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Supermassive Black Hole Mergers: Probing Gravitational Waves and Cosmology

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Abstract. The potential importance of supermassive black holes (SMBHs) in the centers of galaxies to the evolution of galaxies is known. As galaxies merge, their central SMBHs can become binary and eventually coalesce, emitting copious amounts of energy in the form of low-frequency GWs. These mergers provide a unique window into both astrophysics and cosmology—they reveal how galaxies evolve, how black holes transform, and how the large-scale structure of the universe forms. This paper summarizes the current knowledge of SMBH binary formation and evolution, of the theoretical and observational obstacles to modeling their dynamics, and the existing evidence of a gravitational wave background from pulsar timing arrays (PTAs) prospectively. This paper also addresses the prospective event rate for space-based detectors like the Laser Interferometer Space Antenna (LISA), which can directly detect single SMBH mergers. Multi-messenger astronomy is highlighted, and electromagnetic `counterparts', such as AGN flaring or jet activity, can be expected with the GW signal, providing information about the merger environment. Merging SMBHs are likely to be “standard sirens” when both their electromagnetic and some combination of gravitational wave and electromagnetic signals are observed, allowing for distance measurements and cosmological tests by the independent constraint of the Hubble constant and knowledge of dark energy. Future high-energy observatories should turn SMBH mergers into one of the most powerful probes of the universe.

Keywords: Supermassive black holes, Black hole mergers, Gravitational waves, Pulsar timing arrays.

1. Introduction

It is known for some time now that at the center of galaxies reside supermassive blackholes (SMBHs) with masses in the range of millions to billions of solar masses. They have significant implications for galaxy evolution via their active processes, such as AGN feedback.

The most spectacular event of SMBHs is the mergers, which commonly happen after the galaxies merge. These mergers are not just aiding black hole mass growth, but they also produce loads of gravitational waves (GWs). GWs can aid us in detecting the kinematics of massive galaxies directly by which is essential for observing the universe.

The gravitational wave detectors such as LIGO and Virgo had discovered the GWs of the massive blackholes. But SMBHs produce GW in considerably lower frequencies only. Therefore, scientists

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have to look for new technologies like pulsar timing arrays (PTAs) and the proposed Laser Interferometer Space Antenna (LISA). It will offer a unique opportunity to probe the astrophysics and cosmology of the Universe for scientists to study the signals.

In this paper, the author discusses the role of SMBH mergers as astrophysical laboratories and cosmological probes. Specifically, it can be asked: What do SMBH mergers tell about galaxy build-up and growth? What information about the black hole masses, spins, and orbits is contained in the gravitational wave signals from such mergers? How can SMBH mergers act as "standard sirens" to limit cosmological parameters, such as the Hubble constant and properties of dark energy? These three questions form the main structure of this paper, illustrating the most direct and crucial value of observing SMBH mergers. The paper emphasizes the theoretical implications of SMBH binaries, discuss how to detect them in gravitational wave observations, and explore their cosmological connections. This work does not present new observational data, but rather provide a summary of results from contemporary simulations, models, and indirect evidence, with a focus on the continued promise for next-generation GW observatories.

2. Formation and evolution of supermassive black hole mergers

2.1. Formation of SMBH binaries

Supermassive black hole mergers are always created from the combination of their host galaxies. As the universe's structure is changing over time, the galaxies will collide and combine. When two galaxies both have a central SMBH, the black holes will combine through dynamic friction.

As the SMBH sinks to the center of the combined galaxy, it will form a bound binary system. However, when the distance between them has decreased from kiloparsec scales down to parsec and sub-parsec scales, it poses the well-known "final parsec problem." At these scales, the kinematic friction becomes less effective, and scientists need an extra process to shrink the bound binary system, including Three-body interactions with stars (stellar hardening), which eject stars and extract energy from the binary. Interactions with gas in circumnuclear disks provide torques that drive orbital decay. These processes will work together to help the SMBHs finally combine.

2.2. Evolution of SMBH binaries

Once the bound binary system has formed, its future depends on its surroundings. Normally, it will have three classic endings: The first situation is that its orbits will shrink after it meets nearby stars, by losing its angular speed and momentum. This process typically happens in a dense stellar environment.

