Analysis of Active Galactic Nuclei Feedback in Cosmological Simulations: IllustrisTNG and EAGLE

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Abstract

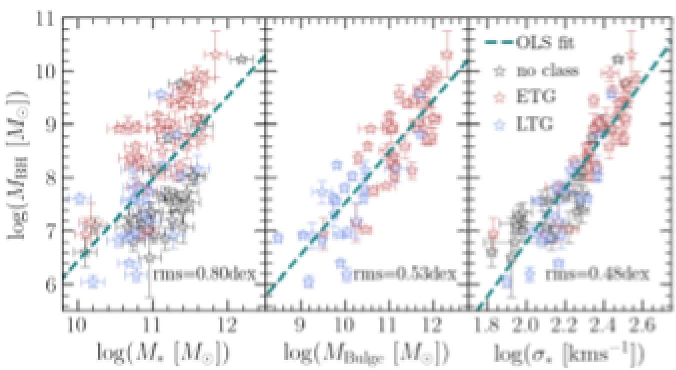
Active Galactic Nuclei (AGN) are compact and energetic regions at the centers of galaxies powered by accretion onto a supermassive black hole which emit energy across the electromagnetic spectrum. AGNs alter their host galaxies by releasing large outflows of radiation and ionized gas which impacts a variety of host galaxy properties including star formation rates, gas cooling rates, mass distribution, velocity dispersion, and luminosity. This paper presents a comprehensive overview of the mechanisms by which AGNs affect their host galaxies, with an emphasis on their implementation within cosmological simulations. It reviews the underlying physical processes, theoretical models, and observational detection methods, emphasizing how AGN impacts the ISM, drives multiphase gas outflows, and quenches star formation. To explore these effects in practice, this paper analyzes two cosmological simulations that incorporate AGN feedback: IllustrisTNG and EAGLE. Using python scripts, this paper analyzes the publicly released data from the IllustrisTNG and EAGLE data repositories, analyzing trends within black hole mass and AGN luminosity. Galaxies within this analysis are categorized into either AGN or non-AGN galaxies depending on their eddington ratio. This study found black hole mass to be the strongest predictor of AGN activity in both simulations, while AGN luminosity showed weaker correlation. Understanding the interactions between AGNs and their host galaxies is essential for building accurate simulations of galactic evolution.

1. Introduction

1.1 Active Galactic Nuclei: Historical Context and Observations

During the 1950s, astronomers discovered intense sources of electromagnetic radiation in nearby galaxies characterized by unusually broad emission lines which could not be attributed to stars. These point-like sources that resembled stars were dubbed “quasi stellar radio sources”, or quasars. The sources of power for these active galactic nuclei (AGN) were theorized to be matter accretion into supermassive black holes at the centers of galaxies. AGNs are dense regions at the center of galaxies emitting intense amounts of radiation across the electromagnetic spectrum due to accretion of matter into a supermassive black hole. Due to the extreme environments near their central black hole, AGNs are some of the most powerful objects in the universe, ejecting material across the scale of entire galaxies. The high mass to energy conversion rate means that AGNs release enough energy to quench star formation, prevent gas cooling around galaxies, and disperse gas on galactic scales. *The exact method that AGN deposits energy into the surrounding galaxy is still uncertain.*

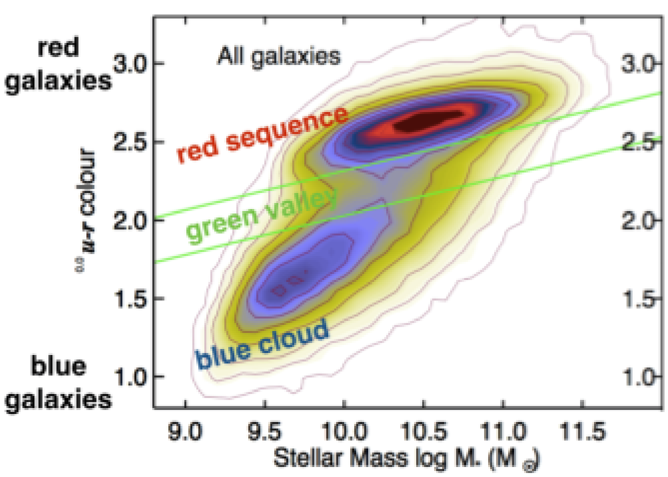
Composed of active supermassive black holes that release energy through accreting gas and dust, AGNs release large outflows of ionized gas, collimated radio jets, and radiation fields that significantly impact their host galaxy properties. These effects include structural modifications to the galactic bulge, star formation rates, the interstellar medium, and gas distribution patterns. One example of this is strong correlation between central supermassive black hole mass and the stellar mass, as well as the velocity dispersion and luminosity of the galactic bulge. The relation between black hole mass and stellar velocity dispersion in the galaxy bulge, known as the M–σ relation, is frequently used to estimate the mass of supermassive black holes (Figure 1), demonstrating the key connection between black holes and their host galaxies.



Plots showing a correlation between black hole mass and various physical parameters of a sample of galaxies. Taken from Piotrowska et al (2021).

