EUROPEAN VLBI NETWORK

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European Commission

Acknowledgements

Following on from the EVN Directors' decision to commission a new science vision document for the EVN, the EC-H2020 project JUMPING JIVE (grant agreement No. 730884) dedicated a Work Package (WP7, "VLBI Future") to provide the organisational and financial support for its development. A core team formed by R. Beswick, T. Bogdanović, W. Brisken, P. Charlot, M. Lindqvist, A. Lobanov, Z. Paragi, A. Szomoru and T. Venturi started the process and led the discussion and coordination effort. While the main focus of this report is the EVN instrument, VLBI as a technique is a global effort, and indeed some science goals are best addressed by the EVN making joint observations with other VLBI networks around the world. Most of the science goals identified in this report apply to VLBI in general, even if the specific recommendations of the report apply mainly to the EVN; hence this document's title *VLBI20-30, a scientific roadmap for the next decade: The future of the European VLBI Network*.

The first face-to-face meeting of the project was held in Zaandam, Netherlands on February 28th – March 1st, 2018 and involved invited experts covering a wide variety of VLBI science. Further progress was made during the European Week of Astronomy and Space Science in Liverpool, at the Special Session 11, "Exploring the Universe: A European vision for the future of VLBI". At the 14th EVN Symposium, held in Granada on October 8-11, 2018 and attended by 170 people, an early draft of this science vision document was presented and received further input from the participants.

The VLBI community of users has provided enthusiastic and constructive input to this science roadmap document, which is updated as of November 30th, 2019. We thank all who have contributed as chapter authors and co-authors (see below) and all the many others from the community who have provided comments and advice on specific scientific questions. We warmly thank Prof. R. Schilizzi and Prof. P. Wilkinson for insightful suggestions. Thanks are due to Emma van der Wateren for careful proofreading.

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EXECUTIVE SUMMARY

The European VLBI Network (EVN) Consortium Board of Directors commissioned in Autumn 2016 the EVN community to produce a Science Vision document covering the period till 2030. Since the last such document (EVN2015) was issued over a decade ago, the technical capabilities and scientific potential of Very Long Baseline Interferometry (VLBI) have considerably expanded. New technical developments on the horizon promise even greater future capabilities and scientific possibilities for VLBI in the future. Additionally, since the last science vision report many new exciting questions have emerged within astrophysics, and VLBI observations have already proved to be invaluable. Finally, the coming decade will see the beginning of operations of the Square Kilometre Array (SKA), alongside major new telescopes at other wavebands, which will significantly change the overall radio astronomy landscape. The above considerations make it timely to consider EVN and VLBI science priorities for the period 2020-2030.

The EVN is a distributed long-baseline radio interferometric array, that operates at the very forefront of astronomical research. Recent results, together with the new science possibilities outlined in this vision document, demonstrate the EVN's potential to generate new and exciting results that will transform our view of the cosmos. Together with *e*-MERLIN, the EVN already provides a range of baseline lengths that permit unique studies of faint radio sources to be made over a wide range of spatial scales. A major role for the EVN now and in the future relates to making initial or follow-up observations of transient sources, which are increasingly important areas of modern astronomy. In order to fully capitalise on its unique transient source capabilities, the EVN should develop new operational procedures that will permit it to respond to events triggered by other instruments. This may require more regular sessions, new advanced interfaces to react on triggers (with at least a flexible sub-array), and developments in the correlator and the EVN pipeline to aid searching for a broad parameter space for transient detection.

Anticipated technical upgrades to all aspects of the EVN's telescope and correlator facilities in the years ahead are expected to revolutionise the EVN's technical capabilities. New receiver developments will furnish low-noise systems that incorporate large instantaneous bandwidths and/or simultaneous multi-band capability. These new wide band receivers will improve continuum sensitivity by factors greater than 4 and also give broad band spectral and polarisation information for every continuum source. By facilitating simultaneous observations of multiple lines, similar increases in sensitivity can be realised for spectral line observations. Future EVN technical upgrades will support observing modes that allow joint observations with the SKA1-MID telescope. This will allow the phased-up SKA1-MID to be used as an element of EVN/global-VLBI giving an additional factor in sensitivity improvement larger than a factor of 2 to VLBI. In summary, the overall increase in sensitivity compared to today's VLBI is expected to be larger than a factor of 8. In the future, the EVN, either acting alone or in combination with SKA1-MID, will provide huge increases in performance relative to its present day capabilities. Such improvements will open a whole new set of scientific opportunities that can benefit from the exquisite spatial and spectral resolution of VLBI.

As the community prepares for the era of SKA science operations, the way in which the European radio astronomy facilities collaborate and organise themselves is likely to change. Already, there is significant discussion of these issues among the radio astronomy institutes in Europe. For the EVN a more centralised approach, in which JIVE plays an increasingly prominent role, is likely to emerge. In the future, close engagement with the SKA, its regional centres and other complementary telescopes, such as the International LOFAR Telescope (ILT), will be mandatory. Within the coming decade extending the application of SKA technologies to VLBI can also be expected. It is noteworthy

that the e-EVN is already an SKA pathfinder, and crucial SKA technologies (such as real-time data transport and correlation over 1000s of kilometres, as well as central distribution of highly accurate time and frequency signals) have already been developed by our community. Developments of ultra-wideband receivers going significantly beyond the present SKA1-MID specifications could be a future example where EVN develops crucial technology for an SKA upgrade.

Role of EVN/VLBI in the future astronomy landscape

Complementary to other radio astronomy facilities, VLBI provides (sub-)milliarcsecond angular resolution and $\sim$10 microarcseconds relative astrometric precision at cm wavelengths, and event-horizon scales in supermassive black holes (SMBHs) at the extreme and challenging mm and sub-mm wavelengths. The current role VLBI is playing in the astrophysical landscape has been assessed very favourably in the past, and over the past few years VLBI science has considerably broadened in the scientific topics covered. While parsec-scale imaging of the inner radio jets of Active Galactic Nuclei AGN as well as masers in early stages of star formation, are still important areas of research, a burst in the successful applications of VLBI within new emerging topics has recently taken place. The current level of image sensitivity, reaching μJy levels for VLBI arrays at 18 cm and 6 cm has allowed remarkable, novel science applications, which were unforeseen in previous VLBI science cases. Most noticeably, the EVN has responded very skillfully to a range of astrophysical transients, from the counterparts of gravitational waves, to the still elusive Fast Radio Bursts, Tidal Disruption Events, Gamma-ray bursts and supernova explosions. For all of these transients the combination of astrometric precision, angular resolution and imaging capability which only VLBI can deliver, provides unique and essential information for unlocking the astrophysics of these sources and using them as tools for cosmology. A niche application only possible by arranging an ad-hoc network is imaging the event-horizon scales in selected super-massive black holes, as provided by the Event Horizon Telescope project with the recent success of the first image of a black hole in Messier 87 at 1.3 mm wavelengths. Figure 1 clearly shows how the science distribution of VLBI papers has broadened from 1980-1999 to 2000-2019.

At the same time radio astronomy is starting to unveil the faint slowly varying Universe at milliarsecond resolution. The (sub-)μJy sensitivity of the EVN will throw a light on the formation of supermassive black holes at high redshift and cosmic star formation history of the Universe; in particular only VLBI can provide the angular resolution needed to discriminate between the activity of the nuclear and stellar components in distant galaxies during their most significant evolutionary stage. Much closer, in our home Galaxy, we have the chance to study in detail the life cycle of baryons through the formation and death of stars. VLBI offers unique tools to zoom in on the formation of stars through molecular masers that probe kinematics, physical (and chemical) states and even magnetic field strengths. VLBI astrometry provides a unique contribution to mapping the structure of our Galaxy by providing distances to stars behind interstellar and circumstellar dust. Pulsar proper motions and parallax distances can be refined, which, together with accurate pulsar timing will let us probe neutron star interiors, test fundamental physics, and detect the low-frequency gravitational wave background. Finally, absolute VLBI astrometry has been used to define the terrestrial and celestial reference frames, and it provides the only way to tie those to dynamical reference frames. By applying similar tools to spacecraft signals it is also possible to study the Solar System by measuring the gravitational fields of planets and moons with extreme accuracy.

The challenge for the future is how to optimise this unique role of VLBI in the context of a rapidly evolving set of global astronomical facilities as planned for the next few decades. Clearly, astronomy is set to go through another revolution, as leaps forward in sensitivity, survey speed, agility, frequency range and post-processing capabilities change how observations are made. Fundamental science questions will be addressed both by very detailed observations and extremely large surveys. Major impacts are expected from the ELT and other 30 m-class optical telescopes, the LSST, LIGO/Virgo, CTA, *Euclid*, the *JWST*, *Athena*, opening exciting new frontiers in our knowledge and understanding of the Universe and the fundamental laws governing it. Many of these observatories will provide massive datasets with sub-arcsecond angular resolution, available for statistical analysis.

Radio astronomy will be a vital part of the above revolution. With ALMA we now have an unprecedented view on the cold Universe, to be complemented by NOEMA soon in the Northern hemisphere. In the m- and cm-range the SKA is designed to survey and monitor the radio sky, providing more sensitive coverage than we have ever seen before. Additionally, dedicated arrays such as CHIME, and HERA are focusing on new phenomena. The current plans for the ngVLA are particularly relevant, as the integration of very long baseline capabilities in this unique project reinforces the role of very high angular resolution in the landscape of future radio astronomical facilities.

At present a number of facilities, such as LOFAR, uGMRT, APERTIF at the WSRT, VLA and MeerKAT are bridging the gap between the past and the future in terms of sensitivity, already challenging data transfer, storage, calibration and analysis methods. It is foreseen that VLBI in general, and the EVN in particular, will be a vital part of the above data revolution. Expected increases in correlator and data imaging capacity, possibly combined with Phased Array Feeds on the larger EVN telescopes, will make imaging over large fields of view a standard capability. This will for instance allow complementary very high spatial resolution centimetre-wave simultaneous imaging of large numbers of weak extragalactic sources. In this way the EVN/*e*-MERLIN can follow up sources first detected by radio survey instruments such as LOFAR and SKA with sub-arcsecond to millarcsecond resolution. Moreover, the EVN will also be flexible to follow up transient events detected either in large field of view radio surveys, or by instruments operating in other parts of the electromagnetic spectrum.

