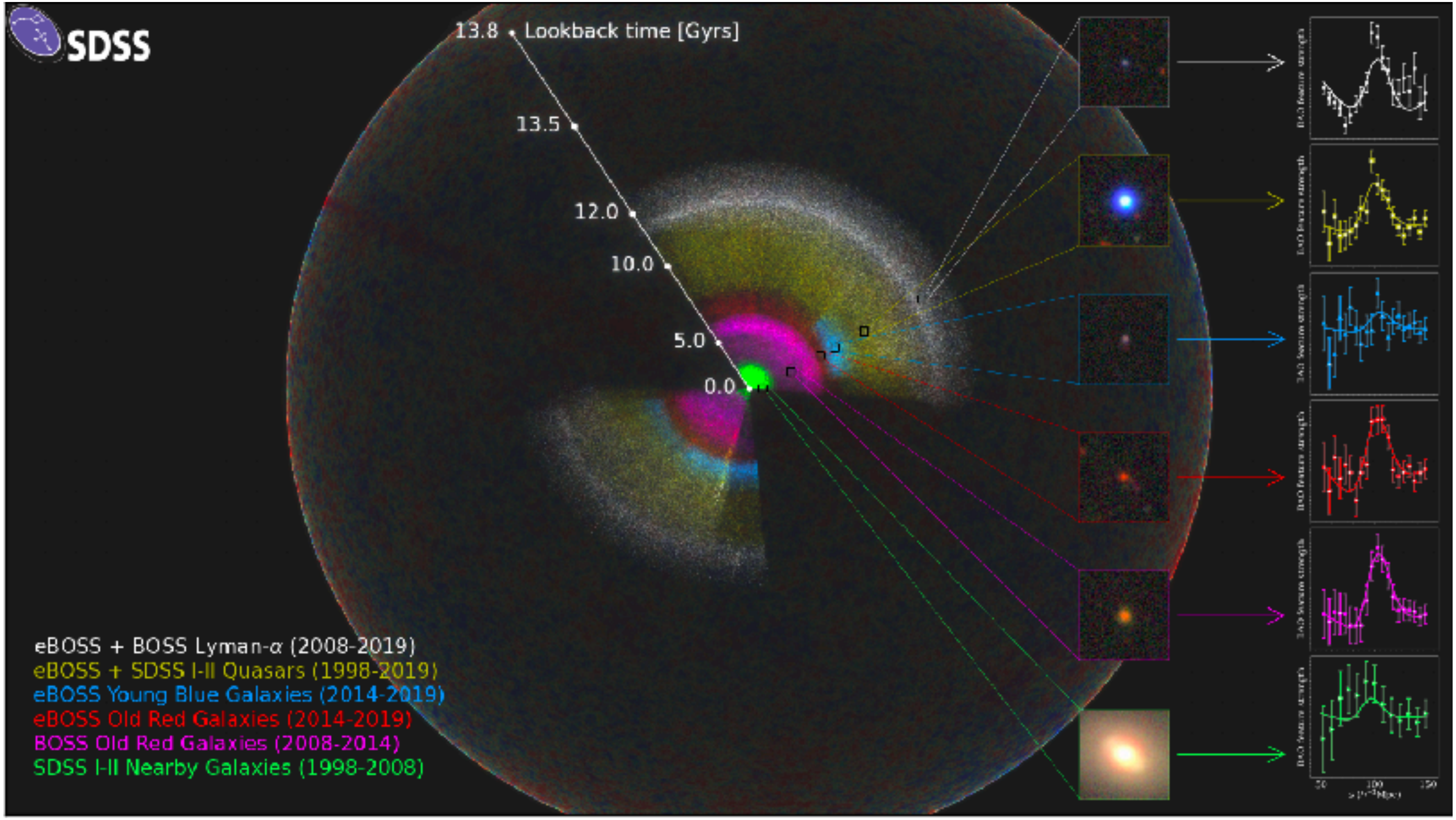
Neutral Hydrogen Intensity Mapping in the post-reionization Universe

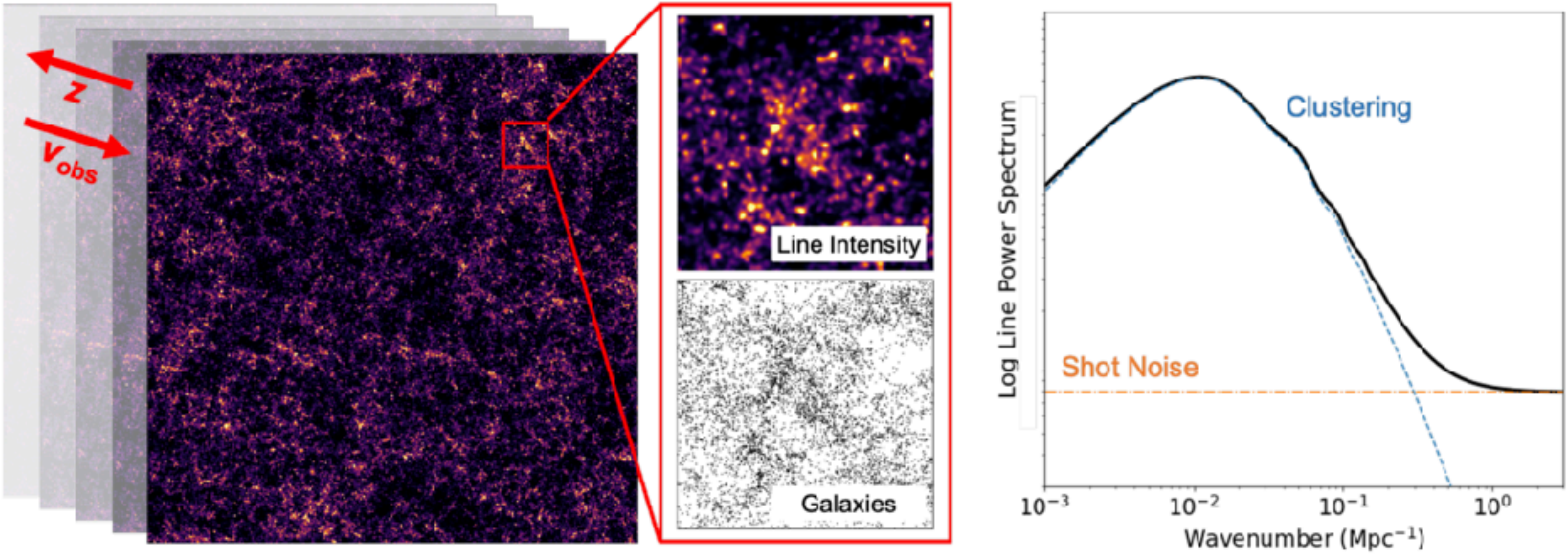
Sourabh Paul

Jodrell Bank Centre for Astrophysics

University of Manchester, UK.

3D map of the Universe

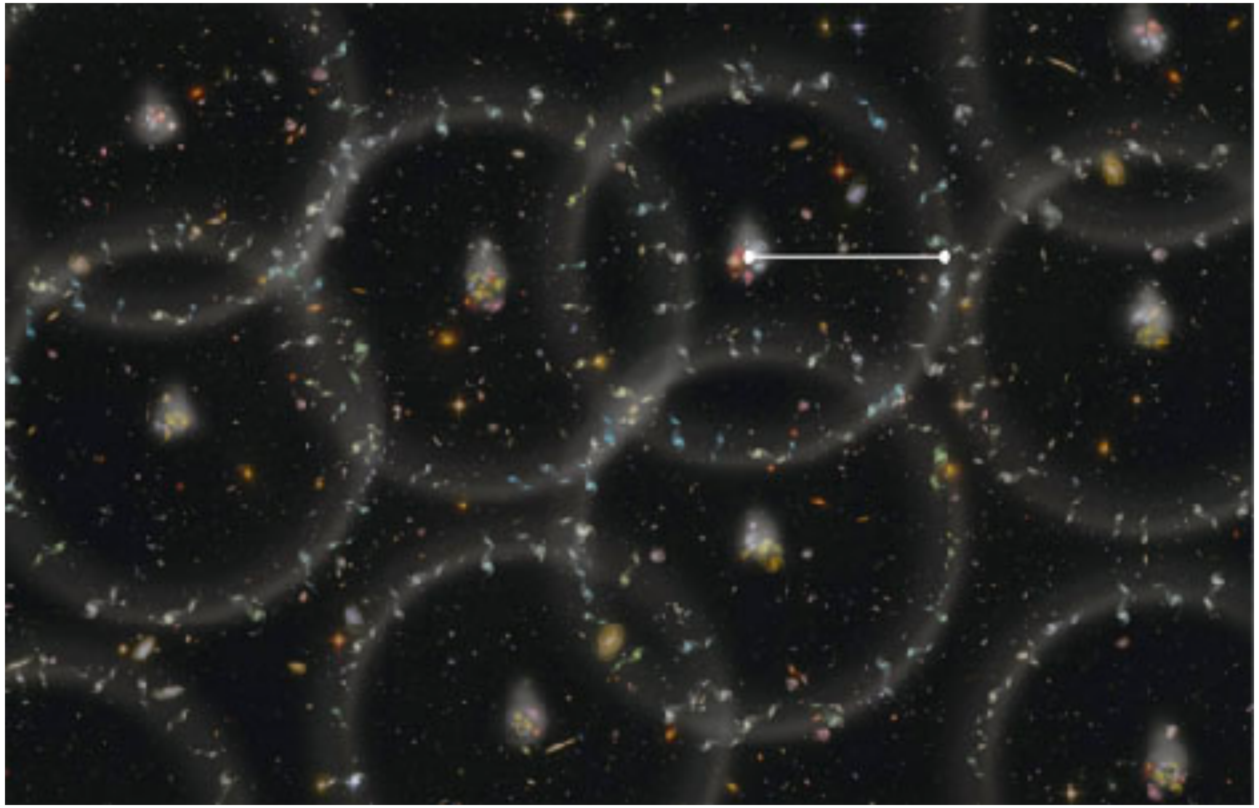




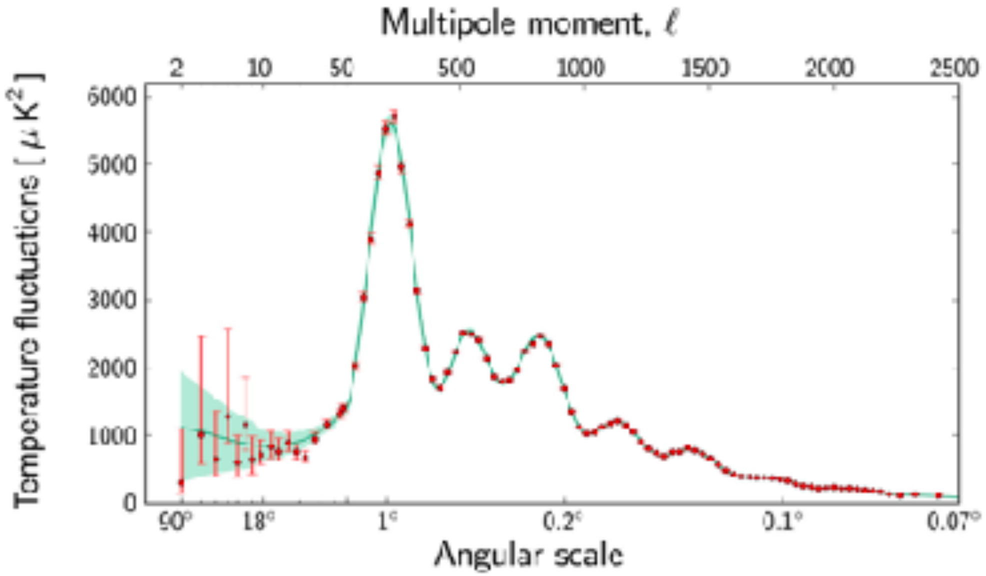
Schematic of a 100 deg^2 line-intensity map
(Aguirre et al. 2022, arXiv:2203.07258)

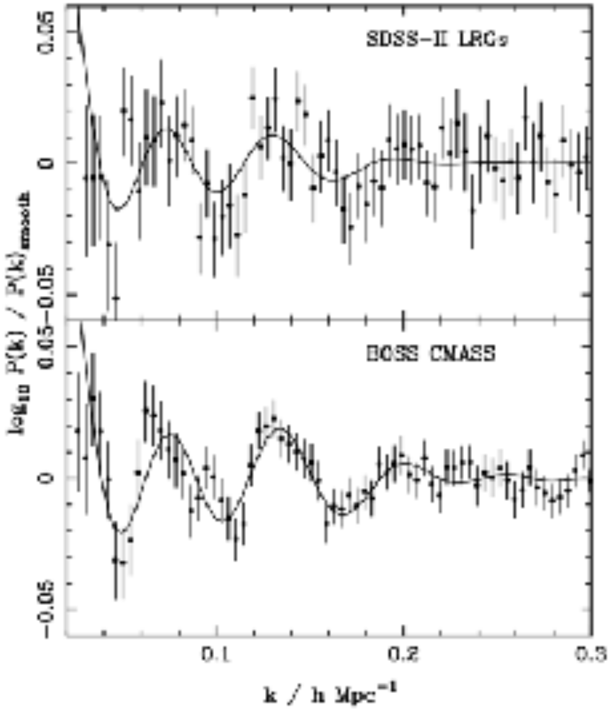
- Dark energy
- Age, Geometry, expansion rate
- Early Universe
- Growth and evolution of structure

