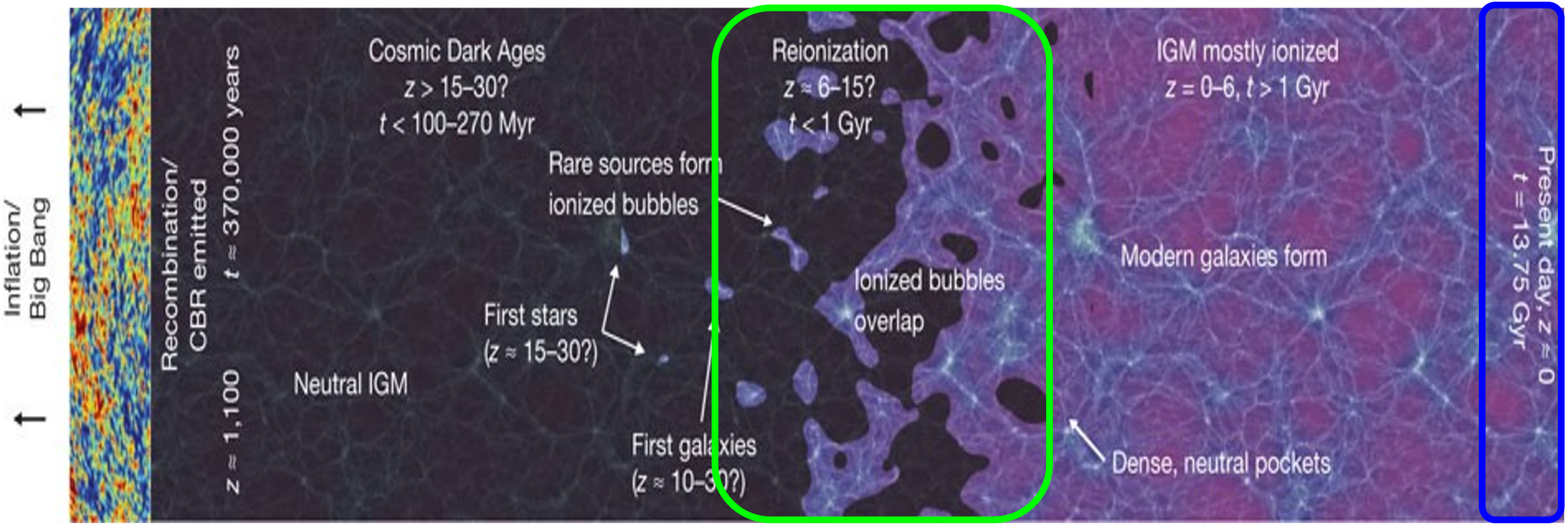
Constraining the ionospheric effect on EoR observation with the SKA1-Low Telescope

Advanced 21-cm Cosmology, 18th - 21th December 2023, NISER, Bhubaneshwar

Samit Kumar Pal
Indian Institute of Technology Indore, India
in collaboration with Abhirup Datta, Aishrila Mazumder

