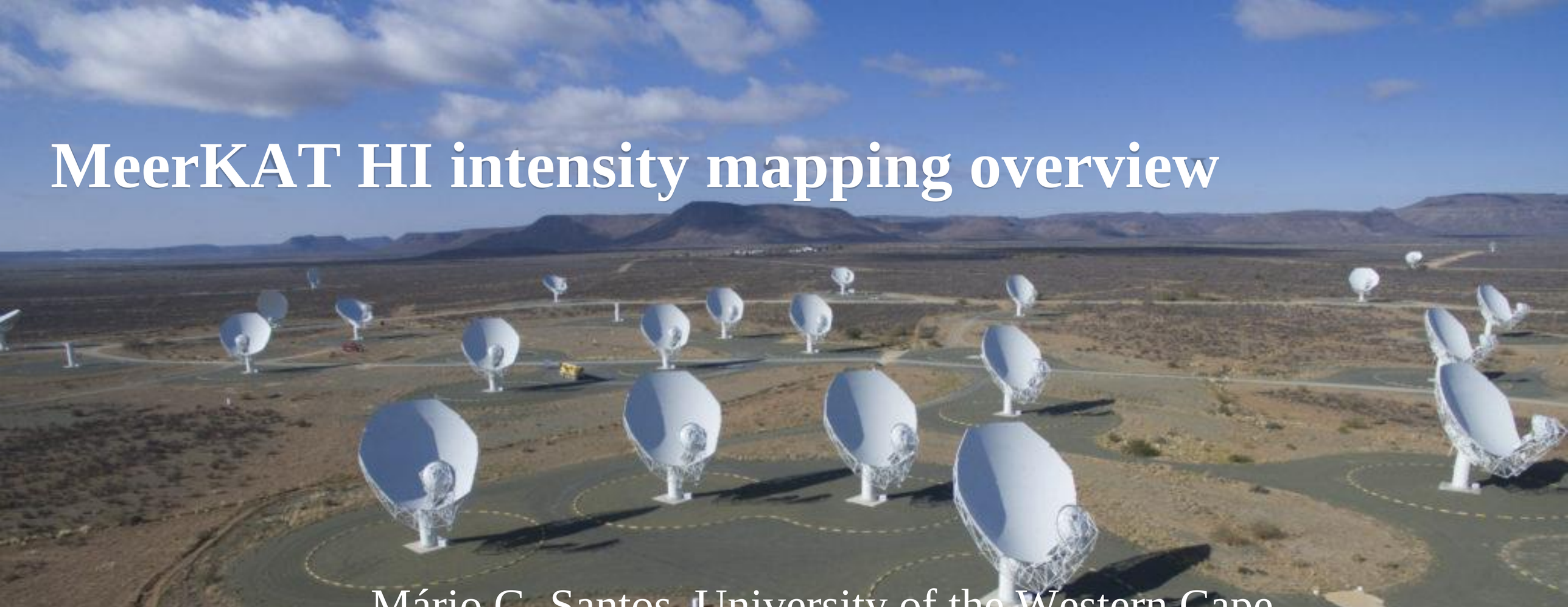
MeerKAT HI intensity mapping overview



Mário G. Santos, University of the Western Cape

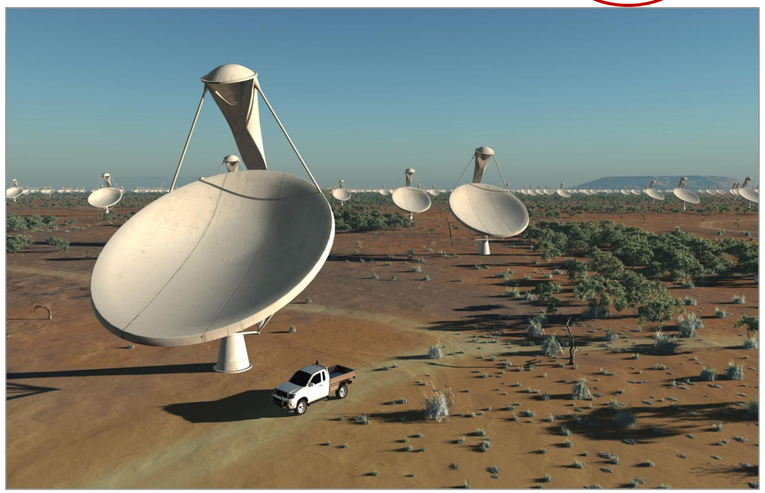
SKA Cosmology meeting

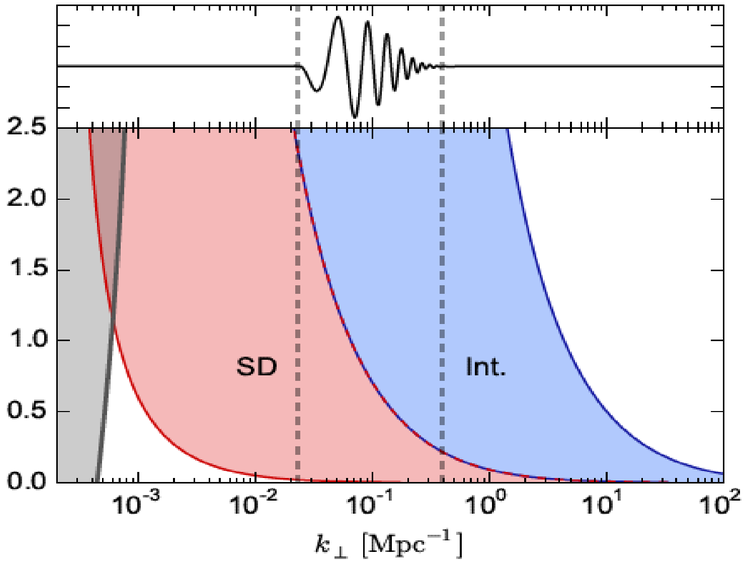
January 19, 2023

Back to basics: SKA1-MID (and MeerKAT) as an intensity mapping “machine”

- Interferometer: baselines not small enough to probe BAO scales and above
- Use each dish in “single observation mode”
- Save interferometer data for other science/calibration
- Only way to really go after the unexplored very large scales (specially in combination with LSST)
- Papers: arXiv:1501.03989; arXiv:1405.1452; arXiv: 1509.07562; arXiv: 1811.02743
- Science drive: competitive constraints on BAO/RSDs. Ultra large scale measurements/non-Gaussianity with multiple tracers

SKA1-MID (~200 dishes by 2023)





BAO scales

The near future: an SKA cosmology survey precursor with MeerKAT

- ***MeerKLASS: MeerKAT Large Area Synoptic Survey:*** http://arxiv.org/abs/1709.06099
- Aim: Cosmology (HI intensity mapping and continuum) but commensal with lots of other science
- Focus on sky patches with multi-wavelength data for cross-correlation (DES, 4MOST, etc)
- L-band: 900-1670 MHz (z<0.58) or UHF band: 580 MHz-1015 MHz (0.40 < z < 1.45)
- Boundaries: > 4,000 deg^2, < 4,000 hours (total)
- Use on-the-fly scanning in order to use the interferometer data

https://github.com/meerklass

PROCEEDINGS OF SCIENCE

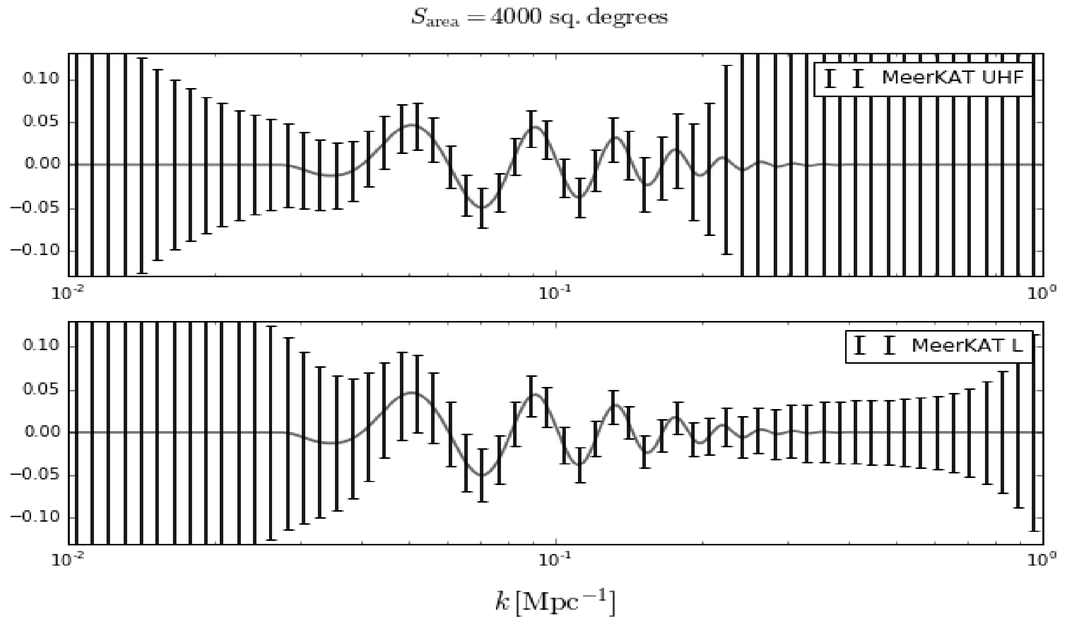
A large sky survey with MeerKAT

Mário G. Santos[*,a,b] **Philip Bull**[c,d] **Stefano Camera**[e] **Song Chen**[a] **José Fonseca**[a] **Ian Heywood**[f] **Matt Hilton**[g] **Matt Jarvis**[a,f] **Gyula I. G. Józsa**[b,h,i] **Kenda Knowles**[g] **Lerothodi Leeuw**[j] **Roy Maartens**[a,k] **Eliab Malefahlo**[a] **Kim McAlpine**[a] **Kavilan Moodley**[g] **Prina Patel**[a,b] **Alkistis Pourtsidou**[k] **Matthew Prescott**[a] **Kristine Spekkens**[l] **Russ Taylor**[a,m] **Amadeus Witzemann**[a] **and Imogen Whittam**[a]

