Towards Realistic Mock Observations

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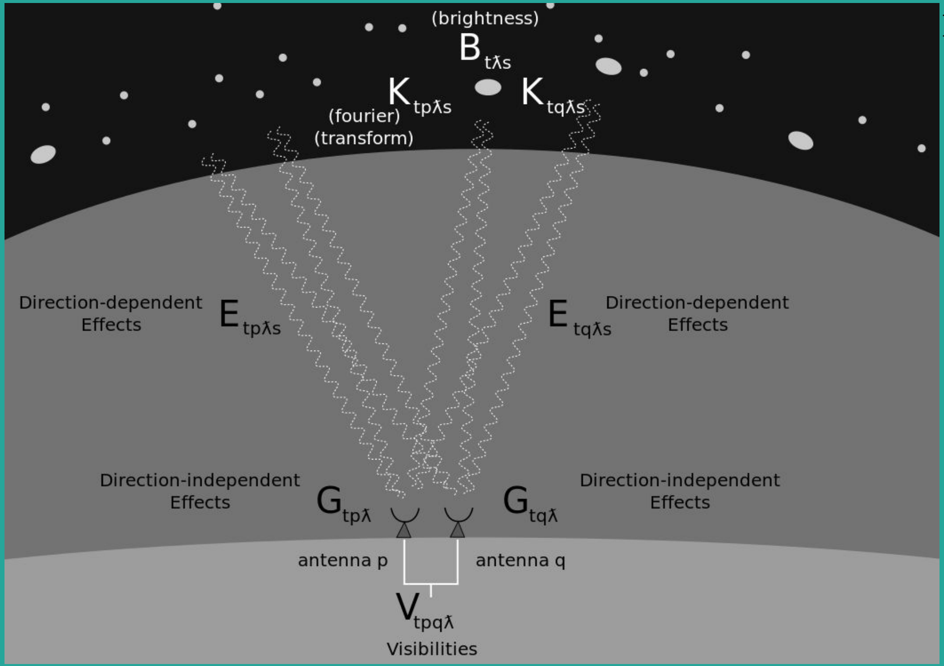
(Simplified) Radio Interferometric Measurement Equation



[1]

$$V_{tpq} = G_{tp} E_{tps} B E_{tqs} G_{tq} + N_t$$

G_p - Direction Independent (DI) gains for antenna p
E_p - Direction Dependent (DD) gains for antenna p in direction s
B - Sky brightness as seen by the baseline pq
N - Additive Receiver Noise

1:[RATT RU Radio Interferometry Course, EPFL Radio Sky II]

21 CM IM/EoR Papers	Additive Noise	DI Gain Errors	DD Gain Errors
Removing Astrophysics in 21 cm Maps with Neural Networks	X	X	X
Deep learning approach for identification of H ii regions during reionization in 21-cm observations		X	X
THE APPLICATION OF CONTINUOUS WAVELET TRANSFORM BASED FOREGROUND SUBTRACTION METHOD IN 21 cm SKY SURVEYS		X	X
21 cm TOMOGRAPHY WITH FOREGROUNDS		X	X
Separating the EoR signal with a convolutional denoising autoencoder: a deep-learning-based method	X	X	
Machine Learning to Decipher the Astrophysical Processes at Cosmic Dawn		X	
Foreground removal and 21 cm signal estimates: comparing different blind methods for the BINGO Telescope		X	X
Blind foreground subtraction for intensity mapping experiments		X	
SKAO Hi Intensity Mapping: Blind Foreground Subtraction Challenge		X	