Meanwhile, the bound binary system can accelerate by gaining strong torques and even fueling accretion from circumbinary disks, which happen more frequently in galaxies that are filled with gas. Specifically, this can be shown in the model made by Shihong Liao and his team, which performs idealized gas-rich disc galaxy merger simulations using pure thermal or pure kinetic active galactic nuclei (AGNs) feedback. Finally, at a small separation with sub-parsec scale, the emission of GWs will dominate the decay and finally lead to mergers.

2.3. Cosmological context

SMBH mergers are closely related to the development of the Universe. Galaxies are formed through a combination process, which is similar to the one that forms SMBHs. Therefore, SMBH mergers

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can help track back to the history of the early universe, especially at high redshift, and they can help scientists to better understand the way of the early universe developed.

3. Gravitational waves from supermassive black hole mergers

When two SMBHs combine and form into a bound binary system, they will lose orbital energy. In this way, they will create a lot of GWs, which contain their information about mass, orbital period, and spin. The characteristic of these GWs is their low frequencies, normally about several years, which is way lower than the stellar-mass black holes. At the same time, the frequency and wavelength are totally dependent on the mass of the black hole, its orbital separation, and whether the spins are aligned or misaligned. Because there are a lot of SMBH mergers happening in different locations of the Universe, their GWs will form a random background with low-frequency GWs.

As the GWs are undetectable to ground-based interferometers like LIGO and Virgo, it is very hard to detect them. Therefore, scientists will use other technologies such as Pulsar Timing Arrays (PTAs), which use Millisecond pulsars to detect the signal of GWs for their stability [1]. Scientific institutions in different countries, such as NANO Grav (North America), EPTA (Europe), and IPTA (international), have already used thousands of pulsars to detect GWs. Meanwhile, new approaches such as the Laser Interferometer Space Antenna (LISA), planned by ESA and NASA, which will operate in space to detect GWs directly, are also in the schedule to help scientists better detect these GWs, and the scales of each method can be shown in Figure 1.

In 2023, PTAs, including NANO-Grav, EPTA, and PPTA, announced strong evidence for a gravitational-wave background consistent with the signal expected from SMBH binaries throughout cosmic history. This finding means the first time humans have found large-scale GWs, which provide a lot of data for modeling the early universe, as it can be seen in the Figure 2. On the other hand, the problem of a lack of direct detection of a single SMBH merger still exists, and LISA plans to solve this problem by the 2030s. These detections have already provided evidence for the theories about SMBH mergers and galaxy formation.

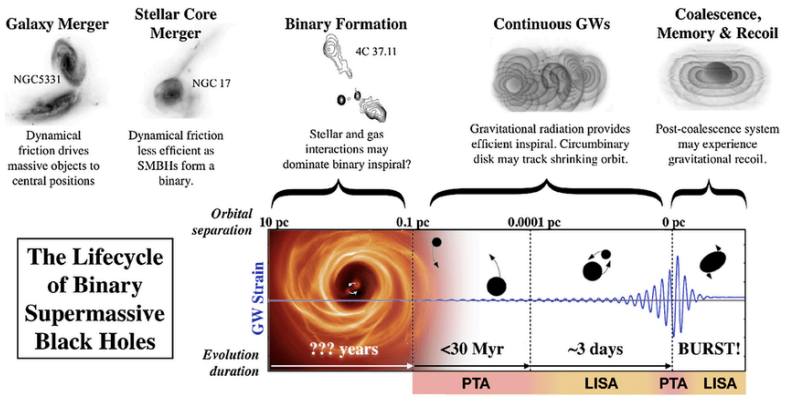

Figure 1. This figure illustrates the scales of each method [2]

