Everything everywhere all at once: the MeerKLASS project

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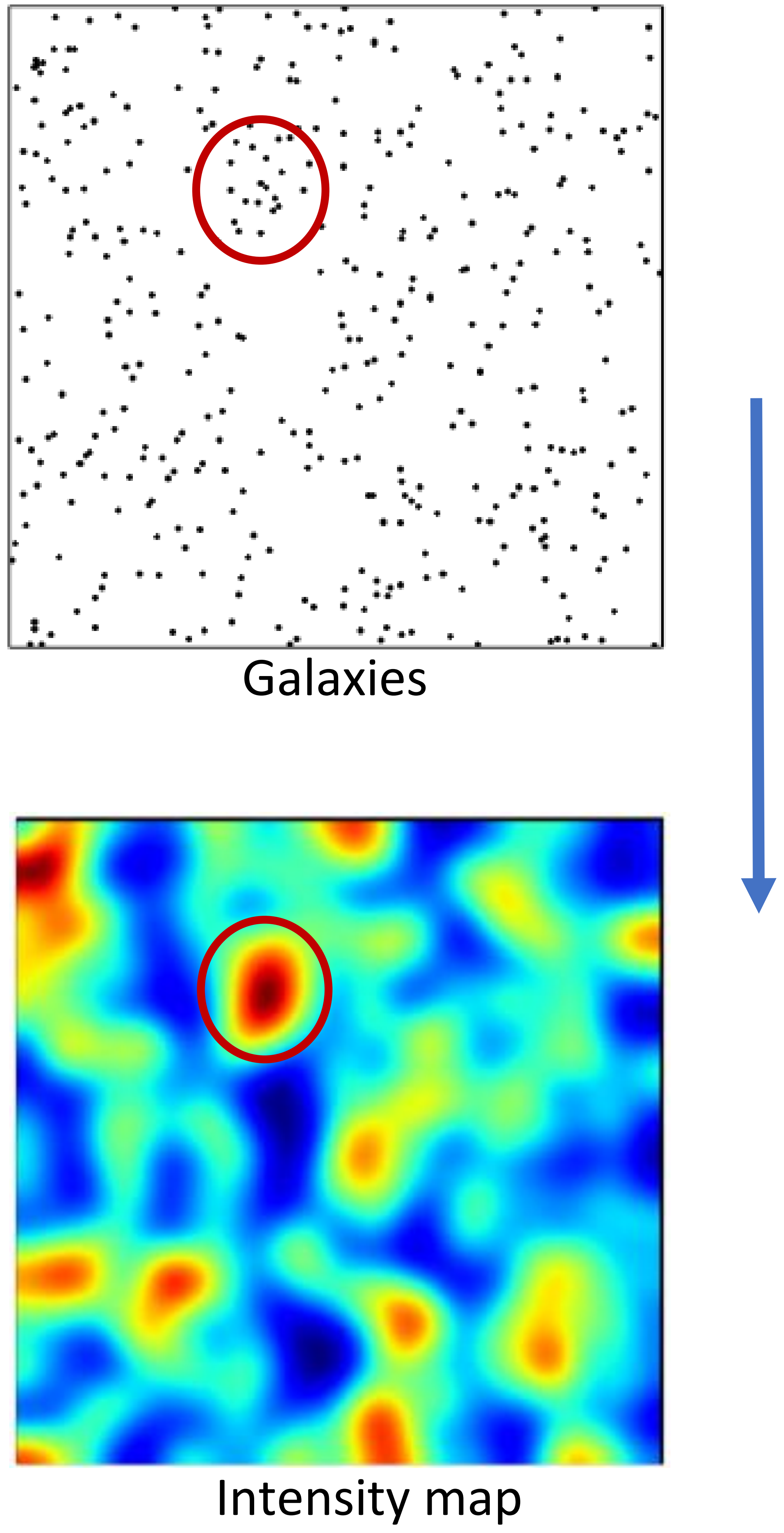
Cosmology in the Alps 2024

Switzerland, 18th March 2024

CRC · UNIVERSITY of the WESTERN CAPE · UWC ASTROPHYSICS · NRF National Research Foundation · SARAO South African Radio Astronomy Observatory

The beginning (circa 2012)
Spectroscopic cosmology with the SKA?

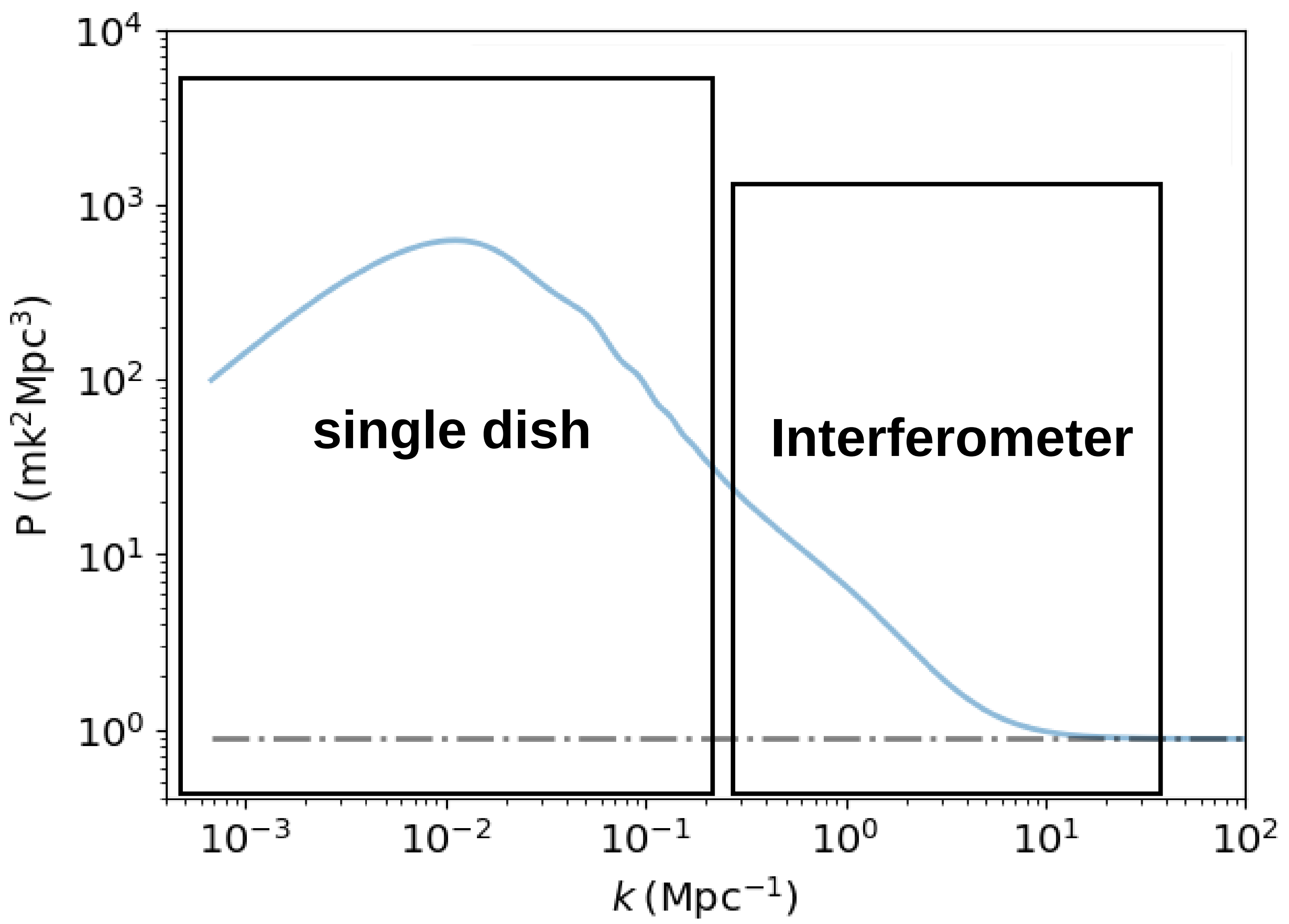
- 3d information (angle+redshift) is crucial for Cosmology
- Not enough sensitivity for a large HI galaxy survey with the SKA (z>0.4)
- HI intensity mapping to the rescue: no need to detect galaxies - low angular resolution intensity maps of the 21cm HI line emission will trace dark matter fluctuations
- Pixel will have joint emission from multiple galaxies
- Very high redshift resolution
- Signal ~ 200 uK at z~1

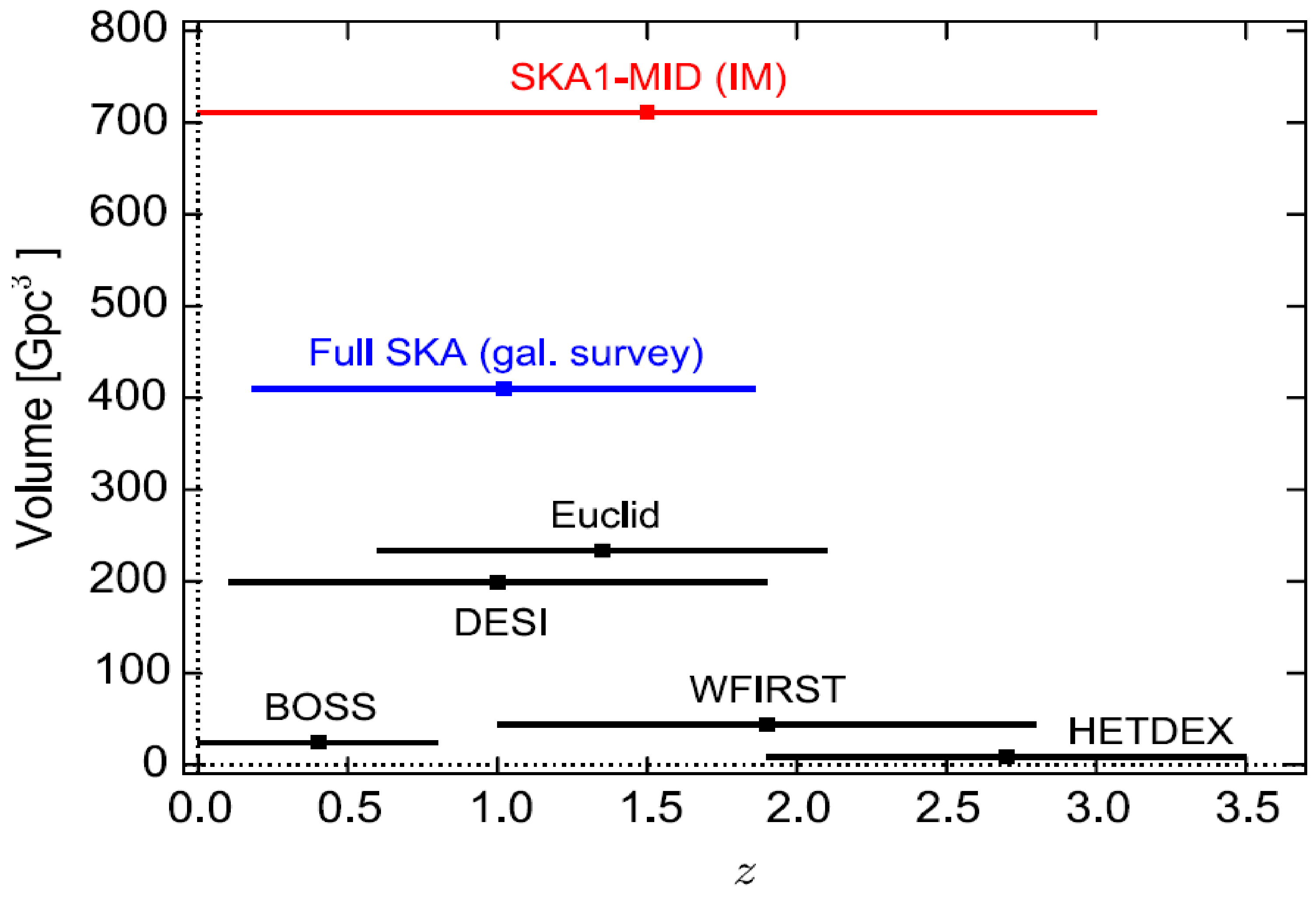


- SKA: S. Camera et. al, arXiv:1305.6928; P. Bull et al, arXiv:1405.1452; M. G. Santos et al., arXiv:1501.03989
- Previous: S. Bharadwaj, et al., arXiv:0003200; R. Battye et al., arXiv:0401340

HI intensity mapping with SKA/MeerKAT?

- Baselines not short enough - need to use single dish data (auto-correlations from each dish) in order to probe large scales (> ~ 10 Mpc)
- 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





See: arXiv:1305.6928, arXiv:1405.1452, arXiv:1501.03989, arXiv: 1509.07562, arXiv:1811.02743

Finally the South!

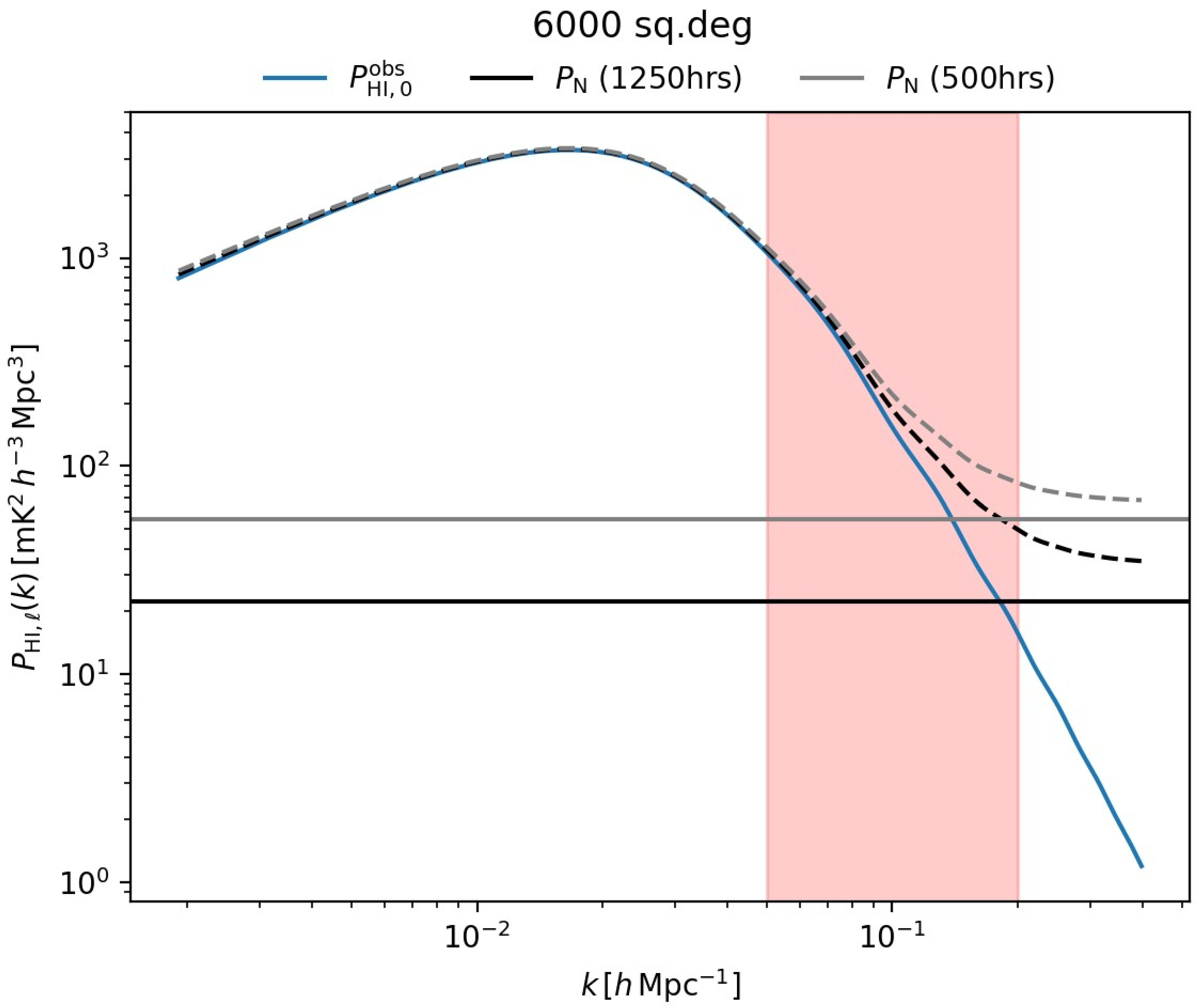
MeerKAT

- 64, 13.5 m dishes – 2018
- Soon + 16 SKAO 15m dishes
- Maximum baseline: 8 Km - soon ~ 20Km
- Single pixel feeds
- L-band: 900-1670 MHz (z<0.58)
- UHF band: 580 MHz-1015 MHz (0.40 < z < 1.45)

SKA-Mid

- 194 dishes: 130 SKAO (15 m) + 64 MeerKAT
- Up to 120 Km baselines
- Band 1: 350-1050 MHz (0.35 < z <3)
- Band 2: 950-1750 MHz (0 < z < 0.5)

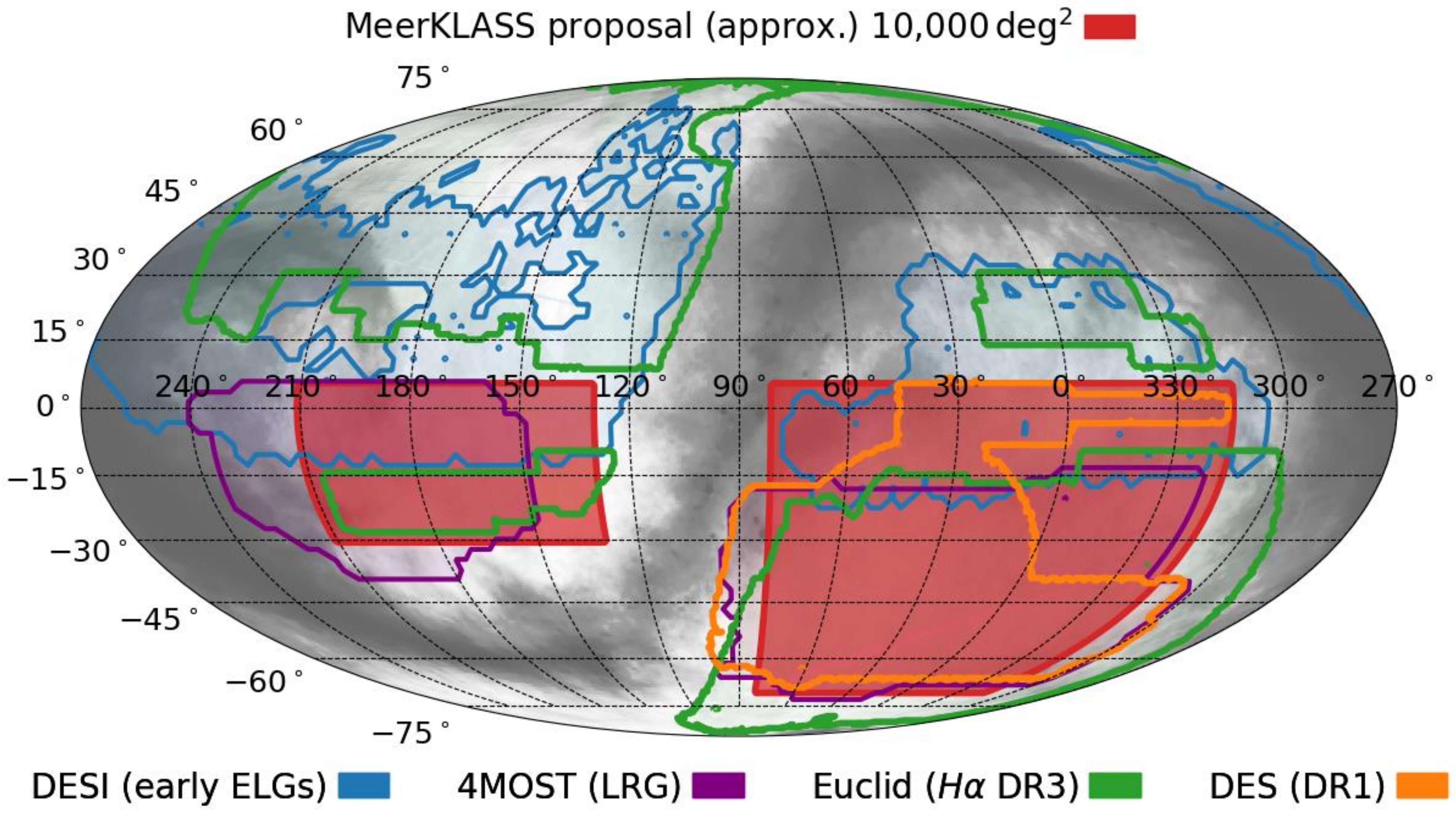
HI IM makes it “easy” to probe the dark matter power spectrum



