Cosmology with MeerKAT and the SKA

Mário G. Santos, University of the Western Cape

SubirFest, Oxford

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CRC

UNIVERSITY of the WESTERN CAPE

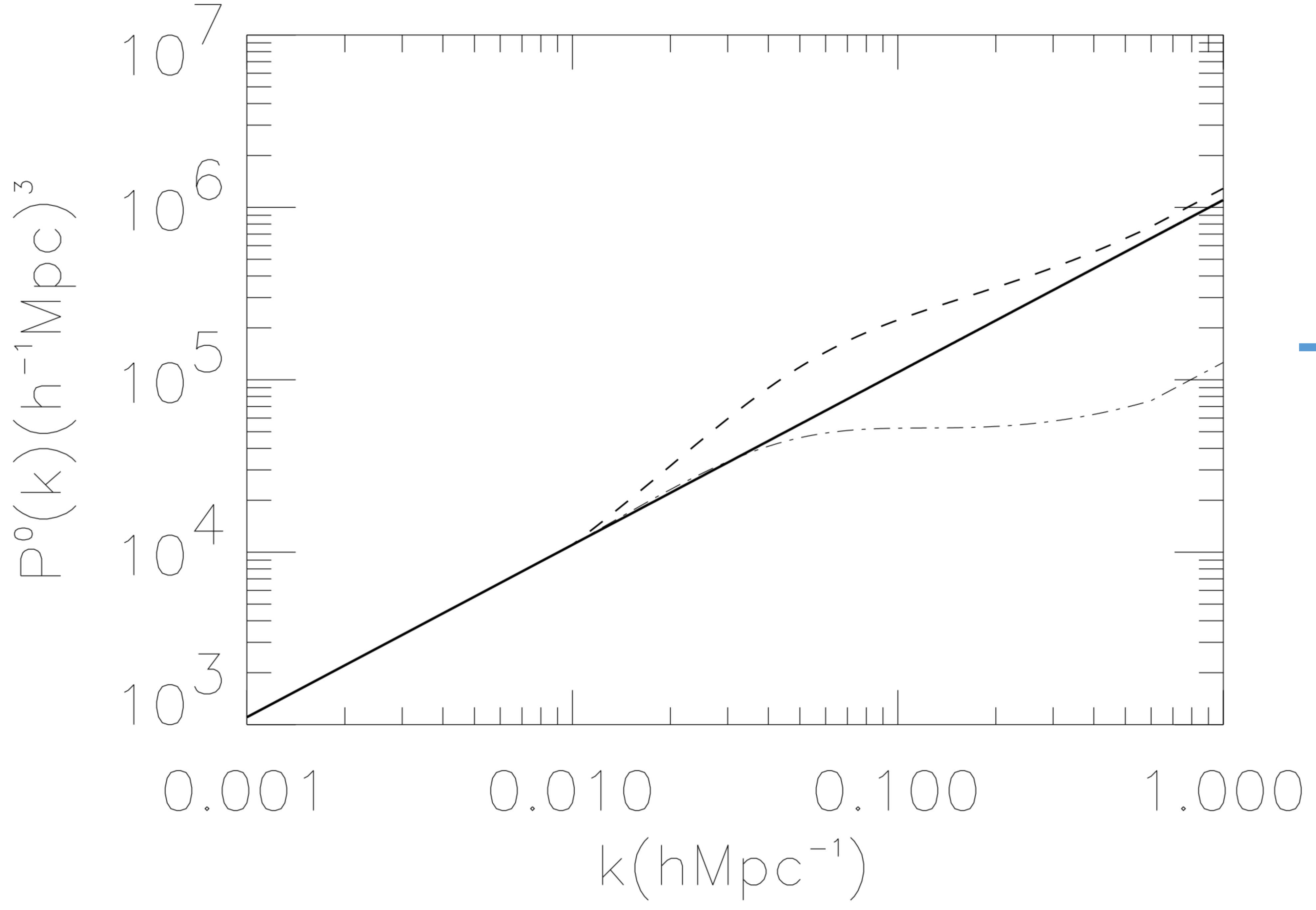
RESPICE PROSPICE

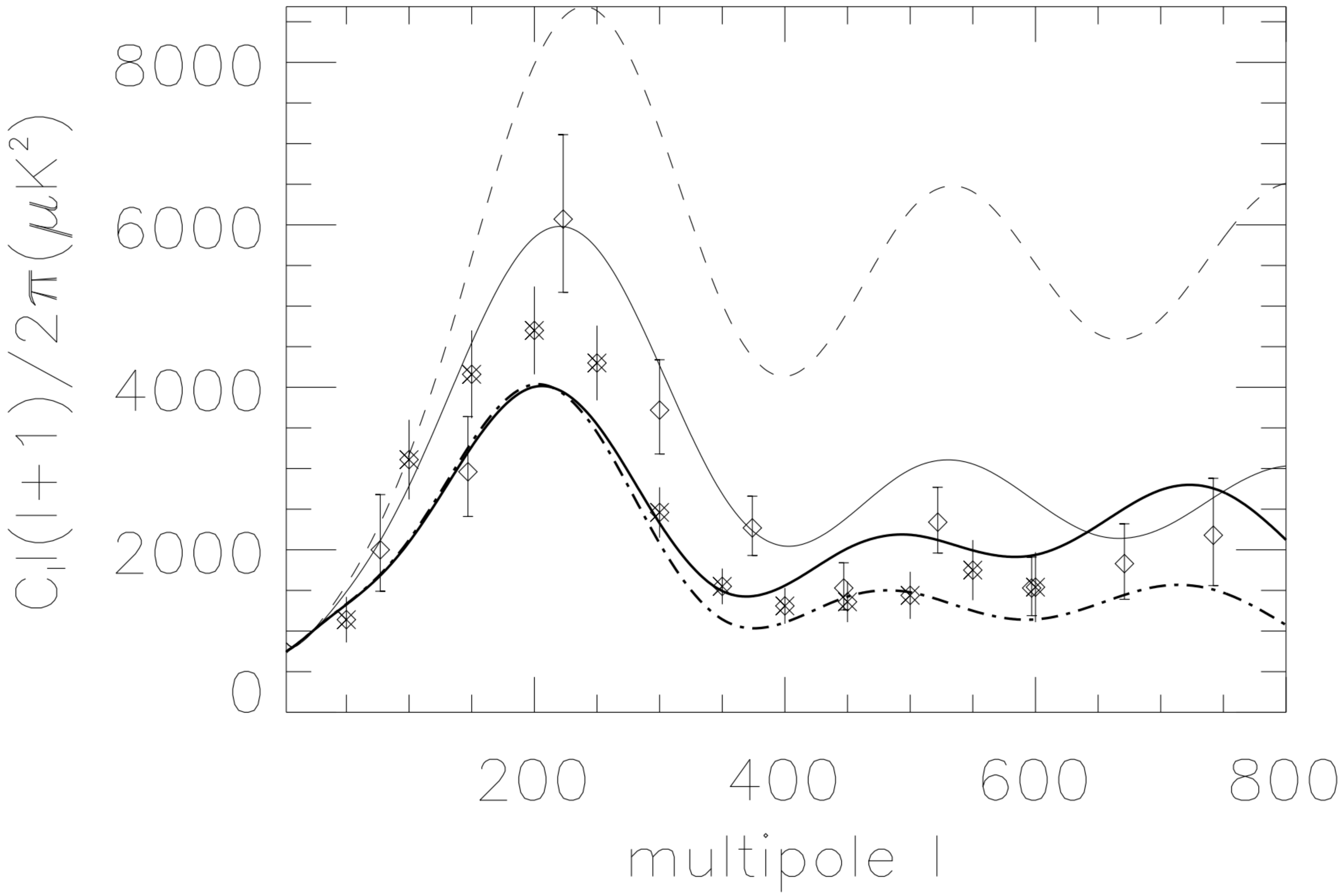
UWC ASTROPHYSICS

NRF National Research Foundation

SARAO South African Radio Astronomy Observatory

Signatures of new physics?

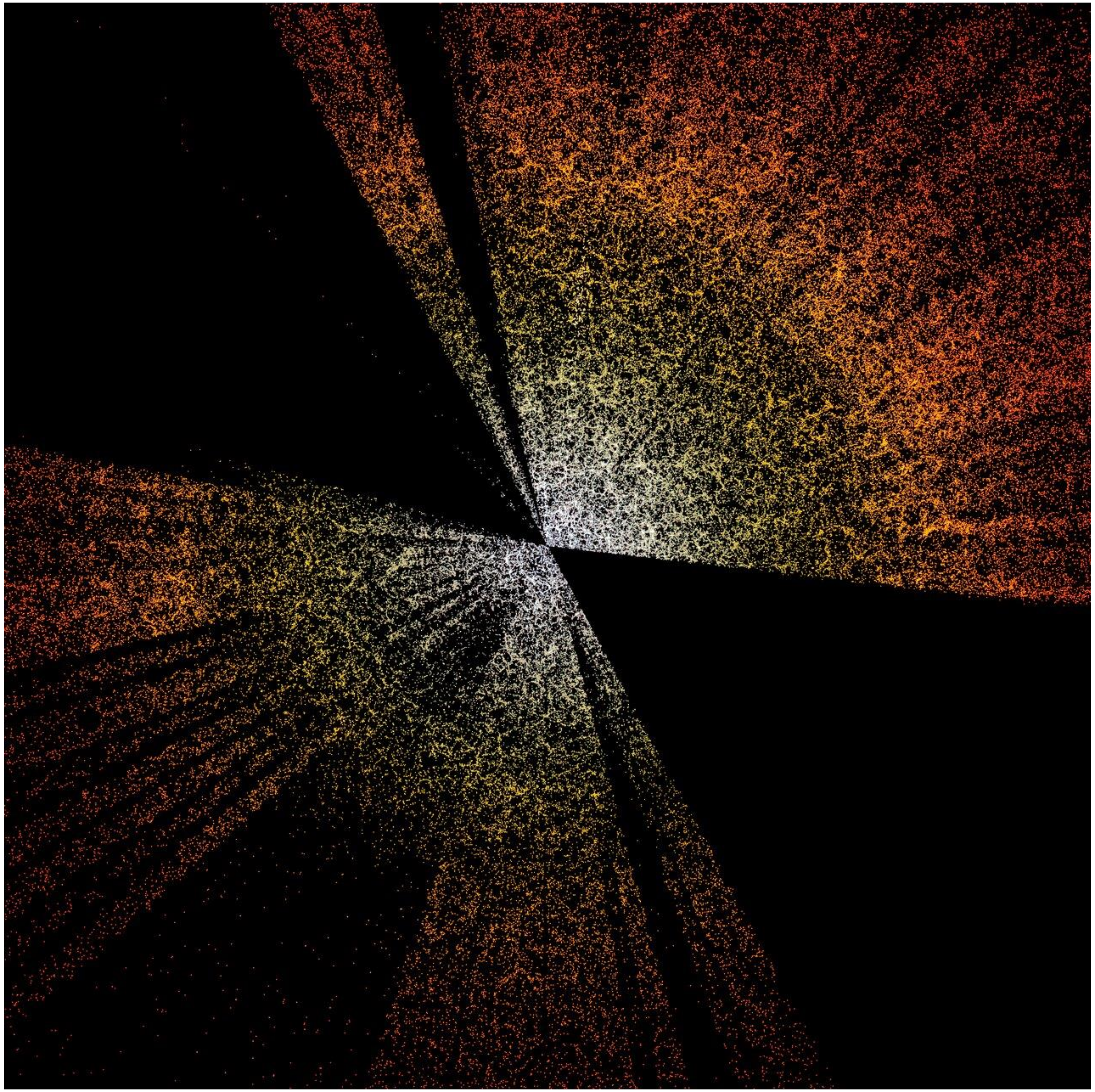




SJ. Barriga, E. Gaztanaga, M.G. Santos and S. Sarkar, Mon.Not.Roy.Astron.Soc.324:977, **2001**

CMB -> LSS?

