# VLBI studies of DAGN and SMBHB hosting galaxies

T. An<sup>\*1</sup>, P. Mohan<sup>\*2</sup>, S. Frey<sup> $\dagger$ 3</sup>

\*: Shanghai Astronomical Observatory, 80 Nandan Road, Xuhui District, Shanghai 200030, China.

<sup>†</sup>: Konkoly Observatory, MTA Research Centre for Astronomy and Earth Sciences, Konkoly Thege Miklós út 15-17, H-1121 Budapest, Hungary.

### ABSTRACT

Dual active galactic nuclei (DAGN) and supermassive black hole binaries (SMBHBs) at kpc and pc-scale separations, respectively, are expected during stages of galaxy merger and evolution. Their observational identification can address a range of areas of current astrophysics frontiers including the final parsec problem and their contribution towards the emission of low-frequency gravitational waves. This has however been difficult to achieve with current spectroscopy and time domain strategies. Very long baseline interferometry (VLBI) as a method of directly imaging radio structures with milli-arcsecond (mas) and sub-mas resolutions is introduced as a possible means of detecting DAGN and SMBHBs. We motivate its usage with expected observational signatures and cite some studies from literature to illustrate its current status, and present an updated list of candidates imaged with high-resolution radio observations. We then recall some shortcomings of the method with possible solutions and discuss future directions, relevant to large surveys with the upcoming Square Kilometer Array and future space VLBI missions.

## Key points

- Dual active galactic nuclei (DAGN) and supermassive black hole binaries (SMBHBs): observational status.
- Very long baseline interferometry (VLBI): a promising tool to detect dual AGN and SMBHBs.
- Observation strategies for the future.

 $<sup>^1</sup>$ antao@shao.ac.cn

 $<sup>^2</sup>pmohan@shao.ac.cn$ 

<sup>&</sup>lt;sup>3</sup>frey.sandor@csfk.mta.hu

#### 1. Introduction and motivations

Hierarchical models of cosmological structure formation (e.g. Springel et al. 2005) expect major mergers shaping galaxy evolution. Binary evolution up to kpc scales are governed by dynamical friction (Chandrasekhar 1943) which here involves a decreasing binary separation through the extraction of their effective angular momentum and energy through stellar encounters (e.g. Milosavljević & Merritt 2001; Merritt & Milosavljević 2005) over < 10 Myr timescales, which can be sped up by gravitational encounters with intervening gas (e.g. Mayer et al. 2007; Dotti et al. 2007; Tang et al. 2017); the kpc-separated central objects appear as a dual AGN (DAGN) (e.g. Milosavljević & Merritt 2003; Merritt & Milosavljević 2005), possibly owing to rapid accretion. A continued merger aided by stellar gravitational interactions leads to a pc-scale separation Keplerian bound supermassive black hole binary (SMBHB) (e.g. Begelman et al. 1980). The SMBHB is expected to be strongly gravitationally bound when its specific binding energy exceeds the nuclear stellar velocity dispersion based energy with a fiducial separation of  $\sim 2.7$  pc marking this transition assuming a SMBH mass (smaller mass binary companion) of  $10^8 M_{\odot}$  and a stellar bulge velocity dispersion of  $200 \text{ km s}^{-1}$  (Merritt & Milosavljević 2005). The central core is now depleted of stars and gas rendering dynamic friction ineffective in enabling further merger, the 'final parsec problem' (e.g. Begelman et al. 1980). This could be overcome through three-body interactions involving a companion massive black hole (e.g. Bonetti et al. 2016), if the initial extraction of angular momentum and energy proceeds through episodes of stellar and gas interactions (e.g. Goicovic et al. 2017), or if the stellar loss cone can be re-populated efficiently thus enabling a continuity in stellar encounters (e.g. Gualandris et al. 2017). These cause the bound SMBHB to enter the gravitational wave regime and tend towards coalescence rapidly. Alternatively, simulations of mergers in triaxial rotating galaxies indicate that the binary hardening rates are sufficient to enable efficient coalescence, avoiding stalling of the merger at pc-scales (Berczik et al. 2006).

