Interferometric IM with MeerKAT & The MIGHTEE Survey

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Supervisors: Prof Mario Santos, Dr Sourabh Paul

HITS 2022 - HI Intensity Mapping in Trieste
23 May 2022

National Research Foundation
SARAO South African Radio Astronomy Observatory
CRC Centre for Radio Cosmology
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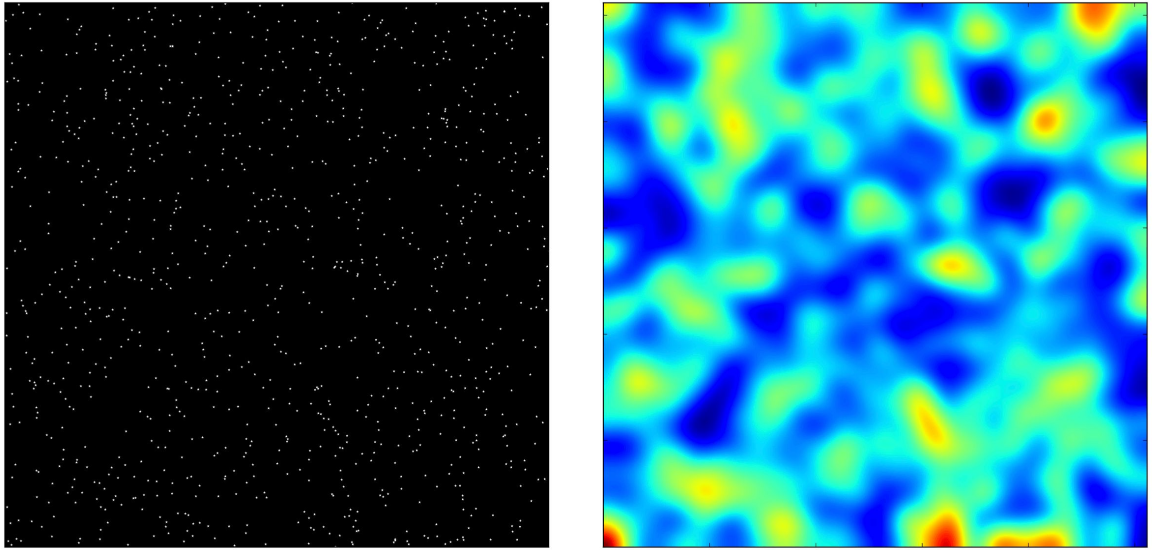
UNIVERSITY of the WESTERN CAPE

Background: Intensity Mapping

- **Intensity mapping (IM)** is concerned with measuring the HI signal fluctuations without the need to resolve structures such as galaxies.



Credit: Francisco Villaescusa-Navarro

Background: Intensity Mapping

- **Intensity mapping (IM)** is concerned with measuring the HI signal fluctuations without the need to resolve structures such as galaxies.

- Many Advantages:
  - Excellent redshift information
  - Survey large volumes more efficiently than galaxy surveys
  - Can be used as a tracer for the large-scale structure of the Universe and a probe of cosmological phenomena such as BAO and RSD

- We are primarily concerned with **interferometer-mode** intensity mapping in the post-reionization era.

Background: MeerKAT & MIGHTEE Survey

- The MeerKAT International GHz Tiered Extragalactic Exploration (**MIGHTEE**) survey is ideal for IM, with a large main survey area (20 deg^2) over well studied fields.

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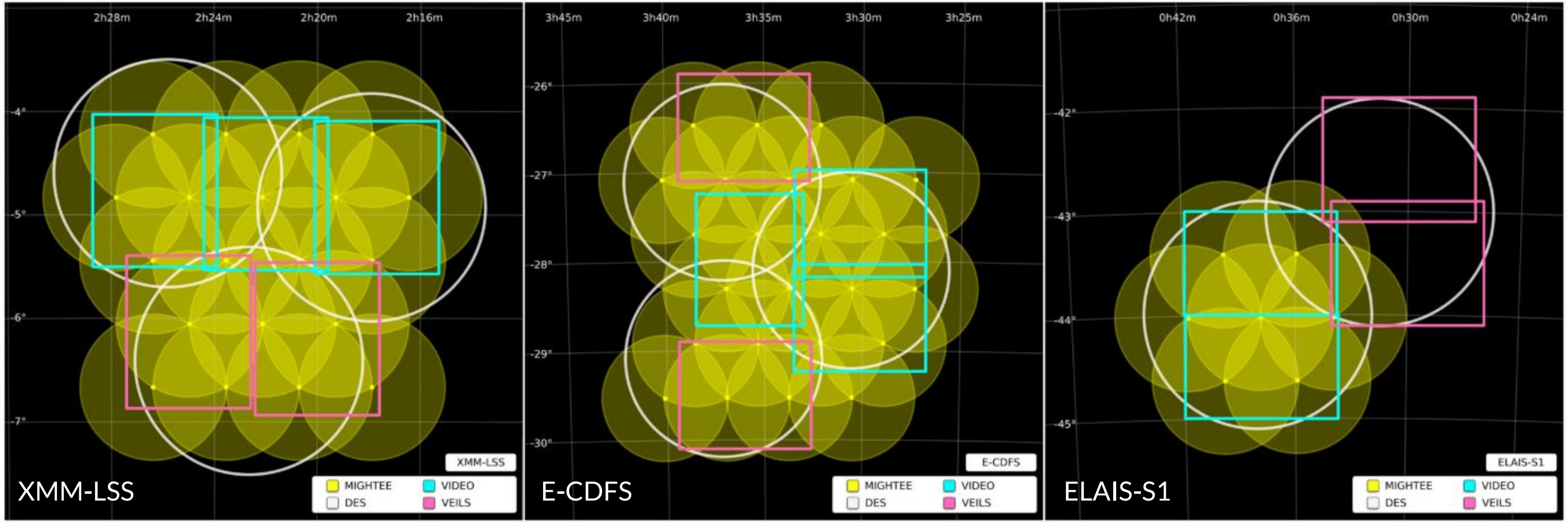

Jarvis et al., 2016

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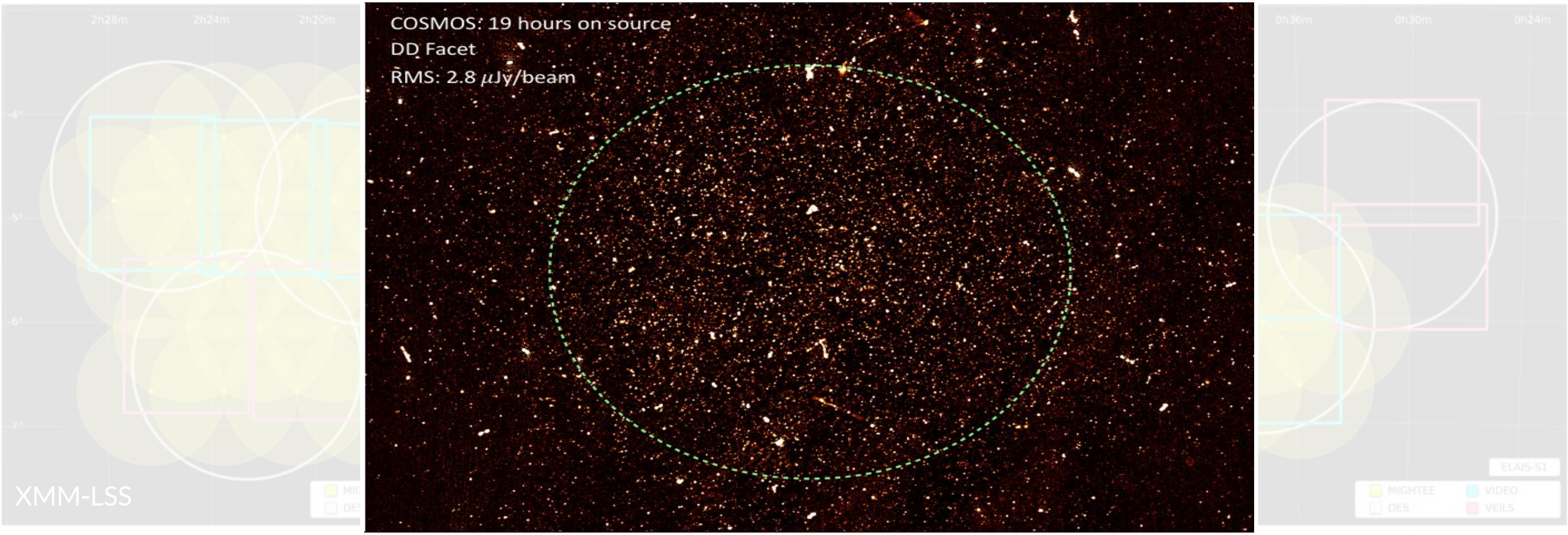

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Field Name	Area (deg^2) Full Survey	Centre Coordinates
COSMOS	2	10h01m, +02d12m
XMMLSS	8	02h20m, -04d50m
ECDFS[a]	8	03h32m, -28d00m
ELAIS-S	2	00h40m, -44d00m
MFS	12	03h38m, -35d27m

Area covered	32 deg^2
Frequency range	900–1420 MHz
Redshift range for H I	$0 < z < 0.58$
Nominal angular resolution	12 arcsec
Velocity resolution	5.5 km s^{-1} (1420 MHz)
Per channel flux sensitivity	100 μJy beam^{-1} (1420 MHz)
Column density sensitivity (22 km s^{-1})	2.6×10^{19} cm^{-2}

Maddox et al., 2020

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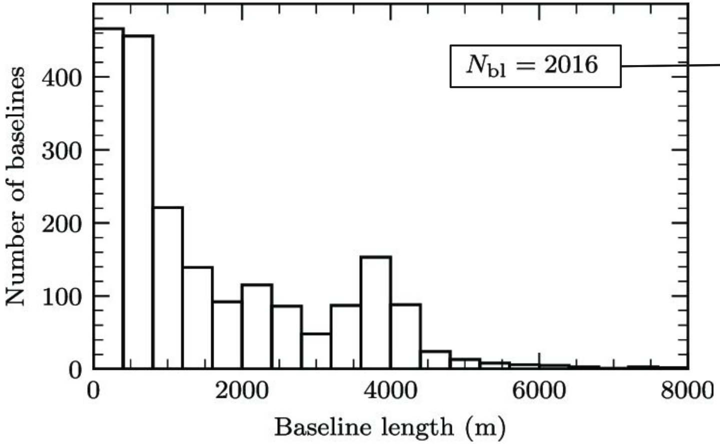
- The MeerKAT International GHz Tiered Extragalactic Exploration (**MIGHTEE**) survey is ideal for IM, with a large main survey area (20 deg^2) over well studied fields.
- MeerKAT's angular resolution and dense core allows us to probe quasi-linear scales relevant to cosmology.



$$N_{\rm b} = \frac{N_{\rm A}(N_{\rm A}-1)}{2}$$

Mauch et al., 2020

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- MeerKAT's angular resolution and dense core allows us to probe quasi-linear scales relevant to cosmology.

- MIGHTEE opens the possibility of making a statistical detection of the HI power spectrum on these scales using HI intensity mapping.

