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Review

Impact of AGN Feedback on the Dynamics of Gas; A Review across Diverse Environments

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Abstract: This review examines the relationship between blackhole activity and kinematic gas-star misalignment in brightest group galaxies (BGGs) with different merger rates. The formation history of galaxy groups is assessed through "age-dating" as an indicator of distinct major mergers involving the BGG. BGGs within groups characterized by a higher frequency of major mergers are more likely to host active SMBHs. A consistent correlation is identified between the level of black hole activity, as indicated by the 1.4 GHz and 325 MHz radio emissions, and the degree of kinematic misalignment between the gas and stellar components in BGGs. In dynamically relaxed groups, where blackhole accretion rate is relatively ($\sim$ 1 dex) lower due to the lack of recent ($\leq$ 1 Gyr) major mergers, there is reduced ($\sim$ 30%) misalignment between the gas and stellar components of BGGs compared to unrelaxed groups. Additionally, the study reveals that BGGs in unrelaxed groups show higher levels of star formation rate and increased occurrence of mergers, contributing to observed color differences. Exploring the properties and dynamics of the gas disc influenced by mechanical AGN feedback through hydrodynamic simulations suggests that AGN wind-induced effects further lead to persistent gas misalignment of the disk around the supermassive blackhole.

Keywords: galaxy groups; blackhole activity; AGN feedback; kinematic misalignment; mergers; group dynamics; radio luminosity; stellar populations; galaxy formation

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1. Introduction

The presence of super massive blackholes (SMBH) at the centers of massive galaxies provides a mechanism for the existence of Active Galactic Nuclei (AGN), which can suppress excessive star formation and regulate galaxy growth [1,2]. AGN feedback, through processes such as heating the surrounding gas with AGN jets, plays a crucial role in quenching massive galaxies and controlling the growth of SMBHs [3]. This feedback has a direct influence on the gas content of the galaxy, resulting in negative/positive feedback on star formation [4–8]. The role of AGN feedback in shaping galaxy properties is supported by numerous studies [9–15].

Brightest galaxy groups (BGGs), at the core of galaxy groups, serve as windows into the intricate processes governing galaxy assembly, star formation, and the interplay between SMBHs and their host galaxies[16,17]. In a group, galaxy interactions shape galaxy evolution by leaving observable marks like tidal features and kinematic perturbations in stars and gas [18–20]. A remarkable perturbation is the stellar-gas misalignment, where stars and gas rotate in different (in case of conter-rotation, opposite) directions due to their various (opposite) angular momentum[21] . A mismatch bigger than 30° (between the kinematic position angle of gas and stars) shows special events (either internal or external), such as mergers or gas accretion from nearby galaxies or blackhole activity (i.e. AGN feedback) [22–24]. Dynamically relaxed groups, which lack recent group-scale mergers and major galaxy mergers, are particularly suitable for such studies [25,26]. The dynamical state/age of galaxy groups can be characterized by indicators such as the luminosity gap and the offset between the BGG and the luminosity centroid, with the luminosity gap being a key factor [27]. A large luminosity gap suggests the absence of recent major mergers that could trigger cold mode accretion. In dynamically

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relaxed groups, where the intergalactic medium (IGM) reaches its peak density at the bottom of the group/cluster potential well, an AGN is subject to hot gas accretion. On one hand, [28] found a combination of the low luminosity gap (an indicator for internal event and cold accretion) and the large BGG offset from the centre (an indicator for external event and hot accretion) in a group, is the key driver behind the observed high AGN activity probed by the radio emission. The presence of nuclear gas that can be accreted by a central supermassive blackhole is considered crucial for fueling and powering AGN [29]. On the other hand, the prevalence of misalignments in early-type galaxies (which is mostly locate at the center of groups and clusters), along with the possibility of aligned stellar-gas kinematics resulting from external gas accretion depending on the interaction geometry and galaxy morphology, indicates a substantial contribution of external accretion to the total gas content in these galaxies[30], which in turn affects the availability of gas for blackhole fuelling.

