Analysing the effect of calibration errors and instrumental noise on HI 21-cm maps from the EoR using the LCS

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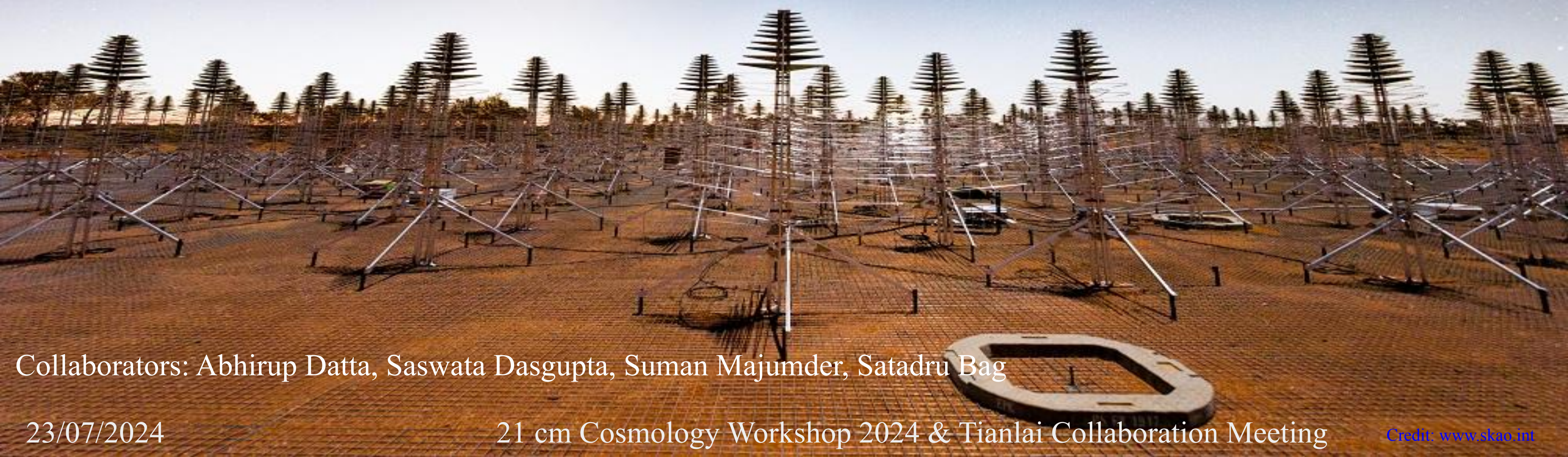

Collaborators: Abhirup Datta, Saswata Dasgupta, Suman Majumder, Satadru Bag

23/07/2024   21 cm Cosmology Workshop 2024 & Tianlai Collaboration Meeting

Credit: www.skao.int

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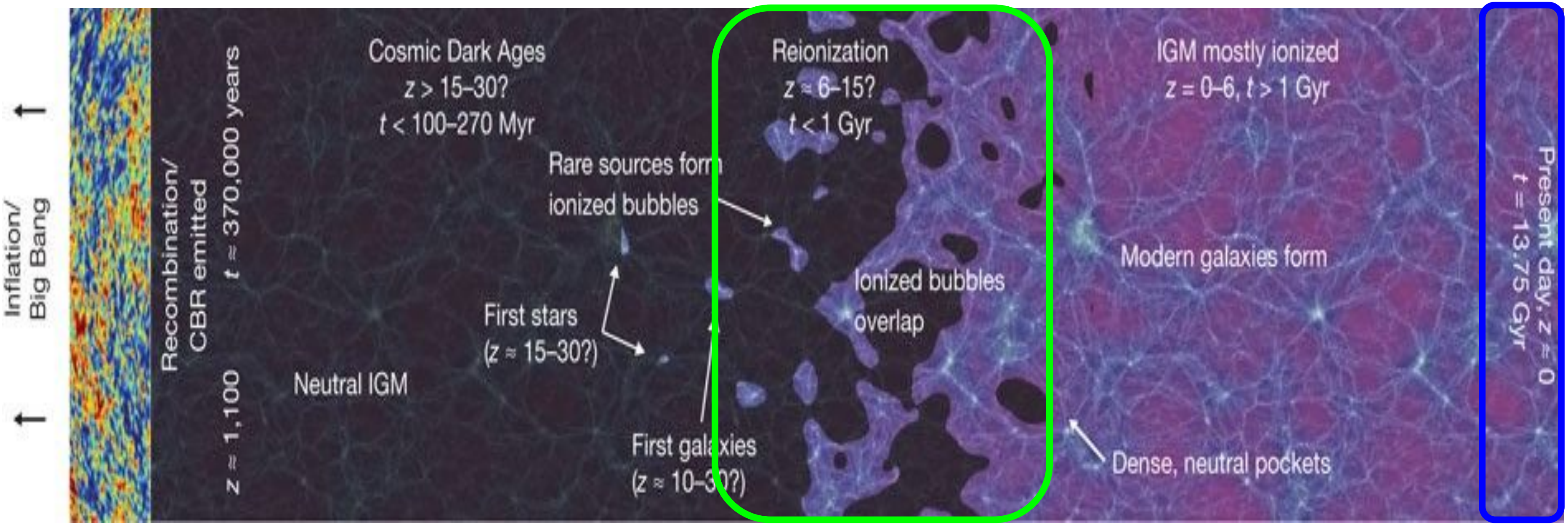
History of the Early Universe

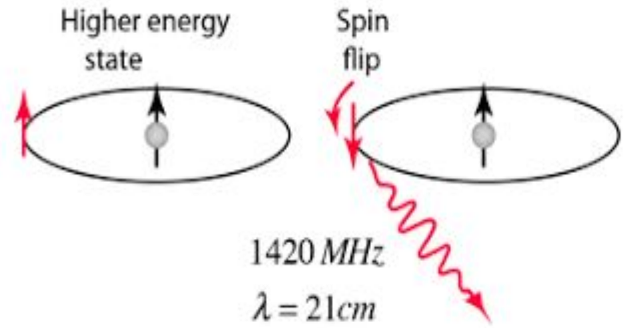


Credit: Robertson et al., 2010

Motivation

❖ What is the HI 21 cm emission ?

➢ spin-flip transition line of neutral hydrogen



❖ How can it help?

