## Section A: Overview of the Research Project

1. Title of the research project

   **Photometric galaxies cross-correlation with MeerKAT 21-cm intensity mapping data**

2. Broad area of research: **Science**

3. Academic level of research project: **Masters**

4. Abstract of research project

   Large-scale 21-cm intensity mapping from radio telescopes and massive galaxy surveys are the major driving force of future cosmology. In the next few years, MeerKAT will observe larger and larger volumes, and LSST (Vera C. Rubin Observatory) will map billions of galaxies out to redshift 2, so we should develop the cross-correlation technique between these two surveys to extract cosmological information. In our previous work (Cunnington et al., 2023), we used the spectroscopic survey (WiggleZ Dark Energy Survey) to cross-correlate the MeerKAT radio intensity mapping data in L-band ($0.4 < z < 0.459$ in redshift; MeerKLASS project). We obtained a $7.7\sigma$ C.L. detection of the signal, and derived the joint constraint on HI fractional density and HI bias. Photometric data has larger redshift errors than spectroscopic data but higher surface density (# of galaxies per $\mathrm{arcmin}^2$). We will use the WiggleZ spectroscopic data as a base dataset for the photometric data, in the way that we will re-sample each galaxy for a given photometric redshift error range, and then try cross-correlation between the two. This practice serves as a roadmap to utilize the full SKAO intensity mapping data with LSST galaxy samples.

5. Primary supervisor's details:

   Professor Yin-Zhe Ma, mayinzhe.pi@gmail.com, ma@ukzn.ac.za, Stellenbosch University

6. Co-supervisor/Research supervisor's details (if relevant)

   Professor Mario Santos, mariogrs@gmail.com, University of the Western Cape (UWC)

## Section B: Details of Research Project

1. Scientific/Engineering merit: describe the objectives of the research project, placing them in the context of the current key questions and understanding of the field.

   Probing the large-scale structure of the Universe is a crucial step towards the precision cosmology which aims to constrain the nature of dark energy, understand the nature of dark matter and test the theories of gravity. Typically, this is done by using the galaxy surveys with spectroscopic or photometric redshifts in the optical or near-infrared. Radio observations (e.g. MeerKAT, Parkes telescopes) of 21-cm intensity mapping is a relatively new technique, which measure the HI intensity at low and high redshifts and constrain the growth of structure.

   Because the HI emission line is faint against the bright foreground, we try to use the "intensity mapping technique" to sample the integrated emission over a larger voxel (typically ~50 Mpc), and scan the space relevantly fast to observe a large volume of cosmic structure. This technique is novel and has been proven to work well (Bharadwaj et al. 2001; Battye, Davies & Weller 2004; Chang et al. 2008; Wyithe, Loeb & Geil 2008). However, one of the major challenges to detect HI intensity map is the presence of foregrounds that are at least four orders of magnitude brighter. Removing these requires precise instrumental calibration. Cross-correlating with galaxy surveys helps mitigating residual systematics from foregrounds, radio frequency interference (RFI), and thermal noise (Wolz et al. 2016; Pourtsidou, Bacon

& Crittenden 2017). Moreover, it can improve constraints on cosmological parameters and provide insight into the HI astrophysics of the correlated galaxies (Anderson et al. 2018; Tramonte et al., 2019; Tramonte & Ma 2020). In Cunnington et al., 2023 (Figure 1), we used the spectroscopic survey (WiggleZ Dark Energy Survey) to cross-correlate the 11-hr MeerKAT radio intensity mapping data in L-band ($0.4 < z < 0.459$ in redshift), and obtained a $7.7\sigma$ C.L. detection of the signal. This is proven to be successful, but spectroscopic survey does have its limitation: the precise determination of redshift via spectrum analysis makes the mapping speed of galaxies much slower than photometric survey. In fact, Large Synoptic Survey Telescpe (LSST, or Rubin Observatory) will use photometric survey technique to map billions of galaxies. Therefore, it is essential to develop cross-correlation technique for photometric data with MeerKAT 21-cm intensity mapping data and to extract cosmological information. This project serves as the first attempt, and will develop the technique to pave the road for MeerKAT-LSST cross-correlation.