[a] *Department of Physics & Astronomy, University of Western Cape, Cape Town 7535, South Africa*
[b] *SKA SA, The Park, Park Road, Cape Town 7405, South Africa*
[c] *California Institute of Technology, Pasadena, CA 91125, USA*
[d] *Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA*
[e] *Jodrell Bank Centre for Astrophysics, The University of Manchester, Manchester M13 9PL, UK*
[f] *Department of Physics, Oxford University, Oxford OX1 3PU, UK*
[g] *Astrophysics & Cosmology Research Unit, Univ. of KwaZulu-Natal, Durban 4041, South Africa*
[h] *RARG, RATT, Rhodes University, Grahamstown, 6140, South Africa*
[i] *Argelander-Institut für Astronomie, Auf dem Hügel 71, D-53121 Bonn, Germany*
[j] *School of Interdisciplinary Research & Graduate Studies, UNISA, Pretoria 0003, South Africa*
[k] *Institute of Cosmology & Gravitation, University of Portsmouth, Portsmouth PO1 3FX, UK*
[l] *Department of Physics, Royal Military College of Canada, Kingston, ON K7K 7B4, Canada*
[m] *Department of Astronomy, University of Cape Town, Cape Town 7701, South Africa*

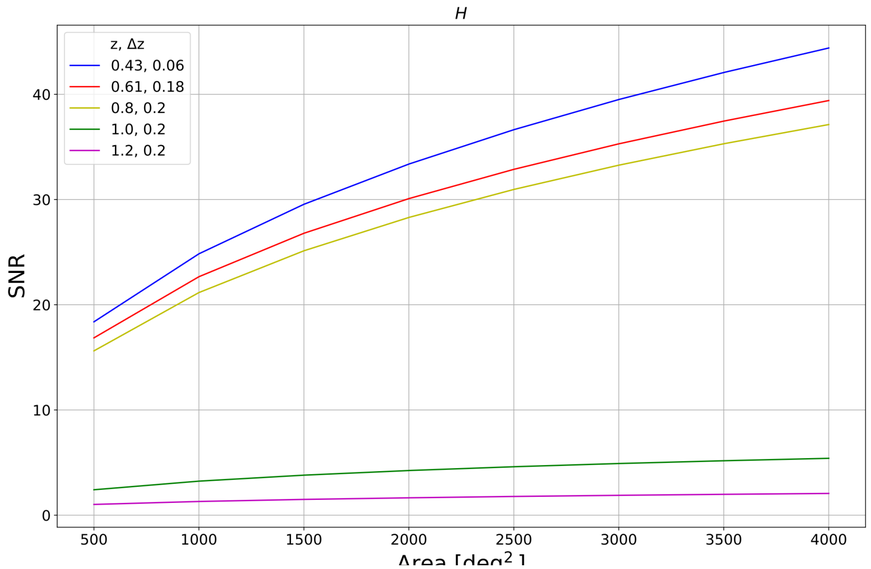
Driving objectives

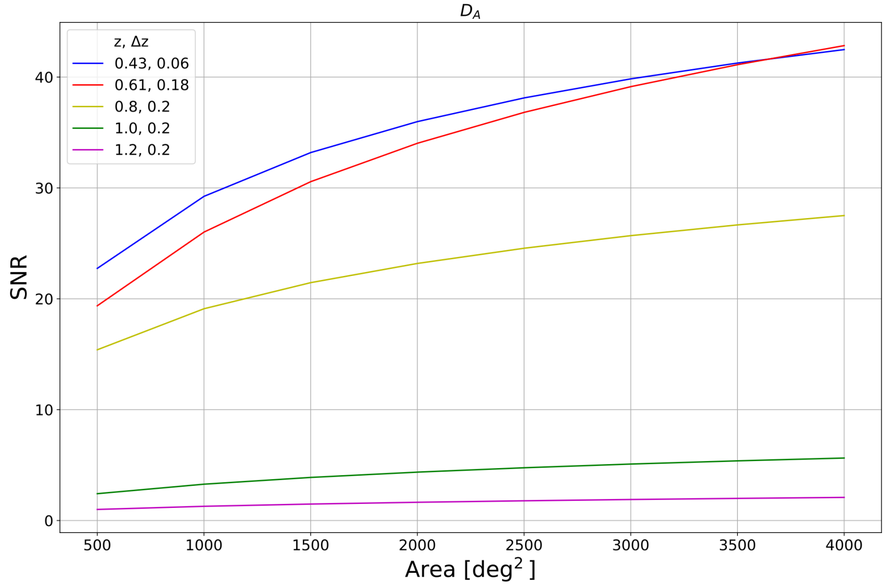
- Detection of Baryon Acoustic Oscillations (BAO) using HI
- Measure the Hubble rate at low z
- Measure redshift space distortions (to constrain modified gravity theories)
- Cross-correlations with galaxy surveys
- Constraints of primordial non-Gaussianity by measuring large scale correlations

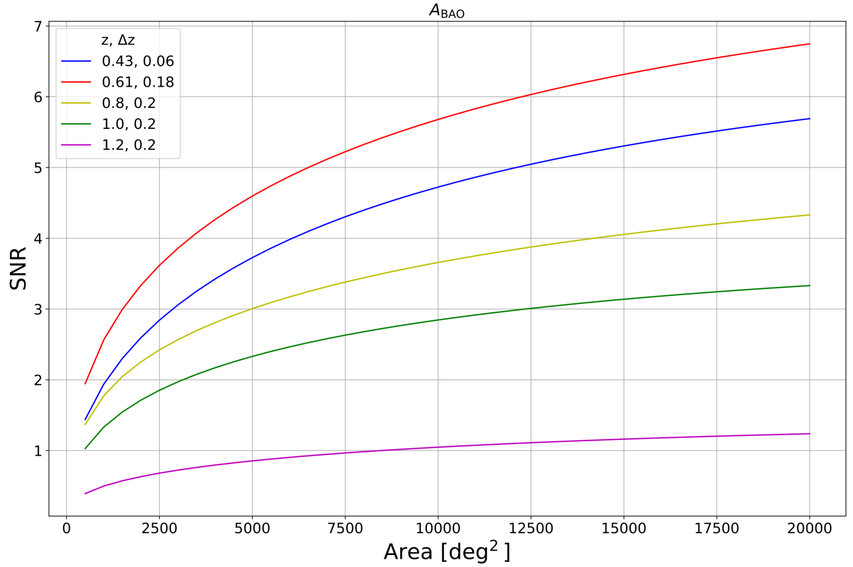


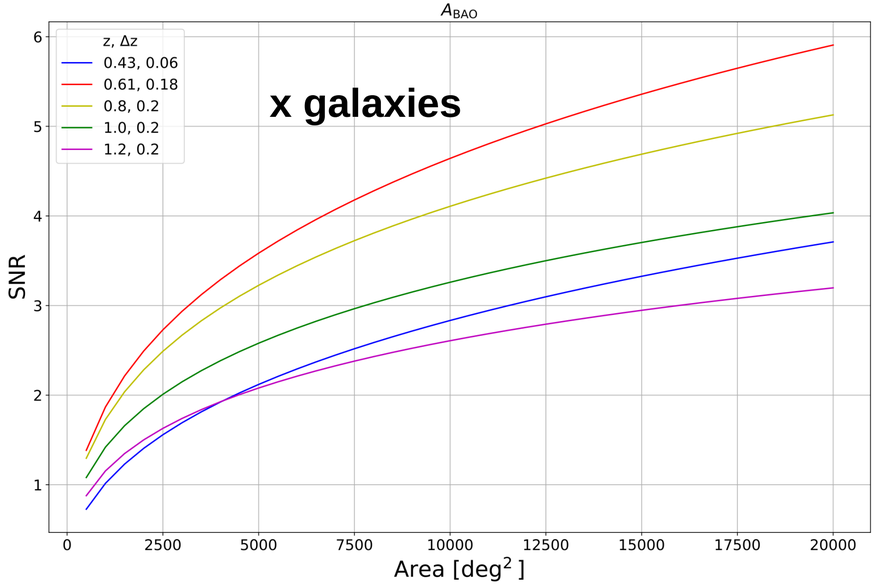
BAO

Forecasts: UHF (1000 hours)









(Jose Fonseca)

Current status

- 1st open time call: ~ 15 hours over WiggleZ 11h field (after some flagging). L-band. Fully processed. Aim was to test technique and maybe detect the power spectrum in cross-correlation with galaxy surveys