➢ It creates a map of the evolving hydrogen density distribution over a large redshift range.

➢ We can tell about the sources and their properties of the sources that might have ionised the surrounding IGM

❖ How do the topology of ionized region changes with redshift ?

➢ Evolution of largest ionized regions

Credit: www.hyperphysics.phy

The 21-cm Experiments

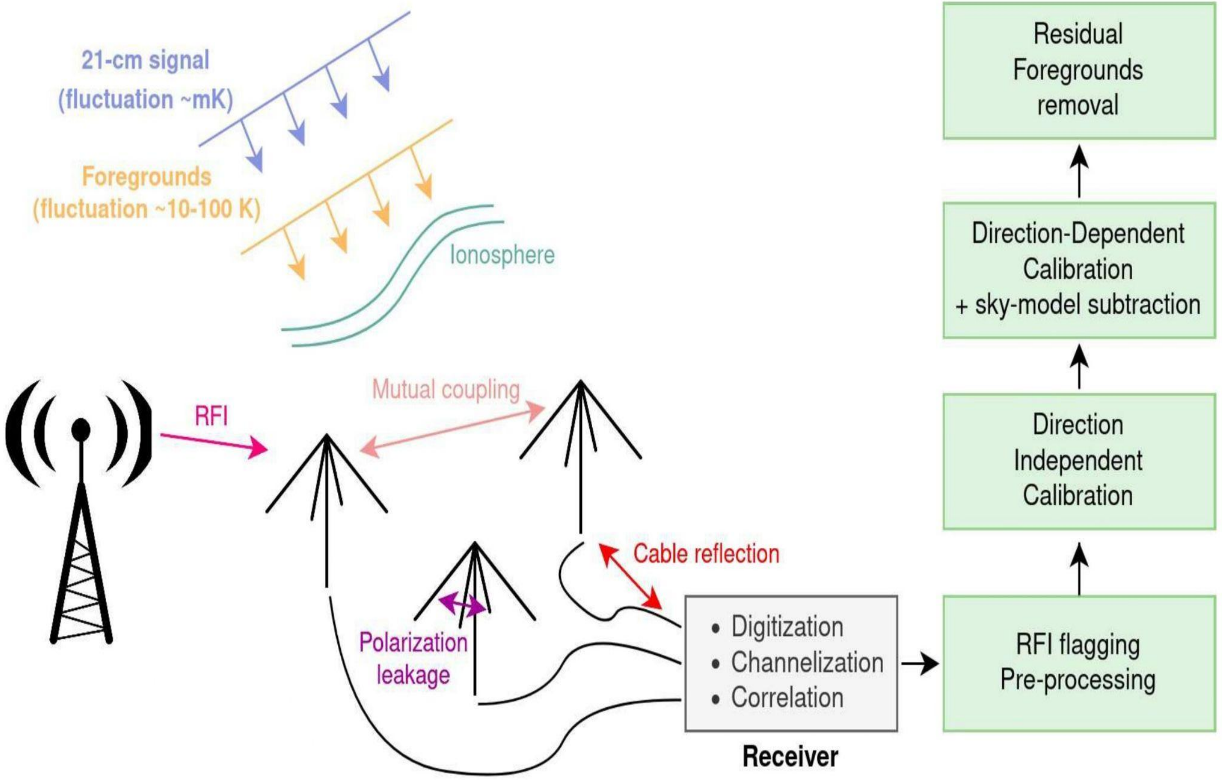
1. Murchison Widefield Array (MWA)
2. Hydrogen Epoch of Reionization Experiment (HERA)
3. Low Frequency Array (LOFAR)
4. Giant Metrewave Radio Telescope (GMRT)
5. Square Kilometer Array (SKA)

- https://www.mwatelescope.org/
- https://public.nrao.edu/news/2016-hera-grant/
- https://www.astron.nl/telescopes/lofar/
- http://www.gmrt.ncra.tifr.res.in/
- www.skao.int/

A challenging experiment

Observation of redshifted 21 cm signal are challenging because of :

- ❑ Astrophysical foreground
- ❑ Earth's Ionosphere
- ❑ Radio Frequency Interference (RFI)
- ❑ Thermal Noise
- ❑ Instrumental Systematics



Courtesy: F. Mertens

Percolation Transition - LCS

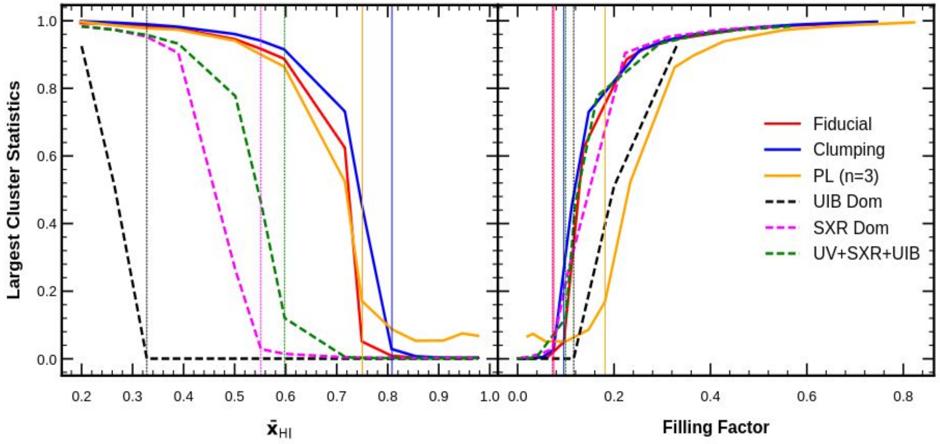
- The percolation transition - a group of small ionized regions merge to form a large, singly connected region.

- Percolation as happening when the largest ionized region stretches from one end to the other end of our simulation volume due to periodic boundary conditions.

- Estimate the shape and size of ionized regions using shape finding algorithm - SURFGEN2.