History of Early Universe

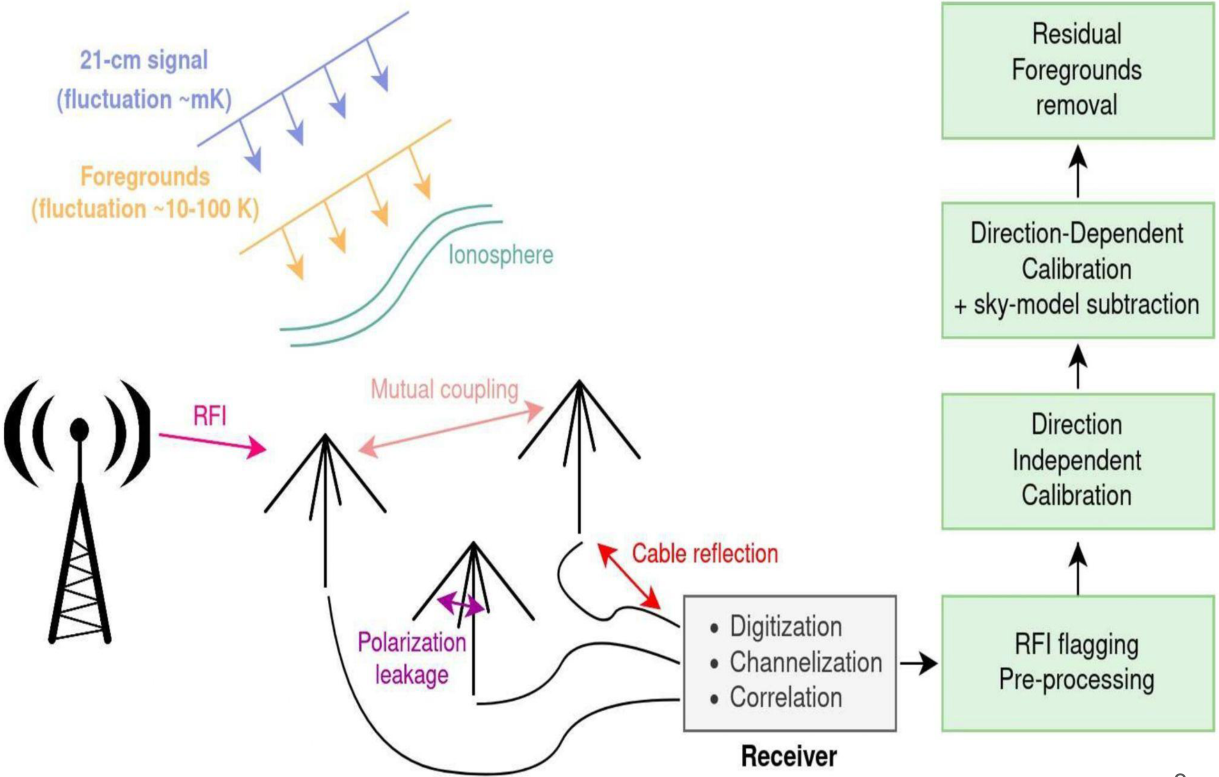


Credit: Robertson et al. (2010)

Observational Challenges

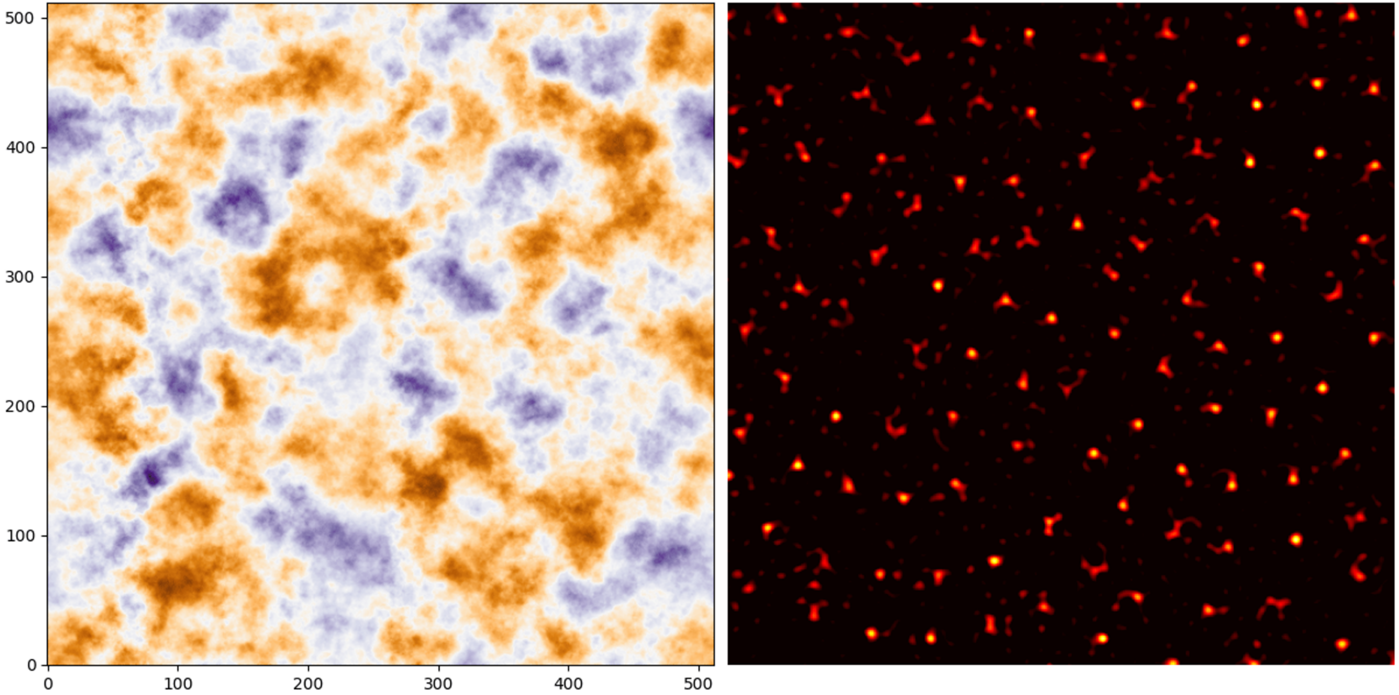
Observation of redshifted 21 cm signal are challenging because of :

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



Courtesy: F. Mertens

The ionosphere



Animation of source offset in presence of Kolmogorov turbulence

Continued ..

