HI intensity mapping with MeerKAT

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21 cm Cosmology Workshop 2023 & Tianlai Collaboration Meeting

Northeastern University & National Astronomical Observatories CAS, China, July 17, 2023

CRC

UNIVERSITY of the WESTERN CAPE

UWC ASTROPHYSICS

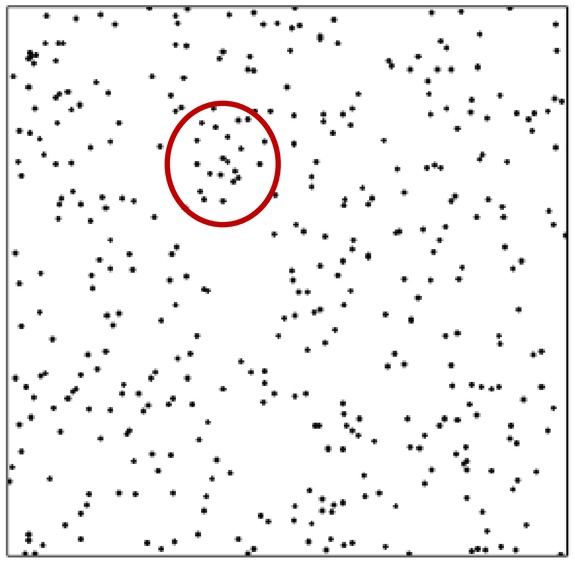
NRF National Research Foundation

SARAO South African Radio Astronomy Observatory

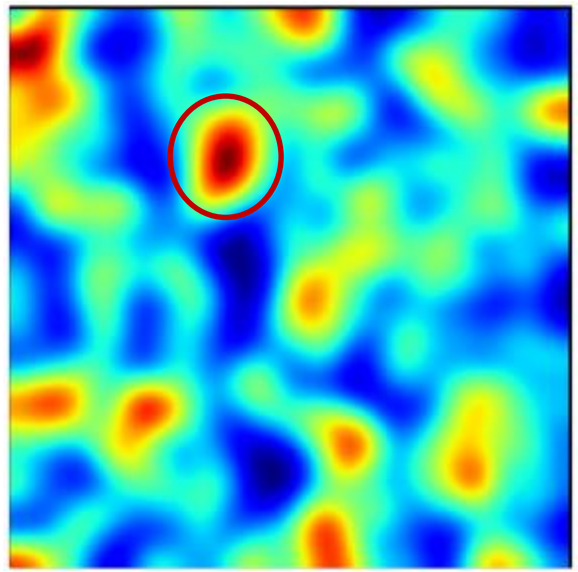
Probing LSS with intensity mapping

- For Cosmology, scales of interest are well beyond galaxy scales (Baryon Acoustic Oscillations ~ 150 Mpc)
- Intensity mapping is very fast → no threshold cutoff
- Provides high frequency/redshift resolution (in the radio…)
- Pixel will have joint emission from multiple galaxies
- Signal ~ 200 uK at z~1
- Usual assumption: HI is a continuous field (shot noise negligible, sensitivity independent of dish size…)

Note: only way to probe the HI in the inter-galactic medium

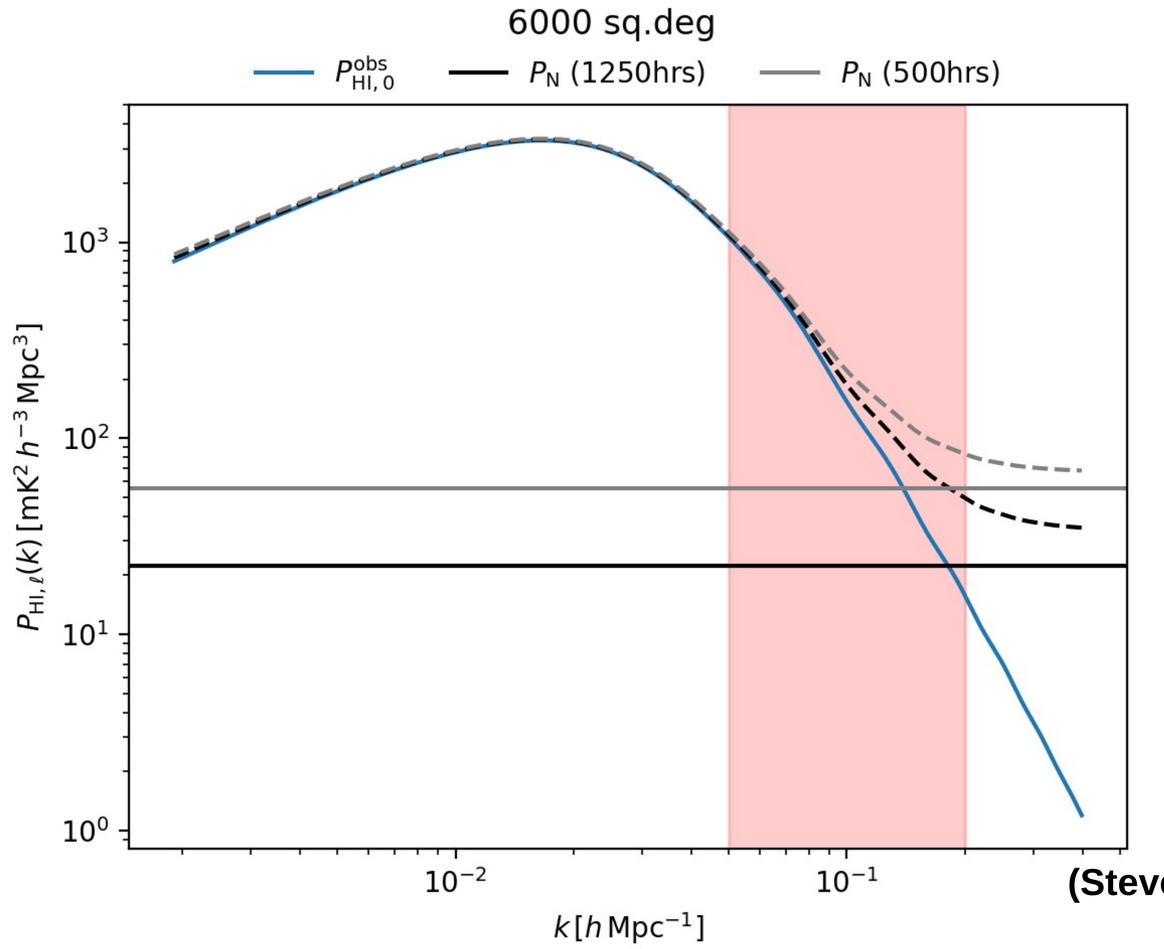


galaxies



Intensity map

HI IM makes it “easy” to probe the 3D power spectrum

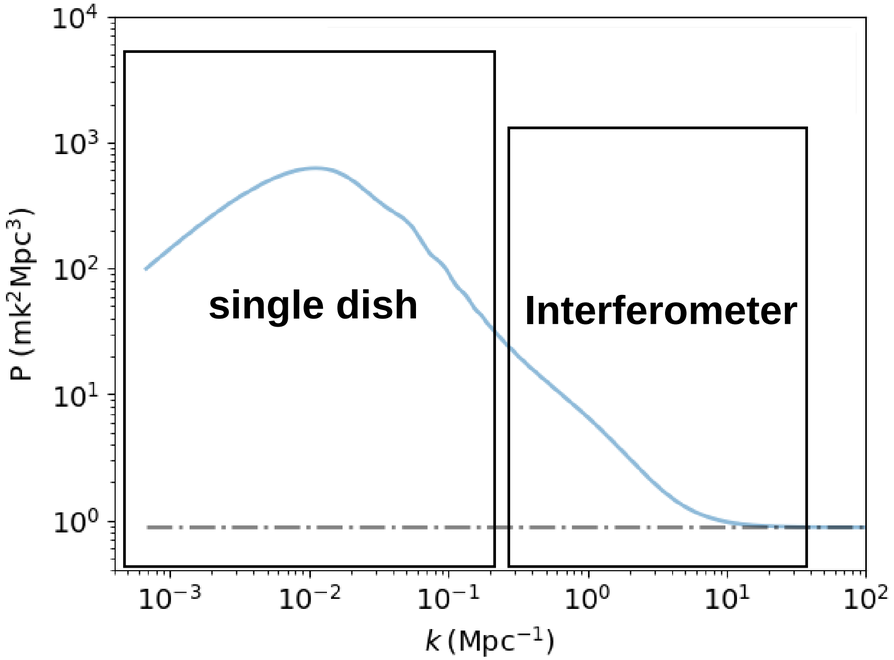


(Steve Cunnington)

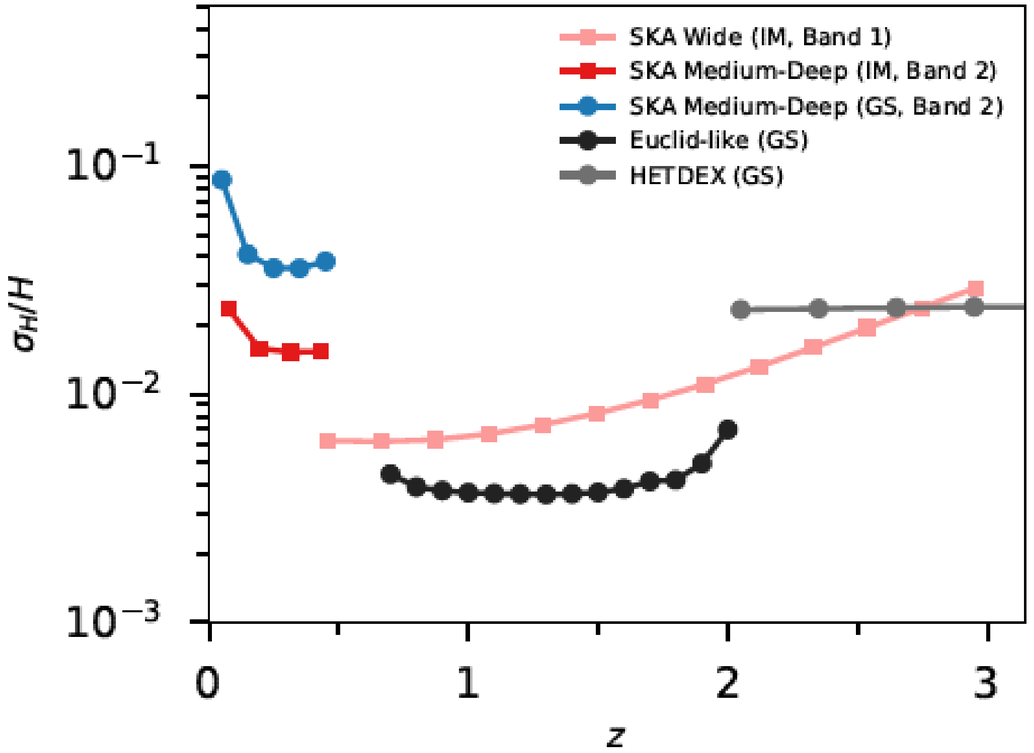
- An example with the MeerKAT telescope: 500 hours is enough to detect the baryon acoustic oscillations. Noise is well below the signal on large scales

