

Review Article

Host Galaxy Properties and AGN Clustering: Insights from X-ray Observations and Their Impact on Cosmic Evolution

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Abstract

This review examines the connection between X-ray-selected Active Galactic Nuclei (AGN) and their host galaxies, focusing on how X-ray observations provide insights into AGN structure and clustering. AGNs, powered by supermassive black holes, are key drivers of galaxy evolution, and X-ray data play a critical role in studying these energetic phenomena. The unified model of AGNs, which attributes differences between type 1 (unobscured) and type 2 (obscured) AGNs to orientation effects, is discussed. However, variations in clustering between these two types challenge this model, suggesting additional factors influence their evolution. Detecting AGN clusters in the X-ray band remains difficult due to observational biases and limitations, but such studies are vital for understanding how AGNs form and interact within large-scale structures. Host galaxy properties, including luminosity, stellar mass, and star formation rate, are analyzed for their impact on AGN clustering. Research indicates that AGN luminosity is strongly linked to the mass of the dark matter halos surrounding their host galaxies. This relationship may vary depending on the triggering mechanism of the AGN, such as galaxy mergers or internal instabilities. Differences in AGN clustering patterns provide insights into the diverse pathways through which AGNs are activated. AGN feedback, which describes how AGNs influence star formation in their host galaxies, is another key focus. Observations suggest that at higher redshifts, brighter AGNs tend to enhance star formation rates, showing a complex interplay between AGN activity and galaxy growth. By synthesizing recent observational results, this review highlights the central role of AGNs in shaping galaxies and their environments. It provides a deeper understanding of how AGNs interact with their host galaxies and larger cosmic structures, offering valuable insights into the processes driving galaxy evolution over cosmic time.

Keywords

Active Galactic Nuclei (AGN), Host Galaxy Properties, Star Formation

1. Introduction

The study of Active Galactic Nuclei (AGN) has evolved significantly since the early 20th century, marked by pivotal observations that revealed extraordinary phenomena at the

cores of galaxies. In 1909, E. Fath observed strong emission lines in the spectrum of NGC 1068, then classified as a 'spiral nebula', hinting at energetic processes within its nucleus.

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Initially interpreted as stellar clusters obscured by nebular gas, these observations laid the groundwork for understanding the active nature of galactic nuclei [1].

The establishment of general relativity by Einstein in 1915 spurred further exploration, with E. Hubble's spectroscopic observations in 1926 of NGC 1068, NGC 4051, and NGC 4151 revealing broad emission lines. These findings, combined with subsequent discoveries by Seyfert in 1943 of galaxies with bright, high-excitation nuclei and broad emission lines (Seyfert 1943), marked the identification of a distinct class known as Seyfert galaxies [2, 3].

The advent of radio astronomy in the mid-20th century catalyzed another leap in AGN discovery. Radio surveys, such as the 3C, 3CR, and 4C catalogs revealed objects like Cygnus A, characterized by intense radio emission and faint optical counterparts [4, 5]. These findings culminated in the identification of quasi-stellar radio sources (quasars) by Matthews and Sandage in 1963, which exhibited high redshifts and broad emission lines indicative of immense energy output [6].

It is now established that Seyfert galaxies, quasars, and other variants collectively fall under the umbrella of AGN. At the heart of these systems lies a supermassive black hole actively accreting matter, manifesting as the observed high-energy phenomena [4, 7]. Understanding the mechanisms driving AGN activity remains a cornerstone of modern astrophysics, offering insights into galaxy evolution and the dynamics of supermassive black holes.

Both observational data and theoretical models indicate a linear relationship between the growth of a supermassive black hole (SMBH) and the evolution of its host galaxy. The SMBH expands as matter is drawn into the inner region of the galaxy, close to the black hole. During this process, the SMBH emits vast amounts of energy across the full electromagnetic spectrum. When this happens, a previously inactive galaxy can transform into an active galactic nucleus [3].

