First direct detection of the HI intensity mapping signal

Sourabh Paul

(McGill University)

with

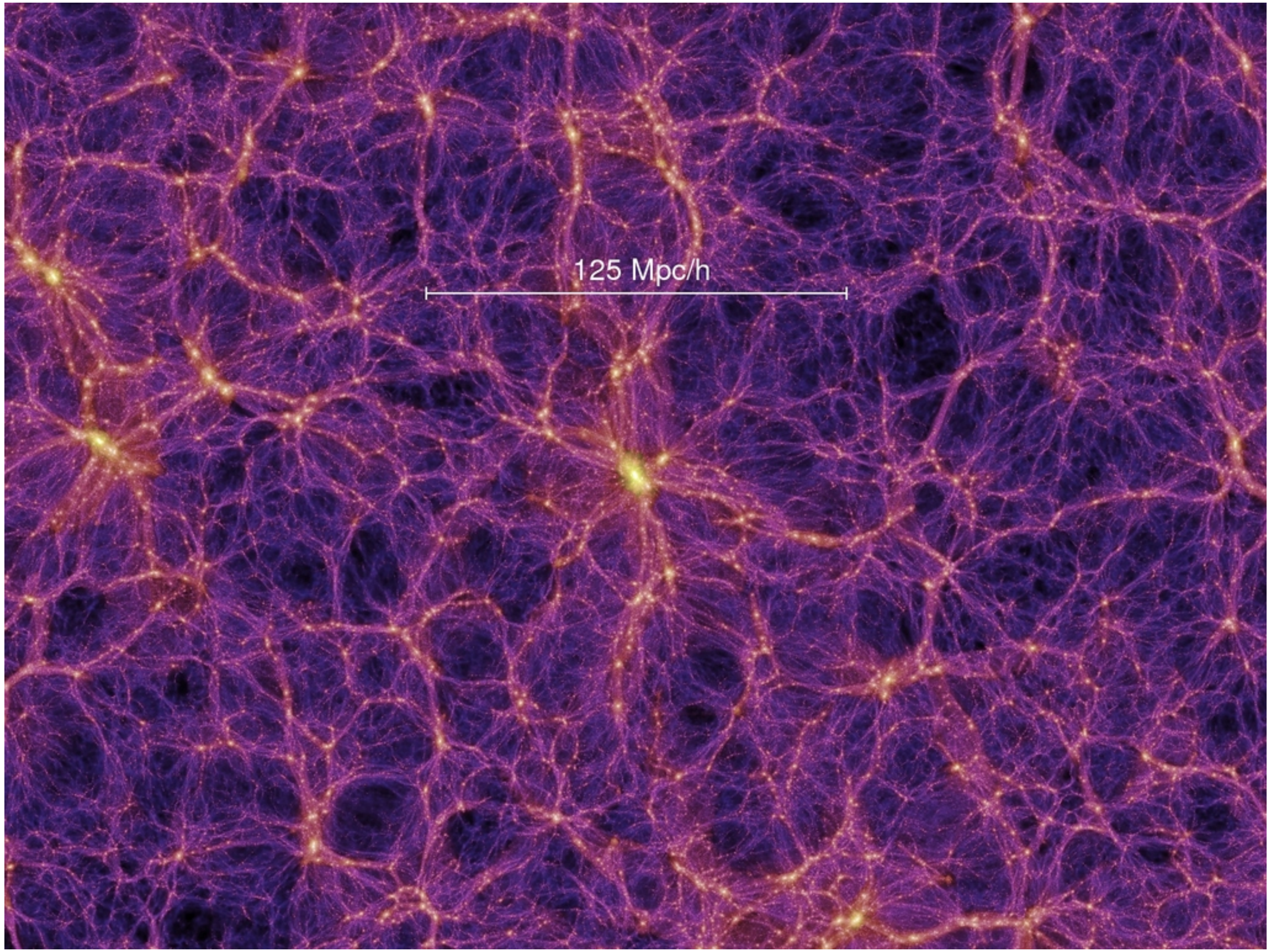
Zhaoting Chen

Mario Santos

Laura Wolz

MeerKAT

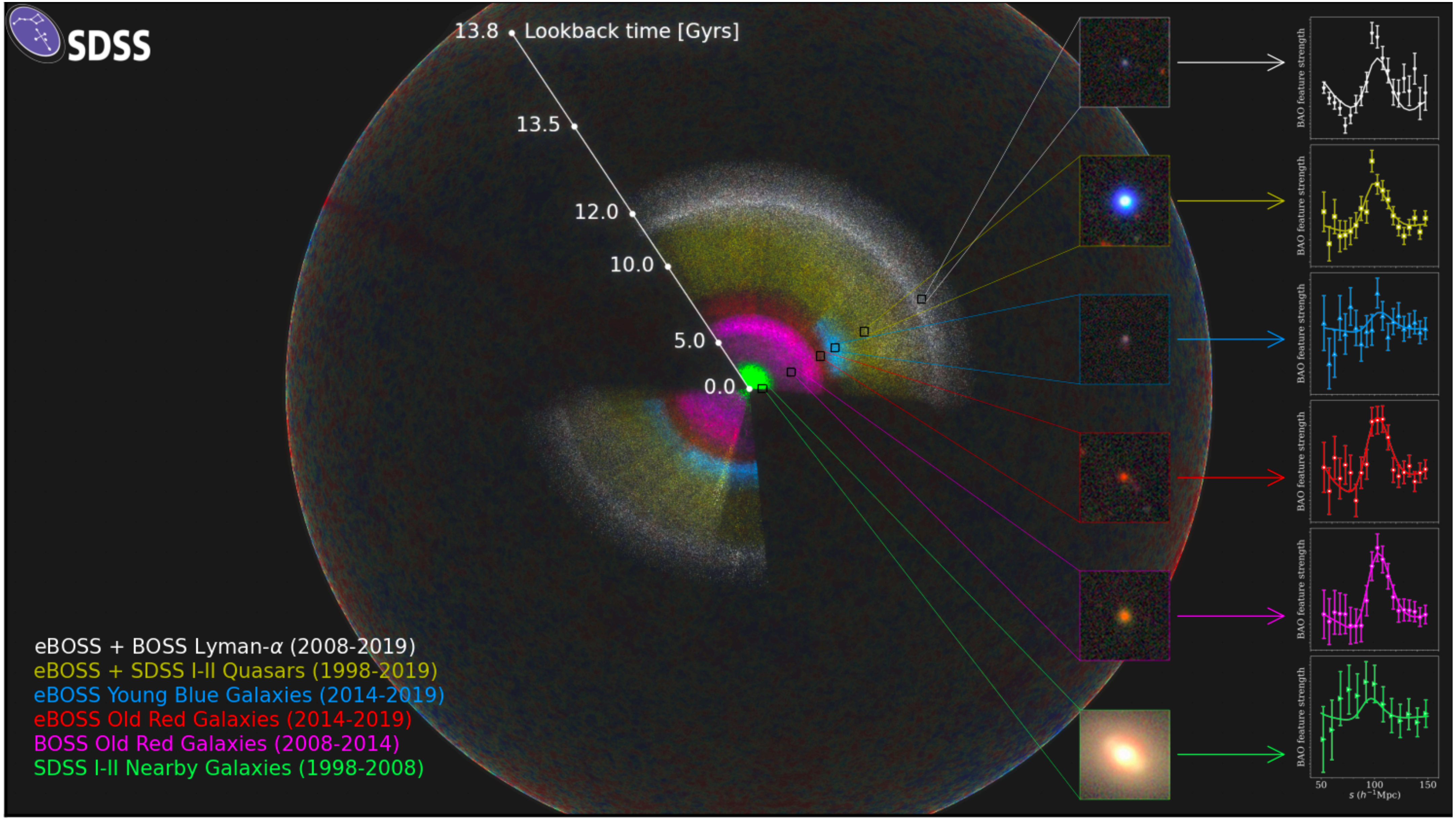
Large scale structure



(Millenium simulation)

- Age, geometry, expansion rate of Universe
- Content and nature of Dark matter and dark energy
- Determine parameters of the cosmological model.
- Test theories: The distribution of galaxies and clusters on large scales can be used to test the predictions of different models of the universe
- Initial conditions of the Universe

3D map of the Universe



- Alternate method to probe the large scale structure.
- Each Galaxy hosts a given HI mass. Neutral hydrogen resides within damped Ly-alpha systems within galaxies.
- Detect collective 21cm emission from cosmic neutral hydrogen
- Alternative and more promising tracer than galaxy surveys if number counts are steep and survey depth is shallow.
- Provides a one to one correspondence between observed frequency and redshift, thereby delivering a very high redshift resolution.
- Generally less time consuming compared to a spectroscopic galaxy survey which requires very high sensitivity to detect each individual galaxy.