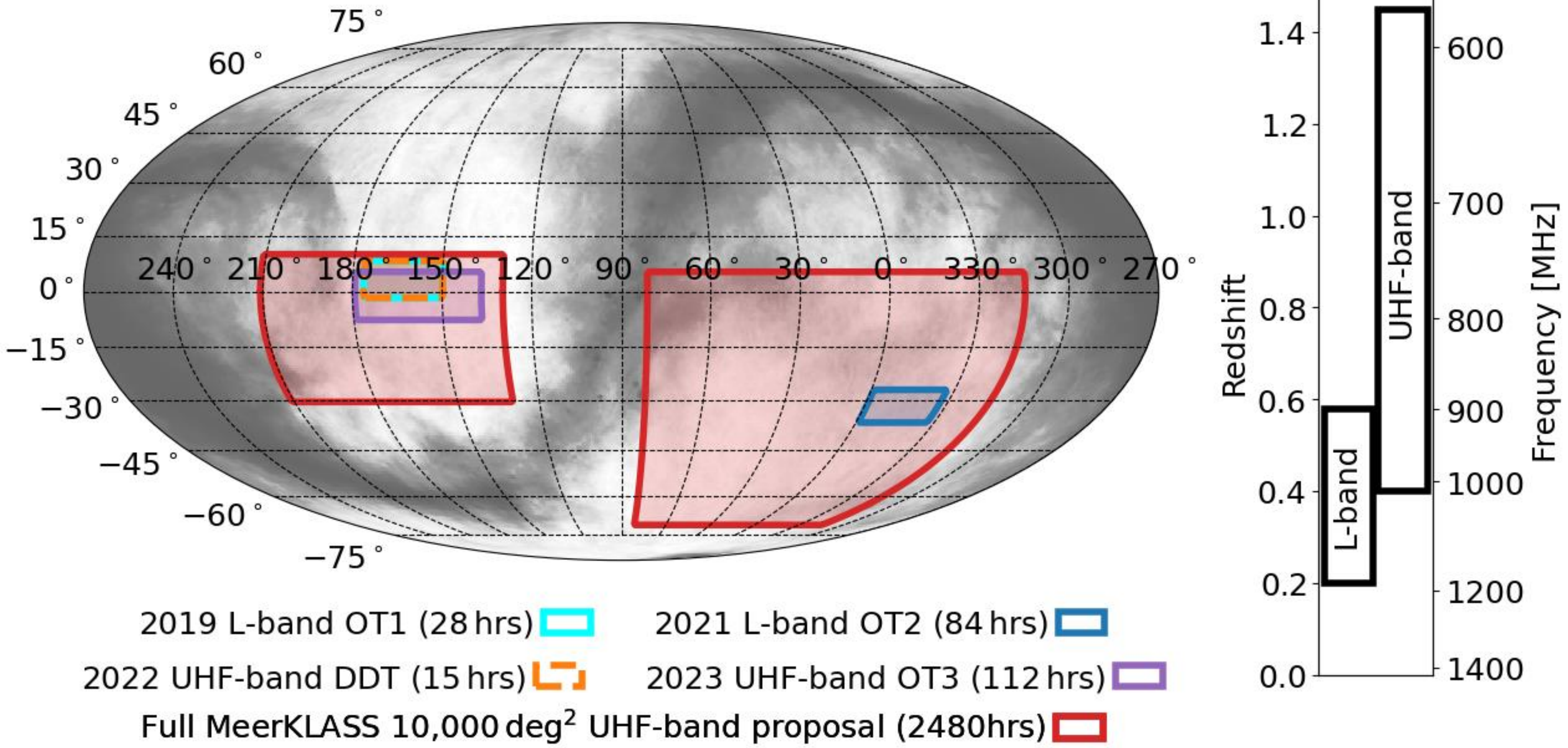
- An example with the MeerKAT telescope: 500 hours is enough to detect the baryon acoustic oscillations at one z bin. Noise is well below the signal on large scales

MeerKLASS: MeerKAT Large Area Synoptic Survey

- Aim: Cosmology (HI intensity mapping) but commensal with lots of other science (continuum survey) - Santos et al., arXiv:1709.06099
- Unique approach: combine single dish data (autos) + interferometer data from telescope correlator
- Focus on sky patches with multi-wavelength data for cross-correlation (DESI, 4MOST, Euclid, Rubi/LSST, DES)
- Goal: 2,500 hours over 10,000 deg^2 (25 uJy rms, 13'' in continuum) within next 5 years
- An SKA cosmology survey precursor
- International collaboration ~ 40 members

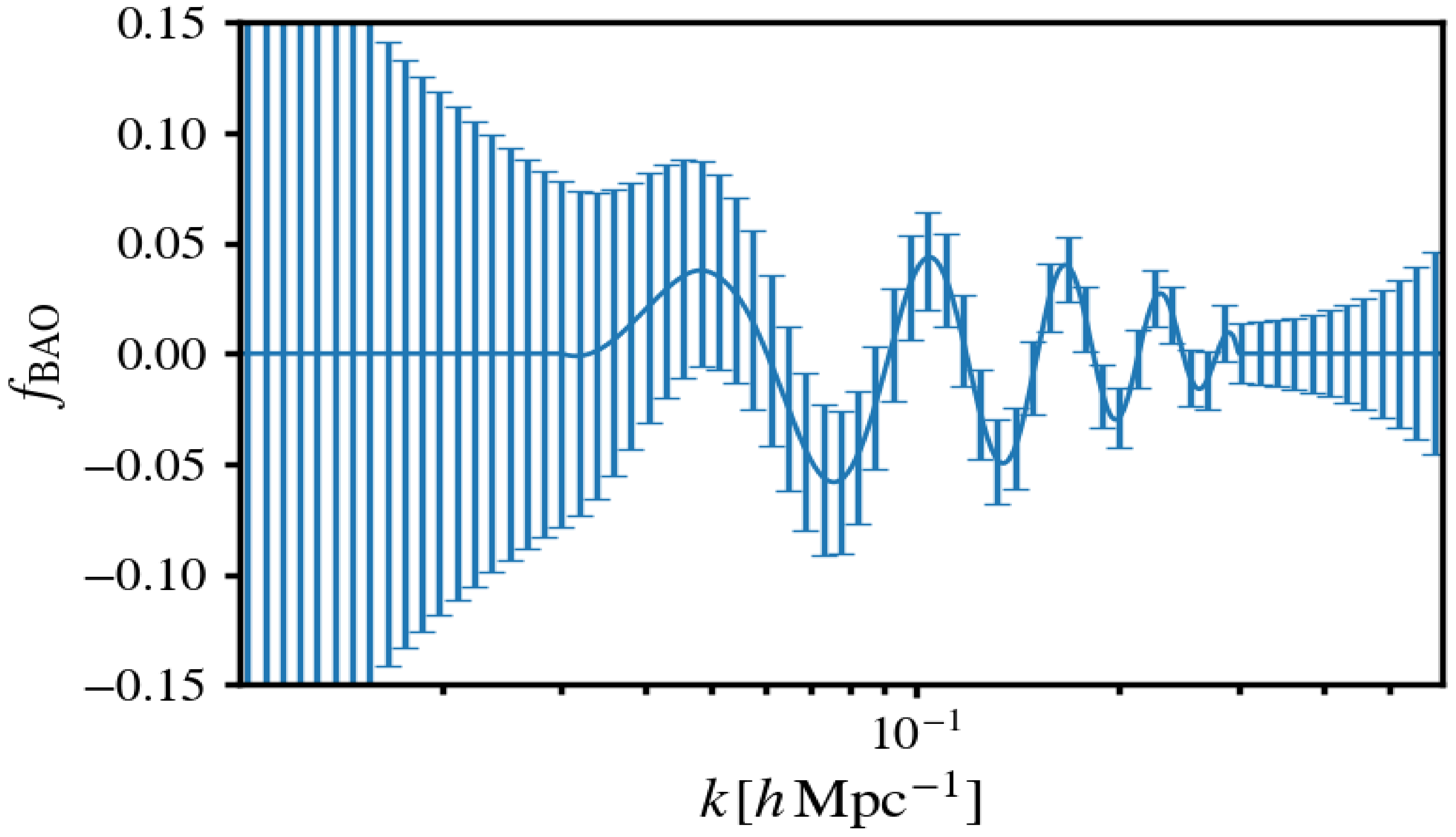


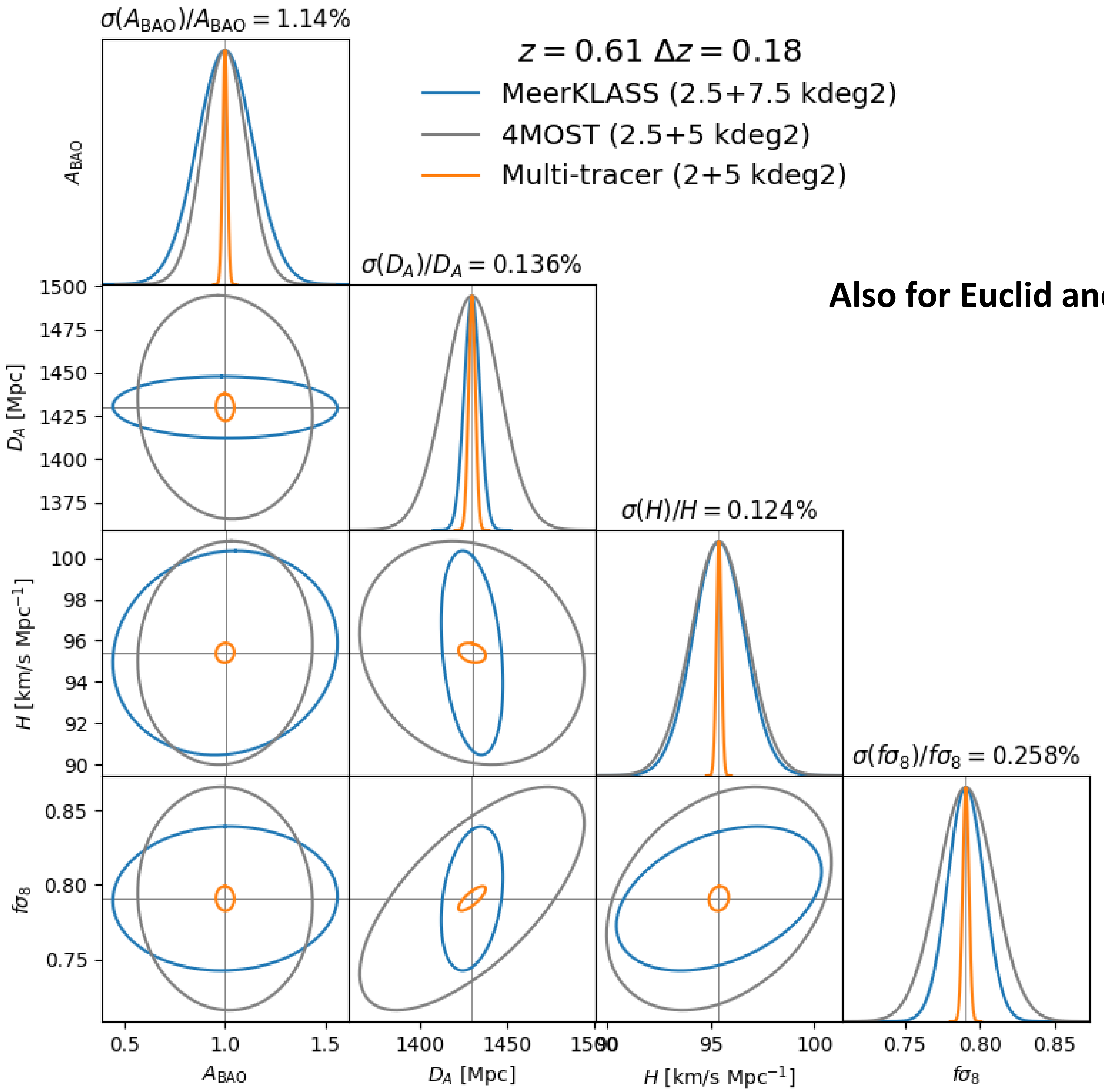
Completed observations



S. Cunnington

MeerKLASS: Cosmology





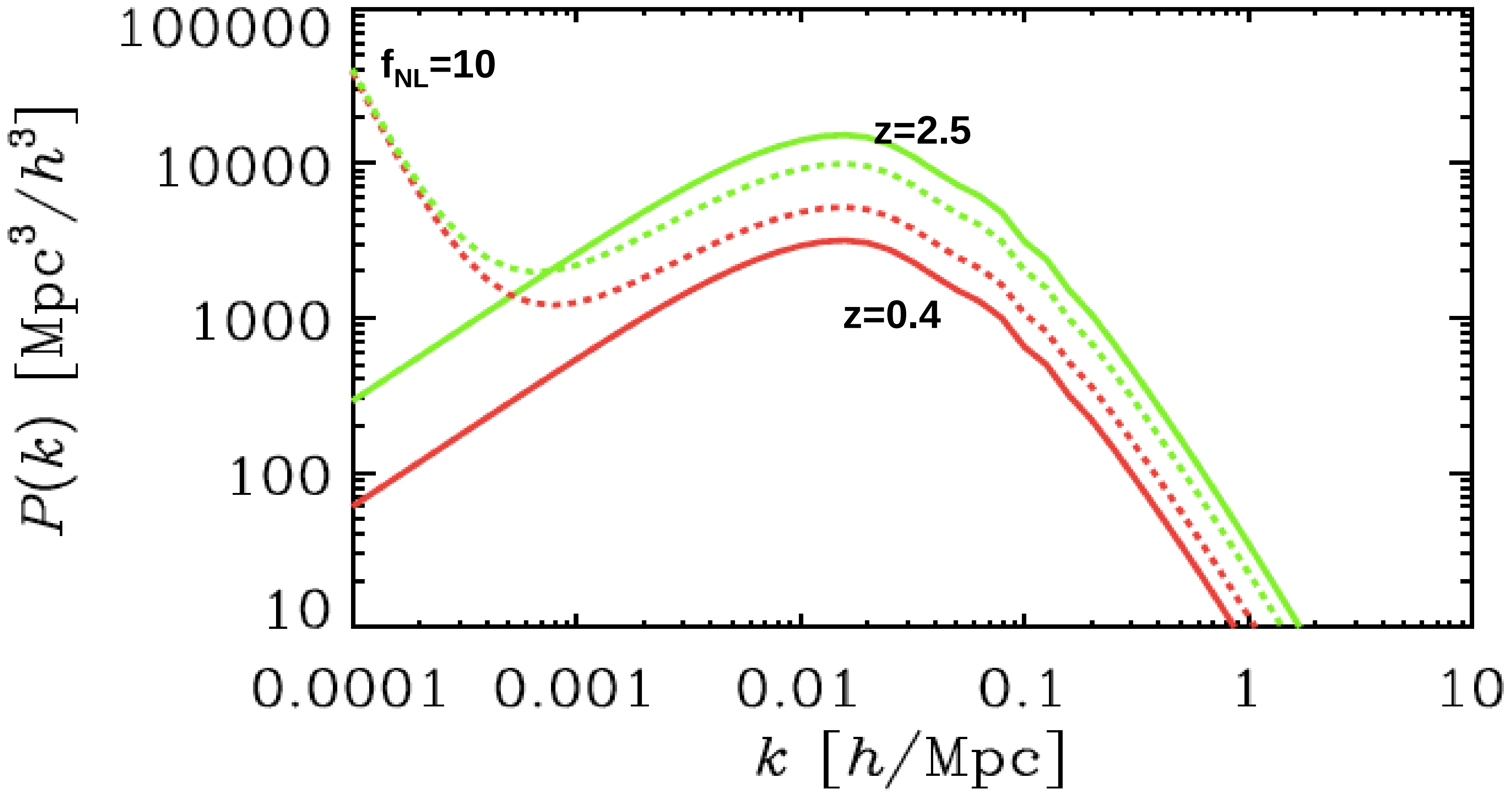
Also for Euclid and DESI

- 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 -> large improvements on the errors**

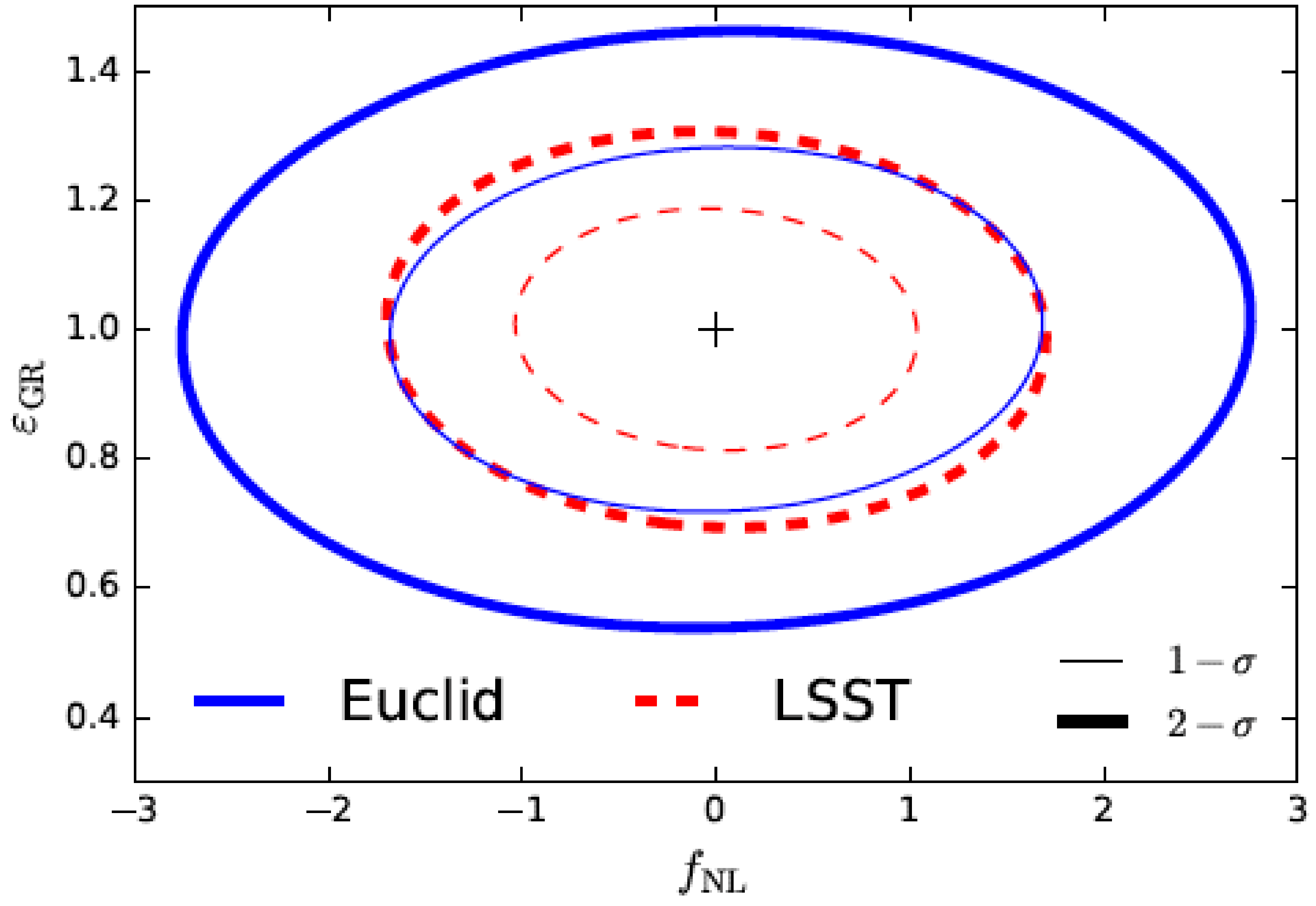
MeerKAT: 1,300 hours. 60 dishes

J. Fonseca, S. Cunnington

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



Camera, Santos, et al., PRL, arXiv: 1305.6928

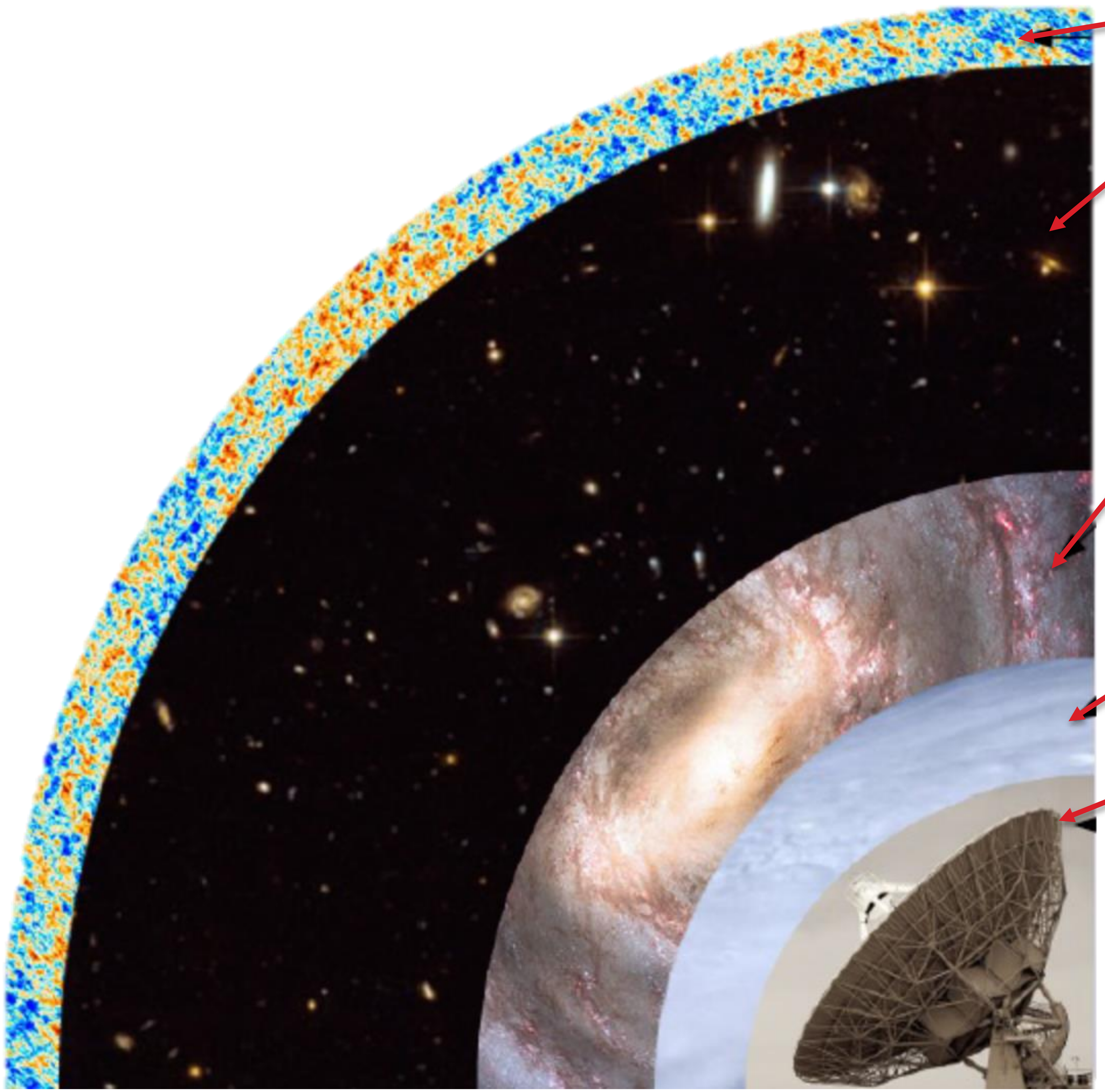


SKA1 Cosmology “red book”: arXiv:1811.02743

- 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 SKAO-Mid Band 1 with LSST will detect f_{NL} ~ 1 as well as GR corrections
- A good way to “fight” systematics

