Chapter 6
Conclusions and future prospects

In this thesis, the combination of very high angular-resolution observations and gravitational lensing was used to address some open questions in galaxy formation at the smallest-scales. In Chapters 2 to 4, the results of an in-depth analysis of the lensing mass distribution and source properties of three gravitationally lensed radio sources (MG J0751+2716, JVAS B1938+666 and MG B2016+112) with extended radio jets was presented. In Chapter 5, the first search for gravitationally lensed radio sources using wide-field Very Long Baseline Interferometry (VLBI) was presented, with the aim of demonstrating the feasibility of such surveys with the next generation of VLBI arrays in the future. In this chapter, a summary of the main results from each of these science chapters is given (Sections 6.1 to 6.4). The general conclusions of this thesis are presented in Section 6.5, while a discussion of the prospects for future research in these different science areas is given in Section 6.6.

6.1 The mass density profile of lensing galaxies at milliarcsecond scales

*VLBI observations at milliarcsecond angular resolution of gravitationally lensed radio jets give a large number of constraints on the mass density distribution of a lensing galaxy, which is not necessarily smooth on the smallest angular scales.*

In Chapter 2, sensitive global VLBI observations at 1.65 GHz of the gravitationally lensed radio source MG J0751+2716 were presented. The background jetted active galactic nucleus (AGN) at redshift $z = 3.2$ is gravitationally lensed by a foreground group of galaxies at redshift $z = 0.35$. The distorted view of the distant radio jets consists of four spectacular gravitational arcs that are extended by 200 to 600 mas; these observations represent the highest angular resolution
imaging of extended gravitational arcs produced by a gravitational lens. The mas-resolution global VLBI observations of these gravitational arcs provided a large number of constraints to the lensing mass model, which were used to search for any deviation from a globally smooth mass distribution on small angular-scales. By identifying groups of lensed images that corresponded to the same part of the background source, two models for the MG J0751+2716 lensing mass distribution were investigated. The first model included the main lensing galaxy and an additional external shear component. The second, more realistic model included the lensing galaxy, an external shear component, and five additional haloes representing all of the spectroscopically confirmed group-member galaxies.

Given the exquisite quality of the radio imaging, the lens mass model parameters could be inferred with a precision of less than a per cent, even though the simple smooth models were not accurate enough to fit the positions of the observed images to within the measurement error level. Furthermore, the slope of the mass density distribution of the main lensing galaxy was found to be steeper than isothermal at the 4.2$\sigma$ level and at the 6.8$\sigma$ level for the two models, respectively. This mass density slope is consistent with studies of low-mass early-type satellite galaxies within groups or clusters, and can be taken as evidence that supports the two-phase galaxy formation scenario. Therefore, gravitational lensing can provide a description of the projected mass density distribution of complex galaxy groups, which is generally challenging to map at high redshift. Moreover, the excellent sensitivity and high angular resolution of the VLBI imaging of MG J0751+2716 allowed the measurement of small offsets between the observed and predicted positions of the lensed images, with an average positional rms of the order of 3 mas for the simple parametric models tested here, that is, on the order of the point spread function of the observations. These astrometric offsets suggested that, at the mas level, the standard assumption of a smooth mass distribution fails, requiring additional mass structure in the model. Therefore, these results challenge the hypothesis that galaxy haloes are smoother than what is predicted by the ΛCDM model to explain the low number of sub-structures associated with massive haloes. However, this extra mass cannot be unequivocally attributed to a population of low mass sub-haloes within the lensing galaxy, as predicted by cold dark matter models for galaxy formation, but may be due to a more complex mass distribution within the lensing group or along the line-of-sight. Nevertheless, this result disfavours the presence of a completely smooth mass density distribution, as expected from warm dark matter formation models, and emphasizes the need for using the entire flux density of the gravitational arcs for performing grid-based corrections to the gravitational potential, which can
The results from Chapter 2 demonstrated that sensitive high angular resolution observations can directly test complex mass models for lensing galaxies, going beyond the usual assumption of a smooth power-law elliptical mass density distribution, which was shown to be insufficient to describe the small angular-scales probed by the data.

6.2 Cold molecular gas at the early stages of galaxy formation

There is evidence of extended cold molecular gas reservoirs on 5 to 15 kpc-scales in two strongly lensed dust-obscured AGN at $z \approx 2-3$, whose properties revealed that they are likely undergoing a complex gas-rich merger phase, as expected from a hierarchical structure formation scenario. Gravitational lensing allowed the connection between AGN activity, star-formation and galaxy merging to be probed on sub-kpc scales, which for non-lensed objects is otherwise unaccessible with current instruments.