Key science goals for VLBI in the next decade

This document provides a comprehensive roadmap of science cases whose progress relies on VLBI, and represents the starting point for the technological and operational priorities of the European VLBI Network. Based on the scientific content of the document the following are the main questions, which VLBI can provide a unique contribution to during the coming decade.

WHAT IS THE NATURE OF DARK MATTER AND DARK ENERGY?

Dark matter and dark energy are the key ingredients to understand the evolution of our Universe. Primary goals of VLBI are to determine the nature of dark matter and its distribution, and probe the equation-of-state of dark energy in the Universe. The former will be achieved by high dynamic range VLBI imaging of gravitational lenses, which can reveal the distribution of dark matter halos in a range of mass scales around galaxies. The latter requires measuring the expansion history of the Universe at different epochs. There are a number of ways VLBI can determine H_0, the rate of expansion: by spatially resolving H_2O megamasers in nearby galaxies, by observing variability time delays between gravitationally lensed components of high-redshift quasars, and by high-resolution imaging of the electromagnetic counterparts to gravitational wave “standard sirens”, mergers of compact objects (neutron stars and black holes).

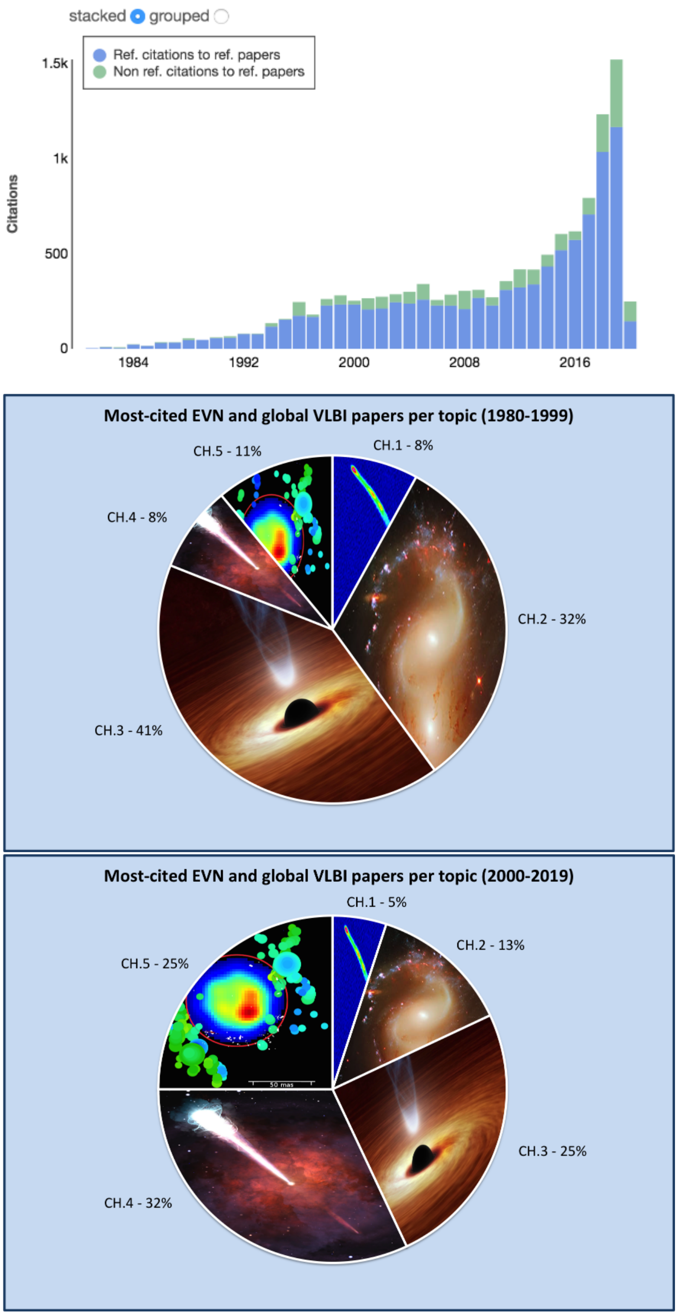

Figure 1: How the science done with the EVN and global VLBI has changed in the past 40 years. (upper panel) The citation history to papers with EVN data. (lower panel) The distribution of science topics addressed by the EVN before and after 2000. Cosmology (CH.1), Galaxies and AGN feedback (CH.2), Blazars and peculiar massive black hole systems (CH.3), Transient phenomena and stellar compact objects (CH.4), Stars/ISM (CH.5), Earth and Space applications (CH.6). Based on the top-100 most cited papers with EVN data, using NASA ADS. See also Chapter 7.

WHEN AND HOW DID THE FIRST BLACK HOLES FORM?

Our knowledge of the co-evolution of supermassive black holes and their host galaxies from the early Universe till today is still limited. At the same time this is a fundamental question for our understanding of the Universe. VLBI provides a very powerful tool to detect nuclear activity from massive black holes, especially in regions of space where emission from other parts of the electromagnetic spectrum is absorbed by dense nuclear dust and gas. This allows us to separate emission from AGN powered by black holes and radio emission from star-formation in the early Universe. It also lets us detect peculiar objects like the elusive intermediate-mass black holes (possible seeds of supermassive black hole formation), and small-separation binary AGN undetectable by other techniques, that are potential sources for low-frequency gravitational waves that will be studied by future space interferometers such as *LISA*.

HOW DO RELATIVISTIC JETS FORM? WHAT IS THEIR IMPACT ON THE HOST GALAXY?

The jet-launching mechanism by supermassive black holes as well as their exact physical conditions are still a mystery. This can be probed by very high resolution total intensity and polarisation VLBI imaging, as well as joint multi-messenger observations, including in particular those with neutrino observatories and high energy particle detectors. Measuring the jet polarisation over a range of angular scales and a very broad bandwidth is crucial to determine the strength and 3-D structure of magnetic fields, but also provides invaluable information on the surrounding ionised medium in which the jets propagate. VLBI also has a unique power to reveal the impact of AGN jets on their large-scale galactic environment (“AGN feedback”) by high angular and velocity resolution imaging of the 21 cm spin-flip spectral line of atomic hydrogen, known to be associated with AGN-driven massive outflows.

WHAT IS THE PHYSICS OF EXPLOSIONS FOLLOWING GRAVITATIONAL WAVE EVENTS?

The detection of gravitational waves has opened the door to what is now referred to as multi-messenger astrophysics. VLBI plays an invaluable role in the detection and classification of the radio counterparts of gravitational waves at medium and high redshifts. Particularly relevant are the determination of the morphology, velocity and orientation of any relativistic jets produced and of the accurate positions needed to locate these sources within their host galaxies.

WHAT ARE THE ELUSIVE FAST RADIO BURSTS?

The recent developments in time-domain radio astronomy have led to the discovery of fast radio bursts, whose nature, origin and environment are still unknown. Only VLBI can locate such transients to high astrometric accuracy within their parent galaxies, and has the potential to address their relation, if any, to other non-transient radio emitting sources in these galaxies. This is important to reveal their immediate environment, and eventually the nature of their progenitors.

ARE WE ALONE?

The detection of signatures of extraterrestrial intelligence is a key goal of all the new forthcoming radio facilities, which will provide an enormous increase of the observables parameter space. At that point it will be critical to “clean” the detected signal. VLBI will be crucial to SETI to separate detections from spurious signals, as it is much less sensitive to Radio Frequency Interference RFI than other radio detection methods and exploits consistent sky positions to filter signals. Follow-up of candidate positive signals can successfully be carried out with very sensitive VLBI arrays, which can uniquely locate the origin of any detection, including determining the originating stellar system and the parallax, orbit or other motion of the transmitter.

HOW WAS THE MILKY WAY BORN?
The accurate morphological classification of our Milky Way, the knowledge of the kinematics in its inner parts and the structure of the molecular clouds in its spiral arms are essential to understand and constrain the nature and history of the Milky Way. VLBI uniquely contributes to the above through astrometry of young and evolved stars in the spiral arms or inner regions of the Milky Way. Such observations are highly complementary to those from the *Gaia* satellite which in the galactic plane is limited to stars within a few kpc due to interstellar extinction.

HOW DO STARS FORM? HOW DO THEY IMPACT THE ENVIRONMENT AT THEIR DEATH?
As of today, after almost a century of stellar evolution studies, the processes giving birth to stars are still largely unknown. VLBI is essential to our knowledge and understanding of stellar evolution, particularly in the pre-main sequence and last evolutionary stages. The unique study of several species of masers allows us to disentangle the kinematics of the star-forming clouds. At the same time the monitoring of supernova explosions, which can be followed up for several years, can uniquely discriminate among different models of stellar evolution, and derive information on the environment in which the material ejected by the supernovae propagates.

Technological priorities for the next decade

The European VLBI Network, as a consortium of individual observatories plus JIVE - which contributes central correlator and central support functions - operates by dedicating observing time, consumables and expertise to the common goals of the network. The Memorandum of Understanding establishing the EVN consortium commits its members to maintain common inter-operable observing capabilities. The development of the array compliant with the scientific requirements implies the agreement on a common strategic technical roadmap. This document is the inventory of selected scientific areas of investigation, as suggested by the user community and constrained by the expected future technical capabilities, which should be taken into account in the development of the future technological roadmap for the EVN. Based on the science cases presented here, the EVN Consortium Board of Directors has prioritised the following changes and upgrades of the network:

- Develop broad-band EVN antenna/receiver systems that are compatible with SKA1-MID on the short term, and can be further upgraded to larger bandwidths and higher frequencies in the long term. This may include both C/X/U (SKA Band5a,b) and possibly the L- ($\sim$SKA Band 2) and UHF bands ($\sim$SKA Band 1).
- Increase the recording bit-rate to at least 32 Gbps to ensure the requested forward leap in sensitivity.
- Increase the number of telescopes operating at frequencies above 22 GHz.
- Consider the VLBI antennas distributed in the African Continent as an attractive option to enhance the European distributed radio astronomy facilities with more optimal frequency and *uv*-coordinates-coverage.
- Develop an EVN correlator platform that is capable of handling a large number of telescopes ($N > 30$), some of which supply multiple beams, and that has modes optimised for processing a) wide fields of view, b) short transients and c) high spectral resolution modes (for masers, SETI and Spacecraft applications).
- Develop a large field of view archive that provides advanced access to VLBI and other radio astronomy data products in support of the science goals of other instruments such as SKA and LOFAR in the radio and survey data at other wavebands, also complementing efforts at shorter wavelengths like the Global mm-VLBI Array and the Event Horizon Telescope (EHT).