MeerKLASS: f_{NL} ~< 2 (Fonseca et al., arXiv1611.01322)

From theory to observations: challenges



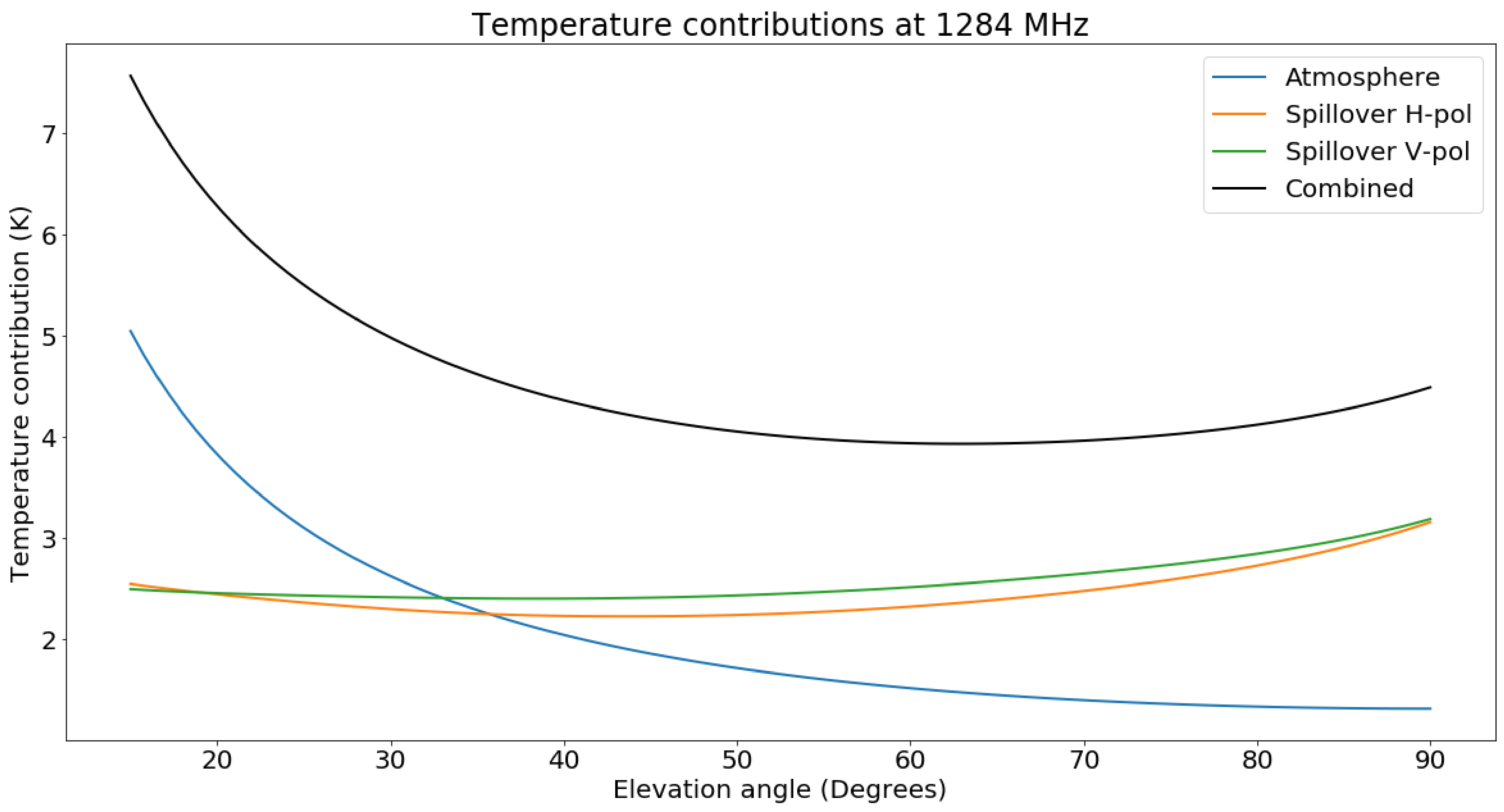
- HI IM signal
- Extragalactic foregrounds:
  - Point sources
  - E.G. free-free

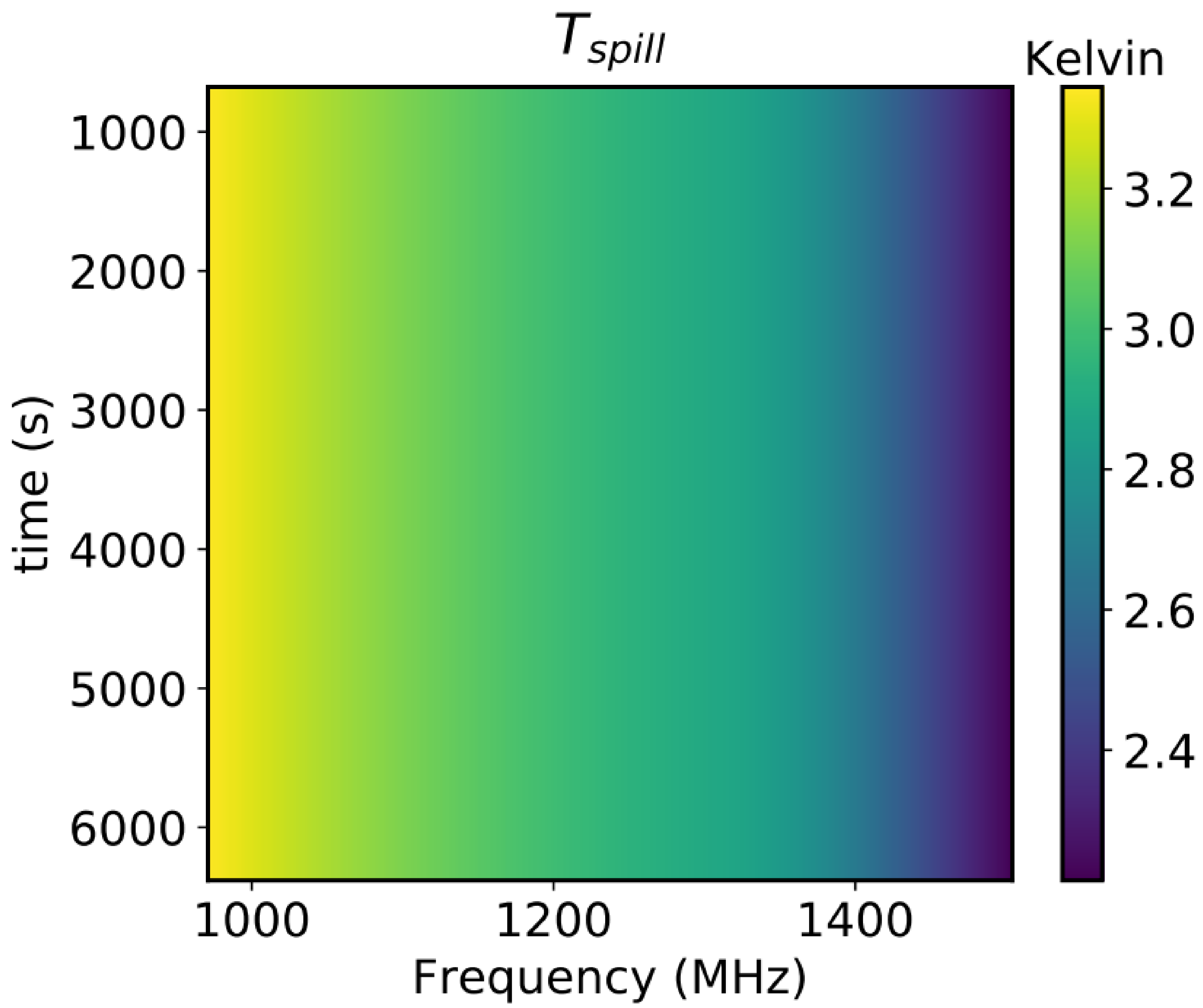
  (might be a background)
- Galactic foregrounds:
  - Synchrotron (I,Q,U)
  - Free-free
  - Dust
- Earth:
  - Atmosphere: clouds, H_2O, Ionosphere
  - RFI
- Instrument:
  - Spillover
  - Gain fluctuations
  - Beam fluctuations
  - Polarization leakage

D. Alonso

Challenges: ground “pickup”

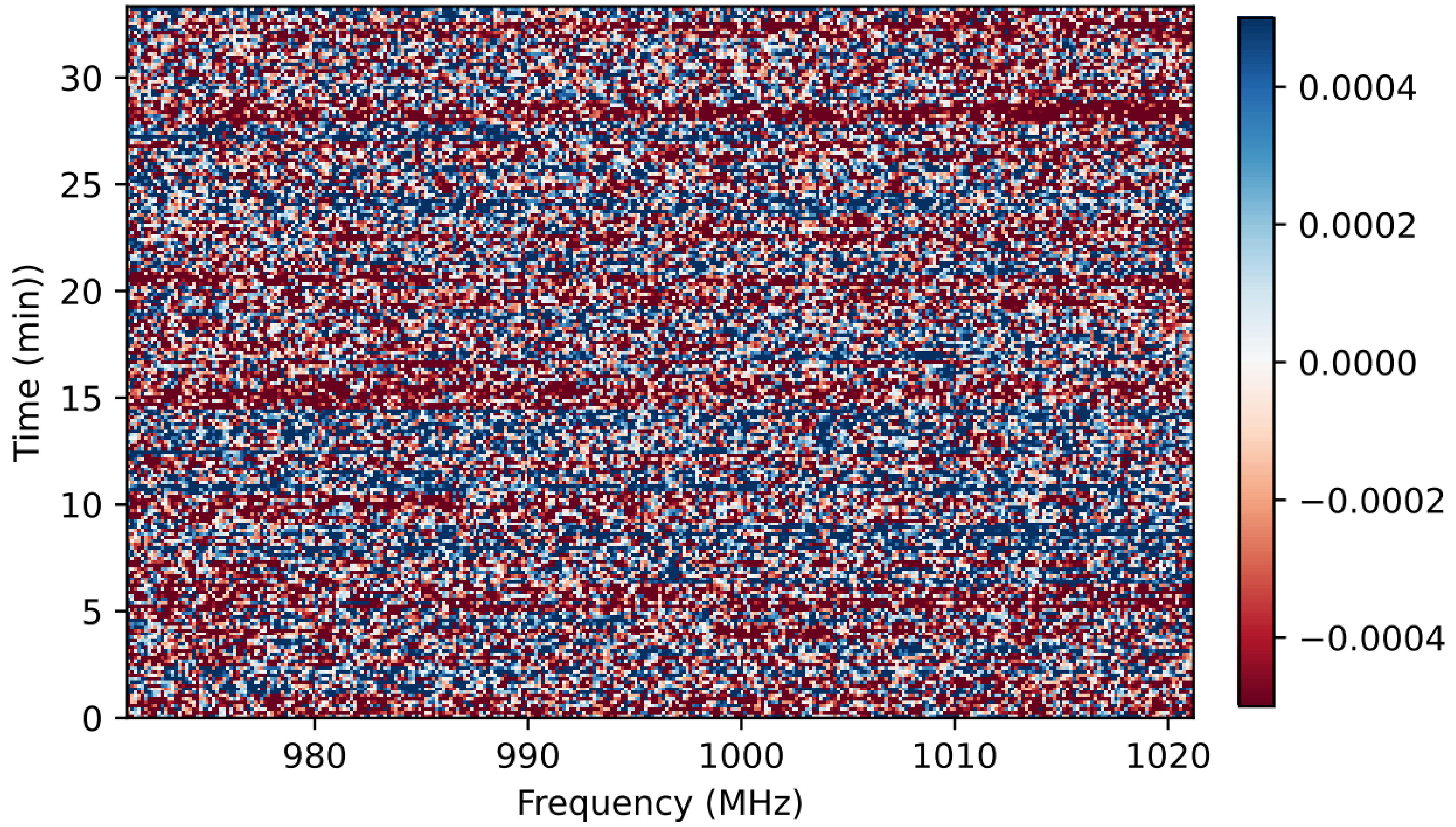
- Ground is “hot” -> observe at constant (high) elevation to avoid fluctuations

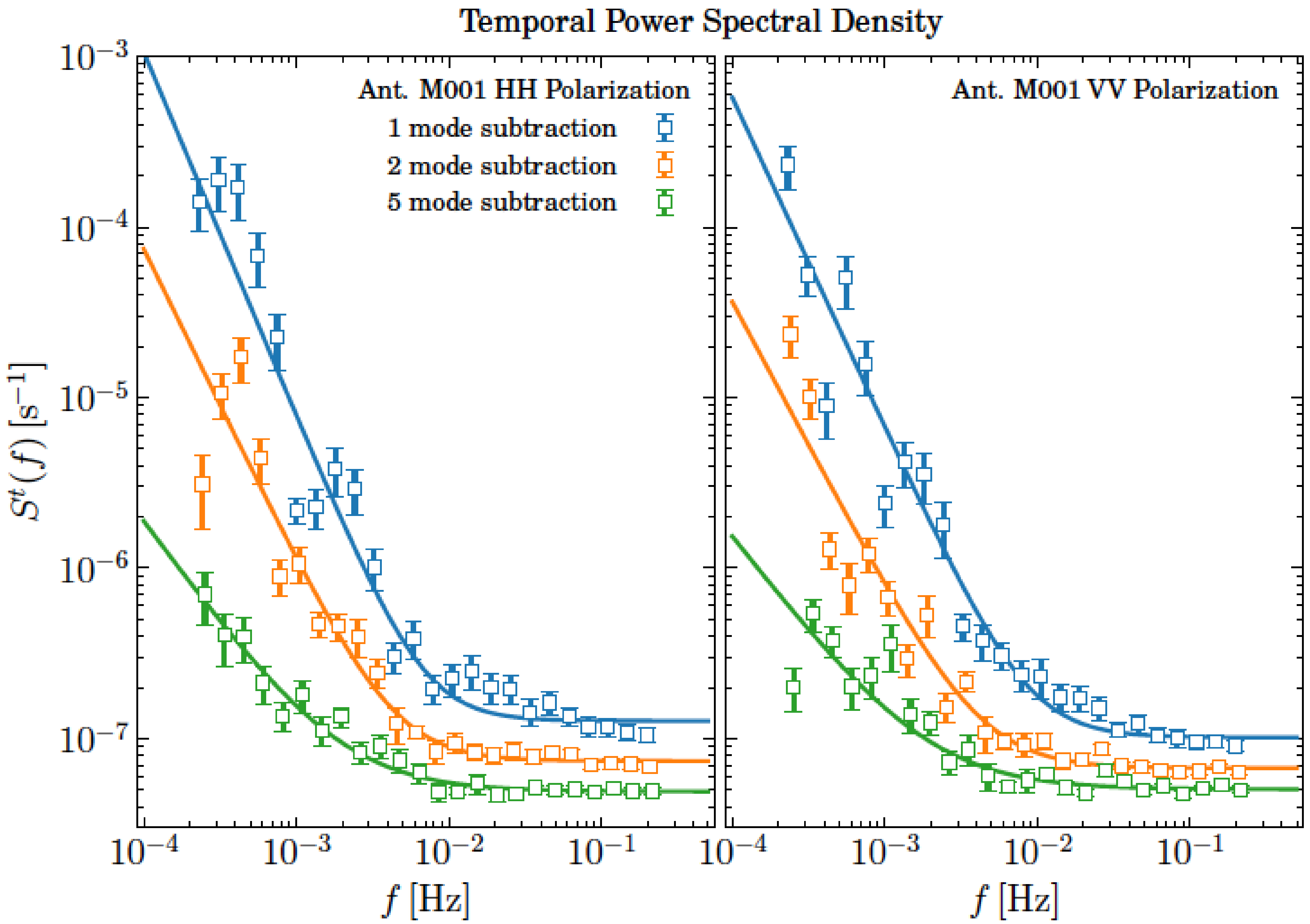




Challenges: correlated noise/gain fluctuations

- Gain fluctuates in time -> generates correlated noise in time even after calibration
- Need to scan the sky fast
- We can clean it as a foreground -> correlated scale of 100s of seconds

