

# Astro2020 Science White Paper: THE GRAVITATIONAL WAVE VIEW OF MASSIVE BLACK HOLES

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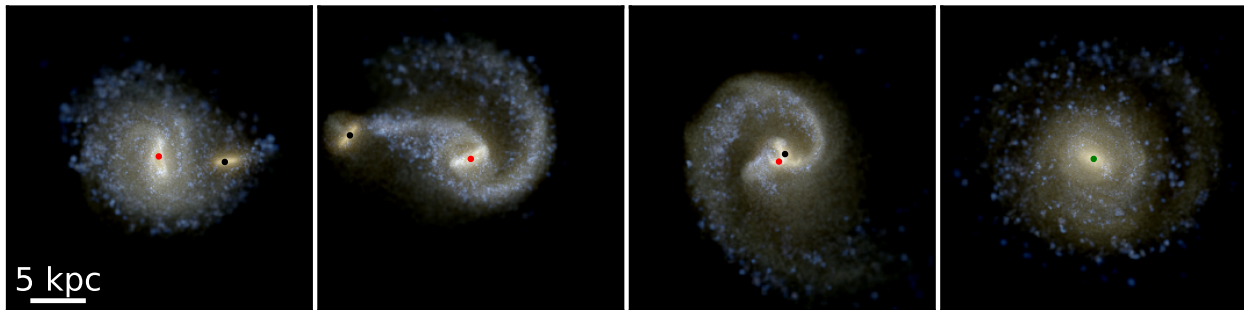


Figure depicting the merger of two galaxies with their nuclear MBHs (circles), adopted with permission from Tremmel et al. [1]

Coalescing, massive black-hole (MBH) binaries are the most powerful sources of gravitational waves (GWs) in the Universe, which makes MBH science a prime focus for ongoing and upcoming GW observatories. The Laser Interferometer Space Antenna (LISA) – a gigameter scale space-based GW observatory – will grant us access to an immense cosmological volume, revealing MBHs merging when the first cosmic structures assembled in the Dark Ages. LISA will unveil the yet unknown origin of the first quasars, and detect the teeming population of MBHs of  $10^4\text{--}7 M_\odot$  forming within protogalactic halos. The Pulsar Timing Array, a galactic-scale GW survey, can access the largest MBHs the Universe, detecting the cosmic GW foreground from inspiraling MBH binaries of  $\sim 10^9 M_\odot$ . LISA can measure MBH spins and masses with precision far exceeding that from electromagnetic (EM) probes, and together, both GW observatories will provide the first full census of binary MBHs, and their orbital dynamics, across cosmic time. Detecting the loud gravitational signal of these MBH binaries will also trigger alerts for EM counterpart searches, from decades (PTAs) to hours (LISA) prior to the final merger. By witnessing both the GW and EM signals of MBH mergers, precious information will be gathered about the rich and complex environment in the aftermath of a galaxy collision. The unique GW characterization of MBHs will shed light on the deep link between MBHs of  $10^4 - 10^{10} M_\odot$  and the grand design of galaxy assembly, as well as on the complex dynamics that drive MBHs to coalescence.

**Thematic Science Areas:** Galaxy Evolution, Multi Messenger Astronomy and Astrophysics, Cosmology and Fundamental Physics

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## A New Window into the Cosmos

Gravity has its own messenger: GWs are ripples in the fabric of spacetime produced by non-axisymmetric motions of matter. Traveling essentially unimpeded throughout the Universe, GWs carry unbiased information on their sources, from binary stellar remnants, to MBH collisions, to the Big Bang itself. GWs provide a clean way to measure the geometry of black hole spacetimes, including masses and spins, and even characterize their horizons [2, 3, 4]. With their strongly curved geometry and relativistic motion, coalescing MBH binaries generate a highly warped and dynamic spacetime – the strongest gravitational signals expected in the Universe. Moreover, their amplitude and frequency show a simple and universal scaling with mass, inherited from the fact that general relativity has no built-in fundamental scale. This gives us direct access to a huge range of black holes – from primordial to ultra-massive – by exploring different GW bands. With gravity as a messenger, we stand to revolutionize our understanding of the birth, growth, and evolution of MBHs, as well as their role in sketching the cosmological canvas of the Universe.

Most of what we know about MBHs thus far has been informed by EM observations of active galactic nuclei (AGN) over several epochs of cosmic evolution [5, 6]. During the *Cosmic Dawn*, starting at  $z \sim 20$ , mostly-neutral baryons in low-mass dark matter halos began to collapse and fragment, forming the first stars and seed black holes. The physics in this era is all but invisible to us in the EM window until it ends at  $z = 7.5$ , when a myriad of sources of ultra-violet radiation, including accreting MBHs, reionized the intergalactic neutral hydrogen into a hot, tenuous plasma [7]. The most distant quasars are now found at  $z \sim 7$ , when the Universe was less than one billion years old, posing extreme constraints on their formation squarely in this heretofore unobserved era [8]. These rare, overluminous sources are probing the tip of an underlying population of yet undiscovered much fainter objects. GW observations will be key to unveiling the existence of and physics governing MBHs within the Cosmic Dawn.

