



Search for Axion Dark Matter with MeerKAT UHF Sideband in 1051–1088 MHz

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Abstract

The axion, a leading dark matter (DM) candidate, can convert to photons in neutron star (NS) magnetospheres via the Primakoff effect, producing narrow-band radio emission that may be detected with high-sensitivity radio telescopes. Previous studies searched for axion DM-induced signals from the isolated NS J0806.4-4123 using observations of the MeerKAT UHF band (544–1088 MHz), but excluded the 1051–1088 MHz subband to mitigate potential sideband contamination. To probe this unexplored parameter space, we reprocessed the 1000–1088 MHz subband data using optimized radio frequency interference (RFI) flagging and meticulous sideband calibration. The flux stability of the calibrators and the consistency with MeerKAT’s system equivalent flux density confirmed the reliability of the data within the 1000–1080 MHz range, while the 1080–1088 MHz subband was omitted due to flux anomalies. No significant signals exceeding 5σ significance were detected within the axion mass range of 4.136–4.467 μeV (1000–1080 MHz), including the previously unprobed range 4.347–4.467 μeV (1051–1080 MHz). Our null detection sets new stringent constraints with MeerKAT NS data, excluding axion-photon couplings $|g_{a\gamma\gamma}| \gtrsim 8.2 \times 10^{-12} \text{ GeV}^{-1}$ at the 95% confidence level for DM masses between 4.347 and 4.467 μeV .

Key words: (cosmology:) dark matter – methods: observational – stars: neutron – radio lines: general

1. Introduction

It has been firmly established that the majority of the matter content in the Universe consists of dark matter (DM) (Hinshaw et al. 2013; Ade et al. 2016), a substance that interacts extremely weakly with visible matter. Despite its ubiquity, the nature of this elusive component remains largely unknown (see Bertone et al. 2005; Feng 2010 for comprehensive reviews). The quantum chromodynamics (QCD) axion, originally proposed to solve the strong CP problem in QCD (Peccei & Quinn 1977; Weinberg 1978; Wilczek 1978), also serves as a compelling DM candidate (Dine & Fischler 1983; Abbott & Sikivie 1983; Preskill et al. 1983; Marsh 2016). The interaction between axion DM and photons forms the basis for axion DM searches, as described by the Lagrangian equation $L = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$, where $\mathbf{E}$ and $\mathbf{B}$ denote the electric and magnetic fields respectively, a represents the axion DM field, and $g_{a\gamma\gamma}$ is the axion-photon coupling parameter (Irastorza & Redondo 2018). Both ground-based experiments and astrophysical observations (DePanfilis et al. 1987; Wuensch et al. 1989; Hagmann et al. 1990; Bähre et al.

2013; Ajello et al. 2016; Anastassopoulos et al. 2017; Brubaker et al. 2017; Du et al. 2018; Xia et al. 2019; Braine et al. 2020a, 2020b; Ahn et al. 2024; Guo et al. 2024; Zhu et al. 2025) have explored a wide range of the axion-photon coupling parameter space.

A novel axion DM detection method has attracted significant attention recently. When the axion DM traverses a neutron star (NS) magnetosphere, resonant conversion could occur if the plasma frequency matches the axion DM mass ($\omega_p \approx m_a$) via the Primakoff effect (Primakoff 1951), making the μeV scale axion DM convert into monochromatic radio photons (Pshirkov & Popov 2009; Hook et al. 2018; Safdi et al. 2019; Battye et al. 2020; Leroy et al. 2020; Witte et al. 2021; Foster et al. 2022; McDonald et al. 2023). The photon flux primarily depends on the local axion DM density (ρ_{DM}^∞), the axion DM mass (m_a), and the axion-photon coupling parameter ($g_{a\gamma\gamma}$), as well as NS parameters such as its radius (r_{NS}), mass (M_{NS}), surface magnetic field strength (B_0), rotation period (P), and distance to Earth (D) (Hook et al. 2018). Subsequent theoretical work has refined these flux calculations by incorporating various effects, such as photon refraction, reflection, plasma broadening effects, anisotropic

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medium responses, and general relativistic corrections (Huang et al. 2018; Safdi et al. 2019; Battye et al. 2020, 2021; Leroy et al. 2020; Millar et al. 2021; Witte et al. 2021; McDonald et al. 2023).