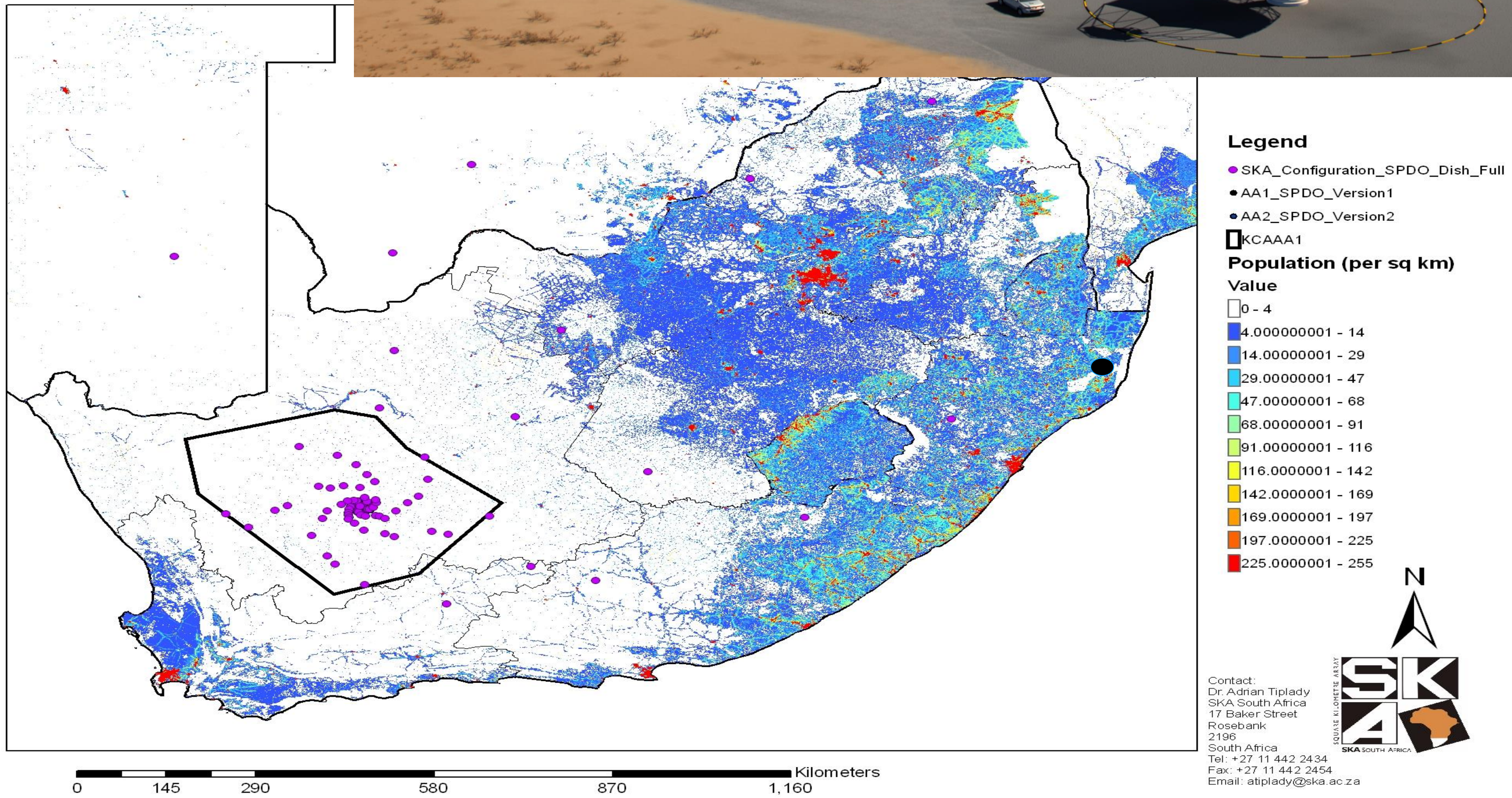
- Current questions: dark energy? dark matter? modified gravity? Primordial fluctuations?
- We are in the era of systematic limited measurements
- We need 3D measurements of large scale structure across time to probe fundamental questions in Cosmology
- Usually this is done through galaxy redshift surveys: Euclid, DESI, Roman/WFIRST…
- For the radio: HI 21cm line from each galaxy
- Very “expensive”…



(SDSS/DESI)

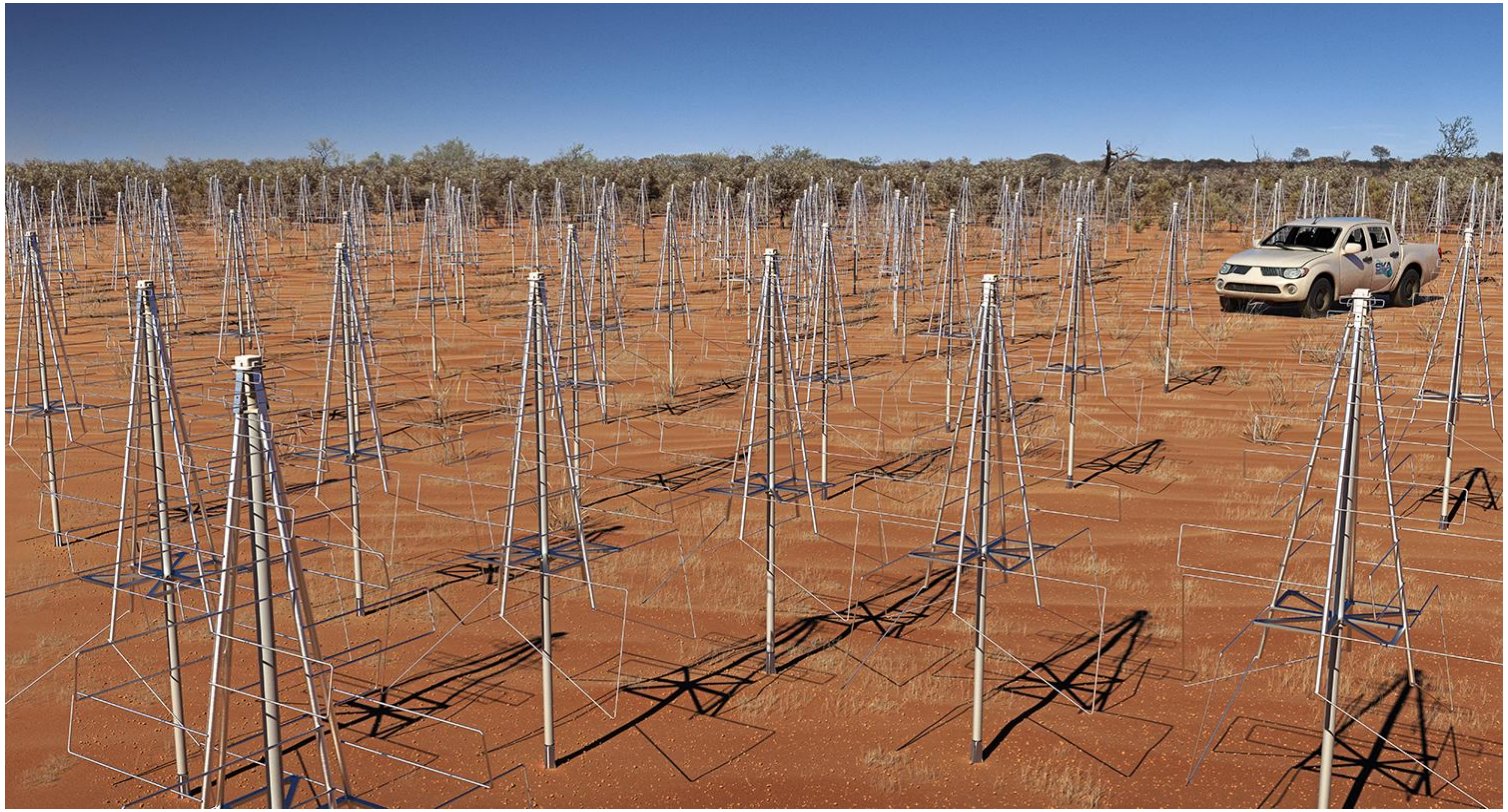
SKA1-MID

- South Africa
- 130, 15m dishes plus 64, 13.5m dishes (MeerKAT)
- Single pixel feeds
- Up to 120 Km baselines
- From 350 MHz to 14 GHz
- Cosmology: $0 < z < 3.0$
  - Band 1: 350-1050 MHz ($0.35 < z < 3$)
  - Band 2: 950-1750 MHz ($0 < z < 0.5$)

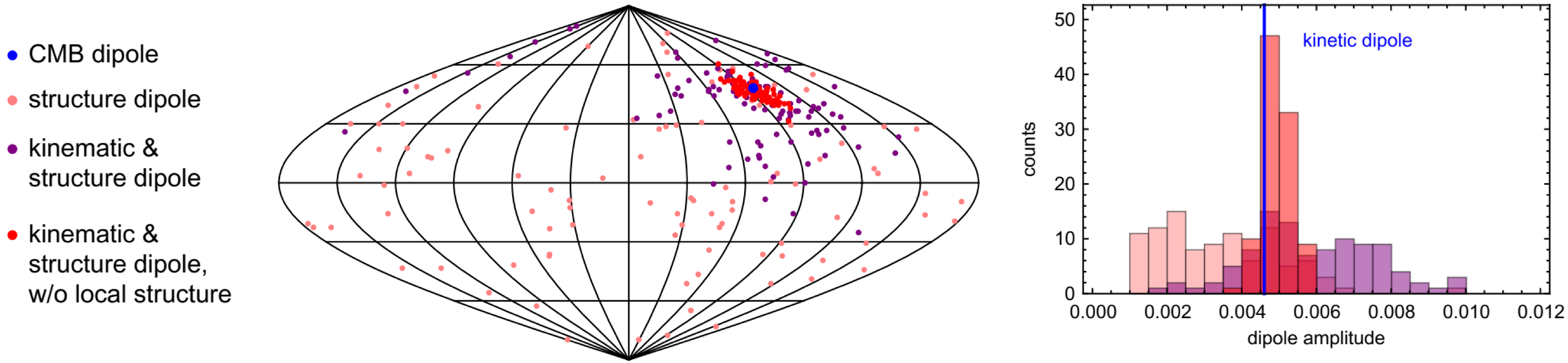


SKA1-LOW

- Australia
- About 121,000 dipole antennas over 476 stations
- up to 40 Km baselines
- 50 – 350 MHz
- 3.0 < z < 27
- Mostly to probe the Epoch of Reionization…



SKA1: LSS with a radio continuum survey -> dipole



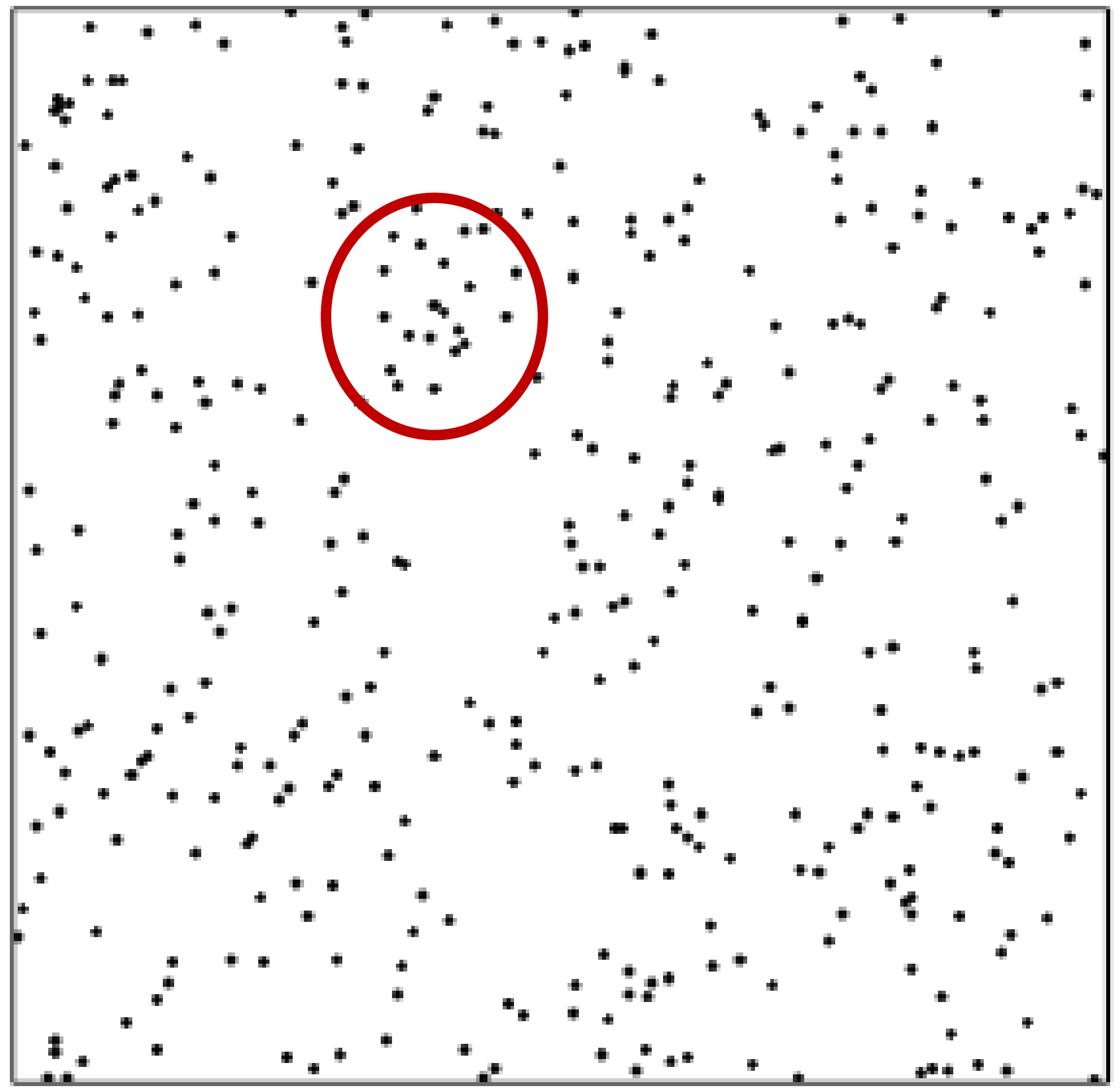
Dipole directions (left) and histogram of dipole amplitudes (right) based on 100 LSS simulations each for a flux density threshold of 22.8μJy at 700 MHz without kinetic dipole (pink), with kinetic dipole (purple) and with the contribution from the local structure dipole removed (red). The blue dot shows the direction of the CMB dipole. The results are displayed in galactic coordinates and in stereographic projection

