



Evolution of AGN Across Cosmic Epochs with the SKAO

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Understanding the evolution of active galactic nuclei (AGN) and their host galaxies across cosmic epochs is one of the key science drivers of extragalactic astronomy. The detection of AGN residing in dusty environments and at high redshifts is difficult due to obscuration and faintness which poses a challenge in understanding AGN evolution across cosmic time. Deep radio continuum surveys (rms noise $< 1 \mu\text{Jy beam}^{-1}$) from the Square Kilometre Array Observatory (SKAO) will be an efficient means to detect and study a broad population of AGN across cosmic history. In this chapter, we present radio luminosity functions, source counts, and detection rates of AGN based on the SKAO simulated radio source catalogues. We demonstrate that the SKA-Mid multi-tiered surveys, in particular, reaching sub- μJy depths, will allow us to characterise the bulk of the radio-AGN complete down to $L_{1.4\text{GHz}} \sim 10^{23} \text{ W Hz}^{-1}$ and enable us to probe the evolution of radio-AGN across a wide range of luminosities and all galaxy environments up to $z \sim 6$. Overall, our work highlights the importance of deep multi-tiered SKAO radio continuum surveys for studying the evolution of radio-AGN activity across cosmic time.

1 Introduction

Active galactic nuclei (AGN) are the manifestation of accretion onto super-massive black holes (SMBHs; $M_{\text{SMBH}} \sim 10^6 - 10^{10} M_{\odot}$) residing at the centres of galaxies and they are thought to play a vital role in the growth of galaxies via feedback mechanisms (Fabian, 2012; Fiore et al., 2017; Matzeu et al., 2023). The well-known correlations between host galaxy parameters such as total stellar mass, bulge mass, central stellar velocity dispersion and the mass of SMBHs (Gebhardt et al., 2000; Merritt and Ferrarese, 2001; Kormendy and Ho, 2013) have been explained by invoking feedback mechanisms wherein AGN can regulate the growth of their host galaxies and play a key role in shaping the observed properties of galaxies in the nearby Universe (McNamara and Nulsen, 2007; Cattaneo et al., 2009; Fabian, 2012; Heckman and Best, 2014; Hickox and Alexander, 2018). Of particular importance in the lifecycle of massive galaxies are ‘radio-loud AGN’ – displaying powerful bi-polar radio jets – feedback from AGN-jet activity is thought to keep massive galaxies quenched. Thus, feedback from AGN is a critical ingredient in galaxy formation models and cosmological simulations (e.g. Bower et al., 2006; Croton et al., 2006; Kaviraj et al., 2017; Davé et al., 2019) that enables us to reproduce the observed local galaxy properties such as galaxy stellar mass function (Bower et al., 2006; Croton et al., 2006) and galaxy colours (Cattaneo et al., 2006).

To study the evolution of AGN across cosmic time it is important to note that the emission from AGN and galaxies can be significantly affected by dust extinction in the optical, ultra-violet (UV), and even in the X-rays (e.g. Fabian, 2012; Hickox and Alexander, 2018). The extinction becomes more prominent in dusty galaxies, providing a biased view of AGN activity; moreover, deep radio surveys have shown an enhanced radio detection fraction for quasars with increasing dust obscuration (e.g. Klindt et al., 2019; Fawcett et al., 2020; Petley et al., 2024; Yue et al., 2024). The mid-infrared colour selection criteria are arguably advantageous in identifying and studying dust-obscured AGN (e.g. Lacy et al., 2004; Donley et al., 2012), however, such studies are typically biased towards high-luminosity AGN.

Radio continuum observations are unaffected by dust obscuration and also directly trace the synchrotron emission arising from AGN-jets which makes them well-suited to identify and study AGN jet-activity across cosmic time and over a broad range of luminosities. We note that while radio observations offer the only way to identify jetted-AGN across all environments and all epochs, they may miss non-jetted-AGN powered by radiatively-efficient accretion (Padovani, 2017) emitting mostly thermal radiation from the accretion disk. Indeed, no single-band observations alone can provide a complete census of *all* AGN – multi-wavelength observations are crucial for gaining a more complete understanding.

AGN can broadly be classified into two different modes: (i) radiatively efficient AGN, and (ii) radiatively inefficient AGN, typically based on the Eddington-scaled accretion rate (ratio of the bolometric to the Eddington luminosity; $\lambda_{\text{Edd}} = L_{\text{bol}}/L_{\text{Edd}}$). Radiatively efficient AGN accrete matter at high fractions of the Eddington-scaled accretion rate ($\lambda_{\text{Edd}} \gtrsim 0.01$), with accretion occurring from a standard geometrically thin, optically thick accretion disk (Shakura and Sunyaev, 1973) and resulting in strong forbidden optical emission lines. A small fraction of radiatively efficient AGN can also display powerful radio jets; traditionally, these sources have been classified as high-excitation radio galaxies (HERGs) based on the nature of their optical spectra (Best and

Heckman, 2012; Mingo et al., 2014). Conversely, the radiatively inefficient AGN are often referred to as low-excitation radio galaxies (LERGs) and accrete at low rates (typically $\lambda_{\text{Edd}} \lesssim 0.01$) in an advection dominated accretion flow through a geometrically thick accretion disk (Narayan and Yi, 1995; Yuan and Narayan, 2014). The radiatively inefficient AGN can launch powerful radio jets (Blandford et al., 2019), however, as these sources lack a standard stable accretion disk, they may not be easily identified as AGN at other wavebands; radio observations offer a unique window into tracing this population of AGN.

Over the past two decades, detailed characterisation of the two modes of radio-loud AGN (HERGs and LERGs) has revealed significant differences in their host galaxy properties. LERGs tend to be hosted in massive, quiescent, ‘red and dead’ systems, and are typically found in rich environments such as in galaxy clusters; in contrast, the HERGs tend to be hosted by lower mass, more star-forming systems, and also tend to be more prevalent in poorer environments (e.g. Hardcastle et al., 2007; Tasse et al., 2008; Smolčić et al., 2009; Best and Heckman, 2012; Gendre et al., 2013; Sabater et al., 2013; Mingo et al., 2014; Ching et al., 2017; Williams and Röttgering, 2015; Williams et al., 2018; Croston et al., 2019; Magliocchetti, 2022). However, recent deep observations from SKA pathfinders and precursors have found evidence for more overlap in the accretion and host galaxy properties of radio-loud AGN at higher redshifts than expected (e.g. Kondapally et al. 2022; Whittam et al. 2022; see also discussion in Sect. 2). These results present challenges to our current understanding of radio-AGN and their role in galaxy evolution. Also, present knowledge about radio AGN and their role in influencing galaxy evolution, particularly at higher redshifts, is incomplete.

In this chapter we aim to (i) demonstrate the capability of SKA design baseline Array Assembly 4 (AA4) to probe the evolution of AGN across cosmic epochs; (ii) the role of SKAO multi-frequency radio continuum surveys in unveiling the hidden population of AGN hosted in dust-obscured galaxies; (iii) synergies between SKAO and other multi-wavelength facilities in investigating the evolution of AGN across cosmic epochs. This chapter also offers an update of a chapter on ‘Exploring AGN Activity over Cosmic Time with the SKA’ authored by Smolcic et al. (2015) in ‘Advancing Astrophysics I’ book. Moreover, unlike previous work we use a mature set of SKAO specifications and also place an emphasis on the detection of dust-obscured AGN.

2 Radio continuum surveys: From pathfinders and precursors to the SKAO

Over the past decade or so, SKAO pathfinder and precursor telescopes in both Northern and Southern hemispheres have been carrying out deep as well as wide-area radio continuum surveys ranging from a few square arcminutes to tens of thousands of square degrees across a wide range of frequencies e.g., 40-66 MHz Low Frequency Array (LOFAR) LBA Sky Survey (LoLSS; de Gasperin et al. 2023), 144 MHz LOFAR Two-metre Sky Survey (LoTSS; Shimwell et al. 2017, 2022), 150 MHz TIFR-GMRT Sky Survey (TGSS; Intema et al., 2017), 72–231 MHz GaLactic and Extragalactic All-sky MWA survey (GLEAM; Hurley-Walker et al., 2017), 940 MHz Evolutionary Map of the Universe (EMU; Norris et al., 2011), 1250 MHz Rapid ASKAP Continuum Survey (RACS; McConnell et al., 2020), Jansky Very Large Array (VLA) COSMOS 3.0 GHz large project (Smolčić et al., 2017a), 3.0 GHz VLA Sky Survey (VLASS; Lacy et al. 2020), and 1.3 GHz MeerKAT International Giga-Hertz Tiered Extragalactic Exploration (MeerKAT; Heywood et al.