Active Galactic Nuclei (AGN) are among the brightest and most consistent X-ray emitters beyond our galaxy. These X-rays are generated by a region known as the corona, located close to the supermassive black hole at the core of the AGN. These emissions result from the inverse-Compton scattering of optical and UV photons from the accretion disk by electrons within the plasma [3]. X-ray observations provide a powerful tool for examining the physical conditions within the central engine of AGN. X-ray astronomy, which began in the 1960s and 1970s, significantly advanced our understanding of Active Galactic Nuclei (AGN). The first successful X-ray detections of AGN were made during the 1960s using rockets and balloons, revealing emissions from the luminous quasar 3C273. Later, the Uhuru catalog, the first comprehensive list of X-ray sources, identified three of the brightest AGNs observed in the X-ray spectrum. [8-10].

Over the past decade, evidence has increasingly supported the simultaneous growth of galaxies and their resident supermassive black holes [11, 12]. Delvecchio et al. (2014)

conducted a broad-band spectral energy distribution decomposition to differentiate the potential AGN contribution from that of the host galaxy. They demonstrated the relationship between the AGN bolometric luminosity function and the supermassive black hole growth rate over cosmic time up to $z \sim 3$ from a far-IR perspective. Additionally, there is a strong correlation between the black hole mass and the properties of the host galaxy, such as the mass of the bulge, measured by luminosity or velocity dispersion [13, 14].

X-rays are among the most effective tools for identifying AGN, especially those that are obscured and may not be visible in the optical spectrum. Obscured AGN represent a large portion of the overall AGN population, making it challenging to fully understand their origin and nature and to uncover the complete AGN population. Some research suggests that varying levels of obscuration might correspond to different phases of supermassive black hole growth, differing from geometric models such as the unification model, which attributes the observed differences between type 1 and type 2 AGNs to the angle from which they are observed. To determine whether type 1 and type 2 AGNs belong to the same or distinct populations, the properties of their host galaxies can be studied. Key factors associated with the early stages of galaxy formation and evolution include luminosity, stellar mass, and star formation rate. [12, 15, 16].

This review explores the foundational aspects of the unified model of Active Galactic Nuclei (AGN) and how it serves as a framework for understanding the diverse observational characteristics of AGNs. It then delves into the detection of AGN clusters in the X-ray band, emphasizing the underlying physics of X-ray emission in AGNs and addressing the challenges associated with their identification in this spectral range. A detailed examination of host galaxy properties, including luminosity, stellar mass, and star formation rate, is provided to understand their relationship with X-ray-selected AGNs. Finally, the review synthesizes these topics to offer a comprehensive understanding of the interplay between AGNs and their host galaxies, drawing conclusions that highlight key insights and future directions in the field.

2. The Basic Unified Model of AGN

Antonucci (1993) proposed the first formalism for the fundamental unified model of AGN, which attributes the differences between observational classes of AGN to an orientation effect. According to this model, the varying perspectives from which the supermassive black hole (SMBH) and torus are observed along the observer's line of sight explain the observed differences. In the framework of the basic unified model, a typical AGN consists of several main components arranged in order from the smallest scales outward: the supermassive black hole, X-ray corona, accretion disk, broad line region, torus, and narrow line region. Figure 1 provides an overall schematic of an AGN, offering a perspective on the different components at various distances [17, 18]. Let's

begin exploring the central engine in more detail.

The supermassive black hole (SMBH) is positioned at the core of an AGN and plays a pivotal role in generating the luminous emissions observed. Its energy originates from the gravitational infall of surrounding matter. SMBHs are known to possess a mass range between $10^5 - 10^{10} M_{\odot}$. The linear size of the event horizon, which marks the boundary of the black hole, is directly linked to the mass of the SMBH. Typically, this size spans a range of approximately $10^{10} - 10^{15} \text{ cm}$, equivalent to a few light-seconds to a few light-days in scale [19, 20].

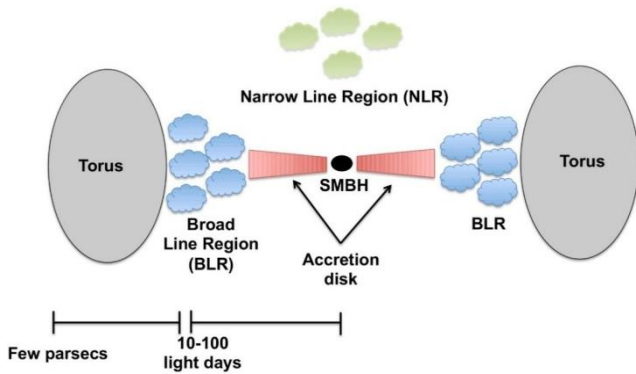


Figure 1. Schematic of AGN. Image credit: Claudio Ricci.

