SKA Cosmology SWG meeting 2023

Analysis of HI 21-cm images to probe the Epoch of Reionization using Largest Cluster Statistics (LCS)

By Saswata Dasgupta

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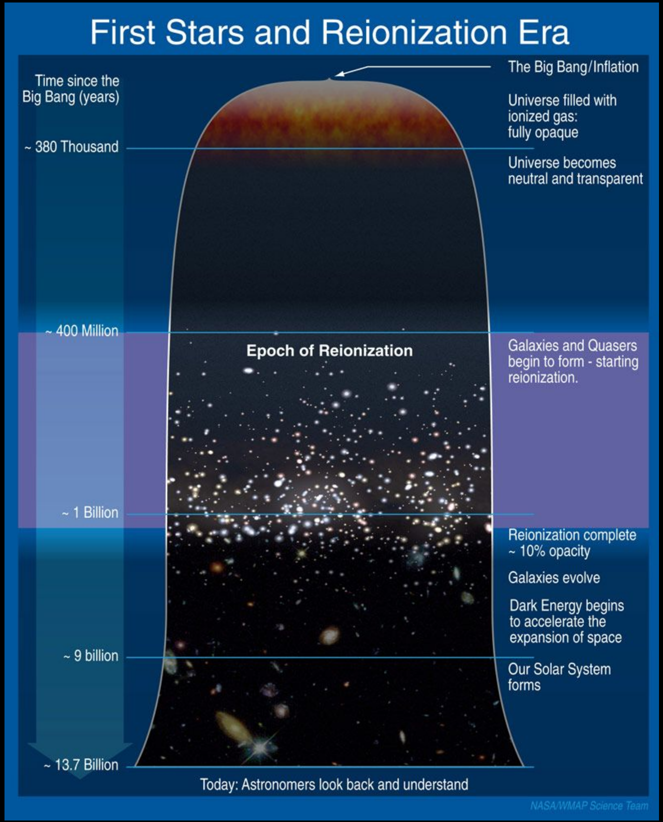
Contents

- Brief on CD-EoR 21 cm signal
- Motivation
- Overview on Image analysis and LCS
- LCS as a tool to analyse 21 cm signal
- Summary of previous work
- Current work
- Future plans
- References

Cosmic Dawn and Epoch of Reionization

- What (rather, when) is it?

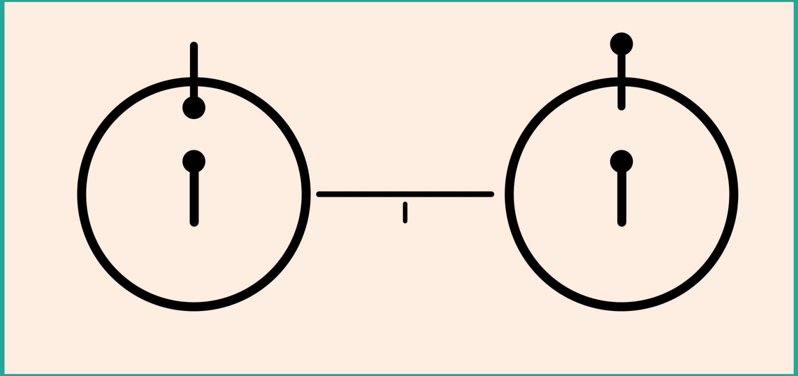
- Why are they important to study?



Credit: NASA

21-cm signal to probe CD and EoR

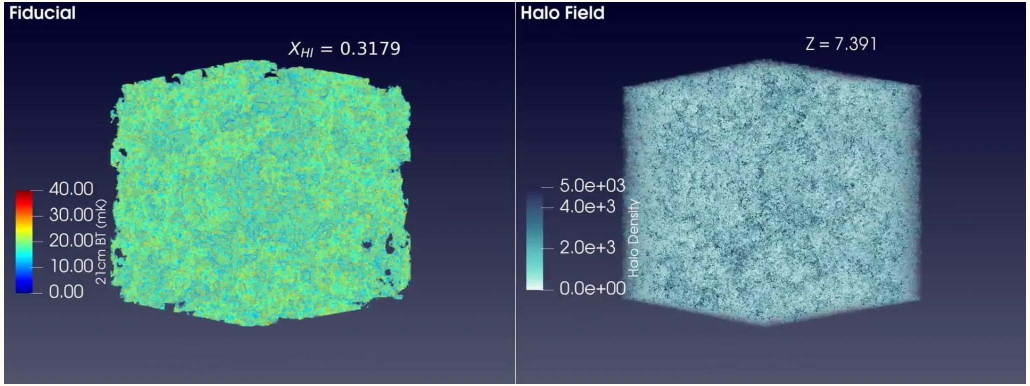
- What is the HI 21 cm emission?
- How can it help?
- What are the potential challenges?



Credit: NASA

Motivation

1. Tomographic imaging
2. Source properties
3. IGM properties
4. Tracking the entire Reionization



Experiments that are being done

- Murchison Widefield Array (MWA)
- Hydrogen Epoch of Reionization Experiment (HERA)
- Low Frequency Array (LOFAR)
- Atacama Large Millimeter/submillimeter Array (ALMA)
- Square Kilometer Array (SKA) *

* upcoming

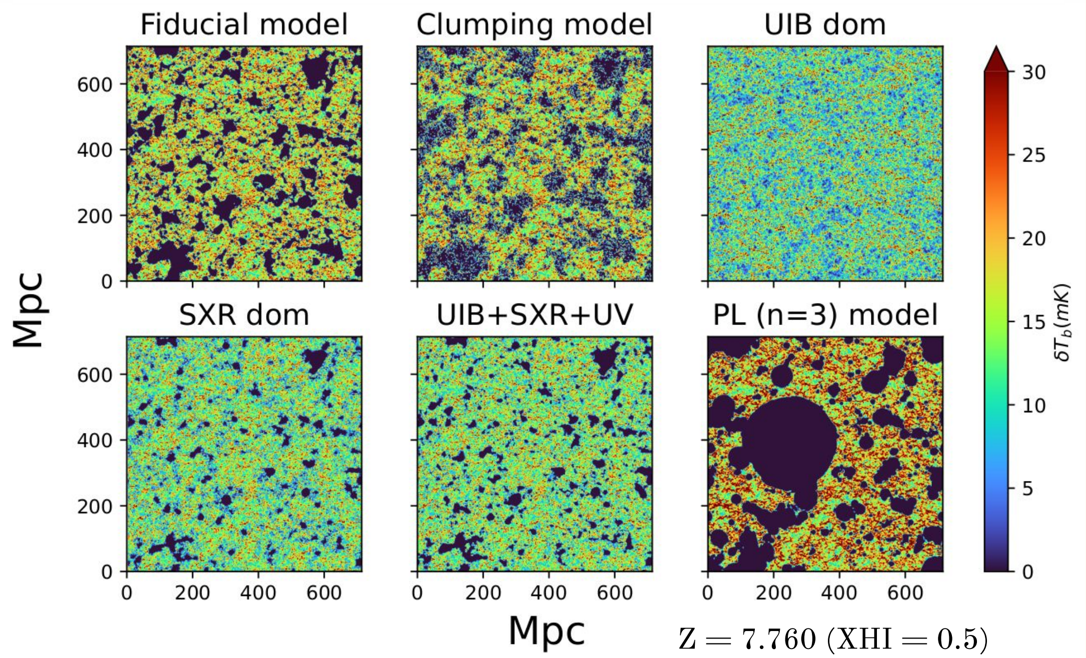
1. https://www.skatelescope.org/wp-content/uploads/2013/07/P2140244.jpg
2. ALMA -ESO
3. https://www.astron.nl/telescopes/lofar/
4. https://www.atnf.csiro.au/projects/ska/index.html

Primary work with 21cm image analysis

AIM:

To distinguish between the major

Reionization scenarios



Z = 7.760 (XHI = 0.5)

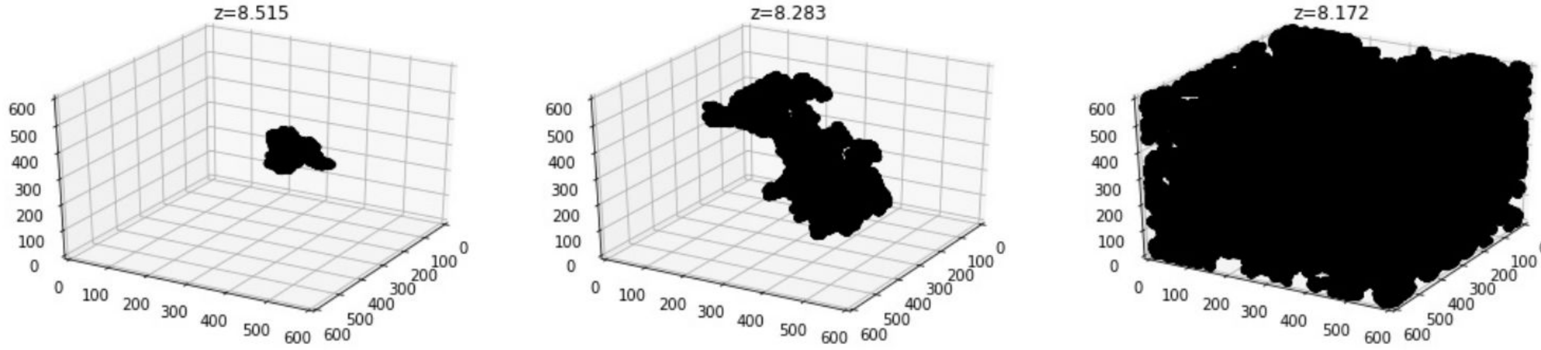
Pathak+Dasgupta et al., 2022,

DOI: 10.1088/1475-7516/2022/11/027

Methodology

1. **Percolation Transition - LCS**

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



(a) $\bar{x}_{\rm H\,I} = 0.80$, before percolation (b) $\bar{x}_{\rm H\,I} = 0.75$, onset of percolation (c) $\bar{x}_{\rm H\,I} = 0.72$, just after percolation