- SURFGEN2 requires a threshold that distinguishes between ionized and neutral pixels

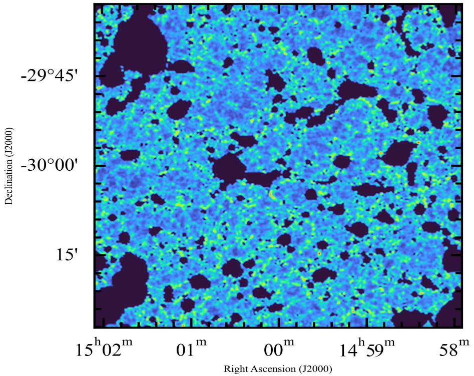
$$\text{LCS} = \frac{\text{volume of the largest ionized region}}{\text{total volume of all the ionized regions}} .$$

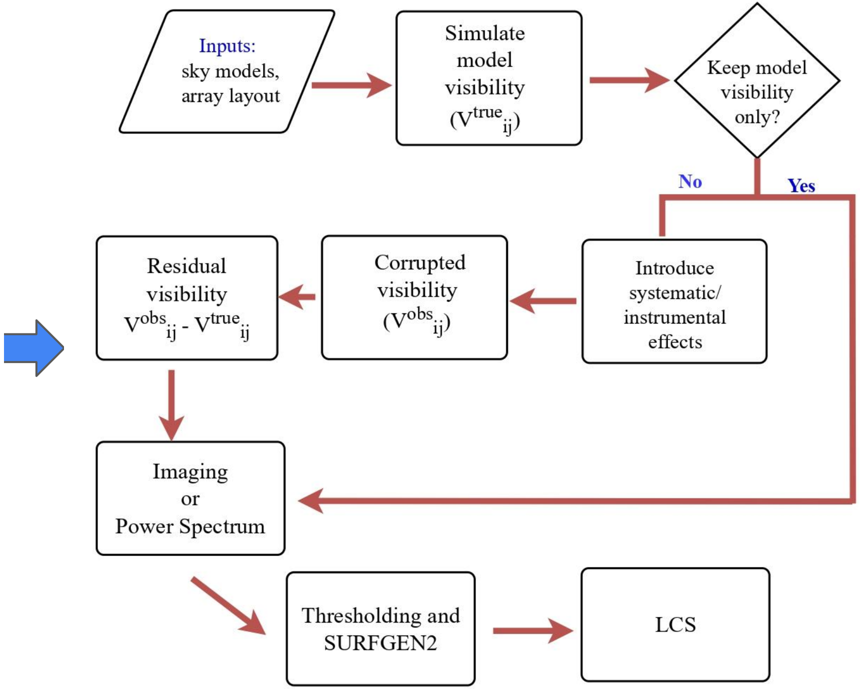


Bag et. al., 2019
Pathak et. al., 2022

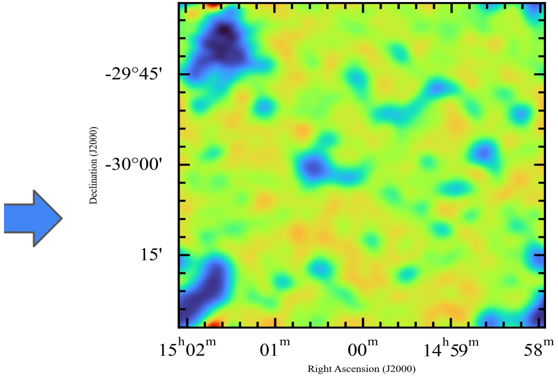
21cmE2E pipeline

HI signal from ReionYuga





Observed Image

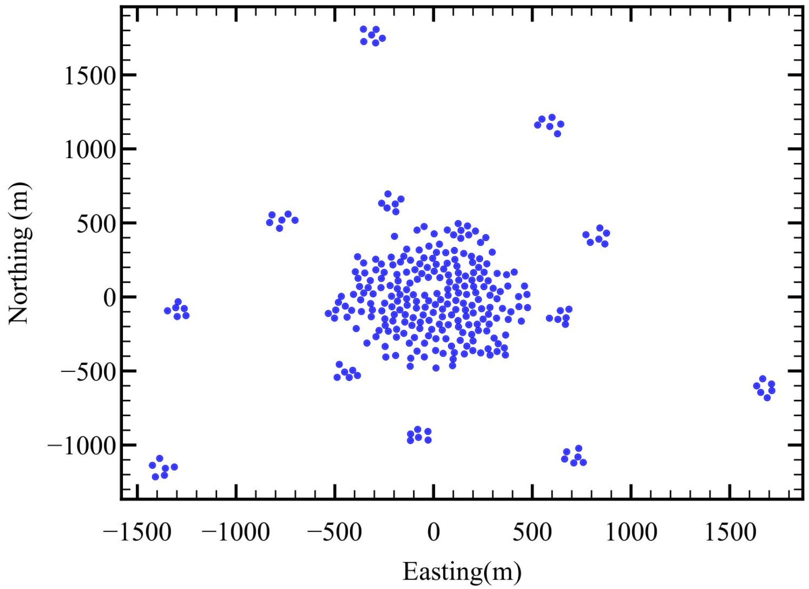


Pal et al., in prep

Observational Parameters & Telescope Layout

Input Parameters:

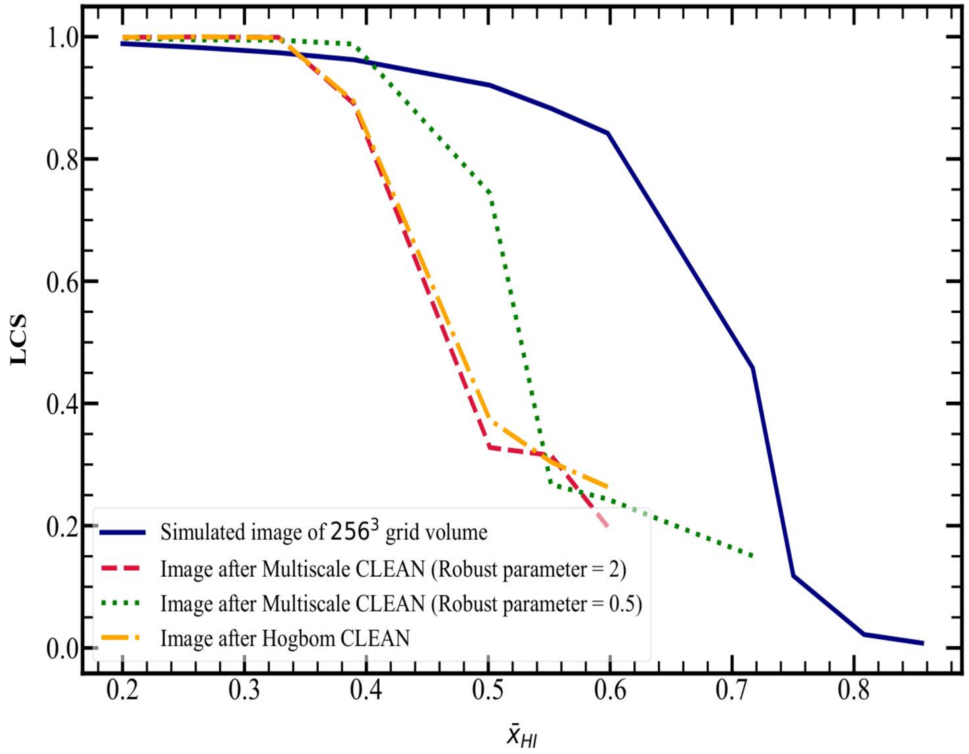
Observations time: 0.5hr
Channel no: 256
Redshift range: 7.2 ~ 8.8
Integration time: 120 second
Telescope: SKA1-LOW
Baseline: Stations around ~ 2 km of the central station.