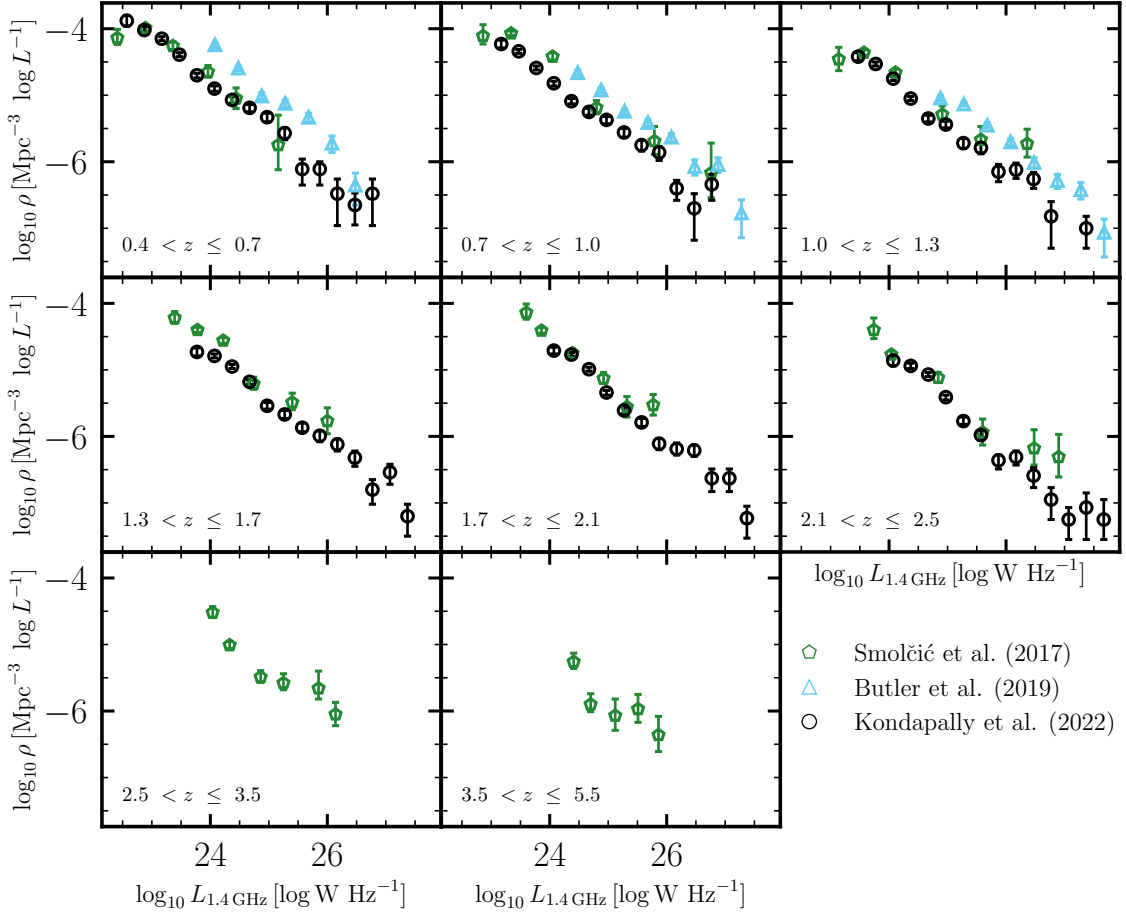


Figure 1: The 1.4 GHz radio luminosity functions in eight redshift bins over the redshift range $0.4 < z \leq 5.5$. The 150 MHz radio luminosity functions from Kondapally et al. (2022) across $0.4 < z \leq 2.5$, based on LoTSS Deep Fields, are shown as black circles (scaled to 1.4 GHz using a spectral index $\alpha = -0.7$). The luminosity functions derived from the VLA-COSMOS 3 GHz Large program across $0.4 < z \leq 5.5$ by Smolčić et al. (2017b) are shown in green. The LFs derived based on ATCA observations by Butler et al. (2019) are shown in cyan. Figure adapted from Kondapally et al. (2022).

2022; Hale et al. 2025).

Deep radio continuum surveys from SKA pathfinders and precursors over several fields with high-quality multi-wavelength datasets have been crucial in tracing the low luminosity AGN population out to $z \gtrsim 1$. Figure 1 shows the evolution of the 1.4 GHz radio luminosity function (RLF) across the redshift range $0.4 < z \leq 5.5$ from various existing surveys. The RLFs (taken from Kondapally et al. (2022); black open circles) extending out to $z \sim 2.5$ are determined from the deep tier of LoTSS: the LoTSS Deep Fields (Tasse et al., 2021; Sabater et al., 2021; Kondapally et al., 2021; Duncan et al., 2021; Best et al., 2023) that covers $\sim 25 \text{ deg}^2$ down to an rms level of $\sim 20 \mu\text{Jy/beam}$. In Figure 1 (depicted via triangles), we also show RLFs (from Butler et al. (2019)) compiled using data from 2.1 GHz observations of the XMM-LSS field by the Australian Telescope Compact Array (ATCA), out to $z \sim 1.4$. The LFs by Smolčić et al. (2017b) based on the VLA-COSMOS 3 GHz

Large project are shown in green, providing measurements out to $z \sim 5$. We point out that the VLA-COSMOS 3 GHz Large project and the LoTSS Deep Fields represent the deepest degree-scale radio-continuum surveys that exist. While these surveys have provided the first measurements of the radio luminosity functions for AGN out to $z \sim 5$ (in the case of the VLA-COSMOS project), this is based only on a few hundred sources beyond $z \sim 2.5$ and only on a few tens of sources at $z \gtrsim 4$. Hence, the luminosity function remains poorly constrained at the bright end due to the relatively small areas covered by these deep surveys, and also at the faint end (at high redshift) due to the small numbers of sources.

Deep surveys from LOFAR and MeerKAT have also enabled studies of the different modes of radio-loud AGN (i.e. the LERGs and HERGs) out to $z \sim 2$ and beyond (e.g. Kondapally et al., 2022; Mingo et al., 2022; Whittam et al., 2022). Such studies have revealed that the host galaxies of LERGs and HERGs show considerable overlap at these moderate redshift ($z \sim 2$; Kondapally et al. 2022; Whittam et al. 2022; Delvecchio et al. 2022), with a significant population of LERGs hosted by star-forming galaxies rather than quiescent galaxies (Kondapally et al., 2022, 2025). Whittam et al. (2022) also found that the Eddington-scaled accretion rate distributions for LERGs and HERGs showed significant overlap, however, uncertainties in SED fitting of photometry, which was used to derive the classifications, and bolometric luminosities can complicate the interpretation of these results. More recent studies incorporating spectroscopic classifications have shown that the accretion rate distributions appear more similar to studies at low redshift (e.g. Arnaudova et al., 2025). These results highlight that our understanding of the radio-loud AGN population at moderate redshifts may be incomplete based on studies in the local Universe; such studies at earlier epochs have only been possible in recent years. The evolution of the radio-loud population at even higher redshifts towards cosmic dawn remains largely unexplored.

3 SKAO view of radio-AGN activity across cosmic time

In this chapter, we focus on addressing the open questions highlighted above by discussing the broad population-level studies on the evolution of radio-AGN that will be possible with the SKAO. Specifically, we aim to show that the SKAO will be able to:

- Chart the complete census of radio-AGN down to $L_{1.4\text{GHz}} \sim 10^{23} \text{ W Hz}^{-1}$ all the way up to $z \sim 6$ and provide the first robust statistical constraints on their evolution up to $z \sim 6$.
- Assess the detection and evolution of hitherto, hidden population of AGN in obscured environments across large redshifts.
- Characterise the evolution of AGN activity at each cosmic epoch as a function of various properties (e.g. stellar mass, star-formation rate, environment) simultaneously.