Pathak+Dasgupta et al., 2022, DOI: 10.1088/1475-7516/2022/11/027

Methodology

2. Shapefinders - Minkowski functionals

- Surface Area (S)
- Volume (V)
- Integrated Mean Curvature (C)
- Euler characteristic (χ)

(R_1, R_2 are principal radii of curvature)

$$S = \sum_{i=1}^{N_T} S_i$$

$$V = \sum_{i=1}^{N_T} V_i, \quad V_i = \frac{1}{3} S_i (\hat{\mathbf{n}}_i . \mathbf{P}_i)$$

$$C = \frac{1}{2} \oint \left(\frac{1}{R_1} + \frac{1}{R_2} \right) dS$$

$$\chi = \frac{1}{2\pi} \oint \frac{1}{R_1 R_2} dS$$

Pathak+Dasgupta et al., 2022, DOI: 10.1088/1475-7516/2022/11/027

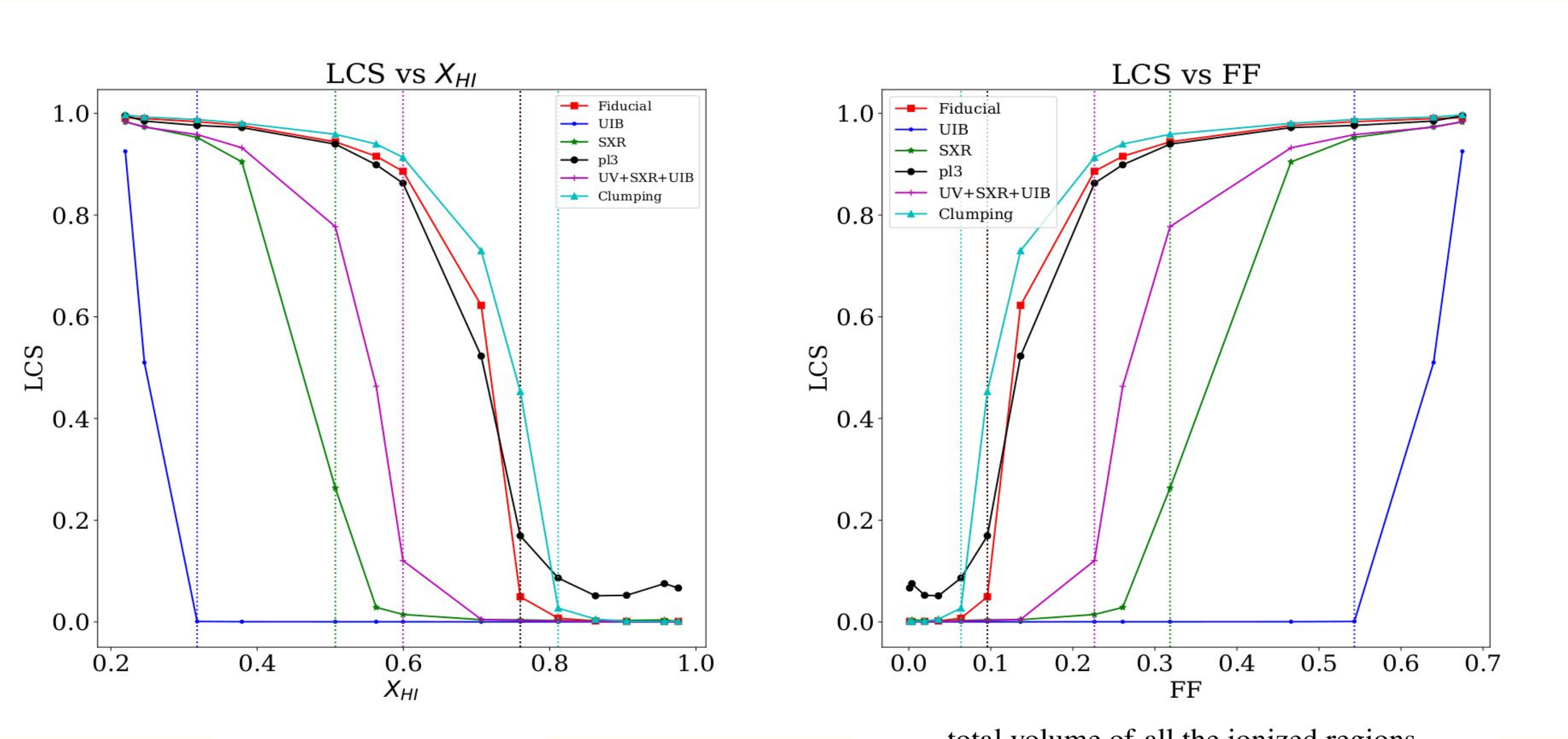
Tools used

- SURFGEN2
  - Thickness : T=3V/S
  - Breadth : B=S/C
  - Length : L=C/(4**π**)
- Morphology of the region
  - Planarity : P=(B-T)/(B+T)
  - Filamentarity : F=(L-B)/(L+B)

Pathak+Dasgupta et al., 2022,

DOI: 10.1088/1475-7516/2022/11/027

Results from Pathak+Dasgupta et al., 2022



$$\bar{x}_{\mathrm{H\,I}}(z) = \bar{\rho}_{\mathrm{H\,I}}(z)/\bar{\rho}_{\mathrm{H}}(z)$$

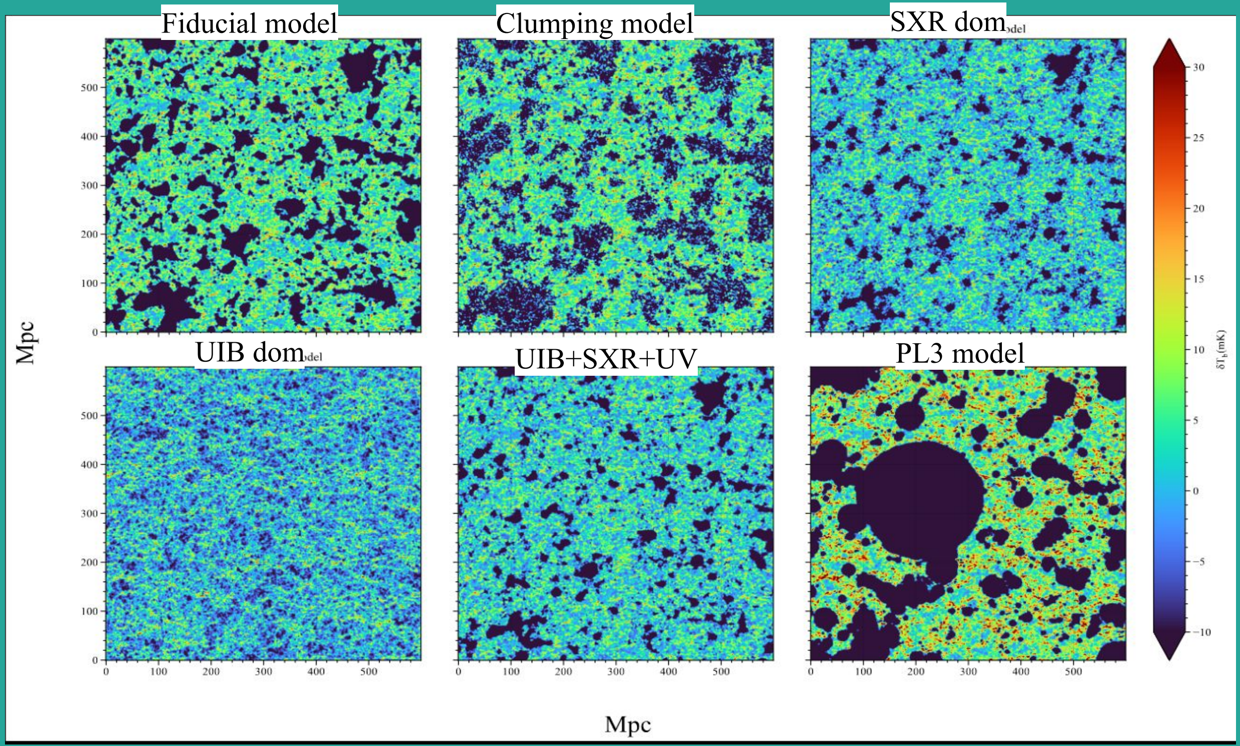
$$\mathrm{FF} = \frac{\text{total volume of all the ionized regions}}{\text{simulation volume}}$$

Results from Pathak+Dasgupta et al., 2022

Reionization Scenarios	Critical $\bar{x}_{HI}$	FF_C	Planarity	Filamentarity
Fiducial	0.75	0.095	0.162	0.998
Clumping	0.81	0.063	0.837	0.922
UIB dominated	0.31	0.543	0.201	0.999
SXR dominated	0.50	0.318	0.126	0.984
UV+SXR+UIB	0.60	0.226	0.147	0.995
PL 3.0	0.75	0.095	0.872	0.997