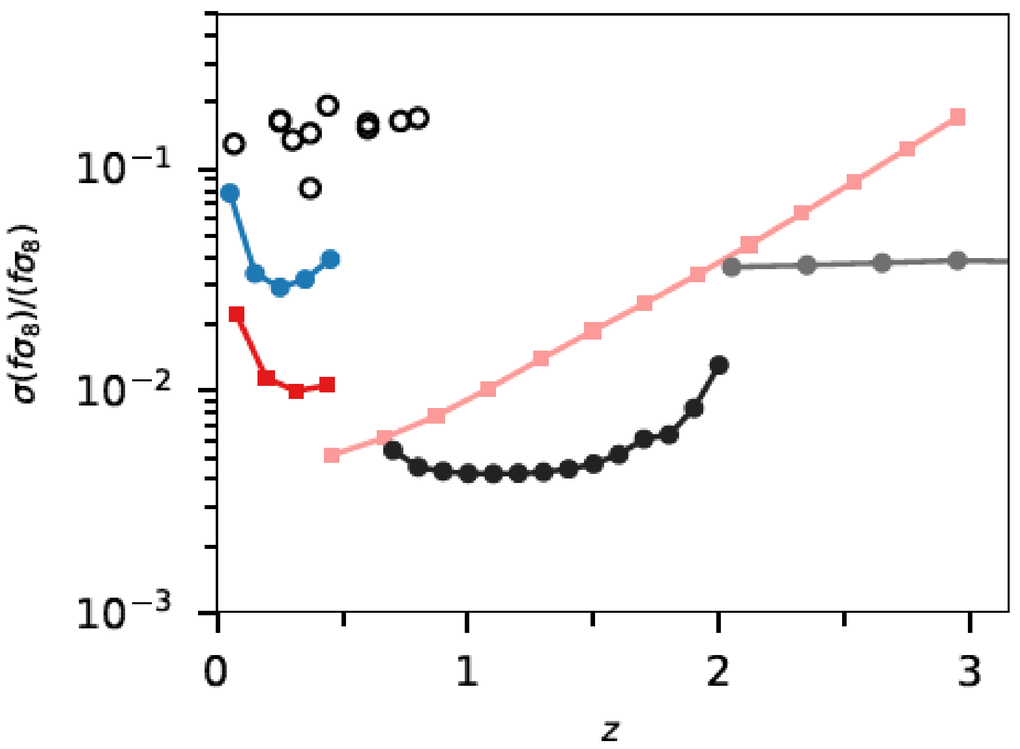
SKA1?

- Need SKA1-MID for z < 3 but baselines not small enough to probe BAO scales and above…
- Plan: use the array in “single dish mode”
- SKA1-MID single dish HI intensity mapping survey will turn SKA into a state of the art cosmology machine
- Only way to really go after the unexplored very large scales
- See: arXiv:1305.6928, arXiv:1405.1452, arXiv:1501.03989, arXiv: 1509.07562, arXiv:1811.02743



“Standard” Cosmology with SKA1-MID

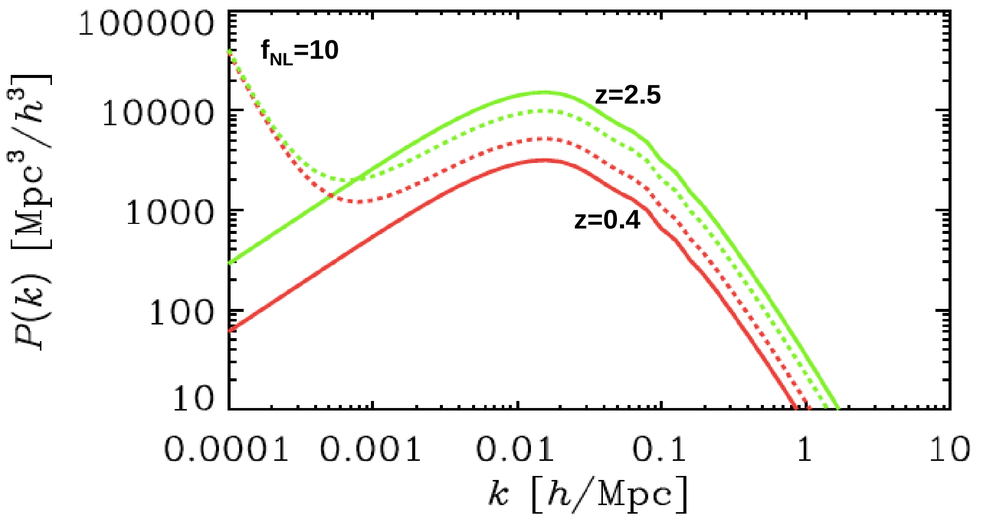




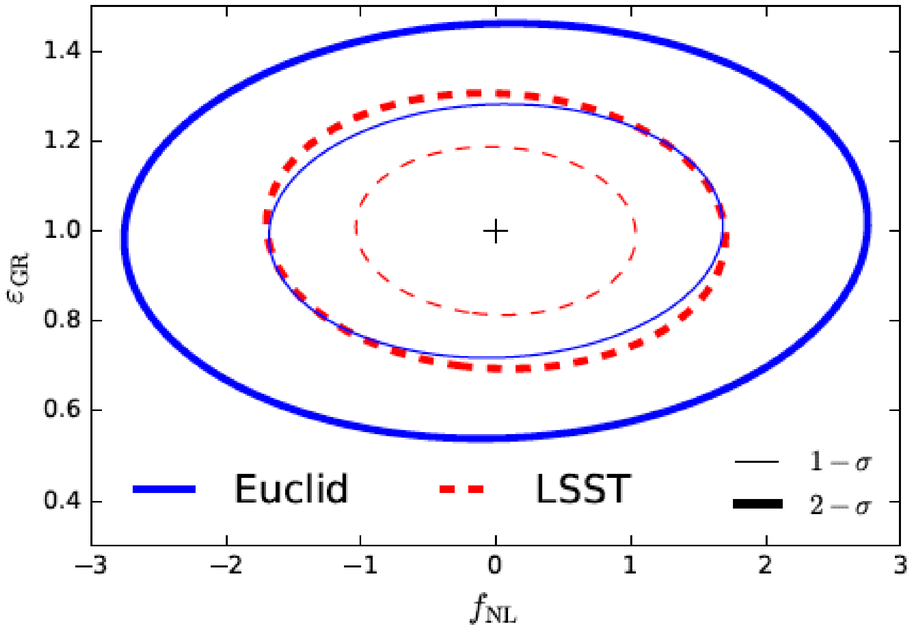
- Error forecast for the Hubble rate
- Error forecast for the growth rate

- SKA1 Cosmology “red book”: arXiv:1811.02743

Constraints on large scale effects with SKA1-MID and multi-tracers



Camera et al., PRL, 2013



SKA1 Cosmology “red book”: arXiv:1811.02743

- The information is in the bias with respect to the dark matter field -> use multi-tracers to beat cosmic variance
- Combining an HI intensity mapping survey using SKA1-MID Band 1 with LSST will detect fNL ~ 1 as well as GR corrections
- A nice way to “fight” systematics
- See also: Alonso and Ferreira, PRD, 2015; Alonso et al. ApJ 2015; Fonseca et al., ApJ Letters, 2015; A Witzemann, et al., MNRAS, 2019; Matarrese and Verde, Astrophys.J. 2008; Dalal et al., PRD 2008; Squarotti et al., arXiv:2307.00058v1; Karagiannis et al., arXiv:2305.04028v1; Jolicoeur, arXiv:2301.02406v3…

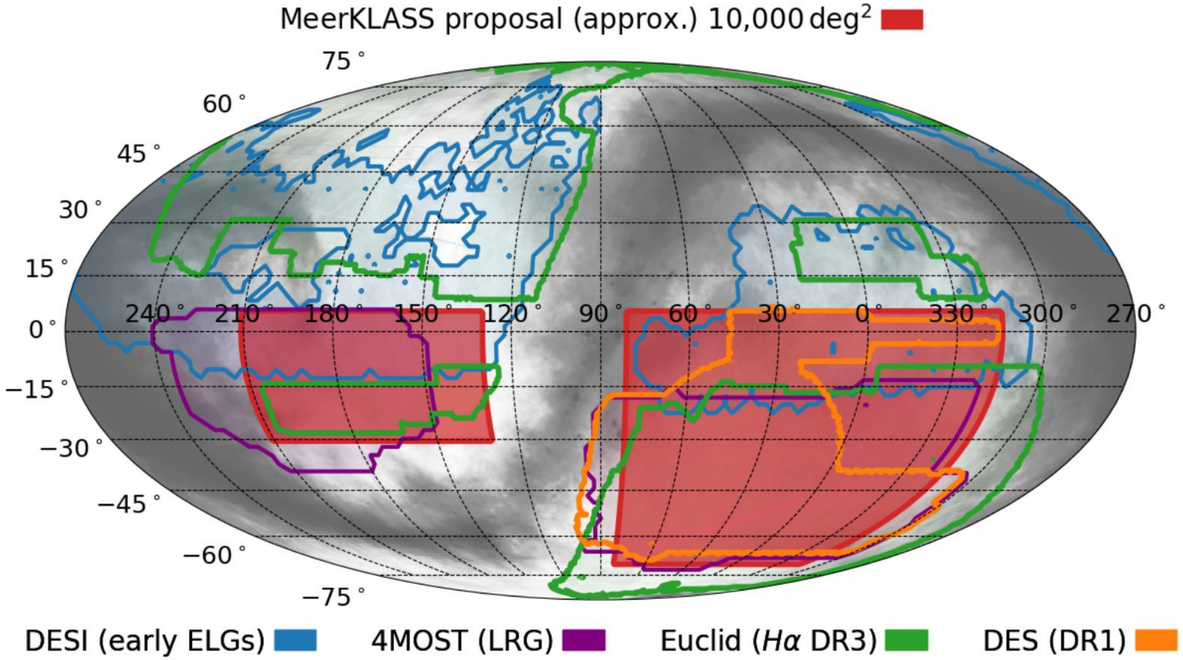
MeerKAT?

