A Comprehensive Review of the Formation, Growth and Influence of Supermassive Black Holes

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Abstract. Supermassive black holes (SMBHs) are fundamental components of galactic ecosystems, with their origins, growth processes, and feedback mechanisms central to our understanding of cosmic evolution. This review synthesises current theories on SMBH formation, including the Population III star seeding and direct collapse models, as well as more speculative ideas, such as primordial black holes. Key mechanisms driving SMBH growth, primarily accretion and mergers, are explored in detail, with an emphasis on the dynamics of accretion disks, angular momentum transfer, and instances of super-Eddington accretion that challenge established growth models. The impact of SMBHs on their host galaxies is analysed through feedback processes, which regulate star formation and structural evolution, with galaxy mergers playing a pivotal role in accelerating SMBH mass accretion and active galactic nucleus (AGN) activity. Empirical scaling relations, such as the $M_{\text{SMBH}} - M_{\text{bulge}}$ and $M_{\text{SMBH}} - \sigma$ relations, are examined to illustrate the intertwined growth of SMBHs and galaxies. Additionally, this review evaluates observational techniques, including gravitational wave detection, gravitational lensing, and radio observations, noting their respective strengths, limitations, and the challenges they pose for high-redshift SMBH studies. Recognising significant gaps in the current understanding of SMBH formation and early growth, this review highlights the need for advanced observational technology and refined simulations to advance the field. Ultimately, the findings underscore the complex roles of SMBHs in cosmic evolution, as both the architects and beneficiaries of galactic environments.

1 Introduction

Supermassive Black Holes (SMBHs) are among the most intriguing objects in astrophysics, residing at the centres of nearly every galaxy and exerting a profound influence on their evolution. Studying the formation, growth, and impact of SMBHs is essential for understanding fundamental cosmic processes. This review synthesises current research to critically examine several key areas in SMBH studies, from foundational theories to recent developments. Key theories regarding SMBH formation—such as seeding through Population III stars, the direct collapse model, and alternative concepts like primordial black holes and dark matter's role—provide insights into the conditions of the early universe. This includes the influence of metal-free gas and dark matter halos on the initial stages of SMBH development. Moving to the processes that drive SMBH growth, mechanisms such as accretion and mergers are explored in the context of their contributions over cosmic time, with attention to the dynamics within accretion disks, the role of angular momentum, and conditions that may lead to super-Eddington accretion, especially in high-redshift environments. The influence of SMBHs on galaxy evolution through feedback mechanisms that affect star formation and galaxy structure reveals essential insights into the co-evolution of galaxies and their central black holes. Additionally, the interactions between SMBHs and their host galaxies during events like galaxy mergers illustrate the dynamic processes that shape both SMBHs and their environments. Finally, an assessment of observational techniques—including gravitational wave measurements, gravitational lensing, and radio observations—highlights the strengths and limitations of each method while identifying opportunities for further research. By integrating these diverse perspectives, this review underscores the importance of SMBHs in cosmic evolution, offering insights not only valuable to astrophysicists but to anyone intrigued by the universe's most profound questions.

2 Formation of Supermassive Black Holes

The formation of SMBHs remains a central issue in cosmology, with there being several competing theories and models attempting to explain how these massive objects formed. Two of the most widely accepted models – seeding via Population III stars and the direct collapse model propose different pathways for the initial formation of SMBHs.

2.1 Seeding Via Population (III) Stars

Population III stars refer to hypothetical extremely massive, hot and luminous objects believed to be some of the first stars to formed shortly after the big bang. Originating from primordial interstellar gas clouds, these stars would have been composed almost entirely of hydrogen, helium and very small amounts of metals such as lithium and beryllium.[1] Due to their metal-poor composition, these stars would've burnt at extremely high temperatures but would have only live relatively short lifespans, as the absence of heavier elements limited their ability to sustain fusion. Within the seeding model, the collapse of these stars after exhausting their nuclear fuel is thought to lead to the formation of black hole seeds.[1] These seeds, typically ranging in masses between 100 and 1000 solar masses, would have grown into SMBHs through accretion and mergers since the early stages of the universe, thereby offering an explanation for their substantial size. While cosmological simulations have demonstrated that population III stars could reach masses high enough to collapse into black holes thus providing seeds in the required mass range,[1] a significant limitation to this model is the lack of direct evidence for population III stars as none have been observed so far.[1] Additionally, it is not yet clear whether the formation rate of Population III stars was high enough to account for the observed population of SMBHs in high-redshift quasars.[2]

2.2 Direct Collapse Model

The direct collapse model provides an alternative to seeding model where the intermediate stage of stellar evolution is bypassed. Instead of stars being formed that eventually collapse into black holes, this model suggests that under certain conditions, massive gas clouds are able to directly collapse into black holes with masses ranging from 10,000 to 100,000 solar masses.[3] Key conditions include low metallicities and high gas densities, as low metallicity prevents cooling and fragmentation to ensure the gas remains hot enough for collapse while high gas density facilitates the required rapid mass accumulation. Furthermore, mechanisms such as Lyman-Werner radiation suppress the formation of molecular hydrogen while angular momentum loss is necessary to avoid the formation of a rotating disk.[4] Finally, the gas cloud

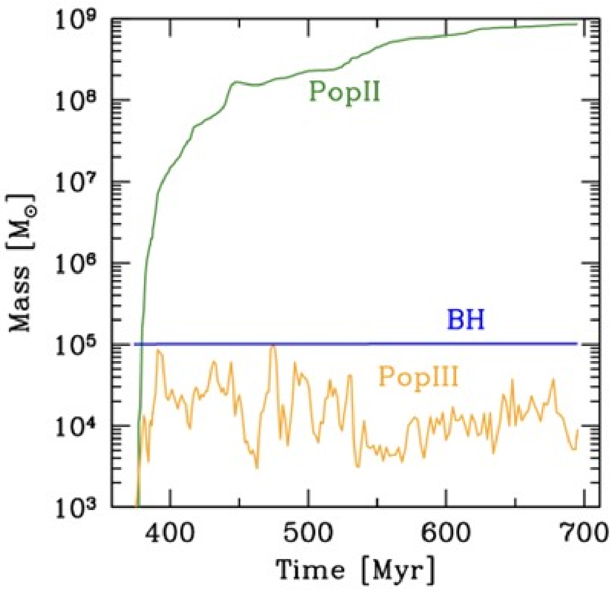

Figure 1. Evolution time of stellar population II + III and Black Hole masses in the Early Universe (Credits: Latif MA et al. (2018), "Early growth of typical high-redshift black holes seeded by direct collapse")

needs to sit inside a sufficiently massive dark matter halo in order to provide the required gravitational framework to cause the collapse.[5] This model is convincing as its able to account for the rapid formation of SMBHs, especially those found in high-redshift quasars (z ¿ 6) which have been found possess black holes equalling more than a billion solar masses.[4] With these objects having the capability to be formed relatively early in the universe's lifespan, this model also reduces the need for Super-Eddington accretion. Additionally, there is strong theoretical support for this model with radiation hydrodynamics simulations showing that Lyman-Werner radiation can suppress molecular cooling, allowing for the direct collapse of molecular clouds without fragmentation,[6] However, this model still faces challenges as direct observation of the precise conditions required for this form of collapse have yet to be observed.[4]

2.3 Speculative Theories for SMBH Formation

In addition to these models, there are also lesser explored, more speculative theories that aim to explain the formation of SMBHs. One theory involves the existence of primordial black holes, their formation made possible due to unique density regions existing only a second after the big bang. Its theorised that if these objects existed, they could have acted as seeds for SMBHs, their large mass providing a head start to becoming SMBHs.[7] This is supported by large scale cosmological simulations conducted through the IllustrisTNG project which showed how black hole seeds, including primordial black holes could explain the early growth of SMBHs.[8] However, this theory faces notable limitations as none have been observed so far and constraints haven been placed on their theorised abundance based on data from the cosmic microwave background (CMB). Regardless, research hasn't slowed in the area with recent detections of gravitational waves by LIGO and VIRGO from stellar mass black holes suggesting the possibility that some of the black holes could be primordial in nature.[9] Another possible theory is that SMBHs could have from through stellar collisions in dense star clusters. Within this setting, massive stars would merge to form intermediate mass black hole precursors which would later grow through accretion.[10] While a possibility, this theory faces challenges in explaining how such collisions would occur frequently enough to facilitate the rapid formation of SMBHs.[10]

3 Growth and Accretion Processes

The growth of SMBHs is driven by two primary mechanisms: accretion and mergers. Each of them plays a critical role in how SMBHs gain mass over time and understanding them is crucial in discerning how these massive objects grow and form.