Pathak+Dasgupta et al., 2022, DOI: 10.1088/1475-7516/2022/11/027

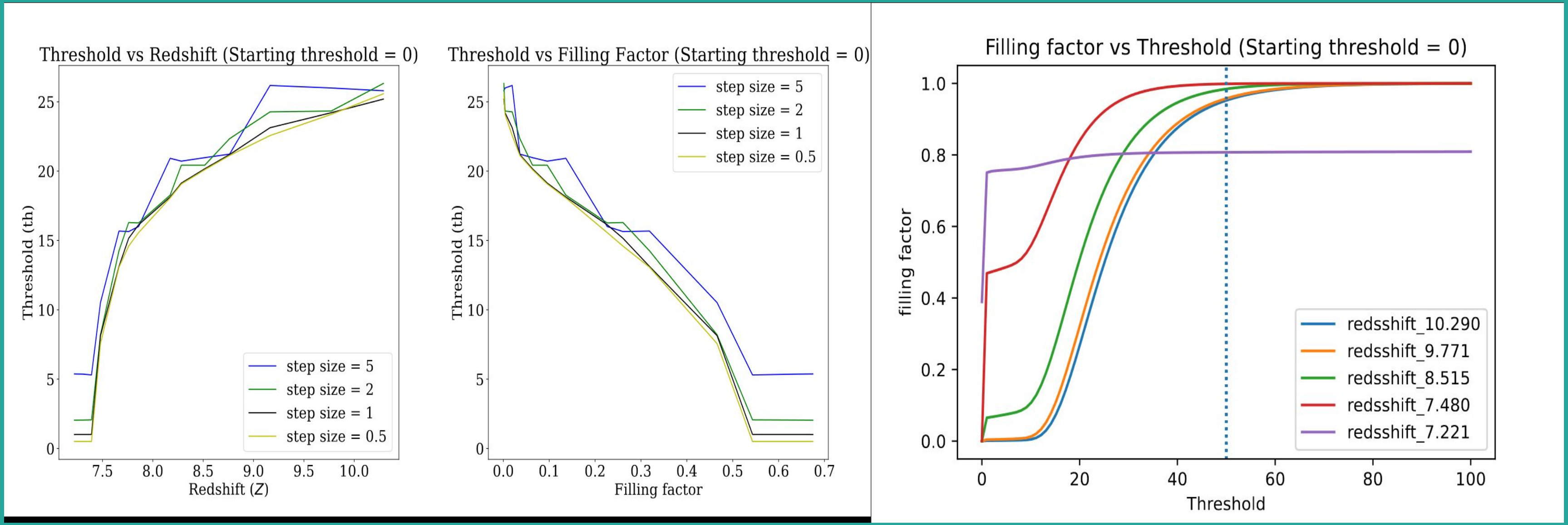
Moving towards the mean subtracted field



Dasgupta et al., 2022, in prep

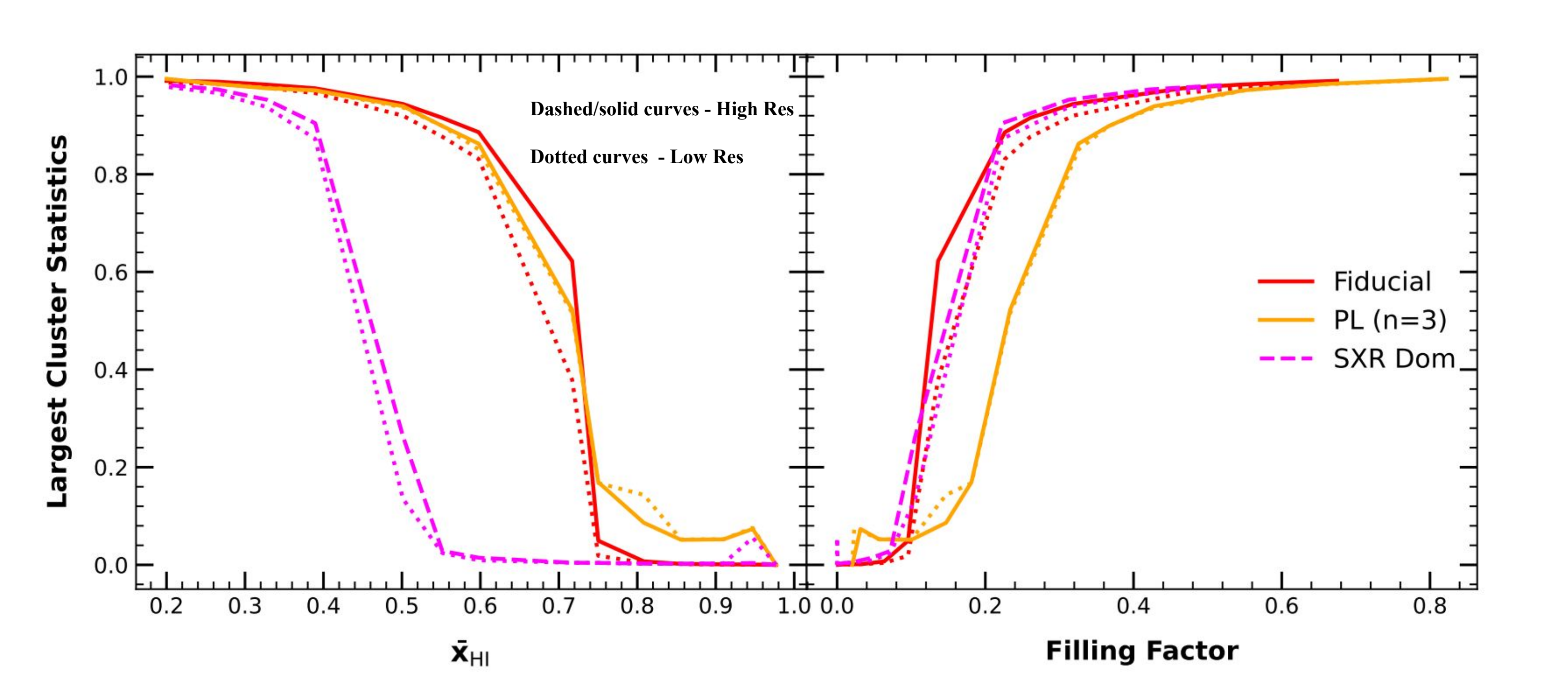
Analysis on the threshold

Variation of threshold with different parameters:



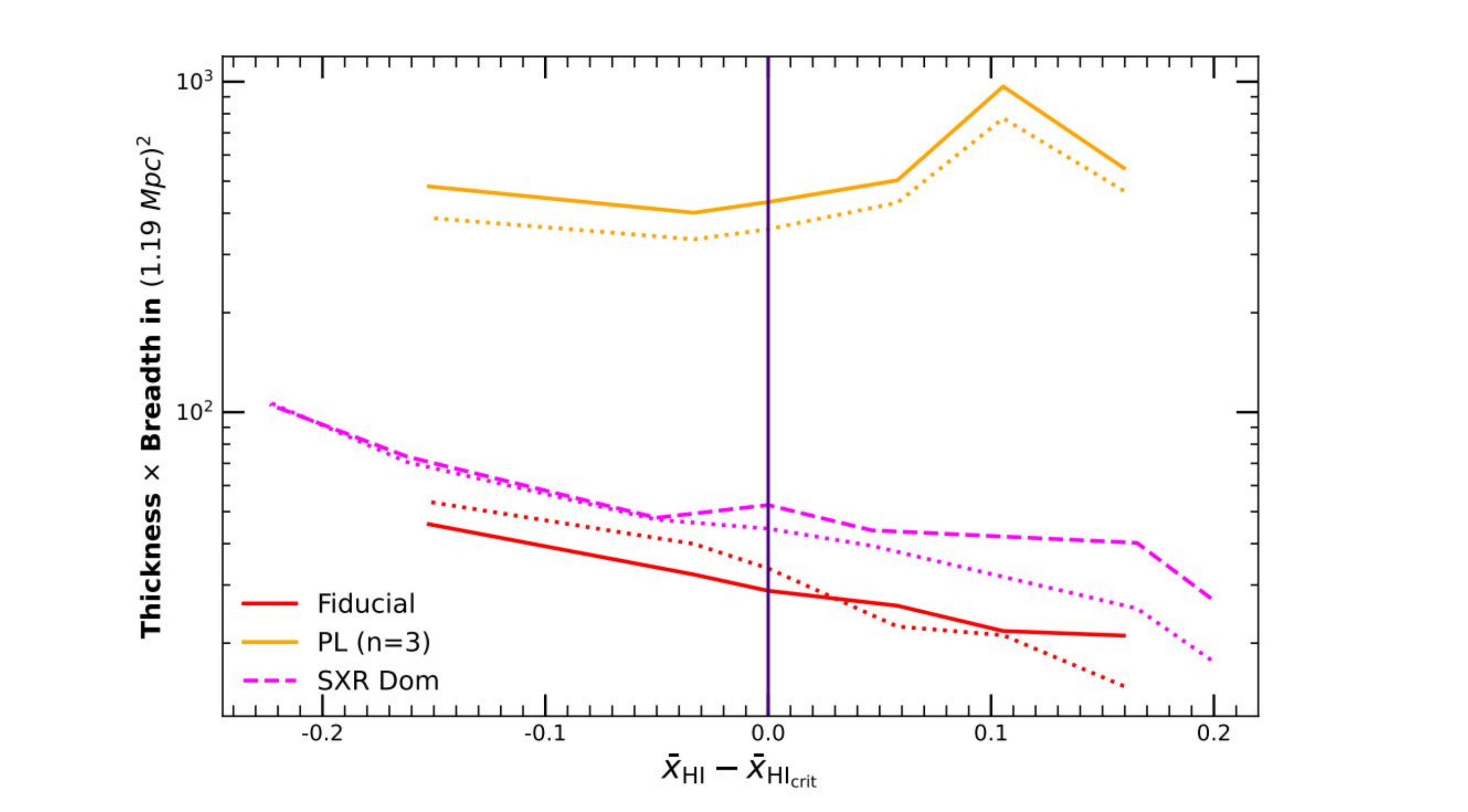
Dasgupta et al., 2022, in prep

Testing with low-resolution fields



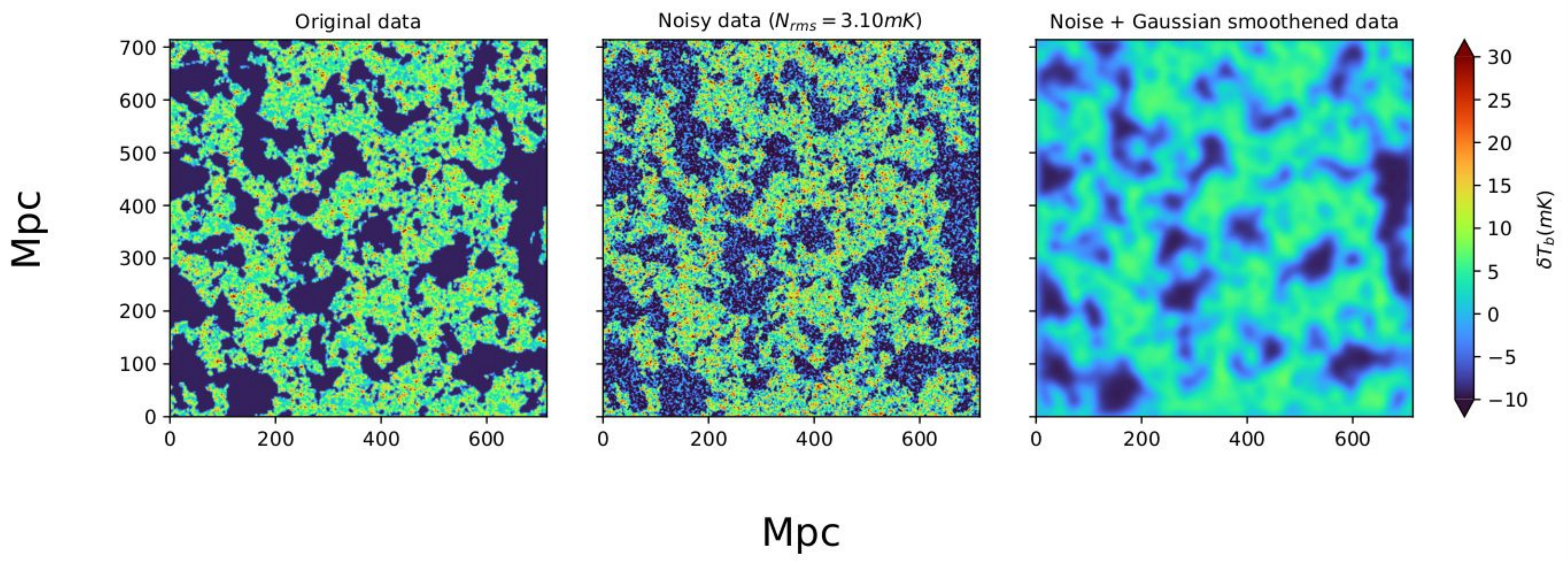
Pathak+Dasgupta et al., 2022, DOI: 10.1088/1475-7516/2022/11/027

Testing with low-resolution fields



Pathak+Dasgupta et al., 2022, DOI: 10.1088/1475-7516/2022/11/027

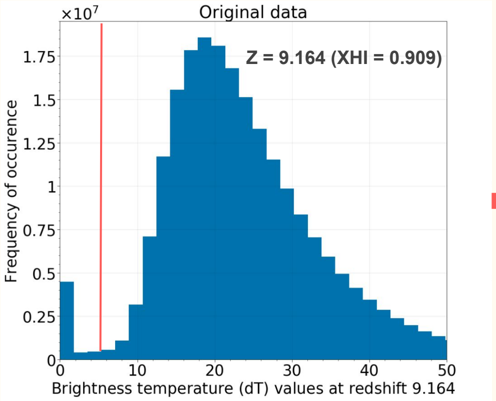
Moving towards a more realistic scenario

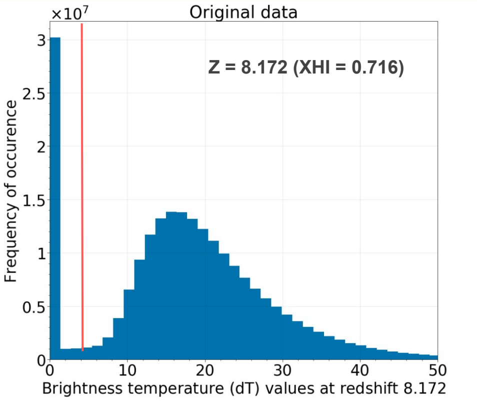


All maps are shown for the first slice of a HI cube of $Z = 7.480$ ($X_{HI} = 0.38$) for the Fiducial model

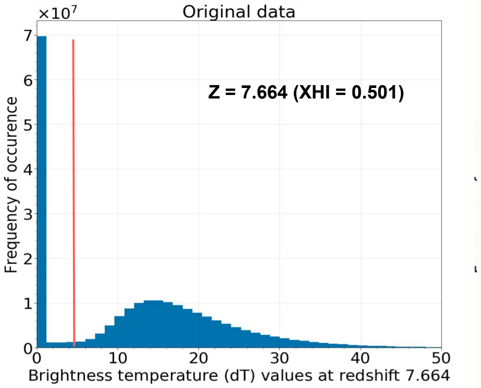
Dasgupta et al., 2022., in prep

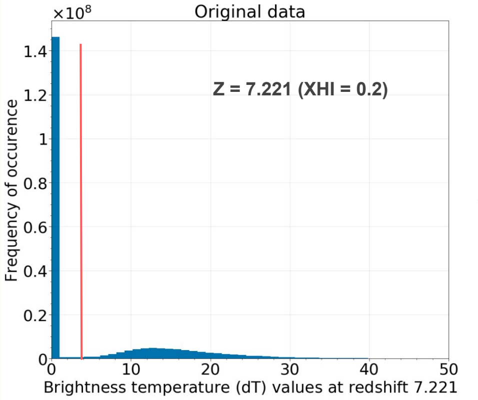
Choosing a proper threshold - gradient descent