- SKA1 Cosmology “red book”: arXiv:1811.02743

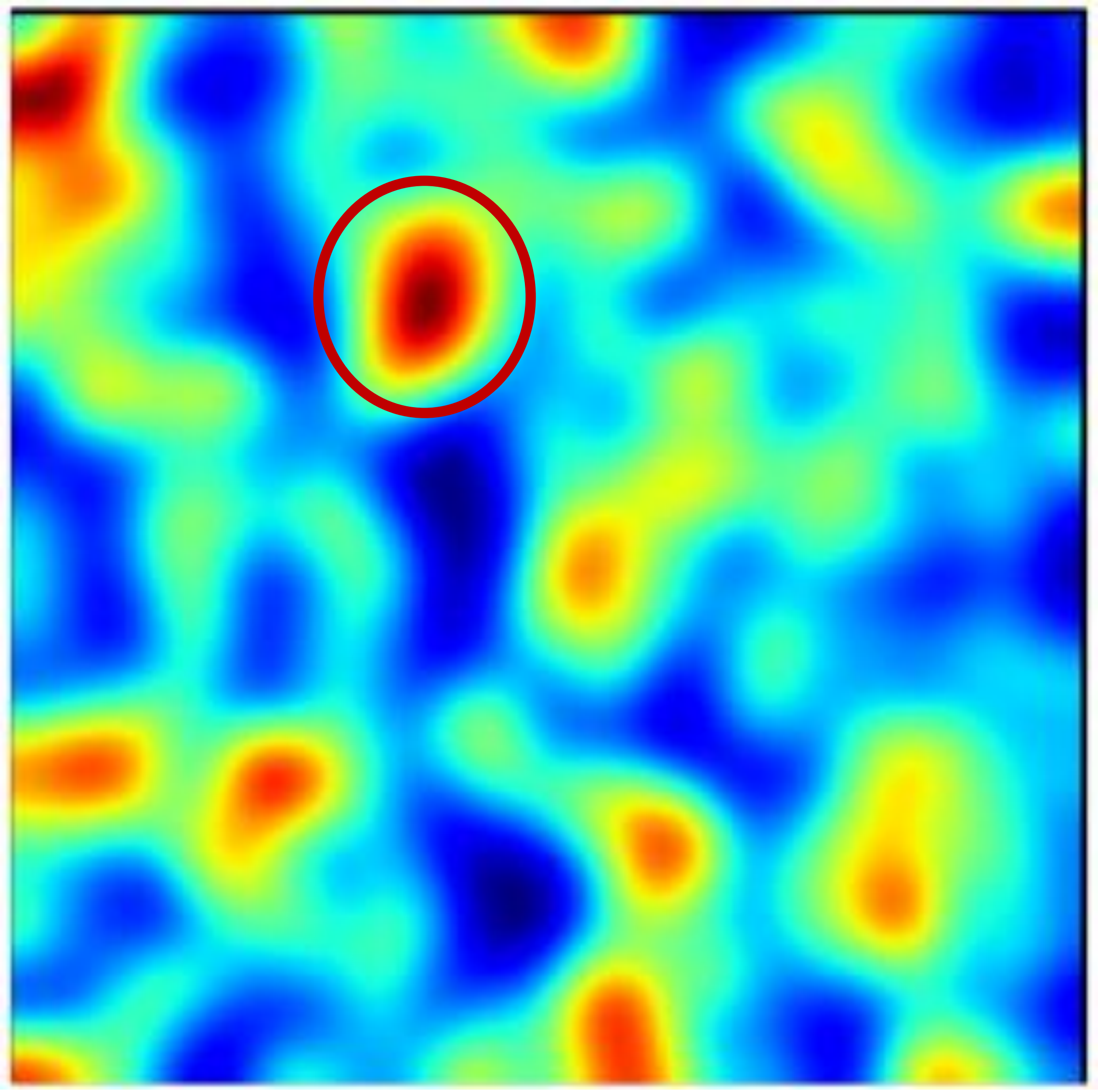
Probing LSS with intensity mapping

- 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

Note: only way to probe the IGM HI

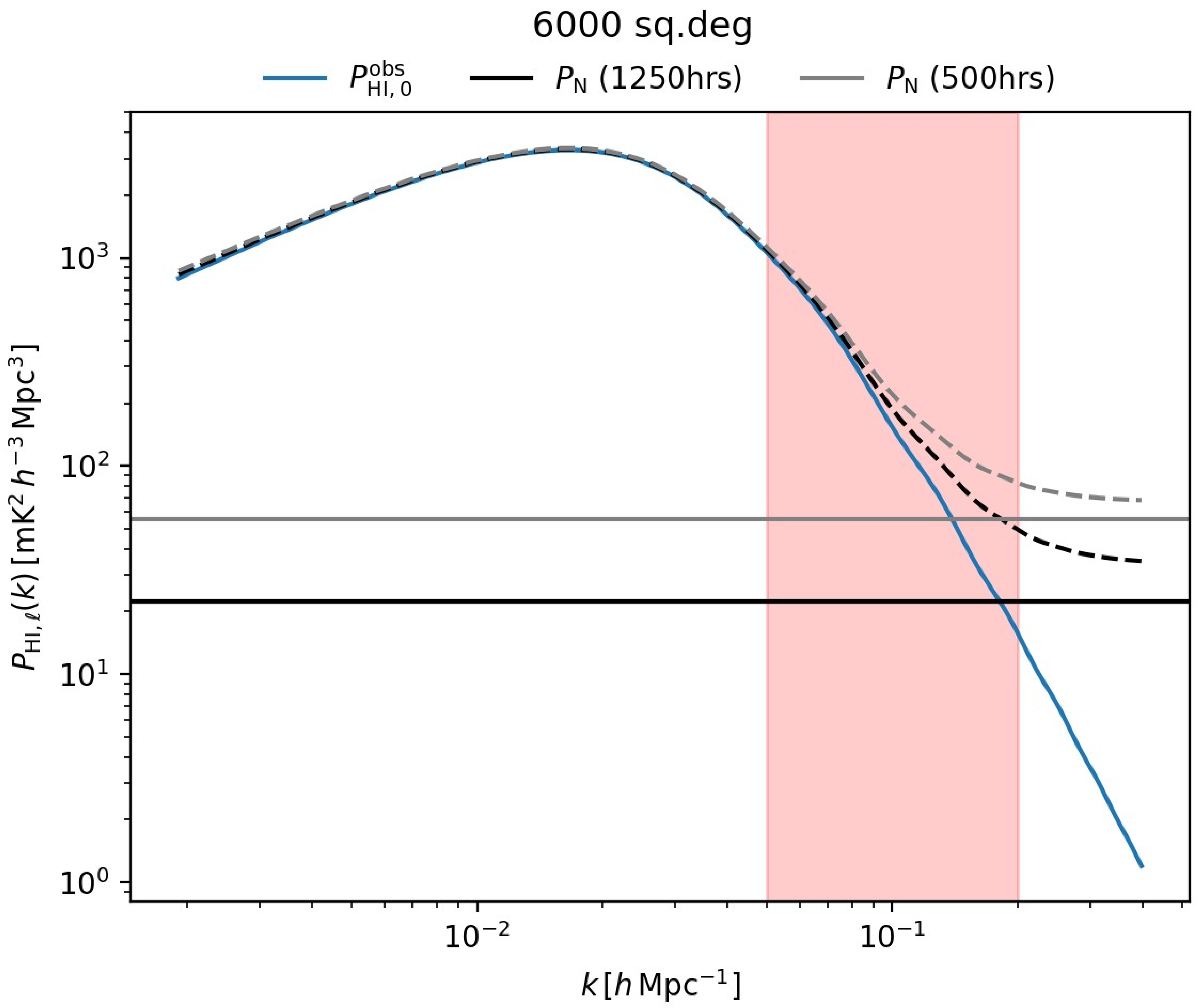


galaxies



Intensity map

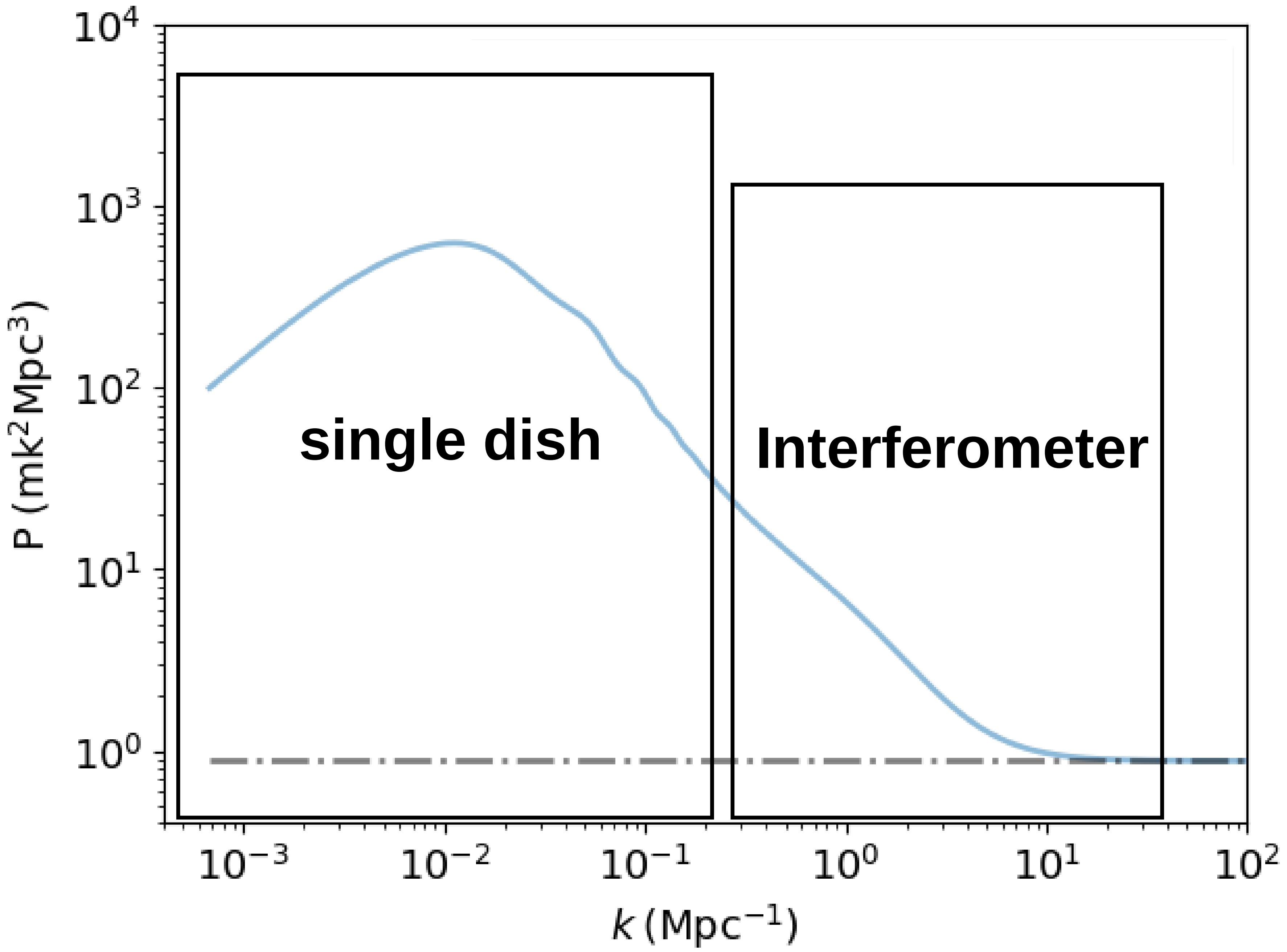
HI IM makes it “easy” to probe the power spectrum



