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# Extracting the HI 21 cm Signal from the Ground Based Observation using ANN


**Anshuman Tripathi**

Department of Astronomy, Astrophysics and Space Engineering

Indian Institute of Technology, Indore (IITI)


Collaborators: Abhirup Datta (IITI), Aishrila Mazumder (Univ. of Manchester), Madhurima Choudhury (Brown University, USA), Suman Majumdar (IITI)

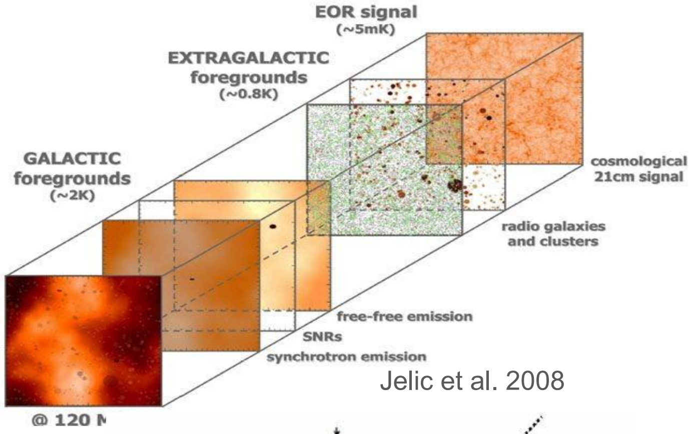
Credits : SKAO

# 21CM Cosmology: Observational Challenges

- **Galactic and Extragalactic Foreground**

Mostly due to synchrotron radiation with expected smooth spectrum.

$$\ln T_{FG} = \sum_{i=0}^{n} a_i[\ln(\nu/\nu_0)]^i$$




Jelic et al. 2008

- **Earth's Ionosphere**
- The ionosphere refracts all trans-ionospheric signals (radio wave), including Galactic and Extragalactic foregrounds, attenuates any trans-ionospheric signal, and emits thermal radiation.
- In E. Shen et al. 2022, it is demonstrated that, under turbulent ionospheric conditions, an error exceeding 5 percent in our understanding of the ionospheric parameters could result in false or null detection.

- **Radio Frequency Interference (RFI)**

- **Other Systematics effects**

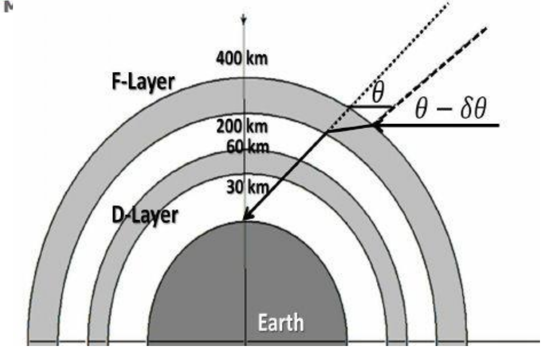
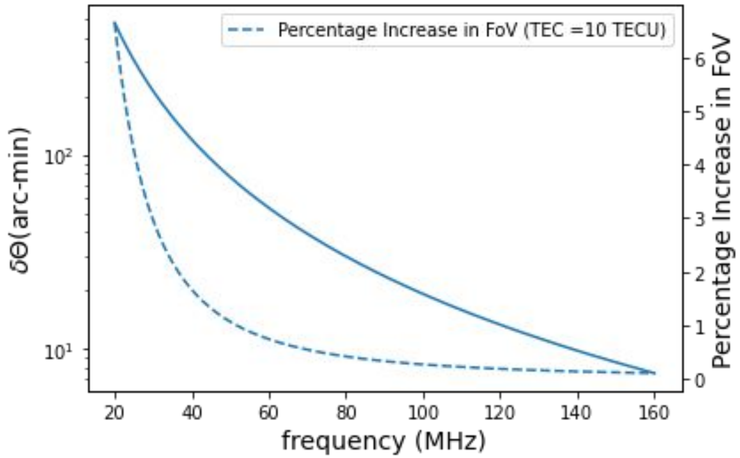


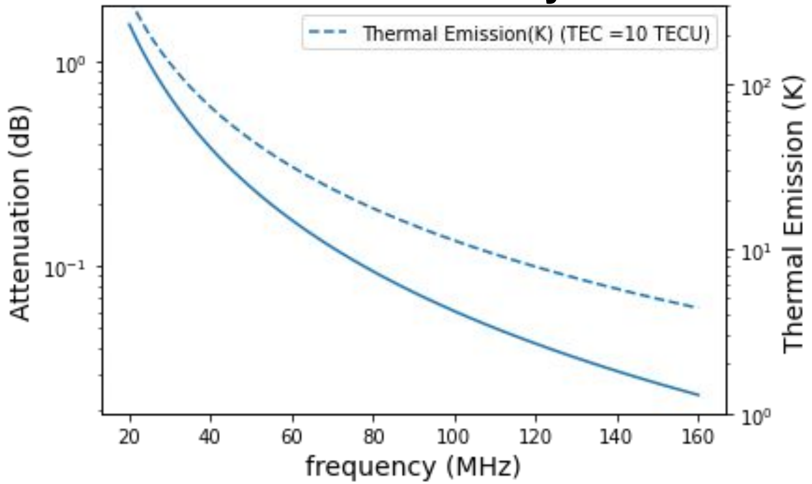

Fig : Schematic representation of the ionosphere showing the F- and D- layers (not scaled), which show the refraction. (Datta et al. 2016)

# 21CM GLOBAL SIGNAL: Effect of Ionosphere

## Ionospheric Refraction due to F-layer




## Ionospheric Absorption and Thermal Emission due to D-layer




Increase in the effective FoV

$$T_{\mathrm{sky}}^{\mathrm{iono}}(\nu, t; \Theta_0, \Phi_0) = \int_0^{2\pi} d\Phi \times \int_0^{\pi/2} d\Theta B'(\nu, \Theta - \Theta_0 - \delta\theta(t), \Phi) \times T_{\mathrm{sky}}(\nu, \Theta - \Theta_0, \Phi - \Phi_0) \sin\Theta$$

Signal ($T_{21}$) + Foreground ($T_{FG}$)

$$T_{Ant}^{iono}(\nu, TEC(t), \Theta_0, \Phi_0) = T_{sky}^{iono}(\nu, t; \Theta_0, \Phi_0) \times (1 - \tau(\nu, TEC(t)) + \tau(\nu, TEC(t)) * < T_e >$$

*Tripathi A. et al. (2023,Submitted to MNRAS, Under review)*

# A MODEL PARAMETERIZED 21CM GLOBAL SIGNAL

**Parameters evolve according to a tanh model**

J(z) : Lyman-alpha background (which determines the strength of WF coupling)

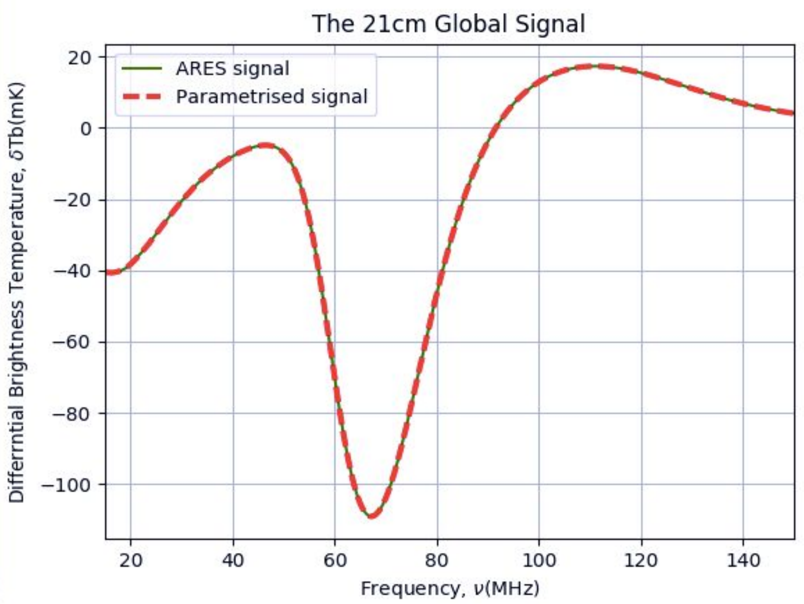
Xi(z) : Ionized fraction of hydrogen.