Baryon Acoustic Oscillation



A cartoon produced by the BOSS project showing the spheres of baryons around the initial dark matter clumps

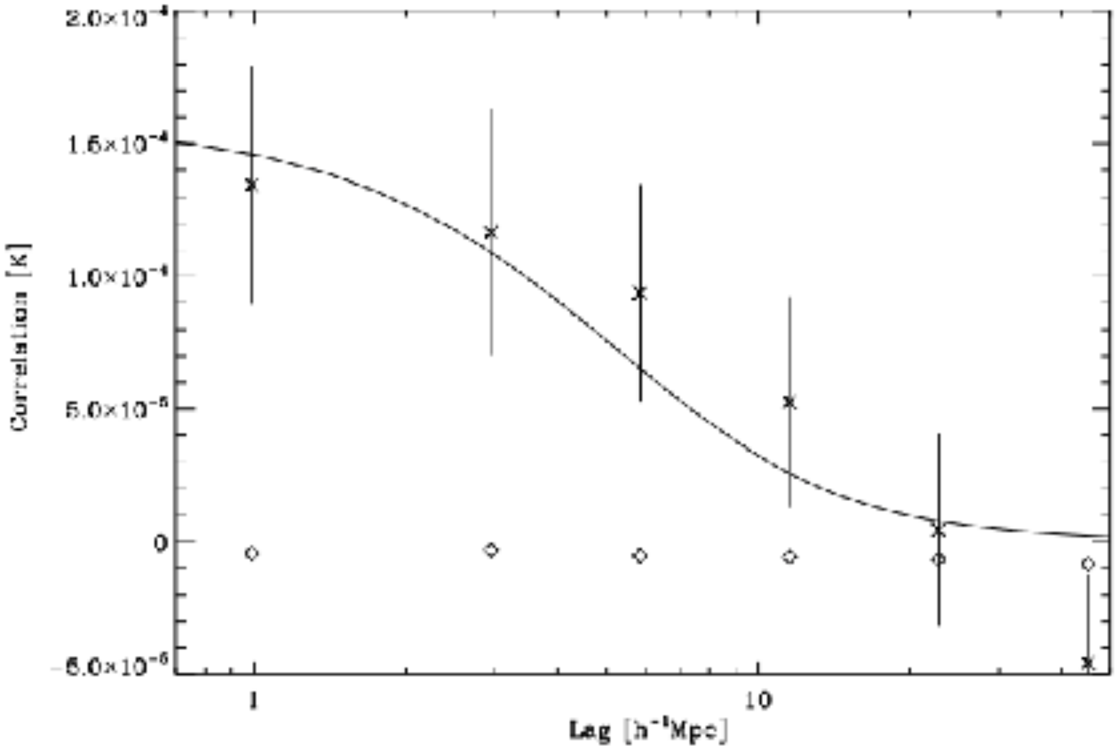




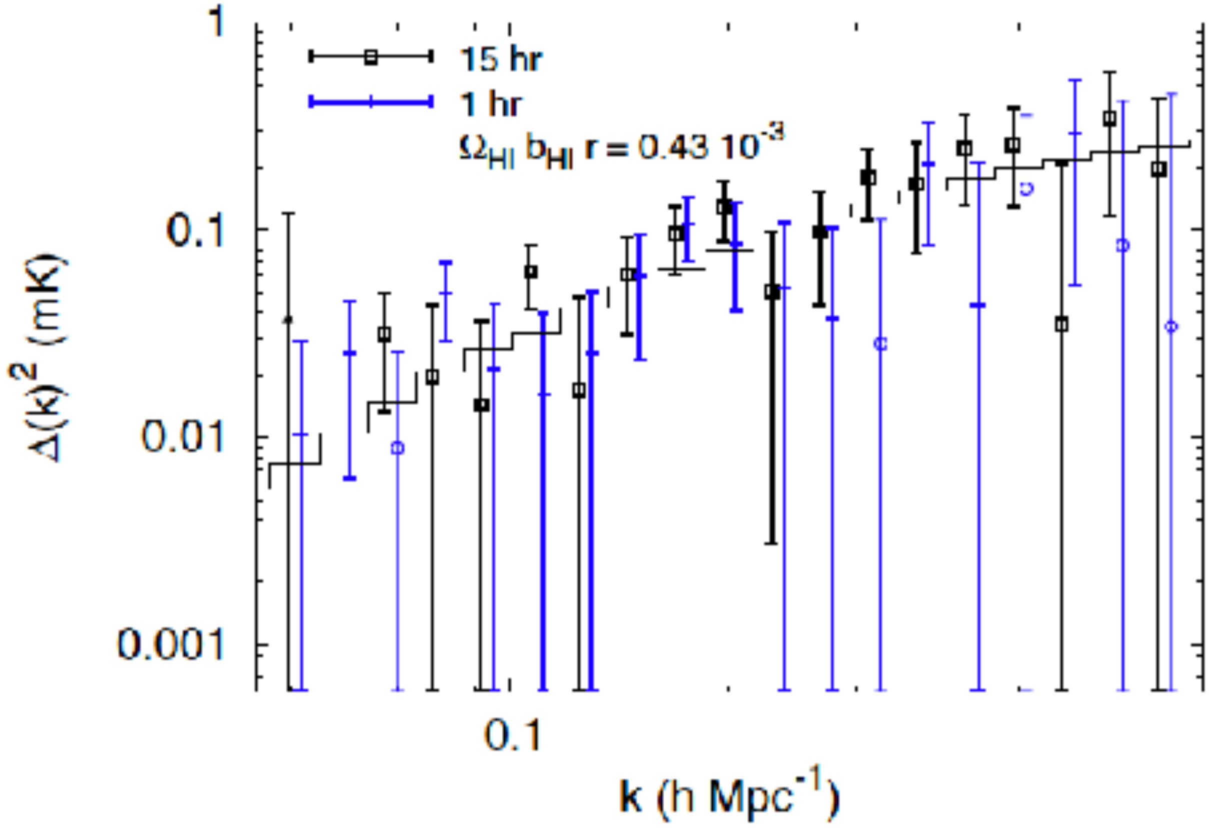
Challenges in HI Intensity Mapping

- **Sensitivity**: limiting factors are noise, interference from other sources (RFI), quality of data
- **Foregrounds**: 21cm signal is intrinsically weak compared to astrophysical foregrounds, small k modes are contaminated.
- **Calibration**: requires precise calibration to ensure that the measurements are accurate.
- **Data processing and storage**: data volumes produced by HI intensity mapping surveys can be enormous, making data processing and storage a significant challenge.
- **Computational challenges**
- **Instrumental effects**

DETECTIONS IN CROSS-CORRELATION

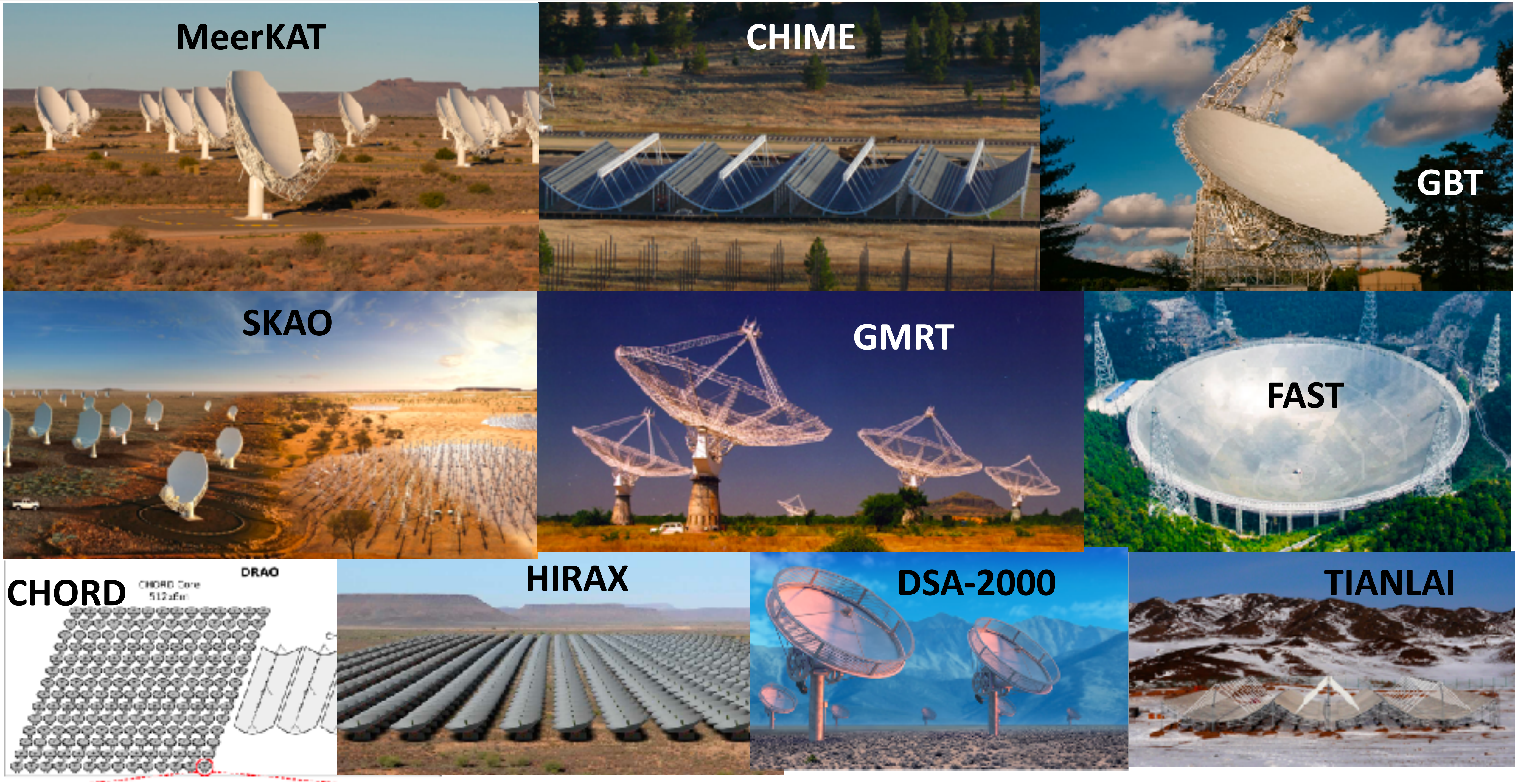


GBT observations X DEEP2 optical galaxy survey at z ~ 0.8 (Chang et al. 2010)

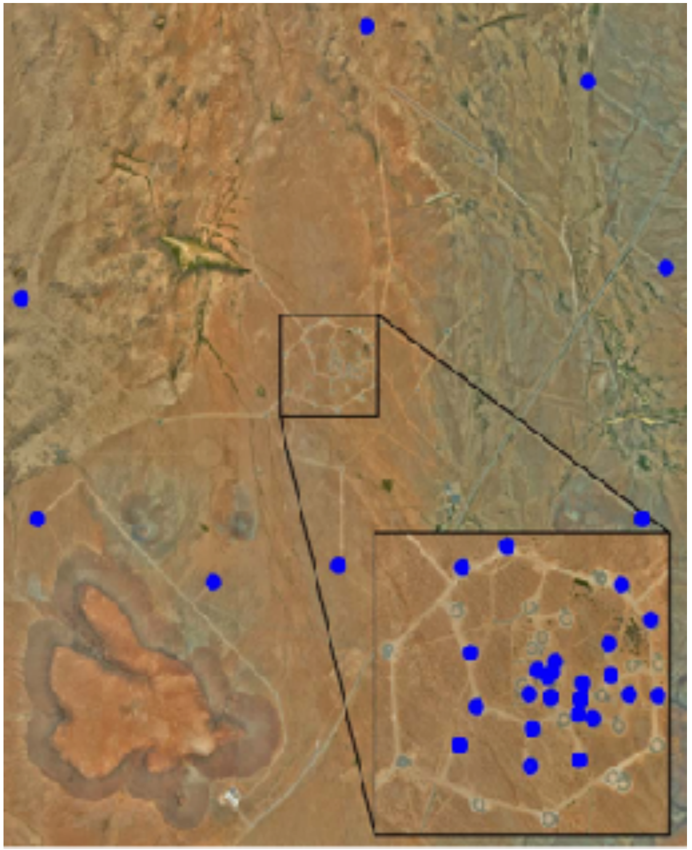


GBT observations X WiggleZ Dark energy survey at z ~ 0.8 (Masui et al. 2013)