Figure 1

These powerful outflows play a key role in heating the intracluster medium (ICM) between galaxies which would otherwise rapidly cool due to X-ray emission—a phenomenon known as the cooling flow problem. In fact, AGN feedback remains the only method for cosmological simulations capable of reproducing the observed rates of cooling for intergalactic gas. Furthermore, AGNs explain the presence of X-ray cavities carved out from radio jets observed within galaxy clusters (Fabian, 2012). The slow ICM cooling rate is responsible for quenching star formation by preventing the consolidation of new fuel for stellar formation. This matches observations of a bimodal distribution in the color magnitude of galaxies, in which galaxies either reside in the younger star forming "blue cloud" or in the older quenched "red sequence" (Figure 2). The red sequence is observed to contain more early type elliptical galaxies while the blue cloud contains late type spiral and irregular galaxies. Recognizing the importance of AGN feedback in galaxy formation, most cosmological simulations include feedback mechanisms for regulating star formation and gas cooling.



Color magnitude diagram of galaxies showing a clear distinction between a high mass "red sequence" and a low mass blue cloud. The red sequence is populated by older ellipticals while the blue cloud consists of younger spirals. Image from Schawinski et al (2013).

Figure 2

1.2 AGNs in Cosmological Simulations

With increased computational power and a more advanced understanding of galaxy formation physics, cosmological simulations have begun to play a more prominent role in the study of the formation of galaxies and large scale structure of the universe. These simulations provide cosmologists insight into how different physical processes play a role in creating the observable universe by generating large samples of simulated galaxies. The large statistical samples produced by such simulations can be used to analyze whether predictions made by certain astrophysical models reproduce results from the observed galaxy population. Cosmological simulations also allow researchers to study galaxy populations at various cosmic epochs. Moreover, cosmological simulations serve as tools for studying different models of dark matter and gravity while investigating several problems in astrophysics, many of which involve supermassive black holes, and AGN feedback mechanisms.

To achieve a realistic galaxy population, cosmological simulations model several complex physical processes including gas cooling, the ISM, star formation, radiation, magnetic fields, and cosmic rays. Energy is injected into the galaxy through stellar winds, supernovae, and feedback from Active Galactic Nuclei. For massive galaxies, feedback from stellar winds and supernovae are insufficient to explain observed properties. These simulations model galaxy formation and evolution based on initial conditions derived from cosmic microwave background observations. Cosmological simulations model both dark matter and baryonic physics. Dark matter, essential for modelling galaxy formation, shapes galaxy structure and dynamics,with galaxies forming within dark matter halos (Vogelsberger et al., 2020).

Dark matter is most often modelled using N-body methods to solve the equations of collisionless gravitational dynamics. N-body methods calculate gravitational forces acting on each dark matter particle through solutions to Poisson’s equation. Baryons, which interact with light, encompass what astronomers can directly observe. Ordinary baryonic matter is simulated using the Lagrangian or Eulerian techniques to solve hydrodynamic equations. In hydrodynamical simulations, Eulerian methods treat the gas / fluid as a collection of fixed cells. Properties of the fluid and flow between neighboring cells are then calculated for each individual cell in each time step. Lagrangian methods on the other hand treat fluids as individual particles (Barkana et al., 2018, p. 61). Other methods for simulating baryonic physics include moving mesh and mesh-free models. Cosmic magnetic fields, important for modelling the interstellar medium, are simulated through ideal magnetohydrodynamic equations. These equations combine electrodynamics with fluid dynamics to model magnetic fields within plasma.

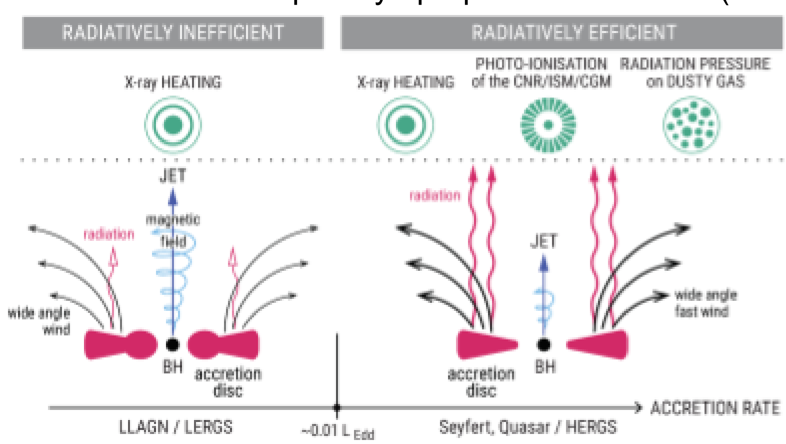
2. AGN Feedback Mechanisms

2.1 Black Hole Dynamics

Due to the multi-phase nature of the outflows and the various length scales involved, cosmological simulations are unable to precisely model every aspect of AGNs and are forced to make several approximations using a *subgrid model*. To model black hole dynamics, simulations typically “seed” supermassive black holes in dark matter halos with masses greater than 10^{10} solar masses. These black holes are implemented as collisionless sink particles which accrete nearby gas based on the Bondi–Hoyle–Lyttleton accretion model, which assumes isotropic gas inflow (Edgar, 2004). The accretion rate of supermassive black holes is often capped at the Eddington limit—the theoretical maximum luminosity at which a body's radiation pressure balances the gravitational force. In addition to accreting matter, these supermassive black holes also grow through mergers during galactic interactions.