Observational identification of DAGN and SMBHBs, however, has mostly been indirect and serendipitous so far, mainly owing to the small separation and associated physical processes involved in both being distinct, thus requiring different search strategies in these classes of objects. Employed strategies have mainly involved spectroscopy and timing based on the double-peaked line profiles and continuum light curves from candidate sources. A range of multi-wavelength searches have been met with varying levels of success (e.g. Komossa et al. 2003; Komossa 2006; Koss et al. 2012; Comerford et al. 2013). Double peaked spectral emission lines (e.g. H $\beta$ , [O III]) separated in radial velocity by ~ few hundred – thousand km s<sup>-1</sup> are expected in a merging system hosting narrow- and broad-line regions (at larger and smaller physical distances from the central engine, respectively) (e.g. Gerke et al. 2007; Xu & Komossa 2009). Double peaked narrow lines are expected to indicate a DAGN while broader peaked lines could indicate a SMBHB. Though, these lines could originate from the superposition of unrelated overlapping AGN, peculiar geometry of the narrow line region (NLR) and kinematics within a single cloud (e.g. clumpy structure), powerful biconical outflows, jet-NLR interaction (e.g. Xu & Komossa 2009; Comerford et al. 2012) or as equal strength peaks from a rotating disk or ring ionized by a single underlying source (e.g. Smith et al. 2012). In fact, only a tiny fraction of AGN showing double-peaked emission line profiles have been identified as DAGN (e.g. Shen et al. 2011; Fu et al. 2012; Müller-Sánchez et al. 2015). Updated lists of inferred DAGN compiled from the literature are presented in Rubinur et al. (2018) and Das et al. (2018). The continuum or line-based optical light curves may indicate quasi-periodicity over timescales of a few to tens of years, possibly related to the orbital period of a Keplerian SMBHB (e.g. Graham et al. 2015; Charisi et al. 2016; Mohan et al. 2016). The well studied AGN OJ 287 putatively hosts a SMBHB, inferred through a pair of periodic optical outbursts every  $\sim 12$  yr (e.g. Sillanpaa et al. 1988; Valtonen et al. 2011) resulting from the impinging of the accretion disk of the primary by the secondary SMBH at these intervals during its orbital motion (e.g. Lehto & Valtonen 1996). However, the recent study of Britzen et al. (2018) notes that jet precession can explain the periodic variability though the driver of precession may still be a SMBBH.

As spectroscopic and timing searches are indirect, they require ruling out competing models and need independent confirmation. High resolution X-ray imaging spectroscopy observations with Chandra have resulted in the discovery of DAGNs (e.g. NGC 6240: Komossa et al. 2003), (Mrk 463: Bianchi et al. 2008), (Mrk 739: Koss et al. 2011), (Mrk 266: Mazzarella et al. 2012), and others from studies of candidate samples (e.g. Koss et al. 2012; Comerford et al. 2013). Similar targeted X-ray and optical imaging observations are often hampered by obscuration and scattering of the central kpc-scale region by interstellar gas in the host galaxy or unsuitable orientation of the galaxy. Further, there is not sufficient resolution to clearly separate the two nuclei in these images, especially in objects at cosmological distances (well beyond the local Universe). Very long baseline interferometry (VLBI) was developed during the 1960s to resolve fine structures of compact bright radio sources, and is the highest-resolution imaging technique (Kellermann & Moran 2001); VLBI observations with baselines  $\sim$  few thousand kilometers can resolve milli-arcsecond (mas) structures (physical sizes of pc to kpc) and directly image even closely-separated nuclei, thus offering a promising method of spatially identifying DAGN and SMBHBs. In comparison, the angular resolutions achievable in other wavebands are  $\sim 0.5$  arcsec with the *Chandra* X-ray Observatory, and  $\sim 0.1$  arcsec with the Hubble Space Telescope in the optical and ultraviolet and with the W. M. Keck Observatory adaptive optics system in the near infrared. The VLBI radio observations are then indispensable in studying binary evolution from kpc to pc scales (e.g. Pfister et al. 2017) and constructing a statistically viable sample through direct imaging observations, clarifying mechanisms enabling coalescence of a binary before gravitational wave emission becomes dominant (to avoid or overcome the final parsec problem), and helping to understand the nano-Hz gravitational wave background emission (e.g. Mingarelli et al. 2017) using pulsar timing arrays (e.g. Sesana et al. 2008; Hobbs et al. 2010).