Current and Future Intensity Mapping experiments



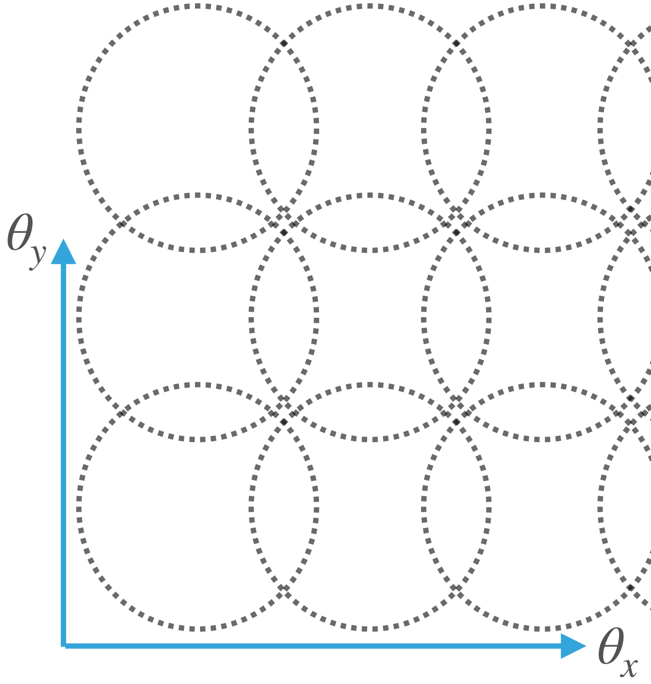
MeerKAT Radio telescope



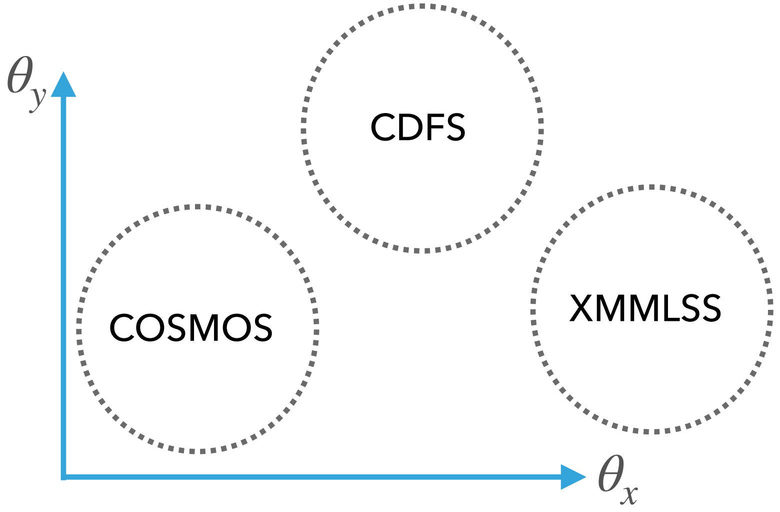
- MeerKAT, precursor to SKA, managed by SARAO. Located in the Karoo region, South Africa.
- 64 dish antennas of 13.5 meter diameter.
- Central core region of 1km houses 48 antennas, other 16 antennas are distributed upto a radius of 4km from the center.
- Dense core facilitates higher sensitivity at low $k_\perp$ modes.
- L-band range: 856 ~ 1712 MHz.
- UHF-band range: 544 ~ 1087 MHz.

(https://www.sarao.ac.za/gallery/meerkat/)

Single Dish & Interferometric IM (MeerKAT)

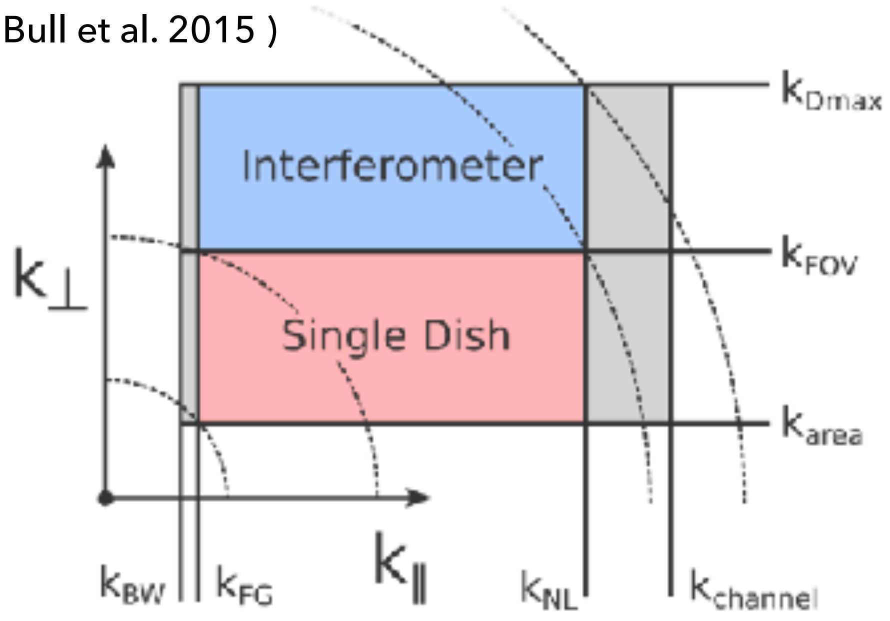


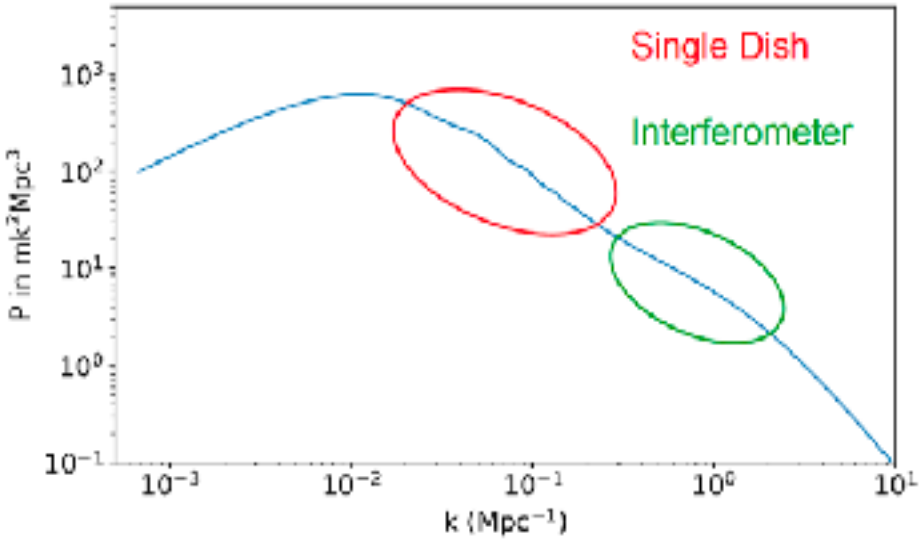
Single Dish



Interferometer

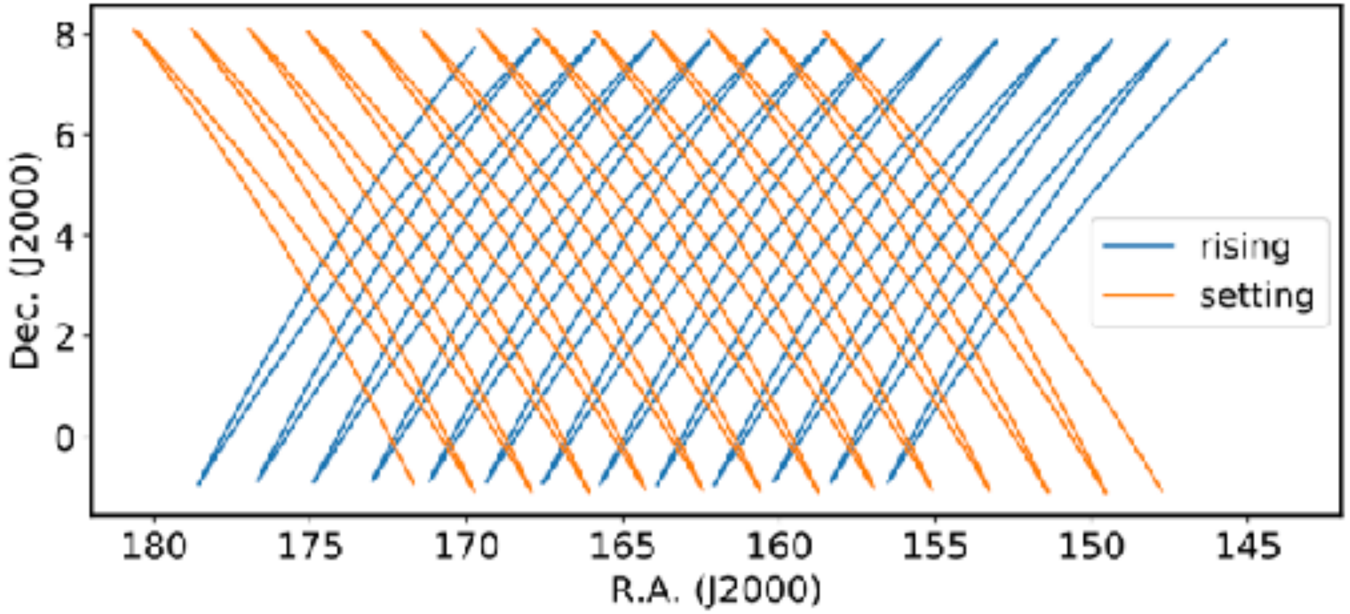
(Bull et al. 2015)