- 64, 13.5 m dishes – 2018
- Maximum baseline: 8 Km - soon ~ 20Km
- Frequencies: 580 MHz – 3500 MHz (0 < z < 1.5)
- It’s in the South!
- Part of SKA1-MID in the future

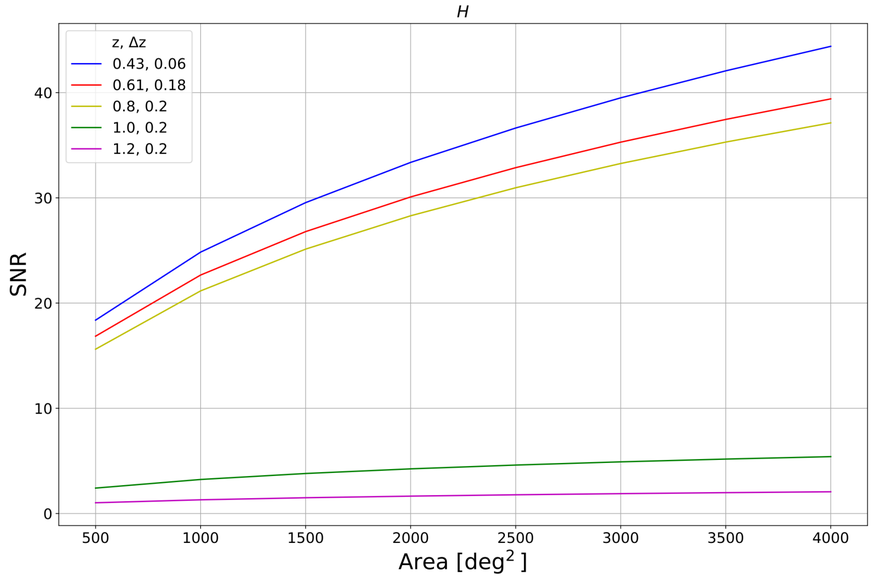
The present: an SKA cosmology survey precursor with MeerKAT

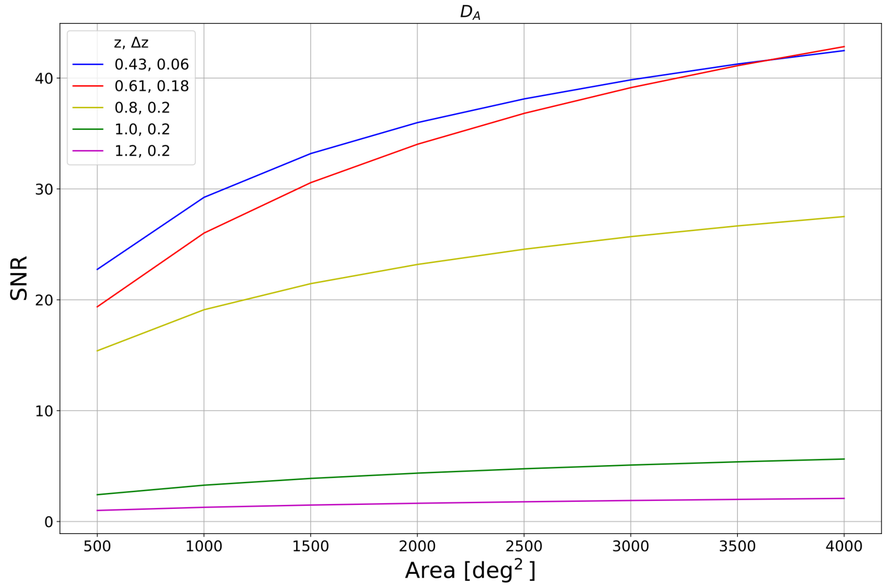
- ***MeerKLASS: MeerKAT Large Area Synoptic Survey:*** http://arxiv.org/abs/1709.06099 (40+ members)
- Aim: Cosmology (HI intensity mapping) but commensal with lots of other science (continuum survey)
- Focus on sky patches with multi-wavelength data for cross-correlation (DESI, 4MOST, Euclid, Rubi/LSST, DES)

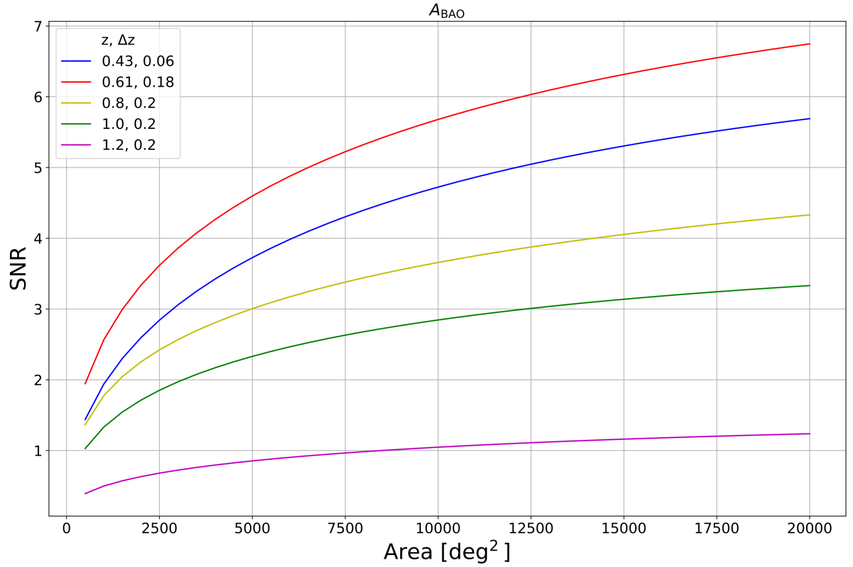
- L-band: 900-1670 MHz (z<0.58) ~ 100 hours observed
- **UHF band:**
  - 580 MHz-1015 MHz (0.40 < z < 1.45)
  - ~ 130 hours observed
  - Goal: 2,500 hours over 10,000 deg^2 (25 uJy rms in continuum) within next 5 years

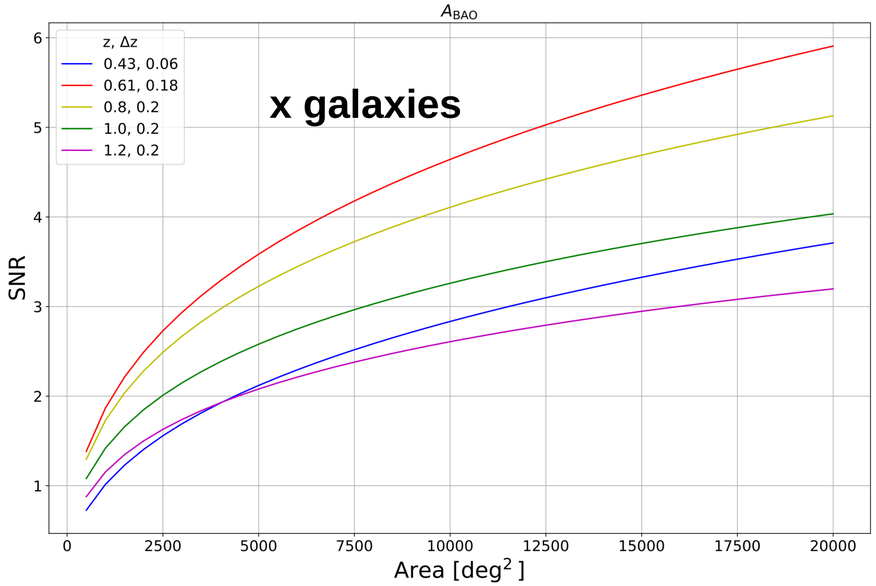


SNR vs area: UHF (1000 hours)