3.1 Overview of Accretion Mechanisms

In astrophysics, accretion is the process in which a massive object such as an SMBH will grow by capturing matter such as gas and dust from the surrounding environment through its gravitational influence.[11] This inflow of material forms a structure known as an accretion disk around the SMBH, where the loss of angular momentum outwards allows the material to spiral inwards. The gas within the disk also becomes heated to extremely high temperatures due to viscous dissipation and gravitational interaction, thus causing the emission of intense radiation across multiple wavelengths.[12] The efficiency of accretion is determined from several factors such as the black hole's spin, the angular momentum of the accretion disk and innate properties of the accretion disk. A rapidly spinning black hole will have enhanced accretion when compared to a slower one due to decreasing the innermost stable circular orbit (ISCO). By decreasing the radius of the ISCO, more energy is able to be extracted from a material before it crosses the event horizon.[12] Temperature and density also play a major role as they affect the ease with which material can flow into the SMBH. A higher temperature can lead to greater thermal pressure that resists gravitational force while lower temperatures allow gas to contract and readily flow into the black hole.[12] Accretion processes are also not uniform, and their growth rates can significantly vary over time. When there is an abundance of gas and it is able to steadily flow into the SMBH, this accretion is known as 'quiescent'. Alternatively, events such as galaxy mergers or tidal interactions can cause rapid fluctuations in the inflow, leading to the accretion become 'bursty' and causing changes in outflows and the emission characteristics of the black hole. Accretion rates can also be temporarily boosted by stellar tidal disruption – an event where a star is ripped apart by the gravity of a black hole.[12]

3.2 Accretion Disk Formation and Angular Momentum

The formation of an accretion disk is critical for the maintained growth of a SMBH. When gas, dust and other matter fall towards a SMBH, they carry angular momentum which prevents them initially falling directly into the hole. Instead, the inflowing material self-organizes into a rotation-supported disk in which magneto-rotational instability (MRI) plays the crucial role of promoting inward material flow.[11] MRI is caused due to the interaction between the SMBH's magnetic field and the different velocities of the gas layers in the accretion disk.[11] This instability amplifies existing magnetic fields within the disk, generating turbulence in the process which aids to the outward transfer of angular momentum and allows gas to spiral inward to the SMBH more efficiently. One of the main dynamics of accretion disks is the balance between the efficiency of the mass inflow versus energy dissipation. If the accretion disk radiates energy at an effective rate, it can limit the amount of mass the SMBH can capture. Alternatively, if the disk is less efficient as radiating energy, the SMBH may experience an increase in rapid growth.[11] The interaction between an SMBH and its accretion disk can also result in powerful jets – narrow streams of particles that are ejected at nearly the speed of light.

3.3 Super Eddington Accretion

In certain circumstances, SMBHs may undergo a process known as Super-Eddington accretion. This is when the flow of material into a SMBH exceeds the Eddington limit, a theoretical maximum rate at which a black hole can accrete matter without destabilising due to its own radiation pressure [13]. By means of this type of accretion, SMBHs can grow at rates significantly exceeding those predicted by conventional models, potentially explaining their presence in high-redshift quasars.[13] When the accretion rate passes the Eddington limit, the intense radiation generated by the heated material would cause major outward radiation pressure. This radiation pressure can exceed the gravitational pull of the SMBH, leading powerful outflows that expel large amounts of gas away from the SMBH.[13] These expulsions sometimes can manifest as relativistic jets, a phenomenon that can regulate galactic evolution by supressing star formation.

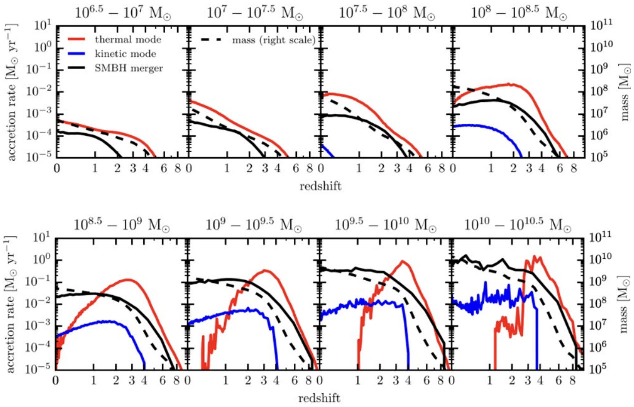

Figure 2. Mass Growth History of SMBHs by accretion mode and mergers across redshift (Credits: Weinberger et al. (2018), "Supermassive black holes and their feedback effects in the IllustrisTNG simulation")

3.4 Overview of Mergers

In addition to accretion, mergers are another primary mechanism through which SMBHs are able to increase their size substantially. Mergers occur when two black holes combine and can happen in different circumstances.[12] One scenario involves galactic collision which is where the SMBHs at the centre of galaxies gradually coalesce. During these interactions, the attraction between the galaxies causes their respective SMBHs to gravitationally bind to each other, leading into a spiral trajectory where they would gradually lose energy through dynamical friction before merging.[12] Additionally, gravitational torque produced by the combination of the galaxies gravitational fields assists in driving matter towards the central SMBHs. Merging can also occur in a more localised environment when two stellar black holes exist together in a binary system before combining. Other than increasing an SMBH's mass, mergers also have a significant influence on their spin. The spin of the resultant SMBH is determined by the initial mass and spin of the merging SMBHs. Depending on the alignment of the spins, a rapidly spinning SMBH may be produced which can lead to increased accretion rates and luminous AGN activity.[14] The merger process also creates a feedback loop with the energy released during the merger and subsequent accretion can alter the gravitational potential of the area. The merging of SMBHs is also noteworthy due to their generation of gravitational waves in the final stages of the merger. These waves carry vital information about the SMBHs such as their mass, spin and energy released during the merger [15]. Although only stellar black hole mergers have been detected so far by observatories such as LIGO (Laser Interferometer Gravitational-Wave Observatory), the detection of SMBH mergers should be made possible soon with projects such as LISA [15]. The study of these events will further refine models of SMBH populations and growth.

4 Feedback Mechanisms

4.1 Introduction to Feedback Mechanisms

Feedback mechanisms are essential in astrophysics for regulating galaxy formation and evolution, particularly within the framework of supermassive black hole (SMBH) and galaxy co-evolution. In this context, feedback refers to the processes through which SMBHs influence their host galaxies by releasing energy and materials, which then impact gas dynamics and star formation. Two primary forms of feedback are AGN (Active Galactic Nucleus) feedback and stellar feedback. AGN feedback, driven by accretion processes around SMBHs, involves energy ejected through outflows and jets, impacting star formation by either quenching or stimulating it within galaxies.[16] Stellar feedback, predominantly from supernovae, contributes similarly to regulating gas availability, influencing galaxy-wide star formation rates.[17] These feedback processes are particularly significant in managing gas distribution, as they heat and displace gas, affecting the availability of star-forming material within galaxies. AGN feedback, for example, can suppress star formation by expelling gas or heating it, rendering it inaccessible for new stars. However, in certain cases, AGN feedback has also been observed to compress gas clouds, thereby triggering star formation in specific galactic regions.[17] These dual effects underscore the complexity of feedback mechanisms, with AGN activity functioning as both a regulator and, at times, an enhancer of star formation.

4.2 AGN Feedback

4.2.1 Radiative (Thermal) Feedback Active galactic nuclei (AGN) significantly influence their host galaxies through radiative, or thermal, feedback mechanisms. This process involves high-energy radiation from the AGN heating the surrounding gas, which can inhibit star formation by preventing the gas from cooling and condensing into molecular clouds.[18] Observational studies, such as those by Treister et al., show that thermal feedback regulates star formation by altering the energy balance within the galactic core.[19] Simulations further support these findings, indicating that AGN-driven thermal feedback can halt star formation in regions surrounding the AGN by heating the interstellar gas to temperatures unsuitable for star formation.[16] This dual role highlights the AGN's position in controlling the star formation rate, as intense radiation from the AGN can create vast ionized bubbles, which prevent gas from accumulating into dense star-forming regions.[20] Furthermore, high-energy radiation can disrupt the cooling flow of gas onto the galactic core, thus establishing a feedback loop where the AGN moderates its own growth by reducing available fuel sources.[17,20]

4.2.2 Mechanical (Kinetic) Feedback In addition to radiative feedback, AGNs also exert mechanical, or kinetic, feedback through jets and outflows that inject kinetic energy into the galaxy, impacting both gas distribution and star formation rates. Studies have shown that powerful AGN jets can clear gas from the galactic centre, effectively quenching star formation by removing the material necessary for star formation.[16,22] However, in some cases, AGN outflows also compress nearby gas clouds, triggering localized bursts of star formation in regions where gas density is increased.[23,24] This kinetic feedback has a dual impact: it can act as a quenching mechanism, dispersing gas and limiting star formation in the galactic core, or as a triggering mechanism, where shock compression from AGN outflows stimulates star formation in more distant regions of the host galaxy.[25,26] These interactions between AGN activity and the surrounding gas illustrate the complexity of feedback mechanisms and their importance in regulating galactic evolution.[27]

4.3 Stellar Feedback

4.3.1 Supernova and Stellar Winds Feedback Stellar feedback plays a significant role in redistributing gas within galaxies, particularly through supernova explosions and stellar winds. Massive stars, in the final stages of their lives, undergo supernova explosions that inject energy into the interstellar medium, heating and dispersing gas. This process regulates star formation rates by either clearing out regions of gas, which prevents new stars from forming, or by compressing surrounding gas, which can trigger localized star formation.[20,24] Additionally, stellar winds from young, massive stars drive gas outward from the galactic core, influencing the distribution and density of gas, which impacts the galaxy's star formation potential and energy balance.[16,21] The feedback from supernovae and stellar winds is essential to galaxy evolution, as it continuously redistributes gas and alters the temperature and density conditions required for star formation. By creating hot, low-density regions, stellar feedback mechanisms inhibit the formation of molecular clouds, the sites of star formation, thus moderating the overall star formation rate within galaxies and contributing to a balanced galactic ecosystem.[16,26]