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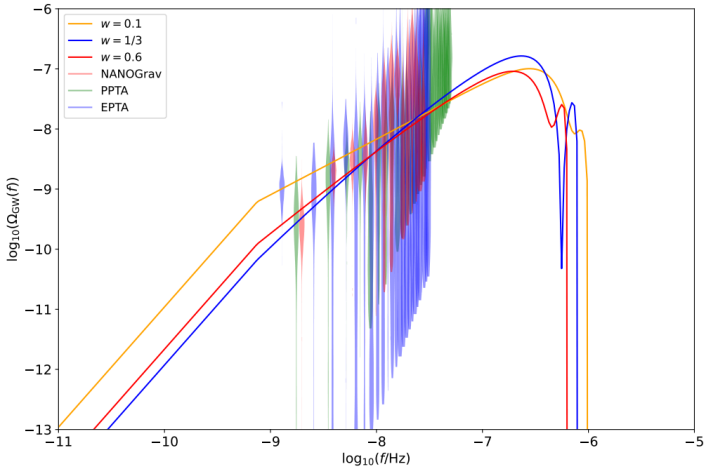

Figure 2. The energy density spectrum of SIGW with different EoS parameters as a function of the GW frequency. With data from the PTAs [3]

4. Cosmological implications of SMBH mergers

SMBH mergers can be alarms in the universe. Through investigating their GWs, scientists can calculate the distance from the origin directly. If an electromagnetic counterpart is found (e.g., an active galactic nucleus flare), the redshift can also be measured. Together, this will restrain the Hubble constant(H0) so that it can solve the problem of using different measures. Also, it can help scientists to observe dark energy by providing different inflation rates in other parts of the universe.

As the mergers of SMBH mainly come from the combination of galaxies, it can also reveal the early universe structure by the different rates and distributions of SMBH mergers. Observing these can help scientists to understand the way clusters group better together, the accuracy of the known universe model, and how feedback from SMBH mergers can affect the heating process between galaxies' gas and formation.

Before the first billion years of the Big Bang, some of the first quasars observed at redshift $z > 6$ already hosted SMBHs. This raises a question: how do these SMBHs grow so fast? By detecting the GWs from high-redshift SMBH mergers, scientists can provide evidence for the way early black holes formed, and constrain the growth history of black holes during the Epoch of Reionization, a critical period in early cosmic evolution.

5. Challenges and future prospects

It is very hard for scientists to detect SMBH mergers, because their gravitational-wave signals lie in the nanohertz to millihertz frequency range, which current ground-based detectors (like LIGO) cannot reach. In the previous part of the paper, this work also discussed two other ways to detect SMBH mergers, but they also have drawbacks. Pulsar Timing Arrays (PTAs), for example, are sensitive to the nanohertz to millihertz frequency range and thus can detect SMBH mergers precisely, but they often take tens of years for precise detection. At the same time, Space-based detectors (e.g., LISA) are theoretically useful for detecting SMBH mergers, but it is still being developed, and scientists who want to use it will have to wait until the 2050s. Modeling SMBH binaries remains a complex problem because multiple physical processes are involved: Stellar dynamics: hardening due to three-body interactions with stars. Gas dynamics: influence of accretion disks and inflows. Spin and mass ratios: affect the gravitational-wave waveform, recoil velocities,

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and post-merger SMBH properties. Simulations need to incorporate all of these factors across many scales, from parsecs to sub-parsec regions, which is computationally demanding [4]. The next few decades, though not without challenges, offer tantalizing possibilities: LISA will make the first direct detections of SMBH mergers, which will allow detailed tests of general relativity and galaxy formation. Multi-messenger astronomy: gravitational waves together with electromagnetic signals (AGN flares, jet activity, tidal disruption events) can be used to accurately localise mergers and to measure their redshift. Synergies with large surveys: complementary instruments, e.g, Rubin Observatory (optical) and SKA (radio), will aid in the detection of electromagnetic counterparts, and the exploration of merger environments

6. Multi-messenger astronomy and SMBH mergers

Although GWs can provide information about SMBH mergers directly, detecting Electromagnetic (EM) signals is still important for understanding their environment and cosmology. Including AGN variability: if the SMBHs are embedded in a gas-rich environment, their accretion disks may show periodic variability before merger in Figure 3.

