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Session 1: Formation and early growth of galaxies and SMBHs

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INVITED LECTURES

Recent insights into massive galaxy formation from observing structural evolution (Review)

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Abstract. New observations are probing the structures and kinematics of massive galaxies at a much greater level of detail than previously possible, especially during the first half of cosmic history. ALMA data now resolve the distribution of dust and molecular gas in massive galaxies to $z \sim 5$. The stellar kinematics of several massive galaxies at $z \sim 2-3$ have been spatially resolved using gravitational lensing, providing new information on the connection between quenching and morphological transformation. Star formation histories have been reconstructed for growing samples at $z \sim 0.8-2$, revealing a wide range of timescales that correlate with galaxies' sizes and environments, providing evidence for multiple paths to quiescence. I review these and other developments and summarize the insights they have provided into massive galaxies' evolution.

Keywords. galaxies: high-redshift, galaxies: kinematics and dynamics, galaxies: structure

1. Introduction

The evolution of galactic structures and kinematics offers many insights into massive galaxies' histories. First, galaxy structures are indicative of the formation physics, although the connection is sometimes direct and uncontroversial (e.g., classical ellipticals experienced dry mergers, high central densities require dissipation) and sometimes not (major mergers may not always destroy disks). Second, particularly in massive galaxies, the evolution of surface brightness profiles is intimately linked to mergers and accretion and so can be used to study these processes. Third, galactic structures (e.g., bulge fraction, central density) are strongly correlated with the quenching of star formation empirically, although the origin of this correlation, and even whether there is a causal relationship, is a subject of debate.

Since massive galaxies formed most of their stars very early, understanding their formation history requires observations at high redshifts, when much of the action occurred. This poses a number of observational difficulties: high-z galaxies are faint, small in angular size, and dusty (particularly high-mass galaxies). This short review will consider recent observations that address these challenges using various techniques, including deep near-infrared spectroscopy, radio interferometry, and gravitational lensing. I will attempt to highlight areas where recent observations have been particularly illuminating, but naturally the scope of this review only permits a small subset of results in this developing area to be discussed. We will proceed chronologically, starting with observations of very early massive galaxies at $z = 3-6$; we will then turn to some observations that resolve distribution, kinematics, and chemistry of gas and stars in the "cosmic noon" era at $z \sim 2-3$;

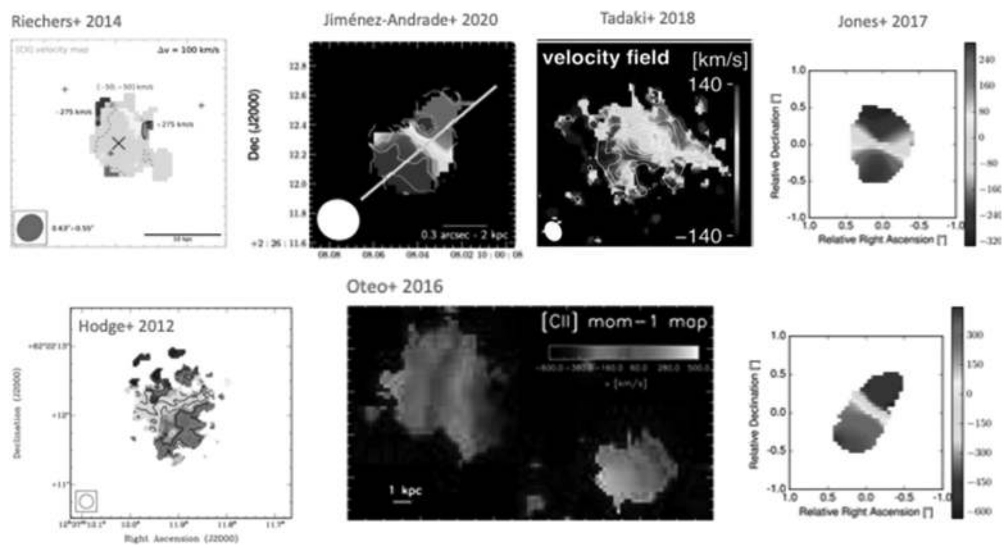

Figure 1. Velocity fields of massive, highly star-forming galaxies at $z > 4$ derived from radio interferometry, reproduced from Hodge *et al.* (2012); Riechers *et al.* (2014); Oteo *et al.* (2016); Jones *et al.* (2017); Tadaki *et al.* (2018); Jiménez-Andrade *et al.* (2020). The majority are remarkably kinematically mature with high V and V/σ as discussed in the text.

and finally we will review evidence for multiple evolutionary tracks at $z \sim 0.8-2$ that has come from connecting galaxies' star formation histories and structures.

