Systematic Effect in HI IM

Dr. LI, Yichao

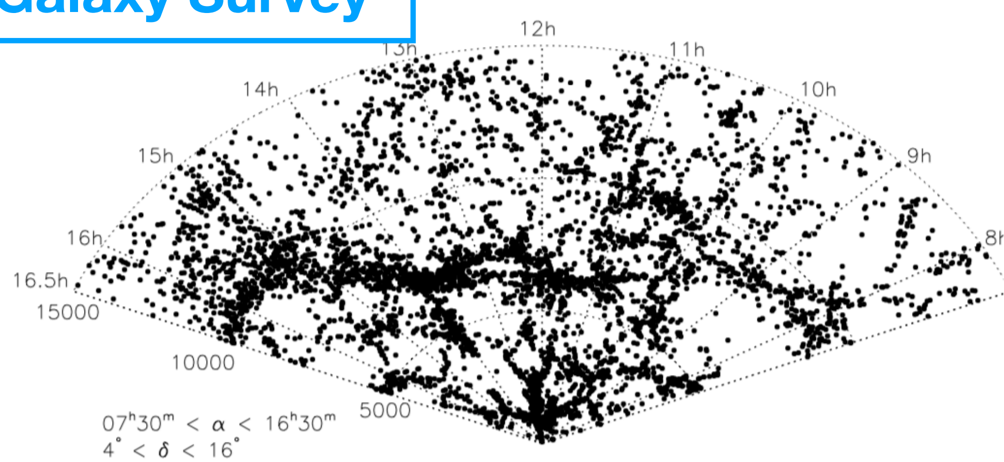
Northeastern University

HITS 2022 - Hi Intensity Mapping in Trieste

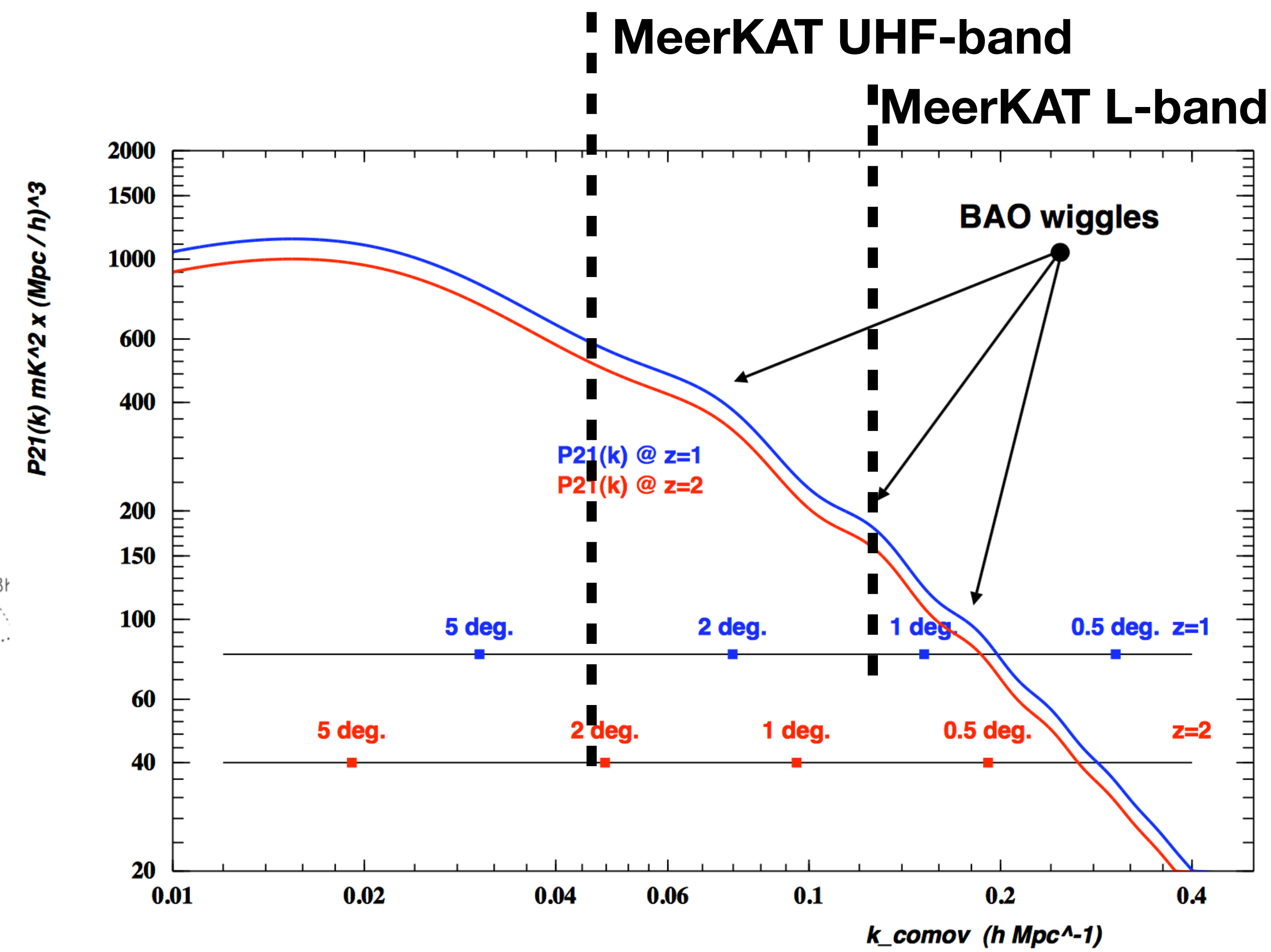
2022 May 25th

HI Intensity Mapping (IM)

Galaxy Survey



Intensity Mapping Survey



Ansari et. al. 1108.1474

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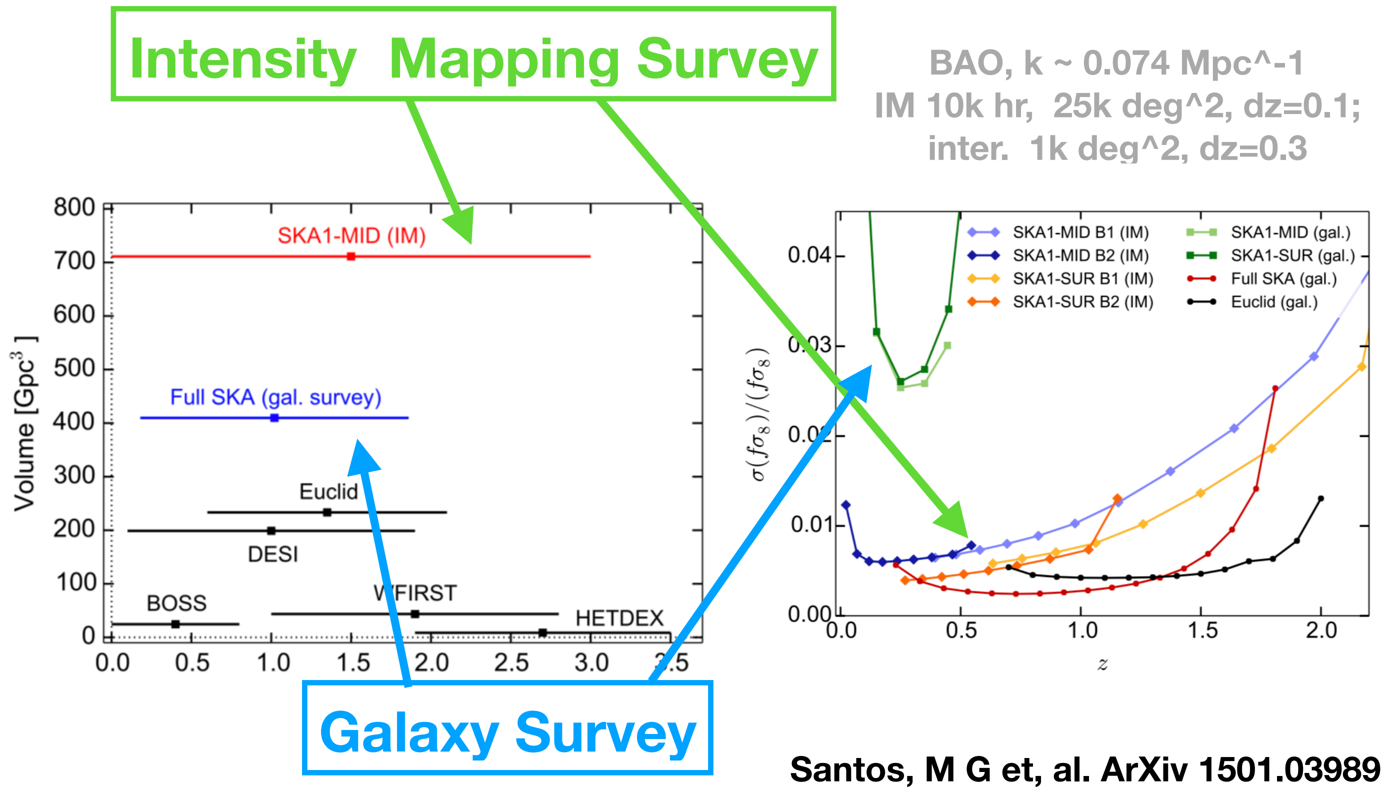
HI IM for cosmology

- **Provide huge observation volume for cosmology studies**
- Multi redshifts
- Multi tracer



Santos, M G et, al. ArXiv 1501.03989

- Cosmological Large-scale structure (LSS)
- Baryon Acoustic Oscillation (BAO)
- Redshift space distortion (RSD)
- Dark Energy
- Omega HI
- primordial non-Gaussianlity
- EoR

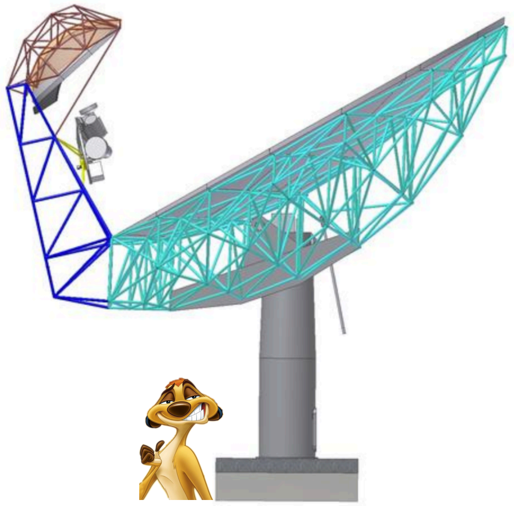
Current stage

- GBT/Parkes
- Tianlai (天籁)
- CHIME
- HIRAX
- BINGO
- FAST
- MeerKAT/SKA

- PAPER/HERA
- 21CMA
- LOFAR
- MWA

- Edges/PRIZM/DSL(鸿蒙)

MeerKAT/SKA



In the Future

Cosmology with Phase 1 of the Square Kilometre Array Red Book 2018: Technical specifications and performance forecasts

Square Kilometre Array Cosmology Science Working Group: David J. Bacon[1], Richard A. Battye[2], Philip Bull[3], Stefano Camera[2,4,5,6], Pedro G. Ferreira[7], Ian Harrison[2,7], David Parkinson[8], Alkistis Pourtsidou[3], Mário G. Santos[9,10,11], Laura Wolz[12], Filipe Abdalla[13,14], Yashar Akrami[15,16], David Alonso[7], Sambatra Andrianomena[9,10,17], Mario Ballardini[9,18], José Luis Bernal[19,20], Daniele Bertacca[21,22], Carlos A. P. Bengaly[9], Anna Bonaldi[23], Camille Bonvin[24], Michael L. Brown[2], Emma Chapman[25], Song Chen[9], Xuelei Chen[26], Steven Cunnington[1], Tamara M. Davis[27], Clive Dickinson[2], José Fonseca[9,22], Keith Grainge[2], Stuart Harper[2], Matt J. Jarvis[7,9], Roy Maartens[1,9], Natasha Maddox[28], Hamsa Padmanabhan[29], Jonathan R. Pritchard[25], Alvise Raccanelli[19], Marzia Rivi[13,18], Sambit Roychowdhury[2], Martin Sahlén[30], Dominik J. Schwarz[31], Thilo M. Siewert[31], Matteo Viel[32], Francisco Villaescusa-Navarro[33], Yidong Xu[26], Daisuke Yamauchi[34] and Joe Zuntz[35]

SKA dishes	133
SKA dish diameter	15m
MeerKAT dishes	64
MeerKAT dish diameter	13.5m

Band	ν/GHz	z range
1	0.35-1.05	0.35-3
2	0.95-1.75	0-0.5

Medium-Deep Band 2 Survey

5000 deg2, 10 000 h;
continuum week lensing survey
HI galaxy survey / HI IM

Wide Band 1 Survey

20 000 deg2, 10 000 h;
continuum survey
HI IM survey

Deep SKA1-Low Survey

100 deg2, 5 000 h;
EoR
Wide-shallow or medium-deep or deep

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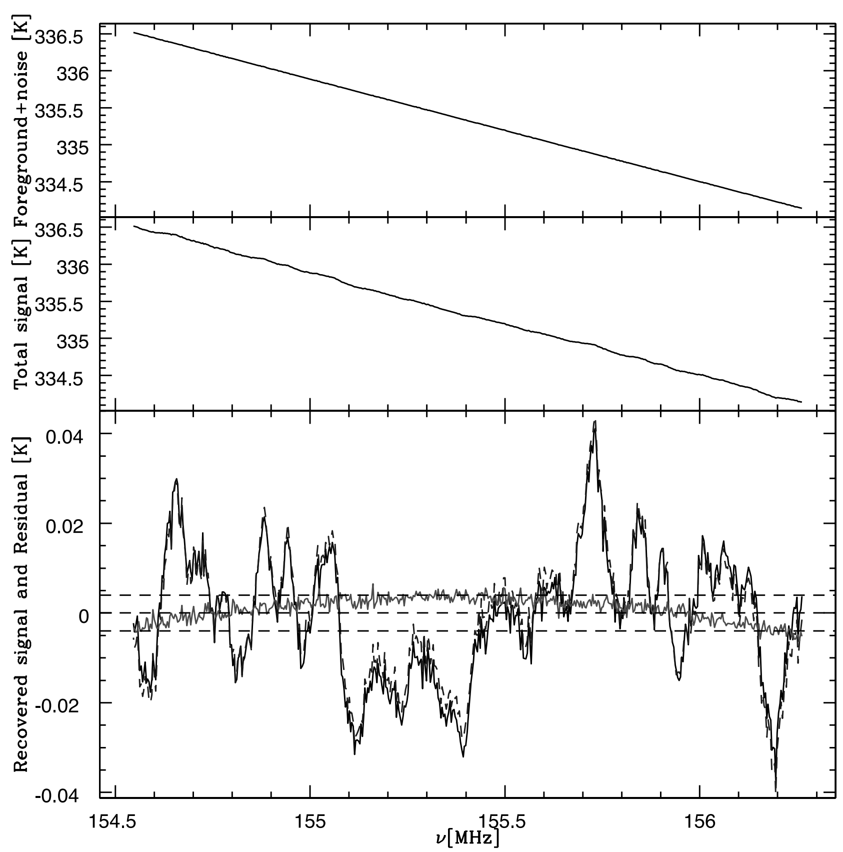
HI IM Challenges

- Foreground contamination
    - Model depended foreground clean



Wang, X., et. al (2006). *ApJ*, *650*(2), 529–537.