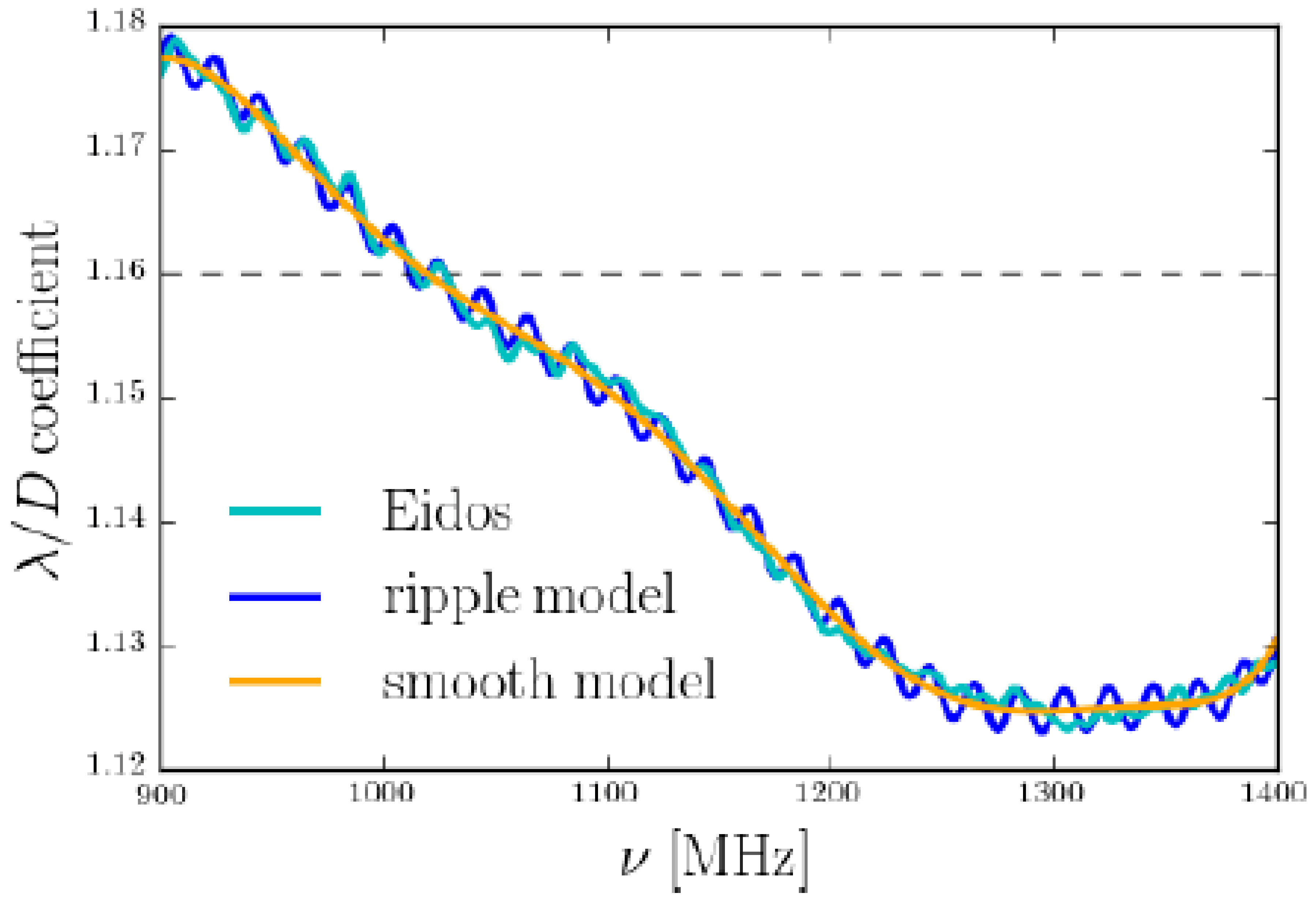


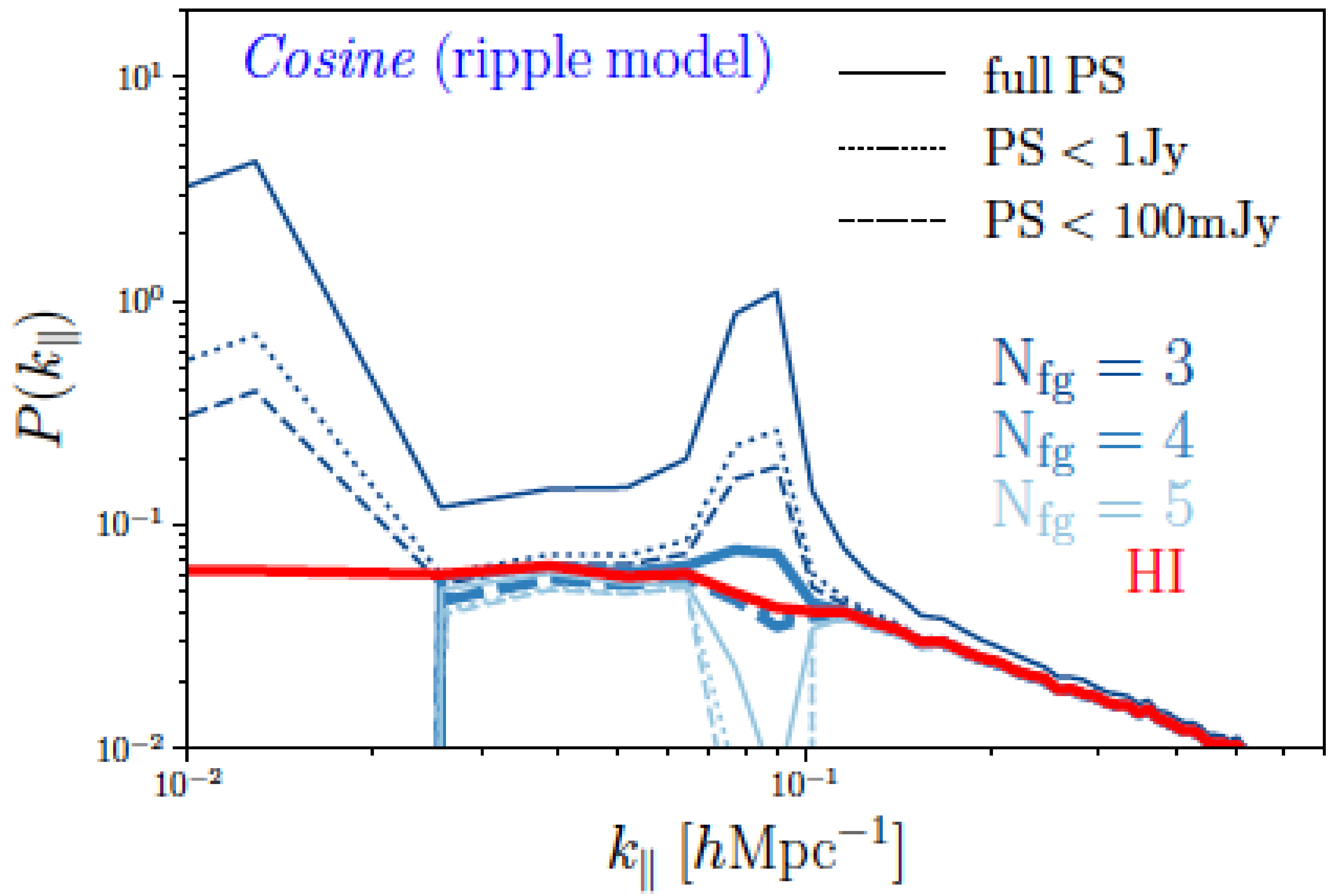


Li et al., MNRAS 2020, arXiv:2007.01767
M. Irfan et al., MNRAS 2024, arXiv:2302.02683

Measured MeerKAT 1/f noise

Challenges: Primary beam frequency ripple





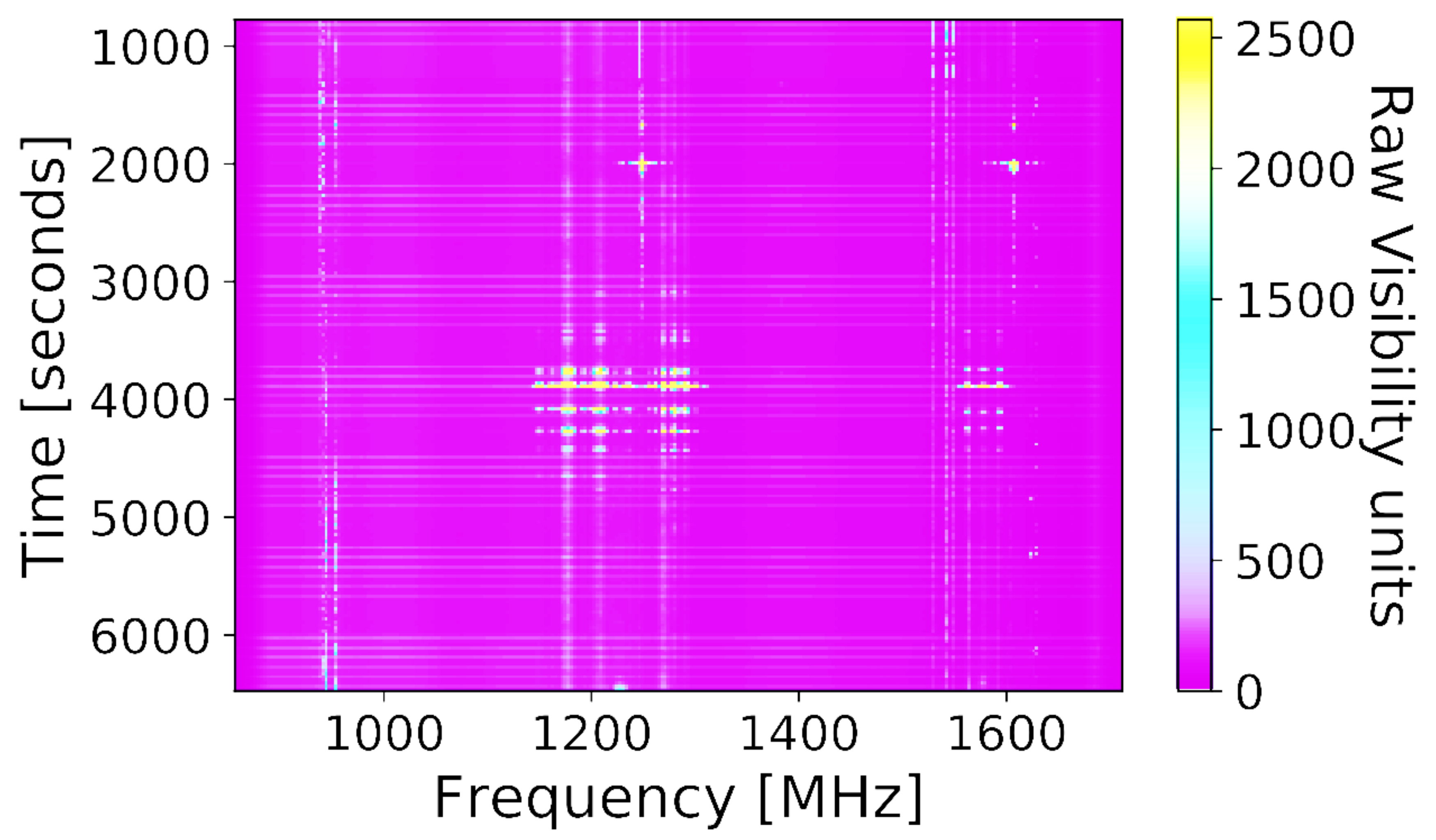
- MeerKAT beam size (FWHM) versus frequency

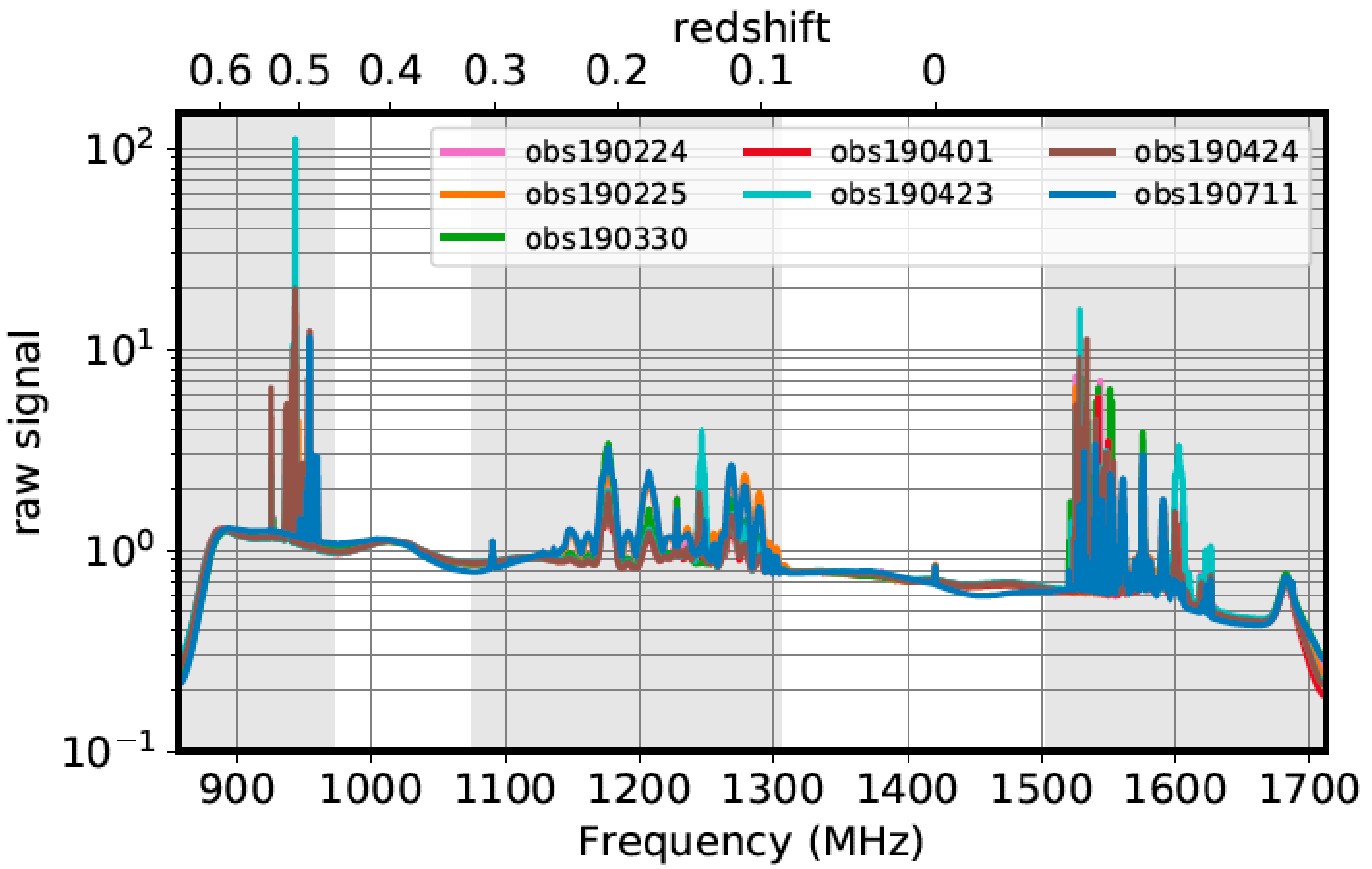
- Effect on foreground cleaning: line of sight power spectrum

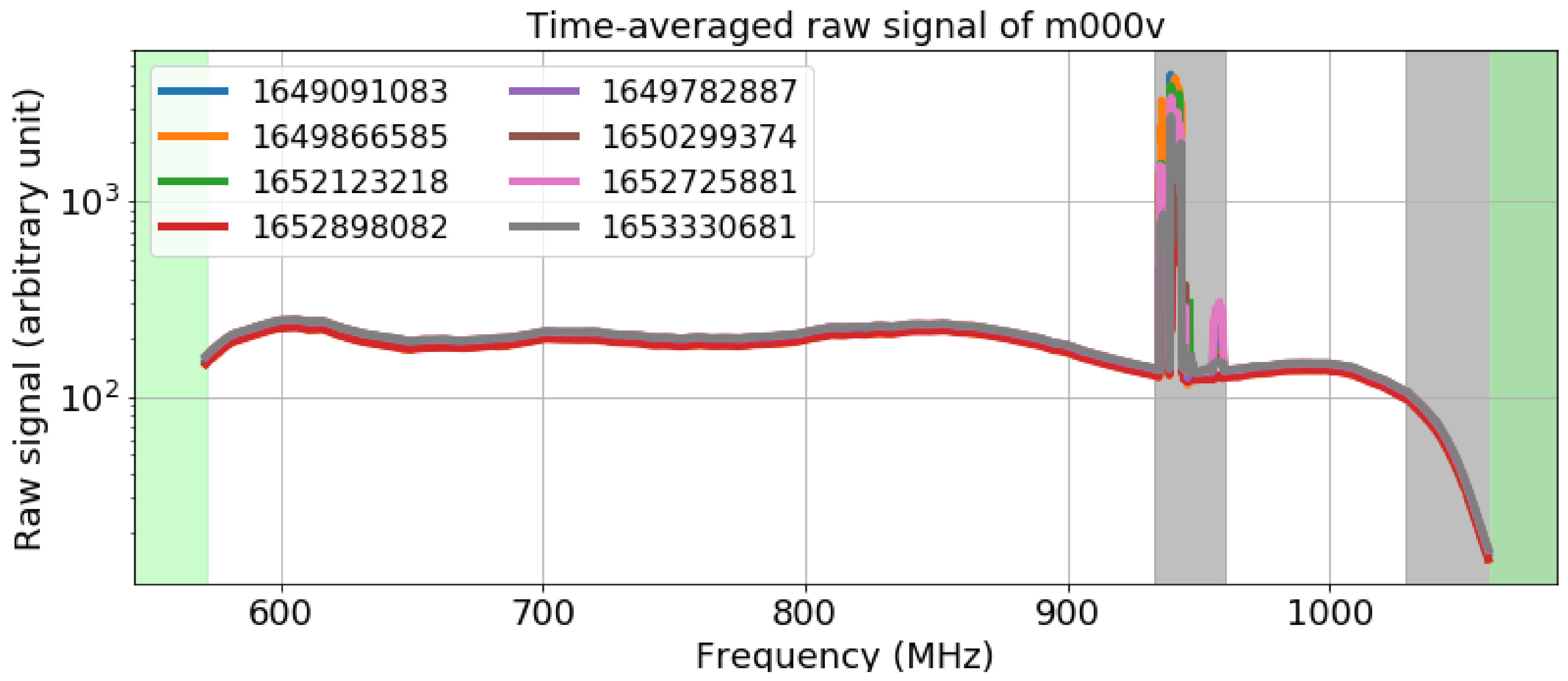
S. Matshawule, et al., arxiv:2011.10815

Challenges: radio frequency interference (RFI)

- Satellites, cell phone towers, radio stations, etc
- Needs to be flagged or smaller than the signal (hard to “clean”)
- Large data loss
- Non-linearities in the instrument





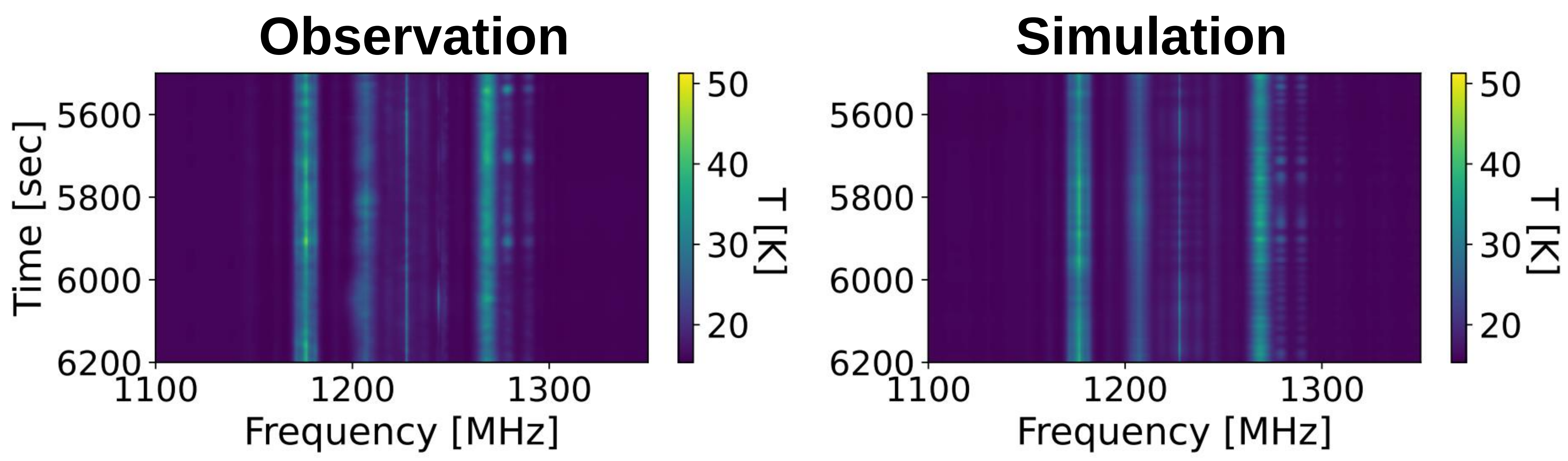


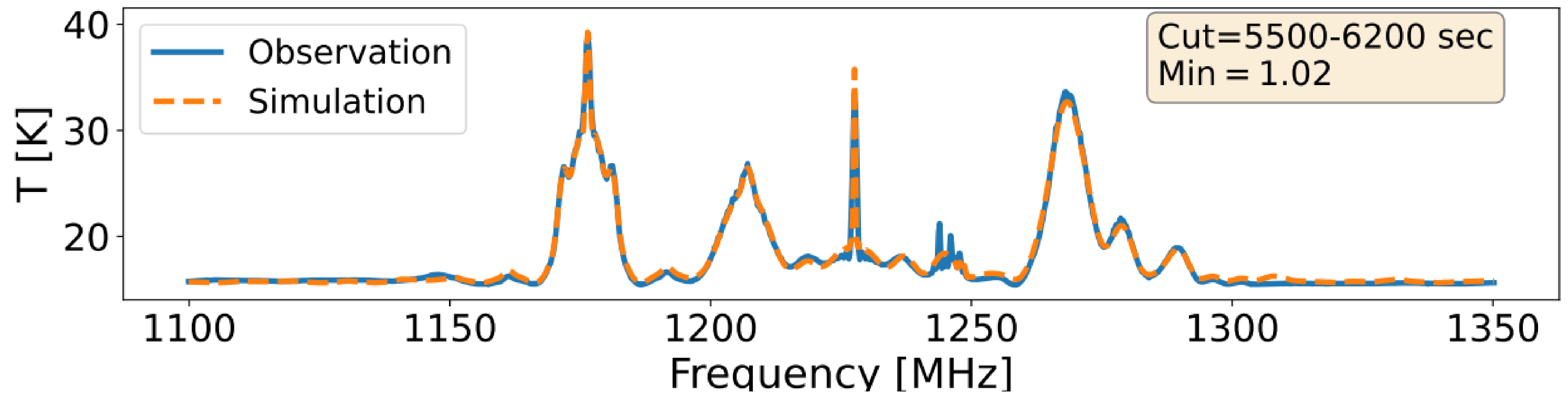
RFI: satellites

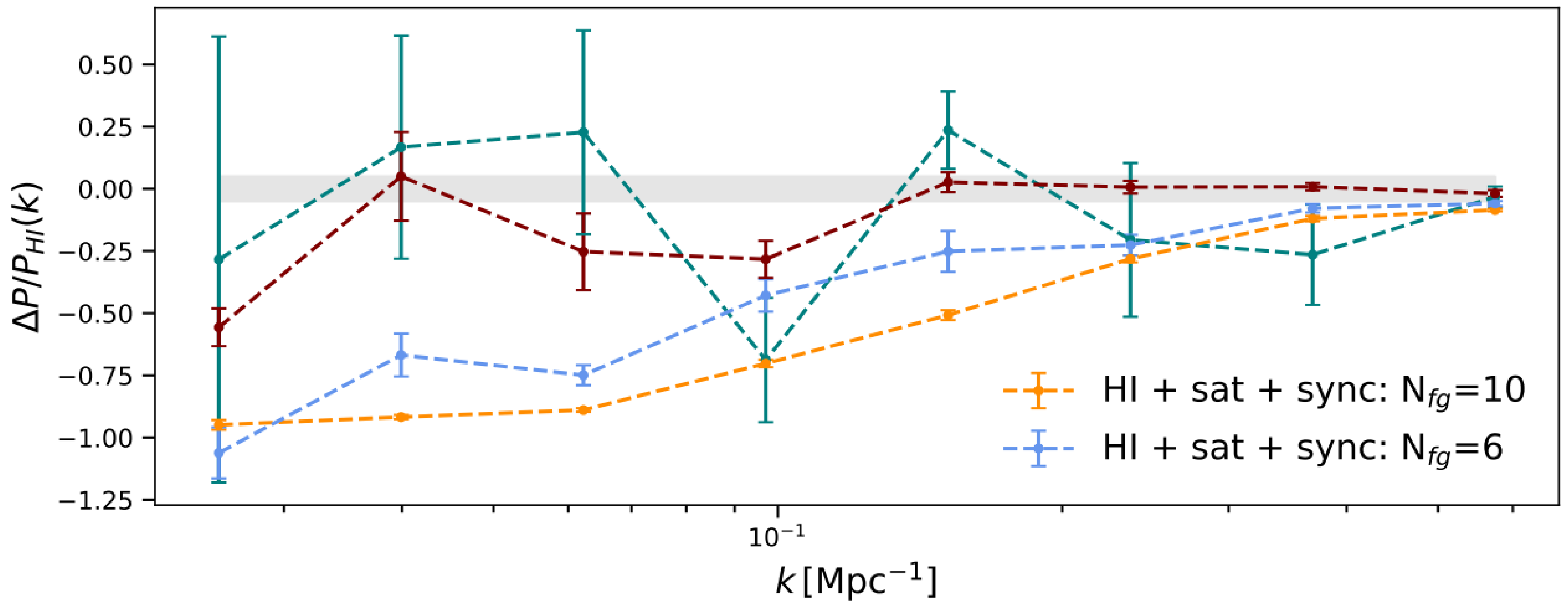
- Developing simulations to test the impact of satellites and ways to remove them