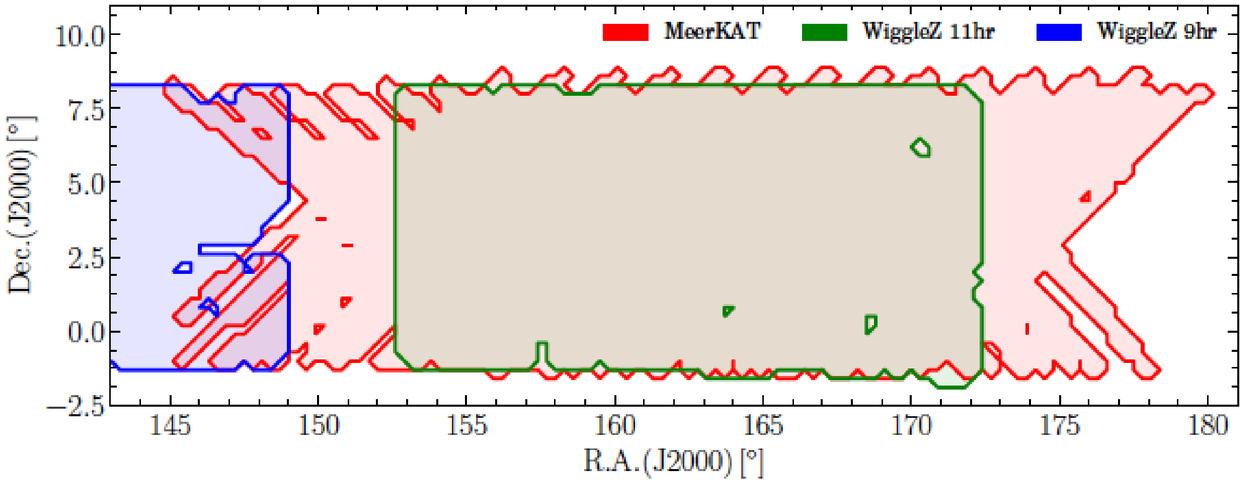
- 2nd open time call: ~ 80 hours. L-band. First calibrated cubes available. Aim is a direct detection of the HI power spectrum

- Director Discretionary Time (DDT): ~ 12 hours over WiggleZ 11h field using UHF band. Data taken and partially calibrated

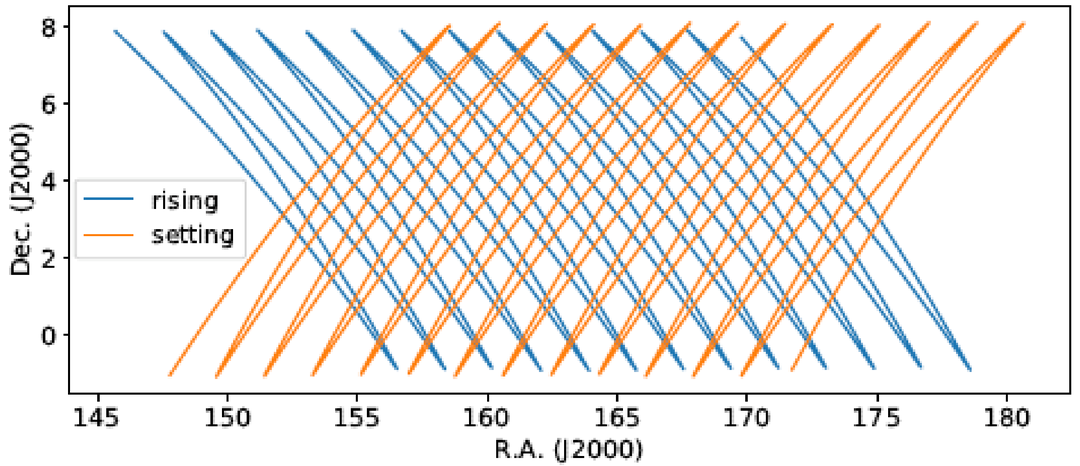
- 3rd open time call: Approved ~ 130 hours using UHF over two fields covering ~ 500 deg^2 of SDSS/DESI

- Ongoing tests for on-the-fly mode so we can use the interferometer data at the same time (see Kristof talk)

Pilot survey (see Wang et al. arxiv:2011.13789)



Footprint



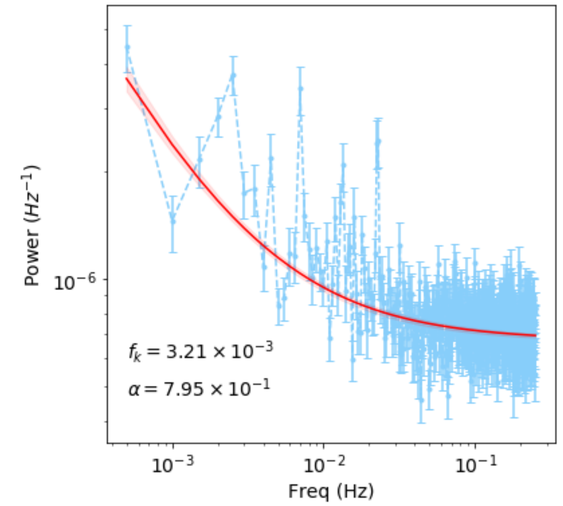
Scanning pattern

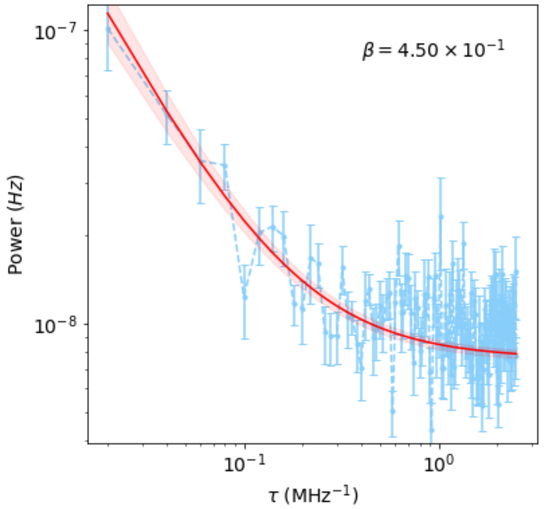
- ~ 10.5 hours (data taken in 2019)
- ~ 60 dishes used (~ 630 hours combined)
- ~ 200 deg^2 over the WiggleZ 11h field
- Band: 900 MHz - 1700 MHz (z < 0.5)

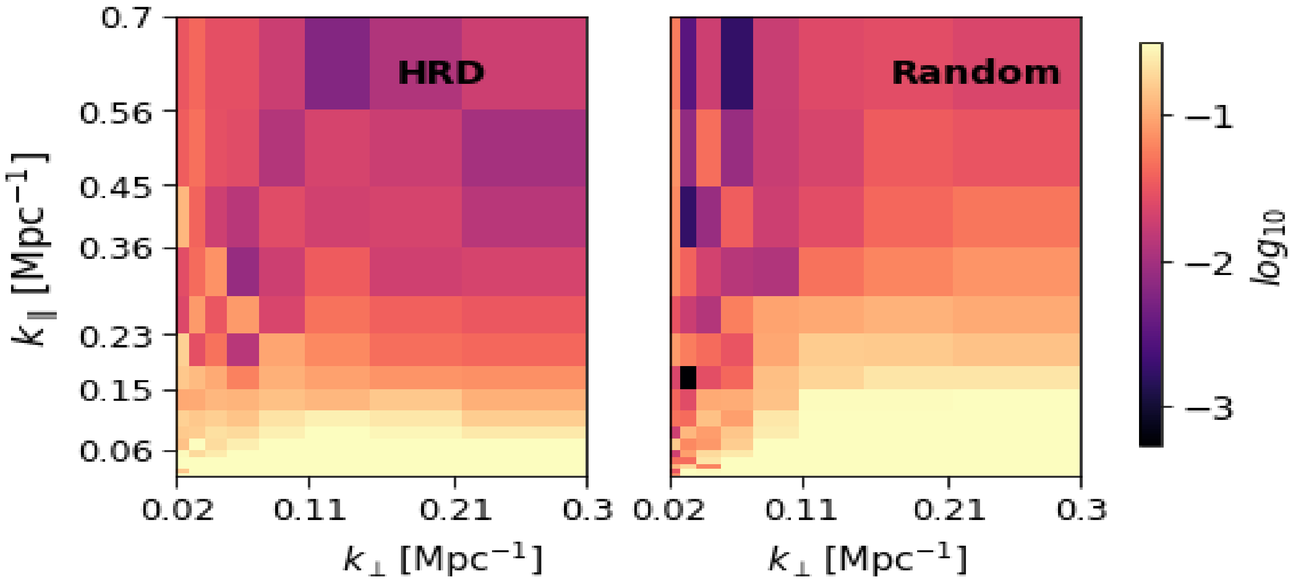
- Resolution: 2 sec/0.2 MHz
- Scans at constant elevation (> 40 deg)
- Speed: 5 arcmin/sec
- ~ 200 sec per line, 1.5 hours per scan (each block ~ 1.2TB)

MeerKAT 1/f noise in one slide

- Noise is correlated in time —> can bias result and increase noise level - need fast scanning to probe relevant angular scales within the time scales of the 1/f noise