Intensity Mapping

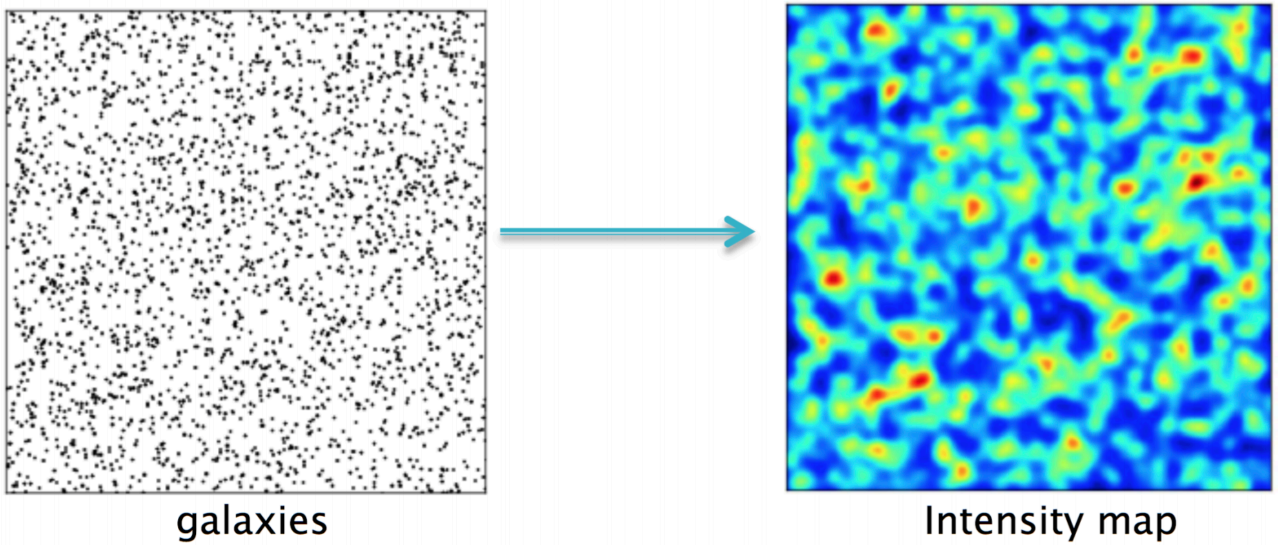
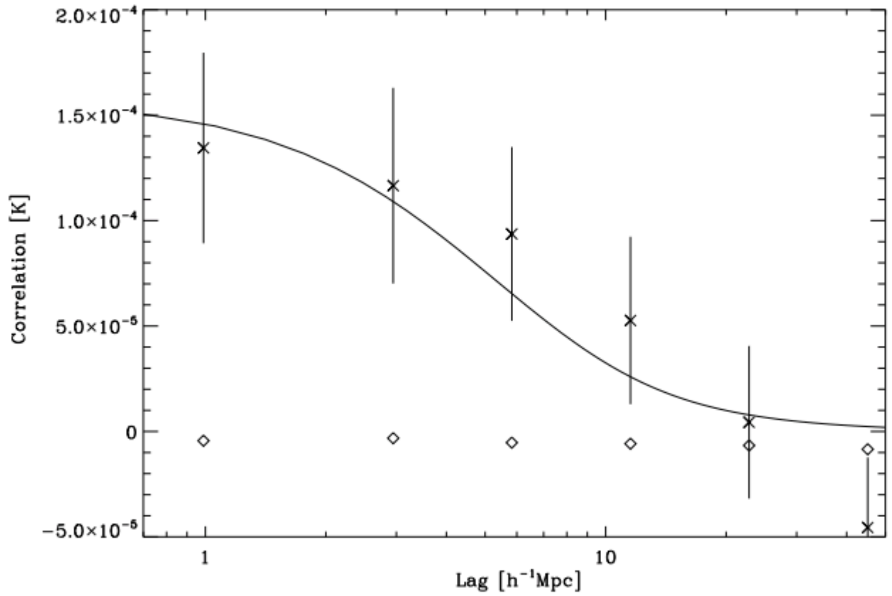
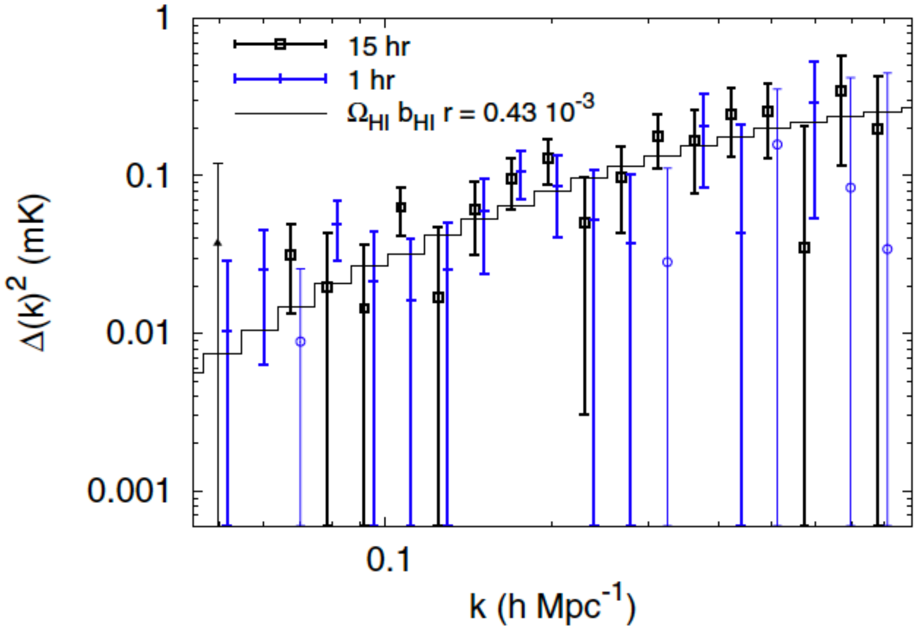


Image credit: Roy Marteens

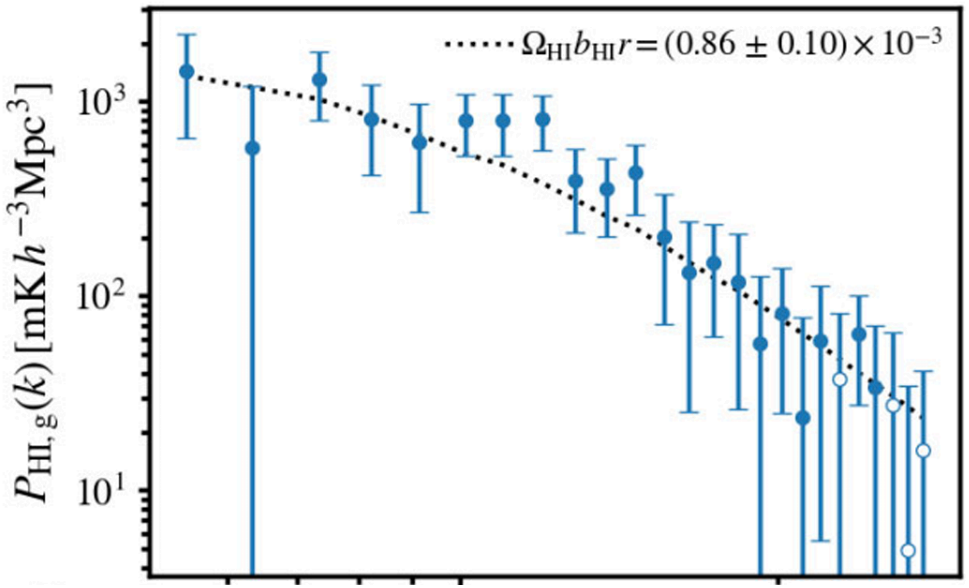
DETECTIONS IN CROSS-CORRELATION



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



Cross-correlation with WiggleZ Dark energy survey (Masui et al. 2013)

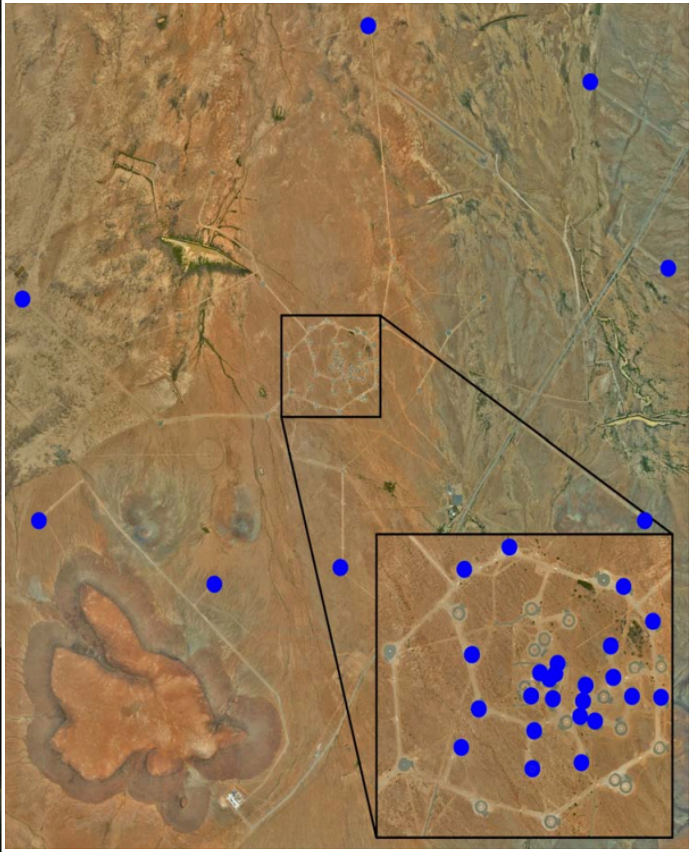


MeerKAT with WiggleZ (Cunnington et al. 2022)

Challenges in HI Intensity Mapping autocorrelation

- **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**

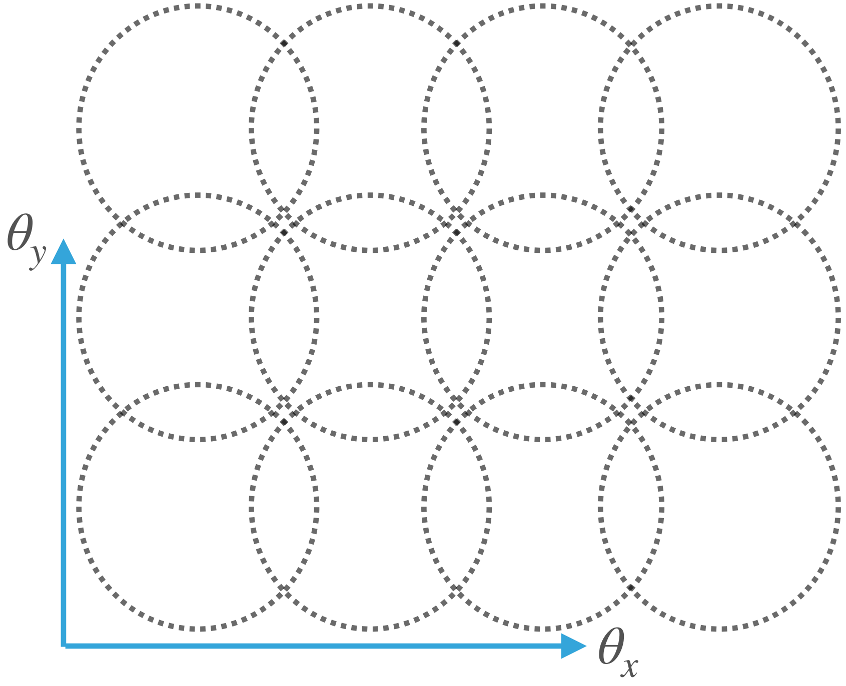
MeerKAT Radio telescope



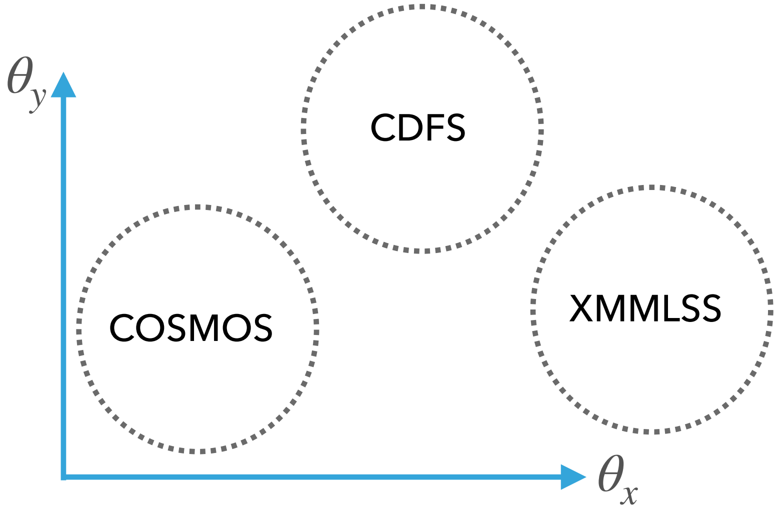
- MeerKAT, precursor to SKA, managed by SARAO. Located in the Karoo region, South Africa.
- 64 dish antennas of 13.5 meter diameter.
- Central core region of 1km houses 48 antennas, other 16 antennas are distributed upto a radius of 4km from the center.
- Dense core facilitates higher sensitivity at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