The alignment or misalignment of gas and stars in galaxies, along with the influence of external gas accretion, plays a crucial role in understanding the fuelling of SMBHs and the AGN. Theoretical studies have proposed that the presence of counter-rotating or significantly misaligned structures facilitates gas inflow and potentially contributes to the fuelling of supermassive blackholes in galaxies of various types [31–35] . Recently, a hydrodynamic simulation of idealised gas disc around SMBH suggested that the stability of the disk's position angle across different radii can be attributed to the mechanical feedback from the AGN, indicating a direct influence of AGN activity on the kinematic properties of the molecular gas [36]. This comprehensive review is structured into key sections, each providing perspective on various dimensions of impacts of blackhole activity on the kinematics of gas in evolution of galaxies: from the dynamical state of galaxy groups, via the complex interplay of blackhole evolution and actions, to the dramatic narratives of major merger history. We further show the variations in radio emissions from BGGs, the varying influence of galaxy groups' dynamical states on their stellar populations, the intricate connections between group dynamics and BGGs, and the intriguing phenomena of gas misalignment in AGN-dominated galaxies via hydrodynamic simulation. Each segment contributes a piece to the puzzle, enriching our understanding of the complex interplay between blackhole activity, kinematic misalignment, and the environments of galaxies.

2. Age Dating Galaxy Groups

Relaxed galaxy groups refer to systems that have undergone relatively few recent mergers or interactions [37]. These groups are characterized by a more stable and virialized state, where the member galaxies and dark matter halos have had sufficient time to settle into a dynamically relaxed configuration. In relaxed groups, the member galaxies tend to have coherent motion, and the overall distribution of galaxies is more centrally concentrated [27]. Additionally, the X-ray emitting hot gas in these groups exhibits a smoother and more symmetric distribution [38]. In contrast, unrelaxed galaxy groups are systems that have experienced recent merger events or interactions with other groups or galaxies. Due to ongoing interactions, the member galaxies in unrelaxed groups may exhibit more chaotic motions, and the spatial distribution of galaxies can be more dispersed [39]. The X-ray emission from the hot gas in unrelaxed groups may show signs of substructures or asymmetries [38]. Such differences in the dynamical state of galaxy groups significantly impact the stellar populations and gas kinematics of the brightest group galaxies (BGGs), with unrelaxed groups showing significantly bluer NUV-r colors and higher star formation rates compared to their relaxed counterparts [17,40]. The advantage of [27] study is its use of optical data to distinguish between these relaxed and unrelaxed groups. By analyzing various measurable parameters derived from optical observations of the galaxy groups, the study aims to distinguish between groups with different merger histories [41]. This approach offers an alternative to relying solely on X-ray data or other observational techniques, which may have limitations in terms of sample size or coverage [42].

The review study of fossil groups of galaxies offers a distinct perspective on the processes influencing galaxy evolution, providing a transitional picture [39]. Fossil groups are characterized by a large luminosity gap ($\Delta M_{12} > 2$ mag) between the BGG and the other group members along

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with relatively high X-ray luminosity ($L_{X,bol} \approx 10^{42}$ h_{50}^{-2} erg s^{-1}) [25,43] , indicating a long period of dynamical relaxation [44,45]. Moreover, by adding the offset from the group luminosity centroid, we can considerably improve the accuracy and precision of *age-dating* techniques for optically (without X-ray criterion) selection fossil groups of galaxies[27]. In this review, we refer to the term "relaxed" to describe a "fossil" group that is more commonly observed and represents an "older" system in simulations, indicating its forming earlier. The unrelaxed group, in contrast, represents the non-fossil or normal groups, which are younger and formed at a later stage.

3. blackhole activity and formation history

The BGGs in relaxed groups typically harbor more massive blackholes, underscoring a correlation between the historical mass assembly of group halos and the growth of SMBHs. Figure 1 provides a visual representation of the variance in blackhole accretion rates and mass within BGGs hosted by relaxed and unrelaxed groups using cosmological simulations [46]. The BGG in the dynamically relaxed galaxy groups display a lower accretion rate (left panel) compared to the BGG in dynamically unrelaxed groups. At the same time the blackhole mass (right panel) in the BGGs dominating the dynamically relaxed groups is larger than in the BGGs of dynamically unrelaxed or young groups. This means that the mass assembly history of the host group (halos) has a significant impact on the activity and growth of BGG's SMBH. The BGGs of relaxed systems, seem to be very efficient in blackhole growth by consuming the gas which could have been generally found with a higher density in early stages of the halo formation [46].