Fulfilling these objectives will allow us to trace in detail how the radio-AGN population evolves across the history of the Universe and to place this in the context of the evolution of the galaxy population to determine the physical processes that govern AGN activity from early epochs to the present day. Achieving these scientific goals requires the combination of a large-area survey that can sample the rarer AGN across a wide range of galaxy environments, and a smaller-area deep survey that can detect and characterise the faint AGN population out to the earliest cosmic epochs.

Our scientific objectives can be primarily facilitated by two large-area SKA-Mid (AA4) surveys in band 2: a 1000 deg² wide-area survey reaching to noise-rms of $\sim 1 \mu\text{Jy beam}^{-1}$, and a deep $\sim 25 \text{ deg}^2$ survey reaching to noise-rms of $\sim 0.2 \mu\text{Jy beam}^{-1}$. These values are based on the proposed SKAO AA4 continuum reference surveys outlined in Prandoni and Seymour (2015) and in the updated version by Prandoni et al. (2026), which we validate and justify below for our scientific objectives. The sensitivity and angular resolution offered by SKA-Mid AA4 design baseline will be crucial for most of the scientific objectives outlined in this chapter. The SKA-Low radio surveys will offer valuable complementary information to AGN studies, although, due to lower resolution they will be confusion limited at the sensitivity level of $5\text{--}10 \mu\text{Jy beam}^{-1}$. Nevertheless, SKA-Low wide-area surveys will enable us to perform resolved spectral-index studies for large samples of predominantly brighter and nearby radio-AGN, offering new insights into the physics of AGN jets (see Hardcastle et al., 2026). To make predictions for the radio-loud AGN population that we can detect in SKAO reference surveys we exploit the Tiered Radio Extragalactic Continuum Simulations (T-RECS; Bonaldi et al. 2019) considering the aforementioned areas and depths for the wide and deep tiers.

3.1 Differential source counts

Radio source counts are commonly used to examine the relative number density of various sub-populations (RL-AGN, RQ-AGN and SFGs) across a range of flux densities and to constrain their evolutionary models (de Zotti et al., 2010; Condon et al., 2012). The source counts extrapolation to fainter flux densities can help us in predicting the radio source populations to be detected in the future SKAO radio continuum surveys. In Figure 2 we show 1.4 GHz differential radio source counts derived from some of the recent radio continuum observations in deep fields (e.g., Prandoni et al., 2018; Heywood et al., 2020; van der Vlugt et al., 2021; Matthews et al., 2021; D’Amato et al., 2022). We also compare these source counts with those derived from SKA simulations *i.e.*, T-RECS (Bonaldi et al., 2019) and SKA Simulated Sky (S³; Wilman et al., 2008) as well as semi-empirical model for various sub-populations reported in Mancuso et al. (2017).

It is evident that the source counts at $S_{1.4 \text{ GHz}} \geq 0.5 \text{ mJy}$ is dominated by RL-AGN (see Figure 2). At bright flux densities, contribution from SFGs and RQ-AGN is nearly insignificant. Although, at fainter flux densities ($S_{1.4 \text{ GHz}} < 0.5 \text{ mJy}$) contribution from SFGs and RQ-AGN begins to rise. At the very faint end ($S_{1.4 \text{ GHz}} < 0.1 \text{ mJy}$), the radio source population is comprised of SFGs and RQ-AGN, however, the number density of RQ-AGN is nearly one order-of-magnitude lower than that of SFGs. These results are similar to several previous works (e.g., Bondi et al., 2008; Vernstrom et al., 2016; Smolčić et al., 2017a; Galluzzi et al., 2025), although, the relative contribution of SFGs and RQ-AGN is still a matter of debate, and we require equally deep multi-wavelength data to identify RQ-AGN hosted in composite SFGs. At $S_{1.4 \text{ GHz}} > 1.0 \text{ mJy}$, T-RECS under-predicts source counts possibly due to its source population inputs derived from the limited sky coverage lacking the complete RL-AGN population (see Bonaldi et al., 2019). The S³ simulated counts generally match well with the observations, except at fainter flux densities ($S_{1.4 \text{ GHz}} < 0.01 \text{ mJy}$) where they under-predict the observations. It is worth noting that the deepest available observations from the pathfinders and precursors till date, are limited only to a few μJy level and the nature of faint radio population is still unexplored. The SKA-Mid band-2 deep radio continuum surveys offering 0.2

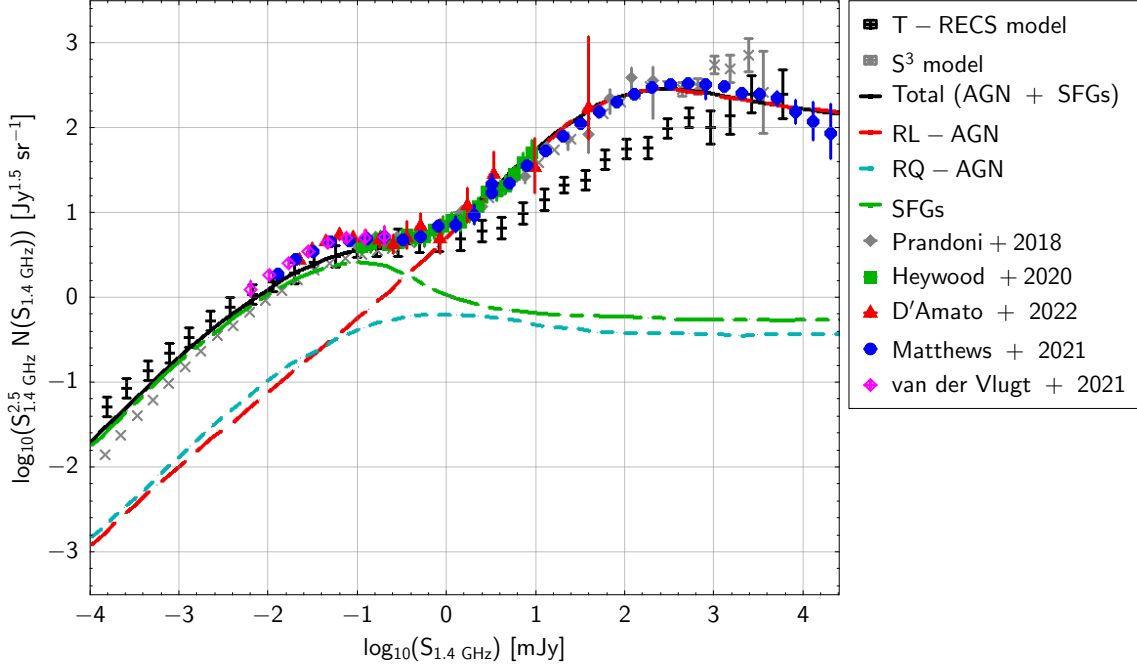


Figure 2: The comparison of differential source counts at 1.4 GHz from T-RECS, different radio source sub-populations (RL-AGN, RQ-AGN, SFGs) models from Mancuso et al. (2017). The available data from recent studies (Prandoni et al., 2018; Heywood et al., 2020; Matthews et al., 2021; van der Vlugt et al., 2021; D’Amato et al., 2022) are also shown.

$\mu\text{Jy beam}^{-1}$ noise-rms and $\sim 0''.5$ angular resolution in AA4 configuration (Prandoni et al., 2026), will open a new window to understand the nature of sub- μJy faint sources without suffering from confusion issues.