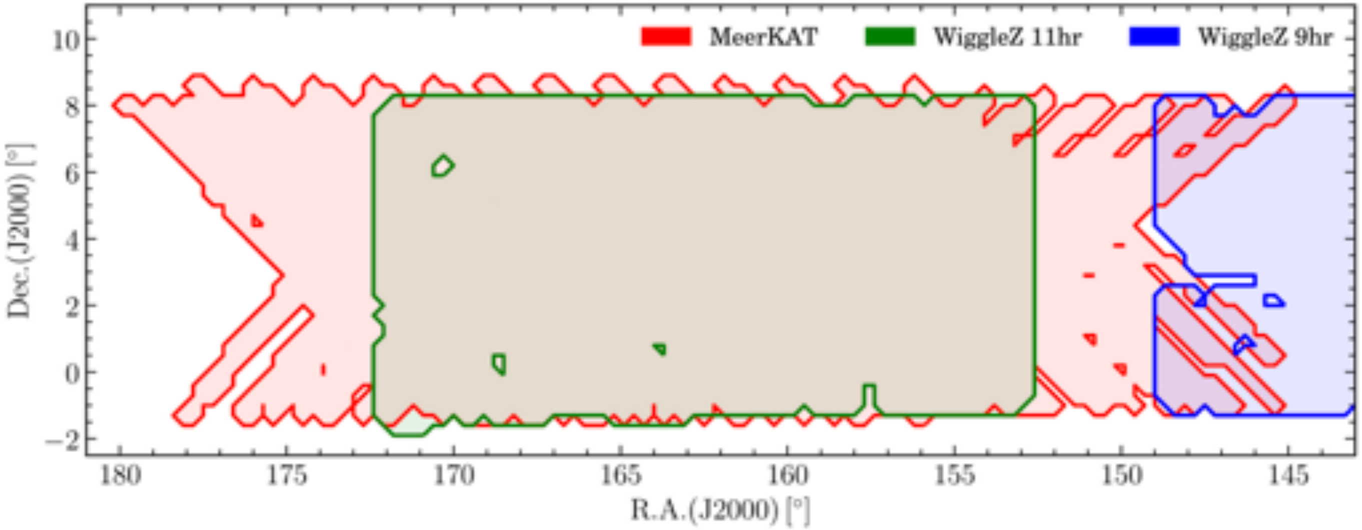


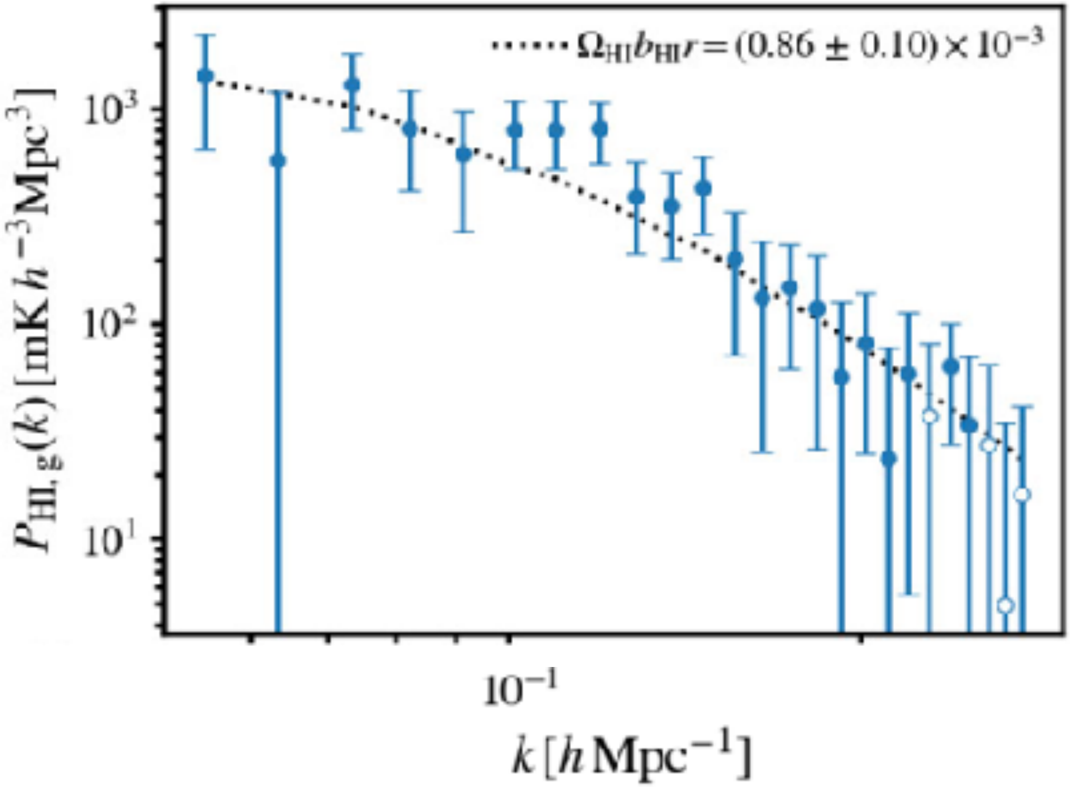


MeerKLASS (MeerKAT Large Area Synoptic Survey)

(Wang et al. 2021)

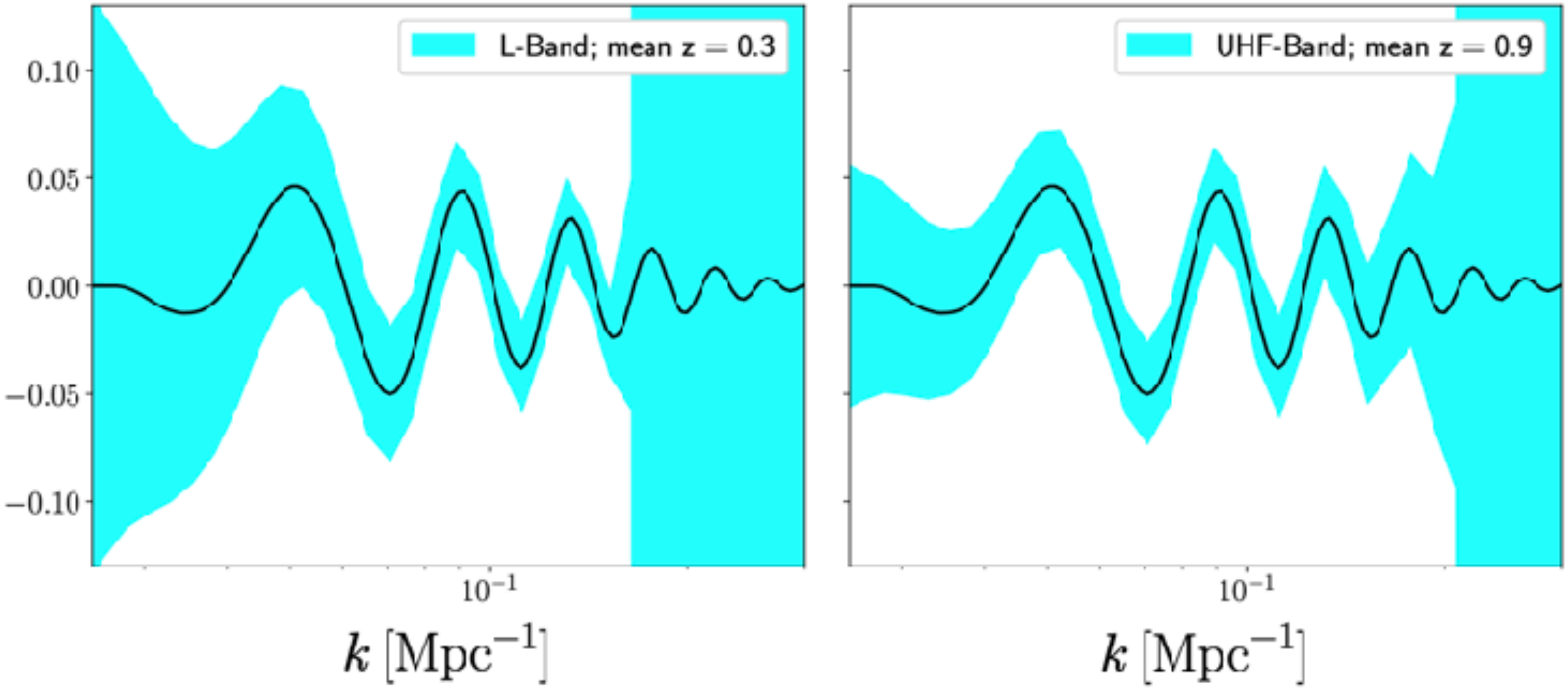






(Cunnington et al. 2022)

MeerKLASS (MeerKAT Large Area Synoptic Survey)



Santos et al (2017), BAO detection forecasts (4,000hr)

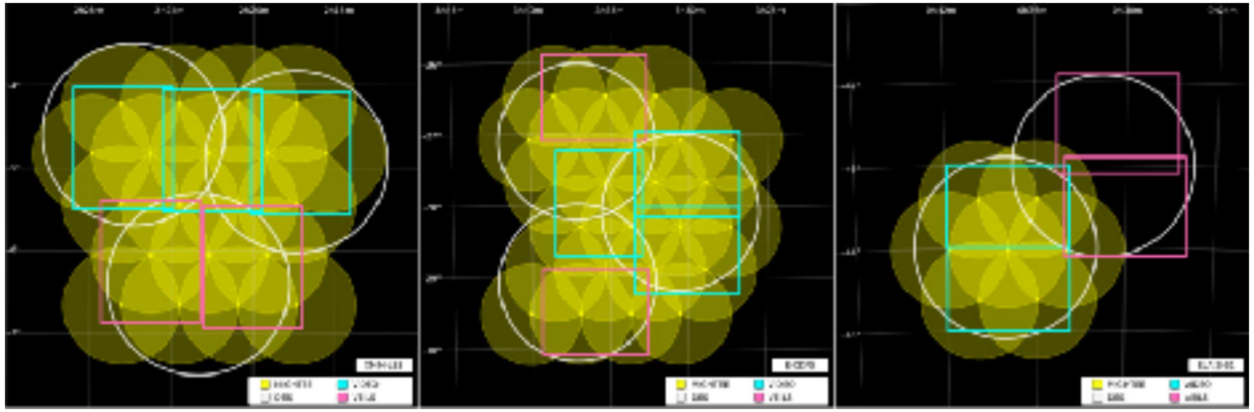
2500 hr in UHF band approved

Intensity Mapping in Interferometric mode

MIGHTEE

(MeerKAT International GHz Tiered Extragalactic Exploration)

- 20 square deg sky area, L and UHF bands
- COSMOS, CDFS, XMMLSS, ELAIS-S1, ~ few thousand hours



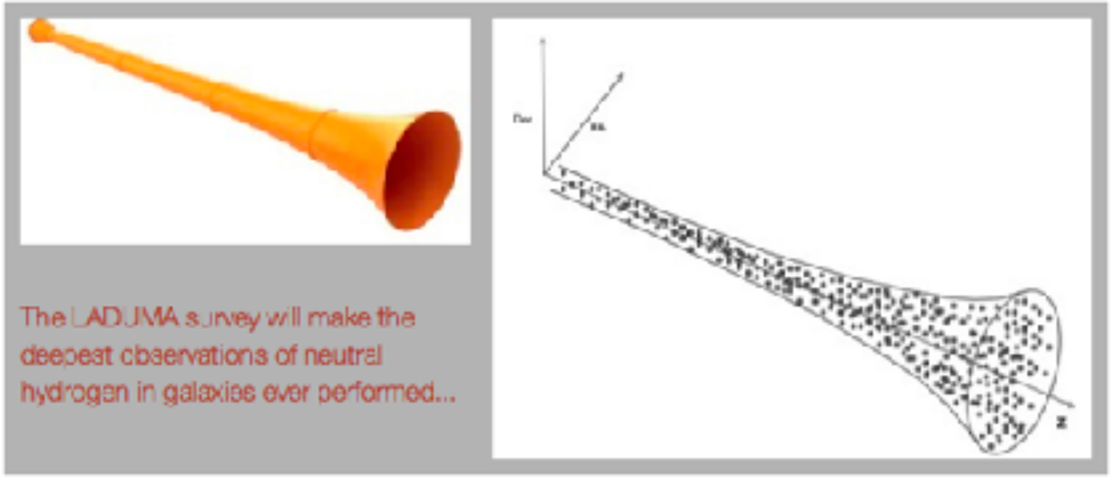
XMMLSS CDFS ELAIS-S1

https://www.mighteesurvey.org/

LADUMA

(Looking at the Distant Universe with MeerKAT Array)

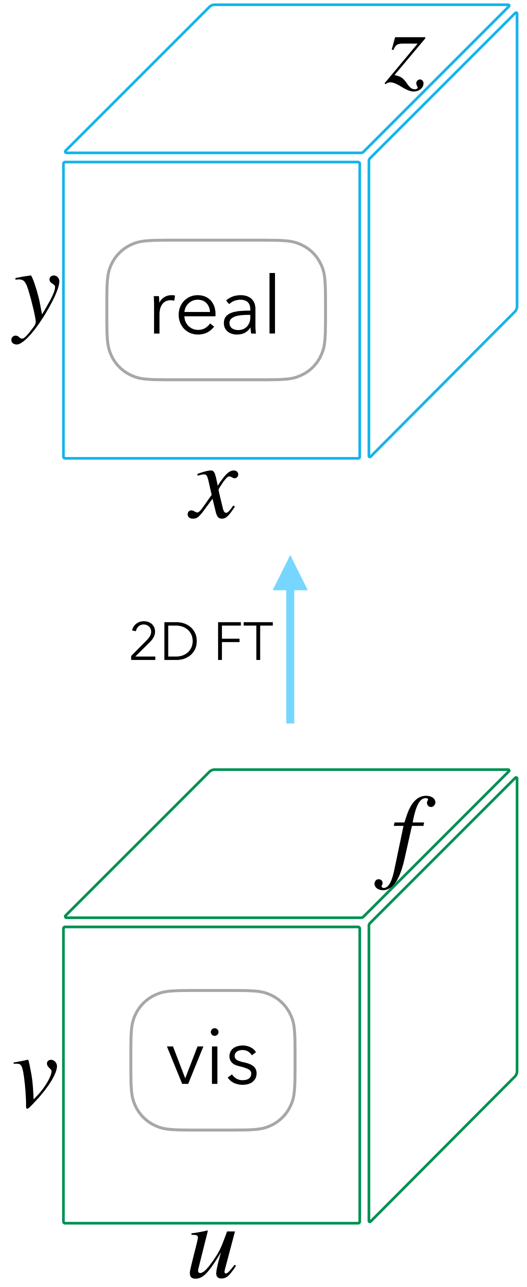
- E-CDFS field, ~ few thousand hours
- L and UHF bands