T(z) : Temperature of the ( Intergalactic Medium) IGM

$$J(z) = \frac{J_{ref}}{2}\left(1 + tanh\frac{(J_{z0} - z)}{J_{dz}}\right)$$

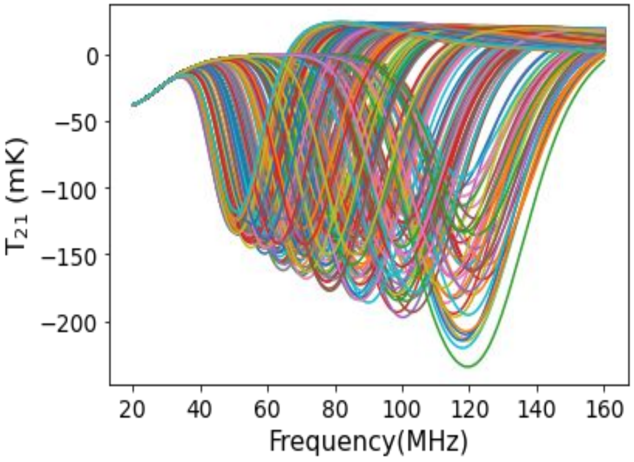
$$\bar{X}(z) = \frac{X_{ref}}{2}\left(1 + tanh\frac{(X_{z0} - z)}{X_{dz}}\right)$$

$$T(z) = \frac{T_{ref}}{2}\left(1 + tanh\frac{(T_{z0} - z)}{T_{dz}}\right)$$

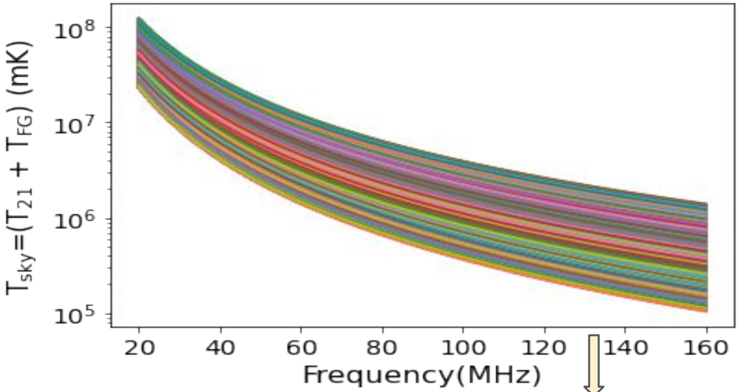



We use the Accelerated Reionization Era Simulations (ARES) code was designed to rapidly generate models for the global 21- cm signal.
(Mirocha et al, 2012, 2015).

# Training Data Sets




\+ **Foreground**




**Training Parameters**

**21-cm Signal :-** $J_{ref}$, $J_{z0}$, $X_{z0}$, $T_{z0}$ $J_{dz}$, $X_{dz}$, $T_{dz}$

**Foreground :-** $a_0$=7.62051, $a_1$= -2.42096, $a_2$= -0.08062, $a_3$ = 0.02898 (Harker (2015))

The foreground parameters varies by (15%, 10% 1%, 1%) respectively.

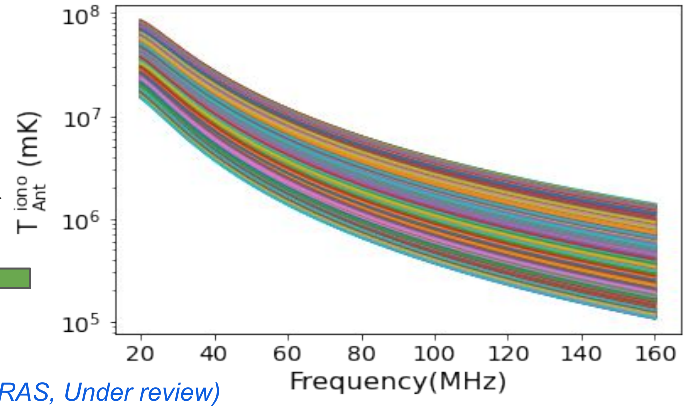
\+ **Foreground + Ionospheric effects**

**Global Signal parameters**

$J_{ref}$= 11.6 9, $J_{z0}$ =18.5, $X_{z0}$=8.68 $T_{z0}$=9.77, $J_{dz}$=3.31, $X_{dz}$= 2.83 ,$T_{dz}$= 2.82

Each parameters varies by ±50 %.

(Harker et al. 2016b)




**Training Parameters**

**21-cm Global Signal :-** $J_{ref}$, $J_{z0}$, $X_{z0}$, $T_{z0}$ $J_{dz}$, $X_{dz}$, $T_{dz}$

**Foreground :-** $a_0$, $a_1$, $a_2$, $a_3$

**Ionosphere :-** TEC=10 TECU, Te= 800 K

Each Ionospheric parameters varies by ±1%.

*Tripathi A. et al. (2023,Submitted to MNRAS, Under review)*

# Test Data Sets & Model Prediction

For the test data sets we added thermal noise (n) which corresponds to the observation time ($N_t$):-

$$T_{test} = T_{21} + T_{FG} + \text{Ionospheric effects} + \text{Thermal noise}$$

Thermal Noise :

$$n(\nu) = \frac{T_{FG}(\nu)}{\sqrt{\Delta\nu \cdot 10^6 \cdot 3600 \cdot N_t}}$$

Observation Time

| Parameters | R2 Score | RMSE |
|---|---|---|
| $J_{ref}$ | 0.9778 | 0.0440 |
| $J_{z0}$ | 0.9780 | 0.0438 |
| $X_{z0}$ | 0.9760 | 0.0453 |
| $T_{z0}$ | 0.9746 | 0.0470 |
| $J_{dz}$ | 0.9735 | 0.0482 |
| $X_{dz}$ | 0.9848 | 0.0467 |
| $T_{dz}$ | 0.9781 | 0.0434 |
| $a_0$ | 0.9936 | 0.0232 |
| $a_1$ | 0.9738 | 0.0477 |
| $a_2$ | 0.9773 | 0.0443 |
| $a_3$ | 0.9774 | 0.0445 |

**Signal + Foreground**


| Parameters | R2 Score | RMSE |
|---|---|---|
| $J_{ref}$ | 0.9614 | 0.0628 |
| $J_{z0}$ | 0.9738 | 0.0605 |
| $X_{z0}$ | 0.9713 | 0.0616 |
| $T_{z0}$ | 0.9668 | 0.0577 |
| $J_{dz}$ | 0.9634 | 0.0608 |
| $X_{dz}$ | 0.9578 | 0.0658 |
| $T_{dz}$ | 0.9595 | 0.0636 |
| $a_0$ | 0.9810 | 0.0439 |
| $a_1$ | 0.9655 | 0.0590 |
| $a_2$ | 0.9586 | 0.0642 |
| $a_3$ | 0.9610 | 0.0625 |
| $TEC$ | 0.9658 | 0.0578 |
| $T_e$ | 0.9728 | 0.0588 |

**Signal + Foreground +ionospheric effects**

*Tripathi A. et al. (2023,Submitted to MNRAS, Under review)*

# Signals generated with a Physical Model

For producing the 21cm global signal they followed the seminumerical code which can easily produced global signal for the redshift range $5 < z < 30$. (Chatterjee et al. 2019)

## Input parameters

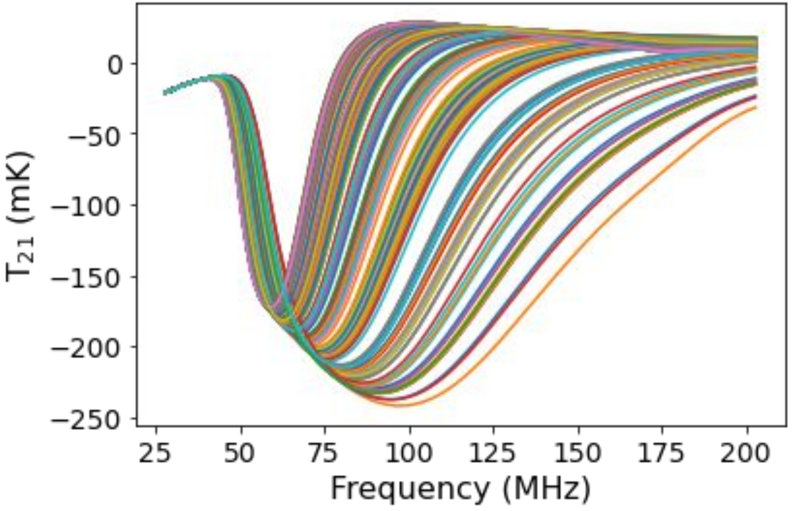
$f_\star$ : Star formation efficiency.

$f_{esc}$ : Escape fraction of ionizing photon.

$f_R$ : Efficiency of the radio background.

$f_{xh}*f_x$ : X-ray heating efficiency.

$N_\alpha$ : Number of Lyα photons.




