Cross-correlation Forecast of CSST Spectroscopic Galaxy and MeerKAT Neutral Hydrogen Intensity Mapping Surveys

Yu’er Jiang, Yan Gong, Meng Zhang, Qi Xiong, Wenxiang Pei,

Xingchen Zhou, Furen Deng, Xuelei Chen, Yin-zhe Ma, Bin Yue

Hangzhou

2024.7.23

中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

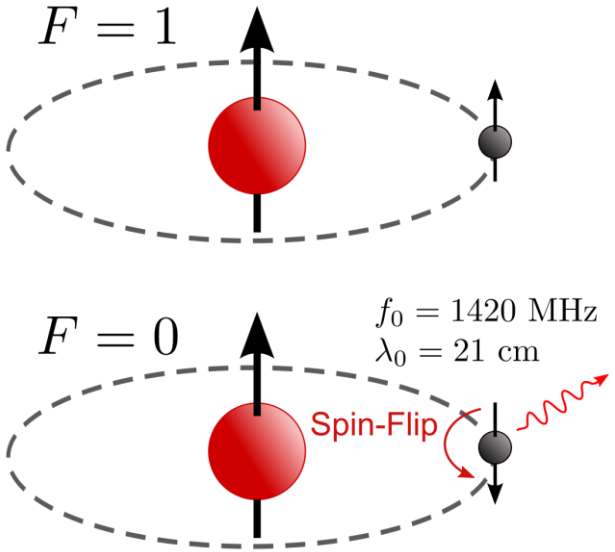
Cross-correlation Forecast of CSST Spectroscopic Galaxy and MeerKAT Neutral Hydrogen Intensity Mapping Surveys

MeerKAT

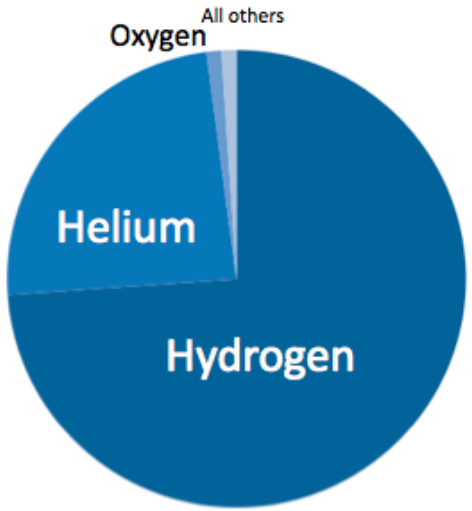
China Space Station Telescope（CSST）

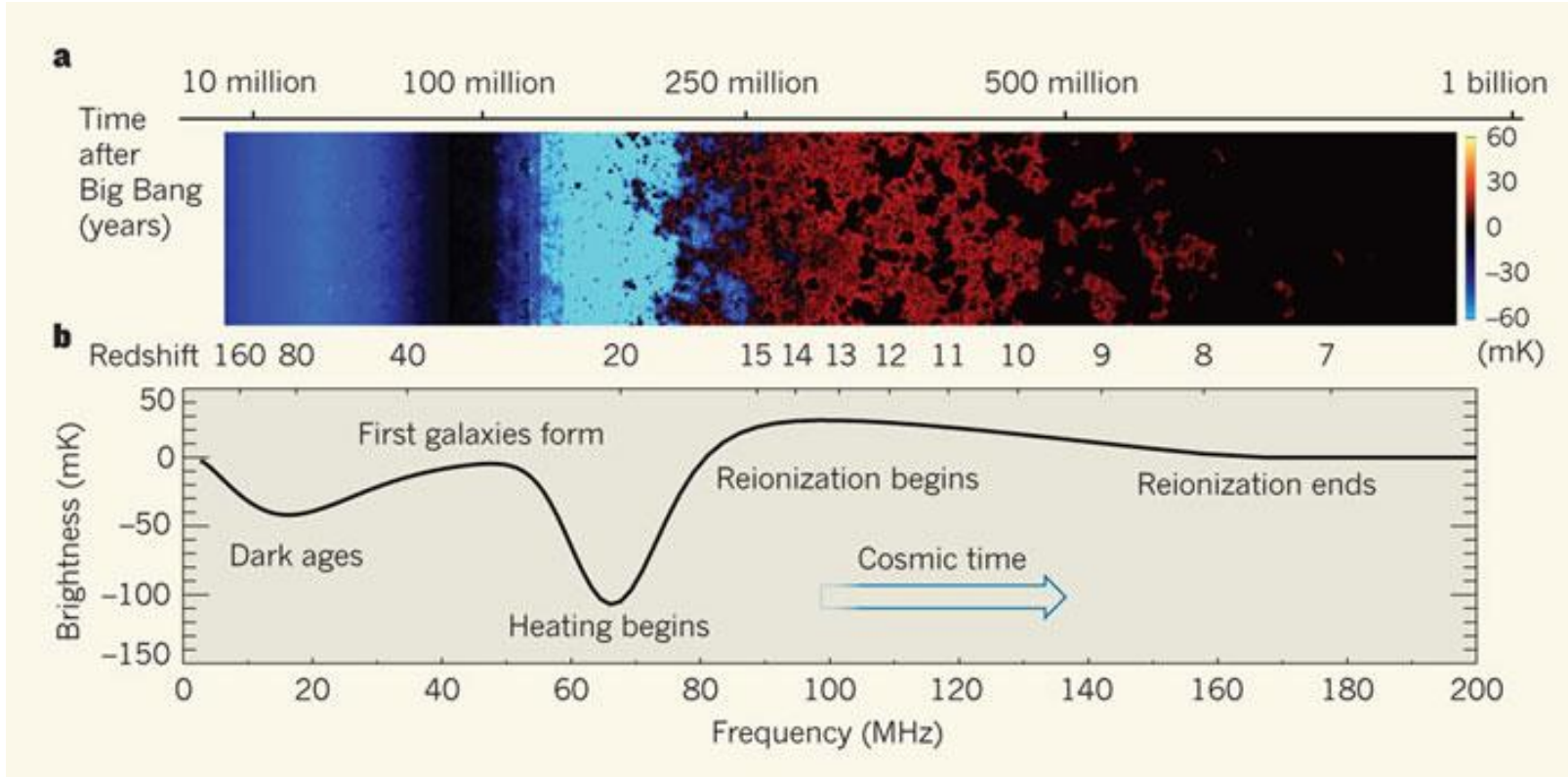
NAOC 中国科学院国家天文台
NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

21cm emission from HI



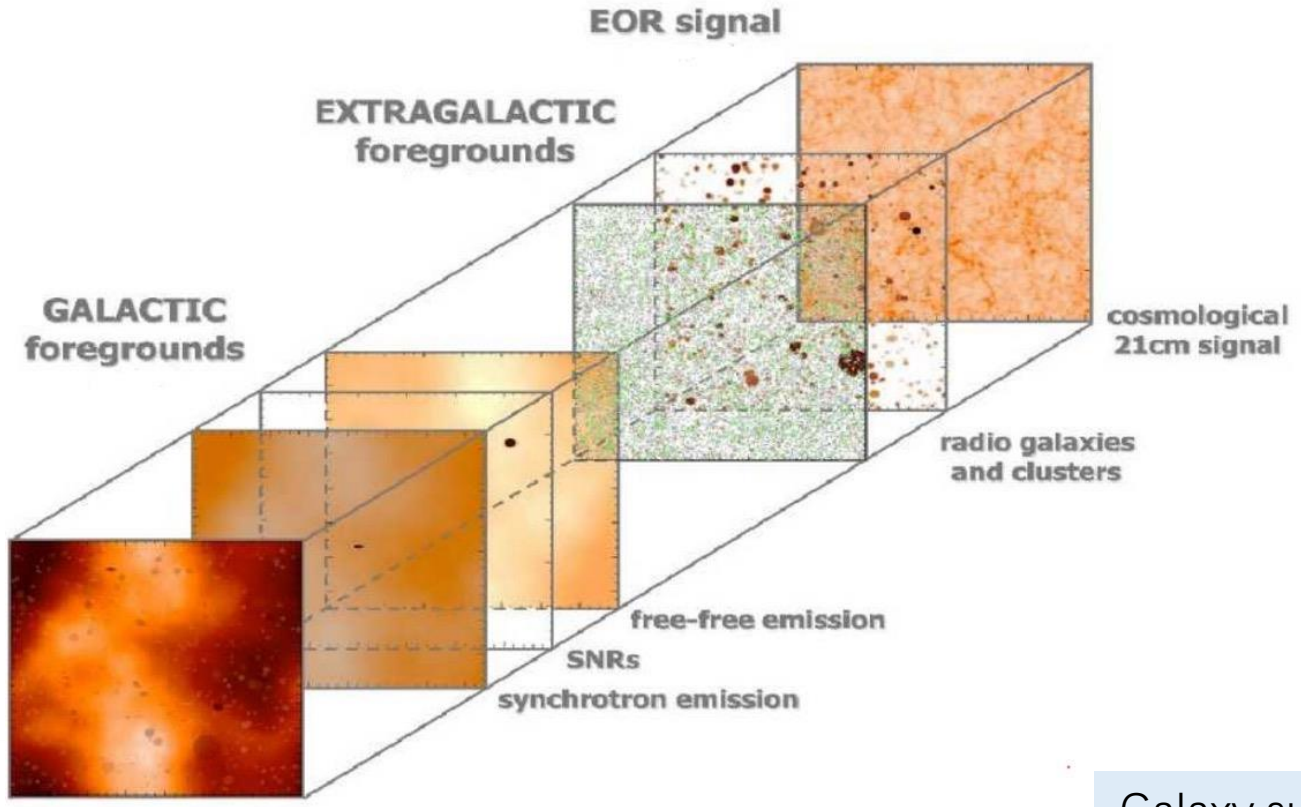
$$\overline{\delta T_b}(z) = \frac{3c^3 h_P A_{10} \overline{n}_{\rm HI}(z)}{32\pi k_B \nu_0^2 (1+z) H(z)}$$





