REPORT

HI-21 CM COSMOLOGY WITH THE HELP OF LIGHT CONES AND COEVOLVING PLOTS

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Introduction

For Astronomers, the fact that the speed of light is finite is the sole reason for their ability to look into the past. The further away an object is located, the longer the light emitted by it takes to reach an observer today. This has helped us improve our understanding of the big bang and the subsequent developments observed at the cosmological scale. Added to this, observations at microwave frequencies reveal the cooling afterglow of the big bang known as Cosmic Microwave Background decoupled from the cosmic gas 400,000 years after the Big Bang when the Universe cooled sufficiently for protons and electrons to combine to form neutral hydrogen. Our understanding of the Universe's structure is based upon the observation of small perturbations in the temperature maps of the CMB.

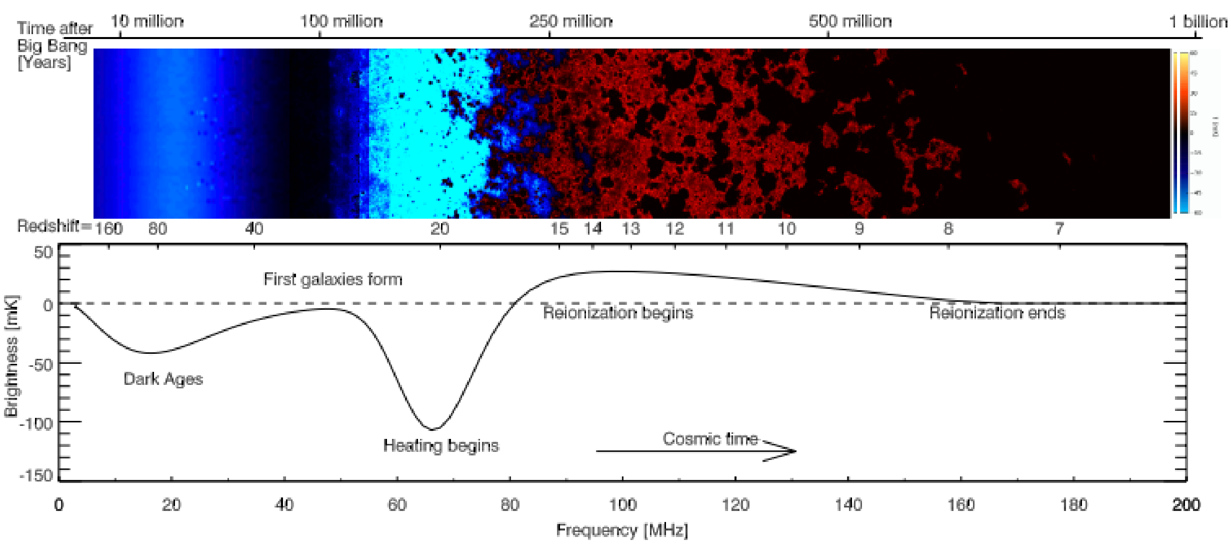
Another important observation that can help in understanding the formation of the Universe is the 21-cm HI line. This line is a hyperfine transition line, arising when electrons and protons align into antiparallel configuration from parallel configuration, releasing a photon of rest wavelength 21-cm (or frequency ~1420MHz). Its optical depth is such that it readily penetrates the interstellar dust clouds that obstruct optical observations, and gives interesting insights into the conditions prevalent in the early stages of the structure formation in the Universe. This line can also be used to probe two important epoch in the evolution of the Universe:

a. Cosmic Dawn - the period in the history of the Universe when the first gravitationally bound structures (i.e. stars and galaxies) started to appear
b. Epoch of Reionization - the last phase transition in the history of the Universe, when the ionizing radiation from the early structures ionized the neutral Universe.

Due to expansion of the Universe, the rest wavelength of the HI signal is stretched to higher wavelengths, and we need to use Radio astronomical telescopes to detect it. However, detection of this signal is extremely challenging. Due to its extremely faint nature, our current technologies cannot detect it directly. However, we can extend current techniques by building larger, more sensitive telescopes. While a number of existing telescopes are trying to put comprehensible limits on the signal amplitude, the upcoming Square Kilometer Array (SKA) , a radio interferometer with unprecedented sensitivity and collecting area, is expected to be able to detect this signal directly.