Well after MBH seeds are sown comes the epoch of *Cosmic Noon*, extending from  $z \sim 6$  to 2. This is the epoch of galaxy growth through repeated major mergers, accretion of lower mass dark-matter halos, and cold gas flowing in along dark matter filaments [9, 10, 11, 12]. Around  $z \sim 2$ , the cosmic integrated star formation rate and AGN activity reach their peak, followed by a decline that extends to the present day [5]. Though it is widely accepted that AGN activity and major mergers are related, the precise details of how MBHs assemble during this epoch is an open question, one that GWs provide unique data to answer.

Upcoming GW observations serve complementary views of the cosmos. GWs at low frequency will observe the origin and evolution of the most extreme and enigmatic objects in the Universe: *massive black holes*. In this whitepaper, we describe the science that can be obtained by LISA, the first-generation space-based GW observatory. By design, LISA will provide key observations needed revolutionize our view of MBHs [13], filling an

### MBH Mysteries

- How are MBHs born and how do they grow?
- How efficiently do MBHs merge and how does this affect their galaxy hosts?
- What are the demographics of MBHs in the Universe?

unobserved gap of  $\sim 9$  orders of magnitude between nHz, where Pulsar Timing Arrays (PTAs) are sensitive to supermassive black holes orbiting on timescales of decades [14], and  $> \text{Hz}$ , where ground-based observatories probe the last fraction of a second of stellar mass black hole mergers.

## Massive Black Holes in the Gravitational Universe

The GW signals from comparable mass ratio coalescing MBHs are similar in shape to the first signal ever detected, GW150914 [15], and the subsequent stellar black-hole binary mergers. Indeed, one simply needs to appropriately rescale the time variable – making the signal longer lasting (from seconds to months)– and the amplitude – which results in signal-to-noise ratios (SNRs) as high as  $\sim 1000$ , to be compared to SNRs of a few tens at most for today’s Advanced LIGO and Advanced Virgo. Because of this rescaling, the GW frequency of merging binary MBHs with total masses of  $10^4 M_\odot - 10^7 M_\odot$  falls squarely within LISA’s bandwidth (which extends from about  $100 \mu\text{Hz}$  to  $100 \text{mHz}$ ) in the late inspiral, merger and ringdown phase of the binary evolution. The best sensitivity will be reached for MBHs with masses comparable to the one residing at the heart of the Milky Way, i.e.  $\sim 10^5 M_\odot - 10^6 M_\odot$ . The galaxy mass function suggests that these ‘low-mass’ MBHs are the most common, but the least well-known in terms of basic demographics, birth, growth, dynamics and connection to their galaxy host [16].

Figure 1 shows the vastness of the LISA exploration volume: lines of constant SNR are depicted in the  $M_B - z$  plane, where  $M_B$  is the mass of the binary in the source frame. LISA will be unique at detecting the GW signal from coalescing binaries between  $10^4 M_\odot$  and a few  $10^7 M_\odot$ , with SNR higher than 20 at formation redshifts  $z$  as large as 20, and SNR as high as a few thousands at low redshifts [2, 13].

### Solving MBH Mysteries

- LISA will measure the masses and spins of coalescing MBHs to a few % accuracy in  $10^4 - 10^7 M_\odot$  binaries out to  $z \sim 20$ .
- GWs will unveil the MBH growth via mergers, and their accretion history via mass and spin measurements.
- GWs will shed light on the co-evolution of galaxies and MBHs.

Detecting coalescing MBH binaries with  $M_B$  of  $10^4 - 10^6 M_\odot$  at  $z > 10$  will provide unique insights into the initial masses, occupation fraction, and early growth of the first seed BHs, ancestors of the MBHs [17, 18]. This will inform us about the physics producing the seeds, whether it involves the first generation of metal-free stars, the direct collapse of massive clouds [19], the collapse of hyper-massive stars formed in stellar runaway collisions [20], or a different process altogether, such as primordial black holes formed in the early Universe, before the epoch of galaxy formation [21]. Knowledge

of this population will anchor the initial conditions of MBH cosmic evolution, setting the stage for their subsequent mass growth and merger rate.