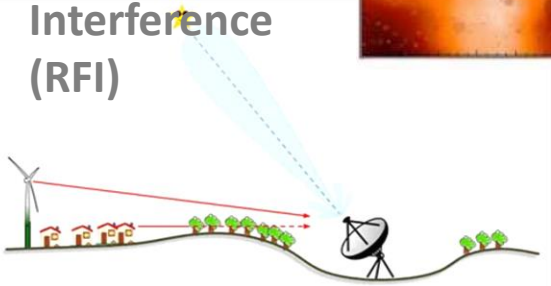
[Ref] https://lunar.colorado.edu/lowfreq/

Challenges to HI intensity mapping

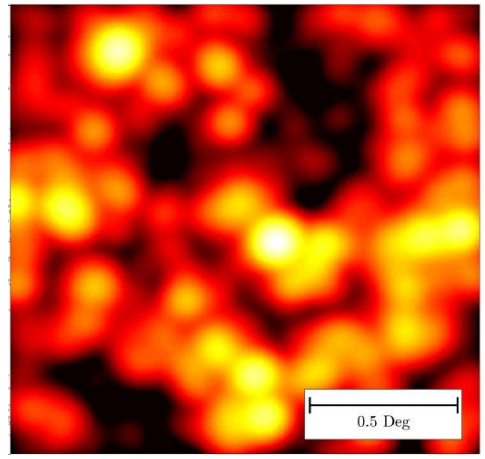


[Ref] https://www.astron.nl/astronomy/cosmology/

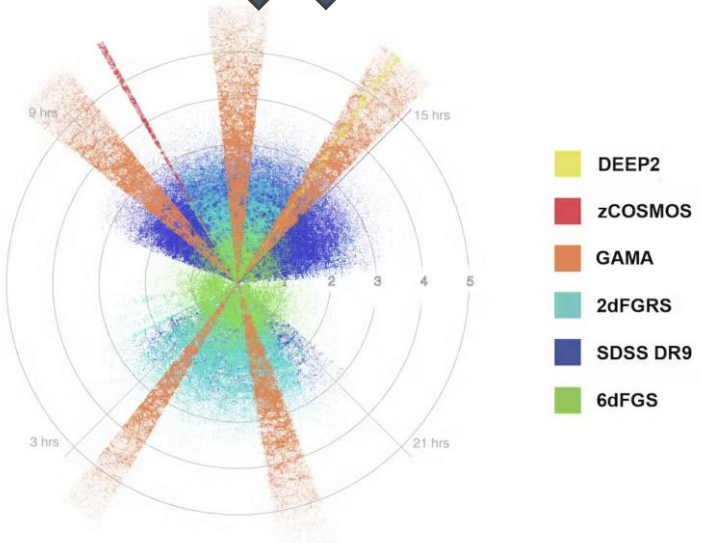
Radio Frequency Interference (RFI)



Intensity Map



Galaxy survey

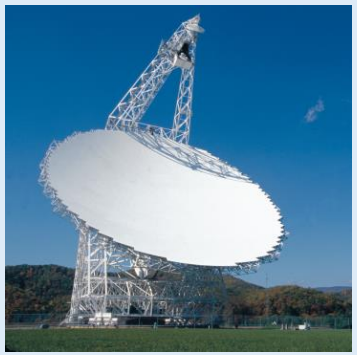


[Ref]https://theconversation.com/dont-panic-but-the-universe-is-slowly-dying-45779

HI x Galaxy Experimental Results

2010

GBT



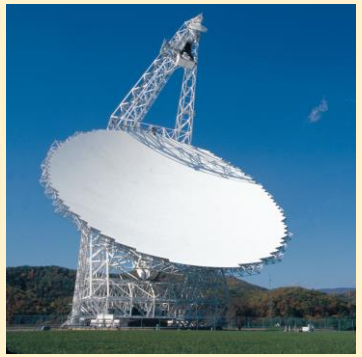
Deep2

$z \approx 0.8$

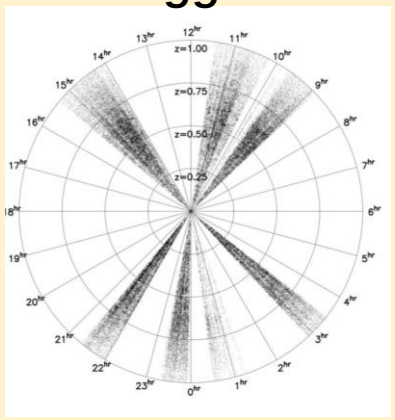
$\Omega_{\rm HI} b_{\rm HI} r_{{\rm HI},g} = (5.5 \pm 1.5) \times 10^{-4}$

2013

GBT



WiggleZ



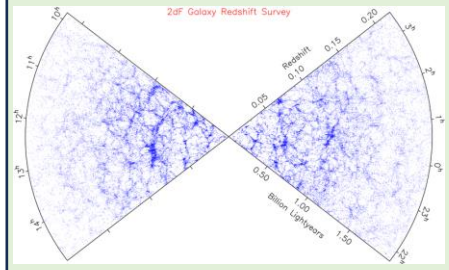
$0.6 < z < 1$

$\Omega_{\rm HI} b_{\rm HI} r_{{\rm HI},g} = (4.3 \pm 1.1) \times 10^{-4}$

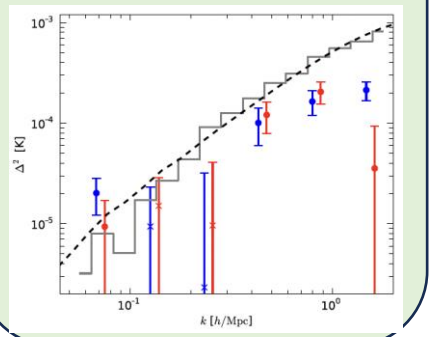
2018

Parks

2dF

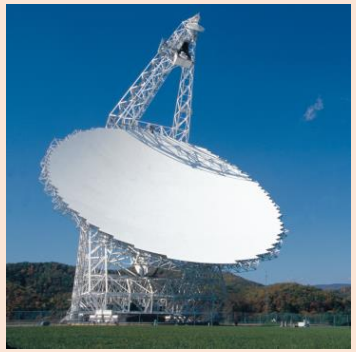


$0.057 < z < 0.098$

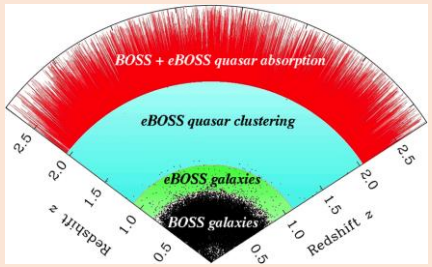


2022

GBT



eBOSS



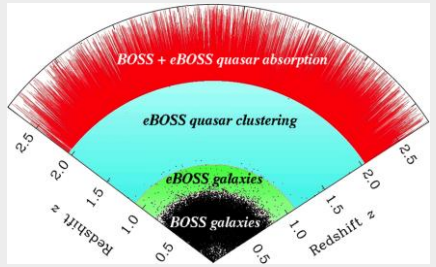
$0.6 < z < 1.0$

$\Omega_{\rm HI} b_{\rm HI} r_{\rm HI,ELG} = (4.0 \pm 1.3) \times 10^{-4}$

2022

CHIME

eBOSS



$0.78 < z < 1.43$

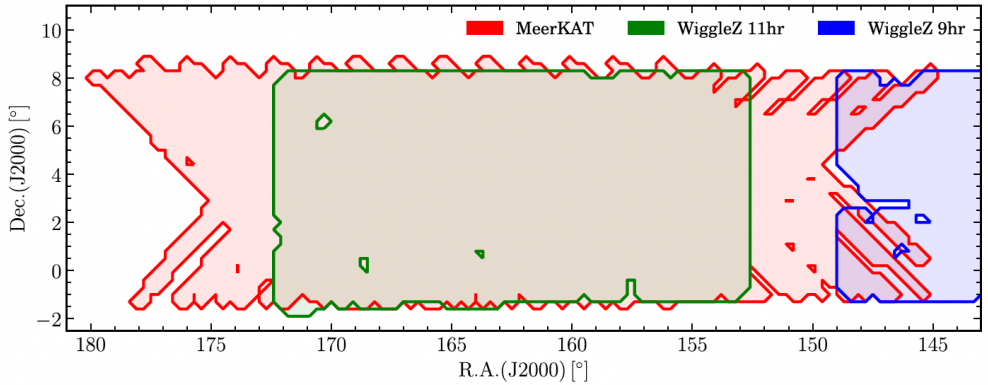
$A_{HI} = 6.76^{+9.04}_{-3.79}$

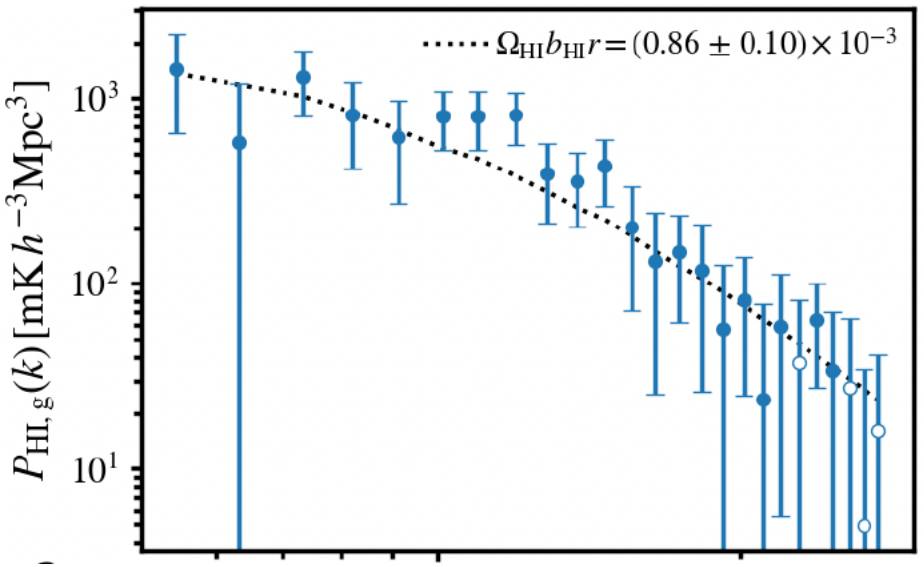
MeerKAT HI Intensity Mapping

MeerKAT dishes	64
MeerKAT dish diameter	13.5m

L-band (0<z<0.58) / UHF-band (0.4<z<1.45)