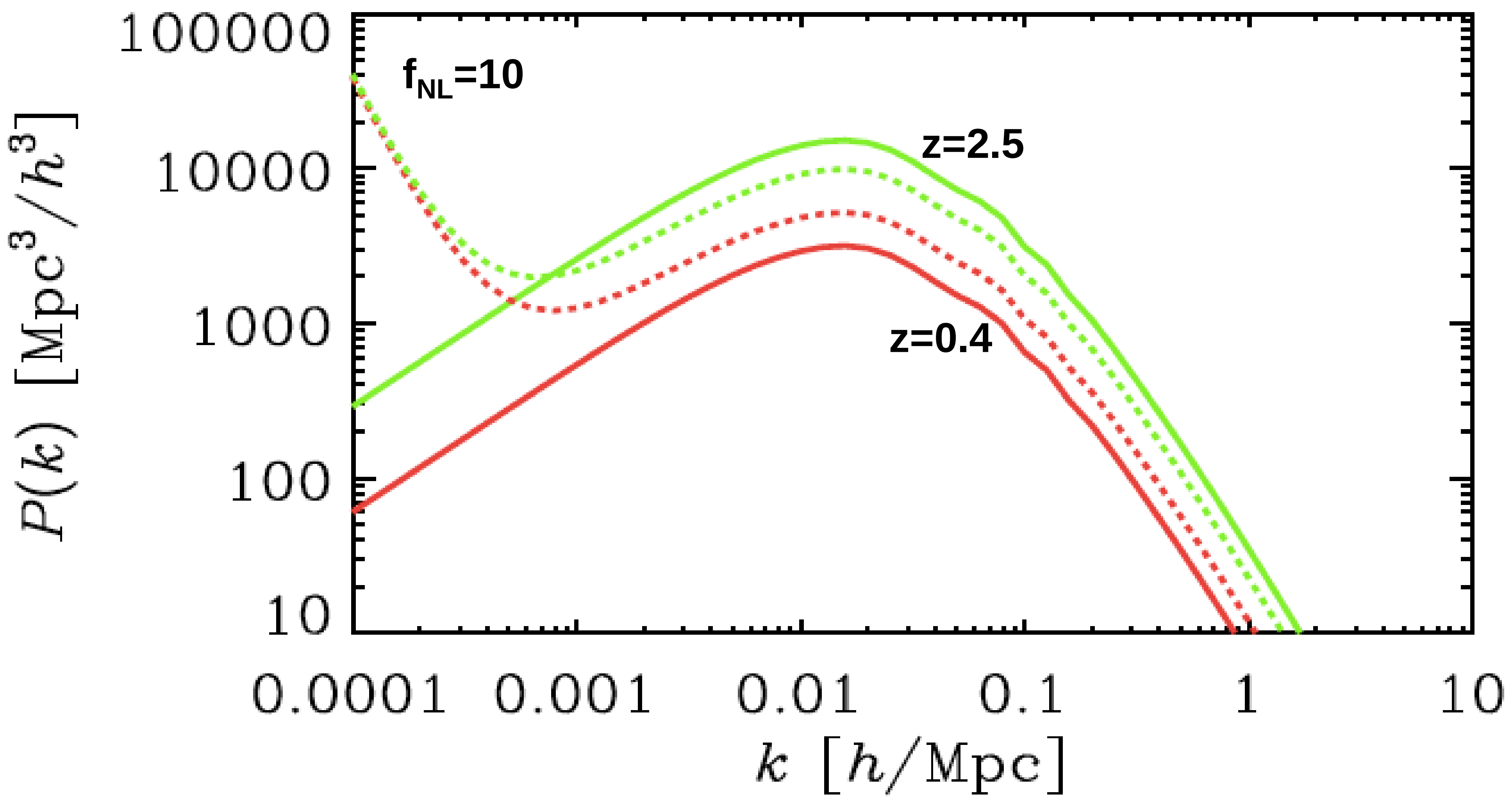
- An example with the MeerKAT telescope: 500 hours is enough to detect the baryon acoustic oscillations. Noise is well below the signal on large scales

SKA1?

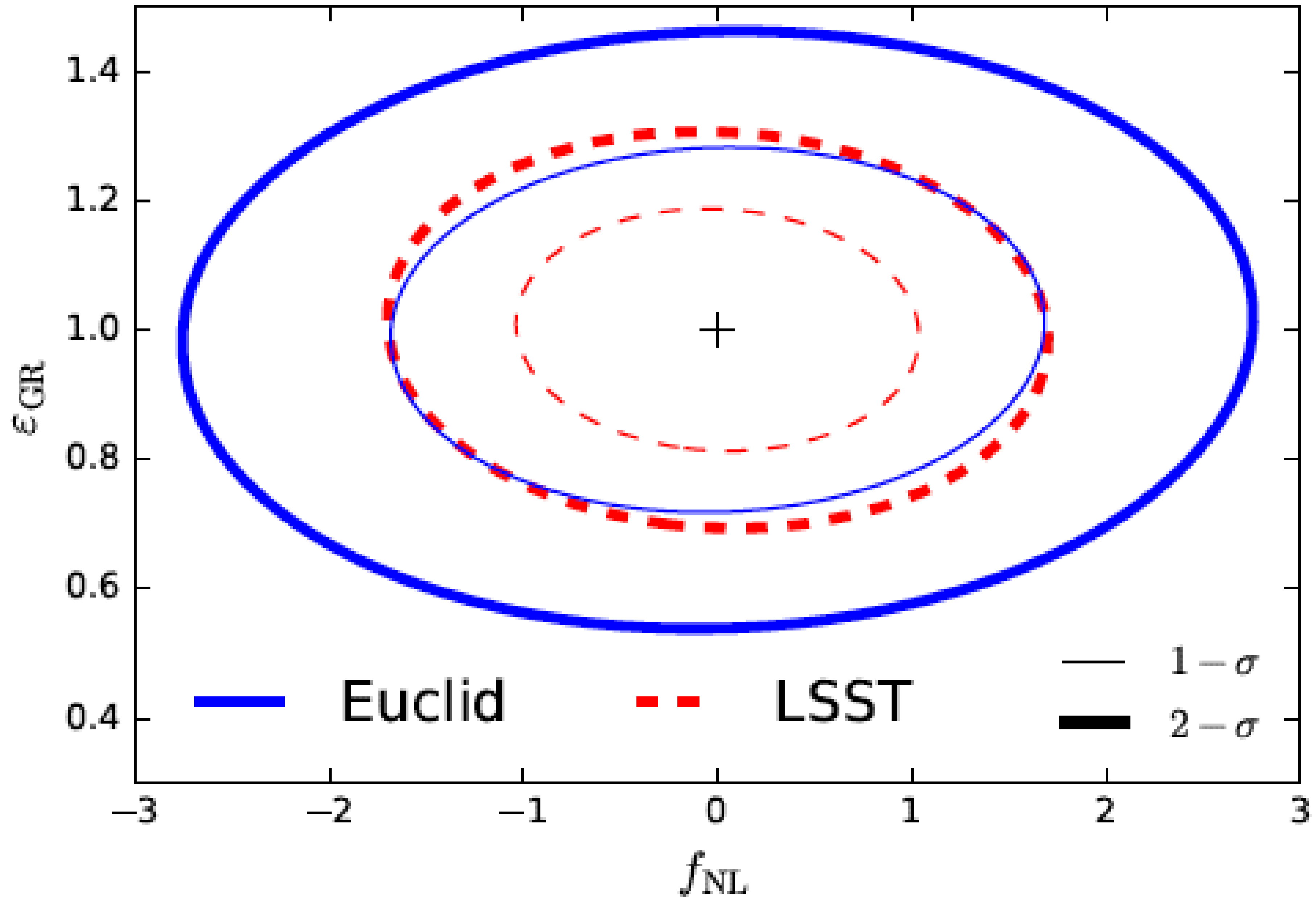
- Need SKA1-MID for z < 3 but baselines not small enough to probe BAO scales and above…
- Plan: use the array in “single dish mode”
- SKA1-MID single dish HI intensity mapping survey will turn SKA into a state of the art cosmology machine
- Only way to really go after the unexplored very large scales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



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 good 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…

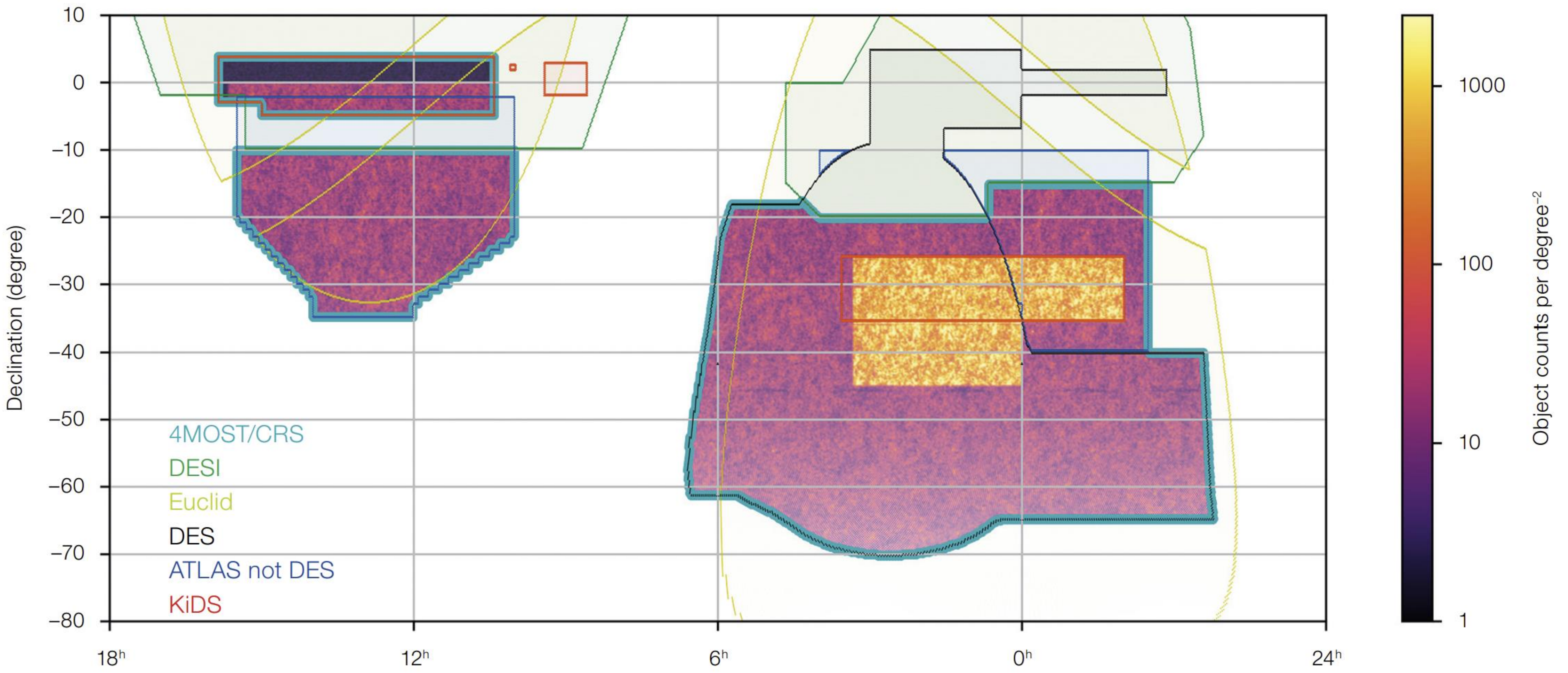
MeerKAT?

- 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

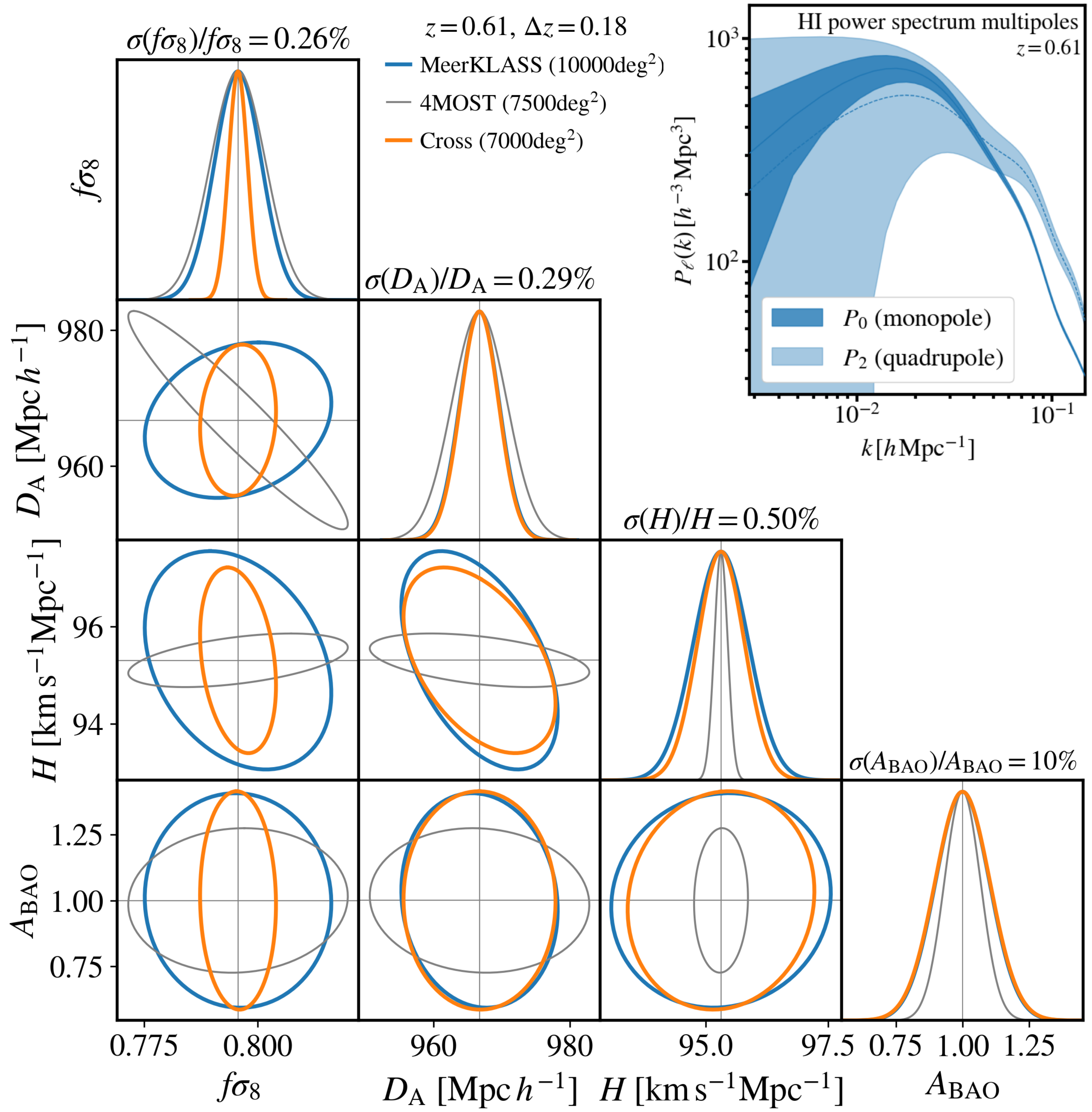
- ***MeerKLASS: MeerKAT Large Area Synoptic Survey:*** http://arxiv.org/abs/1709.06099
- Aim: Cosmology (HI intensity mapping) but commensal with lots of other science (continuum survey)
- Focus on sky patches with multi-wavelength data for cross-correlation (DESI, 4MOST, Euclid, Rubi/LSST, DES)