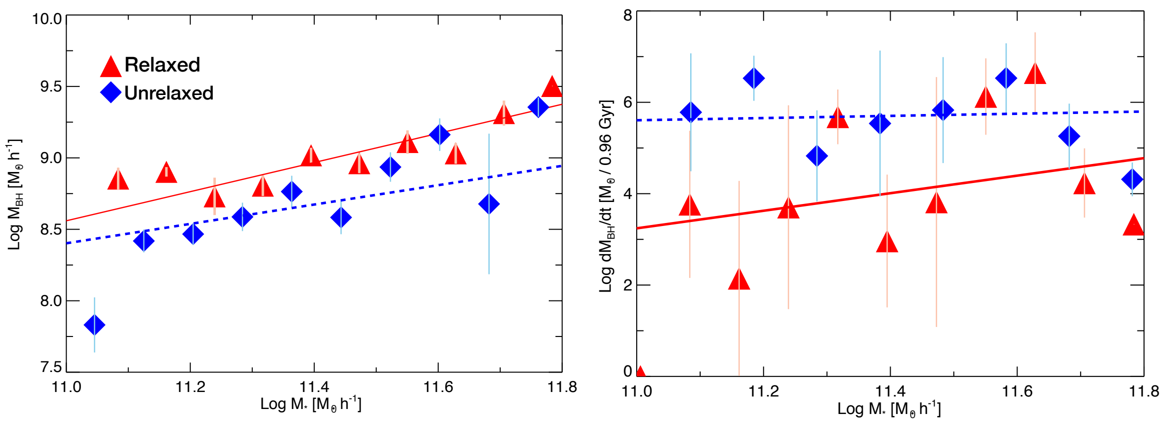

Figure 1. Left: The blackhole accretion rate ($\dot{M}_{BH}$) as function of stellar mass for BGGs, comparing dynamically relaxed groups (red) against BGGs in dynamically unrelaxed groups (blue). The red line and blue dashed line show the linear regressions to the relaxed and unrelaxed systems, respectively. **Right**: The blackhole mass (M_{BH}) as function of stellar mass for BGGs in relaxed and unrelaxed groups. the BGG in relaxed group generally possessing larger blackholes than those in unrelaxed groups, reflecting the influence of the group's dynamical history on blackhole growth. The error bars in all panels are based on the standard deviation over the mean.

Through the growth history of relaxed and unrelaxed halo, we found a significant time difference ($\sim$ 2 Gyr) in their peak merging activity [41]. As shown in left panel of Figure 2, BGGs in unrelaxed groups had their merger peak about 2 billion years (Gyr) later than BGGs in relaxed groups. As expected, galaxies in the two types of groups have different merger histories. Specifically, these unrelaxed groups experience last major mergers that are approximately 45% more frequent within the past 1 Gyr compared to the BGGs in relaxed groups. This relationship is further supported by the increased radio brightness ($L_{1.4GHz}/M_{star}$) illustrate in the right panel of Figure 2 utilising radio semi-analytic galaxy evolution model (Radio-SAGE). In contrast, BGGs in relaxed groups exhibit an earlier peak in merging activity and demonstrate lower levels of radio brightness, even when considering the same duration since the last major merger [41].