#	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-Dl	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

~ 120 satellites and 21 different signals

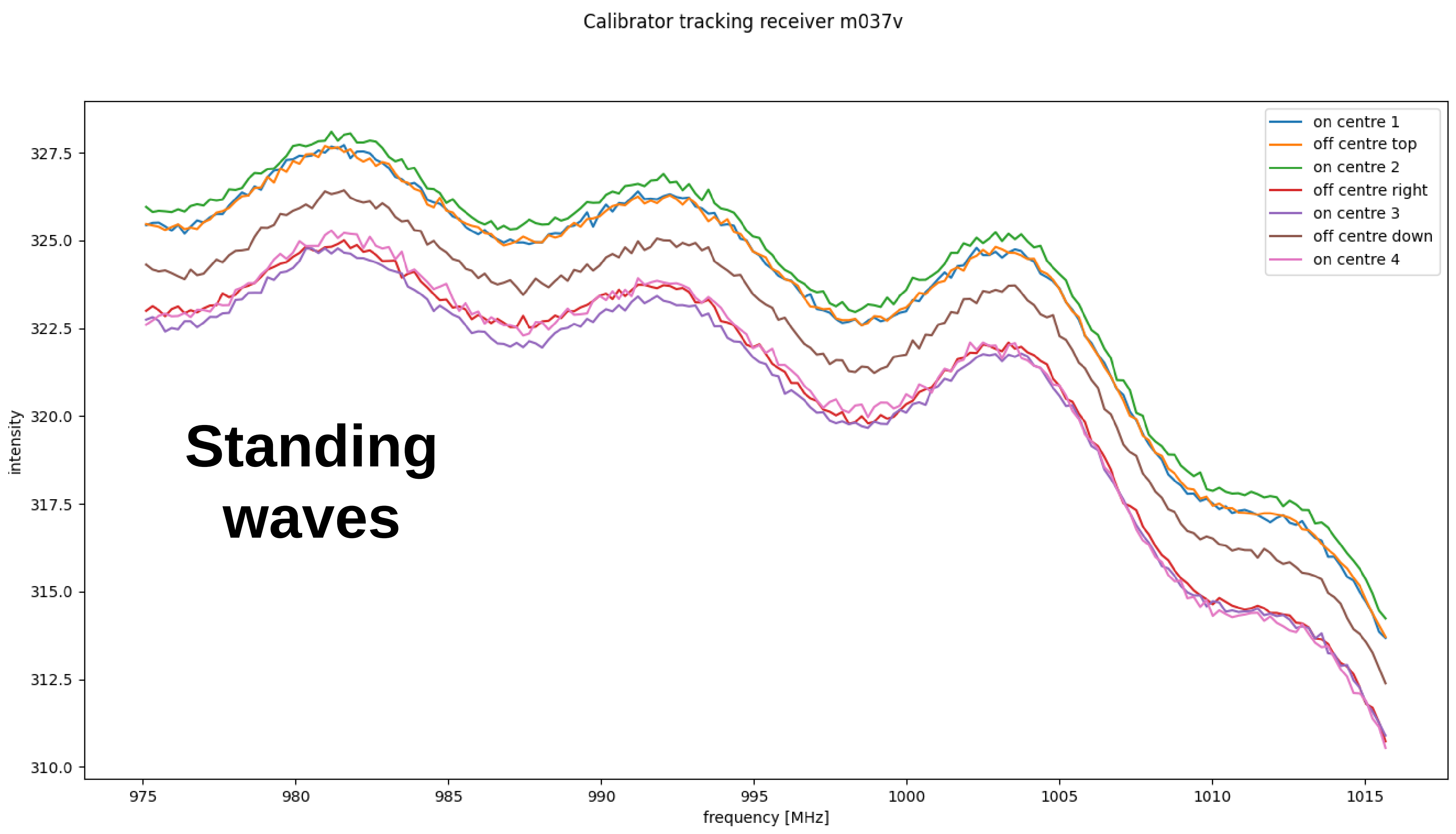






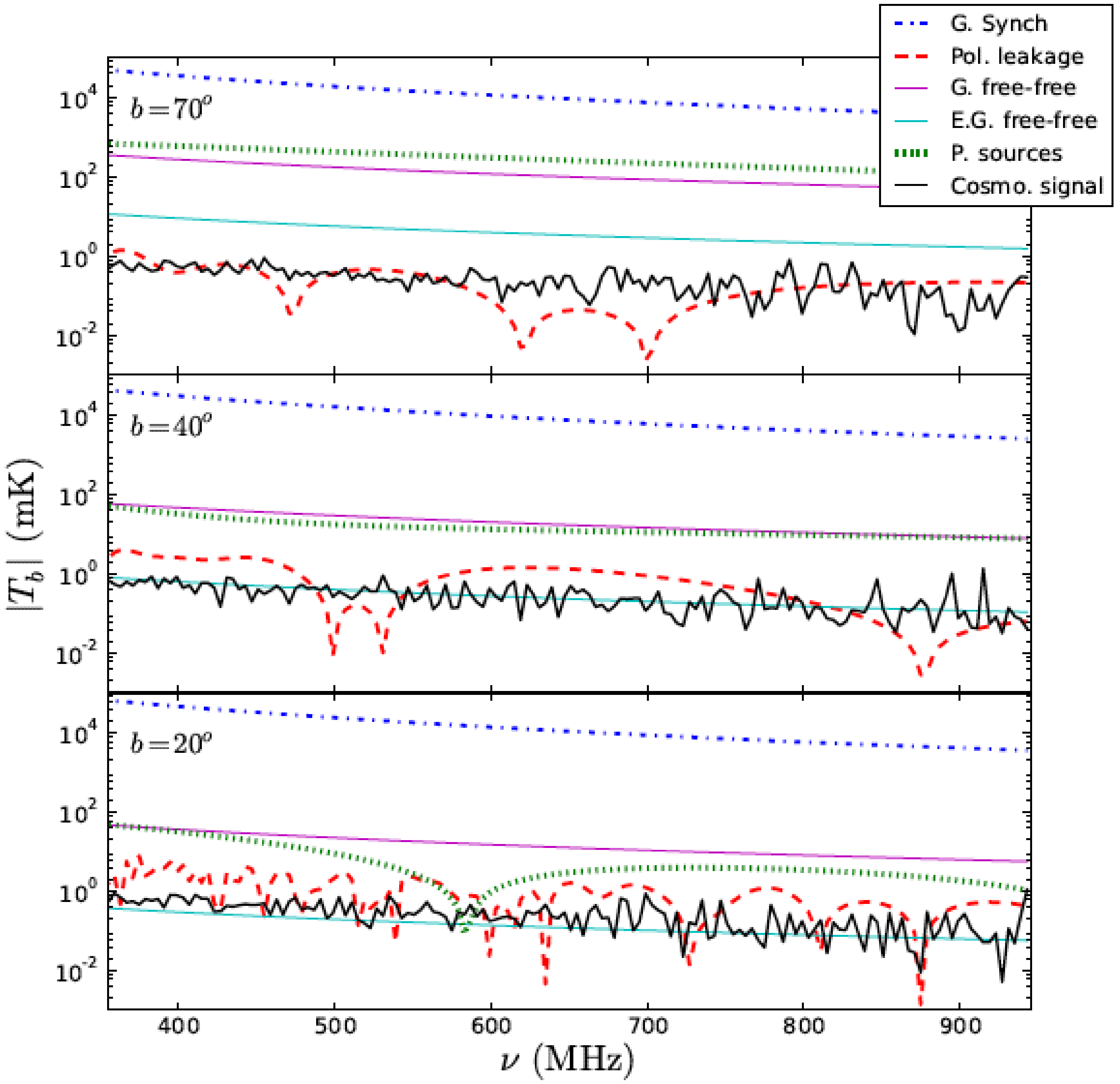
Brandon Engelbrecht, et al. to be submitted

More Contamination…



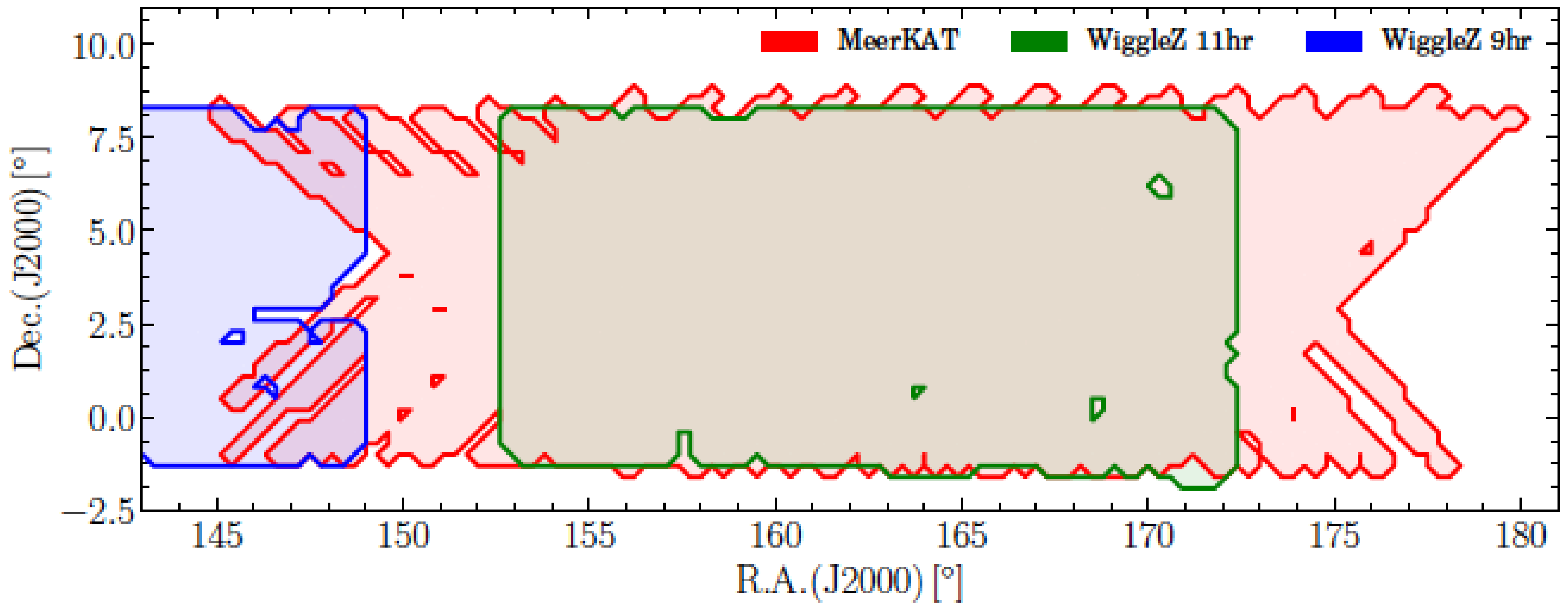
Standing waves

Looking for fluctuations ~ $1/10^5$

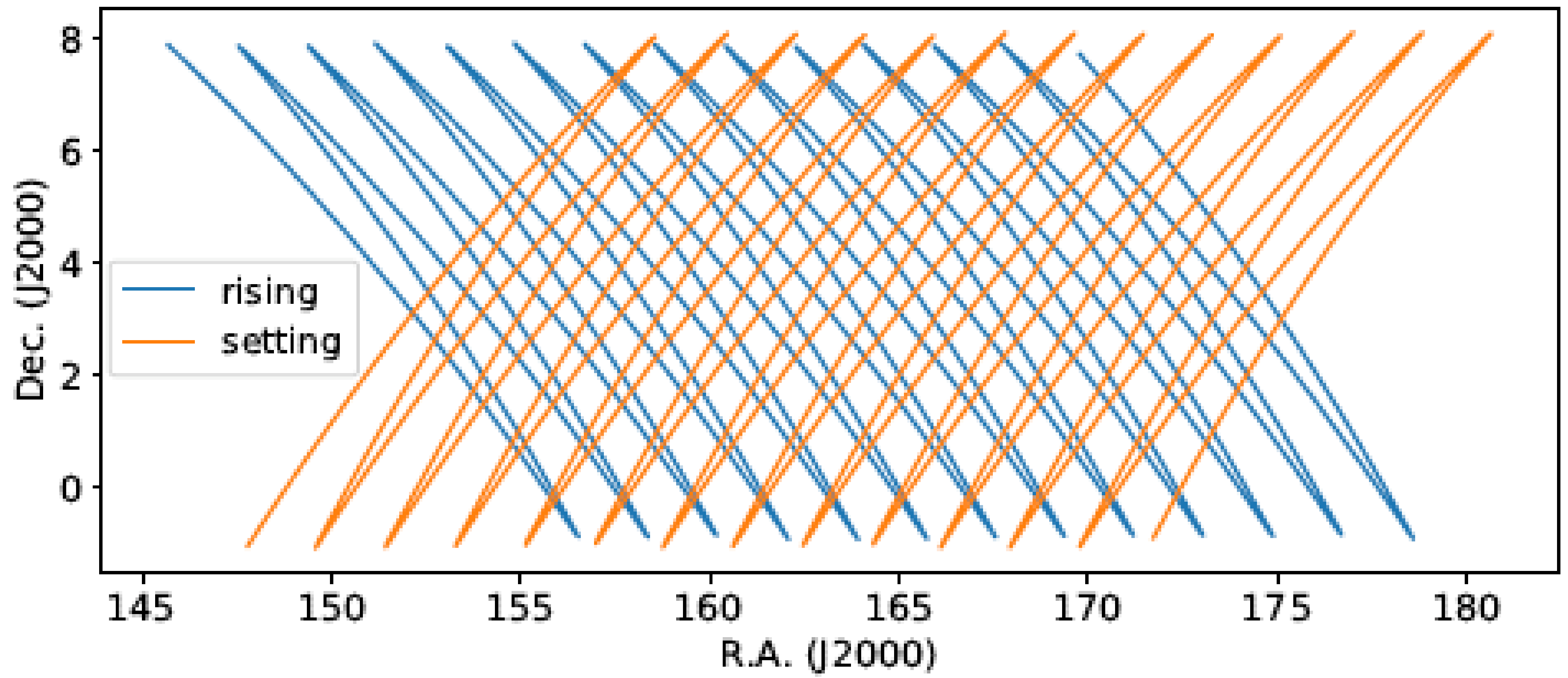


Contrary to the HI cosmological signal, foregrounds are smooth in frequency
Using PCA to clean them

First results with a MeerKAT single dish pilot survey
(Wang et al., MNRAS (2021), arXiv:2011.13789)