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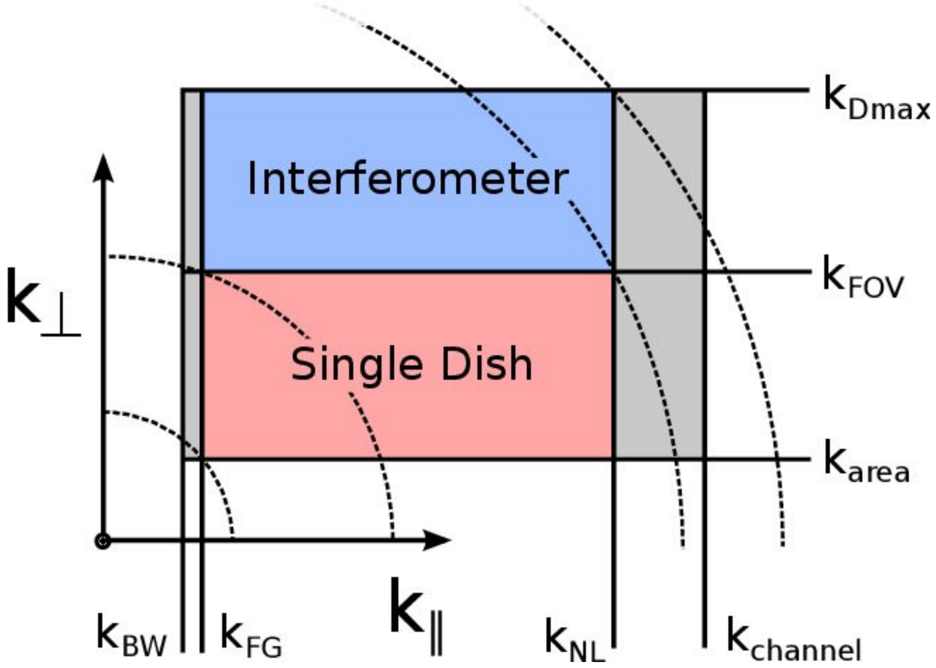

Bull et al., 2015

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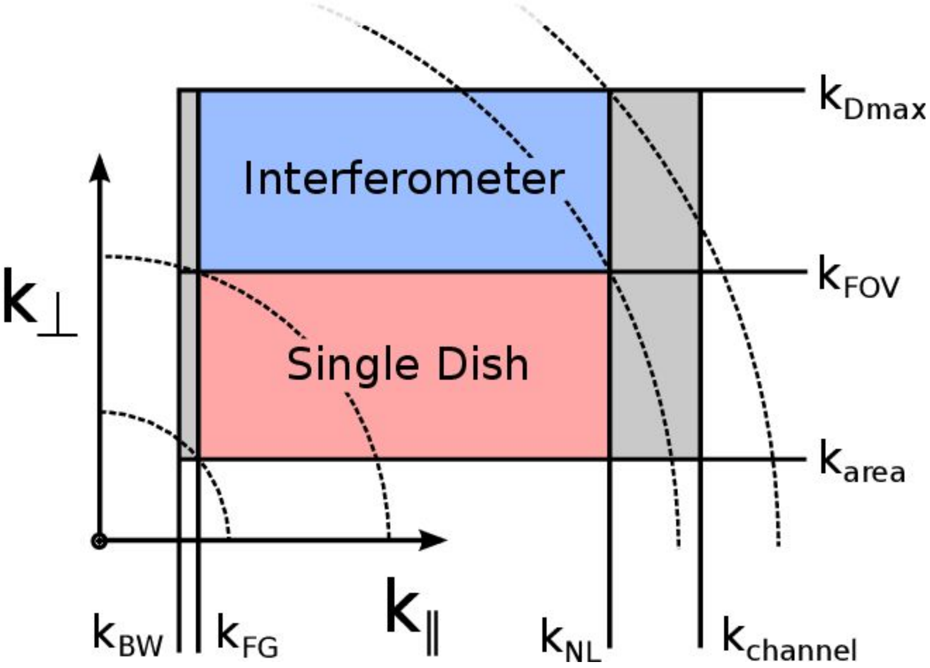

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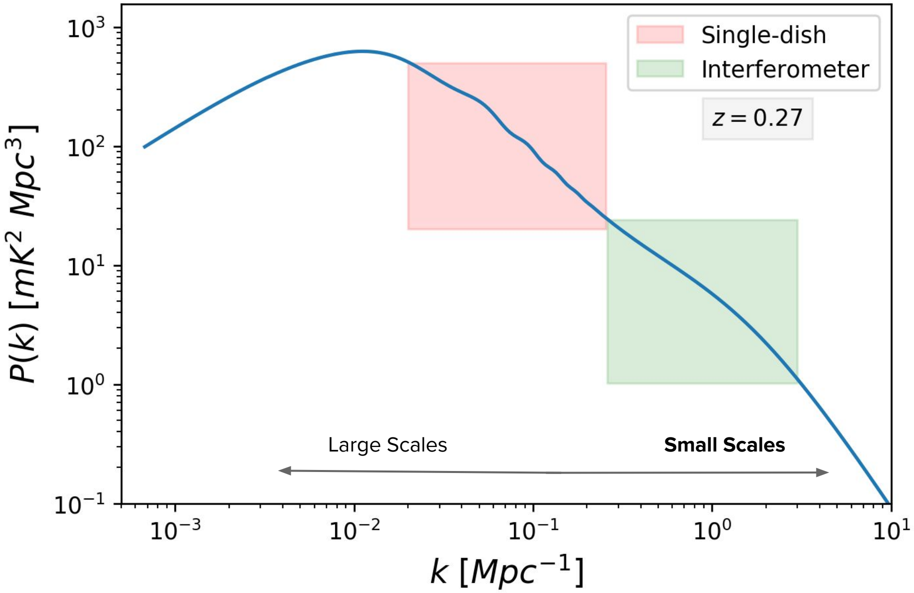
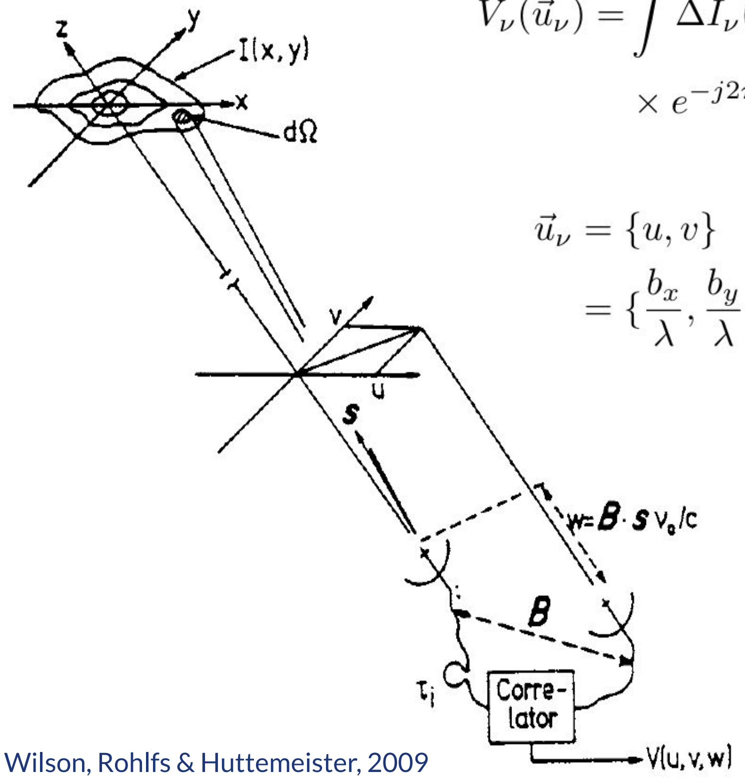


Objectives

- Main objective is to measure the **HI power spectrum** with the **MIGHTEE data** with **interferometric** HI intensity mapping.

1. As a start, **simulations** are run in order to check the S/N for the MIGHTEE data

Analysis: Delay Approximation



Wilson, Rohlfs & Huttemeister, 2009

$$V_\nu(\vec{u}_\nu) = \int \Delta I_\nu(\vec{\theta}) A_\nu(\vec{\theta}) \times e^{-j2\pi \vec{u}_\nu \cdot \vec{\theta}_i} d^2\theta$$

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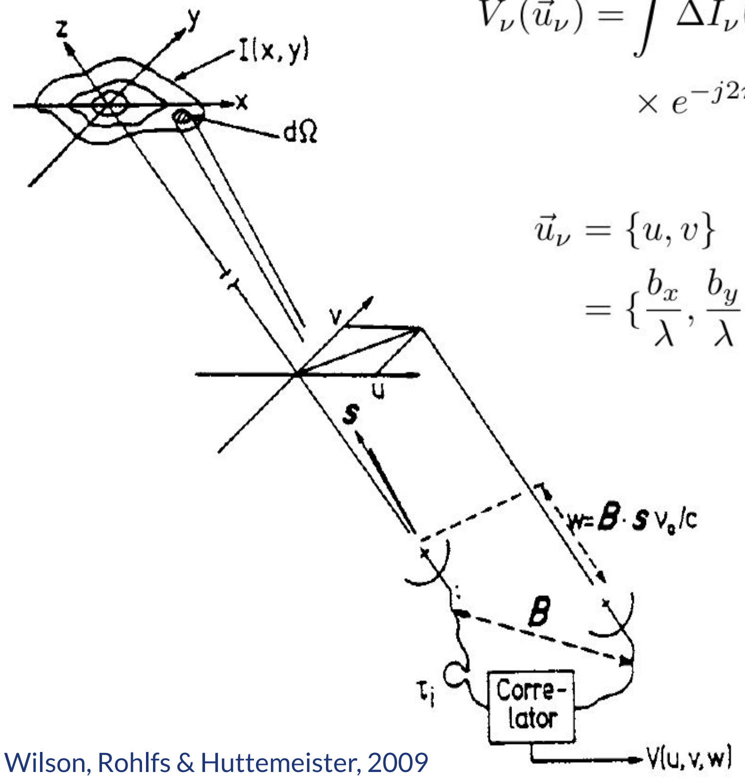

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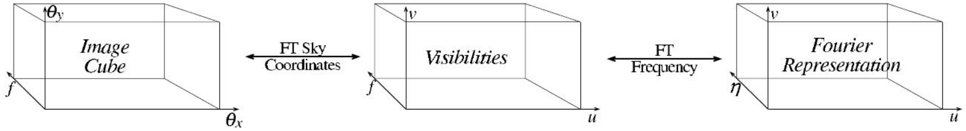

Morales & Jewitt, 2004

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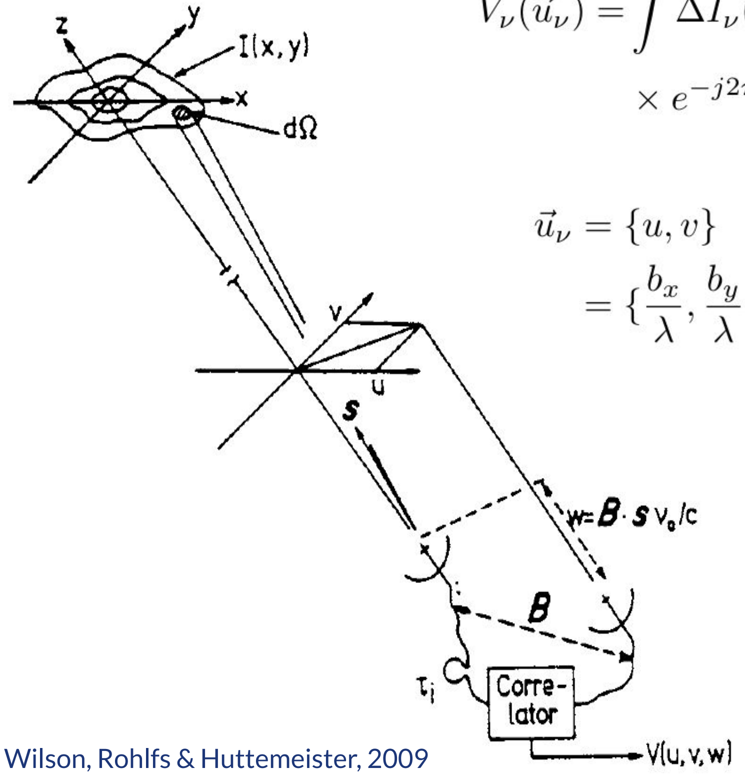