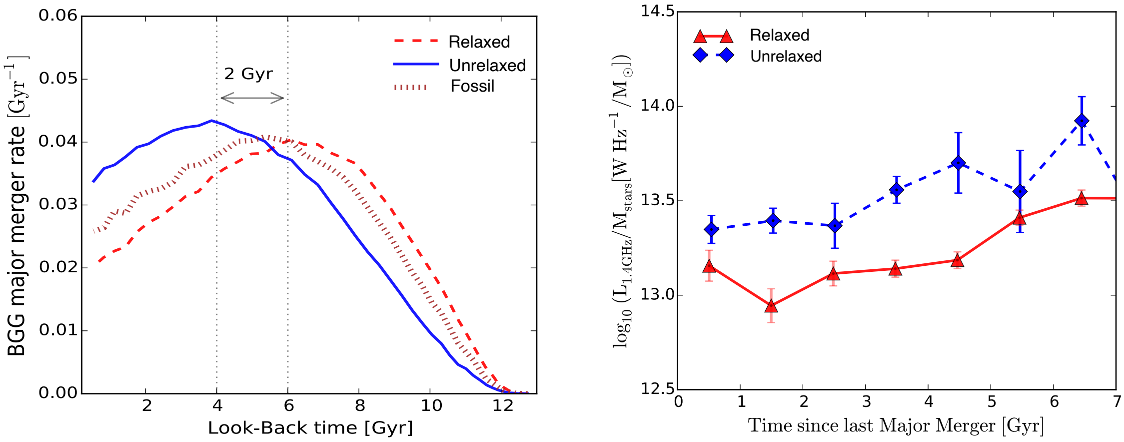

Figure 2. Left: The major merger rates of the BGG in three categories of groups using Radio-SAGE galaxy formation model: dynamically relaxed (red dashed line) and unrelaxed (blue line) groups of galaxies along the fossil ($\Delta M_{12} > 2$) groups (brown dotted line), for halo masses above $10^{13} M_{\odot}$. Major mergers are characterized by mergers with $m_1/m_2 < 3$. As seen, the BGGs of relaxed systems show a higher probability for a major merger at earlier epochs compared with unrelaxed systems (about 2 Gyr in peak). . **Right**: Radio loudness (luminosity at 1.4 GHz divided by stellar mass) of BGGs at z=0 versus the time since the last major merger suffered by the BGG, in subsamples of groups defined by the epoch of their last major merger. The red triangles and blue diamonds show the medians and standard deviation over mean error for BGGs of relaxed and unrelaxed groups, respectively

4. Radio emissions of BGGs

Several observational studies consistently demonstrate a notable increase in AGN activity within merging galaxies [47,48]. As shown in Figure 3 for 1.4 GHz (left panel) and 325 MHz (right panel) radio emission, the study by [28] indicates that in the dynamically relaxed environments, BGGs exhibit a diminished level of radio activity ($\sim$ 1 dex), indicating a relatively quiet phase of AGN activity. Our findings reveal that the proportion of radio-loud brightest group galaxies in observed dynamically unrelaxed groups is approximately twice that found in dynamically relaxed groups. Incorporating the Radio-SAGE[1] [49] model's findings into the discussion on radio emissions in BGGs, it becomes evident that the refined modeling of AGN feedback significantly contributes to our understanding of AGN activity and its various impacts. The model's advanced approach to simulating AGN jets and cooling processes under different dynamical states of galaxy groups complements the observed radio emission patterns in BGGs. This shows the complex connection between the dynamical state of the galaxy group, the behavior of the central blackhole, and the resultant AGN feedback, elucidating the varied radio emission properties of BGGs in different group environments. The successful reproduction of this observation has been achieved through the utilization of a Radio-SAGE model. This model enables us to investigate the different factors contributing to these findings. The consistent agreement between observations and Radio-SAGE model predictions indicates a higher rate of accretion[2] for the central blackhole hosted by the BGG in dynamically unrelaxed (young) galaxy groups compared to those hosted by dynamically relaxed (old) galaxy groups at a given stellar mass. [50] also emphasizing the influence of group dynamics on AGN feedback mechanisms of BGGs through the study of kinematic properties and scaling relations of radio galaxies in galaxy groups. [51] utilized a small sample of fossil groups to investigate the radio emission properties of the most luminous galaxies in these dynamically relaxed halos. Their findings indicated that these galaxies exhibit a lower level of radio emission at

1 https://github.com/mojtabaraouf/sage
2 The stable gravitational potential within relaxed groups reduces the accretion rate onto the central supermassive blackhole compared to more dynamically unrelaxed environments.

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610 MHz and 1.4 GHz. The findings of these studies suggest that mergers, which are the primary events driving the formation of a large luminosity gap, are likely the main factor contributing to the differences observed in the radio properties.