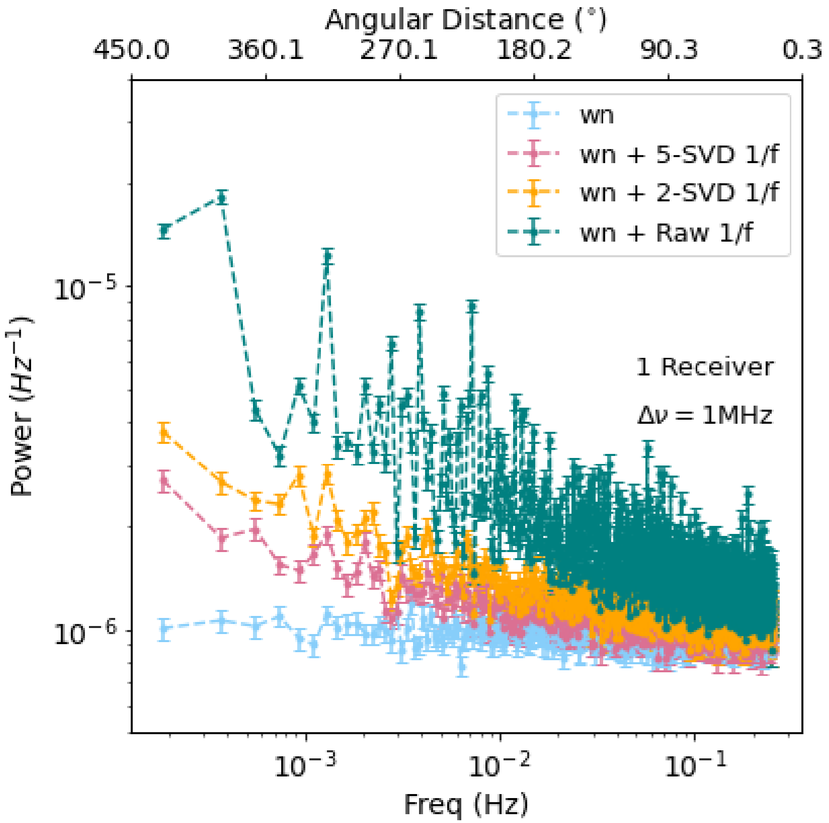


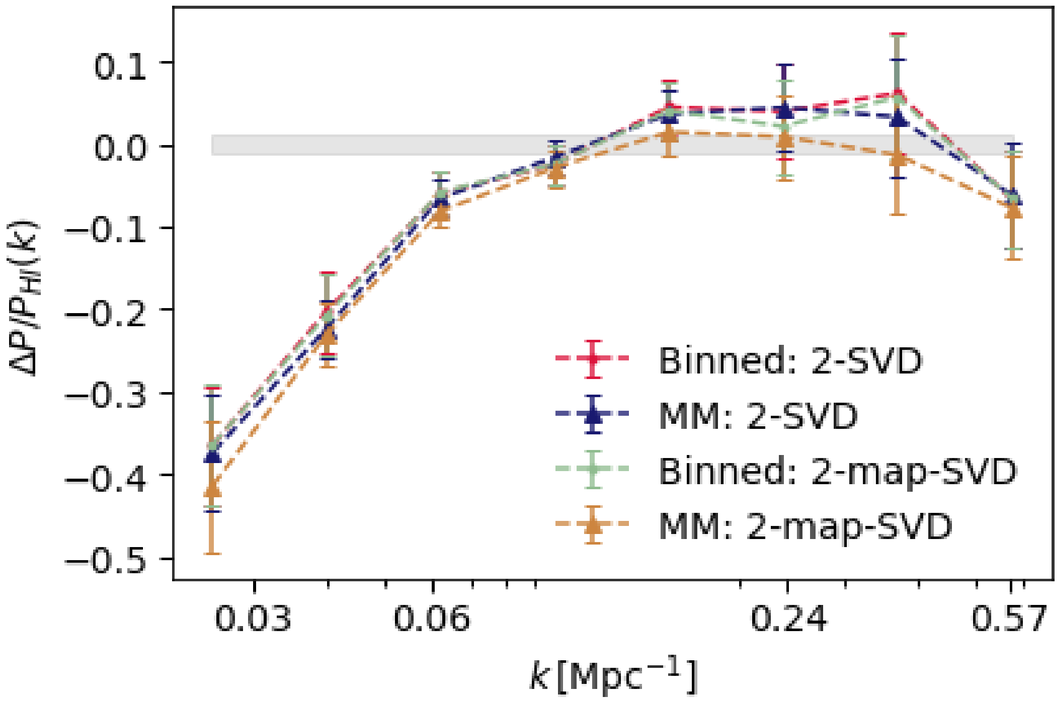




Mel Irfan et al., in prep
(see also Li et al., MNRAS 2020, Arxiv:2007.01767)