The accretion disk is a key component of an AGN and is often described as a geometrically thin, optically thick structure. It forms from the material that rotates in the vicinity of the SMBH. While the commonly used model assumes a thin disk, there are alternative models that propose slim or thick accretion disks, each providing insights into the nature of the disk. As matter spirals inwards towards the SMBH, it gradually loses angular momentum and is eventually accreted onto the black hole. This process leads to the conversion of gravitational energy into thermal radiation, manifesting as a blackbody spectrum. The accretion disk plays a crucial role in fueling the AGN's energy output and influencing its observed properties across various wavelengths [15, 21].

The corona is another key component of an AGN, particularly located near the black hole. It consists of a hot plasma with low density and is believed to contain high-velocity electrons. The main function of the corona is to boost ultraviolet photons from the accretion disk to significantly higher energies, mainly in the X-ray range, through a process called Compton scattering. This interaction produces high-energy X-ray photons. The corona's size is generally comparable to the scale of the black hole's event horizon. [15].

The broad-line region (BLR) is a region of gas surrounding the supermassive black hole that is strongly influenced by the central engine's energy output. The BLR consists of partially ionized, high-density clouds of gas that are free from dust. It takes on either a sphere-like or disk-like arrangement around the black hole. Due to the intense radia-

tion from the central engine, the atoms in the BLR are photoionized, meaning they are ionized by absorbing energetic photons. The BLR emits broad emission lines, which are spectral features corresponding to permitted atomic transitions. These emission lines exhibit significant Doppler shifts, indicating that the gas is moving at velocities greater than 1000 km/s. The broadness and shifting of the emission lines provide valuable information about the dynamics and properties of the gas in the vicinity of the supermassive black hole [21, 22].

The obscuring torus is a geometrically thick structure that extends perpendicular to the accretion disk, providing coverage of a significant portion of the sky as observed from the supermassive black hole (SMBH). While its exact shape remains uncertain, it is known to be inflated in the direction perpendicular to the accretion disk. The inner radius of the torus depends on the luminosity of the central source and can be as close as a few light months in the case of low luminosity AGNs [23].

On the other hand, determining the outer radius of the torus is more complex due to its clumpy nature, which makes it challenging to model accurately. Estimates for the outer radius range from a few parsecs to more extended two-component torus models that have a diffuse region extending hundreds of parsecs [24].

The narrow-line region (NLR) is a bi-conical structure composed of low-density ionized gas clouds that produce both narrow permitted and forbidden emission lines. These emission lines are characterized by velocities below 1000 km/s. The NLR extends from the inner region of about a parsec from the AGN to hundreds of parsecs beyond it, making it the only component of an AGN that can potentially be spatially resolved. The kinematics within the NLR provide valuable insights into how the AGN luminosity and associated outflows may influence the host galaxy. For example, they can shed light on the impact of the AGN on star formation processes, including triggering or suppressing star formation activities [25].

Relativistic jets are energetic outflows of particles that typically exhibit a bipolar and collimated structure, moving at relativistic velocities perpendicular to the accretion disk. These jets can be observed in certain AGNs and can extend over scales of millions of parsecs (Mpc) for particularly powerful jets. The emission from relativistic jets is predominantly non-thermal and is produced through processes such as synchrotron radiation and inverse-Compton scattering. Synchrotron radiation is responsible for the radio emission observed from all AGNs [3]. It occurs when relativistic electrons interact with a magnetic field, resulting in the emission of radio waves. The strength of this radio emission can vary between AGNs, with some being radio-quiet and others being radio-loud. Radio-loud AGNs are capable of generating collimated radio jets and lobes that extend throughout, and sometimes beyond, the host galaxy. These extended structures contribute significantly to the overall bolometric lumi-

osity of the AGN system [26].

The presence of relativistic jets in AGNs plays a crucial role in shaping the properties and behavior of these active galaxies. Their energetic nature and ability to transport material and energy over vast distances have a profound impact on the surrounding environment. Understanding the formation, propagation, and impact of relativistic jets is essential for comprehending the full range of phenomena associated with AGN activity and their influence on the larger-scale structure of the universe.