- L-band: 900-1670 MHz (z<0.58) ~ 100 hours observed
- **UHF band:**
  - 580 MHz-1015 MHz (0.40 < z < 1.45)
  - ~ 120 hours observed
  - Goal: 2,500 hours over 10,000 deg^2 (25 uJy rms in continuum) within next 5 years



MeerKLASS: Cosmology

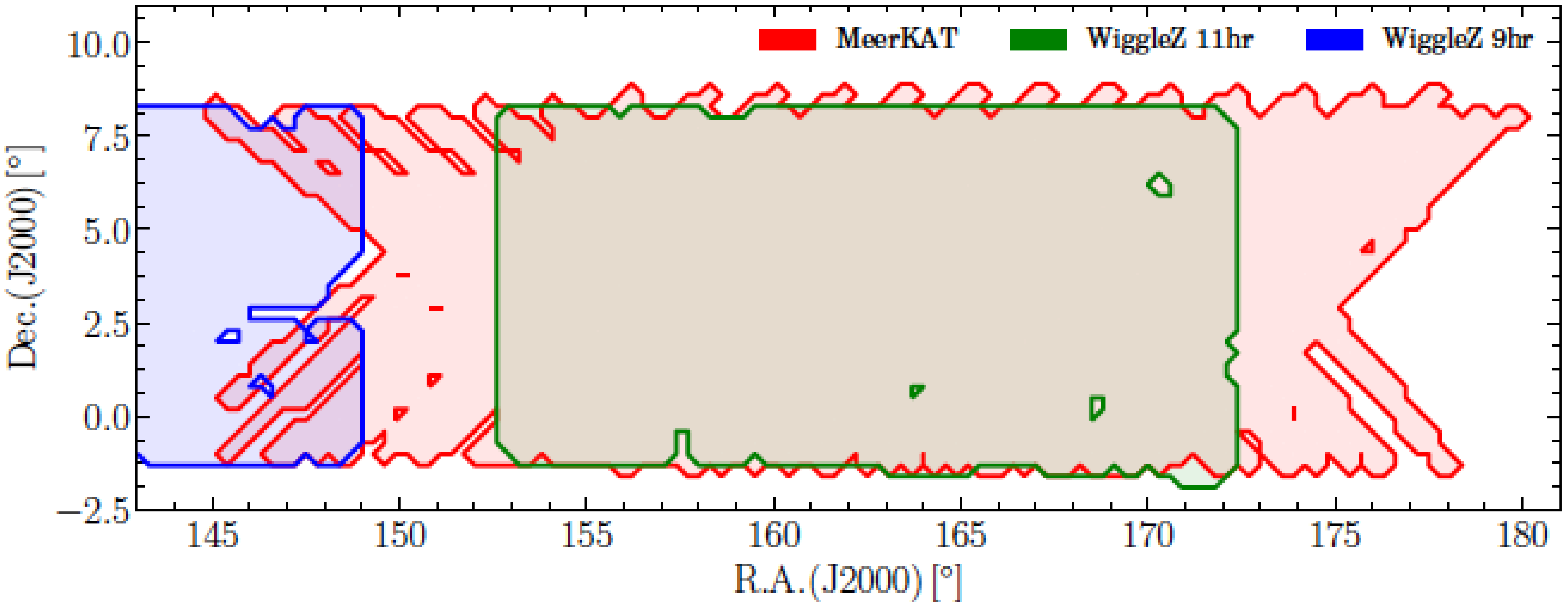
- Measurement of Baryon Acoustic Oscillations (BAO), Hubble rate and redshift space distortions
- Measure the HI content of the Universe at 0.4 < z < 1.4 (UHF-band)
- Cross-correlations with galaxy surveys
- Constraints of primordial non-Gaussianity (f_{NL}) by measuring large scale correlations and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