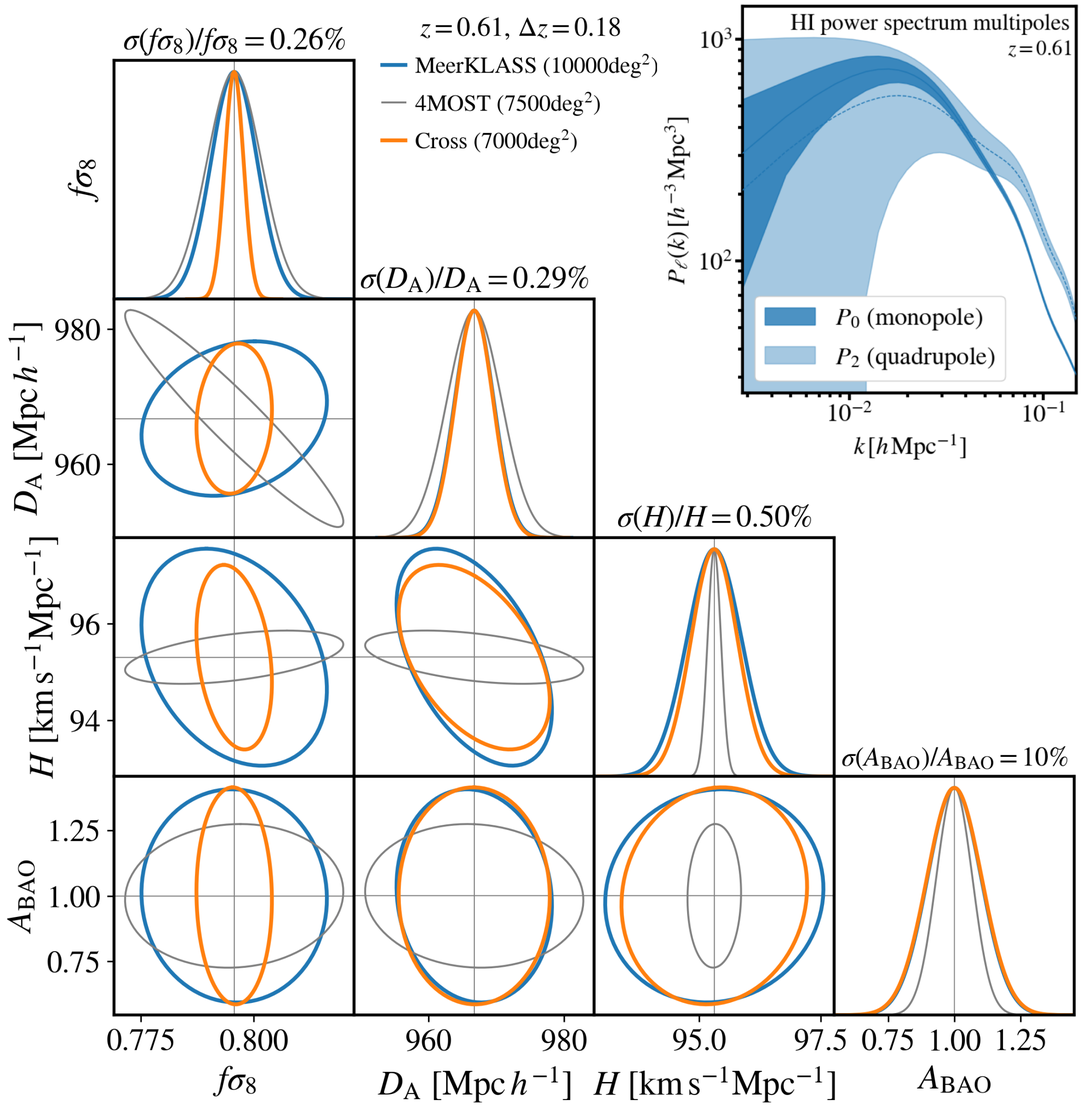




(Jose Fonseca)

MeerKLASS UHF survey: Cosmology

- Measurement of Baryon Acoustic Oscillations (BAO), Hubble rate and redshift space distortions
- Measure the HI content of the Universe at 0.4 < z < 1.4 (UHF-band)
- Cross-correlations with galaxy surveys
- Constraints of primordial non-Gaussianity (f_{NL}) by measuring large scale correlations and multi-tracers (Fonseca et al., arXiv1611.01322)
    - xDESI ~ 4.3
    - x4MOST ~ 3.5
    - xEuclid ~ 1.5
    - xDES ~ 3.5
    - xRuby/LSST ~ 1.8
    - (compare to CMB ~ 5 and eBOSS ~ 20)



MeerKAT: 1,300 hours. 60 dishes

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: ~ 90 hours. L-band. Calibrated cubes. Ongoing power spectrum analysis. Aim is a direct detection of the HI power spectrum

- Director Discretionary Time (DDT): ~ 12 hours over WiggleZ 11h field using UHF band. Calibrated cubes. Goal: cross-correlation with L-band data

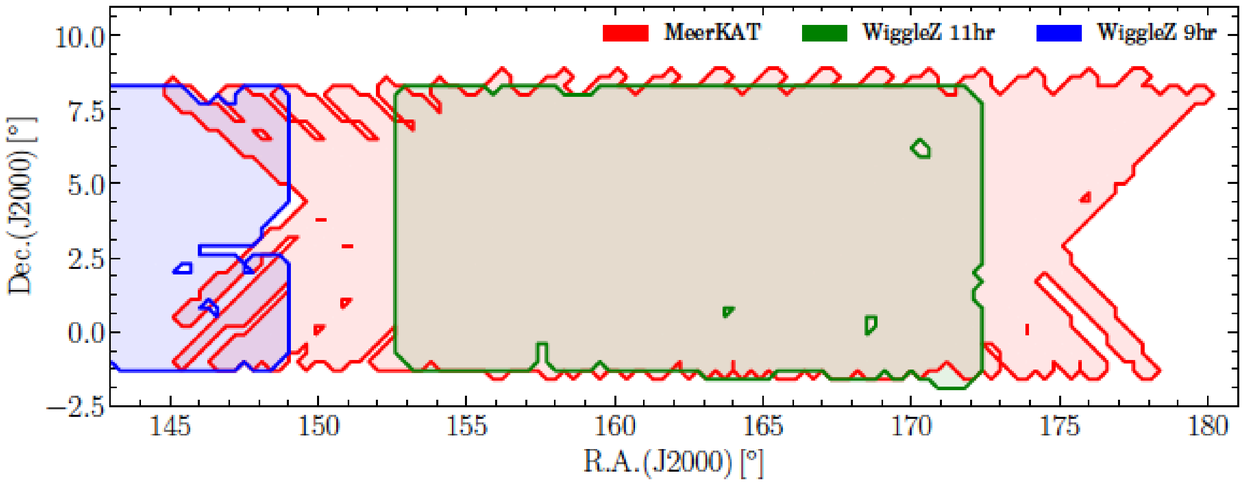
- 3rd open time call: ~ 130 hours using UHF over two fields covering ~ 500 deg^2 of SDSS/DESI. Ongoing observations.

- 4th open time call: Large UHF survey proposed

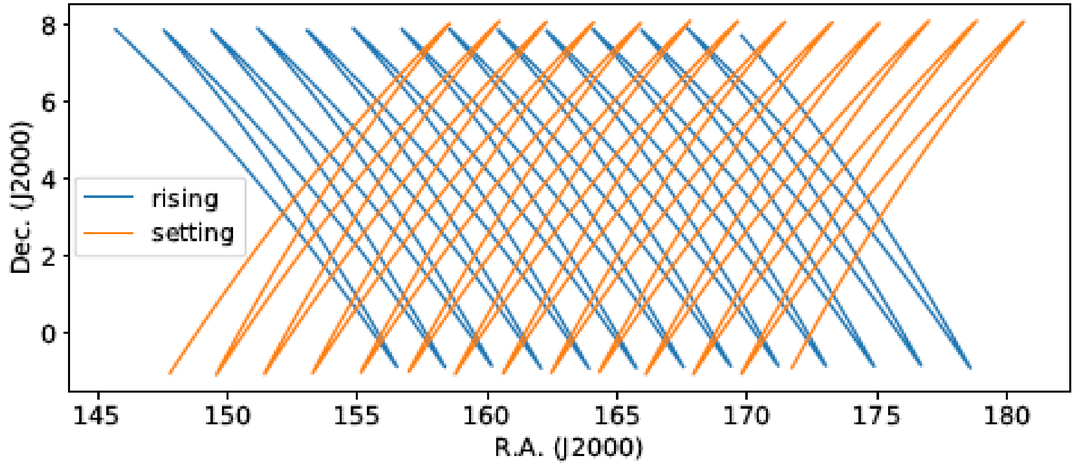
- Ongoing tests for on-the-fly mode so we can use the interferometer data at the same time

First results with a MeerKAT single dish pilot survey

(Wang et al., MNRAS, arxiv:2011.13789)