The connection between gas-accretion, and the star-forming and AGN properties of galaxies is still uncertain. Numerical simulations of galactic-scale systems have shown that gas-rich mergers can cause gas inflows toward the central region on different scales, but that these inflows can also induce the most intense star-formation activity within a galaxy. On the observational side, testing such models is challenging, as it requires both the distribution of the molecular gas reservoir and the AGN activity in high-redshift galaxies to be traced on tens of pc to kpc scales. In Chapter 3, an analysis of multi-wavelength imaging and spectroscopic data for two well known gravitationally lensed radio sources (MG J0751+2716 and JVAS B1938+666), which also have evidence of extremely high far-infrared (FIR) derived star-formation rates, was presented. The aim was to study the triggering mechanism of star-formation and AGN activity in such galaxies at cosmological distances.

The multi-band datasets consisted of Very Large Array (VLA) radio continuum and CO (1–0) spectral line imaging, HST optical and near-infrared (NIR) imaging and Keck adaptive optics NIR imaging. The observations of JVAS B1938+666 represented the highest angular resolution detection of CO (1–0) molecular gas ever achieved for a high-redshift object. After correcting for the distortion due to gravitational lensing, the structure of the CO (1–0) distribution, the stellar light emission and the AGN jets were resolved on about 50 to 300 pc. Both objects were found to have a compact central stellar component and small
AGN radio jets that were embedded within an extended molecular gas reservoir, which was found to be between 5 and 15 kpc in size. Also, the peak in the CO (1–0) distribution was found to be offset from the central AGN by several hundred pc. Moreover, the intrinsic velocity fields showed distinct structures, which could be associated with disks (elongated velocity gradients) and possibly interacting objects (off-axis velocity components).

This morphological and spectroscopic picture of MG J0751+2716 and JVAS B1938+666 supports the scenario in which AGN are formed by gas-rich mergers. Also, this formation scenario predicts a dusty and ultra-luminous infrared star-forming intermediate stage before the so-called dust-obscured quasar phase. It was found that both objects are obscured AGN, and that they have high gas-fractions and an abundance of molecular gas, but that, given the available fuel, they were not forming stars at the level that would be expected if all of the gas was being converted to stars. It was not clear if the extended molecular gas distributions and inefficient star-formation were due to radiative or mechanical feedback from the AGN, or if it was due to a pre-starburst phase as the molecular gas inflows back to the galaxy after a recent interaction/merger. The compact stellar component in each system could be associated with a strong central star-forming region, as observed in LIRGs and ULIRGs, which was also consistent with a possible merger scenario. Further high resolution imaging at mm-wavelengths will be needed to confirm this interpretation.

The results from Chapter 3 provided an un-matched high-redshift view of the early evolutionary stages within star-forming/AGN galaxies, which could be directly observed by combining high sensitivity and high resolution imaging and the resolving power of gravitational lensing.

6.3 Proper motions of SMBH at redshifts $> 3$

Multi-epoch VLBI observations of gravitationally lensed radio sources can directly measure proper motions within the jets of high redshift AGN on tens of pc-scales, testing formation models for super-massive black holes.

There are many properties of super massive black holes (SMBHs) that are still not completely understood, among them being their formation process. In Chapter 4 the first detection of proper motion in the complex jet-structure of a radio-loud gravitationally lensed quasar was presented and used to investigate the properties of SMBHs at a redshift of $z = 3.2773$. By combining the resolving power of VLBI and gravitational lensing, it was possible to make this detection of proper motions at such a high redshift, with a precision of 1 mas yr$^{-1}$. From a lens modelling analysis of the data, it was possible to reconstruct the morphology of a distant
and faint radio-loud AGN. The de-lensed background source showed a complex morphology, where some source sub-components were found to be moving toward each other, and some moving in opposite directions.

These properties led to two possible scenarios. The first interpretation for the source plane consisted of a single AGN, where the observed proper motion was due to possible knots moving along the radio jets, which is observed in many jetted-AGN. Nevertheless, the analysis revealed that the de-magnified flux densities of the components were apparently not consistent with knots moving along an approaching and a receding jet. Therefore, the single AGN scenario will require an exotic and complicated source morphology to explain the observed proper motions. The second possible scenario consisted of two distinct radio-loud AGN, which are separated by \( \sim 175 \) pc in projection, with both having a core-jet morphology. In this scenario, which was mainly driven by the motion of the two flat-spectrum components, the two core-jet AGN orbit around each other and form a dual AGN (DAGN) system. The presence of a DAGN in MG B2016+112 would be strong evidence in favour of the merger-driven SMBH formation scenario, as DAGN represent an intermediate evolutionary stage of such a process. According to the hierarchical formation scenario, DAGN are expected to be observed at high redshift, but the timescales on which multiple SMBHs can coalesce are not known. Therefore, the discovery of a possible orbital motion in a candidate DAGN system presents the unique opportunity to probe the kinematics of two SMBHs at late evolutionary stages of their possible merging.