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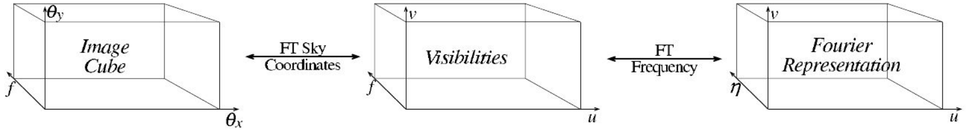

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$$\vec{u}_\nu = \{u, v\} = \{\frac{k_x D(z)}{2\pi}, \frac{k_y D(z)}{2\pi}\} = \frac{\vec{k}_\perp D(z)}{2\pi}$$

$$\tau \approx \frac{c(1+z)^2}{2\pi H_0 \nu_{21} E(z)} k_\parallel$$

$$\vec{u} = \{u, v, \tau\}; \; \vec{k} = \{\vec{k}_\perp, k_\parallel\}$$

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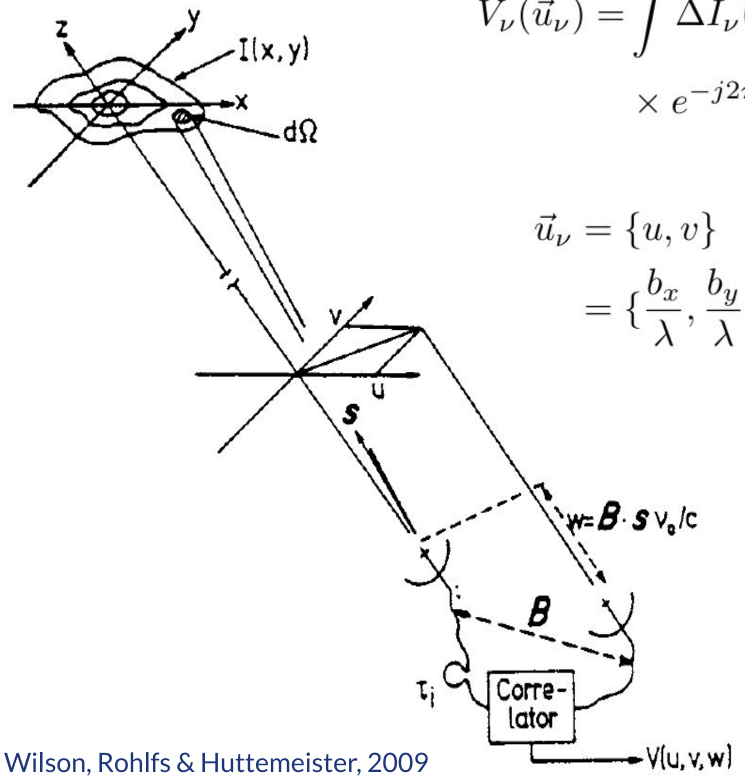

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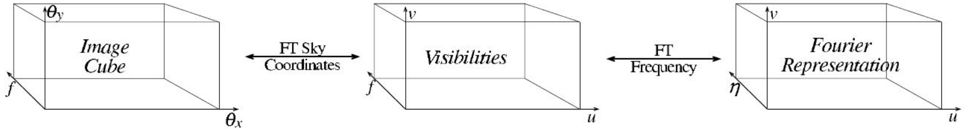

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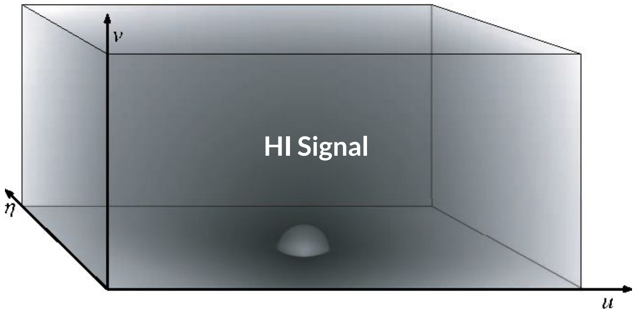
$$\vec{u} = \{u, v, \tau\}; \;\; \vec{k} = \{\vec{k}_\perp, k_\parallel\}$$

$$P_{\mathsf{D}}(\vec{u}) = \left\langle V(\vec{u}_i)^* V(\vec{u}_j) \right\rangle \delta_{ij} = \left\langle \left|V(\vec{u})\right|^2 \right\rangle$$

$$P_{\mathsf{D}}(\vec{k}) = \left\langle |V(\vec{u})|^2 \right\rangle \left(\frac{A_e}{\lambda^2 \Delta B}\right) \left(\frac{D^2 \Delta D}{\Delta B}\right) \left(\frac{\lambda^2}{2k_B}\right)^2$$

Analysis: Delay Approximation



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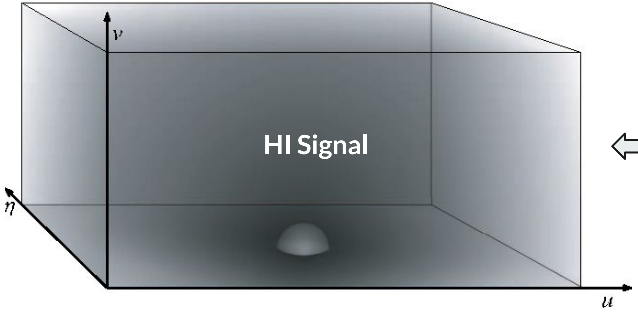
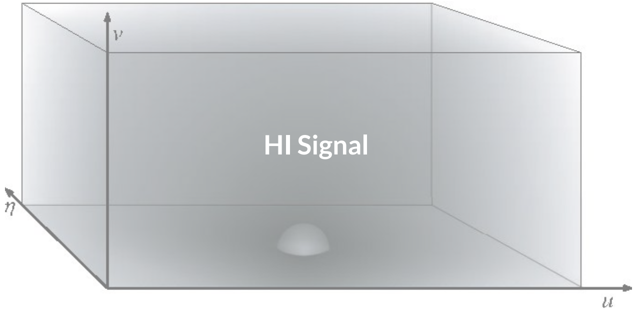


Spherical symmetry

Morales & Jewitt, 2004

Analysis: Delay Approximation



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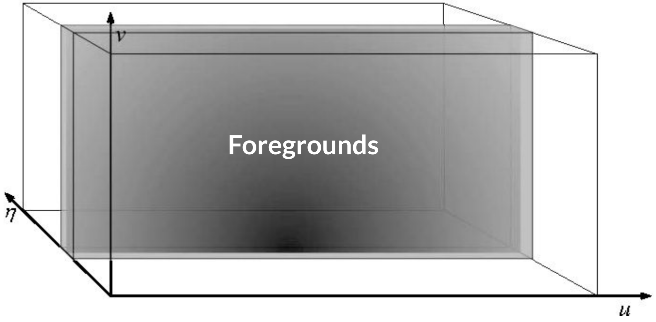

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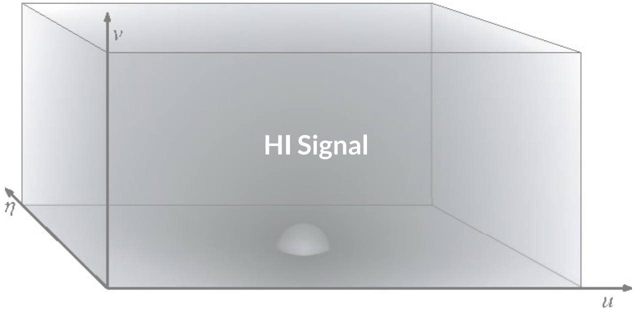

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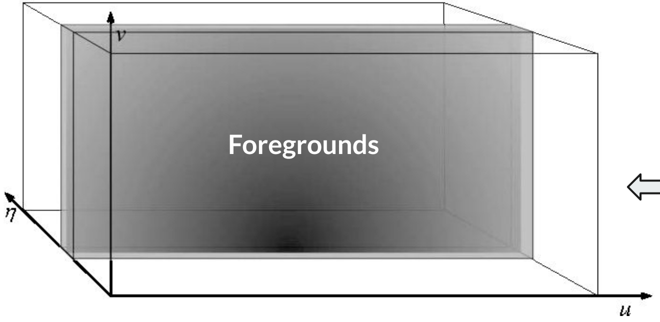
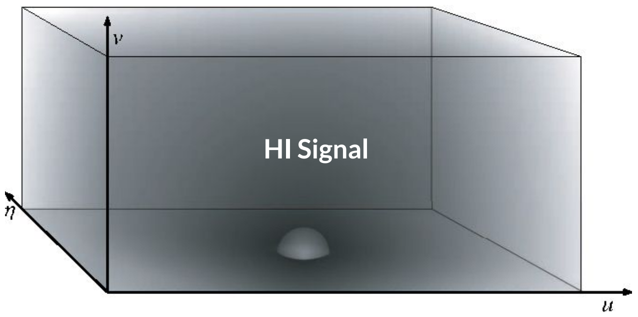


Separable-axial symmetry
Concentrated at small η values

Analysis: Delay Approximation

$$k_{\parallel} = \frac{H_0 E(z) D(z)}{c\,(1+z)} k_{\perp}$$



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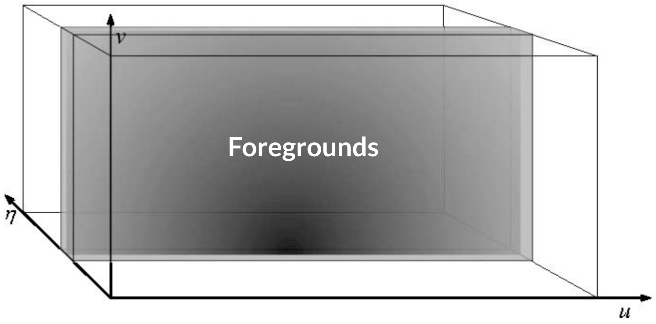

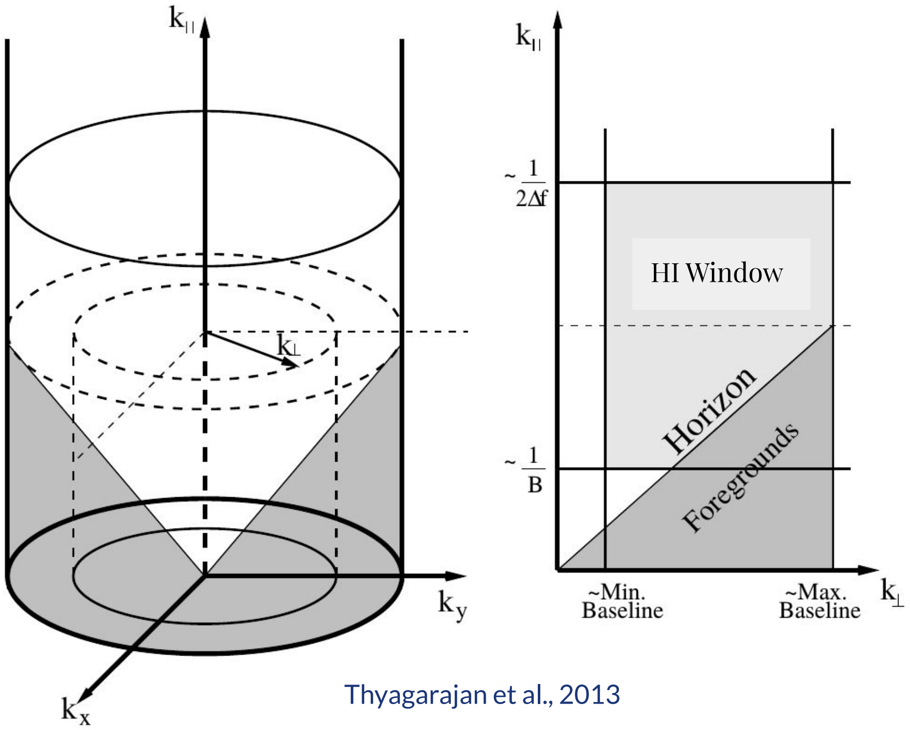

Thyagarajan et al., 2013

Simulations

Visibilities are generated containing information from **three main components:**