Recent studies using high-sensitivity radio telescopes have searched for narrow-band signals from the magnetospheres of individual NSs or NS populations (Darling 2020; Foster et al. 2020, 2022; Zhou et al. 2022). In a notable study, Zhou et al. (2022, hereafter Zhou22) analyzed the UHF-band radio observations of an isolated NS J0806.4-4123 using the MeerKAT telescope (Jonas & Team 2016). Their analysis excluded a parameter space region corresponding to $g_{a\gamma\gamma} \gtrsim 9.3 \times 10^{-12} \text{ GeV}^{-1}$ at the 95% confidence level for the DM masses between 3.18 and 4.35 μeV . Despite this progress, limitations remain in the approach adopted by Zhou22. Specifically, Zhou22 utilized the MeerKAT Science Data Processor (SDP) pipeline products, which cover the UHF band (544–1088 MHz), but exclude the highest frequency 37 MHz subband (1051–1088 MHz) to mitigate potential sideband contamination. However, this extended frequency range provides critical complementarity to cavity-based haloscope experiments for the μeV axion DM mass range, such as the Axion Dark Matter Experiment (ADMX; Braine et al. 2020a) and the Center for Axion and Precision Physics Research (CAPP; Ahn et al. 2024), through an independent astrophysical approach. We reprocessed the raw data from the 1000–1088 MHz subband using an enhanced pipeline with optimized radio frequency interference (RFI) flagging algorithms and meticulous sideband calibration, thereby allowing an axion DM search across the UHF sideband.

The rest of this paper is organized as follows. In Section 2, we describe the observation and data reduction process. Section 3 presents our results and sets constraints on the axion DM parameter space. Finally, Section 4 provides a summary and discussion of this research.

2. Observations and Data Reduction

We used the observational data obtained by Zhou22 in the MeerKAT UHF band (544–1088 MHz), targeting the isolated NS J0806.4-4123 (R.A. = $08^{\text{h}}06^{\text{m}}23^{\text{s}}.3471$, decl. = $-41^{\circ}22'30''.179$, J2000). The observations were carried out from 2020 March to May, with a total integration time of 10 hr and a time resolution of 8 s, divided into six sessions. During each session, 8 minutes were allocated at both the start and the end to observe a bandpass calibrator (J0408-6545 or J1939-6342 depending on the Local Sidereal Time range). In addition, observations included a 2 minute viewing of a gain calibrator, J0828-3731, prior to each target observation. All observations were conducted using the MeerKAT “Spectral Line” observing mode, which provides 32768 frequency channels across the UHF band, reaching a frequency resolution of about 16.602 kHz.

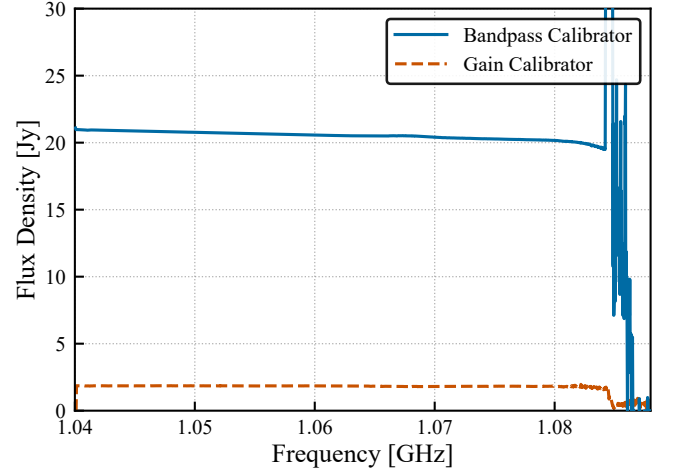


Figure 1. The derived fluxes of calibrators after applying calibration solutions across 1040–1088 MHz.

Data reduction of MeerKAT spectral line observations was performed using the Containerized Automated Radio Astronomy Calibration (CARACal) pipeline (Józsa et al. 2020). First, data in the 1000–1088 MHz frequency range of 4818 channels were split out for processing. Second, we flagged 3σ outliers on calibrators using the automated RFI flagging CASA (Team et al. 2022) task “tfcrop.” Then, the flux and gain calibrators mentioned above were utilized to derive solutions for flux scale, delay, bandpass, and complex gains (amplitude and phase). These solutions were first applied to the calibration sources for diagnosis, so we identified the poor quality of the 1080–1088 MHz data. After 1080–1088 MHz was flagged, the solutions were applied to the target field to correct for flux scale, time delay, frequency response, and time-variable gain fluctuations.