The method and observational signatures relevant to it are discussed in Section 2. Future directions relevant to VLBI observation of DAGN and SMBHBs are then discussed in Section 3.

#### 2. VLBI observations of DAGN and SMBHBs

For a source at z = 0.1, 0.5 and 1, assuming a standard  $\Lambda$ CDM cosmology ( $H_0 = 71$  km s<sup>-1</sup> Mpc <sup>-1</sup>,  $\Omega_M = 0.27$  and  $\Omega_V = 0.73$ ) and a binary separation R = 1 pc - 1 kpc, the required angular resolution  $R/D_A$  (where  $D_A$  is the angular diameter distance) is between 0.12 mas and 0.54 arcsecond, and is summarized in Table 1. The typical angular resolutions of major VLBI networks are 0.26 - 0.5 mas at the 22 GHz frequency band (e.g. An et al. 2018), suitable for imaging most nearby DAGN and SMBHBs.

Prominent signatures of DAGN and SMBHBs directly relevant to VLBI include double compact flat- or inverted-spectrum components, i.e., double cores, merger remnants of two active star forming nuclei and their influence on circumnuclear star formation (Das et al. 2018) and the presence of peculiar jet morphologies including S, Z and X-shapes, and helical pc-kpc scale structures (e.g. Komossa 2006) which can arise due to tidal interaction of a binary SMBH with the accretion disk or jet base causing a precession (e.g. Begelman et al. 1980) or through a flip in the black hole spin during a merger which can re-orient the

z	$D_A$	R	$R/D_A$
	(Gpc)	(pc)	(mas)
0.1	0.38	1	0.54
		1000	542.8
0.5	1.25	1	0.17
		1000	165.0
1.0	1.66	1	0.12
		1000	124.3

Table 1: Required resolution to clearly identify DAGN and SMBHB in the relatively nearby universe  $(z \leq 1)$ .

associated emergent jet (Merritt & Ekers 2002).

With a small field of view, VLBI has not been employed as a powerful searching technique, but its unique high resolution yields stringent evidence to confirm or reject a candidate DAGN or SMBHB identified by other methods. Observations have thus far resulted in the detection of a SMBHB with a separation of ~ 7 pc in 0402+379 (Rodriguez et al. 2006), confirmed with follow-up observations after  $\sim 12$  yr (Bansal et al. 2017) which additionally help constrain the jet radiative properties and the orbital velocity, period and black hole mass of the system. A promising candidate with a sub-pc separation was reported in NGC 7674 (Kharb et al. 2017), and requires follow-up observations (multi-epoch and multifrequency VLBI) to confirm the detection of double radio cores. The imaging of NGC 5252 has been employed in identifying a possible off-nucleus ultra-luminous X-ray (ULX) source as a low luminosity AGN, thus making it a candidate DAGN (Yang et al. 2017). The study of follow-up VLBI observations of NGC 5252 (Mezcua et al. 2018) indicates either a ULX hosting an intermediate-mass black hole or a low-mass AGN. Based on optical periodic variability over a timescale of  $\sim 5$  yr, the source PG 1302-102 was proposed as a SMBHB candidate (Graham et al. 2015). In addition to multi-wavelength periodicity (D'Orazio et al. 2015), PG 1302-102 exhibits interesting pc-scale jet structure, with Kun et al. (2015) and Mohan et al. (2016) exploring its helical nature, and Qian et al. (2018) applying a model of a precessing jet nozzle to infer the association between the pc-scale radio jet and the optical variability timescale.