OK, 2 slides…

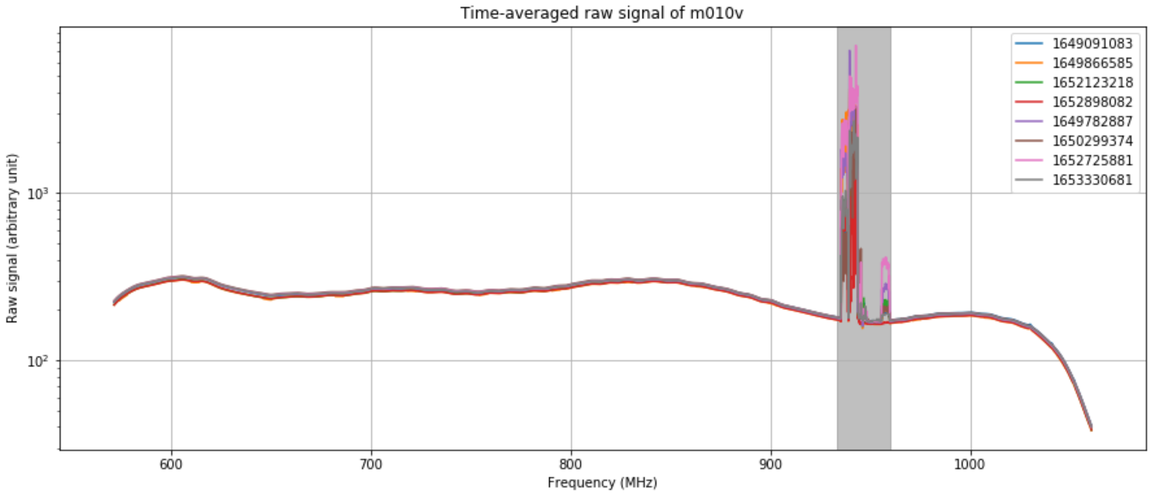


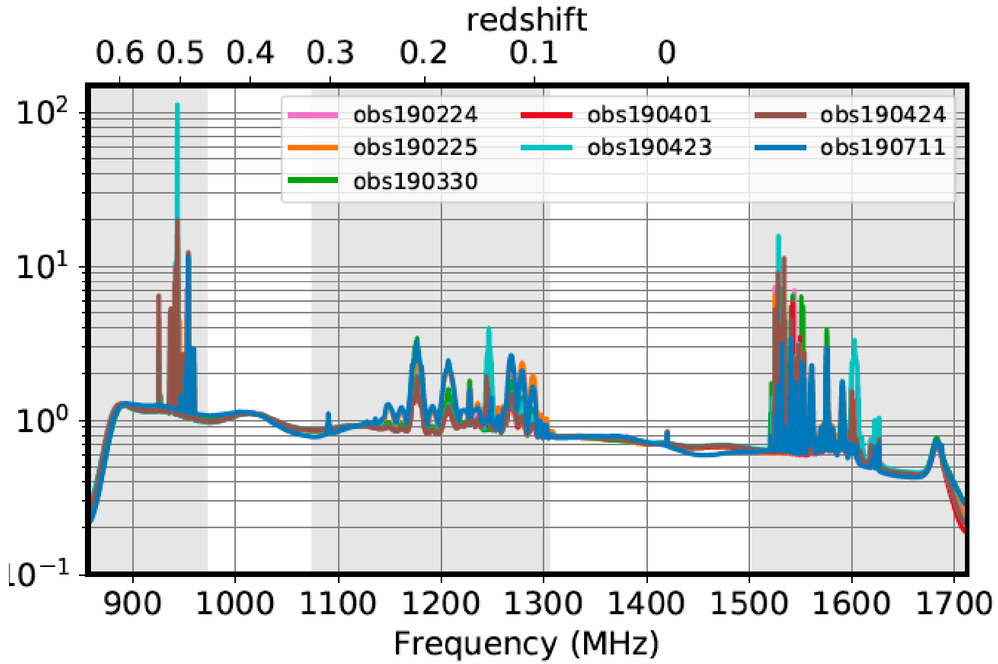


Mel Irfan et al., in prep

- SVD cleaning reduces 1/f noise but need to be careful with signal loss

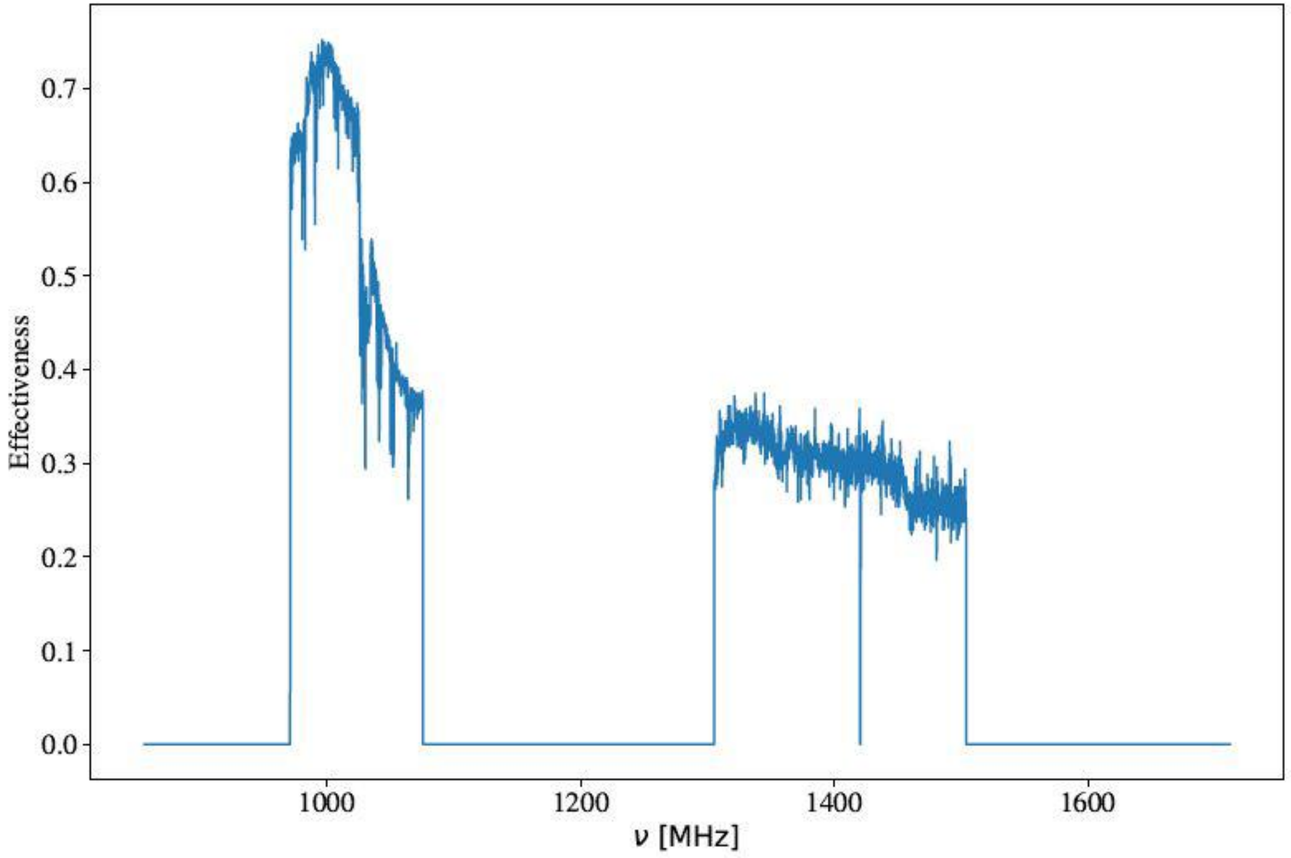
RFI…



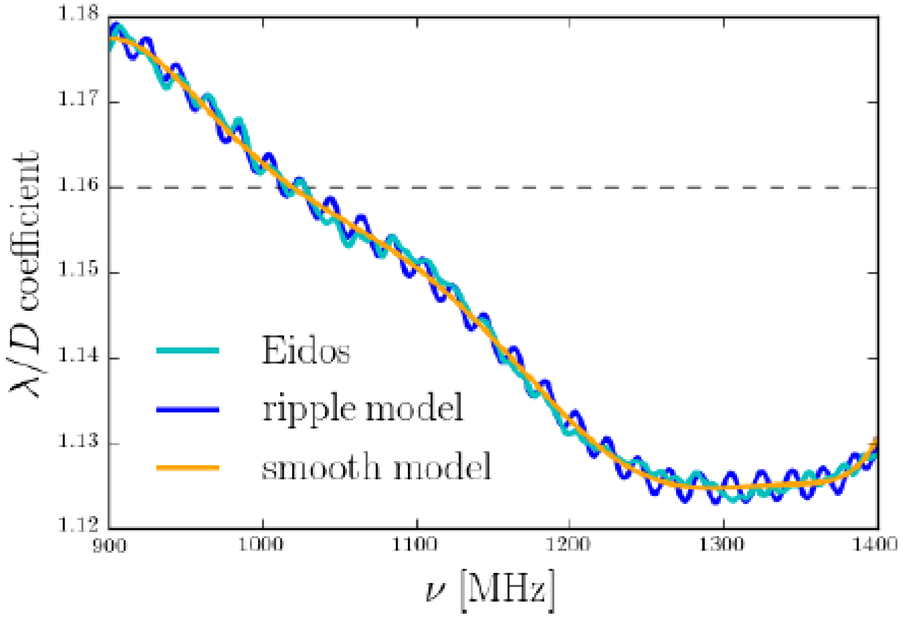


- Satellites are a big concern, in particular with single dish data and in particular from the beam sidelobes
- RFI free regions in L band: 0 < z < 0.09 and **0.32 < z < 0.46**
- Several rounds of RFI cleaning were applied

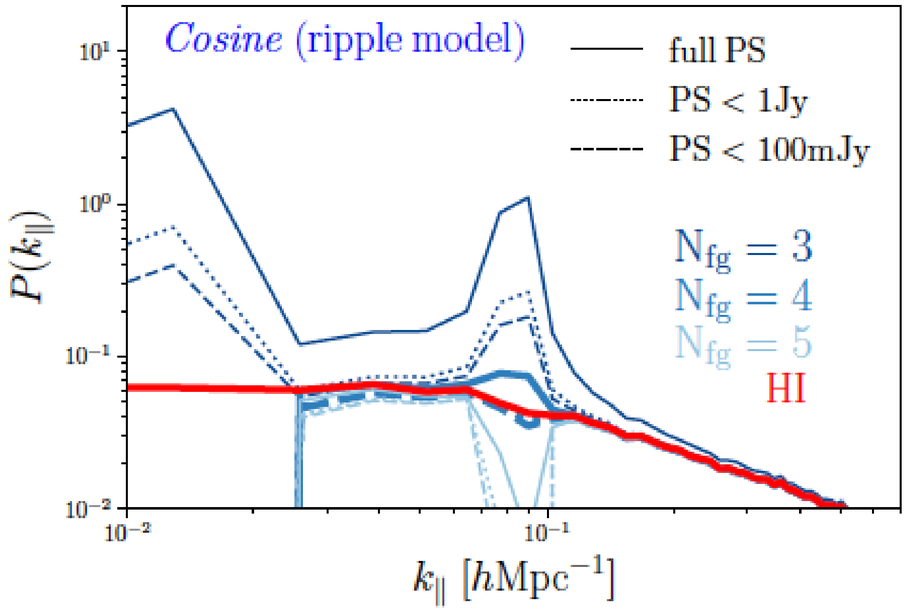
RFI flagging: % data kept in L band



Primary beam frequency effects on foreground cleaning



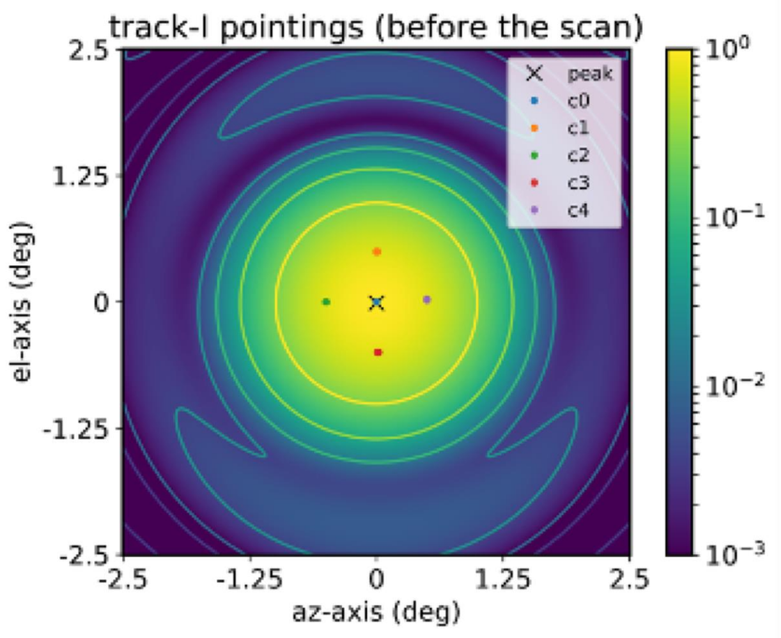
- MeerKAT beam size (FWHM) versus frequency