- The radio interferometer measures the difference in phase.
- We consider the ionospheric phases are both time and direction-dependent for each antenna.
- Traditional self-calibration techniques typically ignore such variations and cannot correct for these errors.
- Apparent position offset of the cosmic sources :

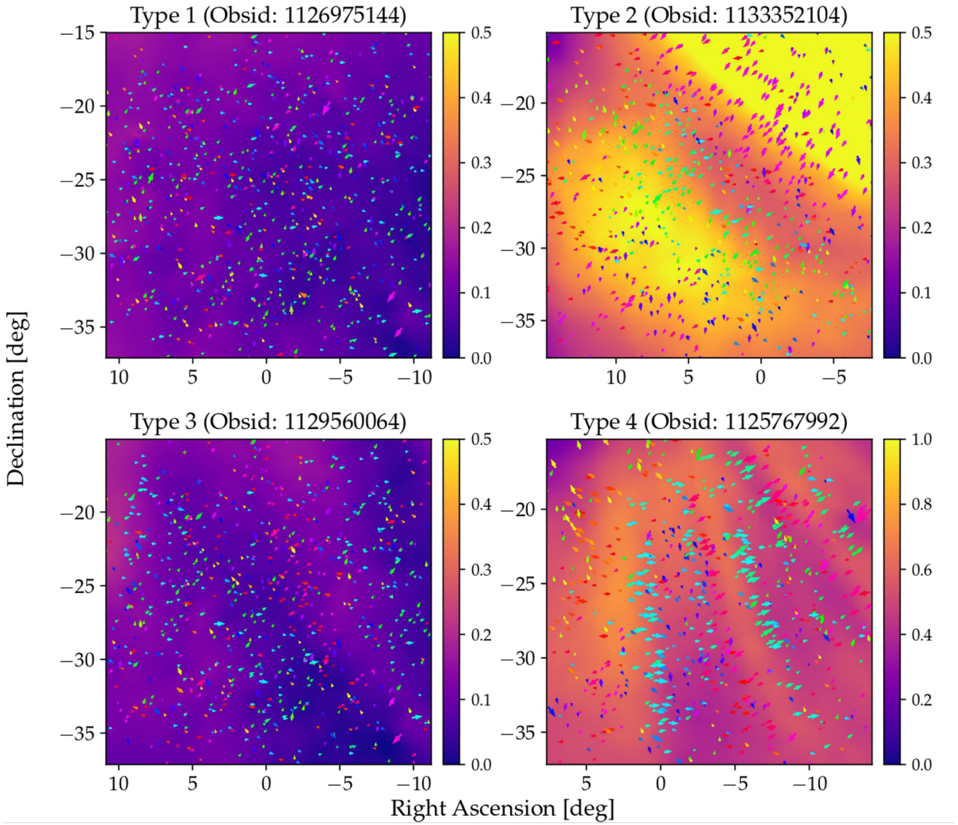
$$\vec{\nabla} TEC = 1.20 \times 10^{-4} \left(\frac{f}{100 MHz} \right)^{2} \left(\frac{\vec{\delta}\theta}{1''} \right) TECU km^{-1}$$

Helmboldt & Hurley-Walker et al., 2020

Ionosphere activity on Murchison Radio--astronomy Observatory location

- 4 main ionosphere activity types categorized at MRO location based on apparent position shift and spatial structure.
  - Jordan et. al. 2017

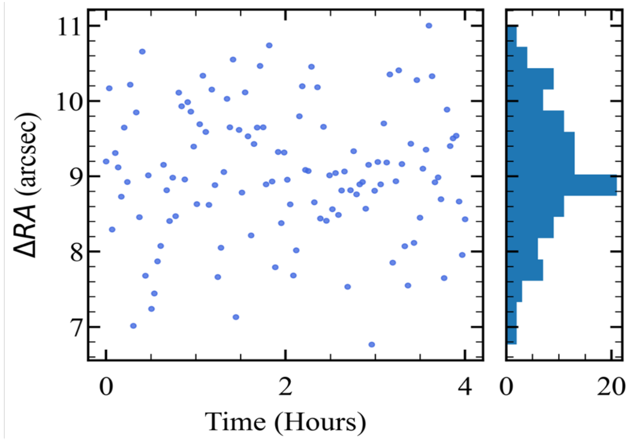
- Galactic and Extragalactic All-Sky MWA Survey shows the the angular scales of the ionospheric structure are typically 100 km.
  - Helmboldt & Hurley-Walker et. al., 2020



