Impact of light cone effect on EoR 21-cm Image analysis using LCS

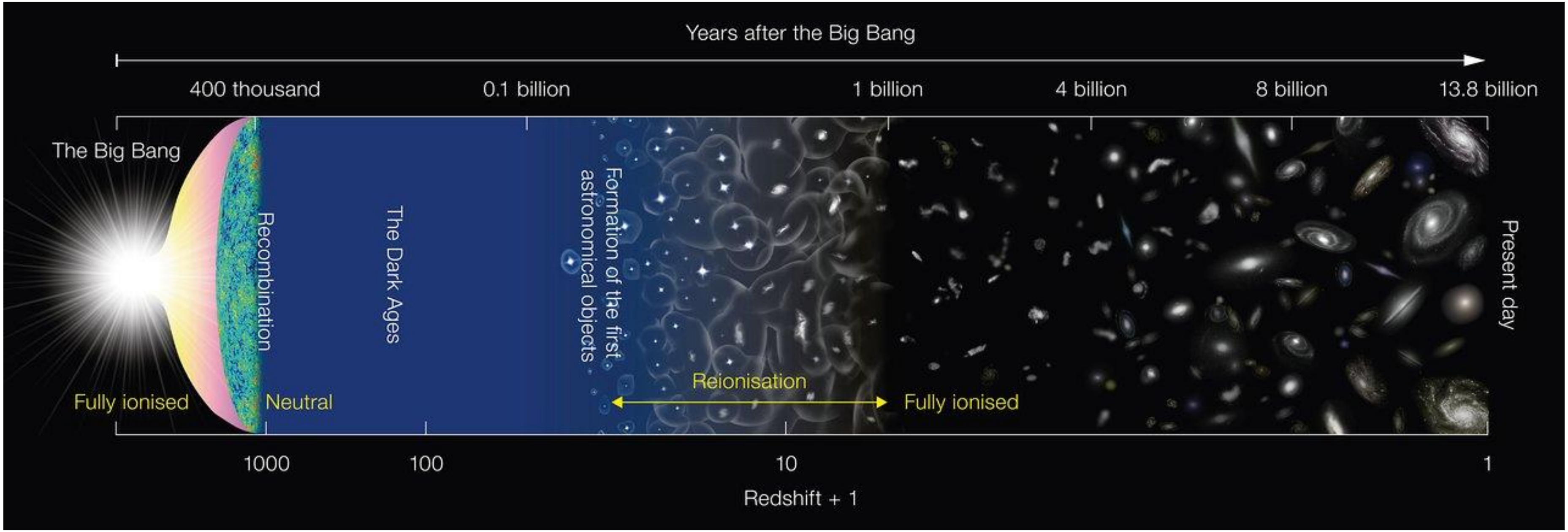
Hemanth Potluri

Roll no : 2203121011

Thesis Supervisor: Dr. Suman Majumdar.

PSPC members: Prof. Abhirup Datta
Dr. Manoneeta Chakraborty.

Evolution of the Universe



Credits: NAOJ

Epoch of Reionization

- Ionized regions, once formed, start growing in size and overlap with each other as the reionization progresses.

Epoch of Reionization

- Ionized regions, once formed, start growing in size and overlap with each other as the reionization progresses.
- Epoch of Reionization (EoR) is the period when the neutral matter present in the Intergalactic medium (IGM) had been gradually ionized .

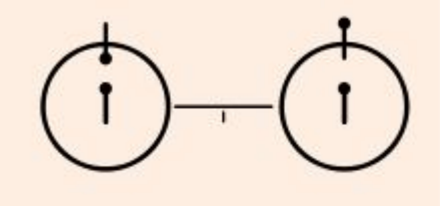
Epoch of Reionization

- Ionized regions, once formed, start growing in size and overlap with each other as the reionization progresses.
- Epoch of Reionization (EoR) is the period when the neutral matter present in the Intergalactic medium (IGM) had been gradually ionized .
- Observationally, the reionization era represents a phase of the Universe which is yet to be probed.

Hyper-fine transition.

- When electron in the ground state of neutral Hydrogen (HI) undergo spin-flip transition from parallel to anti-parallel state it emits 21-cm signal.

- This 21-cm signal can be used to probe the HI distribution in the universe at different cosmic times and determine the reionization history.



Credits : NASA

21-cm Observations

- First generation telescopes like GMRT, LOFAR, MWA etc. are aiming for statistical detection of 21-cm signal.
- The Square Kilometer Array, yet to be commissioned, is expected to have enough sensitivity to make tomographic images of 21-cm signal.

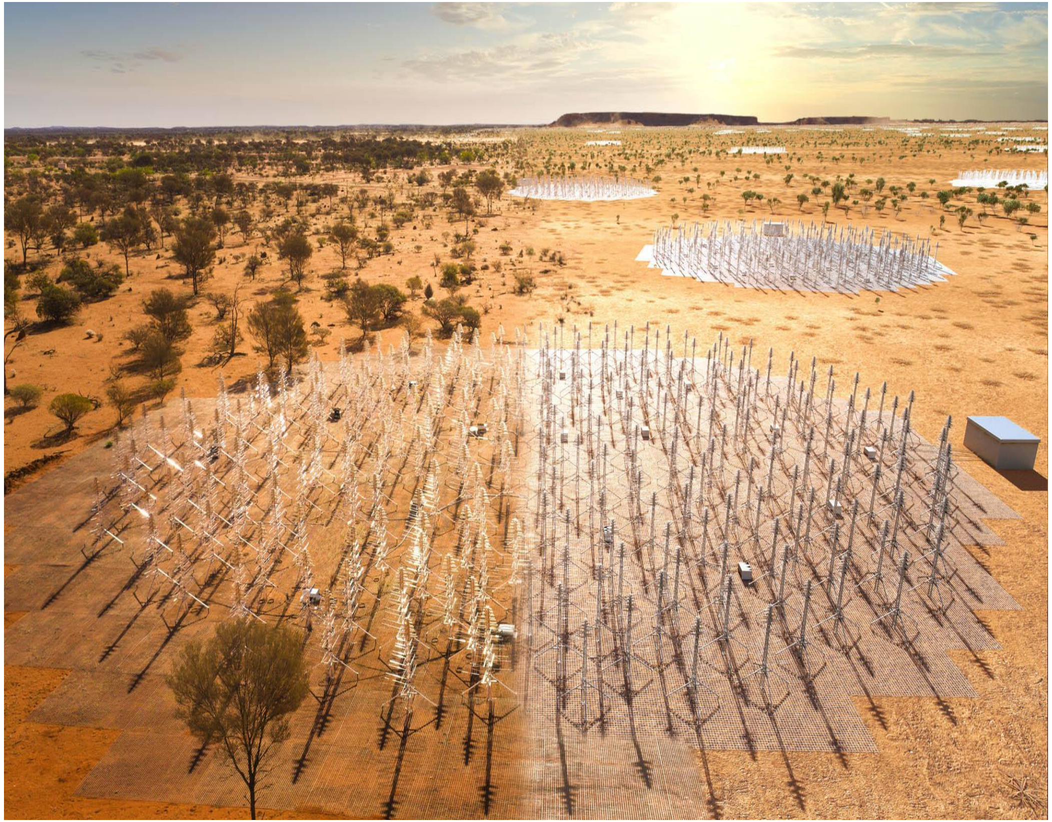


Figure: Artistic image of Square Kilometer Array (SKA)