M. Choudhury et. al. 2021

# Model Prediction

**Signal + Foreground**

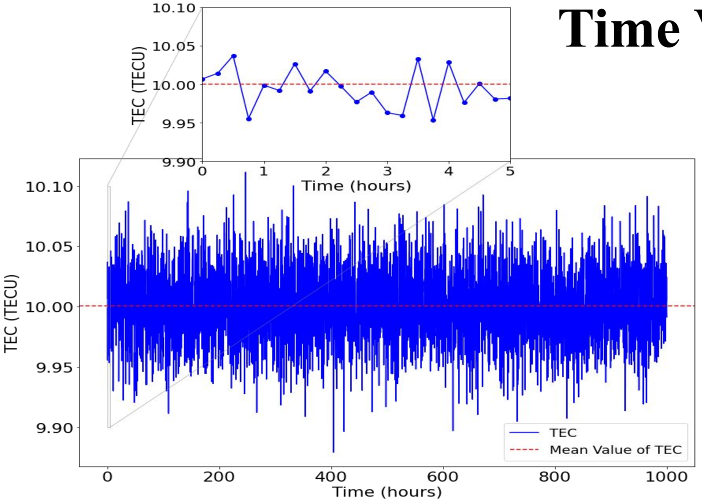
| Parameters | R2 Score | RMSE |
|---|---|---|
| $f_{xh} * f_x$ | 0.9813 | 0.0428 |
| $f_{star}$ | 0.9731 | 0.0476 |
| $f_{esc}$ | 0.9772 | 0.0453 |
| $N_\alpha$ | 0.9607 | 0.0562 |
| $a_0$ | 0.9752 | 0.0473 |
| $a_1$ | 0.9964 | 0.0107 |
| $a_2$ | 0.9739 | 0.0433 |
| $a_3$ | 0.9736 | 0.0481 |

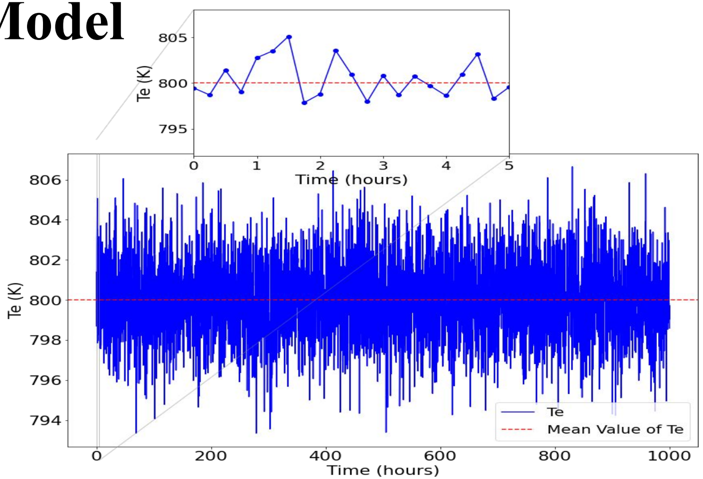
**Signal + Foreground + ionospheric effects**

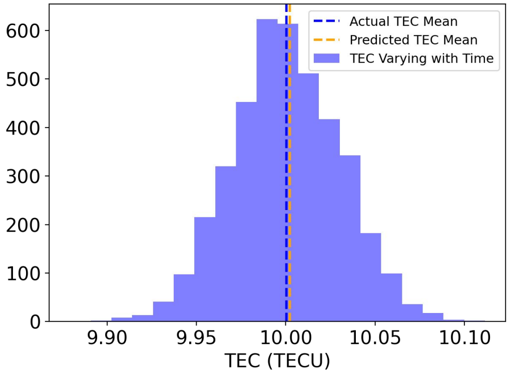
| Parameters | R2 Score | RMSE |
|---|---|---|
| $f_{xh} * f_x$ | 0.9804 | 0.0411 |
| $f_{star}$ | 0.9704 | 0.0488 |
| $f_{esc}$ | 0.9751 | 0.0475 |
| $N_\alpha$ | 0.9620 | 0.0508 |
| $a_0$ | 0.9981 | 0.0442 |
| $a_1$ | 0.9990 | 0.0094 |
| $a_2$ | 0.9793 | 0.0420 |
| $a_3$ | 0.9733 | 0.0445 |
| $TEC$ | 0.9733 | 0.0480 |
| $T_e$ | 0.9742 | 0.0473 |

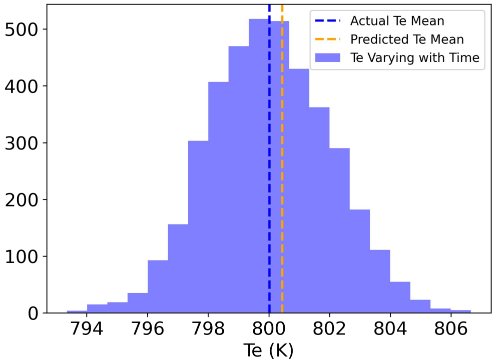
*Tripathi A. et al. (2023,Submitted to MNRAS, Under review)*

# Time Varying Ionosphere Model



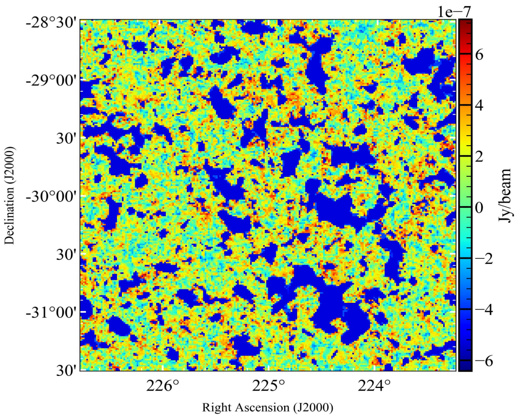

Conclusion: Simple ANN is robust in 21cm signal parameter estimates in presence of slowly varying ionosphere



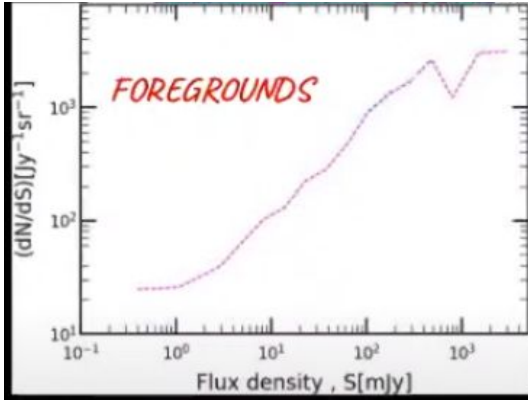
*Tripathi A. et al. (2023,Submitted to MNRAS, Under review)*

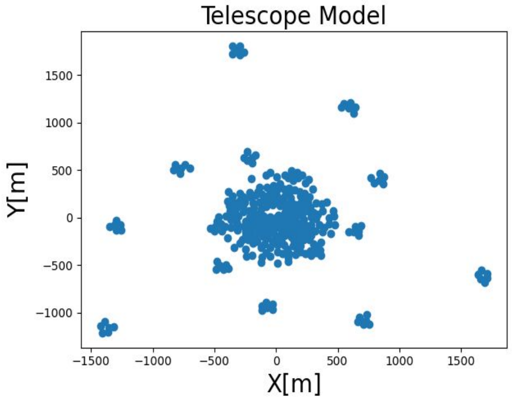
# 21CM Power Spectrum - Signal Parameter Estimation

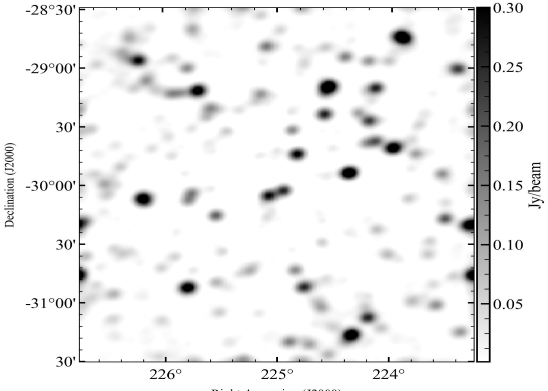
- In A. Mazumder et al. 2022, they have developed the end to end pipeline to simulate interferometric observation.