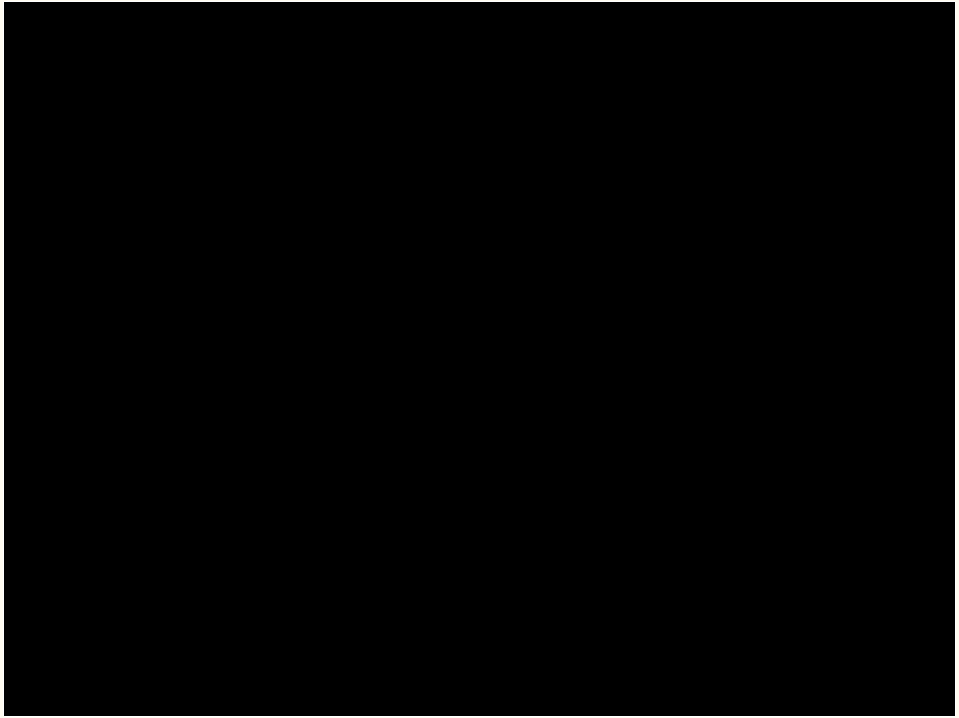
Current State of the Art for 21 cm IM/EoR simulations

- Most do not properly incorporate the complexity of the radio interferometric signal capture process
- Additive Noise - System Equivalent Flux Density (SEFD)
- Where incorporated - DD effects are mostly including gaussian primary/synthesized beams
- No cross-polarisation leakage - only xx and yy components - usually identical

Additive Noise Model

$$\Delta S = \frac{2kT_{sys}}{A_e\sqrt{2N_{pol}\Delta v \Delta t}}$$

- Independent over all dimensions
- Increasing noise buries signal
- Reduce noise with more data
  - Antennas
  - Time integration
  - Antennas
  - Channel width



Direction Independent Gain Model

$$1 + q_{\nu i} = (1 + h_\nu + p_i + \delta_{\nu i})e^{2\pi i(\nu\tau_i + \epsilon_{\nu i})}$$ [1]

$$1 + q_{\nu i} = (1 + h_\nu + p_i + \delta_{\nu i})e^{2\pi i(\nu\tau_i + \epsilon_{\nu i})}$$

h_ν - Band pass error
p_i - Antenna dependent error
$\delta_{\nu i}$ - Statistical amplitude error
τ_i - Antenna phase error
$\epsilon_{\nu i}$ - Statistical phase error

$$1 + G_{pq} = \mathrm{Gain}_p \times \mathrm{Gain}_q$$

1:[Wang, Chen, Masui et al. 2022]