4.3.2 Impact of Stellar Feedback on SMBH Accretion Stellar-driven feedback, primarily through supernovae and stellar winds, also impacts the accretion rates of SMBHs. When stellar feedback disperses gas within the galactic core, it can deprive the SMBH of the fuel necessary for accretion, thereby slowing its growth.[19,23] This feedback loop creates an intricate interplay where the rate of star formation directly influences the availability of gas for SMBH accretion. Conversely, when stellar feedback compresses gas into dense pockets, it can potentially enhance SMBH accretion under certain conditions, further linking star formation activities with SMBH growth.[18,25] This feedback mechanism exemplifies the interconnected relationship between SMBH activity and star formation within galaxies, as each process continually influences the other, maintaining a dynamic equilibrium that shapes the evolutionary path of the galaxy.[17,27]

4.4 Combined Feedback Effects

The interaction between AGN and stellar feedback mechanisms provides a holistic regulatory system for SMBH-galaxy co-evolution. Combined, these feedback types work to either enhance or suppress star formation and SMBH growth, depending on the prevailing environmental conditions. AGN feedback, through thermal and kinetic processes, can heat or clear out gas, while stellar feedback further redistributes gas through supernovae and stellar winds, amplifying the regulatory impact on galactic dynamics.[16,22] Simulations, such as the ROMULUS25 cosmological simulation, have been instrumental in capturing these combined feedback effects. This simulation models both AGN and stellar feedback and demonstrates how their interplay influences galaxy morphology, SMBH growth rates, and star formation patterns across cosmic timescales.[21,24] Such simulations reveal that combined feedback mechanisms are essential for maintaining the balance in galaxies, as they work in tandem to moderate SMBH accretion and star formation cycles, highlighting the complexity of galaxy evolution.[16,28]

4.5 Summary and Implications for Galaxy Evolution

In summary, feedback mechanisms are fundamental to the co-evolution of SMBHs and galaxies, regulating star formation, gas distribution, and SMBH growth. AGN feedback, through thermal and kinetic processes, and stellar feedback, through supernovae and stellar winds, create a balanced interplay that shapes galactic structure and evolution. These mechanisms not only influence the immediate environment of the SMBH but also contribute to larger galactic dynamics over time.[20,26] Despite advances in understanding feedback processes, there remain significant gaps, particularly in accurately modelling the interaction between AGN and stellar feedback at different scales. Future research is needed to refine simulations, like ROMULUS25, and improve observational methods to fully capture the intricacies of feedback mechanisms, which will be crucial for advancing our knowledge of galaxy formation and evolution.[19,23]

5 Co-Evolution of SMBHs and Host Galaxies

5.1 Introduction to Co-Evolutionary Models

5.1.1 Background on SMBH and Galaxy Formation The co-evolution of SMBHs and their host galaxies has become a pivotal area of study in astrophysics. SMBHs, typically residing at the centres of galaxies, are believed to have formed early in the universe's history, shortly after the first stars and galaxies appeared. The formation of SMBHs and galaxies is deeply interconnected. The prevailing hypothesis suggests that SMBHs began as either the remnants of massive Population III stars or from the direct collapse of dense gas clouds.[18,24] As these black holes accreted mass from their surroundings, they exerted a significant influence on their host galaxies. The relationship between a galaxy's growth and its central black hole is governed by various feedback processes that regulate star formation and the distribution of gas within the galaxy.[16] This tight interplay suggests that SMBHs and galaxies grew together, with the SMBH's accretion activity and the galaxy's star formation processes influencing each other throughout their mutual evolution.[17,23,25]

5.1.2 Overview of Scaling Relations The co-evolution of SMBHs and their host galaxies is best demonstrated through the empirical scaling relations between the mass of the SMBH and the properties of the galaxy. Two of the most well-established correlations are the $M_{\mathrm{SMBH}} - M_{\mathrm{bulge}}$ relation, which links the black hole mass to the stellar bulge mass, and the $M_{\mathrm{SMBH}} - \sigma$ relation, which correlates the black hole mass with the stellar velocity dispersion.

5.1.3 $M_{SMBH} - M_{bulge}$ Relation The $M_{\mathrm{SMBH}} - M_{\mathrm{bulge}}$ relation suggests that larger galaxies with bigger bulges tend to host more massive black holes, with a near-linear correlation observed between the logarithm of black hole mass and bulge mass.[20,29] This relation implies a tight co-evolution between the growth of the central black hole and the formation of the galactic bulge. The relationship in Figure 3 highlights how this scaling law applies across a variety of galaxy types.

5.1.4 $M_{SMBH} - \sigma$ (Stellar Velocity Dispersion) Relation Another key empirical scaling relation is the $M_{\mathrm{SMBH}} - \sigma$ relation, which links the SMBH mass to the stellar velocity dispersion

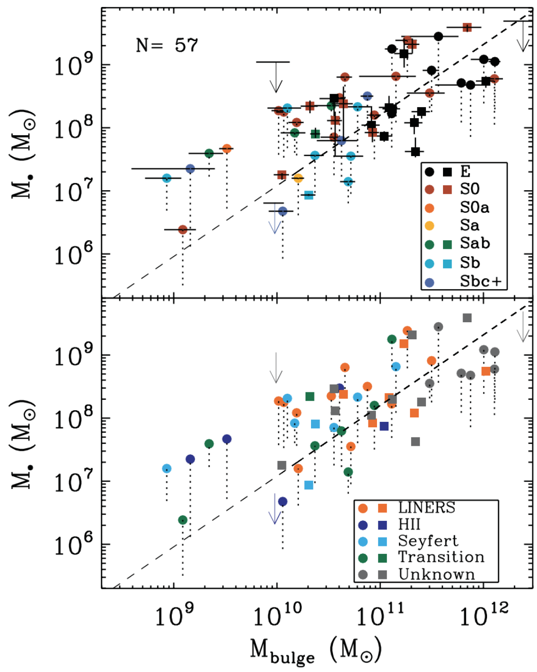

Figure 3. Correlation between SMBH mass M_{SMBH} and bulge mass M_{bulge} across various galaxy types (Haring & Rix scaling relation). The dashed line shows the theoretical prediction for the $M_{\mathrm{SMBH}} - M_{\mathrm{bulge}}$ relation.[24] The top panel displays the correlation based on galaxy morphology, while the bottom panel breaks down the data by AGN activity[29].

of the galaxy. Studies have shown that the mass of the black hole is proportional to the fourth power of the velocity dispersion of stars in the galactic bulge.[16 25] This relation is particularly useful because it suggests a dynamic relationship between the gravitational influence of the black hole and the kinetic energy of the stars in the bulge. Observational data supporting this scaling law has been instrumental in refining our understanding of how SMBHs influence galaxy evolution. Both the $M_{\mathrm{SMBH}} - M_{\mathrm{bulge}}$ and $M_{\mathrm{SMBH}} - \sigma$ relations are fundamental to the study of co-evolutionary models, as they imply that black hole growth is not independent but intricately linked with the evolution of the galaxy itself. These scaling relations provide crucial insights into how galaxies and their central black holes develop over cosmic time.

5.2 Feedback Mechanisms in Co-Evolution

5.2.1 The Role of AGN Feedback Active Galactic Nuclei (AGN) feedback plays a dual role in regulating star formation in galaxies. AGN-driven jets and outflows can expel cold gas from the galaxy, effectively quenching star formation by removing the raw material needed for new stars. However, under different conditions, the outflows can compress gas clouds, leading to bursts of star formation. This dual role means that AGN feedback can either suppress or trigger star formation, depending on the environment and feedback strength.[18 26] AGN feedback impacts the surrounding interstellar medium by heating the gas, raising its temperature, and preventing it from cooling and forming stars. This process, known as quenching, is a key mechanism through which AGNs regulate the star formation rate in galaxies. However, in some cases, feedback can trigger star formation by compressing gas clouds.[21 22] Figure 4 illustrates this process by showing the distribution of gas particles in the density-temperature plane at redshift $z = 6$. The left-hand panels in the figure display how AGN feedback influences gas density and temperature across different regions within the galaxy's virial radius. For example, the simulation labelled

"AGN fid" shows how feedback impacts gas properties compared to other feedback models. The right-hand panels display how AGN feedback affects the metallicity of the gas, a key indicator of star formation processes.[26]