2. Early massive galaxies and quenching ($z = 3-6$)

At the highest redshifts most structural information on massive galaxies comes from radio interferometry due to the high angular resolution it affords and its insensitivity to dust obscuration. For a handful of luminous galaxies at $z > 4$ with extremely high star-formation rates (>1000 $M_\odot$ yr^{-1}), gas velocity fields have been resolved. While the first few objects seemed to have rather mixed properties, it appears now that these early massive galaxies are remarkably dense yet kinematically mature. The ratio of rotational to random motion, $V/\sigma = 3-5$ or more (see references in Fig. 1), a range typical of Milky Way-mass galaxies at much later epochs $z \sim 1.5$ (e.g., Simons *et al.* 2016). However, these $z > 4$ galaxies have reported rotation speeds often exceeding 400 km s^{-1}, indicating that they have reached very high densities.

The high densities and short gas depletion times of these highly star-forming galaxies beyond $z = 4$ make them good candidates for progenitors of the first population of quenched galaxies (e.g., Toft *et al.* 2014) at $z > 3$. Deep near-infrared spectroscopic observations are now confirming the first samples of galaxies that had already quenched by $z = 3$ and have begun to characterize their star formation histories (e.g,. Glazebrook *et al.* 2017; Schreiber *et al.* 2018a,b; Tanaka *et al.* 2019; Valentino *et al.* 2020). The number densities of early quiescent galaxies are remarkably high, comprising perhaps 35% of massive galaxies by some estimates (Straatman *et al.* 2014), in tension with many models. Reconstructions of the past star-formation in these galaxies suggest past averages of 300–1000 $M_\odot$ yr^{-1}, broadly consistent with sub-mm galaxies at $z > 4$. Kinematic or structural data are needed to help evaluate this connection, but so far there is very little of such information for quiescent galaxies beyond $z > 3$.

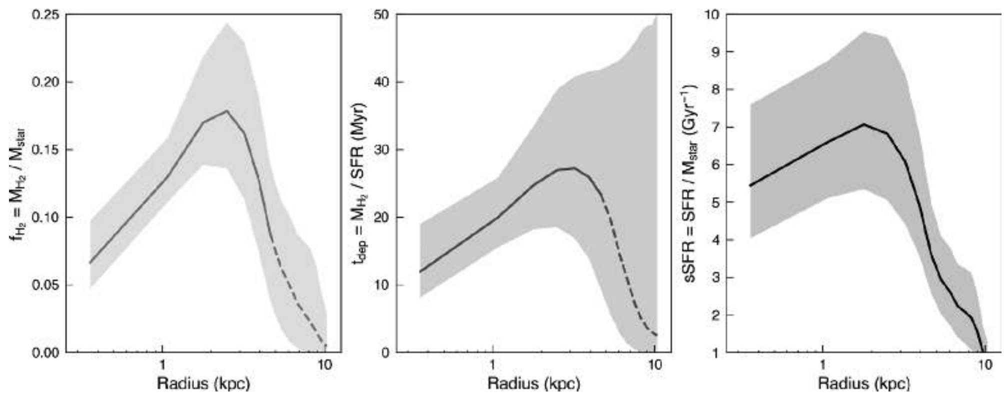

Figure 2. Resolved profiles of H_2, gas depletion time, and specific SFR in a compact star-forming galaxy at $z = 2.2$. Note the decline in gas fraction and depletion time in the inner $\sim$2 kpc, suggesting that star formation will soon cease in the inner galaxy due to rapid gas consumption coupled with likely outflows. Reproduced from Spilker *et al.* (2019).

