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Black Hole and Galaxy Co-Evolution: A Multiwavelength Approach

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Abstract:

The co-evolution of supermassive black holes (SMBHs) and their host galaxies is a fundamental issue in modern astrophysics, but the underlying physical mechanisms remain incompletely understood. This paper emphasizes the crucial importance of adopting a multi-wavelength approach to reveal this complex relationship. By integrating observations across the electromagnetic spectrum (from radio waves to X-rays), we elucidate the key processes involved in controlling black hole growth through accretion and the high-energy feedback from active galactic nuclei (AGN). The findings indicate that AGN feedback is a major regulator of star formation, fundamentally shaping the evolution of galaxies and establishing the observed scaling relations between supermassive black holes and galactic bulges. Scientists highlight the powerful synergy between multi-wavelength observations, theoretical models, and advanced simulations in constructing a coherent picture of this co-evolution. Ultimately, this review argues that sustained and expanded multi-wavelength studies, combined with interdisciplinary efforts, are essential for resolving the enigma of how black holes and galaxies co-evolve over cosmic time.

Keywords: Co-evolution, AGN feedback, multi-wavelength approach, star formation, galaxy formation

1. Introduction

When people start to think about black hole, they will illustrate the image of the dangerous event horizon and misterious singularity of the black hole are engulfing surrounding substances. Black holes be generally considered to be isolated, however a supermassive black hole (SMBHs) which is one of the six principle components of galactic center (A SMBH, circumambient clusters of evolved and early stage stars, a molocular dusty ring, ionized gas streamer, dispersed heat, and a remain after the supernova explosion) is interacting with other surrounding components under an extream gravitational force [1]. Supermassive black holes in a galactic center normally ranged from $10^6 - 10^9$ M $\odot$ (solar masses), which means that its event horizon could exceeds the size of solar system.

To Observe a celetrial object with a uninmagenable size and cosmic level distance from Earth, scientists implemented several approached methods. These methods were applied to reasearch Sagittarius, in another words scientists call it Sgr A*, which is the most powerful radio source in that region of the universe to the direction of the center of our milky way galaxy. The distance of Sgr A* to the solar system is approximately 2.6×10^4 light years which is also the distance to the galatic center. Until the first picture of Sgr A* was captured successfully by The Event Horizon Telescope (EHT) in 2022, it became the strongest evidence to prove the co-evolution between black hole and galaxy. There for the essense of Sgr A* has been considered as a supermassive black hole. Before the picture was captured, the multi-wavelength radio sources and stellar dynamics are the direct evidences. M- σ relation is a correlation that links the mass of black holes (M) and galaxy bulge or stellar velocity dispersion (σ). The correlation illustrates that the mass of SMBHs in a galactic center is directly proportional to the σ^{45} which more precisely explains the co-evolution between the galaxy bulge and SMBHs or the formation of galaxy. Relates to the multi-wavelength radio source, the spectrum of the Sgr A* are well studies from radio and sub-mm wavelengths. These radio sources with various of wavelengths are able to determin different aspects on the properties of an celestrial object in the universe. Scienties determined the sub-mm excess, variability and polarization from the radio sources emitted from Sgr A* which offers an entrence to research the processes on the active galactic nuclei. It is obvious that the importance of the discovery of the multi-wavelength observations. Non-visible lights are the most significant and dramatic sources that relate to the physical processes happened in the universe such as accretion, feedback and star formation. The initial method that scientists were used to discover the Sgr A* was to reveal the large scale structures and stable, fundamental existence of the black hole's accretion system. Thanks to the radio waves which is most famous and stable radio souce that emitted from the outermost regions of the accretion flow and the base of the jets that ejected from the black hole's poles. Other radio sources such as Infrared, Sub-mm waves and X-ray are related to the tracing of the stellar and gas motion, the directly probing the black hole's shadow, and the detection of the most extreme and violent physical processes respectively.