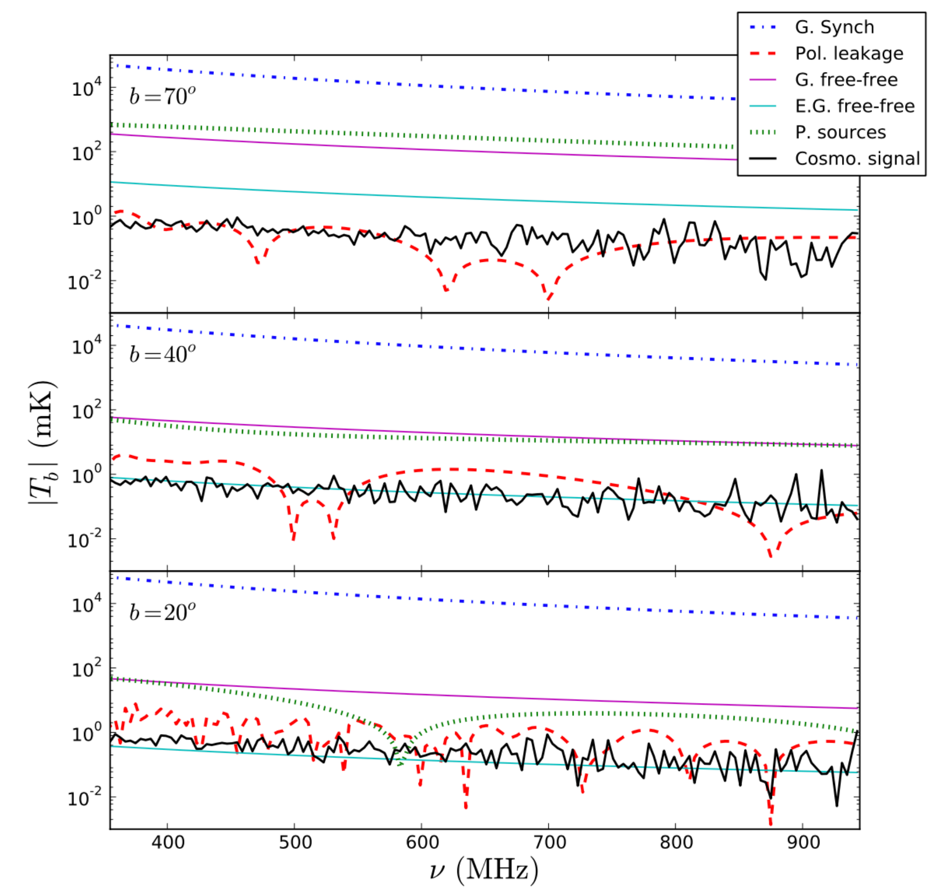


Figure 8. Frequency dependence of the different foregrounds and the cosmological signal along LOS with different galactic latitudes (given in the top-right corner of each panel). The effect of Faraday decorrelation increases as we approach the galactic plane, making the subtraction of the polarization leakage more challenging.

Alonso, D. et al. (2014) *MNRAS* 444, 3183

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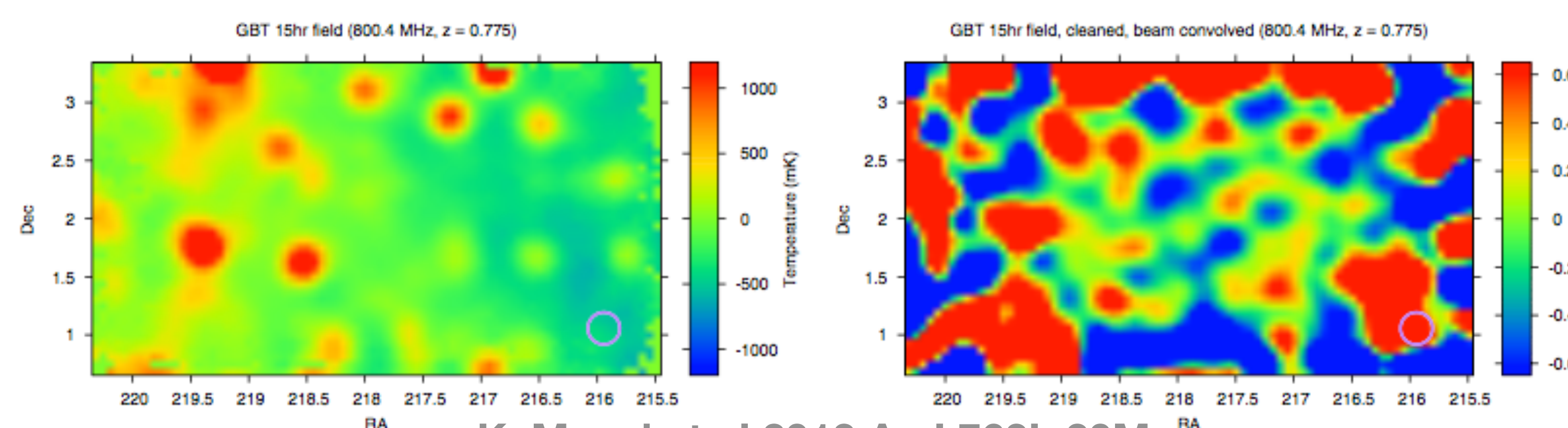
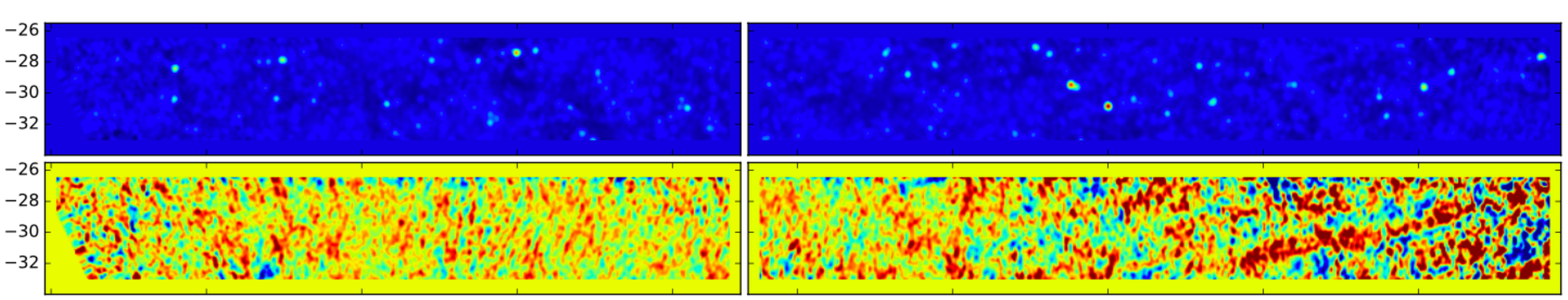
HI IM Challenges

- Foreground contamination
  - Model depended foreground clean
  - Model independent foreground clean
    - PCA/SVD ICA …

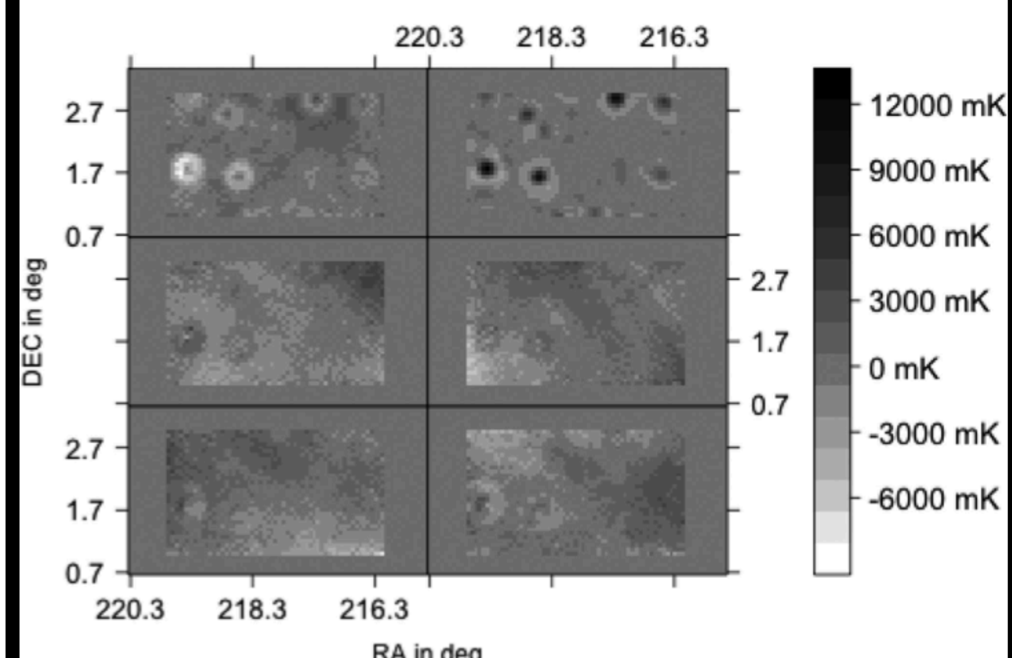


K. Masui et al 2013 ApJ 763L 20M



C. Anderson, N. J. Luciw, Y. Li et, al 1710.00424

PCA



L. Wolz et. al. arXiv:2102.04946

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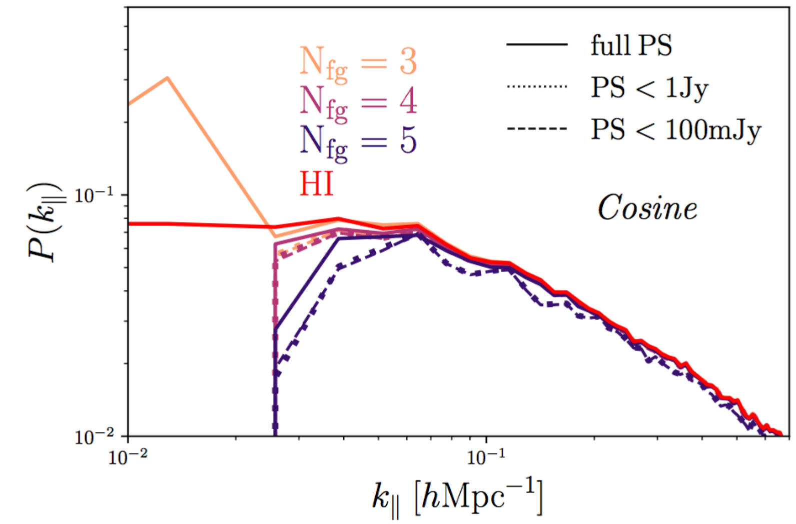
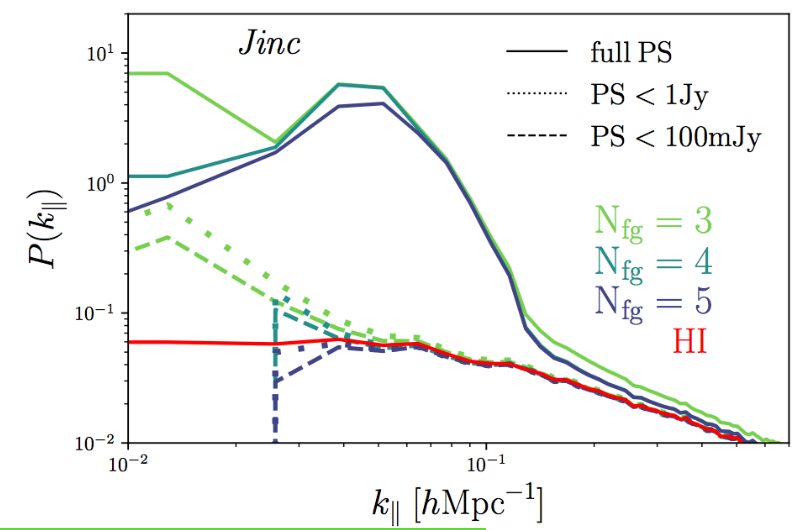
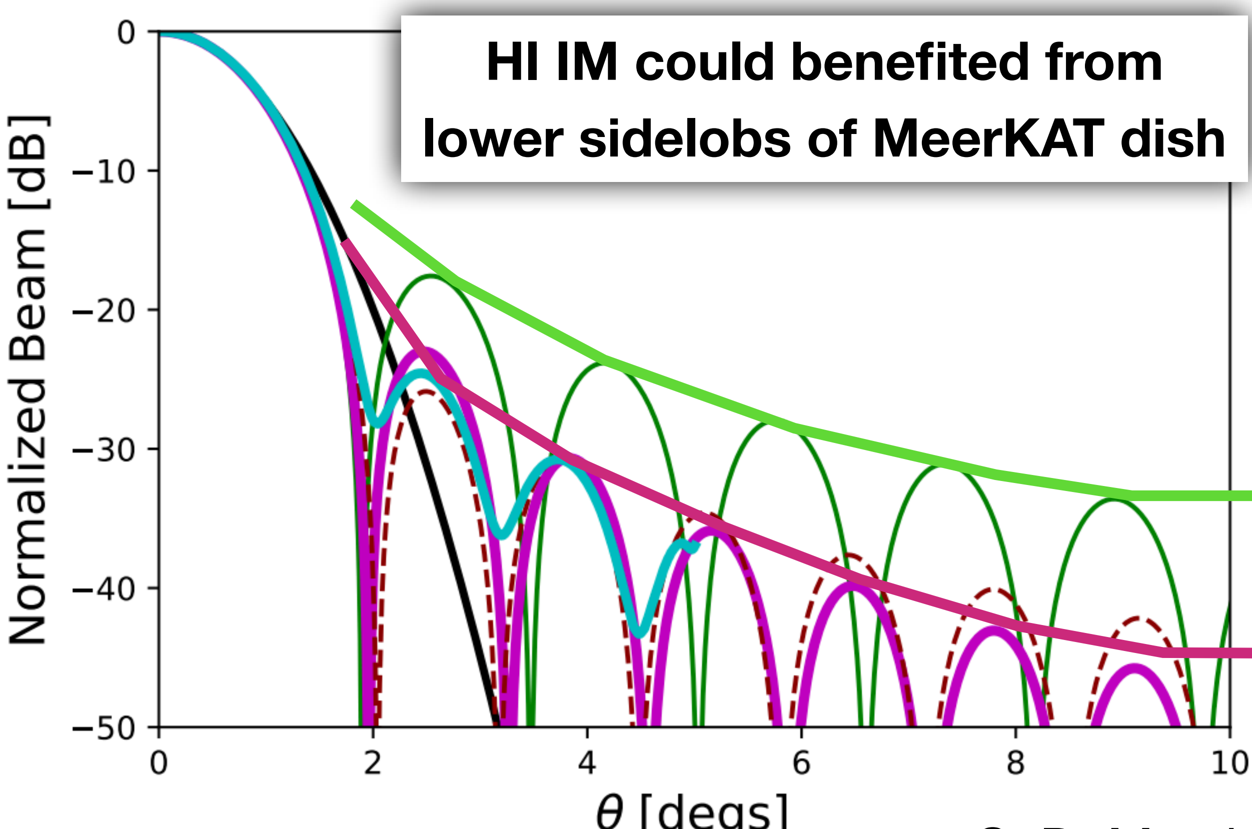
HI IM Challenges