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

Single Dish & Interferometric IM (MeerKAT)

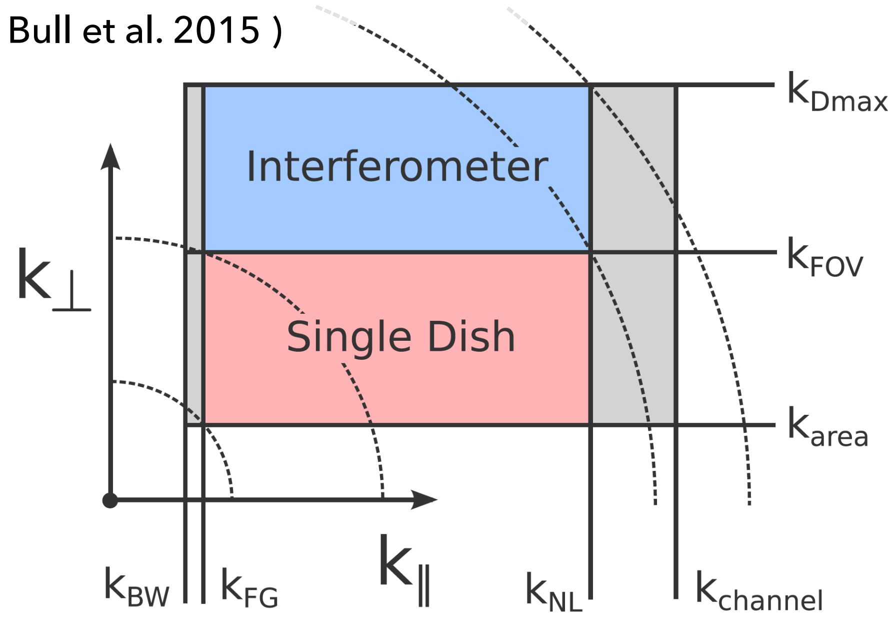


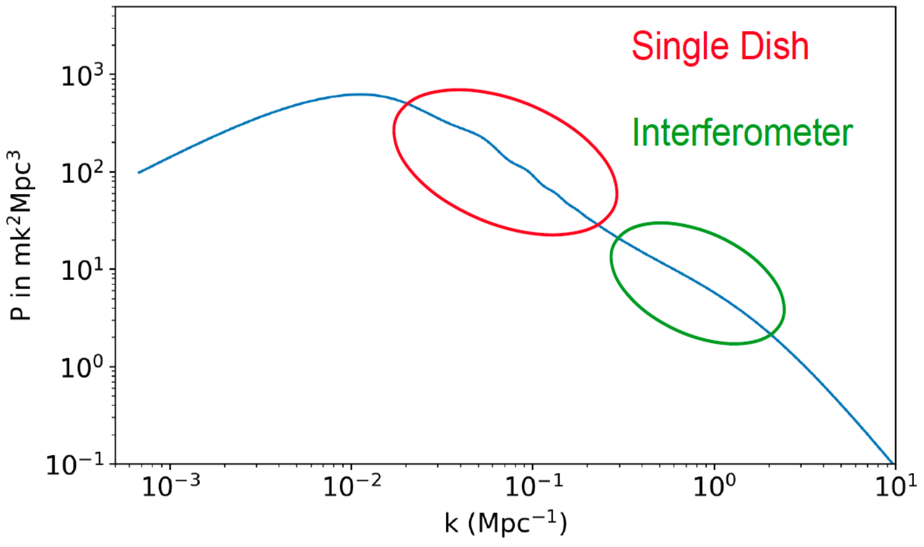
Single Dish



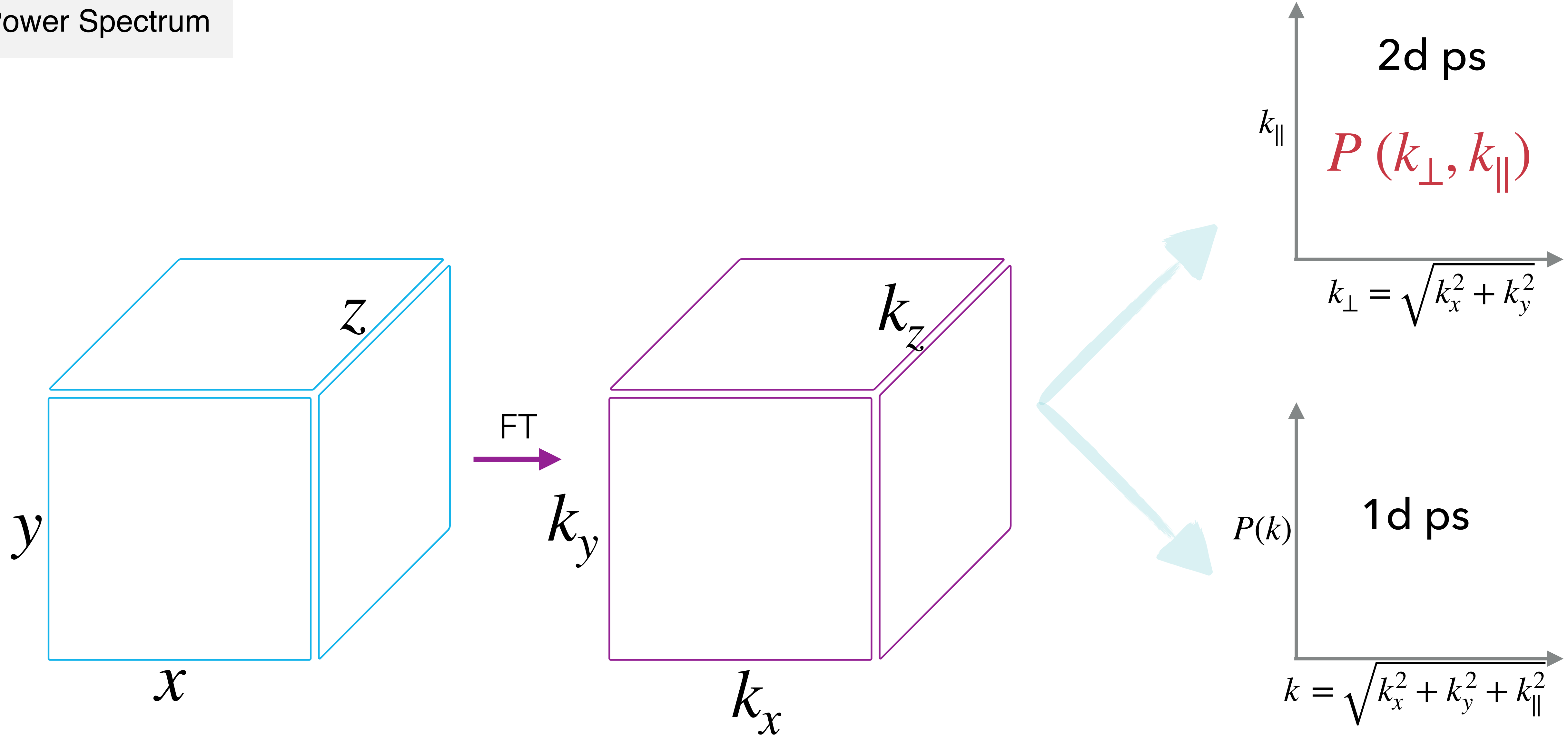
Interferometer

(Bull et al. 2015)