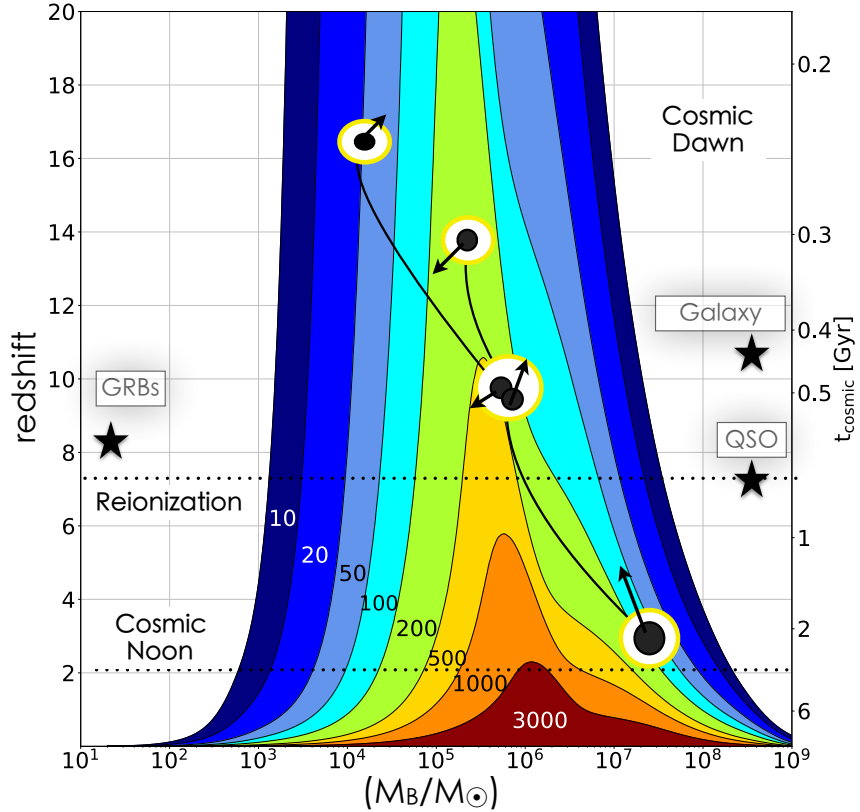


Figure 1: Contours of constant SNR as a function of redshift (cosmic time) and source-frame binary mass  $M_B$  for the LISA observatory. For this figure, the MBHs are non spinning and have mass ratio  $q = 0.5$ . Overlaid is an illustration of evolutionary tracks ending with the formation of a MBH at  $z \sim 3$ . Black dots and arrows represent the MBHs and their spins, respectively. MBHs are embedded in galaxy halos (white-yellow circles) and experience episodes of accretion (black lines) and mergers. Black stars refer to the most distant long Gamma-Ray Burst host, quasar and galaxy detected so far.

Between about  $3 \lesssim z \lesssim 10$ , LISA will detect the inspiral, merger and ringdown of sources with  $10^5 < M_B/M_\odot < 10^7$ , enabling the measurement of their intrinsic masses with accuracies at the percent level [2]. GW signals will also carry exquisite information on the MBH spins, which enhance the GW amplitude, introducing modulations in the signal due to precession. Spins of MBHs powering AGN are difficult to measure from their EM spectra [22]. On the contrary, the spin of the larger (smaller) MBH in a binary will be measured from the GW signal with absolute error of better than 0.01 (0.1) in several LISA events, and the spin misalignment relative to the orbital angular momentum will be determined to within 10 degrees or better [2]. Individual spins prior to the merger encode information on whether accretion, which shaped both the MBH mass and spin evolution, was coherent (leading to spins close to maximal and small misalignment angles) or chaotic (leading to lower average spins and random spin orientations over the black hole life cycle) [23, 24, 25].

This will give us the unprecedented opportunity to reconstruct the MBH cosmic history from GW observations alone [26]. Moreover, by measuring the angle between BH spins and the angular momentum, crucial information will be gathered about the interaction between the MBHs and their environment and about whether the binary evolution is driven by the gas. In particular, gas can exert dissipative torques on the BH spins, potentially aligning them with the gas angular momentum. This also has crucial implications for the fate of the MBH produced by the merger, which could be imparted a large GW recoil velocity in the presence of large spin orbit misalignment prior to merger [27, 28, 29, 30, 31, 32, 33, 34, 35].