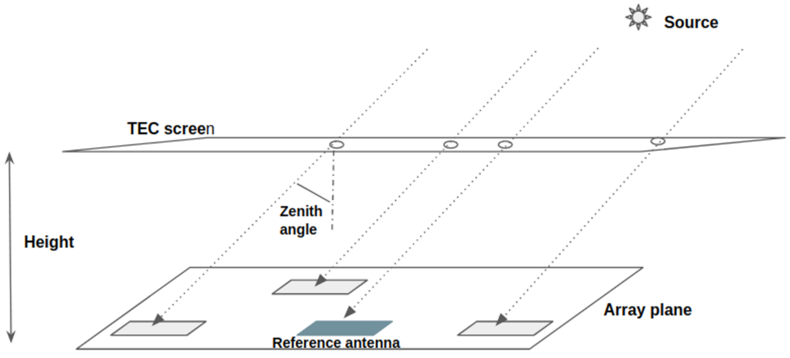
Jordan et. al., 2018

Ionospheric Models

- ❑ Refractive Shift
- ❑ Kolmogorov Turbulence
- ❑ For each timestamp of 2 minutes, the local structure remains the same and consistent.



- ❑ Wayth et al. 2015



Schematics representation of Earth's Ionosphere

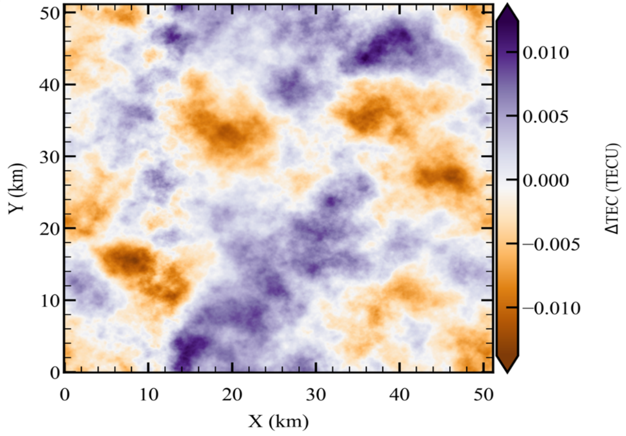
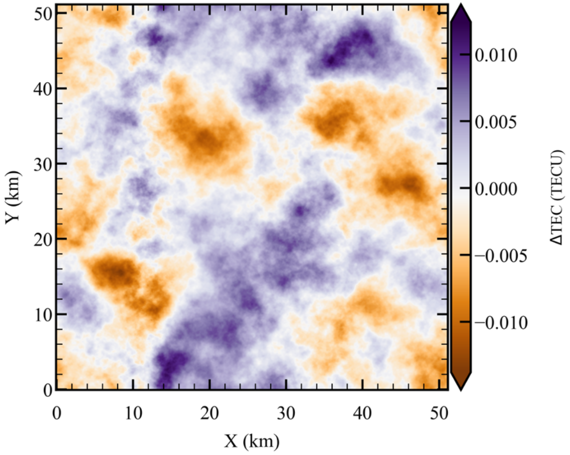
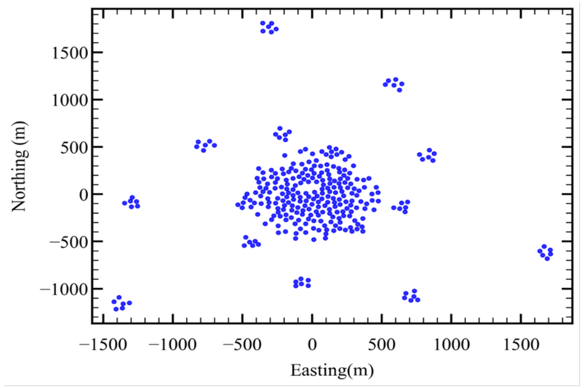
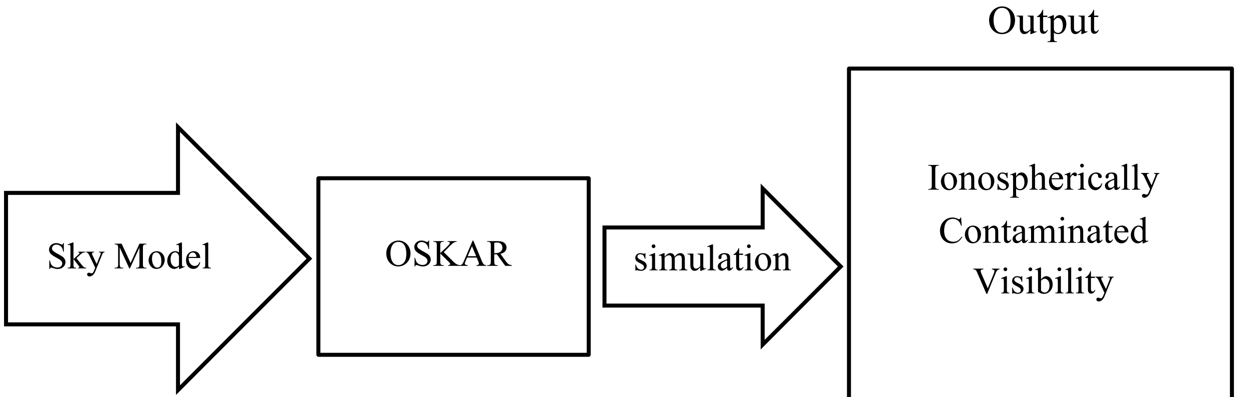