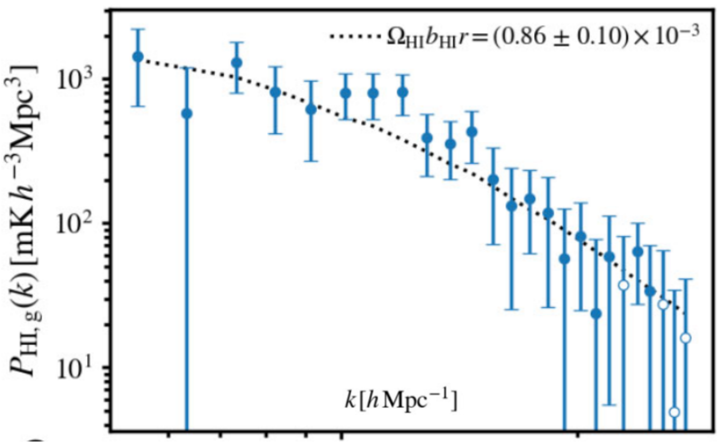


Figure 1: Cross-power spectrum between WiggleZ galaxies and MeerKAT HI intensity maps at 0.400< z < 0.459, with $1\sigma$ error bars. Figure taken from Cunnington et al. (2023).


**References** (supervisor's and co-supervisor's contributions are marked in **bold**):
Anderson C. J. et al., 2018, MNRAS, 476, 3382
Battye R. A., Davies R. D., Weller J., 2004, MNRAS, 355, 1339
Bharadwaj S., Nath B., Nath B. B., Sethi S. K., 2001, J. Astrophys. Astron., 22, 21
Camera, S., Fonseca, J., Maartens, R., & **Santos, M. G.** 2018, MNRAS, 481, 1251
Chang T.-C., Pen U.-L., Bandura K., Peterson J. B., 2010, Nature, 466, 463
Cunnington S., et al. (including **Ma Y.-Z.**, **Santos M.**), 2023, MNRAS, 518, 6262- 6272
Pourtsidou A., Bacon D., Crittenden R., 2017, MNRAS, 470, 4251
Tramonte D., **Ma Y.-Z.**, Li Y.-C., Staveley-Smith L., 2019, MNRAS, 489, 385-400
Tramonte D., **Ma Y.-Z.**, 2020, MNRAS, 498, 5916- 5935
Wolz L., Tonini C., Blake C., Wyithe J. S. B., 2016, MNRAS, 458, 3399
Wyithe S., Loeb A., Geil P., 2008, MNRAS, 383, 1195
Yohana E., **Ma Y.-Z.**, Li Y.-C., 2019, RAA, 19, 186


2. Feasibility: outline the methods that will be used to achieve the objectives. Provide details on the availability of required data / access to required equipment / availability of research facilities and other resources required. Include any relevant expected intermediate milestones and associated timeframes towards attaining the overall objectives of the project.

**Method**: The spectroscopic redshift uncertainty is very small, $\Delta z/z \sim 10^{-4}$. We use the existed WiggleZ data (4031 galaxies) and the 11-hr observations of MeerKAT 21-cm intensity mapping field (MeerKLASS project) as base datasets, then we re-sample the WiggleZ galaxies by inflating the errors of the galaxy redshift to $\Delta z/z \sim 10^{-2}$. We then re-cross-correlate the galaxy samples with MeerKAT IM data, and see if we can make a detection. We will try both in 3-D wavenumber space ($k$-space) and tomographic $\ell$-space (statistics in each slice). The latter is proven to have several advantages (e.g. cosmology model-independent, encompass wide-angle corelations, including lensing effect; See Camera et al. 2018; Yohana et al., 2019). We will then calculate the covariance of the signal and compare it with WiggleZ-MeerKAT cross-correlation result. This will gain a lot of insights for the future photometric galaxies cross-correlation with MeerKAT.

The co-supervisor is the PI of MeerKLASS project and supervisor is a core-member of the team, so we guarantee the accessibility of the data. We will use Ilifu cluster for our study.

**Time Frame**:

| Master student 2-year study (4 semesters) | |
|---|---|
| Semester 1 | Take the same data of 11-hr MeerKAT and WiggleZ galaxy survey, reproduce the results in Cunnington et al. (2023) |
| Semester 2 | Re-sample the galaxies for the error-level of photometric redshift survey, and re-calculate the cross power spectrum with MeerKAT data, trying both 3-D power spectrum ($P(k)$) and tomographic $C_\ell(z)$. |
| Semester 3 | Compute the covariance matrix. |
| Semester 4 | Wrap up the result and finish up the thesis |

3. Link the proposed project to one or more of the SARAO research priority areas for 2023 (refer to Section 5 of the Application Guide), and explain in some detail how the proposed research will contribute to the priority area(s).

   A: This project directly uses MeerKAT large-area synoptic survey data (MeerKLASS) on 21-cm intensity mapping, and use multi-wavelength data (in this case, photometric galaxy survey) to facilitate the measurement of large-scale cross-correlation signals.

4. If relevant, describe any particular qualifications, academic abilities, skills and/or experience that a student should have in order to successfully deliver on the objectives of the research proposed.

   A: Preference is given to the student who has some programming experience.