Image credits: https://www.skao.int/en/explore/telescopes/ska-low

Simulating 21-cm brightness temperature maps

N-body gravity only simulation

↓

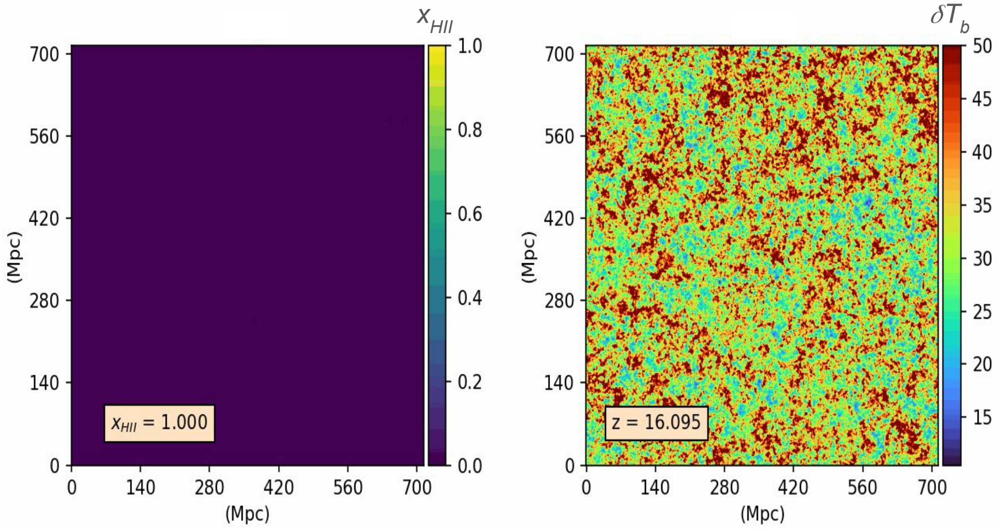
Friends-of-Friends (FoF) halo finder

↓

Excursion-set based semi-numerical method

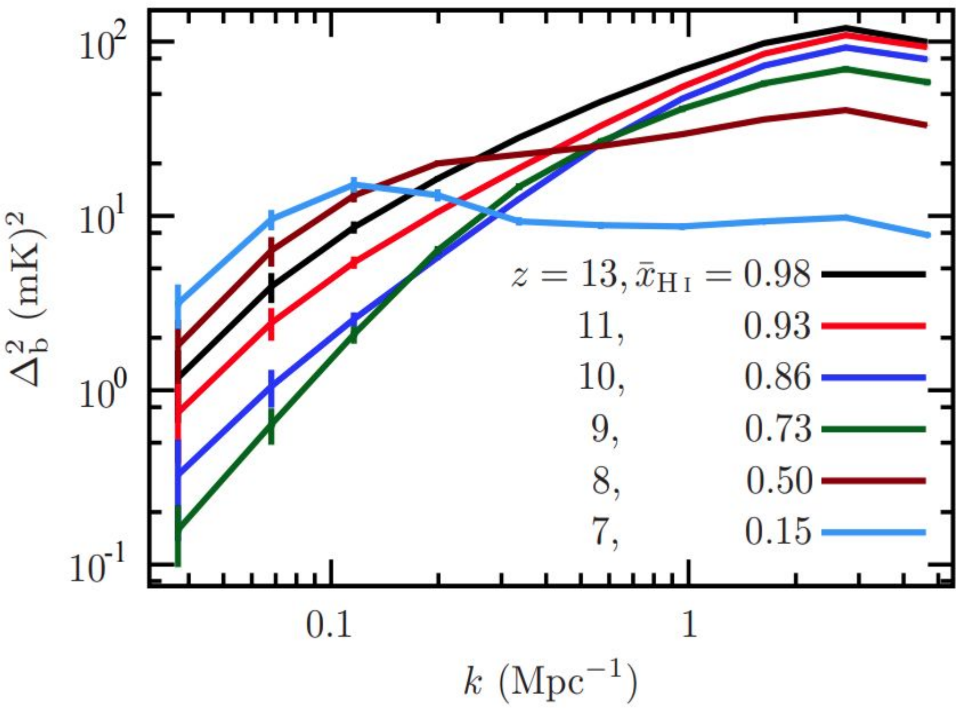
↓

21-cm brightness temperature maps



Analyzing 21-cm Signal.

Power spectrum is used to study the distribution of amplitude fluctuations in the signal at various length scales.



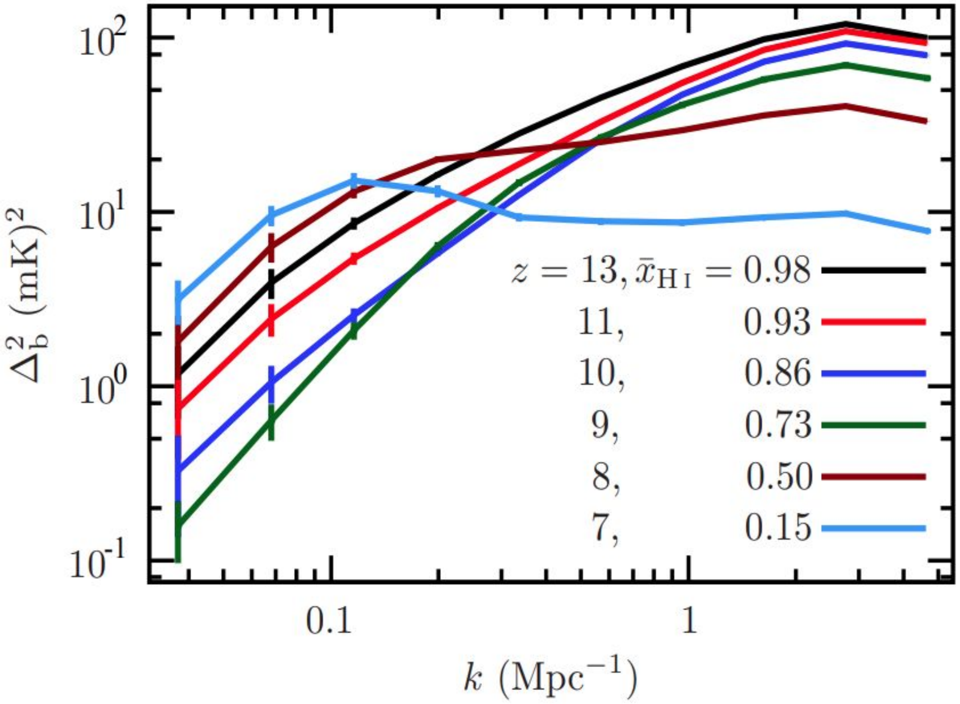
Mondal et.al,2015

(arXiv:1508.00896)

Analyzing 21-cm Signal.

Power spectrum is used to study the distribution of amplitude fluctuations in the signal at various length scales.

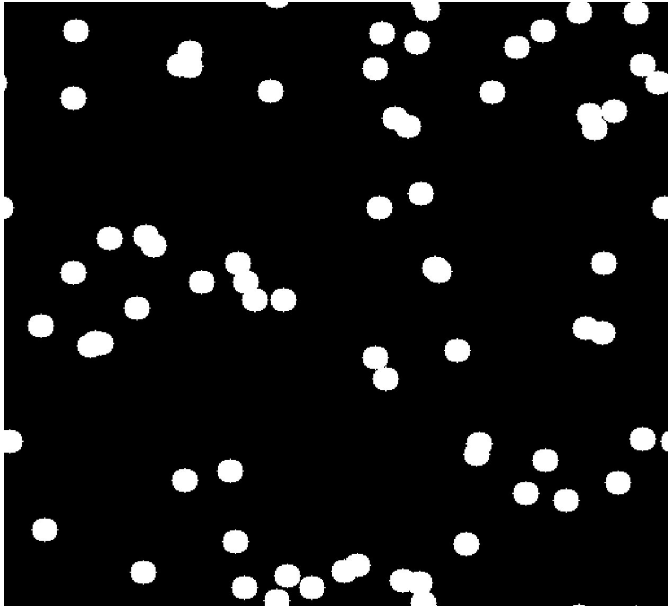
Phase information of the signal is not retained in power spectrum analysis.



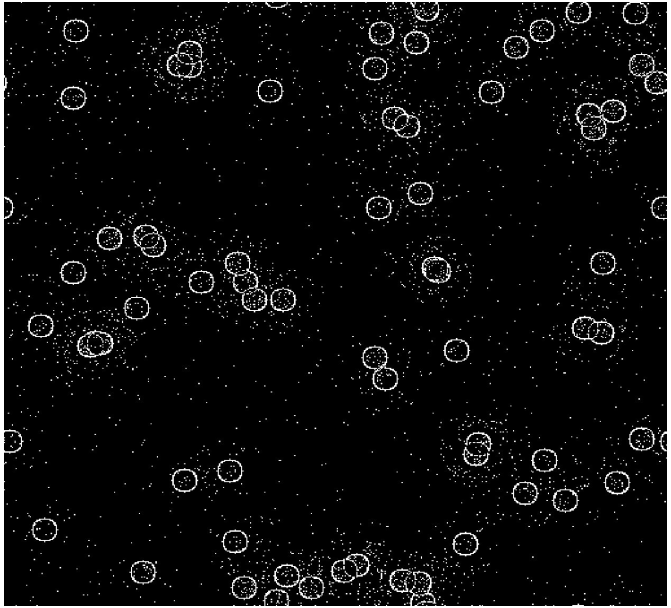
Mondal et.al,2015

(arXiv:1508.00896)

Analyzing 21-cm Signal.