Pal et al., in prep

Effect of array synthesize beam on LCS

- ❑ Different imaging weight scheme and thresholding algorithm create bias estimation of LCS.
- ❑ We use Gradient descent algorithm on the HI 21-cm maps to recovered H II regions.
- ❑ The percolation transition has happened later in reionization.



Dasgupta + Pal et al., 2023., JCAP

Choosing a proper threshold - Triangle method

- Gradient descent failed to reach the global minima in presence of low signal to noise ratio
- We use triangle method to binarize the image.
- The LCS estimation follow the actual reionization scenario represented by red dash-dotted line.

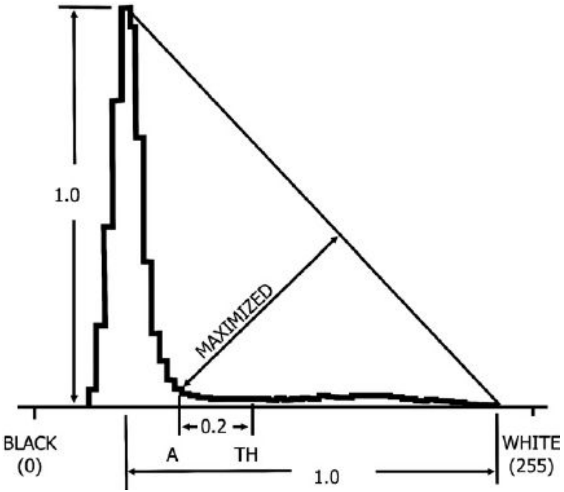
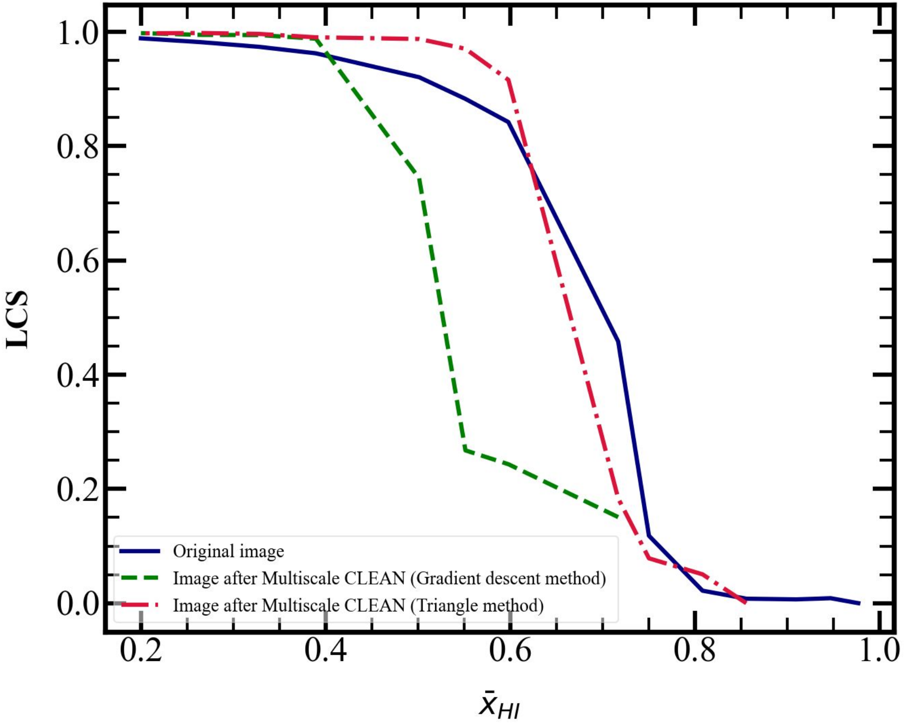