Cross-correlation with WiggleZ $0.400 < z < 0.459$





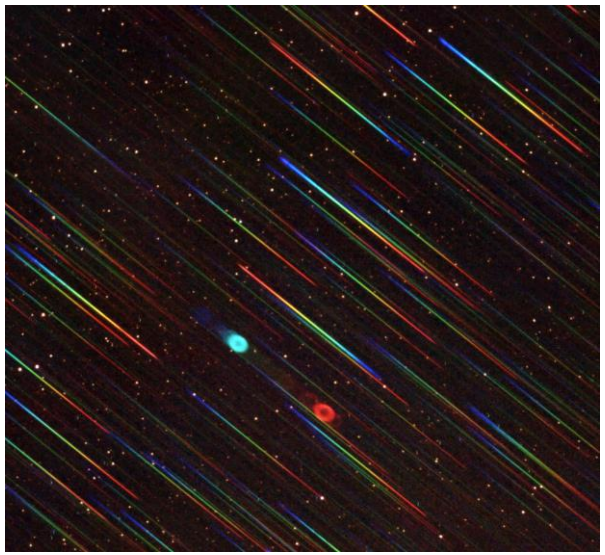
Cunnington et al. 2023

NAOC 中国科学院国家天文台 NATIONAL ASTRONOMICAL OBSERVATORIES, CAS

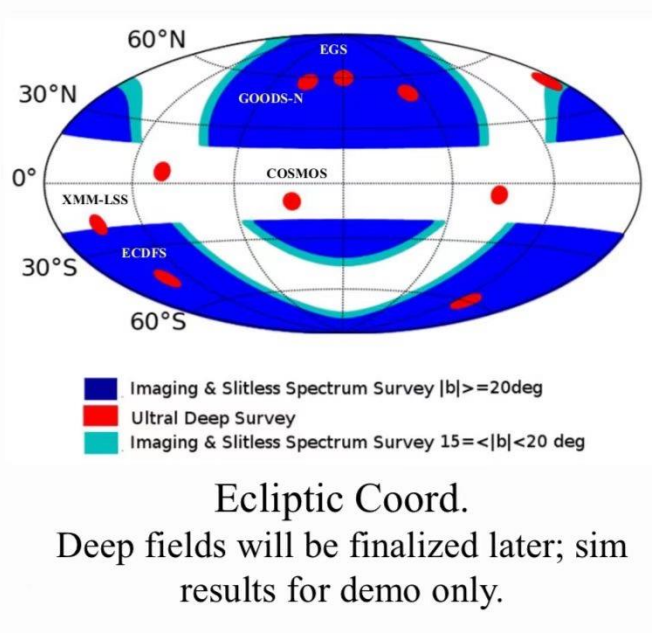
中国巡天空间望远镜 (CSST)

Survey area: 17500 $\mathbf{deg}^2$
Survey time: 10 yrs
FOV: 1.1 $\mathbf{deg}^2$
Survey mode: photometric imaging & slitless grating spectroscopic survey

Slitless spectropic survey (示意图)



[Ref] https://www.astrobin.com/344640/0/



Simulation

JiuTian-1Gpc box	
Simulation code	L-Gadget3
Box size	1 Gpc/h
Number of particles	6144^3
Mass resolution	3.72*10^8 M_sun/h
Redshift range	0~127
Semi-analytical model	L-GALAXIES
Emission line model	CLOUDY
Cosmological parameters	Planck Collaboration I

Snapshot	Redshift	Survey frequency	MeerKAT band	Frequency resolution
97	z=0.5	1015~900MHz	L-band	0.2MHz
90	z=0.7	900~770MHz	UHF-band	0.13MHz
83	z=1	770~650MHz	UHF-band	0.13MHz

Emission lines Pei et al.2024

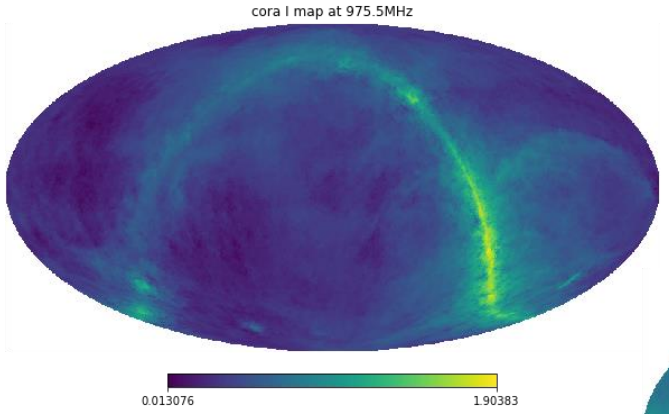
name	wavelength (Å)
Ly α	1216
H β	4561
H α	6563
[O II]3727	3727
[O II]3729	3727
[O III]4959	4959
[O III]5007	5007
[O I]6300	6300
[N II]6548	6548
[N II]6584	6584
[S II]6717	6717
[S II]6731	6731
[Ne III]3870	3870

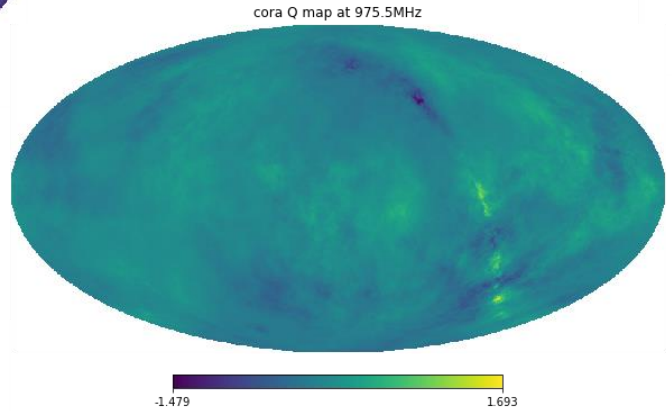
HI model (Obreschkow et al.2009)

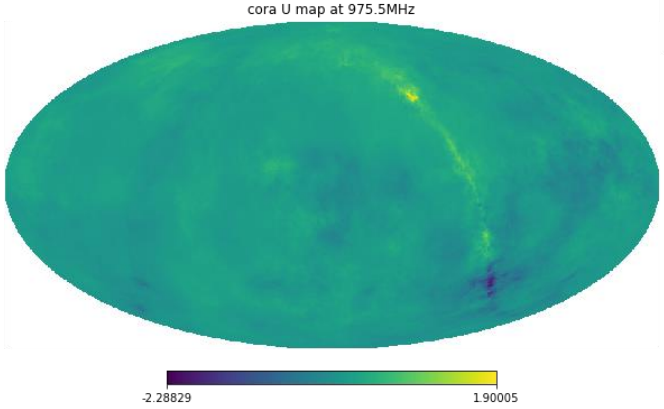
Foreground Simulation - CORA Shao et al.2015