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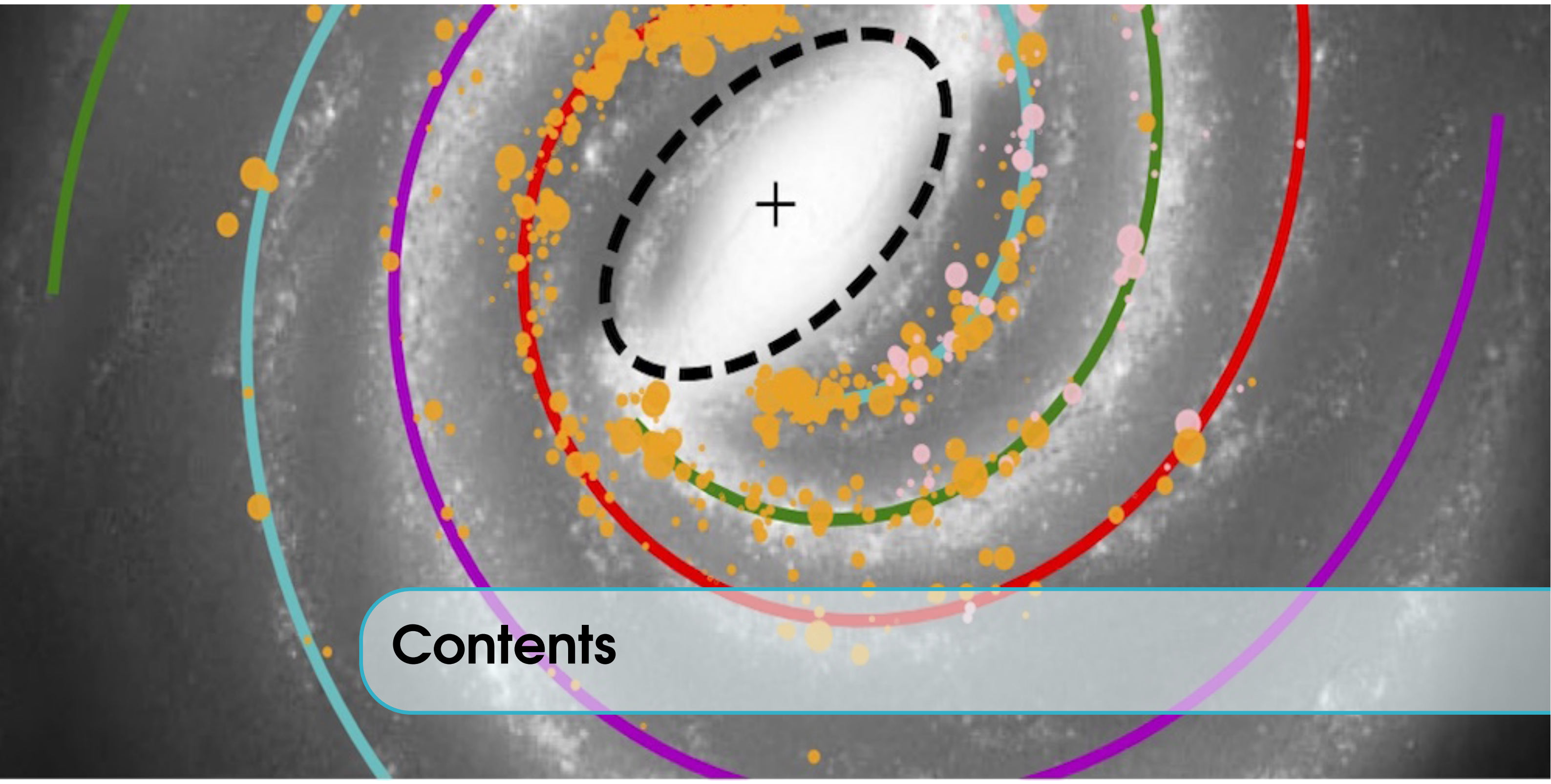

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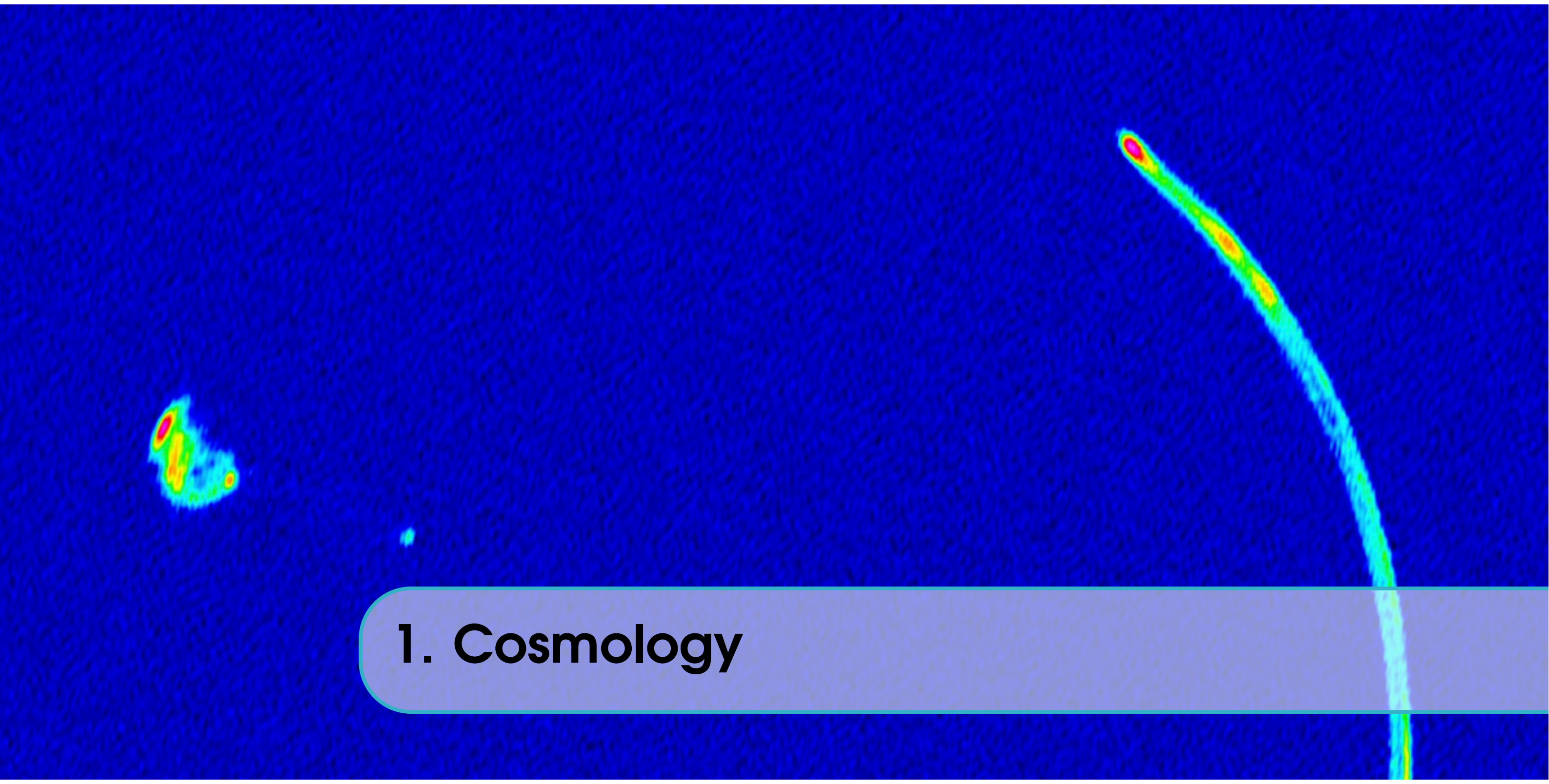
Image: Simulated distribution of High Mass Star Forming Regions in the Milky Way. The star forming regions that could be detected by the VLBA and SKA are represented with pink and orange dots, respectively. Credit: background image adapted from artistic impression of the Milky Way (R. Hurt: NASA/JPL/Caltech, J. Green: CSIRO, J. Urquhart: U. of Kent). Galactic simulations implemented by L.H. Quiroga-Nuñez (NRAO/UNM), H. van Langevelde (JIVE/Leiden) and M. Reid (CfA). Quiroga-Nuñez et al., 2017, *A&A* **604**, A72.



1. Cosmology

Understanding the origin and fate of our Universe has been a major theme within the fields of physics and astronomy for over a century, and although tremendous progress has been made through the discovery of the cosmic microwave background (CMB; Penzias & Wilson 1965) and the accelerating Universe (Riess et al. 1998), there are still controversies and inconsistencies that need to be resolved over the next decade. Typically, the structure of our Universe is defined via the cosmological model, which can be further parameterised into a set of fundamental constants that describe the matter, energy and curvature density of our Universe ($\Omega_{\rm M}$, Ω_{Λ} and $\Omega_{\rm k}$, respectively), the rate of expansion (H_0) and the dark energy equation-of-state (w). Through observations of the CMB power spectrum (only), most recently by the European Space Agency (ESA) *Planck* satellite (Planck Collaboration 2019), this model has become highly constrained, confirming the concordance of ΛCDM (cold dark matter) model for cosmology and galaxy formation. In this model, the Universe is close to flat ($\Omega_{\rm k} = -0.056^{+0.044}_{-0.050}$) and is dominated by the energy density of the Universe ($\Omega_{\Lambda} = 0.679 \pm 0.013$). In addition, the overall matter density ($\Omega_{\rm M} = 0.321 \pm 0.013$) is much higher than the overall baryon density ($\Omega_{\rm b} h^2 = 0.02212 \pm 0.00022$), leading to the need for an extensive dark matter component within our Universe.

