MULTI-MESSENGER ASTROPHYSICS WITH PULSAR TIMING ARRAYS

Astro2020 Science White Paper

Thematic Areas ☒ Multi-Messenger Astronomy & Astrophysics
☒ Galaxy Evolution ☒ Cosmology and Fundamental Physics

Principal Authors

Luke Zoltan Kelley
Northwestern University
LZKelley@northwestern.edu

Maria Charisi
California Institute of Technology
mcharisi@caltech.edu

Co-authors

S. Burke-Spolaor,[1] J. Simon,[2] L. Blecha,[3] T. Bogdanović,[4] M. Colpi,[5] J. Comerford,[6] D. D'Orazio,[7] M. Dotti,[5] M. Eracleous,[8] M. Graham,[9] J. Greene,[10] Z. Haiman,[11] K. Holley-Bockelmann,[12,13] E. Kara,[14,15,16] B. Kelly,[14,15] S. Komossa,[17] S. Larson,[18] X. Liu,[19] C.-P. Ma,[20] S. Noble,[15,21] V. Paschalidis,[22] R. Rafikov,[23] V. Ravi,[7,9] J. Runnoe,[24] A. Sesana,[25,5] D. Stern,[2] M. A. Strauss,[10] V. U,[26] M. Volonteri,[27] & the NANOGrav Collaboration

[1] *West Virginia University/Center for Gravitational Waves and Cosmology/CIFAR Azrieli Global Scholar;* [2] *Jet Propulsion Laboratory, California Institute of Technology;* [3] *University of Florida;* [4] *Georgia Institute of Technology;* [5] *Universita degli Studi di Milano-Bicocca;* [6] *University of Colorado Boulder;* [7] *Harvard-Smithsonian Center for Astrophysics;* [8] *The Pennsylvania State University;* [9] *California Institute of Technology;* [10] *Princeton University;* [11] *Columbia University;* [12] *Vanderbilt University;* [13] *Fisk University;* [14] *University of Maryland;* [15] *NASA Goddard Space Flight Center;* [16] *Massachusetts Institute of Technology;* [17] *Max Planck Institute for Radio Astronomy;* [18] *Northwestern University;* [19] *University of Illinois Urbana-Champaign;* [20] *University of California, Berkeley;* [21] *University of Tulsa;* [22] *University of Arizona;* [23] *University of Cambridge;* [24] *Univeristy of Michigan;* [25] *University of Birmingham;* [26] *University of California, Irvine;* [27] *Institut d'Astrophysique de Paris;*

Related White Papers

This is one of five core white papers written by members of the NANOGrav Collaboration.

1. *Nanohertz Gravitational Waves, Extreme Astrophysics, and Fundamental Physics with Pulsar Timing Arrays*, J. Cordes, M. McLaughlin, et al.
2. *Supermassive Black-hole Demographics & Environments With Pulsar Timing Arrays*, S. R. Taylor, S. Burke-Spolaor, et al.
3. *Physics Beyond the Standard Model with Pulsar Timing Arrays*, X. Siemens, et al.
4. *Fundamental Physics With Radio Millisecond Pulsars*, E. Fonseca, et al.

Abstract

Pulsar timing arrays (PTAs) are on the verge of detecting low-frequency gravitational waves (GWs) from supermassive black hole binaries (SMBHBs). With continued observations of a large sample of millisecond pulsars, PTAs will reach this major milestone within the next decade. Already, SMBHB candidates are being identified by electromagnetic surveys in ever-increasing numbers; upcoming surveys will enhance our ability to detect and verify candidates, and will be instrumental in identifying the host galaxies of GW sources. Multi-messenger (GW and electromagnetic) observations of SMBHBs will revolutionize our understanding of the co-evolution of SMBHs with their host galaxies, the dynamical interactions between binaries and their galactic environments, and the fundamental physics of accretion. Multi-messenger observations can also make SMBHBs 'standard sirens' for cosmological distance measurements out to $z \simeq 0.5$. LIGO has already ushered in breakthrough insights in our knowledge of black holes. The multi-messenger detection of SMBHBs with PTAs will be a breakthrough in the years 2020–2030 and beyond, and prepare us for LISA to help complete our views of black hole demographics and evolution at higher redshifts.

1 Multi-Messenger Science with Pulsar Timing Arrays

Supermassive black holes (SMBHs) reside in the nuclei of massive galaxies [1]. Galaxy mergers deliver two SMBHs, along with massive inflows of gas, to the center of post-merger galaxies [2]. Gravitationally bound SMBH binaries (SMBHBs) can then form, and eventually emit gravitational waves (GWs). If sufficient gas remains, it can power bright active galactic nuclei (AGNs) [3, 4], observable across the electromagnetic (EM) spectrum.

In the coming decade, Pulsar Timing Arrays (PTAs) [5–9], like NANOGrav [10], will likely detect GWs in the nano-Hertz frequency band, confirming the existence of SMBHBs [11–13]. The expected signals are: (1) **Continuous Gravitational Waves** (CGWs) from individual, massive ($10^8 - 10^{10}\,\mathrm{M}_\odot$) and relatively nearby (redshifts $z \lesssim 0.5$) binaries, and (2) a stochastic **Gravitational Wave Background** (GWB) from the superposition of many unresolved SMBHBs [14–21].[1] At the same time, upcoming wide-field, time-domain (e.g., LSST), and multi-epoch spectroscopic (e.g., SDSS-V, DESI) surveys will discover an unprecedented number of SMBHB candidates.

As emphasized by the choice of thematic areas for Astro2020, and the ten NSF Big Ideas, the coming decade promises revolutions in multi-messenger astrophysics. In this white paper, we discuss the astrophysics that is uniquely addressed with the detection of EM and nano-Hertz GW signals from SMBHBs.[2] In particular, we address four fundamental questions:

Q1. How do SMBHBs interact with their environments? SMBHBs evolve towards the GW regime through complex interactions with the galactic cores, e.g., stellar scatterings [23, 24], interactions with nuclear gas [25, 26], and triple SMBH interactions from subsequent mergers [27–30]. The detection of the GWB will strongly constrain these physical processes, since each mechanism affects the shape of the GWB spectrum.