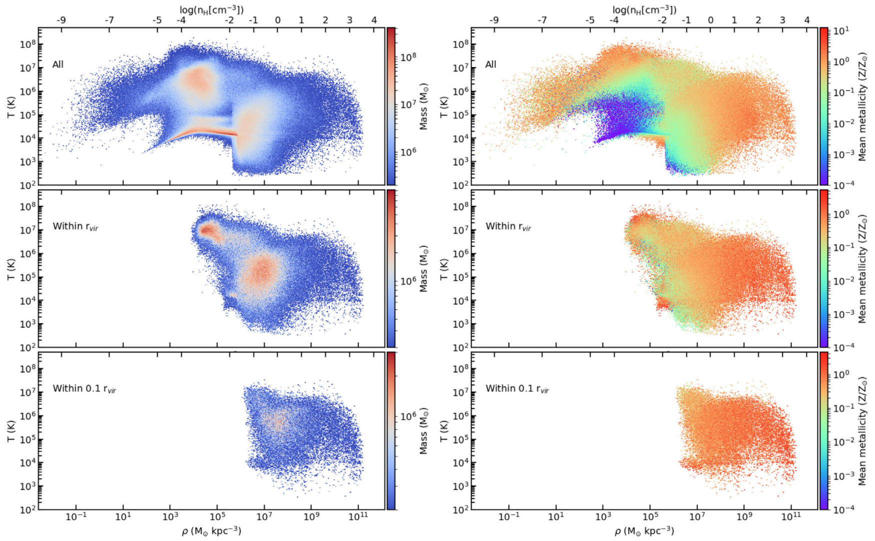

Figure 4. Distribution of gas particles in the density-temperature plane at redshift $z = 6$. The left-hand panels show gas mass per density-temperature bin for different regions in the galaxy, while the right-hand panels show the metallicity of the gas in these regions. The top row represents all gas particles, while the middle and bottom rows focus on regions within the galaxy's virial radius. This figure highlights the complex role of AGN feedback in regulating gas properties, which in turn affects star formation.[21]

5.2.2 The Impact of SMBH Feedback on Star Formation Rates SMBH-driven feedback can significantly alter the star formation rates in galaxies, either by suppressing or triggering star formation. Observational studies have demonstrated that powerful AGN outflows can remove gas from the central regions of galaxies, thereby reducing star formation rates.[16 20] This process is particularly evident in quasar-mode feedback, where high-luminosity AGNs exert strong radiation pressure on the surrounding gas, pushing it out of the galaxy's central regions.[27] Conversely, in certain environments, SMBH feedback can compress gas and initiate bursts of star formation. This is typically seen in radio-mode feedback, where jets from the AGN interact with the surrounding medium.[21] Studies suggest that these jets can play a role in reigniting star formation in gas-rich galaxies.[23 26]

5.3 Evolution through Galaxy Mergers

5.3.1 SMBH Growth During Galaxy Mergers Galaxy mergers are a critical mechanism for driving SMBH growth. During a merger, the inflow of gas into the central region of the galaxy is significantly enhanced, providing fuel for the SMBH to accrete mass rapidly. This process often results in periods of quasar activity, where the SMBH becomes highly luminous due to the large amounts of material being accreted.[25 30] Simulations have shown that the most substantial SMBH growth occurs during the final stages of the merger when the SMBHs of the merging galaxies coalesce.[24 26] This process is often accompanied by the formation of a binary SMBH system, which interacts with the surrounding stars and gas, further influencing the galaxy's structure.[17 21]

5.3.2 Binary SMBHs and Their Effects on Galaxy Structure When two galaxies merge, the SMBHs at their centres can form a binary system. This binary SMBH exerts gravitational forces on the surrounding stars, altering the structure of the host galaxy.[22] One of the most notable effects is the formation of a circumbinary disk, a structure of gas and stars that orbits around the binary SMBH.[16 18] As the SMBHs spiral towards each other, they eject stars from the core of the galaxy, leading to the development of low-density regions, or cores, in the central parts of the galaxy.[25 29] These structural changes are especially prominent in the most massive galaxies, where the influence of the binary SMBH is strongest.[17]

5.4 Early Universe and SMBH Co-Evolution

5.4.1 Rapid SMBH Growth in the Early Universe SMBHs began forming early in the universe, around the same time as galaxies. In this period, dense gas environments provided the necessary fuel for rapid accretion and growth. The direct collapse model is often cited as a plausible scenario, suggesting that SMBHs formed from massive gas clouds instead of star remnants. These SMBHs could rapidly gain mass due to high gas densities present in the early universe, allowing them to reach millions to billions of solar masses by the time galaxies had formed.[19] The link between galaxy formation and black hole growth is strongly supported by cosmological simulations, which show that galaxies and SMBHs co-evolved during this high-redshift phase. However, the precise mechanisms for how SMBHs reached such sizes remain uncertain, with gas accretion rates, mergers, and other environmental factors being areas for further research.[28]

5.4.2 Observational Challenges in High-Redshift Studies Observing the formation and growth of SMBHs in the early universe is fraught with difficulties. At high redshifts, dust and gas obscure the accretion processes, making it hard to track how SMBHs and their host galaxies evolve. X-ray and infrared observations have provided some insights into SMBH growth rates, but they remain limited by technological constraints. The launch of next-generation telescopes, such as the James Webb Space Telescope (JWST), is expected to shed more light on this elusive period. One challenge lies in disentangling the effects of AGN feedback and other cosmic processes from the observational data, further complicating the study of SMBHs in high-redshift galaxies.[16 28]

5.5 Insights from Co-Evolutionary Models

Research into co-evolutionary models has deepened our understanding of the interconnectedness between SMBH growth and galaxy formation. These models highlight how feedback mechanisms, scaling relations, and environmental factors influence both SMBHs and their host galaxies over time. SMBHs do not evolve in isolation; their growth is intrinsically tied to the larger cosmic structures they inhabit. Despite significant advancements, gaps remain, particularly in understanding how SMBH growth mechanisms differ in low-mass vs. high-mass galaxies and how certain feedback processes may have halted star formation prematurely. As we transition to the study of galaxy mergers in the next section, it becomes evident that such events are crucial drivers of both SMBH and galaxy evolution, often leading to dramatic changes in their properties.[19]

6 Galaxy Mergers and the Role of SMBHs

6.1 Introduction to Galaxy Mergers and SMBHs

Galaxy mergers occur when two or more galaxies collide and combine through mutual gravitational forces. Mergers were more prevalent in the early universe, as galaxies were in closer proximity to one another. They play a significant role in the structure of the universe observed today. The structure of a galaxy can be altered entirely, for example when two spiral galaxies collide, an elliptical galaxy forms. Intense star formation rates, also called Starbursts, can often be triggered by galaxy mergers. Additionally, mergers are a crucial mechanism for galaxy growth and development.[31] Simulated and observed galaxy mergers offer different insights, each with unique strengths and limitations. Simulations like the IllustrisTNG allow researchers to model the complex gravitational dynamics, AGN feedback, star formation and gas flows under controlled conditions. The IllustrisTNG runs simulations on a large cosmic scale, covering 300 million light-years per side whilst also capturing small scale details within galaxies. This control allows researchers to adjust variables such as galaxy mass and orbital parameters. However, these simulations may oversimplify assumptions in order to make calculations feasible, thus impacting the precision. On the other hand, observed galaxy mergers capture the natural complexity of events and highlight unexpected features such as irregular starbursts, gas dynamics and gravitational waves from SMBH mergers. The Hyper Suprime-Cam Subaru Strategic Program (HSC-SSP) survey is a large-scale observational project that uses one of the most sensitive wide-field cameras in the world. However, weather and other environmental factors can restrict and impact the amount of data collected.[32] When both simulations and observations are used together, they offer complementary perspectives: simulations provide controlled and testable models, while observations validate and refine the models with evidence. Galaxy mergers can trigger AGN activity through several mechanisms, such as gas inflow and gravitational torque. As stated previously, gas is directed towards the galactic centre, driven by gravitational torques. Torques are created due to the interacting gravitational fields in each galaxy and affect the galaxy's angular momentum.[33] The increased inflow of gas increases the accretion rate of the SMBHs, making it appear more luminous as the AGN becomes more active. The gravitational torques aid in the collision of the SMBHs and redistribute the mass and energy within the merging system.[34]

6.1.1 Effects on SMBHs In major galaxy mergers, the central SMBHs from each galaxy can form a binary system and eventually coalesce. The process begins with the inspiral phase. As both SMBHs begin orbiting each other, the orbital distance between them decreases whilst speed increases causing both SMBHs to rotate around each other. Gravitational waves are released during this phase and increase until both SMBHs collide, allowing for the shed angular momentum and the central black holes to coalesce.[35] Then the merger phase begins when both SMBHs combine into one single entity. This phase takes hundreds of millions of years to complete but differs depending on the size and mass of the SMBHs. Finally, the newly formed single SMBH settles into a stable state.

6.1.2 Influence on Galaxy Structure and Evolution Mergers can dramatically alter the morphology of galaxies, often leading to significant structural transformations. An elliptical galaxy can be formed as a result of significant mergers between two spiral galaxies. This occurs through the disruption of galactic disks and the redistribution of stars into a spheroidal configuration. Post-merger effects include core scouring, a process where SMBHs eject stars from the galactic centre.[36] Additionally, the gas funnelled towards the centre of the merging system can also trigger starbursts. The gravitational interactions between the two galaxies lead to the compression of gas clouds, which ultimately collapse under their own gravity. These dense gas clouds can begin to form protostars and can occur rapidly, resulting in rapid star formation/a starburst that typically lasts for millions of years.[37]

6.1.3 Long-Term impacts on galactic evolution In the long term, galaxy mergers can lead to significant changes in the stability and evolution of the resulting system. SMBHs play a pivotal role in maintaining post-merger stability, primarily through the influence of AGN feedback. This feedback regulates the gas dynamics within the galaxy, effectively suppressing excessive star formation and contributing to the overall stability. Consequently, many post-merger galaxies transition into quiescent states, characterised by greatly reduced star formation rates.[38] These galaxies are typically dominated by older stellar populations and exhibit minimal ongoing star formation, marking a critical stage in their long-term evolutionary trajectory.