Real field



Phase field

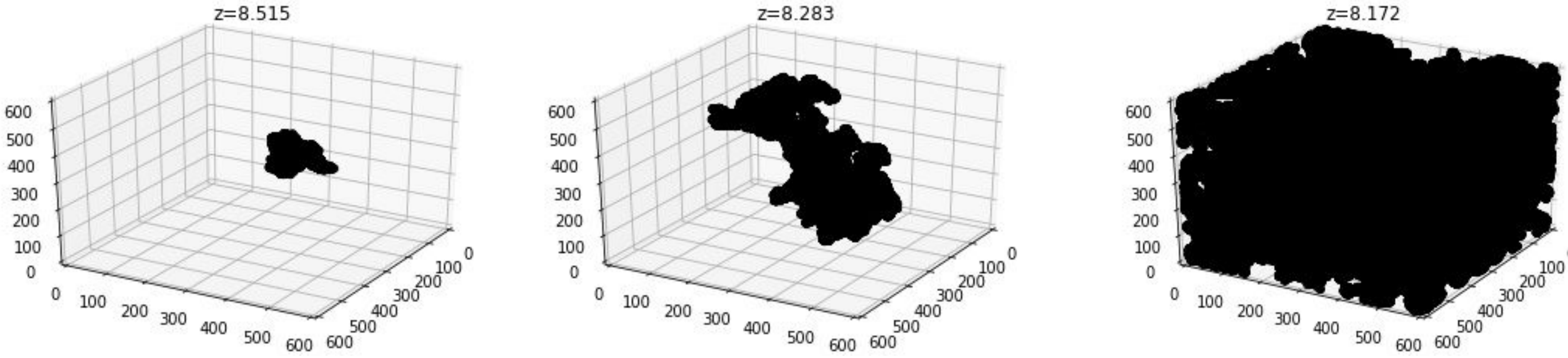
Credits: Gorce and Pritchard, 2019.
(arXiv: 1903.11402)

Percolation analysis

- As the reionization progresses, new ionized regions start forming and existing ionized regions increase in their size and overlap with each other.
- The formation of the infinitely large singly-connected ionized region is called "Percolation transition".

Percolation analysis

- As the reionization progresses, new ionized regions start forming and existing ionized regions increase in their size and overlap with each other.
- The formation of the infinitely large singly-connected ionized region is called "Percolation transition".



Credits: Pathak et.al, 2022.
arXiv: 2202.03701

There are two statistics that play key role in percolation analysis.

- **Largest Cluster Statistics (LCS):**
  The "Largest Cluster Statistics" is defined for the neutral or the ionized region as the ratio of **Volume of the largest neutral (ionized) region** to the **Total volume of neutral (ionized) regions.**

$$\mathrm{LCS} = \frac{\text{volume of the largest ionized region}}{\text{total volume of all the ionized regions}}$$

There are two statistics that play key role in percolation analysis.

- **Largest Cluster Statistics (LCS):**
  The "Largest Cluster Statistics" is defined for the neutral or the ionized region as the ratio of **Volume of the largest neutral (ionized) region** to the **Total volume of neutral (ionized) regions.**

$$\mathrm{LCS} = \frac{\text{volume of the largest ionized region}}{\text{total volume of all the ionized regions}}$$

- **Filling Factor (FF):**
  The "Filling Factor" for the neutral or the ionized region is defined as the ratio of **Total volume of neutral or ionized regions** to the **Volume of the simulation box.**

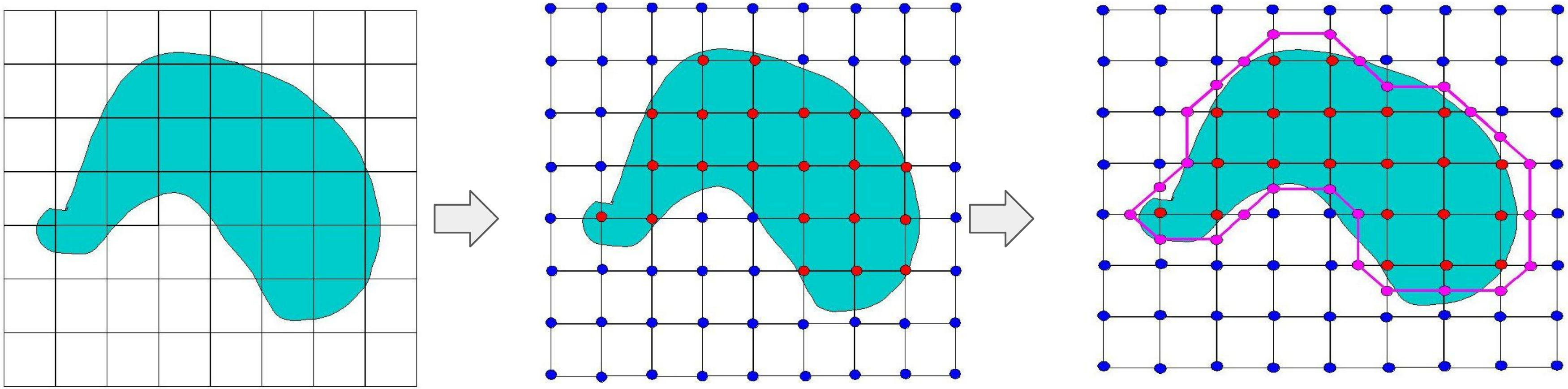
$$\mathrm{FF} = \frac{\text{total volume of all the ionized regions}}{\text{simulation volume}}$$

SURFGEN2

- SURFGEN2 algorithm identifies the isolated ionized regions using 'Friends-of-Friends' algorithm.
- Surface of each ionized region is then mapped using the 'Marching cube 33' triangulation algorithm.

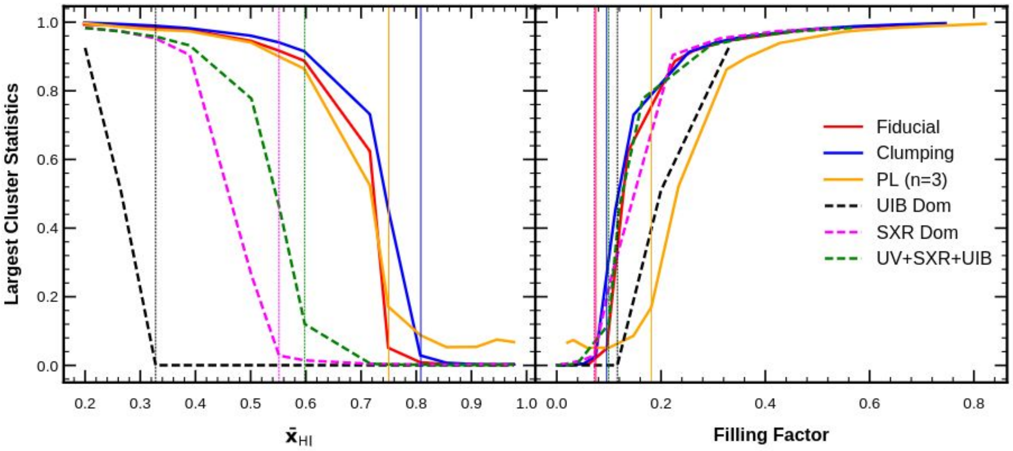
SURFGEN2

- SURFGEN2 algorithm identifies the isolated ionized regions using ‘Friends-of-Friends’ algorithm.
- Surface of each ionized region is then mapped using the ‘Marching cube 33’ triangulation algorithm.



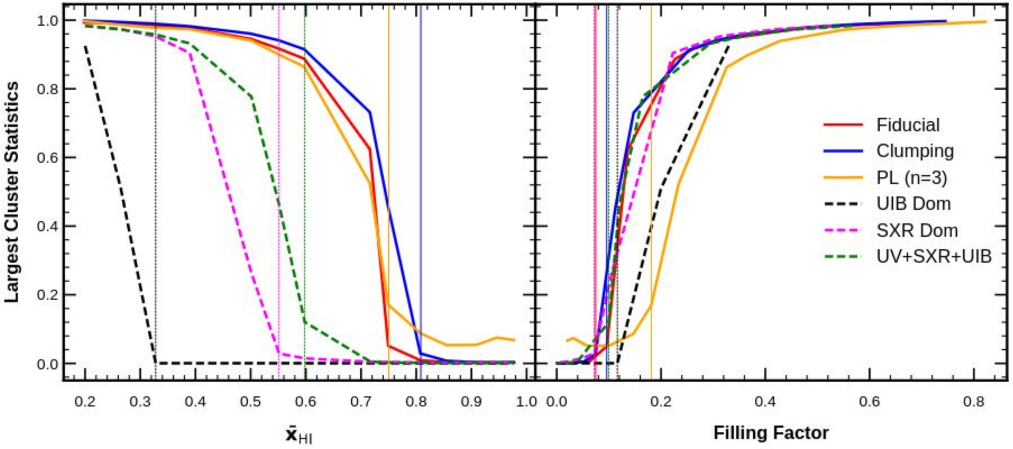
Credits: Ben Anderson (https://www.cs.carleton.edu/cs_comps/0405/shape/marching_cubes.html)