Image Credit : Stefano Mancuso



Pal et al., in prep

Effect of Astrophysical Foreground

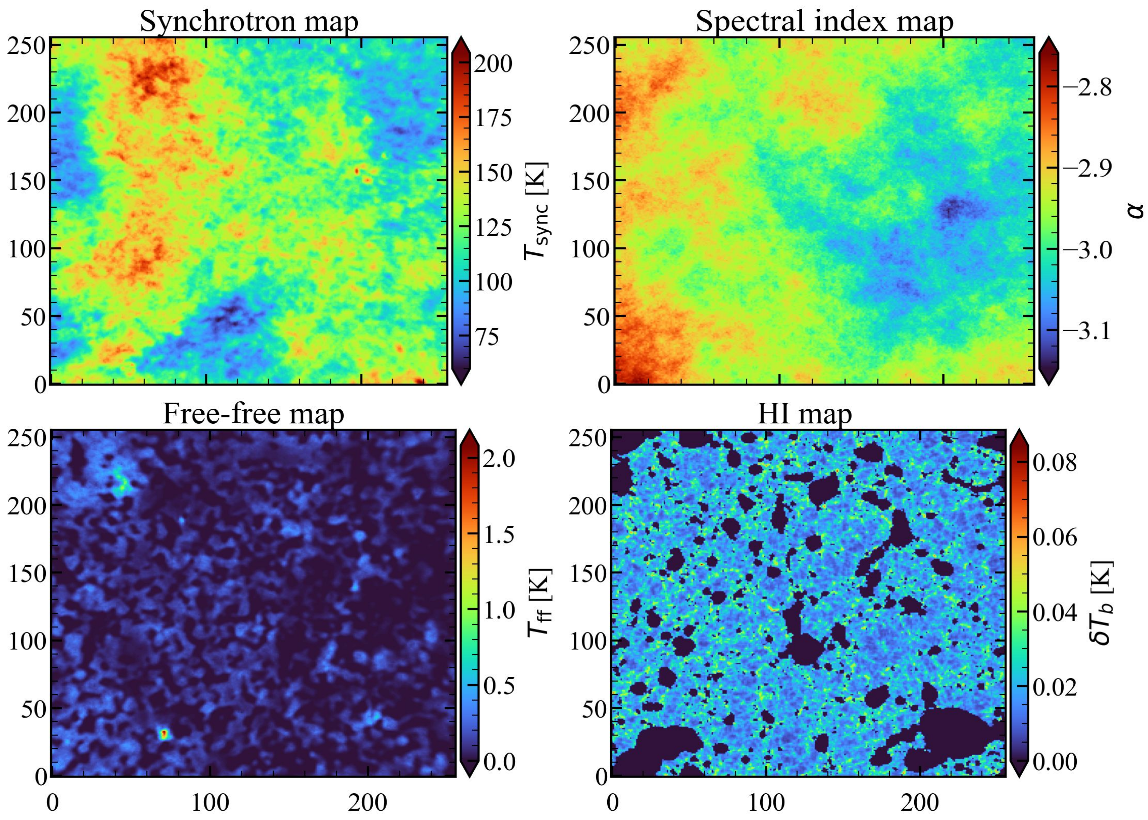
- Diffuse foreground maps from the Planck Sky Model at 217 GHz.
- Extrapolate FG maps for our frequency of interest.

$$T(\nu, p) = T_s \left(\frac{\nu}{\nu_0}\right)^{\beta_s(\nu,p)}$$

Carucci et al., 2020

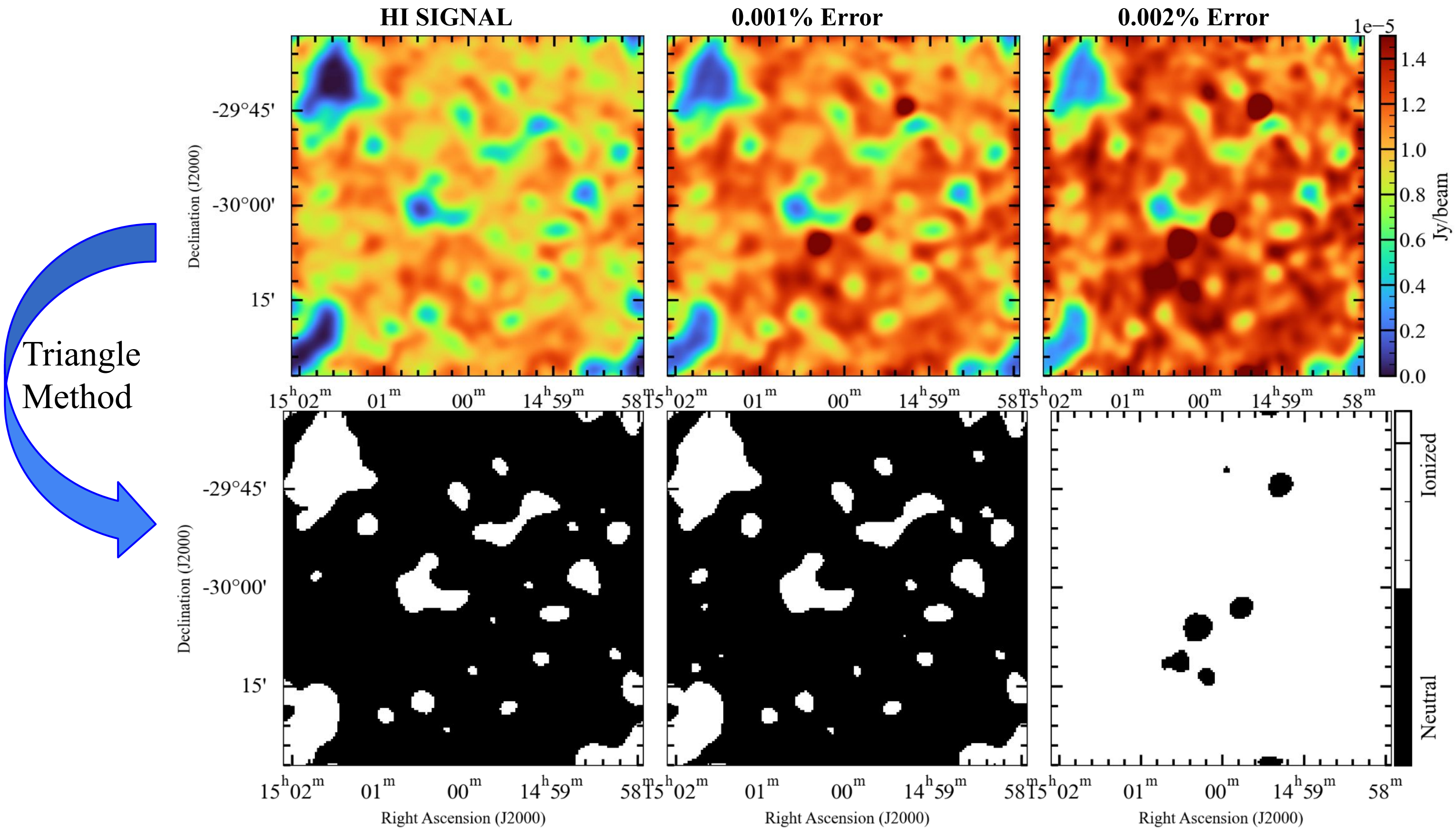
- Extragalactic point sources- Tiered Radio Extragalactic Continuum Simulation (T-RECS) at 150 MHz.