2.2 Feedback Modes

Cosmological simulations implement AGN feedback in a variety of ways, leading to differences in their resulting galaxy populations. Most simulations implement AGN feedback through a combination of high accretion "quasar mode" feedback and low accretion "radio" / "kinetic mode" feedback (Figure 3). However, some simulations prefer to use only one channel of feedback for simplicity. The primary difference between these two modes is the efficiency at which accreting matter is converted into radiation and how this energy is injected into the host galaxy. Quasar mode feedback typically involves radiatively efficient feedback with a bolometric luminosity greater than 1% of the Eddington luminosity, whereas kinetic mode feedback does not. The feedback mechanism in the quasar mode involves photoionized gas and dust driven by radiation pressure as well as X-ray heating of gas. This mode is often nicknamed the "thermal mode" due to the energy being injected isotropically and heating surrounding gas. This feedback mode involves a thin and optically opaque accretion disk (Harrison & Almeida, 2024).

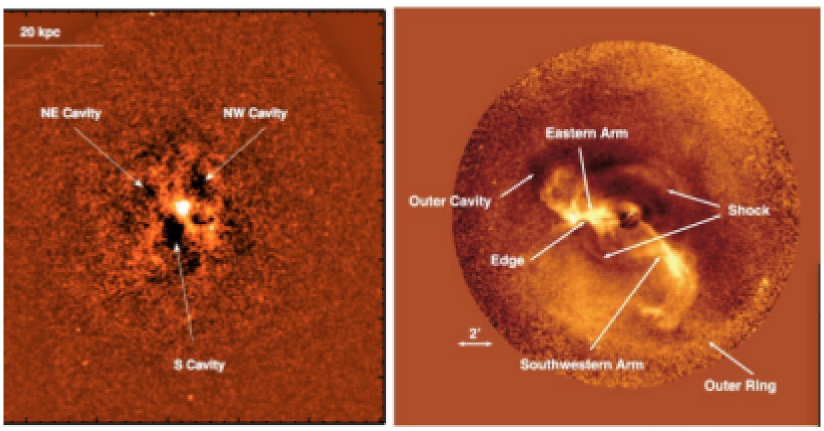


AGN inject energy into their host galaxy with different mechanisms depending on whether they are radiatively efficient / inefficient. Figure cited from Harrison and Almeida (2024).

Figure 3

Most cosmological simulations predict that supermassive black holes in the quasar mode are less massive but more luminous compared to those in the kinetic mode, likely because low-mass supermassive black holes have higher accretion rates while being in the quasar mode. In fact, Terrazas et al. (2020) found that galaxies transition into a quiescent state with little star formation dominated by kinetic mode feedback once the supermassive black hole passes a specific mass threshold of $10^{8.2}$ solar masses. They found that the specific star formation rate of the galaxy drops sharply once the cumulative energy from kinetic winds exceeds gravitational binding energy of the gas. Their findings suggest that kinetic winds were primarily responsible for driving the cold gas out of the galaxy's gravity well. This reduction in star formation rates leads to a reduced bolometric luminosity for kinetic mode AGNs. Additionally, quasar mode AGNs prefer to reside in galaxies with higher star formation rates and a greater concentration of molecular hydrogen.

On the other hand, kinetic mode feedback injects energy back to the host galaxy through collimated relativistic jets of ionized gas. Often called mechanical, radio, or jet mode feedback, this mode is present in galaxies with lower accretion, optically thin, and geometrically thick accretion disks. These jets are observed through giant radio plasma lobes, stretching up to multiple megaparsecs. These radio lobes typically appear on opposite sides of an active galaxy and emit intense amounts of radio waves through synchrotron radiation (Blandford et al., 2019). Radio jets are driven by black hole spin, the accreting matter, general relativistic effects, and interactions with intense magnetic fields. Infalling matter is accelerated to relativistic speeds, producing two narrow beams that can stretch up to millions of parsecs in length (Figure 4).



Cavities and shock fronts in x-ray observations of NGC 5044 (left) and M87 (right). Pictures from (David et al. 2009) and (Forman et al. 2007)

Figure 4

Kinetic mode feedback is theorized to quench star formation in massive galaxies by displacing gas in the intracluster medium, preventing it from cooling and subsequent star formation. X-ray and radio observations have found that the plasma lobes produced by radio jets shocked gas in the intra-cluster medium, leaving large cavities in X-ray imaging.

3. Simulation Analysis: AGN Feedback in IllustrisTNG and EAGLE

This paper examines two hydrodynamical cosmological simulations: IllustrisTNG and EAGLE. These simulations were chosen due to their accessible databases, comprehensive documentation, and the variety of physical processes these simulations employ. Supermassive black holes under both simulations grow via Bondi-Hoyle Lyttleton accretion capped at the Eddington limit. Both simulations seed black holes of mass on the order of $10^5 M\odot$ in unoccupied halos greater than $10^{10} M\odot$. Both simulations employ feedback from AGNs and supermassive black holes, although they implement various modes of feedback differently.