In this paper, the word AGN will appear a lot of times, and it stands for "active galactic nuclei". These AGN normally having masses in the range $106\ M\odot < \mathrm{M} < 109\ \mathrm{M}\odot$.

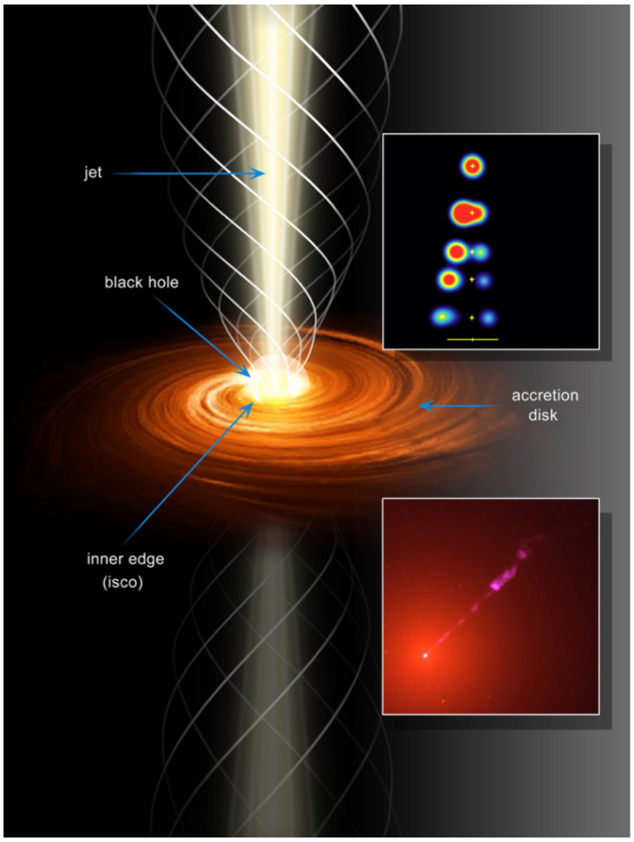

Fig. 1 A classic diagram illustrating the core components of an AGN surrounding a SMBH [2].

Figure 1 shows an artist's rendition of a generic black hole accretion disk and jet, with a figure of sequence of radio images from the jet in microquasar and an optical image of the jet in quasar. Active galactic nucleus (AGN) is a bright and compact region at the center of a galaxy, powered by supermassive black holes. When this black hole sucks in the surrounding gas and dust, these substances form a hot, rotating accretion disk. The incredible friction and gravity inside this disk heat it to extreme temperatures, causing it to emit strong light and release a large amount of energy in the electromagnetic spectrum [2].

The key of the paper is to explore how the black hole growth and galaxy evolution are interconnected, including the formation and growth of SMBHs, several physical processes between celestrial objects and projects that are used to simulate these processes. Another objective is to emphasize and highlight the role of multi-wavelength data therefore to understand the process of the co-evolution, including the observations from multi-wavelength radiowaves.

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2. Theoretical Framework

2.1 Formation and Growth of Supermassive Black Holes.

The eariest formation of a black hole could trace back to the earily light seeding stages when the first generation of stars (Population III stars) are formed. From the observations of the quasars with masses over 10^9 M ⊙ and at redshifts z > 7, scientists estimated that Pop III stars was formed about 100-200 million years after the Big Bang. To understand the formation of SMBHs, scientists formulated two principle classes of seeding machenics including light and heavy seeds. Light seed machenics is the process to describe the formation of SMBHs under the collapse of Pop III stars. These Pop III stars were extremely massive, they were often over 100 M ⊙ and widely spreaded through the early stages of the universe. A single massive Pop III star only last for a short time compares to the stars in this time, they only survive for a few million years and ends its life in a supernova or direct collapse and left a neutron star or straight collapse into a black hole if its mass was large enough. In contrast, the process of star formation was omitted in heavy seeds and straight into the collapse of massive gas clouds with ~10,000-100,000 M ⊙ at ~8000K [3].