Q2. How does accretion in the presence of a SMBHB shape its EM signatures? Dynamical processes in the circumbinary disk induce a unique structure, which affects the resulting EM emission [31–33]. However, AGNs with a single SMBH may mimic these signatures, making EM detections of sub-parsec binaries ambiguous [34, 35]. Multi-messenger detections of SMBHBs will illuminate the origin of the EM counterparts, allowing for direct comparisons against typical AGN.

Q3. How do SMBHs co-evolve with their host galaxies? SMBH–galaxy scaling laws, like the M–σ^* relation, indicate that SMBHs evolve symbiotically with their hosts [36]. PTA upper limits on the GWB already constrain these scalings [37], which will become more stringent with a GWB detection. Mass measurements directly from CGWs will test and calibrate EM-based methods, while also assessing potential biases in SMBH–host scaling laws, which may be significant [38–40].

Q4. How can binaries be used as cosmological probes? If the host galaxy of a SMBHB is identified, we can measure its redshift via spectroscopy and the luminosity distance from the GW signal, turning SMBHBs into standard sirens [41, 42], as LIGO did with the detection of a NS merger [43]. The LISA mission [44] can use massive binaries as standard sirens to even higher precisions and redshifts [45–47]. PTAs will contribute independent siren measurements, will establish the procedure for LISA follow-up strategies, and tune rate predictions in the LISA band.

---

[1] It is unclear if the GWB will be detected first [11], or both types of signals contemporaneously [13, 22].

[2] See Holley-Bockelmann et al. for a discussion of mHz-GW science with higher-z, lower-mass sources.

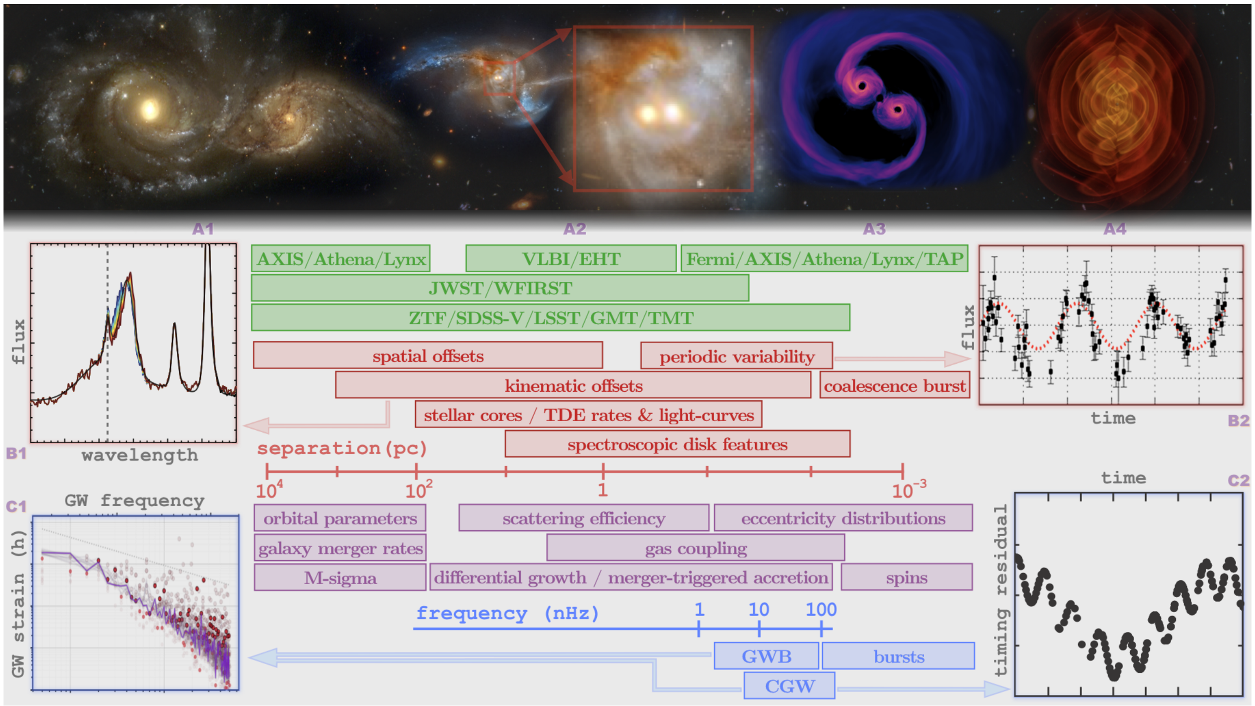

Figure 1: SMBHB evolution begins when galaxies merge (A1), progresses through environmental interactions with dark matter, stars, and gas (A2 & A3), and ends with strong GW emission (A4). EM signatures (red, also B1 & B2) can be observed with current and future telescopes and surveys across the EM spectrum (green). Combined with GW signals (blue & C1, C2) from PTAs, the complex and uncertain physical processes (purple) can be tightly constrained. C1 shows the GWB and CGW sources from mock PTA observations. C2 shows the theoretical timing residuals of a CGW source with high SNR. *Subpanels: A1:The Hubble Heritage Team, A2: mockup with Hubble Legacy/M. Pugh and SDSS; A3: [52]; A4: NASA/C. Henze; B1 [53], B2 [49], C1 [13], C2 [48].*

PTAs already provide insights on SMBHB candidates. For example, a binary proposed in the galaxy 3C 66B was ruled out by the non-detection of GWs at the predicted amplitude and frequency [48]. Additionally, the GWB (see Fig. 1, C1) inferred from the population of quasars with periodic variability [49, 50] is likely inconsistent with current PTA limits, indicating contamination with false detections [51]. These examples speak to the tremendous potential of low-frequency GWs experiments for multi-messenger inference.

2 Electromagnetic and Gravitational Wave Signals

In Fig. 1, we show the expectations of how EM (red) and GW (blue) signals should follow the evolution of a SMBHB from large to small separations. Because accretion onto both SMBHs can continue throughout the merger process [54, 55], numerous overlapping signatures provide the potential for robust multi-messenger and multi-wavelength discoveries.

2.1 Formation and Evolution of SMBHBs

Following a galaxy merger, SMBHs evolve to smaller separations in three main stages [2]:

Large Separations *(∼kpc)*: Dynamical friction drags each SMBH, along with bound gas and stars, towards the center of the common potential [56, 57].