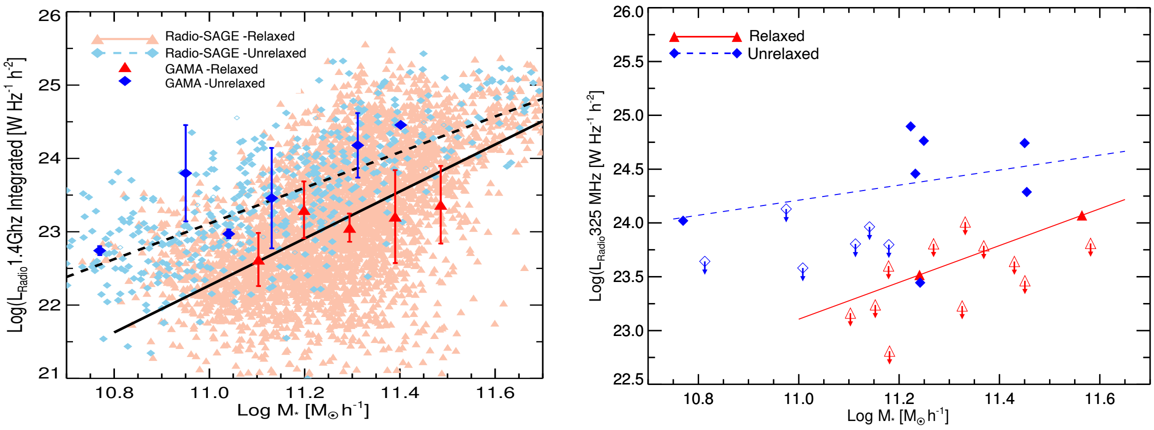

Figure 3. Left: The radio emission at 1.4 GHz for the BGG in relaxed groups (red) and unrelaxed groups (blue) as function of stellar mass. The radio luminosity refers to the integrated flux densities obtained from the VLA FIRST catalog. The bold symbols indicate the average value over the bin. We overlay the central galaxies in relaxed (light red triangles) and unrelxed (sky blue diamonds) galaxy groups corresponding to different stellar masses as a function of the 1.4 GHz radio luminosity predicted by Radio-SAGE galaxy formations model. The solid and dashed-lines represent linear fits to the model data points for the BGGs in relaxed and unrelaxed galaxy groups, respectively. **Right**: 325 MHz radio power of the BGGs in relaxed (filled red) and unrelaxed (filled blue) groups using GMRT observations. An upper limit is given for the undetected relaxed (open red) and unrelaxed (open blue) BGGs. The majority of BGGs in dynamically unrelaxed groups are radio-loud (i.e $L_{radio} > 10^{23}\ WHz^{-1}h^{-2}$).

5. Stellar population of BGGs

Figure 4 shows the metallicity and specific star formation rate (sSFR) derived from SED fitting as a function of stellar mass for a samples of Galaxy And Mass Assembly (GAMA) observations [40]. As shown in the right panel, BGGs in unrelaxed groups tend to show higher levels of star formation rate (SFR) compared to those in relaxed groups. Also, the BGGs in relaxed groups tend to have a higher percentage of red NUV-r colours (with higher precentage of NUV-r > 4.5) considering a fixed Sérsic index and dust mass, again indicating lower star formation rate. This suggests that the increased occurrence of mergers in unrelaxed groups contributes to the observed NUV-r color differences. In the left panel BGGs in unrelaxed groups tend to have higher stellar metallicities (∼0.05 dex) compared to those in relaxed groups. This could be attributed to the mass and metal enrichment history of the building blocks from which the groups formed.

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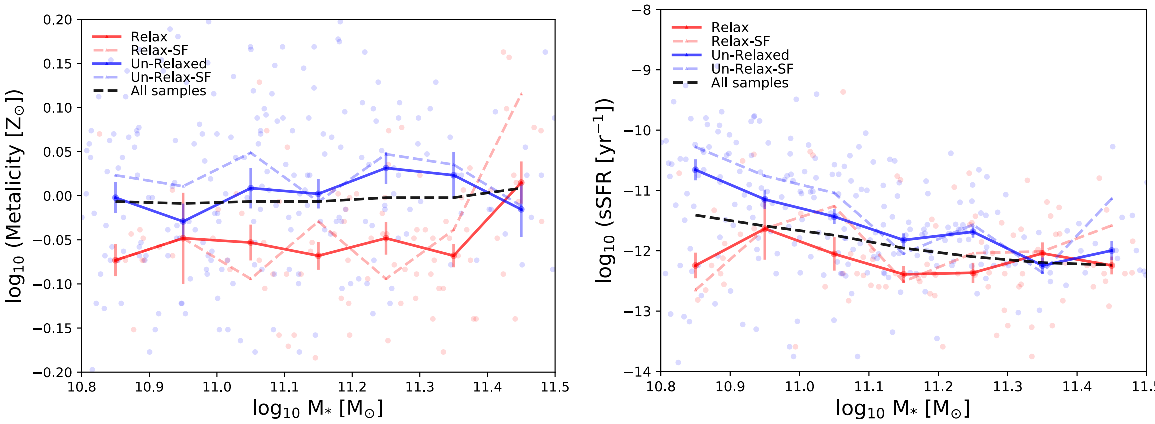