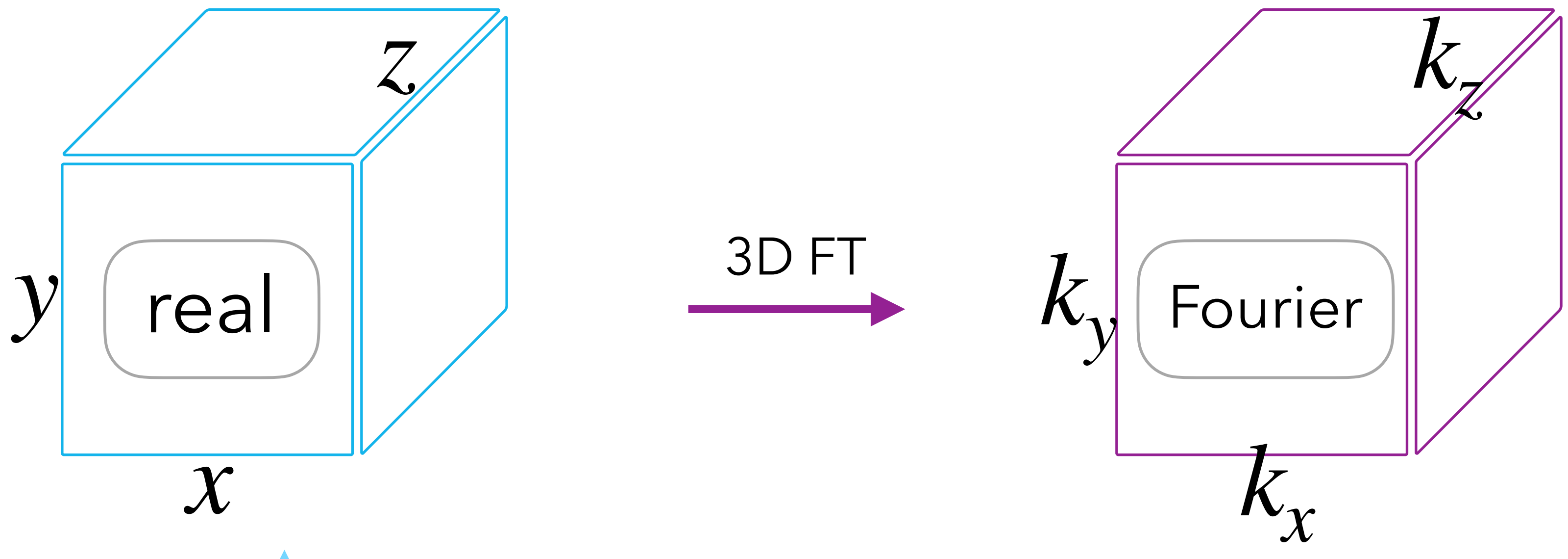


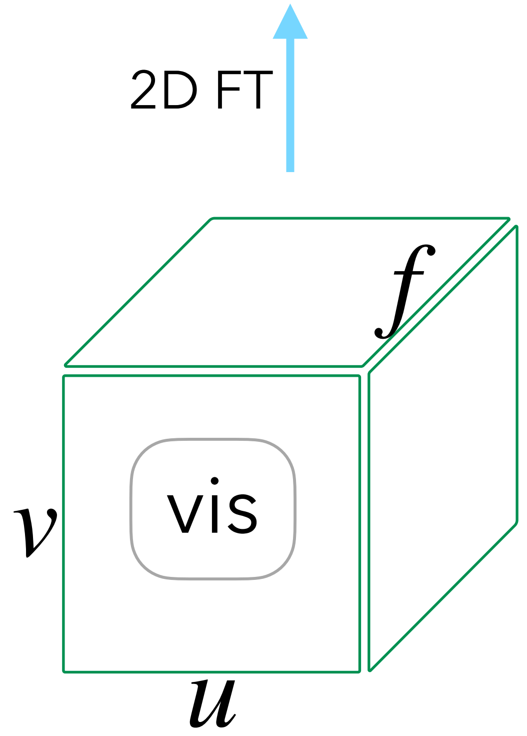
Power Spectrum

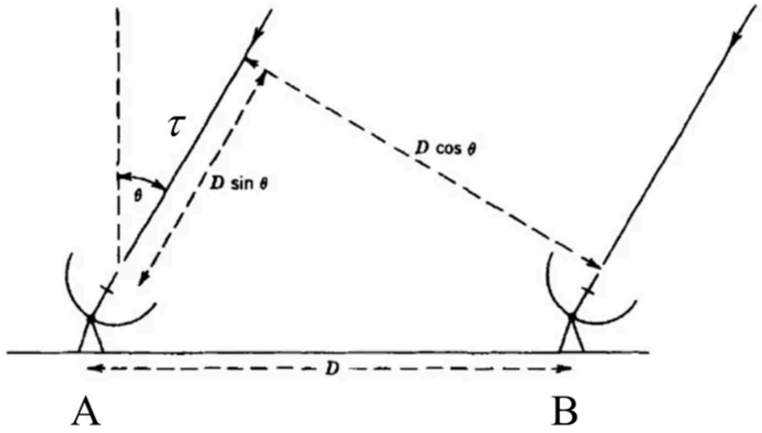


PS from image cube

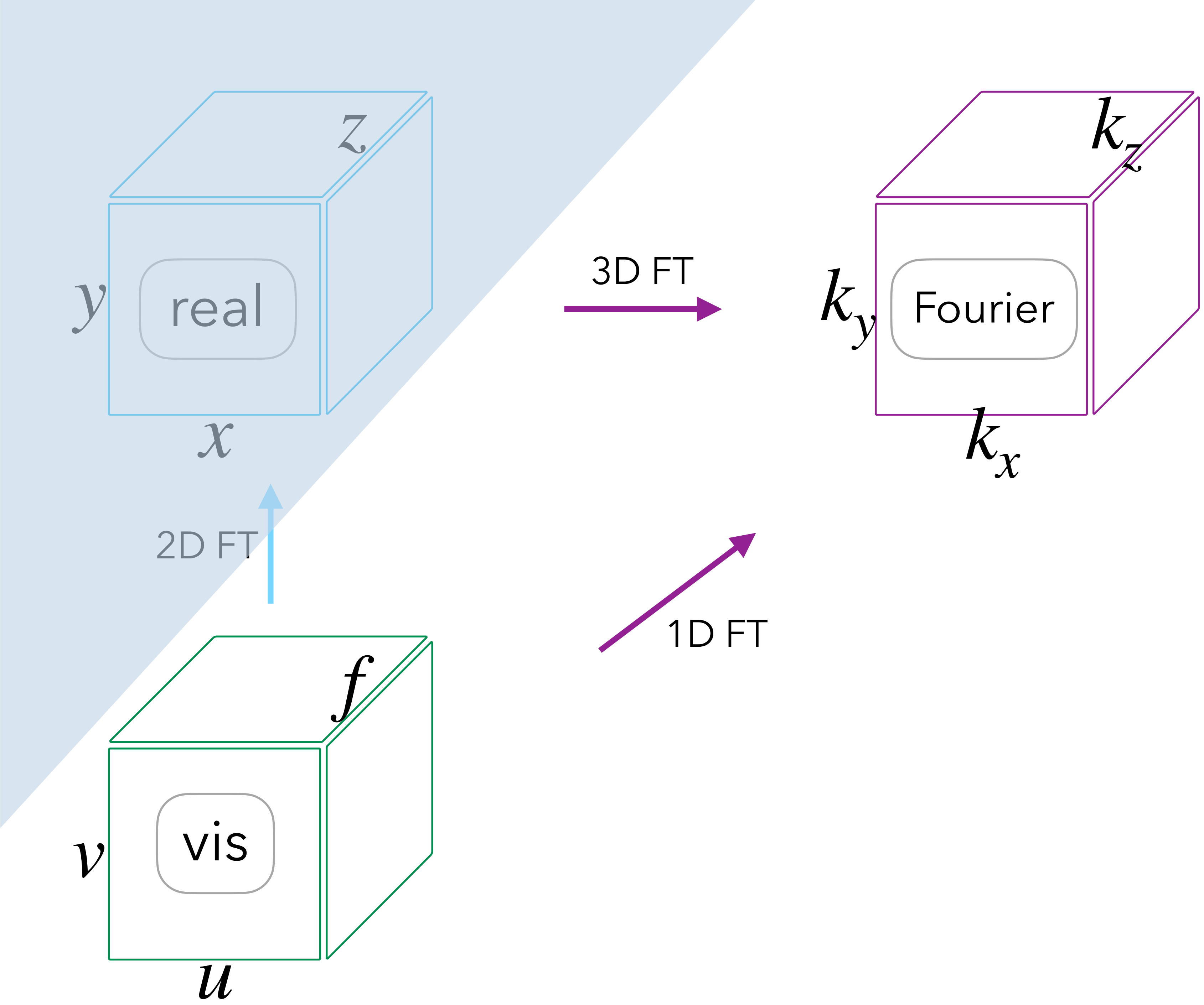
Power Spectrum from visibility data





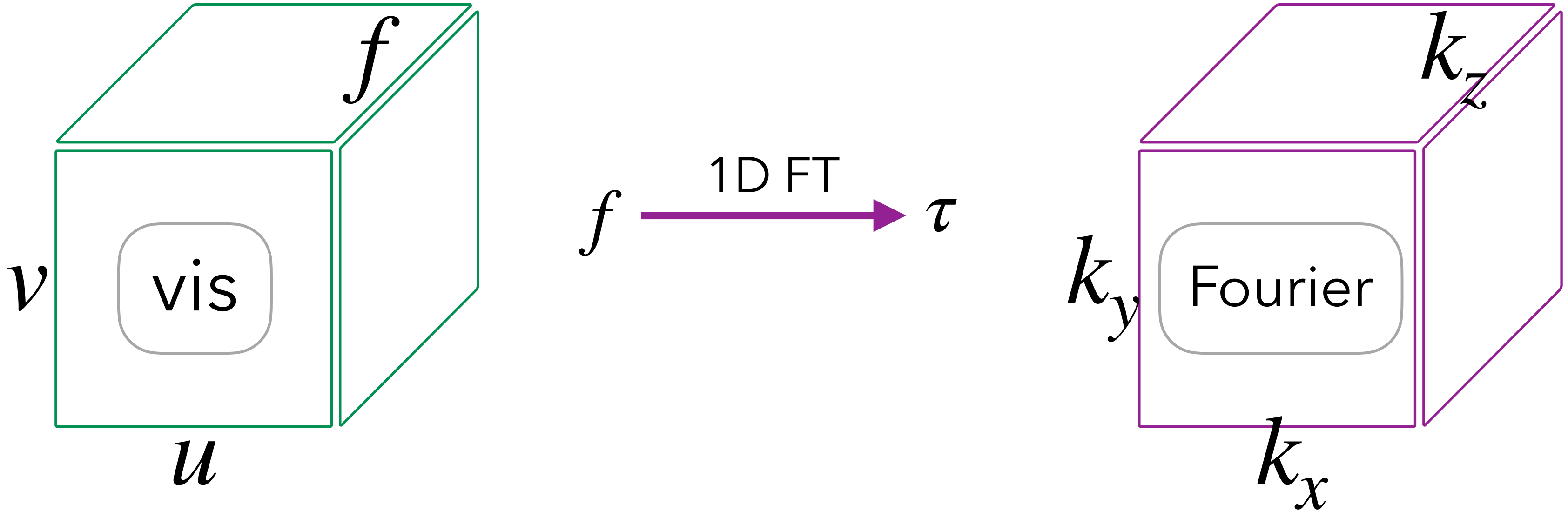


$$I(l,m) = \iint V(u,v)\, e^{-2\pi i(ul+vm)} du\, dv$$



z
y
real
x
3D FT
k_z
k_y
Fourier
k_x
2D FT
1D FT
f
v
vis
u

Power Spectrum from visibility data

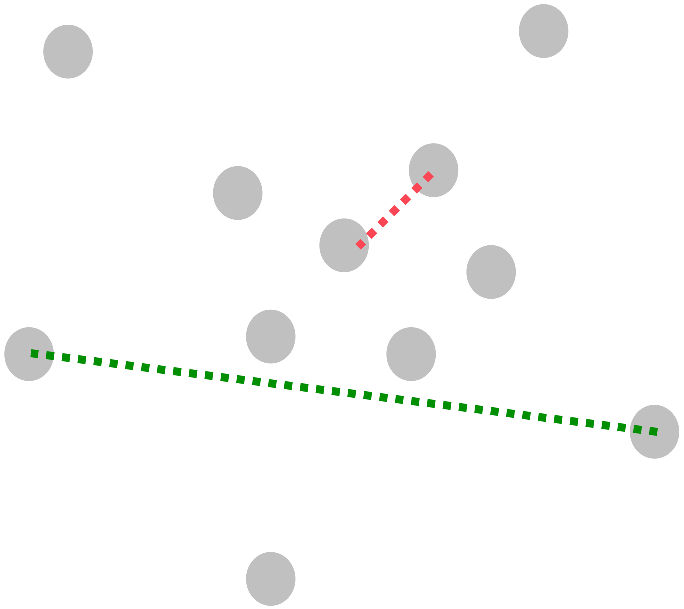


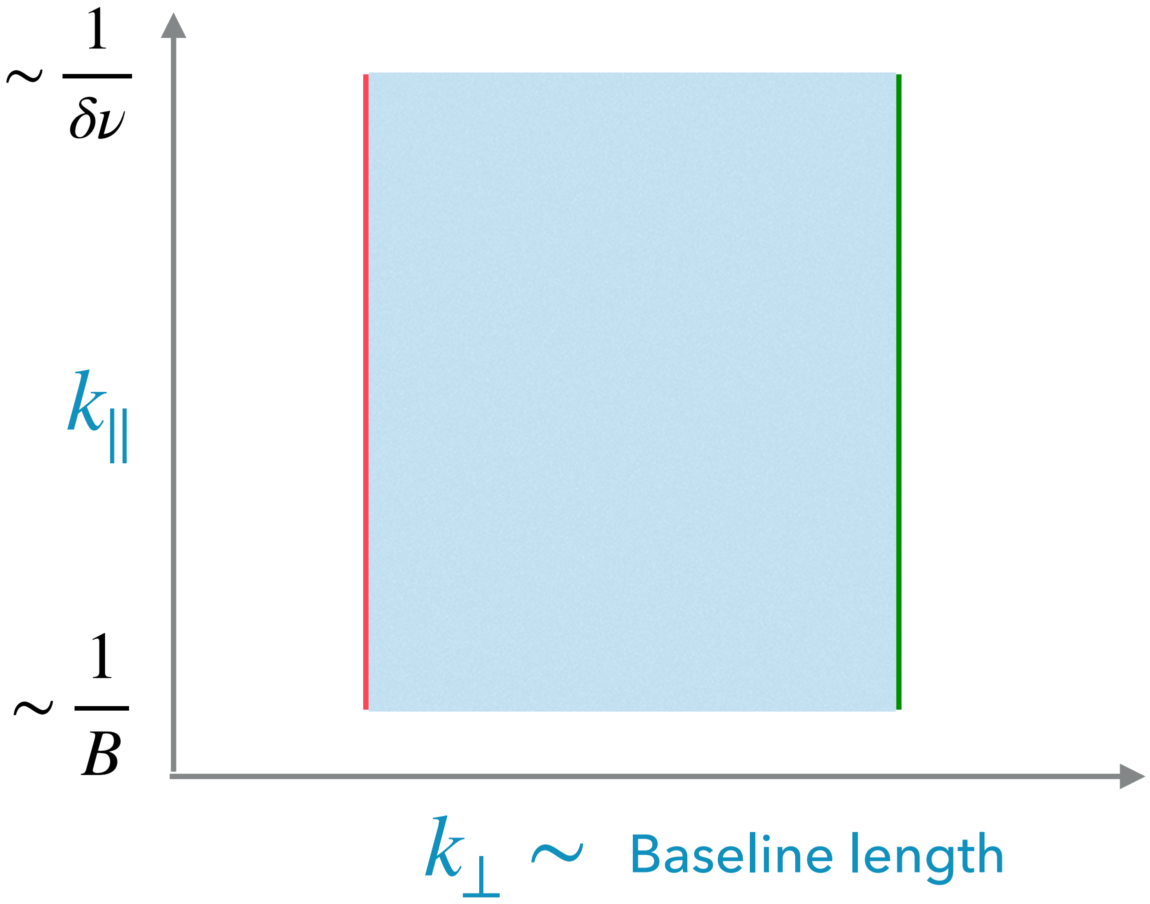