Subsequently, we conducted two rounds of phase self-calibration to correct for residual phase errors caused by atmospheric fluctuations. To remove the contribution of the continuum emission and derive spectral line features, we fitted and subtracted a linear continuum model from the data in the uv plane (Fourier space) in the 1000–1080 MHz frequency range. Then, the spectral line cubes were created with the package “WSClean” (Offringa et al. 2014; Józsa et al. 2020). We adopted natural weighting during the imaging process to maximize imaging sensitivity, thereby enhancing the ability to detect weak signals. They were cleaned to five times the theoretical noise level to suppress the sidelobes of the point-spread function (PSF) and enhance the signal-to-noise ratio (SNR).

Due to the point source properties of NSs, we extracted its spectrum over a single pixel on the NS position (also the phase center of the image), correcting for the beam size variations

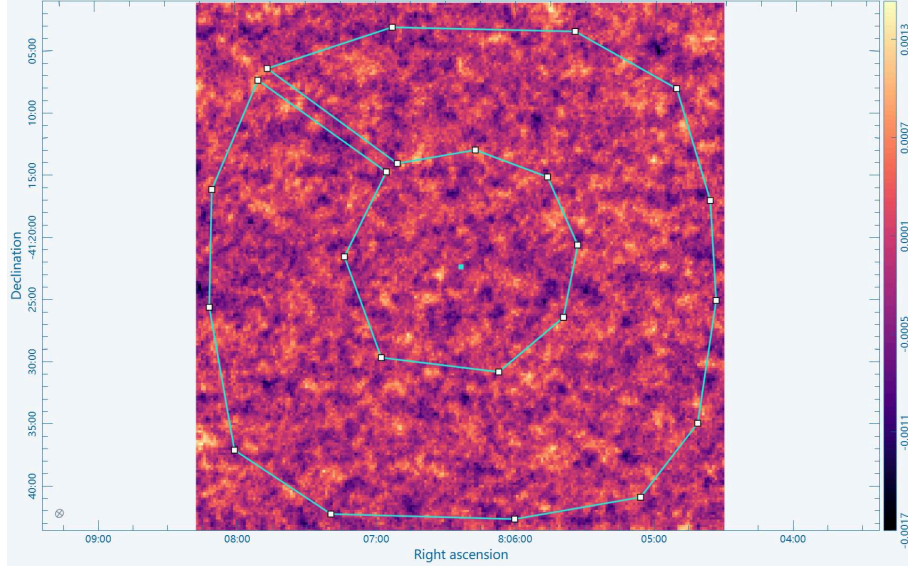


Figure 2. A channel map in 1077 MHz of the final spectral line cube for illumination. The target NS J0806.4-4123 is located at the image center, marked by a square cyan dot. A source-free annulus surrounding the target is drawn to measure the noise spectrum. The lower left ellipse next to the axes shows the synthesized beam size, which is about $42'' \times 36''$.

across channels to accurately capture the total point-source flux density.

3. Results And Analysis

3.1. Cube Reliability Analysis

The fluxes of calibrators across 1040–1088 MHz were derived for calibration checking. Figure 1 shows that both the bandpass and phase calibrators exhibit stable fluxes at 1040–1080 MHz, but abrupt deviations occur above 1085 MHz. The flux of the bandpass calibrator decreases more rapidly with frequency in 1082–1085 MHz, contrasting with the nearly flat spectrum in 1040–1080 MHz. It suggests that the calibration is good at 1040–1080 MHz and poor at 1082–1088 MHz. We conservatively excluded the 1080–1088 MHz subband to avoid possible systematic biases.

Under the assumption of thermal noise dominance, the noise in the NS spectral cube is expected to scale with the MeerKAT system equivalent flux density (SEFD), providing a benchmark to validate the data quality. The noise for each channel was estimated by measuring the rms (σ_{ν_i}) from a source-free annulus surrounding the target in each channel map, as illuminated in Figure 2. The 1040–1042 MHz subband was excluded due to severe RFI contamination. In particular, the rms noise curve at 1060–1080 MHz exhibits a characteristic rise-and-fall fluctuation. This pattern closely matches the frequency-dependent trend of MeerKAT’s SEFD (see bottom panel of Figure 3). The rms-SEFD alignment indicates that the

observed fluctuations are due to MeerKAT’s intrinsic noise properties, validating the robustness of our data reduction pipeline.