As illustrated in Figure 1, GWs from MBHs are incredibly strong, and the advantage of this fact cannot be understated. At Cosmic Noon, right when galaxy mergers are rife, MBH mergers become extraordinarily loud, which enables precise measurements of the source parameters over 12 billion years of cosmic time. MBH coalescences may not occur in vacuum, and low-redshift ( $z \lesssim 2$ ) binaries of  $10^5 < M_B/M_\odot < 10^7$  surrounded by circumbinary gas, may outshine in the optical and X-rays during the inspiral and merger proper, becoming key targets for EM follow up, with advance warning of hours. These mergers will be localized within 10 or even  $0.4 \text{ deg}^2$ , corresponding to the field of view of Large Synoptic Survey Telescope and of the Athena WFI [36], respectively. The science with contemporaneous EM and GW observations is spectacular. It has the potential to discover the yet unknown periodic emission from shocked gas surrounding the two MBHs in the violently changing spacetime before merger [37, 38, 39, 40, 41], flashes, bursts and jetted emission at merger [42, 43], and also post-merger afterglow signatures [44]. Linking masses and spins determined with exquisite precision by the GW signal with EM emission will be paramount.

## Deciphering the Astrophysics Behind the Discovery

At all redshifts, forming a MBH binary after a galaxy merger requires dissipation of orbital energy and efficient transport of angular momentum from the galaxy scale of hundreds of thousands of parsecs to the micro-parsec scale, when the merger gives birth to a new, single MBH [45, 46, 47, 48, 49, 50, 51, 52]. The physics governing the orbital evolution of a MBH pair on each scale is dramatically different. The process starts with the assembly of galaxy haloes and is followed by galaxy collisions, which all occur on cosmological scales [1]. In the new galaxy, the pairing, hardening, and coalescence of two MBHs is a complicated dynamical problem. The processes of galaxy and MBH binary dynamics are intimately connected. The link is provided by several strands of highly-coupled non-linear physics that ignites star formation, triggers nuclear inflows of gas, excites stellar and AGN feedback, and transports the incoming MBHs toward the center of the newly formed galaxy host. The cover page here depicts the merger of two galaxies and their embedded MBHs (circles), extracted from the cosmological simulation Romulus25, which tracks MBH pairs down to sub-kpc distances [1, 53], still too widely separated for GWs to dominate, yet at the frontier of cosmological simulations of our day. Given the overwhelmingly large dynamical range involved in this problem, numerical simulations coupled to semi-analytical models and sub-grid physics are precious tools to assist us in the interpretation of LISA data. Masses, mass ratios, eccentricities and spins, which are encoded in the GW signal, can be connected to the physical processes leading to MBH binary formation and growth. For example, the eccentricity is largely amplified by stellar scatterings [54, 55], which is determined by the

shape and kinematics of the background stellar potential. Meanwhile, the mass ratios and encounter geometries determine the efficiency of dynamical friction and sinking times [56], and spin magnitudes and orientations reflect BH interactions with massive gas discs [26]. *Therefore, not only will LISA detect MBH binaries at the very end of their journey, but it will also unveil the cosmic evolution of the interplay between MBH binary dynamics and their host galaxies properties as they co-assemble in the cosmic web.*

The rates (3-20 per year in a conservative scenario) and properties of merging MBH binaries are inevitably connected with those of their host galaxies, and ultimately to the evolving large scale structure of the Universe [57]. Complimentary to LISA, the North American Nanohertz Observatory for GWs [58] and other PTAs are targeting the GW foreground from very massive MBH binaries of  $10^8 - 10^9 M_\odot$  at nHz frequencies observed during their inspiral phases up to  $z \sim 1$  [59]. The spectrum of the GW foreground contains precious information on how the giant MBHs pair and interact with the broader galaxy dynamics. Deciphering the information encoded in the LISA and PTA observations will grant us access to physics spanning a remarkable range, from the galactic scale down to the MBH horizon some 12 orders of magnitude smaller. In the coming years, observations of galaxies in deep fields coupled to forefront cosmological simulations will help us to interpret rate of MBH mergers as measured by LISA and PTAs in the low-frequency gravitational Universe. With its unique and nearly complete census of coalescing massive black hole binaries, from the Cosmic Dawn to the local Universe, GW observations will be a game changer in our understanding of the deepest mysteries of MBH birth, growth and coevolution, shedding light on structure formation, galaxy evolution and dynamics, accretion and fundamental physics.

Space-based and pulsar timing gravitational wave observatories will cement the role of GWs as precise MBH probes across cosmic history, providing definitive answers about their origins and evolution. Interpreting the GW view of MBHs in the context of large scale structure, galaxy formation, and evolution requires a broad scientific vision that includes detailed modeling, inference, statistics, and input from EM surveys. By using MBH mergers as signposts for galaxy formation and assembly, we are poised for a paradigm shift in our understanding of MBHs and the Universe.