Figure 4. The variation in metallicity (left) and sSFR (right) of BGGs in relation to their stellar mass with the medians and standard deviation over mean errors, for relaxed and unrelaxed groups with specified on all and star forming (SF, light-colors) BGGs selected by BPT diagram. The dashed black line in each panel is the metallicity and sSFR for the full sample. BGGs in relaxed groups (red line) generally have lower metallicity than those in unrelaxed groups (blue line) while the median sSFR is higher for BGGs in unrelaxed groups compared to those in relaxed groups.

6. The Kinematics of BGG

Figure 5 (b_1 and c_1) shows the fraction of misaligned BGGs at a given stellar mass and Sérsic index for sample of BGG in relaxed versus unrelaxed groups using Sydney-Australian-Astronomical-Observatory Multi-object Integral-Field Spectrograph (SAMI) galaxy survey [17]. In the left panel, for a given stellar mass, the fraction of misaligned gas-star systems is primarily lower ($\sim$ 30% less in all masses) in the relaxed group's BGG compared to the BGG in the unrelaxed sample and the median value across all galaxies. In the right, the unrelaxed groups tend to have a higher fraction of misaligned BGGs at fixed Sersic index, again verifying the role of group dynamical state on the BGG dynamics. These differences are likely attributed to the extended period of tranquility experienced by BGGs in relaxed groups, allowing them to settle and relax following earlier mergers and interactions. BGGs in relaxed groups, which are characterized by a more stable and settled environment, exhibit $\sim$35% more regular rotation fields and around 10% more higher fractions of slow rotators compare to BGG in unrelaxded groups. Study of [32] employed cosmological zoom-in simulations to carefully investigate the influence of mergers on the misalignment of gas discs in early-type galaxies. The research demonstrated that a significant merger could give rise to the formation of a new gas disc that is misaligned with the stellar rotation of the galaxy and persists for several gigayears.

7. Gas misalignment in AGN dominated galaxies

Molecular observations of the gas enveloping AGNs have uncovered a intricate scenario in which the observational signatures of mechanical and radiative feedback are confounded by the probable existence of starburst activity [52–55]. Galaxies exhibiting both an AGN and robust circumnuclear star formation are particularly intriguing, as they encompass a intricate amalgamation of energetic processes, such as gas accretion and external infall, which contribute to a complex geometry and kinematics [56–58]. These combined factors give rise to a multifaceted and dynamic system. The ISM gas within the circumnuclear disk (CDN) of an AGN-dominated galaxy, particularly a Seyfert-2 type galaxy like NGC 1068, was extensively investigated through hydrodynamic simulations referred to as HDGAS[3] [36]. The study utilized these simulations to explore the properties and dynamics of the gas in

[3] https://github.com/mojtabaraouf/HDGAS

the CDN influenced by mechanical AGN feedback. The study incorporated mechanical feedback from the AGN and employed the CHIMES non-equilibrium chemistry network to compare models with and without AGN feedback. The results revealed that the presence of an AGN significantly enhances CO formation in dense, clumpy regions surrounding supermassive blackholes. This phenomenon is further elucidated by the examination of the counter-rotating gas disk in NGC 1068, as evidenced by kinematic maps of CO line emission. Further, in the models incorporating AGN feedback, specific regions of the circumnuclear disk (CND) show higher velocity dispersion, represented by the parameter σ, which can be attributed to the superposition of velocity components associated with the outflow phenomenon.

Figure 6 illustrates the variation in the disk's position angle at various CND radii (<50 pc and <100 pc around SMBH) for four distinct AGN feedback models (high/low wind velocity and mass loading, see table 1 in [36]), each differing in energy and momentum loading compared to the model without AGN feedback. The momentum and energy loading driven by the wind's velocity play a crucial role in maintaining the disk's misalignment at a scale of 100 pc over extended periods. The wind-induced effects lead to a persistent misalignment of the disk, characterized by a high offset in position angle (PA) on the 100 pc scale, demonstrating a continued state of misalignment (top-left, AGN-BH3V10B1). However, in the bottom panels, when the wind velocity is lower (AGN-BH3V5B1, AGN-BH3V5B6), the disk appears to realign within a relatively short period of time. Increasing the mass-loading results in the smoothing out of the disk, following an initial substantial offset (top-right panel, AGN-BH3V10B6). Notably, in the top right panel, during earlier timeframes (around 3 to 4 million years), when both mass loading and wind velocity are high, the dynamics are predominantly influenced by the inflow phase. In contrast, the NoAGN model does not exhibit a significant PA offset at any time or radius.