- **HI Signal:** Generated from input model HI power spectrum:

$$P_{\rm HI}(k,z) = \overline{T}_b^2(z) b_{\rm HI}^2 P_M(k,z)$$

Simulations

Visibilities are generated containing information from **three main components:**

- **HI Signal:** Generated from input model HI power spectrum:
- **Thermal Noise:** Randomly generated from Gaussian distribution with zero mean and RMS:

$$\sigma_{\mathrm{TN}} = \frac{2k_{\mathrm{B}}T_{\mathrm{sys}}}{A_{\mathrm{e}}\sqrt{\Delta\nu\Delta t}}$$

Simulations

Visibilities are generated containing information from **three main components:**

- **HI Signal:** Generated from input model HI power spectrum:
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- **Foregrounds:** Point source model generated from MIGHTEE COSMOS image

Simulations

Visibilities are generated containing information from **three main components:**

- **HI Signal:** Generated from input model
- **Thermal Noise:** Randomly generated from Gaussian distribution with zero mean and RMS:
- **Foregrounds:** Point source model generated from MIGHTEE COSMOS image

Visibilities take the form (or any combination of components):

$$V^{\text{simulation}} = V^{\text{HI}} + V^{\text{FG}} + V^{\text{TN}}$$

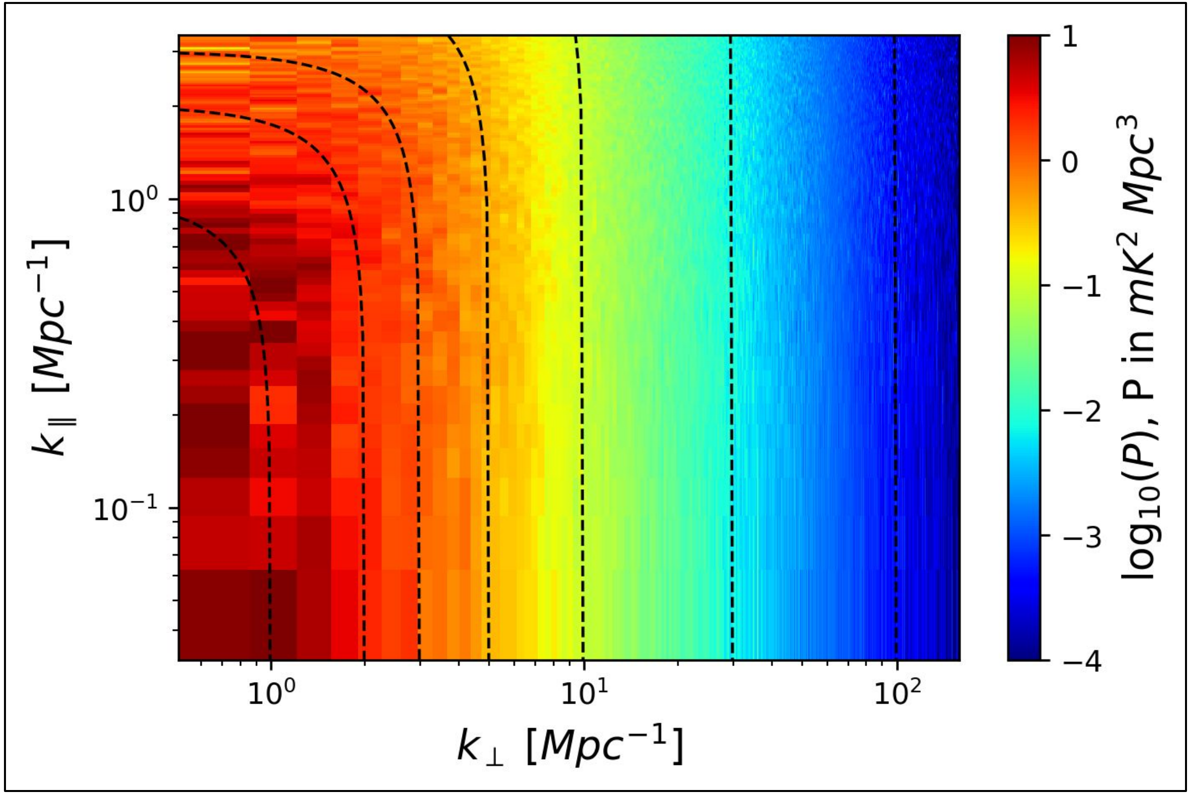
3D Power Spectrum:

$$P^{\text{simulation}}(\vec{k}) = \mathcal{N}\left\langle |V^{\text{simulation}}(\vec{u})|^2 \right\rangle$$

Simulation Outputs (2D power spectra)

HI Signal

z = 0.27



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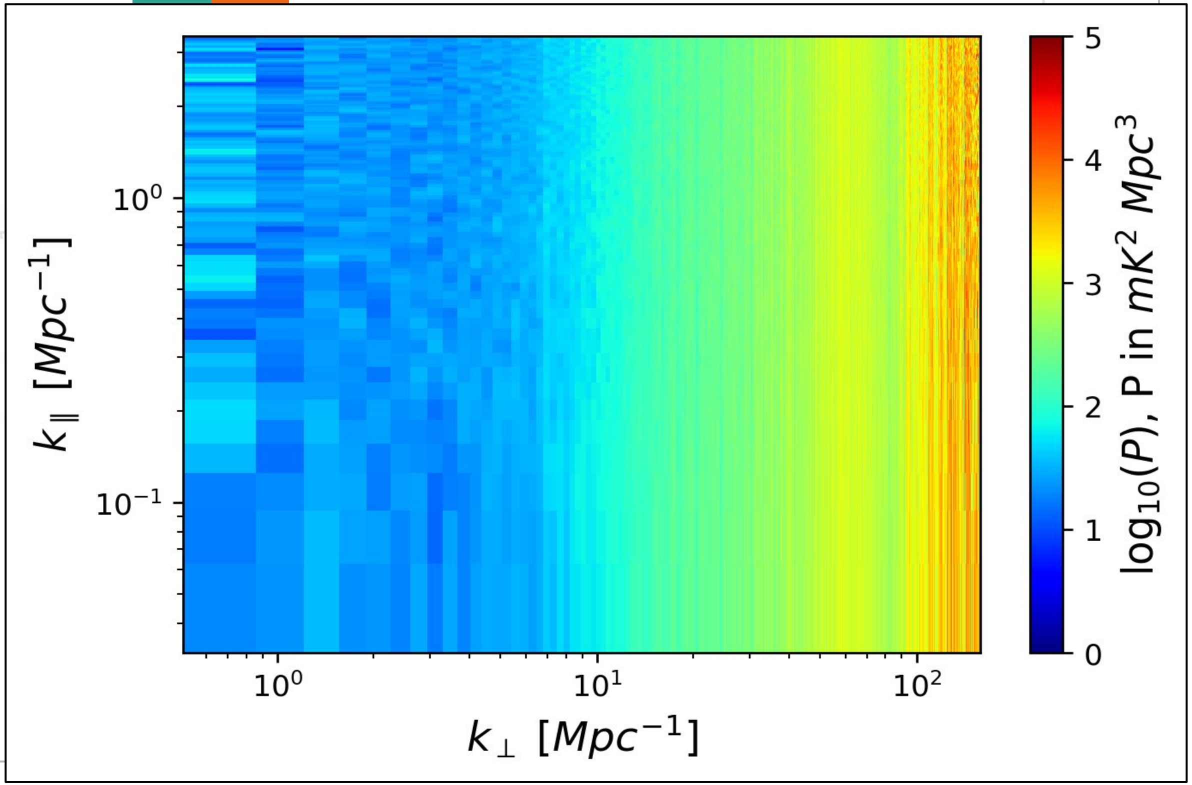

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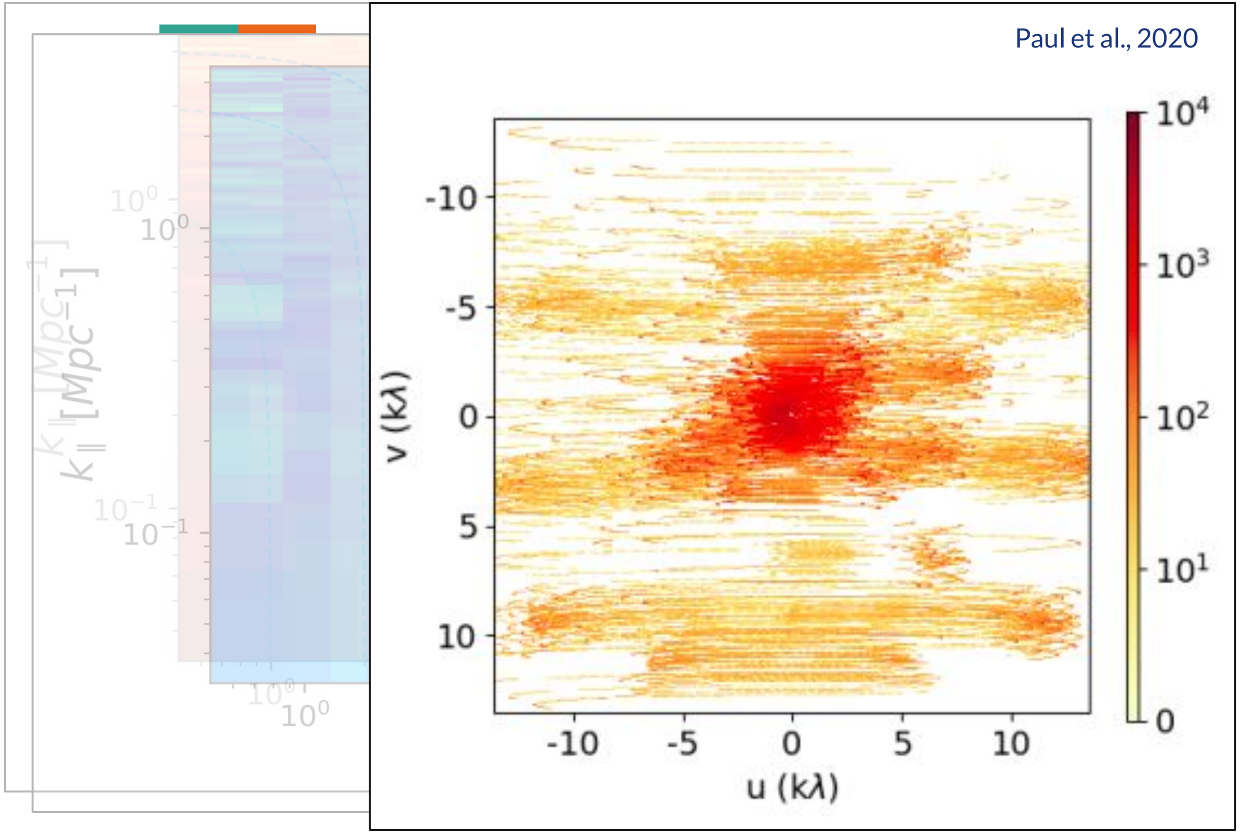