- Foreground contamination
  - Model depended foreground clean
  - Model independent foreground clean
    - PCA/SVD ICA …
- Beam sidelobes







HI IM could benefited from lower sidelobs of MeerKAT dish

Jinc function sidelobs level

Measurements based sidelobs level

S. D. Matshawule et. al. arXiv:2011.10815

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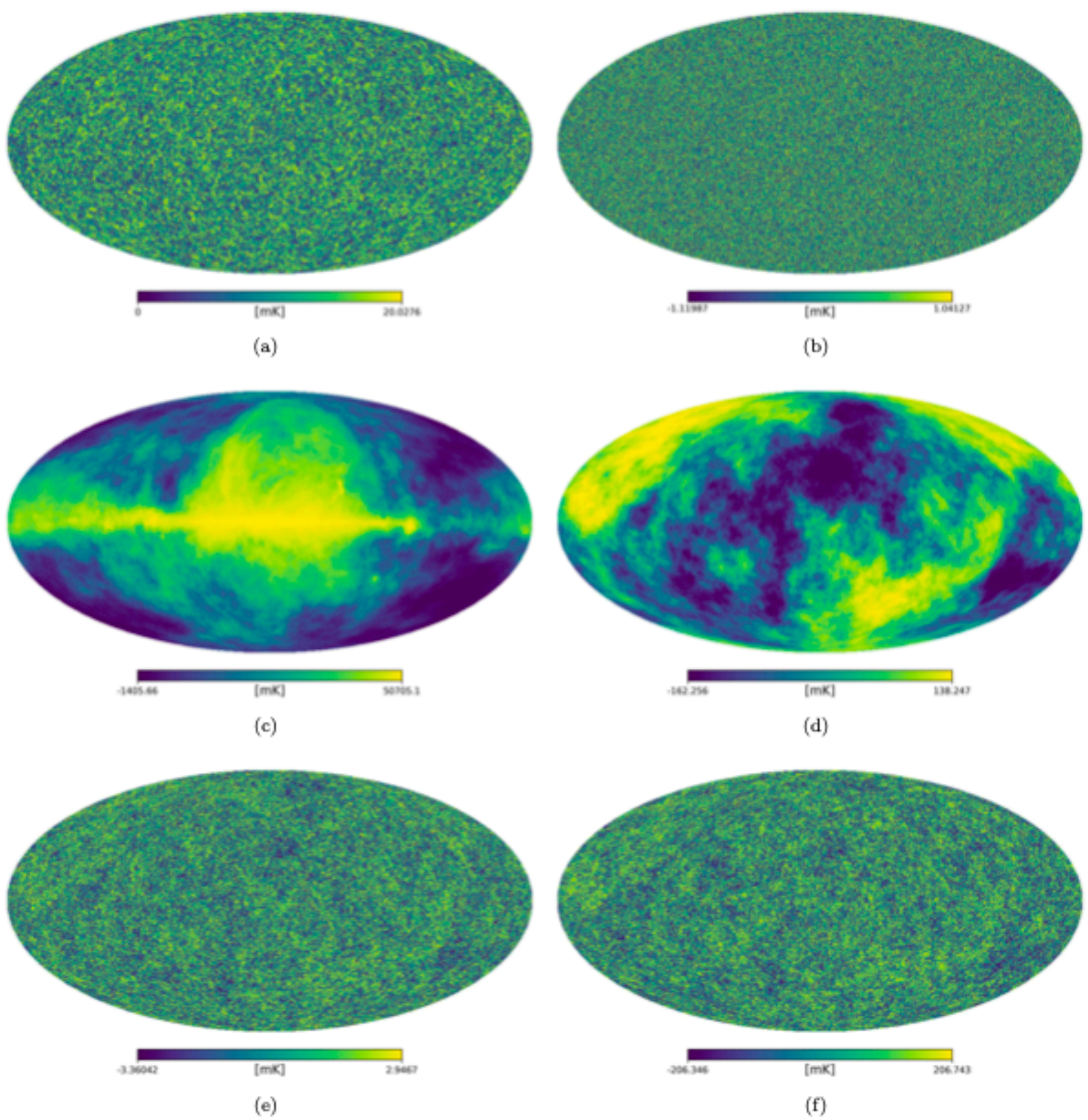
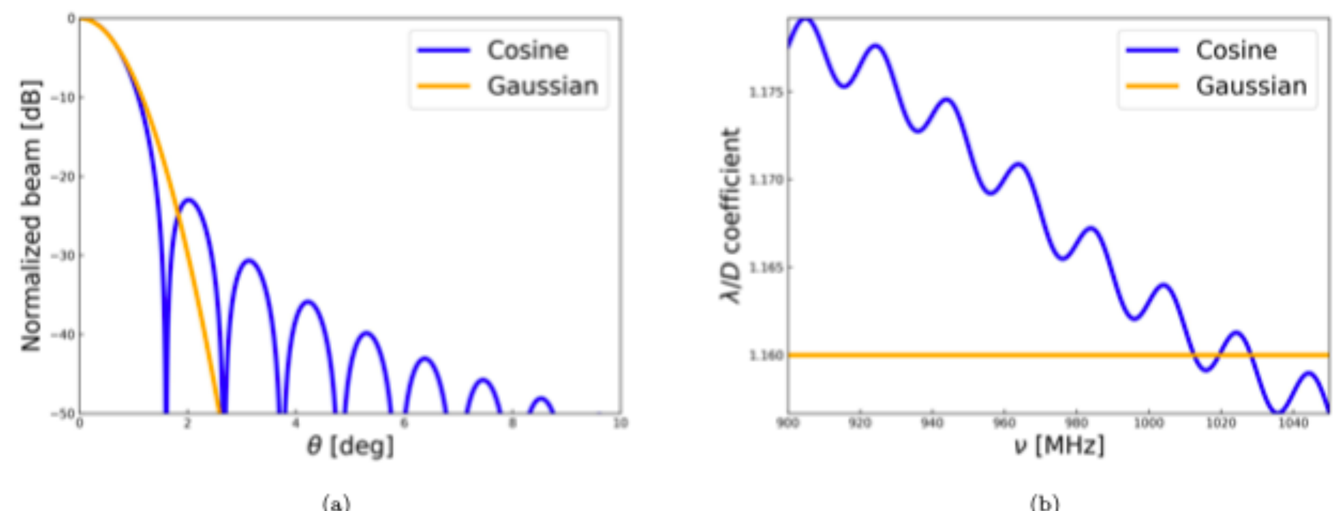
Eliminating Primary Beam Effect



CRIME



$$B_{\rm G}(\nu,\theta) = \exp\left[-4\ln 2\left(\frac{\theta}{\Delta\theta_{\rm G}(\nu)}\right)^2\right] \qquad \Delta\theta_{\rm G}(\nu) = 1.16\frac{\lambda(\nu)}{D}$$

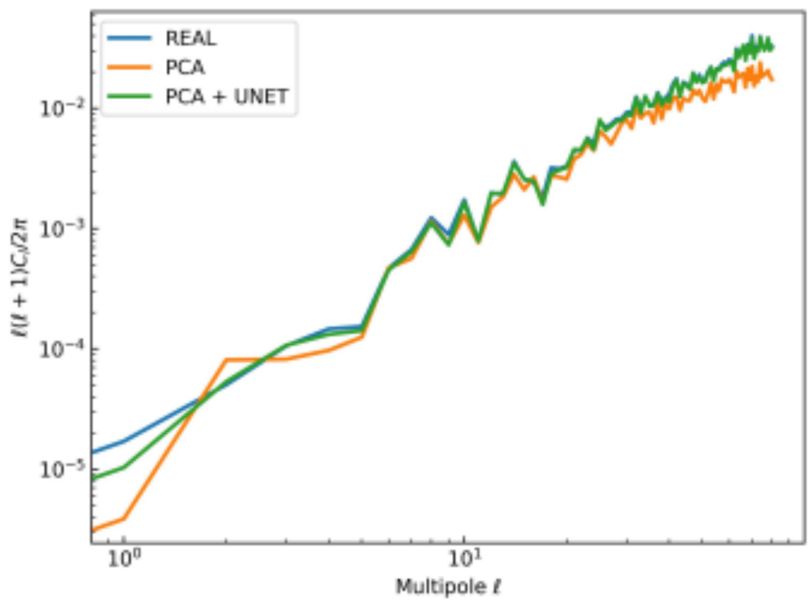
$$B_{\rm C} = \left[\frac{\cos(1.189\pi/\Delta\theta_{\rm C}(\nu))}{1-4(1.189\pi/\Delta\theta^2_{\rm C}(\nu))}\right]^2 \quad \Delta\theta_{\rm C}(\nu) = \frac{\lambda(\nu)}{D}\left[\sum_{d=0}^{8} a_d\hat{\nu}^d + A\sin\left(\frac{2\pi\hat{\nu}}{T}\right)\right]$$

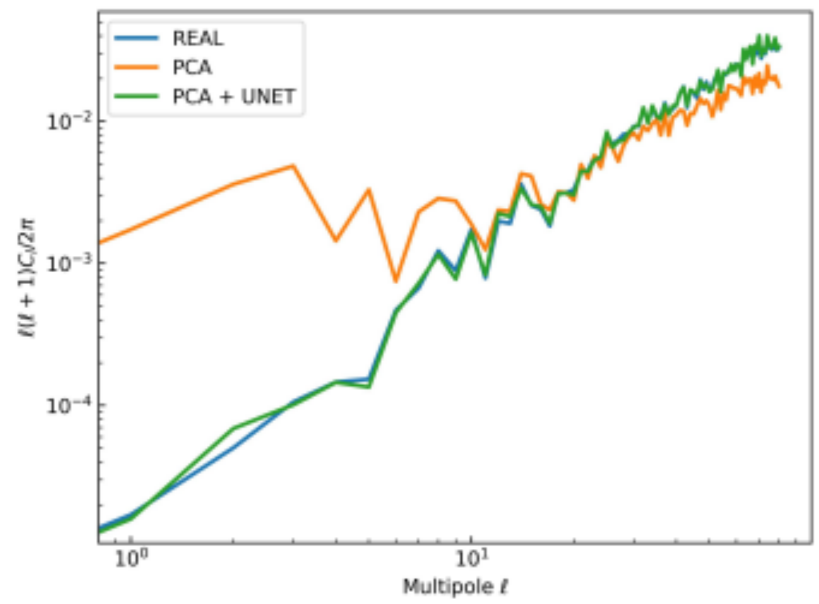
S. D. Matshawule et. al. arXiv:2011.10815

Ni, et al. arXiv:2204.02780

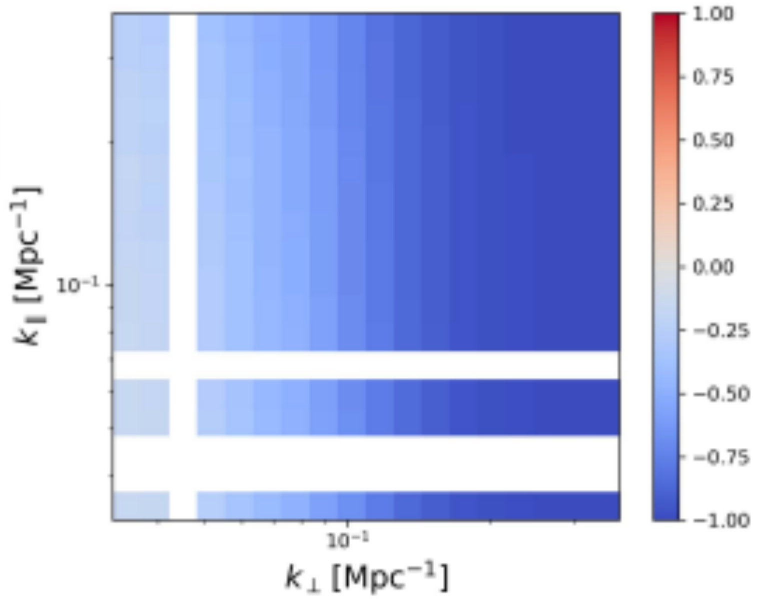
Eliminating Primary Beam Effect

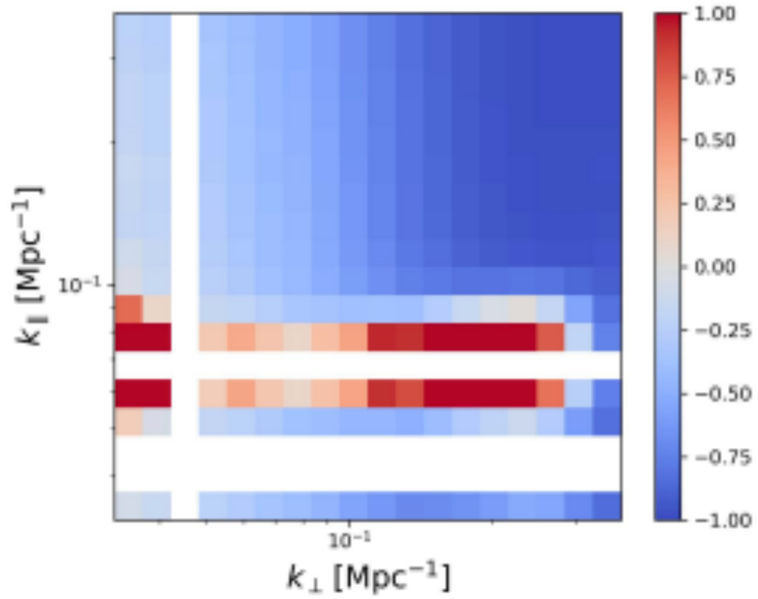
- PCA results





$$R(k_\parallel, k_\perp)_{\rm auto} = \frac{\bar{P}_{\rm cln}(k_\parallel, k_\perp)}{P_{\rm HI}(k_\parallel, k_\perp)} - 1,$$