After the formation of a black hole, accretion process takes place which means swallowing the gas from its surroundings. The efficiency and rate of the accretion process can be described by the Eddington limited accretion and Super-Eddington accretion. The only different between “Super”and “limited” is that the accretion rate exceeds standard Eddington accretion rate in Super-Eddington accretion.However, different to other accretion equations, Eddington accretion is only refers to the engaging of matter and outputting radiation from the black hole. To describe and evaluate the rate of black hole’s gas accretion in another word the growth of a black hole, scientists use the following equation:

$$\dot{M}_{max} = 10\frac{M_{BH}}{t_{edd}} = 10\dot{M}_{edd} \tag{1}$$

Where $\dot{M}_{max}$ describes the maximum allowed accretion rate of a black hole which is also up to 10 times of the standard Eddington accretion rate represent by $\dot{M}_{edd}$. The whole equation is working under a condition of 10% of Eddington luminosity and Eddington-Salpeter time scale ($t_{edd} \cong 45 millionyears$). The first generation of this equation begins with Sir Arthur Stanly Eddington in 1920s, and its initial concept was to describe the stars stability criterion. Until Mid-20 Century, its concepts shifts towards accretion physics: Whether the effect on the surrounding gas are the same according to the radiation from a star’s core or hot accretion disk around an object. Finally in late 20 Century, the concept of the equation was refined to explore the super-Eddington accretion and earily SMBHs formation, therefore it is able to solve the the timing problems of how SMBHs grew at a fast speed in the earily universe [4].

2.2 Galaxy Evolution and Feedback Machenisms.

Galaxy evolution is one of the most discoveries in modern astrophysics, and closely in another word bonded to SMBHs in galactic center. To begins with, the evolution of galaxy is a fundamentally governed by the interaction between star formation and the feedback process. Stars formed when the cold gas clouds collapse under their own gravitational forces. However, when the process were not controlled, it would consume the storage of gases within the galaxy rapidly thourgh an intense starburst[5]. However, the observation shows that the srat formation is considered to be an inefficient process, but is shows that there are existent of regulatory mechanisms that inhibit the process. These kined of machenism achieves through feedbacks, which inject large amount of energy from the supernova explosion or powerful winds that the stars emmited during their lives back into the interstellar medium. These energy were able to heat up the surrounding gases which avoid additional star formation occurs from the collision. Further more, these energy can also expel surrounding gases out from the galaxy by driving large-scale gas outflow. These kind of star feed back are significant to define low density galaxy’s properties, however not adequate to explain the formation of stars in the largest elliptical galaxy.

Active Galactic Nucleus (AGN) feedback appears as a crucial components of the theoretical models, to provide enough amount of energy for the star formation in large-scaled system. The huge energy of AGN was generated by the accretion of matter by a SMBHs, and it was operates though two primary modes. The fisrt mode is the radiative or “Quasar” mode which also known as high-accretion feedback. This mode is active when the gas accretion of a SMBHs is at a high rate, often approach to its Eddington limit, and a large amount of gases would be directly transported to the galactic center at the same time when the galaxy was experiencing combination of violent disturbance. The huge gravitational forces emitted by the accretion gases were transformed into radiations and made AGN into a quasar. These high energetic photons (radiations) were causing two major effects to surrounding matters: radiation pressure in another words the intensity of photons streaming from the accretion disk exerts an pressure on surrounding matters; outwards flow (winds), the radiations ghag drives powerful winds that can blow away the remaining fases inside the galaxy. Another mode is mechanical or radio mode also known as low-accretion feedback. Interestingly, the name of this model was named because it was observed by the multi-wavelength approach. This mode is active when the rate of an SMBH accrete the gases from hot halo gas and at a low and steady rate. During this state, AGN is able to emit jet of relativistic particles from its two poles. Compare to the quasar mode, these jet of particles are using a more gentle and more lasting method to inject energy into the matters surround the galaxy, its porpose is to prevent heated gas cools down and flow back into the galaxy therefore forming new stars. To be more specific, this mode towards to a feedback with properties of preventing and maintaining.

