Section A: Overview of the Research Project

1. Title of the research project

   Neutron Stars Interactions with Axion dark matter seen by MeerKAT telescope

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

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

4. Abstract of research project

   A: Cracking down the nature of dark matter has long been at the forefront of modern astrophysics research. Among the wide range of mass spectrum of dark matter, Axion dark matter has been proposed with strong theoretical and observational motivations, occupying the light end of the mass spectrum (~μeV). In this mass range, the strong magnetic field of neutron stars can cause Axion dark matter to decay, resulting in radiation with frequency detectable by radio telescopes. In 2022, we used the L-band MeerKAT telescope to observe two dwarf spheroidal galaxies (dSphs; Reticulum II and Tucana III), which are supposed to contain a population (~100) neutron stars, to search for the Axion dark matter signal. The data should be able to fill a gap in the Axion parameter space for the mass equivalent frequency of 1051-1090 MHz between MeerKAT UHF observations and results from laboratory experiments. We should be able to use MeerKAT to place a unique constraint on Axion decay constant (Primakoff parameter) in this window. We propose this project for a PhD student to do the data reduction and astrophysical constraints for the Axion dark matter.

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) Dr. Qiang Yuan, yuanq@pmo.ac.cn, Purple Mountain Observatory
   (2) Dr. Geoff Beck, geoffbeck.physics@protonmail.com, University of Witwatersrand

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: Dark matter is a ubiquitous material in the Universe which consists of 25 per cent of the energy density budget. However, apart from the gravitational effect, little is known about its particle nature. The quest to understand DM continues to be one of the pre-eminent scientific

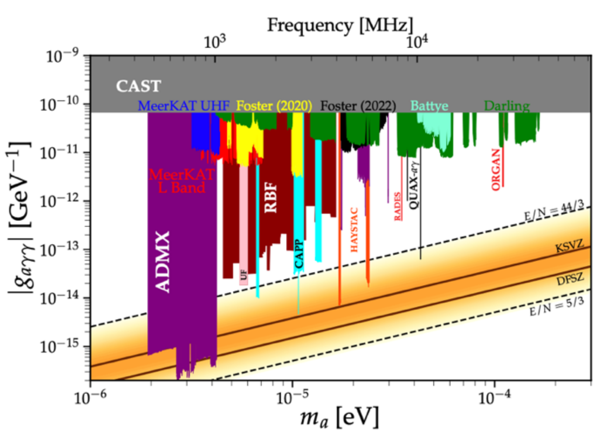

Figure 1: Projected 95% C.L. constraints (red shaded region) on the axion-photon coupling constant $g_{a\gamma\gamma}$ for 5 hours of MeerKAT L-band observations of dSph Reticulum II, compared with that derived from the MeerKAT UHF observation of neutron star RX J0806.4-4123 (blue shaded, Zhou et al. 2022), and other astrophysical and laboratory experiments. We assume a population of 100 neutron stars, and follow the population modelling approach of Safdi et al. (2019). This new observation in L-band is expected to fill the remaining gap between MeerKAT UHF observations and the RBF experiment. The Figure is reproduced in Zhou et al.(2022).

enterprises of the modern era, attracting the efforts of many scientists and experimental collaborations worldwide. Among the vast parameter space, Axion dark matter occupies the light end of the mass spectrum. It is proposed to solve the strong CP problem (Peccei & Quinn 1977) in particle physics (see also Weinberg 1978; Wilczek 1978). Axions can naturally provide DM via the misalignment mechanism, which allows them to behave like ordinary cold DM despite being comparatively much lighter than other DM candidates. Searching for evidence of Axion or constrain its parameters becomes an important topics in astrophysics.

Laboratory experiments in recent years have been conducted to search for Axions in different mass band and place limits on its coupling constant $g_{a\gamma\gamma}$ (Figure 1). Compared with laboratory experiments, the flexibility of frequency coverage available for radio observations is key for axion searches. A particularly appealing observational effect is the conversion of axion DM to radio-frequency photons in neutron star magnetospheres (Figure 2; Hook et al. 2018; Huang et al. 2018). This effect is expected to yield a monochromatic emission line from the neutron star, with a frequency proportional to the axion mass ($h\nu = m_a c^2$) and line strength determined by the pulsar parameters (spin, mass, distance, magnetic field etc) and the coupling constant $g_{a\gamma\gamma}$. In a recent paper (Zhou et al. 2022), we observed the isolated neutron star (RX J0806.4-4123) for 10 hours and obtained the upper limits shown in blue band in Figure 1.

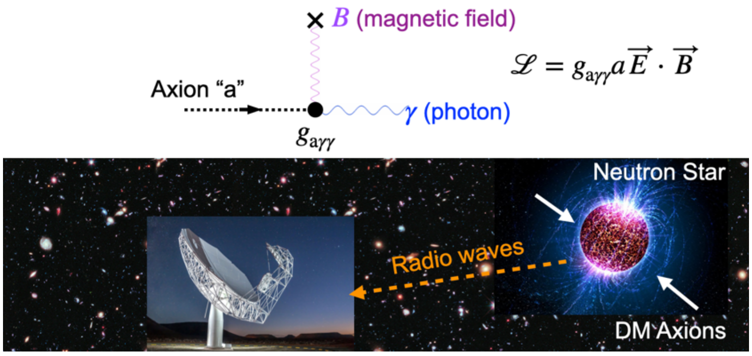

Figure 2: Axion observational effect (Primakoff effect). Axion couples to electromagnetic field with a "Chern-Simons" coupling (the Lagrangian) and can decay into radio waves with frequencies in L-band (a few hundred MHz to ~GHz), under the influence of strong magnetic field around neutron stars.