3.2 Evolution of radio-loud AGN: Robust statistical constraints on radio-AGN luminosity function beyond $z > 4$

In Figure 3, we show the binned (as hex-bins) expected distributions of radio-loud AGN in the 1.4 GHz radio luminosity and redshift plane, based on the assumed survey depths and areas described earlier in this section. The colour bar indicates the number of sources in each bin, where lighter colours indicate a higher density of sources. Using the predicted source population from T-RECS, we construct the expected RLFs for the radio-loud AGN in narrow redshift intervals out to $z \sim 6$, which are shown in Figure 4. At any given epoch, the luminosity functions are expected to reach at least an order of magnitude fainter than those derived from the deepest radio-continuum surveys available to date. We point out that the SKA-Mid band-2 wide-area survey will not only be more sensitive than the exiting deep field radio continuum surveys at similar frequency but also will cover 10-50 times more sky-area, and hence, it will provide more robust constraints at high luminosities and high redshifts, while sampling a wide range of galaxy environments. It is important to note that the shape of the LFs and its detailed evolution are *only indicative* of what we would expect to detect based on the above chosen surveys: these are based on the predictions from the T-RECS simulation which involves extrapolation of the observed source population. We use the LFs in Figure 4 to

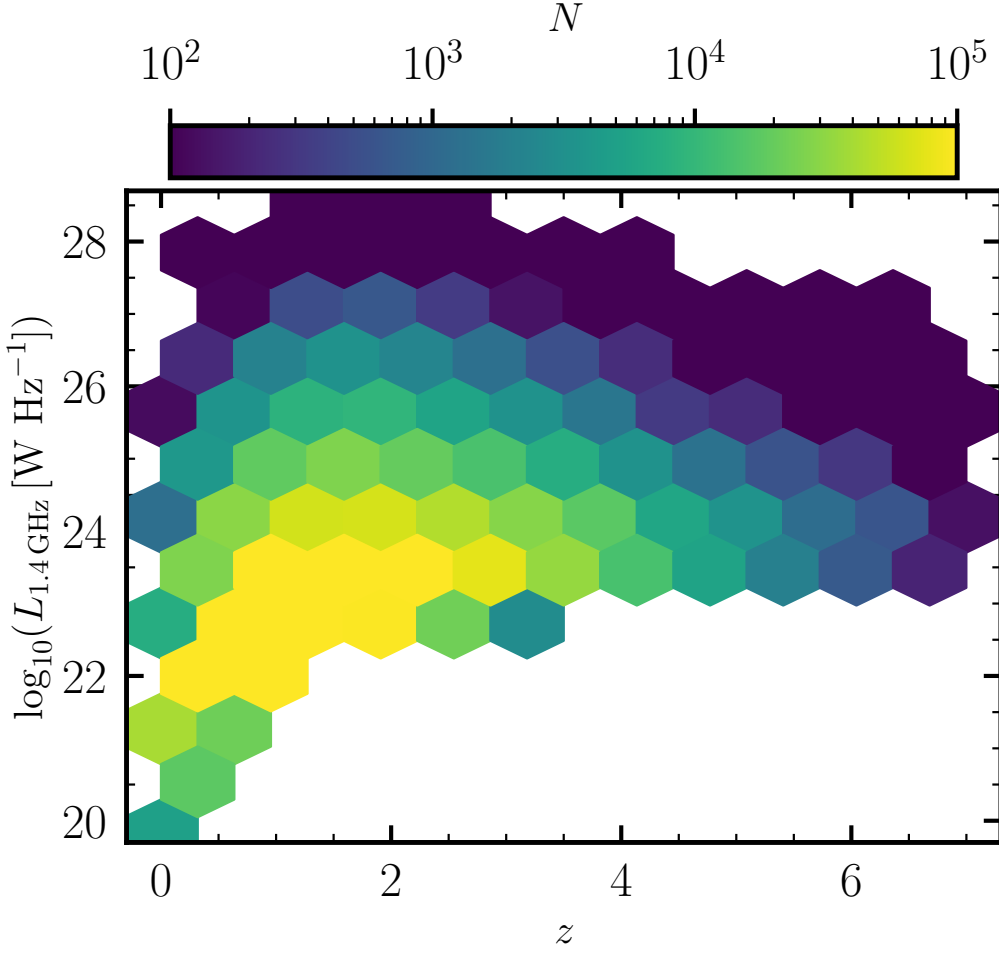


Figure 3: Distribution of sources in the radio luminosity – redshift plane expected for the chosen SKAO reference radio continuum surveys (using 5σ detection; see text). The combination of SKA-Mid band 2 wide and deep surveys will provide a complete census of radio-AGN down to $L_{1.4\text{GHz}} \sim 10^{23} \text{ W Hz}^{-1}$ all the way up to $z \sim 6$.

illustrate the range of parameter space that will be accessible for detailed studies of AGN evolution.

From Figures 3 and 4, it is evident that the SKA-Mid surveys will allow us to detect and study the complete samples of radio-loud AGN down to $L_{1.4\text{GHz}} \sim 10^{23} \text{ W Hz}^{-1}$ and spanning over five decades in radio luminosity across all redshifts. The large samples of AGN that will be detected, in particular at high redshifts, will enable us to perform detailed characterisation of the radio luminosity function and its shape across a wide range of luminosities beyond $z \gtrsim 4$. We predict that the SKA-Mid multi-tiered surveys will be able to detect $> 10^5$ AGN across $3 \lesssim z < 5$, and around 10^4 AGN at $5 < z < 6$. For comparison, the latest results from state-of-the-art radio continuum surveys (e.g. Smolčić et al., 2017b) only contain few tens of sources at $z \gtrsim 5$. Thus, SKA-Mid surveys will provide a fundamental step-forward in our understanding of the evolution of high-redshift radio-loud population by enabling the first robust constraints on the luminosity

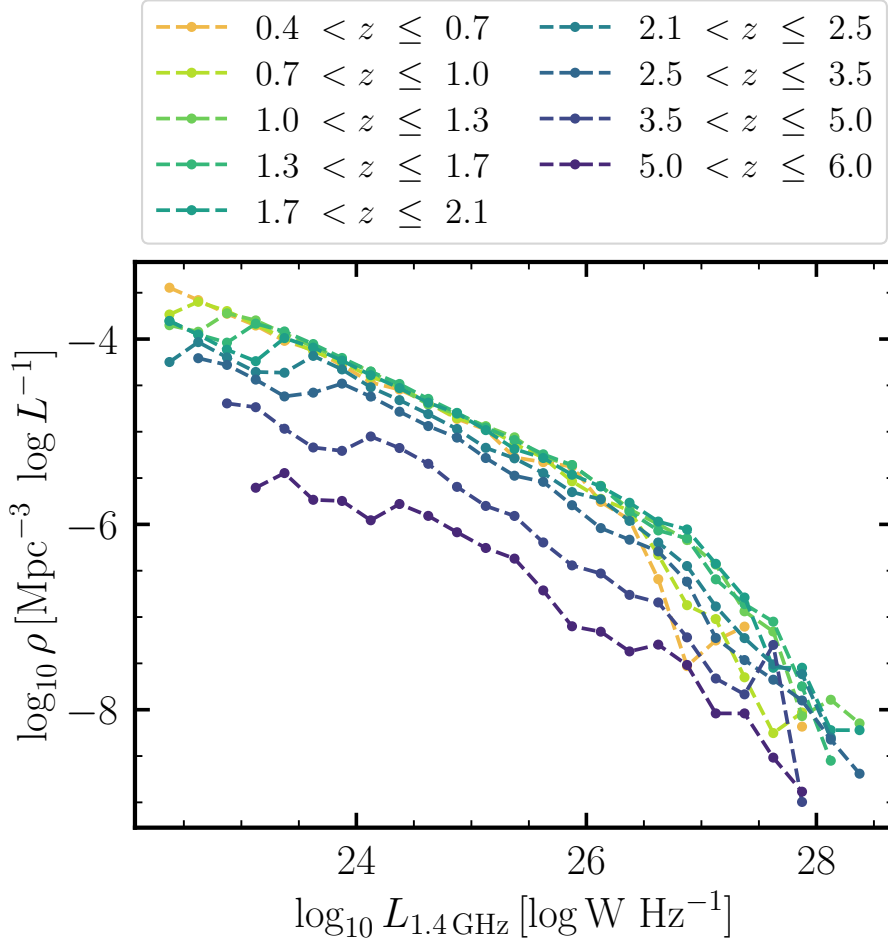


Figure 4: The cosmic evolution of the 1.4 GHz radio luminosity functions based on the T-RECS predicted source population using the reference SKA-Mid wide and deep tier surveys (see text and Prandoni et al. 2026).

functions at $z > 5$.