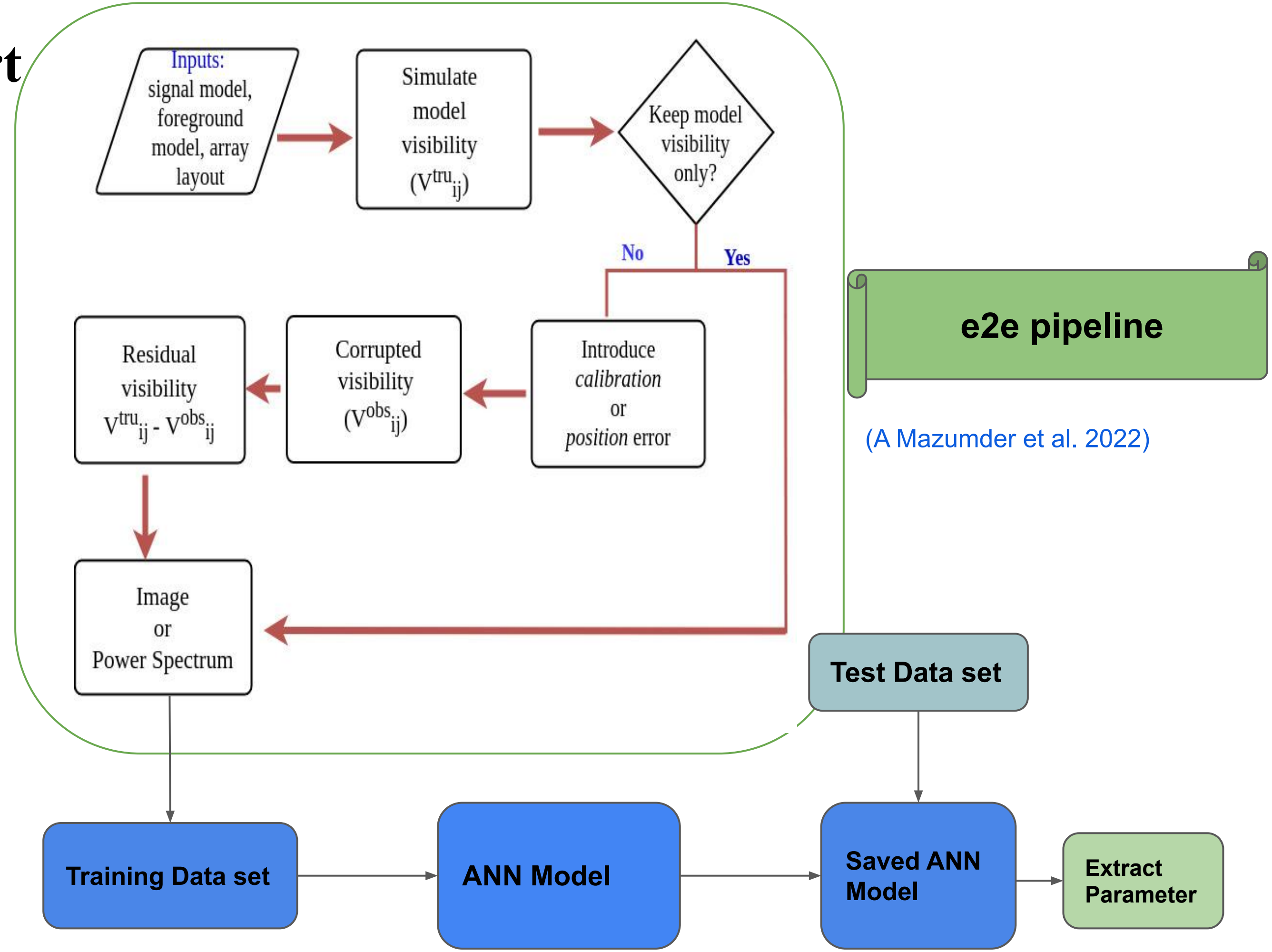

21cmFAST



# Flowchart




(A Mazumder et al. 2022)

*Tripathi A et al. (2023, in prep)*

# Synthetic Observation

**Observational input parameters**

| Parameter | Value |
|---|---|
| Central Frequency | 142 MHz (z~9) |
| Bandwidth | 8 MHz |
| Number of frequency channels | 64 |
| Field of view | 4° |
| Number of array elements: | |
| SKA1-Low Core | 296 |
| Maximum baseline (m): | 2000 |
| Synthesised beam (arcmin): | 2.5 |

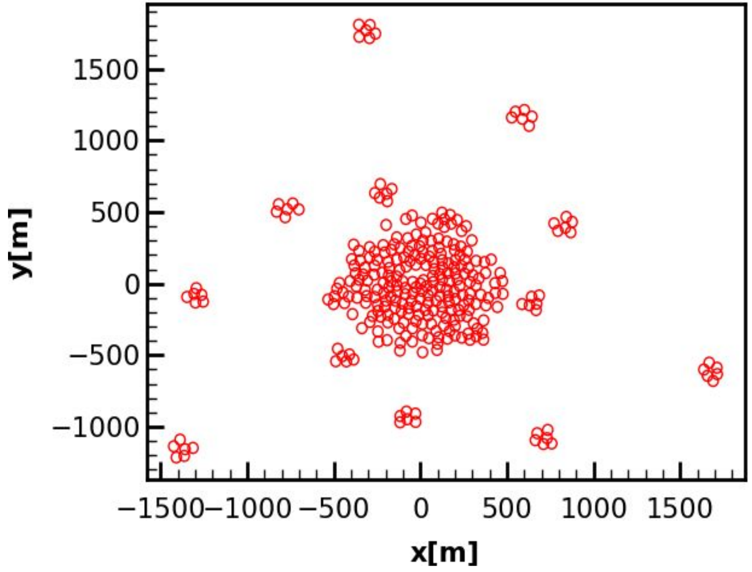
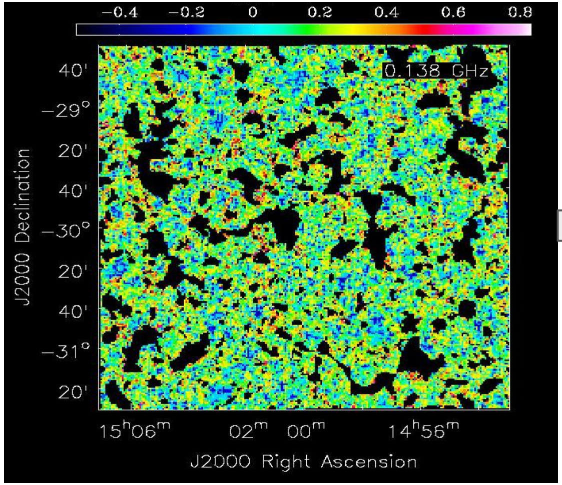



**Fig :** Telescope layouts used in the synthetic observation.

(A Mazumder et al. 2022 )