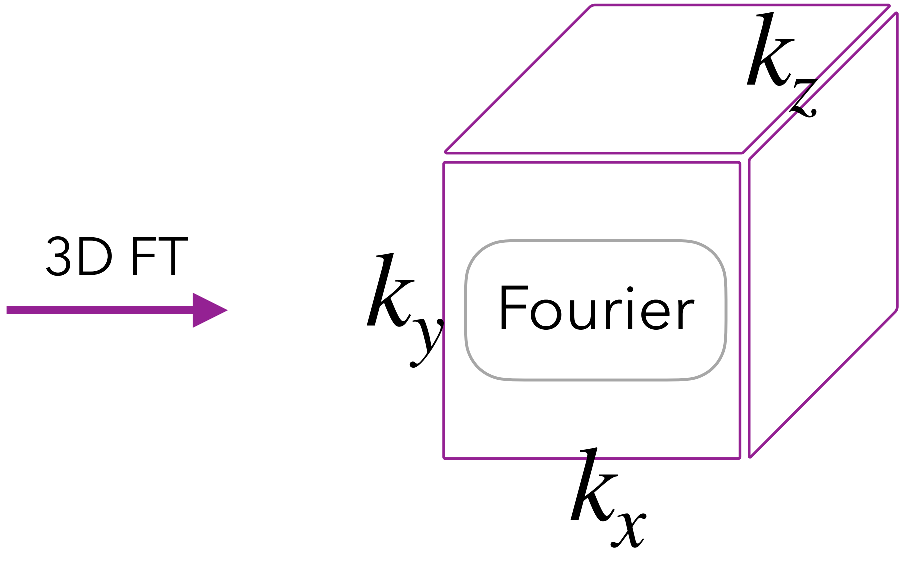


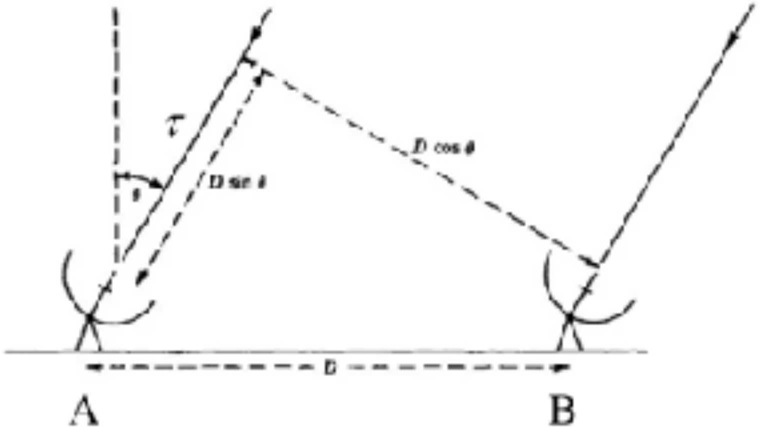
The LADUMA survey will make the deepest observations of neutral hydrogen in galaxies ever performed...

https://science.uct.ac.za/laduma

Interferometric IM, Power Spectrum from visibility data

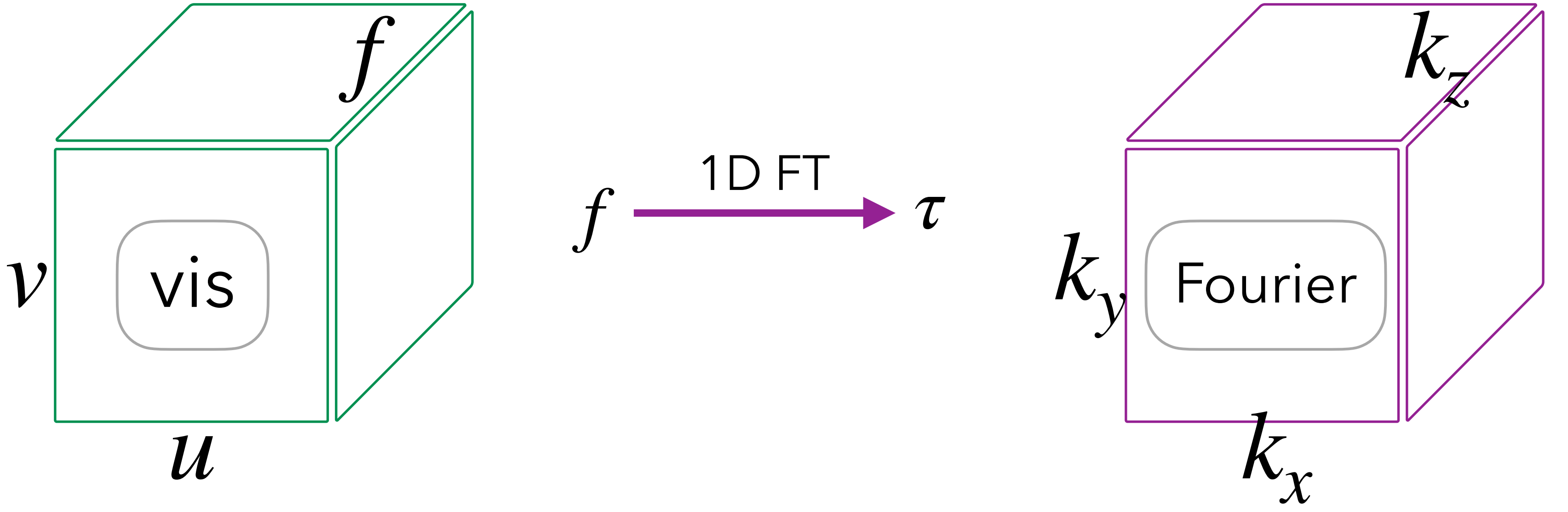






$$I(l,m) = \int\!\!\int V(u,v)\, e^{-2\pi i(ul+vm)} du\, dv$$

Power Spectrum from visibility data

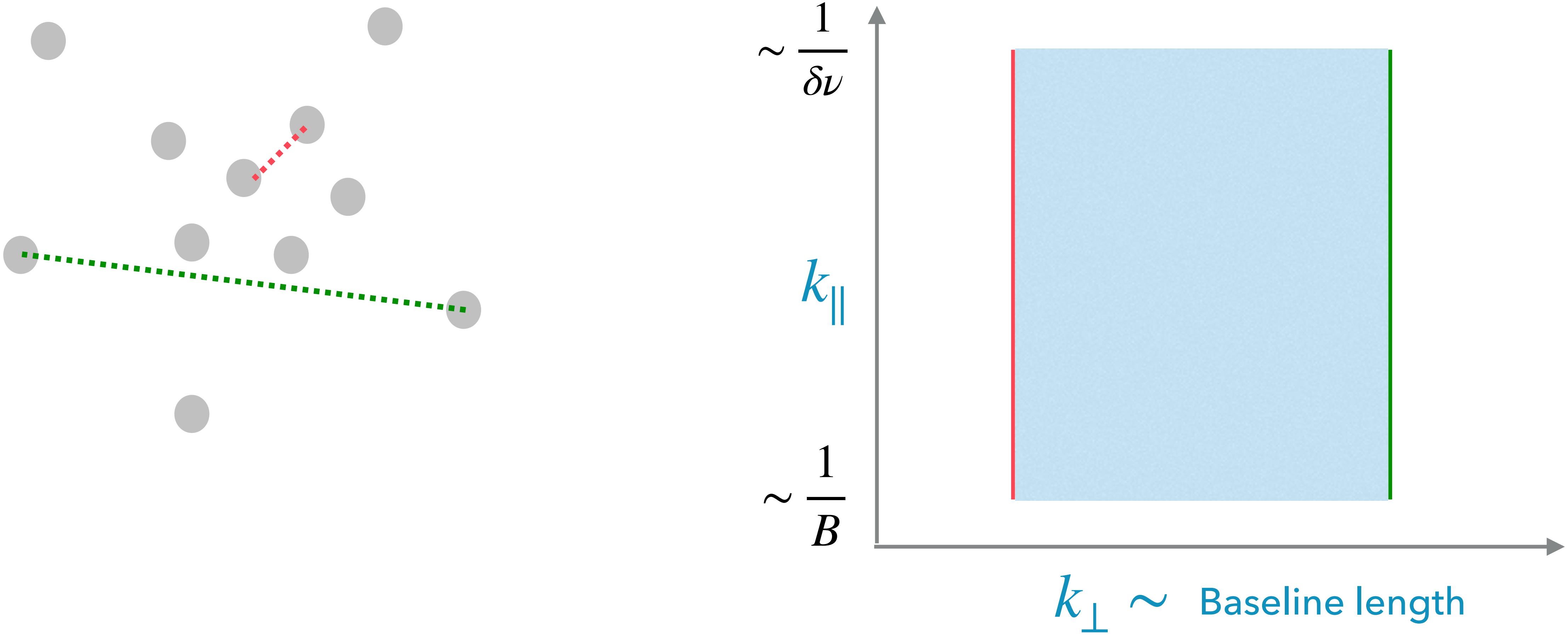


$$k_x = \frac{2\pi}{R} u \; ; \qquad k_y = \frac{2\pi}{R} v \; ; \qquad k_{\parallel} = \frac{2\pi \nu_{21} H_0 E(z)}{c(1+z)^2} \tau$$

Delay PS

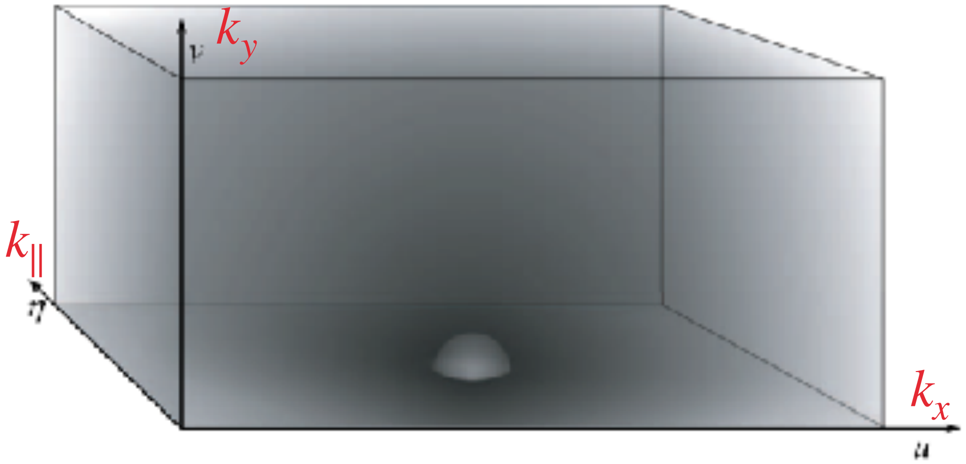
$$P\left(k_{\perp}, k_{\parallel}\right) \equiv \frac{A_e}{\lambda^2 B} \frac{R^2 \Delta R}{B} \, |V(u, v, \tau)|^2 \left(\frac{\lambda^2}{2k_B}\right)^2$$

Power Spectrum from visibility data

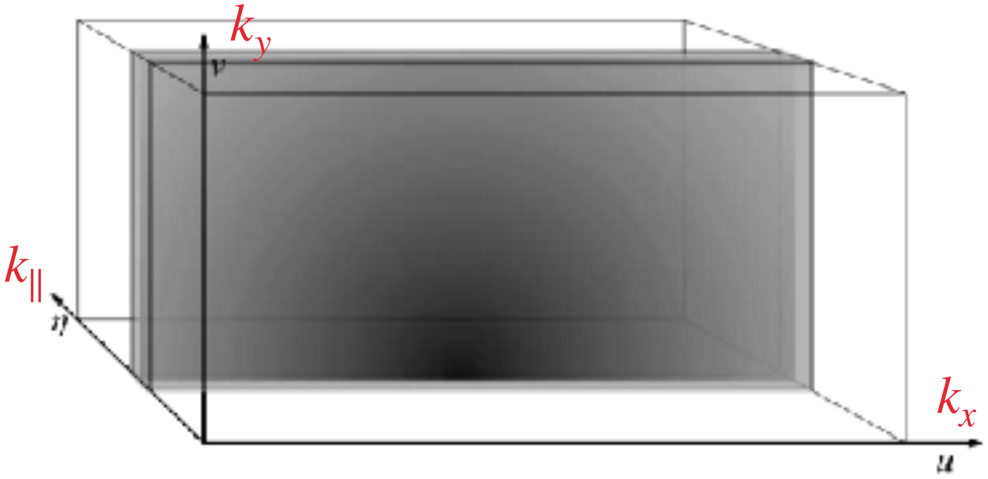


FOREGROUND ISOLATION

HI



Foreground



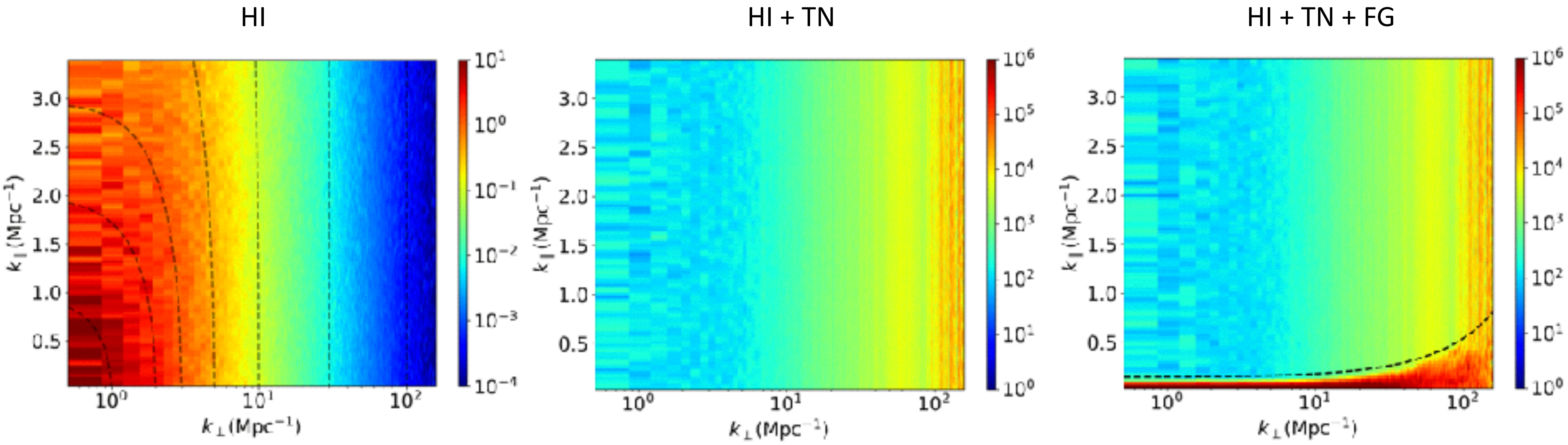
(Morales & Hewitt 2004)

The Cosmological 21cm signal is symmetric in Fourier space.

