Cosmology with MeerKAT: The MeerKLASS Project

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On behalf of the MeerKLASS collaboration

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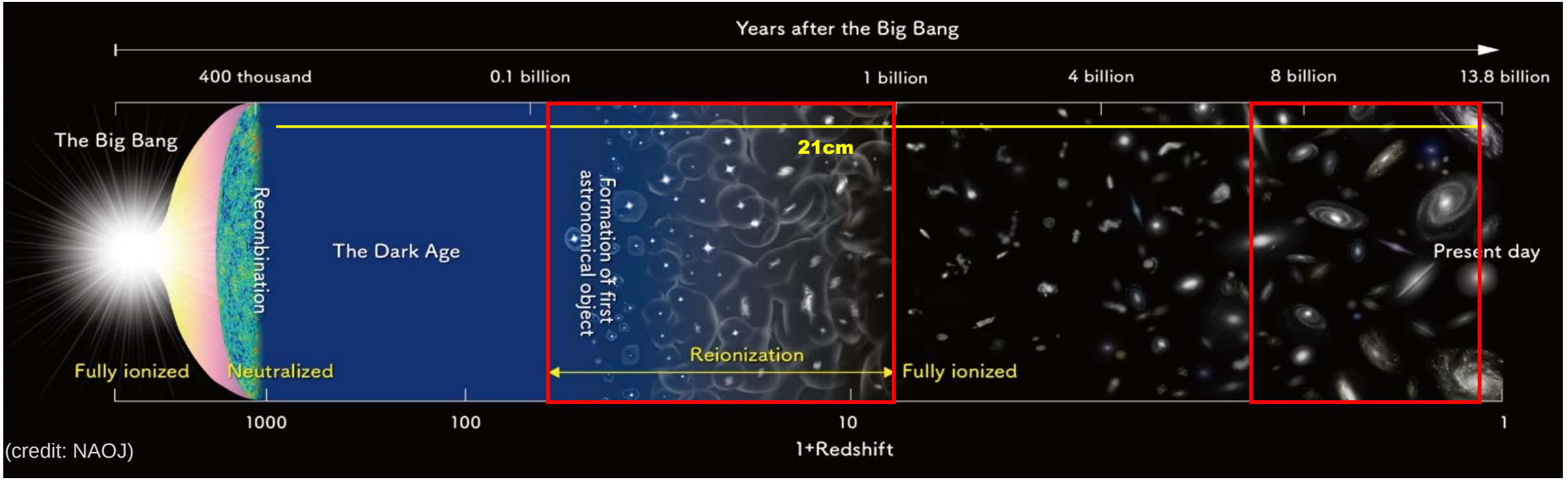
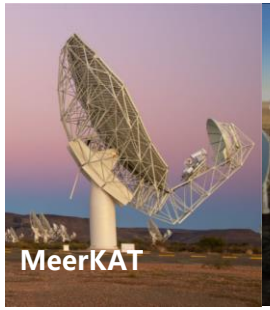
2024-07-22

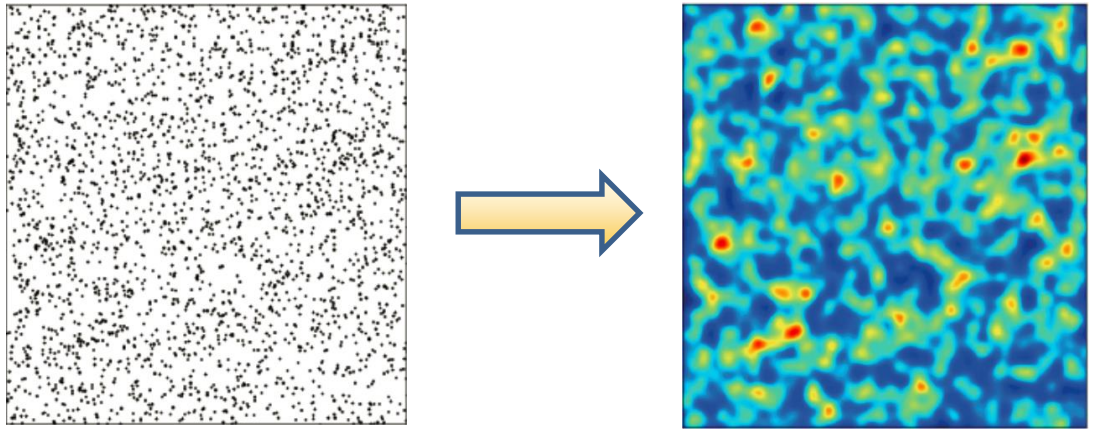
21cm Cosmology + SKA



(credit: NAOJ)



Why HI Intensity Mapping?



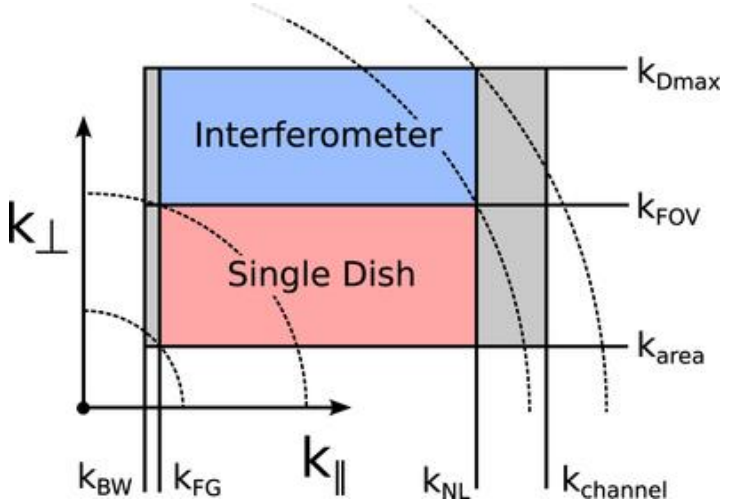
galaxies intensity map

- **3D information (angle+redshift) is crucial for Cosmology**
- **Not enough sensitivity for a large HI galaxy survey with the SKA (z>0.4)**
- HI intensity mapping to the rescue: no need to detect galaxies - low angular resolution intensity maps of the 21cm HI line emission will trace dark matter fluctuations
- Pixel will have joint emission from multiple galaxies
- Very high redshift resolution

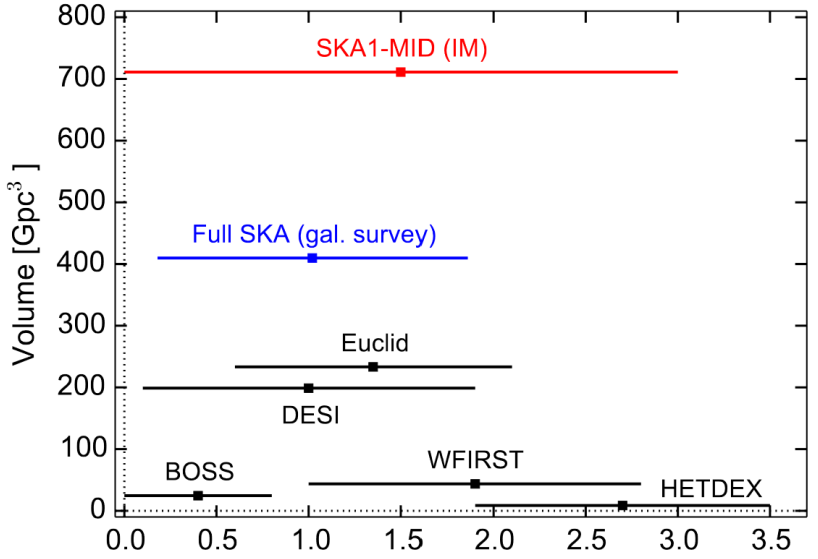
Santos et al. (2015)

HI intensity mapping with SKA/MeerKAT

- Need to use **single dish data** (auto-correlations from each) in order **to probe large scales** (baselines not short enough)
- **New observing mode for SKA/MeerKAT**
- Low angular resolution but extremely high survey speeds!
- Can probe Baryon Acoustic Oscillations (scales ~ 100 Mpc/h, ~ 2 degrees, ~ 20 MHz)
- Great to probe ultra large scales



Bull et al. (2015)



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HI intensity mapping with SKA/MeerKAT

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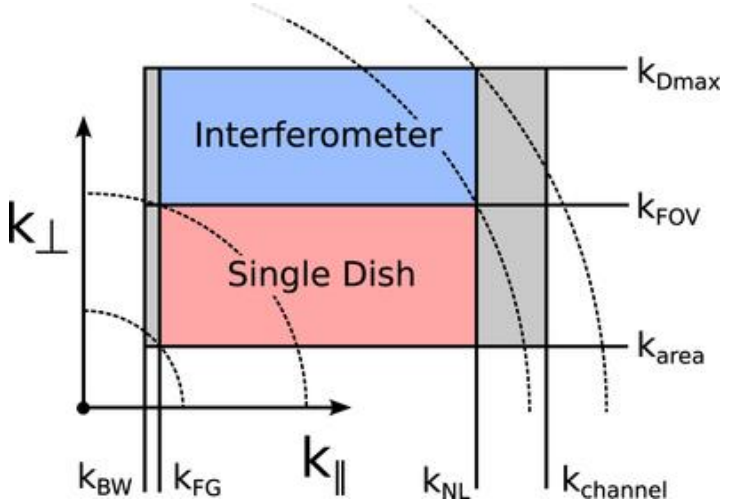
- **Interferometric data can assist in modelling instrument effects (such as 2D beam patterns)**
- **Interferometric gain and single-dish gain are correlated**
- **Interferometric data helps in foreground source investigation**



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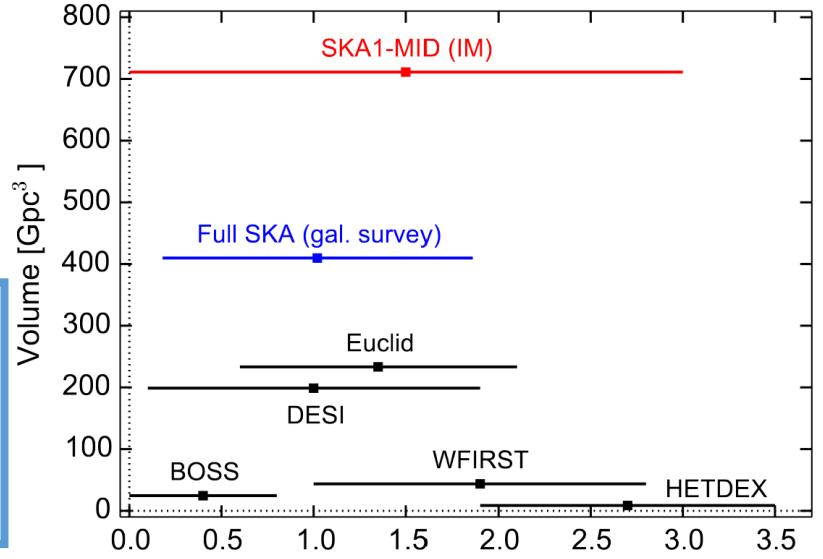


Santos et al. (2015)

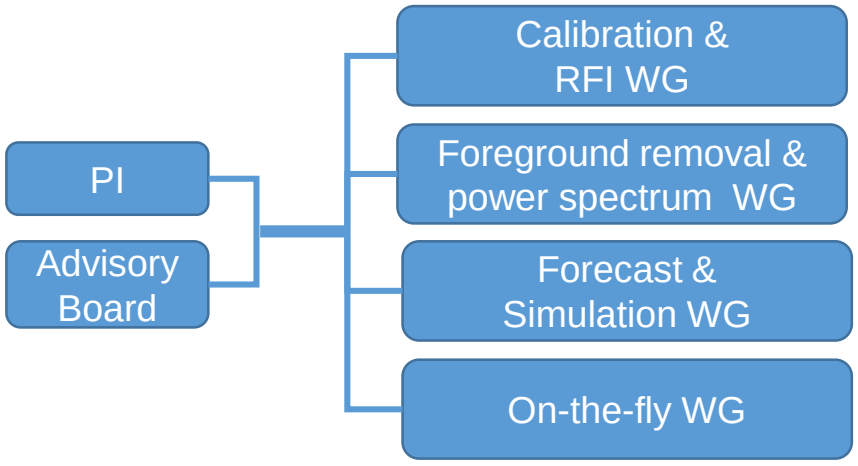
MeerKLASS: MeerKAT Large Area Synoptic Survey

- Aim: **Cosmology** (HI intensity mapping)

  but commensal with lots of other science
- Use output from correlator

  single dish data (autos) + **interferometer data**
- Focus on sky patches with multi-wavelength data for **cross-correlation**