Early VLBI searches based on candidate double-peaked narrow optical emission lines (DPNL) AGN did not detect double cores (e.g. Tingay & Wayth 2011), possibly due to limited sensitivity or as DPNL AGN may not host SMBHBs. Some recent targeted VLBI observations of DPNL AGN, with a typical sensitivity of 20  $\mu$ Jy, show mixed results: inference of double cores in SDSS J1502+1115 (Deane et al. 2014) and SDSS J1536+0441 (Bondi & Pérez-Torres 2010), only a single radio-emitting AGN detected in SDSS J1425+3231 (Gabányi et al. 2017), 3C 316 (An et al. 2013), and some others (Gabányi et al. 2014, 2016), posing an interesting question of whether both SMBHs become active in radio bands. The study of Burke-Spolaor (2011) involves a blind search for sources hosting dual radio bright components in archival multi-frequency VLBI images, finding a general paucity of resolved pc-scale stalled binaries suggesting that they likely exist within a common bright radio envelope and coalescence is rapid. An updated but non-exhaustive compilation of VLBI observed candidate DAGN and SMBHBs is presented in Table 2.

Some general inferences can be drawn from the existing VLBI detection of DAGN and SMBHBs.

• A stringent requirement is that both nuclei are active radio emitters. This may be

Source &	Radio	Redshift	$\nu: S_{\nu,\text{VLBI}}$	Core Sep.
attributes	Morphology	z	(GHz: mJy)	(kpc)
NGC $5252^{(1),F}$	Double compact cores	0.022	1.6: 1.80, 3.60	10.0
$3C \ 75^{(2)F}$	Double components	0.023	1.4: 111.0, 41.0	7.0
			2.4: 63.0, 22.0	
			4.8: 38.0, 13.0	
			8.6: 4.0, 5.0	
NGC $6240^{(3,4)F}$	One compact core $+$ SNR	0.024	1.6: 2.09, 3.95	1.4
			5.0: 2.6, 6.0	
NGC $7674^{(5)I}$	Double compact cores	0.030	15: 0.9, 0.9	$3.5 \times 10^{-4}$
NGC $326^{(6)I}$	Double components	0.047	1.4: 5.33, 1.16	4.8
			4.8: 10.42, 0.78	
$0402 + 379^{(7)I}$	MSO + naked core	0.055	5.0: 53.2, 10.7	$7.3 \times 10^{-3}$
			8.0: 60.5, 15.3	
			15.0: 52.4, 14.8	
			22.0: 35.3, 10.7	
			43.0: 23.4, 8.0	
PKS $1155+251^{(8)F}$	CSO	0.203	24: 2.74, 147.60	$1.2 \times 10^{-2}$
			43: 3.37, 118.87	
J1536+0441 <sup><math>(9,10)S</math></sup>	Double compact cores	0.390	5.0: 0.72, 0.27	5.1
			8.0: 1.17, 0.24	
			8.5: 1.17, 0.27	
J1502+1115 <sup>(11)S</sup>	Double components	0.390	1.4: 2.58, 7.04	7.4
			5.0: 0.93, 2.33	
			8.5: 0.61, 1.28	
J1502+1115 $S^{(12)F}$	Double components	0.390	1.7: 0.95, 0.92	$1.4 \times 10^{-1}$
			5.0: 0.86, 0.87	
J1425+3231 <sup><math>(13)F/S</math></sup>	Double components	0.478	1.7: 0.46, 0.23	2.6
			5.0: 0.35, < 0.09	
$3C \ 316^{(14)S}$	Complex jet	0.580	1.6: 26.2, 16.5	$1.8 \times 10^{-1}$

Table 2: List of candidate and confirmed VLBI observed DAGN and SMBHB hosts. Attributes relating to spectral type include F: flat, S: steep, F/S: flat and steep, and I: inverted. References: (1): Yang et al. (2017), (2): Klamer et al. (2004), (3): Komossa et al. (2003), (4): Hagiwara et al. (2011), (5): Kharb et al. (2017), (6): Murgia et al. (2001), (7): Rodriguez et al. (2006), (8): Yang et al. (2017), (9): Bondi & Pérez-Torres (2010), (10): Wrobel & Laor (2009), (11): Fu et al. (2011), (12): Deane et al. (2014), (13): Frey et al. (2012), (14): An et al. (2013).

the case especially in the SMBHB scenario as they may exist within a common radio bright core (e.g. Burke-Spolaor 2011), thus necessitating high resolution follow-up and monitoring.