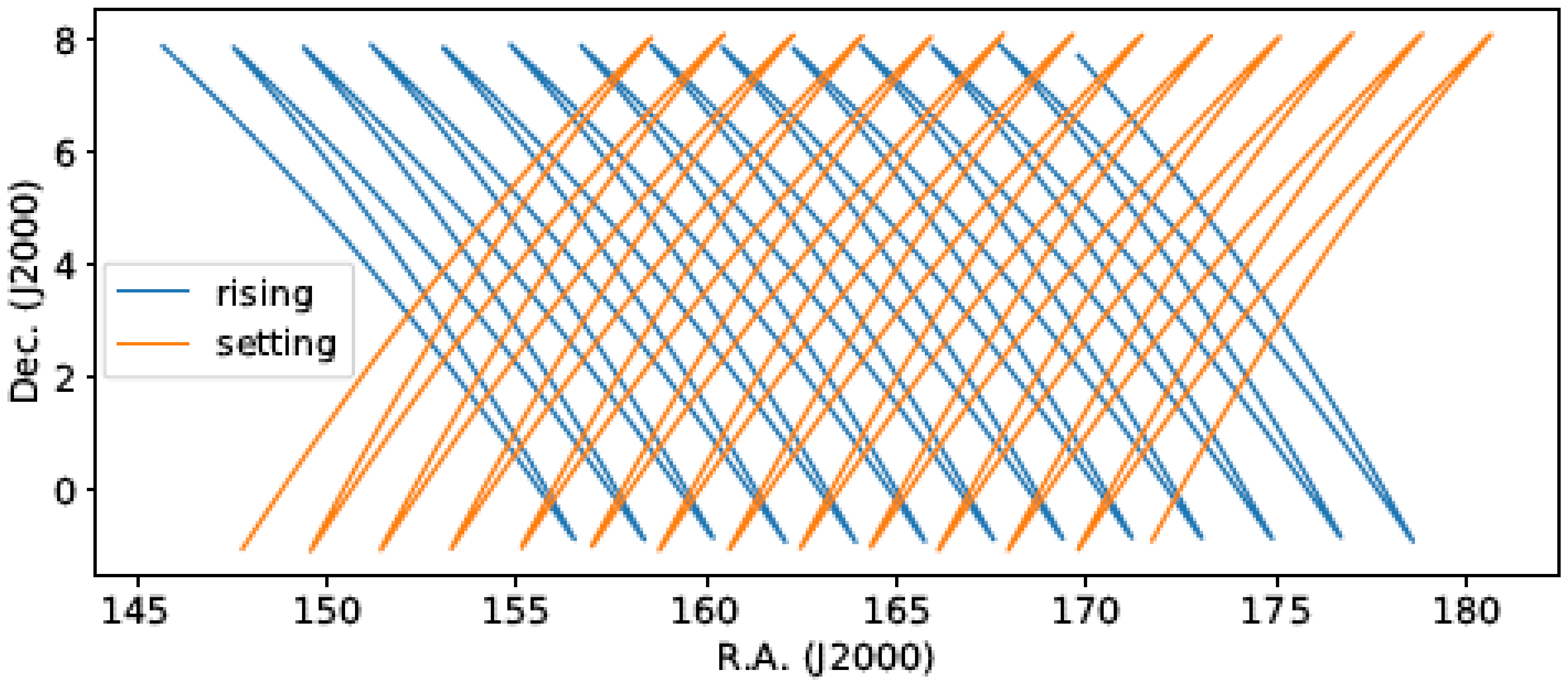
MeerKAT: 1,300 hours. 60 dishes

First results with a MeerKAT single dish pilot survey

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



Footprint

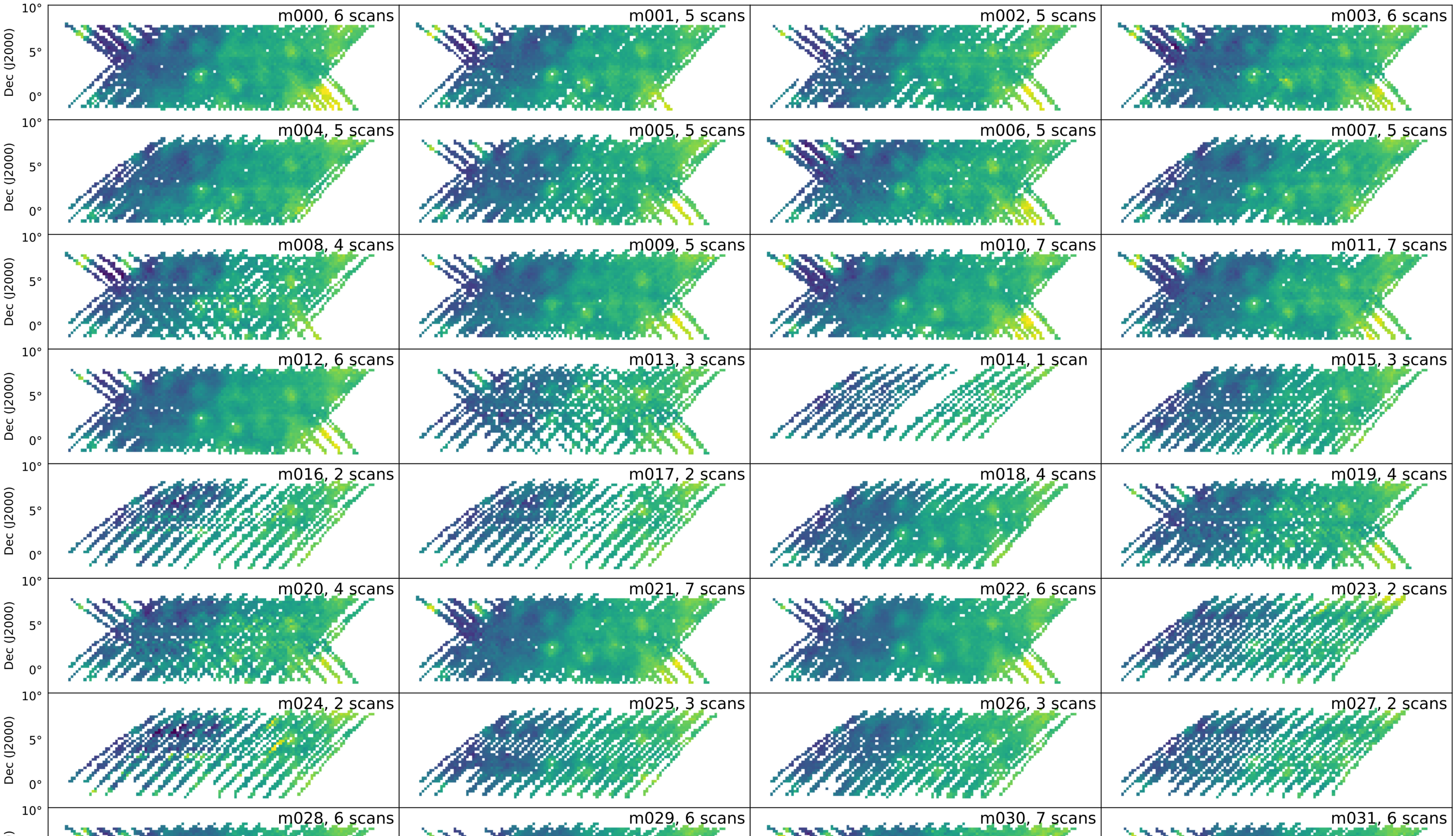


Scanning pattern

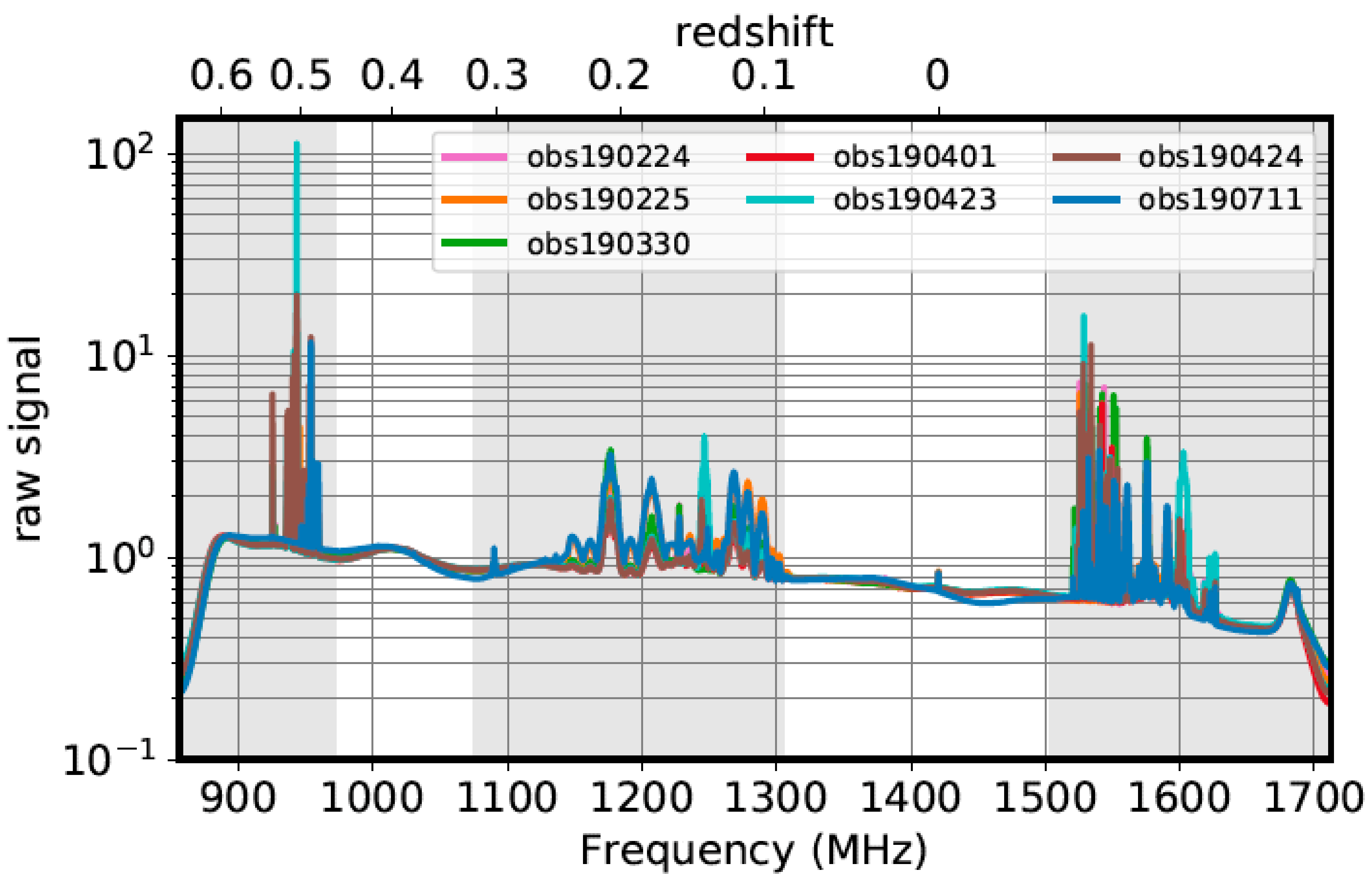
- ~ 15 hours
- ~ 60 dishes used (~ 600 hours combined)
- ~ 200 deg^2 over the WiggleZ 11h field
- L-Band: 900 MHz - 1700 MHz (z < 0.5)

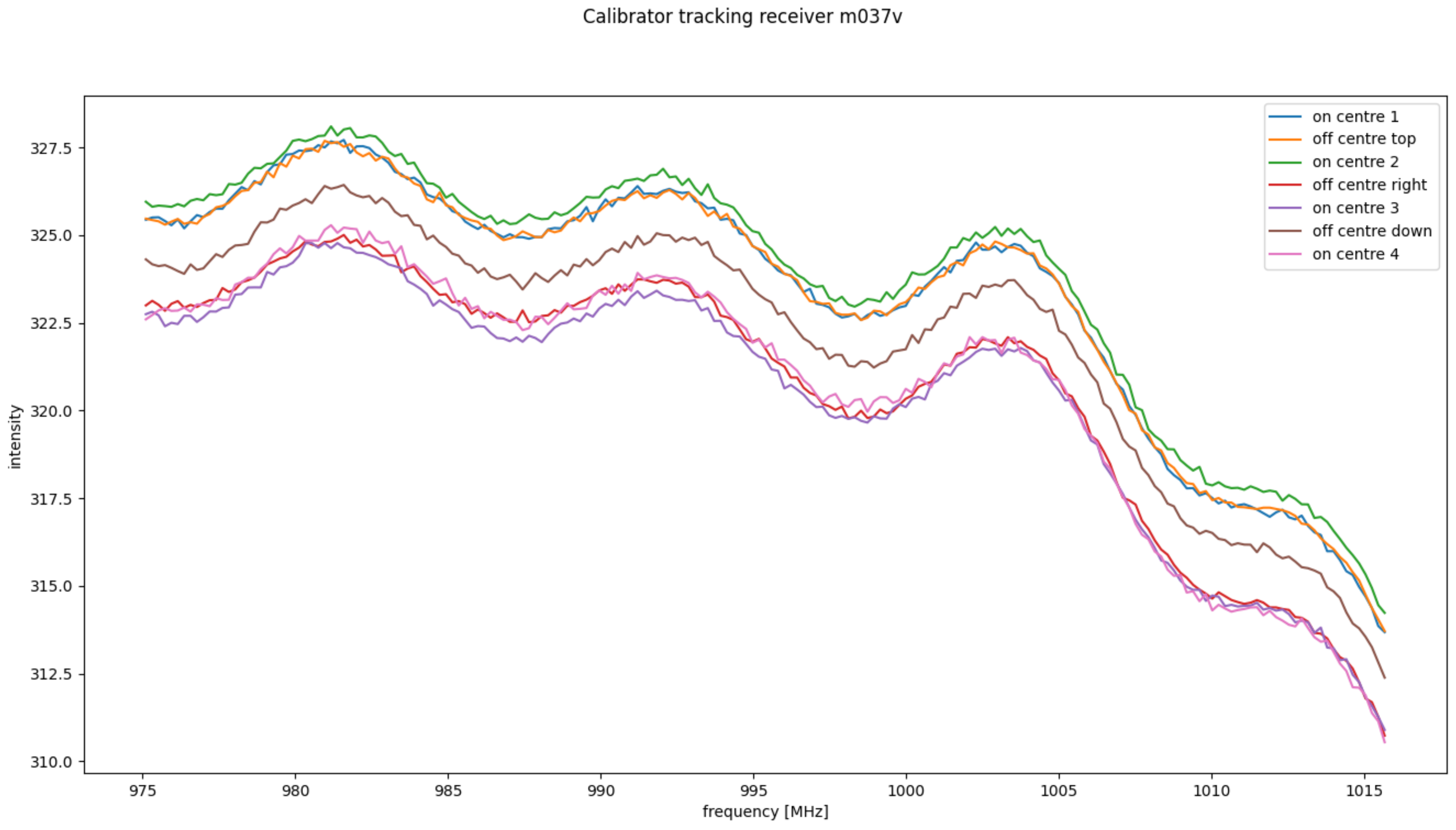
- Resolution: 2 sec/0.2 MHz
- Scans at constant elevation (> 40 deg)
- Speed: 5 arcmin/sec
- ~ 200 sec per scan line, 1.5 hours per block

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



Contamination (sky foregrounds+ground+RFI+instrumental)