This basic model explains why narrow (permitted and forbidden) emission lines are observed in almost all AGN, whereas broad lines are not always visible. Narrow lines are emitted from larger spatial regions, making them observable from any orientation. In contrast, broad lines originate from smaller regions and may be obscured by the torus depending on the observer's viewing angle relative to the AGN. When the inner regions are directly visible, a broad-line (type I) spectrum is observed. If the system is viewed edge-on, the obscuring torus blocks emission from the accretion disk and broad-line region (BLR), resulting in a narrow-line (type II) spectrum. Nevertheless, broad lines can still be detected in polarized light due to scattering by free electrons in the ionized NLR bi-cone [15].

3. Detecting Active Galactic Nuclei Clusters in X-Ray Band

X-ray observations provide a robust method for identifying AGNs with minimal contamination from non-AGN sources. This reliability stems from several key factors: (1) nearly all AGNs emit X-rays; (2) X-rays, especially at higher energies, can penetrate significant amounts of gas and dust; and (3) X-ray emission from processes within the host galaxy is typically much weaker than the AGN's emission. As a result, the most in-depth blank-field cosmic X-ray surveys have achieved the highest reliable AGN source density recorded so far [3, 7].

3.1. Physics Behind the AGN X-Ray Emission

The X-ray emission from Active Galactic Nuclei (AGN) originates from processes associated with the accretion disk surrounding the supermassive black hole at the center. As gas and dust spiral inward, gravitational and frictional forces heat the accretion disk, causing it to emit radiation across a broad range of wavelengths, including X-rays. One key mechanism producing high-energy X-rays is inverse Compton scattering, where low-energy photons from the accretion disk collide with high-energy electrons in the corona, a hot and diffuse region around the disk, boosting the photons to X-ray energies [7]. Additionally, the innermost, extremely hot parts of the accretion disk emit thermal X-rays, particularly at the lower end of the X-ray energy spectrum. Therefore, AGN X-ray emission results from a combination of

high-energy X-rays generated in the corona and lower-energy thermal X-rays from the disk's inner regions, both critical for understanding the complete X-ray spectrum of AGNs [3, 17].

3.2. Selection of AGN in the X-Ray Band: Identification Challenges

X-ray emission from active galactic nuclei (AGN) is nearly ubiquitous, offering a powerful tool for their selection due to its high penetrating power and minimal host-galaxy contamination. This makes X-ray selection particularly effective at high energies (>10 keV), where selection biases are generally modest. However, even X-ray observations have limitations. While they can reveal hidden supermassive black holes (SMBHs) that might be missed in other wavelengths, very thick clouds of gas and dust can still block or scatter X-rays, making it difficult to detect and accurately count all AGN. This introduces biases, as some AGN might remain undetected even in X-rays, leading to an underestimation of the true population of SMBHs. Addressing and correcting for these limitations is essential for providing a complete and more unbiased census of active SMBHs in the universe [27, 28].

One of the most significant challenges in X-ray selection of AGN is absorption, which affects lower energy X-rays more than higher energy ones. The impact of absorption also varies with redshift and rest-frame energy, complicating the detection of heavily obscured AGN. Compton-thick (CT) AGN, where the absorbing column density exceeds $N_H > 1.5 \times 10^{24} \text{ cm}^{-2}$, are particularly difficult to detect even at high energies due to Compton recoil and further absorption. While detection in other wavebands like radio and infrared can be less biased towards CT AGN, unambiguous identification of these heavily obscured AGN relies on X-ray observations and broadband X-ray spectral fitting using instruments such as NuSTAR, Chandra, or XMM-Newton [3].

Furthermore, low observed X-ray luminosities in AGN can be contaminated by emissions from host galaxy processes, notably X-ray binaries. These binaries, categorized into low-mass (LMXBs) and high-mass (HMXBs) based on the mass of the companion star, primarily emit at low energies (<10 keV), which can interfere with AGN signals. Additionally, hot gas from galaxies or galaxy clusters can contribute X-ray emissions at low energies ($<2-5$ keV), though AGN can still be reliably identified at higher energies [3].