Percolation analysis on simulated coeval maps

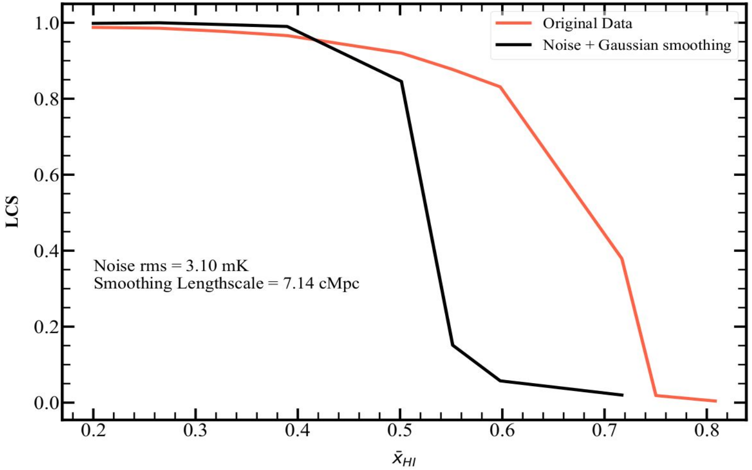


Pathak et.al, 2022.
arXiv: 2202.03701

Percolation analysis on simulated coeval maps



Pathak et.al, 2022.
arXiv: 2202.03701



Dasgupta et.al, 2023.
arXiv: 2302.02727

Light-cone effect

- By looking deep into the space, we are looking at the universe at its younger state due to finite time it takes for the light to travel to us from distant sources.

Light-cone effect

- By looking deep into the space, we are looking at the universe at its younger state due to finite time it takes for the light to travel to us from distant sources.

  - The observable 3D volume of the universe is composed of slices from the past.

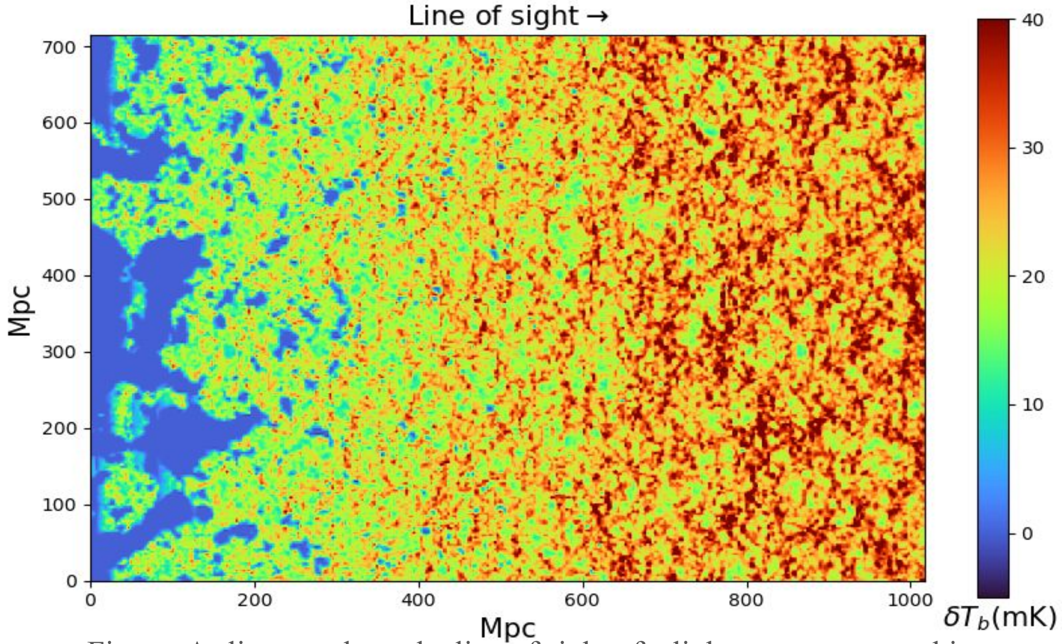


Figure: A slice cut along the line of sight of a light-cone tomographic map.

Light-cone effect

- By looking deep into the space, we are looking at the universe at its younger state due to finite time it takes for the light to travel to us from distant sources.

  - The observable 3D volume of the universe is composed of slices from the past.

  - Coeval maps are used to generate simulated light cone maps.

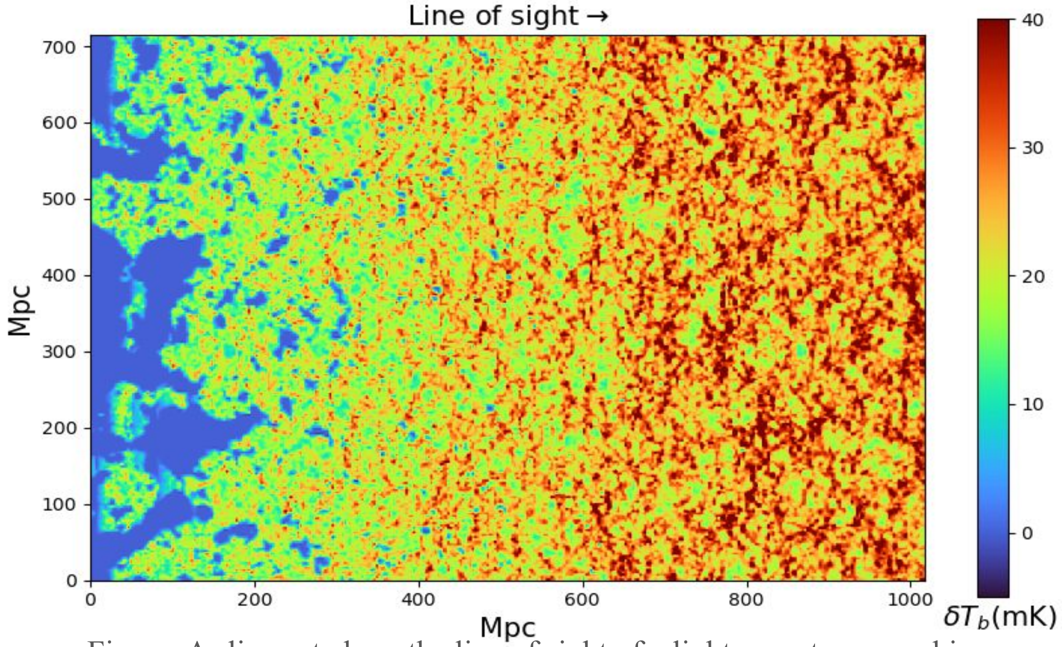
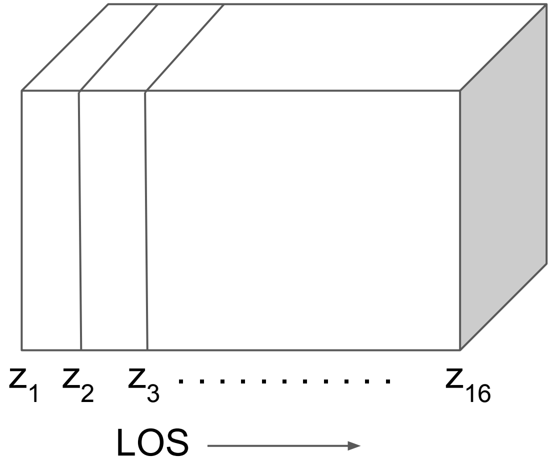


Figure: A slice cut along the line of sight of a light-cone tomographic map.

The light cone simulated cubes are generated from coeval cubes as follows:

- A set of **16** brightness temperature maps at different redshifts each of integer size **600^3** and physical comoving size **(714 Mpc)^3** are considered.
- Starting from the lowest redshift, we create a redshift series , which will constitute the redshift (Line of sight) axis of the light cone cube.
- We then construct the light cone cube by stepping through this redshift series and constructing 21-cm slices for each redshift.
- We use linear interpolation technique to create 21-cm slice at intermediate redshifts of the given redshift series.



- The light cone map is cut into overlapping sub-volumes of uniform sizes (in co-moving distance) of different magnitude and LCS is computed for these chunks of uniform sizes.
- The change in LCS for sub-volumes of different sizes is then quantified and compared with that of LCS of coeval cubes at different redshifts.

Non-overlapping

Overlapping

Percolation analysis on light-cone maps

Fiducial model

- 100% UV photon contribution from galaxies residing in halos.
- Density independent uniform rate of recombination.