## References

- [1] M. Tremmel, F. Governato, M. Volonteri, T. R. Quinn, and A. Pontzen. Dancing to CHANGA: a self-consistent prediction for close SMBH pair formation time-scales following galaxy mergers. *Monthly Notices of the Royal Astronomical Society*, 475:4967–4977, April 2018. doi: 10.1093/mnras/sty139.
- [2] A. Klein, E. Barausse, A. Sesana, A. Petiteau, E. Berti, S. Babak, J. Gair, S. Aoudia, I. Hinder, F. Ohme, and B. Wardell. Science with the space-based interferometer eLISA: Supermassive black hole binaries. *Physical Review D*, 93(2):024003, January 2016. doi: 10.1103/PhysRevD.93.024003.
- [3] E. Berti, A. Sesana, E. Barausse, V. Cardoso, and K. Belczynski. Spectroscopy of Kerr Black Holes with Earth- and Space-Based Interferometers. *Physical Review Letters*, 117(10):101102, September 2016. doi: 10.1103/PhysRevLett.117.101102.
- [4] V. Cardoso, E. Franzin, A. Maselli, P. Pani, and G. Raposo. Testing strong-field gravity with tidal Love numbers. *Physical Review D*, 95(8):084014, April 2017. doi: 10.1103/PhysRevD.95.084014.
- [5] T. M. Heckman and P. N. Best. The Coevolution of Galaxies and Supermassive Black Holes: Insights from Surveys of the Contemporary Universe. *Annual Reviews of Astronomy & Astrophysics*, 52:589–660, August 2014. doi: 10.1146/annurev-astro-081913-035722.
- [6] P. Madau and M. Dickinson. Cosmic Star-Formation History. *Annual Reviews of Astronomy & Astrophysics*, 52:415–486, August 2014. doi: 10.1146/annurev-astro-081811-125615.
- [7] Planck Collaboration. Planck 2018 results. VI. Cosmological parameters. *ArXiv e-prints*, July 2018.
- [8] E. Bañados, B. P. Venemans, C. Mazzucchelli, E. P. Farina, F. Walter, F. Wang, R. Decarli, D. Stern, X. Fan, F. B. Davies, J. F. Hennawi, R. A. Simcoe, M. L. Turner, H.-W. Rix, J. Yang, D. D. Kelson, G. C. Rudie, and J. M. Winters. An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5. *Nature*, 553:473–476, January 2018. doi: 10.1038/nature25180.
- [9] S. D. M. White and M. J. Rees. Core condensation in heavy halos - A two-stage theory for galaxy formation and clustering. *Monthly Notices of the Royal Astronomical Society*, 183:341–358, May 1978. doi: 10.1093/mnras/183.3.341.
- [10] J. E. Barnes and L. Hernquist. Transformations of Galaxies. II. Gasdynamics in Merging Disk Galaxies. *The Astrophysical Journal*, 471:115, November 1996. doi: 10.1086/177957.
- [11] S. D. M. White and C. S. Frenk. Galaxy formation through hierarchical clustering. *The Astrophysical Journal*, 379:52–79, September 1991. doi: 10.1086/170483.

- [12] A. Dekel, Y. Birnboim, G. Engel, J. Freundlich, T. Goerdt, M. Mumcuoglu, E. Neistein, C. Pichon, R. Teyssier, and E. Zinger. Cold streams in early massive hot haloes as the main mode of galaxy formation. *Nature*, 457:451–454, January 2009. doi: 10.1038/nature07648.
- [13] Amaro-Seoane et al. LISA Consortium. Laser Interferometer Space Antenna. *ArXiv e-prints*, February 2017.
- [14] J. P. W. Verbiest, L. Lentati, G. Hobbs, R. van Haasteren, P. B. Demorest, G. H. Janssen, J.-B. Wang, G. Desvignes, R. N. Caballero, M. J. Keith, D. J. Champion, Z. Arzoumanian, S. Babak, C. G. Bassa, N. D. R. Bhat, A. Brazier, P. Brem, M. Burgay, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, I. Cognard, J. M. Cordes, S. Dai, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Fonseca, J. R. Gair, N. E. Garver-Daniels, P. Gentile, M. E. Gonzalez, E. Graikou, L. Guillemot, J. W. T. Hessels, G. Jones, R. Karuppusamy, M. Kerr, M. Kramer, M. T. Lam, P. D. Lasky, A. Lassus, P. Lazarus, T. J. W. Lazio, K. J. Lee, L. Levin, K. Liu, R. S. Lynch, A. G. Lyne, J. McKee, M. A. McLaughlin, S. T. McWilliams, D. R. Madison, R. N. Manchester, C. M. F. Mingarelli, D. J. Nice, S. Osłowski, N. T. Palliyaguru, T. T. Pennucci, B. B. P. Perera, D. Perrodin, A. Possenti, A. Petiteau, S. M. Ransom, D. Reardon, P. A. Rosado, S. A. Sanidas, A. Sesana, G. Shaifullah, R. M. Shannon, X. Siemens, J. Simon, R. Smits, R. Spiewak, I. H. Stairs, B. W. Stappers, D. R. Stinebring, K. Stovall, J. K. Swiggum, S. R. Taylor, G. Theureau, C. Tiburzi, L. Toomey, M. Vallisneri, W. van Straten, A. Vecchio, Y. Wang, L. Wen, X. P. You, W. W. Zhu, and X.-J. Zhu. The International Pulsar Timing Array: First data release. *Monthly Notices of the Royal Astronomical Society*, 458:1267–1288, May 2016. doi: 10.1093/mnras/stw347.
- [15] B. P. Abbott, R. Abbott, T. D. Abbott, M. R. Abernathy, F. Acernese, K. Ackley, C. Adams, T. Adams, P. Addesso, R. X. Adhikari, and et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, 116(6):061102, February 2016. doi: 10.1103/PhysRevLett.116.061102.
- [16] J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *Annual Reviews of Astronomy & Astrophysics*, 51:511–653, August 2013. doi: 10.1146/annurev-astro-082708-101811.
- [17] M. Volonteri. Formation of supermassive black holes. *Astronomy & Astrophysics Review*, 18:279–315, July 2010. doi: 10.1007/s00159-010-0029-x.
- [18] P. Natarajan. Seeds to monsters: tracing the growth of black holes in the universe. *General Relativity and Gravitation*, 46:1702, May 2014. doi: 10.1007/s10714-014-1702-6.
- [19] M. A. Latif and A. Ferrara. Formation of Supermassive Black Hole Seeds. *Publications of the Astronomical Society of Australia*, 33:e051, October 2016. doi: 10.1017/pasa.2016.41.



