.1088/0034-4885/75/8/086901. URL: http://dx.doi.org/10.1088/0034-4885/75/8/086901.