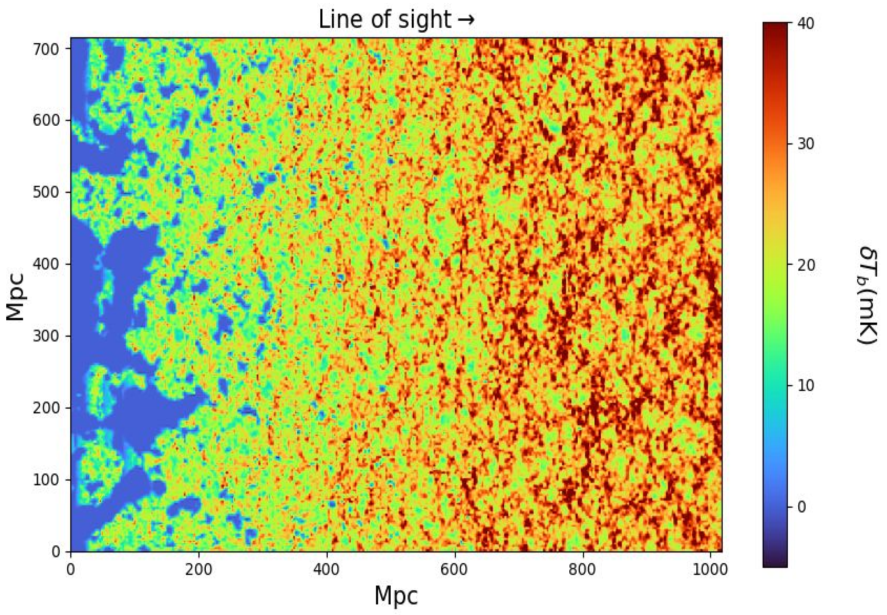


Figure: A slice cut along the line of sight of a light-cone tomographic map of fiducial model.

Percolation analysis on light-cone maps

Fiducial model

- 100% UV photon contribution from galaxies residing in halos.
- Density independent uniform rate of recombination.
- $N_\gamma (M_h) \propto M_h$

Where $N_\gamma (M_h)$ = Total number of ionizing photons emitted from a halo of mass "M"

M_h = Mass of halo.

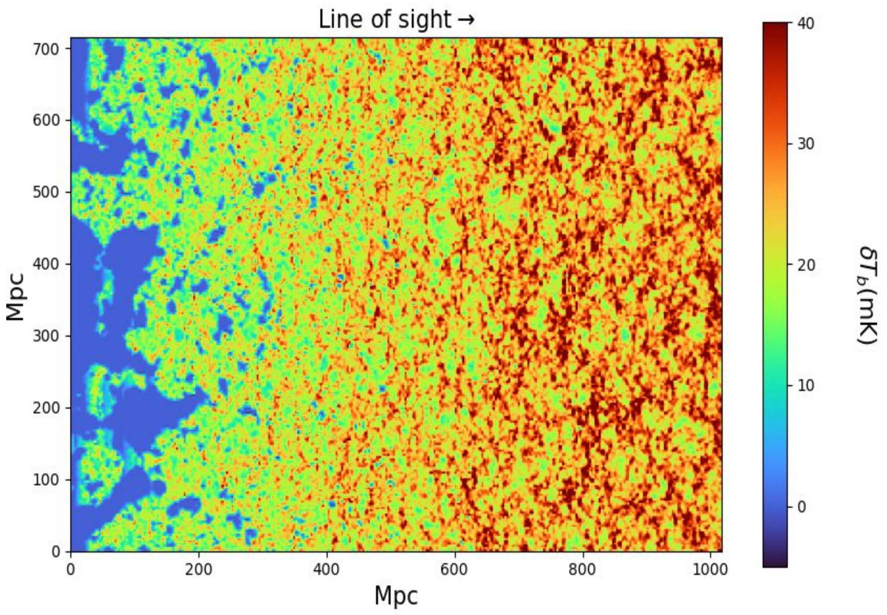
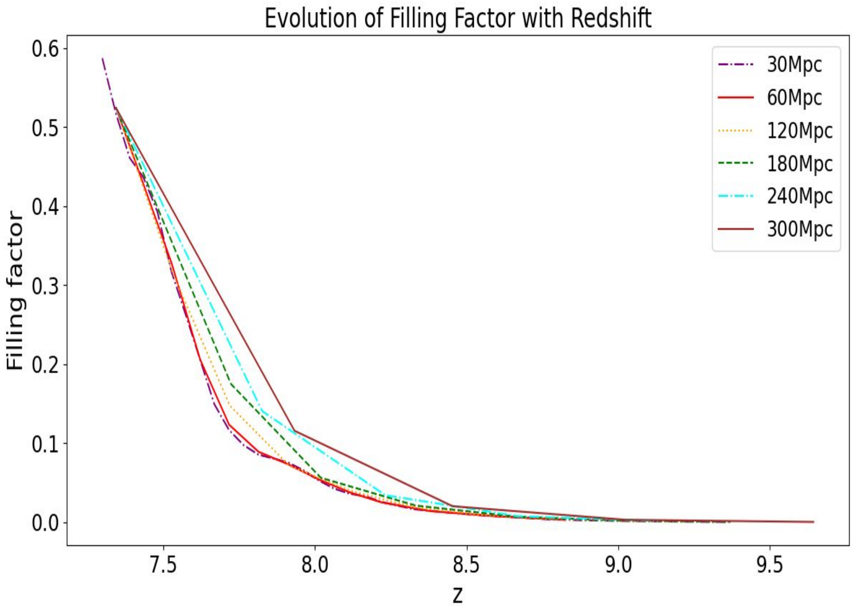


Figure: A slice cut along the line of sight of a light-cone tomographic map of fiducial model.

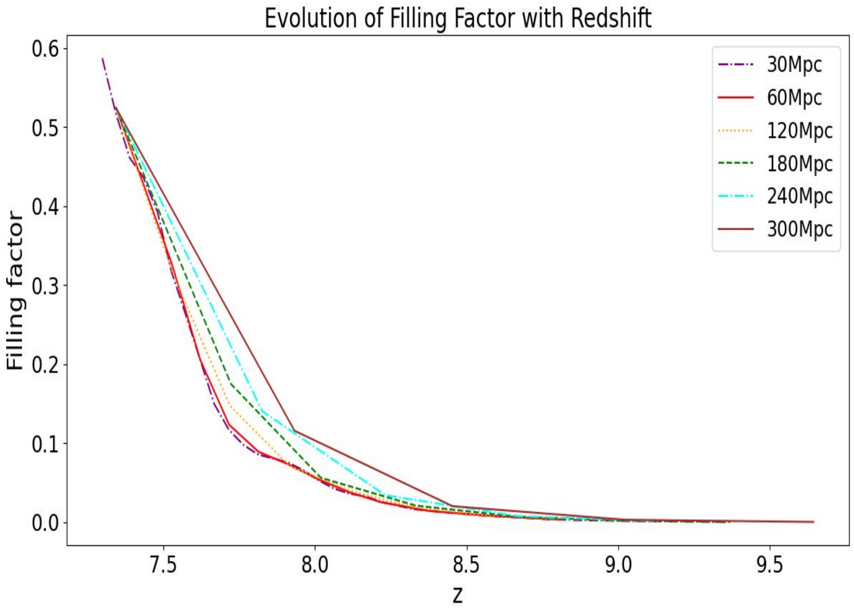
Percolation analysis on light-cone maps

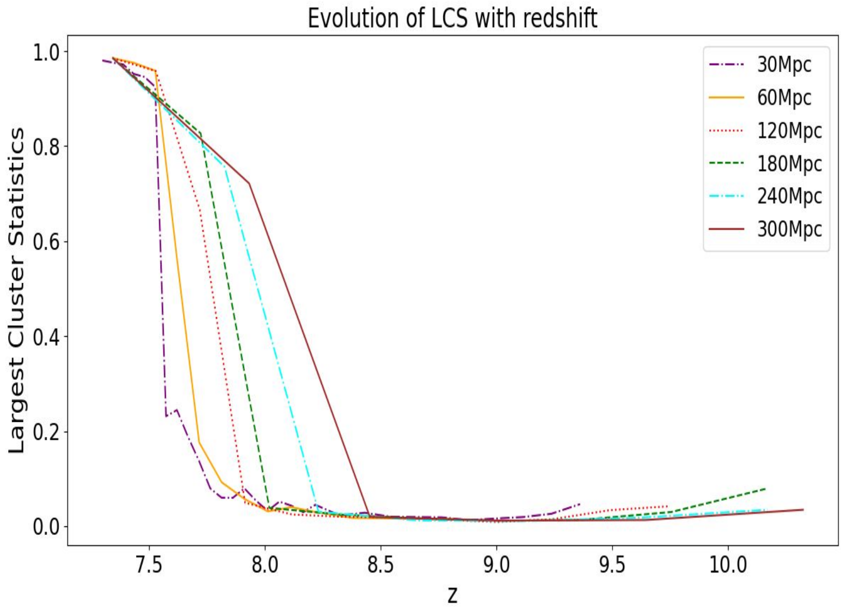
Fiducial model



Percolation analysis on light-cone maps

Fiducial model





Percolation analysis on light-cone maps

Clumping model

- 100% UV photon contribution from galaxies residing in halos.
- Non-uniform density dependent recombination.
- $N_\gamma (M_h) \propto M_h$

  Where $N_\gamma (M_h)$ = Total number of ionizing photons emitted from a halo of mass "M"

  M_h = Mass of halo.