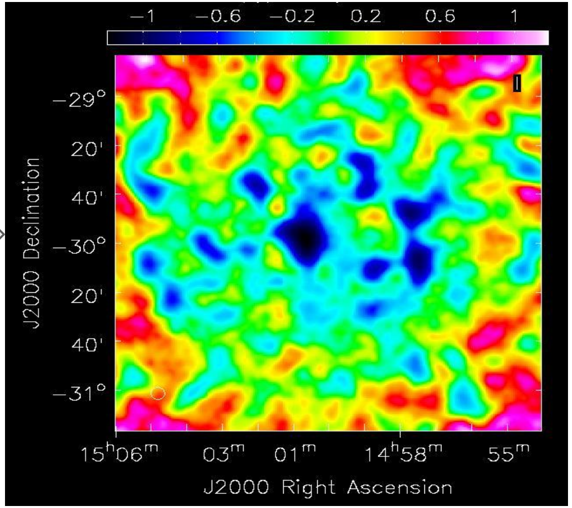
# Simulated Observation

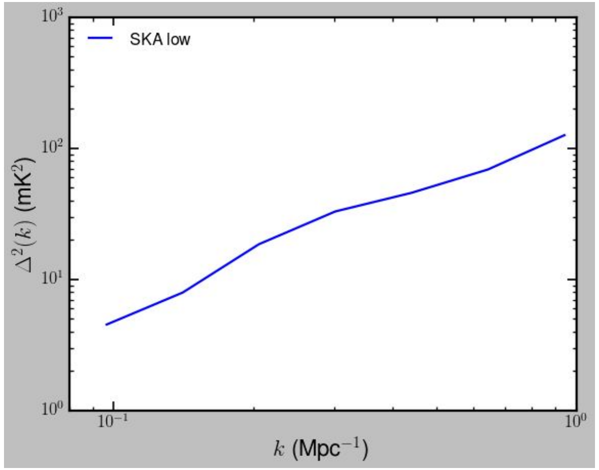
(Jy/beam) x $10^{-6}$




**e2e Pipeline (Telescope Model)**

(Jy/beam) x $10^{-5}$

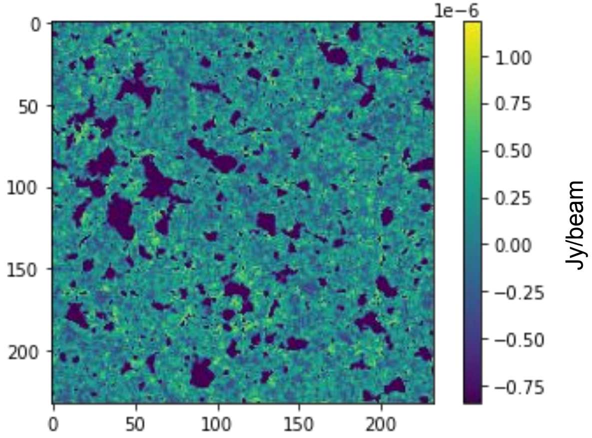


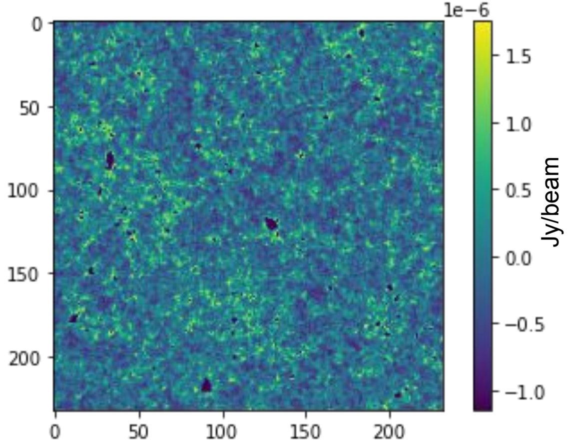

Observed Power Spectrum

*Tripathi A. et al. (2023,in Pre)*

# HI 21-cm Lightcone's slice at 142 MHz (z≃9) with different astrophysical conditions




**$R_{mfp}$**= 33.4, **ζ**= 45.25 , **$T_{vir}$**= 4.8975

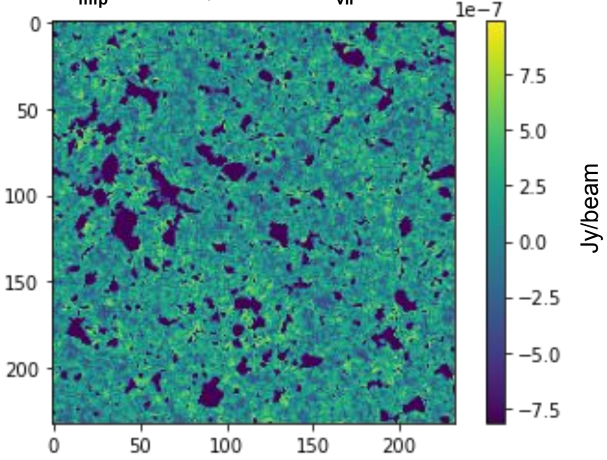



**$R_{mfp}$**= 42.6 , **ζ**= 47.75 , **$T_{vir}$**= 5.6325

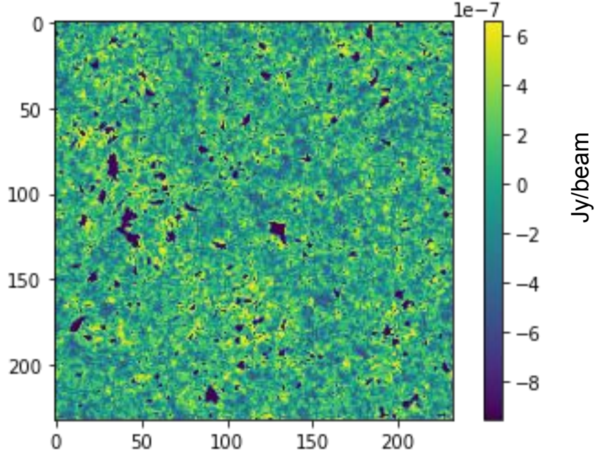
**$R_{mfp}$: Mean Free Path**

**ζ: Ionizing Efficiency**

**$T_{vir}$ : Minimum virial temperature**

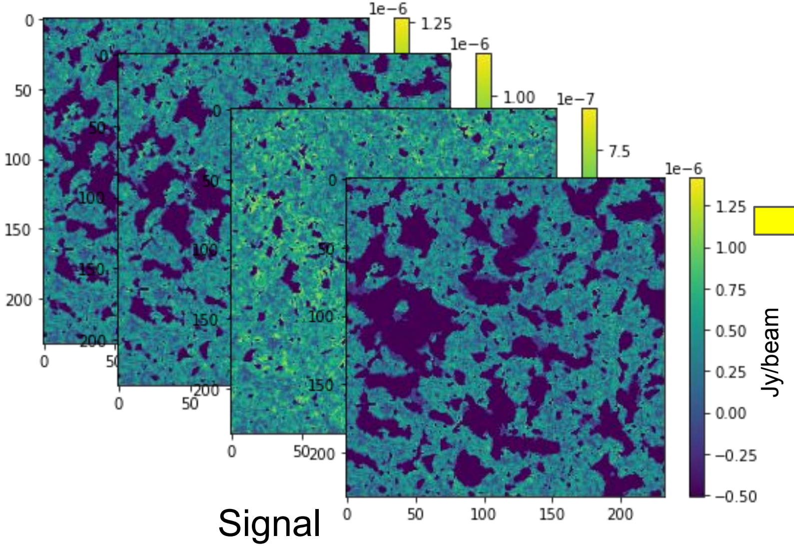



**$R_{mfp}$**= 34.6, **ζ**= 28.25, **$T_{vir}$** = 4.6875




**$R_{mfp}$**= 43.0, **ζ**= 10.25, **$T_{vir}$**= 4.5225

# Training Data sets




Signal

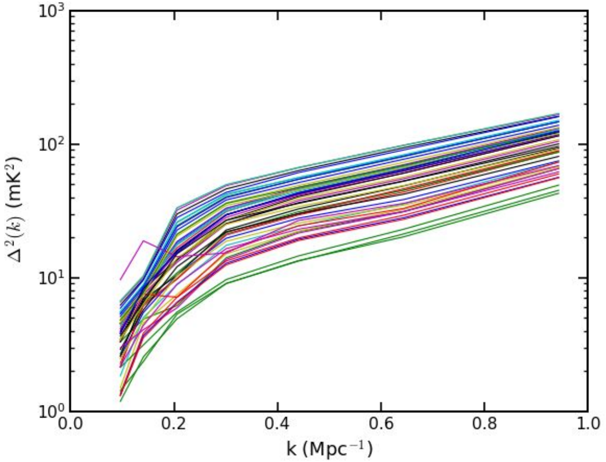



**Fig :** 300 datasets of the HI Power spectrums for the training.

Telescope Model
(SKA1_Low)

**Parameters Ranges**

**$R_{mfp}$** = 10 Mpc to 60 Mpc

**ζ** = 10 to 60

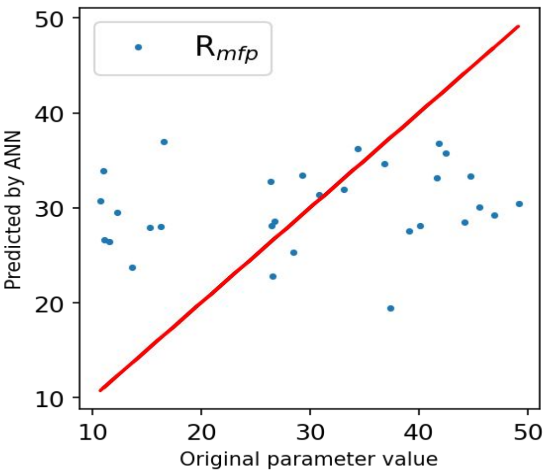
**$T_{vir}$ = 4.5 to 6.0**

(H.Shimabukuro et al. 2017)

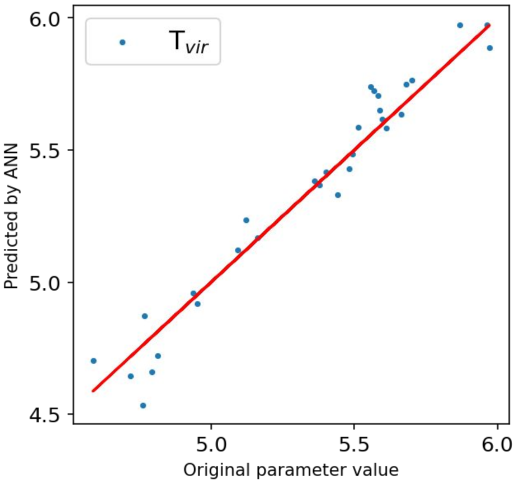
*Tripathi A et al. (2023, in prep)*

# Model Prediction

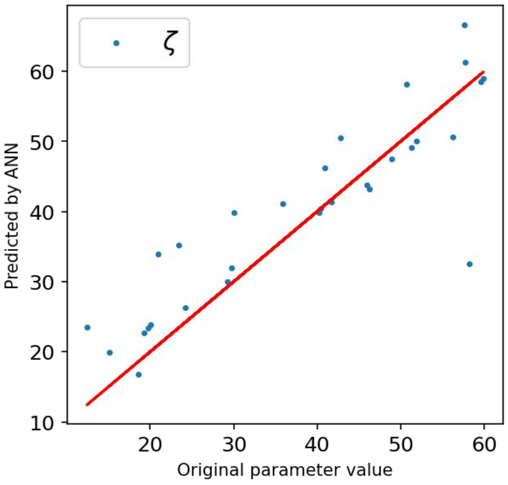
- We tested our trained ANN model with 30 sample of test datasets.




RMSE of Mean free path ($R_{mfp}$ )= 0.310




RMSE of ionizing Efficiency (**$T_{vir}$**)=0.0609

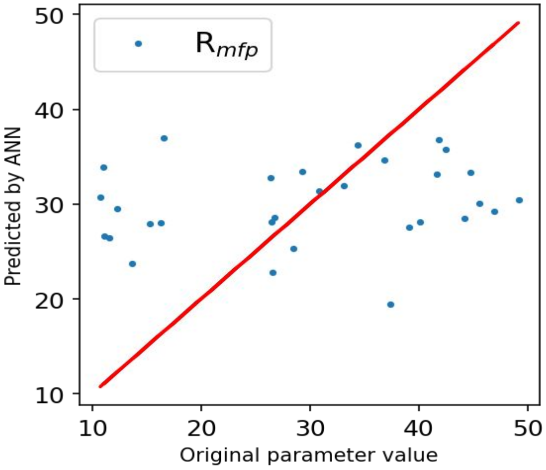


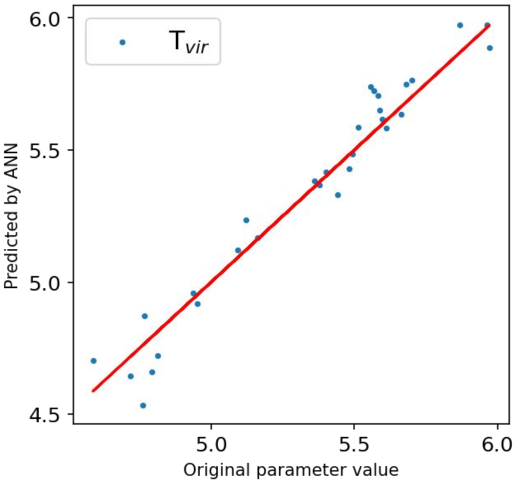

RMSE of ionizing Efficiency (**$\zeta$**)= 0.1460

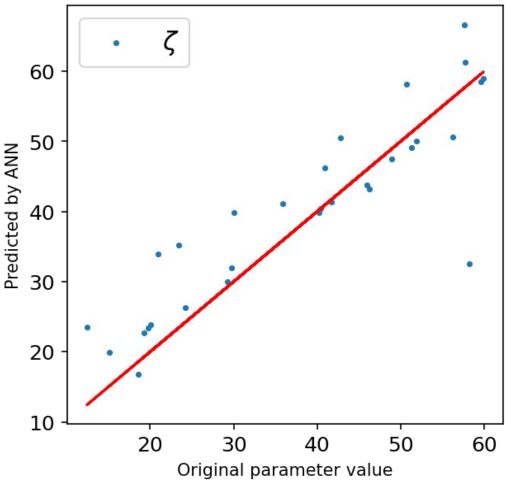
Tripathi A et al. (2023,in prep)

# Model Prediction

- We tested our trained ANN model with 30 sample of test datasets.