Despite lack of real observations due to limitations in the current technologies, theoretical modelling for HI signals from the early universe is quite well developed. Using numerical as well as analytical methods, we are able to simulate the evolution of the signal for variation of different parameters that control it. The quantity of interest, i.e. the one that telescopes detect is the differential brightness temperature (henceforth Tb) which is the contrast of the signal of interest against the CMB.

The figure below shows the evolution of the 21-cm brightness temperature over cosmic time.



Courtesy: **<u>21-cm cosmology in the 21st Century</u>** by Jonathan R. Pritchard and Abraham Loeb (Reports on Progress in Physics, 75(8))

Tb can be expressed mathematically as :

$$\begin{aligned}\delta T_b &= \frac{T_S - T_R}{1+z}(1 - \mathrm{e}^{-\tau_\nu}) \\ &\approx \frac{T_S - T_R}{1+z}\tau \\ &\approx 27 x_{\mathrm{HI}}\,(1+\delta_b)\left(\frac{\Omega_b h^2}{0.023}\right)\left(\frac{0.15}{\Omega_m h^2}\,\frac{1+z}{10}\right)^{1/2} \\ &\quad\times\left(\frac{T_S - T_R}{T_S}\right)\left[\frac{\partial_r v_r}{(1+z)H(z)}\right]\,\mathrm{mK},\end{aligned}$$

Where,

Spin temperature = T_S

Brightness temperature = T_R

H(z) = Hubble constant at varying redshifts

with h = 0.74

Mass densities in non-relativistic matter Ω_m = 0.26 and baryons Ω_b = 0.044 as a fraction of the critical mass density.

Frequency =ν, Optical depth= τ, Redshift = z

x_{HI} is the neutral fraction of hydrogen, δ_b is the fractional overdensity in baryons, and the final term arises from the velocity gradient along the line of sight $\partial_r v_r$.

There are two distinct ways in which we can study the signal theoretically - by observing local effects over a single redshift or studying the overall evolution over redshift. Here we have studied how the morphology of these variations appear in space.

LIGHT CONES vs. COEVOLVING PLOTS

A light cone is a light path emanating from a single event (localized to a single point in space and a single moment in time) and traveling in all directions combining all the changes occurring to the HI-21cm signal within broad redshift range. Since this is an observational effect, this provides a realistic way to determine how a sky with only HI will look to an observer.

Coevolving plots describe conditions at a specific redshift of the Universe in all directions without directly looking into the changes observed in the HI-21 cm line. It helps in the effective comparison of the changes happening to the signal and the factors affecting it.

For this work, we have used the publicly available 21cmFAST to generate a realization of the 21-cm signal with and without light cone effect within a redshift range 7-12.

21cmFAST:

21cmFAST is a powerful, semi-numeric modeling tool designed to efficiently simulate the cosmological 21-cm signal. It generates 3D realizations of evolved density, ionization, peculiar velocity, and spin temperature fields, which then combines to compute the 21-cm brightness temperature. Depending on the desired resolution, 21cmFAST can compute a redshift realization on a single processor in just a few minutes. It is fast, efficient, customizable and publicly available, making it a useful tool for 21-cm parameter studies.

Steps to generate the Light Cone and subsequently the signal cube :

Use 21cmFAST (function p21c.run_lightcone) to generate a lightcone cube. The cube has size 500 cMpc with 232 by 232 grids and all others are the default parameters in 21cmFAST.

Cosmological Parameters:

- 'SIGMA_8': 0.8102
- 'hlittle': 0.6766
- 'OMm': 0.30964144154550644
- 'OMb': 0.04897468161869667
- 'POWER_INDEX': 0.9665

Redshifts used: Light Cone redshift range=7-12

Astrophysical Parameters :

- 'HII_EFF_FACTOR': 30.0
- 'F_STAR10': -1.3
- 'F_STAR7_MINI': -2.0
- 'ALPHA_STAR': 0.5
- 'ALPHA_STAR_MINI': 0.5
- 'F_ESC10': -1.0
- 'F_ESC7_MINI': -2.0
- ‘ALPHA_ESC': -0.5
- 'M_TURN': 8.7
- 'R_BUBBLE_MAX': None
- 'ION_Tvir_MIN': 4.69897
- 'L_X': 40.0, 'L_X_MINI': 40.0
- 'NU_X_THRESH': 500.0

- 'X_RAY_SPEC_INDEX': 1.0
- 'X_RAY_Tvir_MIN': None
- 'F_H2_SHIELD': 0.0
- 't_STAR': 0.5, 'N_RSD_STEPS': 20
- 'A_LW': 2.0, 'BETA_LW': 0.6
- ‘A_VCB': 1.0, 'BETA_VCB': 1.8

Plotting

- Programming Language used: Python
- Ananconda’s Jupyter notebook was used for writing codes.
- Packages used: numpy, h5py, matplotlib

Discussion

These plots are made to study the brightness temperature distribution across a box of length 500 h^{-1} Mpc. The color axis in the plots is the brightness temperature of neutral hydrogen (HI). The colored zones represent HI regions, i.e the regions where the neutral hydrogen is present. The voids are ionized regions thus recording the changes observed in the signal.

