Section A: Overview of the Research Project

1. Title of the research project

   Cross-correlation technique for HERA 21-cm Intensity field with kinematic Sunyaev-Zeldovich effect

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

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

4. Abstract of research project:

   Achieving the first detection of power spectra of 21-cm during the Epoch of Reionization (EoR) is the major scientific aim of HERA. The 21-cm intensity mapping of high-redshift neutral hydrogen distribution severely suffers the foreground contamination and potential uncalibrated systematics in the datasets. These residual foregrounds and possible systematic uncertainties make the detection of the auto-power spectrum of the 21-cm signal hard to achieve: because $P_{\rm tot}(k) = P_{21}(k) + P_{\rm N}(k)$, if $P_{\rm N}(k) \gg P_{21}(k)$, it is very difficult to recover $P_{21}(k)$ from the measured $P_{\rm tot}(k)$. Therefore, we need to use the cross-correlation technique to extract the underlying signal. The cross-correlation between the 21 cm field and the kinematic Sunyaev-Zeldovich effect is a potential probe of the Epoch of Reionization (EoR). The 21cm signal traces neutral gas in the intergalactic medium and, on large spatial scales, should be anti-correlated with the kinematic Sunyaev-Zeldovich (kSZ) at the patchy reionization era, which tracks the ionized gas. As HERA team members, we are working on HERA calibration and data analysis pipeline, which are projected to provide extremely sensitive measurements of the 21cm power spectrum. At the same time, the current ongoing ground-based CMB probes, including SPT-3G (and its extended array) and future CMB Stage-4 (CMB-S4) survey, will produce very sensitive maps of the kSZ effect. We will use the semi-numeric simulations of reionization to explore the prospects for measuring the cross-power spectrum between the 21-cm and kSZ effect during the EoR. We will develop the cross-correlation pipeline, which can take the visibilities of the HERA 21-cm measurements and the map of CMB observations and then cross-correlate the two and compute the covariance of the signal. We will also use the sensitivity of HERA and CMB Stage-4 survey to forecast at what survey area and noise level such cross-correlation can achieve the first detection ($> 3\sigma$). Using this computational pipeline, we will also discuss what limiting factors we should consider and prioritize to achieve detection. *This study will serve as a strategic guideline for HERA EoR measurement*.

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)
   1. Professor Adam Lidz, alidz@sas.upenn.edu, University of Pennsylvania
   2. Professor Paul La Plante, paul.laplante@unlv.edu, University of Nevada, Las Vegas

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.

   A: Cosmology has been revolutionized over the last two decades with the measurement of cosmic microwave background (CMB) radiation and galaxy 3D distribution at low redshifts. However, a very important and extensive period of cosmic evolution, the Epoch of Reionization (EoR) has not yet been fully explored (~1 Gyr after the Big Bang). During this period, the first luminous sources in the Universe formed and gradually photo-ionized neutral hydrogen in the surrounding intergalactic medium (IGM), then the first stars and galaxies formed. However, the detailed physics during this transition period was not yet fully explored. In particular, the redshift evolution of the average ionization fraction of the Universe $x_{\mathrm{e}}(z)$ and the overall topology of the reionization process remain highly uncertain. Providing measurements of the EoR has important ramifications for pinning down the properties of the first stars and galaxies and also constraining cosmological parameters (e.g. optical depth τ, neutrino mass $\sum m_{\nu}$).

South Africa has a unique instrument to achieve this goal: the Hydrogen Epoch Reionization Array (HERA, DeBoer et al. 2017). It is a radio interferometer array which measures the 21 cm signal of neutral hydrogen (Madau et al. 1997). The 21-cm signal is the hyperfine transition of neutral hydrogen atoms while emitting or absorbing radiation with the rest-frame wavelength of 21 cm, which can imprint an excess or deficit in brightness relative to the background CMB. During the EoR, the 21-cm signal is expected to have significant fluctuations due to the presence of large ionized regions because once a bubble is ionized, it can no longer emit a 21-cm signal. In contrast, the ionized bubble can produce the kinematic Sunyaev-Zeldovich effect (kSZ, Sunyaev & Zeldovich 1980; Hernandez-Monteagudo and Ma et al., 2015; Planck Collaboration 2016), which is a secondary anisotropy of the CMB photons due to the inverse Compton-scattering of the free electrons. The ionized bubble expands and inversely Compton-scatters the CMB photons, which can be captured by sensitive CMB experiments, such as SPT-3G (Reichardt et al., 2021; Sobrin et al. 2022) and future CMB-S4 survey (Abazajian et al., 2019; Carlstrom et al. 2019; Chang et al., 2021; Abazajian et al. 2022). So in principle, the kSZ effect and the 21cm signal should be statistically *anti-correlated* on large spatial scales during the EoR because the kSZ effect traces highly biased regions of cosmic structure, but the 21cm signal comes predominantly from lower-density, neutral regions.