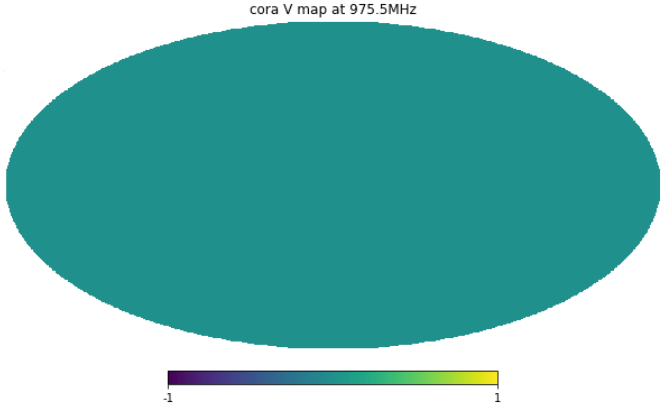
I^2 = Q^2+U^2+V^2

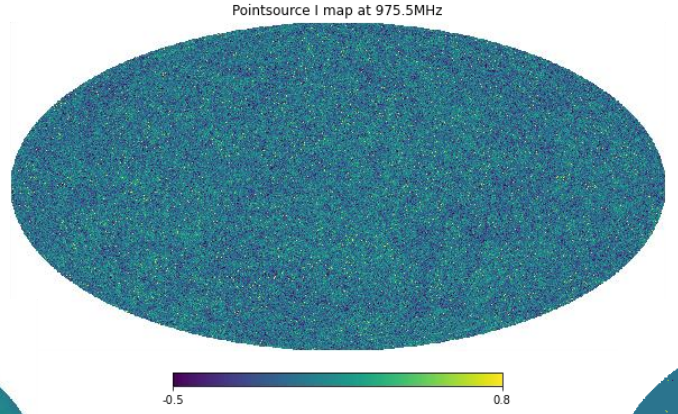
Galaxy model: GSM08

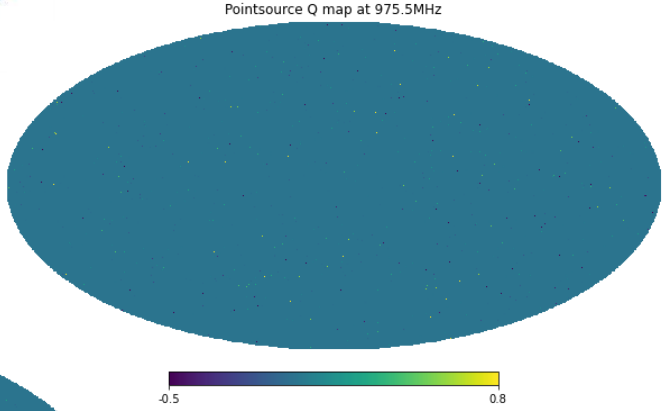


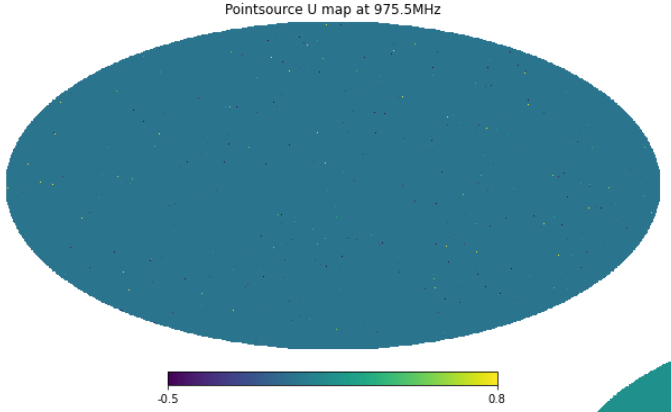


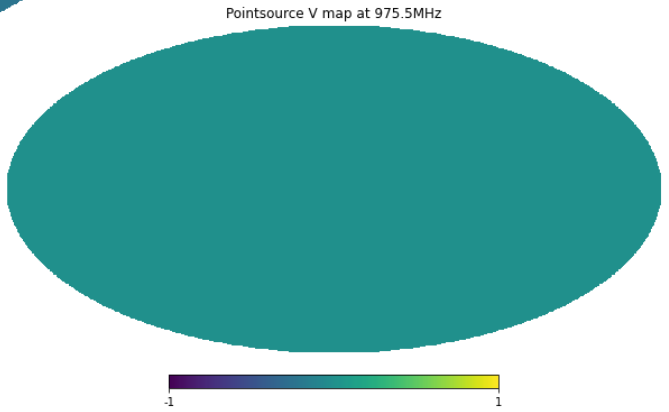




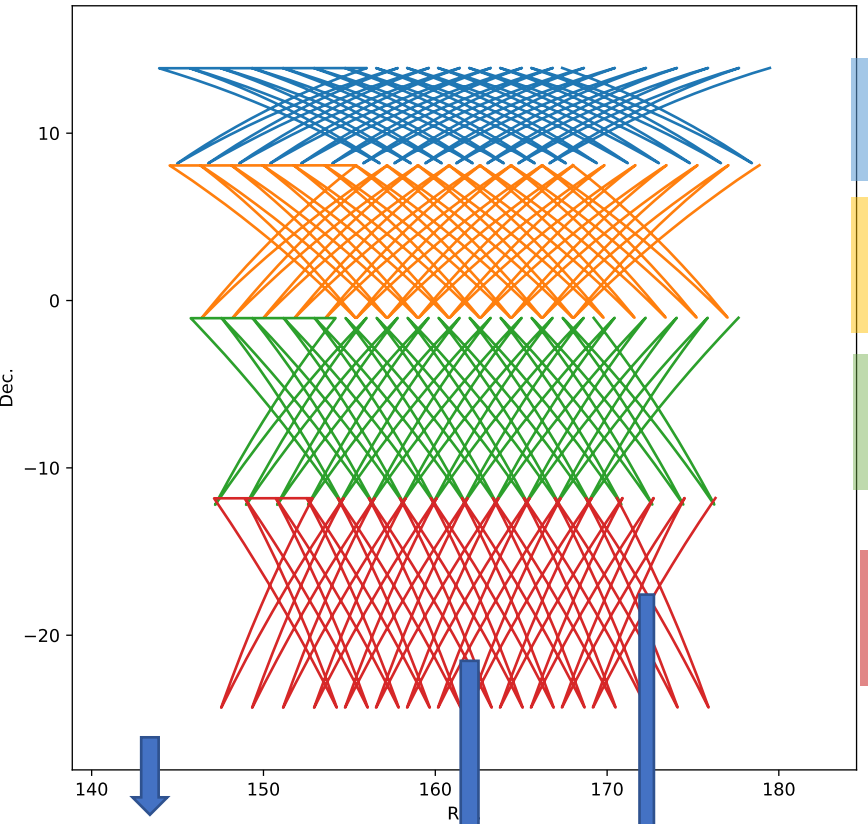








TOD to Map



az = 21
el = 43

az = 43
el = 41

az = 62
el = 40

az = 80
el = 39

1.56h per scan
2 scans per night
25days survey

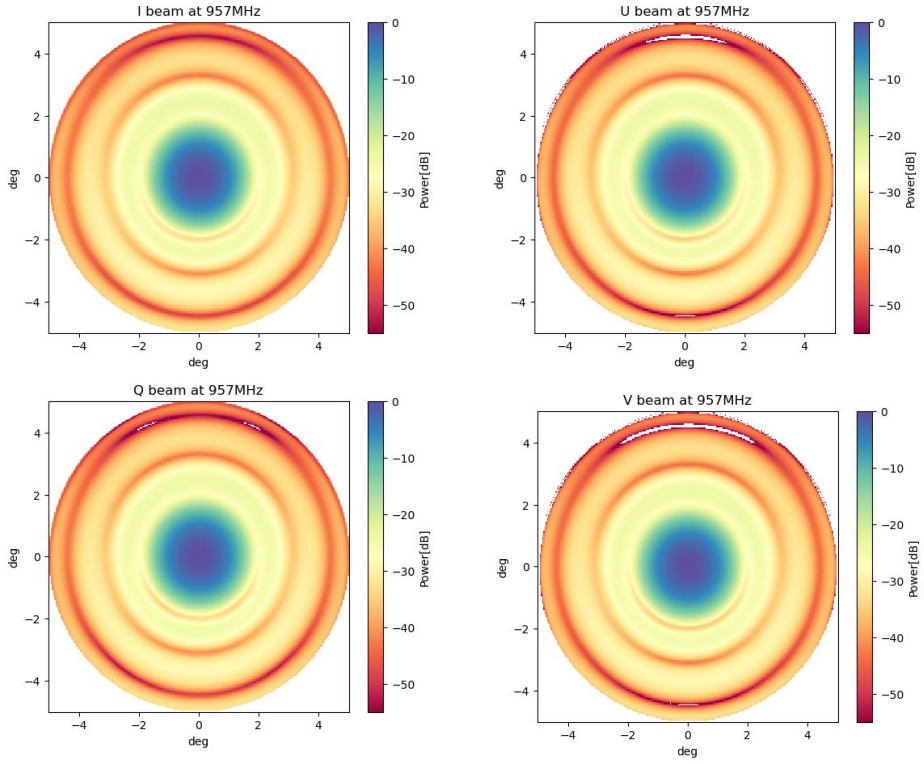
z=0.5 $1722\ deg^2$

z=0.7 $1018\ deg^2$

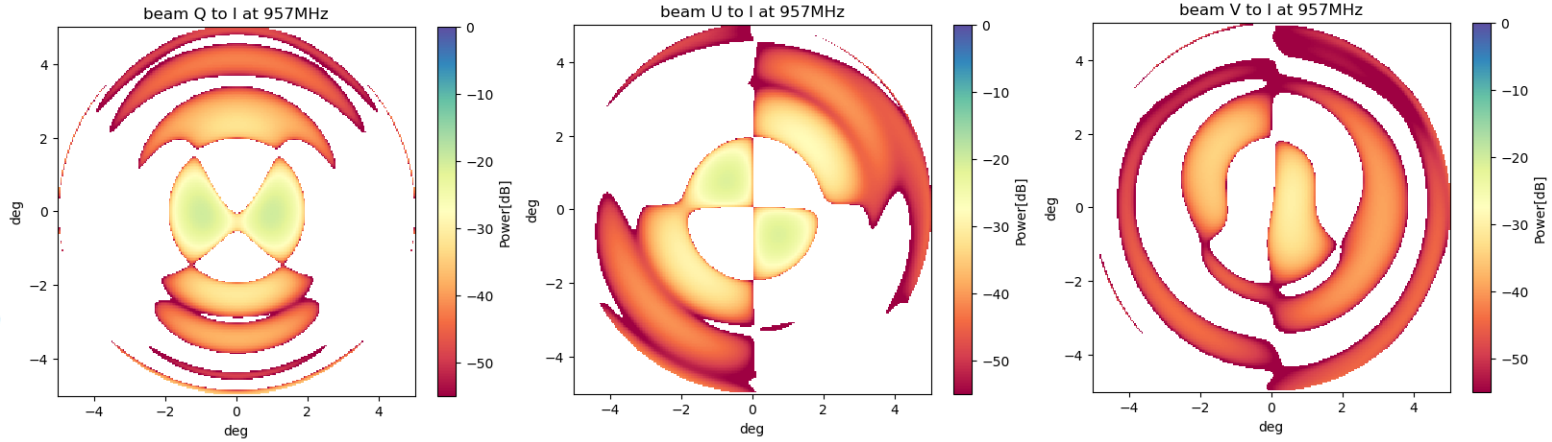
z=1 $600\ deg^2$

$$T_A(x_b, y_b, \tau) = \int T_b(x, y)\mathcal{B}(x, y; x_b, y_b, \tau)dxdy$$

MeerKAT beam simulation - EIDOS package (Asad et al.2021)