$$S_\nu \propto \nu^{-\alpha}$$



Pal et al., in prep

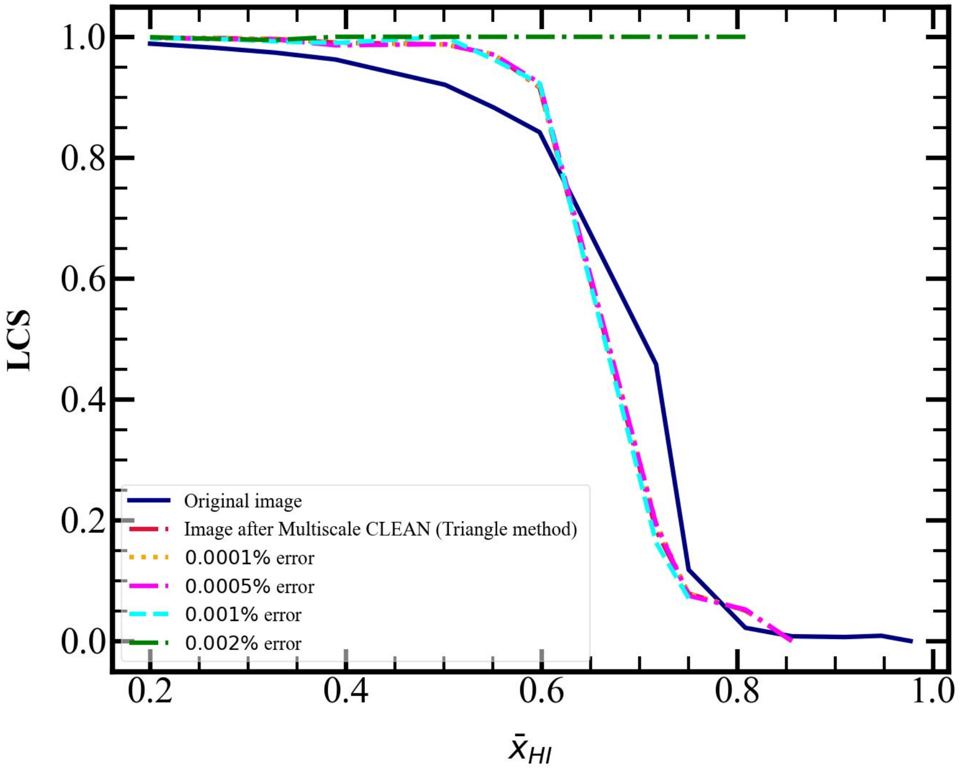
Visual Representation of Residual Foreground



Pal et al., in prep

Effect of Residual Point source Foreground on LCS

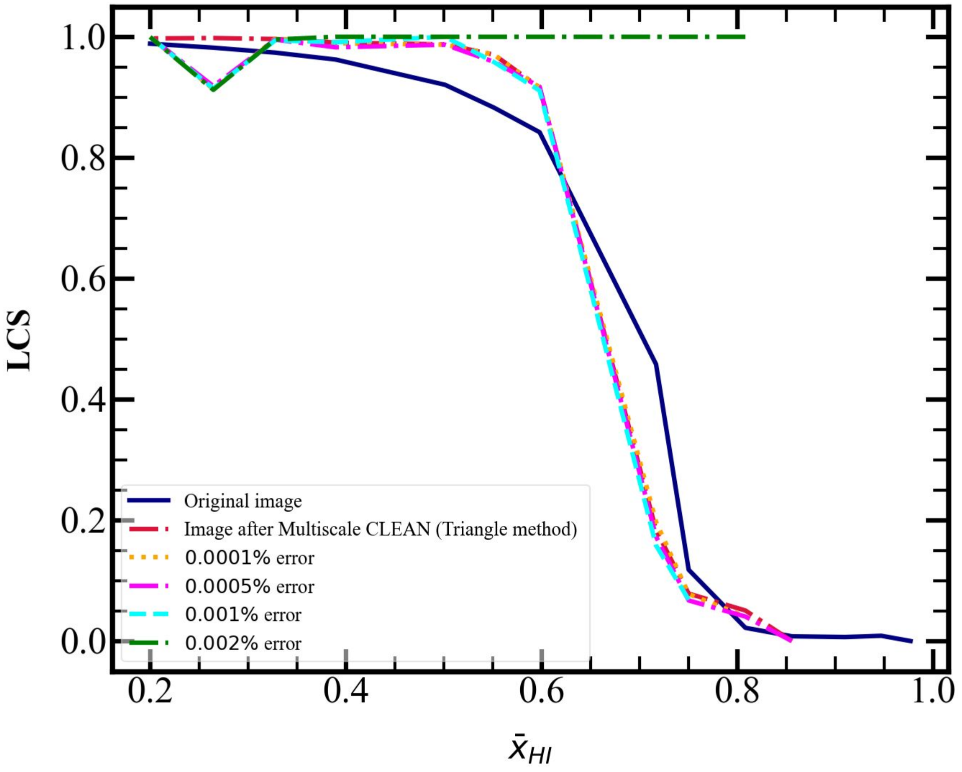
- ❑ Upto the inaccuracy of 0.001 %, residual contamination follow the observed LCS estimation in presence of point source.
- ❑ At the inaccuracy of 0.001% , we as a optimistic case for LCS analysis.
- ❑ Higher calibration errors significantly impact the bimodal distribution of Hi maps



Pal et al., in prep

Effect of Residual Point source & Diffuse Foreground on LCS

- ❑ Upto the inaccuracy of 0.001 %, residual contamination follow the observed LCS estimation in presence of point source and diffuse emission.
- ❑ At the inaccuracy of 0.001% , we as a optimistic case for LCS analysis.
- ❑ Higher calibration errors significantly impact the bimodal distribution of Hi maps