Determining the nature of both dark matter and dark energy is now the focus of several on-going and future large-scale ground-based surveys at optical and infrared wavelengths (e.g. Dark Energy Survey, DES; KIlo-Degree Survey, KIDS; Large Synoptic Survey Telescope, LSST) and future space-based missions (e.g. ESA *Euclid* space mission). When the data from CMB power-spectra measurements are combined with the results from these galaxy surveys, which include information from weak gravitational lensing tomography (e.g. Massey et al. 2007), baryonic acoustic oscillations (e.g. Percival et al. 2010) and high redshift supernovae (e.g. Riess et al., 2004), degeneracies between the different parameters can be broken and the overall precision in the measurements is increased (e.g. Hildebrandt et al. 2017). For example, extracting information on the Hubble constant requires some knowledge about the baryon density of the Universe (Planck Collaboration 2019). These

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Chapter image credit: Global VLBI (EVN, VLBA and GBT) observations of the gravitationally lensed radio source MG J0751+2716 taken at 1.7 GHz (Fig. 1, Spingola et al. 2018).

next generation surveys are predicted to further tightly constrain the dark energy equation-of-state (e.g. see Fig. 1.1). However, even though such observations are predicted to have a high level of precision, it is likely that the measurements of the cosmological parameters will be dominated by systematics. For example, there is currently tension between the measurement of the Hubble constant made using the CMB and with other probes at the 2.9-σ level (e.g. see Fig. 1.1; see also Riess et al. 2018). Therefore, it is important to provide independent, but still competitive constraints to the cosmological model with as many different methods as possible.

Although most cosmological probes involve dedicated wide-field surveys covering a significant fraction of the sky, detailed studies of single objects (or samples of objects) with VLBI have been shown to provide competitive tests for cosmology. Here, the compact radio sources are either standard rulers or standard candles, which can be used to determine the cosmological model via the dependence on the luminosity or angular diameter distances. The best used methods involve imaging on mas-scales the emission from strong gravitational lenses with a variable background radio source (e.g. Wucknitz et al. 2004), the kinematics of water masers within the circum-nuclear accretion disk of a super massive black hole (e.g. Herrnstein et al. 1999) or, as has been shown recently, measuring the expansion velocity of radio-jets associated with gravitational wave events at cosmological distances (e.g. Mooley et al. 2018). A brief summary of these methods and the technical requirements for obtaining competitive constraints to the cosmological model with VLBI are presented in this chapter.

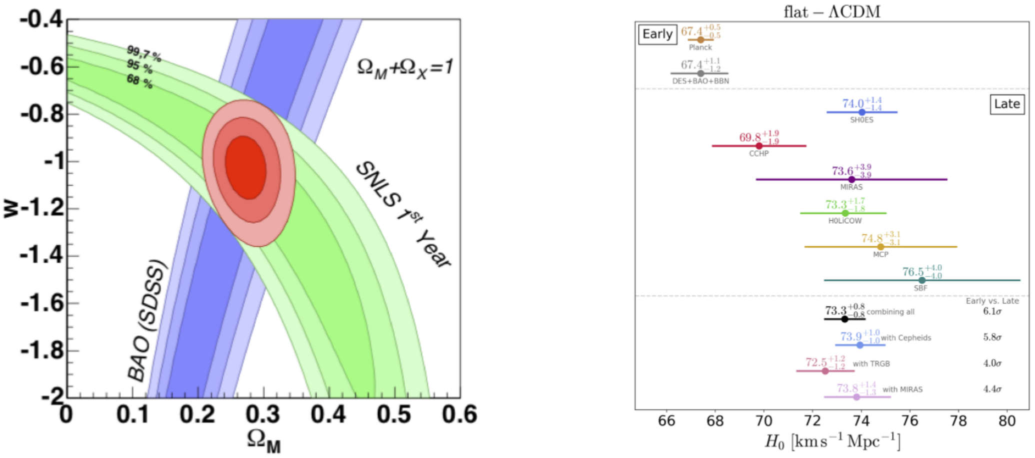

Figure 1.1: (left) The predictions for the dark energy equation-of-state (w) as a function of the matter density (Ω_M), when the results from the *Euclid* supernovae survey (SNLS) are combined with the results from BAO observations from SDSS. Taken from the *Euclid* Science Book (2010). (right) The various current measurements of the Hubble constant from different observational probes (Verde, Treu & Riess 2019).

In addition to constraining dark energy, understanding the nature of dark matter is also a key goal of the galaxy survey experiments described above. Here, the aim is to constrain the parameter space of the different candidate particles for dark matter, which is typically defined as a mass (or energy). In the hierarchical model of galaxy formation, the structure we observe today is predicted to form through the mergers of lower mass haloes, which are dominated by dark matter (e.g. Frenk & White 2012). However, whether dark matter is warm or cold can have a profound effect on the mass structure in our Universe on the smallest-scales, which is best represented by the halo mass function. Simply put, if dark matter is warm, then the formation of structure is suppressed, leading to less low mass haloes in the early Universe that can merge to form larger structures. Also, since warm dark matter haloes are less centrally concentrated, they are more easily destroyed during the merger process. These two effects result in an expected several orders of magnitude difference in the number of dark matter haloes for different models of dark matter on the lowest mass scales (Lovell et al. 2012; see Fig. 1.2). This small-scale crisis in the ΛCDM galaxy formation model has persisted for almost two decades (e.g. Moore et al. 1999). However, observations with VLBI provide a unique probe of galaxy formation on parsec-scales, due to the extremely high angular resolutions that can be achieved. This is typically done through studies of strong gravitational lenses, as the light deflections produced by a 10^6 $M_\odot$ dark matter halo is of the order of 1 to 5 mas, and is therefore, well matched to global VLBI experiments at GHz frequencies (e.g. McKean et al. 2015). This chapter also provides a brief outline to this method, and the requirements needed to test various models for dark matter over the next decade.

In this chapter, each section describes the various observational probes of cosmology that can be carried out with VLBI and also gives a review of what is predicted to be achievable with the advancements in the sensitivity, field of view and frequency coverage of the EVN over the next decade.

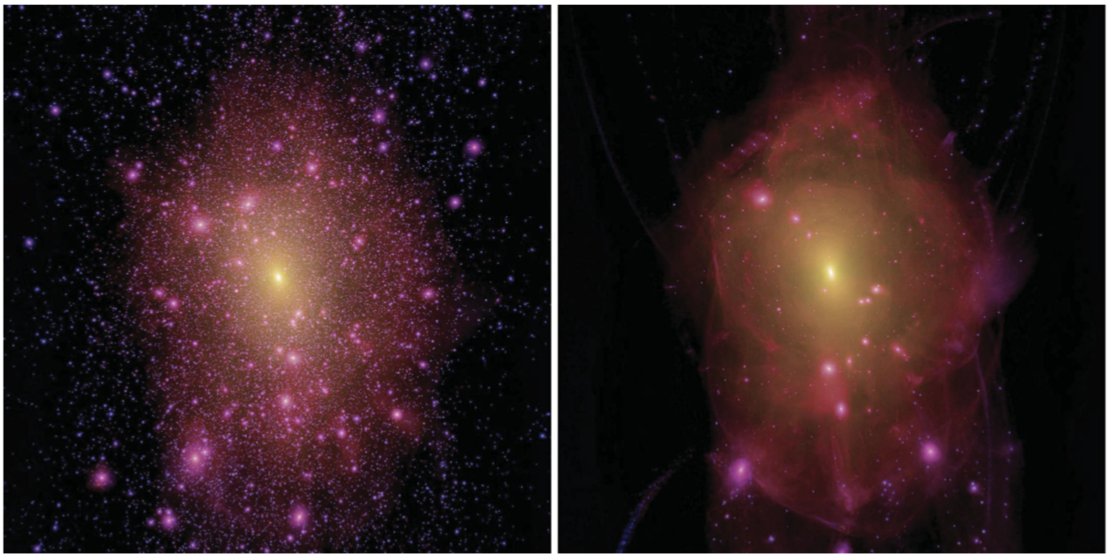

Figure 1.2: The dark matter (only) distribution for a Milky Way sized halo formed in a cold dark matter (CDM; left) and a warm dark matter (WDM; right) Universe (Fig. 3, Lovell et al. 2012).

1.1 Revealing the nature of dark matter

Strong gravitational lensing occurs when a distant background object and a foreground massive galaxy (with a sufficiently high surface-mass density) are suitably aligned, the result of which is the forming of multiple images of the background object. By measuring the distortions of the surface brightness distribution of the gravitationally lensed images, it is possible to place tight constraints on the lensing mass distribution, which can be used to test models for the global (baryonic and dark) matter distribution (e.g. Koopmans et al. 2009), the slope and normalisation of the halo mass function (e.g. Vegetti et al. 2012), and the slope of the stellar initial mass function (e.g. Spiniello et al. 2012). Each of these applications uniquely test the cold dark matter model for structure formation on (sub-)galactic scales. In addition, competitive tests of dark energy (w/ BAO, SN1a) can be made when the background object is variable and the (gravitational + geometrical) time-delay is measured between the different gravitationally lensed images (e.g. Bonvin et al. 2017).