Image Credit: Chage et al., 2021

Simulations



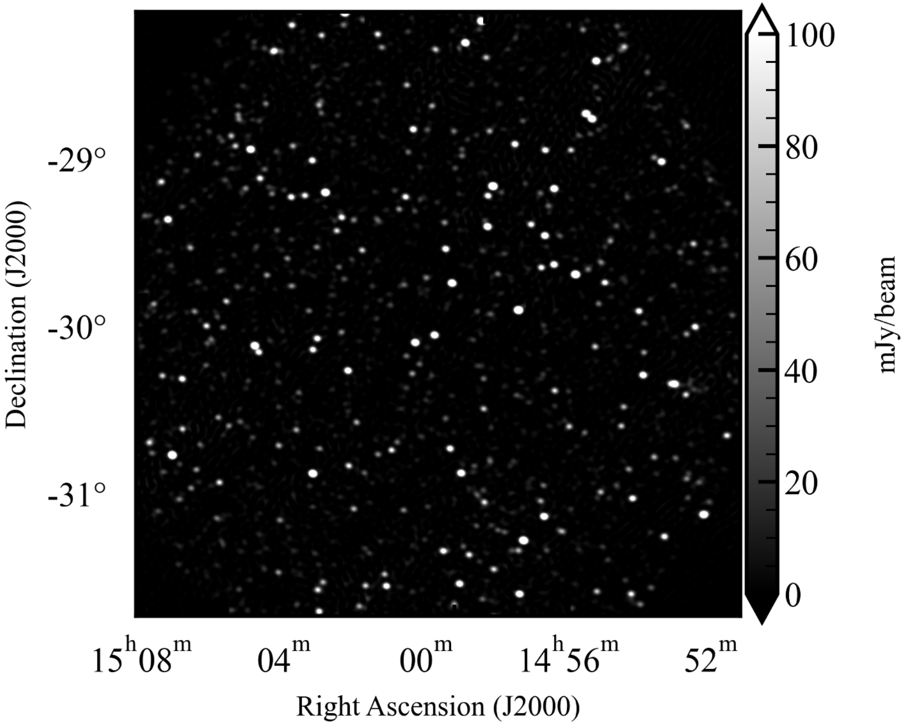




Synthetic Observations

Table 1: Observational parameters used in the simulations

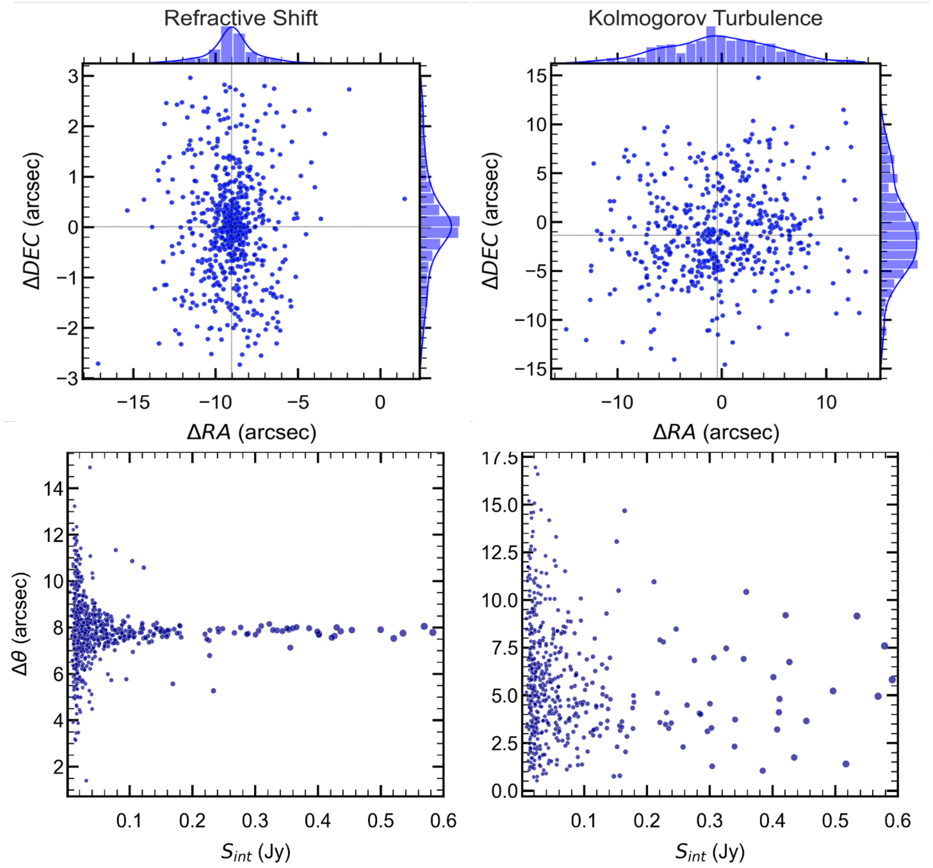
Parameter	Value
Central frequency	142 MHz (z~ 9)
Bandwidth	8 MHz
Spectral Resolution	125 kHz
Field of view (FoV)	4°
Number of array elements(N_a)	296
Maximum baseline	~ 2000 m
Synthesized beam	~ 2.5’
Polarization	Stokes I
No. of snapshots	120
Integration time per snapshot	2 minutes
Phase Center(J2000)	RA, DEC= 5 h, −30 °
Effective collective area ($A_{\rm eff}$)	962 m^2
Core area of an array ($A_{\rm core}$)	12.57 km^2
Total collecting area of the array ($A_{\rm col}$)	$N_a A_{\rm eff}$



Global Sky Model

Offset distribution

- How offset distributed around along the RA & DEC after passing through ionospheric medium after time-averaged position position shifts of the selected sources.
- How offset distribution correlated with the source's integrated flux density.
- The source position offset tends to increase for sources with lower SNR.
- The temporal variation of source offsets produces vastly different sky models.



Offset distribution

- ❑ How offset distributed around along the RA & DEC after passing through ionospheric medium after time-averaged position position shifts of the selected sources.
- ❑ How offset distribution correlated with the source's integrated flux density.
- ❑ The source position offset tends to increase for sources with lower SNR.
- ❑ The temporal variation of source offsets produces vastly different sky models.