Recent studies emphasize the necessity of improved detection methods for uncovering elusive AGN populations. For example, Yang et al. (2023) used the reddest filters of the James Webb Space Telescope (JWST) to identify high-redshift obscured AGN, revealing a black hole accretion rate density (BHARD) at $z > 3$ that is significantly higher than results from X-ray observations. This indicates that a considerable portion of AGN at these redshifts may still be undetected. These findings underscore the importance of identify-

ing obscured Compton-thin ($22 < \log N_H < 24$) and Compton-thick (CT; $\log N_H > 24$) AGN to deepen our understanding of their contribution to supermassive black hole (SMBH) and galaxy coevolution, as well as to refine their physical properties and demographics, particularly in the early universe [29].

Building on the recognition that X-ray observations are essential but limited in detecting obscured supermassive black holes (SMBHs), deep X-ray surveys have shown that the challenge of obscuration becomes even more pronounced at higher redshifts. Research by Vito et al. (2018) reveals that the proportion of AGN obscured by dense gas, with column densities greater than $\log N_H > 23$, increases significantly, reaching around 80% at a redshift of approximately 4 [27, 30].

4. Host Galaxy Properties of X-Ray AGN

The characteristics of the host galaxies of active galactic nuclei (AGNs) at different redshifts offer valuable insights into the processes that initiate AGN activity at various points in the universe's development. For instance, the mass of the dark matter halos (DMH) that house AGNs is associated with the lifespan of the black hole (BH) [31]. Additionally, several researchers have tried to forecast the clustering behavior of AGNs based on the properties of their host galaxies, taking into account factors like luminosity, stellar mass, and star formation rate (SFR). In this review, we will examine the impact of each of these properties on AGN clusters individually.

4.1. The Luminosity of X-Ray AGN

Mountrichas et al. (2016) suggests a negative correlation between AGN clustering and luminosity. This supports the notion that AGNs exhibit a wide range of dark matter halo masses, with a prominent high-mass tail that becomes less influential at higher accretion luminosities. To estimate the average dark matter halo mass of relatively luminous X-ray-selected AGNs [$\log L_{X(2-10\text{keV})} = 43.6^{+0.4}_{-0.4} \text{ergs}^{-1}$] within the redshift range $z = 0.5 - 1.2$ data from the northern region of the wide-area and shallow XMM-XXL X-ray survey field were utilized [32].

Studies on the clustering of moderate-luminosity X-ray-selected AGNs typically find average dark matter halo (DMH) masses of around $10^{13} h^{-1} M_{\odot}$, up to redshifts of about $z \approx 1.5$ [33, 34]. When compared to UV/optically selected high-luminosity quasars, this results in a negative correlation between AGN clustering and luminosity, meaning that as accretion luminosity increases, the average DMH mass decreases. Possible explanations for this include different mechanisms for triggering AGN activity or various accretion modes that dominate at different luminosity levels. While some attempts have been made to study the luminosity dependence of clustering specifically for X-ray-selected AGNs, these efforts have had limited success [35]. On the

other hand, there are also claims of a positive relationship between X-ray luminosity and clustering, although the statistical significance of these results is quite low [36].

A major challenge is that current X-ray AGN samples are generally small, leading to significant statistical uncertainties that prevent clustering studies from covering a wide enough range of luminosities. This issue can be addressed by combining clustering data from X-ray samples of varying depths and survey areas, which sample different sections of the luminosity function at a given redshift. Currently, there are several X-ray surveys with areas typically less than 2 square degrees, which provide valuable constraints on the statistical properties of moderate and low-luminosity AGNs. However, there are still relatively few large-area X-ray surveys that offer enough data for accurate statistical analysis at the higher end of the X-ray luminosity function [32].

Mountrichas et al. (2016) estimate the average dark matter halo mass for relatively luminous X-ray-selected active galactic nuclei (AGN). To reach this result, they use the spectroscopic galaxy sample from the VIPERS survey, which employs the Visible Multi-Object Spectrograph for deep optical spectroscopy over 24 square degrees, divided between the W1 and W4 fields of the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS). The X-ray AGN sample is drawn from the XMM-XXL survey, which covers approximately 50 square degrees, split into two nearly equal regions. The equatorial portion of the XMM-XXL overlaps with the CFHTLS-W1 field, extending over about 25 square degrees. The clustering analysis is focused on X-ray sources within the redshift range of $0.5 < z < 1.2$, enabling cross-correlation with the VIPERS galaxy sample. X-ray luminosities are calculated in the 2–10 keV assuming a power-law X-ray spectrum with $\Gamma = 1.4$ for the k-corrections.