- If a fraction of DAGN are radio loud/quiet or quiet/quiet pairs (e.g., J1643+3156 Kunert-Bajraszewska & Janiuk 2011) either owing to unbeamed emission from a constituent, or the quenching of jet production due to destruction of the primary BH accretion disk by the secondary BH, a blind VLBI search for radio pairs may then fail to identify them, biased towards single radio-loud AGN hosts.
- The radio flux densities are typically at mJy and sub-mJy levels, requiring high sensitivity VLBI imaging.
- Most candidates found in radio so far are DAGN. To discover sub-pc scale SMBHBs (likely sources of low-frequency gravitational waves) by direct imaging, the expected sub-mas resolution with current mm-wavelength VLBI or future space VLBI at centimeter wavelengths would be necessary. The existing VLBA can achieve resolutions of 0.07 mas and 0.18 mas at 86 and 43 GHz, respectively, enabling the resolving of DAGN upto moderate redshifts. For those with steep-spectrum cores, VLBI at lower radio frequency (e.g., ≤ 5 GHz) would be suitable; that has to involve space VLBI to reach sub-mas resolution (0.4 mas resolution at 1.67 GHz with a baseline of 100,000 km, e.g. An et al. 2018).
- The radio activity appears to be recently triggered (by galaxy merger) and can be characterized as systems with high accretion rates. The resulting DAGN and SMB-HBs resemble compact symmetric objects (CSOs) or compact steep-spectrum (CSS) sources, both of which are classified as young radio galaxies. Typical examples include the inverted-spectrum cores in 0402+379 (Rodriguez et al. 2006), and in NGC 6240 (Hagiwara et al. 2011). Further, as their core flux density only accounts for a small fraction of the total flux density, this indicates that their radio emission is dominated by extended jets and lobes.

## 3. Discussion and future directions

The expected number of binary SMBH hosts can be inferred from the AGN luminosity function by accounting for the rate of mergers, the timescale of existence of the AGN phase, the SMBH mass function, and the spatial distribution of AGN in the redshift volume being probed (e.g. Haiman et al. 2009); though, estimates are model dependent and hence could result in large uncertainties. Modeling SMBHBs during the inspiral phase driven by gas and gravitational wave emission, D'Orazio & Loeb (2018) estimate ~ 100 SMBHBs at z < 0.5which can show periodic variability < 10 yr that can be resolved using mm-wavelength VLBI, relevant to facilities such as the Event Horizon Telescope. The study of Graham et al. (2015) predicts 450 candidates showing optical periodic variability (assuming  $R \leq 0.01$  pc, limiting V magnitude of 20 and  $z \leq 4.5$ ) but find only 111 candidates from a sample of 243500 quasars, indicating a conservative agreement. A similar  $\geq 100$  candidate DAGN ( $R \sim \text{kpc}$ ) in high frequency radio (e.g. 1.6 and 5 GHz) surveys with either medium sensitivity  $\sim 0.1$ mJy and sky area of  $\sim$  thousand square degree or high sensitivity  $\sim 10 \ \mu$ Jy and sky area of ~ few hundred square degree is predicted by Burke-Spolaor et al. (2014). The study of Charisi et al. (2016) finds a similarly conservative estimate of 33 candidates indicating periodic optical variability from a sample of 35383 quasars. SMBHBs indicate a transition to the gravitational wave emitting regime and the study of Sesana et al. (2018) characterizes the expected gravitational wave background limits from pulsar timing arrays and finds a moderate tension with the above observational estimates, suggesting that the inferred candidate samples are contaminated with false detections. The above estimates based on periodic variability indicate an efficiency of 0.05 - 0.09 % which may only be upper limits, but are likely to improve with continued monitoring which will enable a more robust statistical identification. With the Square Kilometre Array (SKA) phase 1 Mid configuration in the 4 cm band ( $\sim 8.4$  GHz; applicable to possible SKA-VLBI observation) and a maximum baseline of  $\sim$ 10000 km (between SKA 1-Mid and European VLBI stations), the resolution is about 0.15 mas. The expected image sensitivity is  $3 \mu Jy/beam$  for an integration time of 1 hour with the full SKA1-Mid in the global VLBI network (Paragi et al. 2015) so that the combination of high resolution and high sensitivity with reasonable integration time can resolve sub-mas structures in DAGN and SMBHB candidates (Deane et al. 2015).

