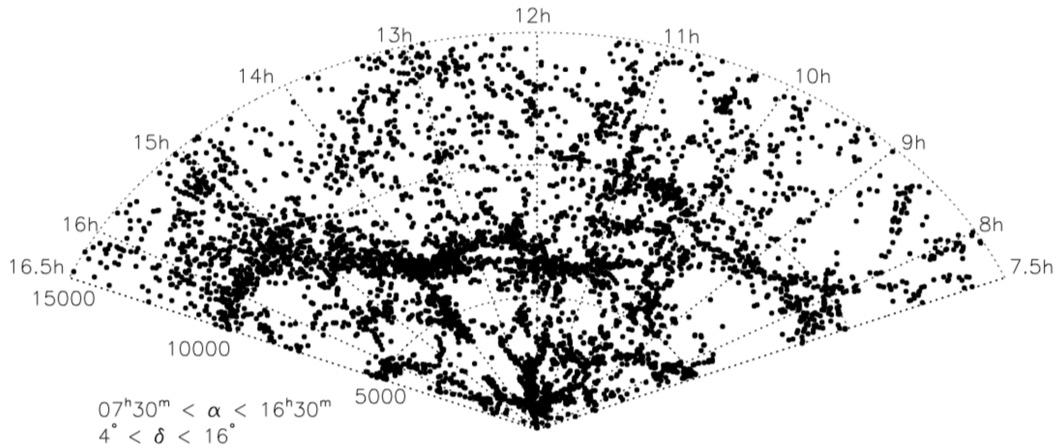
MeerKAT HI Intensity Mapping

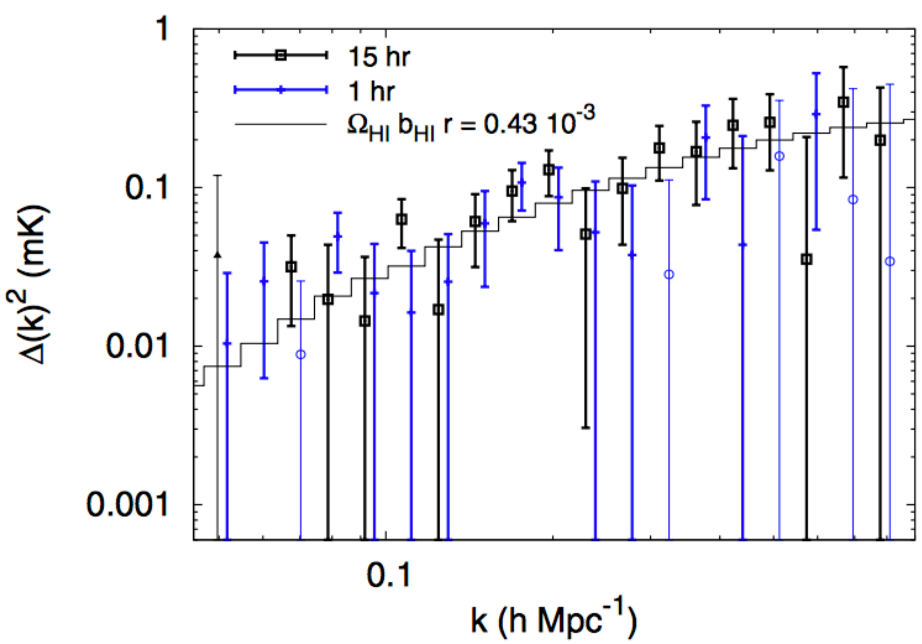
Yichao Li & MeerKLASS collaboration

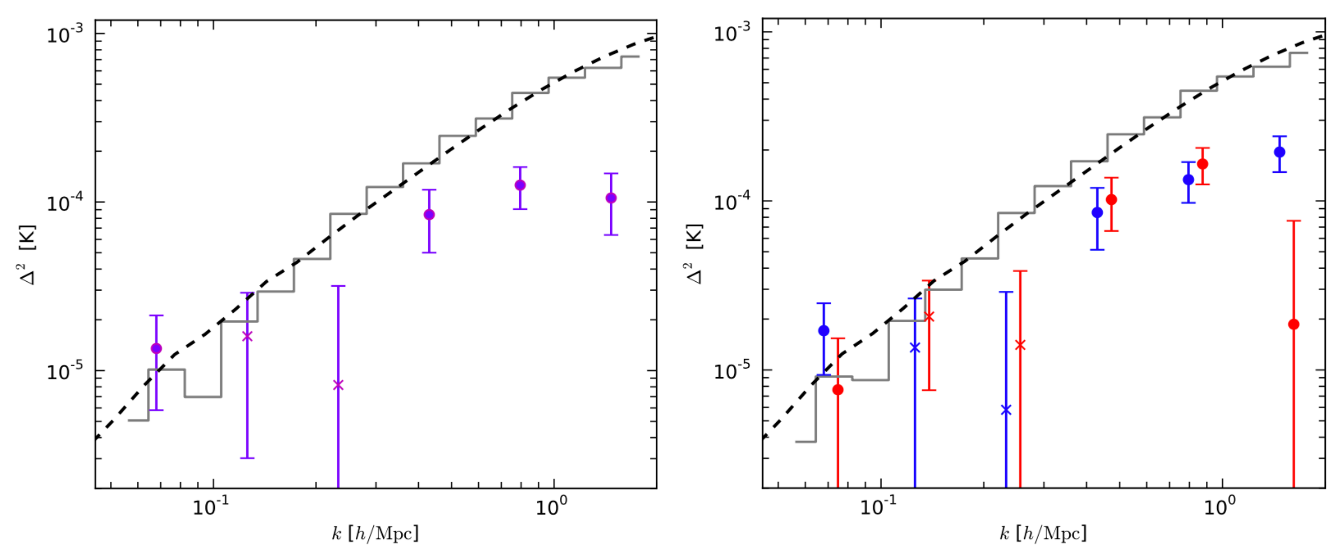
Postdoc, University of the Western Cape, Cape Town, SA

21cm Science Mini-Workshop, in the cloud!

HI Intensity Mapping







Cross PS GBT HIIM x WiggleZ
K. Masui et al 2013 ApJ 763L 20M

Cross PS Parkes HIIM x 2dF
C. Anderson, N. Luciw, Y. Li et. al.
2018 MNRAS 476 3 3382

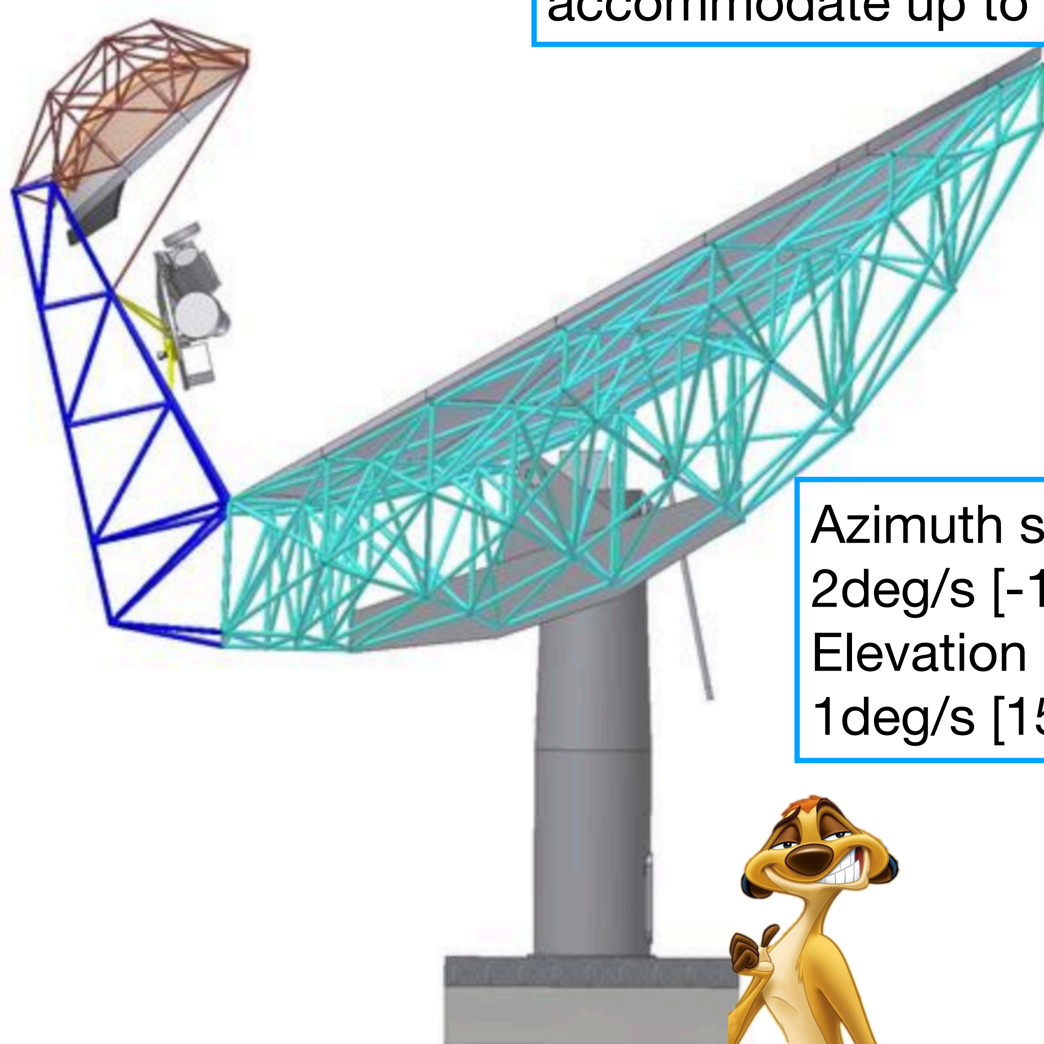
MeerKAT

- MeerKAT
  - Karoo Array Telescope (KAT)
  - meerKAT means “more of KAT”
  - 64 dishes, 13.5 dish diameter
  - 48 in core area
  - maximum baseline 8km
  - L-Band (0.9-1.67GHz)
  - UHF-Band (0.58-1.015GHz)
  - will be part of SKA Phase I
  - MeerKAT extension project: add 20 dishes, increase maximum baseline to 17km

Total hight of 19.5m;
Total structure weight of 42 Tons

Main reflector with effective diameter of 13.5m;
Sub-reflector with diameter of 3.8 m

The L-band/UHF-band receivers and digitizers are mounted on the receiver indexer, which can accommodate up to 4 receivers.



Azimuth speed/range:
2deg/s [-185 to +275 deg]
Elevation speed/range:
1deg/s [15 to 88 deg]

MeerKAT science projects

Priority Group 1
Radio Pulsar Timing: Testing Einstein's theory of gravity and gravitational radiation - Investigating the physics of enigmatic neutron stars through observations of pulsars.
LADUMA (Looking at the Distant Universe with the MeerKAT Array) - An ultra-deep survey of neutral hydrogen gas in the

Priority Group 2
MESMER (MeerKAT Search for Molecules in the Epoch of Re-ionisation) - Searching for CO at high red-shift (z>7) to investigate the role of molecular hydrogen in the early universe.
MeerKAT Absorption Line Survey for atomic hydrogen and OH lines in absorption against distant continuum sources (OH line ratios may give clues about changes in the fundamental constants in the early universe).
MHONGOOSE (MeerKAT HI Observations of Nearby Galactic Objects: Observing Southern Emitters) - Investigations of different types of galaxies; dark matter and the cosmic web.
TRAPUM (Transients and Pulsars with MeerKAT) - Searching for, and investigating new and exotic pulsars.
A MeerKAT HI Survey of the Fornax Cluster (Galaxy formation and evolution in the cluster environment).
MeerGAL (MeerKAT High Frequency Galactic Plane Survey) - Galactic structure and dynamics, distribution of ionised gas, recombination lines, interstellar molecular gas and masers.
MIGHTEE (MeerKAT International GigaHertz Tiered Extragalactic Exploration Survey) - Deep continuum observations of
ThunderKAT (The Hunt for Dynamic and Explosive Radio Transients with MeerKAT) - eg gamma ray bursts, novae and supernovae, plus new types of transient radio sources.