3.1 IllustrisTNG

IllustrisTNG is a cosmological simulation built off an extended version of the AREPO code, a moving mesh framework which models both magnetohydrodynamics and gravitational interactions (Nelson et al., 2021). Magnetohydrodynamics is modelled within a Voronoi tessellation using the finite volume methods. Grid points within the tessellation are able to move around, thus optimizing computational power by adjusting the size and shape of the mesh in areas that would need greater resolution. Each Voronoi cell tracks physical quantities of the gas such as mass, momentum, energy, and magnetic fields. Gravitational interactions are calculated using a Tree-Particle-Mesh algorithm that hierarchically groups particles within high-density regions to calculate gravitational forces.

IllustrisTNG utilizes two main modes of AGN feedback, namely the high accretion quasar mode and the lower accretion kinetic mode. The feedback mode of the central black hole is given by its Eddington ratio, the ratio of the object's luminosity to its Eddington luminosity. The Eddington ratio is compared to a specific cutoff value, with Eddington ratios above this threshold being in the quasar mode and vice versa. This cutoff threshold scales with the mass of the black hole: $\chi = min[0.002(M_{BH} / 10^{8} M_{\odot})^{2}, 0.1]$ (Weinberger et al., 2017).

Quasar mode feedback continuously injects thermal energy into gas cells surrounding the black hole. The amount of energy coupled to the gas is given as a fraction of the bolometric luminosity of the accretion disk. This thermal energy is isotropically released and affects the local environment around the black hole. Conversely, the kinetic mode of feedback is implemented in black holes with lower accretion rates than the cutoff value. In this feedback mode, kinetic feedback builds up energy in a reservoir until it reaches a certain threshold. It is then released as a jet through a “momentum kick” in a random direction. This feedback mode affects the galaxy both in the interstellar and the circumgalactic medium (CGM). Additionally, a weak radiative feedback mode is present regardless of the accretion rate of the AGN, serving to adjust gas cooling rates in the ISM.

IllustrisTNG makes several improvements in its subgrid model over its predecessor, the Illustris simulations, such as including new models of large scale gas outflows launched from AGN, modelling magnetohydrodynamics, and adding seed magnetic fields (Pillepich et al., 2017). Furthermore, IllustrisTNG modifies the implementation for kinetic mode feedback. The original Illustris simulation modelled kinetic mode feedback by placing a hot bubble within the circumgalactic nuclei. These bubbles were meant to represent the effects of radio jets inflating hot radio plasma lobes. Since radio jets were unresolved, Illustris focused on implementing their observed effects on the CGM. The hot bubbles were successful in heating up the CGM, reducing star formation and driving gas away from the halo. However, this led to large discrepancies between the gas fractions of observed vs simulation galaxies.

3.2 EAGLE

EAGLE is a cosmological simulation built off the GADGET-3 tree-SPH code, which utilizes smoothed particle hydrodynamics to model baryonic physics and gravity (McAlpine et al., 2016). Smoothed particle hydrodynamics is a mesh-free Lagrangian method where fluids are discretized into individual particles that are then “smoothed” allowing them to merge with nearby particles. This allows a continuum of substance to be simulated through a set of points which are computationally easier to handle. The SPH code is coupled to a hierarchical tree algorithm to calculate gravitational potentials.

Unlike IllustrisTNG, EAGLE utilizes a single thermal feedback mode for all supermassive black holes regardless of accretion rate. In this feedback mode, energy slowly builds up in a reservoir until is enough to heat up a nearby gas particle by $\Delta T = 10^{8.5} K$ (Booth & Schaye, 2009). The black hole then stochastically heats up the each surrounding gas particle by ΔT, releasing the energy in a thermal pulse. The energy accumulated in the reservoir is proportional to the accretion rate of the black hole multiplied by two factors representing the radiative efficiency of the accretion disk and the fraction of energy which couples to the surrounding gas (Piotrowska, 2021). The threshold for minimum heating temperature prevents the energy from immediately radiating away once released. This would cause the ISM to quickly cool down, making the AGN unable to regulate star formation. ΔT was chosen so that the feedback would be enough to prevent gas cooling while ensuring that the time needed for the AGN to build up enough energy is not longer than the timescale of feedback.

4. Methods and Results

4.1 Methods

Observational studies exploring large scale effects of AGN feedback typically measure and compare the star formation rate, gas fraction, and AGN luminosity of active and nonactive galaxies. These studies can help identify which quantities are most important in predicting the presence of AGNs, aiding future observations. Likewise, it is also important to conduct the same tests on cosmological simulations since each of them use specific feedback models. If both simulation and observation predict a variable to correlate well with AGN presence, one could explain the observations using the model implemented in the simulation. We can better understand the consequences of implementing feedback in a specific way by analyzing trends predicted by two different simulations. Overall, cosmological simulations can fill in gaps in the understanding effects of AGN feedback.