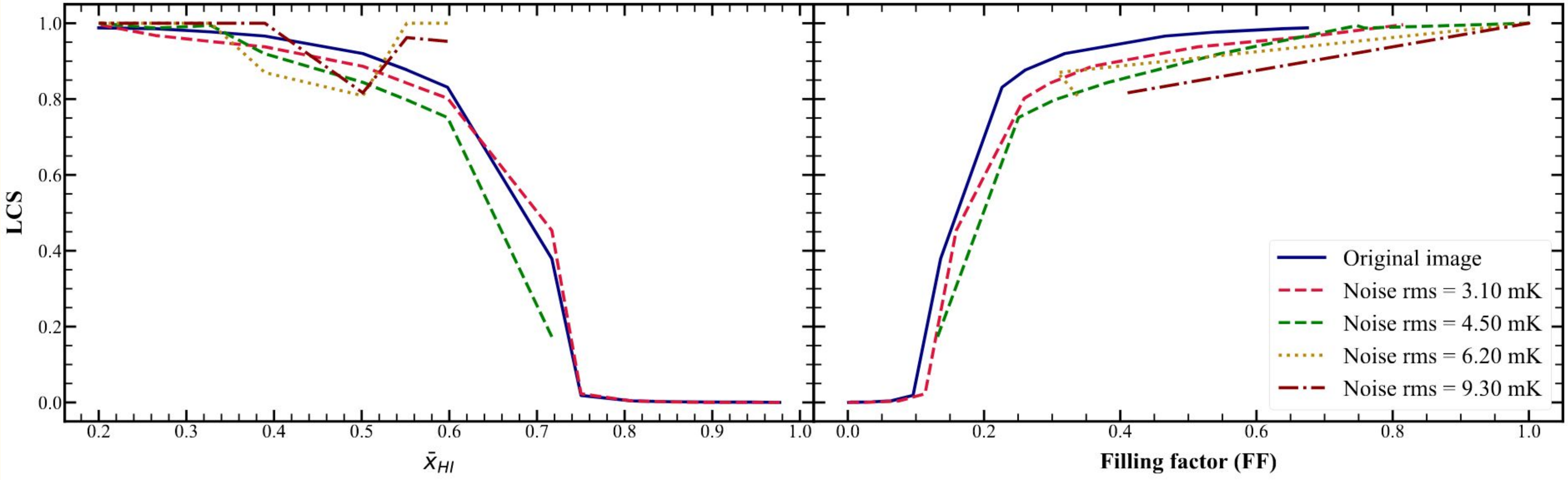


Dasgupta et al., 2022., in prep



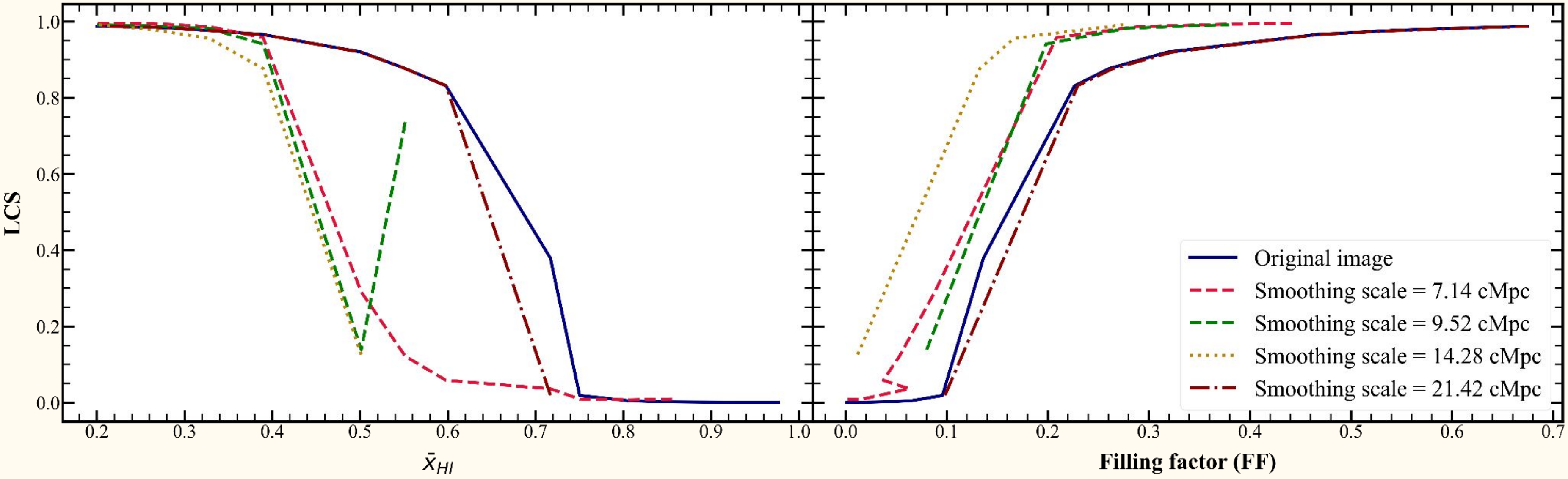


Effect of Noise only



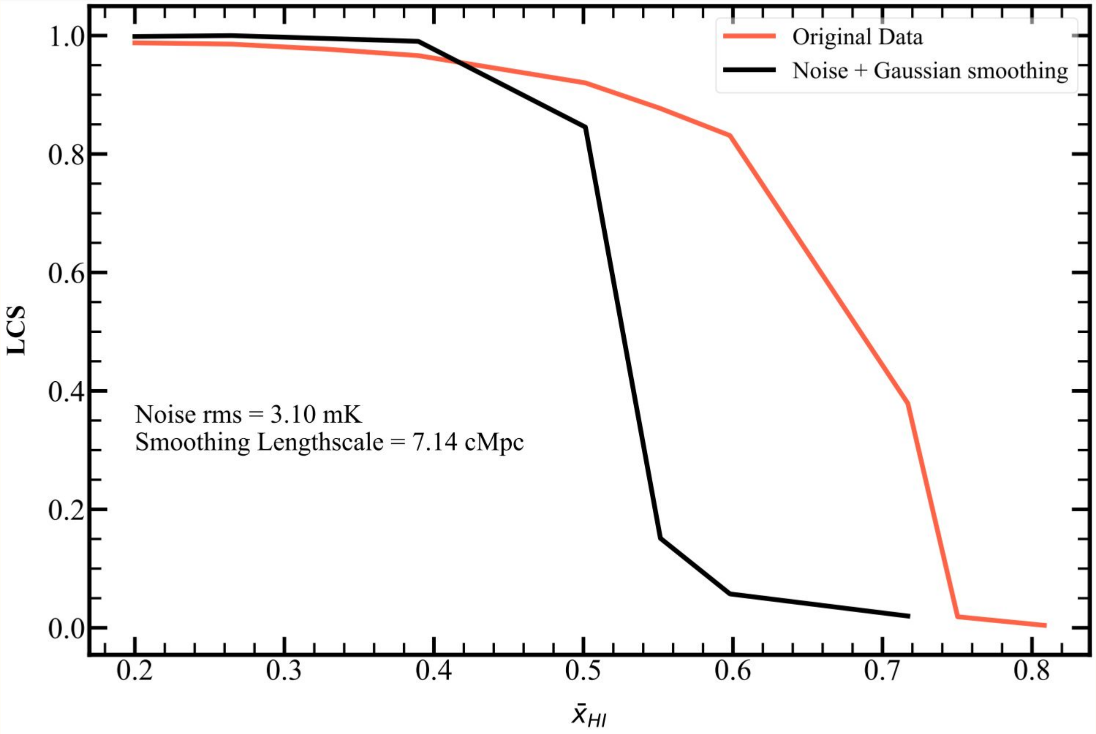
Dasgupta et al., 2022., in prep

Effect of smoothing only



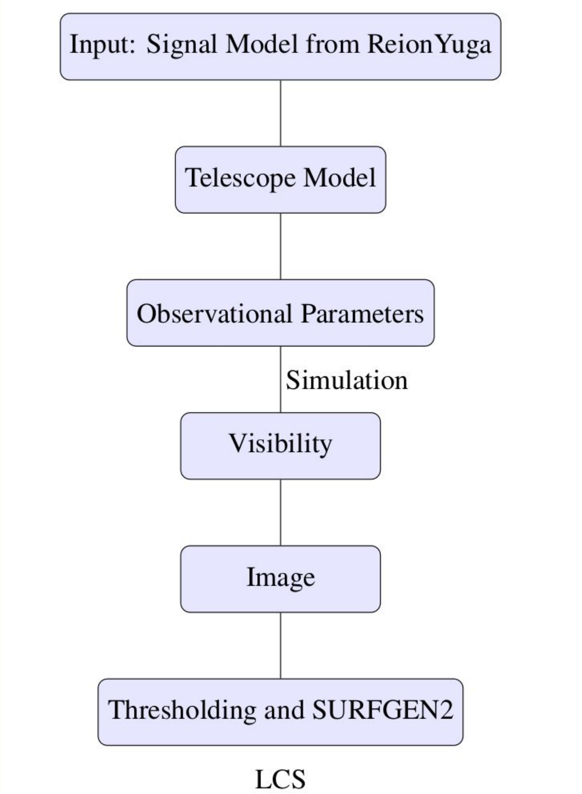
Dasgupta et al., 2022., in prep

Effect of Noise and smoothing combined



Dasgupta et al., 2022., in prep

Going to an even more realistic case ...

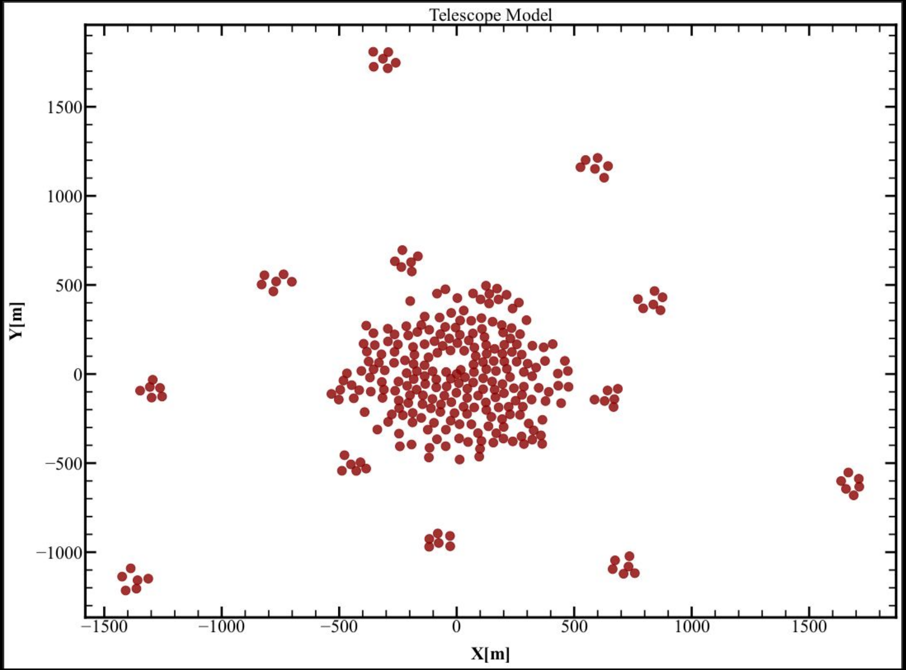


Dasgupta et al., 2022., in prep

Testing LCS on SKA1-low like maps

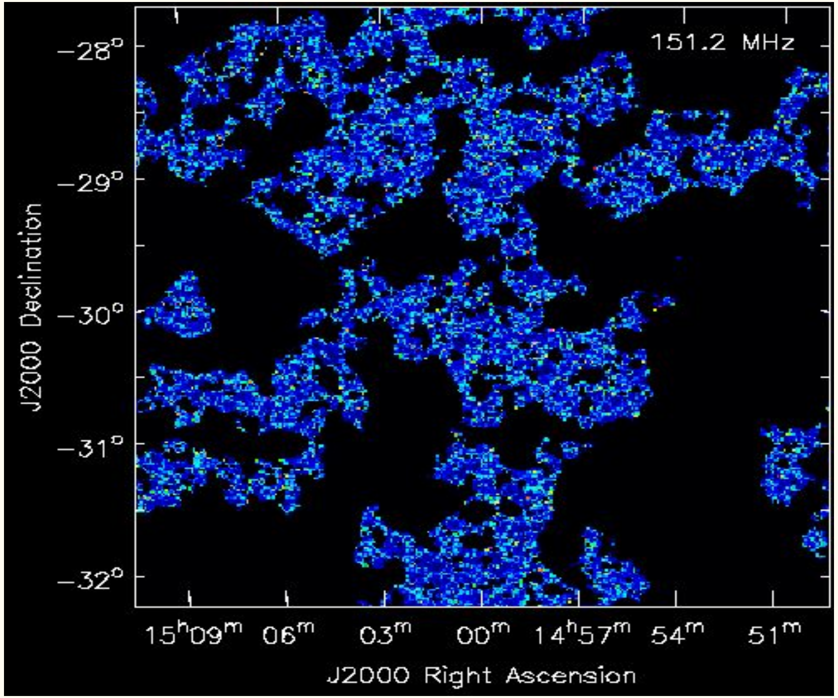
Input Parameters:

Parameter	Value
Field of view (FoV)	4°
Number of array elements	296
Maximum baseline	~ 2000 m
Synthesized beam	~ 2.5
Polarization	Stokes I
Observation Time	30 minutes
No. of snapshots	15
Integration time per snapshot	2 minutes
Phase Center(J2000)	RA, DEC= 5 h, -30°