- [20] B. Devecchi, M. Volonteri, E. M. Rossi, M. Colpi, and S. Portegies Zwart. High-redshift formation and evolution of central massive objects - II. The census of BH seeds. Monthly Notices of the Royal Astronomical Society, 421:1465–1475, April 2012. doi: 10.1111/j.1365-2966.2012.20406.x.
- [21] J. L. Bernal, A. Raccanelli, L. Verde, and J. Silk. Signatures of primordial black holes as seeds of supermassive black holes. Journal of Cosmology and Astroparticle Physics, 5:017, May 2018. doi: 10.1088/1475-7516/2018/05/017.
- [22] C. S. Reynolds. Measuring Black Hole Spin Using X-Ray Reflection Spectroscopy. Space Science Reviews, 183:277–294, September 2014. doi: 10.1007/s11214-013-0006-6.
- [23] A. R. King, S. H. Lubow, G. I. Ogilvie, and J. E. Pringle. Aligning spinning black holes and accretion discs. Monthly Notices of the Royal Astronomical Society, 363:49–56, October 2005. doi: 10.1111/j.1365-2966.2005.09378.x.
- [24] E. Barausse. The evolution of massive black holes and their spins in their galactic hosts. Monthly Notices of the Royal Astronomical Society, 423:2533–2557, July 2012. doi: 10.1111/j.1365-2966.2012.21057.x.
- [25] A. Sesana, E. Barausse, M. Dotti, and E. M. Rossi. Linking the Spin Evolution of Massive Black Holes to Galaxy Kinematics. The Astrophysical Journal, 794:104, October 2014. doi: 10.1088/0004-637X/794/2/104.
- [26] E. Berti and M. Volonteri. Cosmological Black Hole Spin Evolution by Mergers and Accretion. The Astrophysical Journal, 684:822–828, September 2008. doi: 10.1086/590379.
- [27] M. Campanelli, C. O. Lousto, Y. Zlochower, and D. Merritt. Maximum Gravitational Recoil. Physical Review Letters, 98(23):231102, June 2007. doi: 10.1103/PhysRevLett.98.231102.
- [28] T. Bogdanović, C. S. Reynolds, and M. C. Miller. Alignment of the Spins of Supermassive Black Holes Prior to Coalescence. The Astrophysical Journal Letters, 661:L147–L150, June 2007. doi: 10.1086/518769.
- [29] Z. Haiman, B. Kocsis, and K. Menou. The Population of Viscosity- and Gravitational Wave-driven Supermassive Black Hole Binaries Among Luminous Active Galactic Nuclei. The Astrophysical Journal, 700:1952–1969, August 2009. doi: 10.1088/0004-637X/700/2/1952.
- [30] M. Dotti, M. Volonteri, A. Perego, M. Colpi, M. Ruzskowski, and F. Haardt. Dual black holes in merger remnants - II. Spin evolution and gravitational recoil. Monthly Notices of the Royal Astronomical Society, 402:682–690, February 2010. doi: 10.1111/j.1365-2966.2009.15922.x.
- [31] M. Kesden, U. Sperhake, and E. Berti. Relativistic Suppression of Black Hole Recoils. The Astrophysical Journal, 715:1006–1011, June 2010. doi: 10.1088/0004-637X/715/2/1006.