Mountrichas et al. (2016) present evidence showing that the average dark matter halo (DMH) mass of AGNs decreases as their accretion luminosity increases. Their findings support the idea that the DMH mass distribution of AGNs is broad, with a tail at the massive end, which skews the measured mean DMH mass toward higher values. As accretion luminosity increases, this tail becomes less dominant. The authors also interpret their results in the framework of cosmological semi-analytic models, where the broad DMH mass distribution of AGNs is linked to different fueling mechanisms of the central black hole. They show that the observed negative relationship between accretion luminosity and AGN clustering is consistent with predictions from these models [32].

4.2. The Stellar Mass of X-Ray AGN

To investigate the relationship between X-ray AGN clustering and various host galaxy properties, such as stellar mass (M_{\star}) star formation rate (SFR), and specific star formation rate (sSFR), the aim is to isolate the effect of each property on clustering while avoiding confounding factors.

To achieve this, the analysis applies two main criteria: (i) creating subsamples with nearly equal sizes, and (ii) ensuring that only one host galaxy property differs between the subsamples, with the others kept at similar median values. This approach enables any differences in AGN clustering to be attributed specifically to the host galaxy property being studied.

Several studies have attempted to demonstrate the correlation between AGN clustering and host galaxy properties. For example, Mountrichas et al. (2019) utilized the second public data release (PDR-2) from the VIPERS survey to cross-correlate X-ray AGN from the XMM-XXL field with VIPERS galaxy data. Their results, which included the estimation of the dark matter halo mass (DMHM), align with earlier findings by Mountrichas et al. (2016) using the first VIPERS data release (PDR-1). This study focuses on understanding the dependence of AGN clustering and normal galaxy clustering on host galaxy properties at a redshift of approximately $z \approx 0.8$ [37].

They divided a sample of 305 X-ray AGNs into two subsamples based on stellar mass using two cuts: $\log\left(\frac{M_*}{M_\odot}\right) = 10.5, 10.8$. These cuts were selected because they result in subsamples with similar properties, such as star formation rate (SFR), redshift, and X-ray luminosity. The analysis revealed a positive correlation between AGN clustering and galaxy clustering with respect to stellar mass [37].

Zou et al. (2019) demonstrate that, while the host galaxies of type 1 and type 2 AGNs generally have similar star formation rates (SFRs) and cosmic environments, type 1 AGNs tend to have lower stellar masses (M_*) compared to type 2 AGNs. This difference in M_* challenges the strict accuracy of the AGN unification model, suggesting that both the host galaxy and the torus may contribute to the optical obscuration of AGNs. Even when redshift (z) and X-ray luminosity are controlled, type 1 AGNs consistently show a statistically significant ($\approx 4\sigma$) lower M_* than type 2 AGNs. Testing various sample-selection criteria and parameter settings in the Code Investigating GALaxy Emission (CIGALE) further confirms that type 1 AGNs consistently exhibit slightly lower M_* , supporting the reliability of this difference. This disparity in M_* suggests that spectral-type transformation is unlikely to be widespread, as frequent transitions between AGN types would average out differences in host galaxy properties [38].

4.3. The Star Formation Rate of X-Ray AGN

Studies examining AGNs in both the nearby and early Universe have yielded conflicting results. In the low-redshift regime, Shimizu et al. (2017) observed that AGNs tend to have an enhanced star formation rate (SFR) compared to non-AGN galaxies. Their analysis suggested that the SFR in AGNs has a slight dependence on AGN luminosity, with no indication of an increase at high luminosities. On the other hand, Leslie et al. (2016) studied SDSS sources at $z < 0.1$

and categorized them based on their emission line ratios. They found that AGN feedback suppresses star formation in the host galaxies. However, caution is needed when comparing results from different studies, as AGNs are a diverse group, and the selection criteria used in each study can highlight AGNs with different properties [22, 41].