Previous studies (Ma et al., 2018; La Plante et al., 2022b) have looked at similar prospects for cross-correlation between 21cm experiments and the kSZ effect. However, a complicated situation arises due to the necessity to account for the “foreground wedge” (Datta et al. 2010; Pober et al. 2013; Parsons et al. 2014) of 21-cm measurements. For the kinematic Sunyaev-Zeldovich effect, the detailed redshifts of the ionized bubbles are not known, so essentially we lose all of the high $k_{\parallel}$ modes, so only $k_{\parallel} = 0$ mode exists in the map[1]. On the other hand, the 21-cm map is heavily contaminated by foregrounds in the long-wavelength longitudinal mode (low-$k_{\parallel}$). Therefore, all low-$k_{\parallel}$ mode is removed from the dataset after applying the foreground-wedge filter. Therefore, we need to build a higher-order correlator (four-point correlation function) to effectively use the high-$k_{\parallel}$ mode of 21 cm to achieve the detection.

Our plan is to use four-point correlation function $\langle \delta\tilde{T}_{21}^{2} \Delta T_{\mathrm{kSZ}}^{2} \rangle$ to compute the correlation power spectrum and aim to achieve the detection. This is a new correlation technique and it will survive the wedge filter for the 21-cm signal. We will also do forecasts for HERA X SPT-3G and HERA X CMB-S4.

References (The supervisor's and co-supervisors' contributions are marked in **bold**):
Battaglia, N., Trac, H., Cen, R., & Loeb, A. 2013, ApJ, 776, 81
Carlstrom, J., Abazajian, K., et al., 2019, Bulletin of the American Astronomical Society, arXiv.1908.01062
Chang C.L. et al. (including **Ma Y.-Z.**), 2021, arXiv:2203.07638
Abazajian, K., et al. 2019, arXiv:1907.04473.
Abazajian, K., et al. (including **Ma Y.-Z.**) 2022, arXiv:2203.08024.
Datta, A., Bowman, J. D., & Carilli, C. L. 2010, The Astrophysical Journal, 724, 526
DeBoer, D. R., Parsons, A. R., Aguirre, J. E., et al. 2017, PASP, 129, 045001,
The HERA Collaboration, Abdurashidova, Z., Adams, T., et al. (including Ma Y.-Z. and La Plante P.) 2022, arXiv:2210.04912.

---

[1] $k_{\parallel}$ ($k_{\perp}$) is the Fourier mode of fluctuations in the direction parallel (perpendicular) to the line of sight.

Hernandez-Monteagudo, C., **Ma, Y.-Z.**, et al. 2015, Phys. Rev. Lett., 115, 191301
La Plante, P., Battaglia, N., Natarajan, A., et al., 2014, ApJ, 789, 31
La Plante, P. and Ntampaka, M., 2019, ApJ, 880, 110
La Plante, P., **Lidz, A.**, Aguirre, J., et al., 2020, The Astrophysical Journal, 899, 40
La Plante, P., Mirocha, J., Gorce, A., et al., 2022a, arXiv:2205.09770
La Plante, P., Sipple, J., Lidz, A., 2022b, The Astrophysical Journal, 928, 162.
Li, Y.-C., **Ma, Y.-Z.**, Remazeilles, M., et al., 2018, Physical Review D, 97, 023514
Ma, Y.-Z., 2017, Nuclear Physics B, 920, 402
Ma, Q., Helgason, K., Komatsu, E., et al., 2018, MNRAS, 476, 4025
Madau, P., Meiksin, A., & Rees, M. J. 1997, ApJ, 475, 429
Natarajan, A., Battaglia, N., Trac, H., Pen, U.-L., and Loeb, A. 2013, ApJ, 776, 82
Planck Collaboration, Ade, P.~A.~R., Aghanim, N., et al. (including **Ma Y.-Z.**) 2016, Astronomy and Astrophysics, 586, A140
Planck Collaboration, Aghanim, N., et al. (including **Ma Y.-Z.**) 2018, Astronomy and Astrophysics, 617, A48
Parsons, A. R., Liu, A., Aguirre, J. E., et al. 2014, The Astrophysical Journal, 788, 106
Pober, J. C., Parsons, A. R., Aguirre, J. E., et al. 2013, The Astrophysical Journal Letters, 768, L36
Reichardt, C.~L., Patil, S., Ade, P.~A.~R., et al. 2021, The Astrophysical Journal, 908, 199
Sobrin, J.~A., , et al. 2022, The Astrophysical Journal Supplement Series, 258, 42
Sunyaev, R.~A. and Zeldovich, Y.~B. 1980, MNRAS, 190, 413.