- [32] C. Roedig, A. Sesana, M. Dotti, J. Cuadra, P. Amaro-Seoane, and F. Haardt. Evolution of binary black holes in self gravitating discs. Dissecting the torques. *Astronomy & Astrophysics*, 545:A127, September 2012. doi: 10.1051/0004-6361/201219986.
- [33] E. Berti, M. Kesden, and U. Sperhake. Effects of post-Newtonian spin alignment on the distribution of black-hole recoils. *Physical Review D*, 85(12):124049, June 2012. doi: 10.1103/PhysRevD.85.124049.
- [34] C. O. Lousto, Y. Zlochower, M. Dotti, and M. Volonteri. Gravitational recoil from accretion-aligned black-hole binaries. *Physical Review D*, 85(8):084015, April 2012. doi: 10.1103/PhysRevD.85.084015.
- [35] M. C. Miller and J. H. Krolik. Alignment of Supermassive Black Hole Binary Orbits and Spins. *The Astrophysical Journal*, 774:43, September 2013. doi: 10.1088/0004-637X/774/1/43.
- [36] S. McGee, A. Sesana, and A. Vecchio. The assembly of cosmic structure from baryons to black holes with joint gravitational-wave and X-ray observations. arXiv e-prints, October 2018.
- [37] P. J. Armitage and P. Natarajan. Accretion during the Merger of Supermassive Black Holes. *The Astrophysical Journal Letters*, 567:L9–L12, March 2002. doi: 10.1086/339770.
- [38] Z. Haiman. Electromagnetic chirp of a compact binary black hole: A phase template for the gravitational wave inspiral. *Physical Review D*, 96(2):023004, July 2017. doi: 10.1103/PhysRevD.96.023004.
- [39] Y. Tang, Z. Haiman, and A. MacFadyen. The late inspiral of supermassive black hole binaries with circumbinary gas discs in the LISA band. *Monthly Notices of the Royal Astronomical Society*, 476:2249–2257, May 2018. doi: 10.1093/mnras/sty423.
- [40] D. B. Bowen, V. Mewes, M. Campanelli, S. C. Noble, J. H. Krolik, and M. Zilhão. Quasi-periodic Behavior of Mini-disks in Binary Black Holes Approaching Merger. *The Astrophysical Journal Letters*, 853:L17, January 2018. doi: 10.3847/2041-8213/aaa756.
- [41] S. d’Ascoli, S. C. Noble, D. B. Bowen, M. Campanelli, J. H. Krolik, and V. Mewes. Electromagnetic Emission from Supermassive Binary Black Holes Approaching Merger. *The Astrophysical Journal*, 865:140, October 2018. doi: 10.3847/1538-4357/aad8b4.
- [42] C. Palenzuela, L. Lehner, and S. L. Liebling. Dual Jets from Binary Black Holes. *Science*, 329:927–930, August 2010. doi: 10.1126/science.1191766.
- [43] B. J. Kelly, J. G. Baker, Z. B. Etienne, B. Giacomazzo, and J. Schnittman. Prompt electromagnetic transients from binary black hole mergers. *Physical Review D*, 96(12):123003, December 2017. doi: 10.1103/PhysRevD.96.123003.