$$k_x = \frac{2\pi}{R} u \; ; \qquad k_y = \frac{2\pi}{R} v \; ; \qquad k_{\parallel} = \frac{2\pi \nu_{21} H_0 E(z)}{c(1+z)^2} \tau$$

Delay PS

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

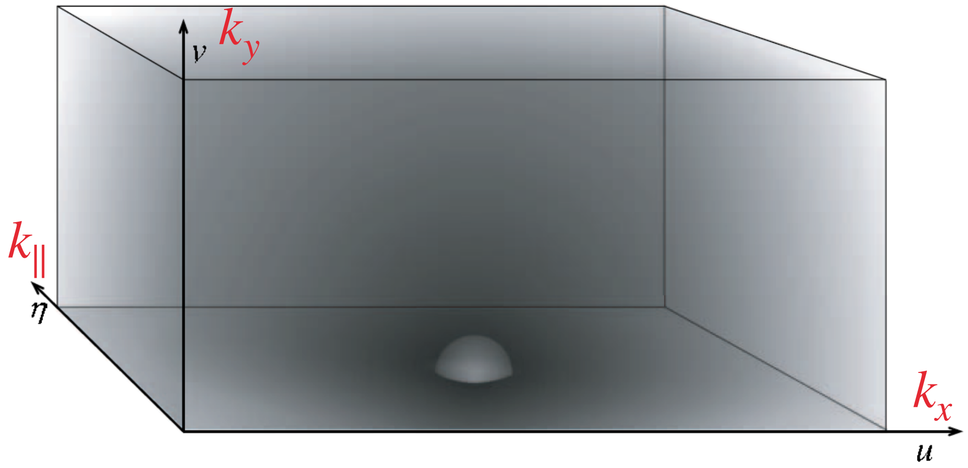
Power Spectrum from visibility data



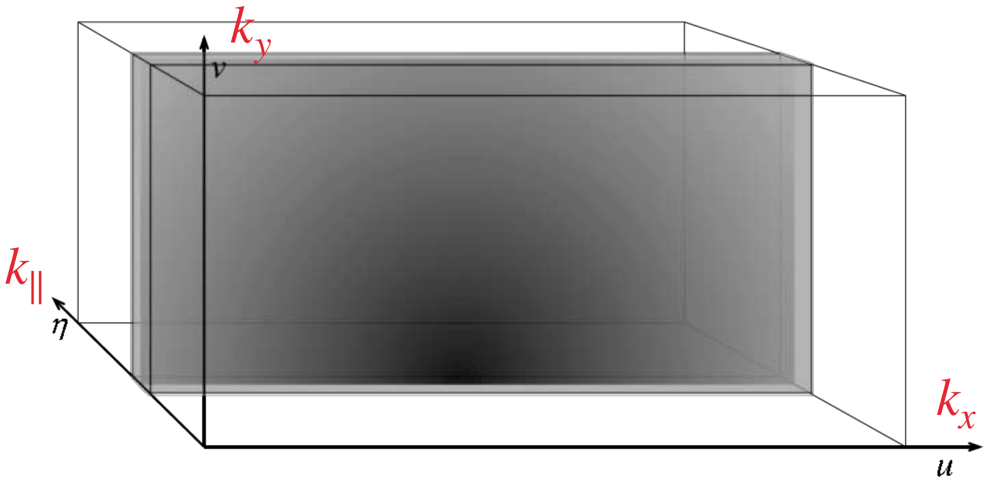


FOREGROUND ISOLATION

HI



Foreground



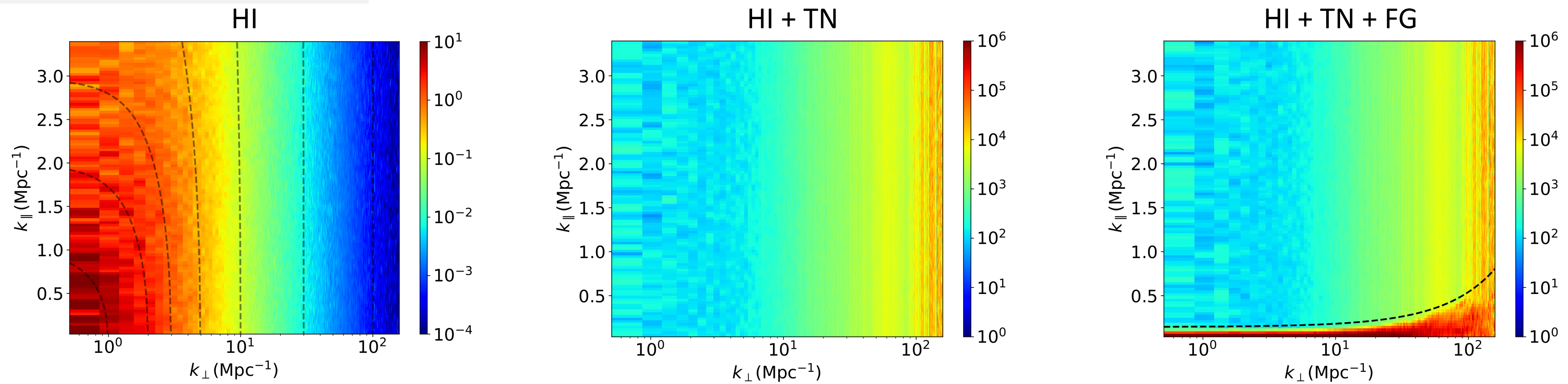
(Morales & Hewitt 2004)

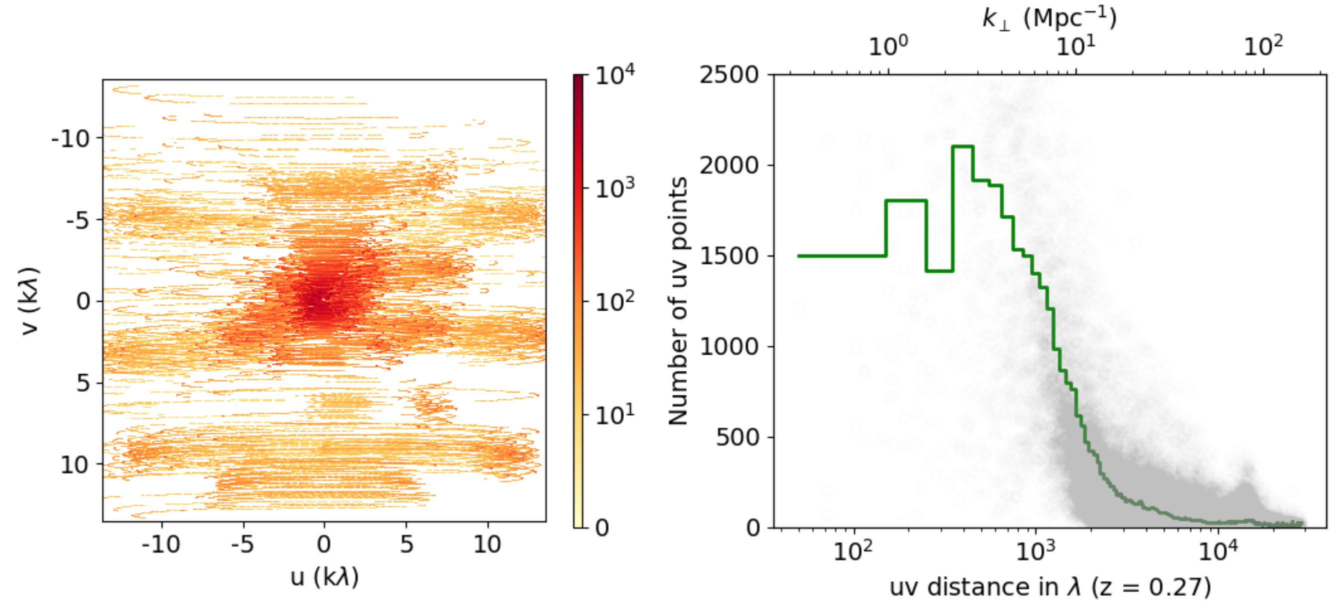
The Cosmological 21cm signal is symmetric in Fourier space.

Foregrounds are NOT.