MeerKAT is ready for open time observation

SARAO

Instructions, documentation, and the tools required to prepare and submit proposals are available on the SARAO website [https://science.ska.ac.za/meerkat]

MeerKLASS

- **MeerKAT Large Area Synoptic Survey** (MeerKLASS)
  - single dish IM & interferometry galaxy survey
  - 4000 square deg;
  - continuum survey sensitivity of 5 microJy
  - L-band ($0<z<0.58$) / UHF-band ($0.4<z<1.45$)

Contents

M. G. Santos et. al. 1709.06099 and references therein

MeerKLASS

- **MeerKAT Large Area Synoptic Survey** (MeerKLASS)

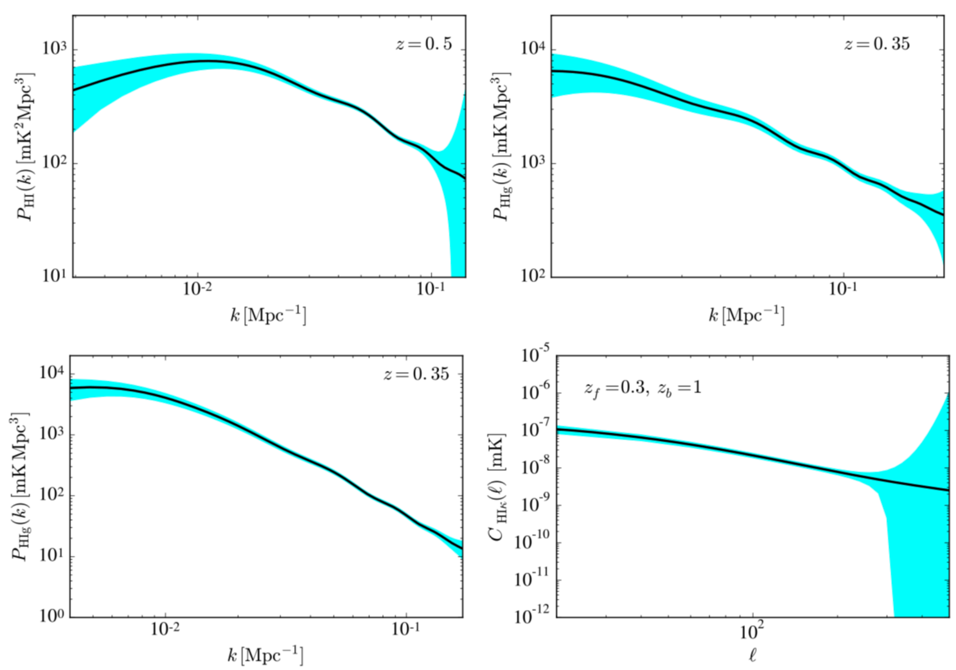
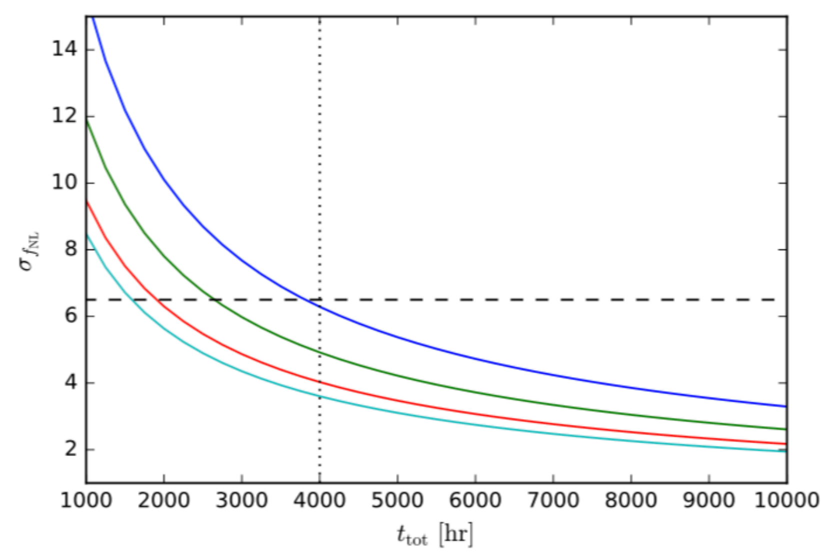
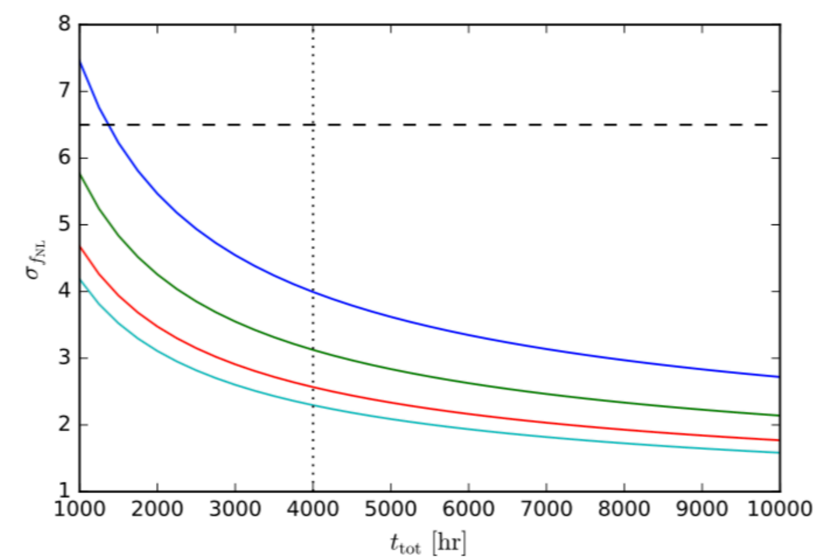


Table 1: Forecast fractional uncertainties on $\Omega_{\rm HI} b_{\rm HI}$.

z	$\delta(\Omega_{\rm HI} b_{\rm HI})/(\Omega_{\rm HI} b_{\rm HI})$	z	$\delta(\Omega_{\rm HI} b_{\rm HI})/(\Omega_{\rm HI} b_{\rm HI})$
L-band		**UHF-band**	
0.1	0.010	0.6	0.011
0.2	0.005	0.7	0.013
0.3	0.005	0.8	0.015
0.4	0.007	0.9	0.018
0.5	0.009	1.0	0.022
		1.1	0.026
		1.2	0.030
		1.3	0.036
		1.4	0.042





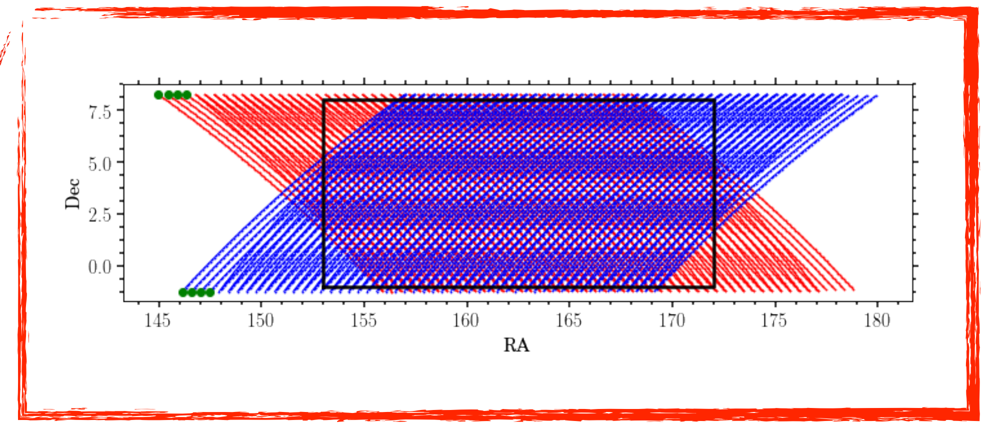
Constrains on primordial non-Gaussianlity with Multi tracer technique U. Seljak 0807.1770

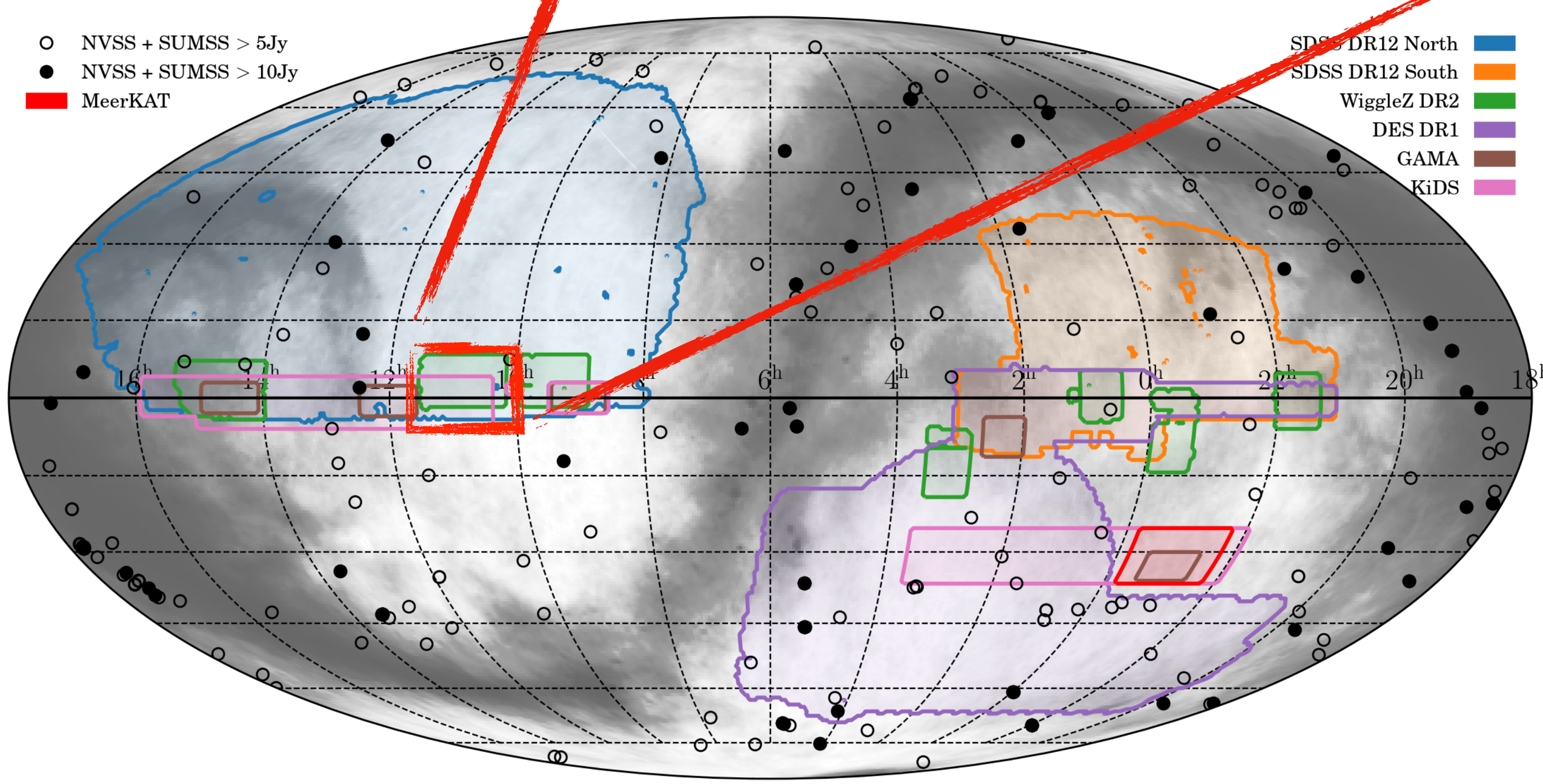
With different dark matter tracer one can directly measure b1/ b2 no cosmic variance