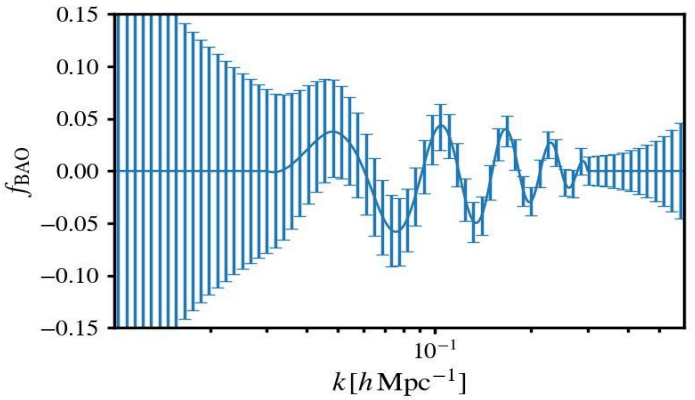
  DESI, 4MOST, Euclid, Rubi/LSST, DES
- An **SKA cosmology survey precursor**

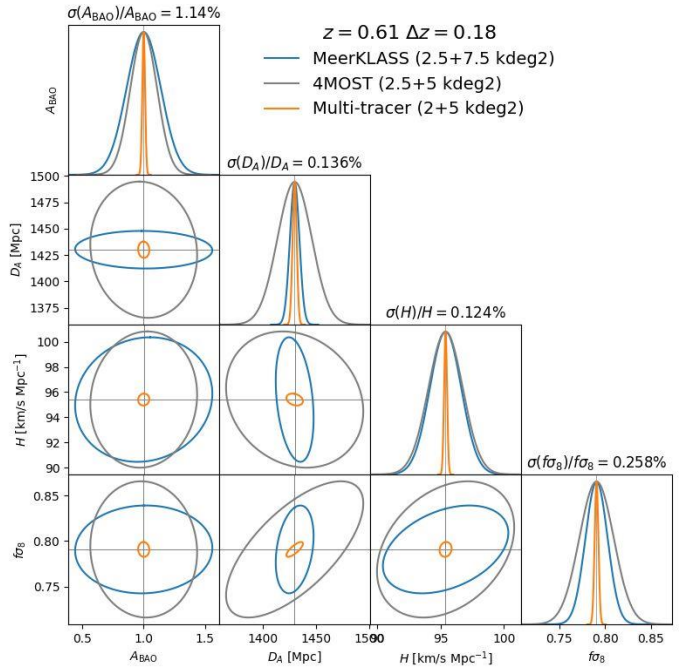


International collaboration ~ 50+ members

MeerKLASS: Cosmology

- Measurement of Baryon Acoustic Oscillations (**BAO**), **Hubble rate** and redshift space distortions (**RSD**)
- Measure the **HI content** of the Universe at 0.4 < z < 1.4 (UHF-band)
- **Cross-correlations** with galaxy surveys -> large improvements on the errors
- Constraints of **primordial non-Gaussianity** (f_{NL}) by measuring large scale correlations and multi-tracers





MeerKAT: 1,300 hours, 60 dishes
Credit: J. Fonseca, S. Cunnington

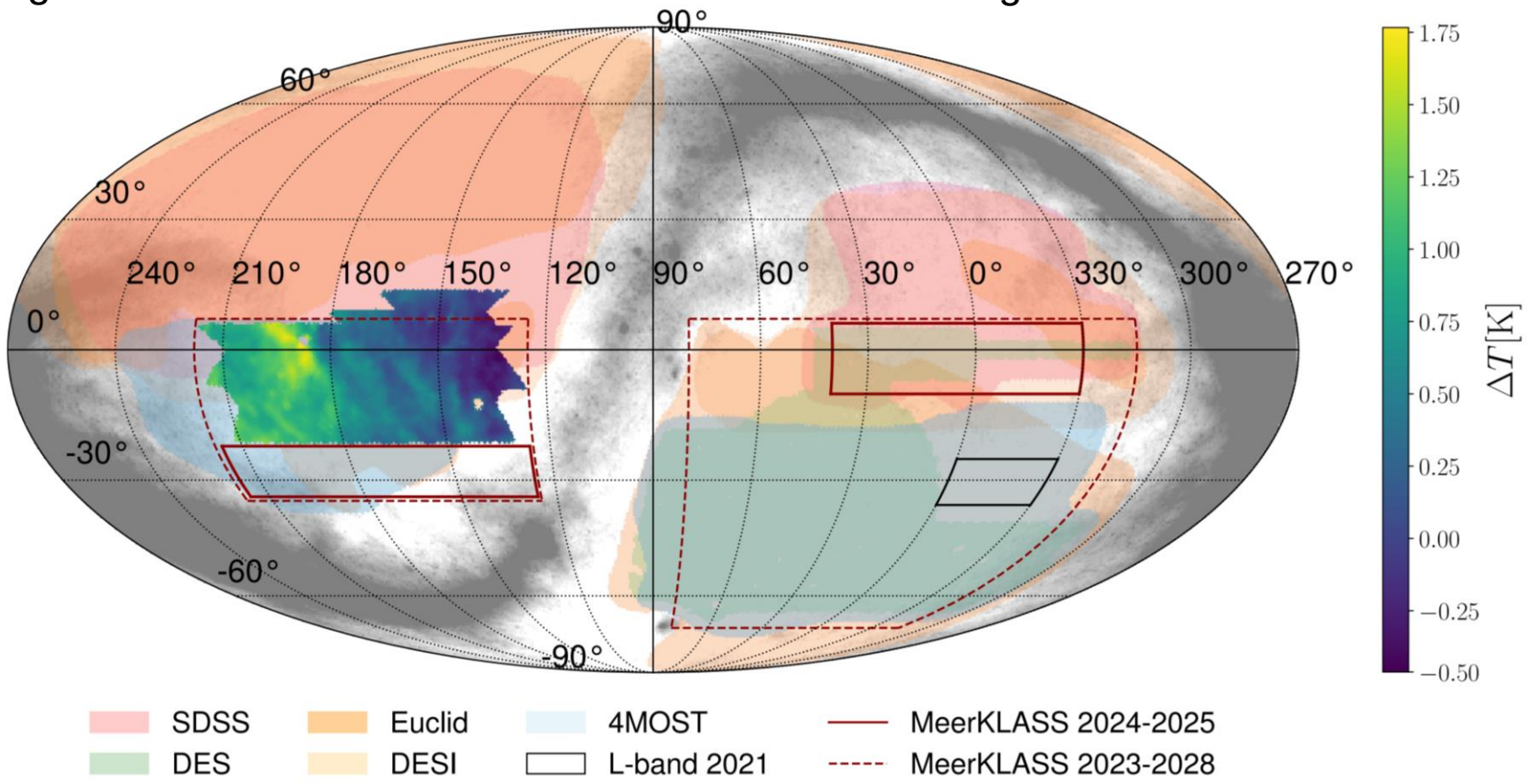
MeerKLASS Survey Plan

L-band 900-1670 MHz (z<0.58)

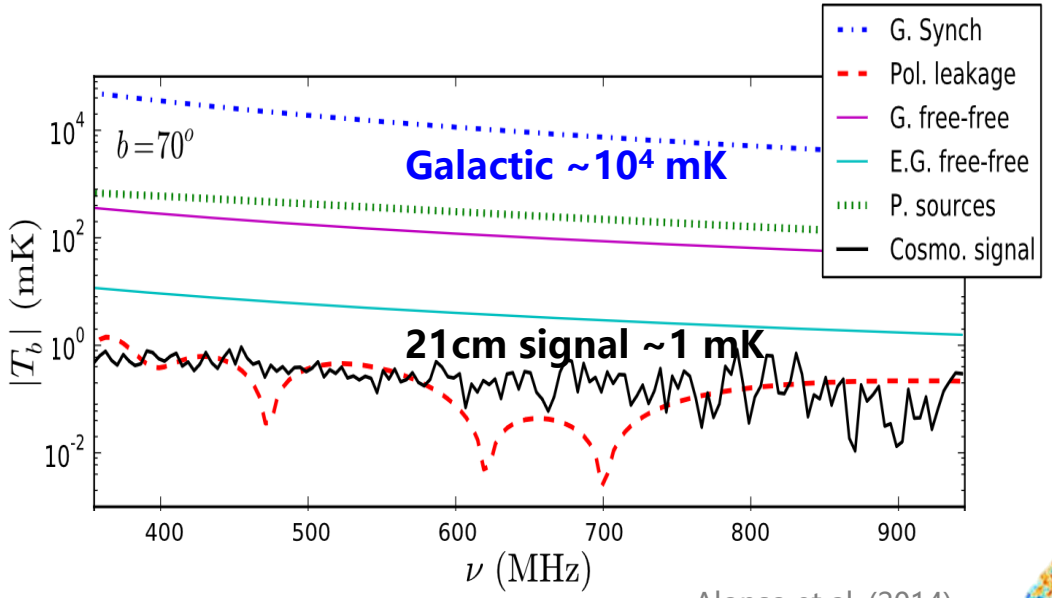
- 100 hours observed
- 600deg^2

UHF band 580 -1015 MHz (0.40 < z < 1.45)

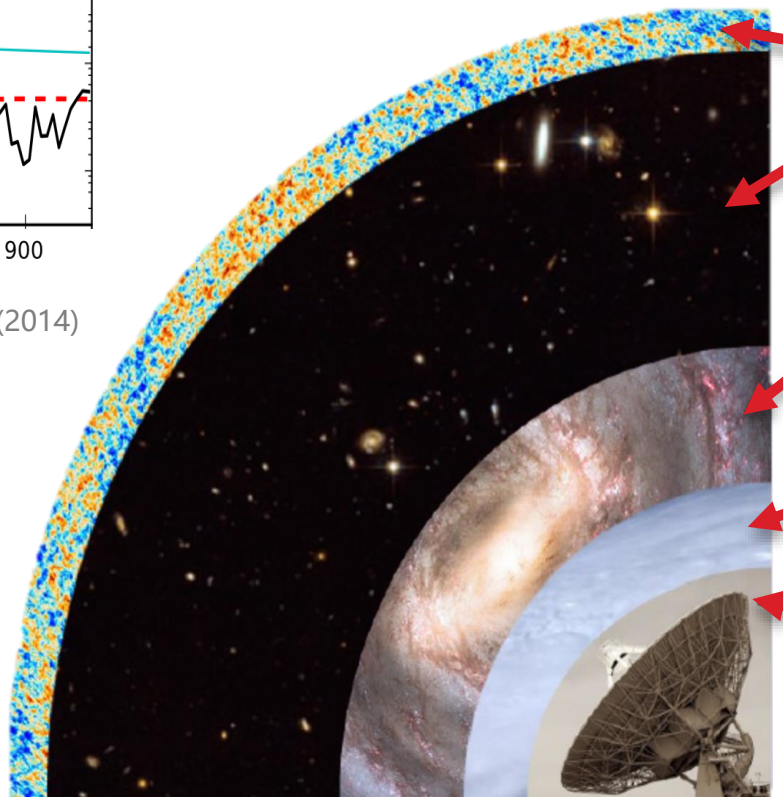
- 380 hours observed
- 1600 deg^2



Challenges



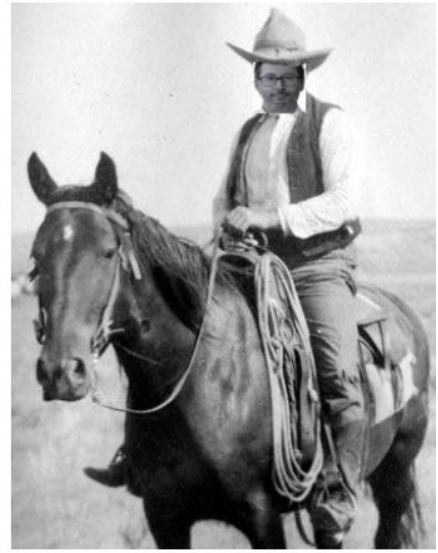
Alonso et al. (2014)

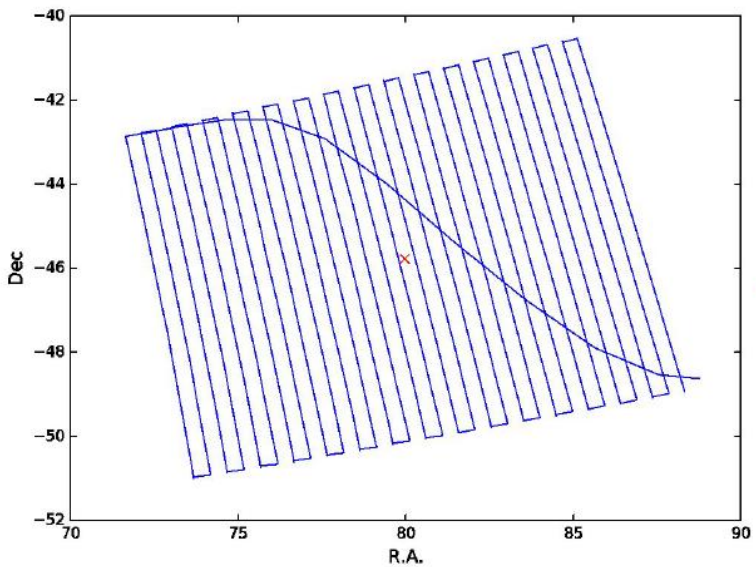


- **HI IM signal**
- **Extragalactic foregrounds**:
  - Point sources
  - E.G. free-free
  - (might be a background)
- **Galactic foregrounds**:
  - Synchrotron (I,Q,U)
  - Free-free
  - Dust
- **Earth**:
  - Atmosphere: clouds, H2O, Ionosphere
  - RFI
- **Instrument**:
  - Spillover
  - Gain fluctuations
  - Beam fluctuations
  - Polarization leakage