Alternatively, one may observe a source containing a population of neutron stars (Safdi et al. 2019). While this approach requires more sophisticated modelling of neutron star populations, it can lead to better sensitivity and offer further variety in terms of target selection. This approach has already been applied to the archival Green Bank Telescope data collected from the Breakthrough Listen Galactic Center Survey (Foster et al. 2022). In late 2022, we geared MeerKAT L-band (856-1711 MHz) telescope towards the two dwarf spheroidal galaxies (dSphs), Reticulum II (Geringer-Sameth et al. 2015) and Tucana III (Li et al. 2016) for 12.5 hours in total.

We will search for the signatures of axion DM conversion in the population of neutron stars they contain, and aim to obtain new constraints of Primakoff constant for the unexploited Axion parameter space. The expected constraint is shown in red region in Figure 1.

References (supervisor's and co-supervisors' contributions are marked in **bold**):

Ayad A. & **Beck G.**, 2020, JCAP, 04, 055.
Ayad A. & **Beck G.**, 2022, JCAP, 03, 005
Foster J.W., 2022, Physical Review Letters, 129, 251102
Geringer-Sameth, A. et al. 2015, Physical Review Letters, 115, 081101
Hook A., Kahn Y., Safdi B.R., and Sun Z., 2018, Physical Review Letters 121, 241102
Huang F.P., Kadota K., Sekiguchi T., and Tashiro H., 2018, Physical Review D 97, 123001
Li, S. et al. 2016, Physical Review D, 93, 043518
Peccei R. D. and Quinn H.R., 1997, Physical Review D 16, 1791
Safdi, B. et al. 2019, Physical Review D, 99, 123021
Weinberg S., 1978, Physical Review Lett. 40, 223

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Zhou Y.-F., Houston N., Jozsa G.I.G., Chen H., **Ma Y.-Z., Yuan, Q.**, et al., 2022, Physical Review D, 106, 083006

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: **Availability of the Data**—We applied the MeerKAT observational time in 2022 and were awarded 12.5 hours for this observation. We finished the observations and currently the data is being transferred to CHPC facility. The observations are towards the Reticulum II (R.A.=$03^h35^m41^s$, DEC=$-54^o03'00''$) and Tucana III (R.A.=$23^h56^m36^s$, DEC=$-59^o36'00''$) by using the L-band receiver.

   Methods, Milestone and Time Frame—The method will be threefold. First, we need to do the data reduction and RFI flagging by using the SDP pipeline. This is the most time-consuming process because our data is quite new and it is our first time to work with L-band data (Previous project used UHF-band). We will follow the route adopted in Zhou et al. (2022). The ending goal is to obtain a synthesized cube in the L-band regime (856-1711 MHz) with RFI bands flagged out. (*First year for the PhD student, i.e. first and second semesters*)

   Second, we can use the existed theoretical likelihood developed in our previous work (Zhou et al. 2022) to calculate the average flux density in L-band. By giving magnetic field strength, pulsar radius and period, surrounding dark matter density and Axion mass and the Primakoff constant, the theoretical model should be able to compute the power of radio emission per solid angle $\mathrm{d}P/\mathrm{d}\Omega$. Then one can calculate the average flux density by knowing the power per solid angle and the distance, and the frequency channel width. So the final theoretical prediction is the average flux density in each channel $S_i = F_i/\Delta\nu$ (Equation 2 in Zhou et al. 2022). (*The third semester*)

   The third step is the likelihood function. We will compare the stitched cube from observations with the above (theoretical) average flux density, and run the multi-parameter likelihood function via Markov-Chain Monte Carlo (MCMC) pipeline, and obtain the final parameter constraints of m_a (Axion mass) and $g_{a\gamma\gamma}$. We will overplot our constraint with previous work as in Figure 1 to compare with other experimental studies. (*The fourth and fifth semesters*)

   The paper writing and thesis finish-up will be done in the *six semester*.

   Research Facilities: We will use CHPC in our work which PI has an account.

   Collaborations: Dr. Qiang Yuan (co-supervisor) is an expert in dark matter particle theory, and has experience in analysing data in radio band. Dr. Geoff Beck has strong experience in radio analysis of dark matter candidate signal.

   Time frame: The time frame is written in the three steps of "Methods". Here we summarize them below

PhD student project for 6 semesters (3-years)	
Semester 1-2	Step 1: Data reduction, RFI flagging, Image cube reconstruction
Semester 3	Step 2: Theoretical calculation of the flux density spectrum
Semester 4-5	Step 3: Likelihood analysis to derive astrophysical parameters
Semester 6	Step 4: Paper writing and Thesis finish-up

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 on MeerKAT. It uses the MeerKAT telescope facility and the data product and will generally research output that has wide impact in physics and astronomy community[1].

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 computational experience.

[1] As a note of the wide impact, our published work on Axion constraints from MeerKAT, i.e. Zhou et al. (2022) has been invited to give in several conferences in radio astronomy, dark matter and particle physics conferences. In addition, its result of the constraints has been recorded in "Particle Data Group" (PDG) 2022 which is a compilation each year of international published results for the properties of particles and fundamental interactions.