The radio luminosity function of AGN is also a key ingredient in determining the kinetic luminosity density, which refers to the total kinetic power per unit volume output by the AGN jets across cosmic time (e.g. Shankar et al., 2008; Smolčić et al., 2009; Best et al., 2014; Pracy et al., 2016; Smolčić et al., 2017b; Kondapally et al., 2023). This is typically determined in the literature by using a scaling relation that converts radio luminosity to jet kinetic power (e.g. Birzan et al., 2008; Willott et al., 1999; Cavagnolo et al., 2010; Godfrey and Shabala, 2013), which is then convolved with the luminosity function and integrated across radio luminosity to determine the volume-averaged kinetic power output. Quantifying this requires both an accurate knowledge of the luminosity function and its evolution, along with an accurate conversion between monochromatic radio luminosity and kinetic power, which are lacking, particularly at higher redshifts. Improved constraints on the latter will be provided by other proposed science cases in this volume which aim to study the physics of AGN jets (Hardcastle et al., 2026), along with accurate size measurements of

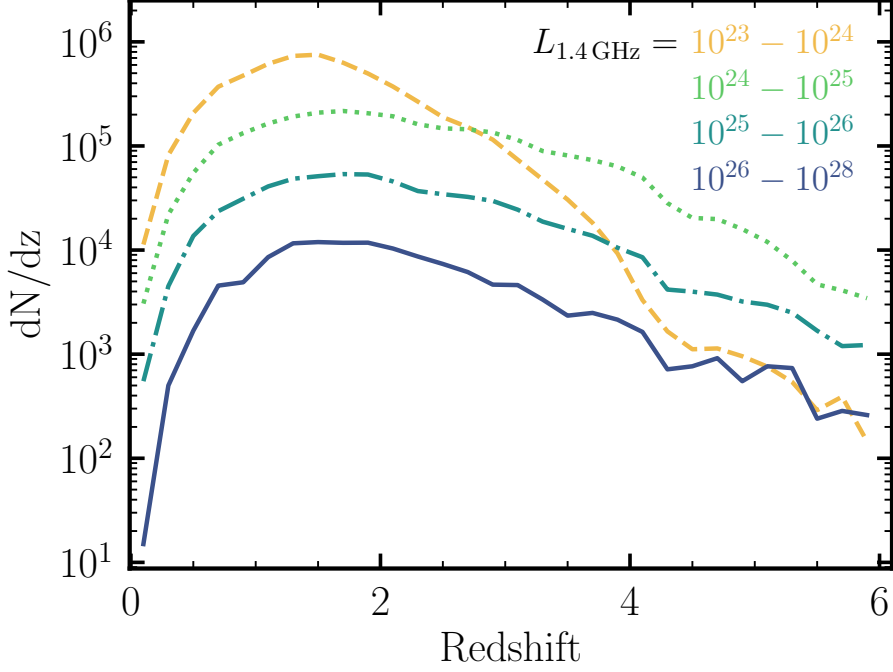


Figure 5: Simulated redshift distribution of radio-loud AGN expected to be detected with the SKA-Mid based on the T-RECS simulations and properties of the proposed wide and deep reference continuum surveys noted in the chapter. The expected redshift distributions are shown separately for four radio luminosity bins across $L_{1.4\text{GHz}} \sim 10^{23} - 10^{28} \text{ W Hz}^{-1}$. At $z > 5$, we predict that the SKA-Mid observations noted here would detect few hundreds of sources in each luminosity bin; this sample size is sufficient to investigate trends as a function of other galaxy properties (e.g. stellar mass, star-formation rate, etc.).

the radio sources and characterisation of broad-band radio spectra for the AGN (through SKA-Low observations) (e.g. [Hardcastle et al., 2019](#); [Yates-Jones et al., 2023](#); [Turner et al., 2023](#)). For the former, observations discussed in this chapter will robustly characterise the shape and the faint-end of the luminosity function across redshift, which will provide considerably improved constraints on the kinetic heating output by the AGN jets at high redshifts.

3.3 Map the evolution of radio-AGN activity up to $z \sim 6$

The SKAO AA4 surveys will also provide large samples of radio-AGN that are complete down to $L_{1.4\text{GHz}} \sim 10^{23} \text{ W Hz}^{-1}$ at $z \sim 6$ (and even fainter at lower redshifts). This radio luminosity limit is critical as studies at low redshift ($z < 0.5$) have focused on the radio-loud population above this luminosity regime (e.g. [Best et al., 2005](#)). The current deep radio surveys are only able to study complete samples of AGN down to this luminosity limit up to $z \sim 1.5 - 2$, while studies at higher redshifts focus on more luminous AGN. Detailed studies of such faint radio-AGN are not possible from the SKAO pathfinders and precursors surveys. The SKA-Mid surveys will provide a transformational increase in our understanding of the faint radio-AGN population out to early epochs.

The expected redshift distribution of AGN as a function of radio luminosity is shown in Figure 5.

Across narrow redshift slices, we expect to detect a few hundreds of thousands of AGN at $z \sim 3$ to a few tens of thousands of AGN at $z \sim 5$. With such large samples we can trace in detail how AGN activity depends on multiple relevant properties by binning (e.g. accretion mode, stellar mass, star-formation rate, galaxy age, galaxy environment), simultaneously, across narrow slices of cosmic time to map out the distribution of AGN activity across the galaxy population. At the highest redshifts ($z > 5$), we expect to detect at least a few hundred to a few thousand sources per luminosity bin (see Figure 5). This sample size will also be sufficient to investigate trends in radio-AGN activity (e.g. with stellar mass, star-formation rate) by binning as a function of radio luminosity.

At faint flux densities, the so-called ‘radio-quiet AGN’, which do not show clear signs of powerful radio jets, form a significant fraction of the overall AGN population (see Best et al., 2023). Whether the radio emission in these sources is dominated by star-formation or by AGN activity is still a topic of debate in the literature (see recent review by Panessa et al., 2019). Recent sub-arcsecond imaging from LOFAR, utilising brightness temperature measurements, has highlighted that the low-frequency radio emission may arise from both star-formation and AGN activity in these sources (Morabito et al., 2022). Other VLBI studies at higher frequencies have also found similar results (e.g. Herrera Ruiz et al., 2017; Radcliffe et al., 2018; Deane et al., 2024; Saikia et al., 2025). Such brightness-temperature measurements have also shown that even for sources not classified as ‘radio-loud AGN’, a significant fraction of the radio emission may arise from AGN activity (Morabito et al., 2025). Other studies using wide-area radio surveys have also highlighted this, finding considerable overlap between sources that have traditionally been classified as radio-quiet or radio-loud (e.g. Yue et al., 2024). In this chapter, we focus primarily on the radio-loud AGN population, whereas the radio-quiet AGN are discussed in detail by Panessa et al. (2026).

We emphasise that SKA-Mid band 2 surveys will detect large samples of the (low-luminosity) radio-quiet AGN which will form the bulk of the overall faint AGN population. The sub-arcsecond resolution offered by SKA-Mid band 2 will allow us to disentangle the emission originating from star-formation and AGN processes by resolving the jets on galactic scales. This will also enable the identification of one of the largest clean samples of jetted-AGN. We will be able to trace the prevalence of jetted sources out to the highest redshifts, extending studies at lower redshifts (e.g. Sabater et al., 2019; Kondapally et al., 2022). Furthermore, accurate size measurements of radio sources will allow us to trace the evolution of the kinetic luminosity density for the bulk of the jetted sources and quantify the role of jet feedback on galaxy formation at early epochs. We focus primarily on SKA-Mid surveys in this section (and more broadly within the chapter) as the high angular resolution (sub-arcsec level) and deep observations (down to sub- μ Jy level) are necessary to achieve many of the key scientific aims relating to the detection and characterisation of large sample of radio-AGN across cosmic time. SKA-Low observation, with its much poorer angular resolution will be significantly affected by confusion noise.