This paper investigates the relationship between the presence of an AGN and the physical properties of galaxies. Specifically, the goal is to determine whether black hole mass or AGN luminosity is better for predicting whether a galaxy hosts an AGN. Additionally, the study examines how the two different feedback modes within IllustrisTNG impact the mass and luminosity of the AGN, and compares the results to EAGLE, which only implements a single feedback mode. To accomplish these goals, this paper utilizes Python scripts to analyze the publicly released data from the IllustrisTNG and EAGLE data repositories, focusing on black hole mass and AGN luminosity. The mass of the black hole was chosen as a parameter since it represents the cumulative mass that has been accreted and is thus related to the total feedback from the AGN. AGN luminosity was chosen as the second parameter as it represents the accretion rate and is thus related to the instantaneous feedback. These parameters were selected for their relevance in comparing simulated results with observations.

The mass of the black hole was a given parameter in the database while the AGN luminosity was calculated using the relation: $L_{AGN} = \epsilon_r \dot{M} c^2$, where $\dot{M}$ is the instantaneous accretion rate of the black hole and ϵ_r is the radiative efficiency of the disk, set at 0.1 for both simulations. In this analysis, the paper makes the distinction between AGN and non-AGN galaxies by defining galaxies with a eddington ratio of $\lambda_{Edd} \geq 0.01$ as AGN and those with $\lambda_{Edd} \leq 0.01$ as not. Finally, this study focuses exclusively on galaxies at a redshift of z=0.

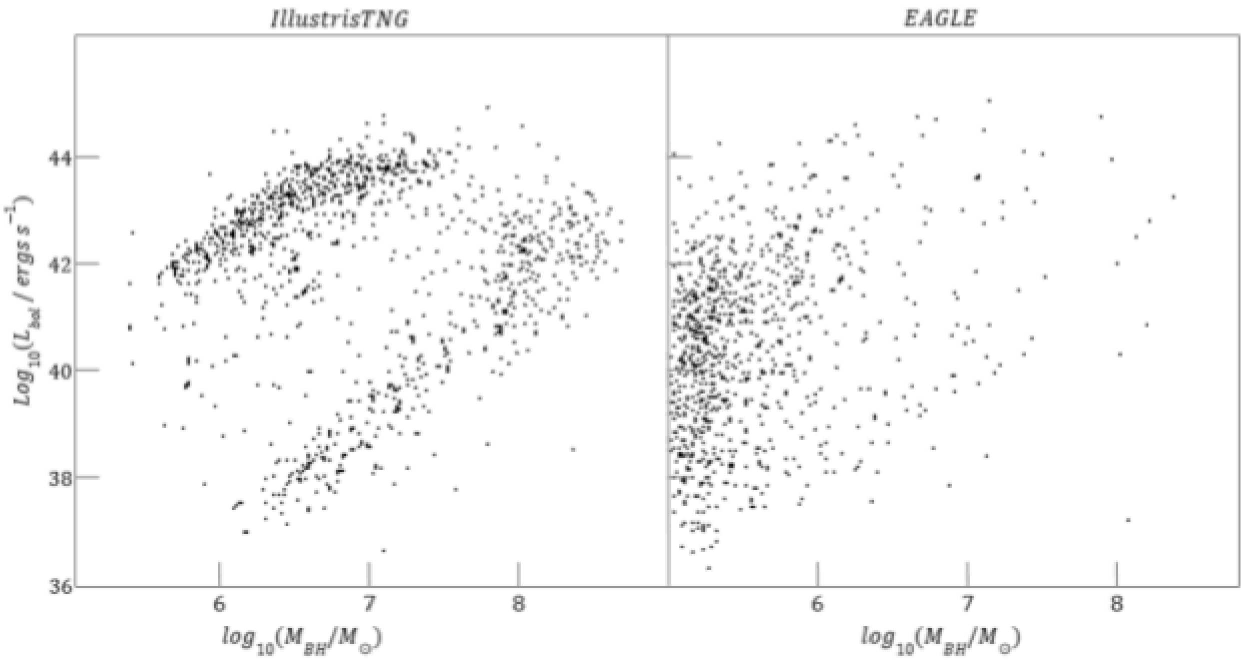


Figure 5

Scatterplot showing the distribution of galaxies across the black hole mass – AGN luminosity plane. Scatterplots include both high and low accretion galaxies. Most galaxies are shown to be residing within 10^40 to 10^42 ergs / second. Data compiled from the IllustrisTNG and EAGLE repositories.

The analysis of data on the galaxy populations of both IllustrisTNG and EAGLE showed different results, possibly because of different feedback modes or variations within the code. Figure 5 shows the distribution of galaxies within the black hole mass (M_{BH}) – AGN luminosity (L_{AGN}) plane. The left scatterplot (IllustrisTNG) shows two subsets significantly differing in luminosity. The more luminous subset consists of galaxies with a AGN luminosity of between $10^{42} - 10^{44} ergs\ s^{-1}$ while the latter consists of galaxies with luminosity between $10^{38} - 10^{42} ergs\ s^{-1}$. In IllustrisTNG, galaxies show a positive correlation between black hole mass and AGN luminosity. The EAGLE galaxy population, shown on the right of Figure 5, shows most galaxies clustering around $M_{BH} \sim 10^5 - 10^6 M_\odot$ and $L_{AGN} \sim 10^{30} - 10^{44} ergs\ s^{-1}$, with little to no correlation between black hole mass and AGN luminosity. The bimodal distribution within IllustrisTNG is most likely due to the presence of two different AGN accretion modes.