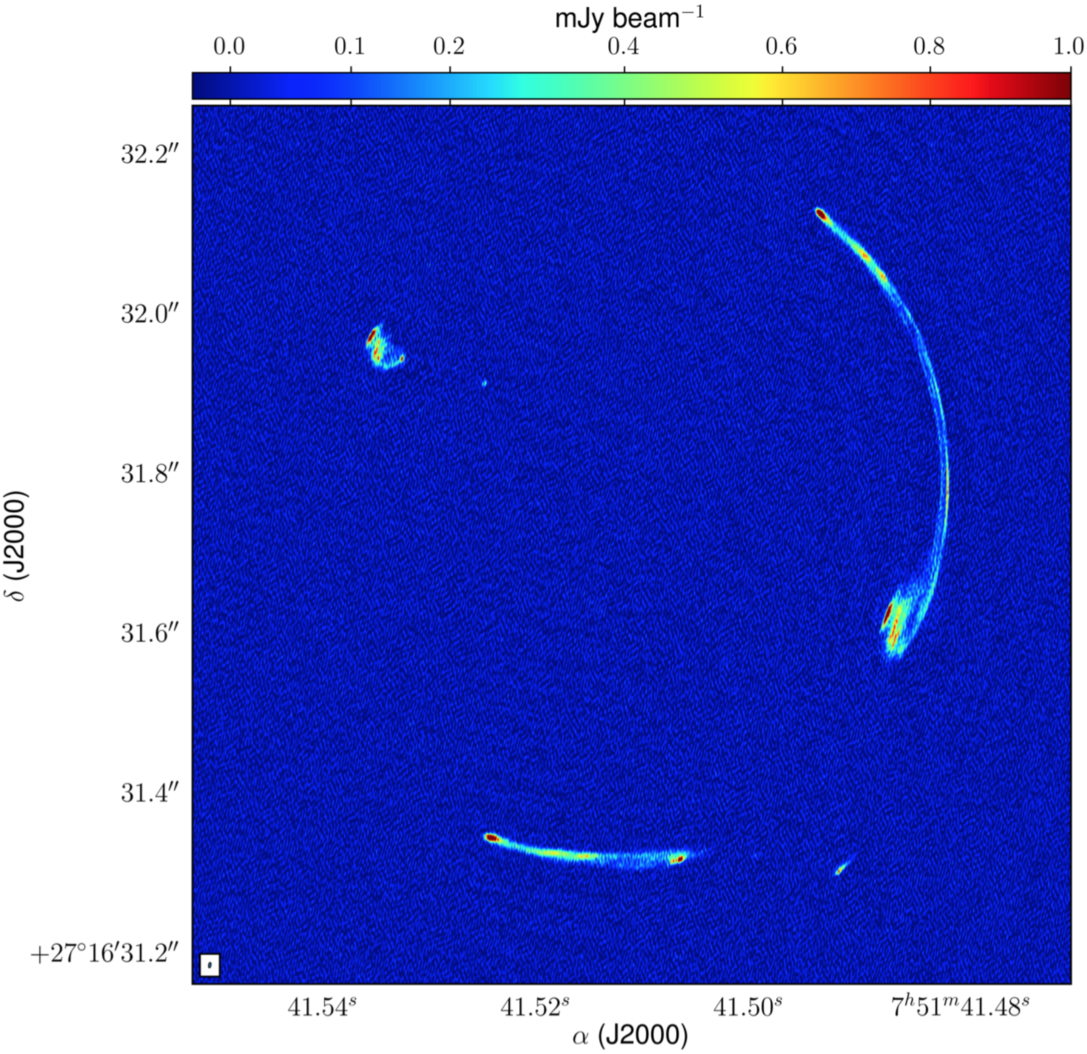

Figure 1.3: Global VLBI (EVN, VLBA and GBT) observations of the gravitationally lensed radio source MG J0751+2716 taken at 1.7 GHz (Fig. 1, Spingola et al. 2018).

Strong gravitational lensing provides a very accurate measurement of the mass within the Einstein radius of the lens, which for galaxy-scale systems is of the order of 0.15 to 2 arcsec, equivalent to a physical projected radius of around 1 to 12 kpc. As lensing is sensitive to the total mass within this radius, it can be used to investigate the contribution of dark and baryonic matter at the inner part of the lensing galaxies. The main astrophysical applications are to i) test hierarchical galaxy formation models by measuring the inner slope of the dark matter halo, ii) test models for dark matter by determining the slope of the dark matter halo mass function, and iii) test models of black hole–host galaxy growth through the detection (or non-detection) of central images. We discuss each of these applications in turn.

1.1.1 Probing the inner mass distribution of dark matter haloes

One of the principle applications of strong gravitational lensing is to test models for the mass distribution of galaxies, that is, determining the overall shape (ellipticity) and radial density profile ($\rho(r) \propto r^{\gamma}$, where r is the radius) of massive dark matter haloes. However, as the lensing mass distribution is only probed where the images are formed, only a few constraints (positions and flux-densities of the images) can be used to constrain the overall mass model when the data are at a low-angular resolution and the lensed images are compact. However, when the lensed images are extended in the form of large (tangential) gravitational arcs, or have structure in the radial direction, then the shape and the radial density profile of the lensing mass distribution can be precisely measured (e.g. in the cases of JVAS B0218+357; Wucknitz et al. 2004, HS 0810+2554; Hartley et al. 2019 and CLASS B1933+503; Suyu et al. 2012). A spectacular example of mas-scale observations tightly constraining the mass distribution of a lensing galaxy was demonstrated from 1.7 GHz global VLBI imaging of the extended radio source MG J0751+2716, where the gravitational lens produces large 200 to 600 mas arcs that are highly resolved in both the radial and tangential direction (see Fig. 1.3; Spingola et al. 2018). Here, the data quality is so high that the parameters of the global mass model can be recovered with sub-percent precision; in fact, the limiting factor in the mass modelling is our knowledge of the complex structure of galaxies on a few tens of parsec-scales (see below). In particular, these data required the gravitational lensing galaxy to have a radial mass-density profile with $\gamma = 2.08 \pm 0.02$, which is significantly steeper than for an isothermal mass distribution ($\gamma_{\rm iso} = 2$). This was taken as evidence for the two-phase galaxy formation model predicted from the hierarchical scheme for structure formation; these measurements, such as for MG J0751+2716 and the other lensed radio sources mentioned above, are only possible due to the unique mas-scale angular resolution provided by VLBI.

1.1.2 Probing low-mass structure in the Universe

In the case of MG J0751+2716, it was also shown that the positions of the lensed images could not be reproduced by a smooth mass distribution within the measurement errors ($\sim 40\ \mu$as), with rms residuals between the observed and predicted positions of around 3 mas; given the sensitivity and angular resolution of the VLBI imaging, this corresponded to a mis-match between the data and the model at up to the 700σ-level. Another example where the image positions cannot be well-fit by a globally smooth mass model is CLASS B0128+437 (Phillips et al. 2000; see Fig. 1.4), which has four images of a distant background radio source at redshift 3.124 (McKean et al. 2004). When observed at 50 mas angular resolution with MERLIN, the source is found to have four unresolved images, which can be well-fit with a simple elliptical mass model with an external shear component (to account for any complexity in the environment); note that this angular-resolution scale is what is also typically obtained with optical imaging with either the *HST* or with adaptive-optics corrections on 8 to 10-m class ground-based telescopes. However, when observed with VLBI at mas-scale angular resolution, the lensed images are resolved into multiple components, providing many more observational constraints, and now, the different image surface brightness distributions can no

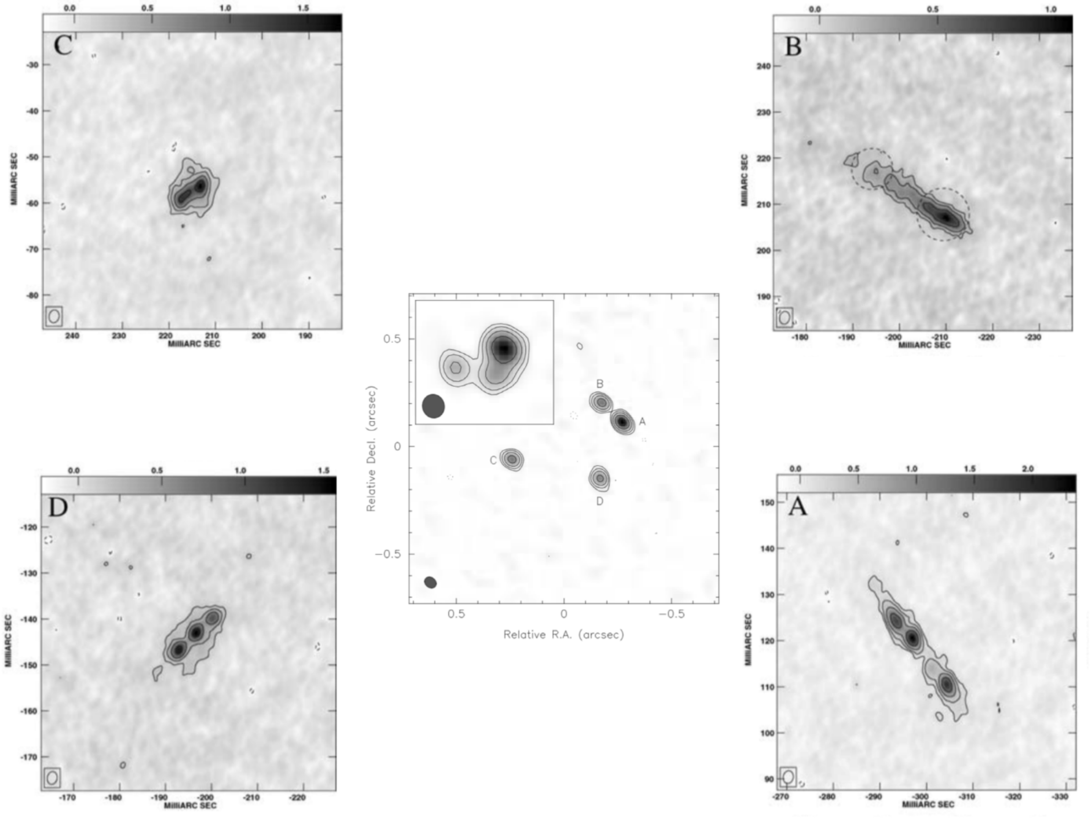

Figure 1.4: Example of the improved angular resolution and information obtained over VLA and MERLIN (centre and inset; Fig. 1, Phillips et al. 2000) when observations are made with VLBI (Fig. 4, Biggs et al. 2004), for the case of CLASS B0128+437.

longer be explained by a simple smooth mass density distribution (Biggs et al. 2004). The reasons for this mis-match between the data and the model are not clear, but could be due to baryonic structures like massive companion galaxies (e.g. in the case of MG B2016+112; More et al. 2009) or galactic-scale disks (e.g. in the cases of CLASS B1555+375 and CLASS B0712+472; Hsueh et al. 2016, 2017) associated with the main lensing galaxy. The high angular resolution provided by VLBI has allowed the lensing effect of these baryonic structures to be quantified and compared with hydrodynamical simulations of galaxy formation (e.g. Hsueh et al. 2018). Also, the multi-frequency capability of VLBI allows the frequency dependent structure of the lensed images to be measured on parsec-scales at different lines-of-sight through the lensing galaxy. This has typically been used to determine the (differential) electron density of large-scale baryonic components like galactic disks, through measurements of interstellar scattering (e.g. Biggs et al. 2003, 2004) and free-free absorption (e.g. Winn et al. 2003; Mittal et al. 2007), but can also be potentially measured through studies of differential Faraday rotation between the lensed images, as has been done at a lower angular resolution (e.g. Mao et al. 2017).