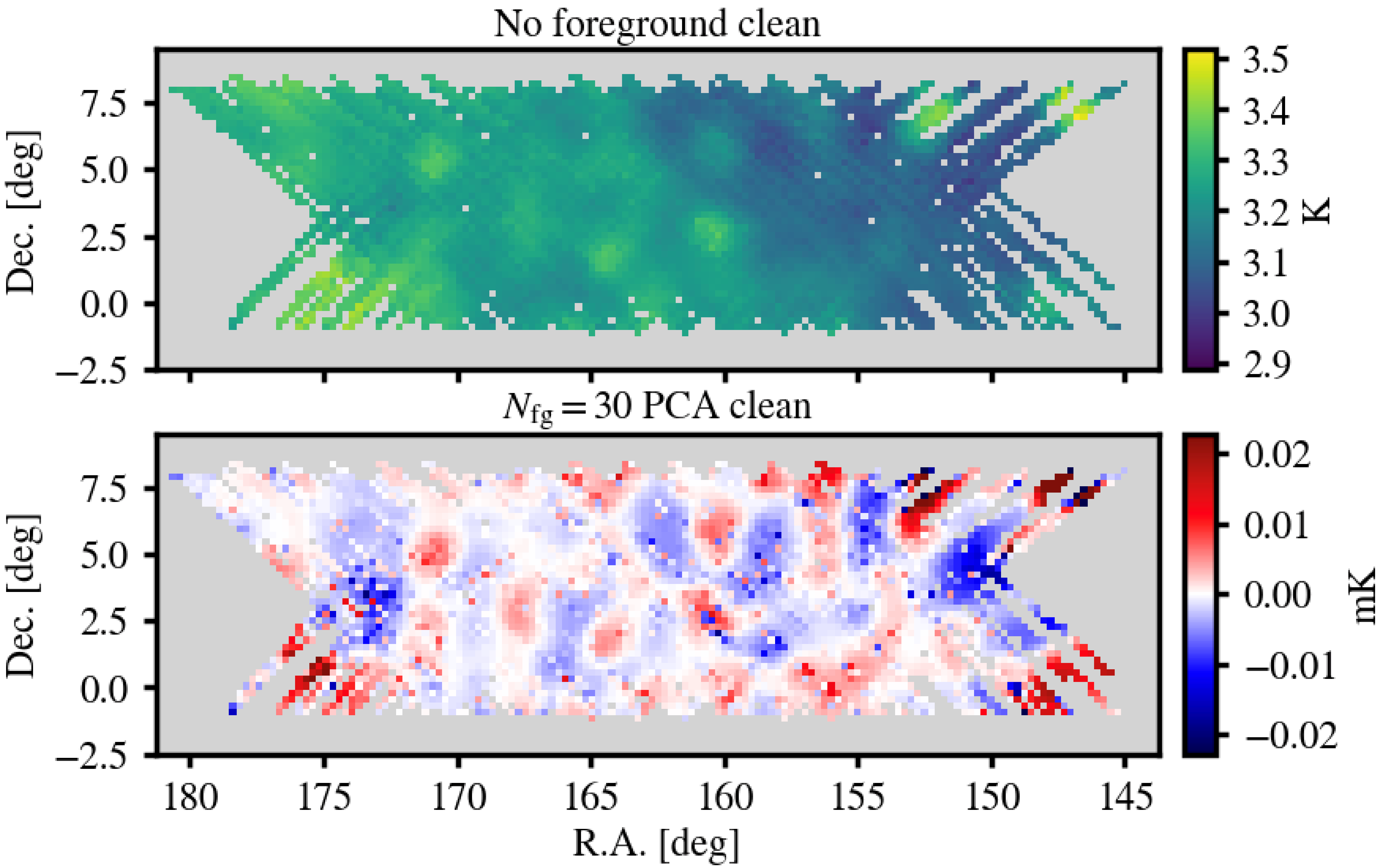




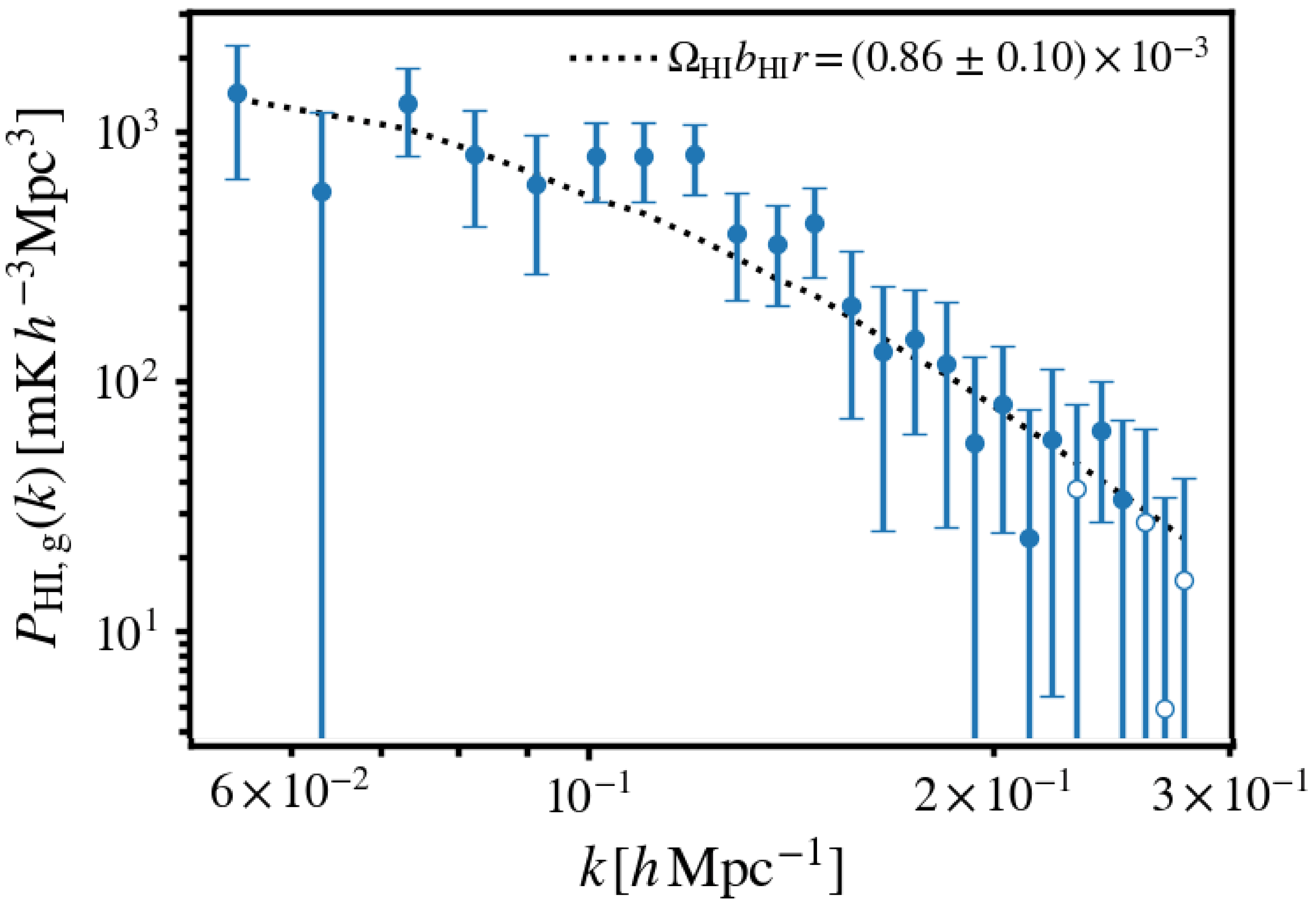
Looking for fluctuations ~ 1/10^5

- 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**
- 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)

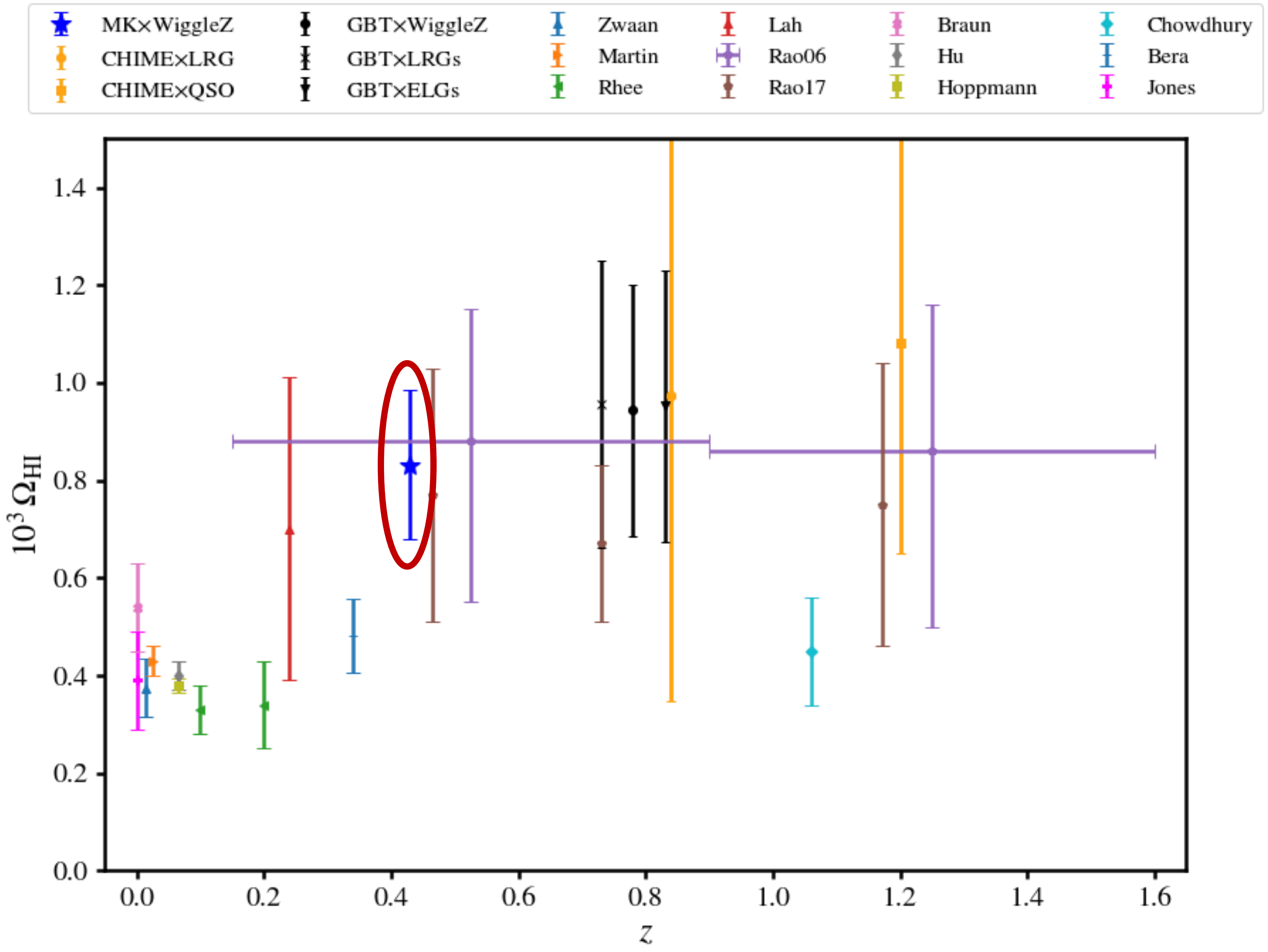
Foreground cleaned maps…



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



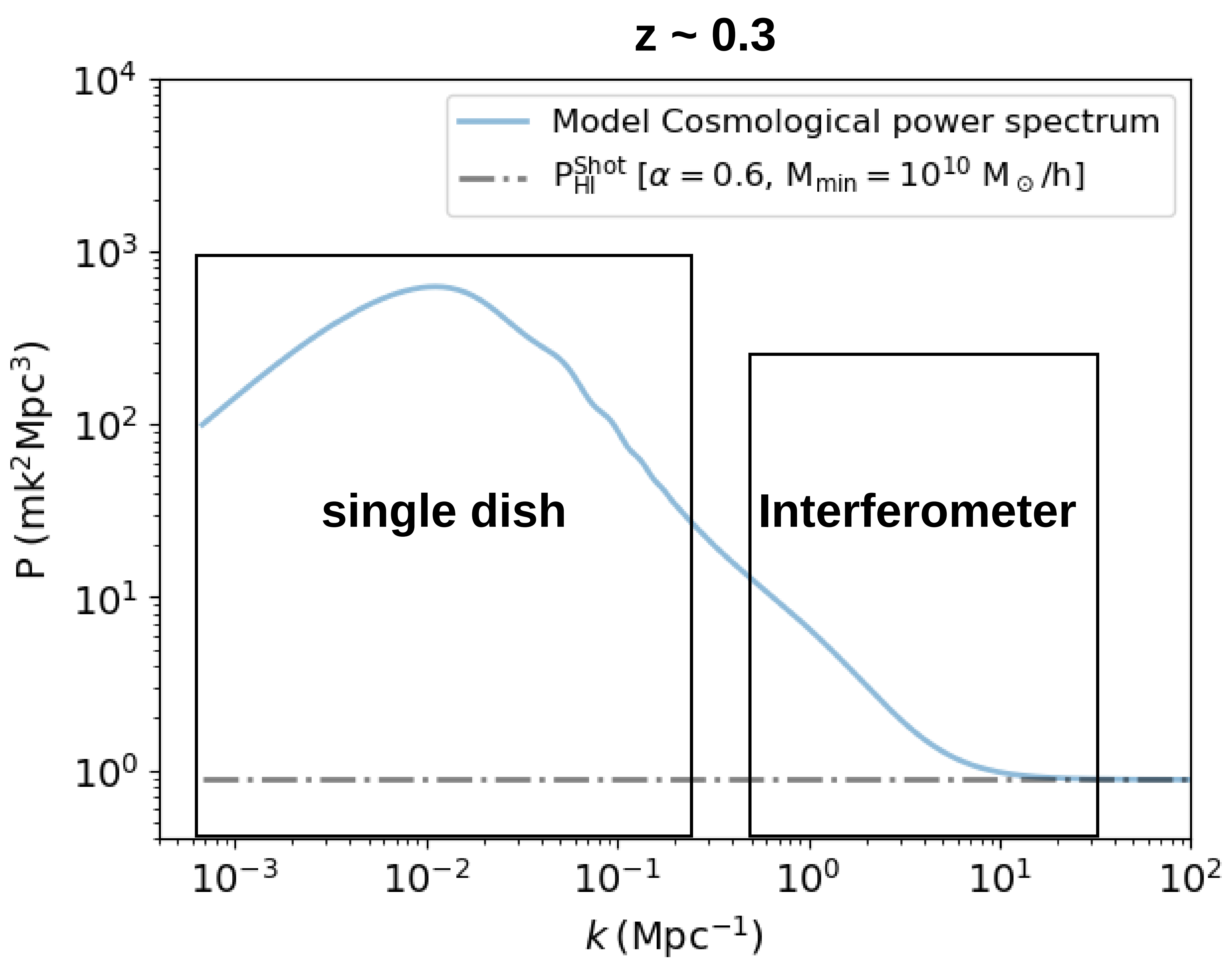
0.400 < z < 0.459



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

HI IM using the MeerKAT interferometer

- HI intensity mapping can still measure quasi-linear cosmological scales (k ~ 1 Mpc-1 and above)
- Great way to test the halo model and compare to HI simulations



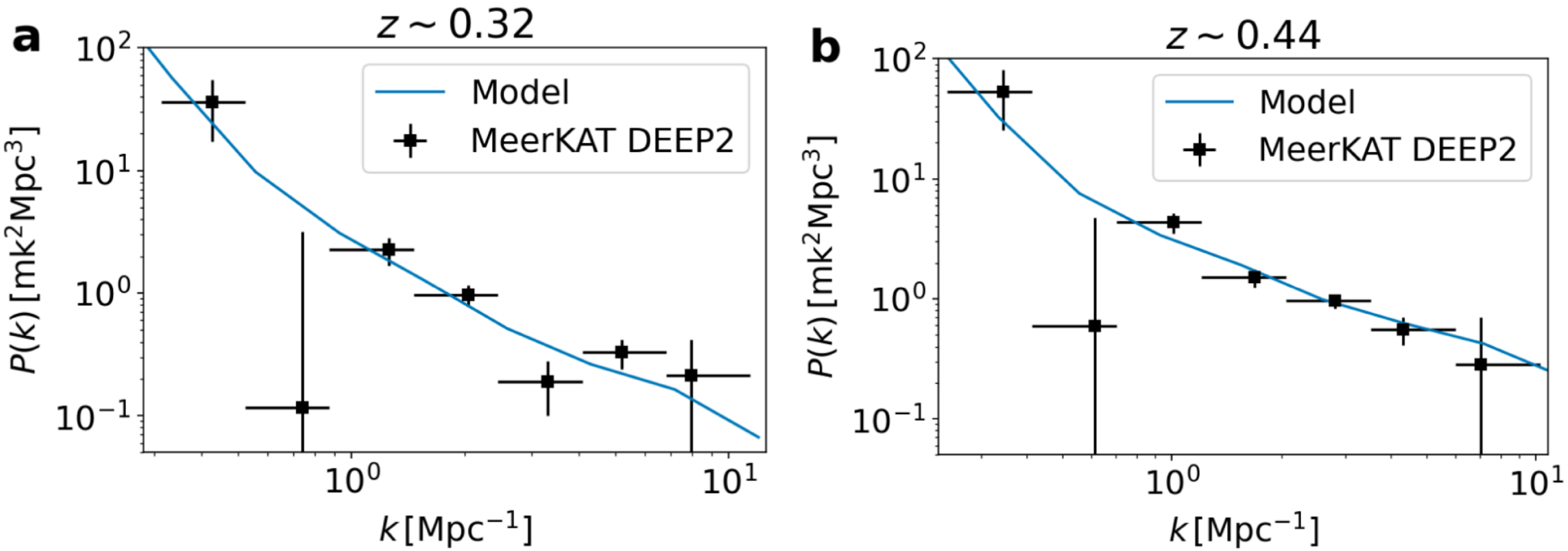
$$P_D(k_\perp, k_\parallel) = P_{2h}(k_\perp, k_\parallel) + P_{1h}(k_\perp, k_\parallel) + P_{SN}(k_\parallel)$$