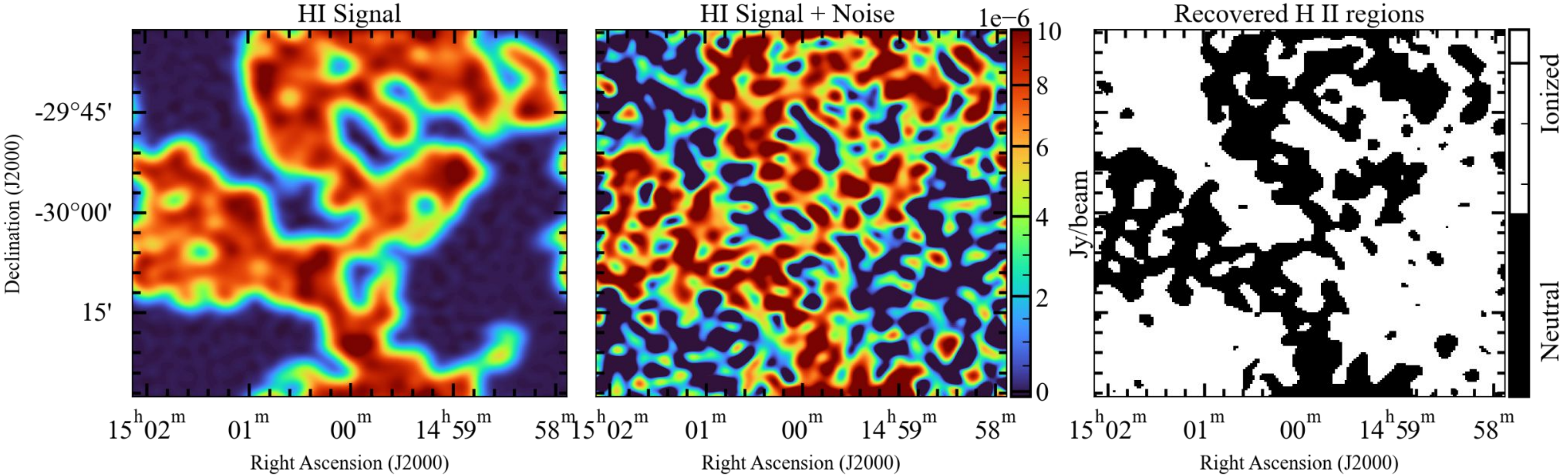
Pal et al., in prep

Adding Instrumental noise

- The total thermal noise contribution in an image plane of a single polarization image from synthesized radio telescopes -

$$\sigma_{im} = \frac{2k_B T_{\rm sys}}{\eta A_{\rm eff}\sqrt{N(N-1)\Delta\nu t_{\rm obs}}}$$

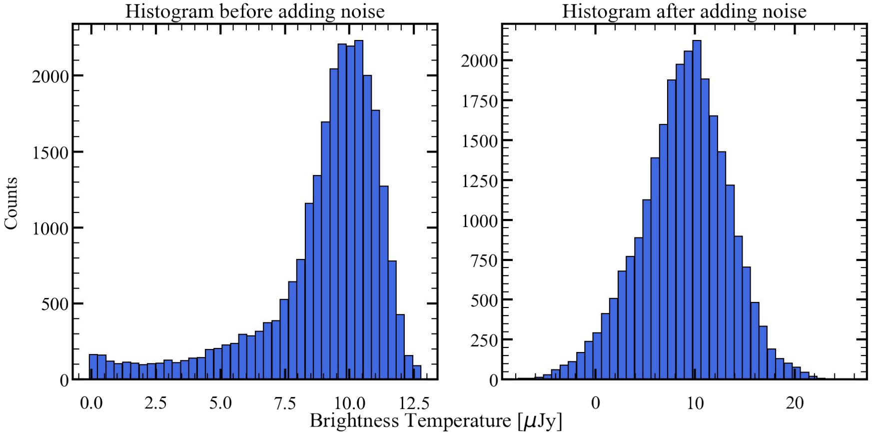
Hamaker, J. P. et. al., 1996

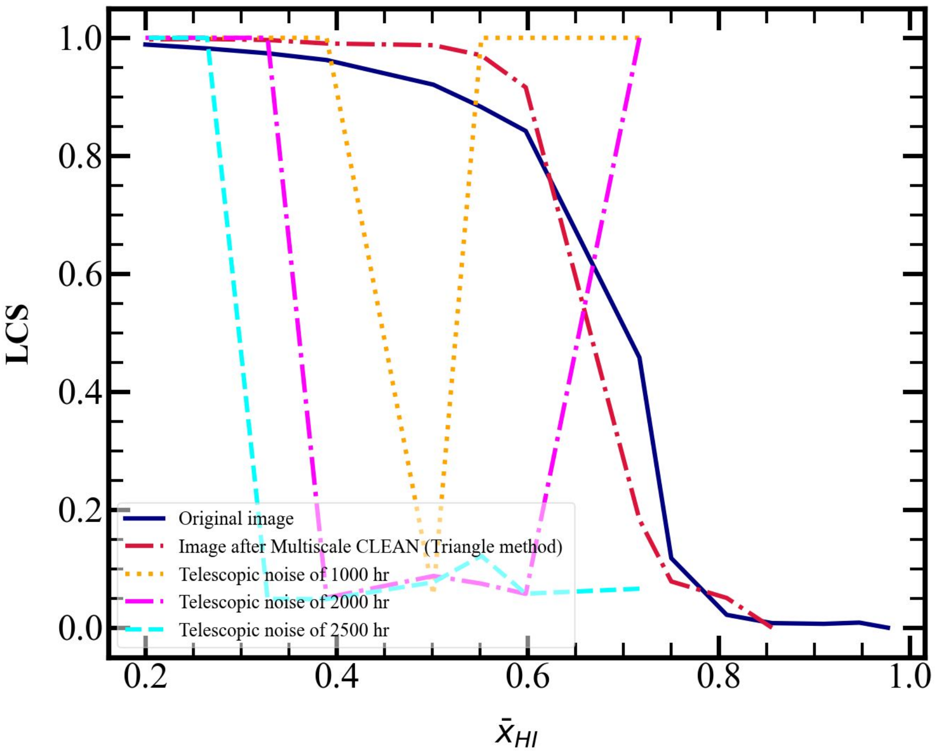


Pal et al., in prep

Effect of telescopic noise after Triangle method

- The triangle method failed to give better thresholding in presence of noisy data.
- This lead to wrong interpretation of LCS estimation.