Ni, et al. arXiv:2204.02780

U-Net

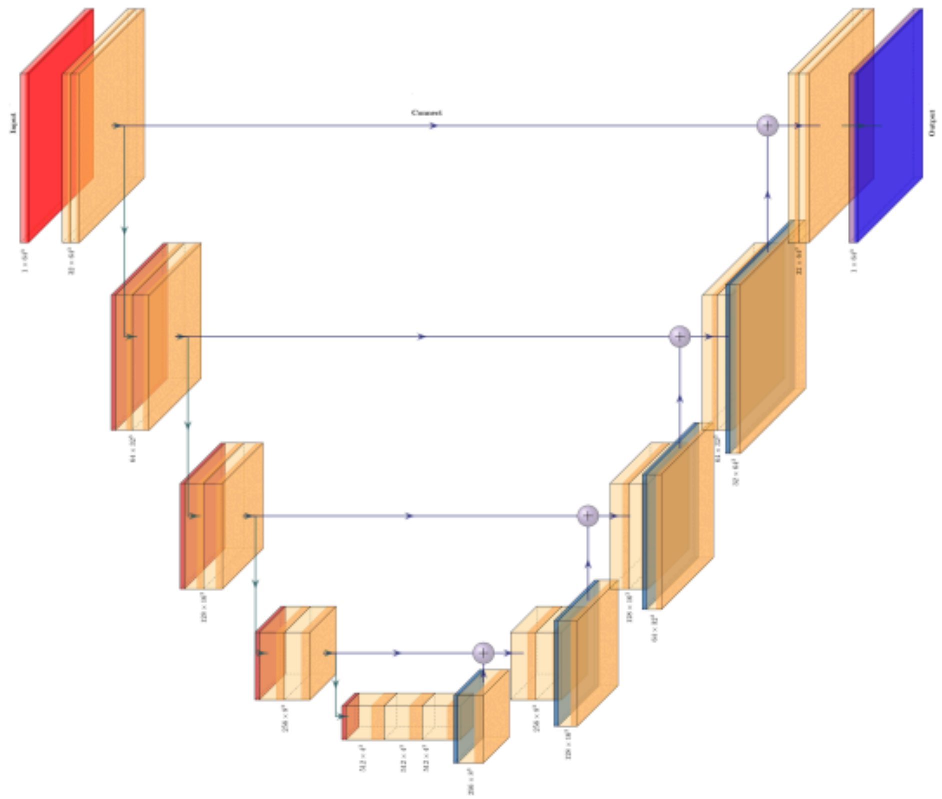


Table 2. Hyper parameters used in U-Net.

Hyper parameter	Description	Value
lr	learning rate	10^{-4}
wd	weight decay	10^{-5}
epochs	number of epochs	20
batch_size	batch size	16
optimizer	optimizer for training	NAdam
act	activation function	ReLU

Ni, et al. arXiv:2204.02780

deep21: a Deep Learning Method for 21cm Foreground Removal

T. Lucas Makinen, [a,b,c,1] Lachlan Lancaster, [a] Francisco Villaescusa-Navarro, [a] Peter Melchior, [a,d] Shirley Ho, [e] Laurence Perreault-Levasseur, [e,f,g] and David N. Spergel [e,a]

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[c] Center for Statistics and Machine Learning, Princeton University, Princeton, NJ 08544, USA
[d] Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY, 10010, USA
[e] Department of Physics, Univesité de Montréal, CP 6128 Succ. Centre-ville, Montréal, H3C 3J7, Canada
[f] Mila - Quebec Artificial Intelligence Institute, Montréal, Canada

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Abstract. We seek to remove foreground contaminants from 21cm intensity mapping observations. We demonstrate that a deep convolutional neural network (CNN) with a UNet architecture and three-dimensional convolutions, trained on simulated observations, can effectively separate frequency and spatial patterns of the cosmic neutral hydrogen (HI) signal from foregrounds in the presence of noise. Cleaned maps recover cosmological clustering amplitude and phase within 20% at all relevant angular scales and frequencies. This amounts to a reduction in prediction variance of over an order of magnitude across angular scales, and improved accuracy for intermediate radial scales ($0.025 < k_{\parallel} < 0.075$ h Mpc^{-1}) compared to standard Principal Component Analysis (PCA) methods. We estimate epistemic confidence intervals for the network's prediction by training an ensemble of UNets. Our approach demonstrates the feasibility of analyzing 21cm intensity maps, as opposed to derived summary statistics, for upcoming radio experiments, as long as the simulated foreground model is sufficiently realistic. We provide the code used for this analysis on GitHub, as well as a browser-based tutorial for the experiment and UNet model via the accompanying Colab notebook.

Keywords: cosmology: radio – reionisation, large-scale structure – foregrounds – deep learning, signal processing

[1] Corresponding author.

Makinen, et al. arXiv:2010.15843

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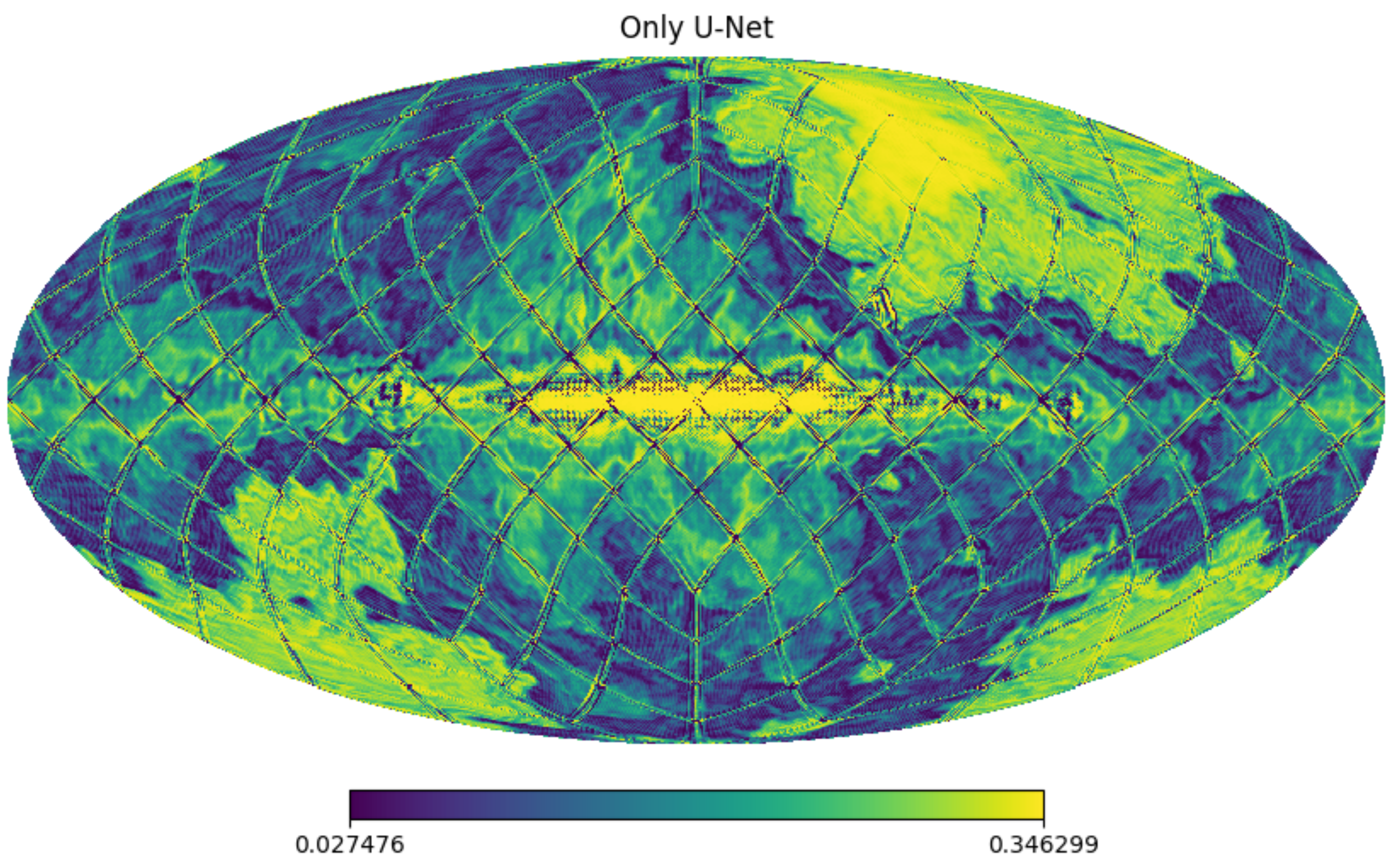
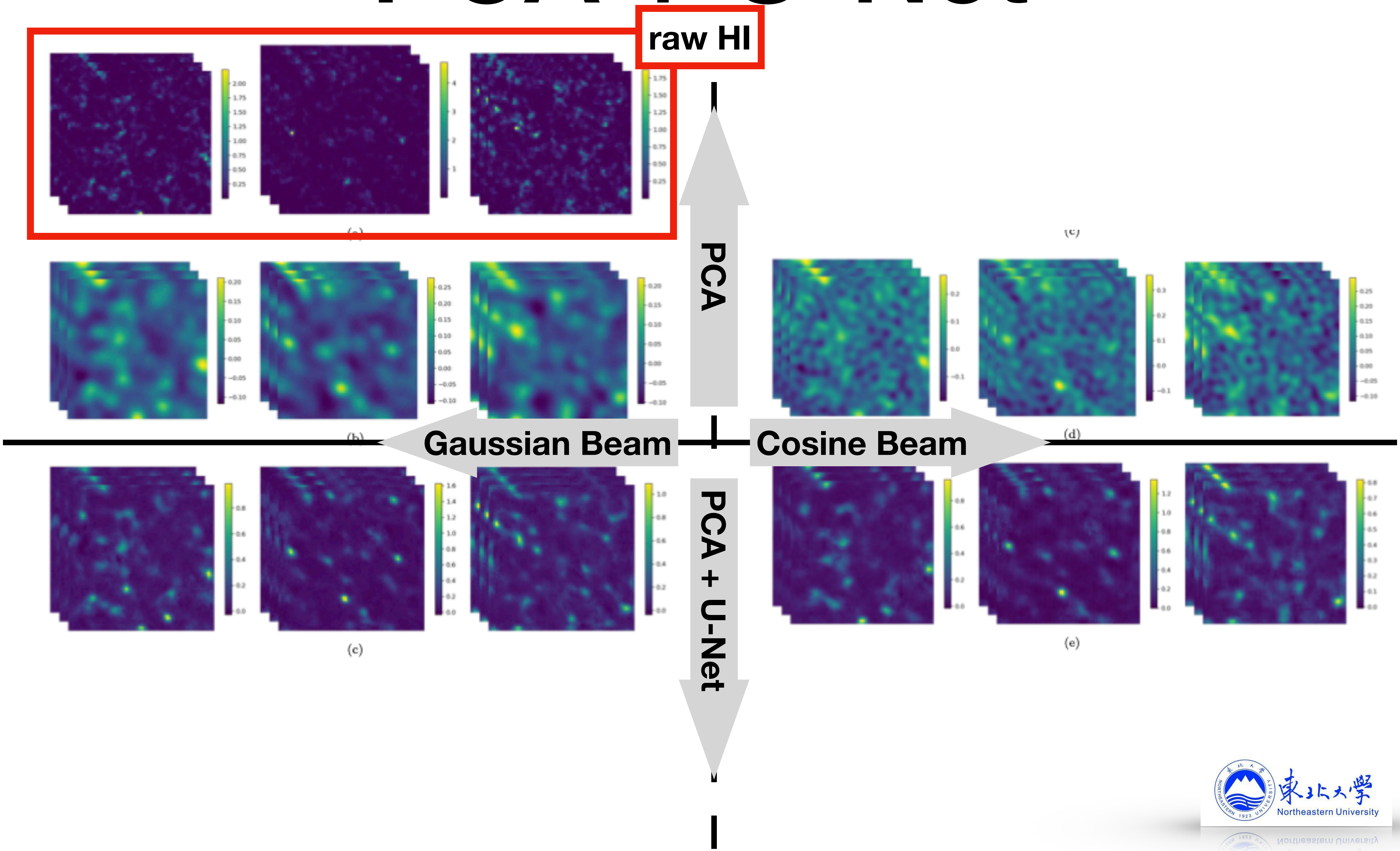
Failed with U-Net Only