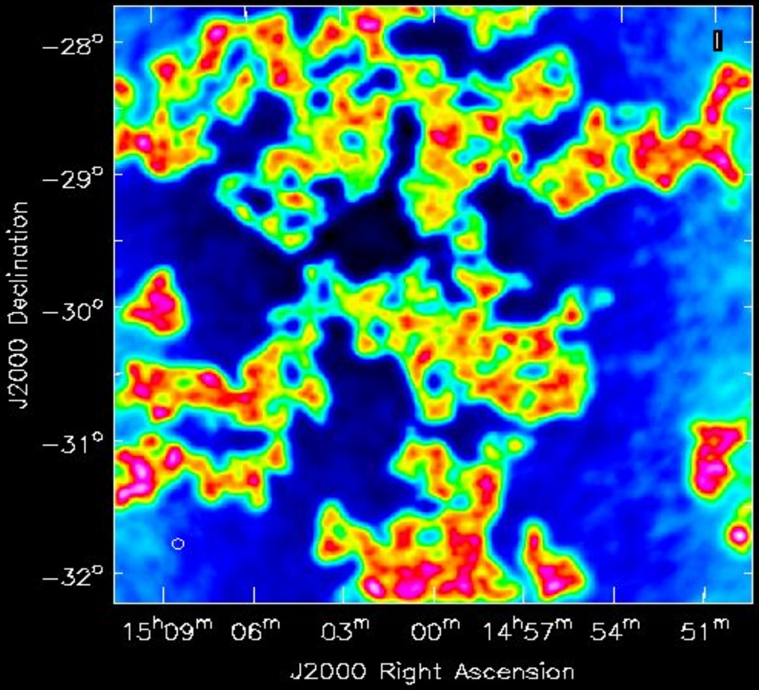
Dasgupta et al., 2022., in prep

Image obtained from OSKAR



$X_{HI} = 0.2$

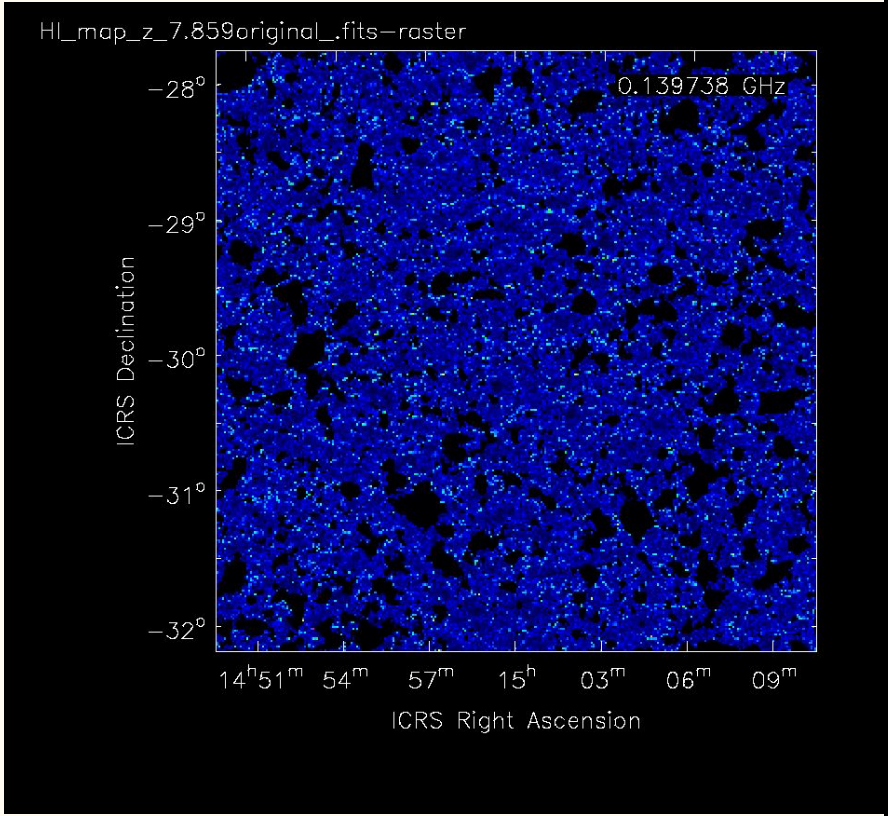
Original simulated image



$X_{HI} = 0.2$

Image obtained from SKA pipeline

Artefacts observed



Original simulated image

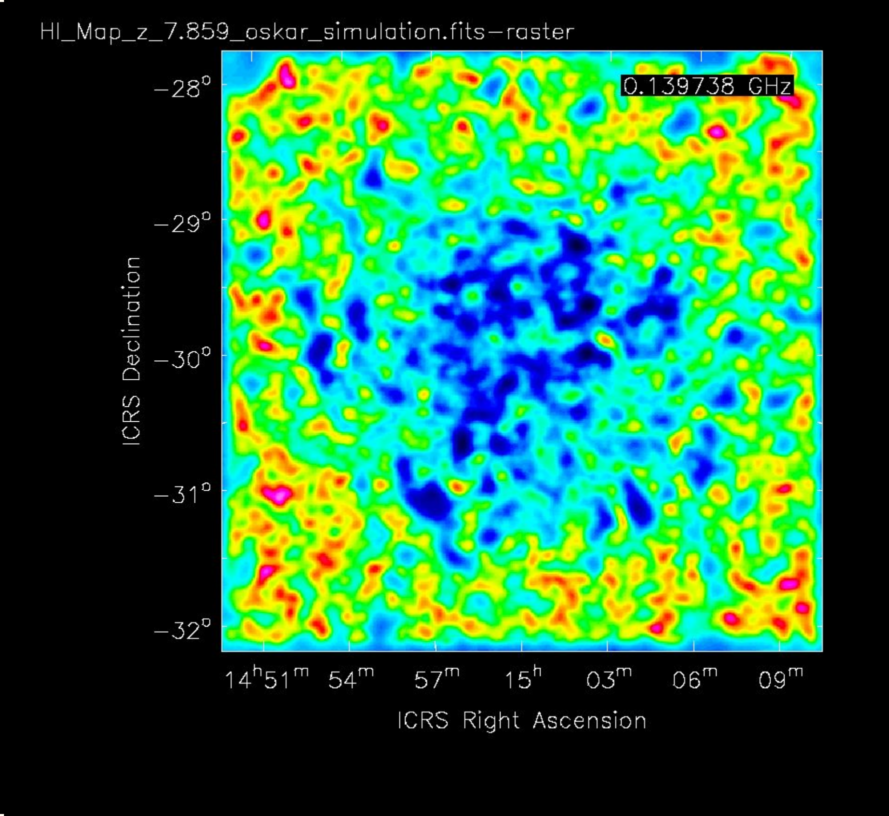
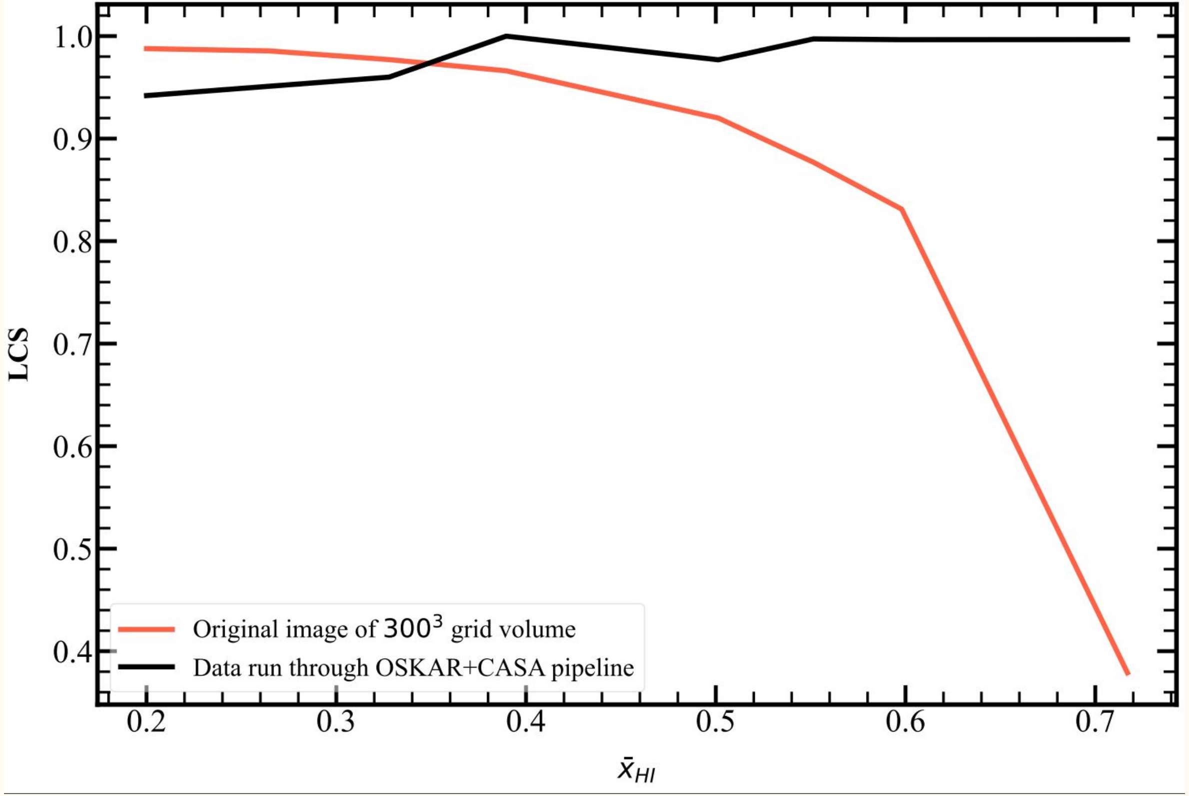