Polarization Leakage



Systematic Noise

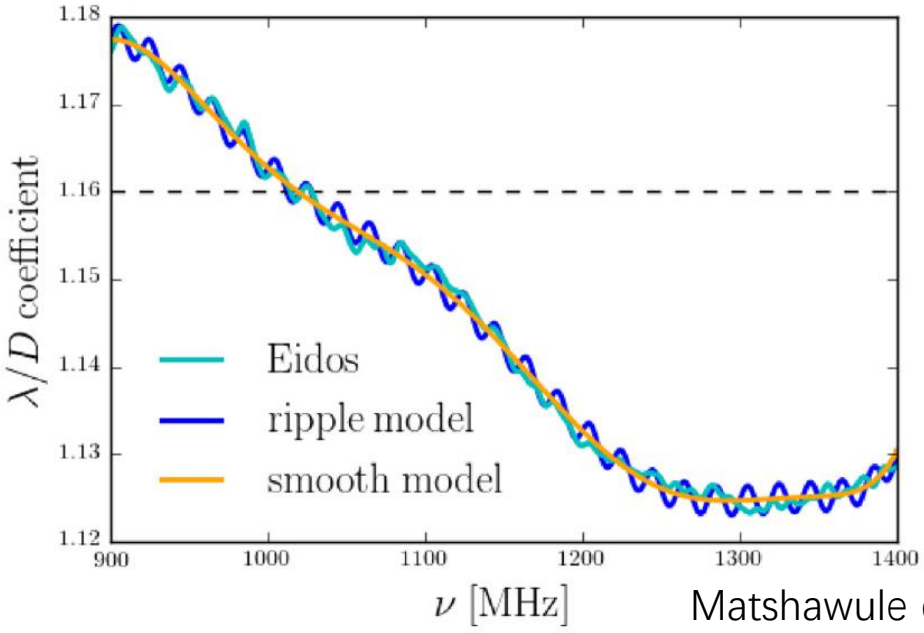
$$\sigma_T = \frac{T_{sys}}{\sqrt{\delta\nu t_{tot}}} \frac{\lambda^2}{\theta_b^2 A_e} \sqrt{A_S/\theta_b^2}$$

$$\Delta\theta_r = \frac{\lambda}{D}\left(\sum_{d=0}^{8} a_d \nu^d + A\sin\left(\frac{2\pi\nu}{T}\right)\right).$$

Table 2. Parameters of the MeerKAT single-dish observations.

Parameter	Value
Number of dishes	64
Observation mode	Single-dish
Dish diameter	13.5 m
System temperature	20 K