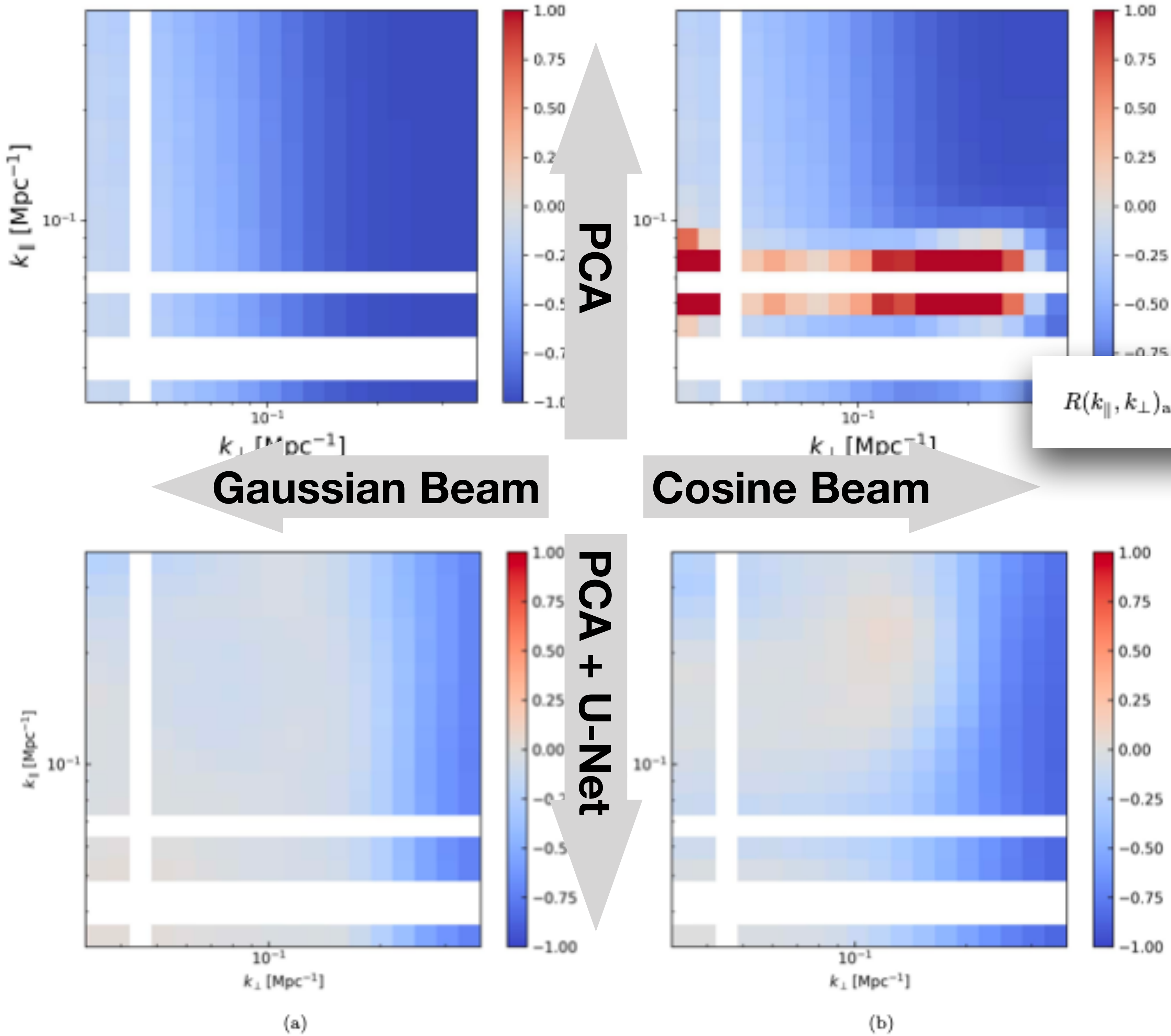
- Due to the huge amplitude dynamic range, U-Net results in serious edge effect
- Need preprocessing step
  - PCA + U-Net
    - PCA -> Foreground
    - U-Net -> Systematic effect



PCA + U-Net



PCA + U-Net



$$R(k_\parallel, k_\perp)_{\rm auto} = \frac{\bar{P}_{\rm cln}(k_\parallel, k_\perp)}{P_{\rm HI}(k_\parallel, k_\perp)} - 1,$$

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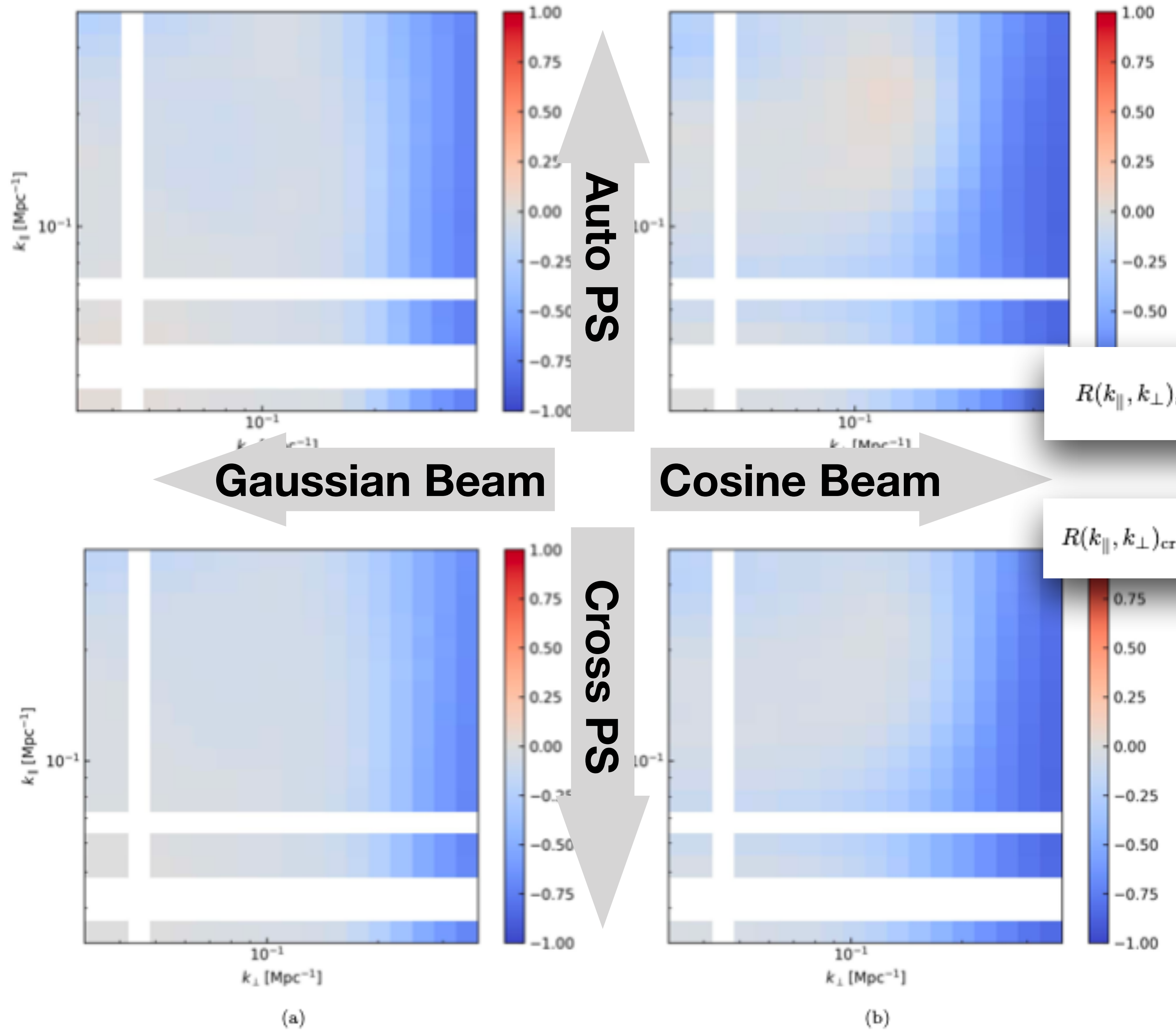
PCA + U-Net



$$R(k_\parallel, k_\perp)_{\rm auto} = \frac{\bar{P}_{\rm cln}(k_\parallel, k_\perp)}{P_{\rm HI}(k_\parallel, k_\perp)} - 1,$$

$$R(k_\parallel, k_\perp)_{\rm cross} = \frac{\bar{P}_{\rm cln,HI}(k_\parallel, k_\perp)}{P_{\rm HI}(k_\parallel, k_\perp)} - 1,$$

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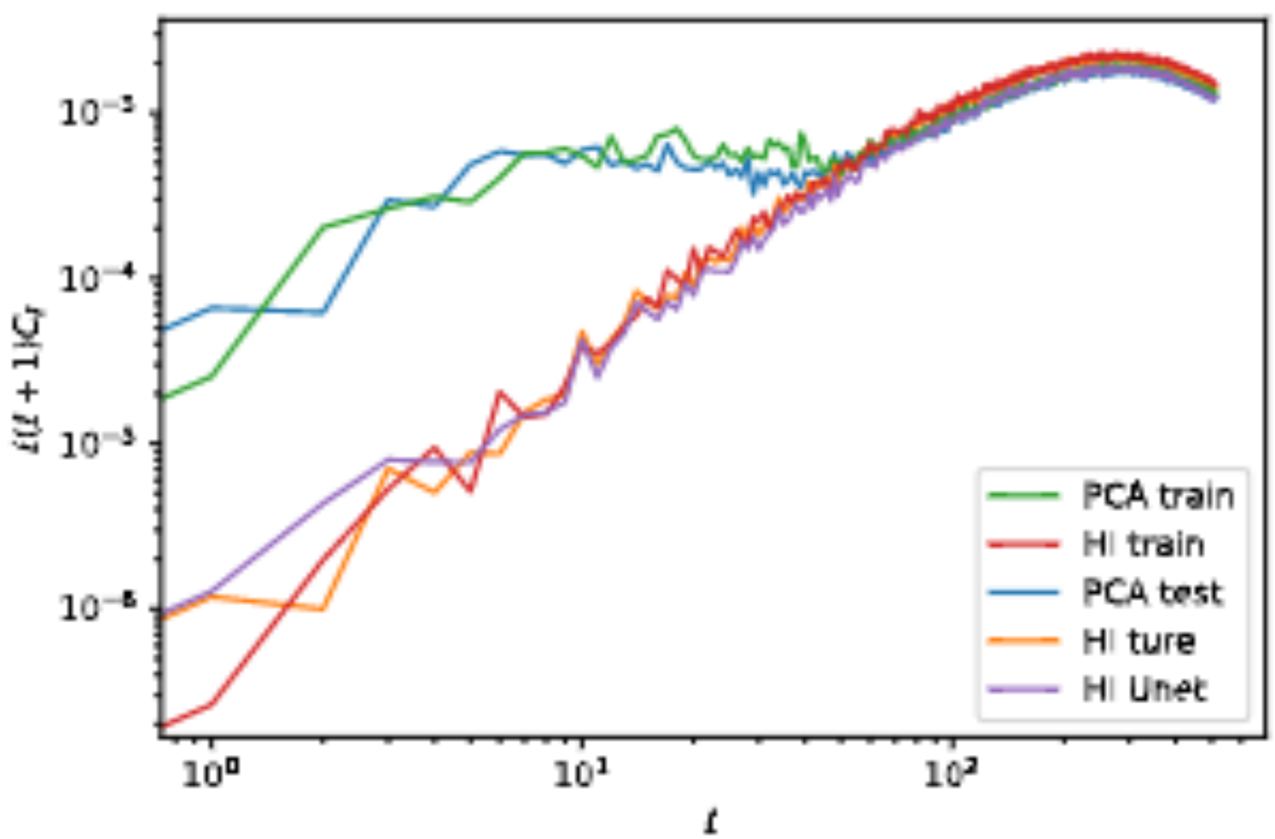
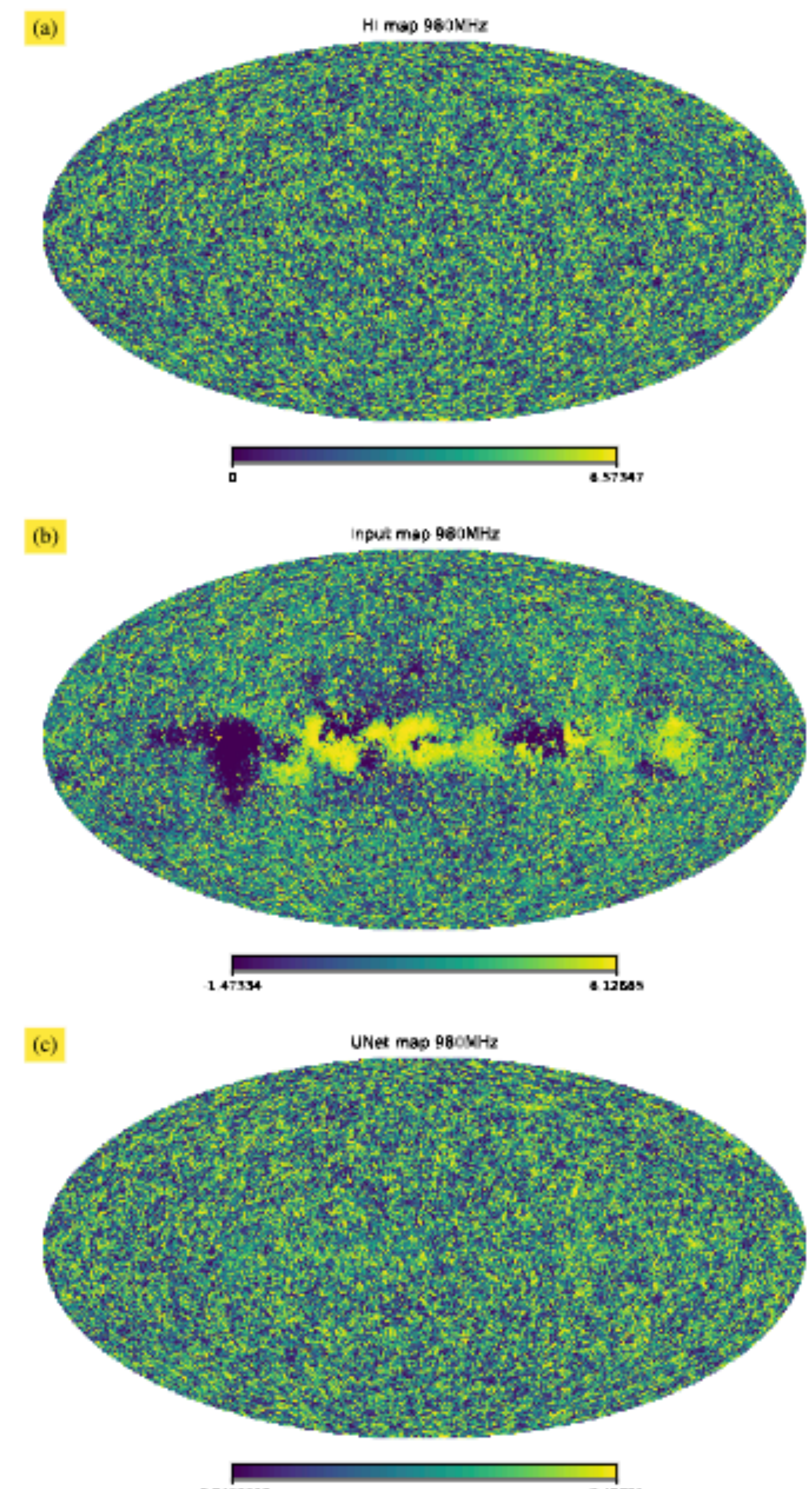
- Eliminating Primary Beam Effect
- Eliminate the effects of polarization leakage