3. Resolving gas and Stellar structure at cosmic noon ($z = 2-3$)

The study of galaxy structure and kinematics at $z \sim 2$ now comprises a large and rich literature. This short review will focus on ALMA and JVLA observations of massive galaxies and systems thought to be on the cusp of quenching.

Many massive ($> 10^{11}$ $M_\odot$) galaxies at $z \sim 2.5$ are in the process of building bulges. In ALMA observations of 25 massive star-forming galaxies at this epoch, Tadaki *et al.* (2017a) detected compact dust emission in 9 cases with a half-light radius more than 2× smaller than the stellar light. The high star formation rate density implies that these nuclear starbursts will assemble a dense stellar bulge with a surface density $\Sigma_{*,1\mathrm{kpc}} > 10^{10}$ $M_\odot$ kpc^{-2} within a few hundred Myr. This is comparable to the gas depletion time, suggesting that gas exhaustion could end star formation after the bulge is formed. These forming bulges remain rotation-dominated with $V/\sigma \approx 4-7$ (Tadaki *et al.* 2017b).

Mapping the star-forming gas in galaxies that are thought to be on the cusp of quenching is particularly interesting. Candidates observed with ALMA or JVLA include compact star-forming galaxies that are already structurally similar to quiescent galaxies (Barro *et al.* 2013, 2014, 2016, 2017; Talia *et al.* 2018) and sub-mm–selected galaxies (Lang *et al.* 2019). The general trends are that (1) the gas, dust, and star formation are centrally concentrated, just as was seen by Tadaki et al. in general samples of massive star-forming galaxies; (2) molecular gas fractions are often low and gas depletion times are short, on the order of 100 Myr or less, suggesting that the central star formation is nearing its end; (3) the galaxies remain rotationally supported. Spilker *et al.* (2019) resolved a compact star-forming galaxy using JVLA (Fig. 2) and showed that the molecular gas fraction declines significantly in the inner 2 kpc. This is perhaps the most direct evidence of star formation ending first in the inner regions of early massive galaxies ("inside out"), as the molecular gas supply is rapidly removed by star formation likely coupled with outflows.

These radio observations have illuminated some key questions concerning massive galaxies' evolution and suggested new ones. *Are quiescent galaxies so compact because they have "shrunk"?* In some systems there is clearly some "shrinking"—as defined by a decline in the half-light radius—that must be produced given that the star formation is more compact than the existing stars. What triggers this nuclear star formation is hard to pin down observationally, but theoretical models suggest that gas-rich high-z disks are very unstable and are susceptible to perturbations from mergers, interactions, accretion flows, etc. (e.g. Dekel & Burkert 2014; Zolotov *et al.* 2015). *Is feedback needed to finish*

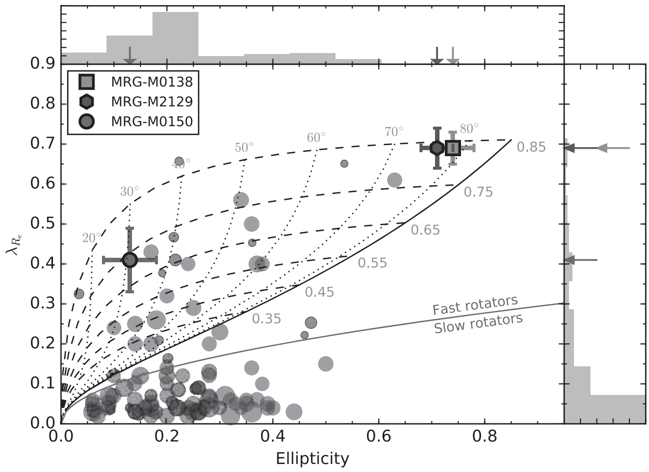

Figure 3. The projected ellipticities and angular momentum parameters λ_{R_e} of 3 lensed quiescent galaxies at $z = 2.0-2.6$ (points with error bars) are compared to local early-type galaxies (circles). The $z = 2$ quiescent galaxies have similar and very flat intrinsic shapes ($e_{\rm intr} \approx 0.75-0.85$) and much more specific angular momentum than a typical early-type galaxy of equal or higher mass in the local universe, represented here by data from the ATLAS^{3D} (red circles; Cappellari *et al.* 2013) and MASSIVE (blue circles; Veale *et al.* 2017) surveys. The grid is a family of models in which dashed lines have constant intrinsic ellipticity $e_{\rm intr}$ (labeled at right) and dotted lines have constant inclination angle (labeled at top). Reproduced from Newman *et al.* (2018b).