IM with MeerKAT interferometer

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

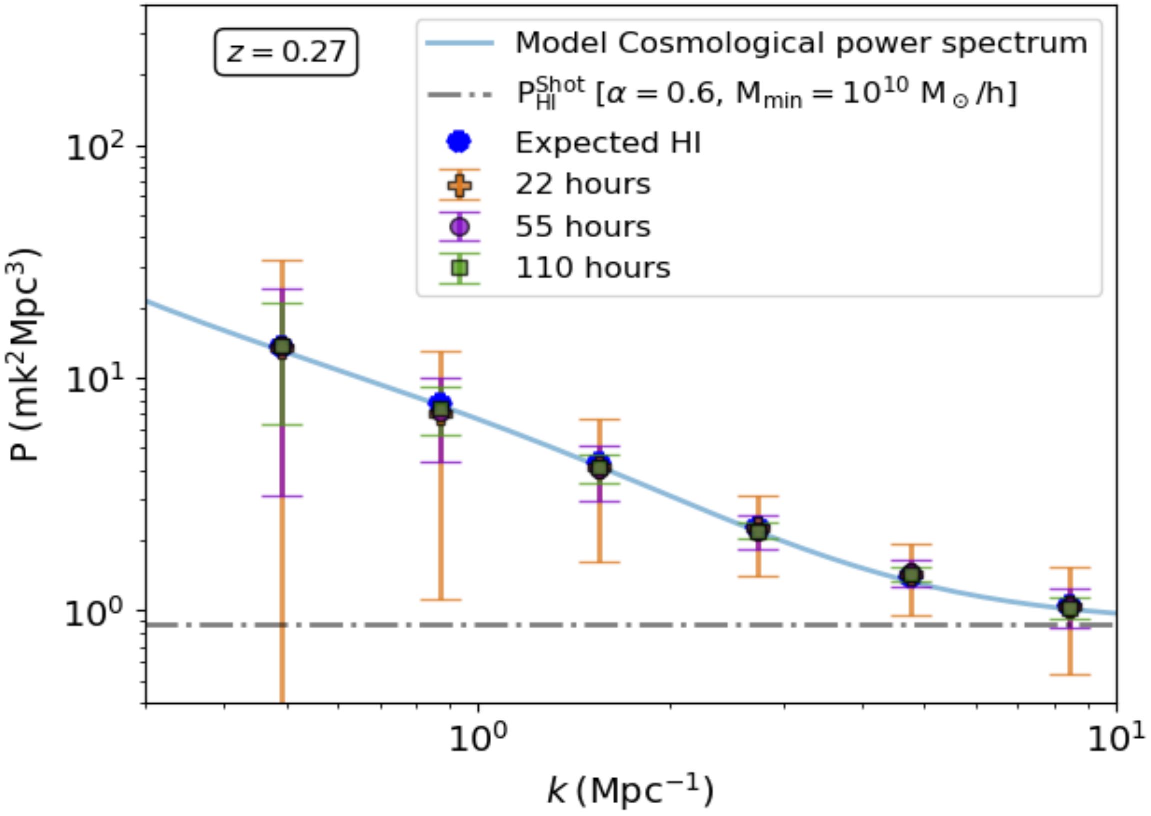




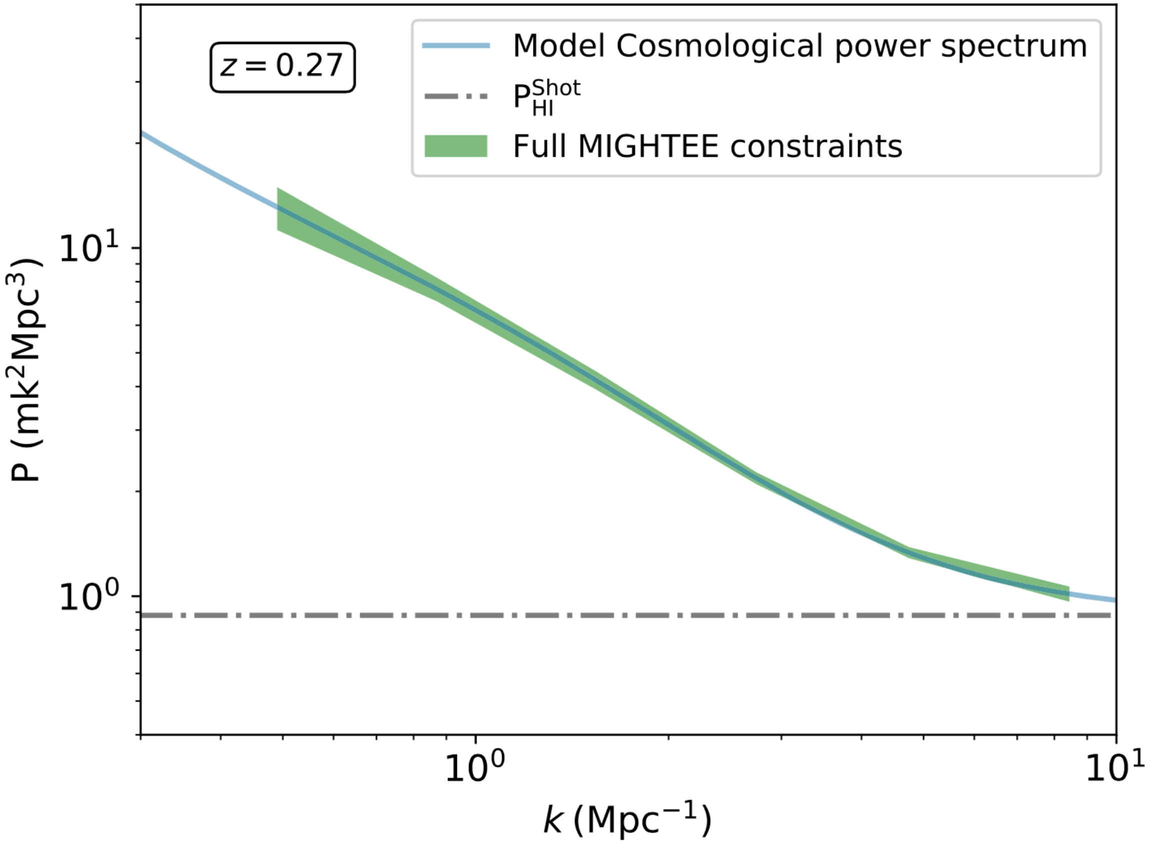
HI intensity mapping with the MIGHTEE survey: power spectrum estimates

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

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

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

Time resolution: 8s

Frequency resolution: 0.209MHz

Calibration: processMeerKAT + selfcals

Bandwidth: 950 ~ 1170 MHz

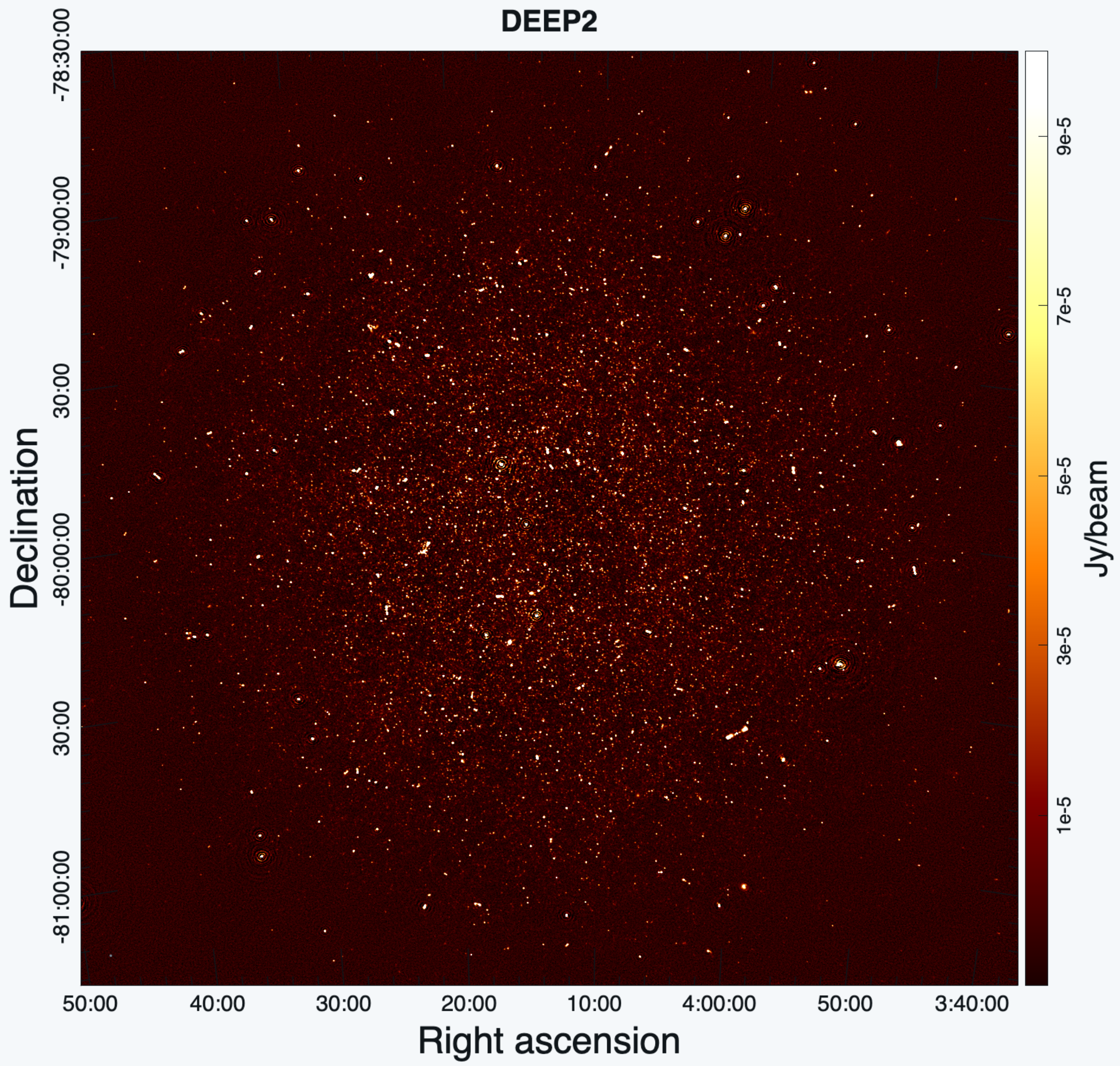
RMS: 3 μJy/beam

Target scan duration: 15 mins

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

(46 MHz) 986 MHz (z ~ 0.44)