We also compared the noise levels in Zhou22 as shown in the top panel of Figure 3. First, in the overlapping 1000–1051 MHz frequency range, our baseline noise ($0.20 \pm 0.01 \text{ mJy beam}^{-1}$) is $1.45\times$ lower than Zhou22’s $0.29 \pm 0.05 \text{ mJy beam}^{-1}$. This improvement aligns with the expected sensitivity gain of MeerKAT of $1.45\times$ when switching from Robust-0 to natural weighting. Second, while Zhou22 showed multiple sharp spectral features, our results demonstrate improvements in RFI removal.

Through comprehensive validation of MeerKAT UHF band (1000–1080 MHz) data quality—including calibrator flux stability, noise SEFD consistency, and comparison with Zhou22—we confirm the reliability of the reprocessed spectral cubes for axion DM searches.

3.2. Axion DM-induced Signal Search

Using this validated spectral line cube, we conducted a blind search for narrowband radio signals throughout the axion mass range 4.136–4.467 μeV , with particular focus on the previously unexplored 4.347–4.467 μeV subrange (1051–1080 MHz).

Following the analysis in Zhou22, the spectral width of the NS radio signal is approximately equal to the MeerKAT 32 k mode channel bandwidth (16 kHz). To quantify the significance of spectral features in each channel, we derived the SNR for each channel, calculated as $\frac{(d_{\nu_i} - \mu_{\nu_i})}{\sigma_{\nu_i}}$. d_{ν_i} is the target flux,