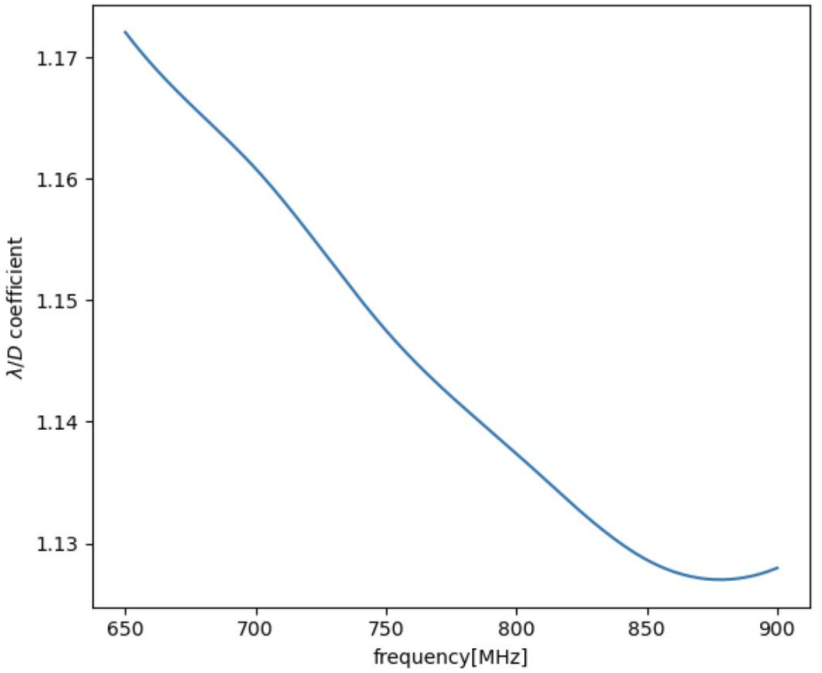
L-band FWHM



Matshawule et al. 2021

UHF-band FWHM

Katbeam package



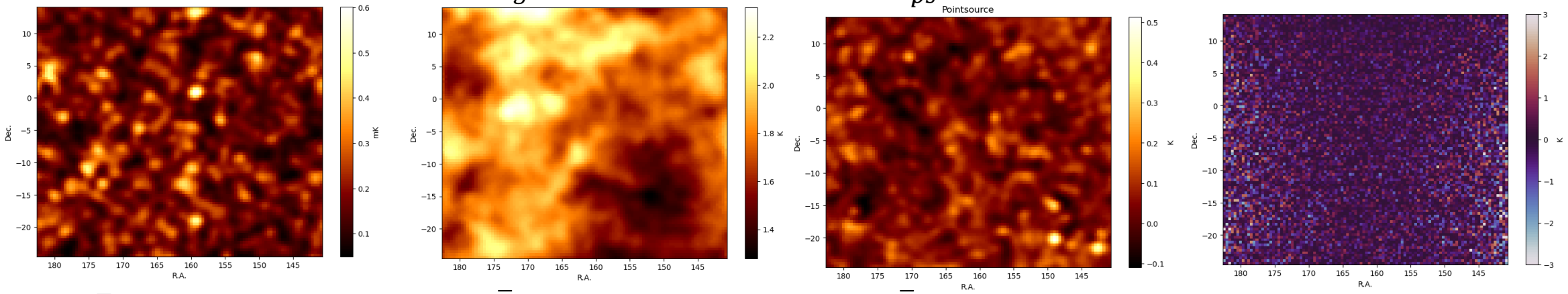
$\bar{T}_{HI} = 0.181\text{mK}$

$\bar{T}_{gal} = 1.774\text{K}$

$\bar{T}_{ps} = 0.049\text{K}$

Systematic Noise

z=0.5

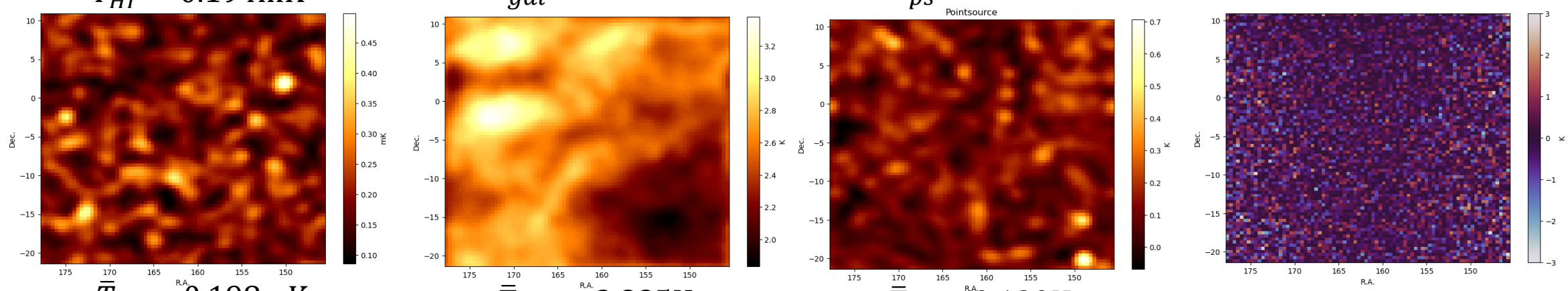


$\bar{T}_{HI} = 0.194\text{mK}$

$\bar{T}_{gal} = 2.579\text{K}$

$\bar{T}_{ps} = 0.121\text{K}$

z=0.7

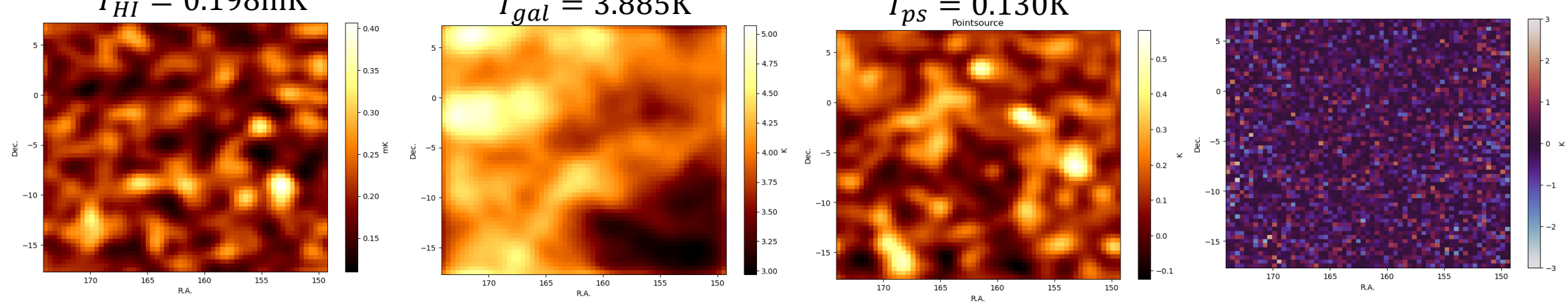


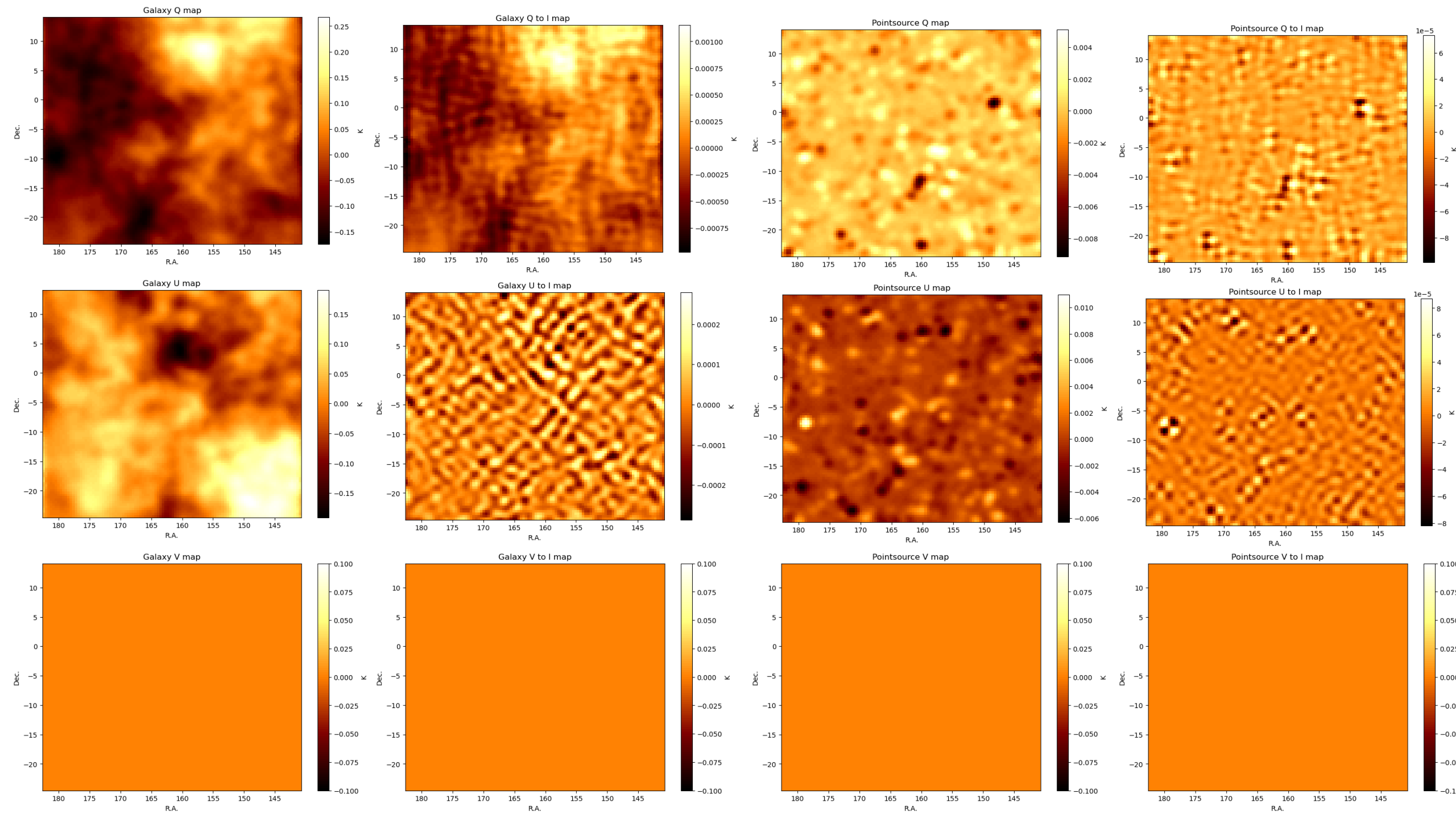
$\bar{T}_{HI} = 0.198\text{mK}$

$\bar{T}_{gal} = 3.885\text{K}$

$\bar{T}_{ps} = 0.130\text{K}$

z=1




Galaxy Q map
Galaxy Q to I map
Pointsource Q map
Pointsource Q to I map
Galaxy U map
Galaxy U to I map
Pointsource U map
Pointsource U to I map
Galaxy V map
Galaxy V to I map
Pointsource V map
Pointsource V to I map
Dec.
R.A.
K
1e−5

CSST Spectroscopic Galaxy Survey

name	wavelength (Å)
H α	6563
H β	4561
[O II]3727	3727
[O III]5007	5007

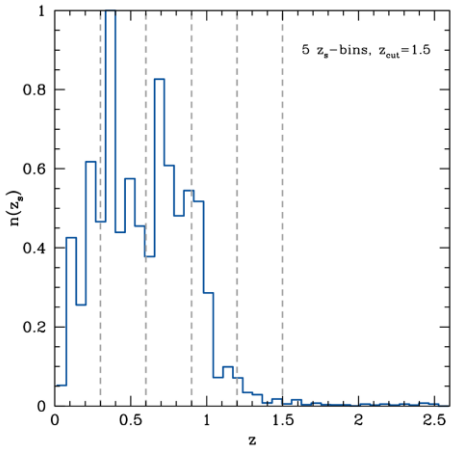
SNR

SNR>5

Qi Xiong

$$\bar{n}_g^a = f_{\rm eff}^{z_s,a}\ \bar{n}_{g,\rm ori}^a$$

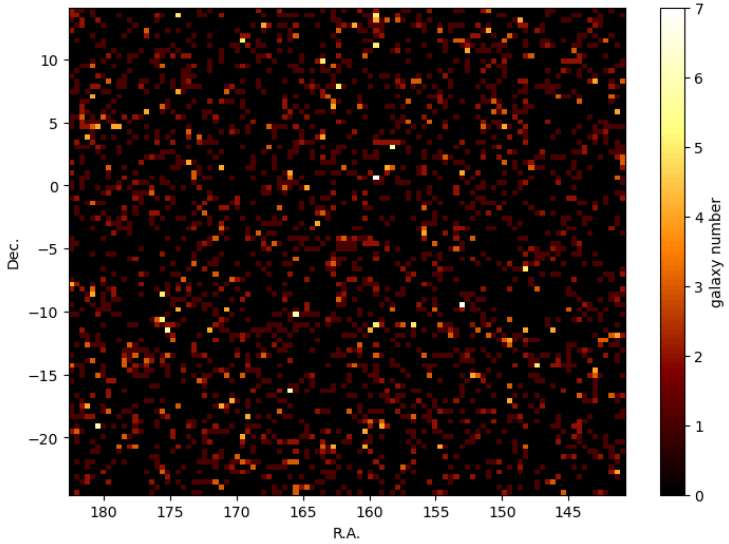
$$f_{\rm eff}^{z_s} = f_{\rm eff}^{z_s,0}/(1+z)$$