Long integration time, avoid bright foreground sources



IM with MeerKAT interferometer

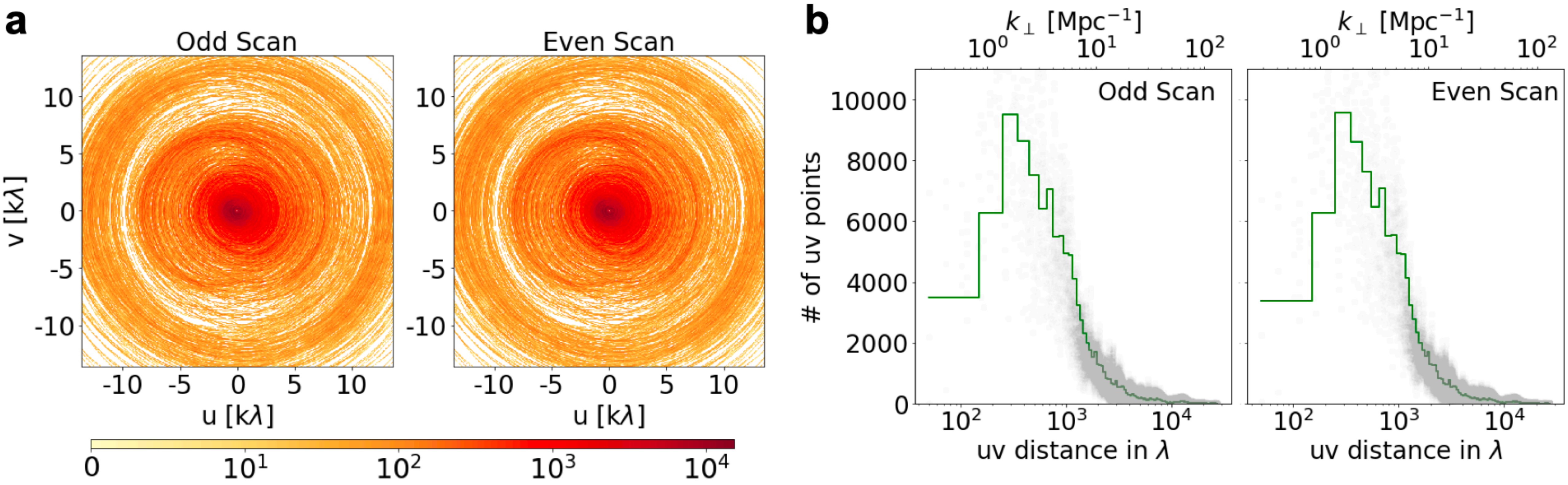
Calibration

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

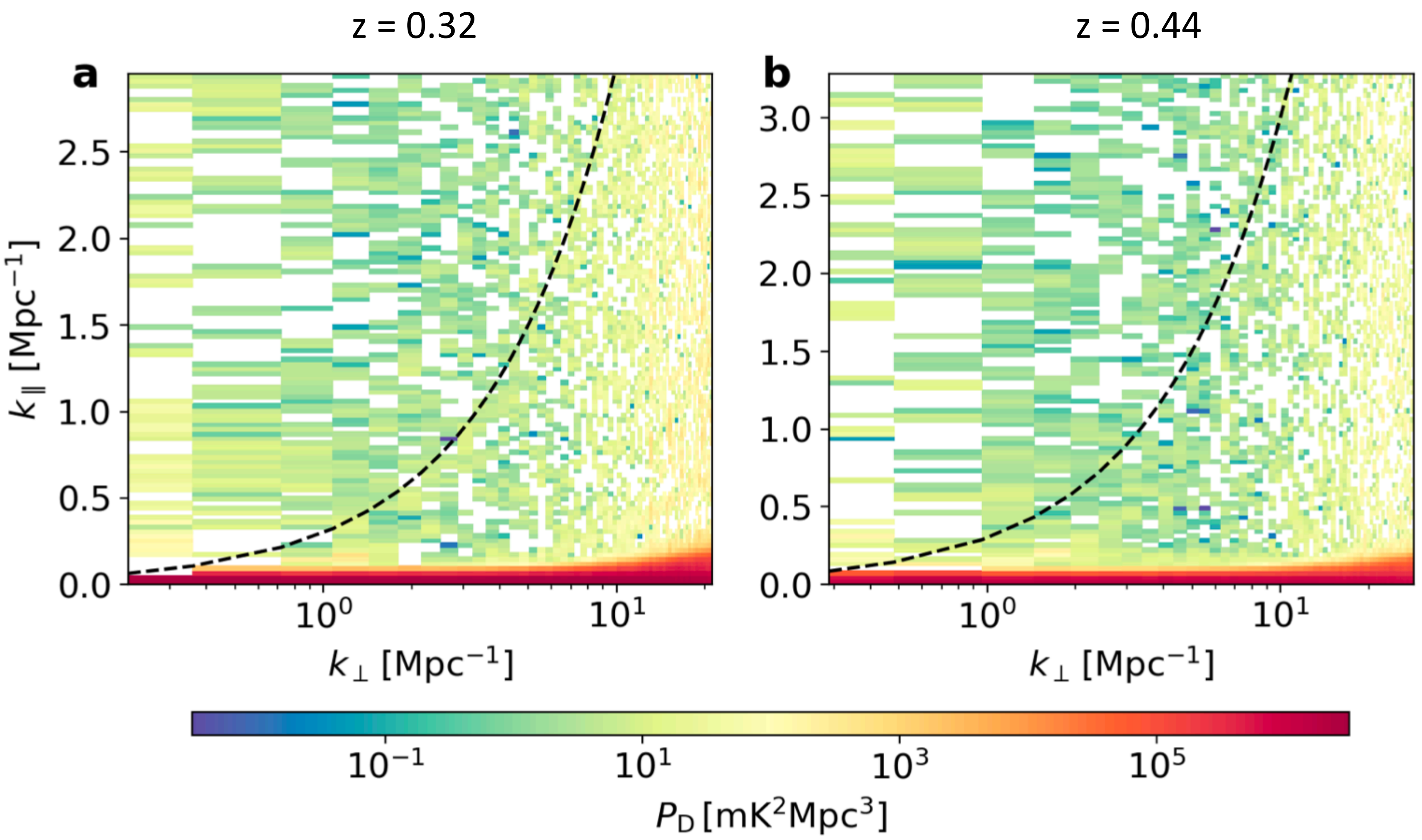
1. Split the sub-band into 2 sub-sub-bands of ~ 46 MHz
2. Only use baselines for which the visibility data has at least 80 percent unflagged channels.
3. Bin the visibilities into a grid in the uv plane with the same bin size across u and v (60 lambda).
4. Split the full observation into 2 uv-nu cubes (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)



Power spectrum (odd scans vis x even scans vis)

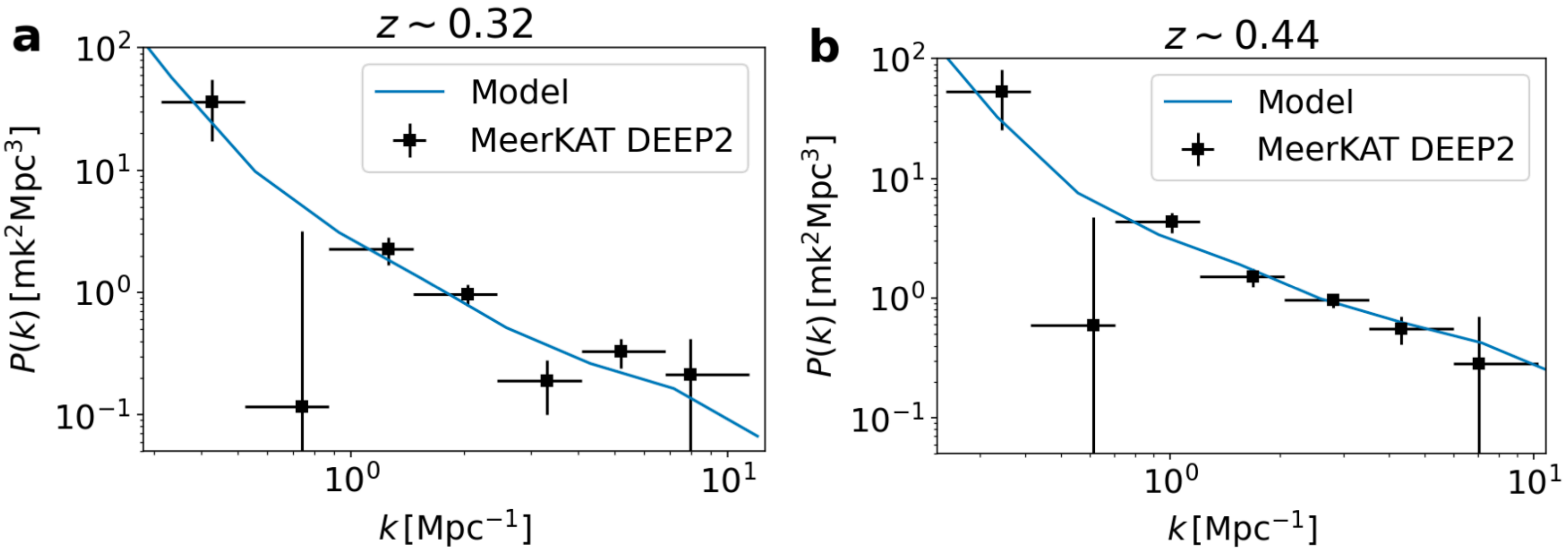
46 MHz band centered at 1077.5 MHz (z = 0.32) and 986 MHz (z = 0.44)