off star formation? Simple consumption by star formation will quickly exhaust the fuel in many of the galaxies discussed in this section that are thought to be in the process quenching. Provided there is a "maintenance" mechanism to block fresh fuel from the disk, must we invoke feedback? Perhaps not, but it is worthwhile to recall evidence that nuclear outflows appear to be quite common in massive $z \sim 2$ galaxies (e.g., Genzel *et al.* 2014). They may well provide an important additional "sink" for star-forming gas. As usual, the difficulty is estimating the mass outflow rate and thus the consequences for modulating the star formation. *When do elliptical galaxies form?* So far all observations discussed have indicated that massive galaxies remain rotation dominated right up until quenching. Yet we know that quiescent galaxies today are very structurally distinct from star-forming systems. When and how did this emerge?

Answering this question requires measuring the structure and kinematics of quenched galaxies all the way back to their formation. Although the morphologies, sizes, and ellipticities have now been measured for large samples of galaxies, arguably the angular momentum is the most fundamental parameter underlying morphological differences. Its measurement has remained elusive for quiescent galaxies much beyond $z \sim 1$ due to their faintness and small angular sizes. The most practical way to circumvent these difficulties is to use gravitational lensing to gain angular resolution. The difficulty is that magnified high-z quiescent galaxies are very rare. Nevertheless, searches have succeeded in turning up modest but very valuable samples (Newman *et al.* 2015; Toft *et al.* 2017; Newman *et al.* 2018a,b).

Newman *et al.* (2018b) spatially resolved the stellar kinematics in 4 lensed quiescent galaxies spanning the redshift range $z = 2-2.6$. These galaxies are viewed typically $\sim$1 Gyr after quenching. Remarkably, all show significant rotation and would be classified as "fast rotators" based on criteria used to classify low-z early-type galaxies (see Fig. 3). For the 3 galaxies with a lens model that permits the source to be reconstructed,

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the inferred dynamical masses exceed $\gtrsim 2 \times 10^{11} M_\odot$, placing them already in the mass range where "slow rotators" (classical ellipticals) are dominant in the local universe. Considering that some mass growth is expected, these galaxies are very likely to evolve into giant ellipticals. Yet just after quenching, they are rotating at 290–352 km s^{-1} and are primarily rotation supported with $V/\sigma \approx 2$ (c.f. $V/\sigma \lesssim 0.1$ for slow rotators). This is smaller than the typical V/σ reported for massive, coeval star-forming galaxies, which might indicate that quenching is accompanied by partial erosion of rotational support, although more data on the kinematics of the $z > 3$ progenitors of $z \sim 2$ quiescent galaxies is needed to ascertain this. However, it seems clear that most of the decline in angular momentum—by a factor of $5-10\times$—comes after quenching. Rather than a single event that simultaneously transforms a galaxy's morphology and kills off star formation, as envisioned in classical major mergers models, the morphological transformation appears to be separate. Simulations indicate that this is likely due to the gas-rich character of high-z mergers, which make disks more robust, while the transformation to an elliptical post-quenching probably arises from a series of mergers that increase the galaxy's size and mass while reducing its net angular momentum.

4. Star-formation histories and galaxy structure ($z \approx 0.8-2$)

A growing number of spectroscopic observations at $z \approx 0.8-2$ reach depths sufficient to reconstruct the past star-formation histories of moderately sized samples of massive galaxies. Even galaxies which are quiescent at the epoch of observation appear to have experienced a wide range of star formation histories over the prior few Gyr, and these star formation histories are correlated with galaxies' structures.