However, there is a core problem called the cooling crisis in massive galaxies. It is obvious that a large amount of heated and high energetic gases are stored inside the large mass galactic disks, and these gases should flow back to the galactic center naturally after cooling down and provide fuels for star formation. Unexpectly, the observations show that the star formation stopped in an early era. This means that the process of fast cooling and vibrate srat formation didn't happened, which give scientists an idea of something was trying to heat the gas avoid from cooling down, The amount of energy produced from the star feedback was not close to oppose the strong gravity of large massed galaxy. Finally, all the elements are pointing to a single but strong source: Supermassive black holes inside the galactic center.

2.3 Co-evolution of black holes and galaxies.

The co-evolution between SMBHs and their host galaxies have been proven by the strong correlation between the SMBHs in galactic center and the large-scale properties of the host galaxy‘s bulge. These kind of co-evolution is running by shared physical processes that regulate the gas flow, the accretion process of SMBH and star formation in galaxies. Overall, there are two modles that could be used to determine the correlation between SMBH growth to galaxy properties.

Self-regulation via AGN feedback which is a scientific name of a self-regulating feed back loop. In this model, the surrounding gases will tend to flow toward the galactic center due to process like galaxy mergers. When the gas flows into the galactic center, it promotes the rapid formation of stars and the accretion of the black hole at the same time. In addition, the high-energy output from the active galactic nucleus often in the form of radiation or jets are being heated and ejected from the surrounding gas reservoir. Apart from the galaxy properties, the phenomenon of reduction in the universe can be illustrised from the observation of the largest black holes and galaxies in the early universe when they completed their growth processes, however, smaller systems seems emerged relatively later. The results seem to contradict the galaxy formation model. The main explanation of the phenomenon is the feedback effect of active galactic nuclei called cosmic downsizing. In the early large galaxies, the powerful feedback generated by their active black holes would vigorously expel gas, thereby rapidly suppressing the formation of stars and the further growth of the black holes themselves. In smaller galaxies, the feedback effect is weaker, allowing the galaxies to undergo a longer and slower growth process, thus forming the scale-reduction pattern, where the peak of activity shifts to smaller celestial bodies over time.

3. Observational Techniques and Multi-wavelength Approach

Non-visible lights are the most significant evidences to prove the co-evolution between SMBHs and their host galaxies. When a SMBH is accreting matters inside the center of an AGN which is a complex system in the universe, it emits enormous amout of energy across the entire electromagnetic wave spectrum. The central idea is a process called “AGN feedback”, the process which the energy released by an accreting SMBH controls the growth of the black hole and affects the evolution of the entire host galaxy. The co-evolution normally happens through this process.

3.1 X-ray Observations

The core concept of x-ray observation is to detect the high energetic processes that are happening surround SMHBs. The Primary X-ray that are emitted by AGNs comes from a hot and magnetized plasma region which is known as “Corona”, which lies on the top of the accretion disk. The photons that were emitted from the heated accretion disk enter the “corona” and gain energy through inverse compton scattering (a process when a high-energetic electron transfers a portion of its own energy to a lower energetic photon), therefore the wavelength of the proton decreases dramatically and goes into the range of x-ray (0.01nm – 10nm). In the x-ray spectrum of AGN, there comes up a significantly crucial feature which is the Iron Kα emission line at 6.4KeV. This line appears due to the extreme gravity and doppler effect happened very close to the event

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horizon of a black hole. Additionally, x-ray is good at penetrating obscuring materials, for instance, x-rays can penetrate through thick clouds of gas and dust, therefore to show the situation of hiddened AGNs. These x-ray spectrum would help scientists to study the temperature and properties of corona, to probe the dynamics of matter in the strong gravity region, also to count the population of hidden, yet actively accreting black holes.