DI Gain Amplitude and Phase Errors

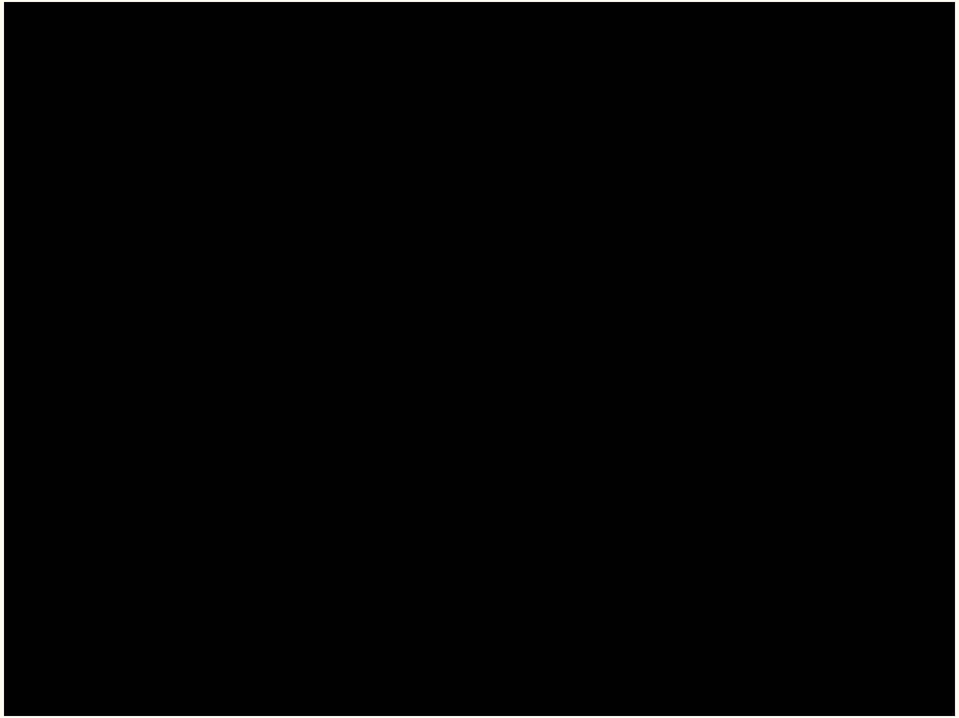
- Varies over time and frequency

Gain Amplitudes

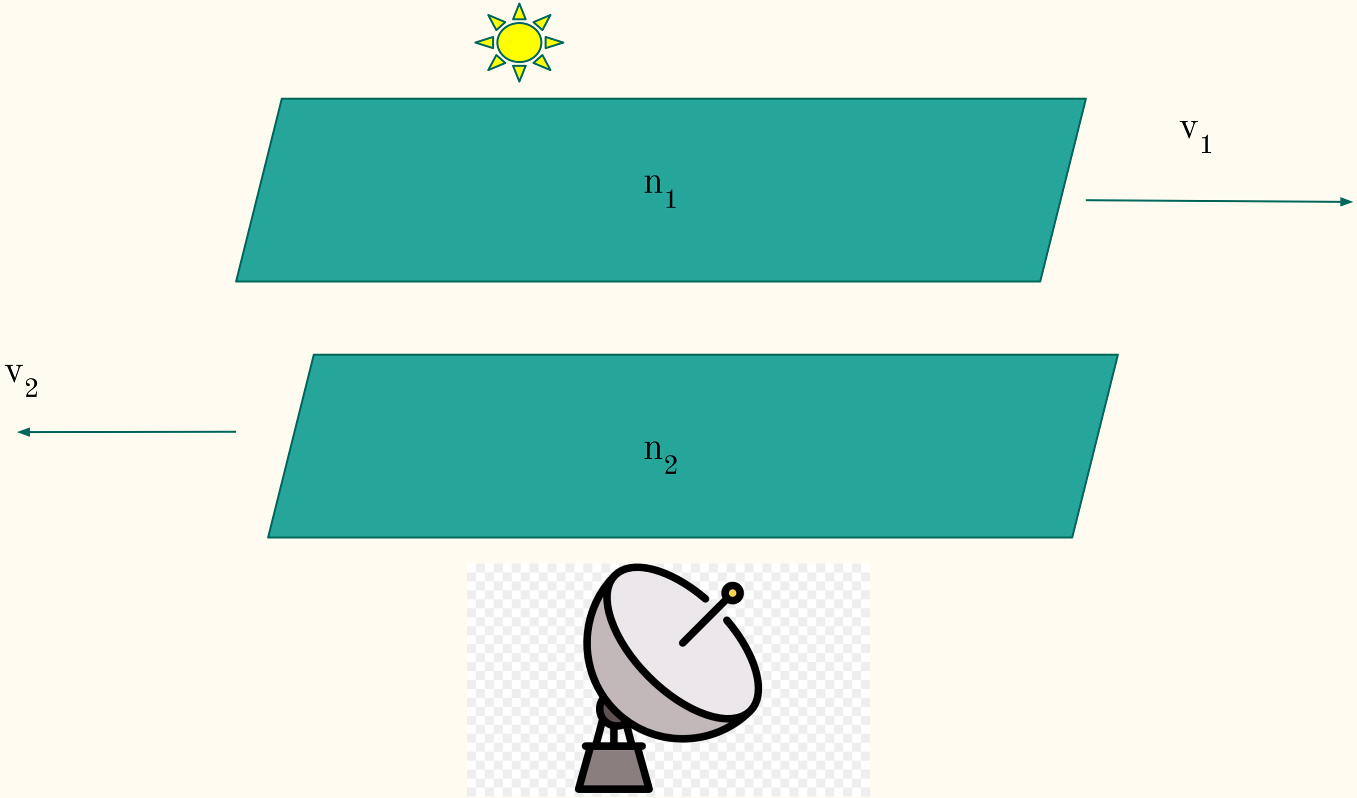
- Amplitudes modulate signal strength
-

Gain Phases

- Phase errors defocus the telescope
- Spread out the signal