Intermediate Separations *(∼pc)*: Three-body interactions with stars in the galactic core

[58, 59], and interactions with a nuclear disk [26, 60–62] extract energy from the binary[3].
Small Separations *($\sim$mpc)*: The SMBHB decay is dominated by the emission of GWs.

The intermediate step remains the most uncertain[4], since it involves complex interactions between the SMBHB and its local environment, which are challenging to tackle theoretically or resolve numerically. The same uncertainties affect LISA massive binary sources. GWB measurements, or the detection of CGWs with associated EM measurements of their galactic environments, will provide crucial constrains on binary evolution and rates (**Q1,Q4**).

2.2 Electromagnetic Signatures of SMBHBs

Observations of sub-parsec SMBHBs are very challenging, due both to their intrinsic rarity and extremely small angular separations. Gravitationally unbound dual AGN, at kpc separations, can be observed with high-resolution IR, optical, and X-ray instruments, and inform galaxy merger rates and initial orbital parameters [67, 68]. However, (sub-)parsec scale *bound* systems can only be spatially resolved with radio Very Long Baseline Interferometry (VLBI). Indeed, VLBI has provided the record-holding binary at a projected separation of 7 pc [69] and, as of last year, an intriguing candidate at 0.35 pc [70]. The exquisite resolution of current milli-meter VLBI, like the Event Horizon Telescope, holds tremendous promise for resolving sub-pc binaries, especially in the nearby universe [71].

Once SMBHB separations fall below the resolution of even VLBI, we can still infer their presence by observing effects of the orbital motion or by identifying features indicative of an ongoing merger. Below we summarize some of these EM signatures (**Q2**):

AGN with Doppler-shifted broad lines: Broad emission lines in AGN spectra arise from gas close to SMBHs, and may track their orbital motion (Fig. 1, B1) [72, 73]. About a hundred candidate SMBHBs have been identified [53, 74–82].[5] However, gas in the accretion flows of single AGN can produce similar features, contaminating this population [35]. Future surveys with multi-epoch spectroscopy, like the BH mapper/SDSS-V (scheduled for 2020 [83]), will reveal additional candidates and provide further tests of known candidates.

AGN with periodic variability: Circumbinary disk simulations predict that SMBHBs can produce bright emission, periodically modulated at the orbital period or its harmonics [61, 84–93]. This may be more pronounced in X-rays, since X-ray emission arises closer to the SMBHs [52, 94–97]. In addition to the well-known blazar OJ 287 [98], candidates have been identified in recent time-domain surveys (Fig. 1, B2) [35, 49, 50]. However, the intrinsic red-noise variability in AGN [99], combined with relatively short baselines, can lead to false detections [51, 100–102]. Extended multi-band and high-cadence data from surveys like ZTF [103] and LSST [104] will test current candidates and discover many new ones [105].

Additional signatures: Many additional features may signify the presence of a binary, such as helical radio jets [106, 107]; relativistic Doppler-boost [108, 109]; periodic self-lensing [110]; double peaked, or extremely broad and oscillating FeKα lines [111–113]; UV/X-Ray deficits, from truncated circumbinary disks [94, 114, 115]; enhanced rates of tidal-disruption events and features in their light-curves [116–119]. These, along with indicators of recent galaxy mergers (e.g., recent star-formation bursts, tidal tails, or 'cored' stellar density profiles [120])

---

[3] Though, at times, energy may be deposited [63–65].

[4] In the '*final-parsec problem*', stellar scatterings may extract insufficient energy, but the growing consensus is that in general the 'loss cone' (the stars able to interact with the binary) is sufficiently replenished [59, 66].

[5] Double-peaked narrow lines have been used similarly as a tracer to select dual AGN.

can be used both for the search of CGW hosts, and for confirming EM binary candidates.

2.3 Multi-messenger Observations

The localization error of PTA detections will be large (typically, $\sim$100s deg^2 [121, 122]), making host-galaxy determination challenging. However, PTAs will detect massive and relatively nearby binaries, which limits the number of potential hosts within the error volume. Also, since PTAs will identify binaries long before coalescence, if there is a bright counterpart, it will be long-lived (decades to millenia). However, post-merger galaxies may be highly obscured [4]. Thus, wide-field IR and X-ray telescopes, like WFIRST and TAP, will be essential in identifying obscured AGN within the error volume, whereas high angular-resolution instruments, like AXIS, Lynx and JWST, will provide more detailed follow-up.

Table 1 highlights important advances that are attainable *only* through multi-messenger observations. Such detections reveal the interaction of SMBHBs with their galactic environments (**Q1**), and decipher the nature of accretion and EM emission around SMBHBs (**Q2**). They can also calibrate SMBH–host scaling relations. These scalings may be substantially biased and are especially uncertain at higher masses, which PTAs naturally probe [123, 124] (**Q3**). Additionally, the identification of the host galaxy allows the measurement of redshift, which, in some cases, can be compared with the luminosity distance measured independently from the GW signal (**Q4**),[6] making SMBHBs cosmological standard sirens [42, 125]. PTAs can detect SMBHBs at larger distances than LIGO can detect NS mergers, and thus can complement LIGO observations to cover a wider range of redshifts. Answers to **Q1**–**Q4** will also shape the predictions and preparations for multi-messenger science with LISA [126].

3 Key Detectors & Requirements

Here, we summarize particular key efforts required to realize these science opportunities.

GW Observations: Current PTAs are approaching the sensitivities required to detect GWs [20, 21]. To ensure the discovery of GWs from SMBHBs, PTA collaborations need access to radio telescopes with large collecting areas operating in the frequency range of $\sim$100s MHz to a few GHz, such as large single-dish telescopes (like Arecibo and the GBT) or dish-arrays with equivalent sensitivities (like the proposed DSA-2000 and ngVLA). PTA collaborations, like NANOGrav, are long-timescale projects requiring continued monitoring of $\gtrsim 50$ pulsars with bi-weekly cadence over the coming years to decades and utilizing substantial amounts of telescope time ($\sim$ 1000s hours per year). Furthermore, the detection and characterization of GWs also necessitates the continuous development and improvement of statistical analysis techniques and infrastructures, in addition to finding new high-precision millisecond pulsars.