HI IM Challenges

- Foreground contamination
  - Model depended foreground clean
  - Model independent foreground clean
    - PCA/SVD ICA …
- Beam sidelobes
- Correlated noise (1/f noise)

1/f Noise

S. Harper et.al. arXiv:1711.07843

$$d(t,\nu) = G(t,\nu)T_{\rm in}(t,\nu) + n(t,\nu),$$

$$\delta_d(t,\nu) \approx \underbrace{\frac{\delta T_{\rm ext}(t,\nu)}{\bar{T}_{\rm in}(\nu)}}_{\textbf{sky}} + \underbrace{\frac{\delta T_{\rm rx}(t,\nu)}{\bar{T}_{\rm in}(\nu)} + \frac{\delta G(t,\nu)}{\bar{G}(\nu)}}_{\textbf{correlated}} + \underbrace{\frac{n(t,\nu)}{\bar{T}_{\rm in}(\nu)\bar{G}(\nu)}}_{\textbf{white}}$$

Temporal PS model

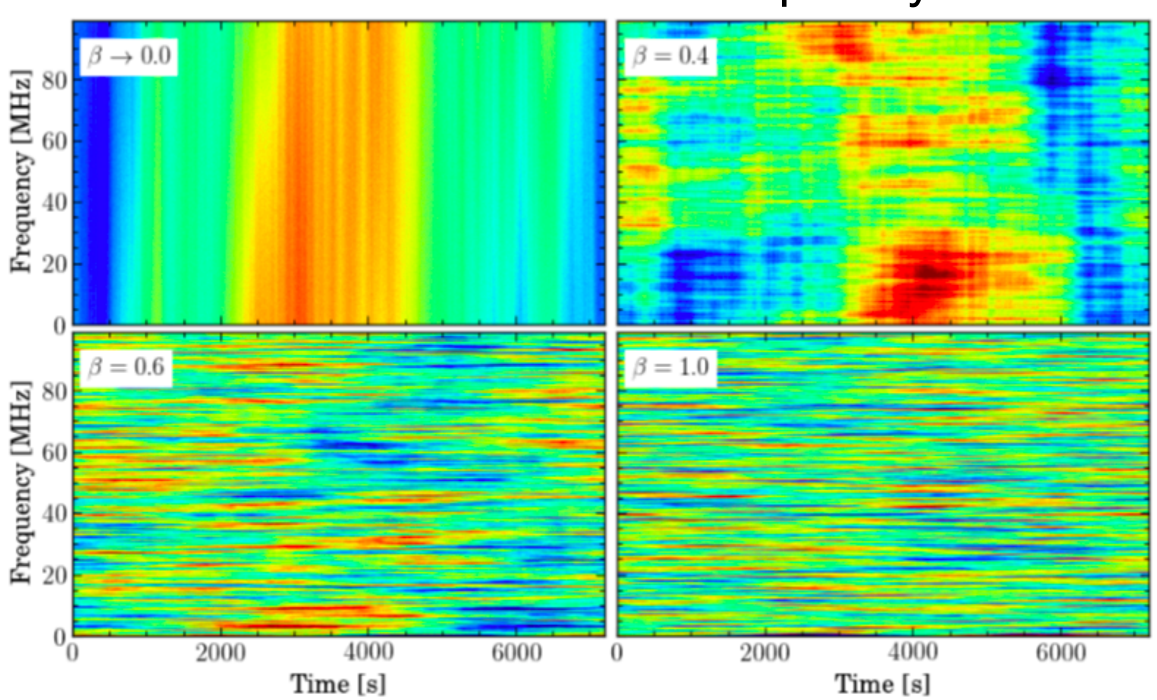
$$S^t(f,\nu) = \frac{A}{\delta\nu}\left(1 + \left(\frac{f_k}{f}\right)^\alpha\right)$$

2D PS model

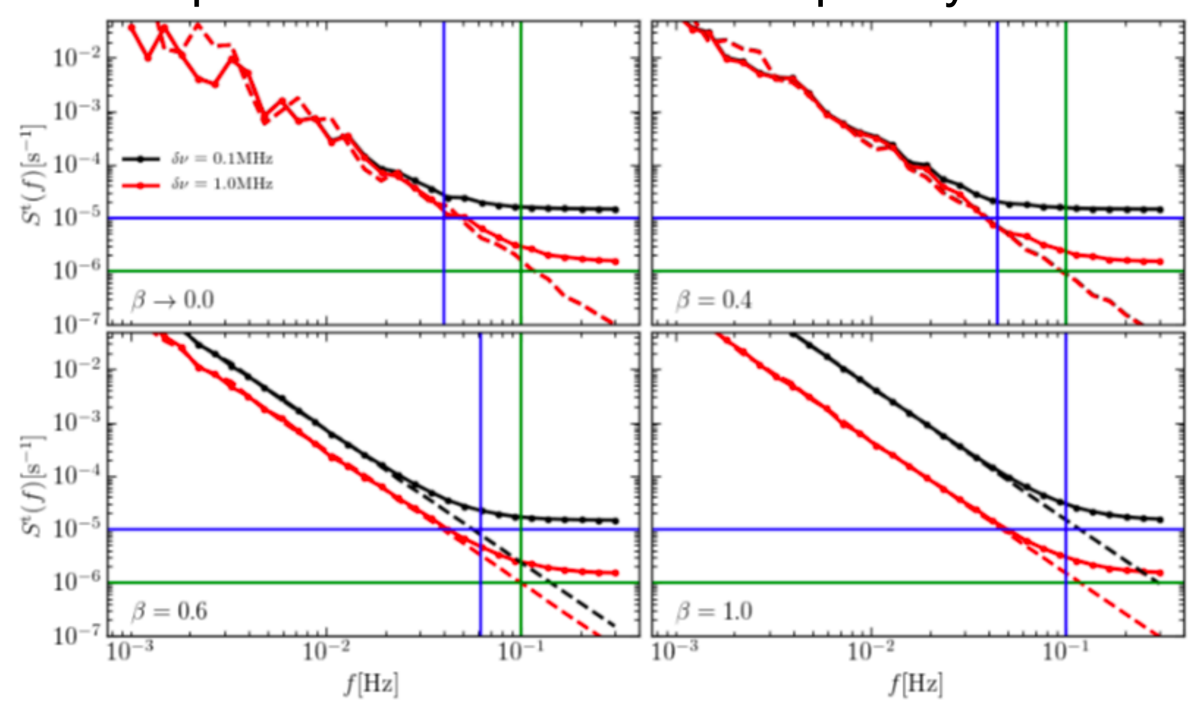
$$S(f,\tau) = A\left(1 + \frac{1}{K\delta\nu}\left(\frac{f_k}{f}\right)^\alpha \left(\frac{\tau_0}{\tau}\right)^{\frac{1-\beta}{\beta}}\right),$$

White Noise (1) **Temporal Correlation** ($\frac{1}{K\delta\nu}\left(\frac{f_k}{f}\right)^\alpha$) **Frequency Correlation** ($\left(\frac{\tau_0}{\tau}\right)^{\frac{1-\beta}{\beta}}$)

Simulated TOD with different frequency correlation



Temporal PS with different frequency resolution

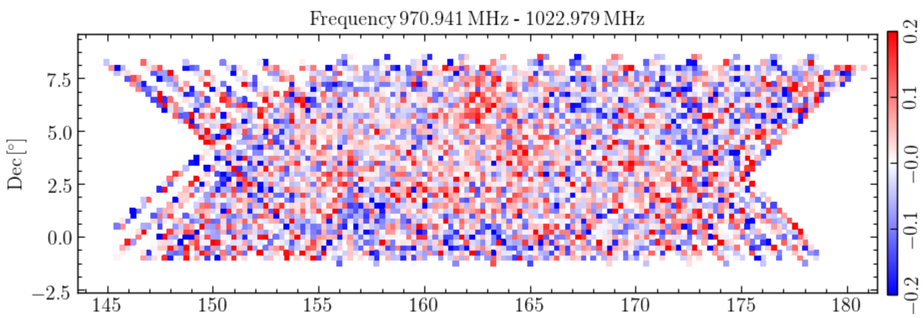


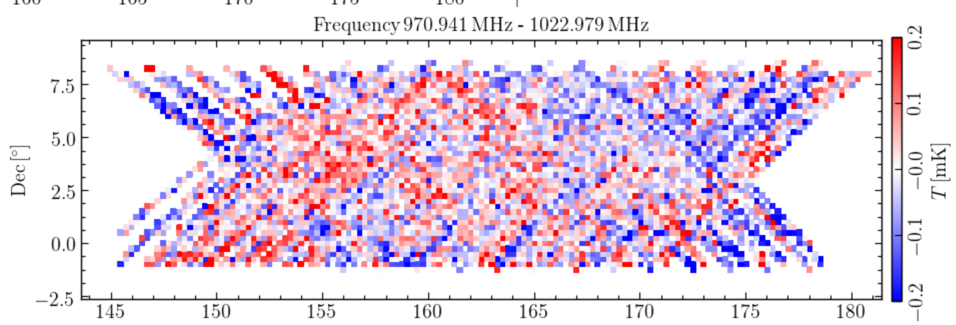
Y. Li et. al (2021) MNRAS 501(3) 4344. arXiv:2007.01767

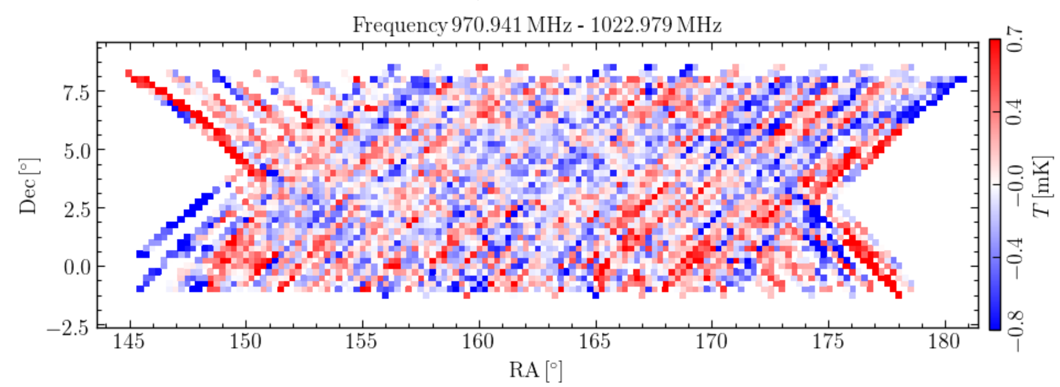
1/f Noise

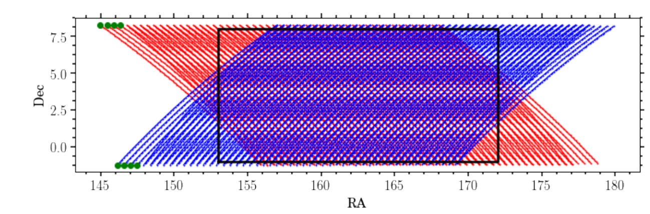
$$S(f,\tau) = A\left(1 + \frac{1}{K\delta\nu}\left(\frac{f_k}{f}\right)^{\alpha}\left(\frac{\tau_0}{\tau}\right)^{\frac{1-\beta}{\beta}}\right),$$

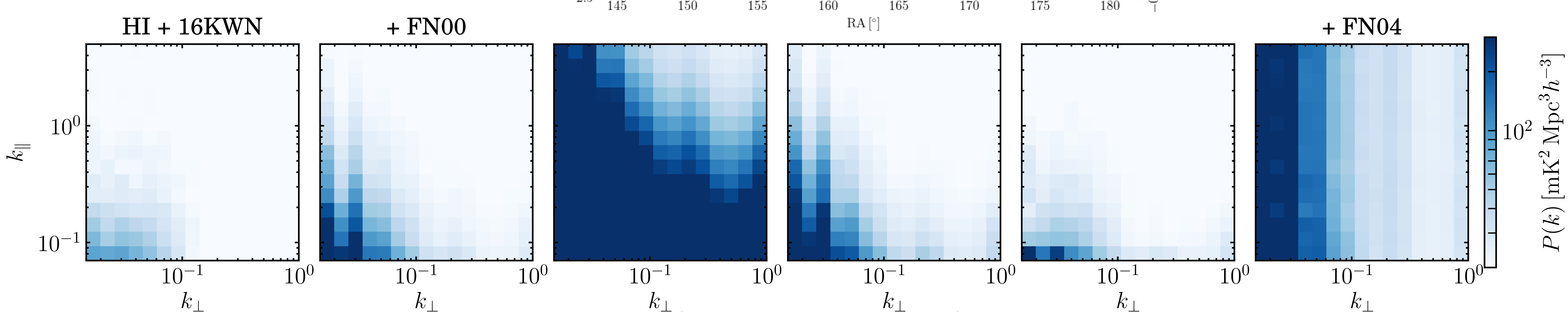
White Noise | **Temporal Correlation** | **Frequency Correlation**