Footprint



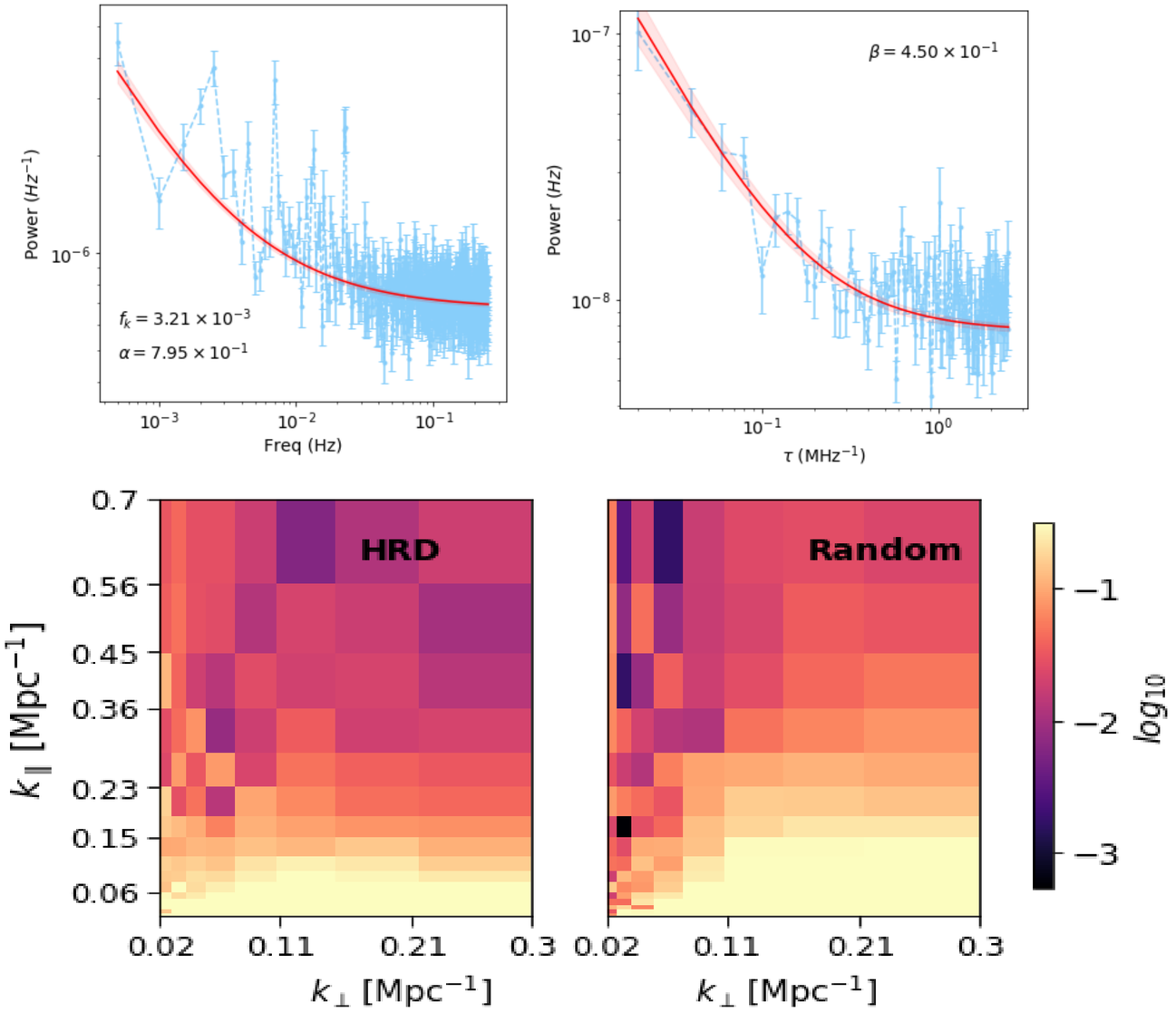
Scanning pattern

- ~ 15 hours
- ~ 60 dishes used (~ 600 hours combined)
- ~ 200 deg^2 over the WiggleZ 11h field
- L-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 scan line, 1.5 hours per block

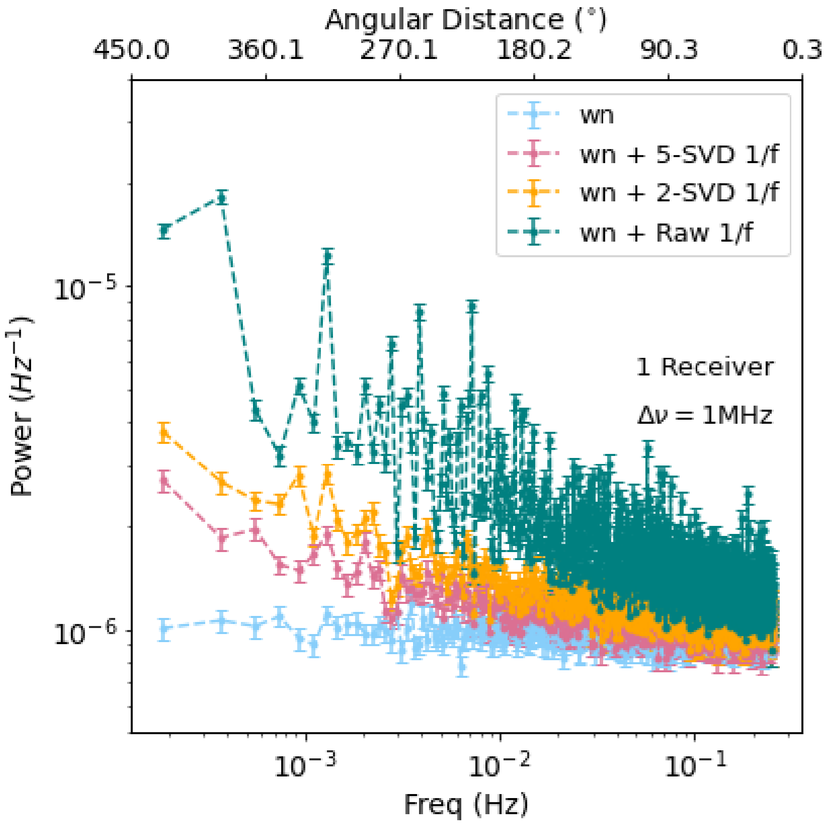
MeerKAT 1/f noise (gain fluctuations in time and frequency)

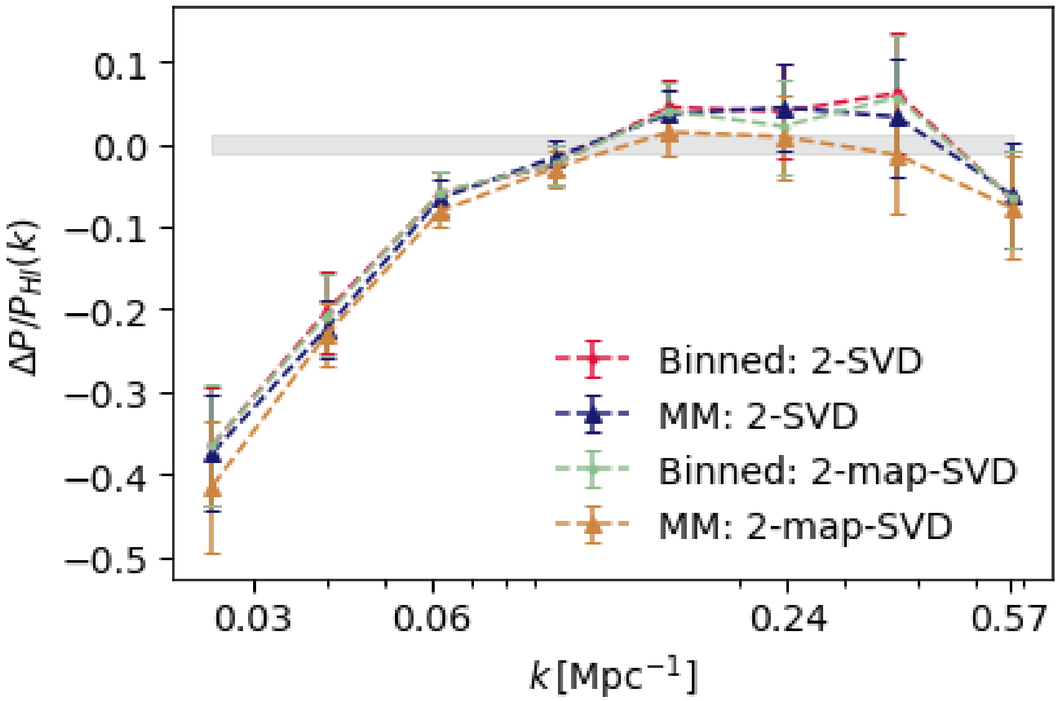
- Noise is correlated in time —> can bias result and increase noise level - need fast scanning to probe relevant angular scales within the time scales of the 1/f noise



Mel Irfan et al., http://arxiv.org/abs/2302.02683 (see also Li et al., MNRAS 2020, Arxiv:2007.01767)

MeerKAT 1/f noise: cleaning

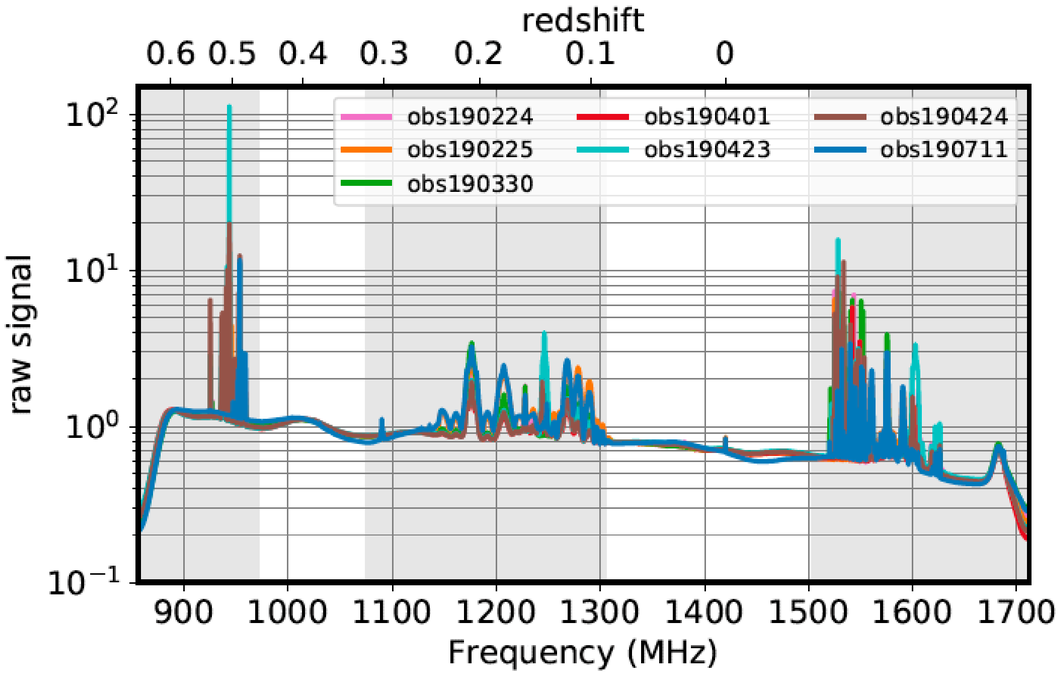


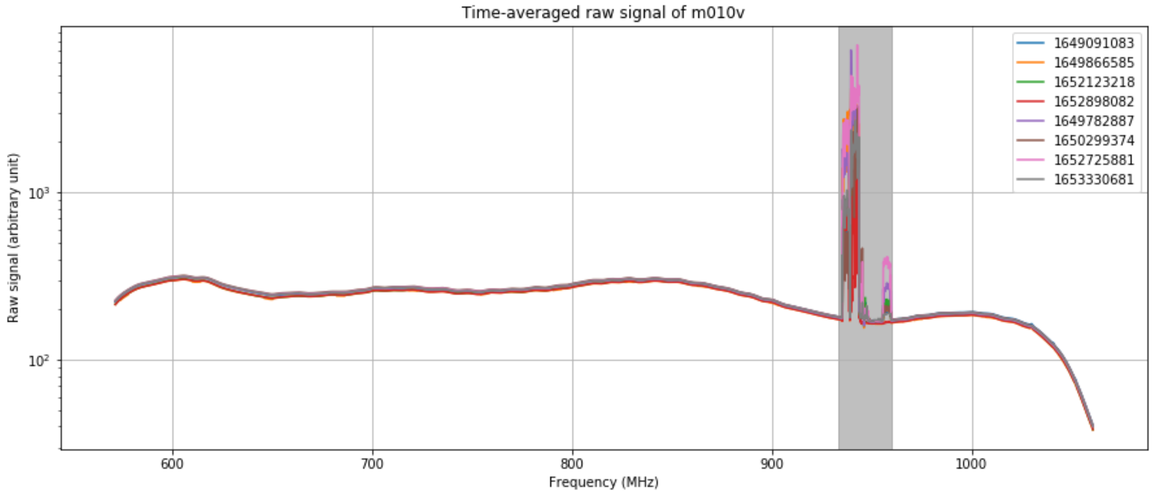


Mel Irfan et al.