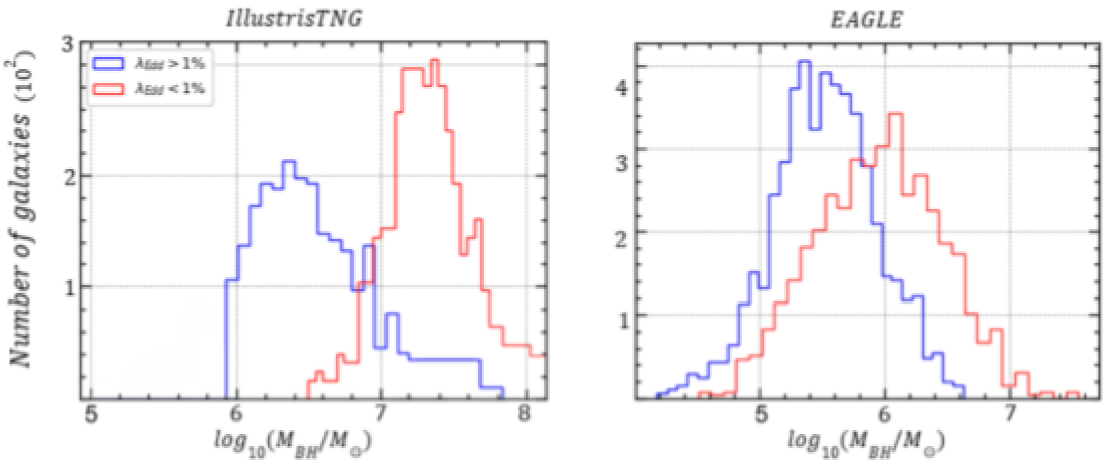


Figure 6

Histogram of galaxies showing the spread of black hole masses across both IllustriusTNG and EAGLE. Red bars show galaxies meeting our definition of AGN based on the Eddington ratio. Data retrieved from the IllustrisTNG and EAGLE repository.

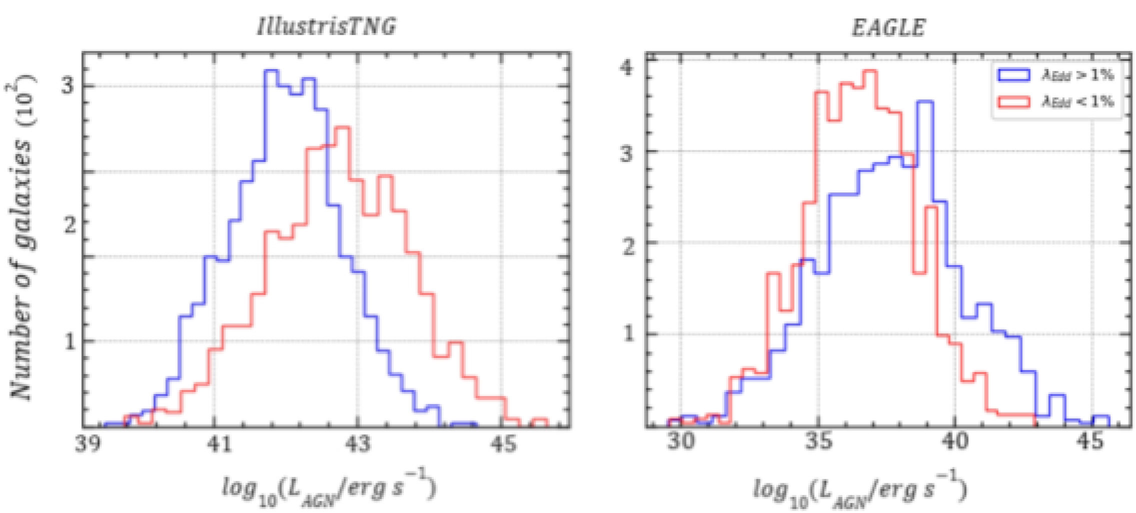


Figure 7

Histogram showing distribution of galaxies across AGN luminosity. Blue bars show galaxies meeting AGN selection criteria. High accretion galaxies within IllustrisTNG are shown to be less luminous in IllustrisTNG while EAGLE shows little correlation. Data retrieved from the IllustrisTNG and EAGLE repositories.

Figures 6 and 7 show histograms of the galaxy populations of IllustrisTNG and EAGLE plotted against black hole mass and AGN luminosity, with the color of the bars signifying whether these galaxies meet the criteria for being classified as AGNs. The left histograms in Figure 6 show that, within IllustrisTNG, high accretion AGNs have lower masses and luminosities in the range of $10^6 - 10^7 M\odot$ and $10^{41} - 10^{43} ergs\ s^{-1}$ respectively. In contrast, low accretion galaxies have comparatively higher masses and luminosities. However, this trend is not present in EAGLE: Galaxies within both accretion modes lie within the $10^{35} - 10^{40} ergs\ s^{-1}$ interval.