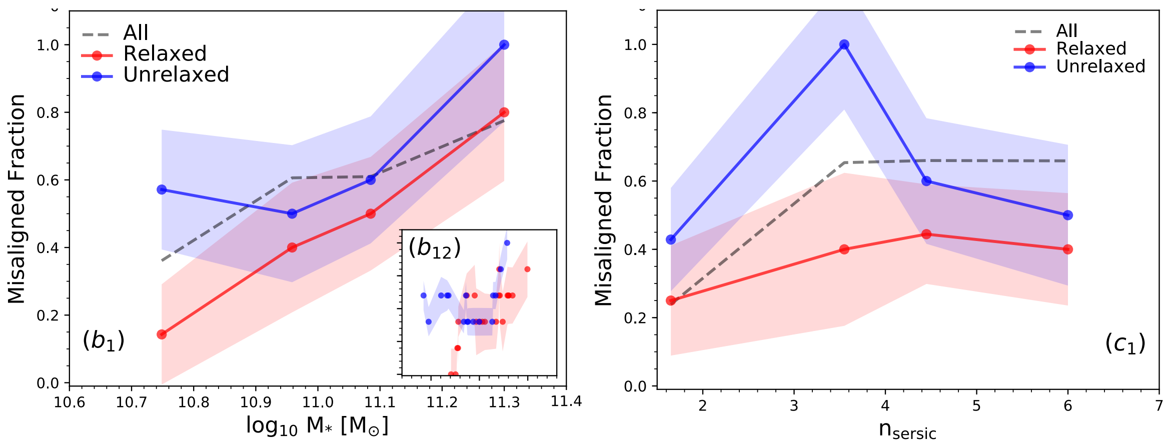

Figure 5. Left: The fraction of star - gas misalignment angel ($\delta PA > 30$ degree) as a function of stellar mass for BGGs hosted by relxed (red) and unrelaxed (blue) groups. Dashed lines show the median trend for all BGGs in our sample (b_1). The inset figure (b_{12}) shows the median fraction of regular rotation BGGs as a function of stellar mass using the moving average method where the axes range is the same as in the main plot. **Right:** The fraction of star - gas misalignment angel as a function of BGGs Sérsic index (c_1), n_{Sersic}, with the same description as given in the left panel. In each panel, the errors (color-shaded lines) are 1σ confidence intervals on the fractions calculated using the bootstrap method.