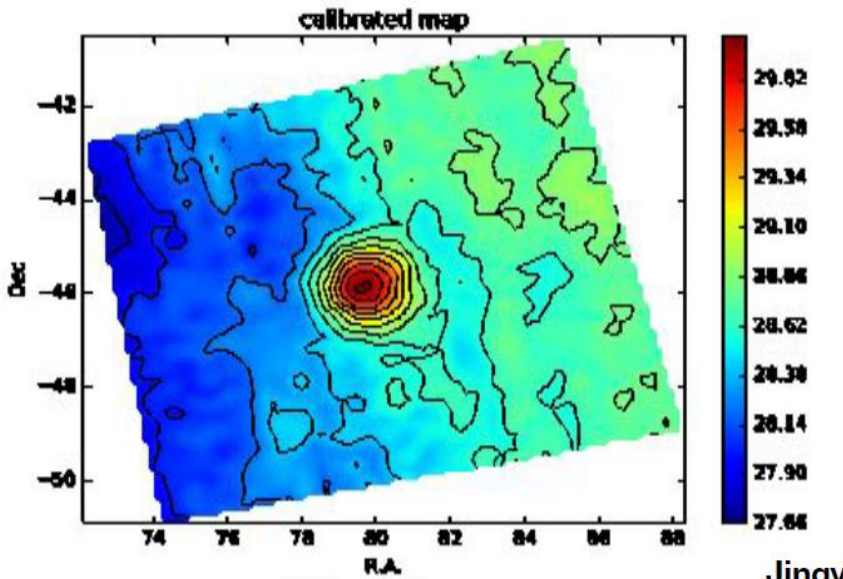
Credit: D. Alonso

From theory to observations
Early days (the cowboy years): tests with KAT7 ~ 2014





Scan pattern

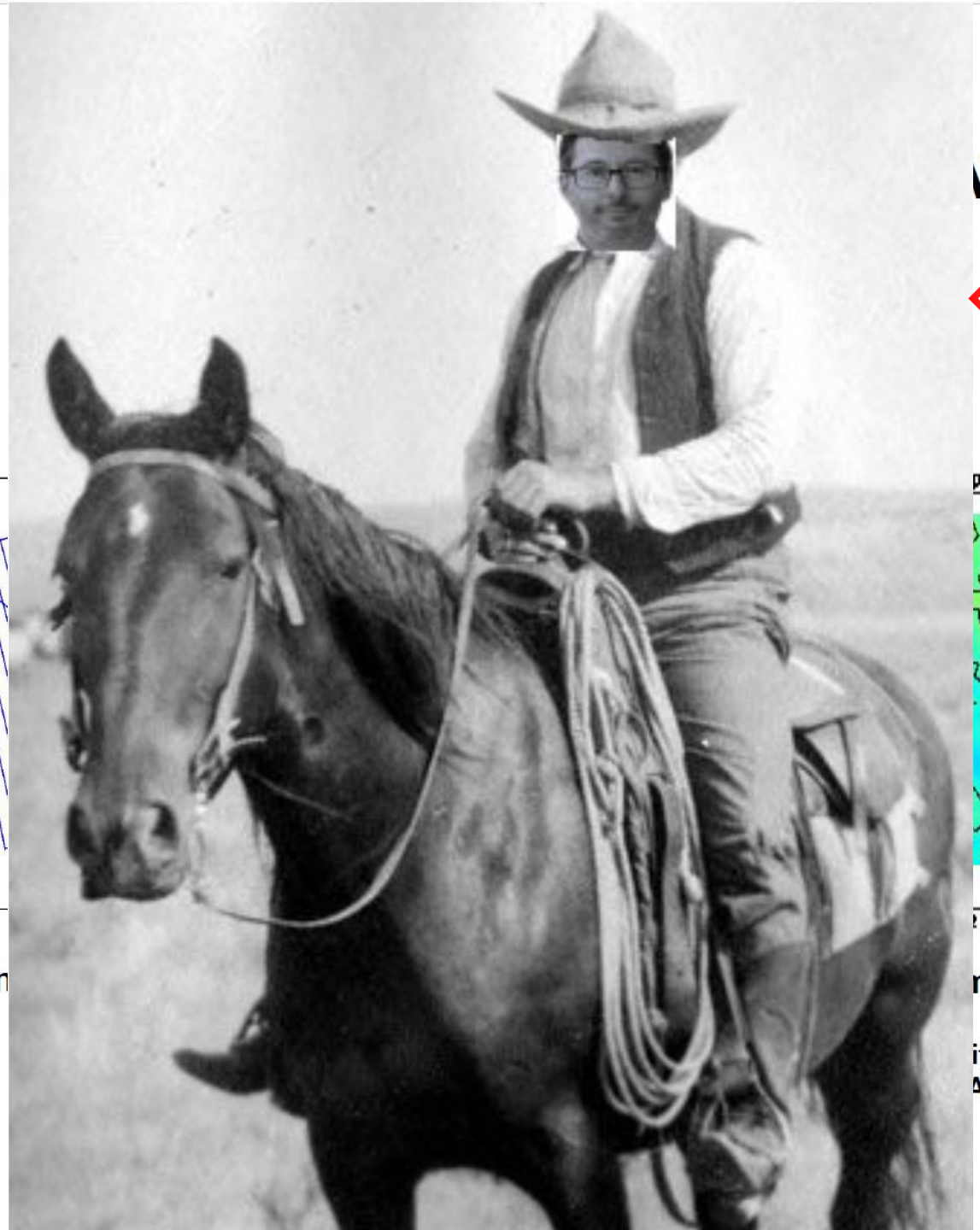


map

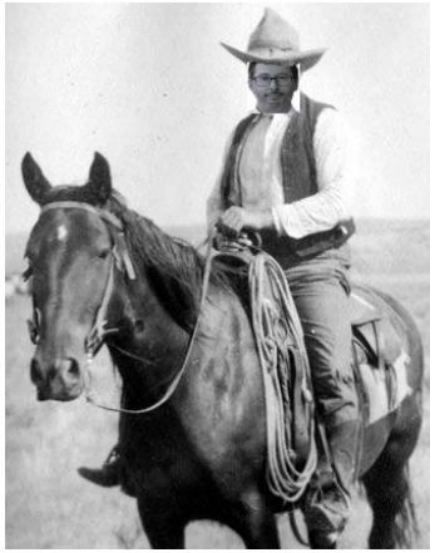
Jingying Wang

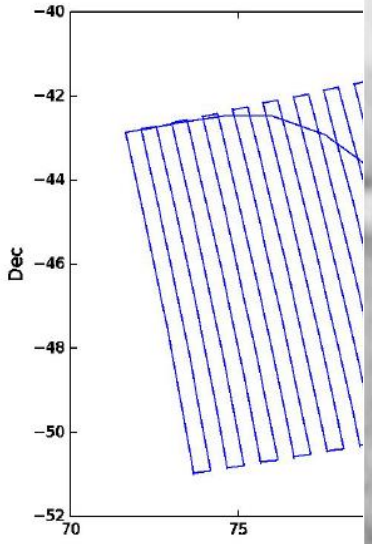
(with lots of help from SARAO people, Tony Foley…)

Early days

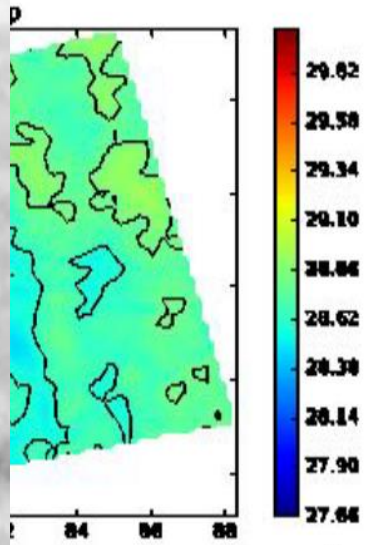


AT7 ~ 2014





Scan



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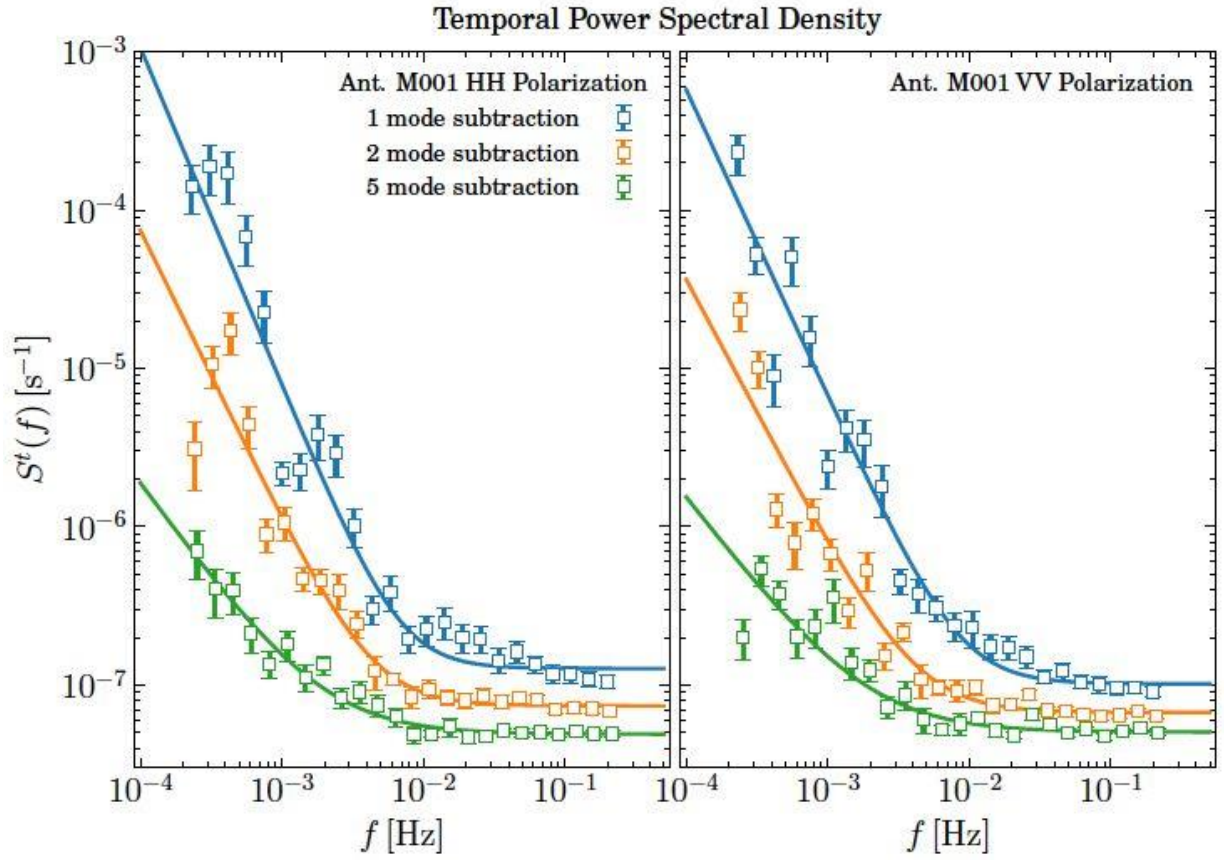
Challenges