4.2 Results

One difference which could have led to differing results between EAGLE and IllustrisTNG is that the former lacks a kinetic feedback mechanism, relying solely on thermal energy for feedback. From Figures 5 – 7, it is evident that galaxies within EAGLE have lower AGN luminosities and black hole masses compared to those from TNG. This result is explained by EAGLEs subgrid model for galaxy formation and black hole physics. Another result from the figures is that black hole mass appears to be the strongest predictor of whether a galaxy hosts an AGN. Across simulations, galaxies with a high eddington ratio were found to have black holes with lower mass than non-active galaxies. However, AGN luminosity was a weak predictor of whether a galaxy would host an AGN, as active galaxies simulated by EAGLE did not share the same correlation between L_{AGN} and AGN activity as TNG had.

The most interesting result from the analysis is the difference between the the distribution of galaxies on the $M_{BH} - L_{AGN}$ plane between the two simulations (Fig. 5). The galaxy distribution in IllustrisTNG shows two data clusters: One consisting of high accretion low mass galaxies while the other consists of low accretion, high mass galaxies. This bimodal distribution can be explained by the AGN switching its feedback modes over time as it accretes matter. Feedback modes are assigned to galaxies based on whether their eddington ratio passes a critical value. Galaxies which begin as high accretion, low mass systems in the quasar mode gain mass through accretion and eventually cross a threshold of around $10^{7.5} M\odot$, at which point they transition into low accretion, kinetic mode galaxies. This transition is not seen to the right of Figure 5 since EAGLE only implements a single feedback mode.

These findings are consistent with those of Terrazas et al. (2020), who found that galaxies in IllustrisTNG are likely to transition into a quiescent low accretion state once their central black holes have accreted more than $10^{8.2} M\odot$. Specifically, they demonstrated that the star formation efficiency dropped significantly once the total energy injected into the ISM exceeded the binding energy of the gas, effectively quenching star formation as the galaxy switched feedback modes.

5. Observational Techniques and Modelling Validation

5.1 Observation Methods

AGN feedback studies typically focus on hot and warm ionized gas outflows from the black hole, traced using emission and absorption lines from ionized gases in the X-ray and UV spectrum. However, recent observations of AGNs have shown outflows more complex than expected, consisting of several complex phases. These outflows have large variations in temperatures, velocities, spatial scales, densities, and phases. Outflows from AGN include warm and hot ionized gas, ultrafast outflows, neutral atomic gas, and cold molecular gas, with each observed using different tracers. These different phases of gas outflows each affect the AGN differently, with some affecting the inner regions of the galaxy while others heat the circumgalactic medium. On the other hand, observational studies of AGN feedback typically focus on a single phase of gas feedback to study, omitting crucial information. This makes it difficult to study quenching efficiencies of observed galaxies and the physical processes affected by each phase of feedback.

Within the inner regions of black holes lies Ultrafast Outflows (UFOs) characterized by their high ionization levels and relativistic outflow speeds ranging from 0.1 - 0.25c. These outflows are traced using highly blueshifted X-ray absorption lines in the Iron K shell. These outflows are hypothesized to be driven by wide angle winds from accretion disks. UFOs are known to impact the galaxy by transferring momentum to the ISM through ram pressure. By injecting large amounts of momentum, they are capable of achieving galaxy wide effects similar to those produced by relativistic jets (Wagner et al., 2012).

Although UFOs are located within subparsec scales, they are hypothesised to impact outflows on longer distances by driving outflows of cold atomic hydrogen gas as well as molecular gasses such as CO and OH (Morganti, 2017). These cold atomic and molecular gasses represent the largest component of AGN outflows. Neutral atomic gasses are traced using HI absorption lines while molecular gasses are traced using submillimeter CO emission lines. However, it is still a subject of research how these massive outflows of cold gases cooled and their impact on galaxies as a whole. For more information on mechanisms which drive gas outflows and their effects on the galaxy, see (King & Pounds, 2015). Other components of the gas outflows are warm and hot ionized outflows, traced using x-ray absorption lines and emission lines in the UV, Optical, and near infrared wavelengths, respectively.

5.2 Tests for Accuracy and Uncertainties

As observatories and space telescopes have increased in power, it has become easier to test cosmological simulations against astronomical surveys. Surveys such as the Sloan Digital Sky Survey and the XMM-Newton x-ray observations have allowed researchers to study a large statistical sample of galaxies at a wide range of wavelengths. Improving spatial resolution and sensitivity of observations has given researchers a greater understanding of the complexity of gas outflows. The increasing sample of observed galaxies has allowed for more low mass and high redshift galaxies to be observed. Large all-sky surveys provide a large sample of potential AGNs to compare against cosmological simulations. The molecular gas content is a useful measure for assessing the impact of AGN feedback as it serves as fuel for stars to form. Researchers estimate the molecular hydrogen concentrations in galaxies through submillimeter CO emission lines. CO serves as a tracer for measuring molecular hydrogen since its emission lines are easier to detect than molecular hydrogen and they are strongly correlated with each other. Physical quantities measured to determine the mechanism which drives outflows include the outflow momentum rate, radiation momentum rate, and jet power. The jet power is estimated using scaling relations between observed radio luminosity and jet power. Another quantity of interest is the kinetic coupling efficiency, the ratio of the kinetic power to the AGN luminosity. This value is often compared to the feedback efficiency used by models of AGN feedback, although the practicality of this has been called into question (Harrison, et al., 2018).