Direction Dependent Gain Model



Ionosphere

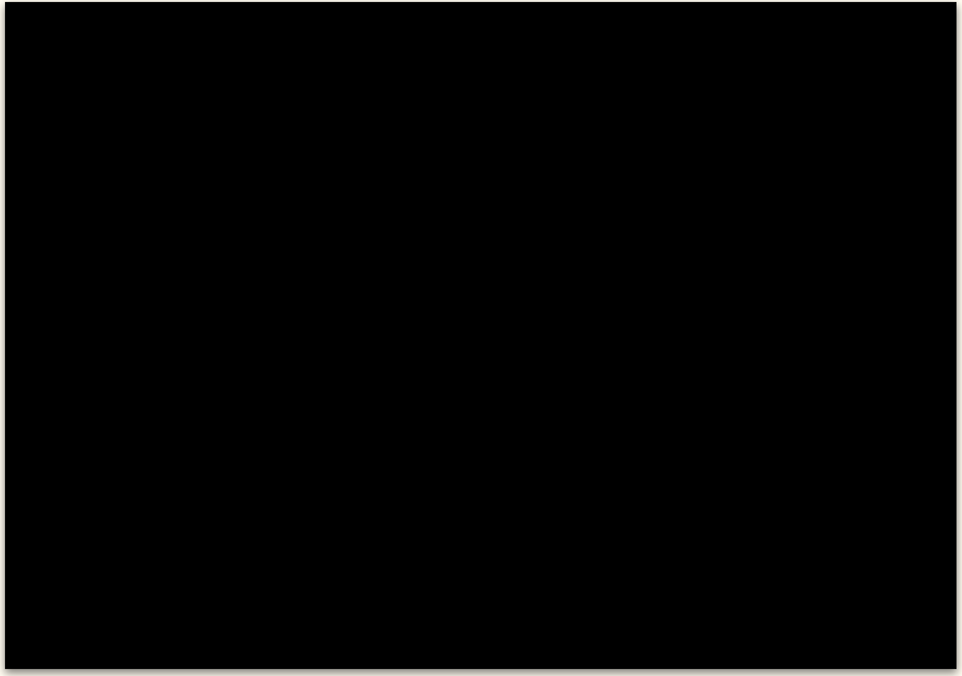
- Varies space, time and frequency

For wide FoV

- Different across the FoV

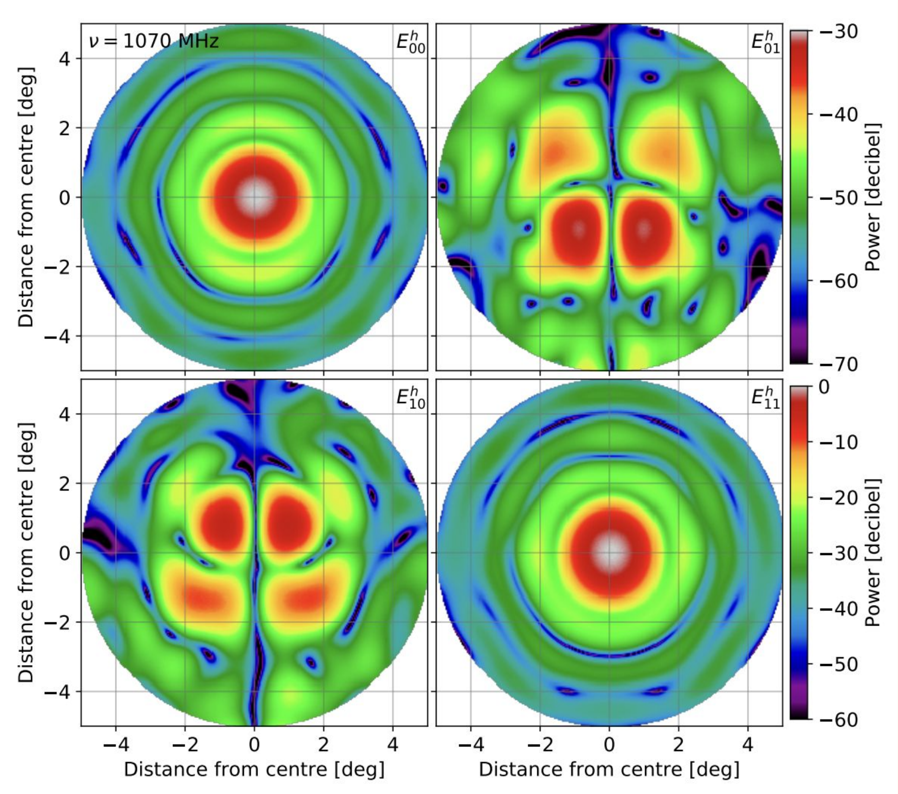
For large arrays

- Each antenna sees a different sky