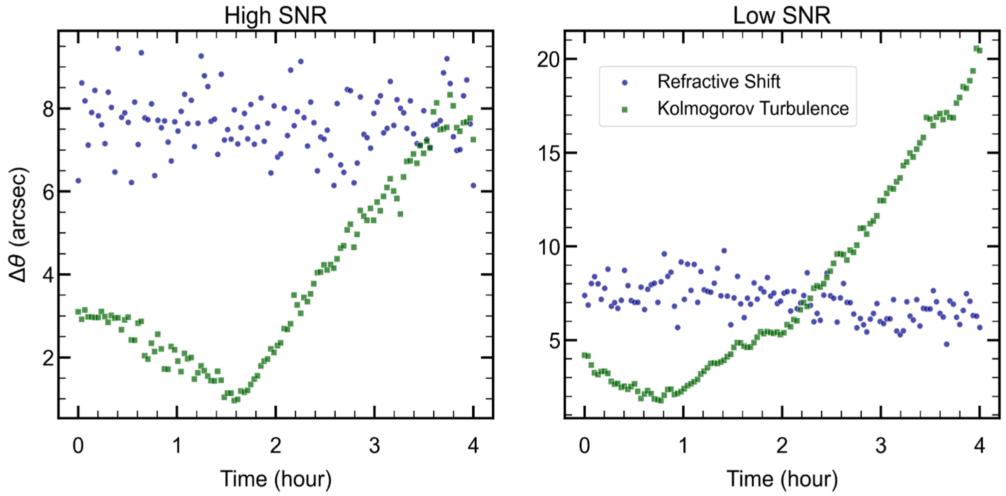
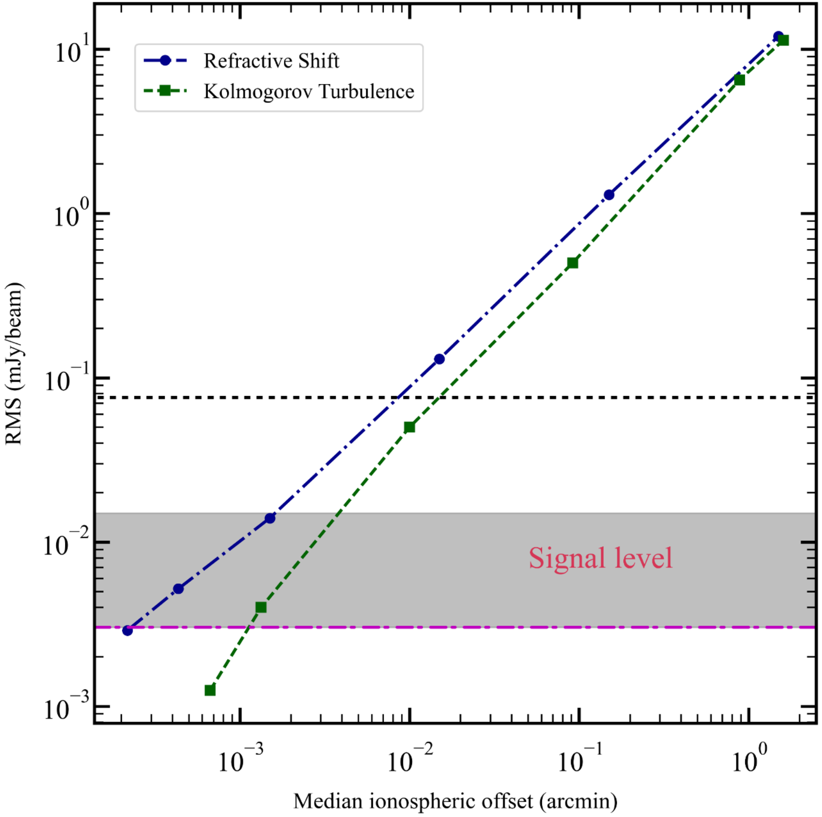


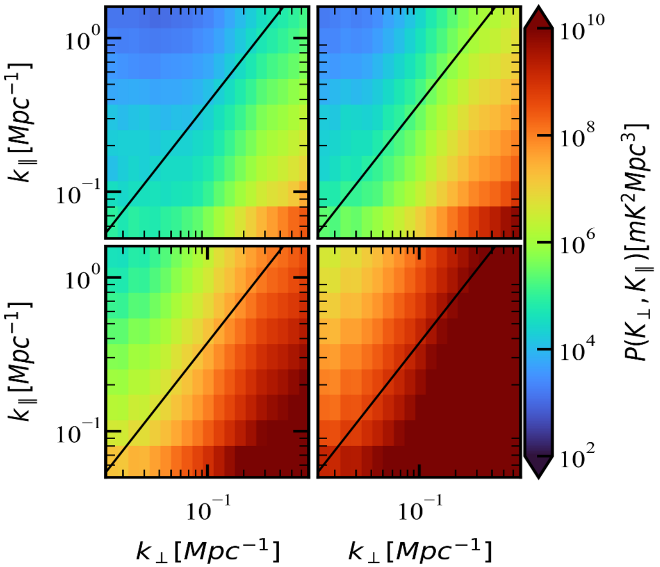
Image Plane Effect

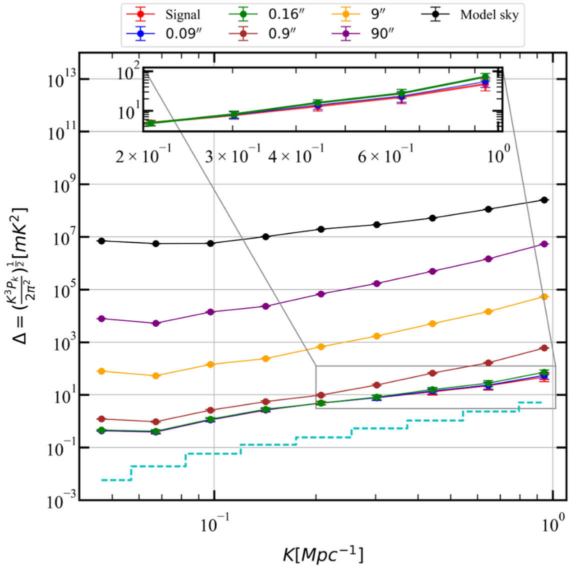
- RMS in residual image taken as metric to analysis image plane performance.
- For refractive shift , the median offset of 0.013 arcsec is below the signal level.
  - DR ~ 10^5 .
- For Kolmogorov turbulence, the median offset of 0.04 arcsec is below the signal level.
  - DR ~ 10^5 .
- The black dashed line is pessimistic scenario of 4 hours of observation.
- The magenta dashed line is optimistic scenario of 2500 hours of observation.