MeerKAT 1/f noise analysis - gain fluctuations

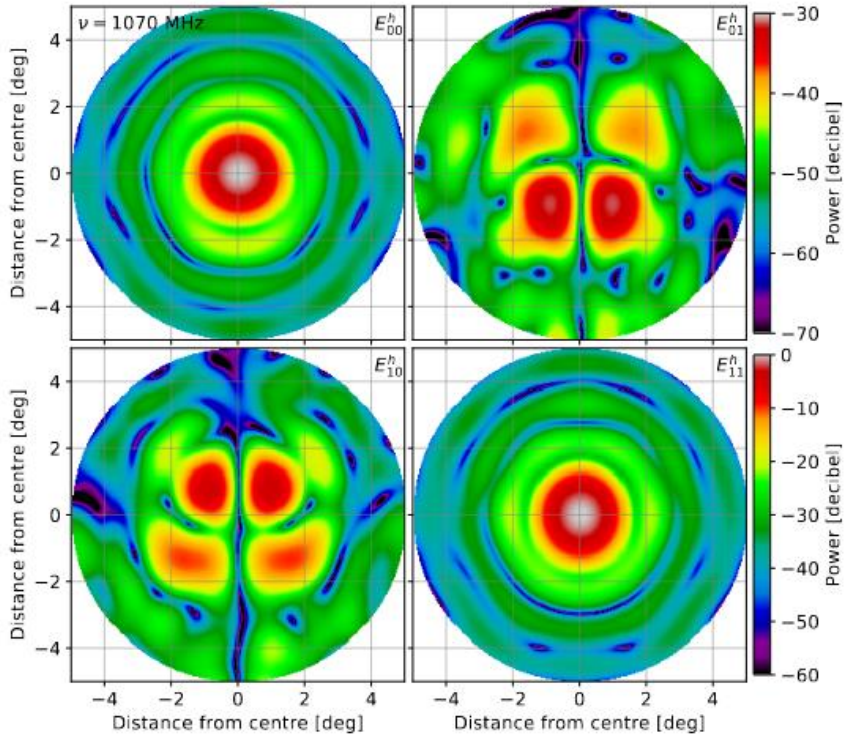


- Noise is correlated in time
- Important to have fast scanning mode
- We can clean it as a foreground
  -> time scale of 100s of seconds

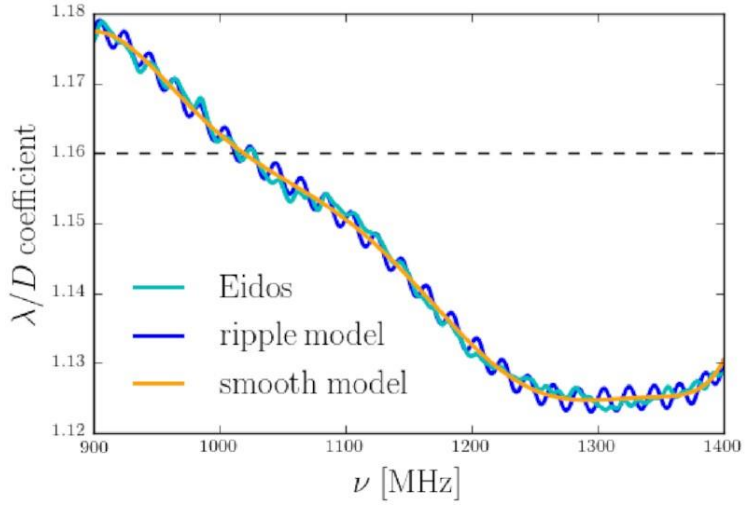
Li et al., 2021, MNRAS;
Irfan et al., 2024, MNRAS

Challenges

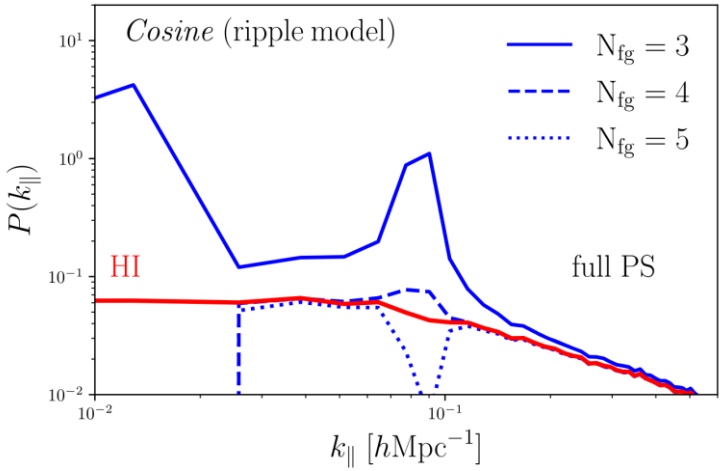
Beam pattern and primary beam frequency effects



Asad et al. 2021, MNRAS



MeerKAT beam size (FWHM) versus frequency

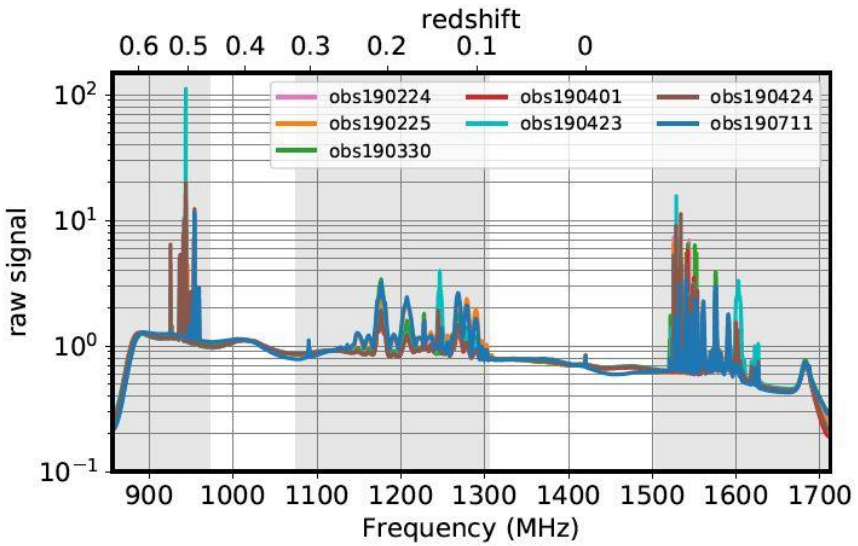


Effect on foreground cleaning: line of sight power spectrum

Matshawule et al. 2021, MNRAS

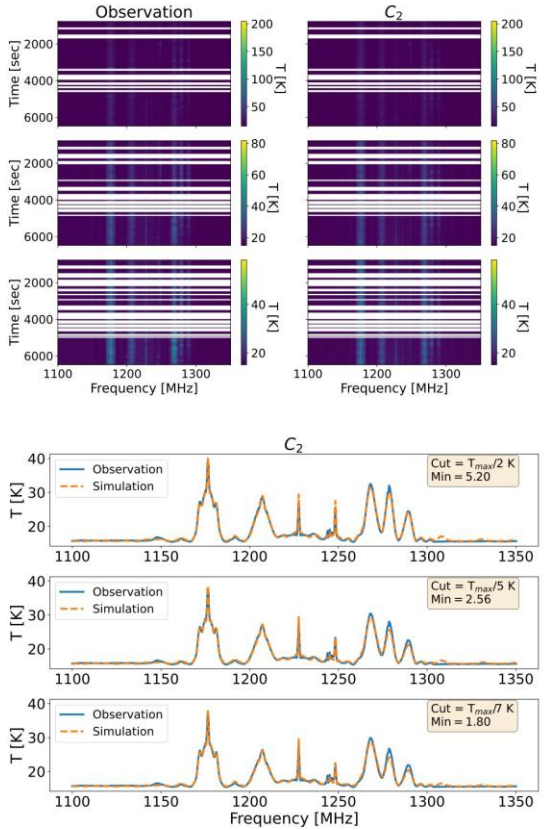
Challenges

RFI: flagging &
Developing simulations to test the impact of satellites and ways to remove them



J. Wang et al. 2021, MNRAS

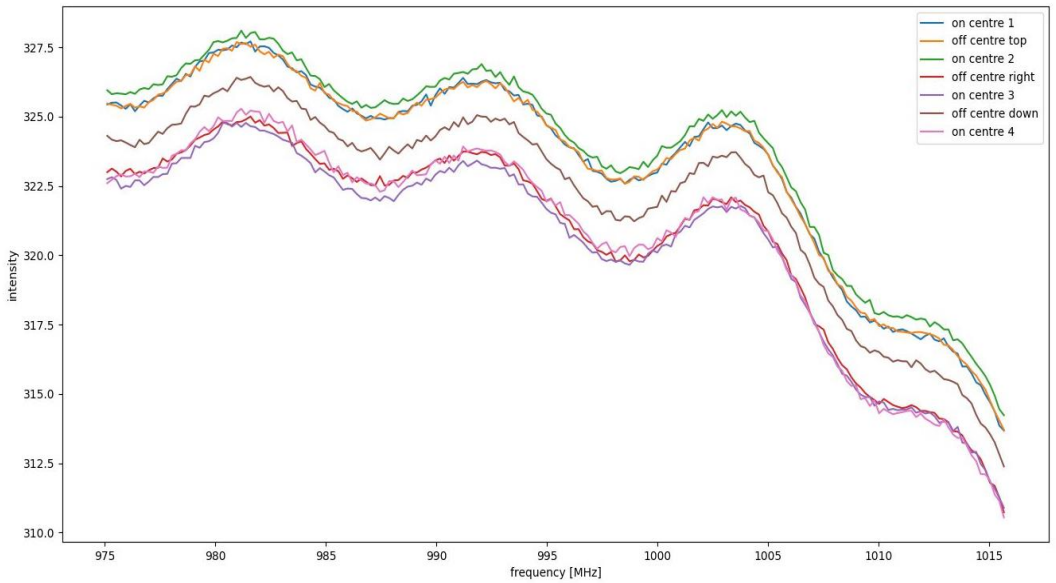
#	Sys	Band	Signal	Frequency [MHz]	Modulation	Rate [MHz]	P_t [dBW]	G_t [dBi]
-	GPS	L1	P(Y)	1575.420	BPSK(10)	10.2300	13.5	13.5
-	GPS	L1	C/A	1575.420	BPSK(1)	1.0230	16.5	13.5
-	GPS	L1	L1C-D	1575.420	TMBOC(6,1,4/33)	1.0230	10.0	10.0
-	GPS	L1	M-D	1575.420	$BOC_{sin}(10,5)$	5.1150	18.2	13.5
1	GPS	L2	P(Y)	1227.600	BPSK(10)	10.2300	10.0	10.0
2	GPS	L2	L2CM	1227.600	BPSK(1)	0.5115	10.0	10.0
3	GPS	L2	M-D	1227.600	$BOC(10,5)_{sin}$	5.1150	16.0	13.5
4	GPS	L5	L5I	1176.450	BPSK(10)	10.2300	18.0	18.0
	GLO	L1	L1SF(P)	1602.000	BPSK(5)	5.1100	10.0	10.0
5	GLO	L2	L2SF(P)	1245.100	BPSK(5)	5.1100	10.0	10.0
6	GLO	L2	L2OF(C/A)	1245.100	BPSK(0.5)	0.5110	10.0	10.0
7	GLO	L3	L3OC-D	1202.025	BPSK(10)	10.2300	10.0	10.0
8	GLO	L2	L2OC-D	1248.300	BPSK(1)	1.0230	13.0	12.0
9	GLO	L2	L2OC-P	1248.300	BOC(1,1)	0.5115	5.0	5.0
-	GAL	E1	OS-D(B)	1575.420	CBOC(6,1,1/11)	1.0230	10.0	10.0
10	GAL	E6	CS-P(C)	1278.750	BPSK(5)	5.1150	16.0	15.0
11	GAL	E6	PRS(A)	1278.750	BOCcos(10,5)	5.1150	18.0	16.0
12	GAL	E5ab	PRS(A)	1191.795	AltBOC(15,10)	10.2300	10.0	10.0
13	GAL	E5a	E5a-D	1176.450	AltBOC(15,10)	10.2300	6.0	6.0
-	BDS-2	B1-2	RS	1561.098	BPSK(2)	2.0460	10.0	10.0
14	BDS-2	B3	RS	1268.520	BPSK(10)	10.2300	16.0	16.0
15	BDS-2	B2b	OS	1207.140	BPSK(2)	2.0460	14.0	12.0
16	BDS-2	B2b	RS	1207.140	BPSK(10)	10.2300	18.0	18.0
-	BDS-3	B1-2	OS	1561.098	BPSK(2)	2.0460	10.0	10.0
-	BDS-3	B1	B1C-DI	1575.420	TMBOC(6,1,4/33)	1.0230	10.0	10.0
17	BDS-3	B3	B3C-Dm	1268.520	BPSK(10)	10.2300	15.0	13.5
18	BDS-3	B3	B3A-Dm	1268.520	BOC(15,2.5)	2.5575	10.0	10.0
-	QZS-1	L1	C/A	1575.420	BPSK(1)	1.0230	10.0	10.0
-	QZS-1	L1	L1C-D	1575.420	BOC(1,1)	1.0230	10.0	10.0
-	QZS-1	L1	L1C-D	1575.420	TMBOC(6,1,4/33)	1.0230	10.0	10.0
-	QZS-1	L1	SAIF	1575.420	BPSK(1)	1.0230	10.0	10.0
-	QZS-1	L2	L2CL	1227.600	BPSK(1)	0.5115	10.0	10.0
-	QZS-1	L6	L61(LEX)n	1278.750	BPSK(5)	5.1150	10.0	10.0
-	QZS-1	L6	L62o	1278.750	BPSK(5)	5.1150	10.0	10.0
-	QZS-1	L5	L5I	1176.450	BPSK(10)	10.2300	16.0	16.0
-	QZS-1	L5	L5Q	1176.450	BPSK(10)	10.2300	16.0	16.0
19	IRNSS	L5	SPS	1176.450	BPSK(1)	1.0230	16.0	14.0
20	IRNSS	L5	RS-D	1176.450	BOC(5,2)	2.0460	18.0	16.0
-	SBAS	L1	C/A	1575.420	BPSK(1)	1.0230	13.0	13.5
21	SBAS	L5	L5I	1176.450	BPSK(10)	10.2300	18.0	16.0