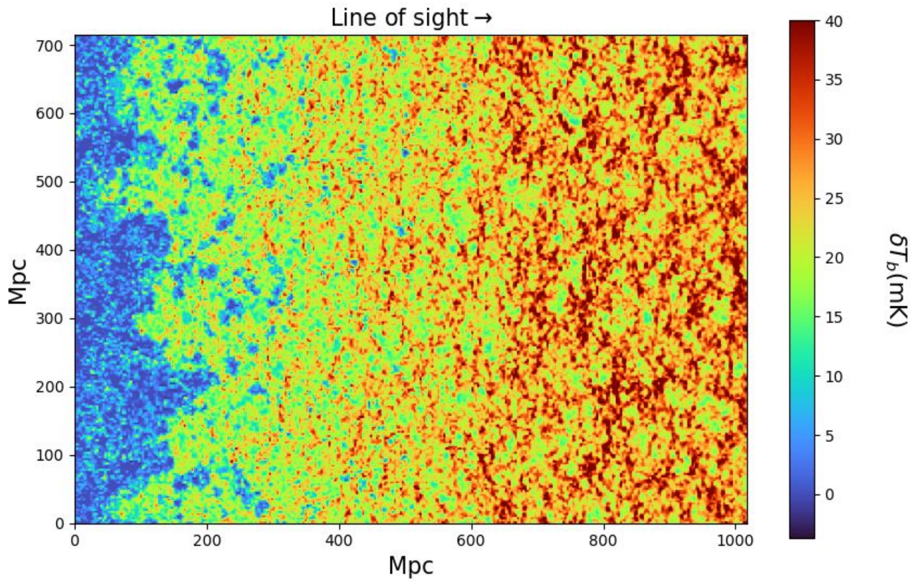
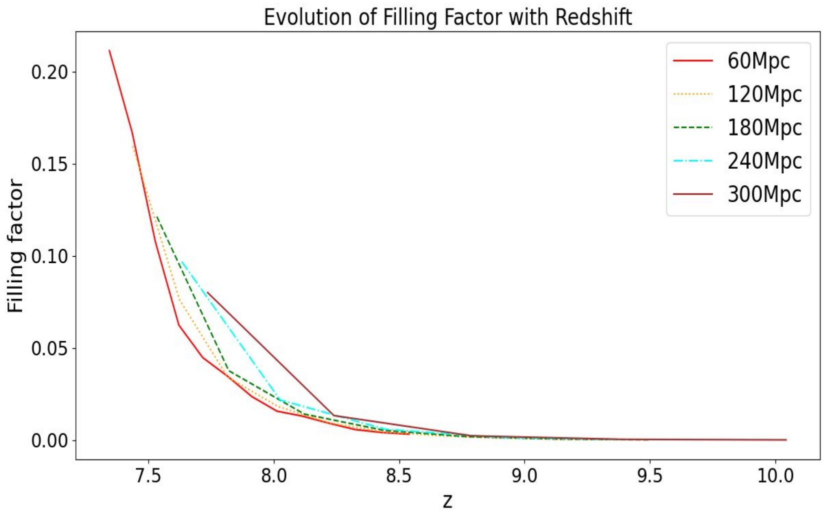
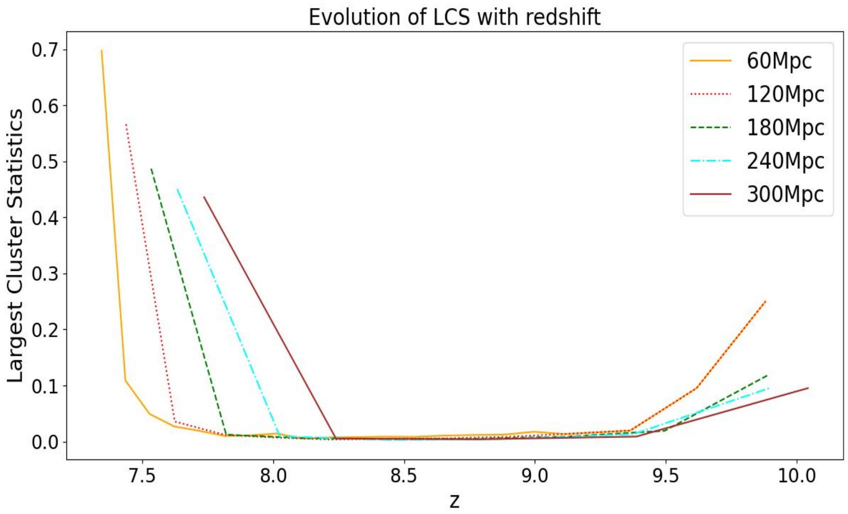


Figure: A slice cut along the line of sight of a light-cone tomographic map of clumping model.

Percolation analysis on light-cone maps

Clumping model





Percolation analysis on light-cone maps

Power law (n=3)

- 100% UV photon contribution from galaxies residing in halos.
- Density independent uniform rate of recombination.

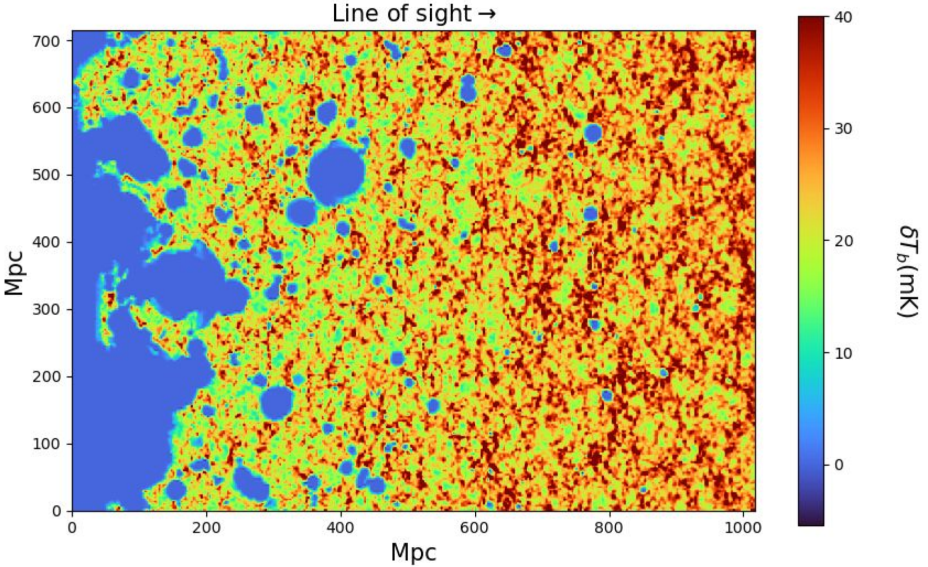


Figure: A slice cut along the line of sight of a light-cone tomographic map of PL (n=3) model.

Percolation analysis on light-cone maps

Power law (n=3)

- 100% UV photon contribution from galaxies residing in halos.
- Density independent uniform rate of recombination.
- $N_\gamma(M_h) \propto M_h^{\,3}$

Where N_γ (M_h) = Total number of ionizing photons emitted from a halo of mass "M"

M_h = Mass of halo.