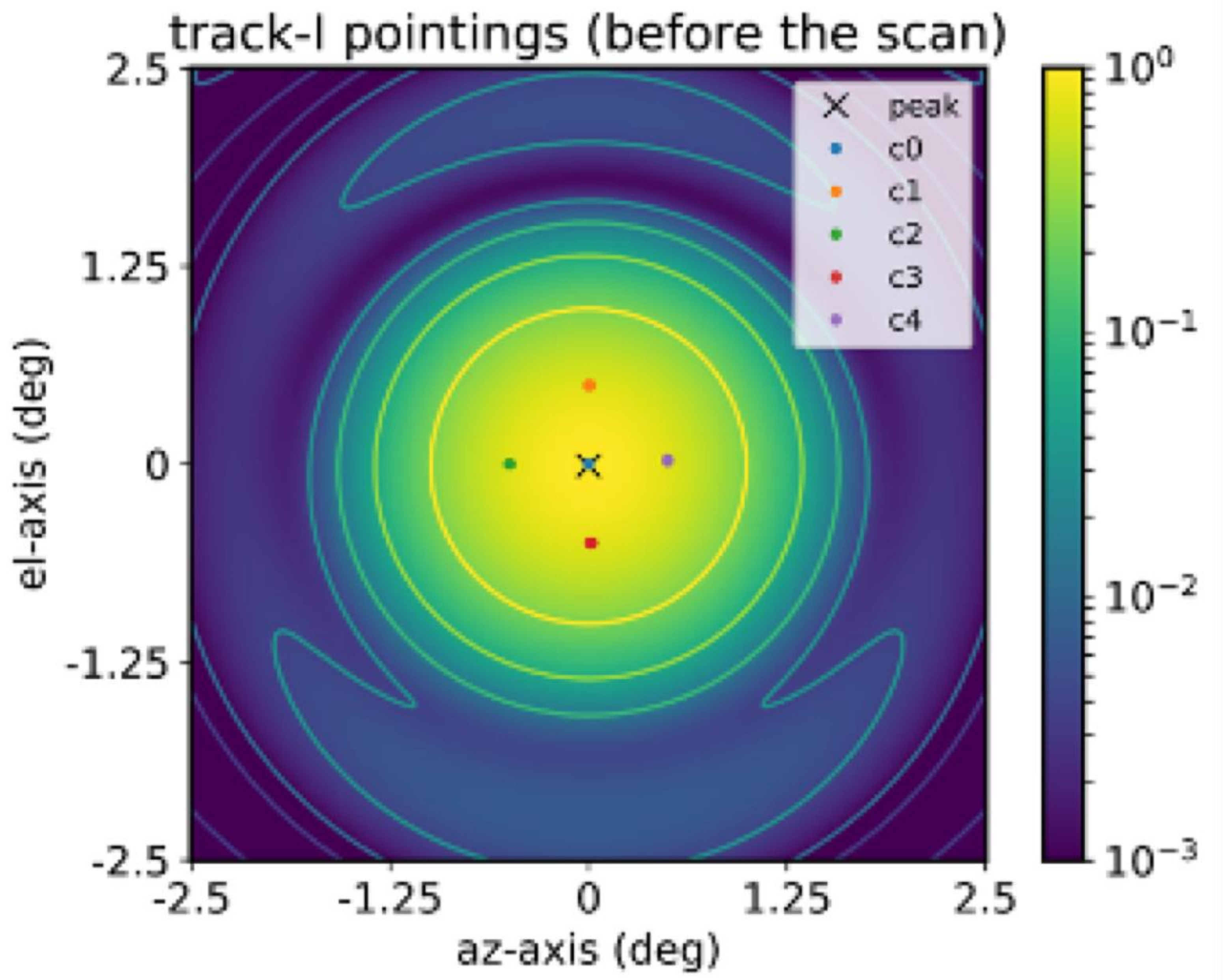
Footprint

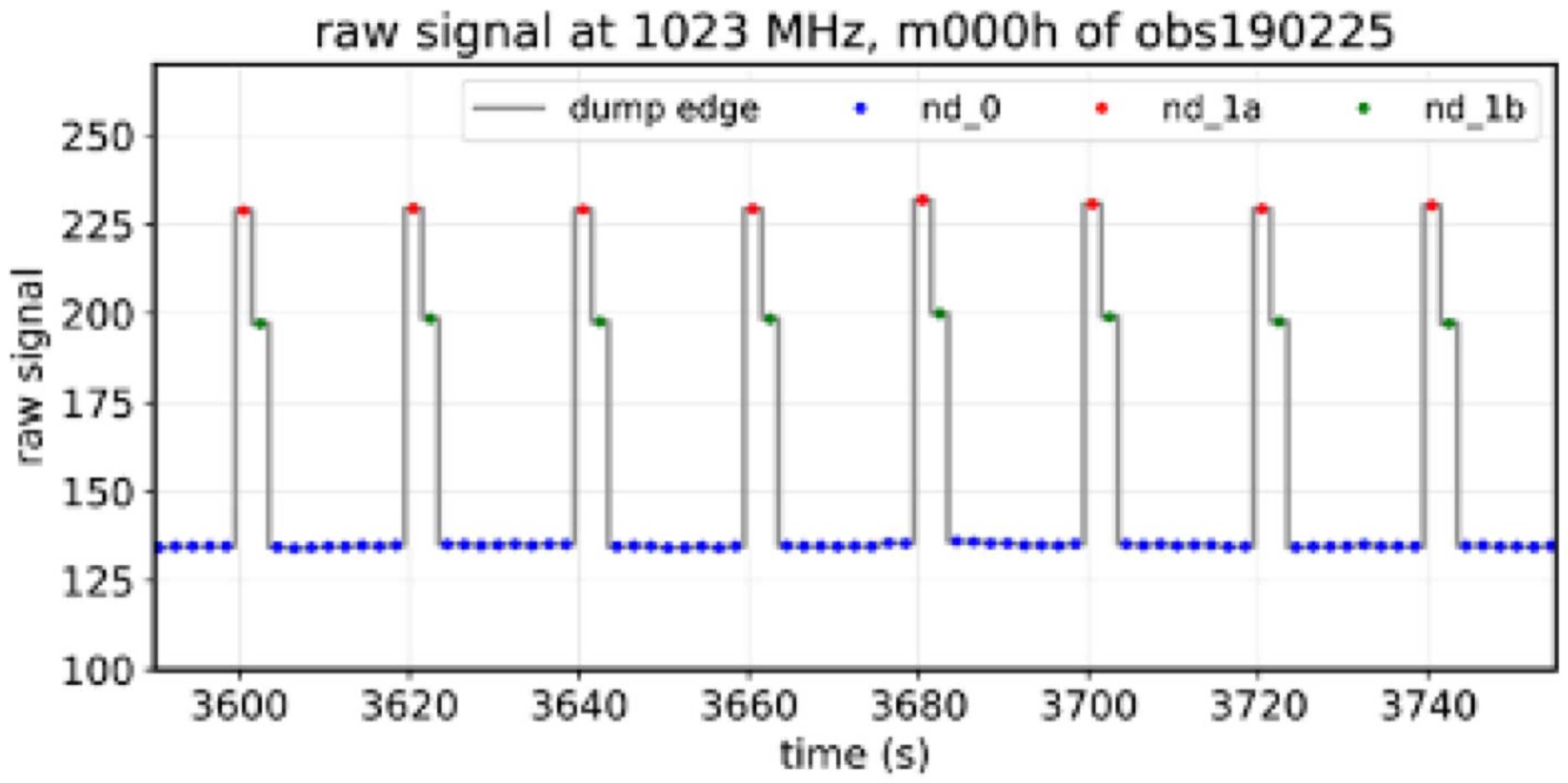


Scanning pattern

- ~ 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

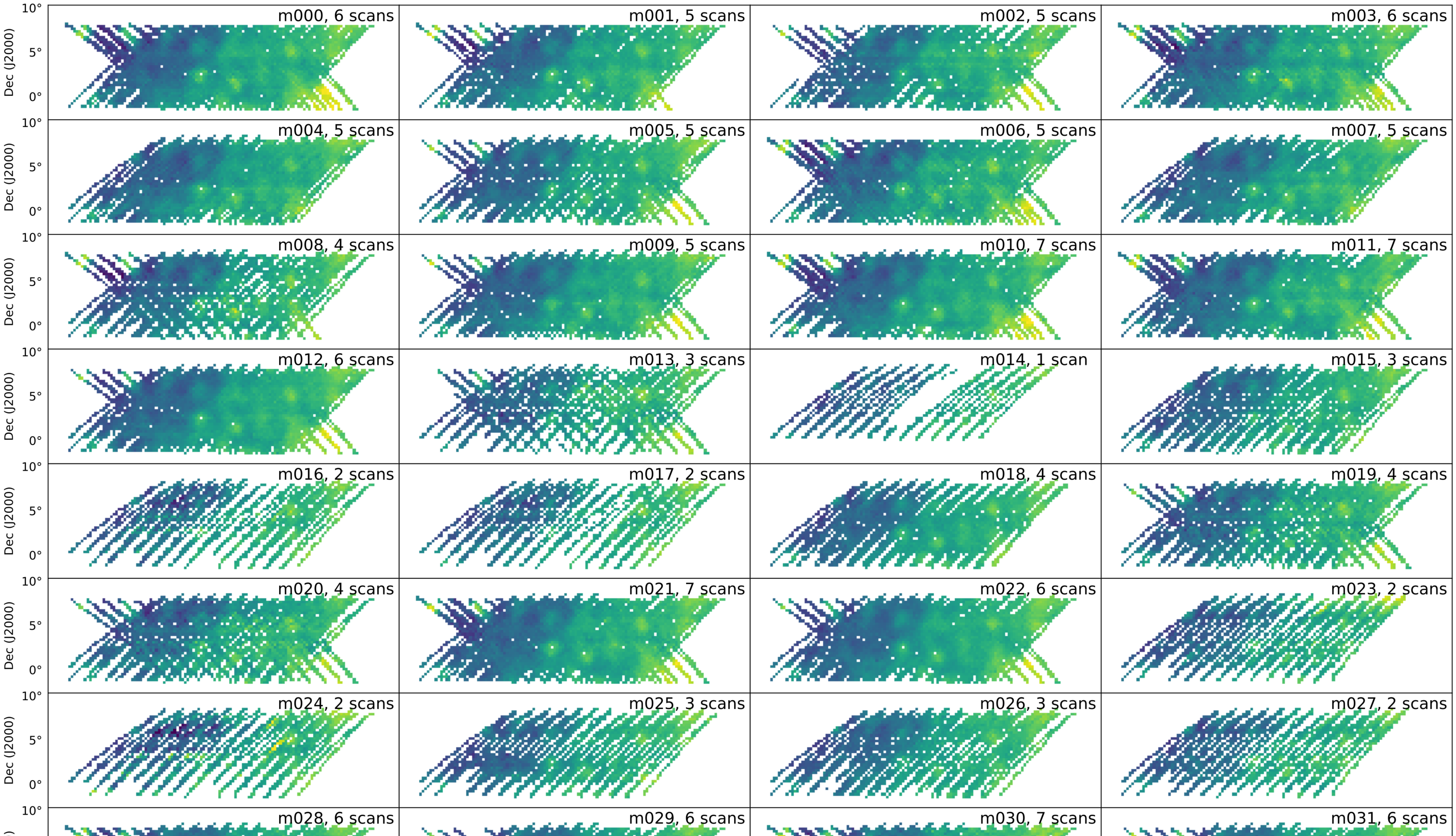
Calibration





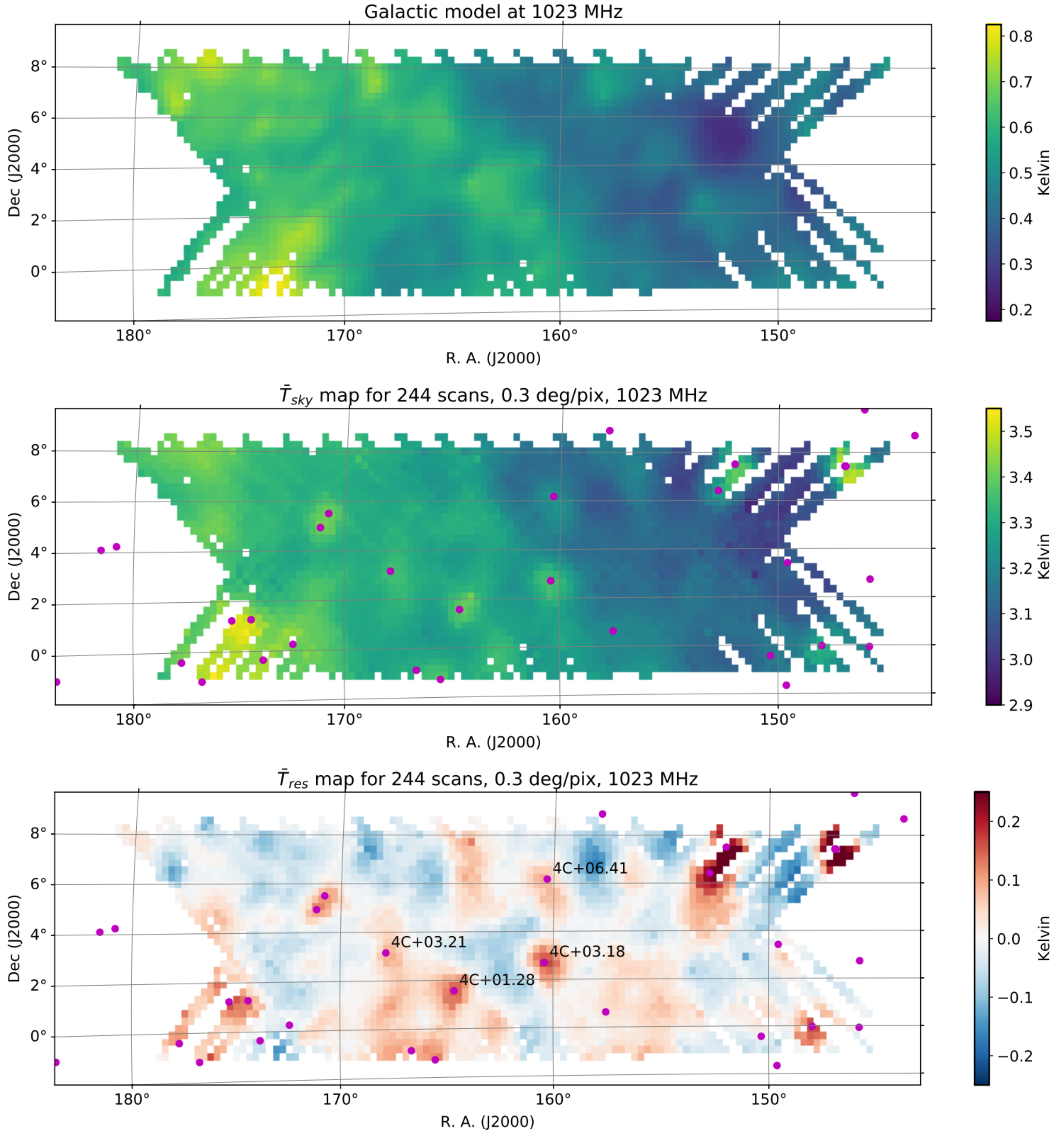
- Observe a calibrator before and after each scan (left)
- Noise diode injection every 20 sec during scan (right)
- Self-calibration during scan

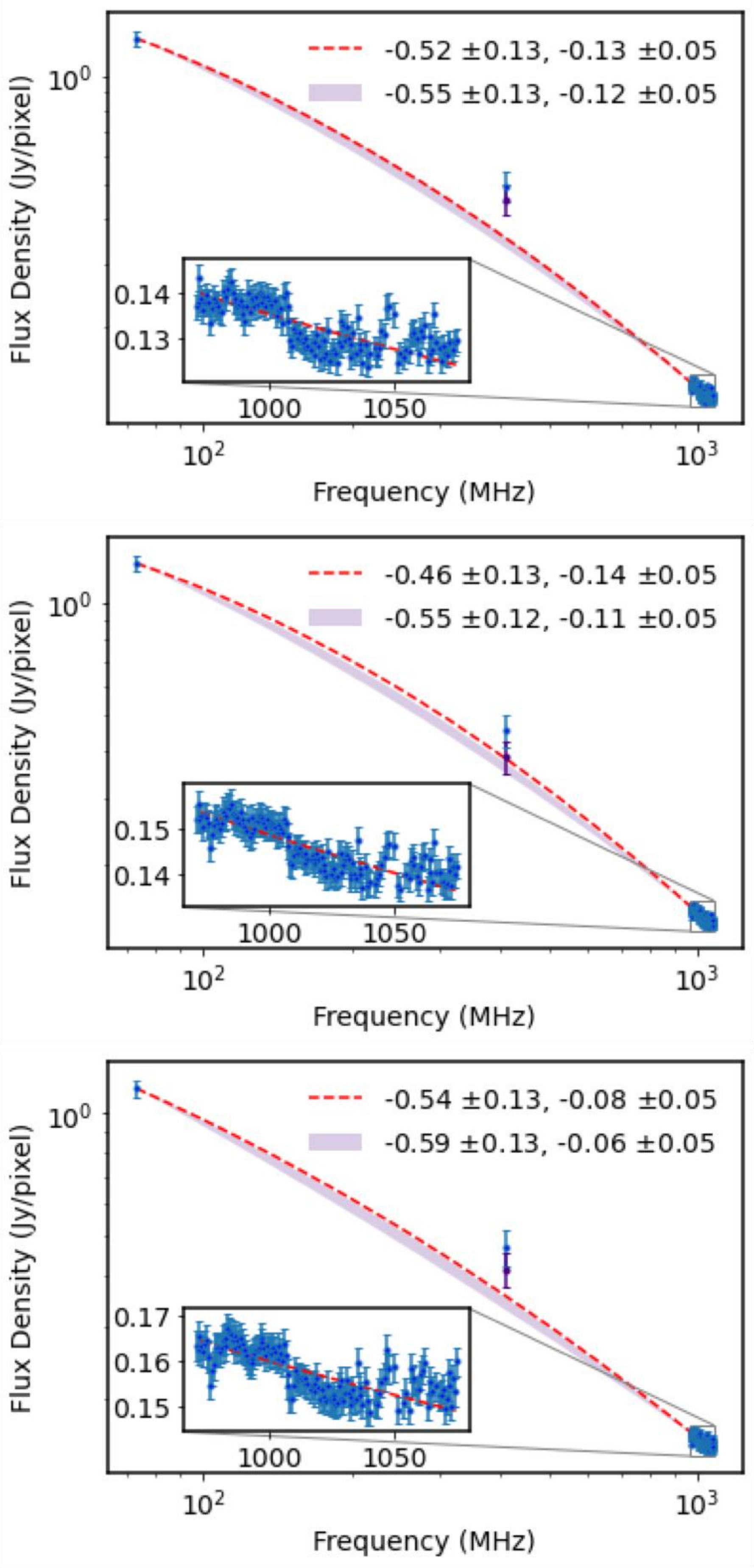
per-dish $\bar{T}_{sky}$ maps at 1023 MHz



Combined maps

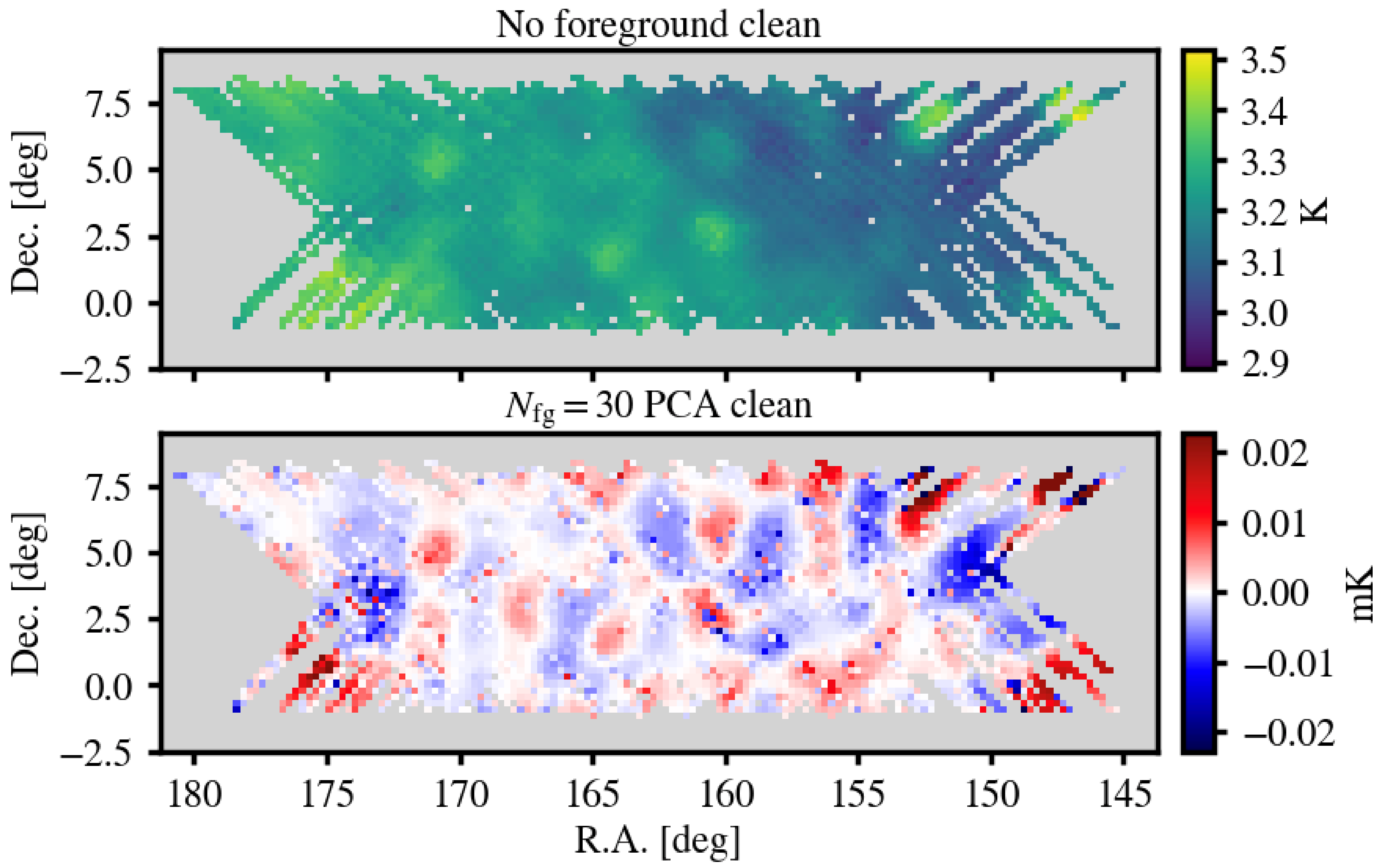
- Final map follows the galactic synchrotron emission (after removing some contaminants)
- Residuals show some strong point sources (galaxies)
- Can measure the diffuse Galactic synchrotron spectral index and curvature with HASLAM and LWA