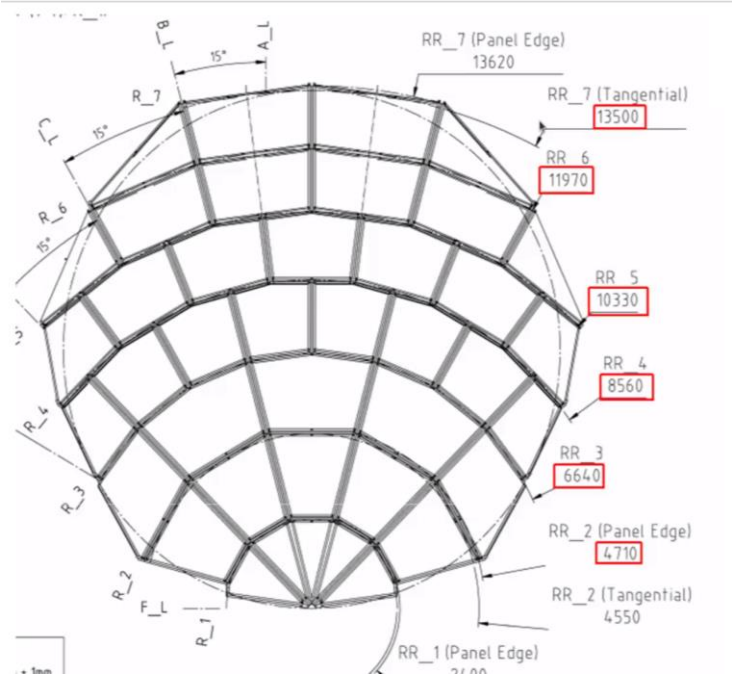


Engelbrecht et al. 2024 under review

Challenges

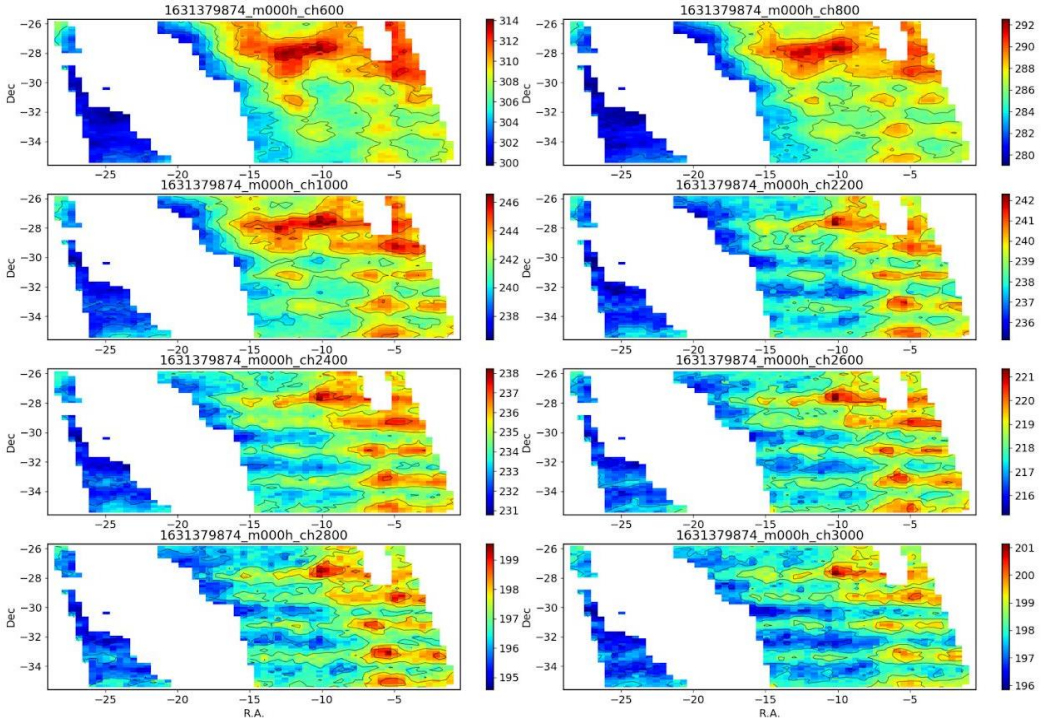
Standing waves: related to gaps on the dish, 1% errors
[to be addressed]



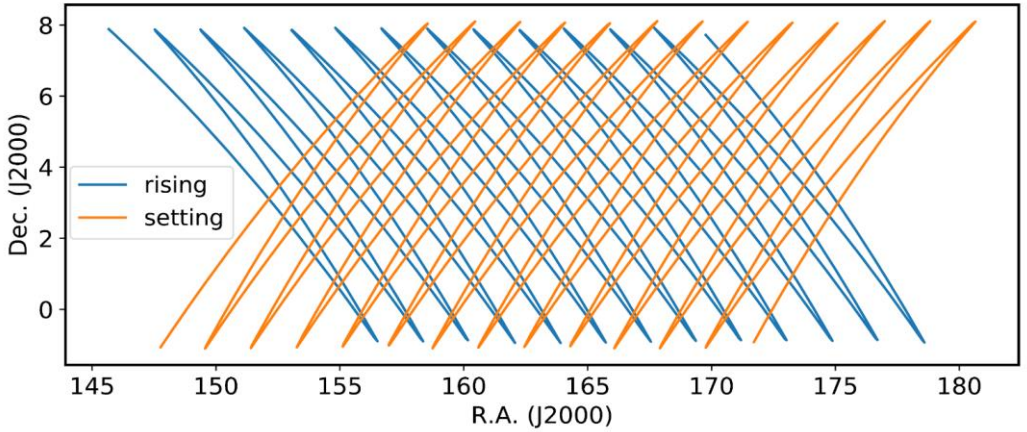


Challenges

Zebra RFI: Some data contaminated by stripes
Traced back to leakage from the Vanwyksvlei GSM tower
[to be addressed]



First results with a MeerKAT single dish pilot survey



Year 2019

- ~ 15 hours ~ 60 dishes used (~ 900 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 line, 1.5 hours per scan

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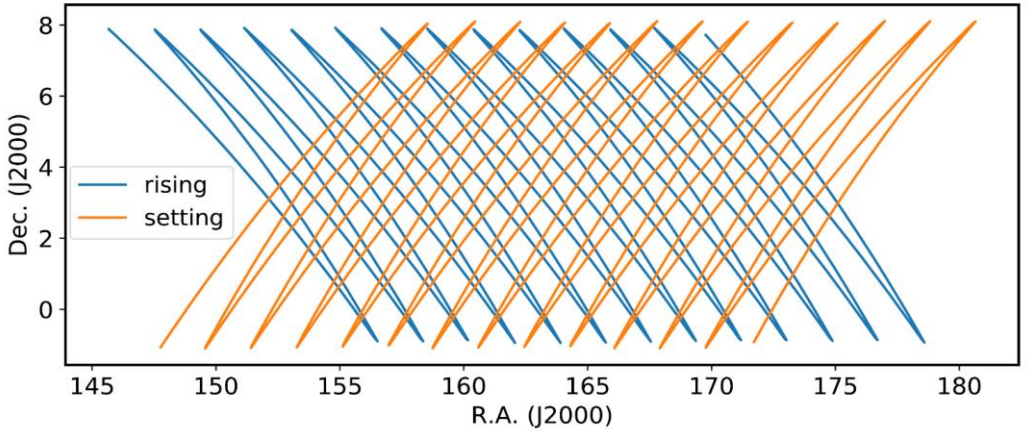

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Calibration

- Modelling **nine** components based on our astronomy/statistical knowledge;
- checking these models with plenty of observations

point source * beam Galactic + CMB ground pickup + atmosphere diode noise

$$T_{\rm model}(t,\nu) = T_{\rm ps}(t,\nu) + T_{\rm diffuse}(t,\nu) + T_{\rm el}(t,\nu) + T_{\rm diode}(t,\nu) + T_{\rm rec}(t,\nu),$$

receiver temperature

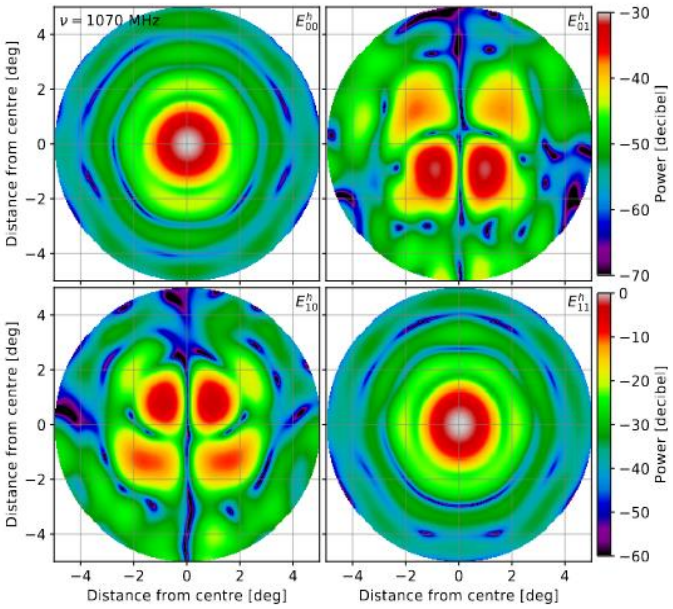
$$\hat{T}_{\rm model}(t,\nu) = g(t,\nu)\, T_{\rm model}(t,\nu),$$

gain

- Bayesian framework to obtain undetermined parameters

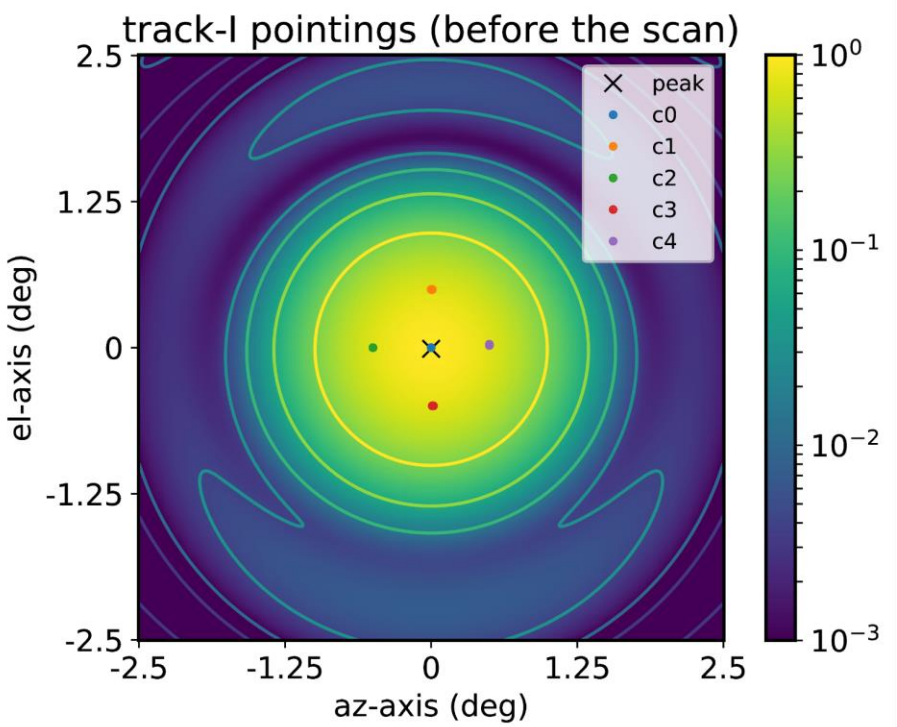
$$p_{\rm post} \propto p_{\rm prior} \cdot \mathcal{L}(\hat{\mathbf{T}}_{\rm raw} | \hat{\mathbf{T}}_{\rm model}),$$