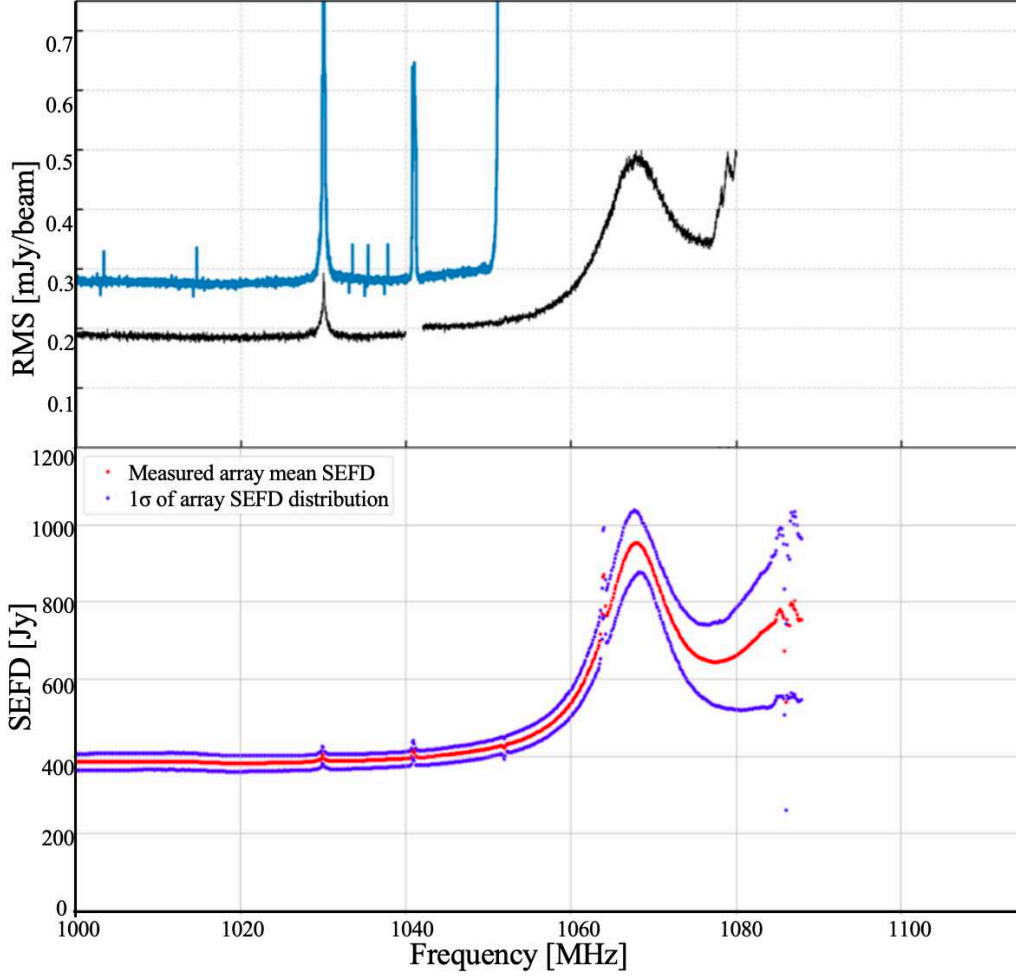


Figure 3. Top panel: The picture displays the rms of noise level of this work (black), with Zhou22 (blue, Zhou et al. 2022) for comparison. In our analysis, we used natural weighting while Zhou22 used a robust parameter of 0, which leads to an improvement in sensitivity by roughly 1.45. Bottom panel: The bottom panel presents the measured MeerKAT UHF-Band SEFD in Jy, provided by the South African Radio Astronomy Observatory (SARAO) via personal communication. The alignment between rms and SEFD suggests that the fluctuations in the noise spectrum likely originate from the telescope’s instrumental performance.

while μ_{ν_i} is the background value and σ_{ν_i} is the uncertainty of the target flux. $(d_{\nu_i} - \mu_{\nu_i})$ refers to the signal from the target compared to the background for each channel. Due to the point-source properties of NSs, we extracted the target flux for each channel (d_{ν_i}) over a single pixel in the NS position, correcting for the beam size variations across channels to accurately capture the total point-source flux density. The background value and flux uncertainty for each channel (μ_{ν_i} and σ_{ν_i}) were estimated by measuring the mean and rms of a source-free annulus surrounding the target in each channel map, as illuminated in Section 3.1 and Figure 2.

The top panel in Figure 4 shows the observed flux density, background value and flux uncertainty of NS J0806.4-4123, while the bottom panel displays the SNR of the target region.

No emission features above the 5σ threshold were detected within the frequency range of 1000–1080 MHz.

3.3. Constraints on Axion Coupling Parameter

In the case of null detection, we placed upper limits on the axion-photon coupling constant $g_{a\gamma\gamma}$ using a Bayesian grid-based parameter estimation framework (Zhou et al. 2022). The likelihood function was constructed as

$$\mathcal{L}(m_a, g_{a\gamma\gamma}, \theta, \theta_m) = \prod_{i=1}^{N_{\text{ch}}} \frac{1}{\sqrt{2\pi} \sigma_{\nu_i}} \times \exp \left[-\frac{(d_{\nu_i} - \mu_{\nu_i} - \tilde{S}_{\nu_i}(m_a, g_{a\gamma\gamma}, \theta, \theta_m))^2}{2\sigma_{\nu_i}^2} \right], \quad (1)$$