Foregrounds are NOT.

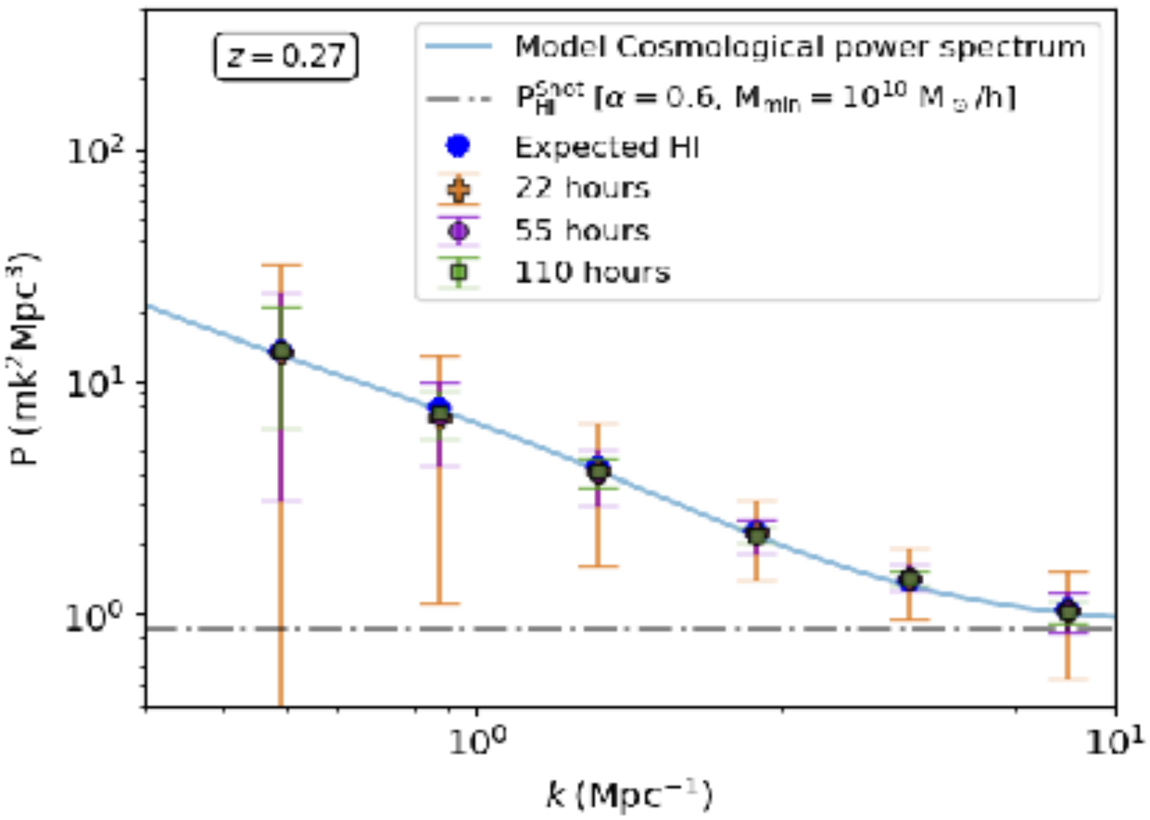
IM with MeerKAT interferometer

2d Power spectrum, 11.2 hours: $P(k_\perp, k_\parallel)$ [mk²Mpc³]

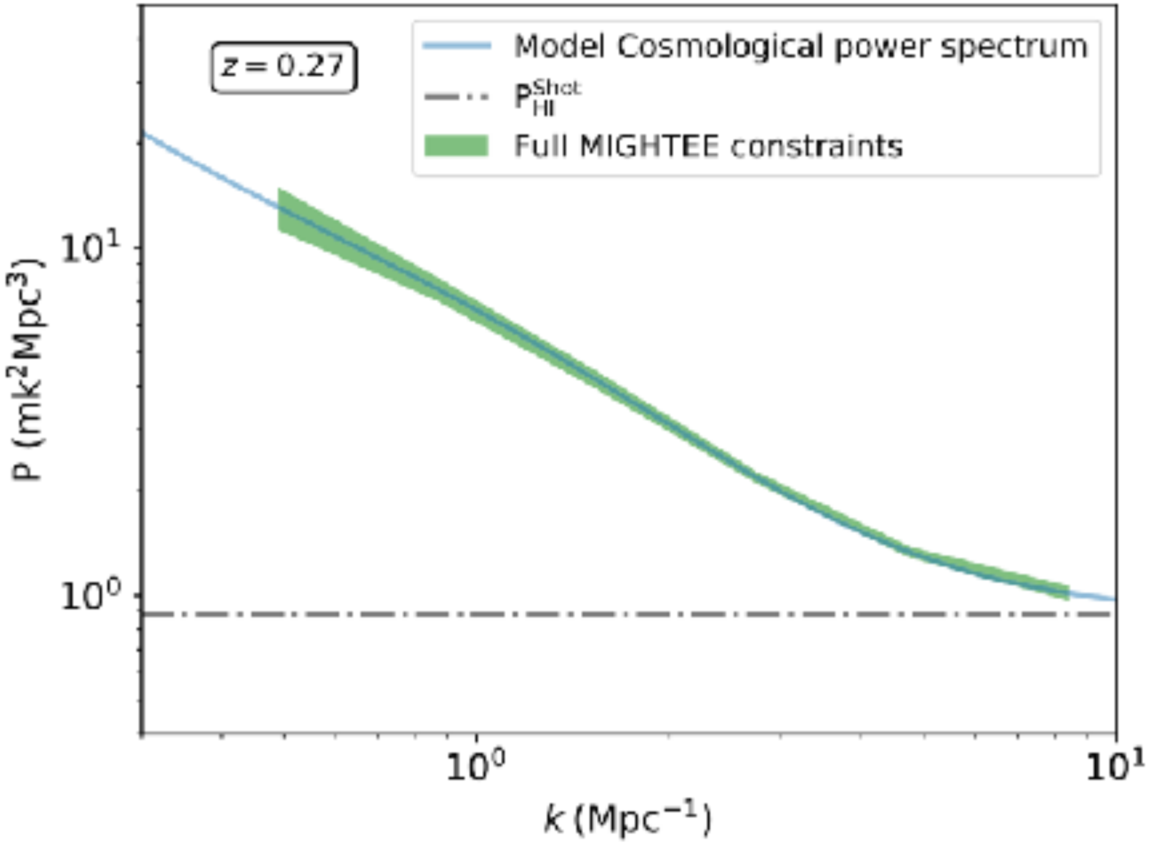


HI intensity mapping with the MIGHTEE survey: power spectrum estimates
Paul, Santos et al., 2021, MNRAS, 505, 2, 2039

IM with MeerKAT interferometer



Expected constraints on HI PS with MIGHTEE (COSMOS)



Full MIGHTEE (COSMOS, CDFS, XMMLSS, ELAIS-S1)
20 square degrees, ~ 1000 hrs observation time

HI intensity mapping with the MIGHTEE survey: power spectrum estimates
Paul, Santos et al., 2021, MNRAS, 505, 2, 2039

IM with MeerKAT interferometer

Long integration time, avoid bright foreground sources

Data used ~ 96 hrs (9 observing sessions, > 58 antennas)

J2000 $\alpha = 04^{\mathrm{h}}13^{\mathrm{m}}26.4^{\mathrm{s}}, \ \delta = -80^{\circ}0'0''$

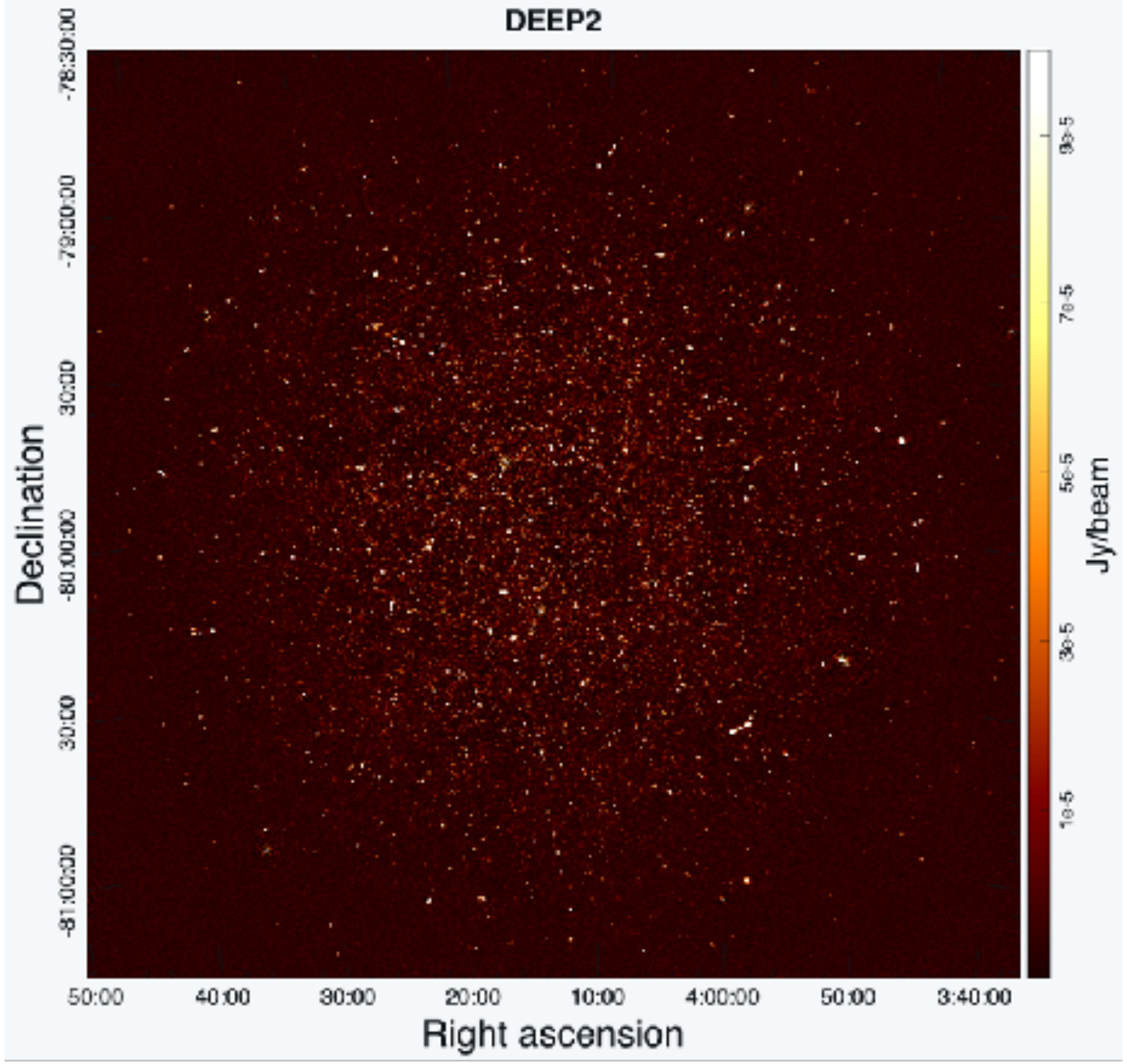
Time resolution: 8s

Frequency resolution: 0.209MHz

Calibration: processMeerKAT + selfcals
Bandwidth: 950 ~ 1170 MHz
RMS: 3 μJy/beam

Target scan duration: 15 mins

Two sub-bands: 1078 MHz (z ~ 0.32)
(46 MHz) 986 MHz (z ~ 0.44)