7 Observational Techniques and Challenges

There are numerus observational techniques used when trying to discover SMBHs. Key methodologies, including gravitational wave observations, gravitational lensing, and radio observations, play pivotal roles in SMBH research. This section aims to provide a critical overview of each method's strengths and limitations while exploring potential future advancements within the field. By identifying gaps in current methodologies, this analysis will offer suggestions for addressing these observational challenges and highlight directions for further investigation.

7.1 Technique 1: Gravitational Wave Observations

Gravitational waves offer an entirely new means of observing SMBHs, particularly through the detection of black hole mergers. When two SMBHs come close enough to become gravitationally bound, they orbit each other, losing energy through gravitational radiation. Over time, this loss of energy brings them closer together until they eventually collide, merging into a single, larger black hole. The massive gravitational disturbance of this merger sends out gravitational waves—ripples in spacetime that can travel vast distances across the universe.

7.1.1 How are Gravitational Waves made? When a black hole merger occurs, initially, two black holes orbit each other, radiating energy as gravitational waves. This energy loss causes the orbits to decay gradually, with the black holes spiraling closer over millions or even billions of years. During the inspiral, the gravitational waves emitted are relatively low in frequency, but they increase in frequency as the black holes approach[39]. In the merger phase, the two black holes reach a point where they coalesce, merging into a single black hole in a highly energetic event. This merger moment releases an enormous amount of energy in the form of gravitational waves, producing a final "chirp" or peak in gravitational wave frequency that detectors like LIGO and Virgo can capture[40 41]. The merger phase is the most energetic and emits gravitational waves at their strongest amplitude. Following the merger, the newly formed black hole is often in an unstable state due to asymmetries from the merging process. During the ringdown, it stabilises by radiating energy as gravitational waves, gradually damping out until it settles into a stable state. The frequency of these waves provides insight into the properties of the resultant black hole, such as its mass and spin[42 43].

7.1.2 Examples of Gravitational Waves Being Used: LIGO and Virgo LIGO (Laser Interferometer Gravitational-Wave Observatory) and Virgo have observed gravitational waves from stellar-mass black hole mergers, paving the way for future observations of SMBH mergers[40]. LIGO has two observatories in the United States—one in Hanford, Washington, and the other in Livingston, Louisiana—with Virgo located in Europe, specifically in Cascina, near Pisa, Italy. Both observatories work together in a global collaboration to detect and study these waves, allowing for better localisation of gravitational wave sources, as having detectors spread across the globe enables more precise triangulation.

Methods and Instrumentation LIGO and Virgo are sophisticated observatories; the waves detected, created by massive cosmic events like black hole or neutron star mergers, stretch and compress space as they pass through, producing tiny changes that LIGO and Virgo are designed to measure with extreme precision[40 44]. Both observatories use a method called laser interferometry. In this setup, a powerful laser beam is split into two perpendicular beams. Each beam travels down a long arm (4 km for LIGO and 3 km for Virgo), reflects off mirrors at the ends, and returns to the origin where the two beams are recombined. If a gravitational wave passes, it will slightly alter the length of each arm differently, causing one arm to stretch while the other contracts. This change in length disrupts the alignment of the recombined laser beams, creating an interference pattern. This pattern reveals the passing of a gravitational wave and allows scientists to measure its characteristics[45]. LIGO and Virgo achieve high sensitivity through extreme precision engineering. Mirrors at the end of each arm are isolated from vibrations and cooled to avoid interference from thermal noise. Additionally, multiple layers of noise reduction help filter out signals from environmental factors. Advanced data processing and analysis techniques then enable scientists to interpret the signals from detected gravitational waves[46]. The collaboration between LIGO and Virgo allows for triangulation of the gravitational waves' origins, giving insight into the location and nature of the cosmic events. Together, these observatories have opened a new field of gravitational wave astronomy, enabling the direct observation of previously invisible events in the universe[47].

7.1.3 Importance of Gravitational Wave Detection Gravitational waves were first predicted by Einstein in 1916 as a consequence of his general theory of relativity, but they were only directly detected by LIGO in 2015, from the merger of two stellar-mass black holes[40]. This groundbreaking detection opened a new "gravitational wave window" into the universe, providing a method to observe cosmic events that would otherwise be invisible. In terms of SMBHs, gravitational wave detectors sensitive to lower frequencies are necessary due to the large masses and relatively slow in-spiral of SMBHs. While current ground-based observatories, such as LIGO and Virgo, are sensitive to high-frequency gravitational waves from stellar-mass black holes, future space-based missions like the Laser Interferometer Space Antenna (LISA) will be sensitive to the low-frequency waves produced by SMBH mergers. LISA, planned for launch in the 2030s, is expected to detect mergers of SMBHs at cosmological distances, providing insights into the population of SMBHs throughout the universe and their role in galactic evolution[48].

7.1.4 Technique Limitations Gravitational wave detectors like LIGO and Virgo face several key limitations, primarily due to sensitivity constraints and environmental noise. These detectors measure incredibly small disturbances in spacetime, often requiring precision down to a fraction of a proton's width. Consequently, any environmental vibrations—such as seismic activity, nearby traffic, or even minor thermal fluctuations—can interfere with measurements, despite the use of advanced noise-canceling systems[46]. Additionally, detectors are limited by frequency sensitivity ranges. LIGO and Virgo can detect frequencies from around 10 Hz to several kHz, which makes it challenging to observe signals from supermassive black hole mergers, whose gravitational waves fall below this range[47]. Furthermore, gravitational wave observatories are highly expensive compared to other astronomical instruments, with projects like LIGO and Virgo costing hundreds of millions of dollars, placing constraints on upgrades and expansions[49]. Another limitation is that gravitational wave signals weaken as they travel across vast cosmic distances, reducing the effective range within which current detectors can detect events. While future detectors like the proposed Einstein Telescope and LISA aim to extend both frequency range and sensitivity, current limitations restrict our ability to fully observe all possible gravitational wave events in the universe[50].

7.2 Technique 2: Gravitational Lensing

Gravitational lensing is a powerful observational technique in astrophysics used to study distant cosmic objects, including supermassive black holes (SMBHs). Predicted by Einstein's theory of general relativity, gravitational lensing occurs when a massive object, such as an SMBH or galaxy cluster, lies between an observer and a distant light source. The immense gravitational field of the intervening object bends and magnifies the light from the background source, creating various distortions like arcs, rings, or multiple images of the source around the lensing object.[51] This effect allows astronomers to indirectly observe and study massive objects that would otherwise be challenging to detect.

7.2.1 The Use of Gravitational Lensing to Locate SMBHs In the context of SMBHs, gravitational lensing is particularly valuable because SMBHs themselves do not emit light directly; however, they affect the light from objects behind them. By studying the gravitational lensing patterns, scientists can infer the mass, size, and structure of the intervening SMBH.[52] Additionally, lensing provides information about the distribution of dark matter in the vicinity of SMBHs, as dark matter also contributes to the gravitational field that bends light.[53] This capability is particularly useful in understanding galaxy centres, where SMBHs are typically located, as the lensing can reveal mass concentrations and gravitational potential. For SMBH research, gravitational lensing is a unique tool because it allows scientists to observe very distant or faint objects that would otherwise be undetectable. Given the immense distances involved, the gravitational lensing of light from SMBHs enables astronomers to study these massive objects across cosmological timescales. For example, the bending of light around a galaxy cluster that contains an SMBH can reveal how mass is distributed within the cluster, offering clues about the SMBH's mass and gravitational influence.[54] Additionally, lensing allows researchers to measure cosmic distances, providing insight into the evolution of SMBHs over time and their role in galactic dynamics.

7.2.2 Examples of Gravitational Lensing in Use

Abell 370 One prominent example of gravitational lensing in action is the study of the galaxy cluster Abell 370, which contains a significant SMBH along with large concentrations of dark matter. Abell 370 is known for its dramatic lensing effects, which include distorted images of background galaxies in the form of arcs and rings, famously called the "Dragon" due to the distinctive curved shape. This configuration has allowed researchers to explore the mass profile of the cluster and the SMBH's influence on light passing through the cluster, revealing insights into both the visible and dark matter in the system[55]. The gravitational lensing of Abell 370 is also used to observe galaxies that lie far behind it, helping scientists study these distant galaxies' structures, star formation rates, and evolution[56].

Hubble Space Telescope's Frontier Fields program Another significant application of gravitational lensing is seen in the Hubble Space Telescope's Frontier Fields program, a project focused on observing the most distant galaxies through lensing effects created by massive galaxy clusters. One notable observation is of the galaxy cluster MACS J0416.1-2403, which acts as a natural lens, magnifying the light from galaxies lying billions of light-years behind it. This allows for detailed observations of galaxies in the very early universe, providing insights into how galaxies and SMBHs evolved soon after the Big Bang[57]. The Frontier Fields program has enabled astronomers to identify faint, small galaxies that otherwise would not have been observable. Through careful analysis, researchers can use the distortions created by gravitational lensing to measure the masses of these distant objects and understand their composition and the early stages of galactic formation[58].