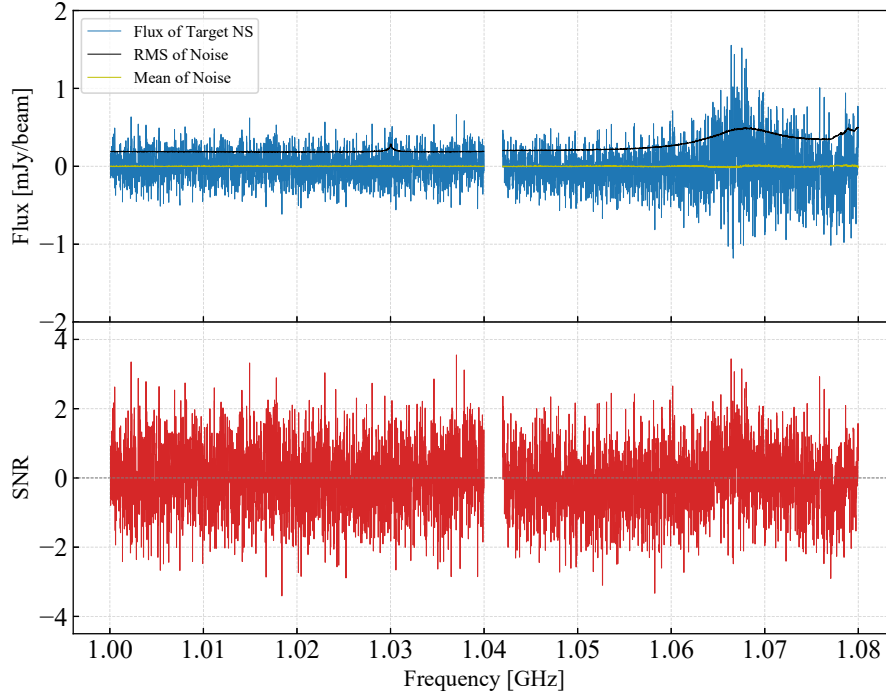


Figure 4. The top panel shows the measured flux density of the isolated NS J0806.4-4123 (blue), with flux uncertainty (1σ , black) and background value (yellow). The bottom panel is the SNR of the target region across the 1000–1080 MHz search range. No significant emission ($\text{SNR} > 5\sigma$) features were detected.

where ν_i represented the index labeling the frequency channel, with a total of N_{ch} channels. d_{ν_i} is the target flux, while μ_{ν_i} is the background value and σ_{ν_i} is the uncertainty of the target flux, which were measured in the i -th frequency channel of the observed data cube (see Section 3.2 for details). μ_{ν_i} and σ_{ν_i} characterize the Gaussian distributed noise in the i -th channel. $\tilde{S}_{\nu_i}(m_a, g_{a\gamma\gamma}, \theta, \theta_m)$ is the expected signal flux density from the conversion of the axion DM in the i -th channel, where m_a is the axion DM mass, $g_{a\gamma\gamma}$ is the axion-photon coupling parameter, θ is the angle between the NS rotation axis and our line of sight, and θ_m is the angle between the NS rotation axis and its magnetic dipole axis. Here, for comparison and compatibility purposes with previous results, we also follow the approach presented in Equation (2) in Zhou22 for computing $\tilde{S}_{\nu_i}(m_a, g_{a\gamma\gamma}, \theta, \theta_m)$.

To obtain the posterior distribution of $g_{a\gamma\gamma}$, we adopted a grid sampling method. The procedure was as follows:

1. We assumed a flat prior distribution for $g_{a\gamma\gamma}$, θ , and θ_m and performed grid sampling on these parameters. For $g_{a\gamma\gamma}$, we uniformly sampled $\log_{10}(g_{a\gamma\gamma})$ in the range $[-13, -10]$, corresponding to the physical values of $g_{a\gamma\gamma}$ in the interval $[10^{-13}, 10^{-10}] \text{ GeV}^{-1}$. For θ and θ_m , we performed a uniform sampling in the intervals $[0, \pi]$ and $[0, \pi/2]$, respectively.
2. For each sampled triplet $(g_{a\gamma\gamma}, \theta, \theta_m)$, we evaluated the likelihood function $P(D_a | g_{a\gamma\gamma}, \theta, \theta_m)$, which quantified

the probability of observing the data D_a given the values of the specific parameters.

3. To eliminate the dependence on the nuisance parameters θ and θ_m , we marginalize them. This marginalization resulted in a likelihood function $P(D_a | g_{a\gamma\gamma})$ that was solely dependent on $g_{a\gamma\gamma}$.
4. Finally, we applied Bayes' theorem to obtain the posterior distribution of $g_{a\gamma\gamma}$ using the marginalized likelihood function: $P(g_{a\gamma\gamma} | D_a) \propto P(D_a | g_{a\gamma\gamma})P(g_{a\gamma\gamma})$, where $P(g_{a\gamma\gamma})$ was the prior distribution.

From the posterior distribution, we derived the 95% upper limits on $g_{a\gamma\gamma}$. Our constraints on $g_{a\gamma\gamma}$, along with other observational and experimental limits, are shown in Figure 5, showcasing the complementarity of our findings to those earlier works and highlighting the potential of radio astronomical observations in searching for axion DM.

4. Conclusions and Discussion

Axion DM, as one of the well-motivated candidates for cold DM, has attracted widespread attention in recent years. The coupling between axion DM and photons allows for the production of photons through the conversion of axion DM in an external magnetic field via the Primakoff effect, providing a solid basis for searching for axion DM.