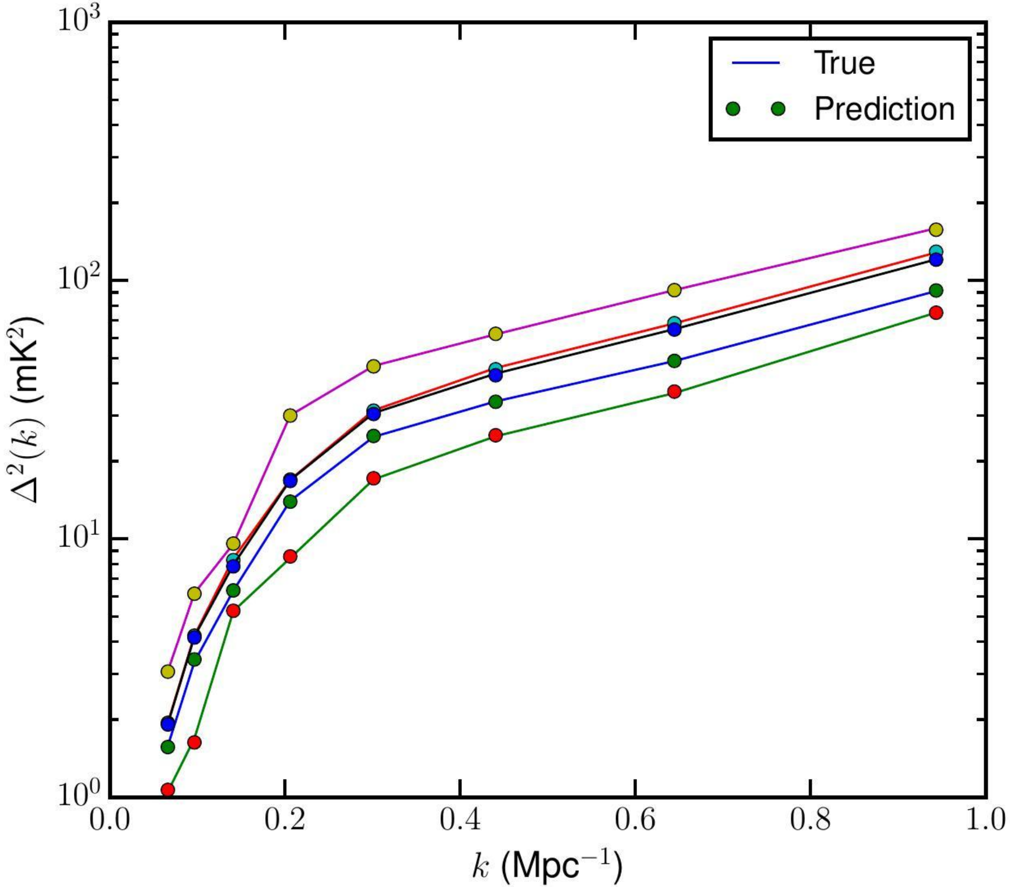

RMSE of Mean free path (**$R_{mfp}$**) = 0.310

RMSE of ionizing Efficiency (**$T_{vir}$**) = 0.0609

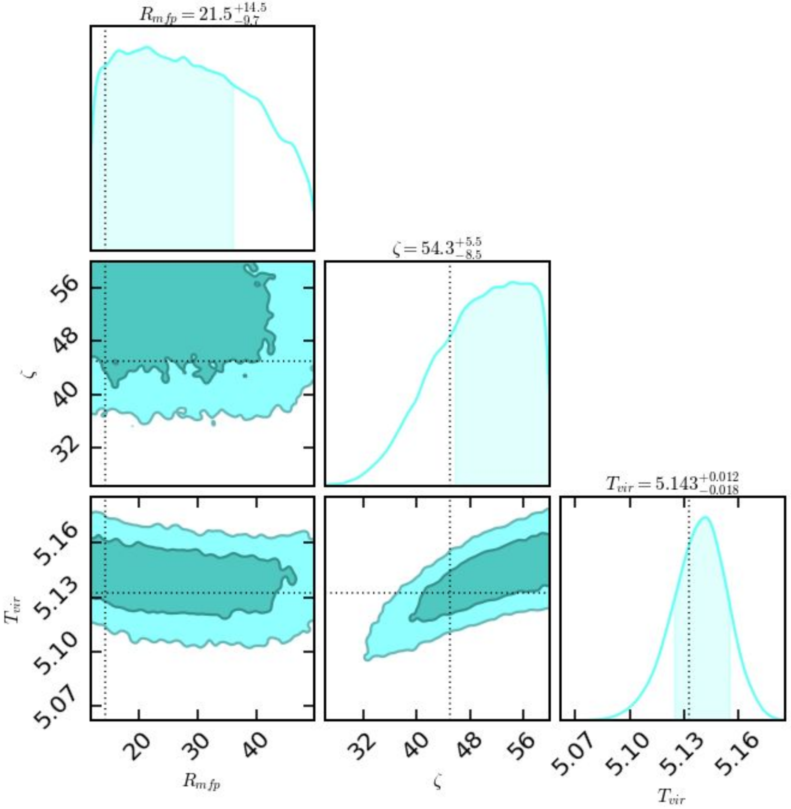
RMSE of ionizing Efficiency (**$\zeta$**)= 0.1460

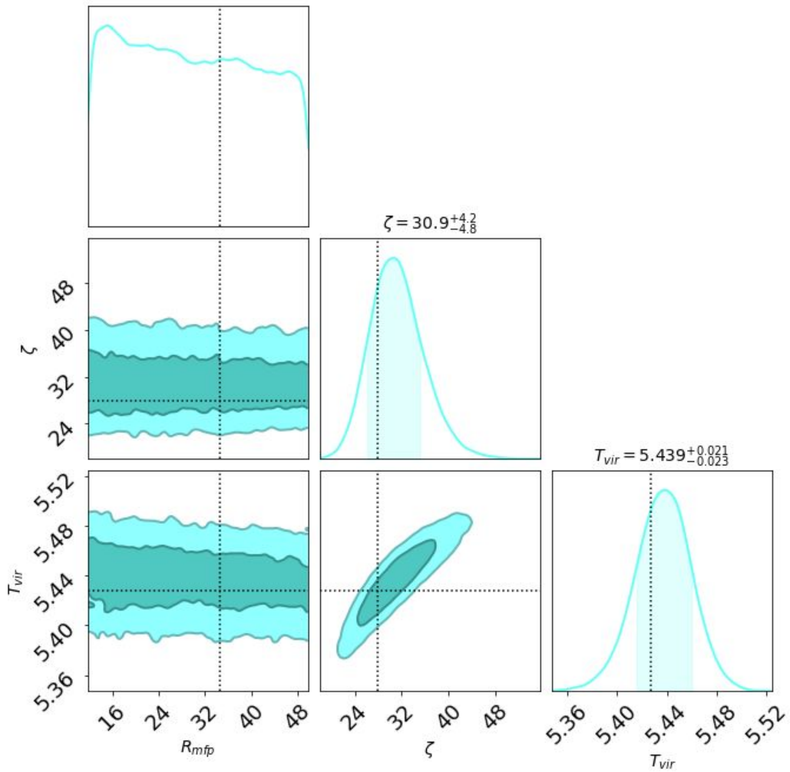
- Probably the astrophysical parameter $R_{mfp}$ is highly degenerate.
- To break the degeneracy, we required more training data sets and a more sophisticated ML model.