$$P_{SN}(k_\parallel) = \frac{P^0_{SN}}{1 + (k_\parallel \sigma_p)^2/2}$$

First direct detection of the HI power spectrum on Mpc scales

$\sigma_{\mathrm{HI}}\,(1\mathrm{Mpc}) = 0.44 \pm 0.04\ \mathrm{mK}$

$\sigma_{\mathrm{HI}}\,(1\mathrm{Mpc}) = 0.63 \pm 0.03\ \mathrm{mK}$

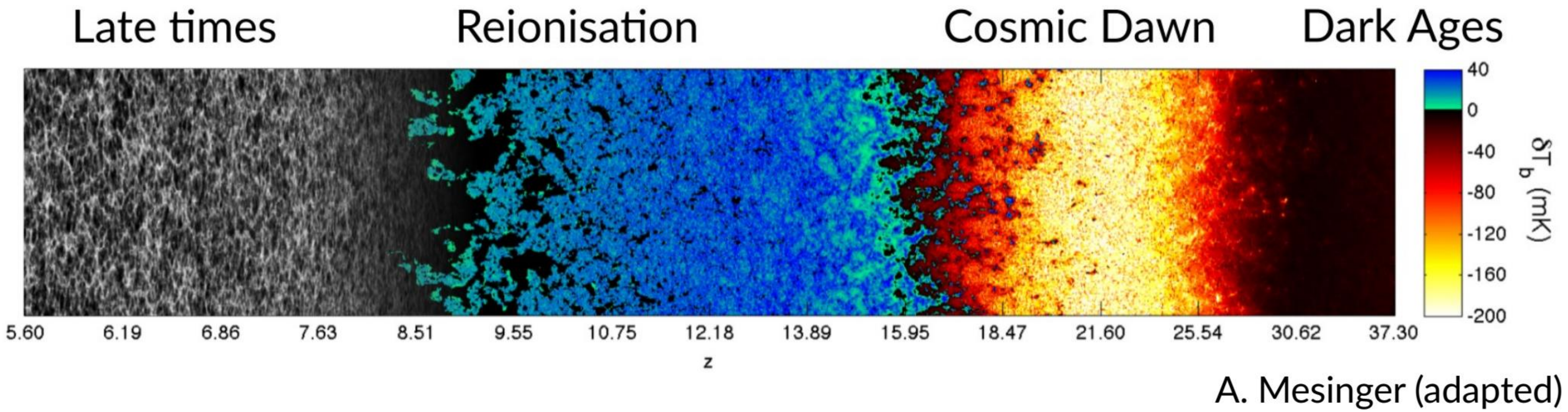


8σ

11.5σ

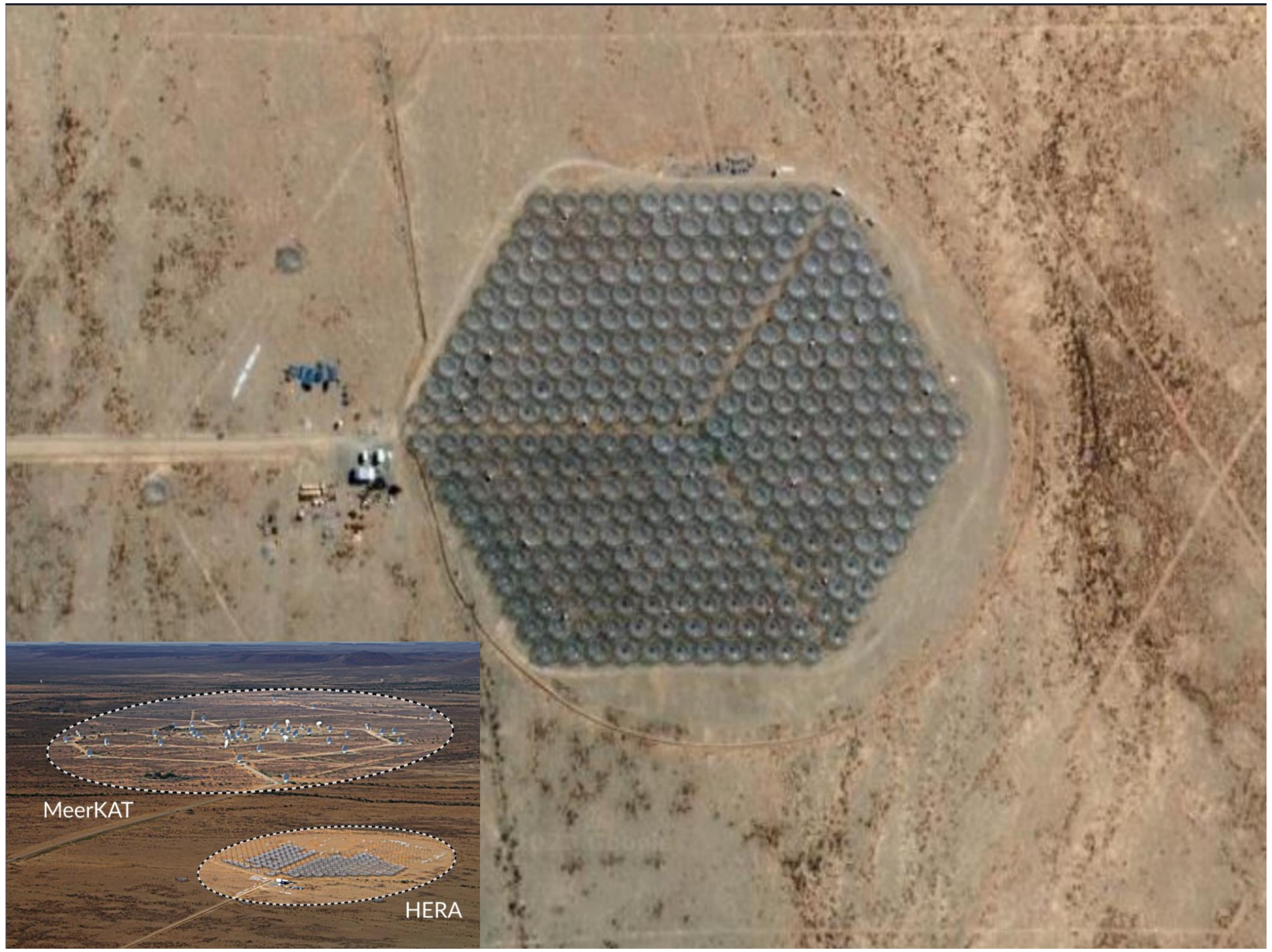
Sourabh Paul, Mario G. Santos ,Zhaoting Chen and Laura Wolz, https://arxiv.org/abs/2301.11943

Going to higher redshifts: the Epoch of Reionization and the dark ages



- Again, use the HI power spectrum
- Properties of early galaxies and galaxy formation/evolution models
- Constraint the CMB optical depth -> better cosmological constraints
- Sensitivity to energy injection (e.g. DM annihilation)
- Dark ages?

Going to higher redshifts: Hydrogen Epoch of Reionization Array (HERA)



- Built on SKA site in South Africa
- 350 dishes with dual-pol. receivers (50 – 220 MHz)
- 14m dishes, 14.6m minimum baseline length in hexagonal layout

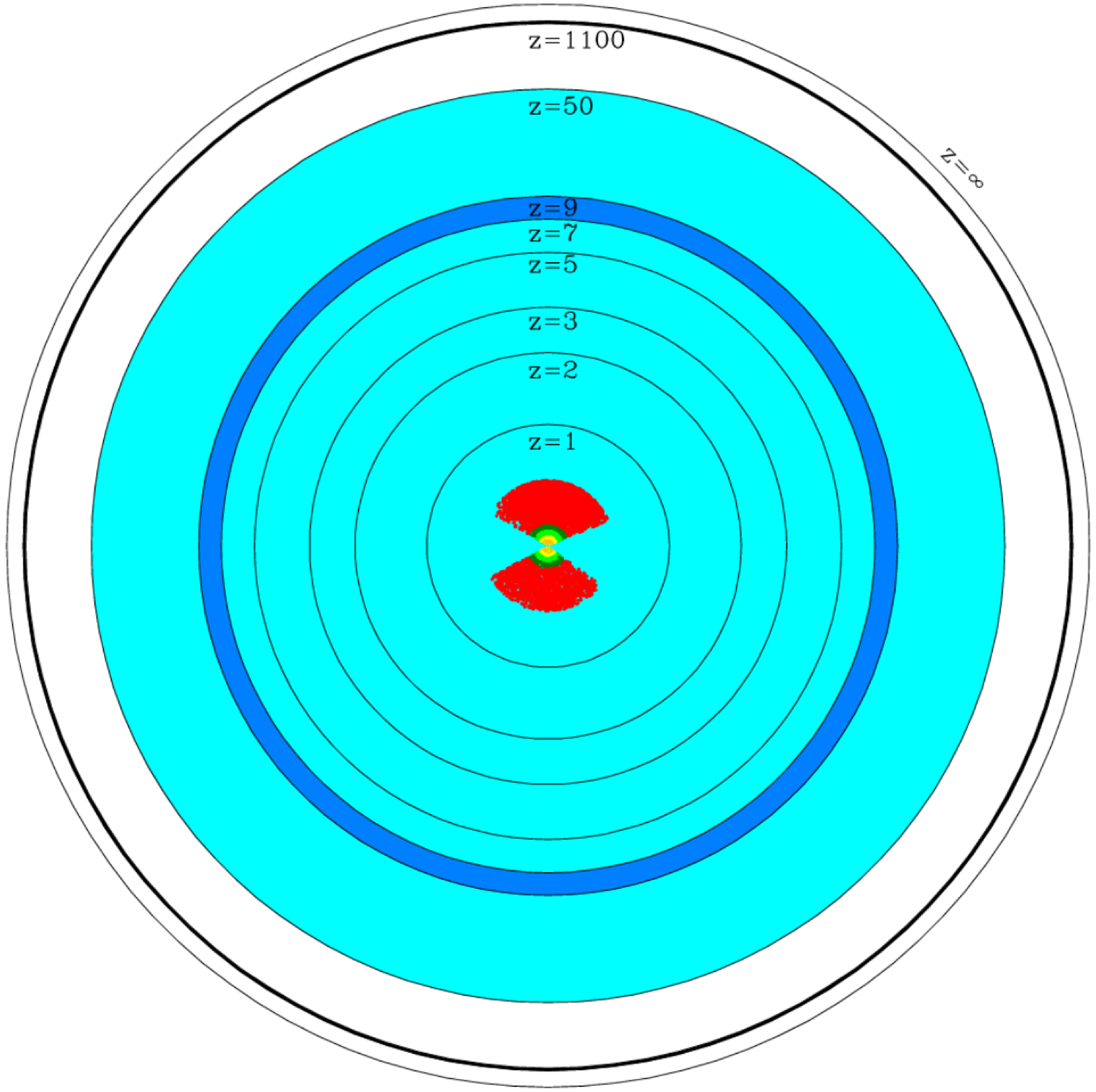
Pushing the limits: 21cm cosmology during the dark ages

- Well understood physics: 30 < z < 150 (10 – 45 MHz)
- Need to go to space (Moon?)
- Huge number of linear modes available:

$$N_{21cm} \sim 3\times10^{16}(l_{max}/10^6)^3(\Delta\nu/\nu)(z/100)^{-1/2}$$

$$N_{cmb} = 2l_{max}^2 \sim 2\times10^7(l_{max}/3000)^2$$

- $\Delta\Omega_k \approx 0.0002$; $\Delta m\nu \approx 0.007$ eV; σ(fNL) ≲ 10−5; high sigma detection of the spectral index running; dark matter properties



Yi Mao, et al. 2008
Loeb and Zaldarriaga, 2003

Summary

- HI intensity mapping with MeerKAT/SKA 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 and auto detections with the interferometer – time to start fitting those theories!
- Dealing with low level systematics is the main challenge
- HI intensity mapping at very high redshifts can be the ultimate cosmology probe – need to go to space/moon
- More results coming soon. Exciting times ahead!

Thank you Subir!

Symposium on Science at PAUL (Paarl Africa Underground Laboratory)

Jan 14 – 18, 2024
Du Kloof Lodge, Du Toitskloof Mountains
Africa/Johannesburg timezone

https://indico.cern.ch/event/1316503
https://arxiv.org/abs/2306.12083

- Overview
- Venue and Accommodation
- Registration
- Important dates
- Call for Abstracts
- Announced Speakers
- Excursions and social programme

The Paarl Africa Underground Laboratory (PAUL) is envisaged being established off the Huguenot Tunnel in the Du Toitskloof Mountains, between the towns of Paarl and Worcester in the Western Cape Province of South Africa. PAUL is envisaged to be an underground laboratory with a floor space of about 600 square metres and a total volume of 10240 cubic metres, Ref: arXiv:2306.12083 [hep-ex]

The following are some of the research topics being considered at PAUL:

- Dark Matter search
- Ultra-low level radioactivity measurements for climate science
- Double beta-decay search
- Radiation biology
- Studies of antineutrinos from the Koeberg PWR (about 70 km away)