3.4 Unveiling AGN in obscured environments

It is well known that intensely star-forming galaxies possessing large reservoirs of gas and dust can host obscured AGN as inflow of gas to the central region triggers AGN activity (Hopkins et al., 2008; Lacy et al., 2020). The circumnuclear gas and dust causes absorption and scattering of optical,

UV and X-ray emission arising from the AGN. Thus, optical, UV and X-ray observations pose limitations in unveiling the complete AGN population across cosmic epochs. Radio emission being optically thin to gas and dust can allow us to detect AGN-jet activity in obscured environments. Using 10 GHz VLA observations Patil et al. (2020) detected young AGN-jets of a few kpc or smaller in heavily obscured quasars hosted in ultra luminous ($L_{\text{bol}} \sim 10^{11.7} - 10^{14.2} L_{\odot}$) galaxies residing at redshifts (z) $\sim 0.4 - 3.0$. The 0.1-10 GHz radio spectral energy distributions (SEDs) of these obscured AGN indicate that the majority of them are Gigahertz-Peaked Spectrum (GPS) sources (Patil et al., 2022). However, most of the radio studies of obscured AGN are limited to radio-bright AGN ($S_{1.4\text{GHz}} > 1.0$ mJy). Also, shallow wide-area radio surveys have found very low detection rates of dusty galaxies due to their limited sensitivities. For instance, using the FIRST survey ($5\sigma \approx 1.0$ mJy beam $^{-1}$), Gabányi et al. (2021) could detect radio emission in only 2.0 per cent of the sources in their sample of 661 dust-obscured galaxies (DOGs).

Leveraging deep band-3 (250–550 MHz) uGMRT (average noise-rms ~ 30 $\mu\text{Jy beam}^{-1}$ and angular resolution $6''.7 \times 5''.3$) and 1.5 GHz JVLA ((average noise-rms ~ 16 $\mu\text{Jy beam}^{-1}$ and angular resolution $4''.5 \times 4''.5$) radio observations in 2.4 deg^2 of the XMM-LSS field Kayal et al. (2022) studied radio properties of 321 DOGs selected by $S_{24 \mu\text{m}}/S_{\text{r-band}} \geq 1000$ criterion (Dey et al., 2008). Both band-3 uGMRT and 1.5 GHz JVLA observations yielded similar detection rates of only 25–28 per cent, and demonstrated that, in general, radio emission in DOGs is faint ($S_{1.5 \text{ GHz}} \sim 0.035\text{--}9.33$ mJy with a median value of 0.13 mJy for 83/321 radio-detected DOGs) at sub-mJy level or even lower. Nevertheless, radio emission in majority of the radio-detected DOGs is inferred to be AGN-jet dominated considering their radio properties *e.g.*, high radio luminosities ($L_{1.5 \text{ GHz}} > 10^{24} \text{ W Hz}^{-1}$), and either steep (≤ -1.0) or flat (≥ -0.5) radio spectral indices ($\alpha_{0.4 \text{ GHz}}^{1.5 \text{ GHz}}$).

We point out that the radio detection rate of DOGs in 1.5 GHz JVLA and band-3 uGMRT is merely 25–28 per cent and the radio properties of more than 70 per cent of DOGs remain unexplored. For radio-undetected DOGs the median stacked images obtained by stacking $1'.0 \times 1'.0$ radio image cutouts at their optical positions show a clear detection of radio emission at $\text{SNR} \geq 20$ with noise-rms of $3.4 \mu\text{Jy beam}^{-1}$ at 400 MHz and $1.5 \mu\text{Jy beam}^{-1}$ at 1.5 GHz (see Figure 6), which in turn implies that, on average, half of the radio-undetected DOGs have 1.5 GHz flux density below $1.5 \mu\text{Jy}$. More sensitive 1.28 GHz MeerKAT ($3.2 \mu\text{Jy beam}^{-1}$ average noise-rms and $8''.9$ angular resolution) and band-4 uGMRT ($8.4 \mu\text{Jy beam}^{-1}$ average noise-rms and $5''.0$ angular resolution) observations performed under the MeerKAT International GHz Tiered Extragalactic Exploration (MIGHTEE) and SuperMIGHTEE projects, respectively, yield nearly 75 and 50 per cent detection rates (Singh et al., *in preparation*). However, we note that MIGHTEE and SuperMIGHTEE observations also fail to detect the complete population of DOGs; we require deep SKAO radio continuum observations to obtain a more complete understanding. We also note that the radio emission in a fraction of DOGs may be powered by star-formation, especially sources with relatively lower radio luminosities ($L_{1.4 \text{ GHz}} < 10^{24} \text{ W Hz}^{-1}$). Indeed, DOGs exhibiting bumps (at NIR–MIR wavelengths) in their SEDs are known to have intense star-formation (Yutani et al., 2022). Multi-frequency radio observations, that allow us to trace the radio SEDs, would be useful in ascertaining the origin of radio emission as SED modelling can allow us to distinguish AGN powered synchrotron emission from star-formation powered by free-free emission (Dey et al., 2024).

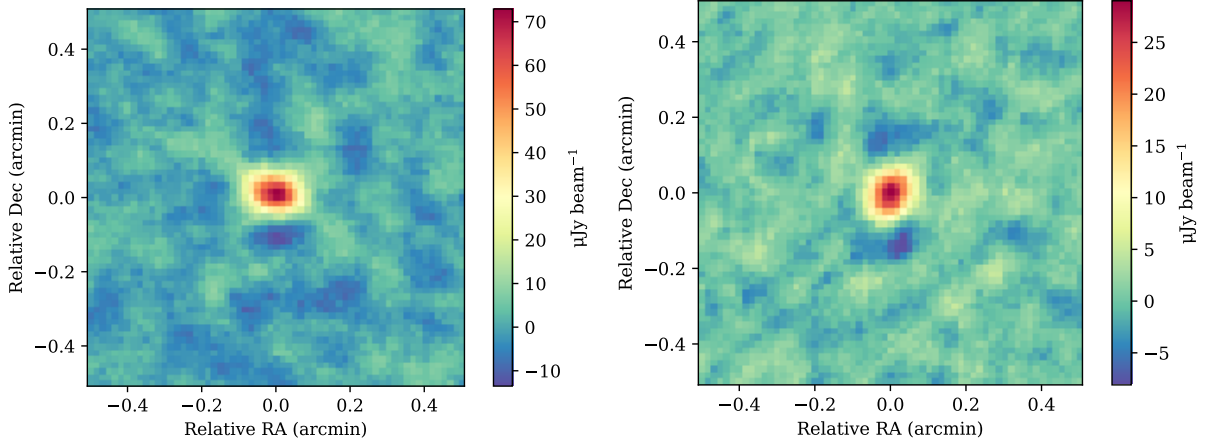


Figure 6: The median-stacked images obtained by stacking radio image cutouts centred at the optical positions of DOGs devoid of radio detection. *Left panel:* 400 MHz uGMRT stacked image. *Right panel:* 1.5 GHz JVLA stacked image. This figure is adapted from Kayal et al. (2022).

To assess the potential of SKA-Low and SKA-Mid surveys in detecting the radio emission from DOGs we compare the radio-detection rates of 321 DOGs using different radio surveys available in the XMM-LSS field (see Figure 7). As expected, the fraction of radio detected DOGs scales up with sensitivity, with both low-frequency as well as high-frequency observations following an increasing trend. The extrapolation of the trend suggests that the deep SKA-Mid band-2 radio