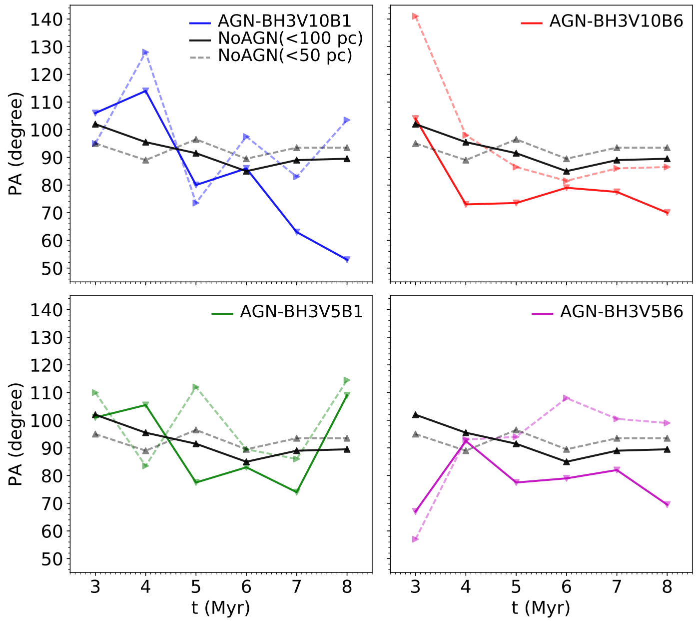

Figure 6. Kinematic position angles of CO(1-0) moment-1 maps within the central 50 (dashed lines) and 100 (solid lines) pc of the disk for AGN models with different energy and momentum loading factors and the model NoAGN (black -lines) measured at times between 3-8 Myr. A large proportion of such PA offsets occur within the central r=50 pc of the disk surrounding the SMBH in low massloading wind models (BH3V10B1, BH3V5B1), where the change in PA occurs within a shorter timeframe. There is a significant early offset (at 3-4 Myr) in models with a high mass-loading factor (BH3V10B6, BH3V5B6), followed by the steady PA trend to the later times. Moreover, different scale radii of AGN models with low velocity winds (BH3V5B6) exhibit a higher PA offset. The different radii reveal similar trends for all models except for the model with high wind velocity (i.e., BH3V10B1), which exhibits a large PA offset at a later time (t$\sim$8 Myr) compared to an earlier times.

8. Discussion

In this review, we have gained valuable insights into the impacts of blackhole activity on the kinematics of gas in galaxies with different merger histories. By utilizing state-of-the-art cosmological simulations and observational surveys, we have explored various dimensions of this complex interplay. We start by examining the dynamics of galaxy groups and their relaxation states. It has been found that the BGGs in relaxed systems, which are characterized by stable and settled environments, exhibit highly efficient blackhole growth. The consumption of gas during the early stages of halo formation significantly contributes to the growth of blackholes in these relaxed systems (Figure 1). Furthermore, we have investigated the growth history of both relaxed and unrelaxed halos and observed a significant difference in the timing of their peak merging activities (Figure 2). In dynamically relaxed environments, the BGGs exhibit lower levels of radio activity (see Figure 3), indicating a relatively quiet phase of AGN activity. On the other hand, BGGs in unrelaxed groups, experiencing more dynamic and turbulent environments, tend to have higher levels of star formation rates (Figure 4). The occurrence of mergers in unrelaxed groups contributes to the observed differences in the stellar populations and colors of BGGs.

A notable finding from our study is that the gas-star misalignment fraction in the BGGs of relaxed groups is predominantly lower compared to both the BGGs in the unrelaxed sample and the median value of all galaxies (Figure 5). This suggests that the alignment between gas and stars in the BGGs is more preserved in relaxed environments. However, the effects of winds on galaxies lead to a persistent misalignment of the disk. The interaction between the galactic disk and the wind disrupts the alignment of gas and stars, indicating that wind-induced effects continue to influence the orientation of the galactic disk over time (Figure 6).

In line with recent studies, we have found that BGGs in relaxed groups with lower blackhole activity display less kinematic misalignment. This finding supports the notion that external accretion events, such as galaxy mergers or the accretion of gas from the immediate environment, play a significant role in disrupting gas kinematics [24]. Misalignment between ionized gas and stellar kinematic angles is more prevalent in galaxies with a higher fraction of active blackholes. Studies have also demonstrated the stable misalignment of gas discs after mergers [32] and the influence of mechanical AGN feedback [36] on the gas misalignment. To further advance our understanding, future research should focus on exploring the sources and dynamics of gas accretion in BGGs, particularly the roles of hot and cold accretion processes and the influence of active galactic nuclei (AGN). Larger samples of BGGs and the integration of data on stellar kinematics will strengthen our understanding of misalignment patterns. Additionally, investigating the temporal dynamics of gas-star realignment within galaxies is crucial, as it may mirror the evolutionary timescales of galaxy groups. This synchronized pattern of internal and external galactic evolution warrants further exploration.

By shedding light on the factors influencing BGG kinematics, this review lays the groundwork for future inquiries into the intricate processes governing the life cycles of galaxies and their group environments. The insights gained from this research will contribute to a more comprehensive understanding of the interplay between blackhole activity, kinematic misalignment, and the environments of galaxies.

Data Availability Statement: Data from observation are publicly available in GAMA (http://www.gama-survey.org/) and SAMI (https://sami-survey.org/) galaxy surveyd. Data from the hydrodynamics simulations are based on the output from publicly available: (a) HDGAS simulation [36] following the GIZMO [59] code at the following repository: https://bitbucket.org/phopkins/gizmo-public/src/master/ and (b) Illustris-TNG simulation (www.tng-project.org). Data from the semi-analytic model are based on the output from publicly availble model of Radio-SAGE. *The data underlying this article will be shared on reasonable request to the corresponding author*.

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