At all epochs since at least $z \sim 3$, there is evidence for a population of recently quenched or "post-starburst" galaxies in which star formation has shut down recently and rapidly. In the local universe, these are rare and typically low-mass galaxies, but beyond $z \sim 1$ they are more frequent and occur at higher masses. Since much of the red sequence was in place at $z \sim 1$, this raises the question of whether most galaxies joined it rapidly or more gradually.

Post-starbursts can confidently be identified by their spectroscopic signatures, but they also present distinctive broad-band colors that are useful to estimate their evolving number density using imaging surveys, particularly at $z > 1$ where continuum spectroscopy is difficult (Fig. 4). A key uncertainty in this approach is the duration of the post-starburst phase, i.e., the length of time galaxies spend traversing the post-starburst box outlined in Fig. 4. Belli *et al.* (2019) used a library of deep Keck/MOSFIRE spectroscopy to calibrate this timescale. They then compared the flux of galaxies through the post-starburst box with the rate that galaxies appear in the quiescent region of Fig. 4.

Belli *et al.* (2019) found that most galaxies at $z \sim 1.5$ are not "quenching" particularly quickly: perhaps 20% pass through a post-starburst phase. Wild *et al.* (2020) inferred a fraction 25–50% that is smaller but still implies that rapidly quenched galaxies are a minority. By necessity, the post-starburst fraction increases with redshift (galaxies cannot end star formation early *and* slowly), but even at $z \sim 2.2$ Belli *et al.* (2019) find that post-starbursts account for half of the growth of the red sequence. Interestingly, the recently, rapidly quenched galaxies tend to be smaller in size and located in overdense environments. This suggests that there are distinct and independent physical mechanisms that produce the "rapidly" and "slowly" quenched galaxies.

Wu *et al.* (2018) investigated similar questions at $z \sim 0.8$ using very deep spectra of massive galaxies collected as part of the LEGA-C survey. They find that, in general, more recently quenched galaxies are larger than older ones. This is expected due to the extra growth they had time to undergo while star-forming. But post-starburst galaxies buck the trend: despite their young ages, they are the smallest galaxy population. Among the

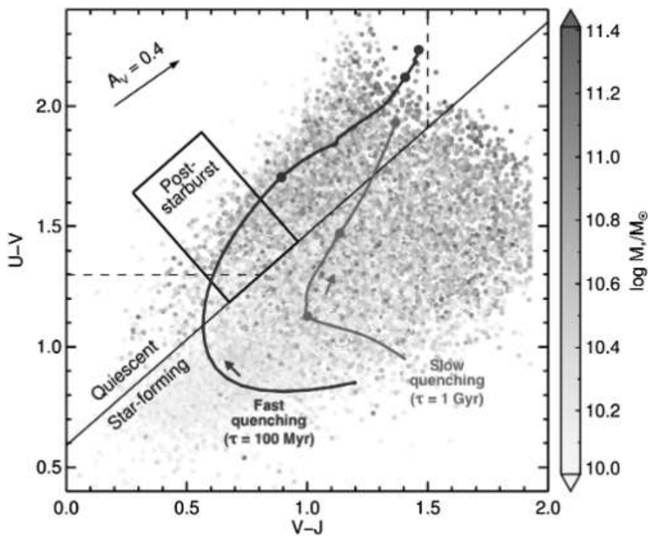

Figure 4. Color-color diagram of $z = 1.5-2$ galaxies separating star-forming (lower-right) and quiescent (upper-left) systems. Galaxies that experience "fast quenching" pass through the blue end of the red sequence, depicted here as the box labeled "Post-starburst". Galaxies that quench slowly join the red sequence without passing through the post-starburst box. Comparing the flux of galaxies onto the red sequence and through the post-starburst box shows that most galaxies quench rather slowly. Reproduced from Belli *et al.* (2019).

post-starbusts, the color correlates with size. This trend can successfully be understood using a simple model in which a brief nuclear starburst occurs within an extended disk, just before the galaxy as a whole is quenched (Wu *et al.* 2020).