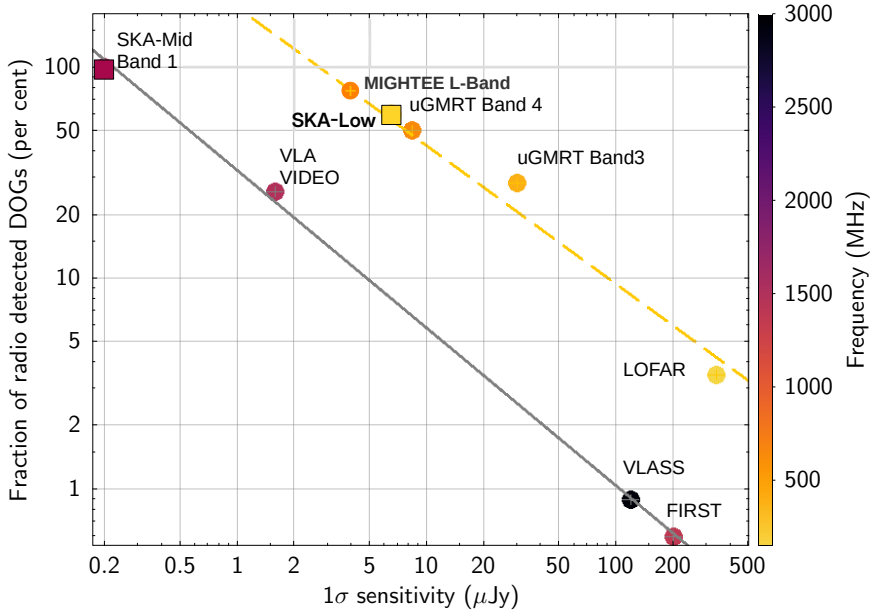


Figure 7: The detection rates of dust-obscured galaxies in different radio surveys available in the XMM-LSS field. The detection rate scales up with sensitivity wherein solid and dotted lines represent the best-fits for high-frequency (≥ 1.4 GHz) and low-frequency (< 1.4 GHz) observations extrapolated to the SKA-Mid and SKA-Low anticipated sensitivities. The SKA-Mid and SKA-Low data points are depicted by square boxes.

continuum surveys achieving noise-rms of $0.2 \mu\text{Jy beam}^{-1}$ would detect almost the entire population of DOGs. We caution that deep SKA-Low observations with integration times of $\gtrsim 1$ hr in the AA4 configuration would result noise-rms of $5\text{--}10 \mu\text{Jy beam}^{-1}$ but they would suffer from confusion limits. Therefore, deep SKA-Low observations are unlikely to achieve 100 per cent detection rate but they can be advantageous in detecting steep spectrum radio sources especially at higher redshifts. Furthermore, combination of SKA-Low and SKA-Mid observations would allow us to study radio SEDs of DOGs that are essential to ascertain the origin of radio emission *i.e.*, AGN versus star-formation.

3.5 Obscured AGN at high-redshifts

Deep X-ray surveys have shown that the fraction of heavily obscured AGN with equivalent hydrogen column density ($N_H > 10^{23} \text{cm}^{-2}$) and high X-ray luminosity $L_X > 10^{44} \text{erg/s}$ (*i.e.* bolometric luminosity $L_{\text{bol}} > 10^{45} \text{erg/s}$) increases from 10 – 20% in the local Universe to 80 – 90% at $z \sim 4$ (Vito et al., 2018). The analytical studies and numerical simulations (Gilli et al., 2022; Ni et al., 2020) addressing the evolution of the physical properties of the inter-stellar medium (ISM) around AGN also support this finding; the latter further predicts that the fraction of obscured AGN may exceed 99% at $z > 6$. Recent works, exploiting *James Webb Space Telescope* (JWST) spectroscopic and photometric data, have found that the obscured AGN number density at $z > 5$ is even larger than previous estimates derived from X-ray studies (Akins et al., 2025; Lyu et al., 2024; Yang et al., 2023), and this is more in line with the results from simulations and models (Sijacki et al., 2015; Shankar et al., 2014; Volonteri et al., 2016). All these results potentially suggest that there exists a population of heavily obscured AGN such that even the deepest X-ray observations would miss them.

The advantage of radio emission being almost unaffected by obscuration is that we can detect AGN activity even in the most obscured environments. The results from analytical models suggest that the deep continuum radio surveys can unveil a large number of obscured AGN, even those missed by other selection techniques. In Mazzolari et al. (2024a), by taking the radio and X-ray images of some known extragalactic deep fields, they showed that, on average, the surface density of Compton-thick (CTK) AGN detectable in the existing radio images is ~ 10 times higher than that in the corresponding X-ray images. While X-ray selection is generally more effective in detecting unobscured, radiatively efficient AGN, radio emission can more easily unveil the most obscured sources, even those for which X-rays are completely absorbed (like CTK AGN, see the results in Mazzolari et al., 2026). Additionally, while the AGN radio selection might be biased towards low accretion rates (Kondapally et al., 2022; Best et al., 2023), the combination of radio-excess selection and multi-wavelength datasets have demonstrated the ability to also select radio-quiet and radiatively efficient AGN (see Sect. 4).

In this sense, the observations that SKA will perform will be transformative. Mazzolari et al. (2024a) simulated the number of AGN and CTK-AGN that will be detectable with the SKAO considering three different tiers – $0.05 \mu\text{Jy}$ noise-rms over 1.0deg^2 (ultra-deep survey), $0.2 \mu\text{Jy}$ noise-rms over $10\text{--}30 \text{deg}^2$ (deep survey), $1 \mu\text{Jy}$ noise-rms over 10^3deg^2 (wide survey), respectively (Prandoni and Seymour, 2015; Prandoni et al., 2026). They made predictions for three different redshift ranges: $z > 3$, $z > 6$, and $z > 10$. The results for the three tiers are reported in Table 1. All the predictions

are computed assuming a flat sensitivity over the survey area. With the wide SKA survey thousands of AGN are expected to be detected at $z > 6$ and a significant fraction of them are expected to be CTK AGN (at least $> 45\%$). With such SKAO surveys, it will be possible to trace the evolution of the obscured AGN population from the end of the reionization through the cosmic noon, down to the present universe, and combine the findings obtained in the radio band with those obtained using obscured AGN selections in the X-rays or mid-infrared. In particular, the $z > 6$ universe is still very unconstrained, particularly in the X-ray and radio waves. The possibility to identify hundreds or thousands of AGN and CTK AGN at $z > 6$ will transform our understanding of the co-evolution of SMBHs with their galaxies in the first Gyr of cosmic time. Also at $z > 10$, a redshift range that was almost completely unexplored before the advent of JWST, the SKAO is expected to be able to detect several tens of radio-quiet AGN, opening a completely new window.

The SKA-Mid predictions for high- z obscured AGN

Area (deg ²)	Sens (5σ) [μ Jy]	$z > 3$			$z > 6$			$z > 10$		
		AGN	CTK	$\log L_{\text{bol}}$	AGN	CTK	$\log L_{\text{bol}}$	AGN	CTK	$\log L_{\text{bol}}$
1	0.25	1870	831	43.8	34	15	44.4	2	1	44.8
20	1.0	13780	6120	44.4	220	98	44.9	6	3	45.6
1000	5.0	182000	81000	45.1	1980	880	45.4	35	16	46.6

Table 1: The expected number of high- z AGN in three 1.4 GHz continuum surveys with SKA-Mid band-2 (as detailed in the text). The areas and sensitivities are in the units of deg² and μ Jy, respectively. $\log L_{\text{bol}}$ gives the median bolometric luminosity of detected AGN (erg s⁻¹).

4 Selection of radio-AGN with SKAO and other multi-wavelength observatories

The results presented in the previous sections can only be obtained if AGN can be properly identified among the many new radio sources that the SKAO will detect. The combination of radio data from the SKAO with multi-wavelength data from current and next-generation facilities will be crucial for selecting distant AGN and distinguishing them from normal SFGs, the main contaminants, particularly at faint radio fluxes. SKAO surveys are planned to overlap with forthcoming wide-area, sensitive optical and near-infrared surveys, such as those by the Vera C. Rubin Observatory Legacy Survey of Space and Time (LSST) and Euclid, but also with the deep surveys performed by JWST NIRCам and MIRI. The LSST will perform photometric imaging of entire southern hemisphere sky repeatedly in six filters (u , g , r , i , z , and y ; covering 320–1060 nm) with time-lapse of few nights and detecting variable sources including AGN. In addition to the wide survey, LSST will also perform deep imaging in five deep-drilling fields (DDFs) namely COSMOS, W-CDFS, ELAIS-S1, XMM-LSS and EDF-S covering a total of nearly 10–20 deg² sky area (Brandt et al., 2018). Euclid is performing optical and near-infrared imaging as well as NIR spectroscopy over the sky-area of nearly 14000 deg² (the wide survey) and 50 deg² of deep fields (Euclid Collaboration et al., 2025). The unprecedented sensitivity of both the LSST Wide and in Deep Drilling Field surveys (r band mag ~ 27 – 28) will enable us to detect the high- z AGN population including those residing in obscure environments that will in turn constrain the AGN luminosity function.