Primary Beam

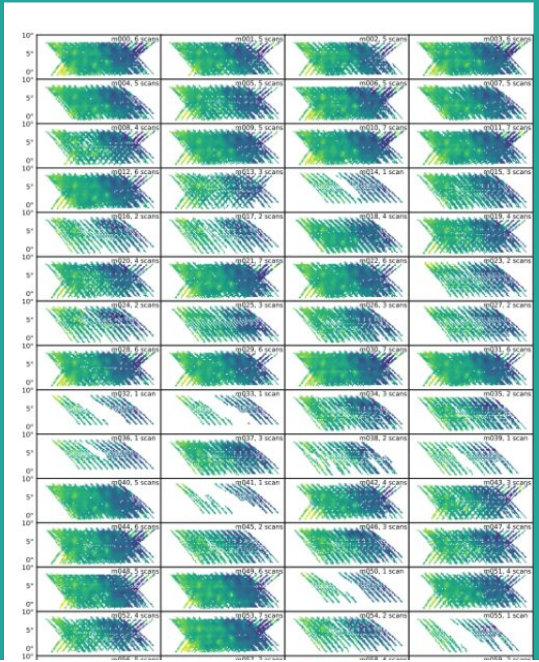
- Directional sensitivity of antenna/station to different polarised components
- Most radio telescopes have finite, non-zero polarisation leakage
- Can cause synchrotron sources to overpower cosmological 21 cm signal