EM Observations: Upcoming time-domain and spectroscopic surveys will provide large samples of quasars. In order to efficiently distinguish binaries from AGNs with a single SMBH (i.e. minimize false detections), it is necessary to develop advanced statistical models of AGN variability (photometric and spectroscopic) over broad timescales. Long-term and multi-wavelength monitoring is critical to exclude false positives, and access a sufficient parameter space of SMBHB orbital periods [105]. Ample access to smaller-scale telescopes

---

[6] In general, measurement of the GW-frequency evolution is required to break the degeneracy between chirp-mass and distance. With LISA and LIGO, the 'chirp' (df/dt) itself can be observed, but this is unlikely for PTAs. Instead, with high signal-to-noise ratio CGW observations, the 'pulsar term' can be recovered (visually apparent in Fig. 1, C2), allowing for measurement of the luminosity distance.

	GW only	EM only	GW + EM
Q1: SMBHB evolution	*GWB* spectrum (slope, amplitude, and features) constrain SMBHB/environment interactions. *CGW* detections will identify small-separation binaries in the GW regime.	*X-ray/Radio* surveys can directly image kpc binaries. *mm/Radio VLBI* can spatially resolve parsec binaries. *X-ray/Optical/IR/Radio* can identify mergers and track star/gas dynamics.	**Directly maps host-galaxy properties to corresponding binary evolutionary stages. Provides a complete sequence of evolution from kpc to sub-pc scales** and associated timescales.
Q2: Accretion & Observables	Detection of *CGWs* will provide measurements of orbital frequency, eccentricity, phase, and a degenerate mass/distance.	EM signatures provide binary candidates. Binaries are cross-checked with other indirect indicators, but may not conclusively confirm the binary nature of candidates.	Definitive detection of SMBHB with host galaxy **allows for in-depth multi-wavelength studies of binary emission.** With known binary parameters, measurements of e.g., Eddington ratio, radiative efficiency and spins are possible.
Q3: SMBH–host co-evolution	*CGW* detection will provide a measurement of the chirp mass divided by the distance to the binary. Sources with high SNR or rapid frequency evolution yield independent distances.	*X-ray/Optical/IR/UV* data will constrain the host galaxy properties (bulge mass, velocity dispersion, virial mass, Sersic index, etc), and potentially binary mass ratio.	**Directly measure SMBH masses and host-galaxy properties. Calibrate scaling relations** without suffering from EM mass-measurement biases.
Q4: Cosmological Distances	*CGWs* allow for independent measurement of luminosity distance, if GW frequency evolution is determined.	*Optical/IR/UV* spectra will constrain or measure the host galaxy redshift. *X-ray* can constrain AGN redshifts directly with iron line detections.	**Use SMBHBs as 'standard sirens' to constrain cosmological parameters**, potentially at larger redshifts than accessible by LIGO, and with independent errors from the supernovae distance-ladder.

Table 1: Summary of major advances attainable through GW and EM observations.

for dedicated follow-up campaigns and searches for multiple binary tracers (e.g., shifted broad lines in photometric candidates) is also necessary. Complete catalogs of massive galaxies out to distances of a few Gpc will significantly aid host galaxy identification [127]. Once host galaxies are identified, VLBI and thirty-meter class telescopes, like GMT and TMT, coupled with adaptive optics, can produce maps of the inner structures of the galaxies and provide detailed information of the SMBHB environments.

Theory and computation: Improvements in the theoretical predictions of EM signatures from binary AGN will drastically improve our ability to detect SMBHB candidates, rule out false-positives, and eventually identify host galaxies following CGW detections. Next-generation 3D simulations of circumbinary disks must be developed to include, for example, the effects of radiation and feedback, and follow binary evolution for more than a small number of orbits. These disk-scale simulations must also be consistently coupled to realistic environments provided by cosmological simulations. Similarly, improvements in simulations of binary-stellar interactions are also required, in particular, expanding to realistic timescales and galactic environments. Once GWs are detected, these models will be crucial in decoding binary parameters from GW+EM observations, both of CGW sources and the GWB spectrum.

References

[1] Kormendy, J. and Richstone, D. *Annu. Rev. Astron. Astrophys.*, 33:581, 1995. `http://dx.doi.org/10.1146/annurev.aa.33.090195.003053`.

[2] Begelman, M.C., Blandford, R.D. and Rees, M.J. *Nature*, 287:307–309, September 1980. `http://dx.doi.org/10.1038/287307a0`.

[3] Goulding, A.D., Greene, J.E., Bezanson, R., Greco, J., Johnson, S. et al. *PASJ*, 70: S37, January 2018. `http://dx.doi.org/10.1093/pasj/psx135`.

[4] Koss, M.J., Blecha, L., Bernhard, P., Hung, C.L., Lu, J.R. et al. *Nature*, 563:214–216, November 2018. `http://dx.doi.org/10.1038/s41586-018-0652-7`.

[5] Hellings, R.W. and Downs, G.S. *Astrophys. J. Lett.*, 265:L39–L42, February 1983. `http://dx.doi.org/10.1086/183954`.

[6] Foster, R.S. and Backer, D.C. *Astrophys. J.*, 361:300–308, September 1990. `http://dx.doi.org/10.1086/169195`.

[7] Manchester, R.N., Hobbs, G., Bailes, M., Coles, W.A., van Straten, W. et al. *PASA*, 30:e017, January 2013. `http://dx.doi.org/10.1017/pasa.2012.017`.

[8] Kramer, M. and Champion, D.J. *Classical and Quantum Gravity*, 30(22):224009, November 2013. `http://dx.doi.org/10.1088/0264-9381/30/22/224009`.

[9] McLaughlin, M.A. *Classical and Quantum Gravity*, 30(22):224008, November 2013. `http://dx.doi.org/10.1088/0264-9381/30/22/224008`.

[10] The NANOGrav Collaboration, Arzoumanian, Z., Brazier, A., Burke-Spolaor, S., Chamberlin, S. et al. *Astrophys. J.*, 813:65, November 2015. `http://dx.doi.org/10.1088/0004-637X/813/1/65`.

[11] Rosado, P.A., Sesana, A. and Gair, J. *Mon. Not. R. Astron. Soc.*, 451:2417–2433, August 2015. `http://dx.doi.org/10.1093/mnras/stv1098`.