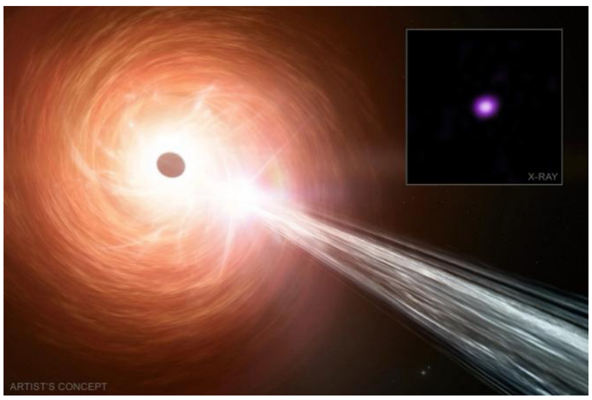

Fig. 2 The concept of an artist of an SMBH compares to the real picture [6].

Based on the theories of how x-ray helps scientists to evidence of co-evolution, substantial data is required to be observed. The black hole in Figure 2 was pirctured by Chandra x-ray observatory, it weighs about a billion times the mass of the Sun and is located about 12.8 billion light-years from Earth. The picture shows an artist's concept of a surrounding disk of material falling towards the black hole and a jet containing particles moving away at close to the speed of light. However, the picture that caught by Chandra determins a black hole which is growing at a rate of eddington limit [6].

3.2 Optical and Ultraviolet Observations

The properties of AGNs, their host galaxies and the accretion disks are crucial, these can be observed by optical and ultraviolet observations. A classic method to find AGN, especially for quasars and Seyfert galaxies (galaxy with an extremely bright, point like AGN), is optical spectroscopy for identification. AGNs are able to produce emission lines from broad to narrow size of widths such as hydrogen balmer lines, these lines indicates that the gas is moving at a speed of over thousands of kilometers per second, far exceeding what is possible from stellar processes. The phrase "Big Blue Bumo" reference to the direct radiation from the heated, inner accretion disk peaks in the Ultraviolet. The bump is a significance signature of accretion in a spectral energy distribution, and its shape and luminosity are able to tell about the accretion rate and the temperature of the disk.

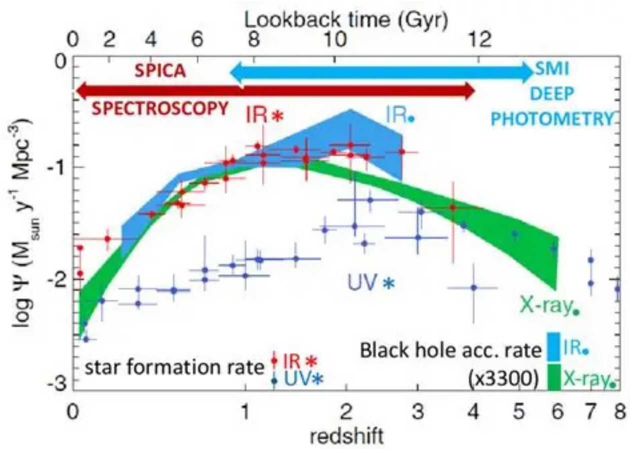

Fig. 3 The cosmic star formation history diagram [7].

Figure 3 illustrates the history of star formation and black hole growth throughout the entire universe. This indicates that both processes have experienced similar dramatic ups and downs. About 10 to 12 billion years ago, the universe was in a vibrant and active youth, with star birth and black hole accretion rates reaching a powerful peak. Since that golden age, there has been a profound and coordinated decline, with both activities declining to the quieter levels observed in the modern and older universe. Overall, the diagram shows that black holes and their galaxies grow and decay together. This indicates a direct connection, where energy from feeding black holes (AGN feedback) may stop star formation and slow down the growth of both [7].