First detection of auto power spectrum

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

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

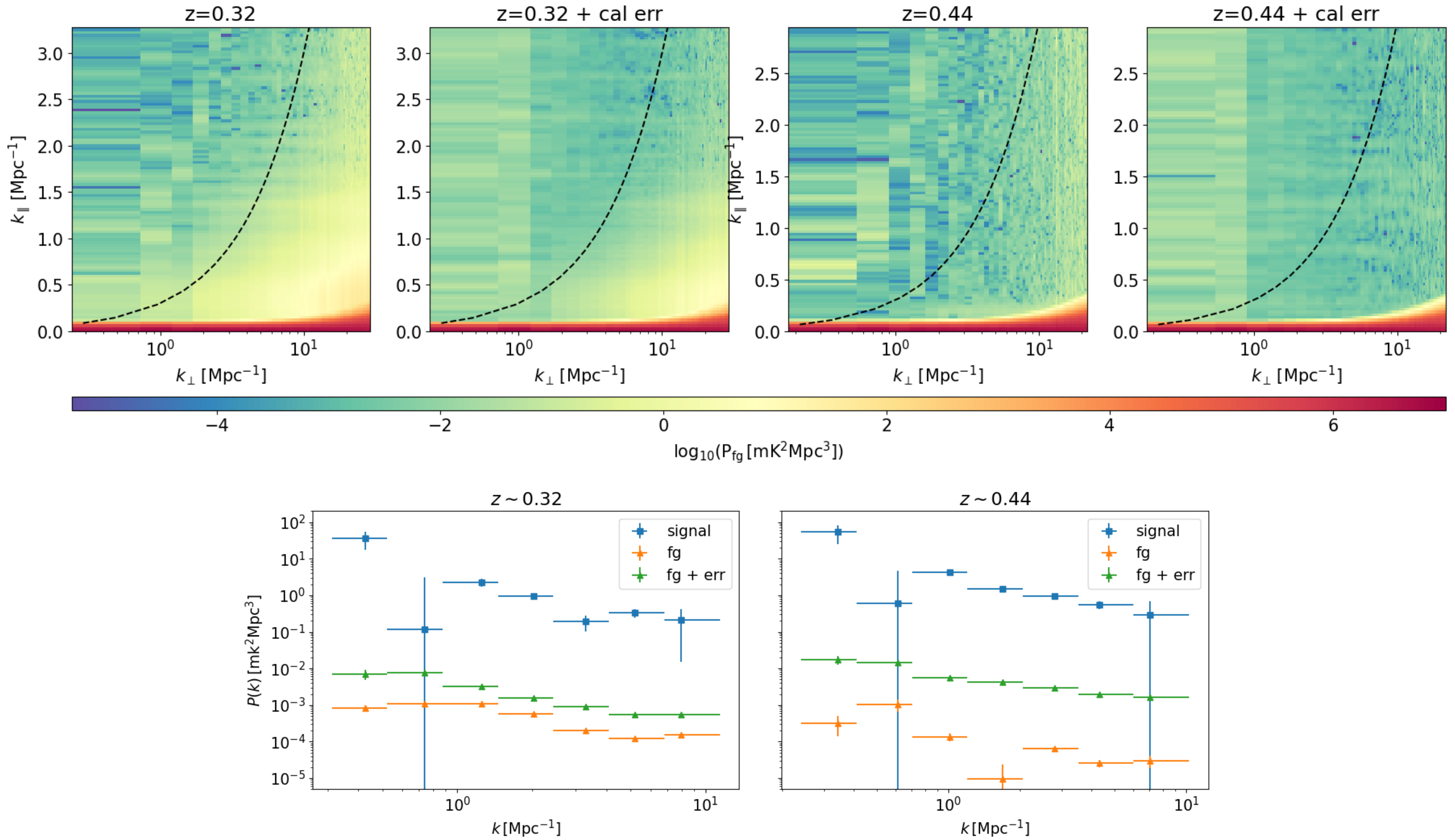


8σ

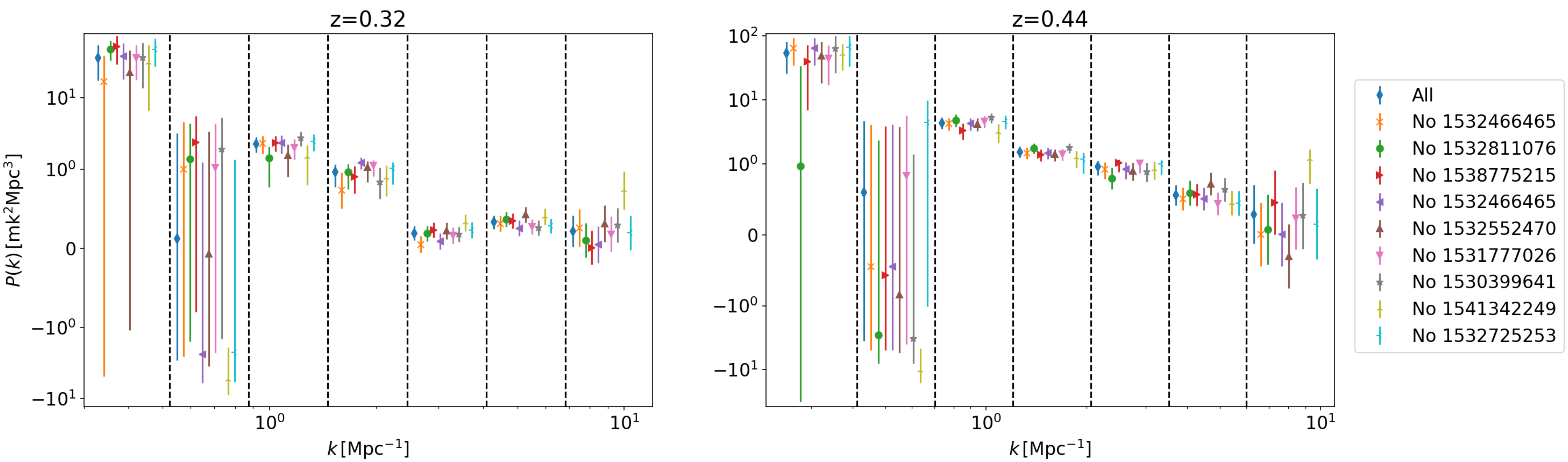
11.5σ

https://arxiv.org/abs/2301.11943

Foreground scatter

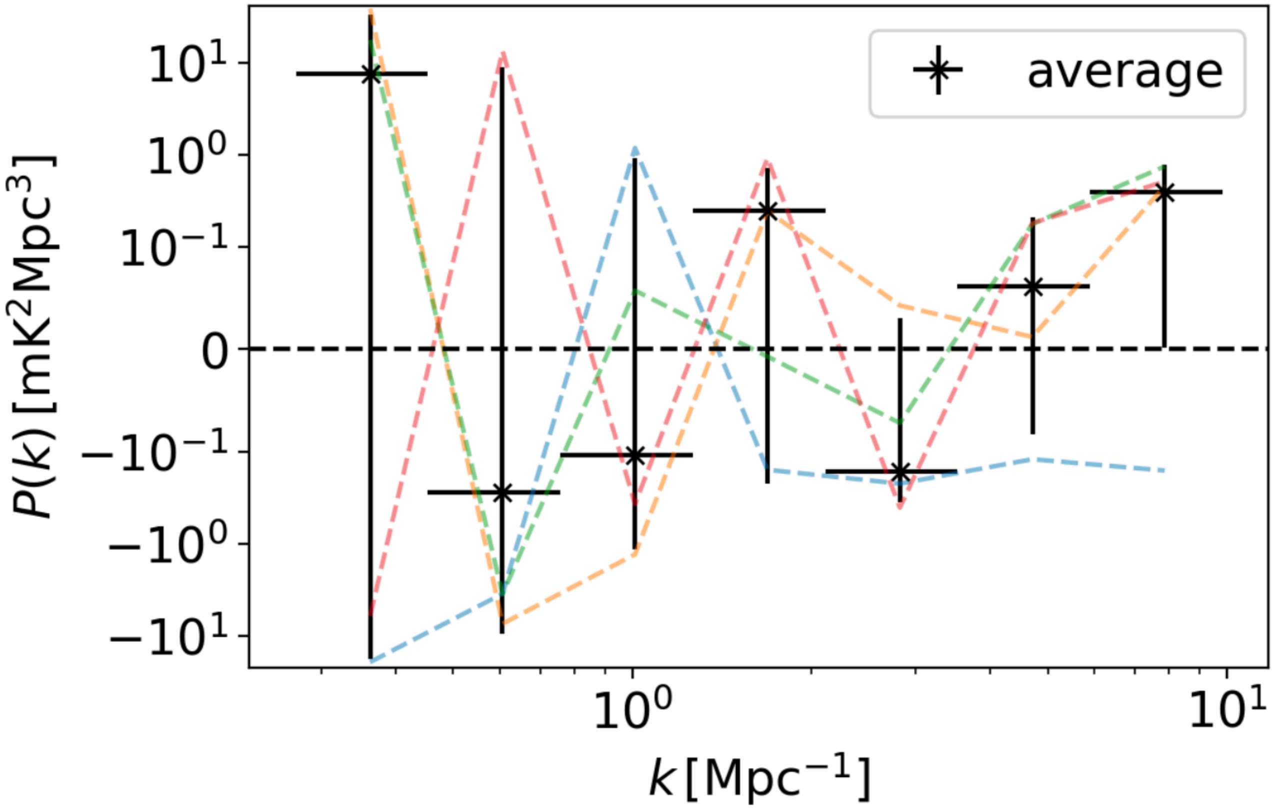


Jackknife test



Null test

Cross-correlating visibility data from two sub-bands



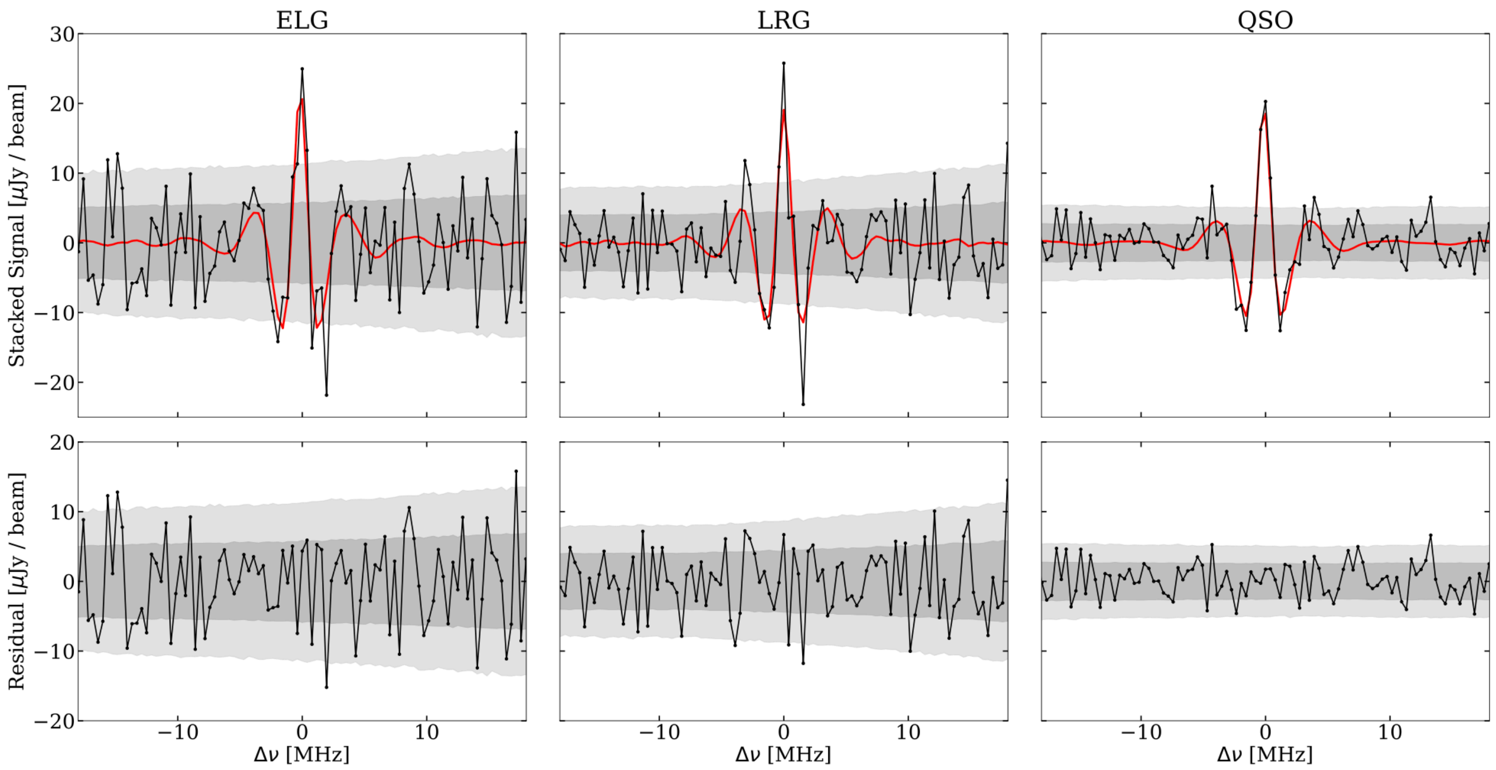
Conclusion

- First direct detection of HI auto-power spectrum using intensity mapping.
- Visibility based pipeline, Foreground avoidance.
- Detection is possible because of precise calibration, large SNR and sufficient RFI mitigation.
- Milestone in 21cm Cosmology — significant step towards precision cosmology with intensity mapping with new Generation of radio telescopes and upcoming SKA.

Next steps:

- Longer integration for 2d PS detection
- IM with full MIGHTEE survey (~ 1000 hrs, 4 fields: COSMOS, XMMLSS, CDFS, ELAIS-S1).
- Intensity mapping with UHF band data (580 - 1015 MHz).

HI Intensity mapping with CHIME



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