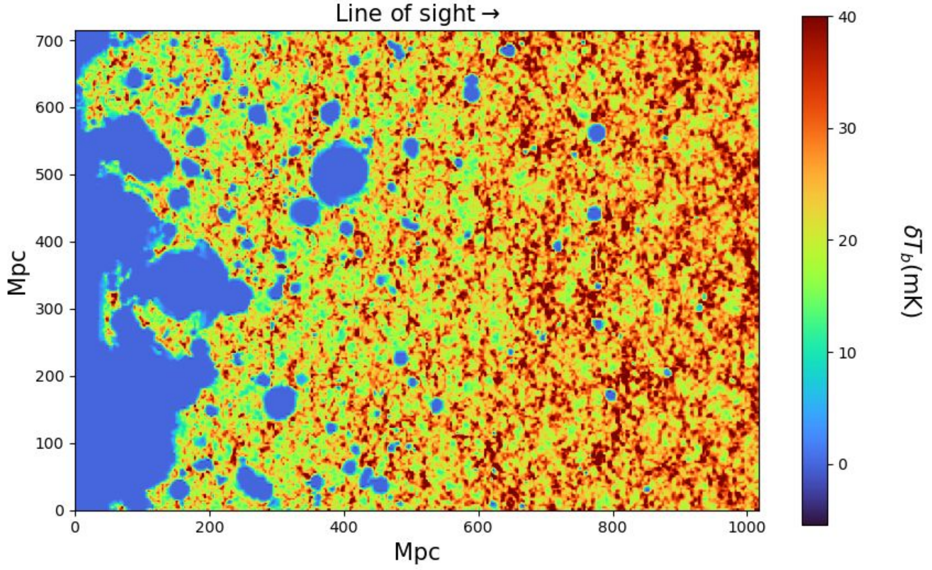
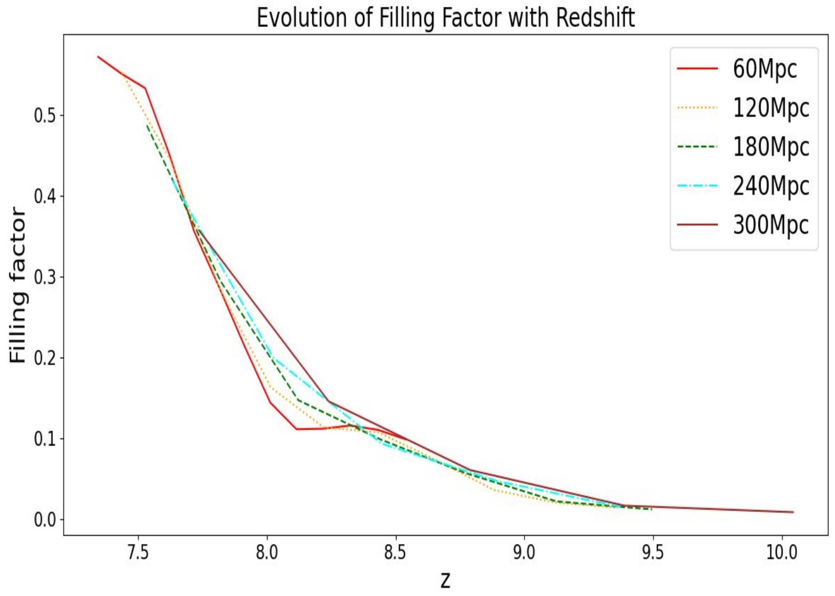
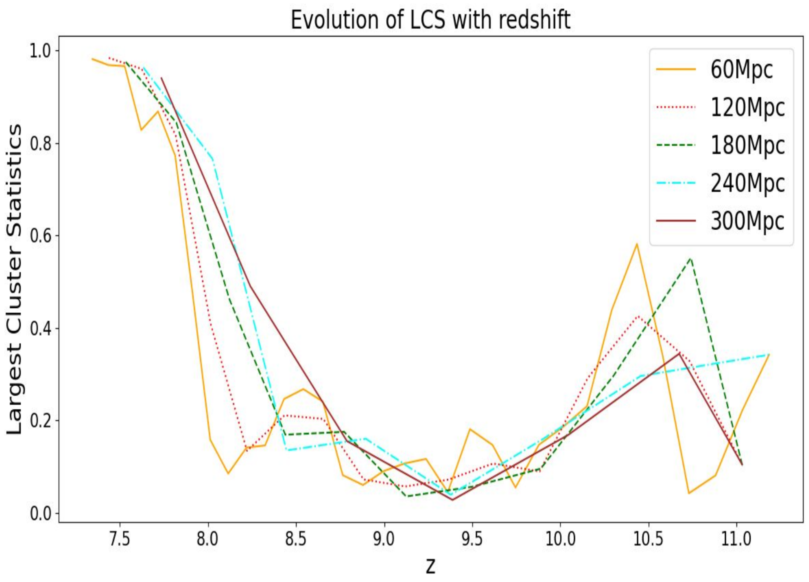


Figure: A slice cut along the line of sight of a light-cone tomographic map of PL (n=3) model.

Percolation analysis on light-cone maps

Power law (n=3)





Percolation analysis on light-cone maps

UV+SXR+UIB

- 50% UV photon contribution + 10% hard X-ray photon contribution + 40% soft X-ray contribution.
- Density independent uniform rate of recombination.

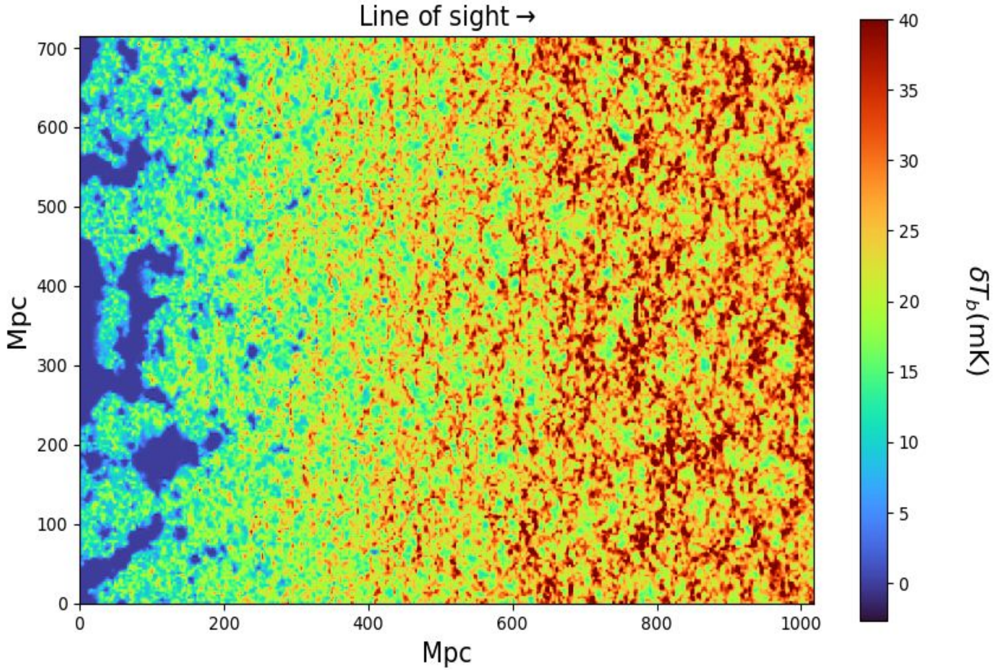
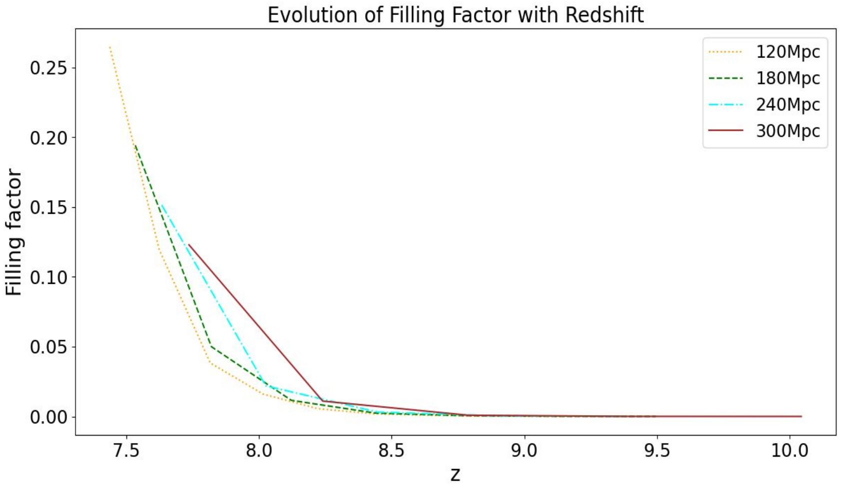
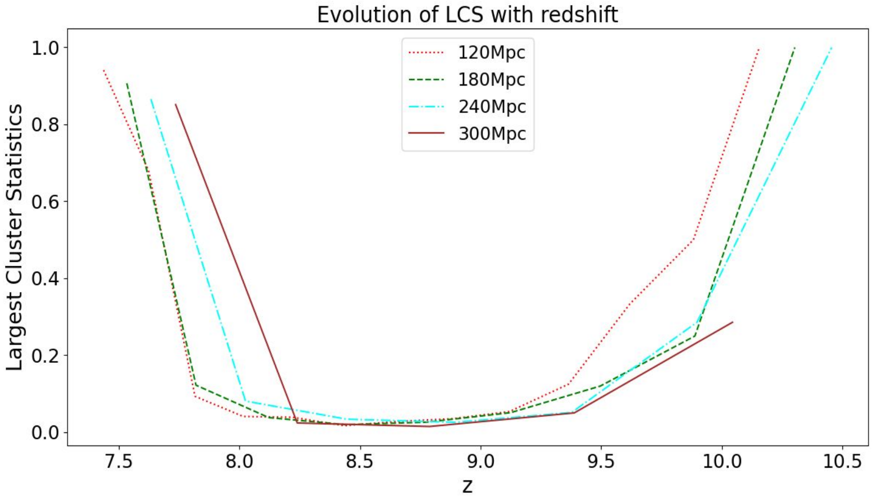


Figure: A slice cut along the line of sight of a light-cone tomographic map of UV+SXR+UIB model.