Understanding the contribution of these baryonic effects to the observed surface brightness distribution (flux-densities and positions) of the lensed images is important if the contribution from clumpy models for dark matter are also to be determined. As shown in Fig. 1.2, different dark matter models predict a varying abundance for low mass haloes both within the lensing galaxy, but also along the line-of-sight to the background object (e.g. Despali et al. 2018). By searching for differences in the structure of the multiple lensed images, deviations from a smooth dark matter model for the lensing potential can be observed. For example, observations at mas-scales with VLBI uniquely probe the deviations caused by a population of $\sim 10^6$ $\mathrm{M}_\odot$ haloes, where the discrepancy between warm and cold dark matter models is most significant (see Fig. 1.5 for an example of the sub-halo mass function), and potentially, different prescriptions for warm dark matter can be ruled-out. Again, this is a science application where the unique angular resolution provided by VLBI can be used to confirm that there is a mass perturbation in the lens model by detecting the localised change in the surface brightness distribution of the lensed images, and quantify it through modelling to determine the location and the mass of the perturbing halo (see Fig. 1.5 for a simulation of the perturbing effect a sub-halo, with a varying mass, has on the extended lensed jet-structure from an AGN observed with VLBI). This is also demonstrated in Fig. 1.4, where the relative magnifications of the lensed images, which equates to the relative flux-ratios when the images are unresolved, disagree from what is expected from a smooth mass model. However, when observed at high angular resolution with VLBI, the magnifications of the different images (their relative sizes) are directly measured, which allows the contribution from low-mass haloes to be directly measured. Of course, our ability to detect the perturbing effect of dark matter clumps depends on the signal-to-noise ratio of the data, and how extended the lensed images are. However, detections have been made using both compact lensed images (extended by 5 to 10 mas; e.g. JVAS B1422+231; Bradač et al. 2002) and large-scale lensed radio-jets (extended by 200 mas; e.g. MG J0414+0534; MacLeod et al. 2013). The current limiting factor in this astrophysical application of gravitational lensing is the relatively low number of objects that can be used in the analysis (see below for further discussion).

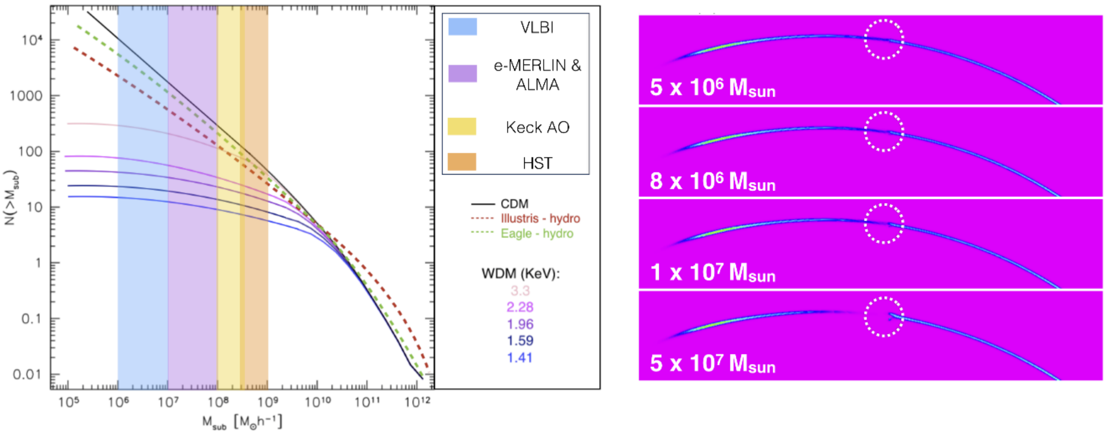

Figure 1.5: (left) The sub-halo cumulative mass function from numerical simulations with different dark matter models (CDM and variants of WDM), and for simulations that include the effect of baryons (e.g. Despali & Vegetti 2017). The coloured regions indicate the varying sub-halo detection sensitivities, given the different angular resolutions of the various instruments. (right) Noiseless simulation of different dark matter halo masses seen against a gravitational arc observed at mas angular resolution (courtesy of Gulia Despali; see also McKean et al. 2015).

1.1.3 Measuring the mass function of black holes throughout the Universe

In addition to the baryonic and dark matter structures discussed above, massive black holes that are either free-floating within a galaxy (e.g. Banik et al. 2019) or located at the centre of a galaxy (Mao et al. 2001) can also have a detectable gravitational lensing signature, which provides an additional unique test of cosmology and galaxy formation with VLBI. The former is expected to be extremely rare, given the abundance of free-floating black holes and the cross-section of the lensed images being quite small. However, detecting super massive black holes at the centres of quiescent lensing galaxies is expected to be possible through the measurement of central lensed images. This application uses the property that all non-singular mass density distributions should produce an odd number of images (3 or 5), as opposed to the even number (2 or 4) that are typically observed. The odd image is predicted to be located very close to the centre of the lensing potential, giving valuable information on the inner mass density slope (which probes dark matter; see above), but also on the presence of a super massive black hole. In this case, the central lensed image is further strongly gravitationally lensed by the super massive black hole, producing another set of lensed images that are separated by 5 to 100 mas, for black hole masses between 10^6 to 10^9 $M_\odot$, which is a resolution scale that is well-matched by VLBI at cm-wavelengths. To date, only one system has been found to produce a central lensed image (see Fig. 1.6, PMN) J1632−0033; Winn et al. 2004), which demonstrates that such detections can be made. However, given that the relative magnification between highest flux-density lensed image and the central lensed image is predicted to be around 10^{-3}, the dynamic range of current facilities has made detecting such central lensed images challenging in other systems (e.g. Zhang et al. 2017; Quinn et al. 2016). In addition, multi-frequency data are required to discriminated between a low-luminosity AGN within the lensing galaxy and a genuine central lensed image (see Fig. 1.6).

1.1.4 Requirements for probing dark matter with VLBI

To realise the scientific potential of investigating dark matter with gravitational lensing will require increasing the number of lensed objects detected on VLBI-scales from around ~ 35 by several orders of magnitude. This is needed to improve on the statistics from studies of individual samples, but also so that rare, special systems can be found for specific science cases. Given the very large sky areas that have already been surveyed for lensed compact objects by the Cosmic Lens All-Sky Survey (CLASS; e.g., Browne et al. 2003; Myers et al. 2003) and the Parkes-MIT-NRAO (PMN; e.g., Winn et al. 2000), this will require more sensitive VLBI arrays in the future. The general requirements for such surveys and follow-up are now discussed.

- **Wide-area surveys with VLBI:** Given the shallow (differential) number counts of compact radio sources (e.g. $n(s) \propto S^{-2}$; McKean et al. 2007), surveys for gravitational lenses are always most efficient when the searches are undertaken over a larger area, as opposed to a greater depth. For this reason, having a wide-field VLBI facility can potentially provide a one-stop survey for lensed objects. This is because the VLBI observations can directly resolve the candidate lensed images, allowing their surface brightness and morphologies to be tested against lens models, as was recently demonstrated by Spingola et al. (2019a), who found two gravitationally lensed radio sources in the mJIVE–20 wide-field VLBI survey. The approximate sky density of faint radio sources at L-band (1–2 GHz; $S_{1.4} > 15$ μJy) is around ~ 750 deg^{-2}. Such objects would be easily detectable within the field of view of the SKA-MID array (phase 1) in a few minutes of integration (e.g., McKean et al. 2015). However,

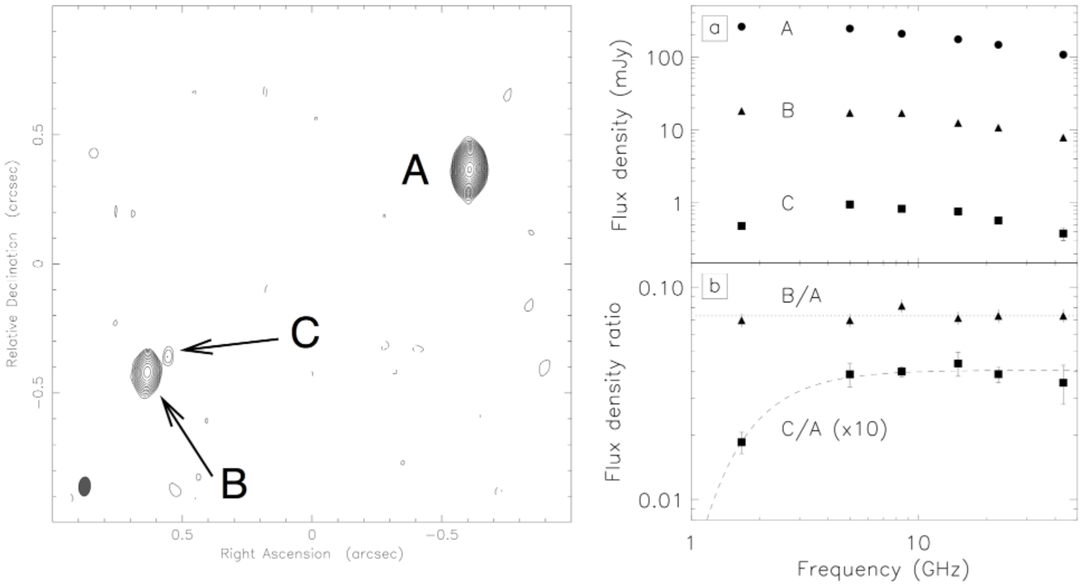

Figure 1.6: (left) A MERLIN 5 GHz image of the gravitationally lensed radio source PMN) J1632−0033, which shows two lensed images (A and B), and an elusive central lensed image (C), which is both highly demagnified relative to the other images and located close to the lensing galaxy position. (right) The radio spectral energy distribution of the three lensed images, showing that at low radio frequencies, image C also shows free-free absorption due to passing through the centre of the lensing galaxy (Winn et al. 2004).

for such objects to be also imaged on VLBI-scales would require the ability to process around $\sim 10^3$ phase centres from each observation. This example is for a low-frequency survey, however, observations at higher frequencies are also advantageous as they can potentially provide a larger instantaneous bandwidth, which is useful for identifying lensed objects through comparing their spectral energy distributions and polarisation as a function of frequency, but also for achieving various science goals (see above). However, observations at higher frequencies (or at lower frequencies with the large antennas of the EVN) are less efficient for surveys given the order of magnitude decrease in the primary beam field of view. This could be mitigated by rolling out phased array feeds on the EVN antennas, which can increase the effective field of view and also provide a more uniform response as a function of position on the sky.