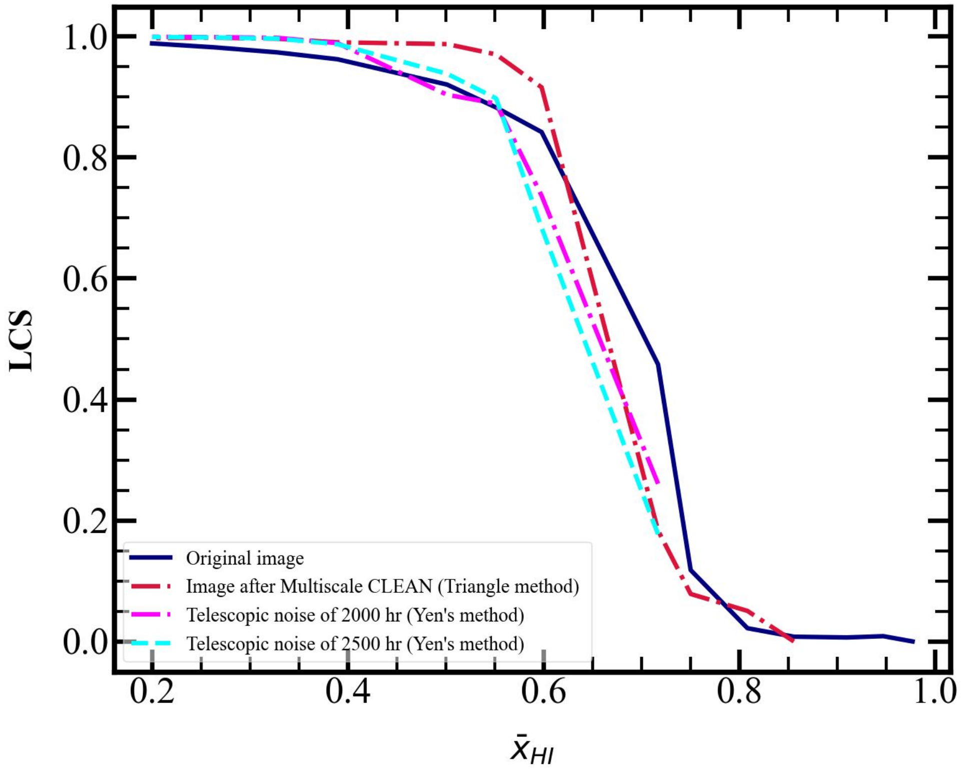




Pal et al., in prep

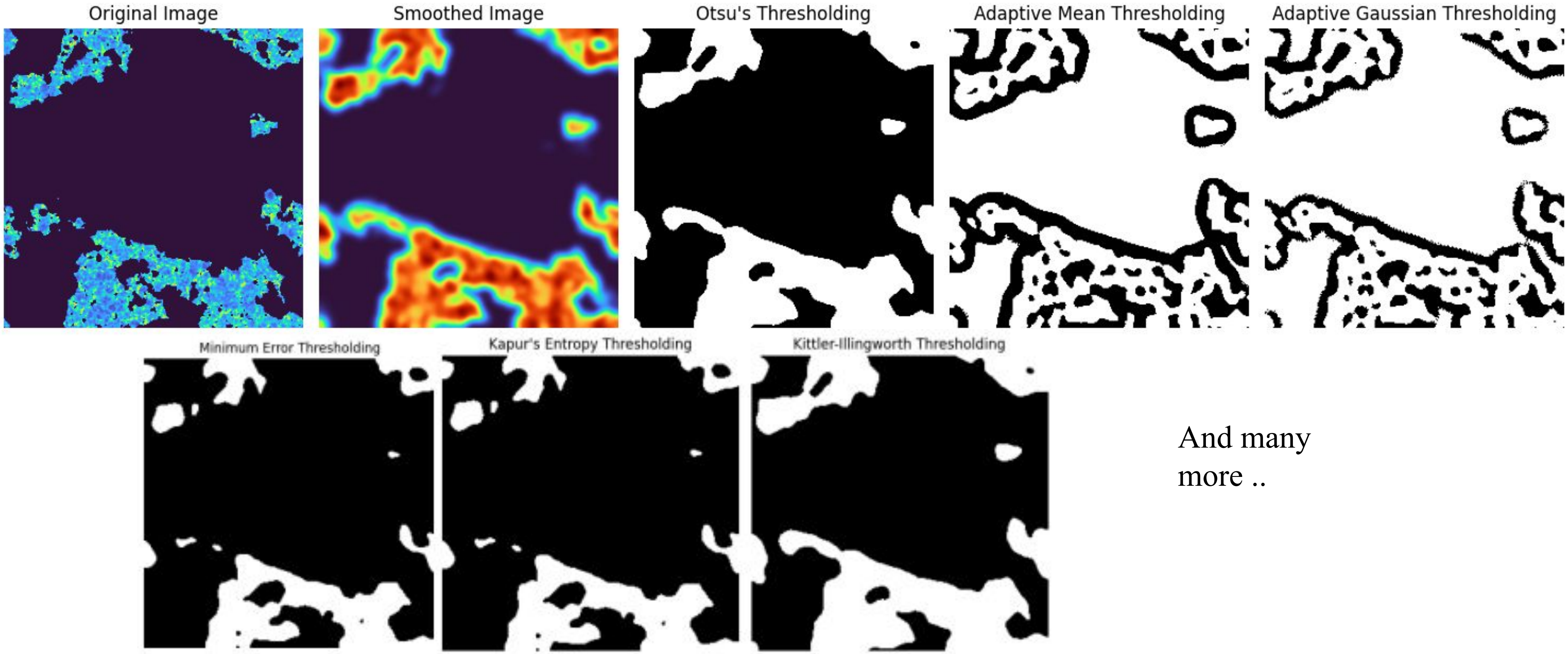
Effect of telescope noise on LCS

- We take 2000 hours of observation as optimistic scenario to estimation LCS represented by magenta dash-dotted line.
- The thermal noise is dominating the 21 cm filed at the early stage of reionization
- The feature of LCS is lost at higher neutral fraction values.



Pal et al., in prep

Different styles of thresholding



And many more ..

Dasgupta + Pal et al., in prep

Summary & Future Work

- This study proposes a novel method using an optimal thresholding algorithm to reduce bias in estimation of LCS.
- We validate the robustness of LCS incorporating the effect of antenna gain calibration error in the presence of various kinds of foreground corruption conditions.
- To accurately estimate the LCS in the presence of telescopic noise, at least 2000 hours of observation are necessary to suppress the small-scale fluctuations of the noise.
- Searching for better thresholding to estimate LCS in presence of both residual foreground and telescopic noise.
- Depending on the RMS variation, find out the optimal thresholding for LCS analysis.

Thank you for your attention!