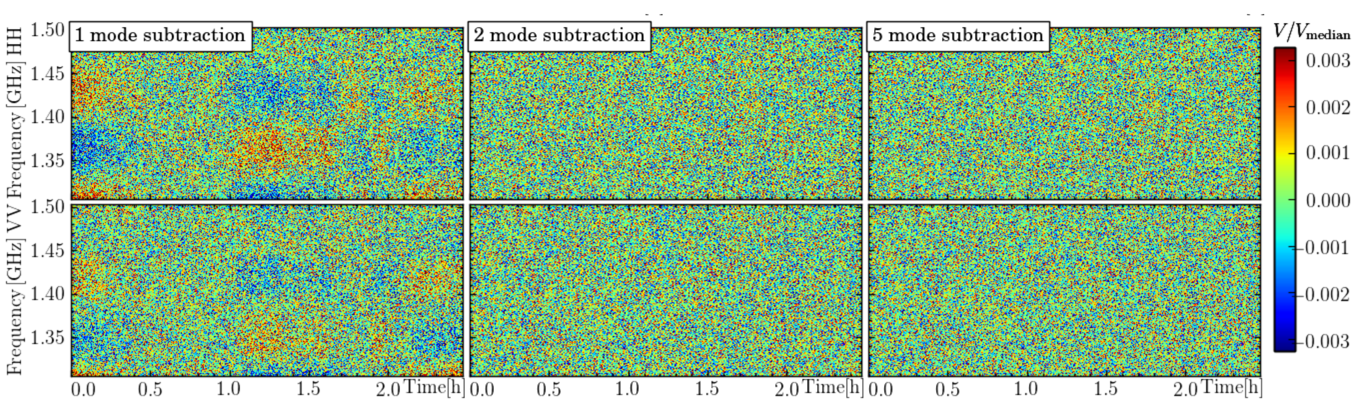


fk ↑ **alpha ↑** **beta~0** **beta=1**

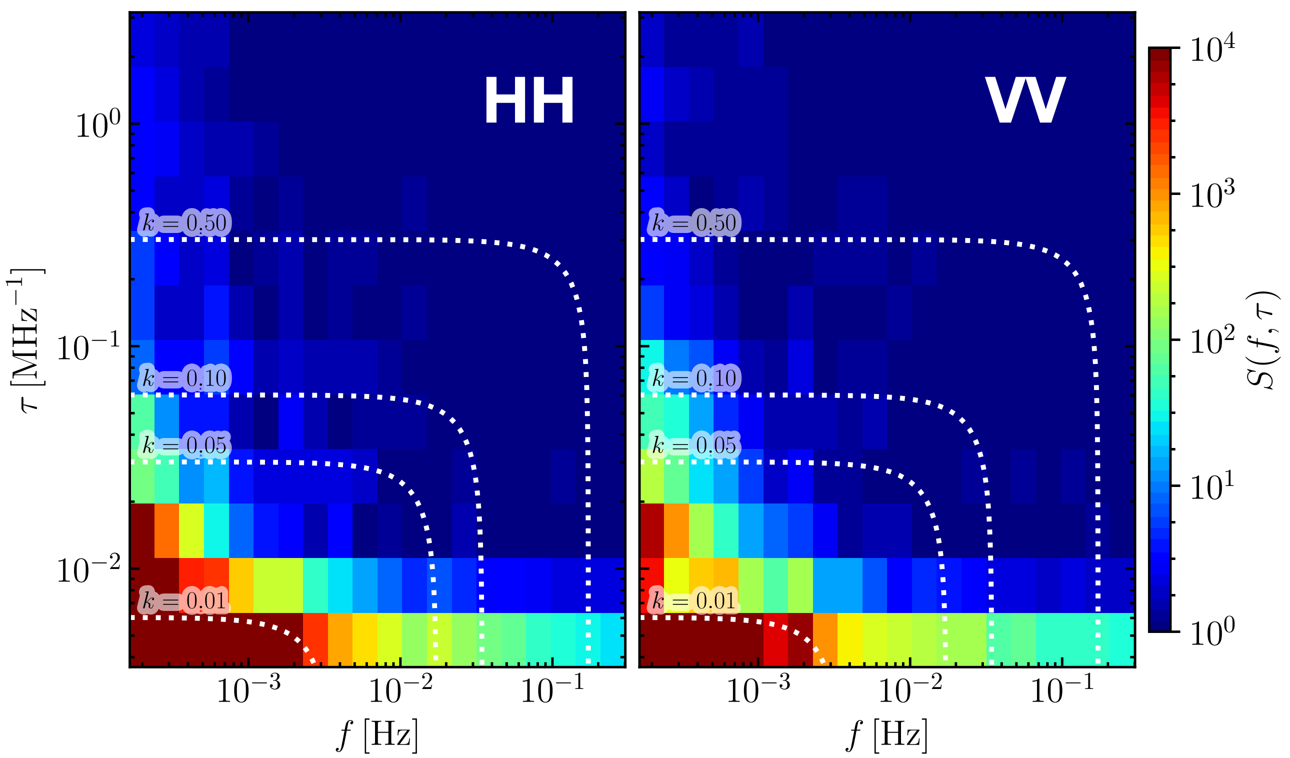
1/f Noise Model

We measured the MeerKAT 1/f noise power spectrum density by tracking the South Celestial Point for 2.5 hours.

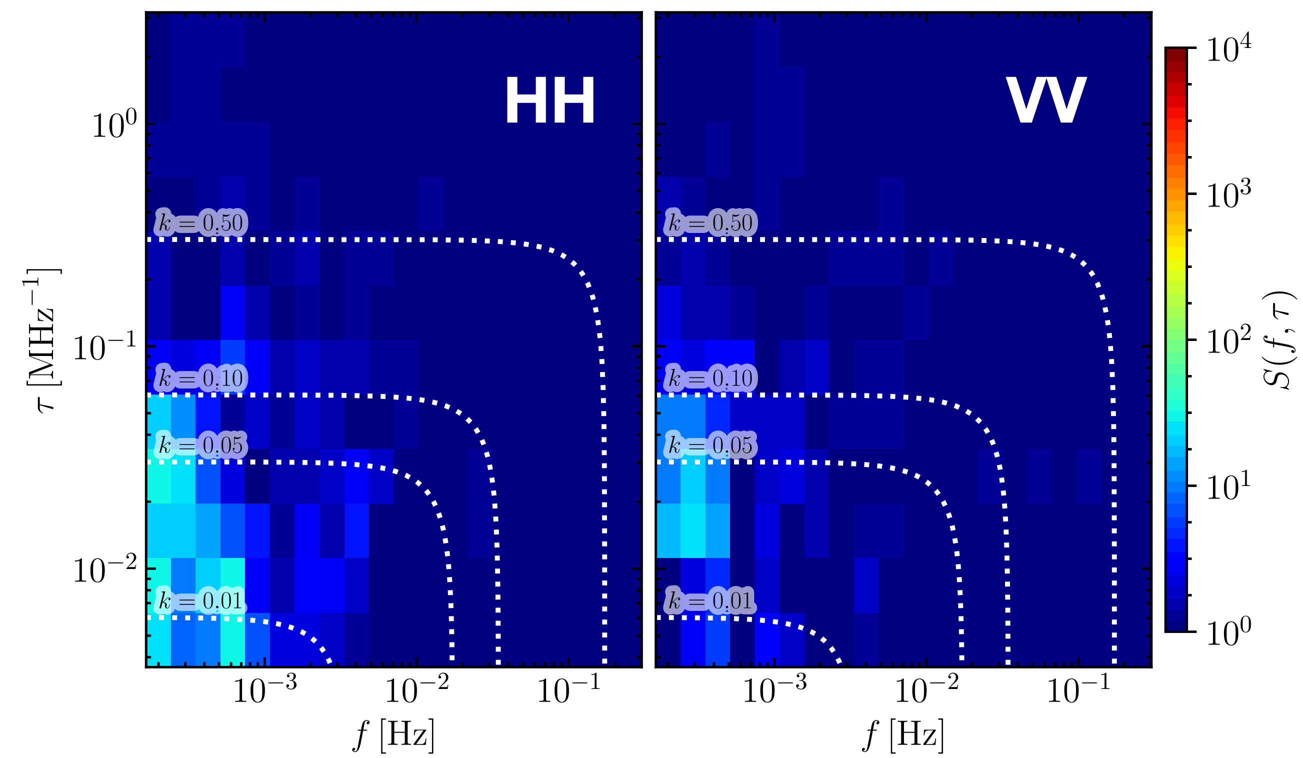
Remove strong correlations with TOD Singular Value Decomposition (SVD)



Before TOD SVD subtraction



After TOD SVD subtraction



Y. Li et. al (2021) MNRAS 501(3) 4344. arXiv:2007.01767

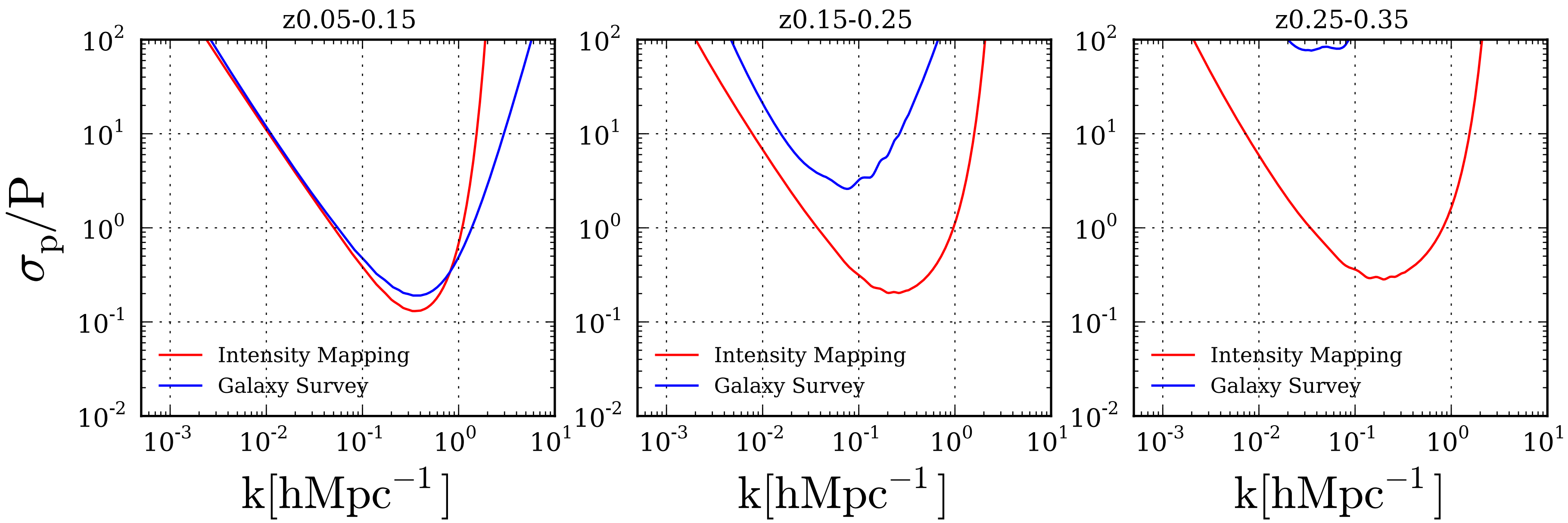
FAST HI IM GS

Xuelei Chen, Yougang Wang et. al NAOC
Yichao LI, Xin Zhang et. al NEU

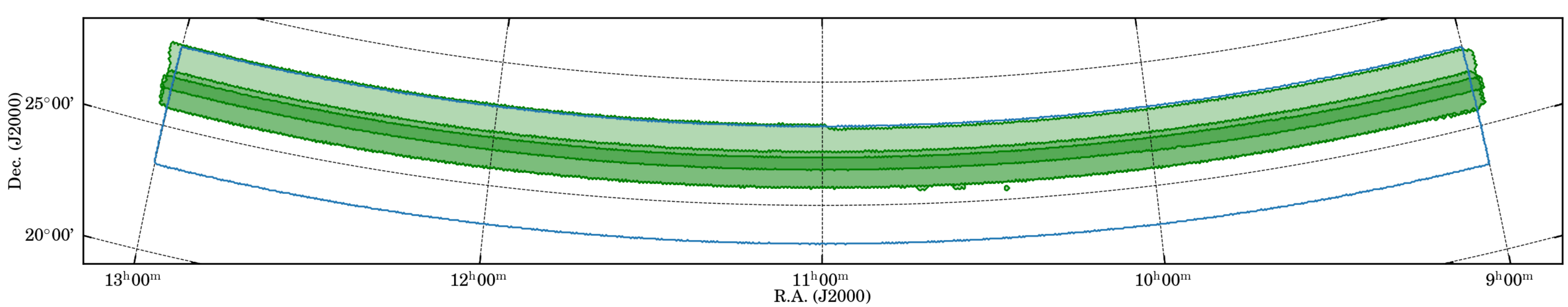
- Five-hundred-meter Aperture Spherical radio Telescope (FAST)

- HI IM + Galaxy Survey

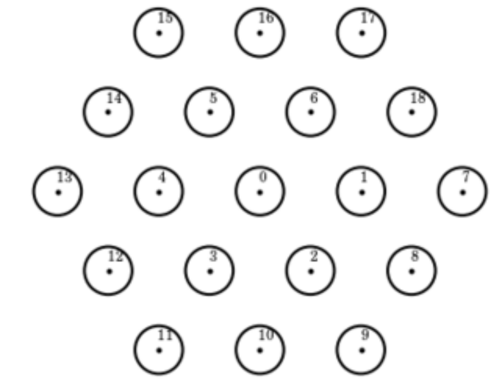
Receiver	Band (GHz)	Beams	$T_{\rm rec}$ (K)
L-band	1.05–1.45	19	20
Wide-band	0.27–1.62	1	60
UHF PAF (future)	0.5–1.0	81	30

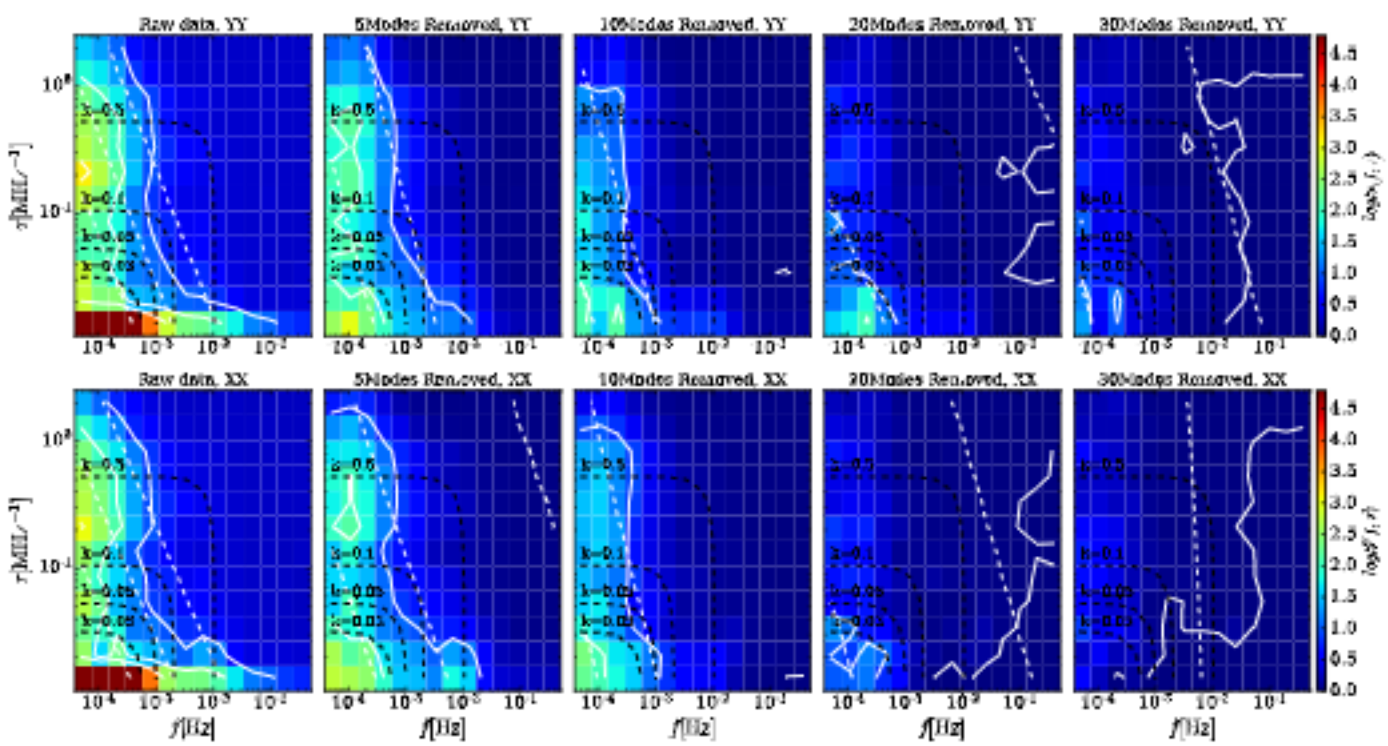


Wenkai Hu et al., , MNRAS, 493, 5854 (2020)