These observations strongly suggest that post-starbursts at $z \approx 1-2$ are generally produced when gas is funneled into galactic centers, producing a brief nuclear star-burst that increases the central stellar density (thus decreasing the half-light radius) and extinguishes star formation in the galaxy (presumably by gas consumption and feedback). The trigger for this phase is less clear. In the theoretical "compaction" paradigm, instabilities in gas-rich disks lead to nuclear star formation, but the timescales are rather long: $0.35t_H \approx 1.6$ Gyr at $z = 1.4$ according to Zolotov *et al.* (2015), more akin to what observational studies typically classify as "slow" quenching. Bursty star-formation timescales of a few hundred Myr are reported in major merger simulations (e.g., Di Matteo *et al.* 2008), but it is not clear whether this is a plausible route for all post-starbusts.

5. Summary

At the highest redshifts probed ($z > 4$), radio observations of intensely star-forming massive galaxies often show them to be dominated by remarkably regular disks. If these galaxies are about to quench, they will produce quiescent galaxies at $z > 3$, a population that is perhaps larger than expected and is just beginning to be studied in detail.

At "cosmic noon", many massive star-forming galaxies are actively assembling bulges, as shown by observations of centrally concentrated, dusty star formation in many systems. The short gas depletion times (∼100 Myr) are comparable to the time required to assemble a stellar surface density approaching the observed maximum, suggesting that the nuclear star formation galaxies will soon end as envisioned in "inside-out" quenching scenarios. Star-forming galaxies that may be on the cusp of quenching remain rotation supported. Initial observations resolving the kinematics of $z \sim 2$ quiescent galaxies show that they, too, are quite disky and rotation supported. This implies that the transformation to an elliptical morphology is not likely to be coincident with quenching in most cases; rather, it probably occurs later through a series of dry mergers.

At $z \approx 0.8-2$, star-formation histories of quiescent galaxies, reconstructed from deep spectra, show a wide range of timescales. Relatively "slow" quenching (multiple Gyr) seems to be dominant and may involve relatively little structural transformation. "Fast" quenching (hundreds of Myr, post-starbursts) is observed in a minority of galaxies that are more compact and are located in denser environments than average. These and other observations imply that "fast" quenching is associated with a short nuclear starburst.

The observations of massive galaxies' evolving structures, kinematics, and star-formation activity covered in this review have provided several insights: quenching at high-z and formation of ellipticals are probably rather disconnected; quenching occurs over a range of timescales likely through multiple independent processes; rapid quenching requires a dissipative process, etc. But they do not uniquely identify physical mechanisms that, for instance, trigger a starburst or terminate star formation. Making such identifications, if possible, will require a synthesis of many observational and theoretical approaches.

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Models for galaxy and massive black hole formation and early evolution

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Abstract. Models for massive black holes are a key ingredient for modern cosmological simulations of galaxy formation. The necessity of efficient AGN feedback in these simulations makes it essential to model the formation, growth and evolution of massive black holes, and parameterize these complex processes in a simplified fashion. While the exact formation mechanism is secondary for most galaxy formation purposes, accretion modeling turns out to be crucial. It can be informed by the properties of the high redshift quasars, accreting close to their Eddington limit, by the quasar luminosity function at peak activity and by low-redshift scaling relations. The need for halo-wide feedback implies a feedback-induced reduction of the accretion rate towards low redshift, amplifying the cosmological trend towards lower accretion rates at low redshift.

Keywords. galaxies: formation, galaxies: nuclei, galaxies: active, methods: numerical, black hole physics, accretion

1. Introduction

Massive black holes (MBHs) are an essential part of cosmological structure formation. Modern simulations of galaxy or galaxy cluster formation rely on models for MBH formation and growth, since feedback effects from these objects have been shown to potentially explain some properties of massive galaxies and galaxy clusters (Somerville & Davé 2015). Two examples are the bimodal distribution of central galaxy colors (Trayford *et al.* 2016; Nelson *et al.* 2018), with more massive galaxies being redder and less star-forming, and the so-called cooling-flow problem, where gas cooling can be commonly observed in galaxy clusters, yet, does not lead to expected levels of star formation (e.g. Fabian 2012).