M. G. Santos et. al. 1709.06099 and references therein

MeerKLASS Pilot Survey

- MeerKAT HI IM Pilot survey
  - 170 square deg, ~10 hours,
  - ~60 dishes, Fix Alt ~ 45deg
  - L-band (856-1712MHz)
  - Overlap with WiggleZ/SDSS
  - Test system, training pipeline



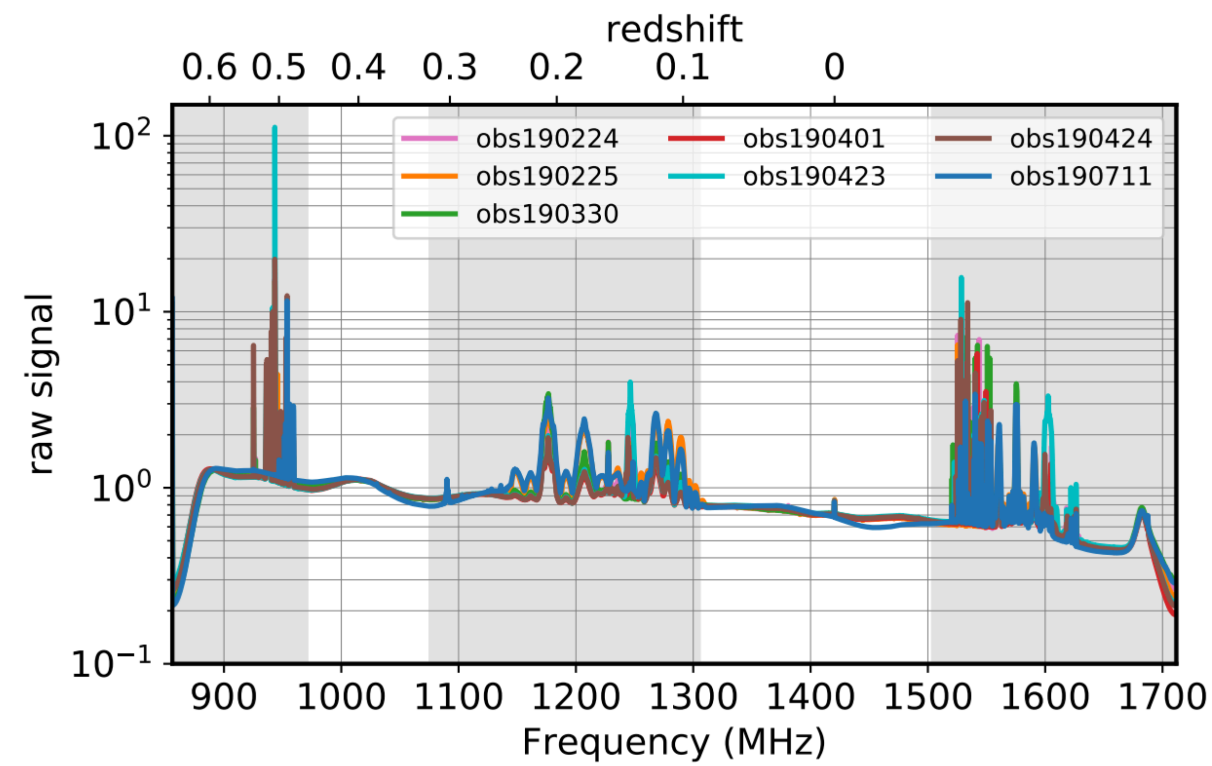


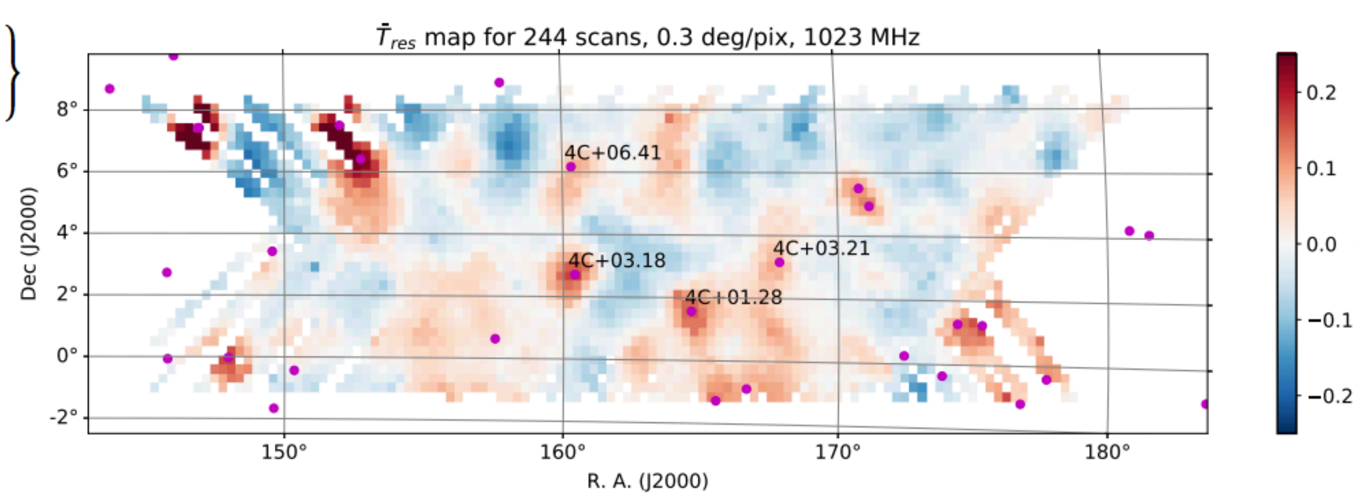
MeerKLASS Pilot Survey

- Time-ordered data analysis
  - RFI flagging: Signal Extraction and Emission Kartographer (SEEK; Akeret et al. 2017)
  - Noise diode as real-time calibrator
  - Point source as flux and bandpass calibrator
  - Bayesian based calibration

$$\mathcal{L}(\hat{\mathbf{T}}_{\rm raw}|\hat{\mathbf{T}}_{\rm model}) = \prod_{t_i=0}^{t_{\rm max}} \frac{1}{\sqrt{2\pi\sigma^2(t_i)}} \exp\left\{-\frac{[\hat{T}_{\rm raw}(t_i) - \hat{T}_{\rm model}(t_i)]^2}{2g^2(t_i,\nu)\sigma^2(t_i)}\right\}$$

  - pixel grid mapmaking





J. Wang et. al. arXiv:2011.13789

MeerKLASS Pilot Survey

- Map-making

$$\tilde{\mathbf{x}} = \mathbf{W}\mathbf{y},$$

No.	Method	Specification
1	Generalized COBE	$\mathbf{W} = [\mathbf{A}^t\mathbf{M}\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{M}$
2	Bin averaging	$\mathbf{W} = [\mathbf{A}^t\mathbf{A}]^{-1}\mathbf{A}^t$
3	COBE	$\mathbf{W} = [\mathbf{A}^t\mathbf{N}^{-1}\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{N}^{-1}$
4	Wiener 1	$\mathbf{W} = \mathbf{S}\mathbf{A}^t[\mathbf{A}\mathbf{S}\mathbf{A}^t + \mathbf{N}]^{-1}$
5	Wiener 2	$\mathbf{W} = [\mathbf{S}^{-1} + \mathbf{A}^t\mathbf{N}^{-1}\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{N}^{-1}$
6	Saskatoon	$\mathbf{W} = [\eta\mathbf{S}^{-1} + \mathbf{A}^t\mathbf{N}^{-1}\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{N}^{-1}$
7	TE96	$\mathbf{W} = \mathbf{\Lambda}\mathbf{S}\mathbf{A}^t[\mathbf{A}\mathbf{S}\mathbf{A}^t + \mathbf{N}]^{-1},\ (\mathbf{W}\mathbf{A})_{ii} = 1$
8	TE97	$\mathbf{W} = \mathbf{\Lambda}[\eta\mathbf{S}^{-1} + \mathbf{A}^t\mathbf{N}^{-1}\mathbf{A}]^{-1}\mathbf{A}^t\mathbf{N}^{-1},\ (\mathbf{W}\mathbf{A})_{ii} = 1$
9	Maximum probability	Nonlinear method if non-Gaussian
10	Maximum entropy	Nonlinear method

arXiv:astro-ph/9611130

- Noise model
  - Assuming white noise only, N ~ Tsys
  - Estimate the noise covariance matrix with data
  - white noise + correlated noise (1/f noise)

Noise Model

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

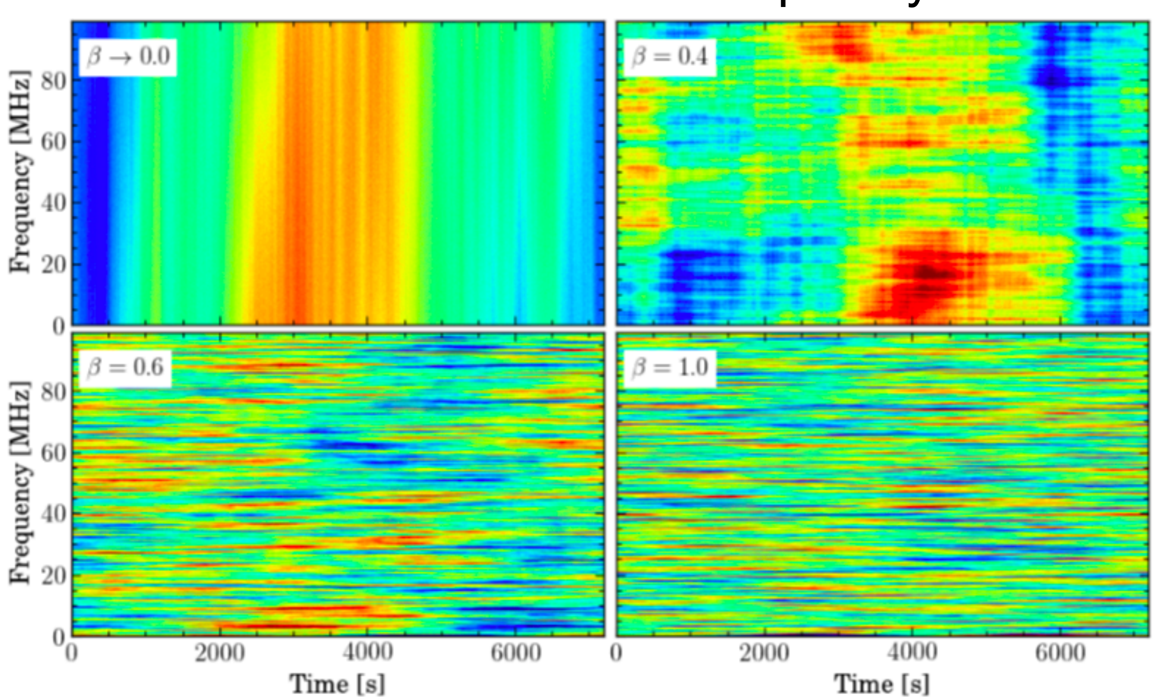
$$S^t(f,\nu) = \frac{A}{\delta\nu}\left(1 + \left(\frac{f_k}{f}\right)^{\alpha}\right)$$