The confirmation of the DAGN scenario would make MG B2016+112 an important target to study the physical properties of SMBHs at high redshift and with an unprecedented level of detail. Given the low flux density of the lensed images, it will be necessary to obtain more sensitive VLBI observations to confirm such a detection and properly characterize the possible orbital motion.

### 6.4 Wide-field VLBI surveys: an efficient way to find radio-loud lenses

*Wide-field surveys with VLBI arrays can efficiently find gravitationally lensed radio-sources by adopting simple selection criteria.*

The first wide-field VLBI search for gravitationally lensed radio sources, using data from the mJIVE–20 survey, was presented in Chapter 5. Among an initial sample of 3,640 compact radio sources detected on VLBI-scales, 81 sources with at least two radio components that were separated by more than 100 mas and with a flux-density ratio of less than 15:1 were selected. From this process,
a sample of fourteen good gravitational lens candidates were identified, that is, those with multiple compact components and a similar surface brightness at 1.4 GHz and, therefore, were likely not simply core-jet type radio sources. By starting directly from the mJIVE–20 VLBI observations, it was possible to skip several steps in the selection of the best lens candidates, making the search more efficient during the observational phase. For example, among the final fourteen lens candidates, two are a re-discovery of the known gravitational lenses CLASS B1127+385 and CLASS B2319+051, which provided an immediate proof-of-concept that this selection method was able to find gravitationally lensed radio sources.

Follow-up observations of the twelve remaining candidates at 4.1 and 7.1 GHz were carried out with the VLBA to measure the spectral index and surface brightness of the individual components as a function of frequency. Ten were rejected as AGN with a core-jet or core-hotspot morphology, as the surface brightness distributions and/or spectral indices were inconsistent with gravitational lensing. Interestingly, one system was rejected after lens modelling demonstrated that the candidate lensed images failed the parity test. The final lens candidate was not detected in the VLBA high frequency follow-up observations, but was found to have an image configuration that was consistent with a simple lens mass model. Further observations are required to confirm the true nature of this lens candidate.

Given the two confirmed gravitational lenses in the mJIVE–20 sample, a robust lensing-rate of at least $\frac{1}{318} \pm \frac{225}{225}$ was found for a statistical sample of 635 radio sources detected on mas-scales, which is consistent with that found for CLASS. This implied that the lensing optical depth of compact radio sources had not changed significantly toward lower flux densities. Observations with a much larger sample of sources detected on mas-scales with wide-field VLBI will be needed to both test whether the lensing statistics, and hence the parent population, from the mJIVE–20 and CLASS surveys are similar, and to detect rare gravitational lenses where the image-separation statistics could potentially constrain models for the halo mass-function at the low mass-end ($>10^7 M_\odot$).

### 6.5 General conclusions

Observing gravitationally lensed radio jets in a configuration that produces extended gravitational arcs is rare. Nevertheless, most of this thesis was devoted to the analysis of three such gravitationally lensed radio sources. This is because, even with only a few of these unique systems in hand, such objects provide a wealth of information on both the foreground lens and the background source at
the smallest angular-scales, which otherwise would not be possible to access at high redshift.

This thesis mainly focused on radio interferometric observations, spanning angular-resolutions from arcsec to mas, with the VLA, VLBA and global VLBI arrays. The exquisite sensitivity and angular resolution that is enhanced by the combination of gravitational lensing and VLBI led to one of the main results of this thesis, which was related to the high complexity of the mass distribution in galaxies at mas-scales. For example, MG J0751+2716 provided a unique opportunity to confidently detect a “granularity” in the mass density distribution, demonstrating that at high angular resolution, the simple assumption that the mass profile is smooth may not be true.