In this study, our objective is to supplement previous axion-DM detection experiments by searching for potential radio

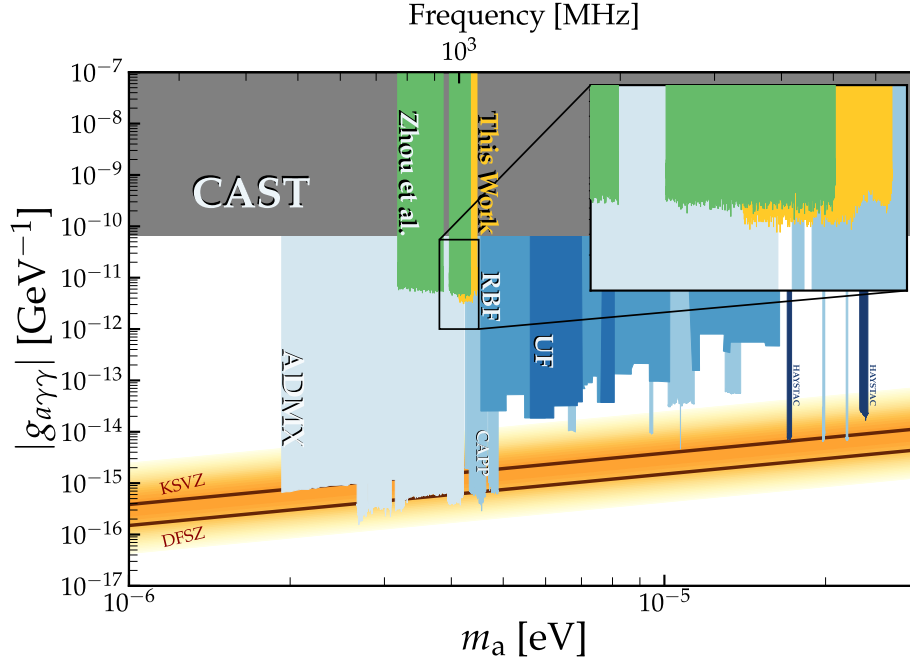


Figure 5. The 95% confidence level upper limits on the axion-photon coupling constant $g_{a\gamma\gamma}$, derived from 10 hr of MeerKAT observations of the NS J0806.4-4123 (highlighted in yellow). These limits are compared with results from laboratory experiments and previous astrophysical constraints reported by Zhou et al. (2022).

signals from axion-DM conversion in the NS magnetosphere. To achieve this, we reprocessed the MeerKAT UHF-band (1000–1088 MHz subband) observations targeting isolated NS J0806.4-4123. We used a customized CARACal pipeline that incorporates two key advancements: (1) refined RFI flagging and sideband calibration, and (2) natural weighting (to maximize sensitivity) during imaging. These optimizations extended the detectable frequency range from 1051 to 1080 MHz, while achieving a noise $1.45\times$ lower than in Zhou22.

We confirmed the reliability of the reprocessed spectral cubes by a series of validations of the MeerKAT UHF sideband (1000–1080 MHz) data quality, including calibrator flux stability, noise-SEFD consistency, and comparison with Zhou22. Despite our efforts, no signals exceeding 5σ were detected within the mass range of $4.136\text{--}4.467\text{ }\mu\text{eV}$ (1000–1080 MHz), with particular emphasis on the previously unexplored $4.347\text{--}4.467\text{ }\mu\text{eV}$ subrange (1051–1080 MHz). Consequently, we set new stringent constraints on the axion-photon coupling by excluding a region of parameter space corresponding to $|g_{a\gamma\gamma}| \gtrsim 8.2 \times 10^{-12} \text{ GeV}^{-1}$ at the 95% confidence level in this mass range.

Notably, we followed the computational approach of Zhou22 for calculating the axion-induced signal flux density, and these results could be further improved via more sophisticated theoretical modeling. In particular, recent works more fully take plasma effects into consideration, which could simultaneously influence the conversion probability and broaden the signal spectral width (Battye et al. 2021; Witte

et al. 2021; McDonald et al. 2023). These broadening effects, as well as the exact photon trajectories (which can be altered due to refraction and reflection in the plasma), can be incorporated via a fuller ray-tracing approach. We leave this analysis for future work.

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