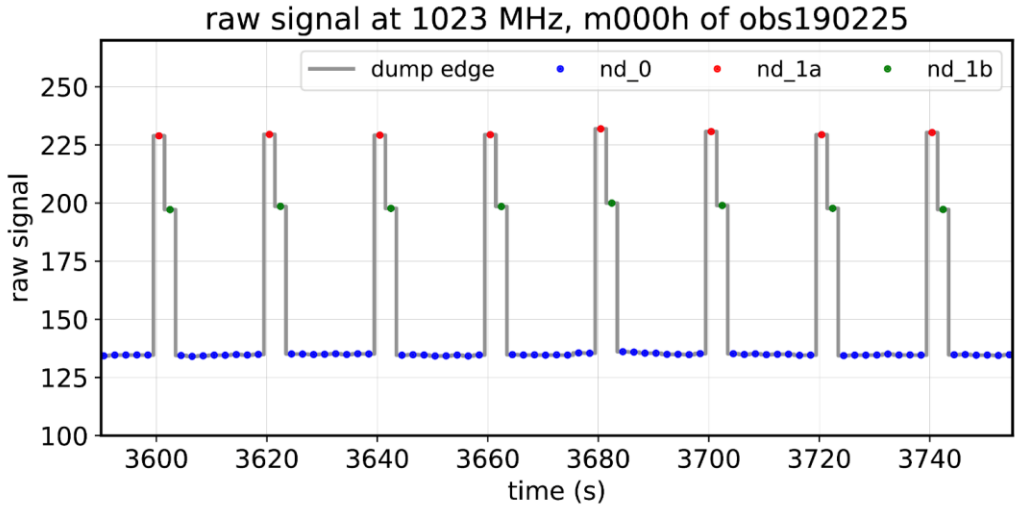
Interferometric data



Asad et al. 2021, MNRAS

Calibration

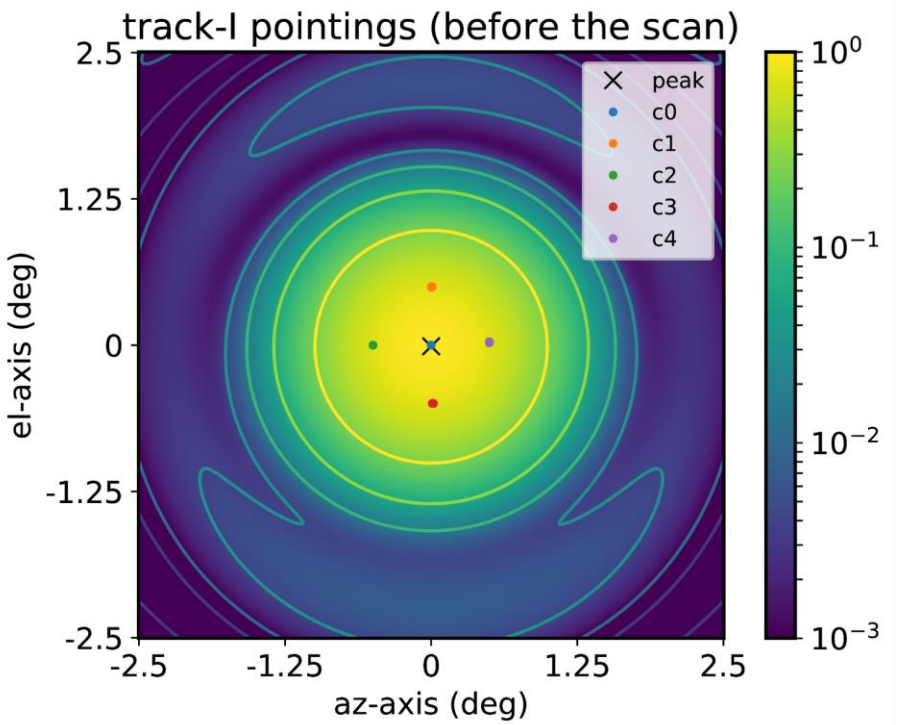


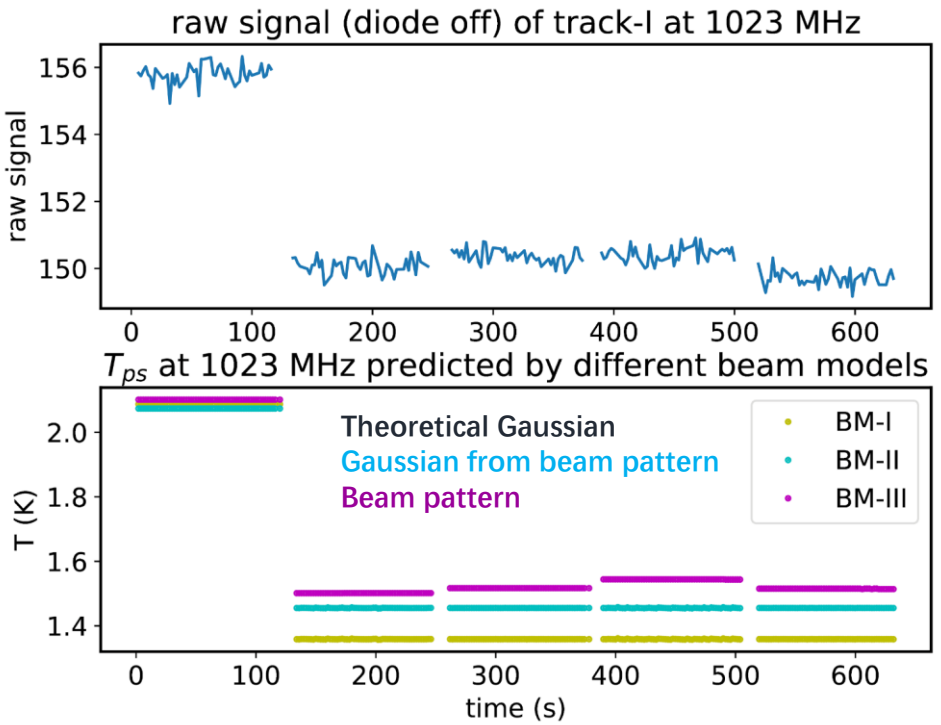


J. Wang et al. 2021, MNRAS

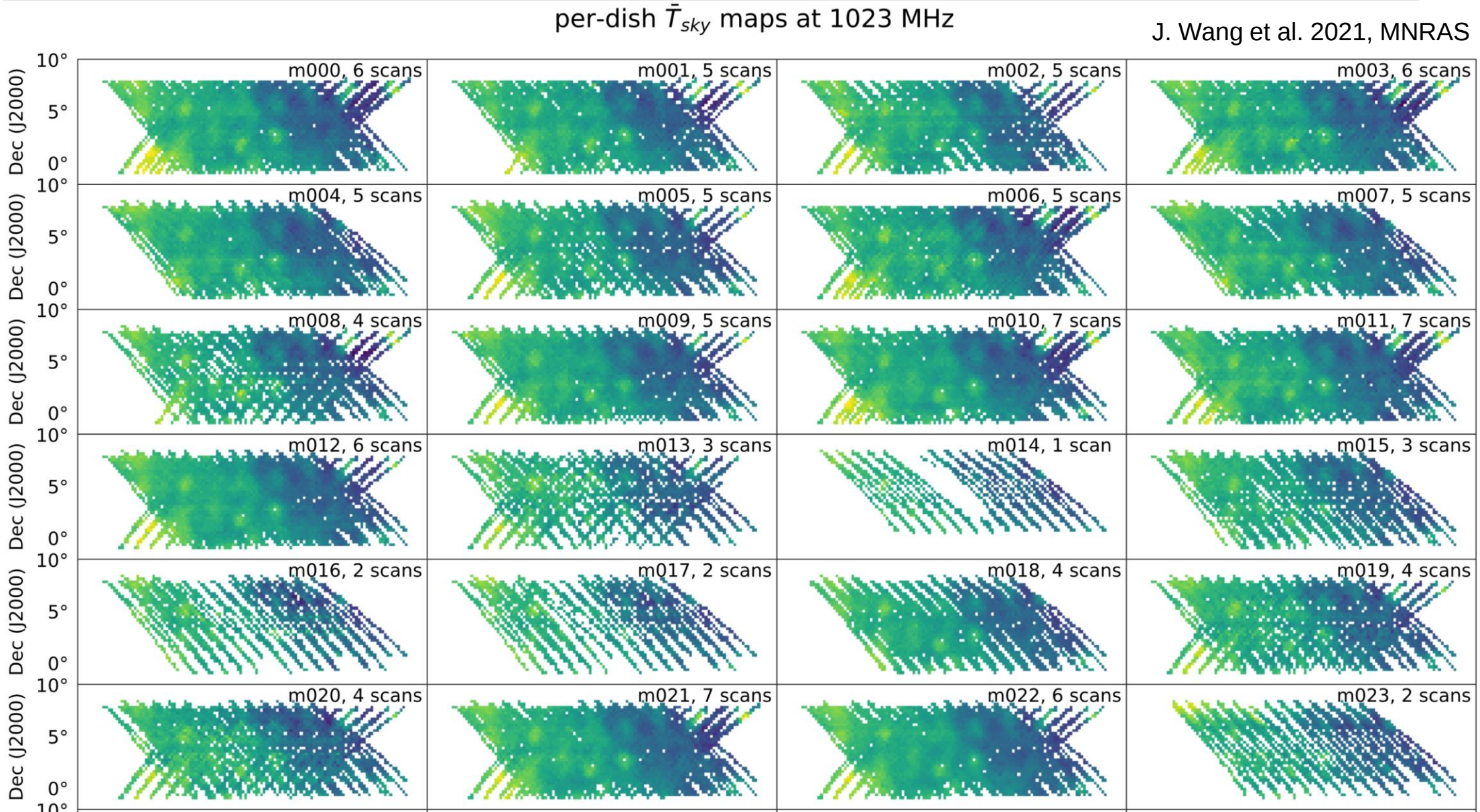
- Observe **a calibrator** before and after each scan (left)
- **Noise diode** injection every 20 sec during scan (right)

Calibration



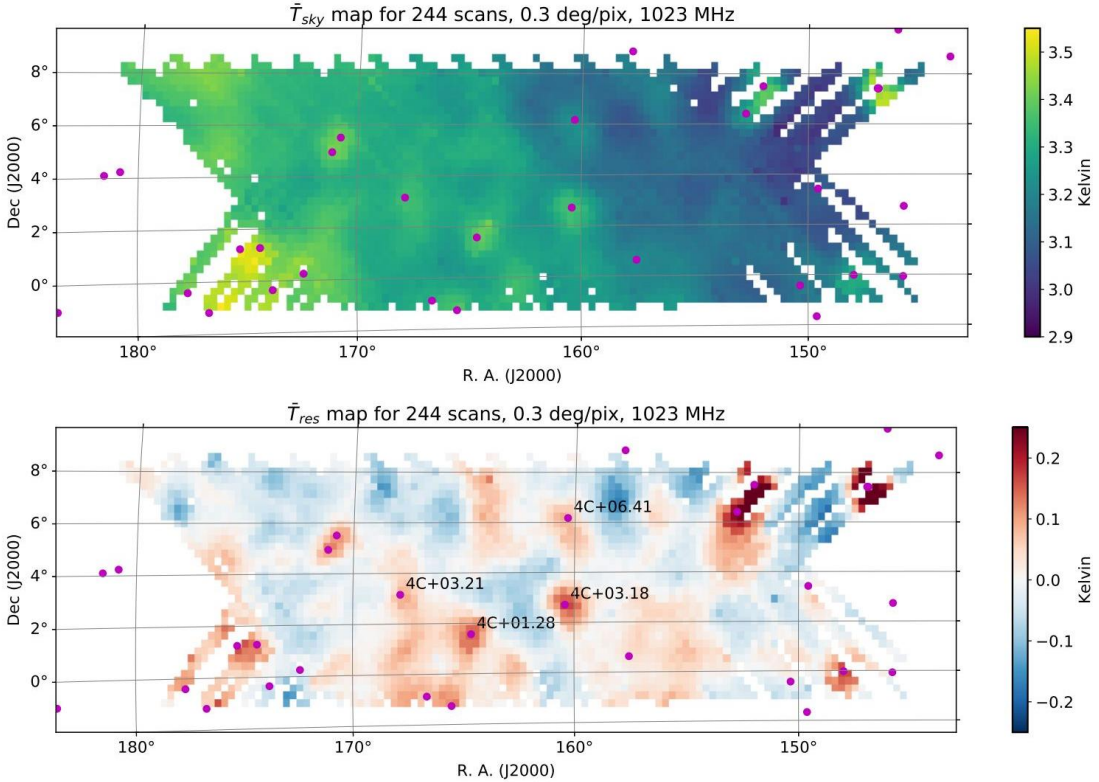


Calibration (MeerKLASS 2019 data)