For example, in the recent research paper Accretion-modified Stars in Accretion Disks of AGN: Gravitational-wave Bursts and Electromagnetic Counterparts from Merging Stellar Black Hole Binaries, massive stars within an SMBH's accretion disk evolve into compact remnants that become embedded in the dense gas. Gravitational interactions and migration in the disk then naturally lead to the formation of binary black holes (BBHs), as illustrated in the figure. When these embedded BBHs merge, several mechanisms can generate EMCs, such as Bondi accretion at hyper-Eddington rates, Powerful outflows and Bondi explosions, and the Blandford–Znajek mechanism. The recent LIGO/Virgo detection GW190521 has even been tentatively associated with a quasar flare, sparking renewed interest in this connection between GWs and AGN activity [5].

For SMBH mergers specifically, the same physical principles apply at larger scales: if the merging SMBHs are embedded in gas (as in merging galaxies with active nuclei), it may observe AGN variability, sudden flares, or jet reorientation linked with the GW signals, and this can be shown in the Figure 3. Detecting such EMCs is challenging, but when successful, they can help pinpoint the sky location of the merger, constrain the merger environment, and add rich astrophysical context beyond the "pure" GW signal [6].

The combined observation of GW and EM signals allows for multi-messenger astronomy with a number of advantages: Accurate localization: GWs provide only a wide sky area, whereas EM emission identifies the host galaxy. Redshift: With an EM counterpart, standard siren cosmology can be performed, combining EM redshifts with the GW ones to determine the Hubble constant and dark energy. Limiting merger physics: EM data provide insight into the gas dynamics, star formation, and AGN activity in the merger environment, which supplement GW constraints on masses and spins.

The near future will bring a revolution in multi-messenger studies of SMBH mergers:

LISA + large EM surveys: The combination of LISA detection with surveys of telescopes like Rubin Observatory (optical), SKA (radio), and Athena (X-ray) will significantly increase our chances of identifying the EM counterparts.

Coherent networks: International GW-EM collaboration will yield the most effective search for GWs. Possible discoveries: The detection of SMBH mergers through GW and EM channels could result in the observation of unexpected systems, like new populations of AGN variability or fingerprints of exotic physics.

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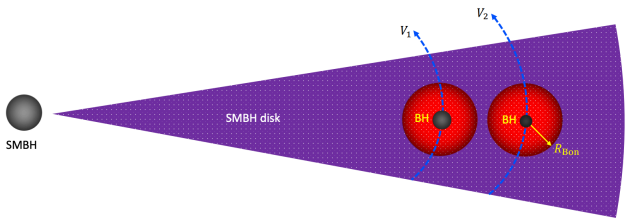

Figure 3. This figure shows stellar-mass black holes embedded in a supermassive black hole's accretion disk. As they accrete gas, each BH carves out a hot, low-density cavity while orbiting the SMBH. Differences in their orbital speeds cause interactions and migration within the disk, naturally bringing them together to form binary black holes (BBHs) [7]

7. Conclusion

The SMBHs is one of the most energetic and important processes in the universe. They are a natural outcome of the hierarchical build-up of galaxies and are key to the interpretation of galaxy formation and evolution. These mergers produce low-frequency gravitational waves that are observable by pulsar timing arrays (PTAs) today and in the near future by space-based observatories such as LISA. Prompt detections of SMBH binaries in the LISA band will be able to measure the correction of the evolution in an angular-averaged limit, while the Bayesian framework will provide constraints for binary evolution for more general populations.

The future is full of great hope for this discipline. With the future in mind, and in the context of next-generation assets, like LISA, the Square Kilometer Array, and the Rubin Observatory, astronomers will investigate the same SMBH mergers at an unprecedented level of accuracy. These are expected not only to enhance the sensitivity of detection but also to carry out joint GW and EM observations, heralding a new era of multi-messenger astrophysics.

In the end, SMBH mergers will facilitate the exploration of the cosmic galaxy assembly history and will make accurate measurements of the universe's large-scale structure and evolution. And as gravitational wave astronomy continues to grow, these cosmic sirens will be indispensable tools for mapping and investigating the universe.

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