# Emulating Power Spectrum using ANN



# Observed Power Spectrum

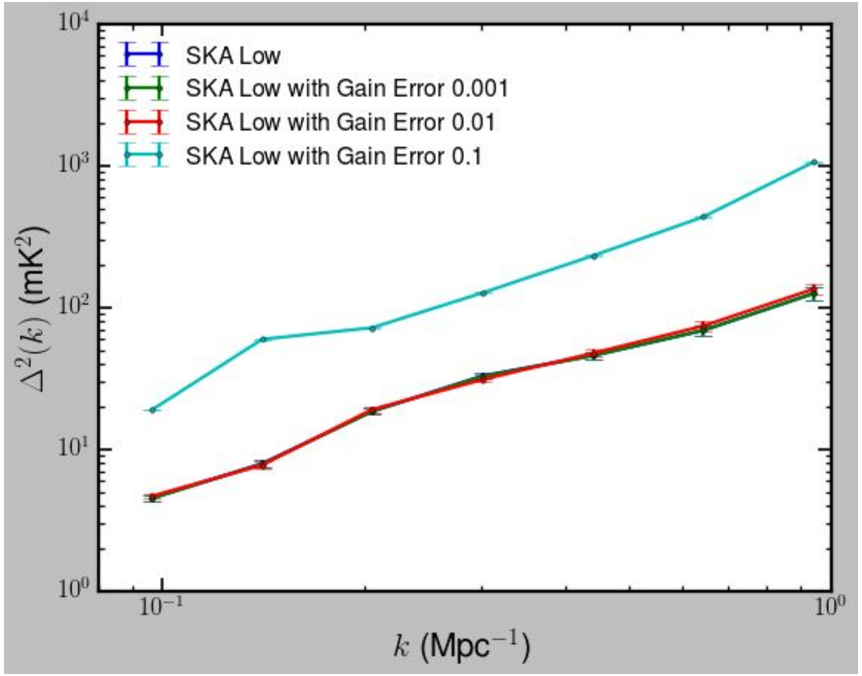


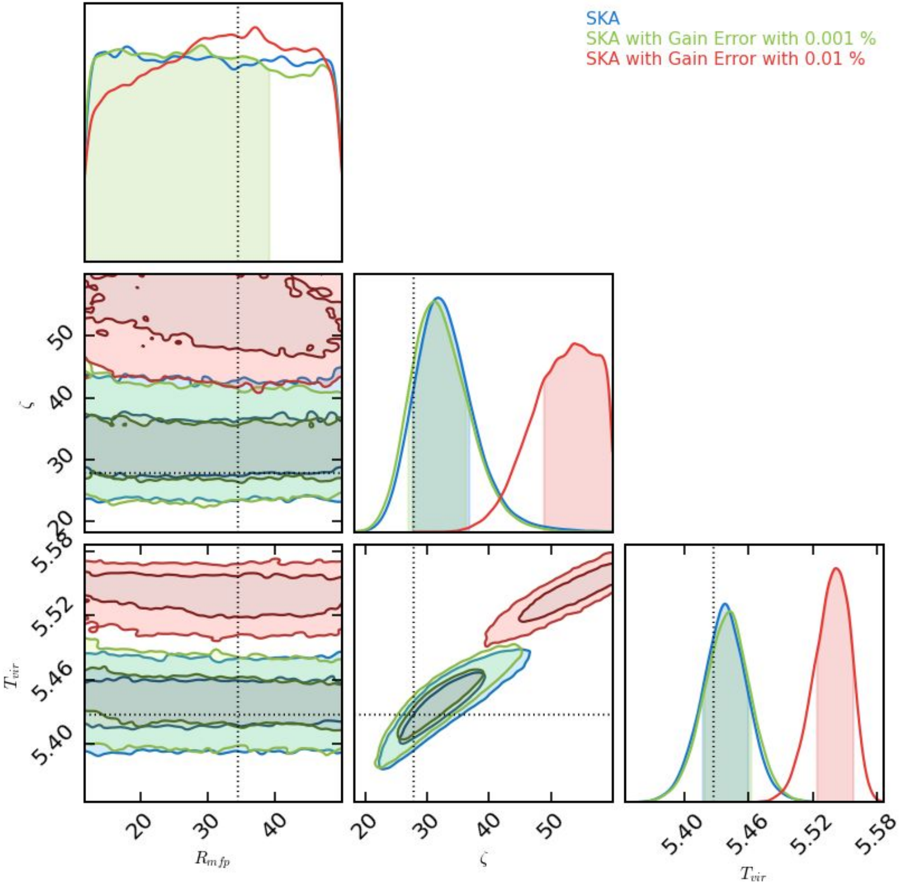




**Predicted by Observational Model (SKA Low)**

*Tripathi A. et al. (in prep)*

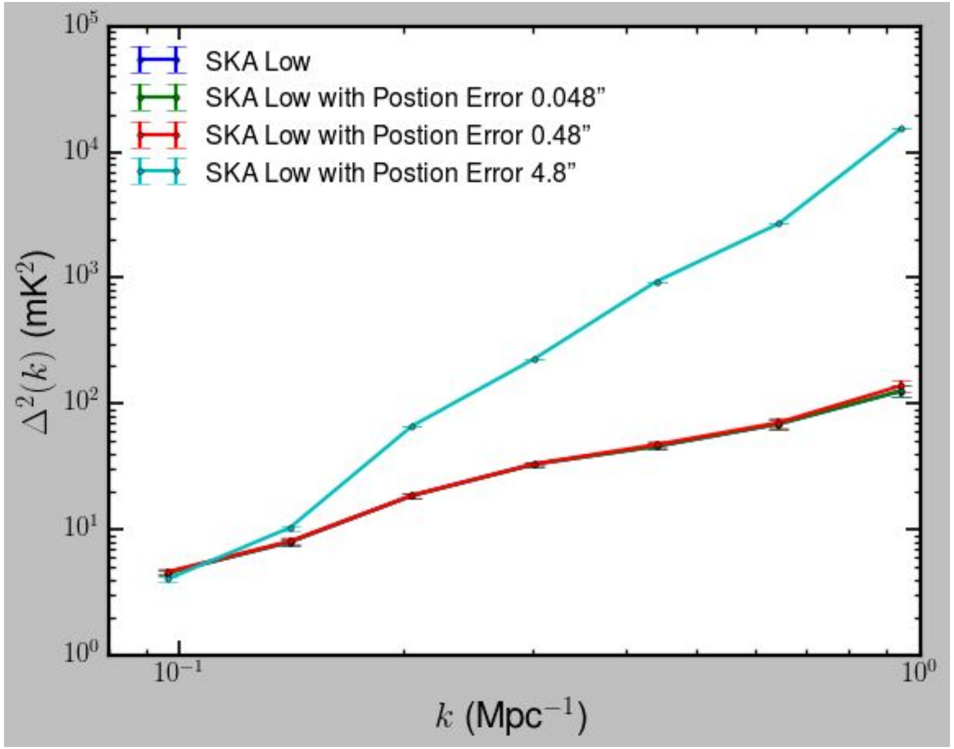
# SKA Low with Gain Error

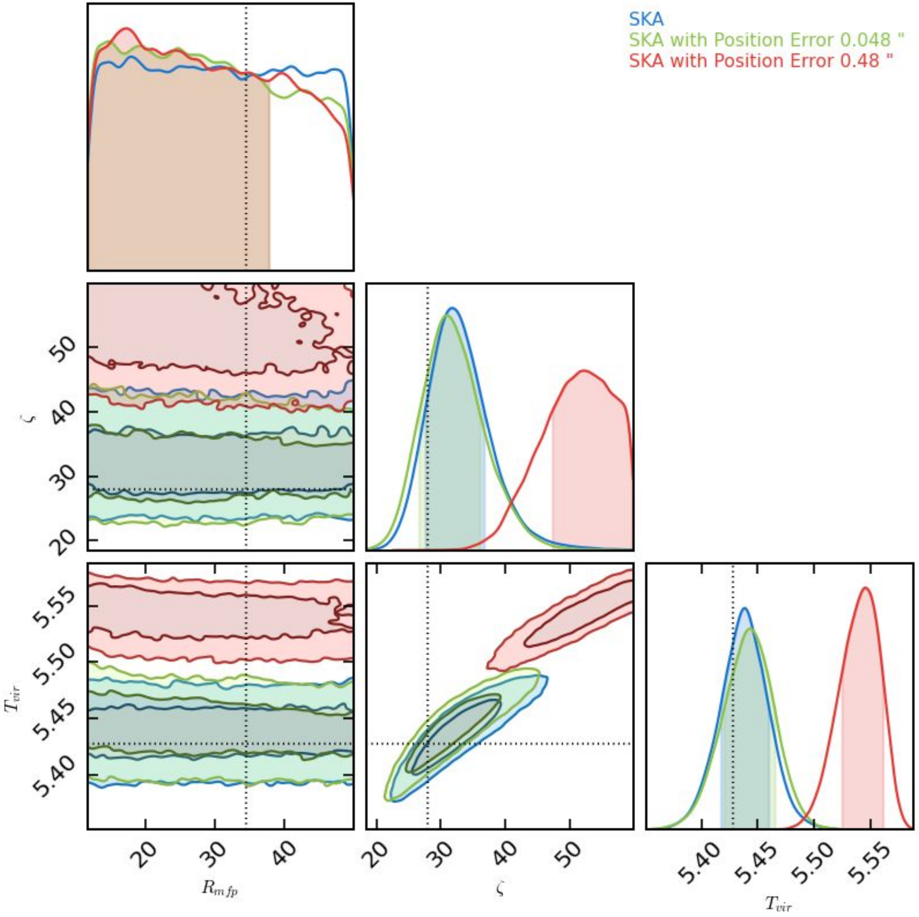



*Tripathi A. et al. (2023,in prep)*

# SKA low with Position Error




*Tripathi A. et al. (2023,in prep)*

# Ongoing/Future Work

## GLOBAL 21 CM SIGNAL EXTRACTION

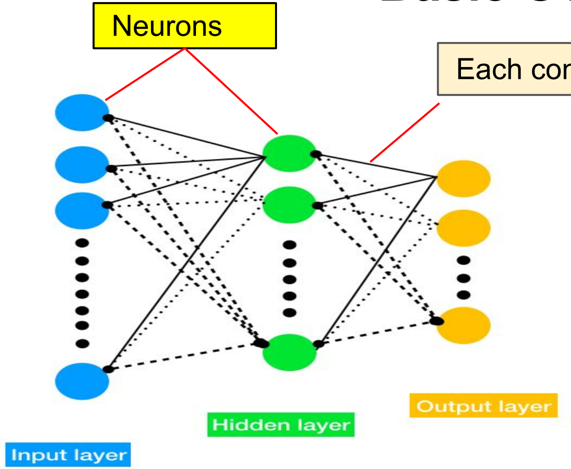
- ANN signal extraction is robust against slowly varying Ionosphere.
- Future work to include more dynamic ionosphere along with chromatic telescope beam.