Gong et al.2019

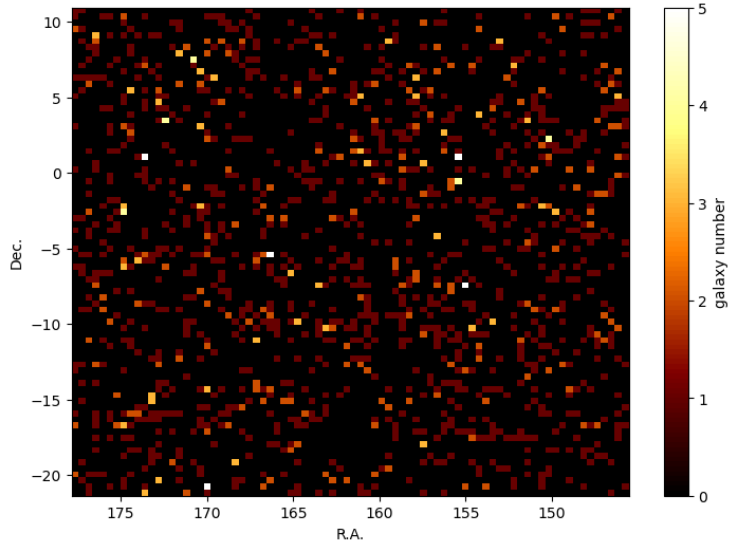
z=0.5

$\bar{N}_g = 5.13 \times 10^{-3} h^3/Mpc^3$



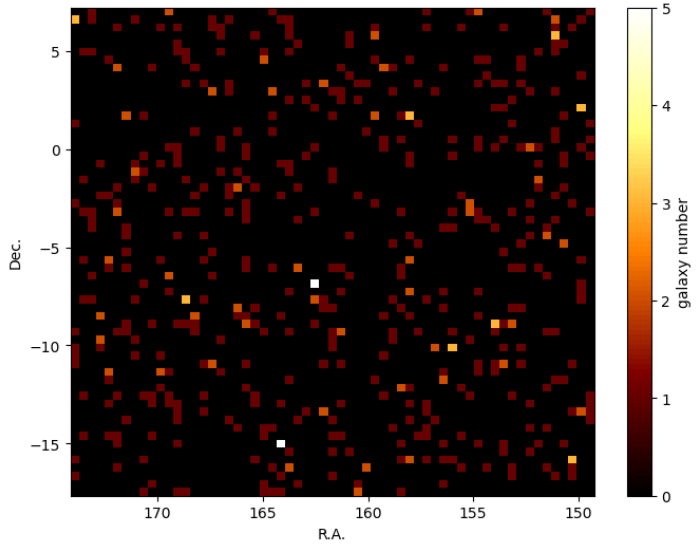
z=0.7

$\bar{N}_g = 2.26 \times 10^{-3} h^3/Mpc^3$



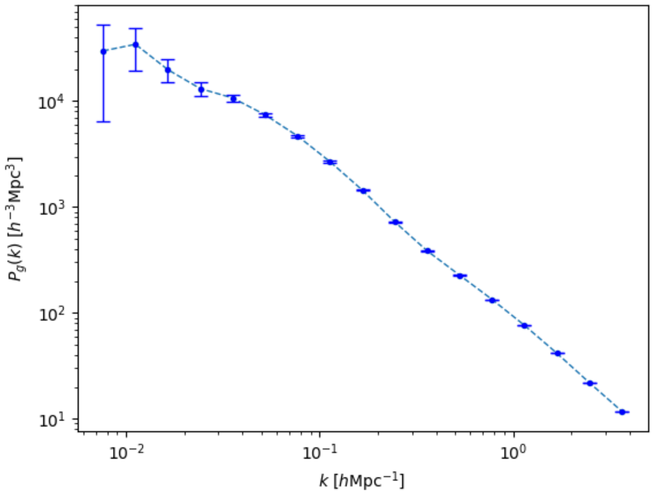
z=1

$\bar{N}_g = 0.42 \times 10^{-3} h^3/Mpc^3$

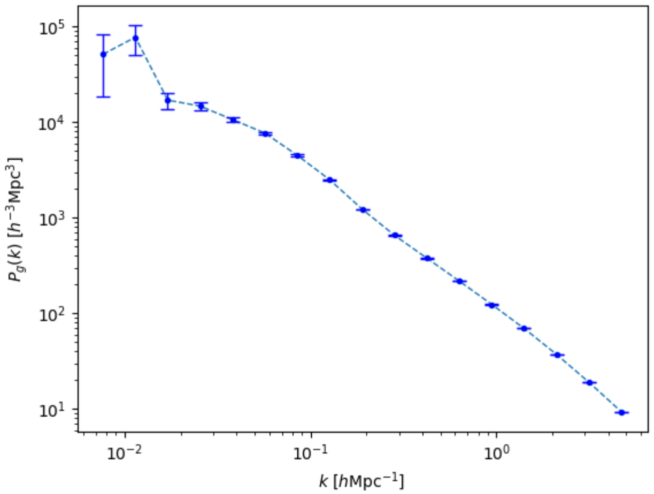


Galaxy auto-correlation power spectrum

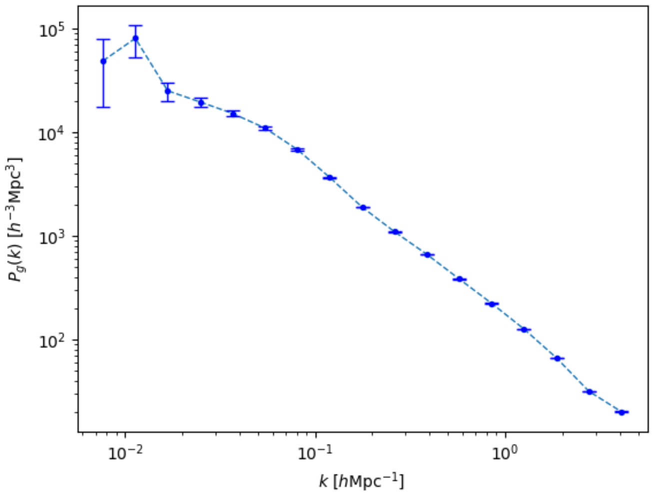
z=0.5



z=0.7

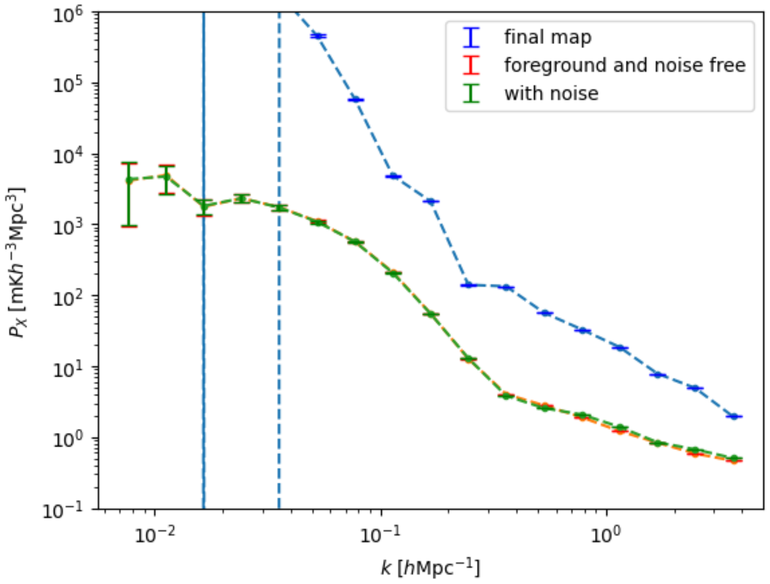


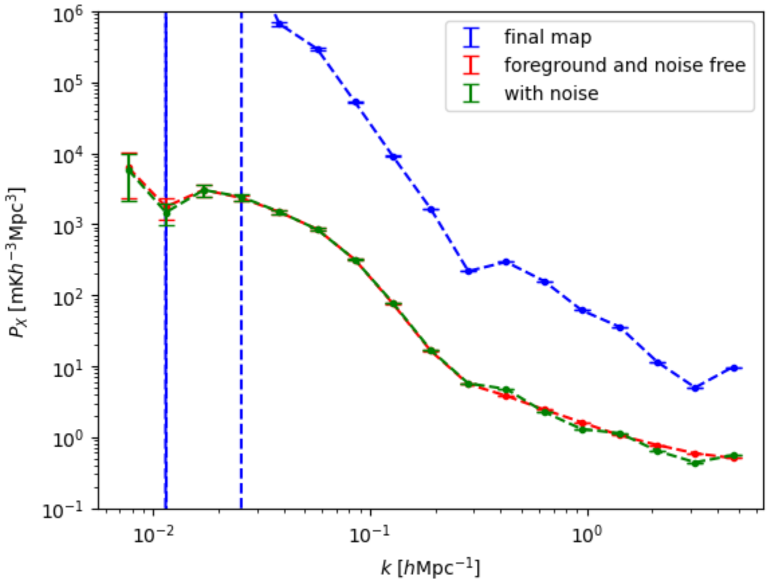
z=1

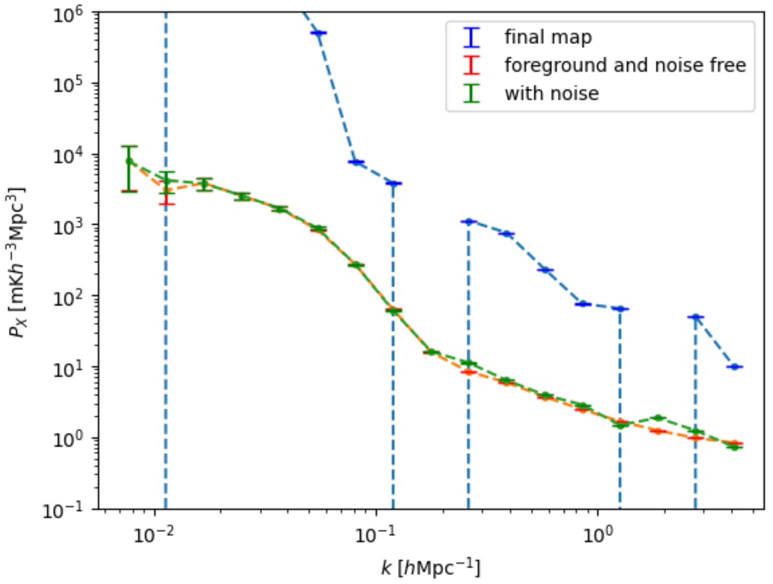


HI – Galaxy cross-correlation power spectrum

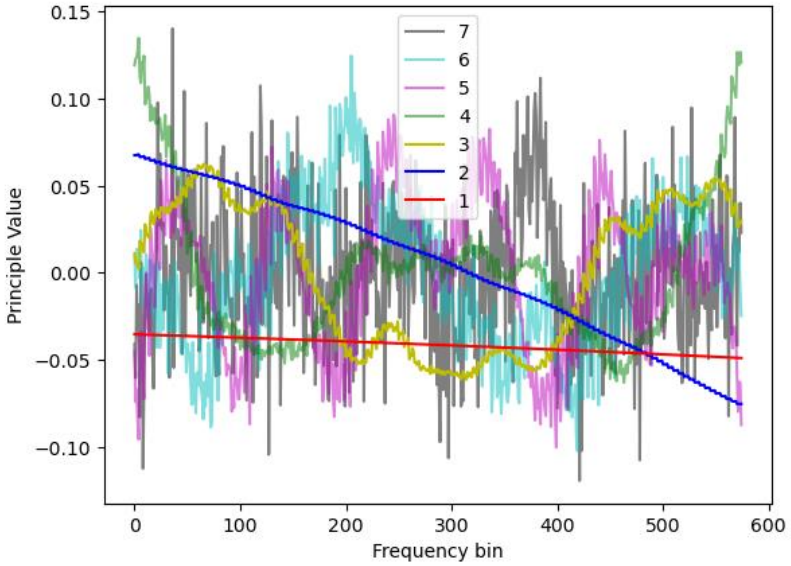
Final IM map = HI+systematic noise + Galactic emission + Point Sources + Polarization leakage from galaxy and point sources