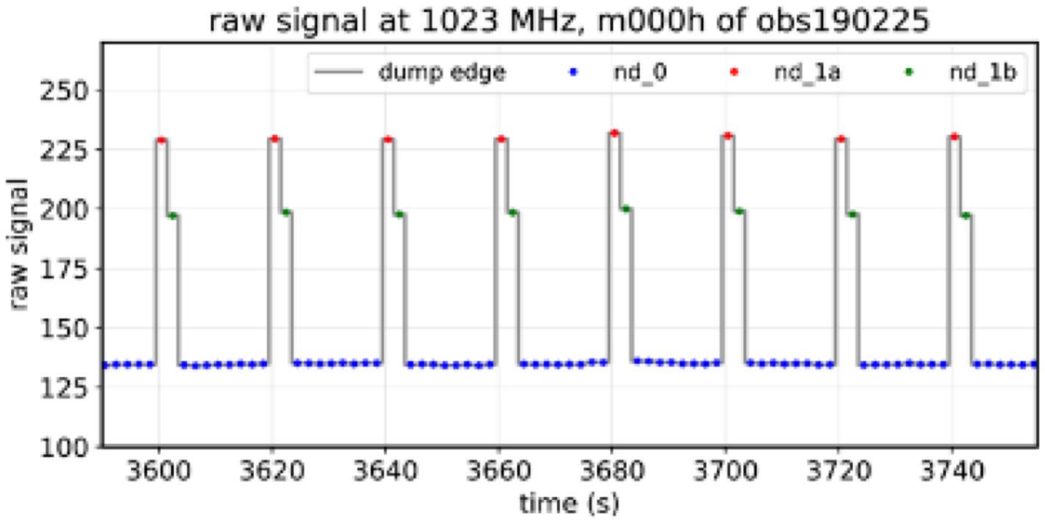


- Effect on foreground cleaning: line of sight power spectrum

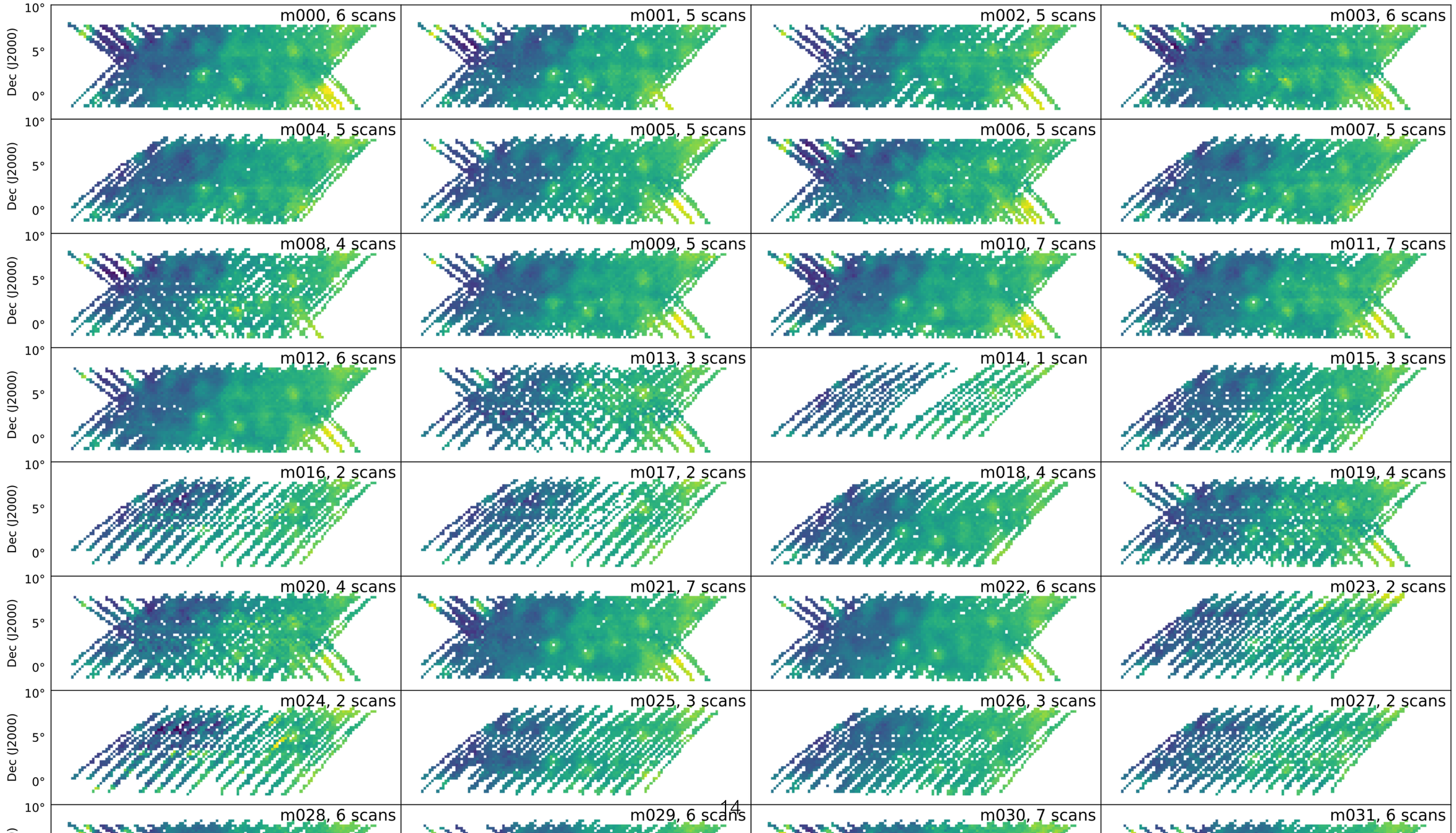
Matshawule, Spinelli, Santos, arxiv:2011.10815

Calibration

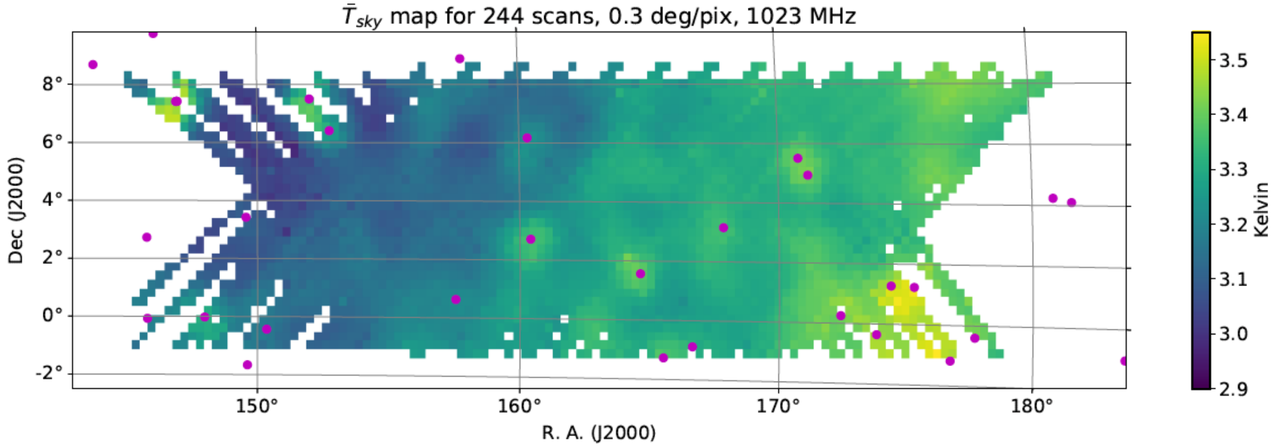


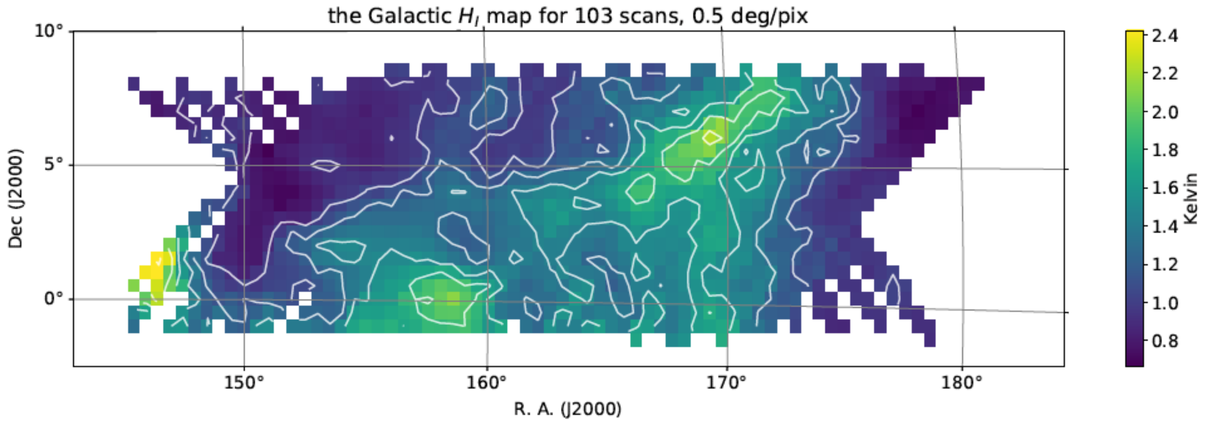


- Observe a calibrator before and after each scan (left)
- Noise diode injection every 20 sec during scan (right)


per-dish $\bar{T}_{sky}$ maps at 1023 MHz
m000, 6 scans
m001, 5 scans
m002, 5 scans
m003, 6 scans
m004, 5 scans
m005, 5 scans
m006, 5 scans
m007, 5 scans
m008, 4 scans
m009, 5 scans
m010, 7 scans
m011, 7 scans
m012, 6 scans
m013, 3 scans
m014, 1 scan
m015, 3 scans
m016, 2 scans
m017, 2 scans
m018, 4 scans
m019, 4 scans
m020, 4 scans
m021, 7 scans
m022, 6 scans
m023, 2 scans
m024, 2 scans
m025, 3 scans
m026, 3 scans
m027, 2 scans
m028, 6 scans
m029, 6 scans
m030, 7 scans
m031, 6 scans
Dec (J2000)
10°
5°
0°