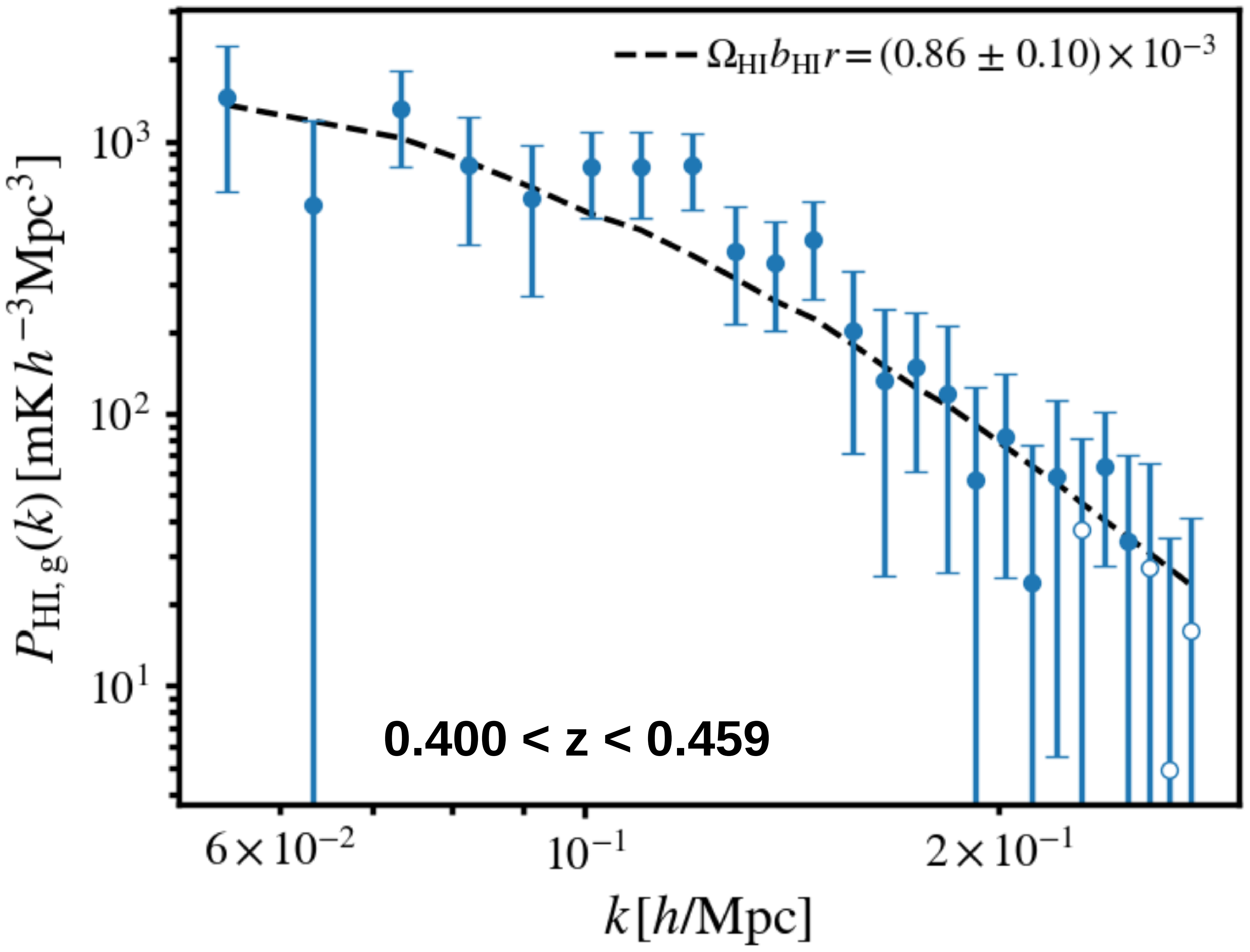


Irfan et al., MNRAS (2021), arXiv:2111.08517

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

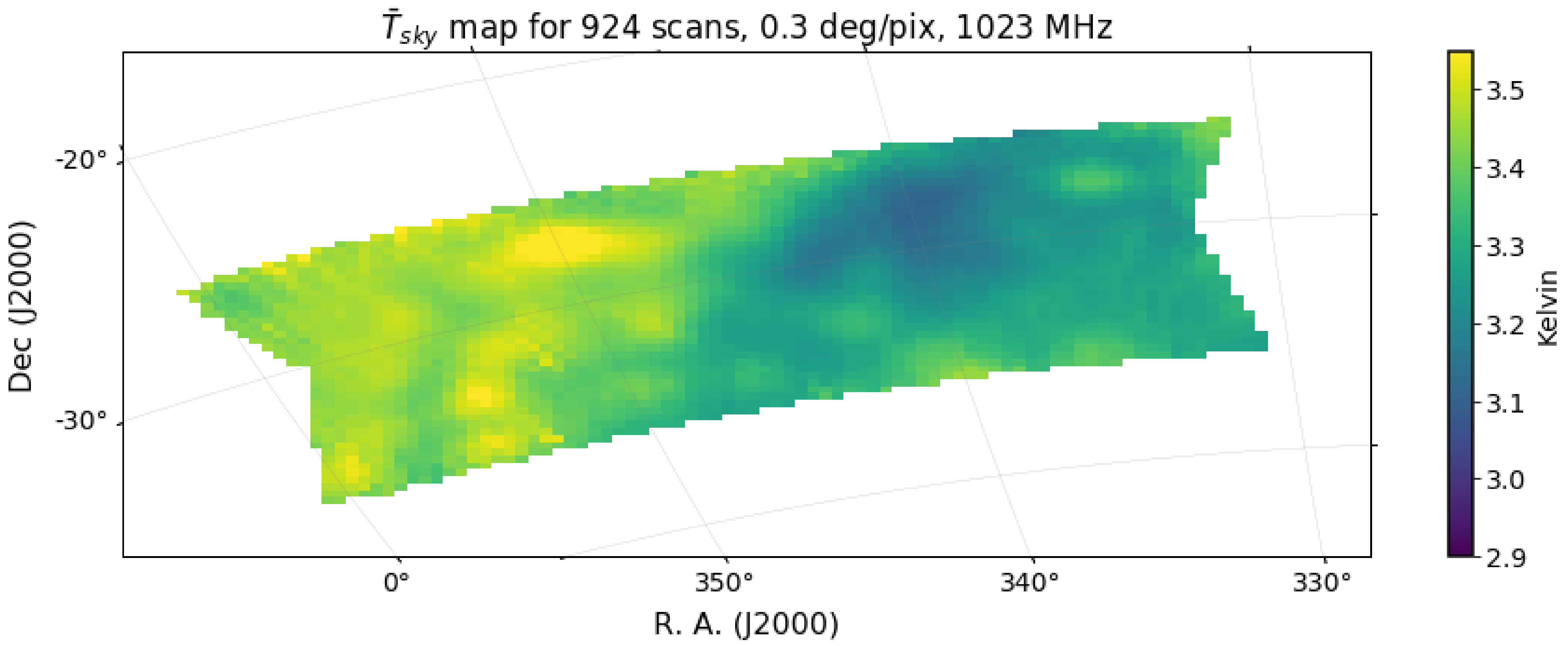


Need transfer functions to correct for signal loss



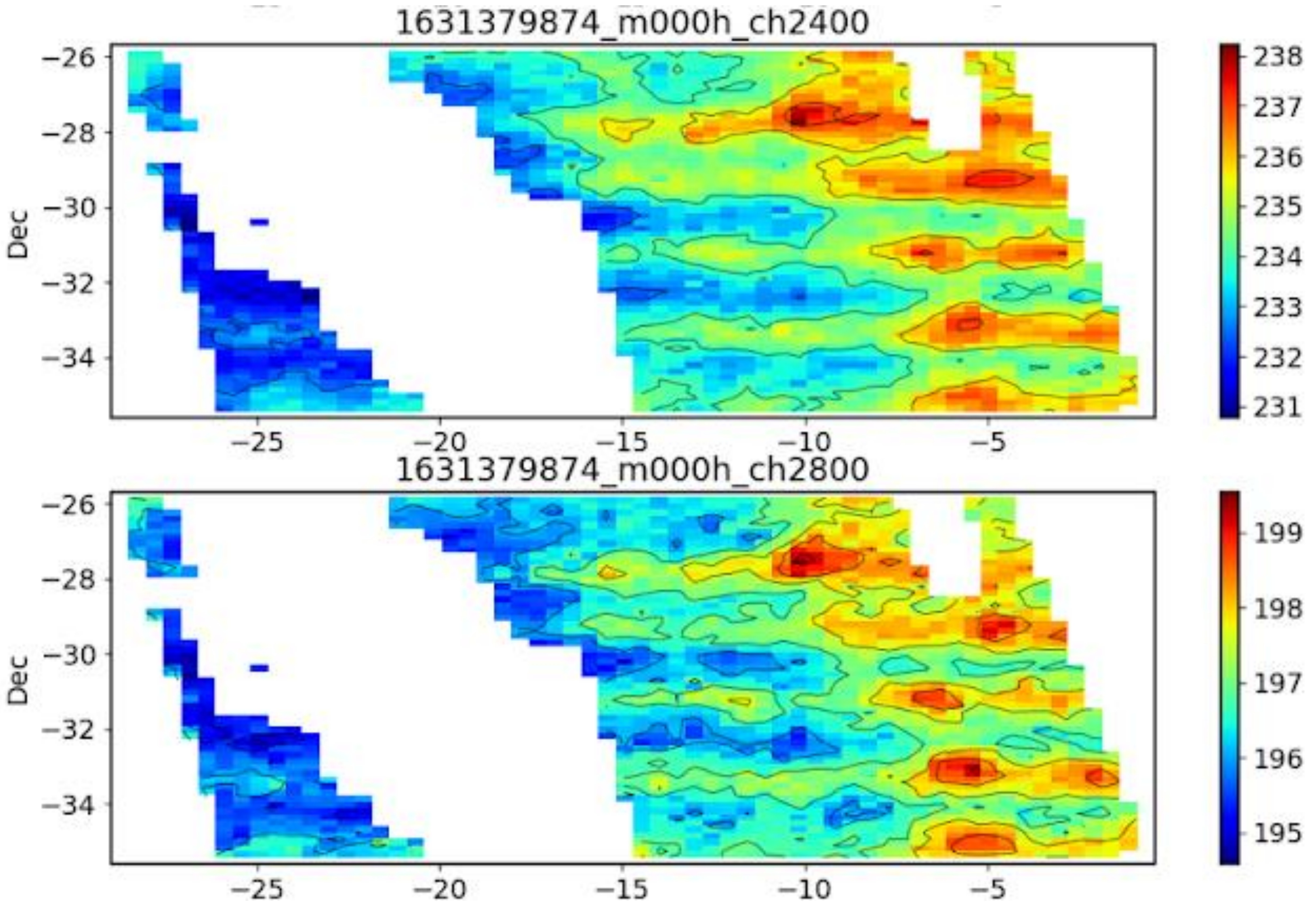
Cunnington, Li, et al., MNRAS (2023), arXiv:2206.01579

Ongoing L-band analysis



J. Wang et al.

~ 70 hours
~ 300 deg^2
Overlapping with
KIDS and GAMA23

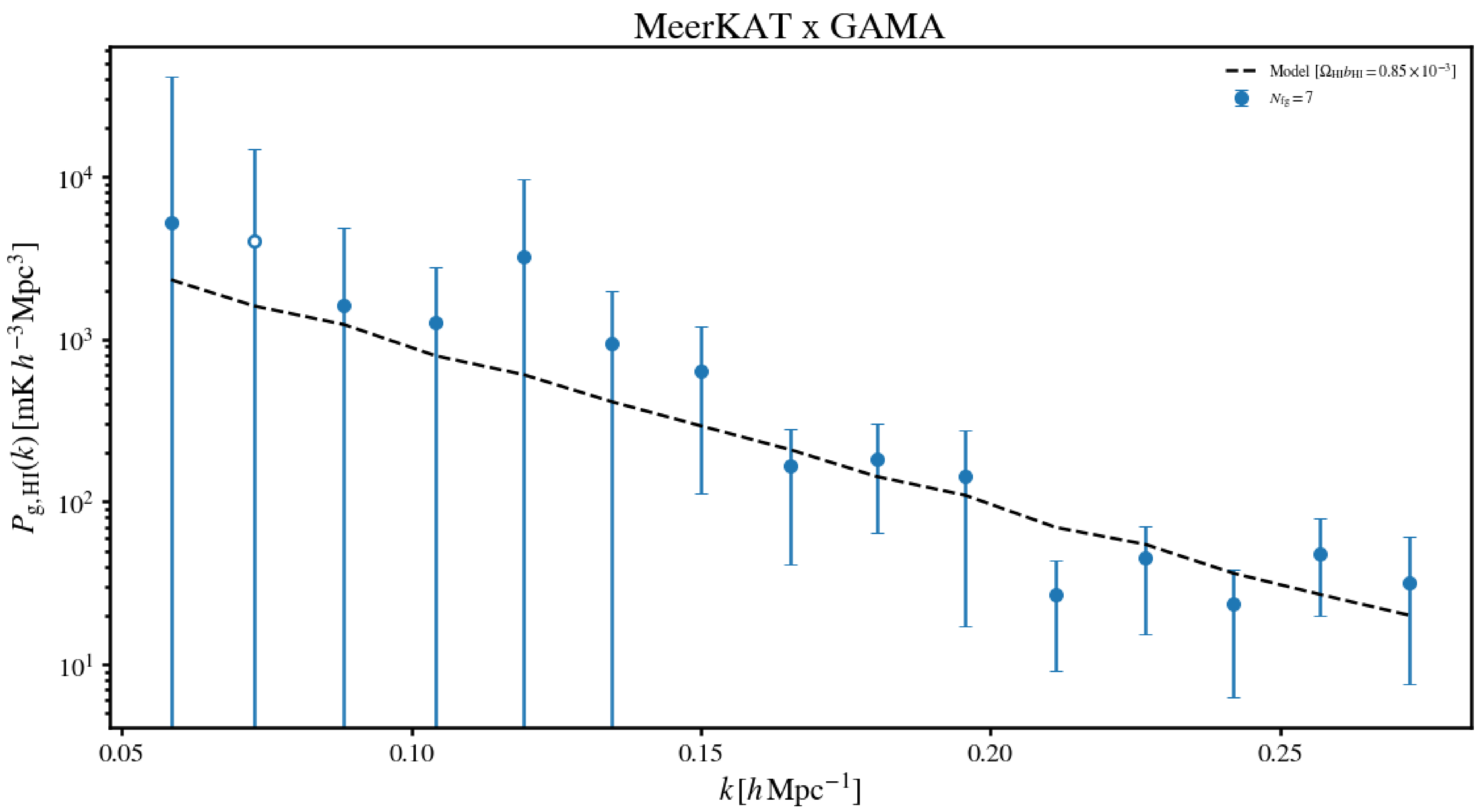


A. Wild, K. Grainge, et al.

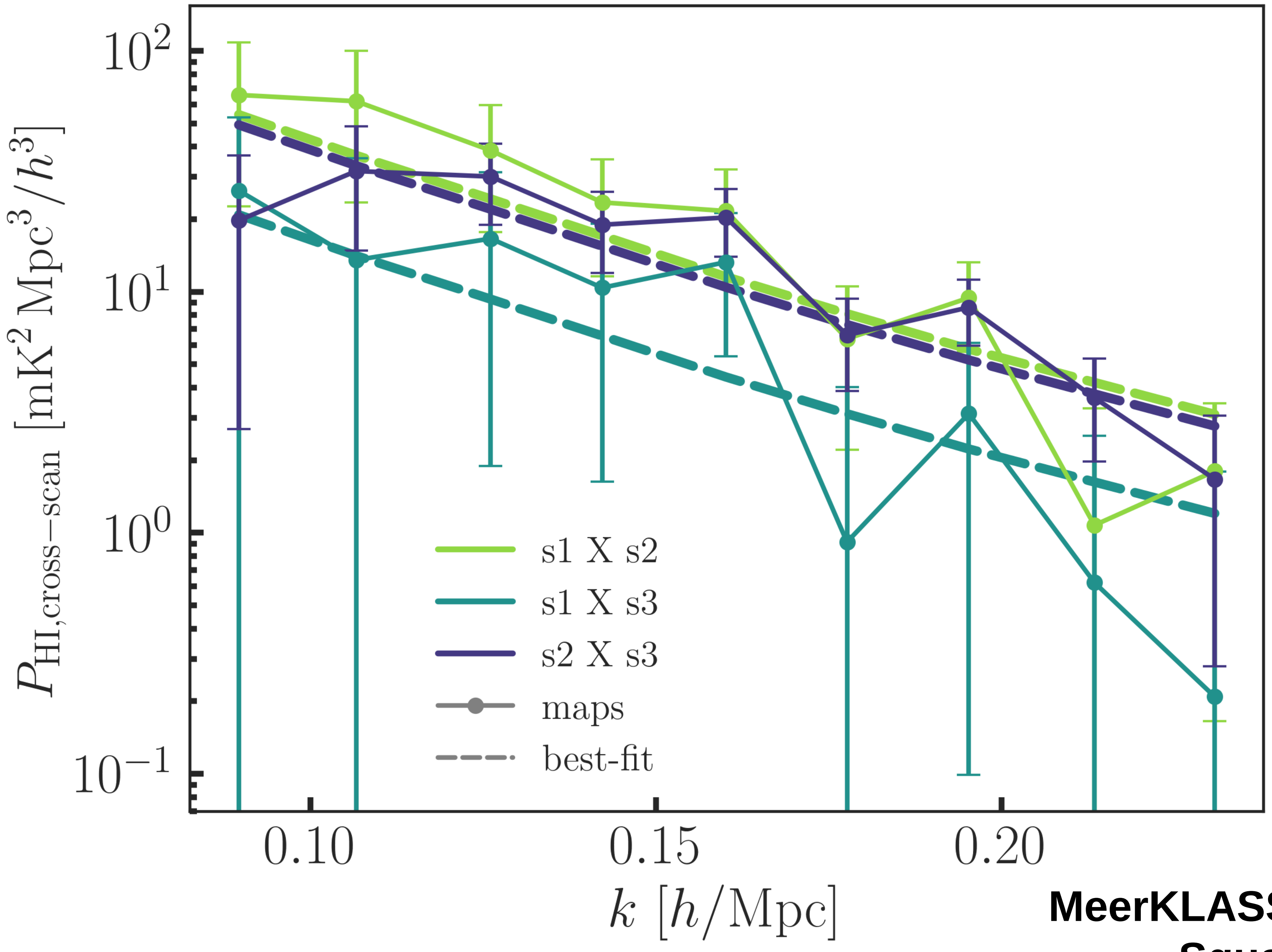
Some data contaminated by stripes
Traced back to leakage from the Vanwyksvlei GSM tower

Ongoing L-band analysis – new Cosmology results

Preliminary



MeerKLASS Collab (S. Cunnington)



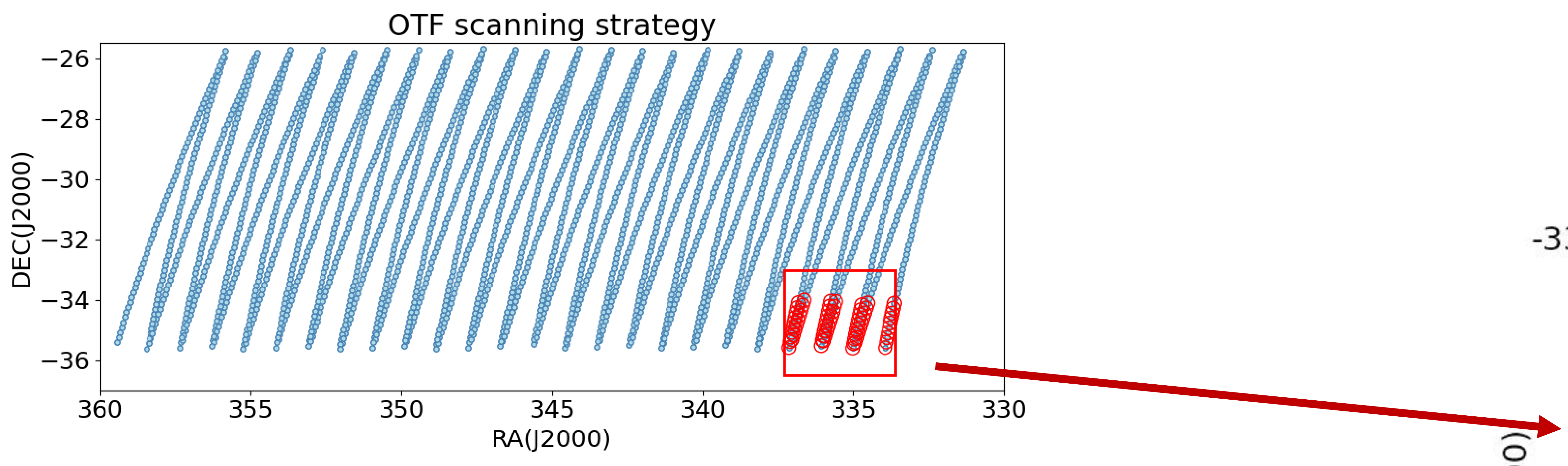
MeerKLASS Collab (M. Squarotti)