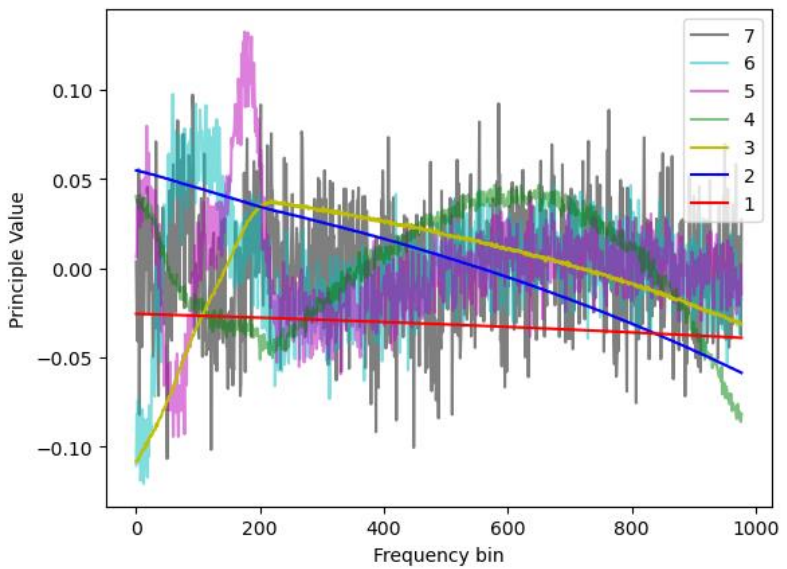


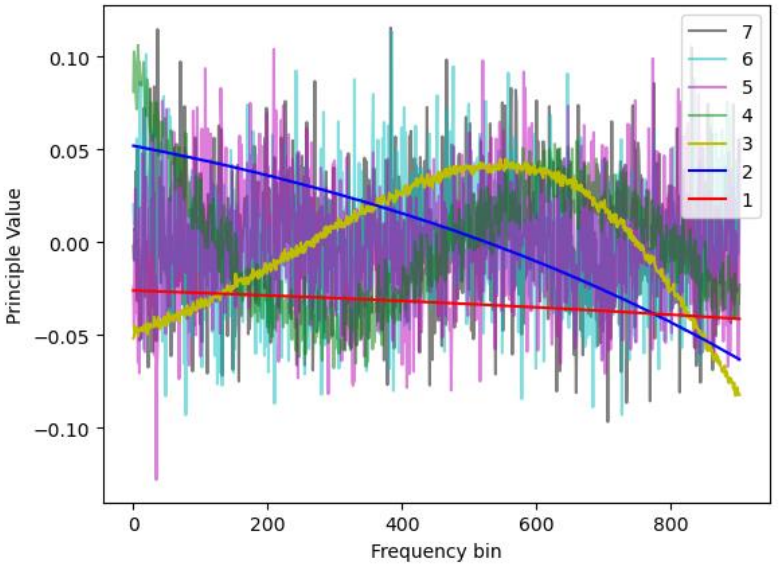


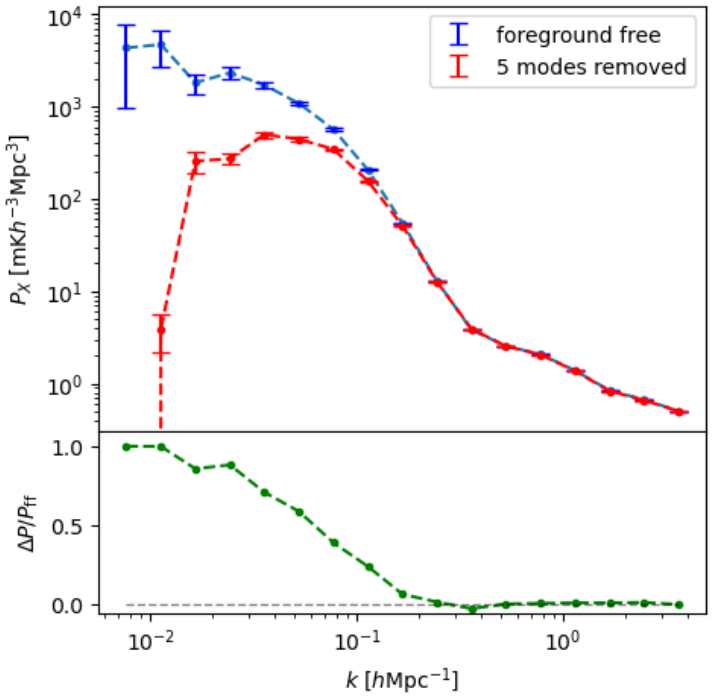


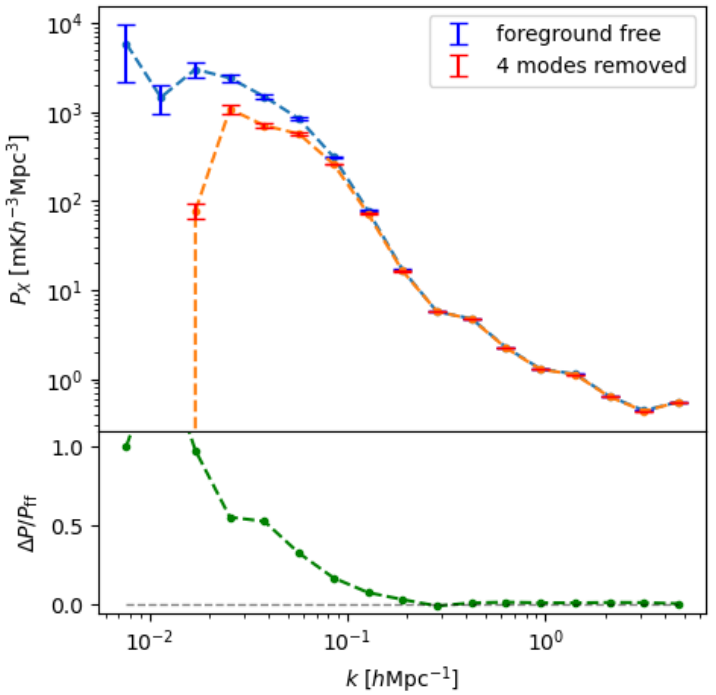
Foreground Removal - PCA

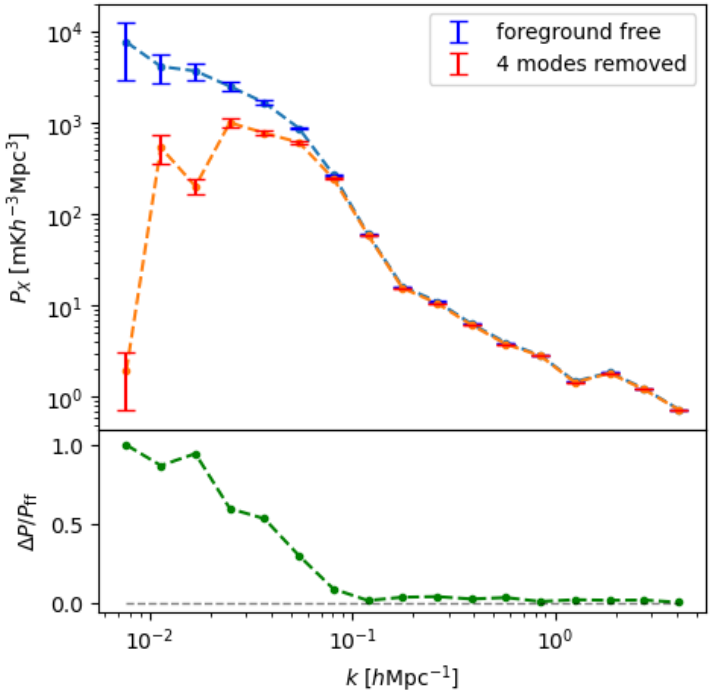












Signal Compensation

Signal compensation procedure

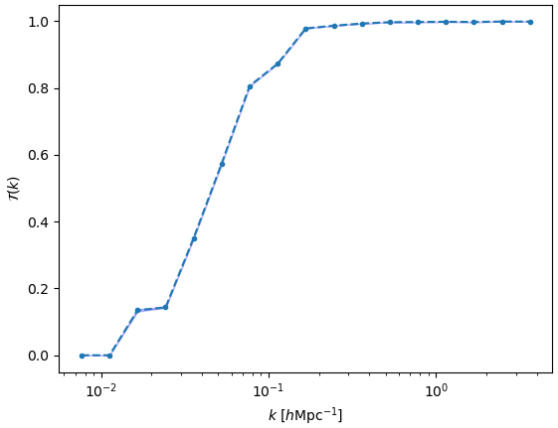
- First, we use **CAMB** to generate **matter power spectrum $P_m(k)$** following the same cosmological parameters that **JiuTian-1Gpc** use.
- We calculate the HI auto-power $P_{HI}(k)$ of the Jiutian-1Gpc, and then calculate the HI power spectrum bias by $b_{HIps}(k) = P_{HI}(k)/P_m(k)$.
- Then we use CAMB to generate matter power spectrum $P'_m(k)$ with our chosen cosmology. The the HI power spectrum of our mock data is calculated by $P_{mock}(k) = b_{HIps}(k) \times P'_m(k)$.
- Then we use $P_{mock}(k)$ to generate lognormal field and transform into mock data matrix **Y**.
- We inject the mock HI data **Y** into the observation data matrix **X**. We apply the PCA clean on this data combination, and the foreground removed mock data can be written as:

$$Y_c = [Y + X]_{PCA} - \mathrm{S_{HI}}$$

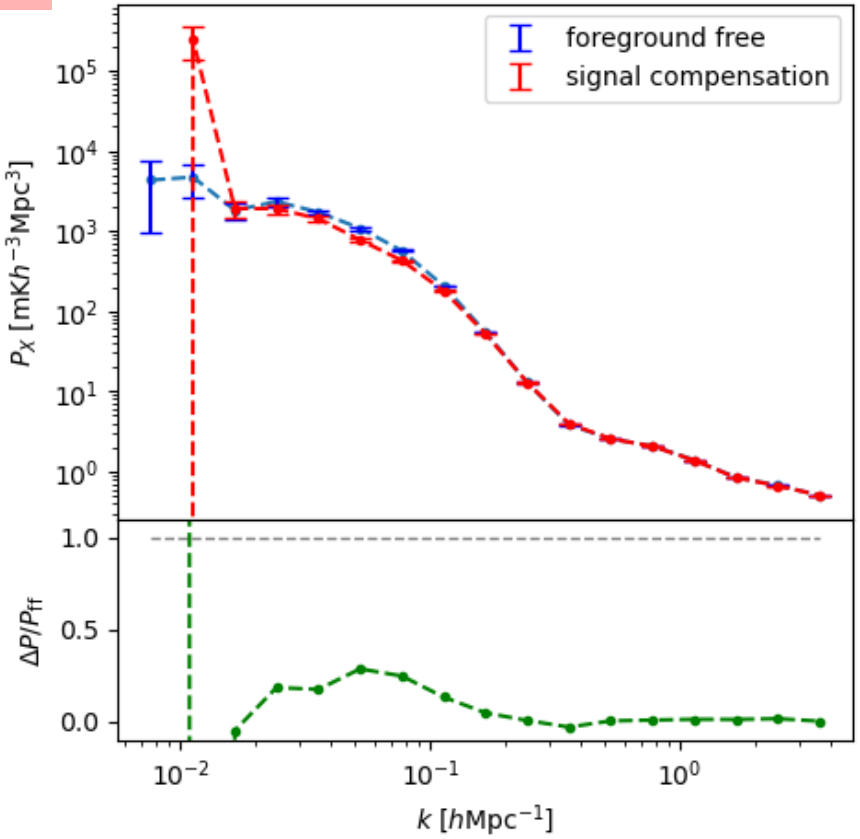
Transfer Function

- The transfer function is constructed as:

$$\mathcal{T}(k) = \frac{\mathcal{P}(Y_c, Y_g)}{\mathcal{P}(Y, Y_g)}$$



Cross-correlation power spectrum of CSST galaxy survey & MeerKAT HI IM (after signal compensation) at z=0.5



Thank You!

中国科学院国家天文台

NATIONAL ASTRONOMICAL OBSERVATORIES, CAS