[12] Taylor, S.R., Vallisneri, M., Ellis, J.A., Mingarelli, C.M.F., Lazio, T.J.W. et al. *Astrophys. J. Lett.*, 819:L6, March 2016. `http://dx.doi.org/10.3847/2041-8205/819/1/L6`.

[13] Kelley, L.Z., Blecha, L., Hernquist, L., Sesana, A. and Taylor, S.R. *Mon. Not. R. Astron. Soc.*, 477:964–976, June 2018. `http://dx.doi.org/10.1093/mnras/sty689`.

[14] Rajagopal, M. and Romani, R.W. *Astrophys. J.*, 446:543, June 1995. `http://dx.doi.org/10.1086/175813`.

[15] Phinney, E.S. *ArXiv Astrophysics e-prints*, August 2001.

[16] Jaffe, A.H. and Backer, D.C. *Astrophys. J.*, 583:616–631, February 2003. `http://dx.doi.org/10.1086/345443`.

[17] Wyithe, J.S.B. and Loeb, A. *Astrophys. J.*, 590:691–706, June 2003. `http://dx.doi.org/10.1086/375187`.

[18] Enoki, M., Inoue, K.T., Nagashima, M. and Sugiyama, N. *Astrophys. J.*, 615:19–28, November 2004. `http://dx.doi.org/10.1086/424475`.

[19] Sesana, A., Haardt, F., Madau, P. and Volonteri, M. *Astrophys. J.*, 611:623–632, August 2004. `http://dx.doi.org/10.1086/422185`.

[20] Arzoumanian, Z., Baker, P.T., Brazier, A., Burke-Spolaor, S., Chamberlin, S.J. et al. *Astrophys. J.*, 859:47, May 2018. `http://dx.doi.org/10.3847/1538-4357/aabd3b`.

[21] Aggarwal, K., Arzoumanian, Z., Baker, P.T., Brazier, A., Brinson, M.R. et al. *arXiv*

e-prints, art. arXiv:1812.11585, Dec 2018.

[22] Mingarelli, C.M.F., Lazio, T.J.W., Sesana, A., Greene, J.E., Ellis, J.A. et al. *Nature Astronomy*, 1:886–892, November 2017. `http://dx.doi.org/10.1038/s41550-017-0299-6`.

[23] Merritt, D. and Milosavljević, M. *Living Reviews in Relativity*, 8, November 2005. `http://dx.doi.org/10.12942/lrr-2005-8`.

[24] Souza Lima, R., Mayer, L., Capelo, P.R. and Bellovary, J.M. *Astrophys. J.*, 838:13, March 2017. `http://dx.doi.org/10.3847/1538-4357/aa5d19`.

[25] Fiacconi, D., Mayer, L., Roškar, R. and Colpi, M. *Astrophys. J. Lett.*, 777:L14, November 2013. `http://dx.doi.org/10.1088/2041-8205/777/1/L14`.

[26] Colpi, M. *Space Science Rev.*, 183:189–221, September 2014. `http://dx.doi.org/10.1007/s11214-014-0067-1`.

[27] Makino, J. and Ebisuzaki, T. *Astrophys. J.*, 436:607–610, December 1994. `http://dx.doi.org/10.1086/174935`.

[28] Blaes, O., Lee, M.H. and Socrates, A. *Astrophys. J.*, 578:775–786, October 2002. `http://dx.doi.org/10.1086/342655`.

[29] Hoffman, L. and Loeb, A. *Mon. Not. R. Astron. Soc.*, 377:957–976, May 2007. `http://dx.doi.org/10.1111/j.1365-2966.2007.11694.x`.

[30] Amaro-Seoane, P., Sesana, A., Hoffman, L., Benacquista, M., Eichhorn, C. et al. *Mon. Not. R. Astron. Soc.*, 402:2308–2320, March 2010. `http://dx.doi.org/10.1111/j.1365-2966.2009.16104.x`.

[31] Schnittman, J.D. *Classical and Quantum Gravity*, 28(9):094021, May 2011. `http://dx.doi.org/10.1088/0264-9381/28/9/094021`.

[32] Dotti, M., Sesana, A. and Decarli, R. *Advances in Astronomy*, 2012:940568, 2012. `http://dx.doi.org/10.1155/2012/940568`.

[33] Burke-Spolaor, S. *Classical and Quantum Gravity*, 30(22):224013, November 2013. `http://dx.doi.org/10.1088/0264-9381/30/22/224013`.

[34] Eracleous, M., Halpern, J.P., M. Gilbert, A., Newman, J.A. and Filippenko, A.V. *Astrophys. J.*, 490:216–226, November 1997. `http://dx.doi.org/10.1086/304859`.

[35] Liu, J., Eracleous, M. and Halpern, J.P. *Astrophys. J.*, 817:42, January 2016. `http://dx.doi.org/10.3847/0004-637X/817/1/42`.

[36] Kormendy, J. and Ho, L.C. *Annu. Rev. Astron. Astrophys.*, 51:511–653, August 2013. `http://dx.doi.org/10.1146/annurev-astro-082708-101811`.

[37] Simon, J. and Burke-Spolaor, S. *Astrophys. J.*, 826:11, July 2016. `http://dx.doi.org/10.3847/0004-637X/826/1/11`.

[38] McConnell, N.J. and Ma, C.P. *Astrophys. J.*, 764:184, February 2013. `http://dx.doi.org/10.1088/0004-637X/764/2/184`.

[39] Reines, A.E. and Volonteri, M. *Astrophys. J.*, 813:82, November 2015. `http://dx.doi.org/10.1088/0004-637X/813/2/82`.

[40] Shankar, F., Bernardi, M., Sheth, R.K., Ferrarese, L., Graham, A.W. et al. *Mon. Not. R. Astron. Soc.*, 460:3119–3142, August 2016. `http://dx.doi.org/10.1093/mnras/stw678`.

[41] Schutz, B.F. *Nature*, 323:310–311, Sep 1986. `http://dx.doi.org/10.1038/323310a0`.

[42] Holz, D.E. and Hughes, S.A. *Astrophys. J.*, 629:15–22, Aug 2005. `http://dx.doi.org/10.1086/431341`.

[43] Abbott, B.P., Abbott, R., Abbott, T.D., Acernese, F., Ackley, K. et al. *Nature*, 551: 85–88, November 2017. `http://dx.doi.org/10.1038/nature24471`.