- **Improved sensitivity (thermal noise and dynamic range):** Although wide-area surveys are needed, an improved sensitivity is also required for such surveys to be efficient. This is because even though there will be a large parent population of sources to be surveyed, sufficiently deep observations are also needed to resolve the different lensed images, which can have flux-ratios of the order of unity to around 40. Also, once cases of multiple imaging have been identified, further long-track observations will be needed to increase the sensitivity to extended structure by improving the *uv*-coverage and the surface brightness sensitivity. For example, to image a lensed object similar to that shown in Fig. 1.3, but with a total flux-density at the few mJy-level would require a thermal noise limited dataset with an rms of 0.5 μJy beam^{-1}. This would require the current set of EVN telescopes to operate with a contiguous bandwidth of around 4 GHz between 1 to 5 GHz, which requires a recording-rate of 32 Gbit s^{-1} (assuming 2 bit-sampling, although increasing this to help mitigate radio frequency interference would also be needed). Such a large bandwidth would also be important for polarisation studies, such as plasma lensing effects, but would improve the overall dynamic range as the *uv*-coverage is better sampled through multi-frequency synthesis.

1.2 Measuring the expansion-rate of the Universe over cosmic time

There are several unique measurements of cosmic expansion that can be carried out with VLBI observations. These are mainly related to measuring the Hubble constant, H_0, but through measuring the change in the rate of expansion, it is also possible to constrain the dark energy equation-of-state, w. There are three main observational channels to measure H_0 with VLBI; these are gravitational lenses, water megamasers and from measuring the jet properties of gravitational wave events.

1.2.1 Probing dark energy with gravitational lenses

Even before the first discovery of gravitational lensing by Walsh et al. (1979), it was already suggested that if the background source is variable, then there would be a time-delay in the fluctuations observed between the different lensed images (Refsdal 1964). This time-delay is related to general relativistic effects as the light rays pass through different parts of the lensing potential, which requires some knowledge of the gravitational lensing mass model, but is also due to the different path lengths that the light from the different images take towards the observer. The latter is dependent on the Hubble constant, and as such, allows a one-step determination of the cosmological model. Although the first precise time-delays were measured at radio-wavelengths (e.g. Biggs et al., 1999; Fassnacht et al. 2002), high cadence monitoring at optical wavelengths with a dedicated network of small to medium sized telescopes now provides accurate light-curves for a large sample of lensed quasars, allowing the effects of micro-lensing (by stars within the lensing galaxy) and the intrinsic variability of the distant quasar to be disentangled (e.g. Bonvin et al. 2018). This, coupled with sophisticated lens modelling techniques, has provided tests of dark energy that are competitive with those from BAO and SN1a observations (see Fig. 1.1). The SKA is predicted to detect 10^5 gravitationally lensed radio sources, from which around 1–2% are expected to be variable, providing a sample of $\sim 10^3$ gravitationally lensed radio sources that can be monitored for variability in both total intensity and polarisation. Although VLBI will be required to also provide the precise lens models to determine the gravitational time-delay (see above), there is also the exciting possibility that through regular monitoring at high angular resolution, variability of individual jet components or proper motion of the lensed radio jets can be measured, which would provide a new avenue for determining time-delays (e.g. Spingola et al. 2019b). This would require a dedicated VLBI facility to monitor gravitationally lensed radio sources at a high cadence of a few hours for up to several weeks.

1.2.2 Probing cosmology and black holes with water vapour emission at high redshift

The luminous emission (> 10 L$_\odot$) from the 6_{16}–5_{23} water maser line (rest-frequency 22.23508 GHz) is exclusively associated with AGN activity, where the large particle densities (10^7 to 10^{11} cm^{-3}) and temperatures (> 300 K) of the molecular gas allow for collisional-excitation to occur (e.g. see Lo 2005 for a review). Also, the strong continuum emission from the powerful AGN jets provide the seed photons needed to stimulate the megamaser emission. Typically, the water megamasers are coincident with the extended radio jets ($<$ 30-pc from the black hole) or the circumnuclear accretion disk ($<$ 1-pc from the black hole), and given the small angular-scales involved, VLBI observations have been vital for mapping the water megamaser regions within nearby AGN (e.g. Miyoshi et al. 1995). In the case of water megamasers related to the radio-jets, it is thought that the conditions for masing are driven by a radiative-shock as the bulk motion of the jet passes through the interstellar medium (ISM) (e.g. Peck et al. 2003). However, water megamasers that are associated with accretion disks are significantly more common (mainly due to observational biases), and these are primarily used to probe cosmology (e.g. Herrnstein et al. 1999), although they also constrain the shape of the accretion disk and provide an accurate measurement of the mass of the central super massive black hole (e.g. Miyoshi et al. 1995). This is done by monitoring the water megamaser lines as a function of time with a large single dish radio telescope to determine the change in velocity as the maser lines orbit the central super massive black hole, from which the centripetal acceleration can be determined. Then, by mapping the positions of the red- and blue-shifted water megamaser regions at the extremity of the disk with VLBI and fitting a (thin) disk model to the resulting position–velocity diagram, the size and structure of the disk can be determined. By comparing the angular- and physical-size of the disk, the water megamaser system becomes a standard ruler, from which the Hubble constant can be derived to a precision of about 10% for an individual system (e.g. Braatz et al. 2010). Thus far, the largest survey for water megamasers has been carried out by the Megamaser Cosmology Project (MCP; Reid et al. 2009) with the VLBA, who have reported measurements of H_0 from four galaxies in the Hubble flow (out to 150 Mpc) that have a weighted mean value of 69.3 ± 4.2 km s^{-1} (Braatz et al. 2018), which is in good agreement with the value obtained from the CMB (see Fig. 1.1). The final precision is expected to be around 4% when the MCP is completed. However, in order to provide a robust and competitive test of the cosmological model to the 1% level, an improved sensitivity of current VLBI facilities at 22 GHz is required. This increase in sensitivity is also needed to test for systematics associated with un-modelled peculiar motions of the central super massive black hole, and uncertainties in the systemic velocity of the galaxies (e.g. Pesce et al. 2018).

As H_0 has thus far been measured using only water megamaser galaxies in the local Universe, this methodology provides only a weak constraint on the dark energy equation-of-state w (see Fig. 1.8). To date, there are only two confirmed detections of AGN hosting water megamasers at cosmological distances; from a type 2 quasar at redshift 0.66 (Barvainis & Antonucci 2005) and from a gravitationally lensed quasar at redshift 2.64 (Impellizzeri et al. 2008). Both of these water megamaser systems are extremely powerful, with intrinsic isotropic luminosities $> 10^4$ $L_\odot$, although whether they are associated with the AGN accretion disk or jets has yet to be determined. However, these detections demonstrate that powerful water megamaser systems can be found at high redshift. By assuming that the slope of the local water megamaser luminosity function does not change with redshift and by using the observed isotropic luminosity of the two detected systems as a normalisation of the luminosity function, McKean et al. (2011) estimated that there are potentially 7 600 water megamaser galaxies per steradian between redshift 1.2 and 4.5 that are detectable with the SKA (Phase-2); an increase of four orders of magnitude over the current sample of known water megamaser systems at high redshift. Such systems can potentially be used to constrain cosmology if they are associated with an accretion disk, and if the high-velocity features can be imaged with VLBI. They would also provide a unique measurement of the black hole mass function within massive galaxies at cosmological distances.

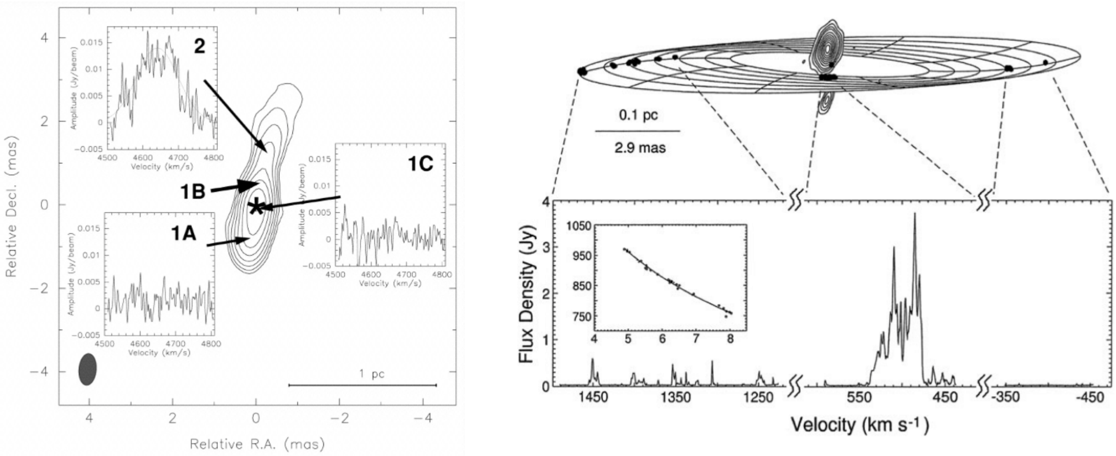

Figure 1.7: (left) Example of the water megamasers associated with the radio jets of Markarian 348, which are thought to be due to radiative-shocks from the jets passing through the ISM of the galaxy (Peck et al. 2003) ©AAS. Reproduced with permission. (right) Example of the water megamasers associated with the accretion disk of NGC 4258, where the systemic lines provide the centripetal accelerations, while the high velocity lines probe the size and structure of the accretion disk (Herrnstein et al. 1999).