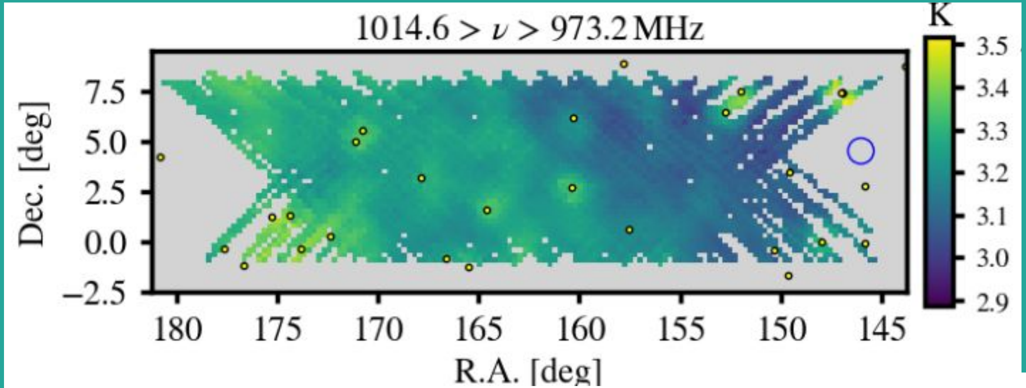


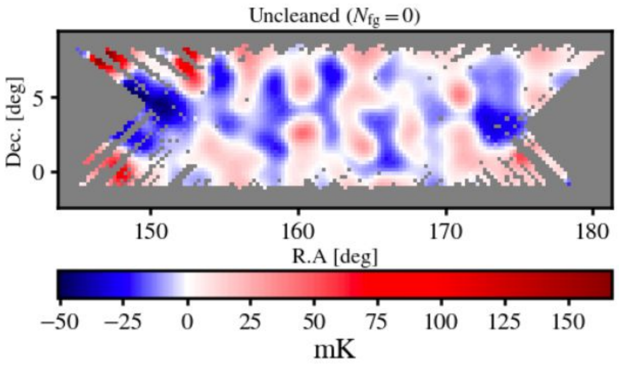
Asad et al 2019

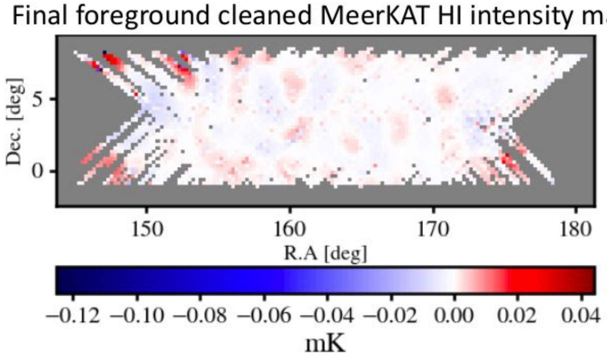
MeerKlass cross-correlation Single dish Intensity Mapping

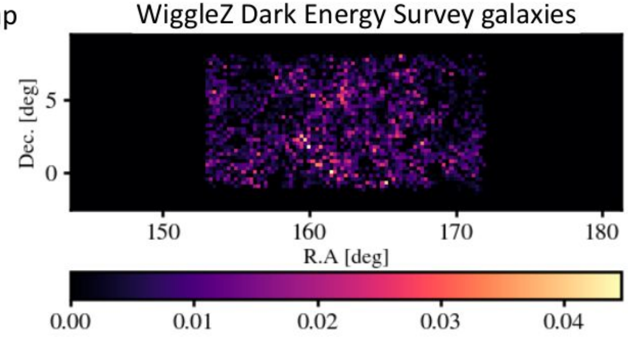
10.5 hours (6 nights) overlapping with the WiggleZ 11hr field (~200 sq. deg.)
973 - 1015 MHz (0.40 < z < 0.46)
30 PCA components removed v/s 8 in simulations