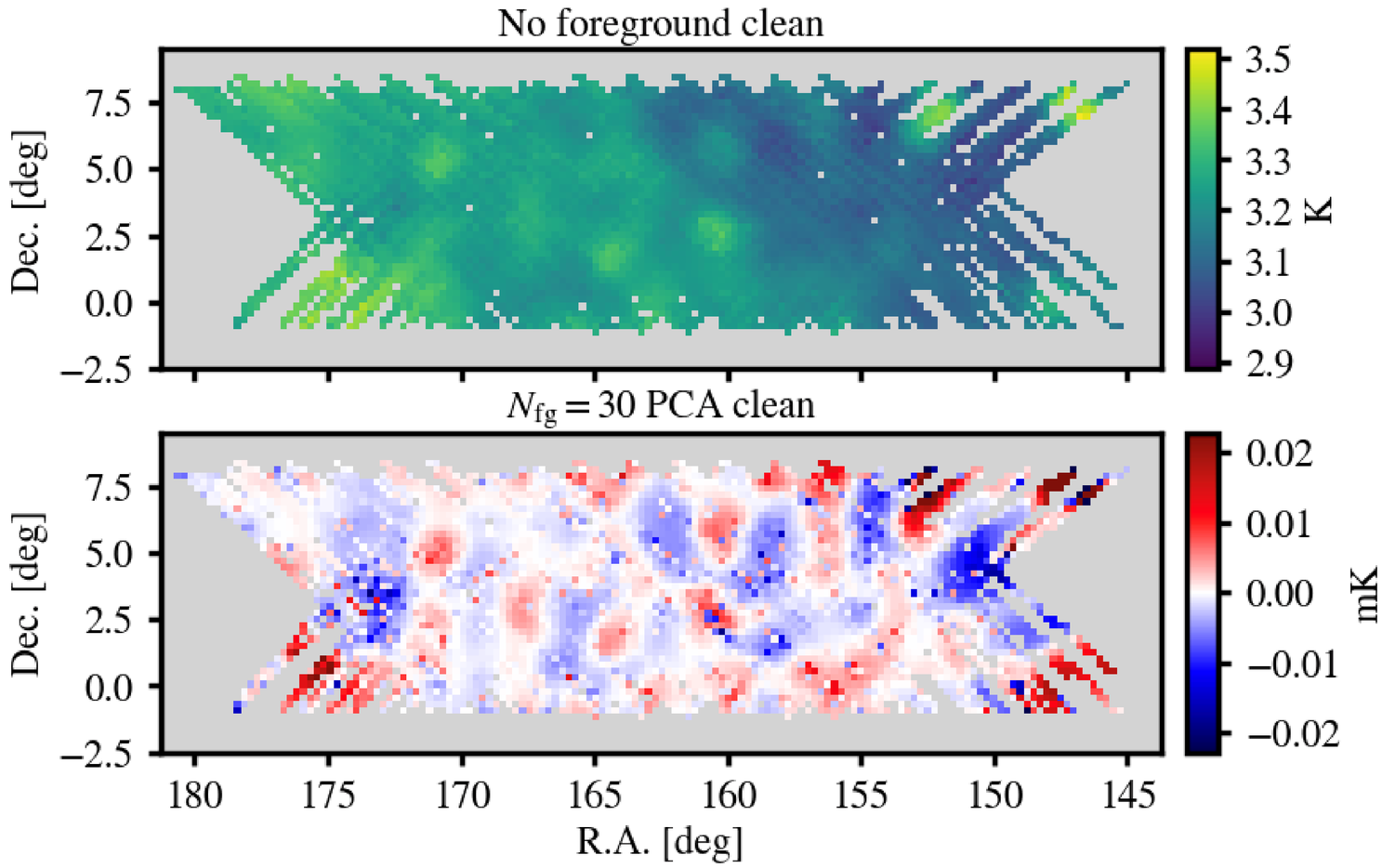
Final maps



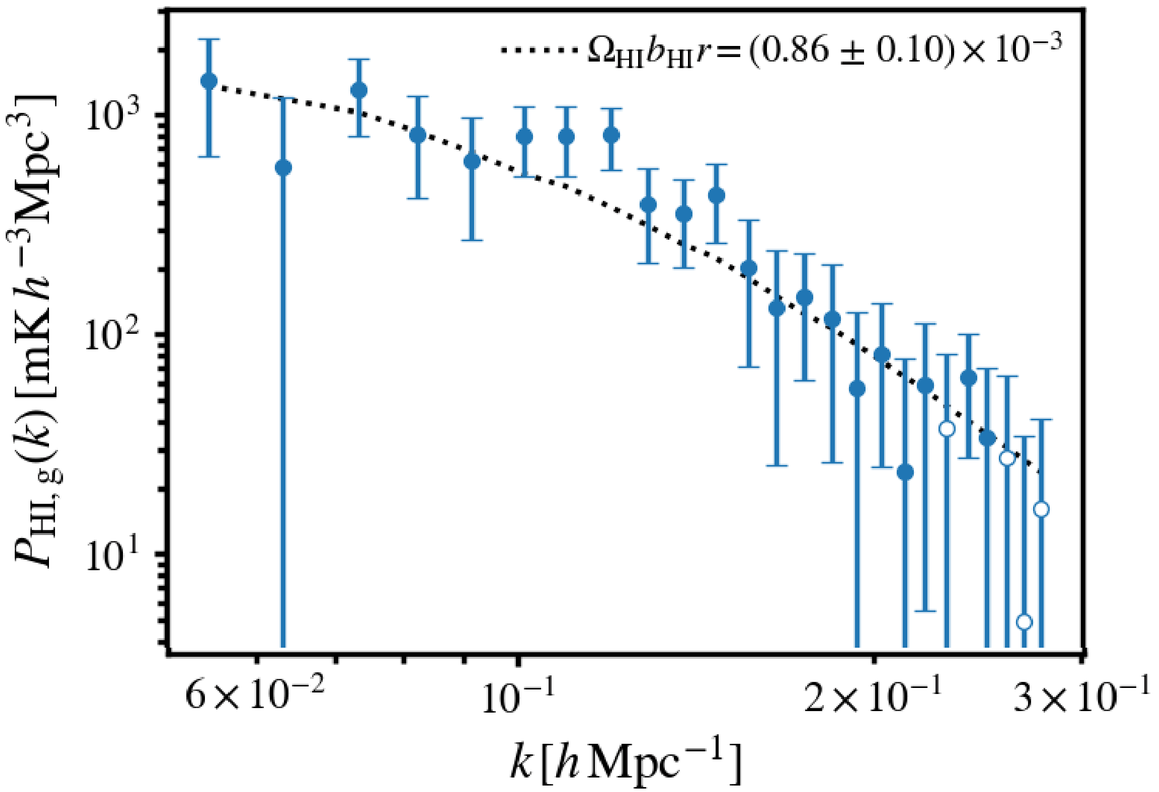


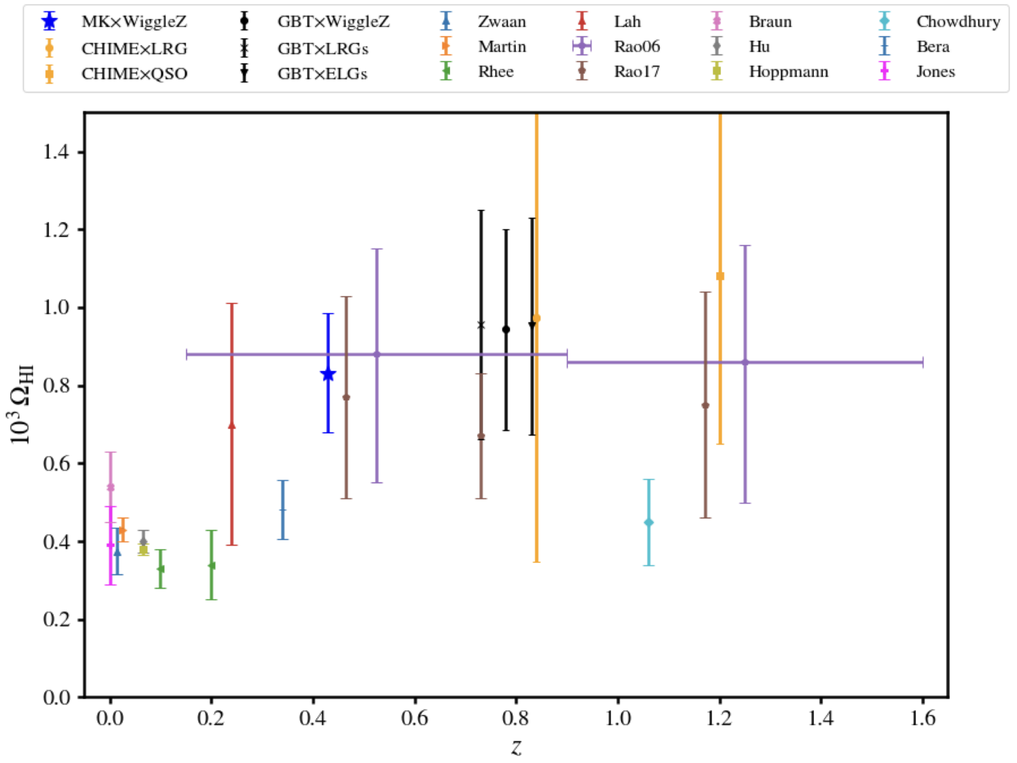
- Full data reduction pipeline: Wang et. al, Arxiv:2011.13789
- Sky map follows the galactic synchrotron
- We recover the Galactic HI with high accuracy