Slice-wise [Plotting of Cubes by varying the redshifts (z-axis i.e. frequency)]:

- With the hdf5 file provided the data was extracted and stored in a variable called 'dataset[corresponding cube number]'

Reference Code:

```
f0 = h5py.File('Lightcone.h5','r')
with f0 as hdf:
        G0 = hdf.get('BrightnessTemp')
        G0_items = list(G0.items())
        dataset0 = np.array(G0.get('brightness_temp'))
```

Reference Result:

```
Out[9]:
array([[[15.032992  ,  5.4406037 ,  0.        , ..., 22.30037   ,
         32.00111   , 50.429127  ],
        [ 8.818636  , 15.751329  , 21.079647  , ..., 24.421011  ,
         32.20871   , 49.515537  ],
        [ 8.755962  ,  7.702602  , 19.439848  , ..., 20.815948  ,
         32.95528   , 49.70009   ],
        ...,
        [19.62505   , 12.379767  ,  0.        , ..., 18.806282  ,
         34.728794  ,  0.        ],
        [ 1.9608952 ,  0.67560804,  0.        , ..., 31.871822  ,
         36.28967   , 44.41584   ],
```

Next, individual slices were plotted from the dataset to compare the changes obtained in the signal at specific redshifts [between 7-12] in the Universe.

Reference Code:

```
p0 = dataset0[:,:,20]
ax0 = plt.imshow(p0)
```

Reference Result:

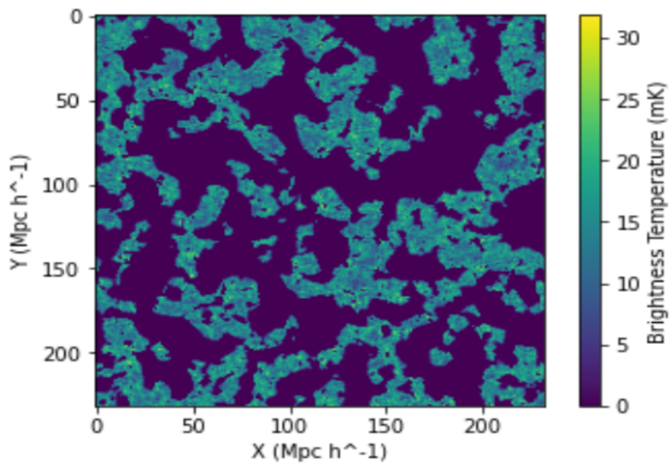


Fig2. **Slice of the lightcone at a redshift of ~7**

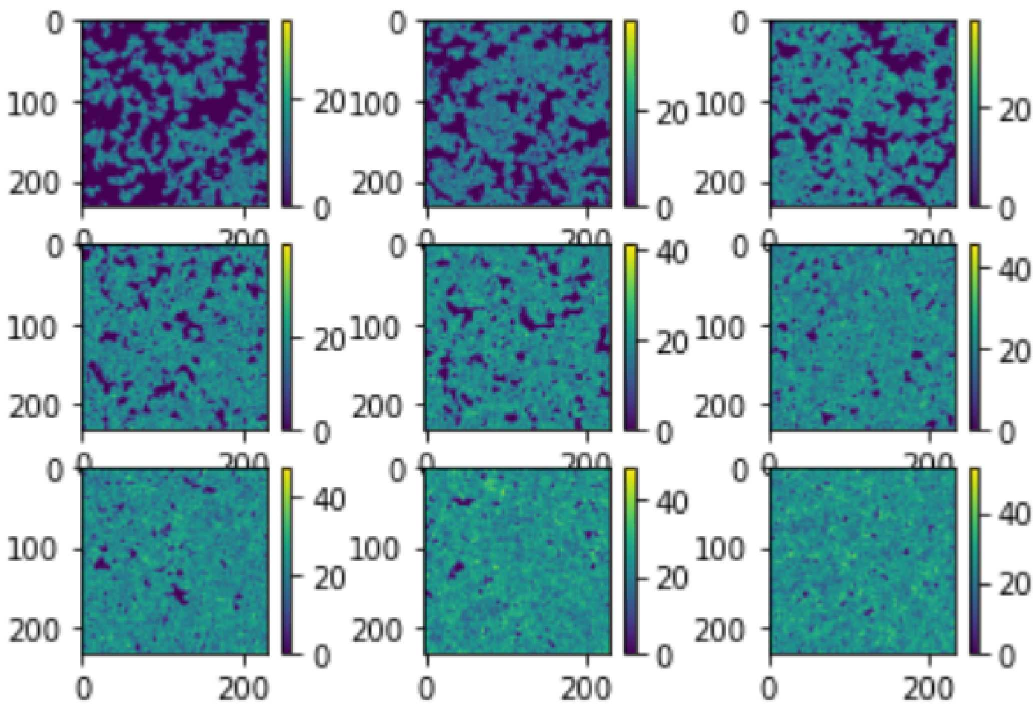


Fig3. **Slices of lightcone ranging from z= 7 to 12**

Slice-wise [Plotting of Cubes by varying the frequency over (x-axis)]:

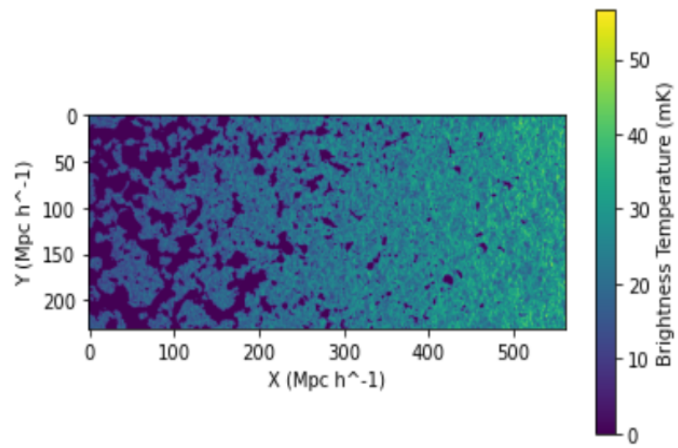
❖ Alternatively, the plots were made by varying the x-axis.

Reference Code:

```
p0 = dataset0[20,:,:]
ax0 = plt.imshow(p0)
```

Reference Result

Fig4. Slice of lightcone recording changes in brightness temperature at 43.1 Mpc distance in x-direction.



Slices of lightcone recording changes in brightness temperature in x-direction at different distances from observer on Earth

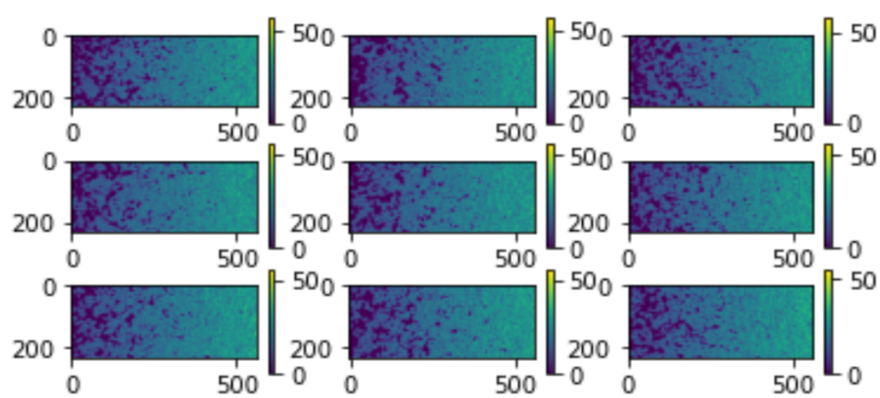


Fig5. First Row: [1. x=43.1Mpc 2. x=107.76Mpc 3. x=215.52Mpc] Second Row: [1. x=258.62Mpc 2. x=323.28Mpc 3. x=366.38Mpc] Third Row: [1. x=431.03Mpc 2. x=452.59Mpc 3. x=495.69Mpc]

Slice-wise [Plotting of Cubes by varying the frequency over (y-axis)]:

❖ Understanding it further we have made slices along y axis variation

Reference Code:

```
p0 = dataset0[:,20,:]
ax0 = plt.imshow(p0)
```

Reference Result:

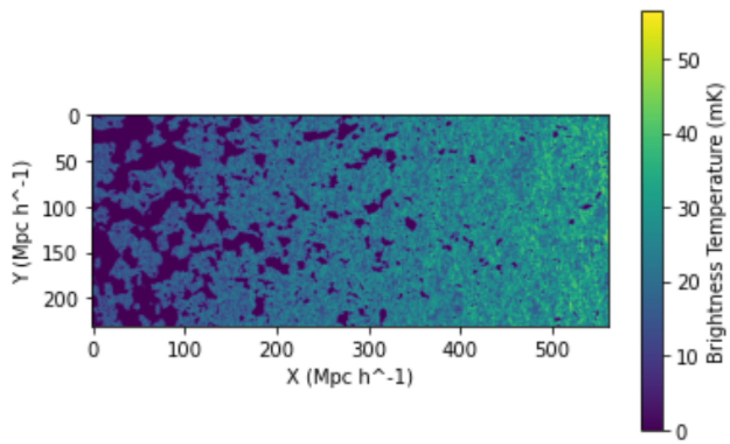


Fig6. Slice of lightcone recording changes in brightness temperature at 43.1 Mpc distance in y-direction between z=7 to 12

Slices of lightcone recording changes in brightness temperature in x-direction at different distances from observer on Earth

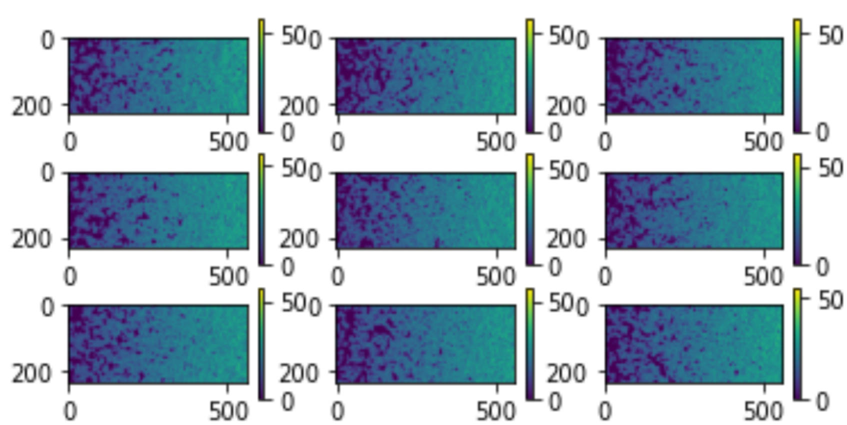
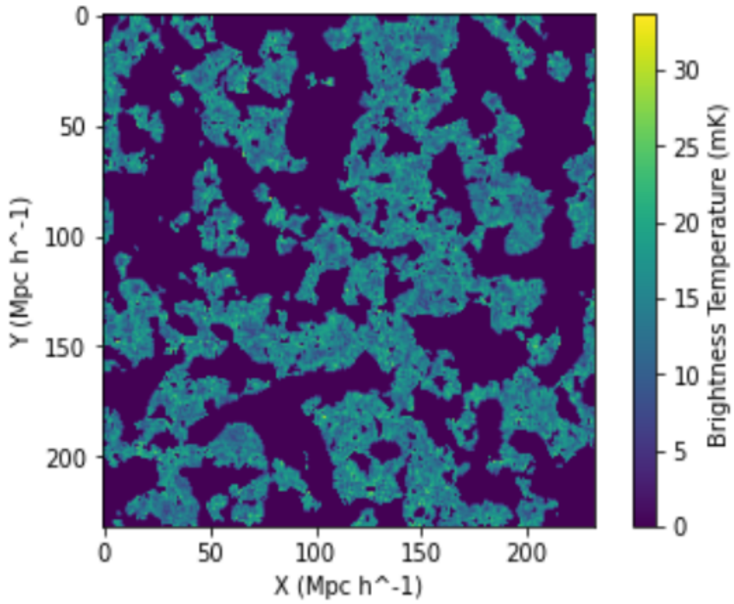