7.2.3 Importance of Gravitational Lensing Gravitational lensing has become a vital technique in modern astrophysics. Its importance extends beyond studying SMBHs; lensing allows for the mapping of dark matter, which makes up a significant portion of the universe's mass but does not emit light. Through gravitational lensing, scientists can visualise the distribution of dark matter around galaxies and galaxy clusters by analysing how light is distorted as it travels through regions dominated by this invisible matter.[59] This has expanded our understanding of the universe's mass distribution and the structure of cosmic filaments that connect galaxy clusters. Gravitational lensing also acts as a "natural telescope," enabling the observation of extremely distant galaxies by magnifying their images, giving insights into early galaxy formation and evolution. Furthermore, gravitational lensing provides a method for testing general relativity on cosmic scales, as the amount of lensing observed can be compared to theoretical predictions, offering potential insights into modifications of gravity or the presence of exotic forms of matter and energy.[60]

7.2.4 Limitations of Gravitational Lensing Despite its utility, gravitational lensing has certain limitations. One key limitation is that it depends on precise alignment of the source, lens, and observer, making suitable cases of gravitational lensing rare and challenging to observe.[61] Many potential SMBHs and distant galaxies remain undetected because they do not align with foreground lenses in a way that produces visible lensing effects. Another challenge is that lensing primarily provides information on the mass and general structure of the lensing object, which can make it difficult to identify finer details about SMBHs, such as their spin, accretion rates, or interactions with nearby stars or gas.[62] Furthermore, gravitational lensing often cannot distinguish between different types of massive objects that cause the lensing effect. While the lensing patterns reveal the presence of massive objects, they do not indicate whether the mass is a supermassive black hole, a galaxy cluster, or another type of structure. To confirm that lensing is specifically caused by an SMBH, researchers usually need additional data from other wavelengths, such as X-ray or radio observations, which can identify energetic emissions characteristic of SMBHs.[63] These additional observations, however, require access to multi-wavelength observatories and further data analysis, which can be resource-intensive. Another technical limitation is the sheer computational complexity involved in modelling gravitational lensing data. Since gravitational lensing provides only indirect information about the lensing object, complex simulations are often necessary to accurately interpret the observations. This modelling process requires substantial computational power and is subject to uncertainties due to assumptions about the shape, density, and distribution of mass within the lensing object. Even minor inaccuracies in these assumptions can lead to significant errors in estimating the characteristics of SMBHs or dark matter distributions.[64]

7.3 Technique 3: Radio Observations

Radio observations are a common and again, vital, tool when in studying SMBHs. By detecting radio waves emitted by astronomical objects, astronomers can gather crucial information about the dynamics, environments, and properties of SMBHs. This technique allows researchers to probe the universe in ways that optical observations cannot, especially when observing obscured regions or extremely distant objects.

7.3.1 How Radio Observations Work to Find SMBHs Radio observations rely on the detection of radio waves, which are electromagnetic waves with longer wavelengths than visible light. Instruments known as radio telescopes collect these signals from cosmic sources, converting them into images and spectra for analysis.[65] In the context of SMBHs, radio emissions often originate from jets or outflows created by material accreting onto the black hole. As gas and dust spiral toward the SMBH, they heat up and emit radiation across various wavelengths, including radio frequencies.[66] The emitted radio waves provide insights into the physical processes occurring near the black hole, including the temperature, density, and velocity of the surrounding material. A particularly important aspect of radio observations is their ability to reveal the presence of relativistic jets—highly collimated streams of charged particles that move at speeds close to the speed of light. These jets are commonly associated with active galactic nuclei (AGN) powered by SMBHs. The detection and analysis of these jets can offer indirect evidence of SMBH activity, as they are often launched along the rotational axis of the black hole, providing insights into the black hole's spin and the mechanisms driving the accretion process.[67]

7.3.2 Example of Radio Observations in Use One notable example of effective radio observations in the study of SMBHs is the monitoring of the nearby galaxy M87. The Event Horizon Telescope (EHT), a global network of radio telescopes, aimed to image the region surrounding the SMBH in M87, which is about 6.5 billion solar masses.[68] In 2019, the EHT collaboration announced the first direct image of the shadow of the black hole in M87, revealing critical details about its structure and environment.[69] This groundbreaking observation was made possible through very long baseline interferometry (VLBI), a technique that combines data from multiple radio telescopes around the world to create a virtual Earth-sized telescope with unprecedented resolution. The M87 study not only provided direct evidence of an SMBH's existence but also offered insights into the physical processes occurring in its vicinity, including the dynamics of the accretion disk and the launching of relativistic jets. This research exemplifies the power of radio observations in advancing our understanding of SMBHs and their role in galactic evolution.

7.3.3 Importance of Radio Observations Radio observations are crucial for several reasons. First, they complement other observational methods, such as optical and X-ray studies, by providing unique insights into the high-energy processes near SMBHs that are often obscured in other wavelengths.[70] Additionally, radio waves can penetrate dense interstellar material that may obscure optical signals, allowing astronomers to study regions of star formation and AGN activity that would otherwise remain hidden.[71] Moreover, radio observations are vital for understanding the relationship between SMBHs and their host galaxies. By studying the correlations between SMBH masses and properties of their host galaxies, such as bulge mass and star formation rates, astronomers can probe the co-evolution of galaxies and their central black holes.[72] This knowledge is essential for piecing together the history and dynamics of galaxy formation in the universe.

7.3.4 Limitations of Radio Observations Despite their importance, radio observations also have limitations. One significant challenge is the need for large, sensitive radio telescopes capable of detecting faint signals from distant sources. Building and maintaining these facilities can be expensive and time-consuming[73]. Additionally, the Earth's atmosphere and ionosphere can distort radio signals, necessitating sophisticated correction techniques to ensure accurate measurements[74]. Another limitation is that radio observations often require extended periods of observation to detect transient phenomena or weak signals, leading to long data acquisition times. This can make it challenging to capture fast-evolving events, such as flares from SMBHs or transient jets. Furthermore, while radio observations can reveal the presence of SMBHs and their associated jets, they do not provide direct information about the black hole's spin or the specifics of the accretion process without complementary data from other wavelengths[75]. There are multiple observational techniques that can be used to discover, locate, and study SMBHs. However, of the three analysed above—the identification of gravitational waves, gravitational lensing, and radio observations—it isn't as simple as saying one is better than the other, as several factors affect not only efficiency and accuracy but also the range of each device, which plays a critical role in all observational techniques. All of these methods are applied across a range of different circumstances to be considered successful; however, ultimately, all are used with the intent of finding and identifying SMBHs. These three techniques are arguably some of the most common and somewhat easy to apply, hence producing a high number of results. Moreover, gravitational lensing and radio observations are methodologies that have been applied numerous times throughout the field of astronomy to identify SMBHs. However, these techniques are quite limited in what they can find and observe, whereas in identifying gravitational waves, the data received provides a broader range. However, the technology and methodologies for this technique are still relatively new and require further research to refine the processes.

8 Conclusion and Future Directions

Supermassive black holes (SMBHs) provide essential insights into their own formation mechanisms and the broader evolution of the universe. Examined theories, such as seeding from Population III stars and the direct collapse model, highlight varied origins shaped by early-universe conditions. The growth of SMBHs unfolds through complex processes primarily driven by accretion and mergers, each contributing uniquely across cosmic timescales. The formation of accretion disks, managed by angular momentum transfer and a balance between mass inflow and radiative efficiency, is essential to sustain SMBH growth. Additionally, cases of super-Eddington accretion propose that rapid SMBH growth in high-redshift environments may be more common than previously assumed, challenging conventional views. Galaxy mergers significantly drive SMBH growth and activate AGN processes, which regulate star formation through feedback mechanisms that influence the structure and evolution of galaxies. These mergers often trigger starbursts and morphological changes within galaxies, underscoring the critical role of SMBHs in shaping galaxy evolution. Despite these findings, considerable knowledge gaps remain, especially in observing SMBHs at high redshifts and understanding the precise interactions of feedback mechanisms at different scales. Future advancements in observational technology and simulations are essential to bridge these gaps, offering clearer insights into SMBH formation and the broader dynamics of the universe.

9 References

[1] Banik N, Tan JC, Monaco P. The formation of supermassive black holes from Population III.1 seeds. I. Cosmic formation histories and clustering properties. Mon Not R Astron Soc. 2019 Mar 1;483(3):3592–606. Available from: https://doi.org/10.1093/mnras/sty3298.

[2] Liu B, Gurian J, Inayoshi K, Hirano S, Hosokawa T, Bromm V, et al. Towards a universal analytical model for Population III star formation: interplay between feedback and fragmentation. Mon Not R Astron Soc. 2024 Sep 13;534(1):290–312. Available from: https://doi.org/10.1093/mnras/stae2066.