2D PS model

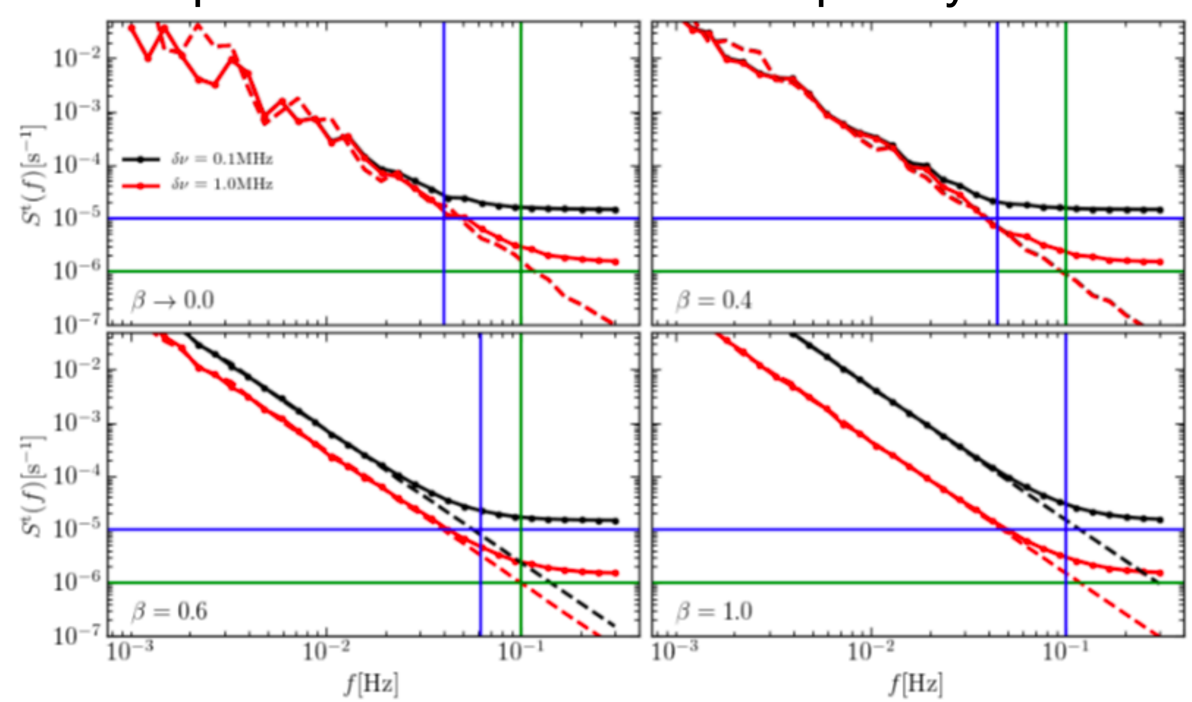
$$S(f,\tau) = A\left(1 + \frac{1}{K\delta\nu}\left(\frac{f_k}{f}\right)^{\alpha}\left(\frac{\tau_0}{\tau}\right)^{\frac{1-\beta}{\beta}}\right),$$

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



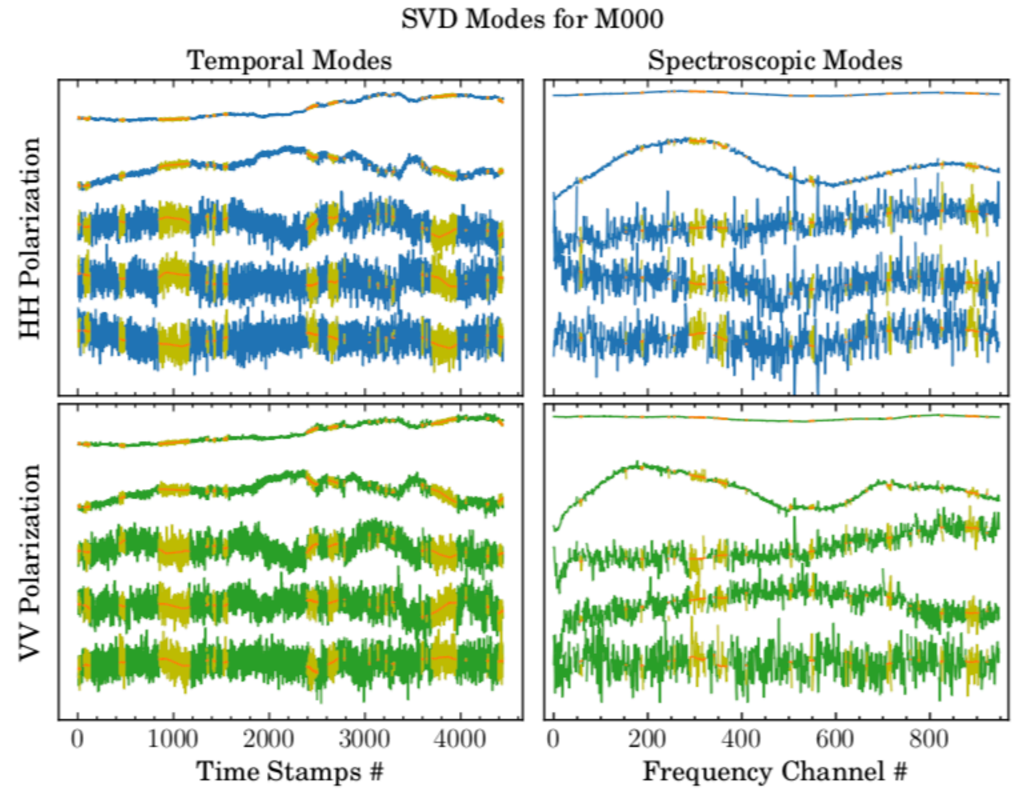
Temporal PS with different frequency resolution

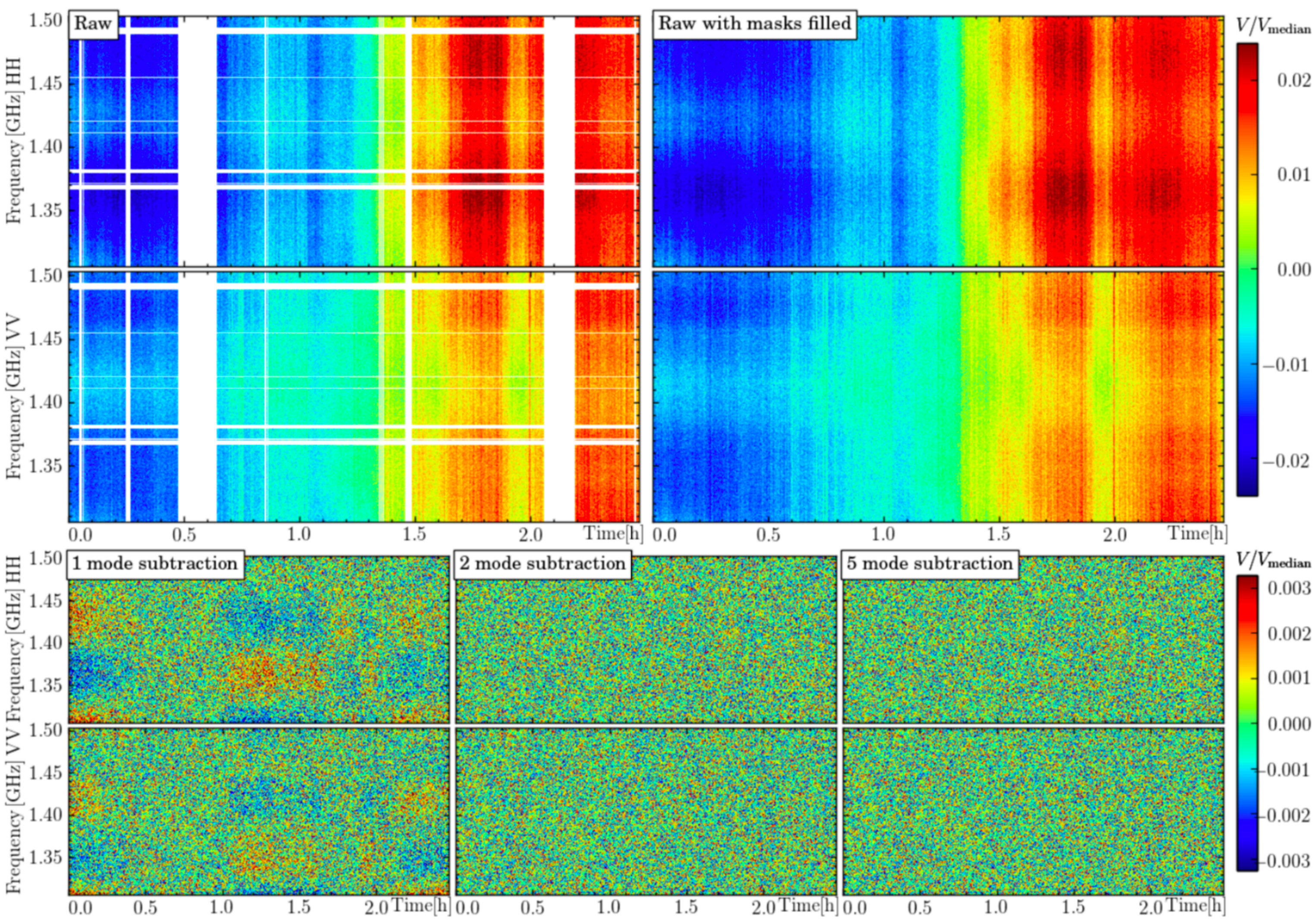


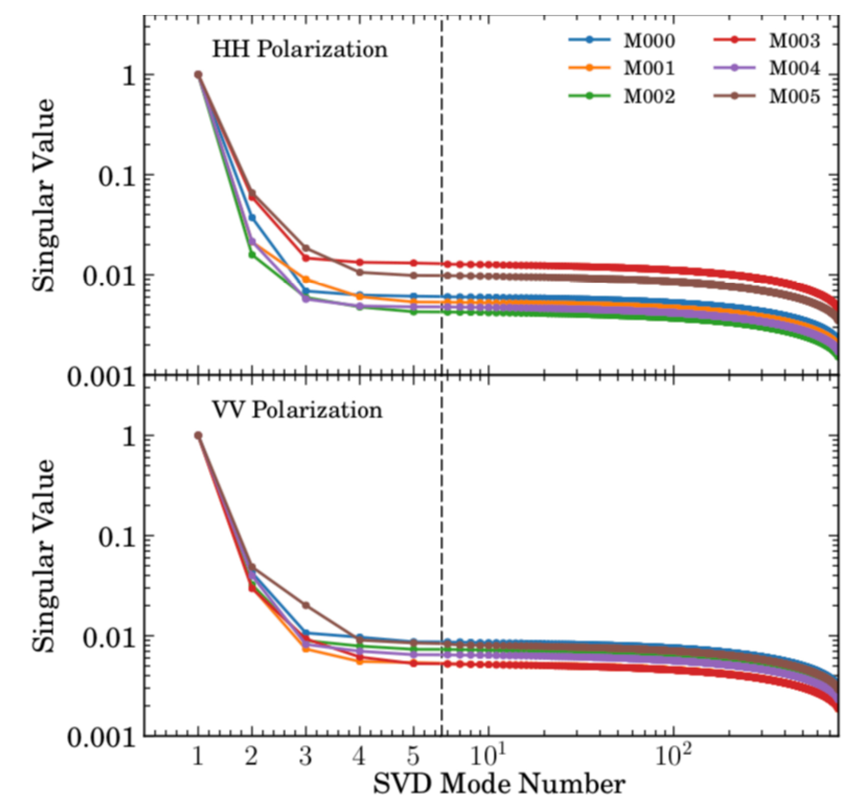
Noise Model

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

Remove strong correlations with Singular Value Decomposition (SVD)