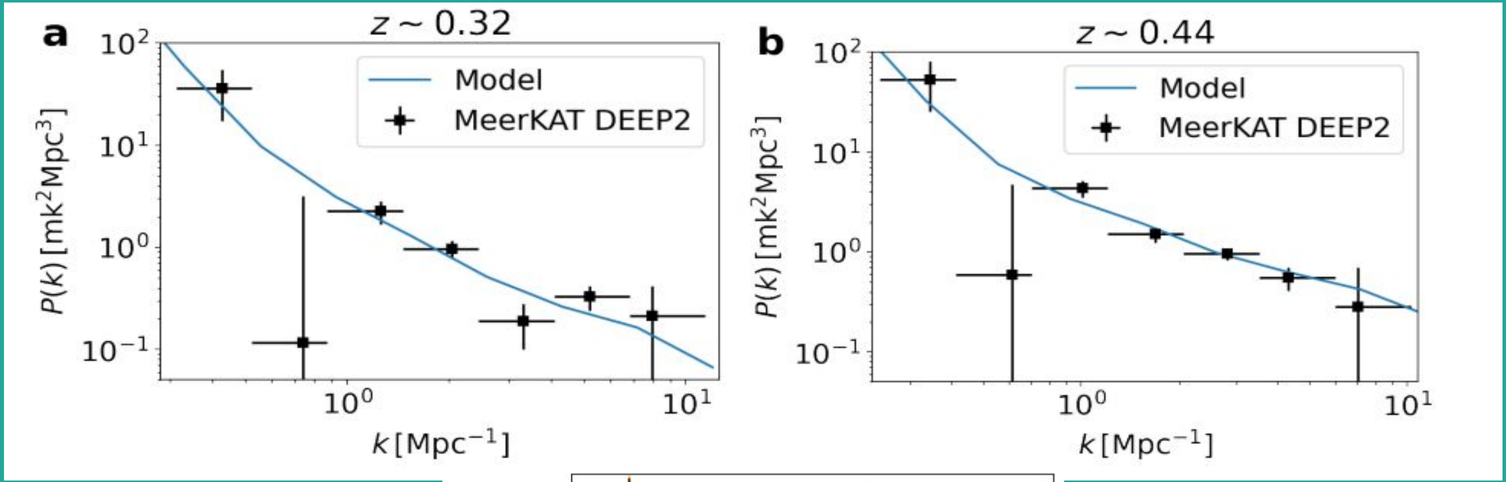


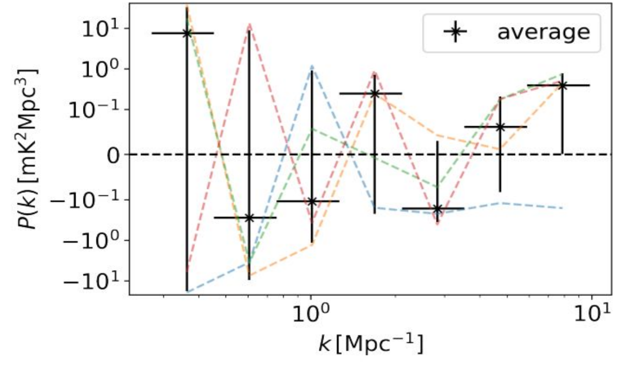




Wang 2021, Cunnington 2022

MeerKAT auto-correlation Single Dish Intensity Mapping





Calibration Errors ~ 10^{-5}

Paul et. al. 2023

Conclusion

- State of 21 cm simulations nowhere close to observations.
- Modelling instrumental effects essential - 0.02% calibration error = contaminant order of magnitude larger than signal AFTER removal
- More complex effects - time varying primary beam, different primary beam for different antennas, coloured noise, gain drift