[3] Lu Y, Picker ZSC, Kusenko A. Direct-collapse supermassive black holes from relic particle decay. 2024 [cited 2024 Oct 26]; Available from: https://arxiv.org/abs/2404.03909.

[4] Latif MA, Volonteri M, Wise JH. Early growth of typical high-redshift black holes seeded by direct collapse. Mon Not R Astron Soc. 2018 Jun 1;476(4):5016–25. Available from: https://doi.org/10.1093/mnras/sty622.

[5] Bansal A, Ichiki K, Tashiro H, Matsuoka Y. Evolution of the mass relation between supermassive black holes and dark matter halos across the cosmic time. 2022 [cited 2024 Oct 26]; Available from: https://arxiv.org/abs/2206.01443.

[6] Ge Q, Wise JH. On the effect of Lyman α trapping during the initial collapse of massive black hole seeds. Mon Not R Astron Soc. 2017 Dec 11;472(3):2773–86. Available from: https://doi.org/10.1093/mnras/stx2074.

[7] Colazo PE, Stasyszyn F, Padilla N. Structure formation with primordial black holes to alleviate early star formation tension revealed by JWST. Astron Astrophys. 2024 May;685. Available from: https://doi.org/10.48550/arXiv.2404.13110.

[8] Weinberger R, Springel V, Pakmor R, Nelson D, Genel S, Pillepich A, et al. Supermassive black holes and their feedback effects in the IllustrisTNG simulation. Mon Not R Astron Soc. 2018 Sep 21;479(3):4056–72. Available from: https://doi.org/10.1093/mnras/sty1733.

[9] Królak A, Verma P. Recent Observations of Gravitational Waves by LIGO and Virgo Detectors. Universe. 2021 May 9;7(5):137. Available from: https://doi.org/10.3390/universe7050137.

[10] Alister Seguel PJ, Schleicher DRG, Boekholt TCN, Fellhauer M, Klessen RS. Formation of SMBH seeds in Population III star clusters through collisions: the importance of mass loss. Mon Not R Astron Soc. 2020 Apr 1;493(2):2352–62. Available from: https://doi.org/10.1093/mnras/staa456.

[11] Montesinos Armijo MA, De Freitas Pacheco JA. The growth of supermassive black holes fed by accretion disks. Astron Astrophys. 2011 Feb;526. Available from: https://doi.org/10.1051/0004-6361/201015026.

[12] Li LX. Accretion, growth of supermassive black holes, and feedback in galaxy mergers: Accretion and growth of black holes. Mon Not R Astron Soc. 2012 Aug 1;424(2):1461–70. Available from: https://doi.org/10.1111/j.1365-2966.2012.21336.x.

[13] Piana O, Pu HY, Wu K. Super-Eddington accretion in high-redshift black holes and the emergence of jetted AGN. Mon Not R Astron Soc. 2024 Apr 13;530(2):1732–48. https://doi.org/10.1093/mnras/stae851.

[14] Khan FM, Preto M, Berczik P, Berentzen I, Just A, Spurzem R. Mergers of unequal-mass galaxies: supermassive black hole binary evolution and structure of merger remnants. Astrophys J. 2012 Apr 20;749(2):147. Available from: https://doi.org/10.1088/0004-637X/749/2/147.

[15] Khan FM, Berczik P, Just A. Gravitational wave driven mergers and coalescence time of supermassive black holes. Astron Astrophys. 2018 Jul;615. Available from: https://doi.org/10.1051/0004-6361/201730489

[16] Dittmann AJ, Miller MC. Star formation in accretion discs and SMBH growth. Mon Not R Astron Soc. 2020;493(3):3732–43. Available from: https://doi.org/10.1093/mnras/staa463.

[17] Arjona-Gálvez E, Di Cintio A, Grand RJ. The role of AGN feedback on the evolution of dwarf galaxies from cosmological simulations: SMBHs suppress star formation in low-mass galaxies. Astron Astrophys. 2024 Feb 5. Available from: https://doi.org/10.1051/0004-6361/202240929.

[18] Ricarte A, Tremmel M, Natarajan P, Quinn T. Tracing black hole and galaxy co-evolution in the Romulus simulations. Mon Not R Astron Soc. 2019;489(1):802–19. Available from: https://doi.org/10.1093/mnras/stz2161.

[19] Franceschini A, Hasinger G, Miyaji T, Malquori D. On the relationship between galaxy formation and quasar evolution. Mon Not R Astron Soc. 1999;310(1). Available from: https://doi.org/10.1046/j.1365-8711.1999.02960.x.

[20] Chen C-TJ, Hickox RC, Alberts S, Brodwin M, Jones C, Murray SS, et al. A correlation between star formation rate and average black hole accretion in star-forming galaxies. Astrophys J. 2013;773(1):3. Available from: https://doi.org/10.1088/0004-637X/773/1/3.

[21] Valentini M, Gallerani S, Ferrara A. Host galaxies of high-redshift quasars: SMBH growth and feedback. Mon Not R Astron Soc. 2021;507(1):1-26. Available from: https://doi.org/10.1093/mnras/stab1992.

[22] Kim JH, Wise JH, Alvarez MA, Abel T. Galaxy formation with self-consistently modeled stars and massive black holes. I. Feedback-regulated star formation and black hole growth. Astrophys J. 2011;738(1):54. Available from: https://doi.org/10.1088/0004-637X/738/1/54.

[23] O'Donnell C, Behroozi P, More S. Observing correlations between dark matter accretion and galaxy growth: II. testing the impact of galaxy mass, star formation indicator, and neighbour colours. Mon Not R Astron Soc. 2022;509(3):3285–3300. Available from: https://doi.org/10.1093/mnras/stab3170.

[24] Beifiori A, Courteau S, Corsini EM, Zhu Y. On the correlations between galaxy properties and supermassive black hole mass. Mon Not R Astron Soc. 2012;419(3):2497–2528. Available from: https://doi.org/10.1111/j.1365-2966.2011.19903.x.

[25] Poitevineau R, Castignani G, Combes F. Black hole and galaxy co-evolution in radio-loud active galactic nuclei at z $\sim$ 0.3–4. Astron Astrophys. 2023;672. Available from: https://doi.org/10.1051/0004-6361/202244560.

[26] Valentini M, Gallerani S, Ferrara A. Host galaxies of high-redshift quasars: SMBH growth and feedback. Mon Not R Astron Soc. 2021;507(1):1-26. Available from: https://doi.org/10.1093/mnras/stab1992.

[27] Hopkins PF, Hernquist L, Cox TJ, Keres D. A cosmological framework for the co-evolution of quasars, supermassive black holes, and elliptical galaxies. I. Galaxy mergers and quasar activity. Astrophys J Suppl Ser. 2008;175(2):356–89. Available from: https://doi.org/10.1086/524362.

[28] Biernacki P, Teyssier R, Bleuler A. On the dynamics of supermassive black holes in gas-rich, star-forming galaxies: the case for nuclear star cluster co-evolution. Mon Not R Astron Soc. 2017;469(1):295–313. Available from: https://doi.org/10.1093/mnras/stx845.

[29] Rantala A, Johansson PH, Naab T, Thomas J, Frigo M. The formation of extremely diffuse galaxy cores by merging supermassive black holes. Astrophys J. 2018;864(1):113. Available from: https://doi.org/10.3847/1538-4357/aada47.

[30] Bluck AFL, Conselice CJ, Almaini O, Laird ES, Nandra K, Gruetzbauch R. On the co-evolution of supermassive black holes and their host galaxies since z = 3. Mon Not R Astron Soc. 2011;410(2):1174–96. Available from: https://doi.org/10.1111/j.1365-2966.2010.17521.x.

[31] Pearson WJ, Wang L, Alpaslan M, Baldry I, Bilicki M, Brown MJI, et al. Effect of galaxy mergers on star-formation rates. A&A. 2019 Nov 1;631

[32] Margalef-Bentabol B, Wang L, Marca AL, Blanco-Prieto C, Chudy D, Domínguez-Sánchez H, et al. Galaxy merger challenge: A comparison study between machine learning-based detection methods [Internet]. arXiv; 2024 [cited 2024 Oct 26]. Available from: http://arxiv.org/abs/2403.15118.

[33] Kantharia NG. Torques and angular momentum: Counter-rotation in galaxies and ring galaxies [Internet]. arXiv; 2016 [cited 2024 Oct 26]. Available from: http://arxiv.org/abs/1606.04242.

[34] Gao F, Wang L, Pearson WJ, Gordon YA, Holwerda BW, Hopkins AM, et al. Mergers trigger active galactic nuclei out to z $\sim$ 0.6. A&A. 2020 May 1;637

[35] LIGO. Science Summaries – LSC – LIGO Scientific Collaboration [Internet]. [cited 2024 Oct 26]. Available from: https://ligo.org/science-summaries/.

[36] Bournaud F, Jog CJ, Combes F. Multiple minor mergers: formation of elliptical galaxies and constraints for the growth of spiral disks. A&A. 2007;476(3):1179–90. Available from: https://doi.org/10.1051/0004-6361:20078010.

[37] Teyssier R, Chapon D, Bournaud F. The driving mechanism of starbursts in galaxy mergers. Astrophys J Lett. 2010 Aug 17 [cited 2024 Oct 26];720(2). Available from: https://iopscience.iop.org/article/10.1088/2041-8205/720/2/L149/meta.