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

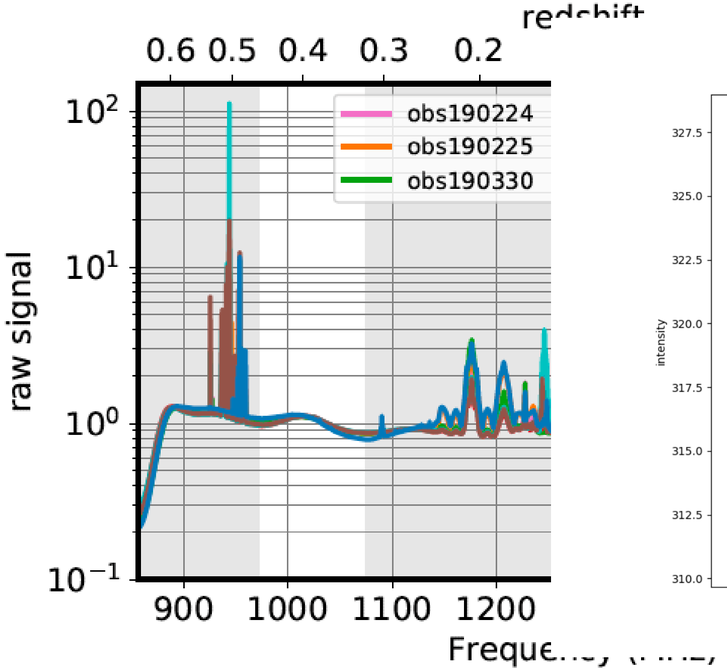
Contamination (sky foregrounds+ground+RFI+instrumental)

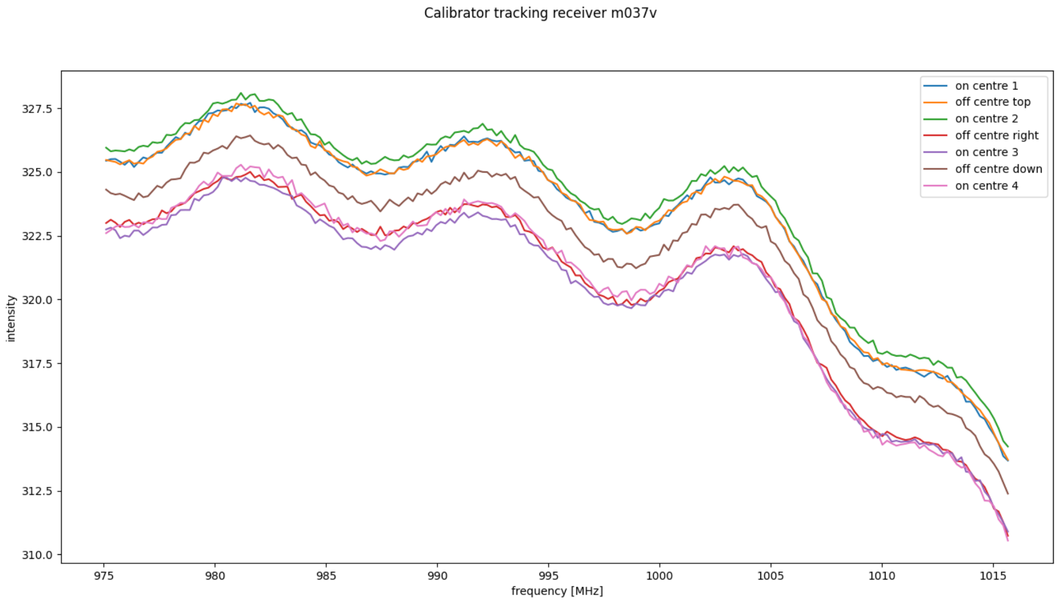


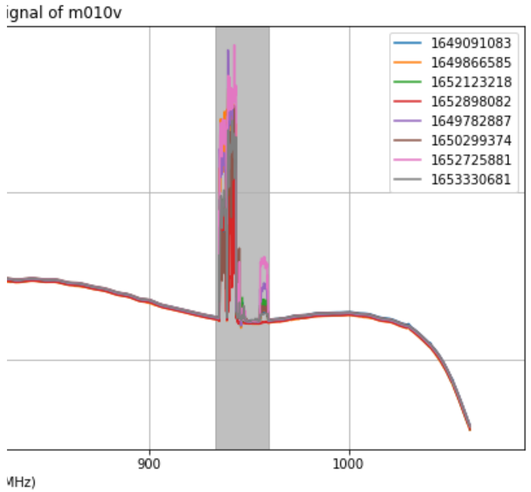


- Satellites are a big concern, in particular with single dish data and in particular from the beam sidelobes
- RFI free regions in L band: **0.32 < z < 0.46**
- Calibration/modelling is crucial
- Methods for foreground cleaning are crucial (PCA, GMCA, Gaussian Processes,Machine Learning…)
- Also important to improve signal extraction methods (power spectrum)

Contamination (sky foregrounds+ground+RFI+instrumental)







Looking for fluctuations ~ 1/10^5

- Satellites are a big concern, in particular with single dish data and in particular from the beam sidelobes
- RFI free regions in L band: **0.32 < z < 0.46**
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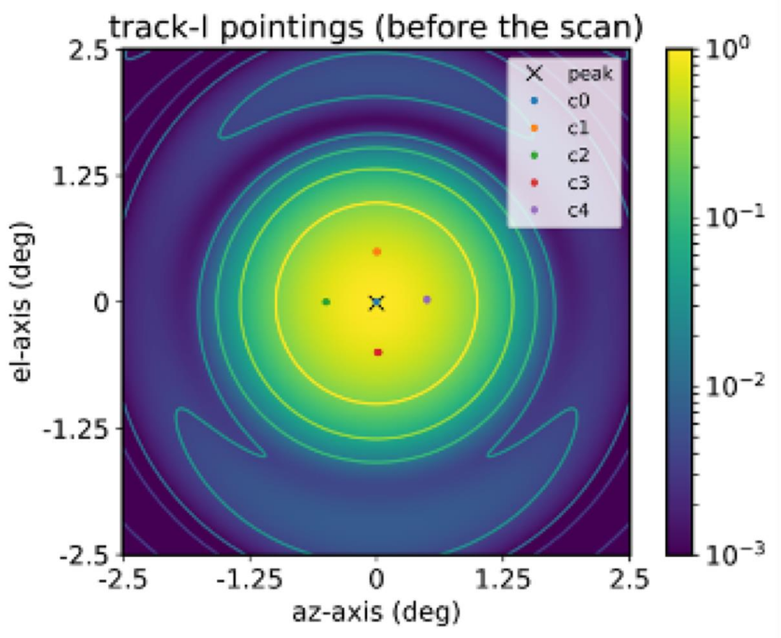
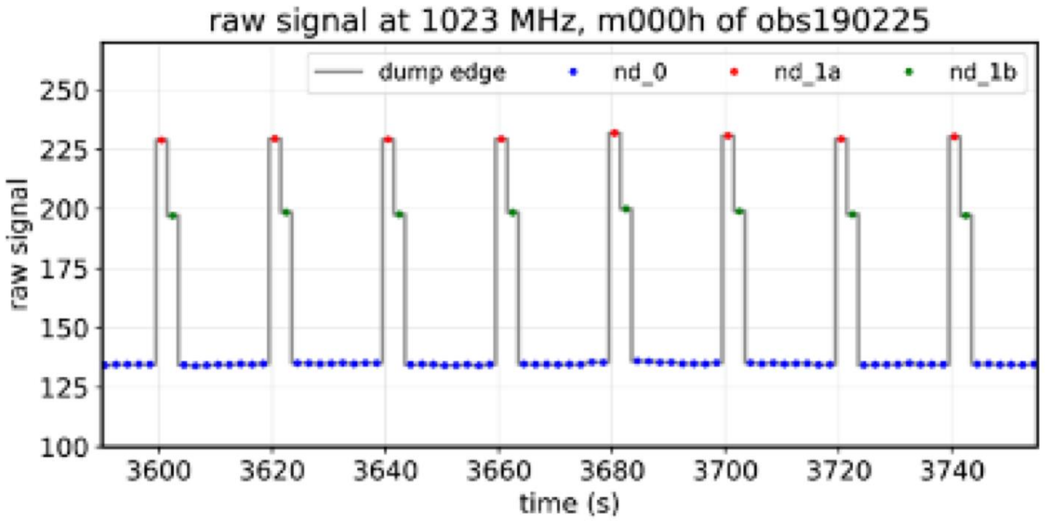
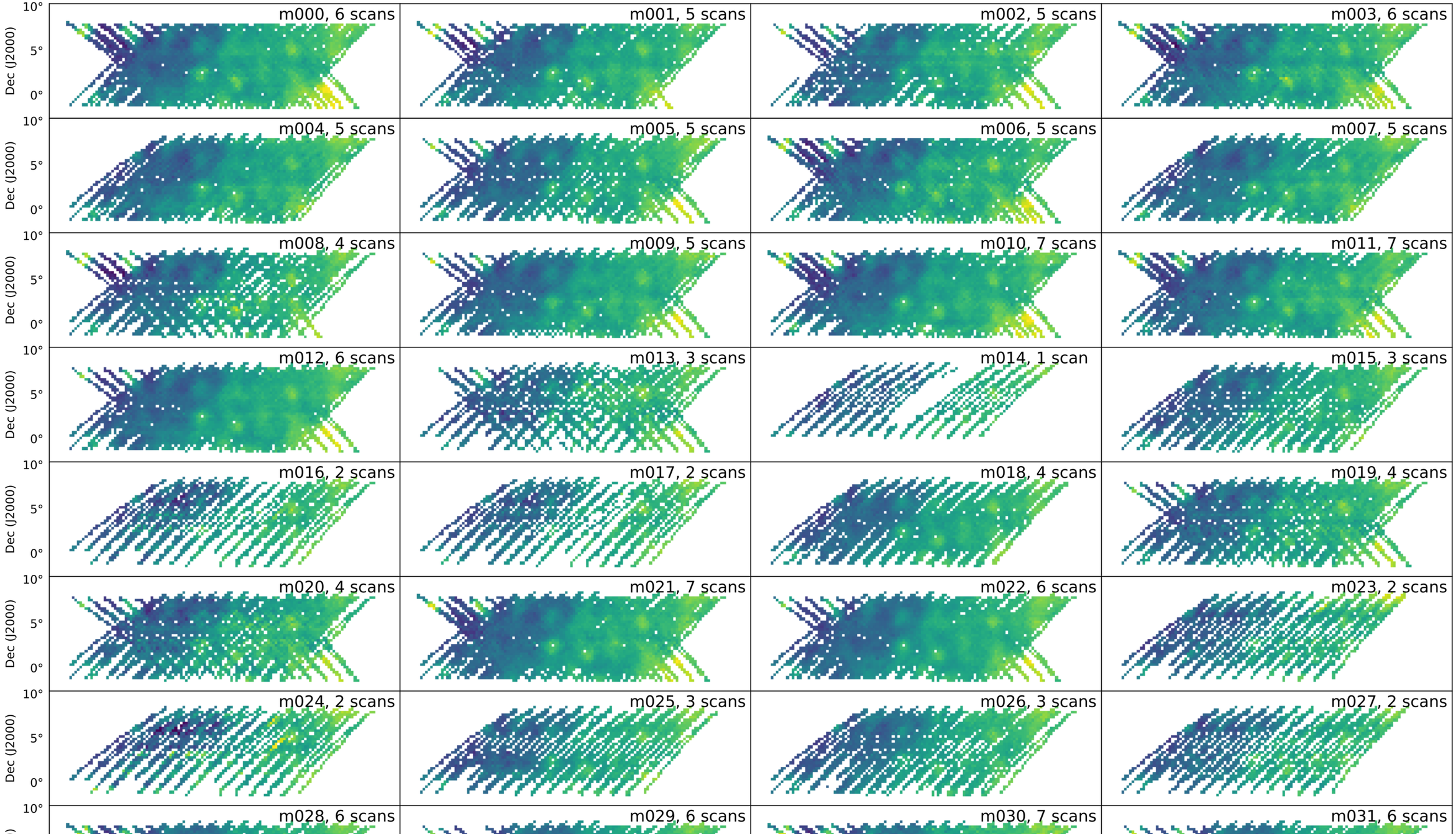
Calibration