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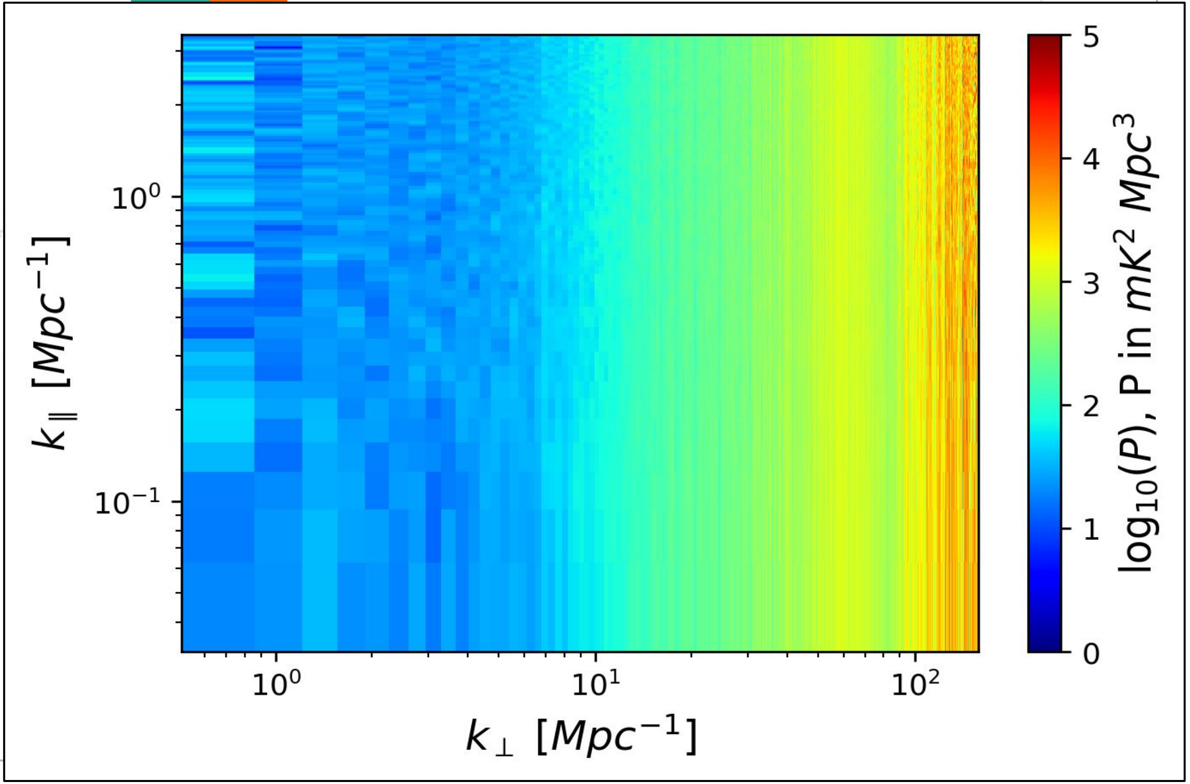

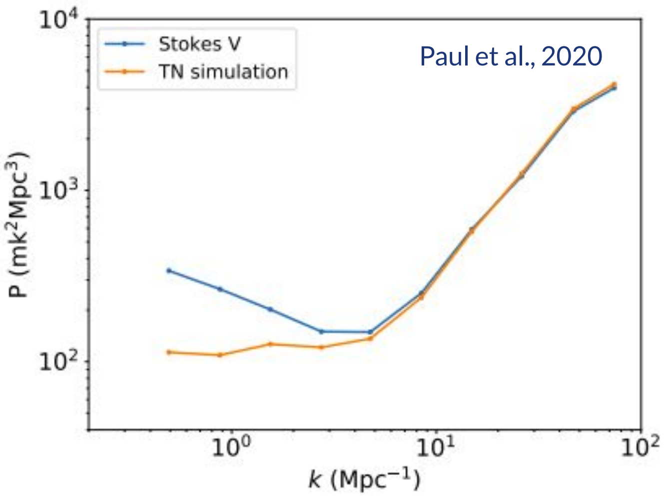

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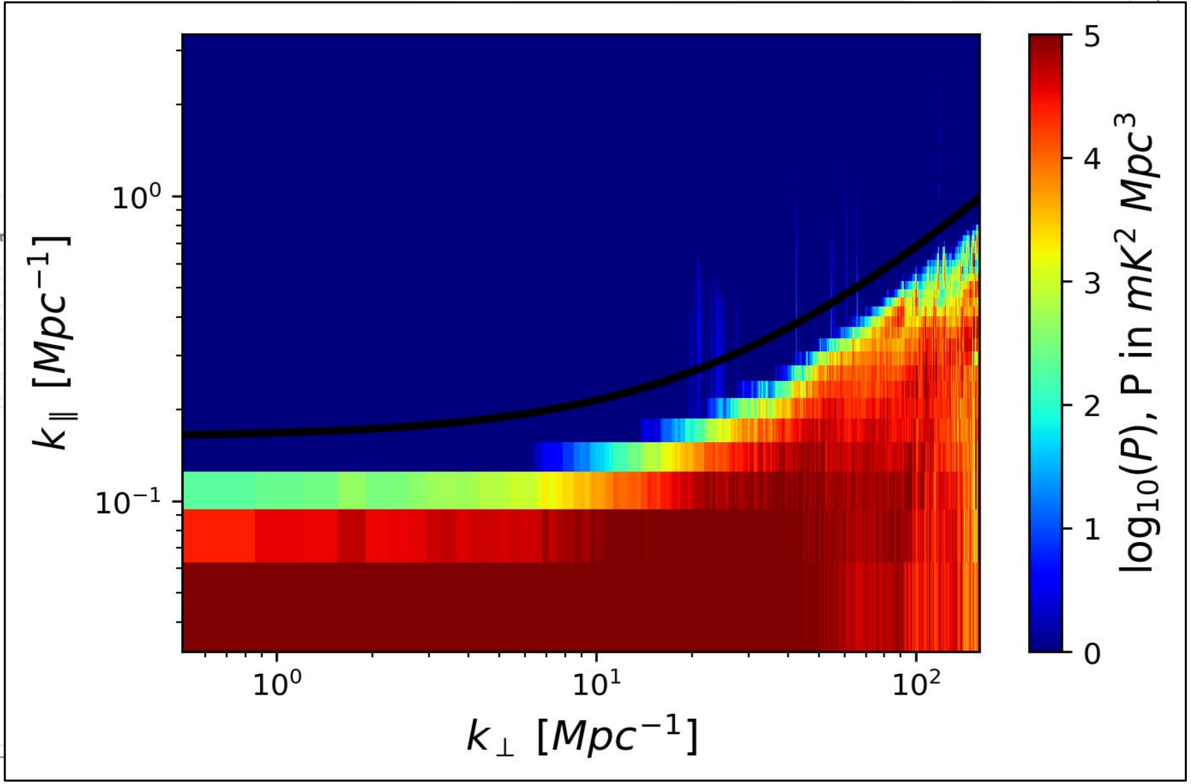

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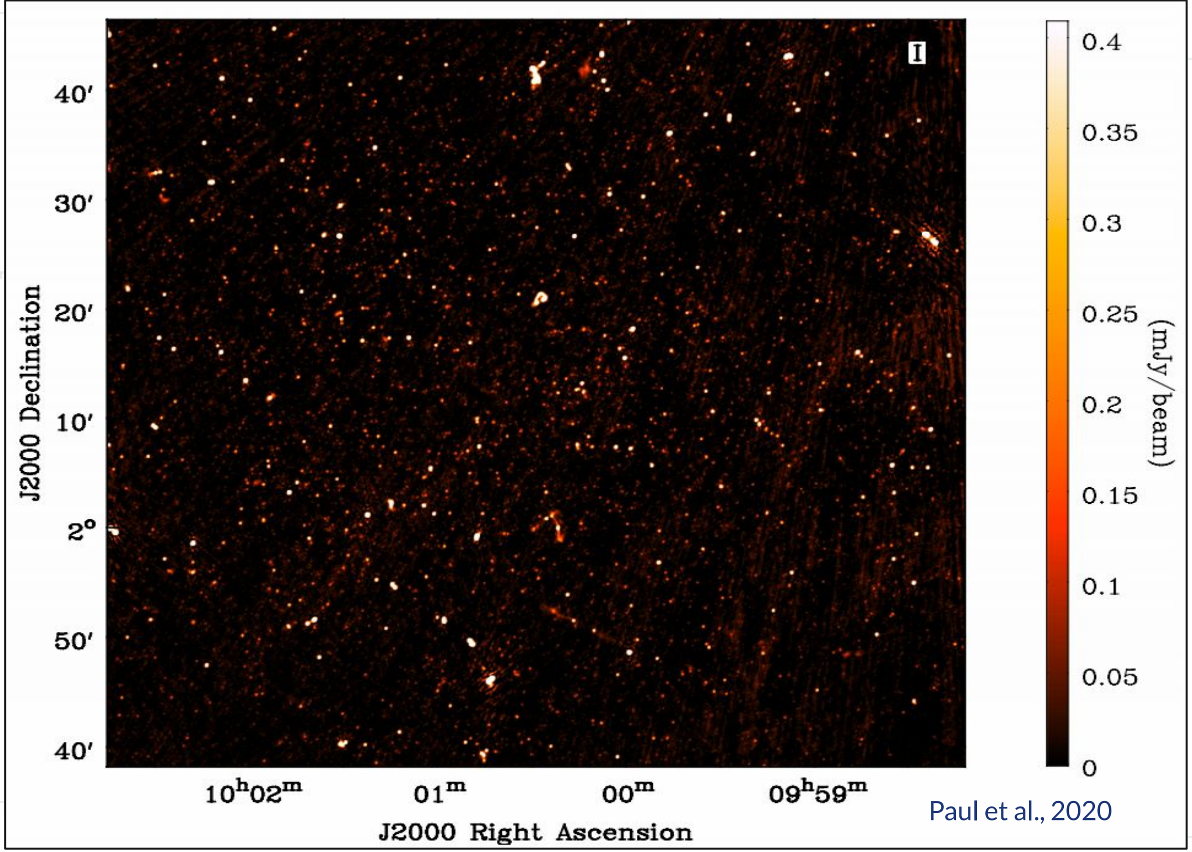