[44] Amaro-Seoane, P., Aoudia, S., Babak, S., Binétruy, P., Berti, E. et al. *Classical and Quantum Gravity*, 29(12):124016, June 2012. `http://dx.doi.org/10.1088/0264-9381/29/12/124016`.

[45] Kocsis, B., Haiman, Z. and Menou, K. *Astrophys. J.*, 684:870–887, September 2008. `http://dx.doi.org/10.1086/590230`.

[46] Tamanini, N., Caprini, C., Barausse, E., Sesana, A., Klein, A. et al. *Journal of Cosmology and Astro-Particle Physics*, 2016:002, Apr 2016. `http://dx.doi.org/10.1088/1475-7516/2016/04/002`.

[47] Del Pozzo, W., Sesana, A. and Klein, A. *Mon. Not. R. Astron. Soc.*, 475:3485–3492, Apr 2018. `http://dx.doi.org/10.1093/mnras/sty057`.

[48] Jenet, F.A., Lommen, A., Larson, S.L. and Wen, L. *Astrophys. J.*, 606:799–803, May 2004. `http://dx.doi.org/10.1086/383020`.

[49] Graham, M.J., Djorgovski, S.G., Stern, D., Drake, A.J., Mahabal, A.A. et al. *Mon. Not. R. Astron. Soc.*, 453:1562–1576, October 2015. `http://dx.doi.org/10.1093/mnras/stv1726`.

[50] Charisi, M., Bartos, I., Haiman, Z., Price-Whelan, A.M., Graham, M.J. et al. *Mon. Not. R. Astron. Soc.*, 463:2145–2171, December 2016. `http://dx.doi.org/10.1093/mnras/stw1838`.

[51] Sesana, A., Haiman, Z., Kocsis, B. and Kelley, L.Z. *Astrophys. J.*, 856:42, March 2018. `http://dx.doi.org/10.3847/1538-4357/aaad0f`.

[52] d'Ascoli, S., Noble, S.C., Bowen, D.B., Campanelli, M., Krolik, J.H. et al. *Astrophys. J.*, 865:140, October 2018. `http://dx.doi.org/10.3847/1538-4357/aad8b4`.

[53] Runnoe, J.C., Eracleous, M., Pennell, A., Mathes, G., Boroson, T. et al. *Mon. Not. R. Astron. Soc.*, 468:1683–1702, June 2017. `http://dx.doi.org/10.1093/mnras/stx452`.

[54] Artymowicz, P. and Lubow, S.H. *Astrophys. J. Lett.*, 467:L77, August 1996. `http://dx.doi.org/10.1086/310200`.

[55] Shi, J.M. and Krolik, J.H. *Astrophys. J.*, 807:131, July 2015. `http://dx.doi.org/10.1088/0004-637X/807/2/131`.

[56] Antonini, F. and Merritt, D. *Astrophys. J.*, 745:83, January 2012. `http://dx.doi.org/10.1088/0004-637X/745/1/83`.

[57] Pfister, H., Lupi, A., Capelo, P.R., Volonteri, M., Bellovary, J.M. et al. *Mon. Not. R. Astron. Soc.*, 471:3646–3656, November 2017. `http://dx.doi.org/10.1093/mnras/stx1853`.

[58] Merritt, D. *Classical and Quantum Gravity*, 30(24):244005, December 2013. `http://dx.doi.org/10.1088/0264-9381/30/24/244005`.

[59] Vasiliev, E., Antonini, F. and Merritt, D. *Astrophys. J.*, 810:49, September 2015. `http://dx.doi.org/10.1088/0004-637X/810/1/49`.

[60] Cuadra, J., Armitage, P.J., Alexander, R.D. and Begelman, M.C. *Mon. Not. R. Astron.*

Soc., 393:1423–1432, March 2009. `http://dx.doi.org/10.1111/j.1365-2966.2008.14147.x`.

[61] Shi, J.M., Krolik, J.H., Lubow, S.H. and Hawley, J.F. *Astrophys. J.*, 749:118, Apr 2012. `http://dx.doi.org/10.1088/0004-637X/749/2/118`.

[62] Fontecilla, C., Haiman, Z. and Cuadra, J. *Mon. Not. R. Astron. Soc.*, 482:4383–4396, February 2019. `http://dx.doi.org/10.1093/mnras/sty2972`.

[63] Miranda, R., Muñoz, D.J. and Lai, D. *Mon. Not. R. Astron. Soc.*, 466:1170–1191, April 2017. `http://dx.doi.org/10.1093/mnras/stw3189`.

[64] Muñoz, D.J., Miranda, R. and Lai, D. *Astrophys. J.*, 871:84, January 2019. `http://dx.doi.org/10.3847/1538-4357/aaf867`.

[65] Moody, M.S.L., Shi, J.M. and Stone, J.M. *arXiv e-prints*, art. arXiv:1903.00008, Feb 2019.

[66] Khan, F.M., Holley-Bockelmann, K., Berczik, P. and Just, A. *Astrophys. J.*, 773:100, August 2013. `http://dx.doi.org/10.1088/0004-637X/773/2/100`.

[67] Comerford, J.M., Gerke, B.F., Stern, D., Cooper, M.C., Weiner, B.J. et al. *Astrophys. J.*, 753:42, Jul 2012. `http://dx.doi.org/10.1088/0004-637X/753/1/42`.

[68] Liu, X., Civano, F., Shen, Y., Green, P., Greene, J.E. et al. *Astrophys. J.*, 762:110, January 2013. `http://dx.doi.org/10.1088/0004-637X/762/2/110`.

[69] Rodriguez, C., Taylor, G.B., Zavala, R.T., Peck, A.B., Pollack, L.K. et al. *Astrophys. J.*, 646:49–60, July 2006. `http://dx.doi.org/10.1086/504825`.

[70] Kharb, P., Lal, D.V. and Merritt, D. *Nature Astronomy*, 1:727–733, Sep 2017. `http://dx.doi.org/10.1038/s41550-017-0256-4`.

[71] D'Orazio, D.J. and Loeb, A. *Astrophys. J.*, 863:185, August 2018. `http://dx.doi.org/10.3847/1538-4357/aad413`.

[72] Nguyen, K. and Bogdanović, T. *Astrophys. J.*, 828:68, September 2016. `http://dx.doi.org/10.3847/0004-637X/828/2/68`.