The possibility to constrain both the radio and the rest frame optical and near-infrared emission of the sources detected with the SKAO will enable the application of radio-excess (REX) selection

techniques that are able to distinguish between accretion, and SF-dominated radio sources (Bonzini et al., 2013; Smolčić et al., 2017a; Delvecchio et al., 2021; Best et al., 2023; Zhu et al., 2023; Zhang et al., 2025; Eberhard et al., 2025; Mazzolari et al., 2026). These radio-excess selections are able to reliably identify not only the most powerful radio AGN but also a consistent fraction of the RQ-AGN population provided that they possess a dominant AGN-driven radio component, independently of which exact mechanism is responsible for it (Whittam et al., 2022; Lyu et al., 2022; Zhang et al., 2025). In addition, the development of new and refined SED fitting codes and techniques will also be crucial for identifying AGN among the sources that the SKAO will detect in its radio-continuum surveys (provided that imaging in other wavelengths is also available). So far, the AGN radio emission has been implemented only in some SED-fitting codes, such as CIGALE (Boquien et al., 2019). A fully consistent modelling of the AGN radio emission in SED-fitting codes is hard, given that, if jet-driven, radio emission is a function of jet power, jet orientation, source age, and environment, none of which can be extracted from the multi-band SED. However, it would be ideal to implement in SED-fitting codes a modelling of the radio emission that could, for example, directly provide an estimate of the AGN-related radio excess, taking into account the constraints on the SF radio emission obtained from the multi-band fit. As demonstrated in this Science Book, the depth of SKAO observations and the possibility of having deep radio images at different frequencies will be extremely useful for constraining the presence of an active SMBH in galaxies that do not show AGN signatures at other wavelengths (for example due to obscuration effects).

Additionally, the combination of mm ALMA and NOEMA follow-up observations, or far-infrared PRIMA surveys (Moulet et al., 2023), with the SKAO will verify whether the far-infrared-radio correlation, typically used to distinguish between AGNs and SFGs, remains valid at high redshifts, as well as for low stellar masses ($M_* < 10^9 M_\odot$, Delvecchio et al., 2021) and SFRs. As an example, the sensitivity of the SKAO deep surveys will allow detection of galaxies with SFR $\sim 10 - 100 M_\odot/\text{yr}$ in galaxies up to $z \sim 3 - 4$, and SFR $\geq 100 M_\odot/\text{yr}$ at $z \sim 6 - 7$ (McAlpine et al., 2015; Prandoni et al., 2026).

JWST and ELT observations will also enable spectroscopic follow-up of radio-selected, high- z AGN candidates to determine their redshifts and ultimately measure the radio AGN luminosity function at $z > 6$. Furthermore, thanks to SKAO, we expect to reveal the radio emission of JWST-discovered AGN, which so far appear to be elusive at X-ray and radio wavelengths (e.g. Maiolino et al., 2025; Lambrides et al., 2024). Indeed, the population of high- z AGN selected using JWST photometry and spectroscopy, including also the so-called Little Red Dots (LRDs), seems to be characterized by a different SED compared to standard AGN, with a peculiar weakness in the X-rays, UV, but also in the radio band (e.g. Matthee et al., 2024; Kocevski et al., 2025). However, it is still not clear whether this is due to intrinsically different accretion properties (such as super Eddington accretion) or due to the presence of an obscuring dense cocoon of gas close to the central SMBH. Current analysis did not reveal, even with stacking techniques on the deepest radio images available, and reaching the ~ 100 nJy noise level, any radio emission in these sources (Mazzolari et al., 2024b; Gludemans et al., 2025; Perger et al., 2025). Instead, ultra-deep SKAO surveys may help detect their radio emission and reveal the origin of this apparent weakness, which is discussed in further detail in a dedicated chapter within this volume by Mazzolari et al. (2026).

The combination of the SKAO radio observations with present and future wide and deep X-ray surveys from eRosita (Predehl et al., 2021), New-Athena (Cruise et al., 2025), and AXIS (Reynolds et al., 2024) will enable improved AGN identification. In particular, the availability of X-ray observations will enable a precise measurement of the obscuring column density of the sources, and therefore facilitate the study of the evolution of obscured AGNs. The combination of both X-ray and radio observations will enable a detailed study of the processes associated with the feedback mechanisms, such as the formation of X-ray cavities resulting from the launch of radio jets (Bîrzan and et al., 2020; Ubertosi et al., 2024).

In addition to multi-wavelength surveys, large spectroscopic surveys, such as those with the SDSS, have been vital in characterising redshifts and properties of radio-detected AGN and their host galaxies (e.g. Best and Heckman, 2012; Pracy et al., 2016). In the coming years, *targetted* spectroscopic surveys of radio-detected sources from LOFAR (with WEAVE-LOFAR; Smith et al. 2016) and MeerKAT (with ORCHIDSS; Duncan et al. 2023) will provide large spectroscopic samples of radio-AGN. Similar large-area and targetted spectroscopic surveys in the SKAO era will be crucial in characterising the AGN population detected by SKAO surveys in detail; this is discussed further by Duncan et al. (2026).

In the absence of other multi-band AGN diagnostics and observations, the identification of AGN and CTK AGN using SKAO data may rely on either multi-frequency radio information, or high-resolution (SKA 10 GHz observations will provide angular resolution of $0.05''$ - $0.1''$ compared to the $0.4''$ - $0.5''$ of 1.4 GHz observations) and/or multi-epoch follow-ups. All these diagnostics are amply used in the literature. Flat or convex radio spectral indices would point to the presence of compact AGN cores (O’Dea and Saikia, 2021). High-resolution follow-ups can pinpoint AGN through the measurement of brightness temperatures (see Morabito et al., 2022, 2025; Radcliffe et al., 2018; Herrera Ruiz et al., 2017; Saikia et al., 2025; Peluso et al., 2025), while multi-epoch observations may identify those variable AGN at μJy flux density levels (Radcliffe et al., 2019). In particular the combination of EVN and SKA-AA4 will allow the measurement of brightness temperatures $T_b > 10^5$ K in $L_{1.4\text{GHz}} > 8 \times 10^{24}$ W/Hz (or equivalently $L_{1.4\text{GHz}} > 10^{41}$ erg/s) and $z \sim 6$ QSO with only few tens of minutes of observations (see Spingola et al., 2026).

5 Conclusions

The capabilities offered by the SKAO surveys will enable us to perform population-based studies of radio-AGN and their evolution across cosmic time. In this chapter, we have highlighted the need for multi-tiered SKAO radio continuum surveys (focusing mainly on the SKA-Mid): 1000 deg^2 wide-area survey down to $\sigma \sim 1 \mu\text{Jy}/\text{beam}$ and a $\sim 25 \text{deg}^2$ deep survey down to $\sigma \sim 0.2 \mu\text{Jy}/\text{beam}$ (both at 1.4 GHz), to transform our view of the faint radio-AGN population at the earliest cosmic epochs. Using T-RECS simulated radio source catalogues, we have shown that such a tiered survey will provide a complete census of the radio-loud AGN population down to $L_{1.4\text{GHz}} \sim 10^{23} \text{W Hz}^{-1}$ all the way up to $z \sim 6$. The large samples of AGN detected with the SKA-Mid surveys will: (i) provide the tightest constraints on the evolution of the radio luminosity function up to $z \sim 6$; (ii) enable robust constraints on the faint-end slope of the luminosity function which will be vital for quantifying the kinetic feedback across redshift; (iii) provide the largest clean sample of jetted-AGN, including those

within SFGs; and (iv) map the distribution of radio-AGN activity as a function of various galaxy properties (e.g. stellar mass, star-formation rate, galaxy environment) in unprecedented detail across all epochs. We have also emphasised that the SKAO will offer new insights into AGN population residing in obscured environments and argued that, unlike, existing radio continuum surveys from the pathfinders and precursors limited up to a few μJy , SKAO continuum surveys that can achieve sub- μJy depths will provide a more complete census of obscured AGN up to $z \sim 6$. Synergies with current and planned multi-wavelength surveys will be crucial in achieving many of the key scientific objectives in studies of the evolution of radio-AGN.

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