To determine the co-evolution, the rate for star formation is also essential. UV light is also a primary observation source of young, hot, massive stars. Some famous obser-vators such as SDSS (Sloan Digital Sky Survey), HST (Hubble Space Telescope) and GALEX (Galaxy Evolution Explore) that are providing important data for galaxies, quasars, brilliant point-like AGNs, and star formations rates in AGN host galaxies.

3.3 Infrared Observations

Infrared Observations bring a significant pathway to revealing AGNs and star formation that are hidden by dust. These dusts are able to hide he light ray in the visible light and UV bands that are emitted by active galactic nuclei, therefore observators won't be able to detect. However, infrared ray is re-radiated from the dust that is heated to hundreds of kelvin by the active galactic nuclei. The mid-infrared spectra typically contain a broad silicate features and a power-law continuum, which are all the signs of the heated torus of dust. Silican grains which are the compounds of silicon and oxygen, those compounds typically found in interstellar dust often have a characteristic. Due to the vibrations occur during the heating process, silicate grains will absorb and emit light, the wavelength range of these light normally lies between 10 μm and 18 μm. The power-law continuum that is mentioned before means that the mid-infrared flux acts as a role of wavelength, which will form a straight line on a log to log graph. This power-law continuum is also a primary signature of a centrally concentrated, extremely luminous heat souce (AGN) that is heating a torus of dust. This torus of dust will not only emit but also absorb the energy from the UV light ray radiated during the young star formation. After the absorbtion of UV light from newborn stars, far-infrared ray is re-emitted.

In obscured systems, it is often imposible to study AGN and star formation separately at other wavelength. Infrared ray is the crucial radiation to decompose the total energy output. Mid-infrared ray normally from the torus of dust that is heated by freely active galactic nuclei, while the far-infrared comes from the star-formation-heated dust. These range of infrared rays allows scientists to observe and study the relationship and co-evolution between SMBHs and it host galaxy.

3.4 Radio Observations

Radio wave is also a common observations in the entire universe, however, it has a key role to observe the co-evolution. Its main idea it to trace the relaticistic jets and their impact on the surrounding environment feedbacks. Radio-mode feedback, a crtical process during the evolution of galaxies is able to inject massive amout of energy into the surrounding interstellar and intergalactic medium through jets and lobes. A more specific way to name these jets and lobes is AGN jets and lobes, they are the plasma that are launched from the immediate vicinity of a SMBH. These plasma are normaly giant and beam-like, at the same time, they have properties of magnetized and high-speed. These jets and lobes can be seen as the most powerful particle accelerators and blowtorches in the universe. During the radio-mode feedback, the jets and lobes would be able to heat the gas in galaxy continuously therefore to prevent from cooling and falling into a further formation of new stars. Another key process to prevent star formation that is done by the jets and lobes is to expelling the reservoir of star-forming fuel from the galaxy, a simpler way to say is to blow the gas out from the galaxy.

This AGN feedback is believed to be the crucial process to prevent the star formation in massive galaxies, the growth of these massive galaxies are stopped effectively and these galaxies leaving themselves behind as "red and dead" ellipticals.

3.5 Black hole accretion and star formation rates

This area of research is to investigate whether the growth of the black hole happen at the same time as the growth of galaxy. The rate of star formation can be determined from the observations of UV light, Infrared, and Specific emission lines appears on the spectrum, just like I mentioned previously.

There are some key findings from Multi-wavelength studies: The first finding is Cosmic Noon Correlation. Cosmic noon stands for the peak epoch of both star formation and AGN activity. Specifically at redshifts of $z \sim 1\text{-}3$, an observation of strong, roughly linear correlation between AGN luminosity and the star formation rate of the host galaxy is discovered [8]. It can powerfully prove that the maximum speed of SMBHs' growth stage happened at the same time with the the strongest period of the star formation. In another word, the relationship between SMBHs' growth and star formation determined that there would be a common fuel souce, and the fuel could be provided by galaxy mergers or efficient gas accretion; The second finding is the redshift dependence. This relationship seems to various with the cosmic time. For example, with in an cosmic area with low redshifts like local and quieter universe around our Earth, the correlation is weaker and more scattered. This phenomenon determined that the tight co-evolution happens at a early and violent cosmic stage.