- [44] E. M. Rossi, G. Lodato, P. J. Armitage, J. E. Pringle, and A. R. King. Black hole mergers: the first light. Monthly Notices of the Royal Astronomical Society, 401:2021–2035, January 2010. doi: 10.1111/j.1365-2966.2009.15802.x.
- [45] M. C. Begelman, R. D. Blandford, and M. J. Rees. Massive black hole binaries in active galactic nuclei. Nature, 287:307–309, September 1980. doi: 10.1038/287307a0.
- [46] F. M. Khan, A. Just, and D. Merritt. Efficient Merger of Binary Supermassive Black Holes in Merging Galaxies. The Astrophysical Journal, 732:89, May 2011. doi: 10.1088/0004-637X/732/2/89.
- [47] F. M. Khan, K. Holley-Bockelmann, P. Berczik, and A. Just. Supermassive Black Hole Binary Evolution in Axisymmetric Galaxies: The Final Parsec Problem is Not a Problem. The Astrophysical Journal, 773:100, August 2013. doi: 10.1088/0004-637X/773/2/100.
- [48] E. Vasiliev, F. Antonini, and D. Merritt. The Final-parsec Problem in Nonspherical Galaxies Revisited. The Astrophysical Journal, 785:163, April 2014. doi: 10.1088/0004-637X/785/2/163.
- [49] M. Colpi. Massive Binary Black Holes in Galactic Nuclei and Their Path to Coalescence. Space Science Reviews, 183:189–221, September 2014. doi: 10.1007/s11214-014-0067-1.
- [50] K. Holley-Bockelmann and F. M. Khan. Galaxy Rotation and Rapid Supermassive Binary Coalescence. The Astrophysical Journal, 810:139, September 2015. doi: 10.1088/0004-637X/810/2/139.
- [51] F. M. Khan, D. Fiacconi, L. Mayer, P. Berczik, and A. Just. Swift Coalescence of Supermassive Black Holes in Cosmological Mergers of Massive Galaxies. The Astrophysical Journal, 828:73, September 2016. doi: 10.3847/0004-637X/828/2/73.
- [52] R. Souza Lima, L. Mayer, P. R. Capelo, and J. M. Bellovary. The Pairing of Accreting Massive Black Holes in Multiphase Circumnuclear Disks: the Interplay Between Radiative Cooling, Star Formation, and Feedback Processes. The Astrophysical Journal, 838:13, March 2017. doi: 10.3847/1538-4357/aa5d19.
- [53] M. Tremmel, M. Karcher, F. Governato, M. Volonteri, T. R. Quinn, A. Pontzen, L. Anderson, and J. Bellovary. The Romulus cosmological simulations: a physical approach to the formation, dynamics and accretion models of SMBHs. Monthly Notices of the Royal Astronomical Society, 470:1121–1139, September 2017. doi: 10.1093/mnras/stx1160.
- [54] A. Sesana. Self Consistent Model for the Evolution of Eccentric Massive Black Hole Binaries in Stellar Environments: Implications for Gravitational Wave Observations. The Astrophysical Journal, 719:851–864, August 2010. doi: 10.1088/0004-637X/719/1/851.

- [55] M. A. Mirza, A. Tahir, F. M. Khan, H. Holley-Bockelmann, A. M. Baig, P. Berczik, and F. Chishtie. Galaxy rotation and supermassive black hole binary evolution. *Monthly Notices of the Royal Astronomical Society*, 470:940–947, September 2017. doi: 10.1093/mnras/stx1248.
- [56] S. Callegari, S. Kazantzidis, L. Mayer, M. Colpi, J. M. Bellovary, T. Quinn, and J. Wadsley. Growing Massive Black Hole Pairs in Minor Mergers of Disk Galaxies. *The Astrophysical Journal*, 729:85, March 2011. doi: 10.1088/0004-637X/729/2/85.
- [57] M. Bonetti, A. Sesana, F. Haardt, E. Barausse, and M. Colpi. Post-Newtonian Evolution of Massive Black Hole Triplets in Galactic Nuclei: IV. Implications for LISA. *arXiv e-prints*, December 2018.
- [58] Z. Arzoumanian, P. T. Baker, A. Brazier, S. Burke-Spolaor, S. J. Chamberlin, S. Chatterjee, B. Christy, J. M. Cordes, N. J. Cornish, F. Crawford, H. Thankful Cromartie, K. Crowter, M. DeCesar, P. B. Demorest, T. Dolch, J. A. Ellis, R. D. Ferdman, E. Ferrara, W. M. Folkner, E. Fonseca, N. Garver-Daniels, P. A. Gentile, R. Haas, J. S. Hazboun, E. A. Huerta, K. Islo, G. Jones, M. L. Jones, D. L. Kaplan, V. M. Kaspi, M. T. Lam, T. J. W. Lazio, L. Levin, A. N. Lommen, D. R. Lorimer, J. Luo, R. S. Lynch, D. R. Madison, M. A. McLaughlin, S. T. McWilliams, C. M. F. Mingarelli, C. Ng, D. J. Nice, R. S. Park, T. T. Pennucci, N. S. Pol, S. M. Ransom, P. S. Ray, A. Rasskazov, X. Siemens, J. Simon, R. Spiewak, I. H. Stairs, D. R. Stinebring, K. Stovall, J. Swiggum, S. R. Taylor, M. Vallisneri, R. van Haasteren, S. Vigeland, W. W. Zhu, and NANOGrav Collaboration. The NANOGrav 11 Year Data Set: Pulsar-timing Constraints on the Stochastic Gravitational-wave Background. *The Astrophysical Journal*, 859:47, May 2018. doi: 10.3847/1538-4357/aabd3b.
- [59] S. Chen, H. Middleton, A. Sesana, W. Del Pozzo, and A. Vecchio. Probing the assembly history and dynamical evolution of massive black hole binaries with pulsar timing arrays. *Monthly Notices of the Royal Astronomical Society*, 468:404–417, June 2017. doi: 10.1093/mnras/stx475.

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