Another important result of this thesis was related to the first detection of proper motion within a high redshift lensed object, which would be impossible to achieve without the excellent astrometric precision of the VLBI observations and the high magnification due to gravitational lensing (of around ~ 350). This detection unlocks a new channel to probe the motion of galaxies, in both the foreground and background, at high redshift. Even if the sample of radio-loud lensed objects is currently statistically limited to around thirty-six objects, a systematic search for proper motions in the current sample could, for example, detect slowly moving AGN radio jets. The exciting scenario of two merging AGN in MG B2016+112 would be significant, given the very few spatially resolved DAGN systems. Gravitational lensing shortens the time needed to detect such orbital motions, whose characteristic properties are to date unknown. Monitoring of the two probable cores could reveal the intrinsic kinematics of the system and put constraints on the fate of the merging at pc-scales, which is still controversial.

Finally, the synergy between radio, optical and NIR observations was demonstrated to uncover the build-up of galaxies at high redshift, for example, as in the cases of MG J0751+2716 and JVAS B1938+666. A single wave-band alone could not infer the complex galaxy formation scenario pictured by the multi-wavelength dataset. The most valuable result of this panchromatic study resided in resolving the cold molecular gas reservoirs that extend out to several kpc-scales. The two dust-obscured active galaxies appeared to have quite different properties in their molecular gas, were one was undergoing a gas-rich merger phase and the other indicated an elongated rotation component, as shown by their spatially resolved velocity fields. This study opens up future opportunities for high angular resolution observations of composite star-forming/AGN galaxies at two billion years after the Big Bang, where both the bulk of AGN and stars are predicted to be forming, and massive active black holes were already in place.
6.6 Future prospects

The next generation of radio and optical survey facilities, such as the Square Kilometre Array (SKA), Euclid and the Large Synoptic Survey Telescope (LSST), will allow the discovery of $\sim 10^5$ strong gravitational lenses with both compact and extended structure. The discovery of thousands of gravitational lenses will have a major impact, especially at radio wavelengths, as the number of radio-loud lensing systems will dramatically increase by four orders of magnitude. These surveys will also provide a large parent sample for detailed studies of individual objects with SKA-VLBI, the European Extremely Large Telescope (E-ELT) and the Atacama Large Millimetre Array (ALMA).

How do we find $\sim 10^5$ radio-loud lensed sources? Following the search methodology described in Chapter [5], which is analogous to the CLASS lensing survey, compact radio sources that are gravitationally lensed can be easily identified from their radio structures, provided multi-frequency information is available. However, the identification of those rare cases with extended gravitational arcs, like those investigated in this thesis, may require a more sophisticated technique in order to not be contaminated by, for example, extended AGN jets. Machine learning may provide efficient automated methods to find both compact and extended lensed objects. Moreover, while our search was restricted by the limited $uv$-coverage of snapshot VLBI observations, the large number of SKA receiving elements will have a better imaging fidelity, and will reach a sensitivity of a few $\mu$Jy beam$^{-1}$ in minutes. This will make possible the detection of compact low surface-brightness radio-loud sources and those with extended gravitational arcs. Moreover, the cross-correlation with Euclid and the LSST surveys will determine if there is a lensing galaxy, and potentially provide also an estimate of a photometric redshift, adding other important parameters to discriminate between genuine gravitational lenses and other types of objects.

What do we do with $\sim 10^5$ radio-loud lensed sources? With thousands of gravitationally lensed radio sources, some even with extended structure, it will be possible to statistically constrain the mass distribution of the lensing galaxies on sub-kpc scales. If the SKA has a VLBI capability, it will be possible to probe even smaller angular-scales of the lensing galaxy mass profile by following-up at higher angular resolution the most promising systems, as demonstrated in Chapter [2]. A large number of VLBI-detected gravitational arcs can provide a sample of well-constrained lens mass models at mas-scales, which can lead to the discovery of low-mass objects, such as dwarf galaxies ($M \sim 10^6-7 M_\odot$), whose abundance is a direct test for different dark matter particle masses.

In addition, the multi-wavelength imaging provided by the SKA, Euclid and
the LSST will be important for investigating the properties of highly magnified lensed sources, as was shown for two systems in Chapter 3. The study of individual lensed objects at the highest possible angular resolution can shed light on the initial stages of galaxy formation, which requires a statistically significant sample of spatially-resolved high-redshift sources to be fully characterized.

Finally, future surveys with the next generation of telescopes will be able to find rare gravitational lens systems, like MG B2016+112, as was discussed in Chapter 4. The SKA sensitivity and angular resolution (SKA-VLBI) will provide an unprecedented detailed view on such unusual gravitational lenses, but for a larger sample of objects. It will be possible to directly image and characterize the most distant and faintest radio-loud objects, giving immediate tests to the formation and evolution of super-massive black holes at high-redshift, when combined with gravitational lensing.