The major shortcoming of the current VLBI technique is the small field of view at a given time, limiting its applicability for blind surveys. Further issue in the observation itself may arise from a combination of selection criteria and biases (methodology), instrumental properties and limitations (detection sensitivity) and intrinsic source-based properties (accretion and jet production mechanisms, radio quietness and non-active galaxies) (e.g. Sokolovsky et al. 2018). Further, as only  $\sim 10\%$  AGN are typically radio loud, fainter sources should be sufficiently radio bright (and compact) to be VLBI detected; more DAGN are expected to be detected with an increasing VLBI sensitivity. Continuing efforts towards addressing these include the upgrading of equipment with higher data recording rate and updated software correlators, developing robust and time optimal algorithms for data handling and reduction, and their deployment and testing on smaller arrays and scaling up (e.g. An et al. 2018). For faint and un-beamed AGN hosting SMBHBs (non-existent or weak large-scale jet), the multi-beam, wide-field SKA can offer fast surveys, and its high sensitiv-

ity allows for discovering even weak radio loud/quiet pairs. It is essential to thus address why a larger number of DAGN and SMBHBs are yet to be observed using current strategies. An alternate means to resolve pc and sub-pc separation SMBHBs is by resorting to space VLBI observations with two or three space-based telescopes, operational in the 1.5 -8.4 GHz frequency range and offering few tens of  $\mu$ as-mas resolutions. The space VLBI is expected to resolve the central regions of nearby bright AGN (e.g. 3C 84, Giovannini et al. 2018) and revealing the precession of the jet nozzle, and to search for sub-pc-separation SMBHBs in elliptical galaxies which have likely experienced multiple mergers. Such space VLBI telescopes can be connected with large ground-based telescopes, such as SKA1-Mid, FAST 500m, Arecibo 300m, Effelsberg 100m and Green Bank 110m, pushing detection limits down to sub-mJy levels. Additionally, one can use ground based mm-wavelength facilities to achieve sub-mas resolutions (e.g. Broderick et al. 2011) and even approach mJy sensitivity in the near future.

#### Acknowledgements

We thank the anonymous reviewers for the comments and suggestions which helped improved our paper. This work is supported by the International Key R&D Program of China (grant number 2018YFA0404603). PM is supported by the National Science Foundation of China (grant no. 11650110438). SF thanks the Hungarian National Research, Development, and Innovation Office (OTKA NN110333) for support. We acknowledge the use of the Cosmology Calculator (Wright 2006) to estimate data presented in Table 1. The data presented in Table 2 is compiled from literature with the appropriate source cited, and is intended in identifying diverse and similar characteristics of DAGN and SMBHB systems relevant to VLBI radio observations.

#### REFERENCES

- An, T., Paragi, Z., Frey, S., et al. 2013, MNRAS, 433, 1161
- An, T., Sohn, B. W., & Imai, H. 2018, Nature Astronomy, 2, 118
- An, T., Jaiswal, S., Mohan, P., Zhao, Z., & Lao, B. 2018, arXiv:1808.10636
- Bansal, K., Taylor, G. B., Peck, A. B., Zavala, R. T., & Romani, R. W. 2017, ApJ, 843, 14

Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307

- Berczik, P., Merritt, D., Spurzem, R., & Bischof, H.-P. 2006, ApJ, 642, L21
- Bianchi, S., Chiaberge, M., Piconcelli, E., Guainazzi, M., & Matt, G. 2008, MNRAS, 386, 105
- Bondi, M., & Pérez-Torres, M.-A. 2010, ApJ, 714, L271
- Bonetti, M., Haardt, F., Sesana, A., & Barausse, E. 2016, MNRAS, 461, 4419
- Britzen, S., Fendt, C., Witzel, G., et al. 2018, MNRAS, 478, 3199
- Broderick, A. E., Loeb, A., & Reid, M. J. 2011, ApJ, 735, 57
- Burke-Spolaor, S. 2011, MNRAS, 410, 2113
- Burke-Spolaor, S., Brazier, A., Chatterjee, S., et al. 2014, arXiv:1402.0548
- Chandrasekhar, S. 1943, ApJ, 97, 255
- Charisi, M., Bartos, I., Haiman, Z., et al. 2016, MNRAS, 463, 2145
- Comerford, J. M., Gerke, B. F., Stern, D., et al. 2012, ApJ, 753, 42
- Comerford, J. M., Schluns, K., Greene, J. E., & Cool, R. J. 2013, ApJ, 777, 64
- Das, M., Rubinur, K., Karb, P., et al. 2018, Bulletin de la Societe Royale des Sciences de Liege, 87,
- Deane, R., Paragi, Z., Jarvis, M., et al. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 151
- Deane, R. P., Paragi, Z., Jarvis, M. J., et al. 2014, Nature, 511, 57
- D'Orazio, D. J., Haiman, Z., & Schiminovich, D. 2015, Nature, 525, 351
- D'Orazio, D. J., & Loeb, A. 2018, ApJ, 863, 185
- Dotti, M., Colpi, M., Haardt, F., & Mayer, L. 2007, MNRAS, 379, 956
- Frey, S., Paragi, Z., An, T., & Gabányi, K. É. 2012, MNRAS, 425, 1185
- Fu, H., Zhang, Z.-Y., Assef, R. J., et al. 2011, ApJ, 740, L44
- Fu, H., Yan, L., Myers, A. D., et al. 2012, ApJ, 745, 67
- Gabányi, K. É., Frey, S., Xiao, T., et al. 2014, MNRAS, 443, 1509

- Gabányi, K. É., An, T., Frey, S., et al. 2016, ApJ, 826, 106
- Gabányi, K. E., Frey, S., Paragi, Z., An, T., & Komossa, S. 2017, New Frontiers in Black Hole Astrophysics, 324, 223
- Gerke, B. F., Newman, J. A., Lotz, J., et al. 2007, ApJ, 660, L23
- Giovannini, G., Savolainen, T., Orienti, M., et al. 2018, Nature Astronomy, 2, 472
- Goicovic, F. G., Sesana, A., Cuadra, J., & Stasyszyn, F. 2017, MNRAS, 472, 514
- Graham, M. J., Djorgovski, S. G., Stern, D., et al. 2015, Nature, 518, 74
- Graham, M. J., Djorgovski, S. G., Stern, D., et al. 2015, MNRAS, 453, 1562
- Gualandris, A., Read, J. I., Dehnen, W., & Bortolas, E. 2017, MNRAS, 464, 2301
- Hagiwara, Y., Baan, W. A., & Klöckner, H.-R. 2011, AJ, 142, 17
- Haiman, Z., Kocsis, B., & Menou, K. 2009, ApJ, 700, 1952
- Hobbs, G., Archibald, A., Arzoumanian, Z., et al. 2010, Classical and Quantum Gravity, 27, 084013
- Kellermann, K. I., & Moran, J. M. 2001, ARA&A, 39, 457
- Kharb, P., Lal, D. V., & Merritt, D. 2017, Nature Astronomy, 1, 727
- Klamer, I., Subrahmanyan, R., & Hunstead, R. W. 2004, MNRAS, 351, 101
- Komossa, S., Burwitz, V., Hasinger, G., et al. 2003, ApJ, 582, L15
- Komossa, S. 2006, Mem. Soc. Astron. Italiana, 77, 733
- Koss, M., Mushotzky, R., Treister, E., et al. 2011, ApJ, 735, L42
- Koss, M., Mushotzky, R., Treister, E., et al. 2012, ApJ, 746, L22
- Kun, E., Frey, S., Gabányi, K. É., et al. 2015, MNRAS, 454, 1290
- Kunert-Bajraszewska, M., & Janiuk, A. 2011, ApJ, 736, 125
- Lehto, H. J., & Valtonen, M. J. 1996, ApJ, 460, 207
- Mayer, L., Kazantzidis, S., Madau, P., et al. 2007, Science, 316, 1874
- Mazzarella, J. M., Iwasawa, K., Vavilkin, T., et al. 2012, AJ, 144, 125