[73] Nguyen, K., Bogdanović, T., Runnoe, J.C., Eracleous, M., Sigurdsson, S. et al. *Astrophys. J.*, 870:16, January 2019. `http://dx.doi.org/10.3847/1538-4357/aaeff0`.

[74] Tsalmantza, P., Decarli, R., Dotti, M. and Hogg, D.W. *Astrophys. J.*, 738:20, September 2011. `http://dx.doi.org/10.1088/0004-637X/738/1/20`.

[75] Bon, E., Jovanović, P., Marziani, P., Shapovalova, A.I., Bon, N. et al. *Astrophys. J.*, 759:118, November 2012. `http://dx.doi.org/10.1088/0004-637X/759/2/118`.

[76] Eracleous, M., Boroson, T.A., Halpern, J.P. and Liu, J. *Astrophys. J., Suppl. Ser.*, 201:23, August 2012. `http://dx.doi.org/10.1088/0067-0049/201/2/23`.

[77] Ju, W., Greene, J.E., Rafikov, R.R., Bickerton, S.J. and Badenes, C. *Astrophys. J.*, 777:44, November 2013. `http://dx.doi.org/10.1088/0004-637X/777/1/44`.

[78] Decarli, R., Dotti, M., Fumagalli, M., Tsalmantza, P., Montuori, C. et al. *Mon. Not. R. Astron. Soc.*, 433:1492–1504, August 2013. `http://dx.doi.org/10.1093/mnras/stt831`.

[79] Shen, Y., Liu, X., Loeb, A. and Tremaine, S. *Astrophys. J.*, 775:49, September 2013. `http://dx.doi.org/10.1088/0004-637X/775/1/49`.

[80] Liu, X., Shen, Y., Bian, F., Loeb, A. and Tremaine, S. *Astrophys. J.*, 789:140, July 2014. `http://dx.doi.org/10.1088/0004-637X/789/2/140`.

[81] McGurk, R.C., Max, C.E., Medling, A.M., Shields, G.A. and Comerford, J.M. *Astrophys. J.*, 811:14, September 2015. `http://dx.doi.org/10.1088/0004-637X/811/1/14`.

[82] Guo, H., Liu, X., Shen, Y., Loeb, A., Monroe, T. et al. *Mon. Not. R. Astron. Soc.*, 482:3288–3307, January 2019. `http://dx.doi.org/10.1093/mnras/sty2920`.

[83] Kollmeier, J.A., Zasowski, G., Rix, H.W., Johns, M., Anderson, S.F. et al. *arXiv e-prints*, art. arXiv:1711.03234, Nov 2017.

[84] MacFadyen, A.I. and Milosavljević, M. *Astrophys. J.*, 672:83–93, January 2008. `http://dx.doi.org/10.1086/523869`.

[85] Roedig, C., Dotti, M., Sesana, A., Cuadra, J. and Colpi, M. *Mon. Not. R. Astron. Soc.*, 415:3033–3041, Aug 2011. `http://dx.doi.org/10.1111/j.1365-2966.2011.18927.x`.

[86] Noble, S.C., Mundim, B.C., Nakano, H., Krolik, J.H., Campanelli, M. et al. *Astrophys. J.*, 755:51, Aug 2012. `http://dx.doi.org/10.1088/0004-637X/755/1/51`.

[87] Farris, B.D., Gold, R., Paschalidis, V., Etienne, Z.B. and Shapiro, S.L. *Phys. Rev. Lett.*, 109:221102, Nov 2012. `http://dx.doi.org/10.1103/PhysRevLett.109.221102`.

[88] Farris, B.D., Duffell, P., MacFadyen, A.I. and Haiman, Z. *Astrophys. J.*, 783:134, March 2014. `http://dx.doi.org/10.1088/0004-637X/783/2/134`.

[89] D'Orazio, D.J., Haiman, Z. and MacFadyen, A. *Mon. Not. R. Astron. Soc.*, 436:2997–3020, December 2013. `http://dx.doi.org/10.1093/mnras/stt1787`.

[90] Gold, R., Paschalidis, V., Etienne, Z.B., Shapiro, S.L. and Pfeiffer, H.P. *Phys. Rev. D*, 89:064060, Mar 2014. `http://dx.doi.org/10.1103/PhysRevD.89.064060`.

[91] Gold, R., Paschalidis, V., Ruiz, M., Shapiro, S.L., Etienne, Z.B. et al. *Phys. Rev. D*, 90:104030, Nov 2014. `http://dx.doi.org/10.1103/PhysRevD.90.104030`.

[92] D'Orazio, D.J., Haiman, Z. and Schiminovich, D. *Nature*, 525:351–353, September 2015. `http://dx.doi.org/10.1038/nature15262`.

[93] Bowen, D.B., Mewes, V., Campanelli, M., Noble, S.C., Krolik, J.H. et al. *Astrophys. J.*, 853:L17, Jan 2018. `http://dx.doi.org/10.3847/2041-8213/aaa756`.

[94] Roedig, C., Krolik, J.H. and Miller, M.C. *Astrophys. J.*, 785:115, April 2014. `http://dx.doi.org/10.1088/0004-637X/785/2/115`.

[95] Shi, J.M. and Krolik, J.H. *Astrophys. J.*, 832:22, November 2016. `http://dx.doi.org/10.3847/0004-637X/832/1/22`.

[96] Ryan, G. and MacFadyen, A. *Astrophys. J.*, 835:199, February 2017. `http://dx.doi.org/10.3847/1538-4357/835/2/199`.

[97] Tang, Y., Haiman, Z. and MacFadyen, A. *Mon. Not. R. Astron. Soc.*, 476:2249–2257, May 2018. `http://dx.doi.org/10.1093/mnras/sty423`.

[98] Valtonen, M.J., Lehto, H.J., Nilsson, K., Heidt, J., Takalo, L.O. et al. *Nature*, 452:851–853, April 2008. `http://dx.doi.org/10.1038/nature06896`.

[99] MacLeod, C.L., Ivezić, Ž., Kochanek, C.S., Kozłowski, S., Kelly, B. et al. *Astrophys. J.*, 721:1014–1033, October 2010. `http://dx.doi.org/10.1088/0004-637X/721/2/1014`.