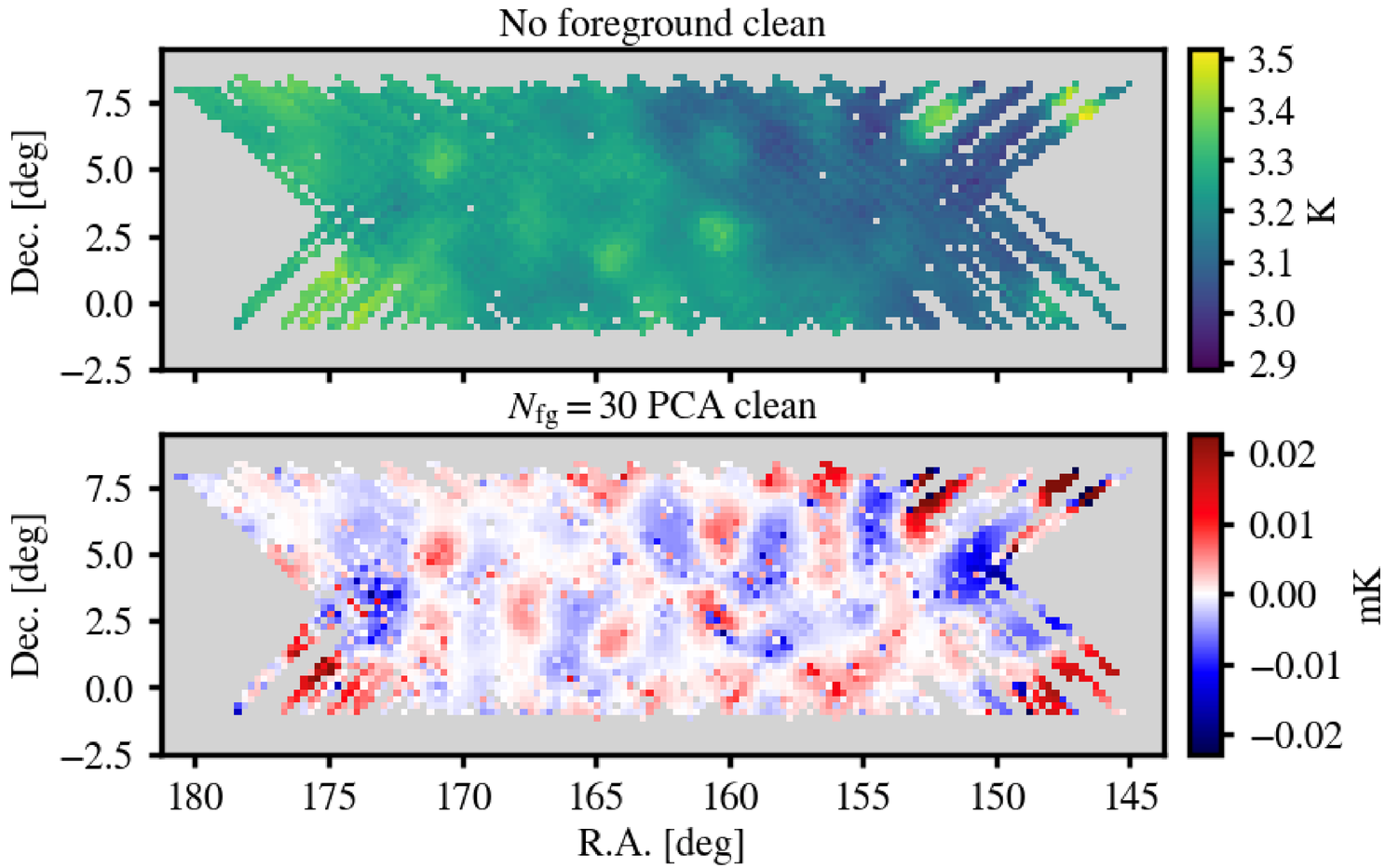


- Observe a calibrator before and after each scan (left)
- Noise diode injection every 20 sec during scan (right)

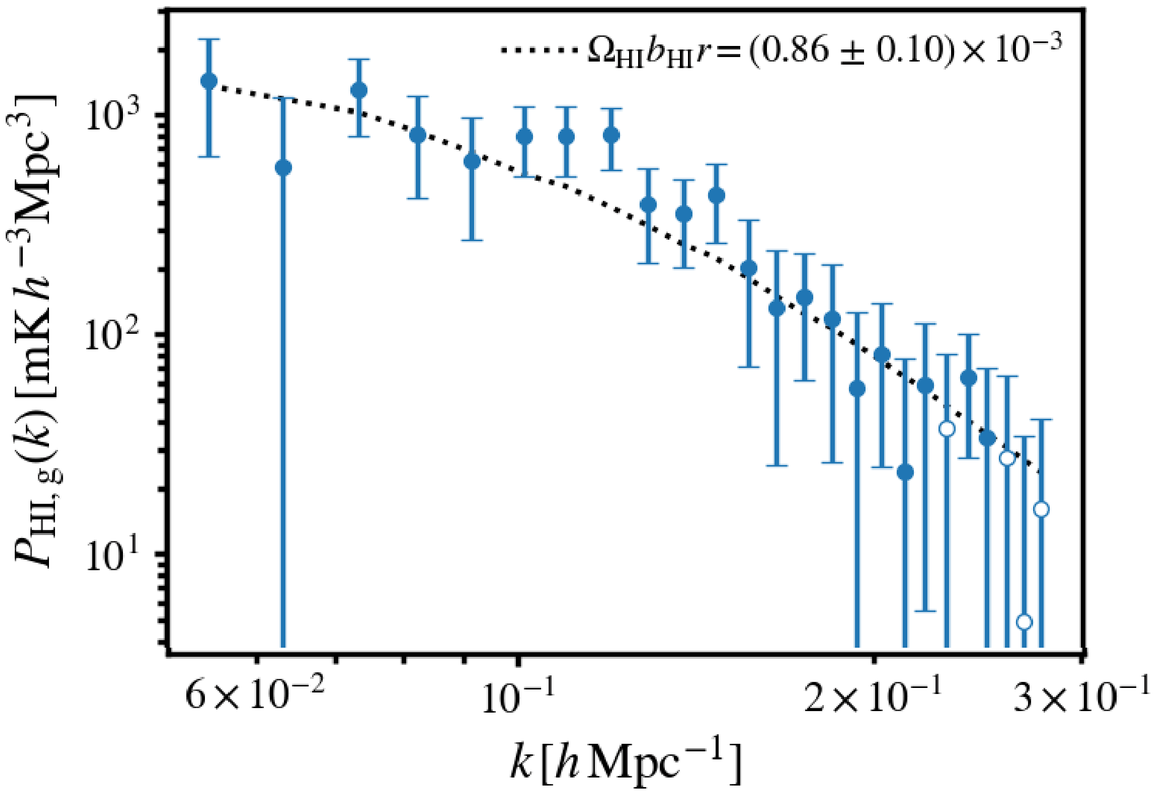
Temperature maps at 1023 MHz – we can cross-correlate between dishes!