- Merritt, D., & Ekers, R. D. 2002, Science, 297, 1310
- Merritt, D., & Milosavljević, M. 2005, Living Reviews in Relativity, 8
- Mezcua, M., Kim, M., Ho, L. C., & Lonsdale, C. J. 2018, MNRAS, 480, L74
- Milosavljević, M., & Merritt, D. 2001, ApJ, 563, 34
- Milosavljević, M., & Merritt, D. 2003, ApJ, 596, 860
- Mingarelli, C. M. F., Lazio, T. J. W., Sesana, A., et al. 2017, Nature Astronomy, 1, 886
- Mohan, P., An, T., Frey, S., et al. 2016, MNRAS, 463, 1812
- Müller-Sánchez, F., Comerford, J. M., Nevin, R., et al. 2015, ApJ, 813, 103
- Murgia, M., Parma, P., de Ruiter, H. R., et al. 2001, A&A, 380, 102
- Paragi, Z., Godfrey, L., Reynolds, C., et al. 2015, Advancing Astrophysics with the Square Kilometre Array (AASKA14), 143
- Pfister, H., Lupi, A., Capelo, P. R., et al. 2017, MNRAS, 471, 3646
- Qian, S. J., Britzen, S., Witzel, A., Krichbaum, T. P., & Kun, E. 2018, A&A, 615, A123
- Rodriguez, C., Taylor, G. B., Zavala, R. T., et al. 2006, ApJ, 646, 49
- Rubinur, K., Das, M., & Kharb, P. 2018, JAA, 39, 8
- Sesana, A., Vecchio, A., & Colacino, C. N. 2008, MNRAS, 390, 192
- Sesana, A., Haiman, Z., Kocsis, B., & Kelley, L. Z. 2018, ApJ, 856, 42
- Shen, Y., Liu, X., Greene, J. E., & Strauss, M. A. 2011, ApJ, 735, 48
- Sillanpaa, A., Haarala, S., Valtonen, M. J., Sundelius, B., & Byrd, G. G. 1988, ApJ, 325, 628
- Smith, K. L., Shields, G. A., Salviander, S., Stevens, A. C., & Rosario, D. J. 2012, ApJ, 752, 63
- Sokolovsky, K. V., Giroletti, M., Corbel, S., Anderson, G. E., & Stappers, B. W. 2018, arXiv:1803.02831
- Springel, V., White, S. D. M., Jenkins, A., et al. 2005, Nature, 435, 629

- Tang, Y., MacFadyen, A., & Haiman, Z. 2017, MNRAS, 469, 4258
- Tingay, S. J., & Wayth, R. B. 2011, AJ, 141, 174
- Valtonen, M. J., Lehto, H. J., Takalo, L. O., & Sillanpää, A. 2011, ApJ, 729, 33
- Wright, E. L. 2006, PASP, 118, 1711
- Wrobel, J. M., & Laor, A. 2009, ApJ, 699, L22
- Xu, D., & Komossa, S. 2009, ApJ, 705, L20
- Yang, X., Yang, J., Paragi, Z., et al. 2017a, MNRAS, 464, L70
- Yang, X., Liu, X., Yang, J., et al. 2017b, MNRAS, 471, 1873

This preprint was prepared with the AAS  ${\rm IAT}_{\rm E}{\rm X}$  macros v5.2.