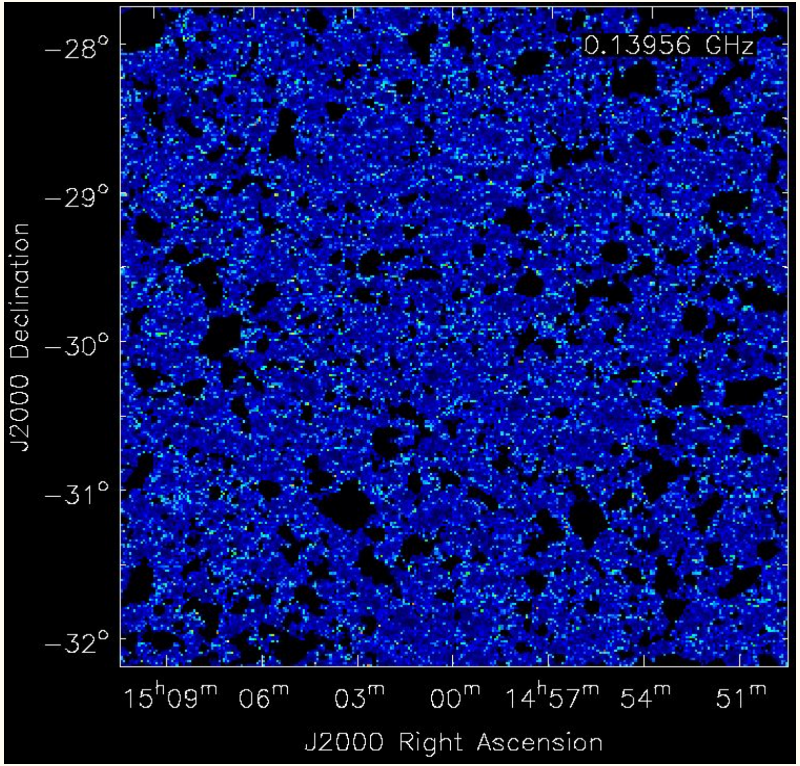
Image obtained from SKA pipeline

Effects of artefacts in LCS



Dasgupta et al., 2022., in prep

Mitigation of the artefacts using Multiscale deconvolution



Original simulated image

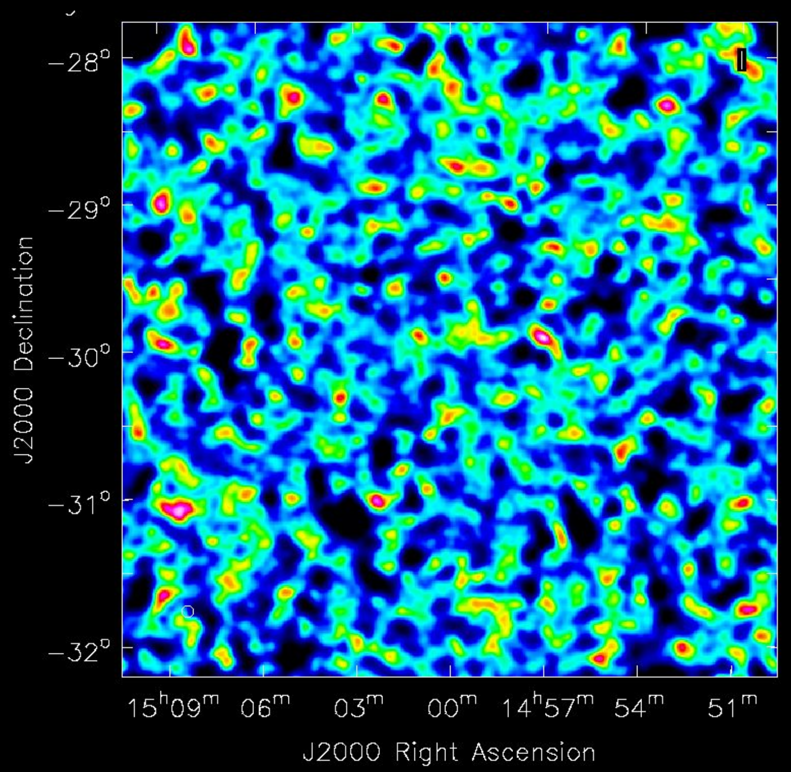
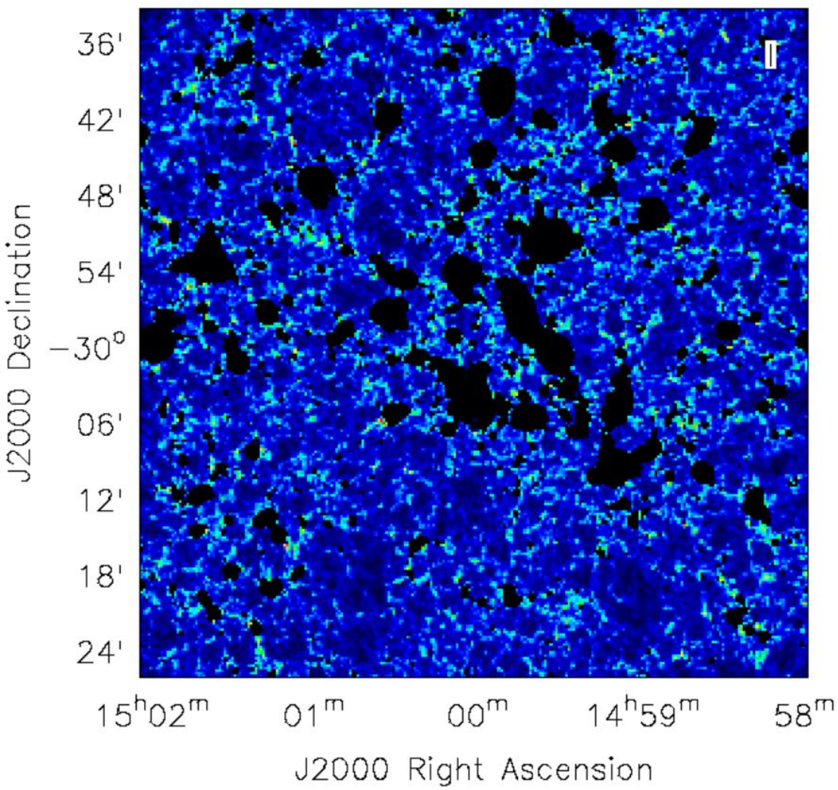


Image obtained from SKA pipeline

Maps after Briggs weighing



Original simulated image

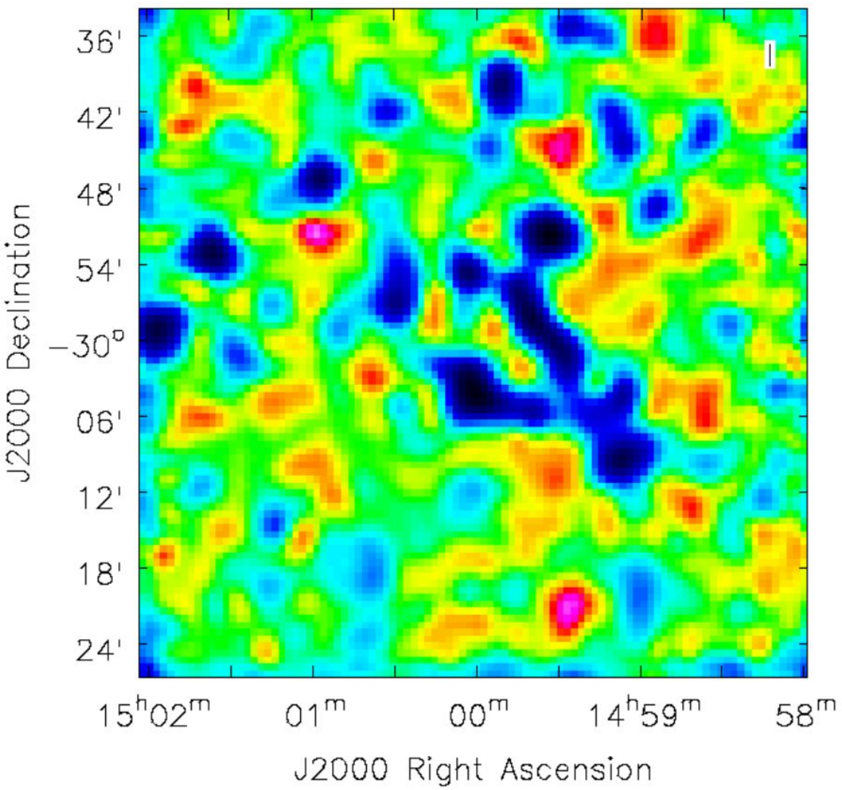
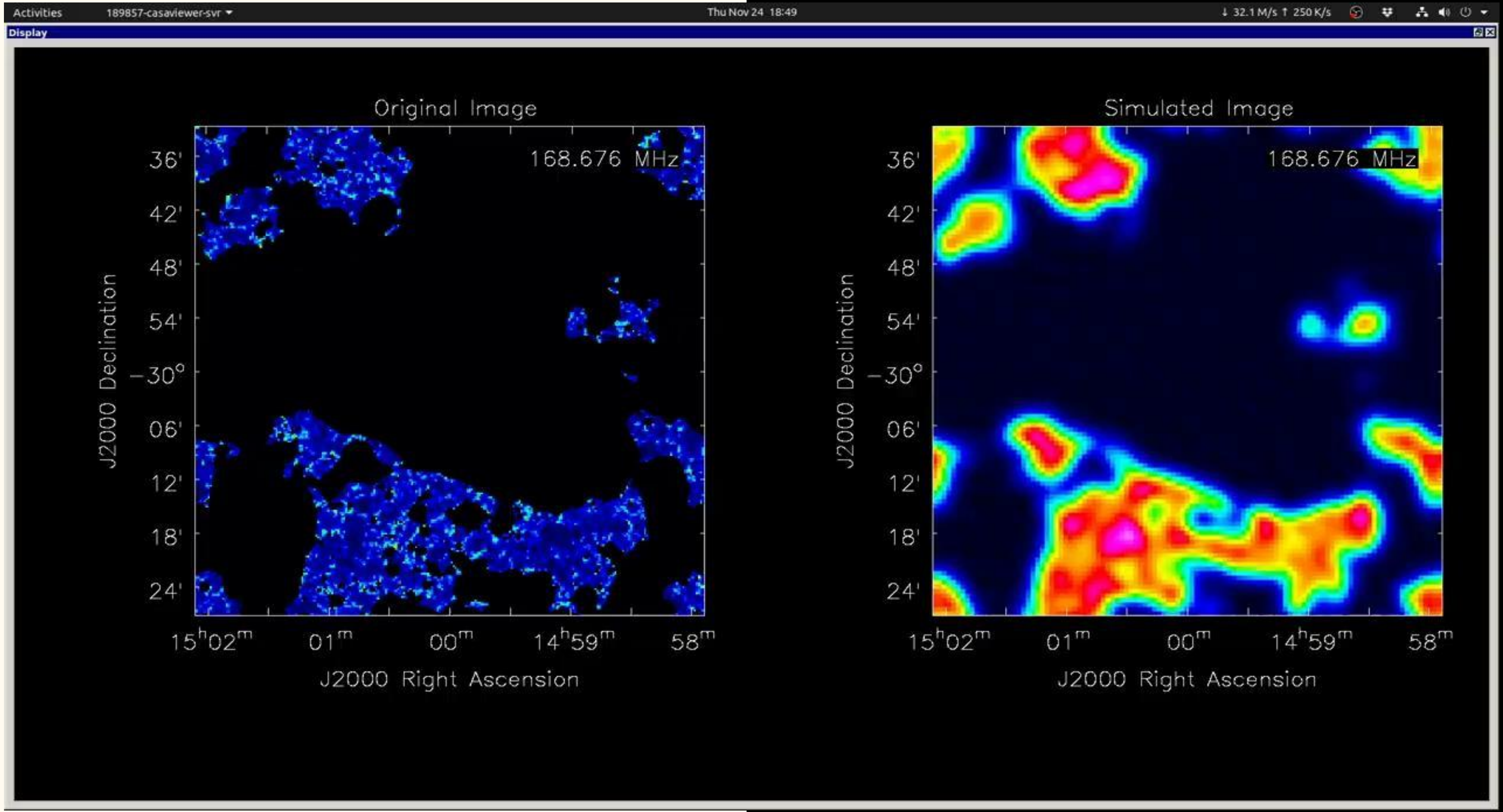