1.2.3 Gravitational wave events

Recently, a new avenue for determining the Hubble constant has emerged from gravitational wave events, which can be used as cosmic sirens to provide an independent test of cosmology. This is done though modelling the gravitational wave data from neutron star–black hole mergers, under the assumption of general relativity, which provides a number of source parameters, including the luminosity distance and the merger orbital inclination (e.g. Schutz 1986). By combining this measurement with the electro-magnetic data (to localise the galaxy, obtain its recessional velocity and determine its proper motion), the Hubble constant can be derived, for example, in the case of GW 170817, where the Hubble constant was found to be $H_0 = 74.0^{+16.0}_{-8.0}$ km s^{-1} Mpc^{-1} from the Virgo/LIGO dataset (Abbott et al. 2017). However, high resolution imaging of the radio emission from GW 170817 with VLBI also revealed evidence for a narrow, relativistic jet from the source (Mooley et al. 2018). Further observations with VLBI determined the apparent velocity of the jet, which constrained the jet-opening angle from this source. By combining this with the model for the gravitational-wave data, which predicts the distance and the observing angle to the source, and the after-glow light-curve, the parameter space is further limited, and a value of $H_0 = 68.9^{+4.7}_{-4.6}$ km s^{-1} Mpc^{-1} was obtained (see Fig. 1.9; Hotokezaka et al. 2019). By adding the data from the VLBI observations to the gravitational wave observations, the degeneracy between the distance and the observing angle in both methods can be broken. Currently, the precision of the measurement is at the 7% level, but it is estimated that with around $\sim$ 15 neutron star–black hole merger events, with similar narrow-jets and small inclination angles to that of GW 170817, where the gravitational wave signal can be measured and the radio emission is resolved, then the overall precision will be reduced to around $\sim$ 1%. As the sensitivity of the gravitational wave detectors increases, and more detectors join the global array, the number of gravitational wave events is expected to increase significantly over the next decade. Having the required sensitivity and resolution

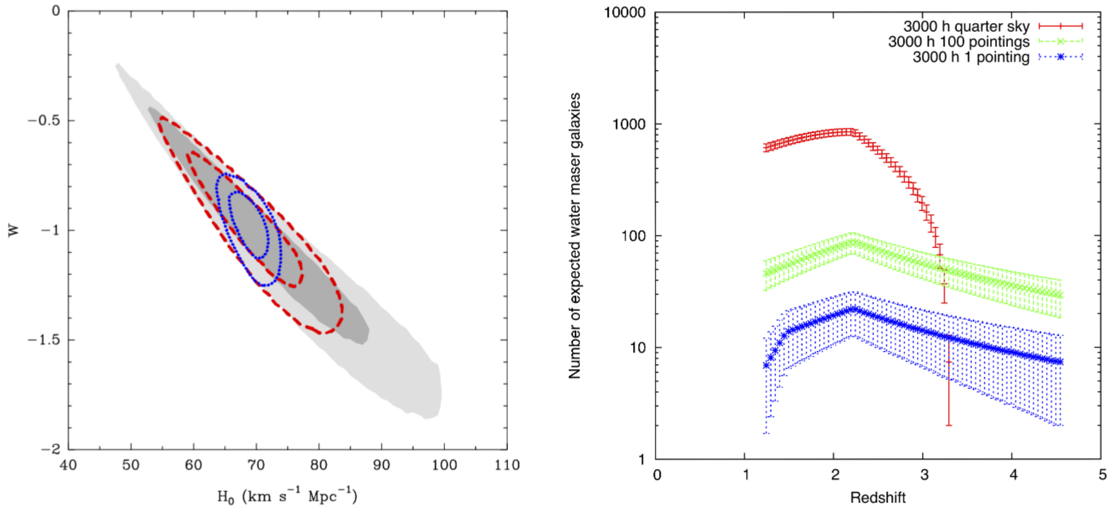

Figure 1.8: (left) The constraints on w and H_0 from WMAP (grey region), and the combined constraints from WMAP and the MCP for one galaxy (red), and those expected when combined with MCP data for ten galaxies (blue) (Reid et al. 2013). ©AAS. Reproduced with permission. (right) Estimated number of water megamaser galaxies that are detectable with the SKA (Phase-2) in 3000 h of integration, for a wide-field, medium deep and deep pointings (Fig. 4, McKean et al. 2011).

from VLBI arrays will also have to be maintained during this period. This science case highlights an important synergy between high quality VLBI imaging and the emerging field of gravitational wave astronomy.

1.2.4 Cosmological tests with precision astrometry

Stochastic gravitational waves deflect light rays in a quadrupolar pattern. The gravitational waves that will produce extragalactic proper motions lie in the frequency range 10^{-18} Hz $< f < 10^{-8}$ Hz, which overlaps the CMB polarisation and the pulsar timing techniques, but uniquely covers about seven orders of magnitude of frequency space between the two methods (e.g. Gwinn et al. 1997). Measuring or constraining the proper motion quadrupole power can therefore detect or place limits on primordial gravitational waves in a unique portion of the gravitational wave spectrum. Measurement of precise proper motions of super massive black holes residing within AGN enables tests of another cosmological parameter: the observed over-density of galaxies on the scale of 150 Mpc in co-moving coordinates from BAO. At redshift 0.5, the proper motions associated with BAO are of order 1 μas yr^{-1} (Darling et al. 2018a). Anisotropic expansion of the Universe will cause a pattern with proper motions of $\Delta H/H_0$ 15 μas yr^{-1} (Darling et al. 2018b). A detection of a signal at the level of 1 μas yr^{-1} with that pattern will correspond to variations in the expansion rate at a level of 7%.

The temperature dipole of the CMB radiation that is caused by the motion of our Solar system barycentre with respect to the CMB rest coordinate (e.g. Hinshaw et al. 2009) is 370 km s^{-1}, which induces a maximum secular parallax of 78 μas yr^{-1} Mpc^{-1}. Proper motions measured with an accuracy of 1 μas yr^{-1} will allow the detection of a secular parallax within 78 Mpc. To date, there are 88 RFC[1] objects within that distance. Although peculiar velocities of individual objects will cause a

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[1] `http://astrogeo.org/rfc/`

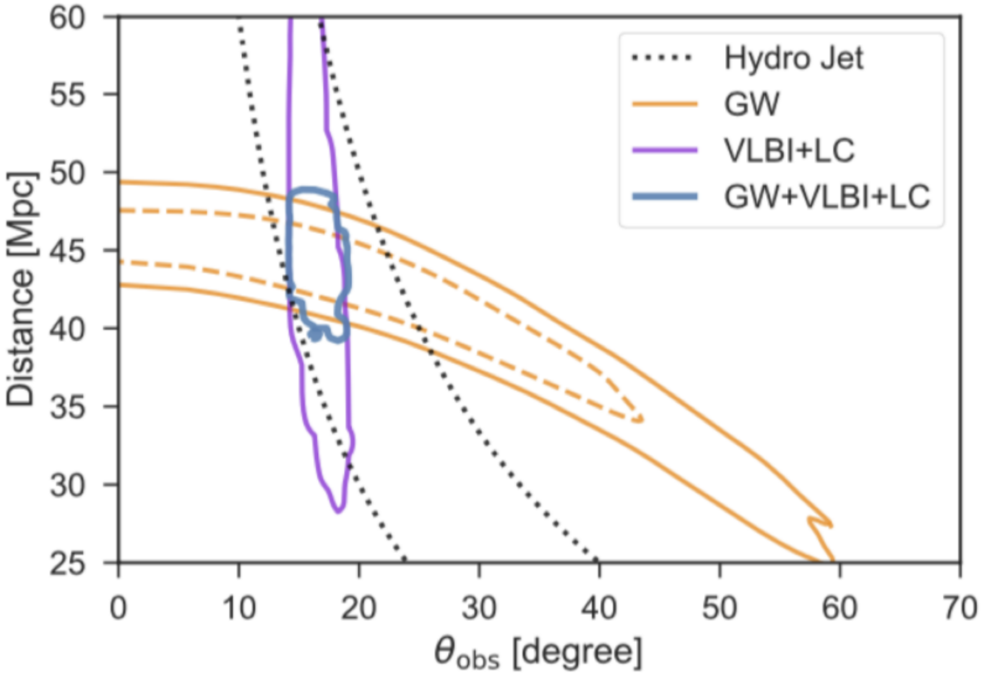

Figure 1.9: The parameter space of the distance and the observing angle for GW 170817 from the gravitational wave data (GW), and from the VLBI and the light-curve data (VLBI-LC). Also shown is the constraint when a hydro-jet model is used. The joint GW+VLBI+LC constraints break the degeneracies in both methods, tightly constraining the distance to GW 170818 (Hotokezaka et al. 2019).

bias and variance in the measurement of the secular parallax, the signal has a distinctive correlation structure with quadrupolar, octupolar, and higher-order angular structure due to correlations in the peculiar velocity field. Hall (2019) explores the measurability of the secular parallax in detail.

In order to make these cosmology tests with precision astrometry, it is crucial to provide a long time series of VLBI astrometric observations, obtain high fidelity images, and trace variability of the core-shift.

1.2.5 Requirements for probing dark energy with VLBI

Similar to the discussion for studies of dark matter above, our ability to test models for dark energy is currently limited by the number of suitable gravitationally lensed sources that can be used for this science case. However, as with the other tests described in this section, an improved imaging sensitivity and dynamic range, and monitoring cadence is needed in the future. We discuss these points here.

- **Imaging cadence:** Observing radio sources at high angular resolution over short and long time-scales is needed for measuring variability in the source surface brightness distribution. In the case of gravitational lensing, this may constrain either the lensing time-delay or the mass distribution on very small spatial-scales, testing models for both dark energy and dark matter. Here, the jet-emission would be strongest a low radio frequencies. As the time-delays in the