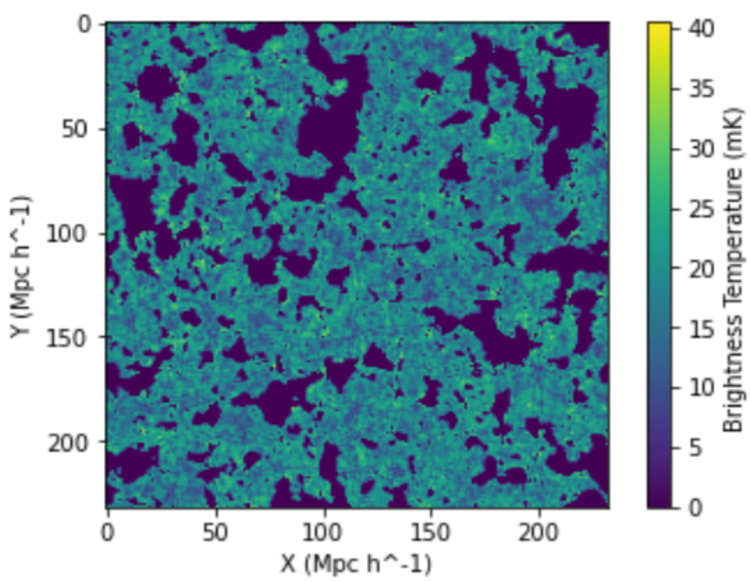
Fig7. First Row: [1. x=43.1Mpc 2. x=107.76Mpc 3. x=215.52Mpc] Second Row: [1. x=258.62Mpc 2. x=323.28Mpc 3. x=366.38Mpc] Third Row: [1. x=431.03Mpc 2. x=452.59Mpc 3. x=495.69Mpc]