[100] Vaughan, S., Uttley, P., Markowitz, A.G., Huppenkothen, D., Middleton, M.J. et al. *Mon. Not. R. Astron. Soc.*, 461:3145–3152, September 2016. `http://dx.doi.org/10.`

`1093/mnras/stw1412`.

[101] Liu, T., Gezari, S., Burgett, W., Chambers, K., Draper, P. et al. *Astrophys. J.*, 833:6, December 2016. `http://dx.doi.org/10.3847/0004-637X/833/1/6`.

[102] Holgado, A.M., Sesana, A., Sandrinelli, A., Covino, S., Treves, A. et al. *Mon. Not. R. Astron. Soc.*, 481:L74–L78, Nov 2018. `http://dx.doi.org/10.1093/mnrasl/sly158`.

[103] Bellm, E.C., Kulkarni, S.R., Graham, M.J., Dekany, R., Smith, R.M. et al. *PASP*, 131 (1):018002, January 2019. `http://dx.doi.org/10.1088/1538-3873/aaecbe`.

[104] Tyson, J.A. Large Synoptic Survey Telescope: Overview. In Tyson, J.A. and Wolff, S., editors, *Survey and Other Telescope Technologies and Discoveries*, volume 4836 of *Proc.SPIE Int.Soc.Opt.Eng.*, pages 10–20, December 2002. `http://dx.doi.org/10.1117/12.456772`.

[105] Kelley, L.Z., Haiman, Z., Sesana, A. and Hernquist, L. *arXiv e-prints*, September 2018.

[106] Roos, N., Kaastra, J.S. and Hummel, C.A. *Astrophys. J.*, 409:130–133, May 1993. `http://dx.doi.org/10.1086/172647`.

[107] Romero, G.E., Chajet, L., Abraham, Z. and Fan, J.H. *Astron. Astrophys.*, 360:57–64, August 2000.

[108] D'Orazio, D.J., Haiman, Z. and Schiminovich, D. *Nature*, 525:351–353, September 2015. `http://dx.doi.org/10.1038/nature15262`.

[109] Charisi, M., Haiman, Z., Schiminovich, D. and D'Orazio, D.J. *Mon. Not. R. Astron. Soc.*, 476:4617–4628, Jun 2018. `http://dx.doi.org/10.1093/mnras/sty516`.

[110] D'Orazio, D.J. and Di Stefano, R. *Mon. Not. R. Astron. Soc.*, 474:2975–2986, March 2018. `http://dx.doi.org/10.1093/mnras/stx2936`.

[111] Sesana, A., Roedig, C., Reynolds, M.T. and Dotti, M. *Mon. Not. R. Astron. Soc.*, 420: 860–877, February 2012. `http://dx.doi.org/10.1111/j.1365-2966.2011.20097.x`.

[112] McKernan, B., Ford, K.E.S., Kocsis, B. and Haiman, Z. *Mon. Not. R. Astron. Soc.*, 432:1468–1482, June 2013. `http://dx.doi.org/10.1093/mnras/stt567`.

[113] McKernan, B. and Ford, K.E.S. *Mon. Not. R. Astron. Soc.*, 452:L1–L5, September 2015. `http://dx.doi.org/10.1093/mnrasl/slv076`.

[114] Tanaka, T., Menou, K. and Haiman, Z. *Mon. Not. R. Astron. Soc.*, 420:705–719, February 2012. `http://dx.doi.org/10.1111/j.1365-2966.2011.20083.x`.

[115] Gültekin, K. and Miller, J.M. *Astrophys. J.*, 761:90, December 2012. `http://dx.doi.org/10.1088/0004-637X/761/2/90`.

[116] Chen, X., Madau, P., Sesana, A. and Liu, F.K. *Astrophys. J.*, 697:L149–L152, Jun 2009. `http://dx.doi.org/10.1088/0004-637X/697/2/L149`.

[117] Liu, F.K., Li, S. and Chen, X. *Astrophys. J. Lett.*, 706:L133–L137, November 2009. `http://dx.doi.org/10.1088/0004-637X/706/1/L133`.

[118] Liu, F.K., Li, S. and Komossa, S. *Astrophys. J.*, 786:103, May 2014. `http://dx.doi.org/10.1088/0004-637X/786/2/103`.

[119] Komossa, S. and Zensus, J.A. Compact object mergers: observations of supermassive binary black holes and stellar tidal disruption events. In Meiron, Y., Li, S., Liu, F.K. and Spurzem, R., editors, *Star Clusters and Black Holes in Galaxies across Cosmic Time*, volume 312 of *IAU Symposium*, pages 13–25, February 2016. `http://dx.doi.`

org/10.1017/S1743921315007395.

[120] Lauer, T.R., Gebhardt, K., Richstone, D., Tremaine, S., Bender, R. et al. *Astron. J.*, 124:1975–1987, October 2002. `http://dx.doi.org/10.1086/342932`.

[121] Sesana, A. and Vecchio, A. *Phys. Rev. D*, 81(10):104008, May 2010. `http://dx.doi.org/10.1103/PhysRevD.81.104008`.

[122] Zhu, X.J., Wen, L., Xiong, J., Xu, Y., Wang, Y. et al. *Mon. Not. R. Astron. Soc.*, 461: 1317–1327, Sep 2016. `http://dx.doi.org/10.1093/mnras/stw1446`.

[123] Bennert, V.N., Auger, M.W., Treu, T., Woo, J.H. and Malkan, M.A. *Astrophys. J.*, 742:107, December 2011. `http://dx.doi.org/10.1088/0004-637X/742/2/107`.

[124] Graham, A.W. and Scott, N. *Astrophys. J.*, 764:151, February 2013. `http://dx.doi.org/10.1088/0004-637X/764/2/151`.

[125] Ellis, J.A. *Classical and Quantum Gravity*, 30:224004, Nov 2013. `http://dx.doi.org/10.1088/0264-9381/30/22/224004`.

[126] The eLISA Consortium, :, Seoane, P.A., Aoudia, S., Audley, H. et al. *ArXiv e-prints*, May 2013.

[127] Goldstein, J.M., Sesana, A., Holgado, A.M. and Veitch, J. *Mon. Not. R. Astron. Soc.*, 485:248–259, May 2019. `http://dx.doi.org/10.1093/mnras/stz420`.