Percolation analysis on light-cone maps

UV+SXR+UIB





Summary

- Volume of chunk chosen impacts the evolution of LCS with redshift for all the reionization scenarios.

Summary

- Volume of chunk chosen impacts the evolution of LCS with redshift for all the reionization scenarios.

- Except power law (n=3) model, all the reionization scenarios retains the trend of the evolution of LCS.

Summary

- Volume of chunk chosen impacts the evolution of LCS with redshift for all the reionization scenarios.

- Except power law (n=3) model, all the reionization scenarios retains the trend of the evolution of LCS.

- Different reionization scenarios can be distinguished from each other by doing LCS analysis even after light-cone effect is taken into account.

Future work

- What happens to LCS when we include the telescope beam, noise, foregrounds etc. on light cone maps?

Future work

- What happens to LCS when we include the telescope beam, noise, foregrounds etc. on light cone maps?

- Is it possible to constrain EoR history using LCS taking light-cone effect into account?

Future work

- What happens to LCS when we include the telescope beam, noise, foregrounds etc. on light cone maps?
- Is it possible to constrain EoR history using LCS taking light-cone effect into account?
- How does the morphology of ionized regions evolve for different reionization models when light-cone effect is taken into account?

Simulating 21-cm ionization maps

Dark matter distribution is obtained from N-body gravity only simulation.

↓

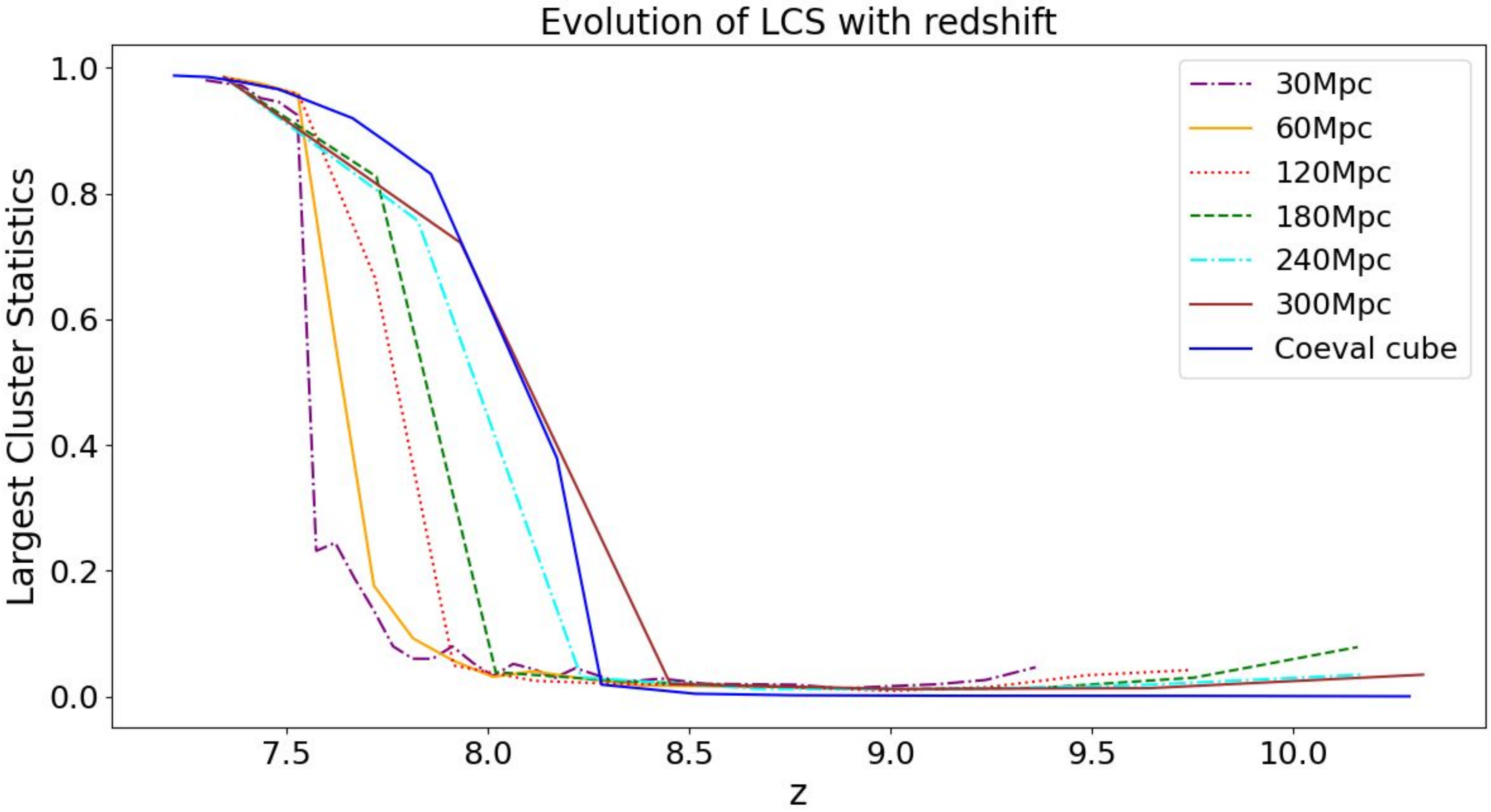
Friends-of-Friends (FoF) algorithm is used to identify dark matter halos

↓

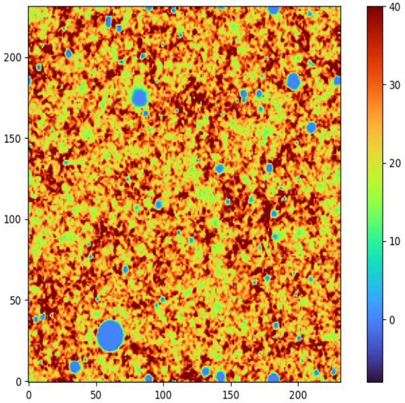
The identified halos are populated with ionizing sources and number of ionizing photons emitted by these sources are ascertained.

↓

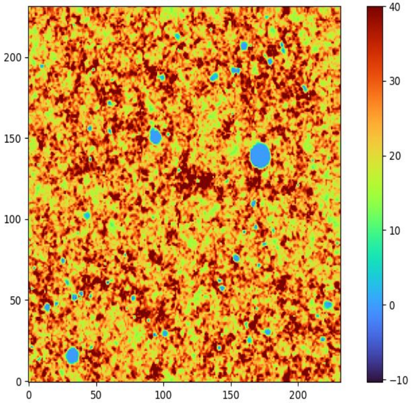
The ionization of neutral hydrogen is modelled by transport of ionizing photons.



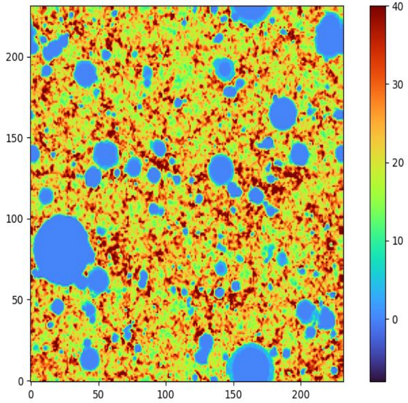
Evolution of LCS with redshift
Largest Cluster Statistics
z
1.0
0.8
0.6
0.4
0.2
0.0
7.5
8.0
8.5
9.0
9.5
10.0
30Mpc
60Mpc
120Mpc
180Mpc
240Mpc
300Mpc
Coeval cube



z=10.3



z=10.0



z=9.92