COEVAL CUBES AT SPECIFIC REDSHIFTS

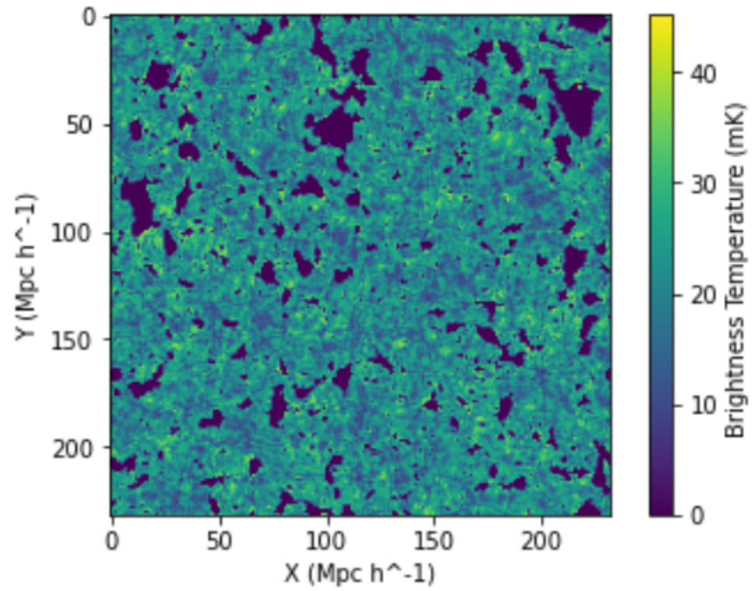
1. **z =7**



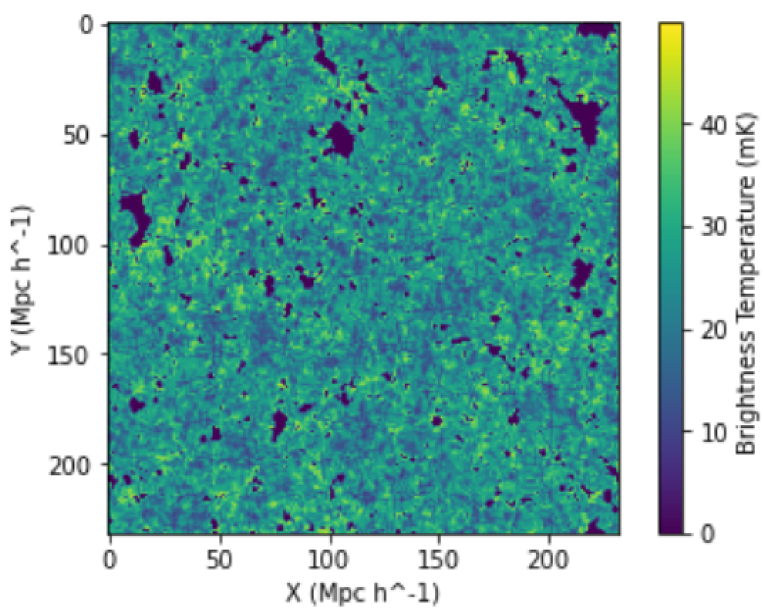
2. **z=8**



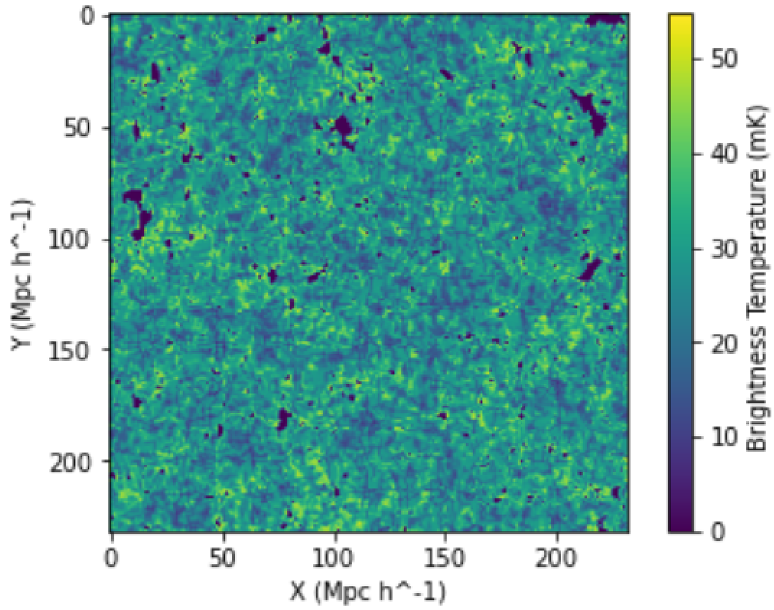
3. <u>z=9</u>



4. <u>z=10</u>

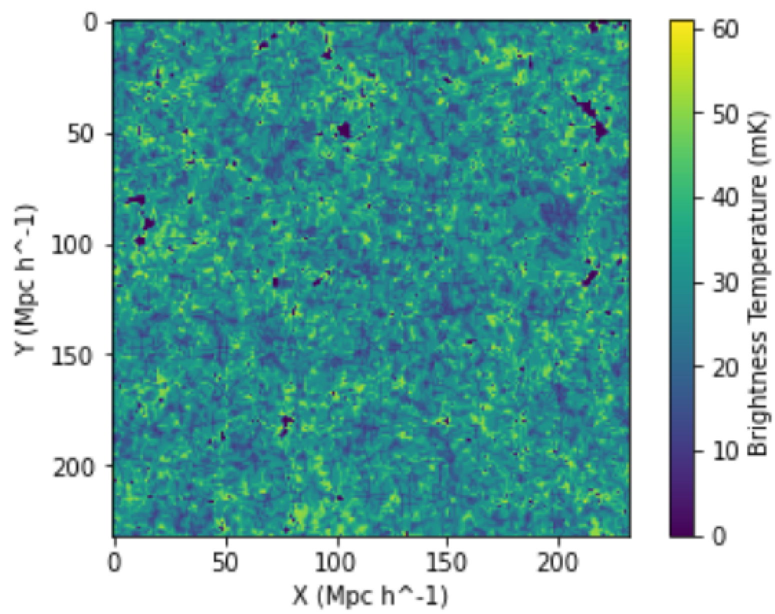


5. **z=11**



Y (Mpc h^-1)
X (Mpc h^-1)
Brightness Temperature (mK)

6. **<u>z=12</u>**



Y (Mpc h^-1)
X (Mpc h^-1)
Brightness Temperature (mK)