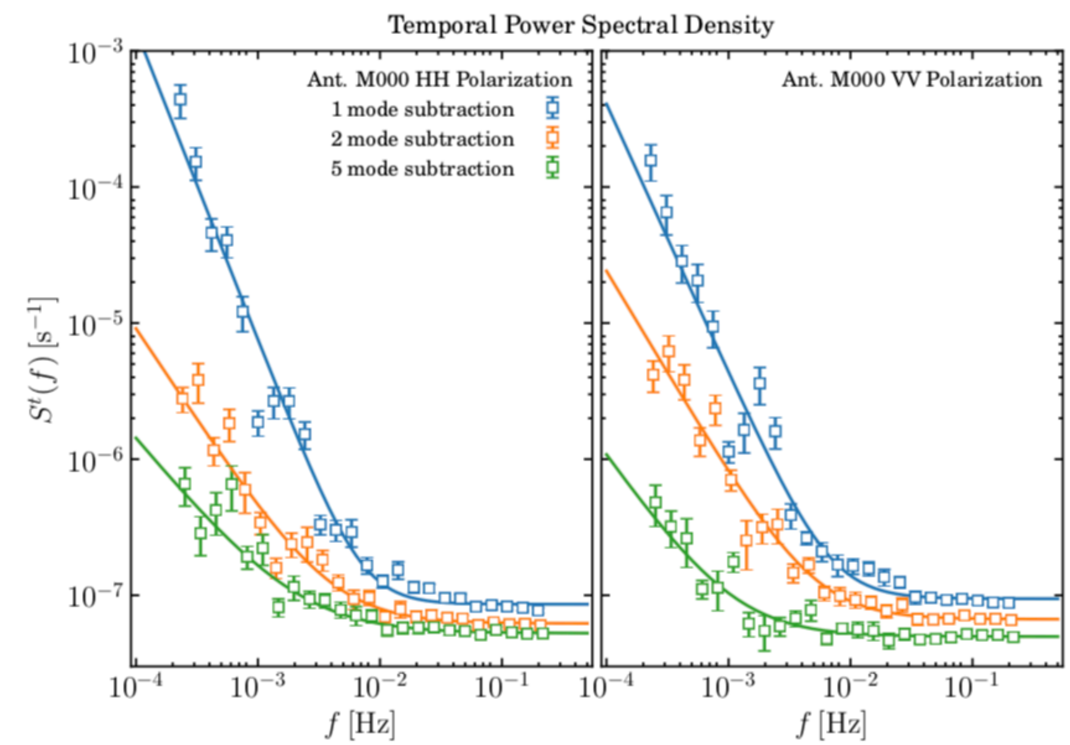
Noise Model

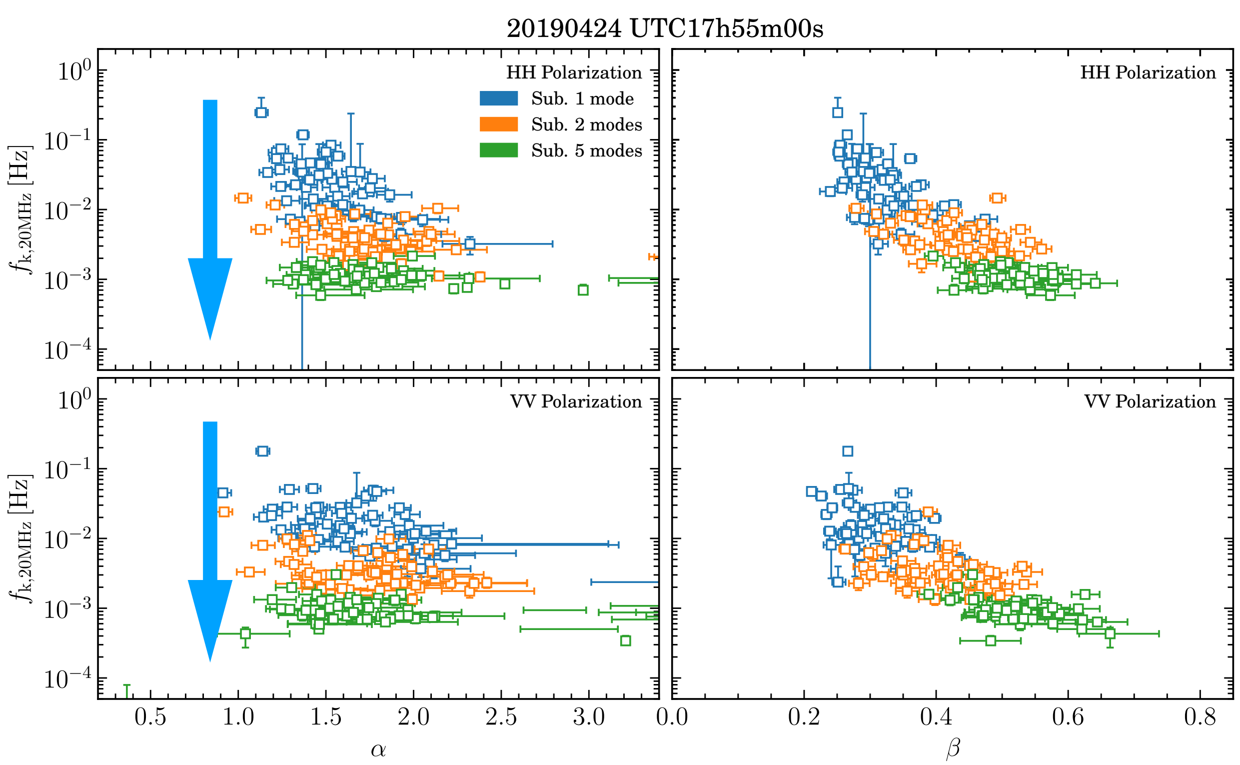
We measured the MeerKAT 1/f noise power spectrum density by tracking the South Celestial Point for 2.5 hours.

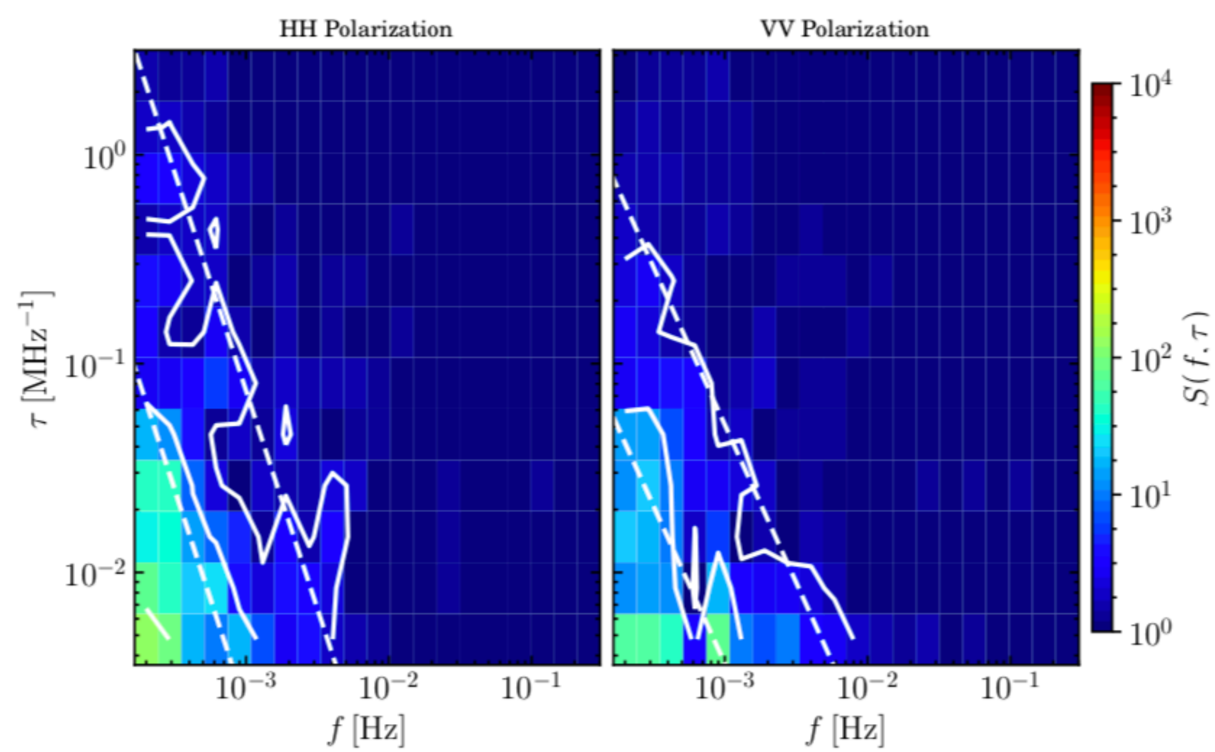
Remove strong correlations with Singular Value Decomposition (SVD)

Fit the 1/f noise model (arXiv:1711.07843) to the data to constrain the 1/f noise parameters

Y. Li, et al. arXiv:2007.01767







MeerKLASS Pilot Survey

Time Ordered

RFI Flagging
Hide & Seek

Calibration
Noise diode
Point source

Noise Analysis
1/f noise

Map-making

- d_t = A m + n_t
- m = (A^T N^{-1} A)^{-1} A^T N^{-1} d_t
- N -> Noise covariance matrix