4. Key Results from Multi-wavelength Studies

4.1 AGN Feedback and Galaxy Quenching

There won't be any star formation in a massive galaxy. The concept of "AGN feedback" act as an important machenics for the explanation. The energy emitted by the accreting SMBHs is able to affect the entire host galaxy, even. Potentially shutting down star formation.

X-ray reveals a phenomenon of high temperature and highly ionized gas outflows, moving at speeds up to tens of thousands of km/s. This is the direct observation of the energy injected by the AGN. UV light is able to detect ionized gas outlows. A broad, blushifted absorption and emission lines will be shown on the spectroscopic obser-

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vations, it indicates that the gas is escaping from the AGn at speeds of 500-2000 km/s. Sub-millimeter/Radio is a crucial observation for molecular gases such as CO emission, which is the direct fuel for star formation. Therefore, when scientists aboserve the outflow of large amount of gases that are running by the AGN, it proved that that AGN is actually removing the star forming fuel from the galaxy.

4.2 Evolution of Black Hole – Galaxy Scaling Relations

The evolution of the proportional relationship between the mass of a black hole and the velocity dispersion of a star (i.e., the M-σ relationship) provides crucial insights into the joint growth of supermassive black holes and their host galaxies over cosmic time scales.

Multi-wavelength observations also have a significant role in constraining this evolution, which indicating that high-redshift observations reveal a similar relationship but with a significantly increased dispersion. This increase in dispersion indicates that this growth was not completely synchronous in the early universe. However, SMBHs and their galactic bulges may have experienced divergent growth periods, with some SMBH accumulating mass at a faster rate than their host bulges during intense merger-driven accretion events. Moreover, studies of extreme environments (such as the brightest galaxy clusters) have revealed systematic differences, where the mass of supermassive black holes often exceeds the values predicted by the local M-σ relationship [9]. These findings challenge simple co-evolutionary models and indicate that the precise calibration of these fundamental proportional relationships is highly dependent on the specific periods of the universe and the environmental background of galaxy growth [10].

5. Conclusion

5.1 Summary of Findings

This study highlights the crucial role of multi-wavelength observations in revealing the complex relationship between supermassive black holes (SMBHs) and their host galaxies. By integrating data from the entire electromagnetic spectrum ranging from the radio band to the X-ray band, we have gained important insights into the growth mechanisms of black holes and the profound influence of active galactic nuclei (AGN) feedback. These findings further confirm the view that the evolution of galaxies and their central black holes are not independent processes but are closely linked, and the activity of active galactic nuclei is a fundamental regulating factor for star formation and galaxy structure.

5.2 Broader Implications for Astrophysics

The co-evolution of supermassive black holes at the centers of galaxies and galaxies has a profound impact on our understanding of the universe. It seems that these supermassive black holes are not merely passive entities but rather the dominant forces shaping the observable universe. They influence various aspects, from the baryonic content of galaxies to the scaling relationships they follow. The progress in this field is attributed to the strong synergy between cutting-edge observations, complex theoretical models, and high-resolution cosmic simulations. This interdisciplinary approach is crucial for interpreting complex data and constructing a unified theory of galaxy formation.

5.3 Final Thoughts

Although significant progress has been made, many mysteries regarding the co-evolution of supermassive black holes and galaxies remain to be solved. To further deepen our understanding, it is crucial to continuously and intensify the investment in multi-wavelength observation activities. Moreover, future advancements will rely on interdisciplinary collaboration, integrating insights from astrophysics, plasma physics, and computational science. By taking this comprehensive exploration approach, we hope to fully reveal the dynamic and interrelated life cycle of black holes and the galaxies they are located in.

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