Image obtained from SKA pipeline

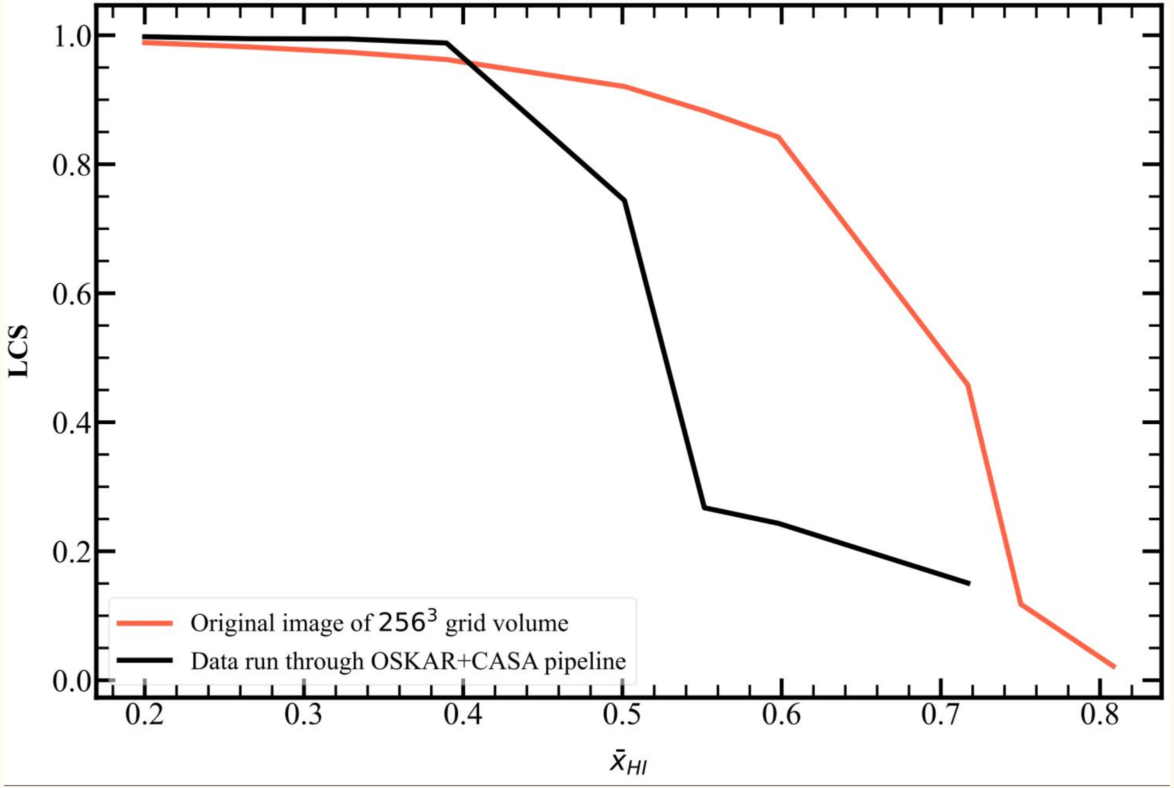
Maps after Briggs weighing



Original simulated image

Image obtained from SKA pipeline

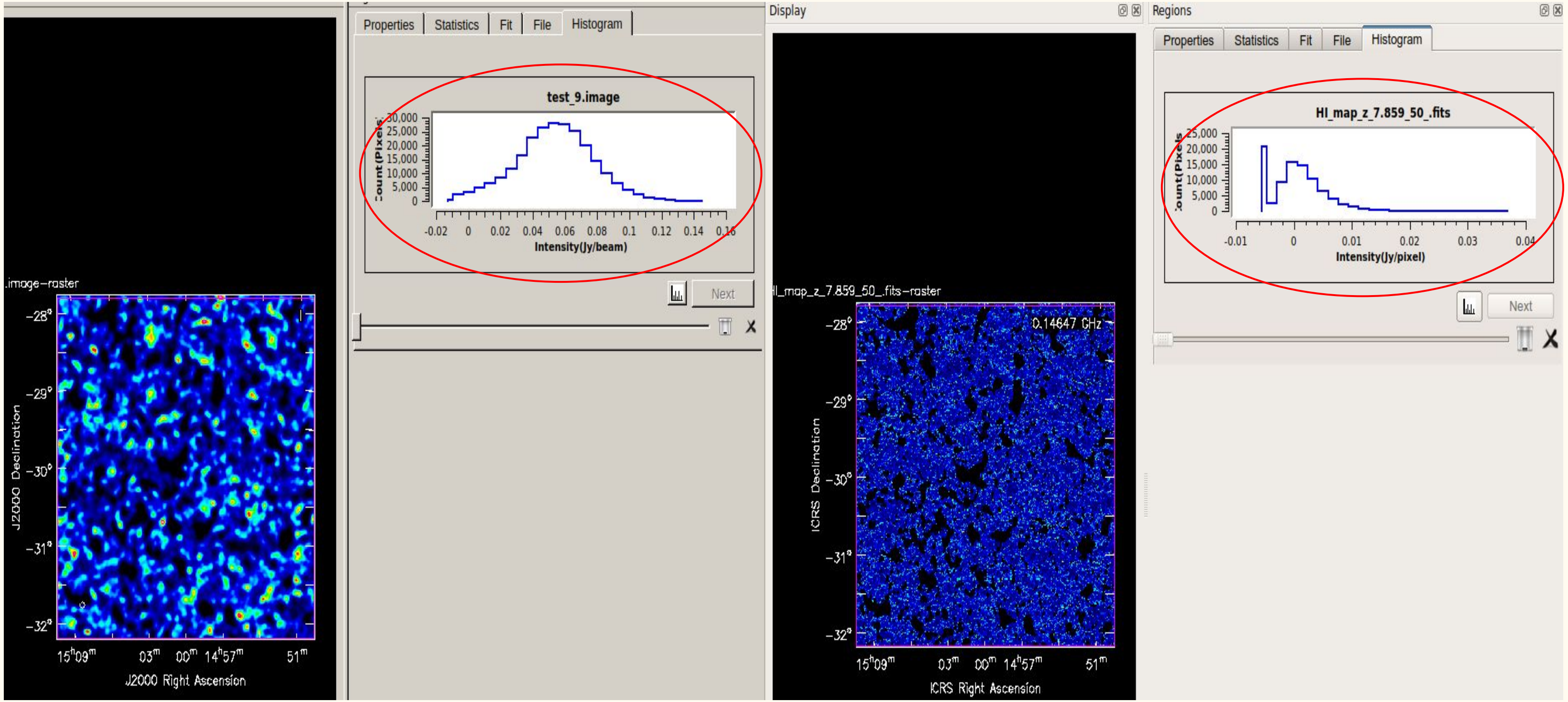
Results after using Briggs weighting scheme



Dasgupta et al., 2022., in prep

Searching for a better threshold-finding algorithm

Dasgupta et al., 2022., in prep



Future plans

- Searching for a better threshold-finding algorithm
- Incorporate the effects of Noise, Foregrounds and Ionosphere using OSKAR pipenine and validating robustness of LCS
- Compare different telescope effects and check validity of LCS-like analyses on the observational maps

Publications & Conferences

1. Contributed as an author in Pathak et al., 2022. It is published in the Journal of Cosmology and Astroparticle Physics, DOI: 10.1088/1475-7516/2022/11/027
2. Talk at SKA EoR-Cosmic Dawn Science Team Meeting: Data Challenges in the SKA Era, Scuola Normale Superiore, Piazza dei Cavalieri 7, 27/09/2022
3. Presented a talk at the workshop on 21-cm Cosmology in the Square Kilometre Array Era, Indian Statistical Institute Kolkata, 1/11/2022
4. Conference paper published in the URSI-RCRS 2022, IIT Indore
5. Talk at Indian Association for General Relativity and Gravitation (IAGRG), IISER Kolkata, 1/12/2022

References

1. Garrelt Mellema et al., *Reionization and the Cosmic Dawn with the Square Kilometre Array*, 2013
2. Bag et al., *Studying the morphology of HI isodensity surfaces during reionization using Shapefinders and percolation analysis*, 2019
3. Pathak et al., *Distinguishing reionization models using the largest cluster statistics of the 21-cm maps*, 2022
4. Bag et al., *The Shape and Size distribution of HII Regions near the percolation transition*, 2018
5. Furlanetto et al., *Cosmology at Low Frequencies: The 21 cm Transition and the High-Redshift Universe*, 2006
6. Giri et al., *Optimal identification of HII regions during reionization in 21-cm observations*, 2018