At higher redshifts, Florez et al. (2020) studied X-ray-selected AGNs in Stripe 82 with X-ray luminosities greater than $L_{(2-10\text{keV})} > 10^{44} \text{ erg s}^{-1}$ and compared their star formation rates (SFRs) with non-X-ray galaxies in the redshift range of $0.5 < z < 3$. Their findings showed that AGNs had SFRs that were 3 to 10 times higher than those of non-X-ray galaxies. Similarly, Mountrichas & Shankar (2022) examined X-ray AGNs from the Bootes, COSMOS, and eFEDS fields, comparing their SFRs with control samples of non-AGN galaxies. They found that for X-ray AGNs with $L_{(2-10\text{keV})} < 10^{44} \text{ erg/s}$, the SFRs were generally lower than those of star-forming galaxies on the main sequence. However, at higher luminosities, AGNs exhibited enhanced SFRs, particularly in galaxies within a specific stellar mass range [43].

At high redshifts ($z > 1$), where non-AGN galaxy samples are often limited in size, several studies have compared the star formation rates (SFRs) of X-ray AGNs with those of non-AGN systems, focusing on the specific star formation rate (sSFR). The sSFR is defined as the ratio of an AGN's SFR to the SFR of a star-forming main-sequence (MS) galaxy with a similar stellar mass and redshift. These studies have found that the sSFR is generally independent of redshift, as noted by Mullaney et al. (2015). Additionally, AGNs with higher X-ray luminosity (L_X) tend to have a narrower sSFR distribution that is shifted to higher values compared to lower L_X AGNs. The effect of AGNs on the SFR of their host galaxy also depends on the galaxy's position relative to the main sequence, with lower luminosity AGNs lying below the MS and higher luminosity AGNs residing above the MS. Moreover, a strong correlation between sSFR and X-ray luminosity has been observed, highlighting the distinct star-forming properties of AGN host galaxies across different luminosity regimes [46].

5. Conclusions

In this review, we have examined the host galaxy properties of X-ray-selected Active Galactic Nuclei (AGN) and their implications for understanding the mechanisms driving AGN activity across cosmic time. The evidence indicates that AGN clustering is intricately linked to various host galaxy properties, including luminosity, stellar mass, and star formation rate (SFR), each contributing to the broader picture of AGN evolution.

The studies reviewed suggest a complex relationship between AGN luminosity and dark matter halo mass (DMH), with a potential negative correlation at higher accretion luminosities. This points to different AGN triggering mechanisms or accretion modes that vary with luminosity. Howev-

er, the limited size of current X-ray AGN samples restricts the statistical power of these findings, highlighting the need for larger and more comprehensive surveys [32-34, 36].

Regarding stellar mass, the clustering of AGNs shows a positive dependence on M_* , and differences between type 1 and type 2 AGNs suggest that the unified model may not fully account for the observed variations in host galaxy properties. These differences imply that both the host galaxy and the torus play roles in the optical obscuration of AGNs [37, 38].

The relationship between AGNs and their host galaxies' SFR is similarly complex, with contrasting trends observed at different redshifts and luminosities. While lower luminosity AGNs often exhibit suppressed star formation compared to non-AGN galaxies, higher luminosity AGNs tend to show enhanced SFRs, particularly at higher redshifts. This variation suggests that AGN feedback and its impact on star formation are highly dependent on the specific characteristics of the AGN and its environment [22, 46-48].

Overall, the host galaxy properties of X-ray AGNs provide valuable insights into the diverse and dynamic nature of AGN activity. Future studies with larger datasets and more refined analysis techniques are essential to further unravel the complexities of AGN evolution and their role in shaping the cosmos.

Abbreviations

AGN	Active Galactic Nuclei
BHARD	Black Hole Accretion Rate Density
BLR	Broad-Line Region
CFHTLS	Canada–France–Hawaii Telescope Legacy Survey
CT	Compton-Thick
DMH	Dark Matter Halos
HMXBs	High-Mass X-Ray Binaries
LMXBs	Low-Mass X-Ray Binaries
NLR	Narrow-Line Region
SFR	Star Formation Rate
SMBH	Supermassive Black Hole

Conflicts of Interest

The authors declare no conflicts of interest.

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