FAST 1/f Noise





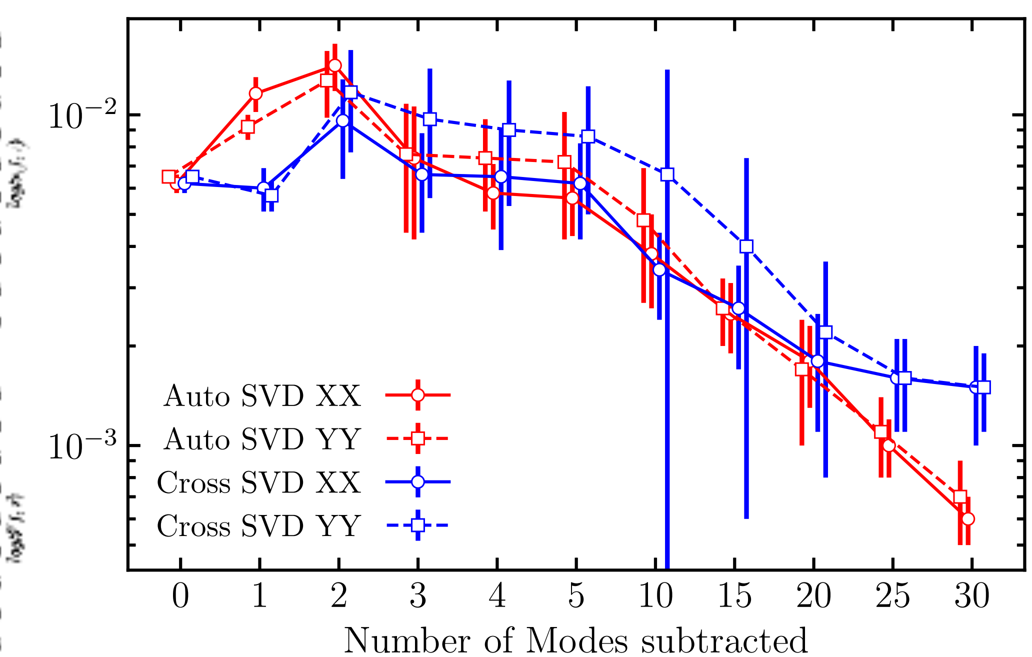
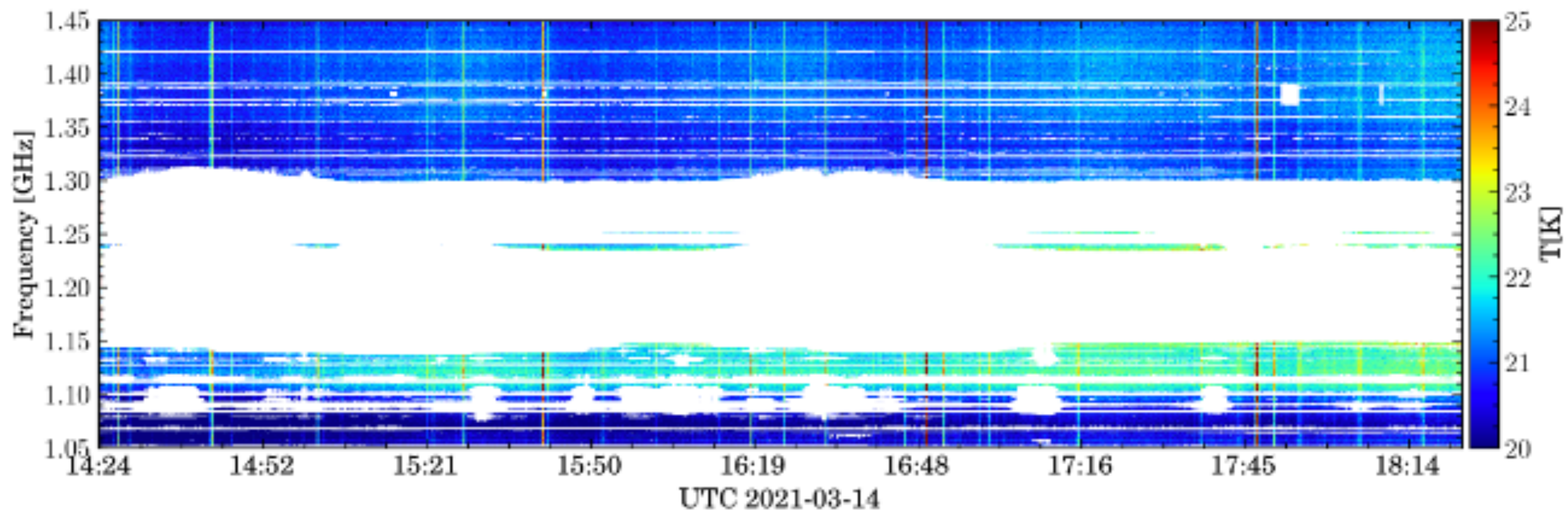


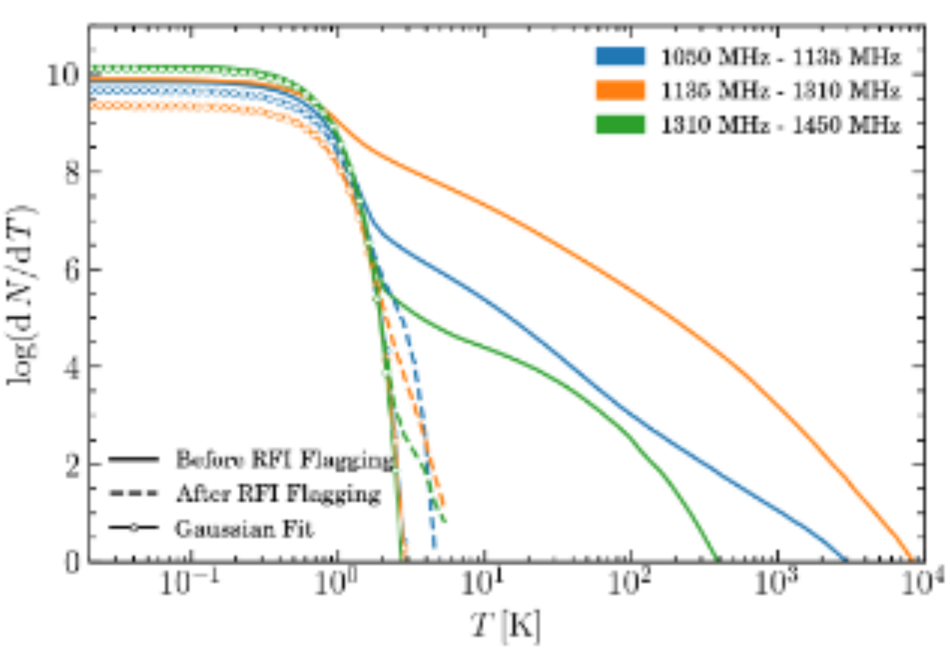
Table 1. The mean value of 10MHz temporal power spectra and 2D power spectra fitting parameters across all feeds except Feed 16 YY and Feed 9 XX, from auto correlation foreground subtraction. The errors are the r.m.s. of the fitting values across all feeds except Feed 16 YY and Feed 9 XX.

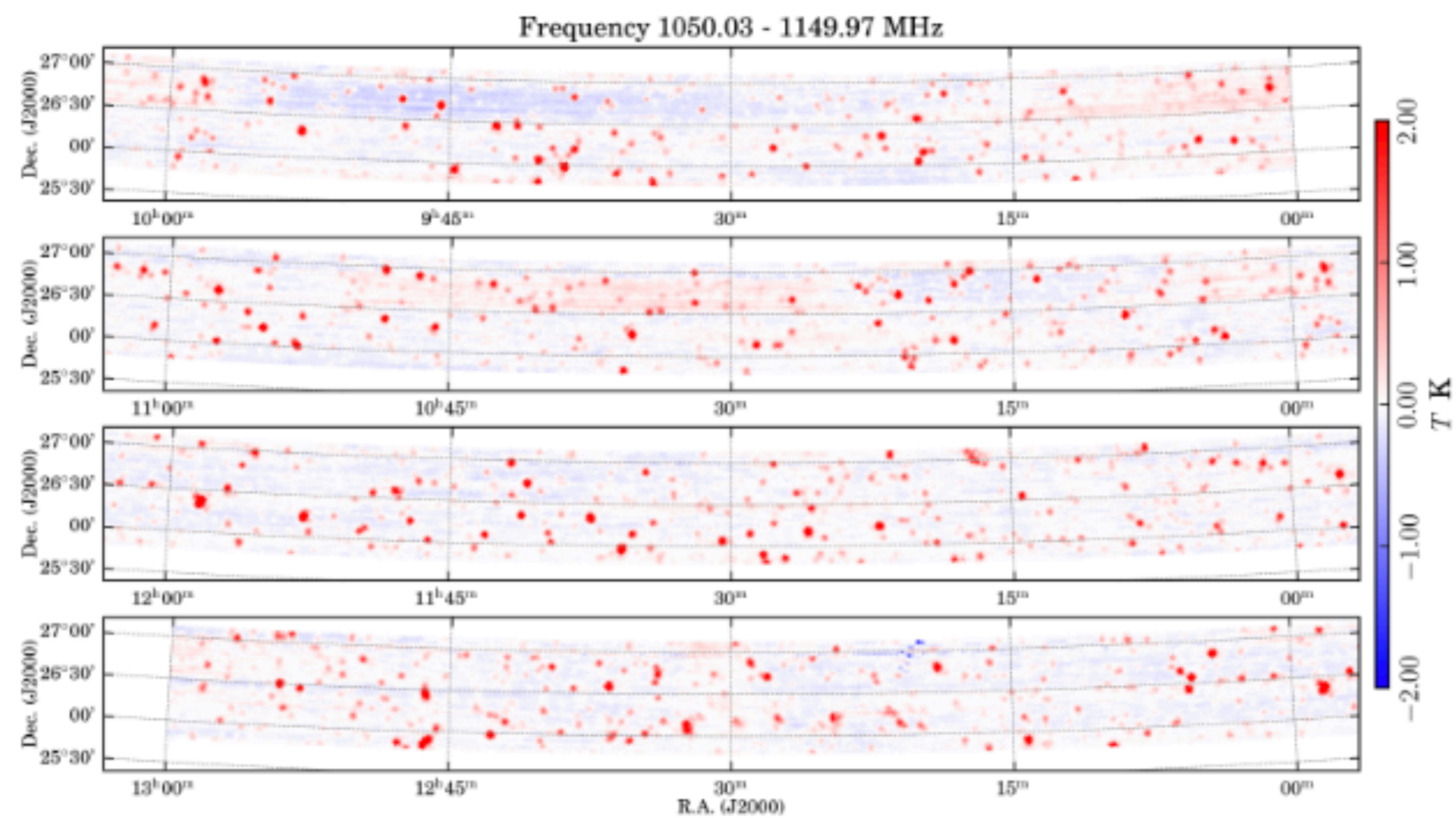
Data	$f_{k,10\mathrm{MHz}} \times 10^2$		$\alpha_{10\mathrm{MHz}}$		$\alpha^{2\mathrm{D}}$		$\beta^{2\mathrm{D}}$	
	XX	YY	XX	YY	XX	YY	XX	YY
raw data	0.62 ± 0.04	0.65 ± 0.03	3.16 ± 0.09	3.15 ± 0.05	1.45 ± 0.06	1.50 ± 0.20	0.40 ± 0.03	0.43 ± 0.02
20 modes removed	0.18 ± 0.05	0.17 ± 0.07	1.08 ± 0.14	1.30 ± 0.20	0.77 ± 0.11	0.78 ± 0.12	0.65 ± 0.07	0.58 ± 0.04
25 modes removed	0.10 ± 0.02	0.11 ± 0.03	1.05 ± 0.18	1.17 ± 0.17	0.72 ± 0.10	0.74 ± 0.10	0.74 ± 0.08	0.63 ± 0.08
30 modes removed	0.06 ± 0.01	0.07 ± 0.02	1.03 ± 0.15	1.12 ± 0.12	0.63 ± 0.10	0.64 ± 0.11	0.84 ± 0.08	0.72 ± 0.10

HU, W.K.; Li, Y.C. et. al 2021 MNRAS 508(2) 2897

FAST HI IM GS


Frequency [GHz]
UTC 2021-03-14
T[K]


1050 MHz - 1135 MHz
1135 MHz - 1310 MHz
1310 MHz - 1450 MHz
Before RFI Flagging
After RFI Flagging
Gaussian Fit
log(d N/d T)
T [K]


Frequency 1050.03 - 1149.97 MHz
Dec. (J2000)
R.A. (J2000)
T K

Summary

- FG is the major challenge for HI IM
- Beam sidelobes make FG hard to be subtracted
- Eliminating beam effect with U-Net network deep leaning
- Systematic 1/f noise injects correlations

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•Thank You !

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