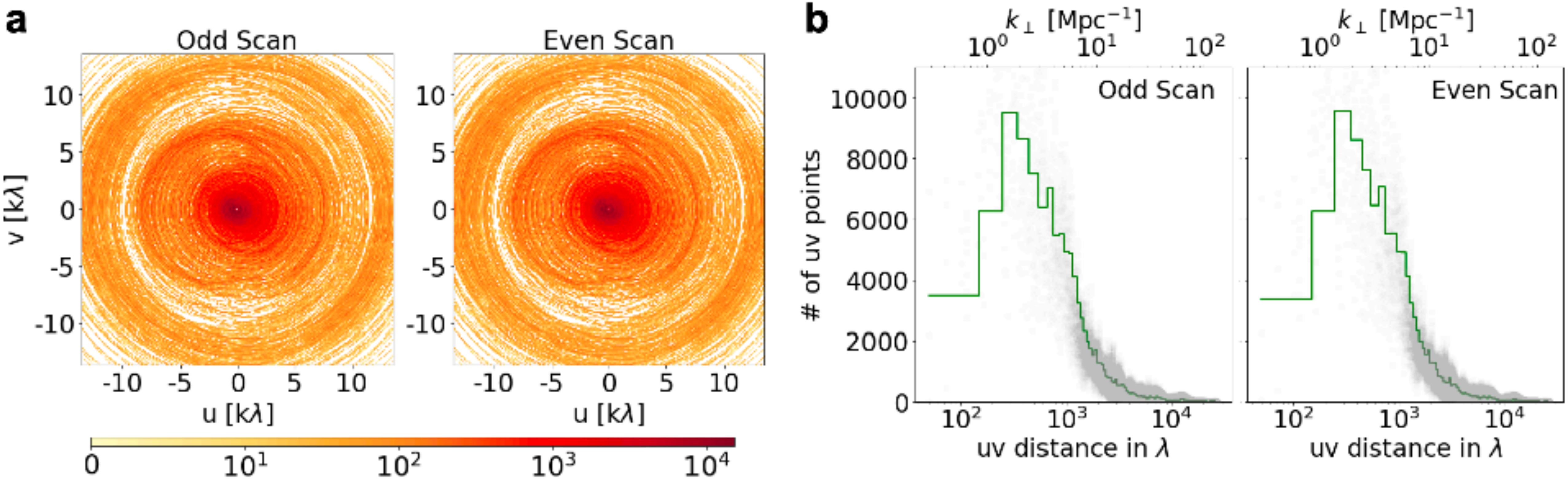
Calibration

1. RFI flagging
2. Primary calibrator to estimate the delay and bandpass solutions (every ~ 3 hours)
3. Secondary calibrator to calculate time dependent complex gains (no frequency dependence on gain solutions; every ~ 15 min)
4. Split data into sub-band: 952 - 1170 MHz
5. 3 rounds of phase only self-calibration with a 60s solution interval (again, no frequency dependence in the gain solutions). Done per night.
6. Visual inspection to check for extra RFI

Power spectrum estimation

1. Split the sub-band into 2 sub-sub-bands of ~ 46 MHz
2. Only use baselines for which the visibility data has at least 80 percent unflagged channels.
3. Bin the visibilities into a grid in the uv plane with the same bin size across u and v (60 lambda).
4. Split the full observation into 2 uv-nu cubes (even - odd)
5. Apply an FFT (w BH window) along the frequency axis for every uv pixel.
6. cross-correlate odd-even cubes, computing the cylindrical 3-d power spectrum. This cross-correlation removes the noise bias in our calculation, and it is also useful to minimize any time-dependent systematics present in the data.
7. Power spectrum values not consistent with the noise are flagged
8. use inverse noise variance weighting to calculate 2d and 1d ps.The 1-d power spectrum is then calculated only using values outside the foreground “wedge”. This guarantees that contamination from point sources, continuum background, systematics, etc is removed

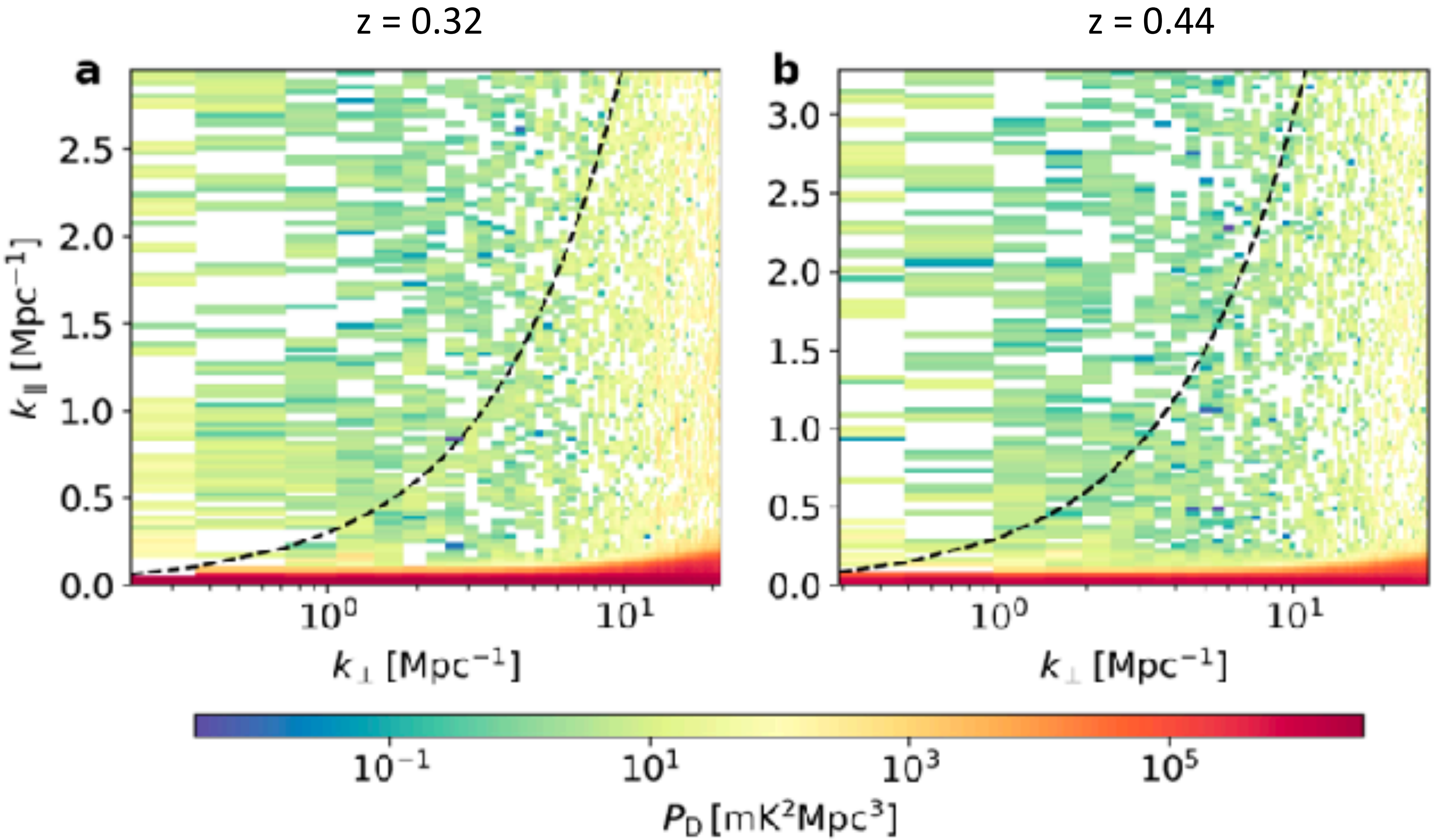
Power spectrum (odd scans vis x even scans vis)



IM with MeerKAT interferometer

Power spectrum (odd scans vis x even scans vis)

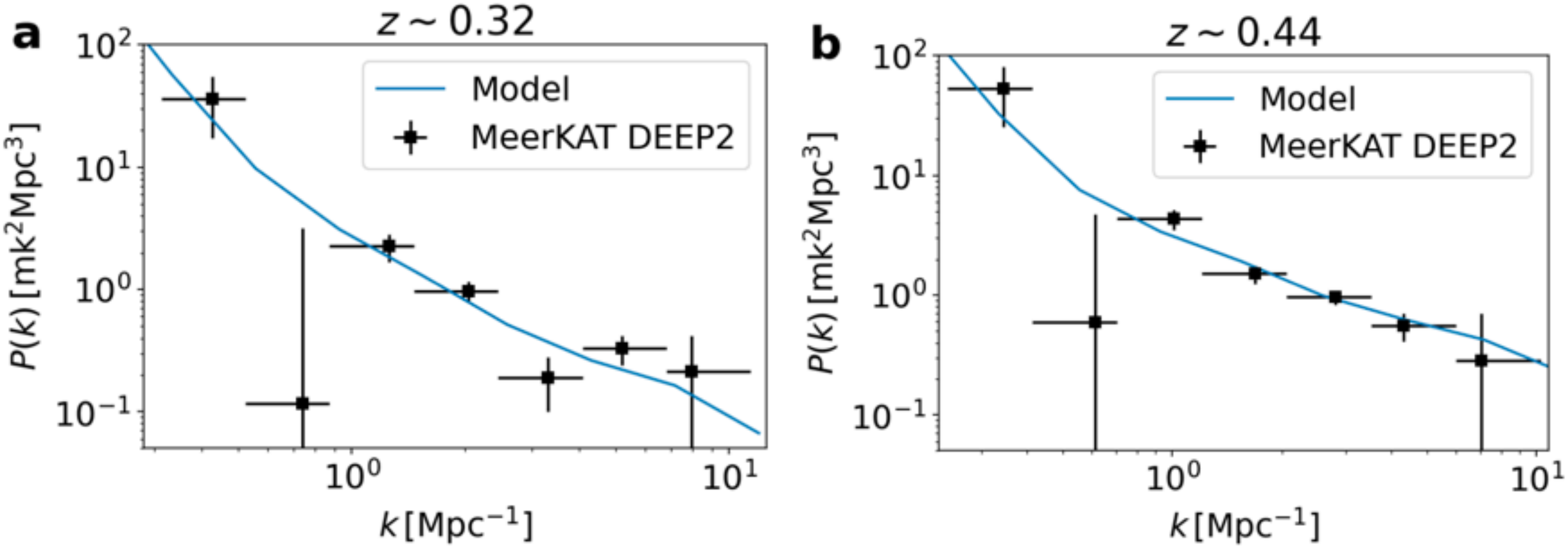
46 MHz band centered at 1077.5 MHz (z = 0.32) and 986 MHz (z = 0.44)