J. Wang et al. 2021, MNRAS

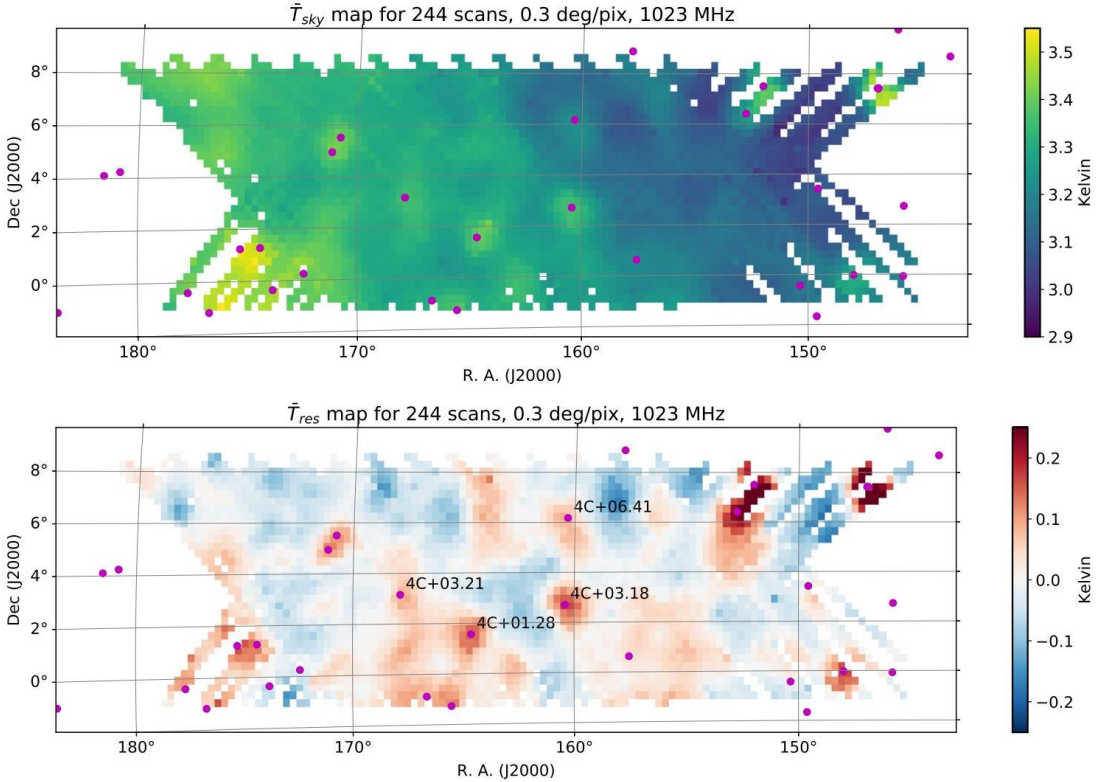
Calibration (MeerKLASS 2019 data)



7 blocks; noise level ~ 2 mK;
3D data cube (971–1075 MHz &1305–1504 MHz, resolution 0.2 MHz)

J. Wang et al. 2021, MNRAS

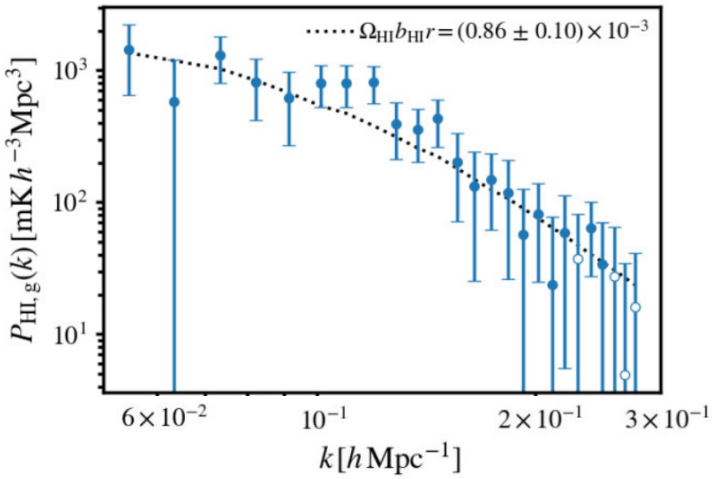
Calibration (MeerKLASS 2019 data)



7 blocks; noise level ~ 2 mK;
3D data cube (971–1075 MHz &1305–1504 MHz, resolution 0.2 MHz)

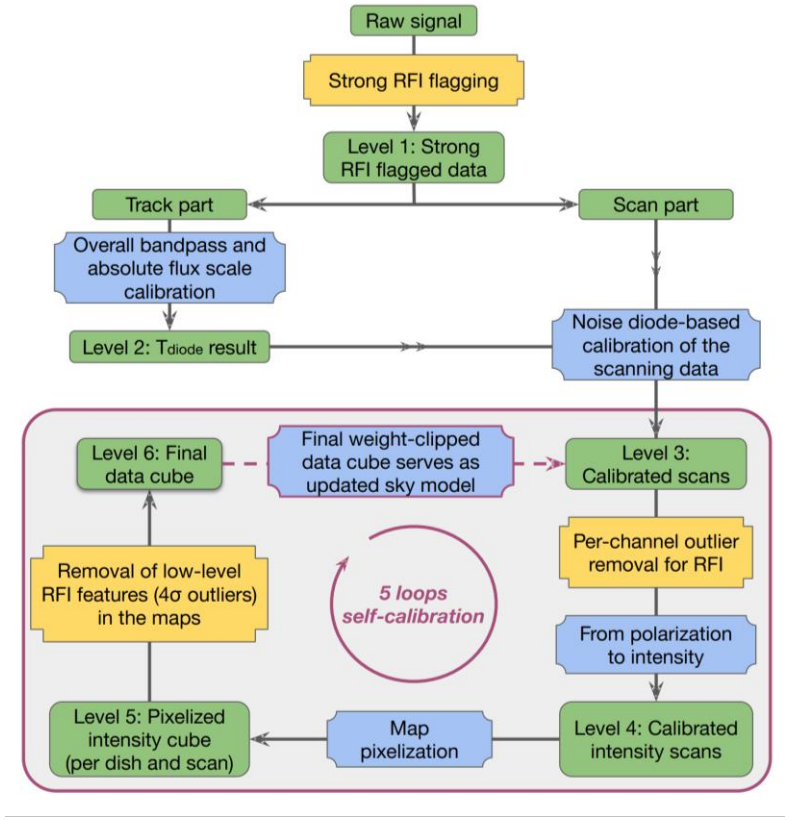
J. Wang et al. 2021, MNRAS

Cross-correlation with WiggleZ galaxies
Please pay attention to Steve Cunnington's talk tomorrow

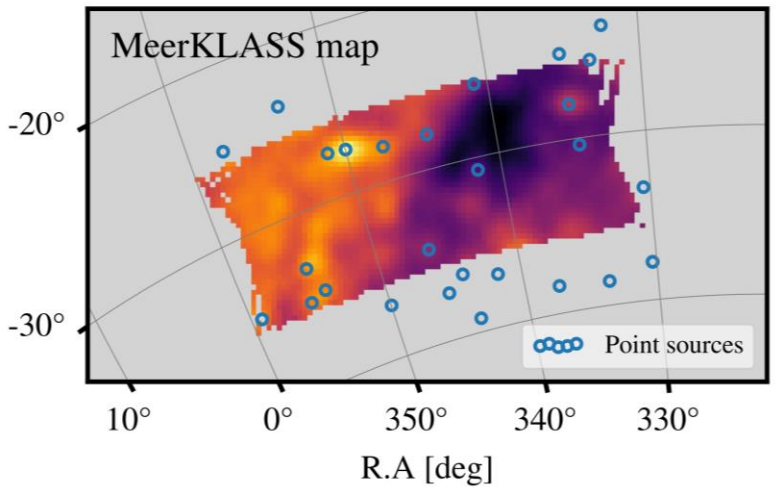


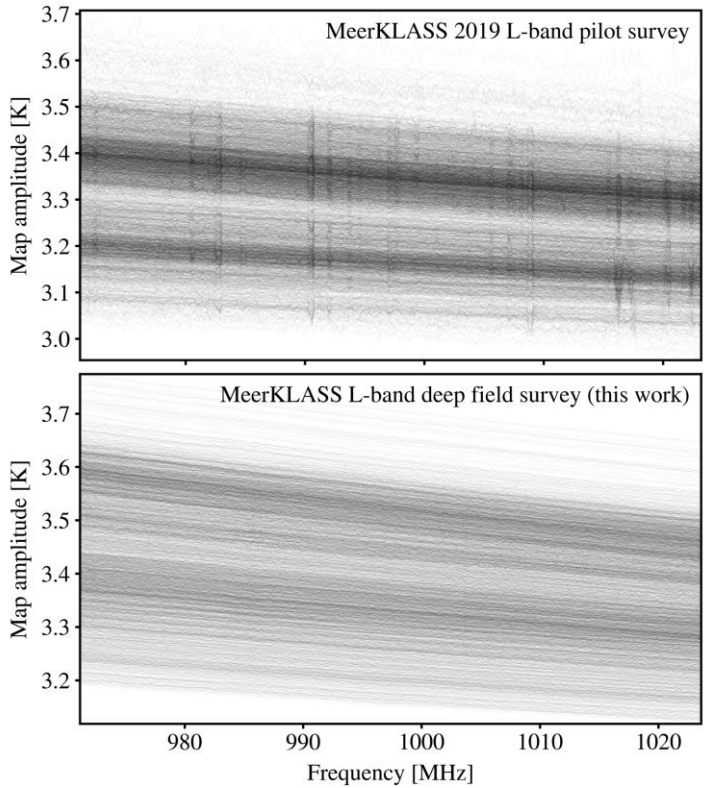
Cunnington, Li, et al., 2023, MNRAS

Calibration (MeerKLASS 2021 data)



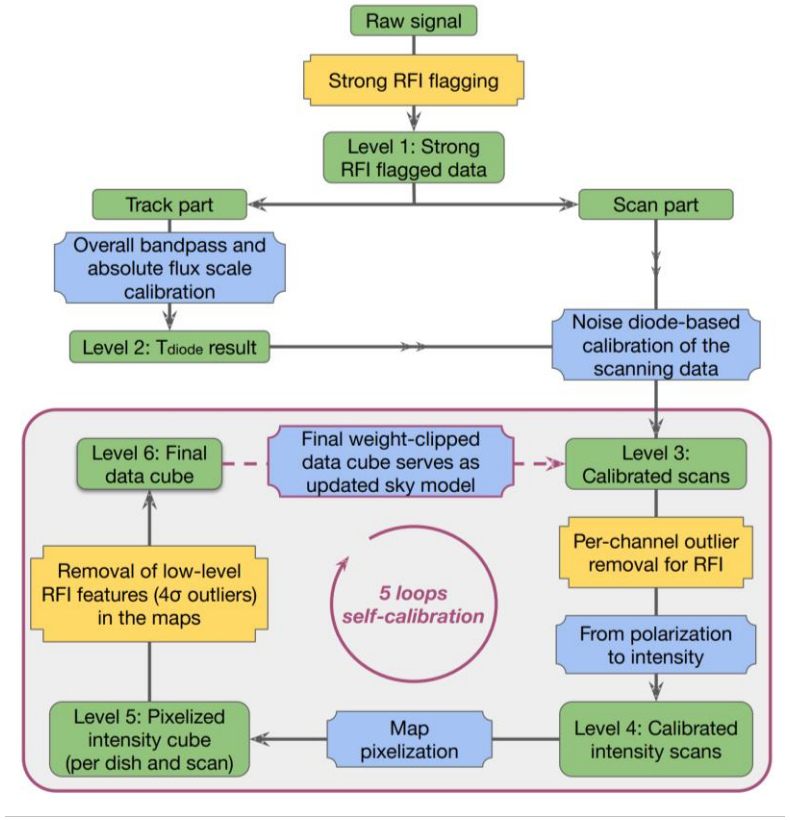
27 blocks; noise level ~ 1.2 mK





MeerKLASS collaboration et al. *to be submitted*

Calibration (MeerKLASS 2021 data)



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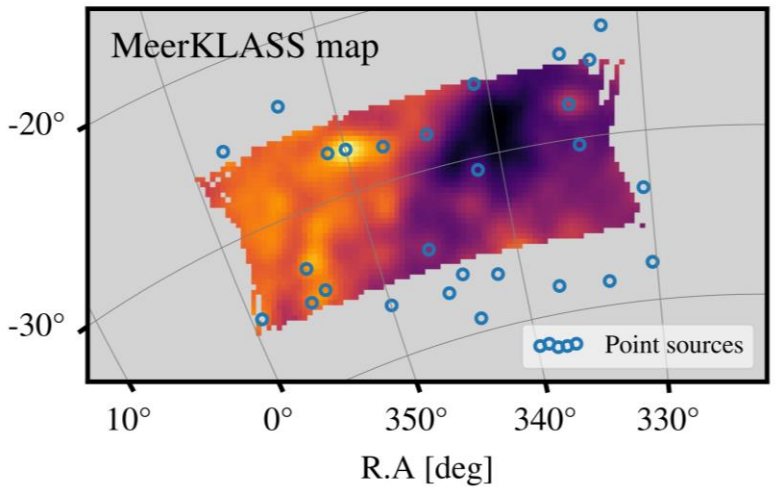