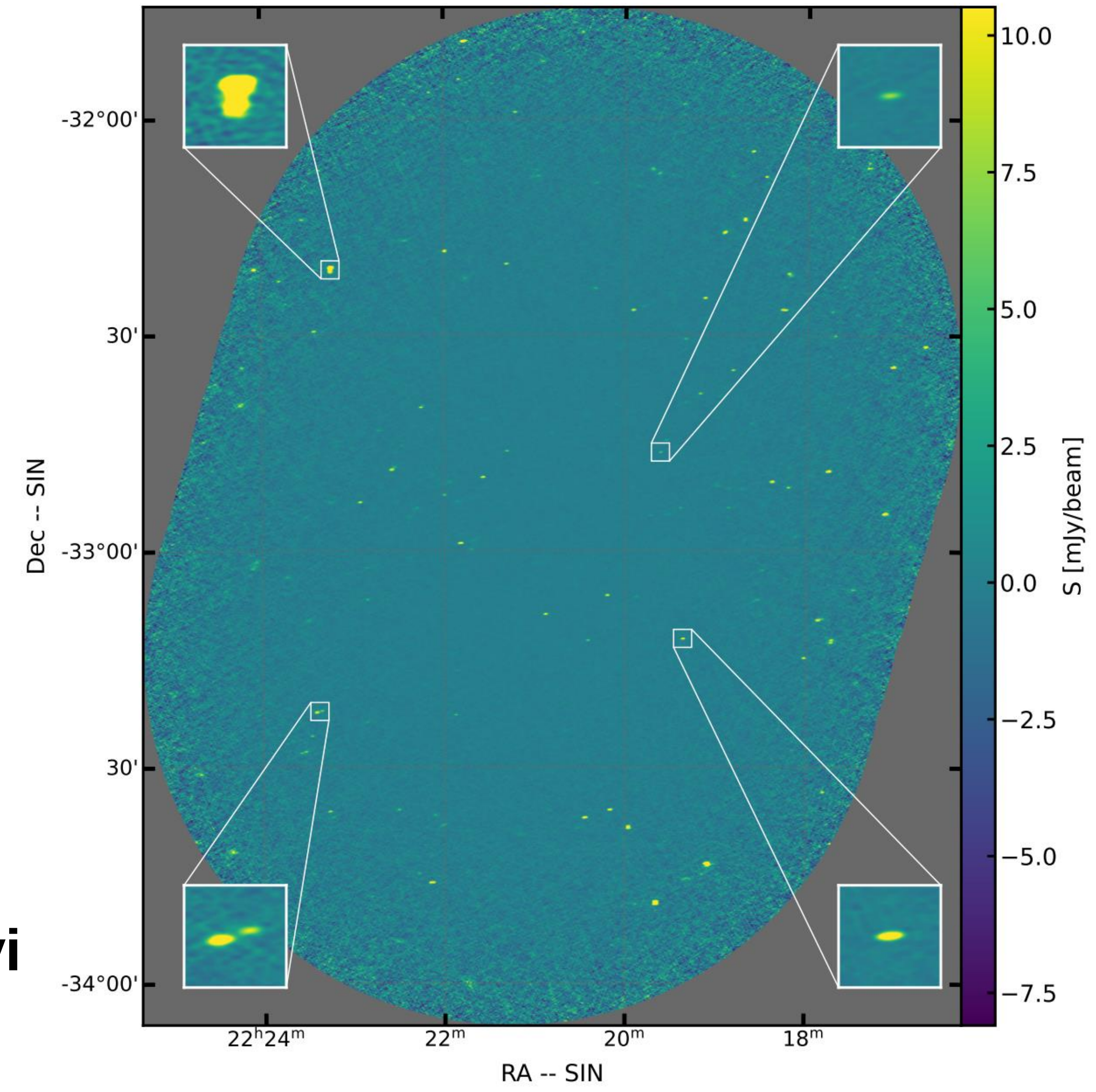
Cross-correlation with the GAMA23 spectroscopic galaxy field
Smaller than WiggleZ but consistent

Measurement of the auto-power spectrum
Again, consistent with cross-correlations

Continuum images with the same data

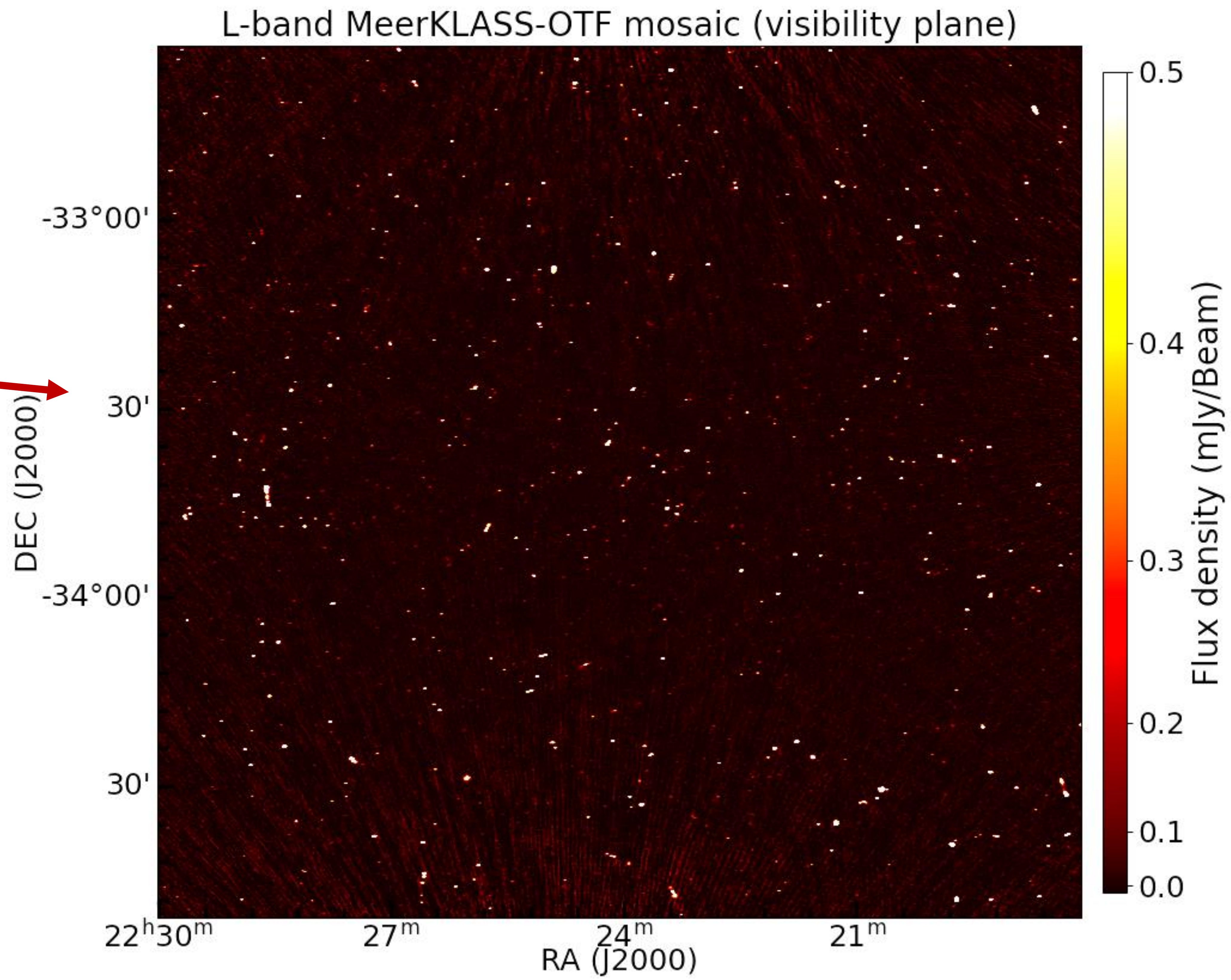
- On the fly mapping technique – need to correct for the fast dish movement
- Two products: 2 second images (slow transients) and deep mosaicked images





Kristof Rozgonyi
Daniel Lang

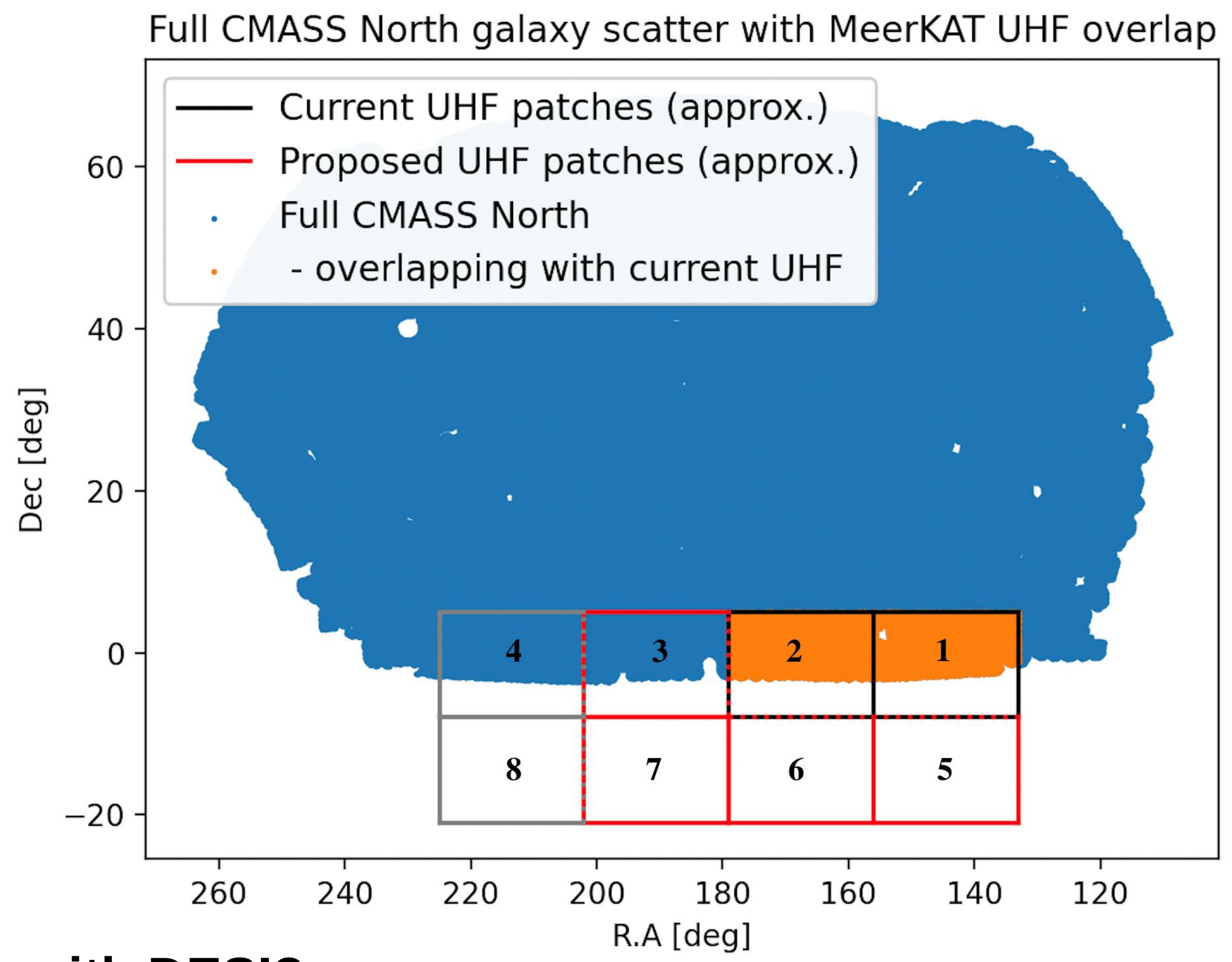
2 seconds snapshot

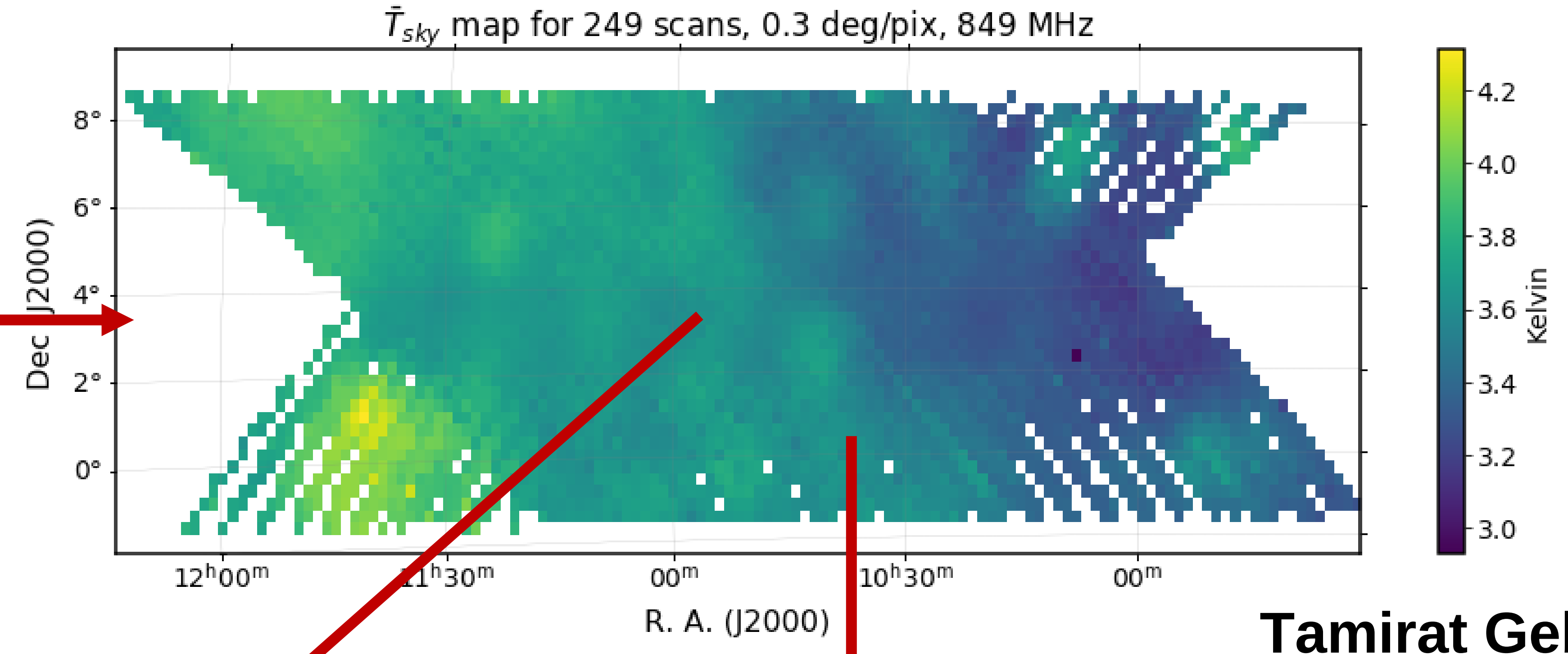


Suman Chatterjee

700 pointings!
44 uJy rms

Ongoing analysis with the UHF band…

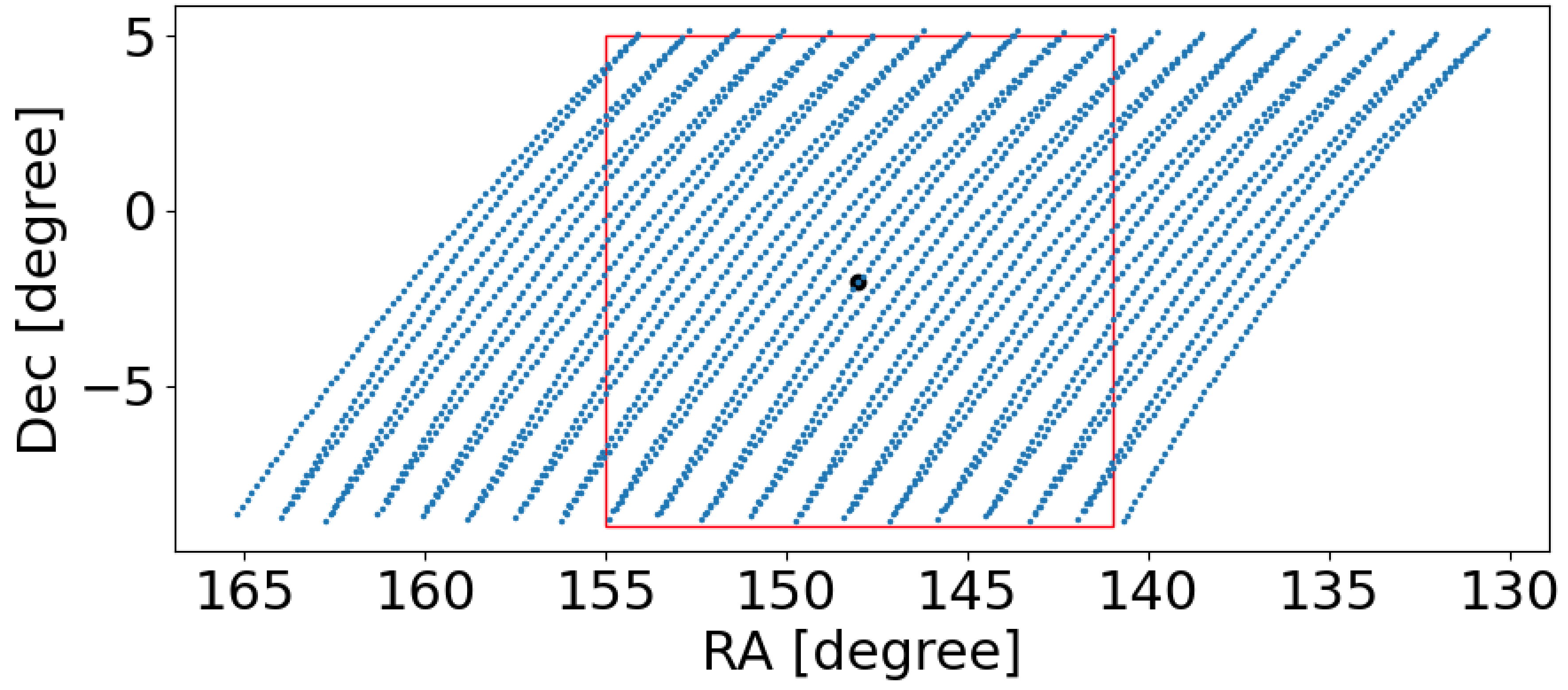


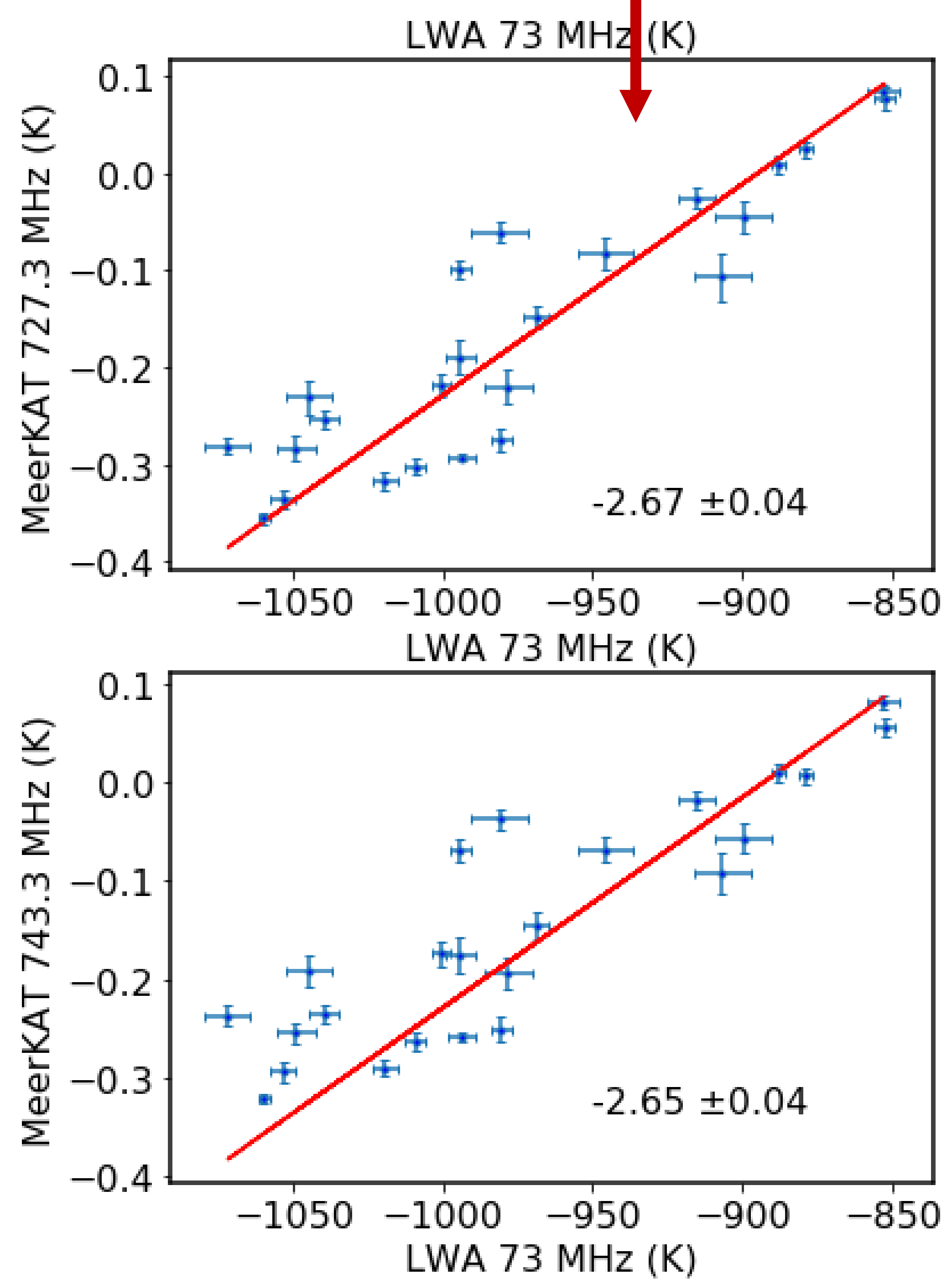


Tamirat Gebeyehu

Cross with DESI?

OTF





Galactic synchrotron spectral index (**Sifiso Mahlalela, Mel Irfan**)


UHF (580 – 1015 MHz) – 1 block
1613 pointings x 2s ~ 54 mins
290 sq degrees
rms ~ 150 muJy/beam
Declination
-2:30:00
-3:00:00
30:00
-4:00:00
30:00
-5:00:00
30:00
Right ascension
04:00
02:00
10:00:00
58:00
56:00
54:00
52:00
9:50:00
48:00
46:00
44:00
0.007
0.005
0.003
0.001
Sourabh Paul

~~Summary~~ Recruitment pitch

- 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 solid detections of the HI IM power spectrum in “cross” and tentative in “auto”
- 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)
- Lots of interesting challenges and cool results ahead – be part of it – join us!