First detection of auto power spectrum

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

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

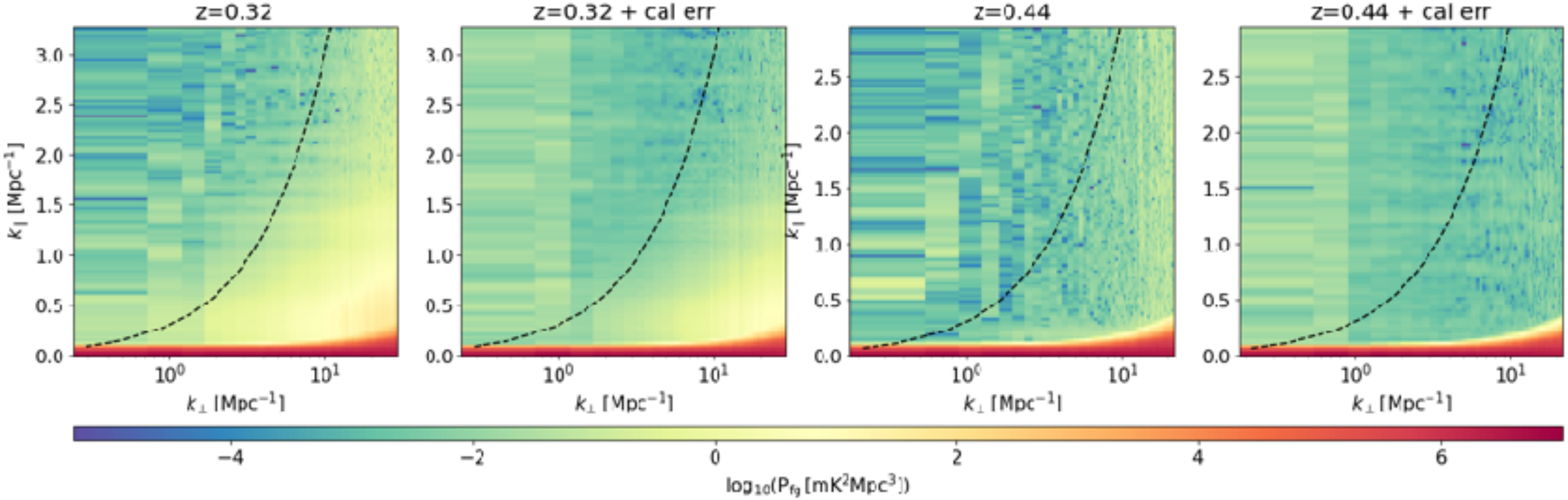


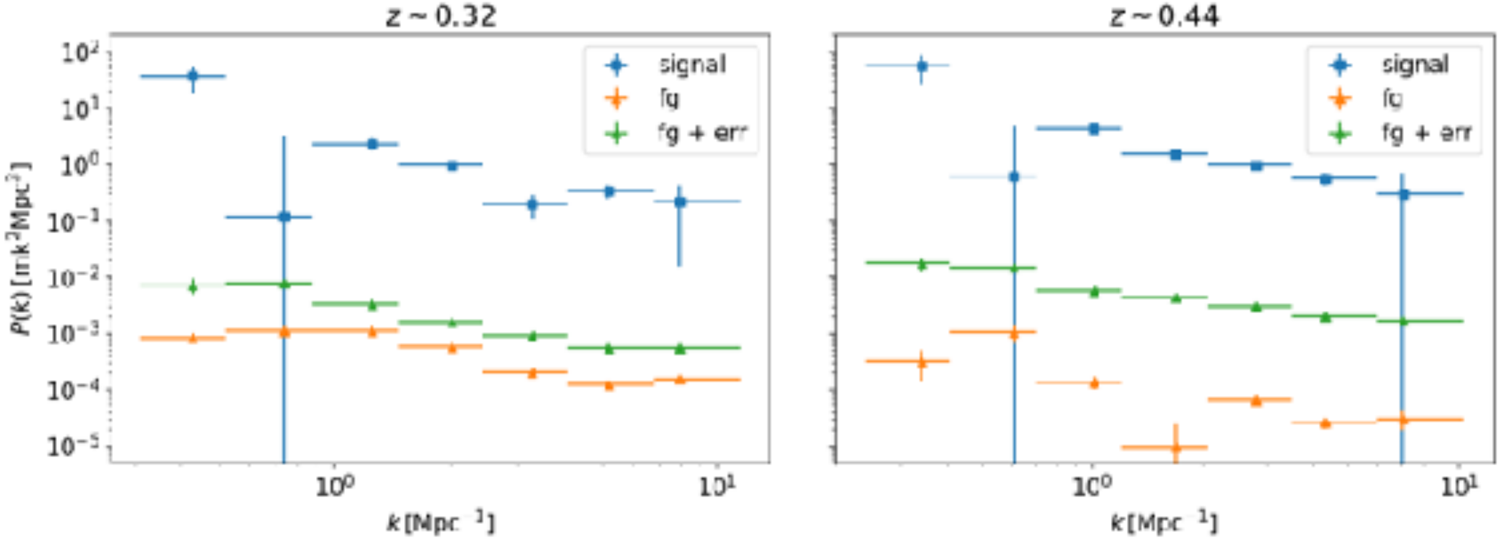
8σ

11.5σ

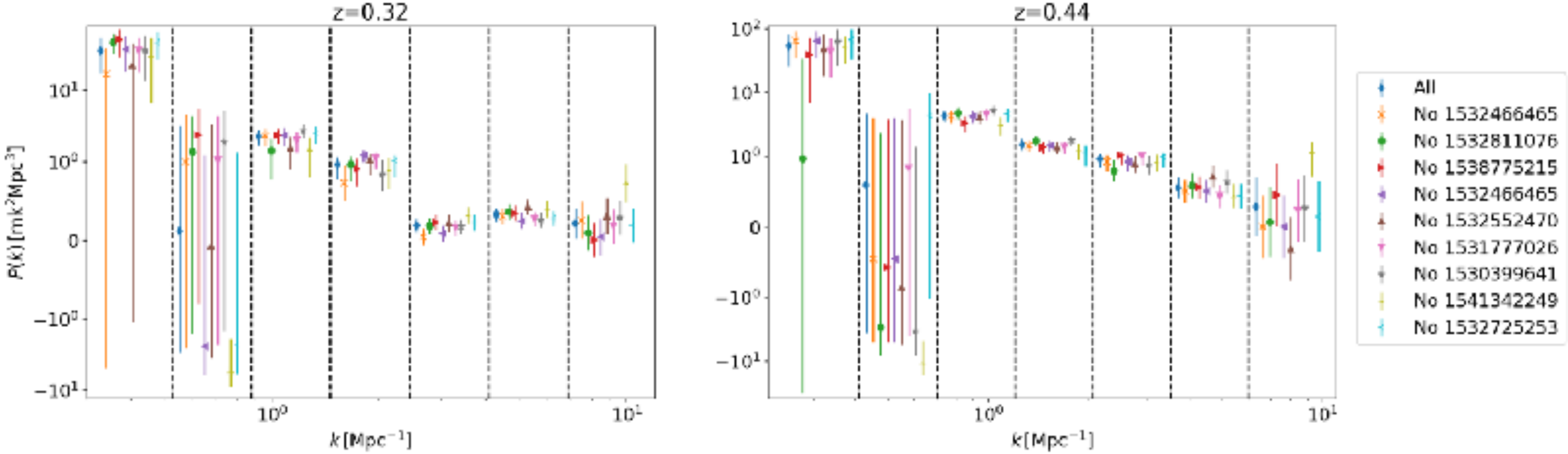
https://arxiv.org/abs/2301.11943

Foreground scatter

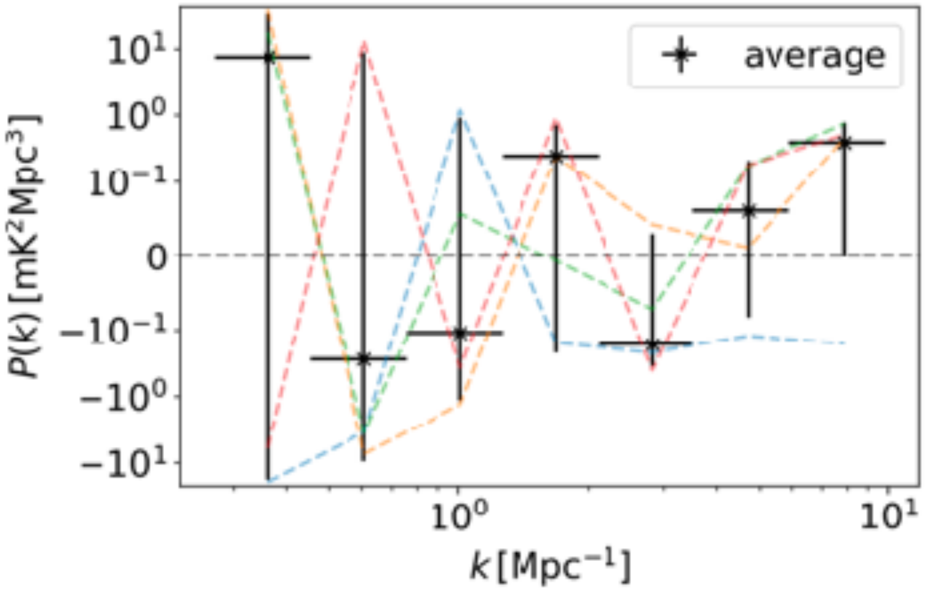




Jackknife test

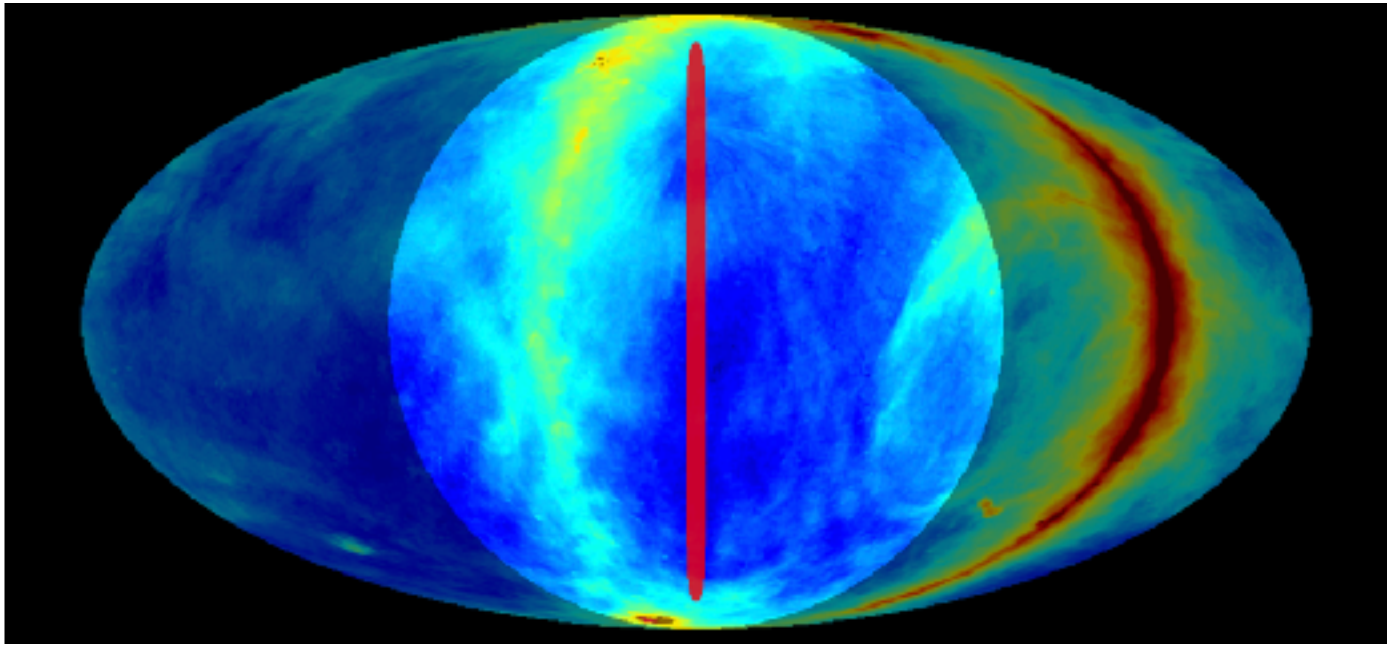


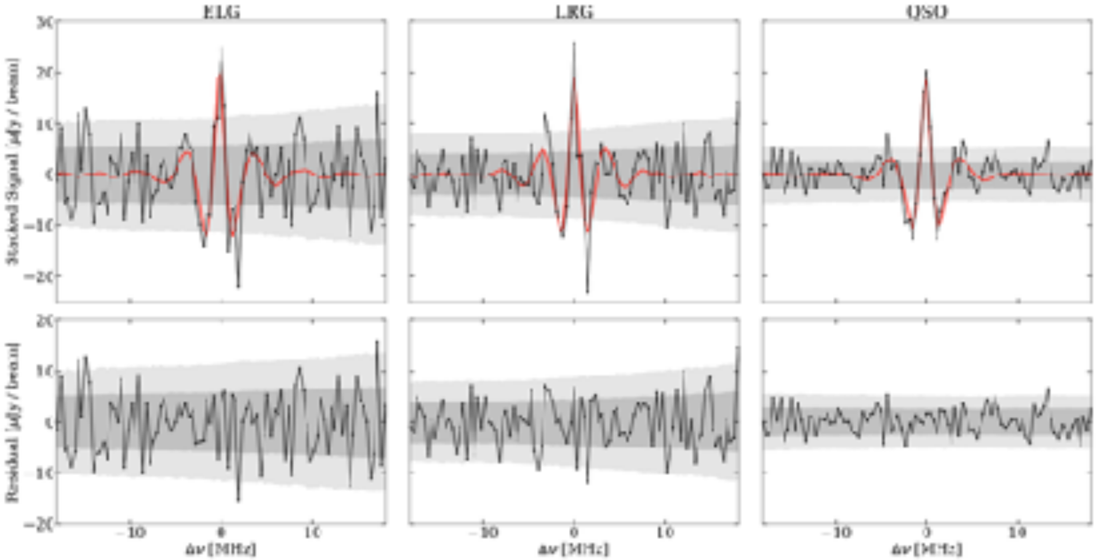
Null test



HI Intensity mapping with CHIME

- DRAO, Penticton, BC, Canada.
- 4 cylinders 20 m x 100 m
- No moving parts
- 256 antennas per axis
- Frequency range 400-800 MHz. Selected for 21-cm cosmology in 0.8 < z < 2.5.





The CHIME Collaboration *et al* 2023 *ApJ* **947** 16

Summary

- 21cm Intensity mapping research is at the forefront of cosmology, with the potential to provide new insights into the large-scale structure of the Universe and the nature of dark energy and dark matter. This is a particularly exciting time in cosmology, with several upcoming surveys and telescopes expected to produce groundbreaking results.

- A number of detections in cross-correlation.

- First detection in auto-correlation with MeerKAT — significant step towards precision cosmology with intensity mapping with new generation of radio telescopes and upcoming SKA.

- Many challenges are yet to overcome, detection are still limited to small scales.

- Future prospects: 21cm Intensity mapping is expected to play a significant role in future cosmological research, contributing to our understanding of the large-scale structure, cosmic history, and fundamental cosmological questions.