## 21CM FLUCTUATIONS - POWER SPECTRA

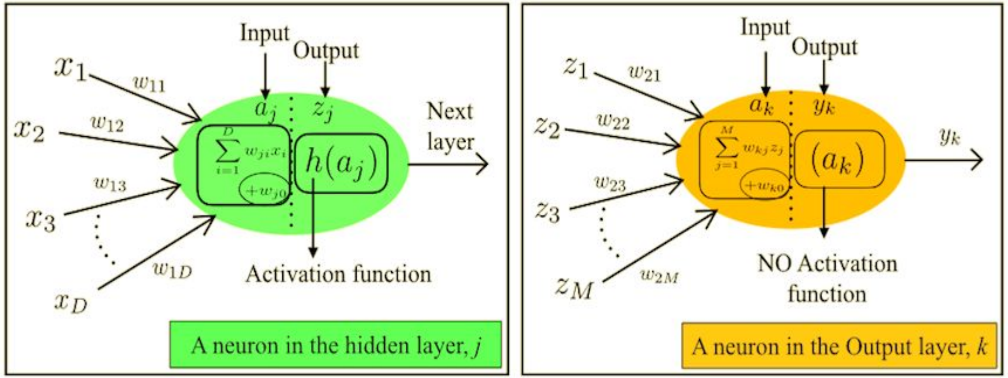
- Inherent bias in the 21cm power spectra due to the effect of the PSF of an radio interferometer
- This pipeline can be extended to study effects of chromatic primary beam, radio frequency interferences, foregrounds with spectral features.

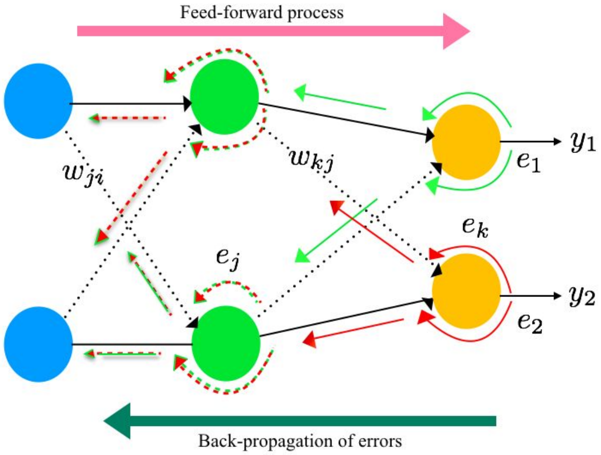
Thank you.

# Basic Overview of Artificial Neural Network (ANN)




Each connection associated with a bias and weight.




This evaluates the average magnitude of the error.

$$\mathrm{RMSE} = \sqrt{\frac{1}{N_{\mathrm{pred}}} \sum_{i=1}^{N_{\mathrm{pred}}} \left( \frac{Y_{\mathrm{ori}} - Y_{\mathrm{pred}}}{Y_{\mathrm{ori}}} \right)^2}$$

This is used to evaluate the performance of a linear regression model.

$$\mathrm{R}^2 = \frac{\Sigma(y_{\mathrm{pred}} - \bar{y}_{\mathrm{ori}})^2}{\Sigma(y_{\mathrm{ori}} - \bar{y}_{\mathrm{ori}})^2} = 1 - \frac{\Sigma(y_{\mathrm{pred}} - y_{\mathrm{ori}})^2}{\Sigma(y_{\mathrm{ori}} - \bar{y}_{\mathrm{ori}})^2}$$

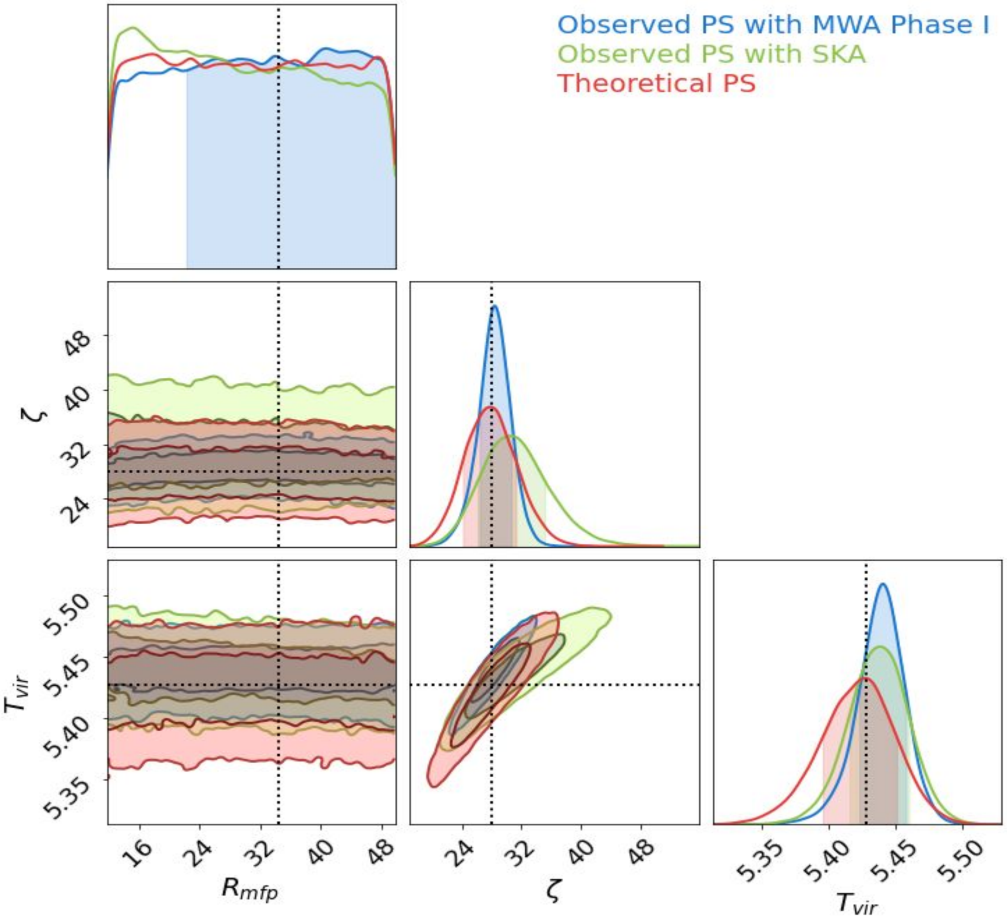
(Image courtesy: M. Choudhury et. al. 2019)

The complex gain can be modeled by

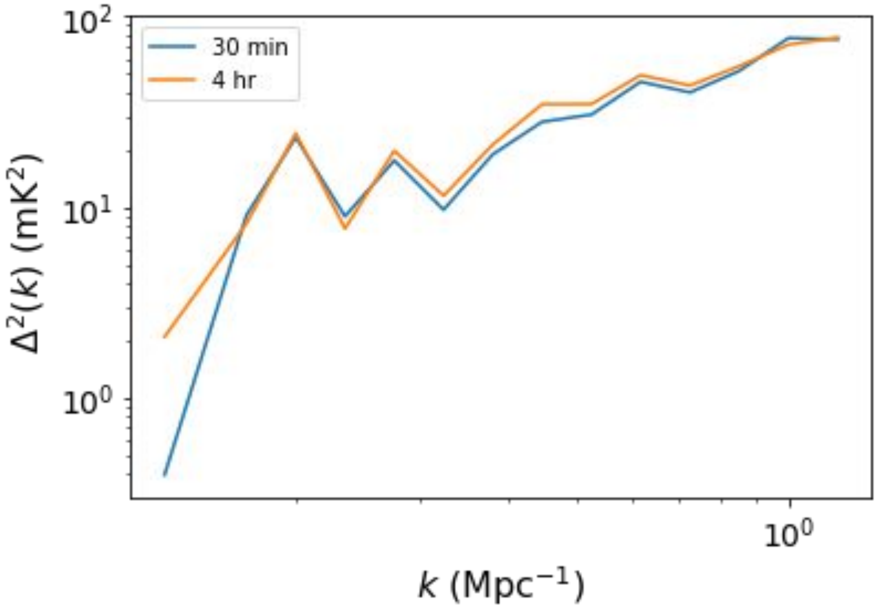
$$g_i = (a_i + \delta a_i)exp(-i(\phi_i + \delta\phi_i))$$

$$g_i = (1 + \delta a_i)exp(-\delta\phi_i)$$

# Observed Power Spectrum with Different Interferometers




*Tripathi A. et al. (2023,in prep)*



30 min
4 hr
$10^2$
$10^1$
$10^0$
$\Delta^2(k)$ (mK$^2$)
$10^0$
$k$ (Mpc$^{-1}$)

# Timeline and Progress