Sub. signal

Map Domain

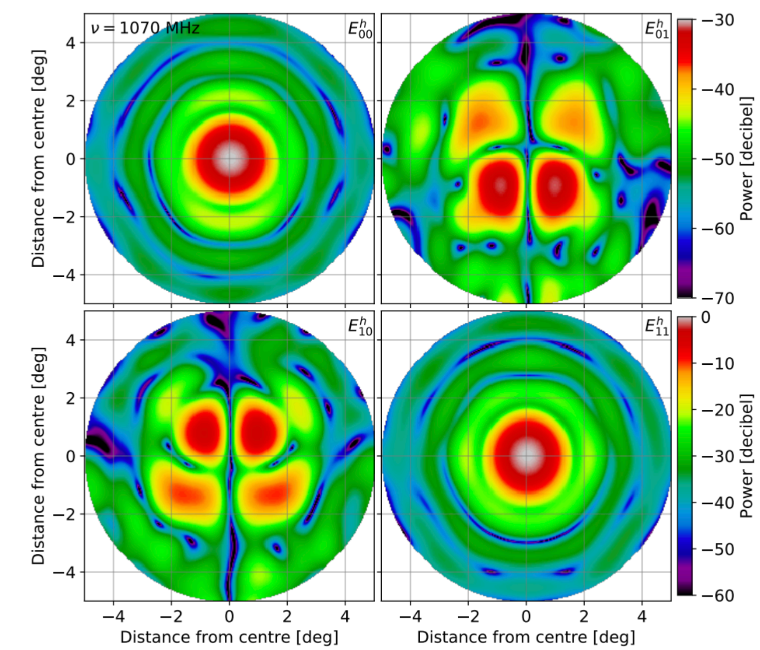
Foreground Clean
PCA/ICA

Power Spectrum
x WiggleZ/SDSS

Stacking Analysis

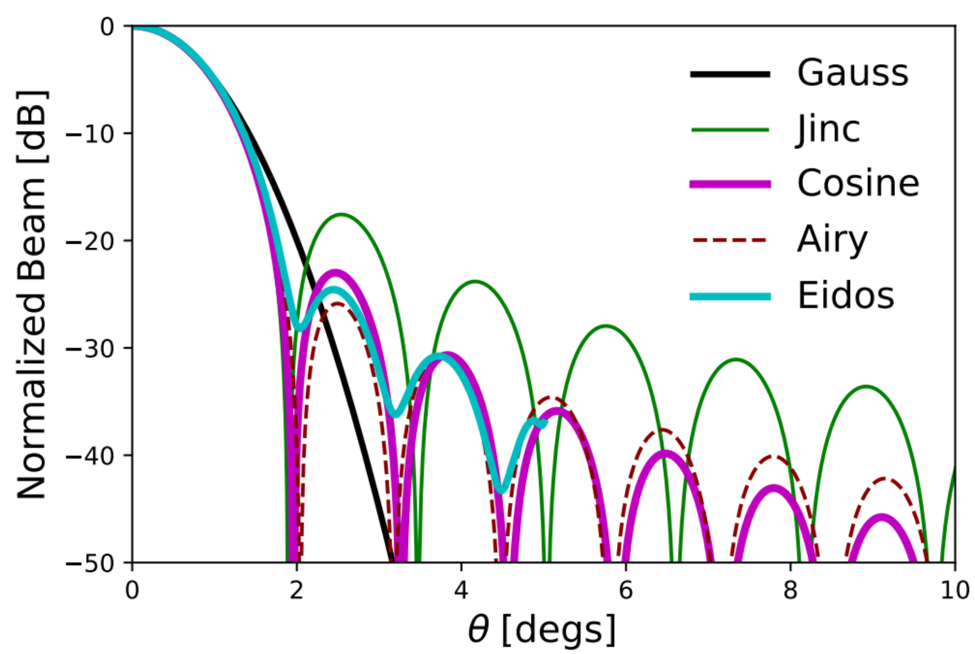
MeerKAT Beam Effect

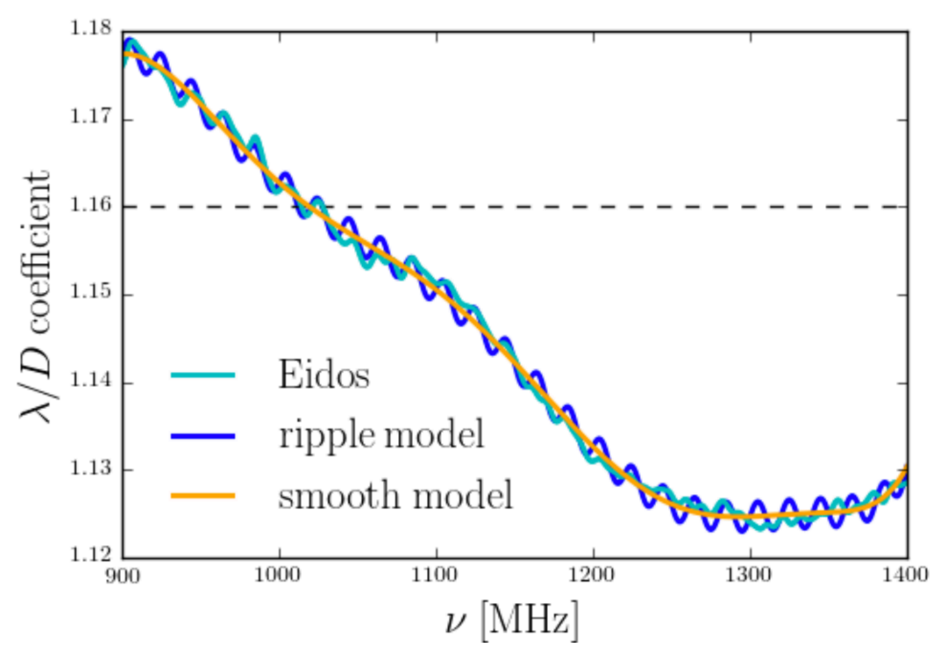
K. Asad et. al. arXiv:1904.07155



- Holographic measurements of MeerKAT primary beam

$$B_{\mathrm{C}}(\nu, \theta) = \left[\frac{\cos(1.189\theta\pi/\Delta\theta)}{1 - 4(1.189\theta/\Delta\theta)^2} \right]^2$$