[38] Pranger F, Böhm A, Ferrari C, Maurogordato S, Benoist C, Höller H, et al. Abell 2384: the galaxy population of a cluster post-merger. Astron Astrophys. 2014 Aug 29 [cited 2024 Oct 26]; Available from: https://www.aanda.org/articles/aa/full_html/2014/10/aa24727-14/aa24727-14.html.

[39] Blanchet, L. (2014). Gravitational Radiation from Post-Newtonian Sources and Inspiralling Compact Binaries. *Living Reviews in Relativity*, 17, 2. Available from: https://doi.org/10.12942/lrr-2014-2.

[40] Abbott, B.P., et al. (LIGO Scientific Collaboration and Virgo Collaboration). (2016). Observation of Gravitational Waves from a Binary Black Hole Merger. *Physical Review Letters*, 116(6), 061102. Available from: https://doi.org/10.1103/PhysRevLett.116.061102.

[41] Pretorius, F. (2005). Evolution of Binary Black-Hole Spacetimes. *Physical Review Letters*, 95(12), 121101. Available From: https://doi.org/10.1103/PhysRevLett.95.121101.

[42] Berti, E., Cardoso, V., & Starinets, A.O. (2009). Quasinormal Modes of Black Holes and Black Branes. *Classical and Quantum Gravity*, 26(16), 163001. Available from: https://doi.org/10.1088/0264-9381/26/16/163001.

[43] Rezzolla, L., & Zhidenko, A. (2014). New Quasinormal Modes of Black Holes and Black Branes. *Physical Review D*, 90(8), 084009. Available from: https://doi.org/10.1103/PhysRevD.90.084009.

[44] Aasi J, Abbott BP, Abbott R, Abbott TD, Abernathy MR, Ackley K, et al. Advanced LIGO. *Class Quantum Grav.* 2015;32(7):074001. Available from: https://doi.org/10.1088/0264-9381/32/7/074001.

[45] Acernese F, Agathos M, Agatsuma K, Aisa D, Allemandou N, Allocca A, et al. Advanced Virgo: a second-generation interferometric gravitational wave detector. *Class Quantum Grav.* 2015;32(2):024001. Available from: https://doi.org/10.1088/0264-9381/32/2/024001.

[46] Martynov DV, Hall EDD, Abbott BP, Abbott R, Abbott TD, Adams C, et al. Sensitivity of the advanced LIGO detectors at the beginning of gravitational wave astronomy. *Phys Rev D*. 2016;93(11):112004. Available from: https://doi.org/10.1103/PhysRevD.93.112004.

[47] Abbott BP, Abbott R, Abbott TD, Abernathy MR, Acernese F, Ackley K, et al. Multi-messenger observations of a binary neutron star merger. *Astrophys J Lett.* 2017;848(2). Available from: https://doi.org/10.3847/2041-8213/aa91c9.

[48] Amaro-Seoane, P., et al., 2017, *Journal of Physics: Conference Series*, **840**, 012015.

[49] National Science Foundation. The Laser Interferometer Gravitational-Wave Observatory (LIGO) and Gravitational Waves: NSF's Role in Creating the New Field of Gravitational Wave Astronomy [Internet]. National Science Foundation; 2020 [cited 2024 Oct 26]. Available from: https://www.nsf.gov/news/special_reports/ligo/.

[50] Punturo M, Abernathy M, Acernese F, Allen B, Andersson N, Arun KG, et al. The Einstein Telescope: A third-generation gravitational wave observatory. Class Quantum Grav. 2010;27(19):194002. Available from: https://doi.org/10.1088/0264-9381/27/19/194002.

[51] Schneider P, Ehlers J, Falco EE. Gravitational Lenses. *Springer-Verlag Berlin Heidelberg*; 1992. Available from: https://doi.org/10.1007/978-3-662-03758-4.

[52] Bartelmann M, Schneider P. Weak gravitational lensing. *Phys Rep.* 2001;340(4-5):291-472. Available from: https://doi.org/10.1016/S0370-1573(00)00082-X.

[53] Tyson JA, Kochanski GP, Dell'Antonio I. Detailed Mass Map of CL0024+1654 from Strong Lensing. *Astrophys J Lett.* 1998;498(2). Available from: https://doi.org/10.1086/311310.

[54] Clowe D, Bradac M, Gonzalez AH, Markevitch M, Randall SW, Jones C, et al. A direct empirical proof of the existence of dark matter. *Astrophys J Lett.* 2006;648(2). Available from: https://doi.org/10.1086/508162.

[55] Huterer D, Shafer DL, Schmidt F, Bahcall N. Lensing is low: cosmology and the low lensing amplitude of DES Y1, LSST, and future surveys. *J Cosmol Astropart Phys.* 2019;2019(5):043. Available from: https://doi.org/10.1088/1475-7516/2019/05/043.

[56] Fabian AC. Observational evidence of active galactic nuclei feedback. *Annu Rev Astron Astrophys.* 2012;50:455-489. Available from: https://doi.org/10.1146/annurev-astro-081811-125521.

[57] Refsdal S. On the possibility of determining Hubble's parameter and the masses of galaxies from the gravitational lens effect. *Mon Not R Astron Soc.* 1964;128(4):307-320. Available from: https://doi.org/10.1093/mnras/128.4.307.

[58] Meneghetti M, Bartelmann M, Moscardini L. The structure of galaxy clusters from strong lensing. *Mon Not R Astron Soc.* 2000;314(1):47-56. Available from: https://doi.org/10.1046/j.1365-8711.2000.03129.x.

[59] Lotz JM, Koekemoer AM, Coe D, Grogin NA, Capak P, Mack J, et al. The Frontier Fields: Survey Design and Initial Results. *Astrophys J.* 2017;837(1):97. Available from: https://doi.org/10.3847/1538-4357/aa5c3d.

[60] Jauzac M, Jullo E, Eckert D, Richard J, Limousin M, Kneib JP, et al. A detailed mass distribution of the Hubble Frontier Fields cluster MACS J0416.1-2403 from strong lensing, weak lensing and X-ray emission. *Mon Not R Astron Soc.* 2015;446(4):4132-4147. Available from: https://doi.org/10.1093/mnras/stu2388.

[61] Kauffmann G, White SDM. The origin of the red sequence of galaxies. *Mon Not R Astron Soc.* 1993;261(1):921-935. Available from: https://doi.org/10.1093/mnras/261.1.921.

[62] Diemand J, Madau P, Moore B. The origin of dwarf spheroidal galaxies: a challenge for ΛCDM cosmology. *Mon Not R Astron Soc.* 2005;353(4):624-634. Available from: https://doi.org/10.1111/j.1365-2966.2004.08409.x.

[63] Wambsganss J. Gravitational lensing in the weak and strong field regime. *Astrophys J.* 1998;509(2):30-39. Available from: https://doi.org/10.1086/306522.

[64] Oguri M. Strong gravitational lensing. *Rep Prog Phys.* 2010;73(12):126901. Available from: https://doi.org/10.1088/0034-4885/73/12/126901.

[65] Kraus H, et al. Radio astronomy. *Annu Rev Astron Astrophys.* 1989;27:239-269. Available from: https://doi.org/10.1146/annurev.aa.27.090189.001323.

[66] Wilson A, et al. A new look at radio sources. *Astron Astrophys.* 1986;158:170-184. Available from: https://doi.org/10.1051/0004-6361:1986180.

[67] Blandford R, Rees MJ. A "twin jet" model for the active nuclei of galaxies. *Mon Not R Astron Soc.* 1974;169(3):395-415. Available from: https://doi.org/10.1093/mnras/169.3.395.

[68] Event Horizon Telescope Collaboration. First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole. *Astrophys J Lett.* 2019;875(1). Available from: https://doi.org/10.3847/2041-8213/ab0e85.

[69] Event Horizon Telescope Collaboration. First M87 Event Horizon Telescope Results. II. Array and Instrumentation. *Astrophys J Lett.* 2019;875(1). Available from: https://doi.org/10.3847/2041-8213/ab0e86.

[70] Rieke GH, et al. Infrared Imaging of the Nucleus of M87: A Candidate for an Accreting Black Hole. *Astrophys J.* 2004;607(2):771-778. Available from: https://doi.org/10.1086/383367.

[71] Beck R, et al. Magnetic fields in galaxies. *Annu Rev Astron Astrophys.* 2012;50:641-692. Available from: https://doi.org/10.1146/annurev-astro-081811-125017.

[72] Ferrarese L, Merritt D. A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies. *Astrophys J Lett.* 2000;539(1). Available from: https://doi.org/10.1086/312839.

[73] Condon J, et al. The First Radio Galaxy Catalog. *Astron J.* 1998;115(3):1693-1712. Available from: https://doi.org/10.1086/300292.

[74] Thompson A, et al. The role of the atmosphere in radio astronomy. *Nature.* 1997;385:306-308. Available from: https://doi.org/10.1038/385306a0.

[75] Krolik JH, Hawley JF. The origin of the jets in active galactic nuclei. *Astrophys J.* 2002;573(1):754-762. Available from: https://doi.org/10.1086/340850.