There are several challenges involved in measuring physical quantities of AGN and their host galaxies. For example, a large portion of AGN is obscured and could be missed from astronomical surveys (Hickox and Alexander., 2018). In addition to uncertain bolometric correction factors, obscuration would complicate observing the luminosity of AGN. Another difficulty is in the scaling relations between radio luminosity and jet power. Whether this scaling relation holds across different environments and jet types as well as whether other factors are involved in producing the relation is still unknown.

While studying the effects of AGN feedback, it is important to take into consideration the wide range of time scales involved. Black holes are known to grow episodically, with periods of intense activity followed by little activity. Black holes are known to have “duty cycles”, which is the amount of time a black hole spends as an AGN accreting matter compared to the time it spends inactive. Central black holes thus spend long periods of their life inactive since they only become AGNs when they are emitting intense amounts of radiation. AGN are predicted to vary on time scales ranging from a few months to millions of years. This complicates the study of feedback since black holes could have periods of activity shorter than the timescale of star formation. This would make it more challenging to connect AGN activity to the star formation of the galaxy. However, short term feedback can still cause localized impacts on the ISM. The long term cumulative effects of feedback would take place over several activity cycles.

Researchers observing the impact of feedback measure the star formation efficiency, star formation rate, and gas fraction, comparing those quantities for active vs inactive galaxies. To study outflow properties, researchers measure the mass rate, kinetic power, metallicity, and outflow density. Other measurements include the geometry of the outflow. It is important to note that many studies only measure the impact of the short term AGN feedback on star formation as compared to long term cumulative feedback. Measurements of the instantaneous luminosity (proportional to the accretion rate) of black holes only measure localized transient feedback. Conversely, measurements of the black hole mass (proportional to the total mass accreted over several cycles) will be better at measuring global effects of feedback.

6. Improvements and Future Studies

This analysis of AGN feedback studied two primary variables: black hole mass and AGN luminosity. Additional variables worth studying include star formation rates, gas fractions, and halo mass. Another topic of interest is the effect of AGN feedback on thermodynamic properties of the gas and the overall galaxy morphology. Due to the multi-phased nature of gas outflows, it would be beneficial to study individual gas phases within each simulation. However, specific components of gas outflows such as molecular hydrogen are unable to be traced in simulations due to resolution limits within the model. Thus many studies prefer to use post processed models to estimate detailed gas properties. Additionally, further studies should focus on other cosmological simulation models such as Horizon-AGN, SIMBA, Romulus25, and Magneticum, which utilize different parameters and AGN feedback methods. Future studies should also evaluate additional mechanisms which could regulate star formation such as supernovae feedback, virial shock heating, or stabilizing torques. Finally, future studies should analyze differences between data from cosmological simulation and observations from different surveys. Since complex outflow behavior such as turbulence and the different gas phases are rarely implemented in simulations, it is important to analyze how simplifications made in the subgrid model affect the outcomes.

7. Conclusion

This paper provided an overview of how AGNs affect their host galaxies, with a focus on their role within cosmological simulations of EAGLE and IllustrisTNG. This paper reviews the observational history of AGN, their importance within the contemporary understanding of galactic evolution, and observations of their feedback. It then explores how cosmological simulations reproduce galaxy evolution, specifically the different ways they implement physical processes such as the ISM in a subgrid model. Several simplifications have to be implemented within the subgrid model for computational efficiency. The study also examines the specific methods by which simulations implement AGN feedback, including the quasar and radio feedback modes. Finally the paper looks into AGN observation techniques, emphasizing on how different phases of the gas outflow are observed. Because AGN outflow tends to be composed of complex multi-phased gas, there is a greater need for multi-wavelength observations. Astronomical surveys and simulations should work in tandem to help researchers create more accurate models of galactic evolution and solve astrophysical questions.

To better understand how the presence of AGNs affects galaxies, this paper analyzed trends within the black hole masses and AGN luminosities of galaxy samples produced by the IllustrisTNG and EAGLE using publicly available data from their repositories. Galaxies were separated into AGN and non-ANG groups based on their eddington ratio. The analysis foundBlack hole mass to be the strongest predictor of whether a galaxy hosted an AGN or not, with AGN selected galaxies having lower black hole mass than non-AGN galaxies in both simulations. However, it found little correlation between AGN luminosity and a galaxy's black hole state within EAGLE while TNG showed some correlation. The results showed that different feedback modes lead to a bimodal distribution in the galaxy population within IllustrisTNG, a consequence of galaxies switching feedback modes as they accrete more matter.

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