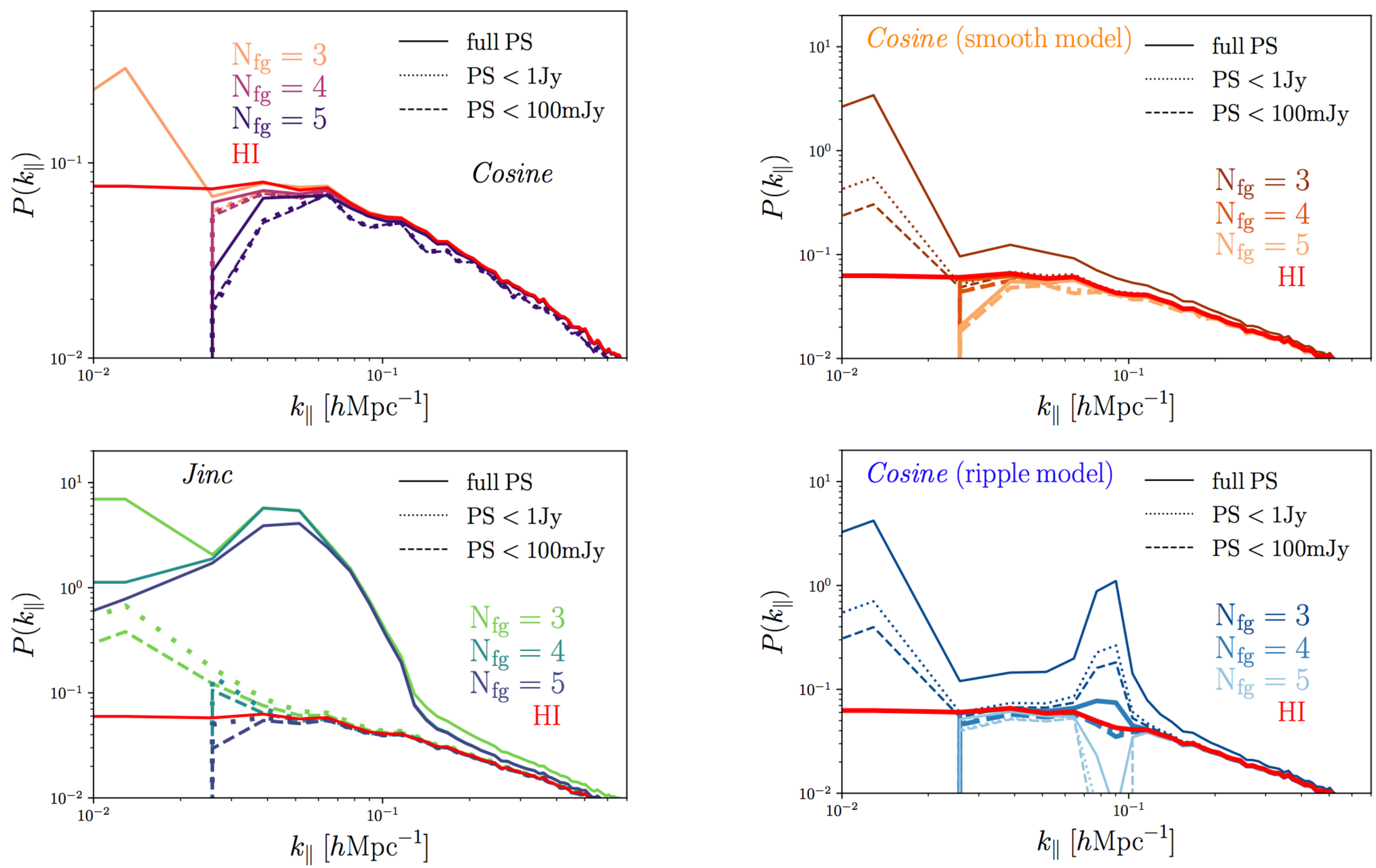


S. D. Matshawule et. al. arXiv:2011.10815

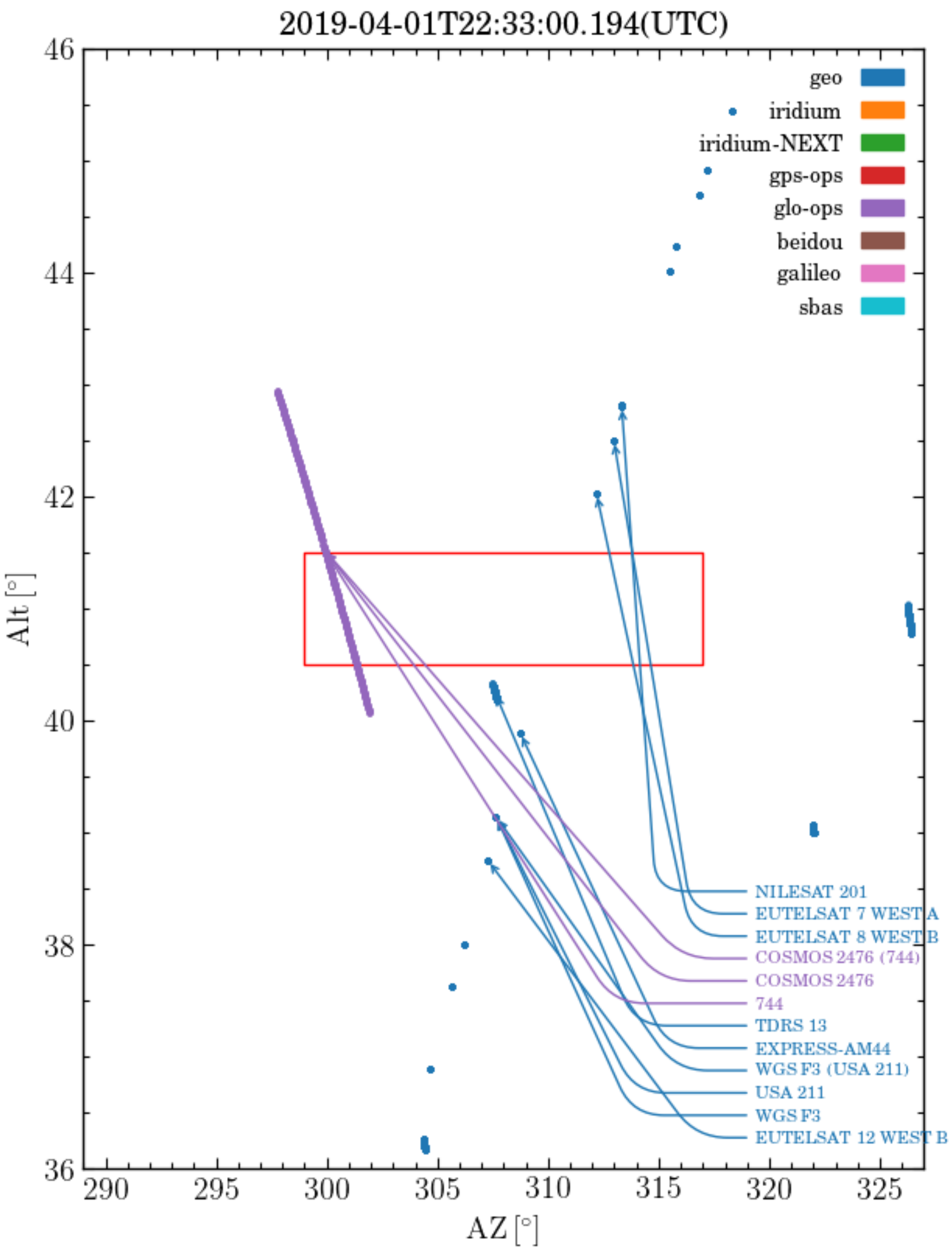
MeerKAT Beam Effect

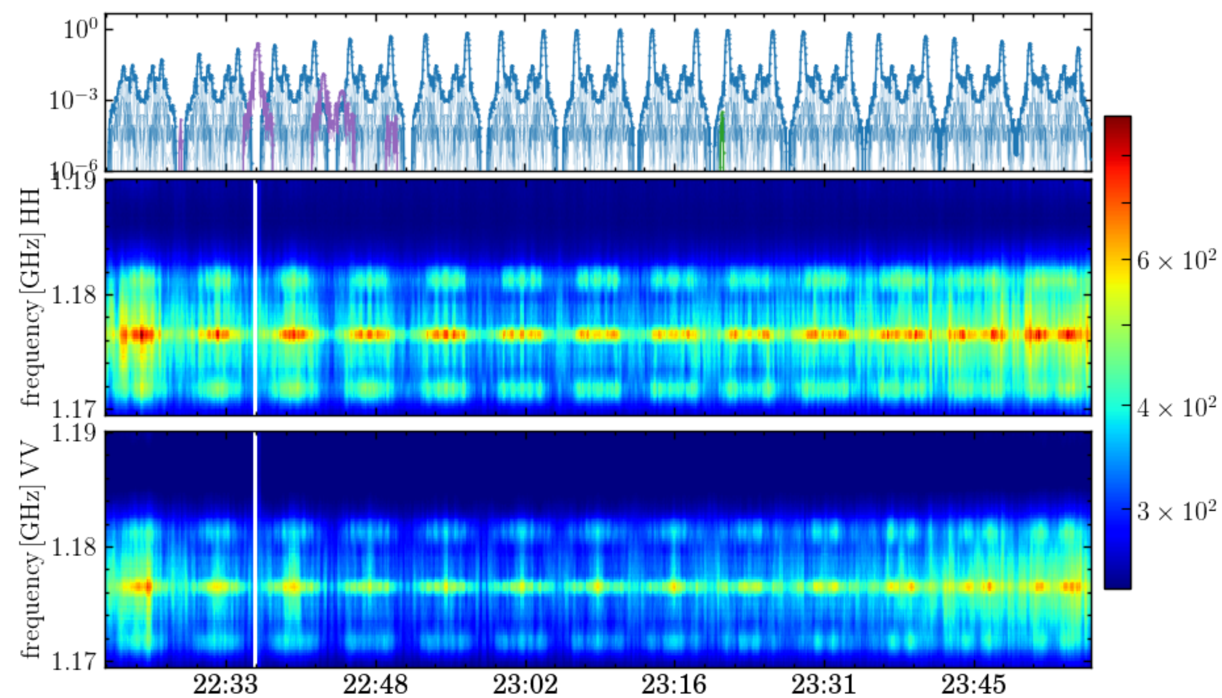
- Beam effect on foreground cleaning

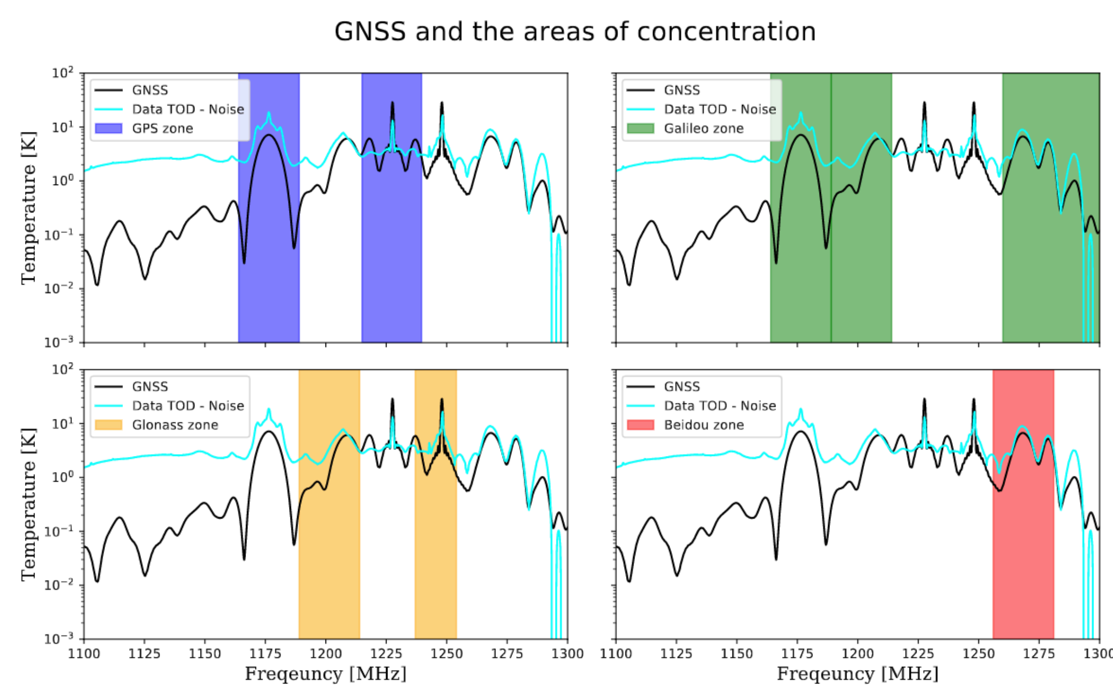
  S. D. Matshawule et. al. arXiv:2011.10815