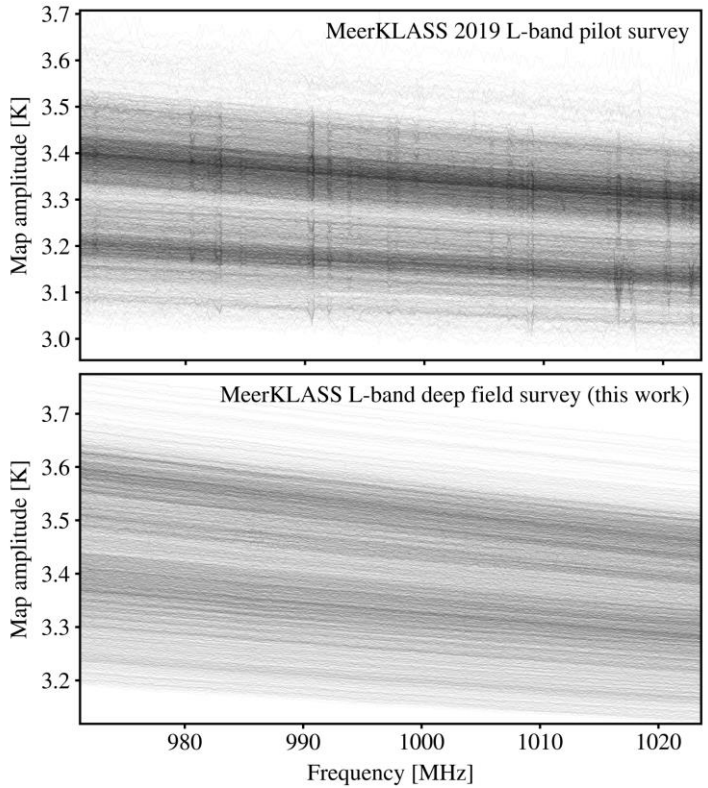

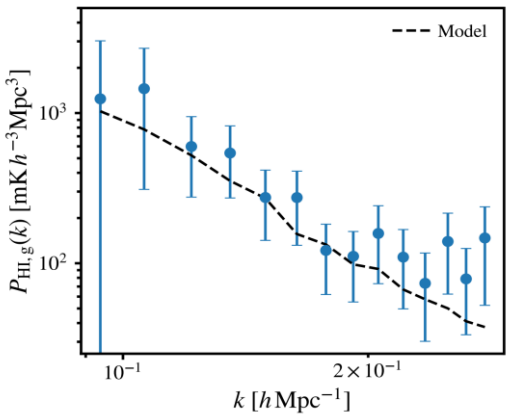

Cross-correlation with GAMA galaxies

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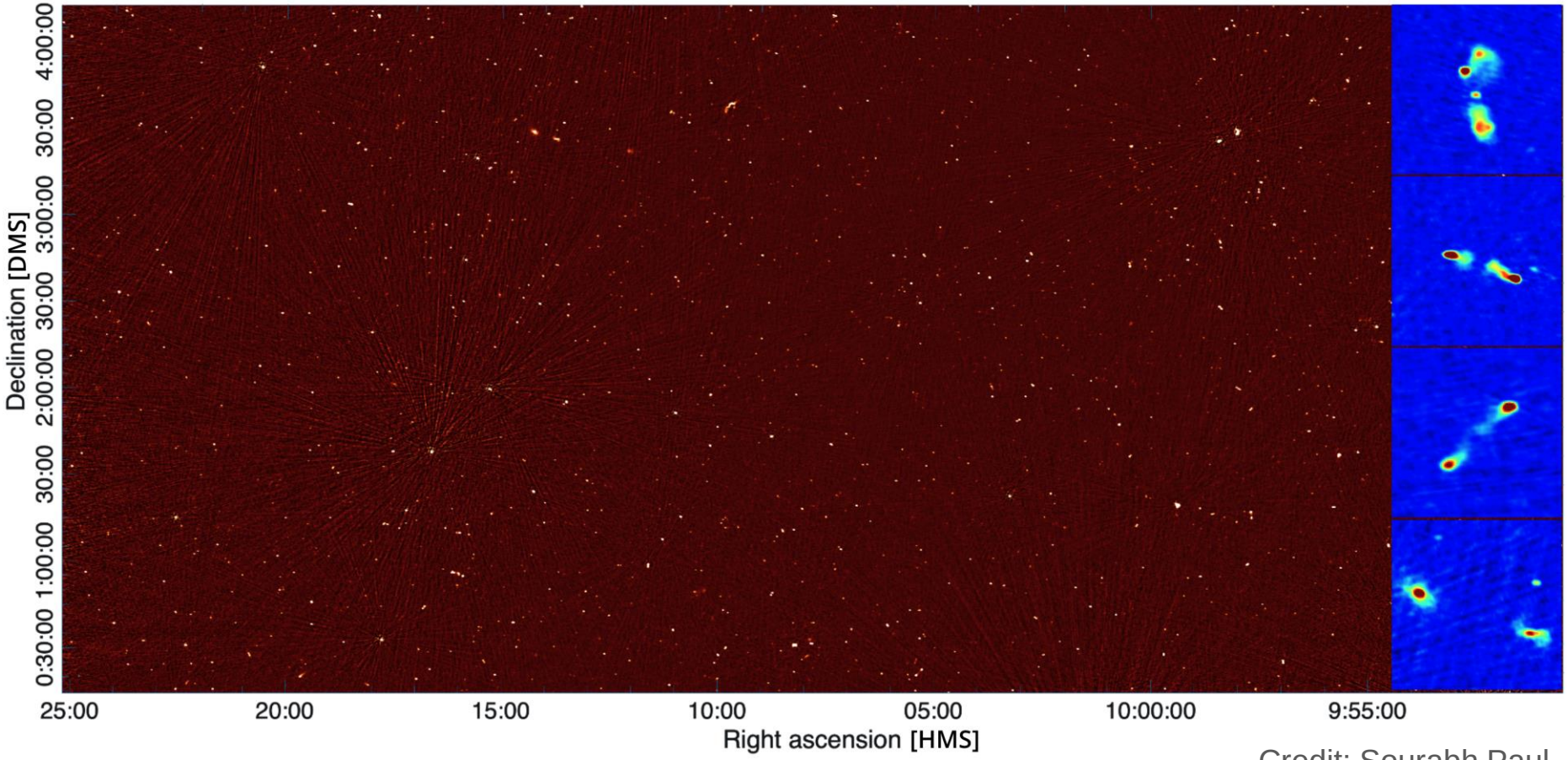
MeerKLASS collaboration et al. *to be submitted*

Continuum images with the same data

- **On the fly** mapping technique – need to correct for the fast dish movement



one block

816 MHz

1613 OTF pointings

2s integration time

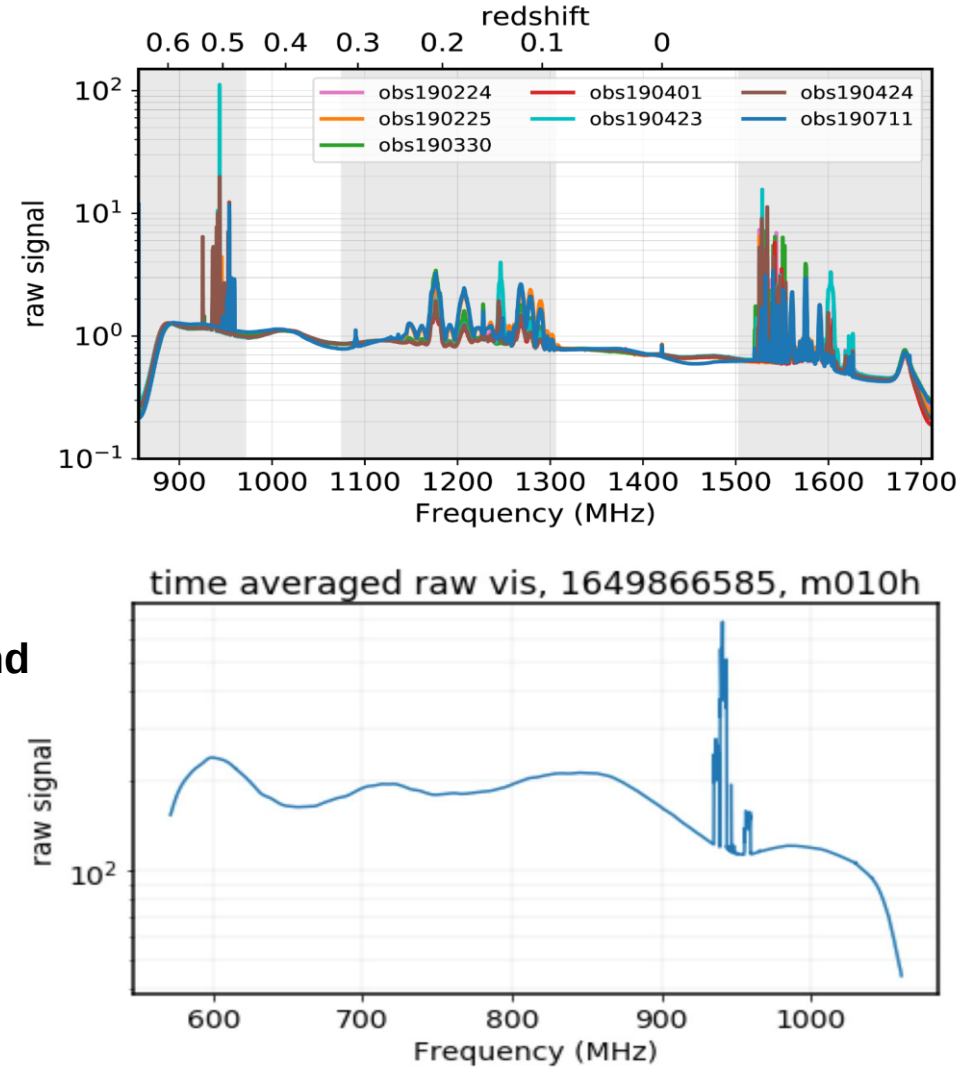
RMS ~ 150 µJy/beam

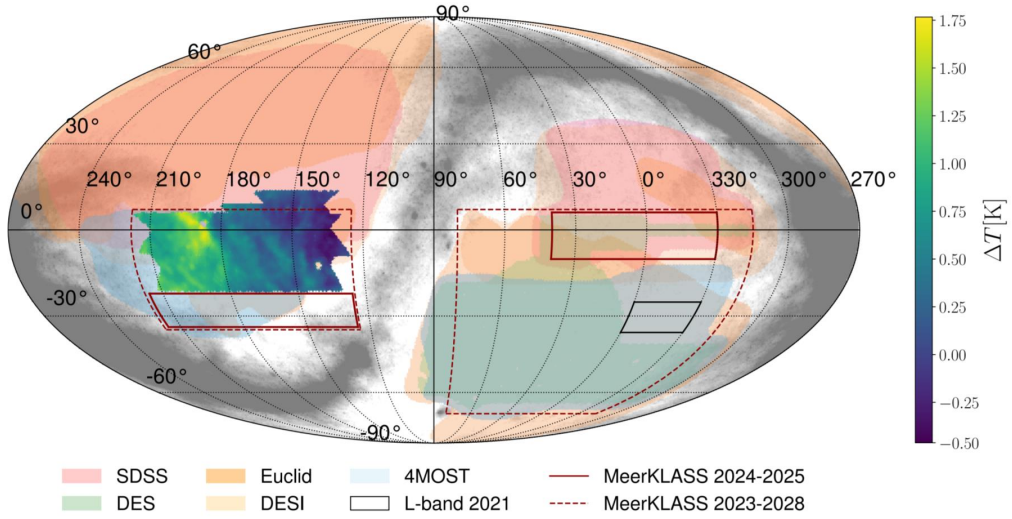
Credit: Sourabh Paul

UHF-band

L-band

UHF-band





Summary

- **HI intensity mapping with MeerKAT in single dish mode** will deliver state of the art cosmological constraints: **BAO in HI – dark energy, RSDs – modified gravity, primordial non-Gaussianity…**
- **Multi-wavelength cross correlations** adds more than the sum of the parts
- **We have detections of the HI IM power spectrum**
- Current tests with MeerKAT **show no major showstoppers**
- **OTF** pipeline is producing continuum images with the MeerKAT interferometer data – **millions of galaxies/transients!**
- Ongoing observations and data processing with MeerKAT UHF data **–** **goal is to observe 2,500 hours over 10,000 deg^2 (25 uJy in continuum)**

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