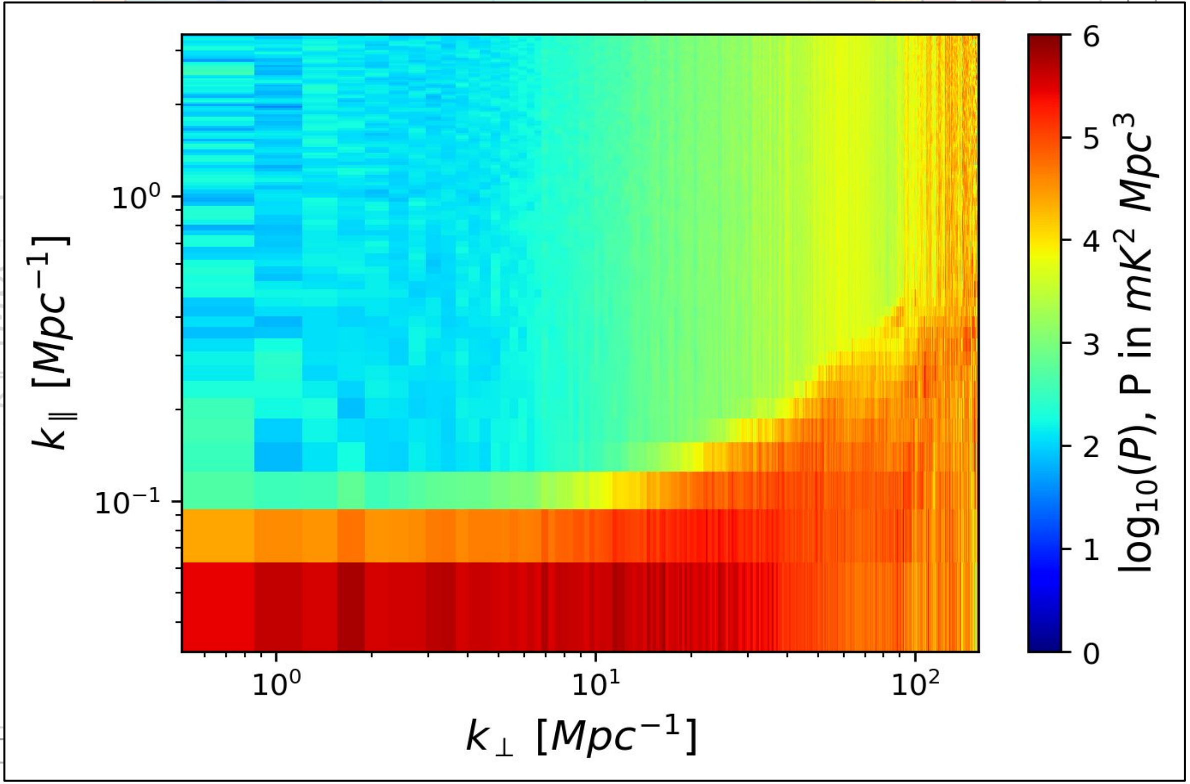
Paul et al., 2020

- MIGHTEE COSMOS image at 1115.14 MHz (**z ~ 0.27**)
- Observation time: ~ **11.2hrs**
- Integral to the modelling of foregrounds in the simulation results shown

Simulation Outputs (2D power spectra)

Full Simulation

z = 0.27



Parameter	Value
Δu	$60\ \lambda$
Δv	$60\ \lambda$
$N_{\rm gridpoints}$	1500
$N_{\rm chan}$	220
Δt	8 s
$\Delta \nu$	0.208984 MHz
ΔB	45.97648 MHz
ν_c	1115.14 MHz
λ_c	26.9 cm
z	~ 0.27
$\frac{A_e}{T_{\rm sys}}$	$6.22\ {\rm m}^2/{\rm K}$
$t_{\rm obs}$	11.2 hours
$\Delta k_\perp$	0.35 Mpc^{-1}
$\Delta k_\parallel$	0.031 Mpc^{-1}
Δk	0.45 Mpc^{-1}

HI power spectrum estimation (Auto-correlation):

Observed power spectrum (**foreground avoidance**):

$$P_{\rm o}(k) = P_{\rm HI+TN}(k)$$

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Estimator:

$$\tilde{P}(k) = P_{\rm o}(k) - \overline{P_{\rm TN}}(k)$$

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For i$^{\rm th}$ realisation:

$$\tilde{P}^i(k) = P_{\rm o}^i(k) - \overline{P_{\rm TN}}(k)$$

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Thermal noise model:

$$\overline{P_{\rm TN}}(k) = \frac{\sum_i^N P_{\rm TN}^i(k)}{N}$$

HI power spectrum estimation (Auto-correlation):

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$$P_o(k) = P_{HI+TN}(k)$$

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Thermal noise model:

$$\overline{P_{TN}}(k) = \frac{\sum_i^N P_{TN}^i(k)}{N}$$

<u>For N realisations:</u>

Mean of estimator:

$$\overline{\tilde{P}}(k) = \frac{\sum_i^N \tilde{P}^i(k)}{N}$$

Estimator error:

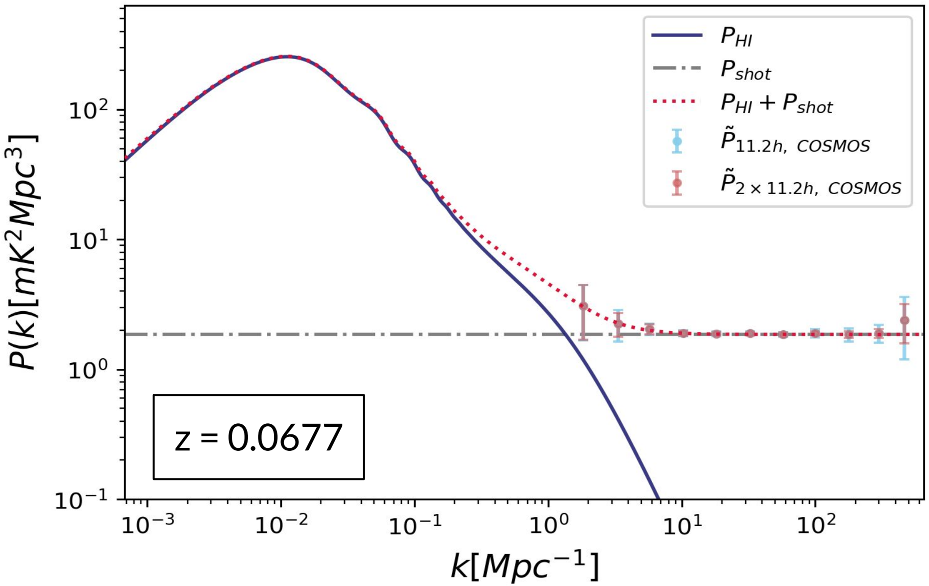
$$\sigma_{\tilde{P}(k)} = \sqrt{\frac{\sum_i^N \left[\tilde{P}^i(k) - \overline{\tilde{P}}(k)\right]^2}{N}}$$

$$= \sqrt{\frac{\sum_i^N \left[P_o^i(k) - \overline{P}_{TN}(k) - \overline{\tilde{P}}(k)\right]^2}{N}}.$$

Simulation Results at low-z:

- The objective is to run these simulations for low z ($\nu \sim 1310$ - 1420 MHz) COSMOS in order to check the S/N for the MIGHTEE data:

Parameter	Value
Δu	60 λ
Δv	60 λ
$N_{\mathrm{gridpoints}}$	1500
N_{chan}	150
Δt	8 s
$\Delta \nu$	0.208984 MHz
ΔB	31.3476 MHz
ν_c	1330 MHz
λ_c	22.56 cm
z	~ 0.0677
$\frac{A_e}{T_{\mathrm{sys}}}$	6.22 m^2/K
t_{obs}	11.2 hours
$\Delta k_\perp$	1.81 Mpc^{-1}
$\Delta k_\parallel$	0.058 Mpc^{-1}



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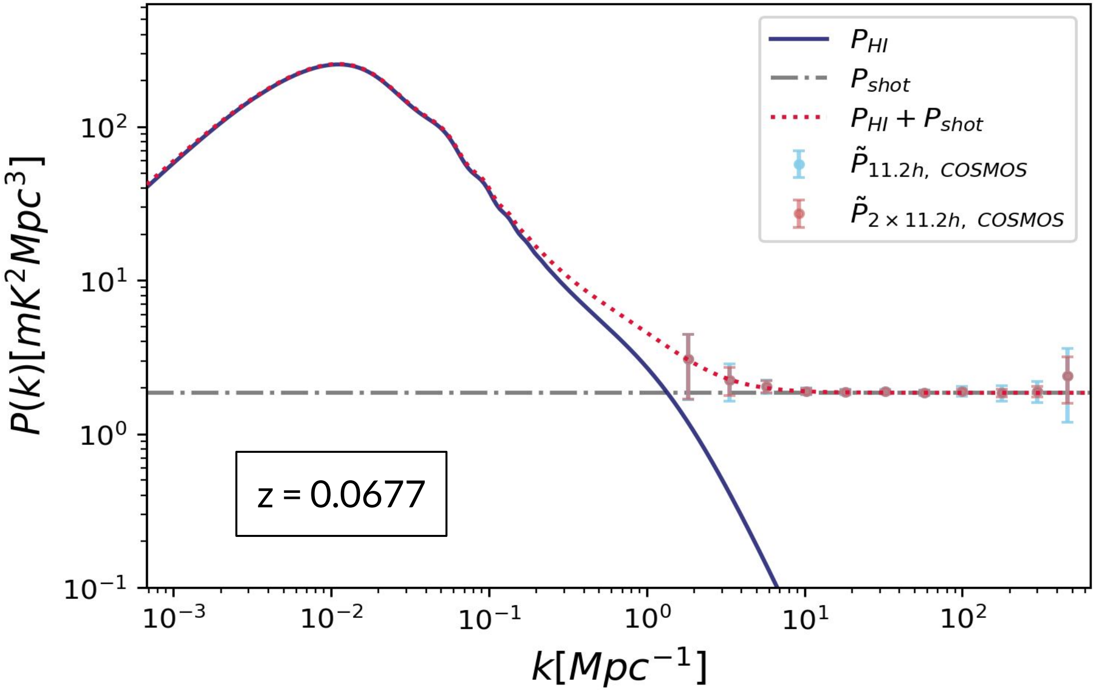

- At very low-z, one expects the shot noise to dominate
- The results shown provide a further validation test for the simulations

Objectives

- Main objective is to measure the **HI power spectrum** with the **MIGHTEE data** with **interferometer-mode** HI intensity mapping.

1. **Simulations** are run in order to check the S/N for the MIGHTEE data
2. Measure the HI power spectrum from **Early Science MIGHTEE-HI galaxy catalogue**