Satellites

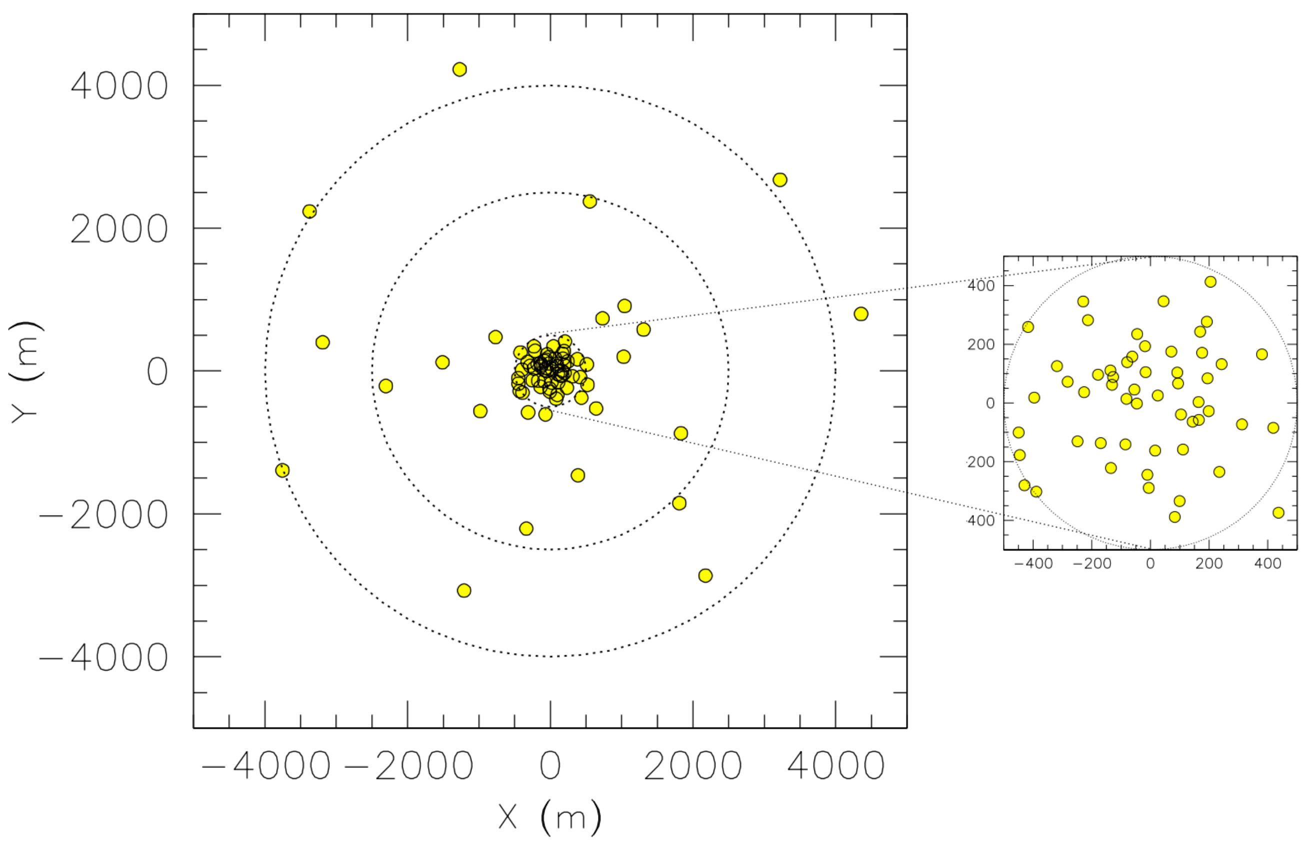


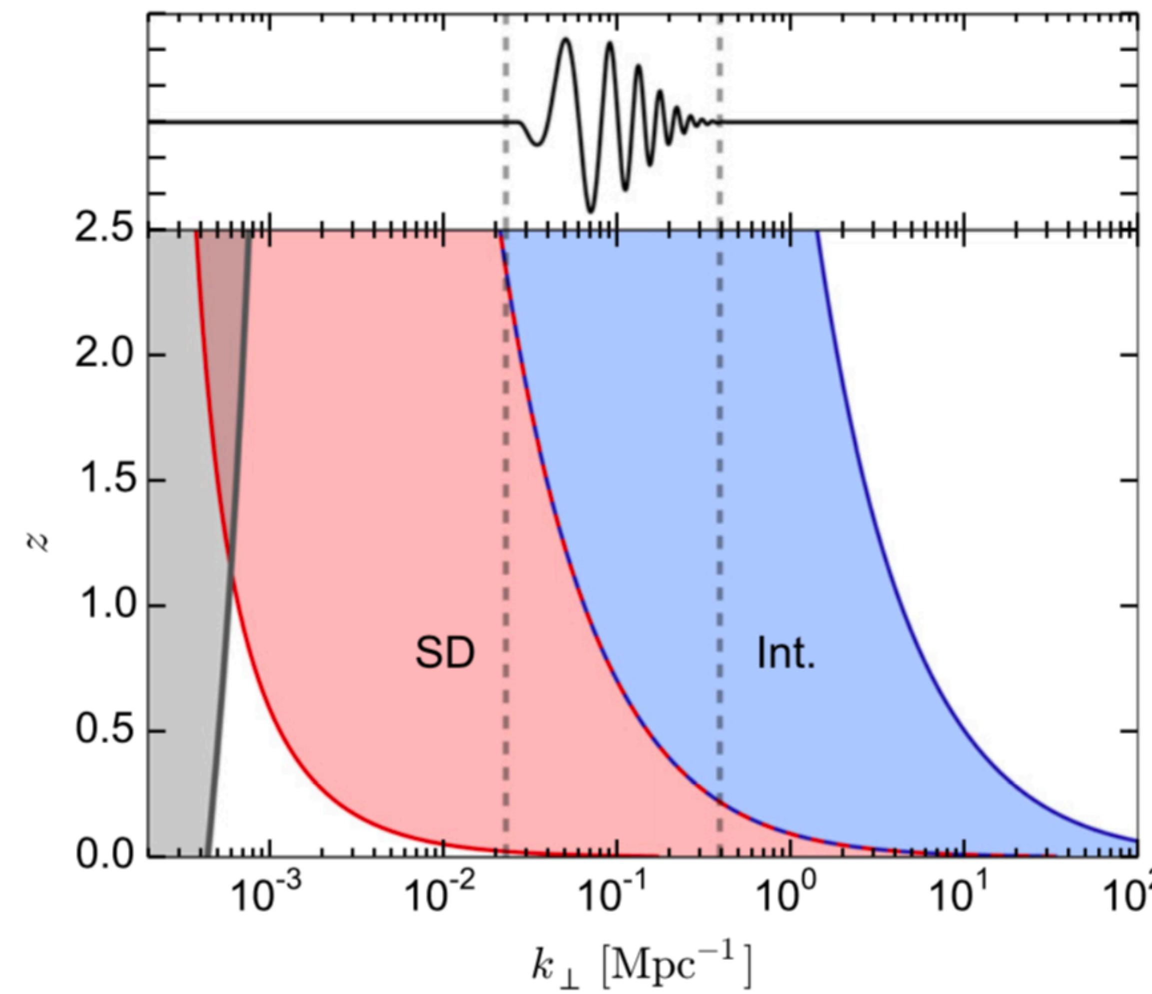




Ph.D. project Brandon Engelbrecht

Single dish or Interferometry



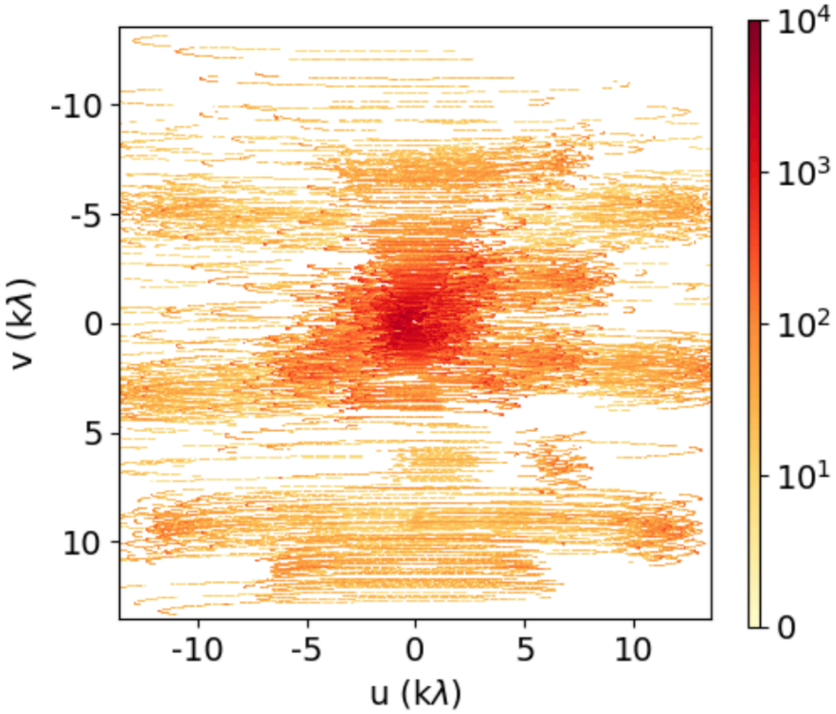


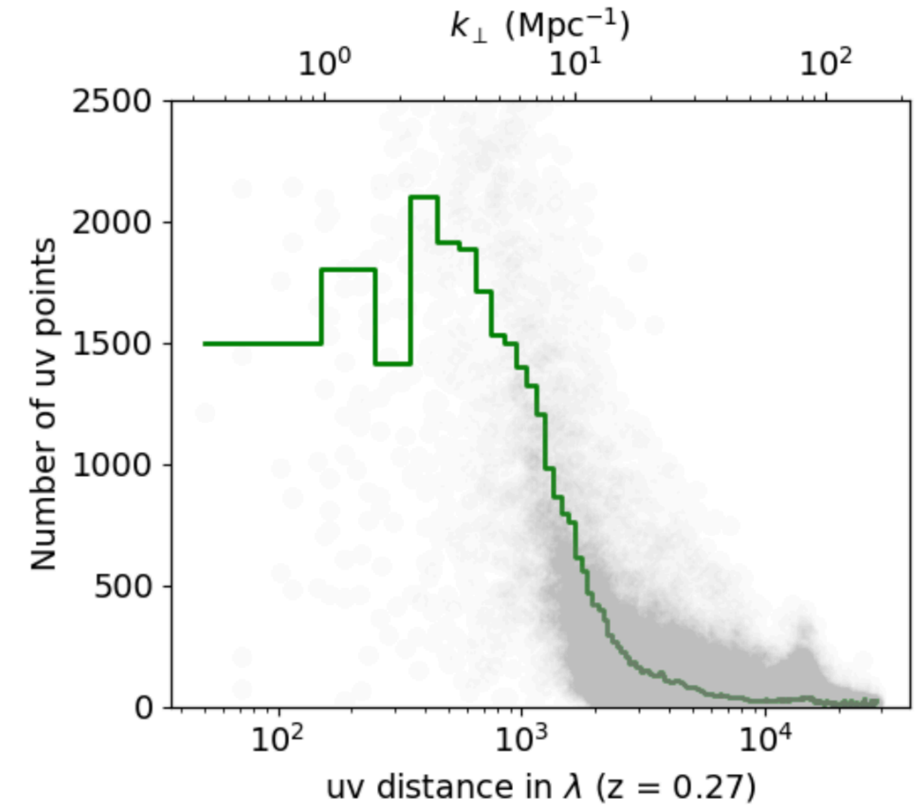
Bull, P., Ferreira, P. G., Patel, P., & Santos, M. G. (2015). ApJ, 803(1), 1–33.

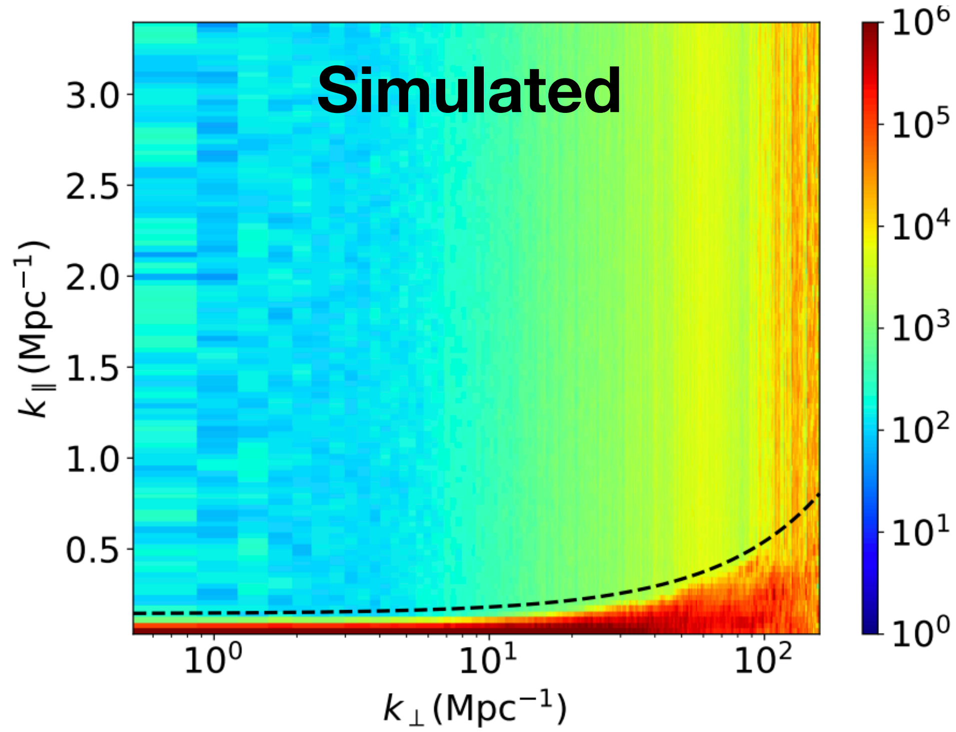
Single dish or Interferometry

MIGHTEE provides HI cube
11.2 hours tracking of
COSMOS field

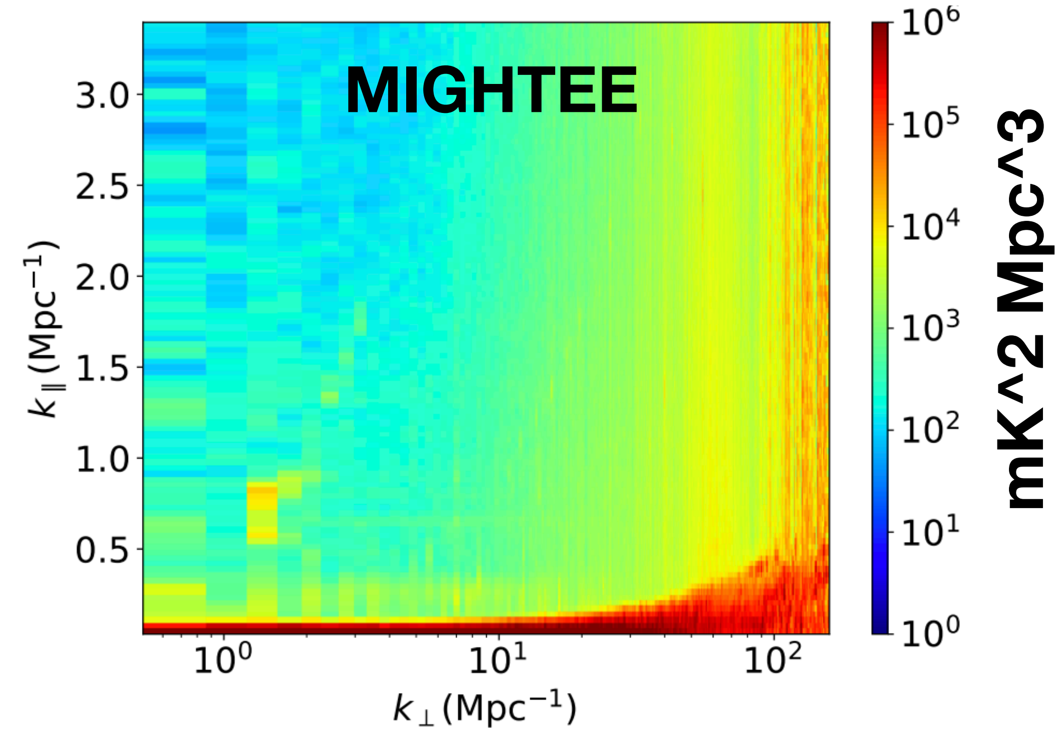
S. Paul et. alt. arXiv: 2009.13550







(a) Full Simulation



(b) Calibrated data (Stokes I)

Summary

- HI IM is considered promising as a probe of cosmological LSS;
- With MeerKLASS, we have a good opportunity to test HI IM with multi dishes before SKA operating;
- With current pilot survey, we test our calibration pipeline;
- We have done detailed analysis about the noise model for MeerKAT;
- With 2 SVD modes removed, the gain is stable over about 100s; With 5 SVD modes removed, the gain is stable over 1000s
- We test the beam effect on foreground cleaning;
- We also simulated the satellite contamination during the observations.
- Working hard on cross power spectrum detection

Thanks !