Power Spectrum Estimation : Refractive Shift

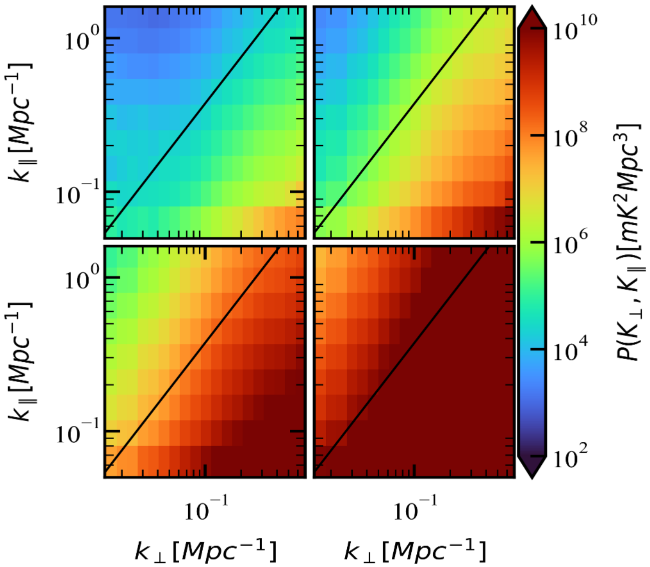
- Foreground leakage to the EoR window with increasing source displacement.
- Power spectrum analysis - Spherical averaged PS follows signal power if sources are displaced by ionospheric median offset of 0.16 arcsec , greater error lead to higher amplitude of residual power wrt signal power.
- At median offset of 0.16 arcsec , the residual PS deviates from the signal PS for $k \geq 0.6$ Mpc^{-1} .

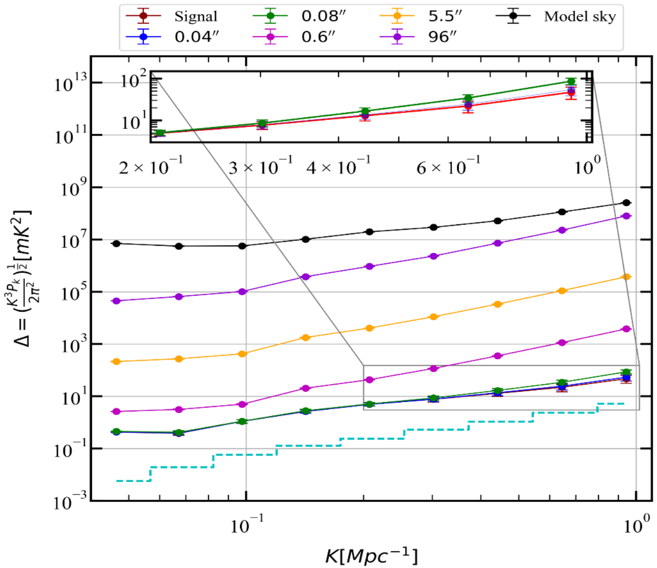




Power Spectrum Estimation : Kolmogorov Turbulence

- Foreground leakage to the EoR window with increasing source displacement.
- Power spectrum analysis - Spherical averaged PS follows signal power if sources are displaced by ionospheric median offset of ~0.1 arcsec , greater error lead to higher amplitude of residual power wrt signal power.
- At median offset of ~ 0.1 arcsec , the residual PS deviates from the signal PS for $k < 0.6\ \mathrm{Mpc}^{-1}$.
- The turbulence length scale destroy the small scale structure of the target signal.





Summary

- ❑ We assess the effects of different ionospheric conditions ranging from quiet to extreme conditions.
- ❑ We observed that depending on the specific type of disturbance induced, ionospheric corruption significantly affects the recovery of the target signal in the smaller scales .
- ❑ For the case of a time-varying phase offset, if sources are shifted by up to $0.2''$ on average, the HI power spectrum is recoverable.
- ❑ The most realistic turbulent condition generated using Kolmogorov's statistics shows that beyond $\sim 0.1''$, residual power is too high for 21 cm signal recovery.
- ❑ These results indicate that understanding the ionospheric conditions during observation runs for EoR science is essential since such unaccounted effects, even to first order, can adversely affect signal recovery.

THANK YOU