Power spectrum from MIGHTEE HI galaxies:

```
#Created by Natasha on Wed Nov 11 19:09:39 2020
#Early science data from COSMOS and XMMLSS, 1310-1420MHz
#Only objects with an optical counterpart are included, duplicates have been removed
#Objects with Mstellar -99 are outside the deep imaging footprint
#Name RA Dec freq z Log(MHI) Log(Mstellar) Log(SFR) Log(Age) EBV umag gmag rmag Semimaj Semimin PA
MGTH_J100128.0+022025   150.366572     2.340383     1.410788     0.006817     7.080000     6.359910     -2.141720     8.656548     0.200000     20.146570     19.492781     19.237109     8.873000     4.541000
20.000000
MGTH_J100153.8+022449   150.474191     2.413661     1.410788     0.006817     7.694000     7.453160     -2.033580     9.698970     0.050000     18.461895     17.777561     17.452504     16.103000     5.710000
90.000000
MGTH_J100227.1+021000   150.613031     2.166756     1.412042     0.005923     7.309000     6.921620     -2.254760     9.380211     0.100000     19.133808     18.439042     18.134389     7.679000
6.642000     0.000000
MGTH_J100030.1+020859   150.125251     2.149586     1.414550     0.004140     6.694000     6.031490     -2.295570     8.306547     0.300000     20.172159     19.408106     19.146548     7.576000     5.710000
120.000000
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HI galaxy catalogue from MIGHTEE; Credit: Natasha Maddox

- The goal with this catalogue was to produce an intensity map and measure the HI power spectrum from this

Steps:

1. Gain an understanding of the catalogue (distances between galaxies, sizes of biggest galaxies, etc)
2. Assign the M_{HI} to a grid (with the insights from having had a thorough look at the catalogue)
3. Convert this M_{HI} to HI temperature and measure the power spectrum using the FFT method (refer to [Jing, 2005] and [Cui et al., 2008] for details)

Power spectrum from MIGHTEE HI galaxies: Methodology

- Mass assignment scheme is used to assign masses from galaxy catalogue (discrete objects) onto a mesh grid using *nbodykit**:

* https://nbodykit.readthedocs.io/

Power spectrum from MIGHTEE HI galaxies: Methodology

- Mass assignment scheme is used to assign masses from galaxy catalogue (discrete objects) onto a mesh grid using *nbodykit**:

Assume objects assign to the grid have a given “shape”: $s(\vec{x} - \vec{X})$

Nearest Grid Point: Assumes particles are point-like with all mass assigned to a single grid cell

$$S(x) = \frac{1}{\Delta x}\delta\left(\frac{x}{\Delta x}\right)$$

Cloud-in-Cell (CIC): Assumes particles are cubes of uniform density and one grid cell size

$$S(x) = \frac{1}{\Delta x}, \text{ if } |x| < \frac{1}{2}\Delta x,$$

Triangular Shaped Cloud: Similar to CIC, but has an extended mathematical expression

$$S(x) = \frac{1}{\Delta x}\left(1 - \frac{|x|}{\Delta x}\right), \text{ if} |x| < \Delta x$$

* https://nbodykit.readthedocs.io/

Power spectrum from MIGHTEE HI galaxies: Methodology

Fraction of a particle's mass assigned to cell ijk is then the shape function averaged over this cell:

$$W(x_p - x_{ijk}) = \int_{x_{ijk}-\Delta x/2}^{x_{ijk}+\Delta x/2} dx' \, S(x_p - x')$$

with

$$W(\vec{r}_p - \vec{r}_{ijk}) = W(x_p - x_{ijk}) W(y_p - y_{ijk}) W(z_p - z_{ijk})$$

The density in a given cell is then

$$\rho_{ijk} = \sum_{p=1}^{N_p} m_p W(\vec{r}_p - \vec{r}_{ijk})$$

Power spectrum from MIGHTEE HI galaxies: Methodology

Interpolation scheme (mostly relevant to CIC and TSC mass assignments):

$$\rho_{i,j,k} = \rho_{i,j,k} + m_{\mathrm{p}} t_x t_y t_z$$

$$\rho_{i+1,j,k} = \rho_{i+1,j,k} + m_{\mathrm{p}} dx t_y t_z$$

$$\rho_{i,j+1,k} = \rho_{i,j+1,k} + m_{\mathrm{p}} t_x dy t_z$$

$$\rho_{i,j,k+1} = \rho_{i,j,k+1} + m_{\mathrm{p}} t_x t_y dz$$

$$\rho_{i+1,j+1,k} = \rho_{i+1,j+1,k} + m_{\mathrm{p}} dx dy t_z$$

$$\rho_{i+1,j,k+1} = \rho_{i+1,j,k+1} + m_{\mathrm{p}} dx t_y dz$$

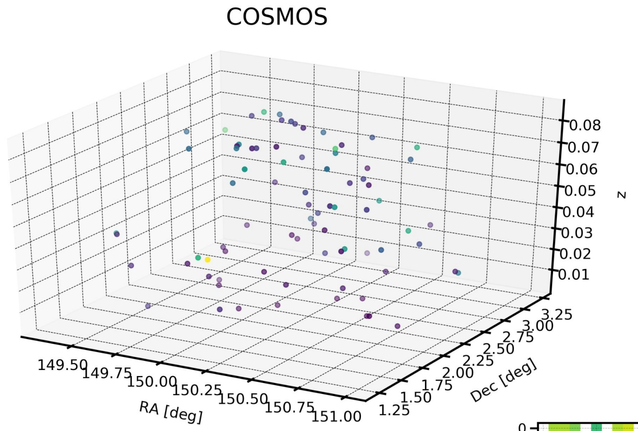
$$\rho_{i,j+1,k+1} = \rho_{i,j+1,k+1} + m_{\mathrm{p}} t_x dy dz$$

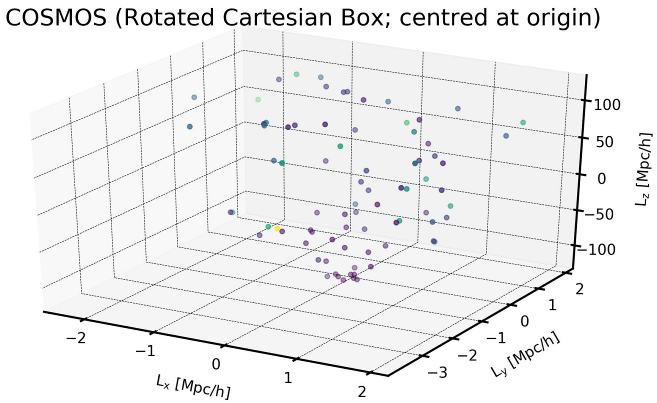
$$\rho_{i+1,j+1,k+1} = \rho_{i+1,j+1,k+1} + m_{\mathrm{p}} dx dy dz,$$

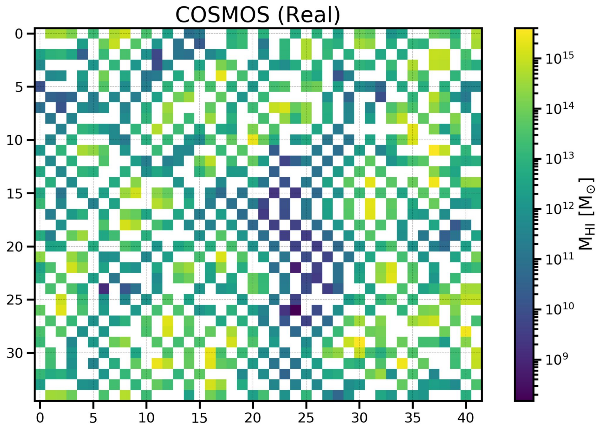
$$dx = x_{\mathrm{p}} - x_c,\ dy = y_{\mathrm{p}} - y_c,\ dz = z_{\mathrm{p}} - z_c$$