Cosmological simulations of galaxy formation model the formation of structure of the Universe as an initial value problem, numerically evolving the dark matter and gas distribution over most of cosmic time to redshift zero (for a detailed review, see Vogelsberger *et al.* 2020). While non-radiative, or generally non-dissipative simulations can be readily run and result in virialized halos, the introduction of dissipative terms in the form of radiative cooling of the gas will lead to a runaway collapse which will prohibit a numerical time-integation over cosmic timescales. The introduction of a simple closure at small scales, in which gas exceeding a certain density threshold is transformed to a collisionless 'star-particle' will alleviate this computational problem, however, yield vastly different results when compared to the observed galaxy population.

Significant progress has been made in recent years, showing that a more multi-facetted closure, including the effects of stellar feedback (e.g. Springel & Hernquist 2003; Dalla Vecchia & Schaye 2008) as well as a feedback component from active galactic nuclei (e.g. Sijacki *et al.* 2007; Dubois *et al.* 2012), can produce broad agreement between the simulated and observed galaxy population (e.g. Vogelsberger *et al.* 2013; Crain *et al.* 2015;

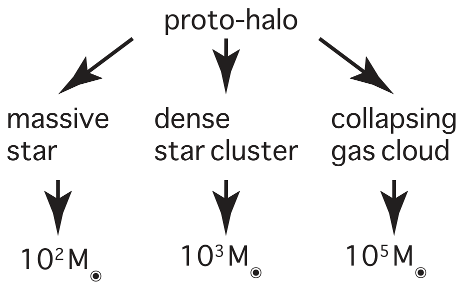

Figure 1. Broad classification of massive black hole seeding channels with expected seed mass.

Pillepich *et al.* 2018). Since these closure or sub-grid models are inspired by a simplified physical understanding, they do not cover the full complexity of the underlying process, therefore limiting the predictive power of the simulation. Yet, these models can be used as a guiding line and a test of plausibility of specific ideas which astrophysical processes are responsible for specific observational signatures.

I will review models for MBHs in cosmological simulations from seeding at high redshift until the onset of quenching around redshifts $z = 1-2$, discuss some of the difficulties related to these models and present open questions about the evolution of MBHs over cosmic time.

2. Different phases

The evolution of MBHs can be divided into 4 phases. First, MBH seed formation; second, early growth and the highest redshift quasars; third, the peak of the cosmic accretion rate density, and finally the epoch in which active galactic nucleus (AGN) feedback impacts the evolution of the entire host galaxy.

2.1. *Seeding*

One of the most uncertain aspects of MBHs is their formation. Since structure formation of non-dissipative components such as dark matter stops at virialization, further gravitational collapse is only possible via dissipative processes, i.e. radiative cooling of gas. It is therefore unsurprising that the formation of MBHs depends critically on the physics of radiative cooling, which in itself depends on chemical composition as well as external radiation fields. Theories for different channels of high redshift MBH formation have been around for some time (see Rees 1984 and Volonteri 2010 for reviews on this topic), yet the precise mechanism and possible observational evidence for it are subject to active research. Figure 1 shows a broad categorization into three different channels.

The first is the stellar-remnant channel, in which black holes of mass of order 10^2 M$_\odot$ are produced as remnants of massive, so-called population III stars (Carr *et al.* 1984). These short-lived stars are the first stars in the Universe, and form only in the absence of chemically enriched gas in so-called mini-halos.

The second channel is operating when cooling is slightly more efficient. Cool gas can form in the halo center, fragment and collapse into individual stars, thus forming a dense star cluster. In this star cluster, through collisional n-body dynamics, core-collapse can occur (Begelman & Rees 1978), which leads to the formation of a MBH in the center, with masses of order 10^3 M$_\odot$ (Devecchi & Volonteri 2009).

A third channel is possible if the formation of molecular hydrogen and consequently cooling to low temperatures is inhibited, e.g. by a sufficiently strong UV radiation flux. This leads to a larger Jeans length, i.e. prevents fragmentation, and a direct collapse of an entire massive gas cloud into a MBH seed (Bromm & Loeb 2003). The expected mass of a black hole forming via this channel is of the order of 10^5 $M_\odot$.

While none of these channels is fully understood, there are only a comparably small number of properties of crucial importance for cosmological simulations of galaxy formation: when these seed MBHs form, which mass they have and how frequent they are.