Comparison between Coeval plots and Light Cones

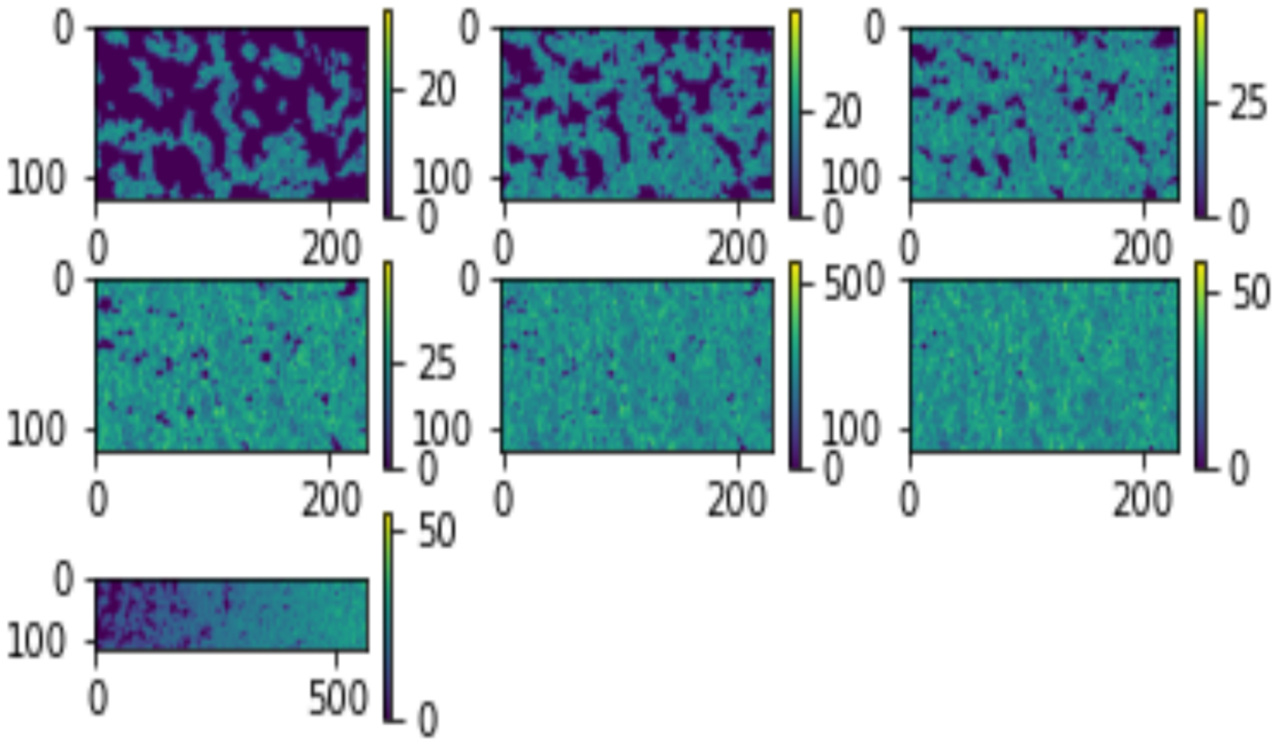


Fig8. Top Row : plot 1 is coeval at z=7, plot 2 is coeval at z=8, plot 3 is coeval z=9
Middle Row : plot 1 is coeval at z=10, plot 2 is coeval at z=11, plot 3 is coeval at z=12
Bottom Row : lightcone for z=7-12

Inference

- Higher redshifts like z= 12,11 etc. have large numbers of HI regions compared to void regions (ionised hydrogen zones) that are more prominently visible in lower redshifts like z= 8,9 etc.
- It can be seen from the last figure that using a coeval box we can determine the local variations in the signal very well. Local variations are important since they provide information of the astrophysical parameters at a particular time instance.
- It should be noted that these effects cannot be very well studied in observations, we require theoretical simulations for them.
- Light cone effect is an observational effect. Thus when we take real data, it is expected we will get a lightcone (i.e. a signal varying over frequency, i.e. redshift). While this may not provide as detailed information about local conditions at a particular time instance, it will help in determining how the astrophysical parameters that control the signal have evolved with time. This can provide information about the nature, distribution, composition of these very early sources in the universe.
- This study can be extended further in the future by quantifying morphology and distribution of the voids and HI areas and see how this differs between lightcone and coeval cases for a similar redshift range.

During the Epoch of Reionization, astrophysics mixed with cosmology and the possible bifurcation is yet to be understood. In the future, 21 cm observations of the cosmic dark ages provide a long-term hope that most of the volume of the Universe could one day be mapped and used for cosmology. This provides another window into the properties of the Intergalactic Matter (IGM) at the end of reionization. The 21 cm forest would allow the small-scale properties of the IGM to be studied in great detail and so constrain the properties of dark matter. It is a powerful technique, and the main uncertainty is abundance. It is hoped that in the decades to come, 21 cm observations will transform our understanding of the cosmic dawn and the epoch of reionization, pushing further our detailed knowledge of the cosmos.

References:

1. 1109.6012v2.pdf (arxiv.org)
2. 1003.3878.pdf (arxiv.org)
3. 21 cm background - Philosophy of Cosmology (ox.ac.uk)
4. Probing the Cosmic Dawn - Public Website (skatelescope.org)
5. Physicists in Earth's remotest corners race to reproduce 'cosmic dawn' signal (nature.com)
6. 21-centimeter radiation | Definition, Importance, & Facts | Britannica