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.

A: **Methods**—We will utilize the semi-numerical simulation of reionization to conduct the study. This approach provides a fast and flexible treatment of the reionization process, which can span large volumes, average over many independent simulation realizations, and explore a few different reionization models in a relatively efficient way. One such semi-numerical method for modelling reionization is ***zreion*** (Battaglia et al. 2013), which has been applied to several kSZ (Natarajan et al. 2013; La Plante et al. 2020) and 21-cm studies (La Plante et al. 2014; La Plante & Ntampaka 2019). The first step is to use the code to produce ionized bubbles in a light cone and then produce the observed kSZ map and 21-cm intensity map. (*first two semesters*)

The second step is to put a realistic effect on the observed maps. These include putting noise and possible residual foreground signals on the CMB map and then applying a filter to suppress the primary CMB and improve the SNR of the kSZ effect during patchy reionization. In addition, we need to apply the wedge filter to the 21-cm cube and produce a realistic HERA 21-cm cube in $(k_{\parallel}, k_{\perp})$ space. (*the third semester*)

During the third year (2026), HERA Phase-II (being commissioned now), will have 350 antennas observing from 50–250MHz (i.e. $4.7 < z < 27.4$ in redshifts). HERA Phase-II has an entirely new signal chain—from feeds to correlator—and will likely have to contend with somewhat different systematics (HERA Collaboration 2022). Given this experimental development, our third step is to use the four-point correlation function $\langle \delta\tilde{T}_{21}^{2}\Delta T_{\mathrm{kSZ}}^{2}\rangle$ to compute the correlation power spectrum and the covariance of the signal at different wave numbers $(k_{\perp}, k_{\parallel})$. This is a new correlation technique and it will survive the wedge filter, because kSZ completely loses the $k_{\parallel}$-mode and the squared 21-cm field will allow $k_{\parallel}^{(1)} + k_{\parallel}^{(2)} \simeq 0$. *This technique will enable the cross-correlation between kSZ and 21-cm field, and might yield the first detection of 21-cm signal at EoR*. Then we will discuss that, given the experimental condition of HERA and CMB-S4, the significance of the measurements at different k-mode in the EoR window (Forecast, *the fourth and fifth semesters*). Then we write a paper and integrate the result into the thesis (*the sixth semester*).

Time Frame:

PhD student research projects for 3-years (six consecutive semesters)	
Semester 1-2	Use the semi-numerical simulation of reionization to produce kSZ map and 21-cm observed volume
Semester 3	Put realistic effect on the observed maps and volume, then apply relevant filters to the data
Semester 4-5	Apply the higher-order correlator to compute the cross-correlation function, and forecast the feasibility of the HERA X CMB Stage-4.
Semester 6	Finish up the thesis, and prepare for the publication

If the student progresses faster than the above schedule, we can use the SPT-3G extended survey with the HERA Phase-II data to give a first try to cross-correlate real data. The SPG-3G extended survey is supposed to survey the area covering $\mathrm{DEC}=-30^{\mathrm{o}}$ area for $\mathrm{R.A.}=0^{\mathrm{h}}-6^{\mathrm{h}}$ and $11^{\mathrm{h}}-15^{\mathrm{h}}$ (Figure 6 in Sobrin et al. 2022), which should have $1500\,\mathrm{deg}^2$ overlapping with HERA Phase-II data (Figure 8 in La Plante 2022a). The first detection is not guaranteed, but it is certainly worth trying.

Collaborated Supervisors: Professor Yin-Zhe Ma is an expert in 21-cm cosmology and CMB data analysis. He was a core-team member of the Planck satellite and led several papers on the kinematic Sunyaev-Zeldovich effect (Hernandez-Monteagudo and Ma et al., 2015; Planck Collaboration, 2016; Ma 2017; Planck Collaboration 2018; Li & Ma et al. 2018). He is heavily involved in the HERA experiment and was elected as a "Builder" in 2021. He is also involved in the CMB Stage-4 project as a faculty PI. Therefore, he has the advantage of combining HERA with CMB experiments.

Professor Adam Lidz is a leading expert in 21-cm astrophysics and early structure formation in theoretical and observational probes.

Professor Paul La Plante is an active member of the HERA collaboration and has done original work on 21-cm cross-correlations (La Plante et al. 2014; La Plante et al. 2019; La Plante et al. 2020; La Plante et al. 2022a; La Plante et al. 2022b).

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 works for the HERA project. It utilizes the multi-wavelength probe to help extract the Epoch of the Reionization signal.

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: The student should have some programming skills, ideally in Python. Though not entirely required, we prefer the student who has taken a cosmology course, even at the introductory level.