$$t_x = 1 - dx,\ t_y = 1 - dy,\ t_z = 1 - dz.$$

Power spectrum from MIGHTEE HI galaxies: Methodology







Power spectrum from MIGHTEE HI galaxies: Methodology

To convert the HI mass on the mesh grid to temperature, apply the conversion and obtain an **Intensity Map**:

$$T_{\rm HI}(\vec{r}, z) = \frac{3h_p c^2 A_{12}}{32\pi m_h k_B \nu_{21}} \frac{1}{[(1+z)\chi(z)]^2} \frac{M_{\rm HI}(\vec{r}, z)}{\delta\nu\delta\Omega}$$

Cunnington et al., 2019

An FFT is applied to the temperature mesh to obtain the HI power spectrum with k modes sampled using:

$$k_{x,\rm min} = \frac{2\pi}{L_x};\ k_{y,\rm min} = \frac{2\pi}{L_y};\ k_{z,\rm min} = \frac{2\pi}{L_z}$$

$$k_{x,\rm max} = \frac{\pi}{dx};\ k_{y,\rm max} = \frac{\pi}{dy};\ k_{z,\rm max} = \frac{\pi}{dz}$$

Power spectrum from MIGHTEE HI galaxies: Methodology

The shot noise on the power spectrum estimate can then be obtained with:

$$P_{\mathrm{SN}}(\vec{k}) = \frac{A^2(\Delta V)^2 \sum_n M^2_{\mathrm{HI},n}}{V}$$

Sum over galaxies in catalogue

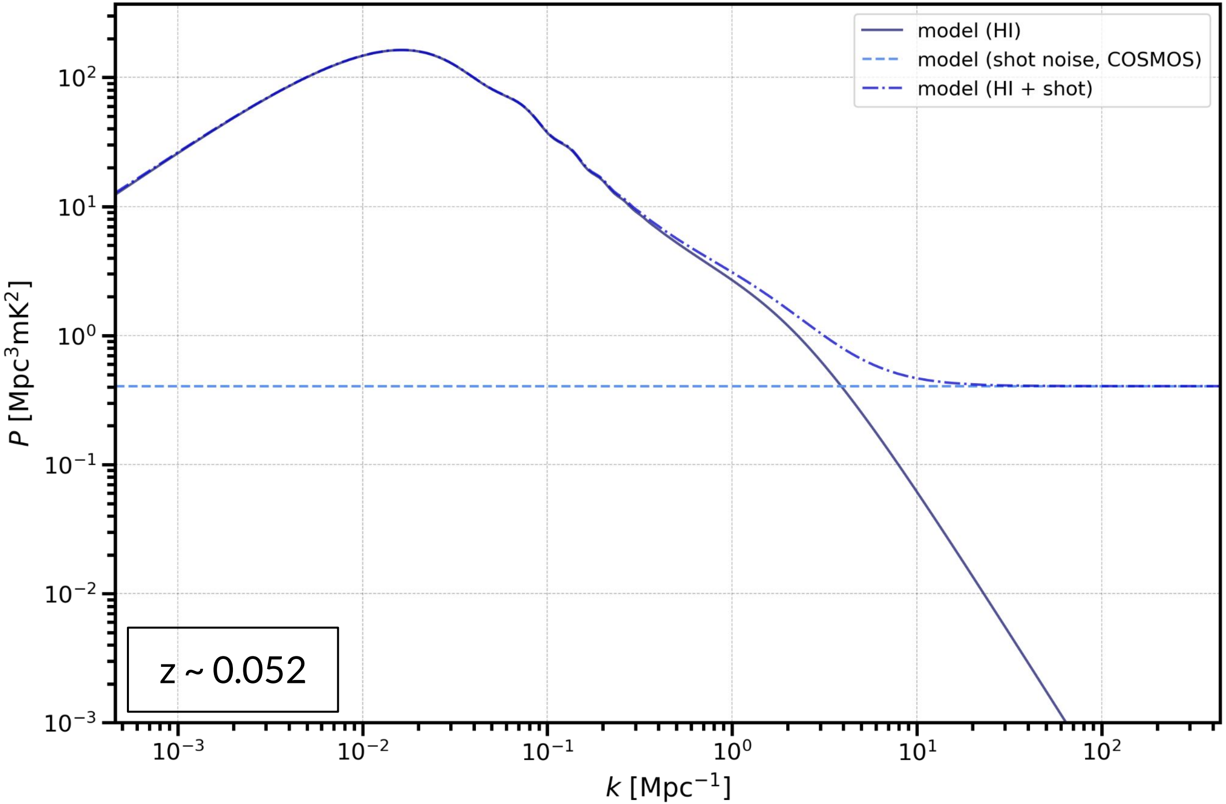
With the error obtained using (while **excluding the instrumental noise term**):

$$\sigma_{\mathrm{P}}(k) = \frac{1}{\sqrt{N_{\mathrm{mode}}}}(P_{\mathrm{HI}}(k) + P_{\mathrm{N}}(k))$$

$$N_{\mathrm{mode}} = \frac{V_{\mathrm{surv}}}{(2\pi)^3} 2\pi k^2 \Delta k$$

Chen et al., 2021

Power spectrum from MIGHTEE HI galaxies: Results - HI power spectrum model and assumed cosmology



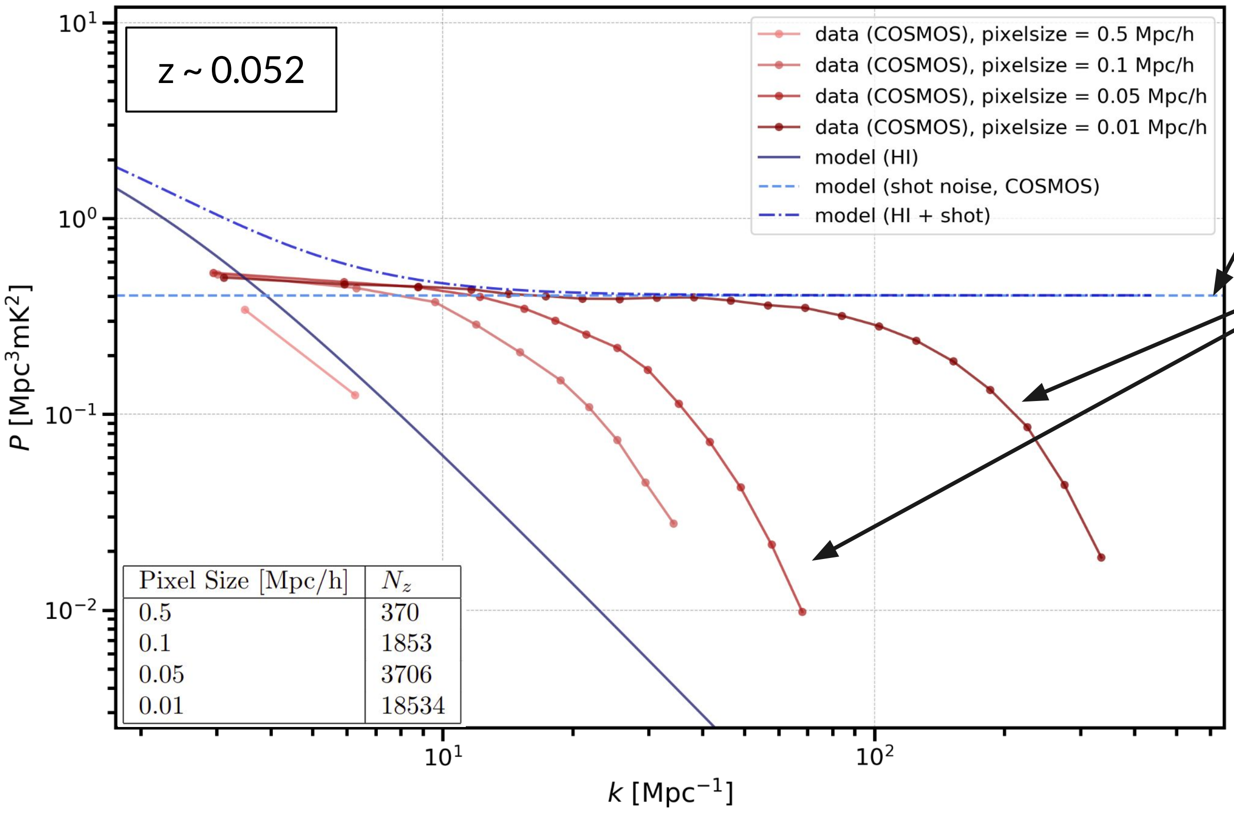
$$(h, \Omega_M, n_S) = (0.677, 0.31, 0.9667)$$

Paul et al., 2020

- Goal is to compare power spectrum result from galaxy catalogue to model
- Model shown also contains shot noise
- At smaller scales, the shot noise is expected to dominate

Power spectrum from MIGHTEE HI galaxies: Results - pixel size comparison for CIC

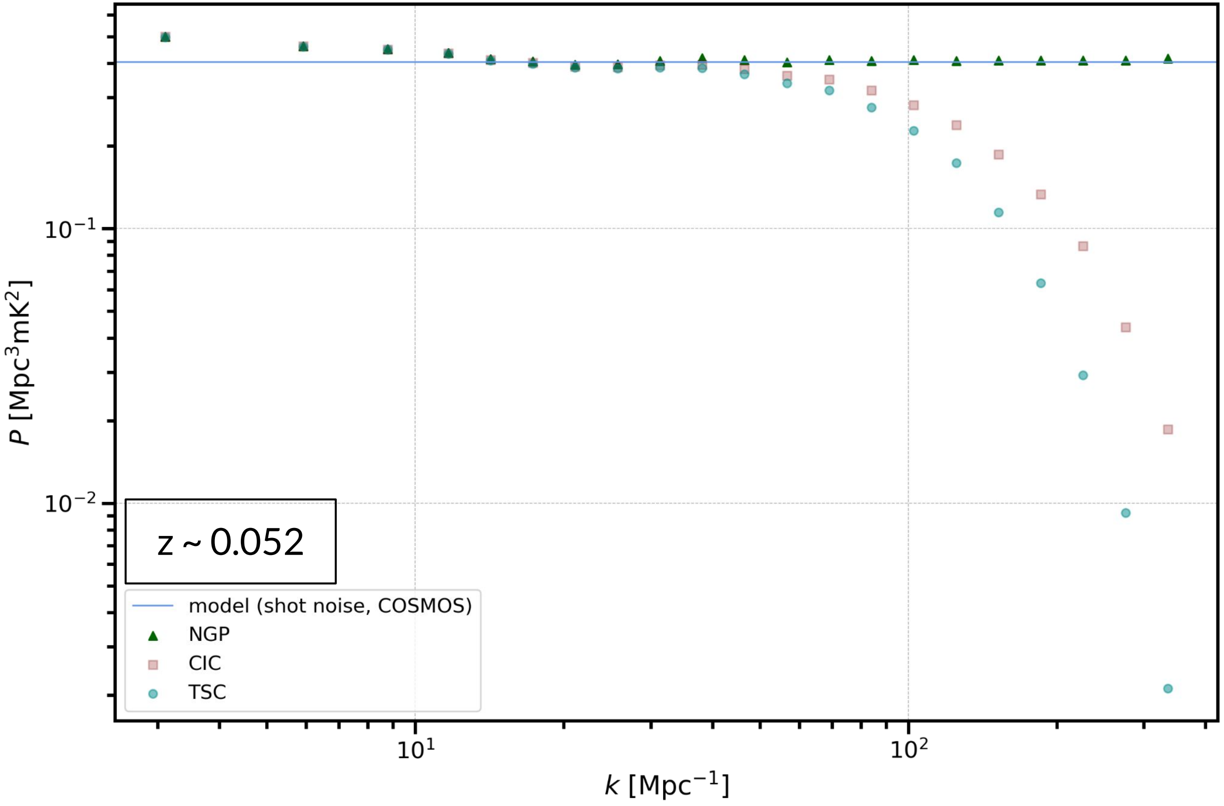
$$P_{\mathrm{SN}}(\vec{k}) = \frac{A^2(\Delta V)^2 \sum_n M^2_{\mathrm{HI},n}}{V}$$



Pixel Size [Mpc/h]	N_z
0.5	370
0.1	1853
0.05	3706
0.01	18534

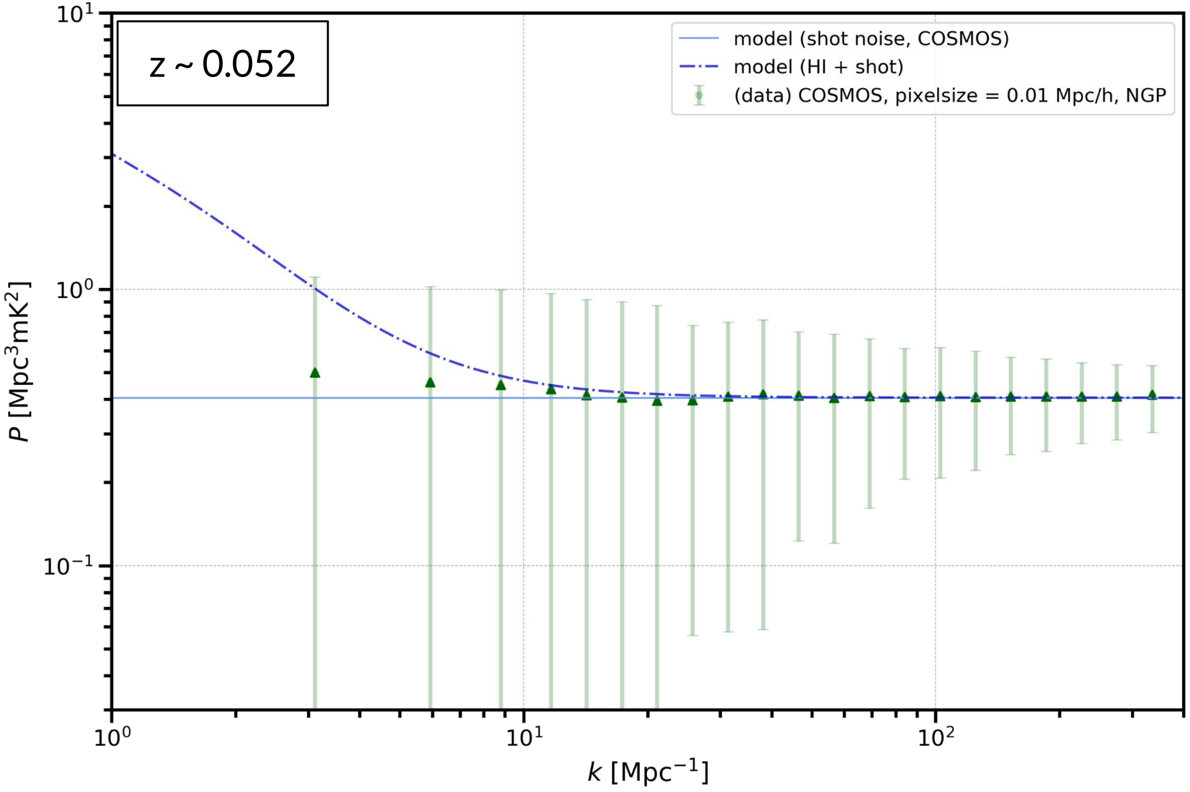
- Smoothing effect in high-k end of power spectrum
- This effect becomes more apparent with larger pixel size
- Same effect would be observed with TSC scheme

Power spectrum from MIGHTEE HI galaxies: Results - mass assignment scheme comparison



- Higher order mass assignment schemes cause drop in power due to shape function (see Jing 2005 & Cui 2008 for elaboration on this)
- Assuming that the galaxies in the catalogue can be modelled as point sources, NGP is sufficient
- This implies no need for higher order schemes (or the need to correct for drop in power)

Power spectrum from MIGHTEE HI galaxies: Results - MIGHTEE COSMOS shot noise measurement



- Measurement from the galaxy catalogue demonstrates expectation of shot noise dominance at smaller scales
- The next step is to measure the power spectrum at small scales with the MIGHTEE visibility data and compare it to this result

Objectives

- Main objective is to measure the **HI power spectrum** with the **MIGHTEE data** with **interferometer-mode** HI intensity mapping.

1. **Simulations** are run in order to check the S/N for the MIGHTEE data
2. Measure the HI power spectrum from **Early Science MIGHTEE-HI galaxy catalogue**
3. Measure the HI power spectrum from the Early Science MIGHTEE-HI **visibility data** (work in progress)

Summary & Current work

- **Current focus** is on using HI IM to study the HI content of the local universe (very low z ; $\nu \sim 1310 - 1420$ MHz)
- The simulations demonstrate the plausibility of doing so with MeerKAT & the MIGHTEE survey in interferometer-mode with the delay spectrum method: $V(\boldsymbol{b}, \nu) \rightarrow \tilde{V}(\boldsymbol{b}, \tau) \rightarrow P_{\mathrm{D}}(\boldsymbol{k}, z)$
- The **current work** consists of:
    - Relooking the simulations and theoretical models at low z for MIGHTEE COSMOS
    - Performing checks on the result from the MIGHTEE-HI galaxy catalogue
    - Analysing the visibility data (COSMOS) and then comparing the HI power spectrum obtained from it to that obtained from the **galaxy catalogue** and the expectation from **theory** (via the simulations)