Foreground cleaned maps



Detection of the cross-correlation power spectrum with WiggleZ galaxies

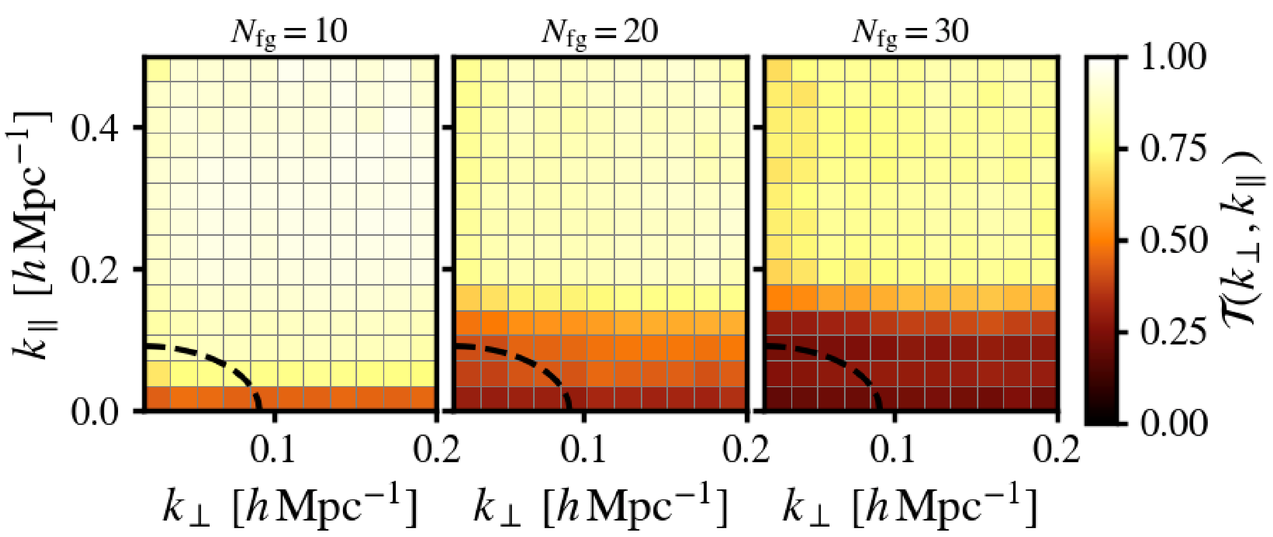


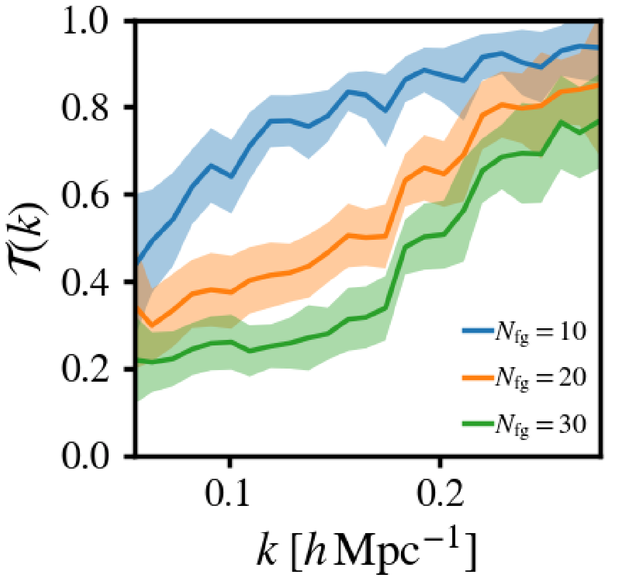


0.400 < z < 0.459

Cunnington, Li, et al. 2022

Transfer function / signal loss

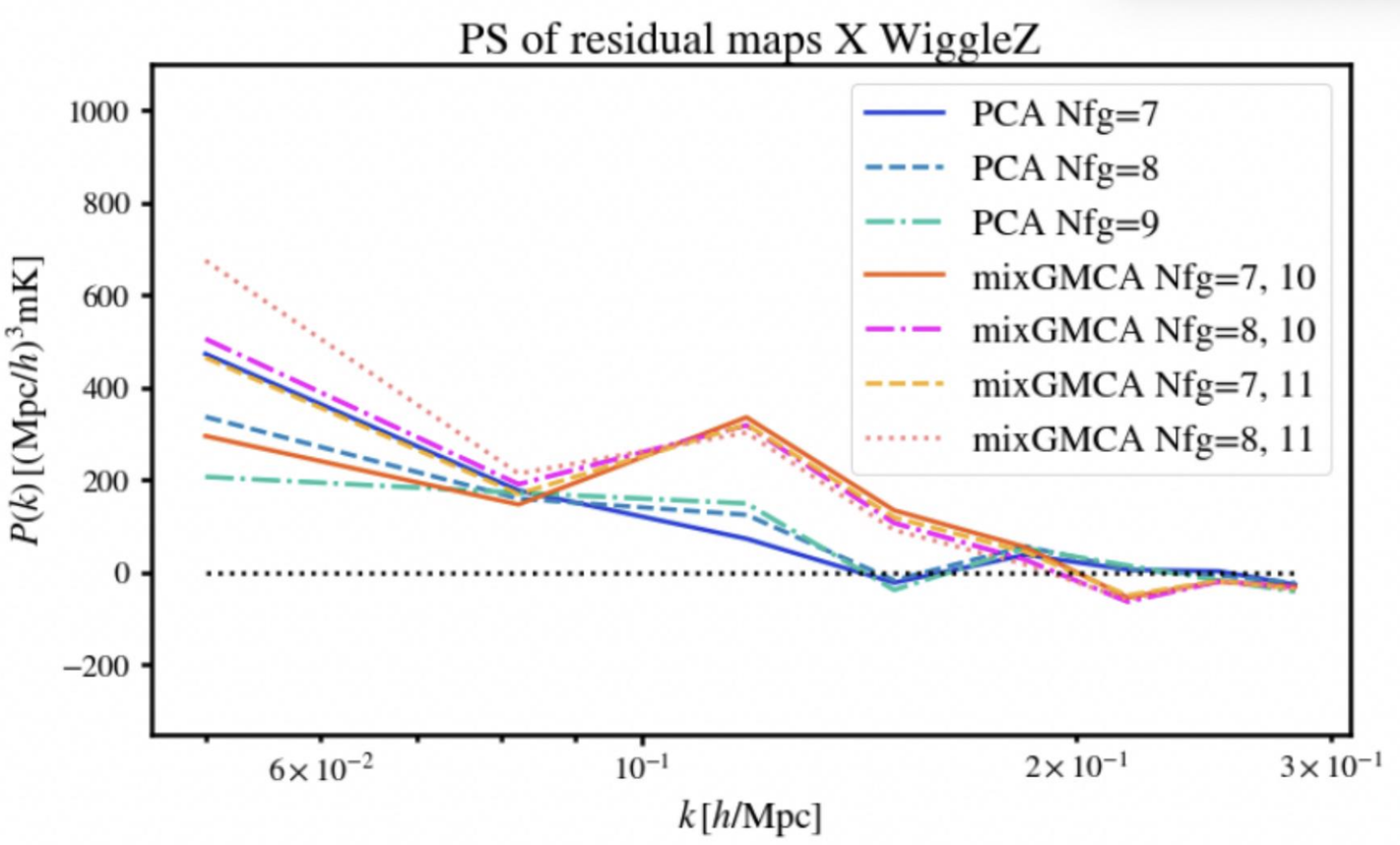




- Signal loss due to foreground cleaning affects all scales but mostly small k_par
- Transfer function crucial to unbias the power spectrum estimator
- Calculated through signal injection
- Need to improve calibration to reduce foreground cleaning!

Steve Cunnington

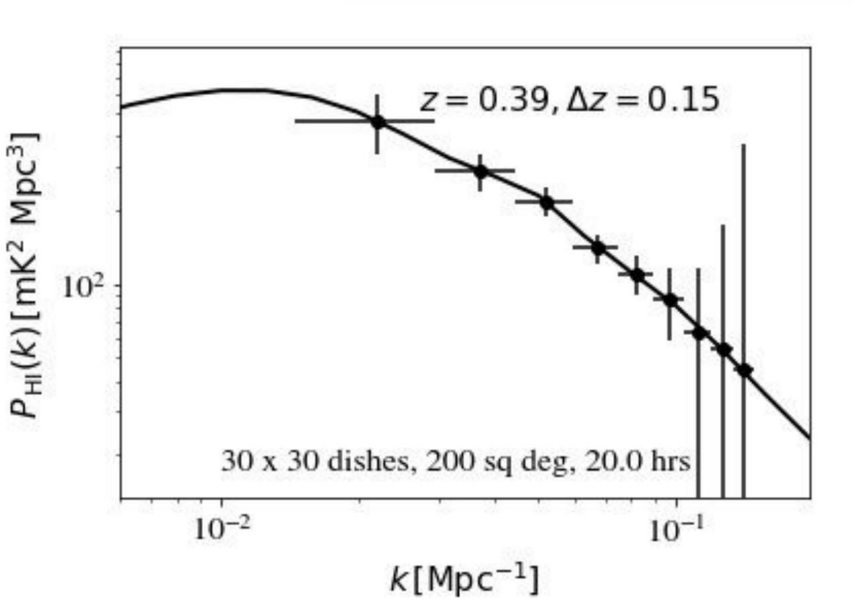
Foreground removal methods?

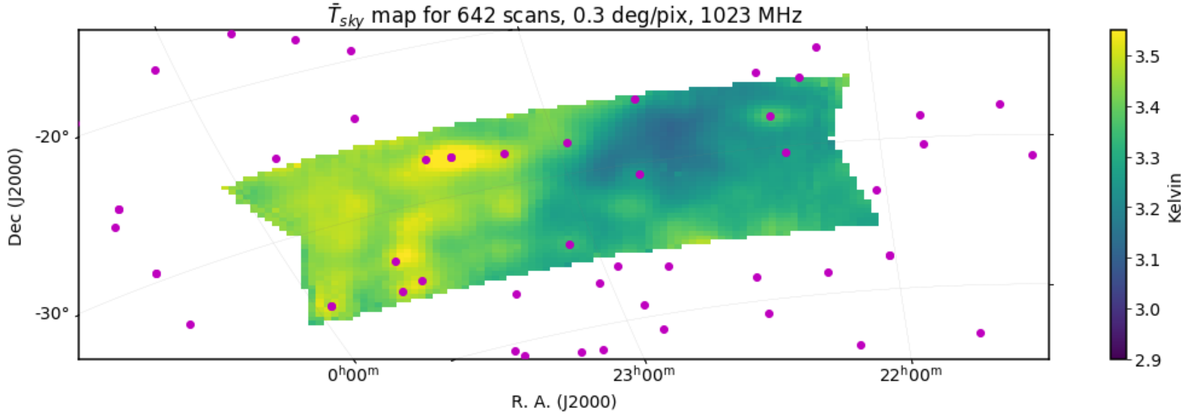


Iisabella Carucci

Next steps

- Processing 40 observation blocks from 2021 data (~ 60 hours on target)
- Some goals:
  - Get the auto-power spectrum
  - Cross-correlations with photometric survey





Jingying Wang

Plan/thoughts

- HI intensity mapping is allowing MeerKAT to do cosmology. With more data, it can deliver first detections of the signal, BAO and RSDs measurements and large scale probes beyond the equality peak
- Current tests with MeerKAT data show no major issues - we have an end to end pipeline producing calibrated data with 64 dishes
- Lots of data available! We need more people to work on improving the pipeline and doing more tests.
- Plan is to continue accumulating more data in the next 4-6 years (with another ~300 hours already in 2023)
- Crucial to have a more automatic pipeline for flagging (RFI, bad dishes, etc) and calibration
- Improve mapmaking (include beam, etc)
- Improve calibration (self cal, gain models…)
- Polarisation maps
- Foreground cleaning
- …