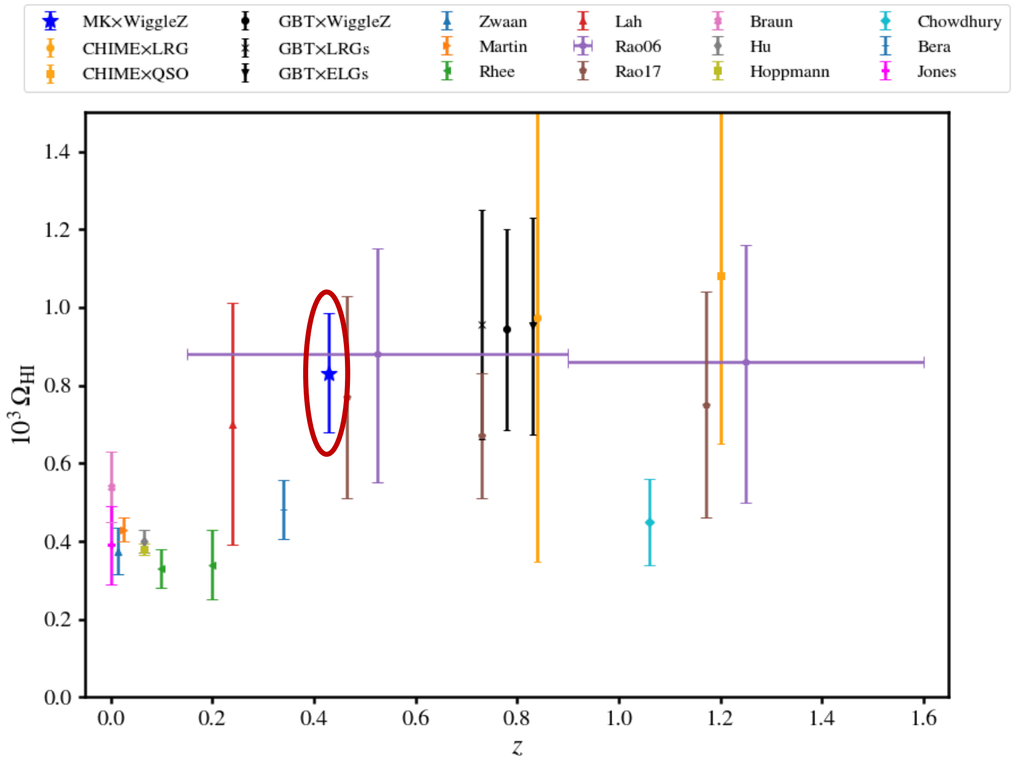
Foreground cleaned maps: PCA



First cosmological results with MeerKAT: Detection of the cross-correlation power spectrum with WiggleZ galaxies



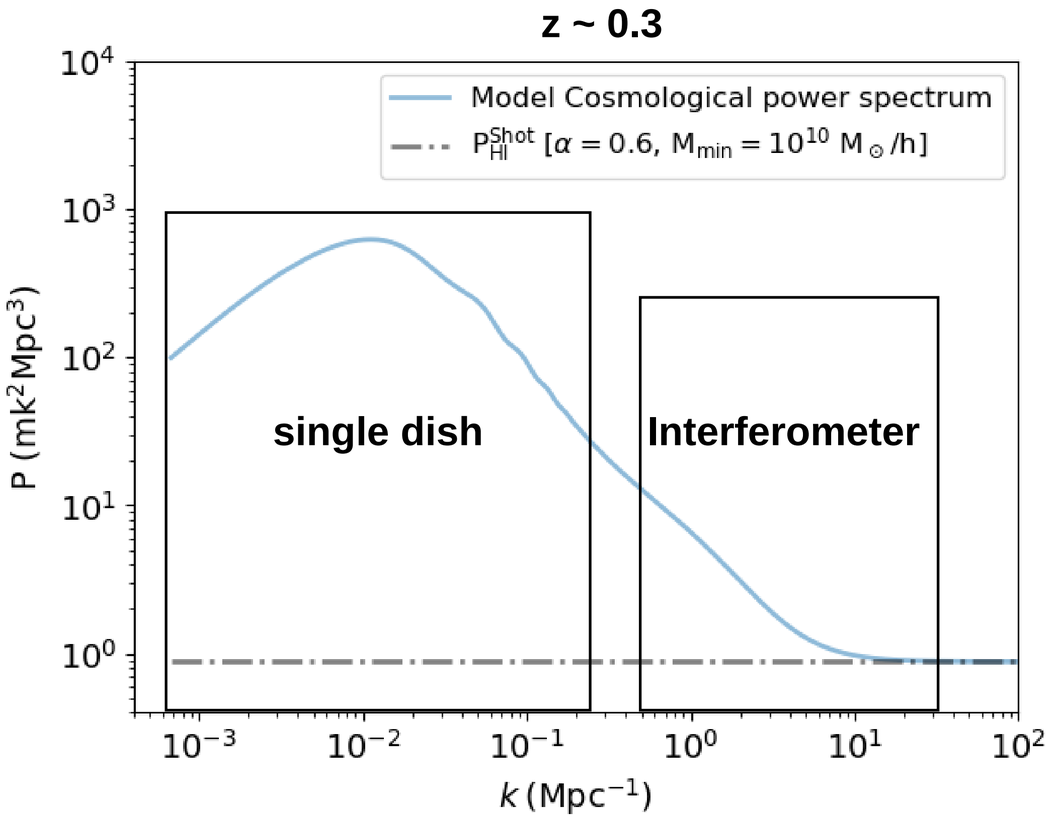
0.400 < z < 0.459
(7 sigma detection)

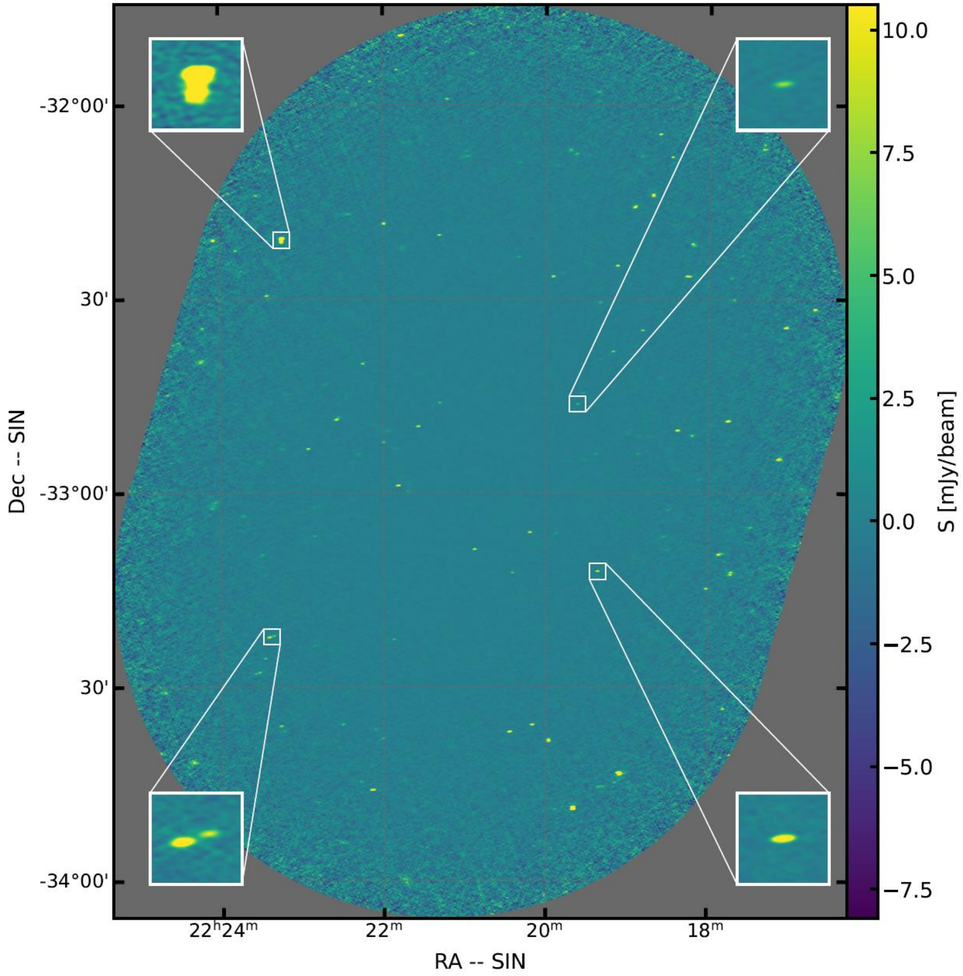


Cunnington, Li, Santos, et al., MNRAS 2023

What about the interferometer data?

- HI intensity mapping can still measure quasi-linear cosmological scales (k ~ 1 Mpc^{-1} and above)
- Great for comparison to full HI simulations
- Can be used for other science (continuum…)





Kristof Rozgonyi

Summary

- HI intensity mapping with MeerKAT/SKA in single dish mode will deliver state of the art cosmological constraints: BAO in HI – dark energy, RSDs – modified gravity, primordial non-Gaussianity…
- We have HI IM detections using the MeerKAT single dishes in cross with optical galaxies
- Ongoing observations and data processing with MeerKAT UHF single dish – plan is to observe 2,500 hours over 10,000 deg^2 in the next 5 years to probe Cosmology
- Robust measurements should rely on a combination of estimators:
  - Cross-correlation between dishes
  - Cross-correlation with other surveys: galaxy spectroscopic, photometric, CMB lensing, etc
  - Cross-correlations with other HI IM surveys (FAST? Tianlai?)
  - Power spectrum, Bispectrum…
  - Use specific features: Alcock-Paczynski, BAO, RSDs, equality peak, scale dependent bias
- Also commensal with MeerKAT interferometer high resolution continuum imaging
- More soon!