Given the typical mass resolution of a cosmological volume simulation (targeted towards a $z = 0$ galaxy population) is around 10^5 to 10^6 $M_\odot$, it is often omitted to distinguish between different seed scenarios. Instead, a commonly used way to seed MBHs in simulations is to simply assume that they are present in every halo exceeding a specific mass, typically around $10^{10}-10^{11}$ $M_\odot$. While the exact numbers are somewhat arbitrary, this is a numerically very robust way to introduce MBHs in the simulation. However, implicitly assumes that low-mass MBHs grow in the same way as halos, which leads to a relatively flat distribution of seed times. A metallicity and gas density based seeding, which is an alternative and used in some simulations, leads to a peak of seeding at high redshift, with practically no seeding events at lower redshift, reflecting more the theoretical expectation that MBH seeds require a low metallicity environment to form (Tremmel *et al.* 2017). While these vastly different ways to introduce MBHs in the simulation likely lead to very different predictions about the early and the low-mass MBH population, it is important to keep in mind that the properties of the high-mass population is strongly influenced by gas accretion and hierarchical merging of halos (Weinberger *et al.* 2018), which leads to similar properties at low redshift independent of the details of the seeding.

2.2. *Early growth*

Once formed, MBHs grow in two different ways: via mergers with other black holes, and via gas accretion. While mergers will contribute, the initial growth is dominated by rapid accretion of gas. Evidence for this is provided by the existence of high redshift quasars with associated MBH masses of order 10^9 $M_\odot$ at redshifts $\gtrsim 7$ (Bañados *et al.* 2018). These high mass MBHs at these redshifts place strict constraints on the combination of seed redshift, seed mass and maximum accretion rate at which a MBH can accrete. Assuming this maximum accretion rate is the Eddington limit, it becomes very hard to explain these black holes from population III remnants. Viable solutions are high-mass seeds from direct collapse or accretion rates that exceed the Eddington limit (see Smith *et al.* 2017 for a more detailed discussion).

Simulations of these high redshift quasars are very challenging, since the low number density of these objects requires to simulate a significant fraction of the visible universe to obtain a meaningful sample. An illustration of the scales involved is shown in Figure 2. The mean inter-object separation of high redshift quasars is of the order 10^9 pc, beyond the reach of most cosmological simulations targeting galaxy formation. Simply increasing the simulated volume is not possible, since there are resolution requirements to consider for modeling MBH seeds, even the direct collapse ones, as well as for black hole accretion. Fully satisfying these two opposing requirements is not possible at present day, yet some studies exist trying to address this problem in cosmological volume simulations that stop at high redshift (Di Matteo *et al.* 2017) as well as dedicated zoom simulations focusing on single halos (Smidt *et al.* 2018). In the latter case it has recently become possible to include the effects of radiation self-consistently in the simulation, which, by definition is crucial for objects accreting at the Eddington limit.

Cosmological volume simulations to $z = 0$ focusing on galaxy formation to-date do neither include radiation-hydrodynamics nor have the volume to produce these rare, high redshift quasars, which implies on the one hand that dedicated simulations are required to study them, on the other hand that their presence and abundance cannot be used as a

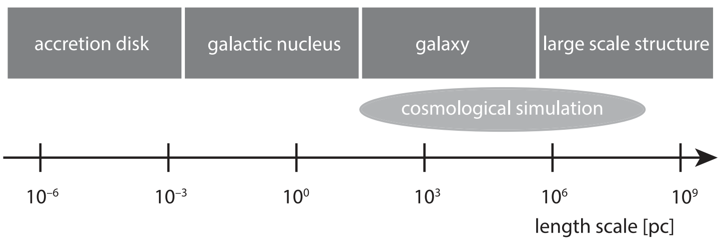

Figure 2. Spatial scales relevant for massive black holes. Cosmological simulations typically cover spatial scales from 300 Mpc to 30 pc. Therefore the covered volume is too small to contain rare objects such as the most luminous quasars, while the resolution limits require to marginalize over 6 orders of magnitude in spatial scales and related small-scale processes around massive black holes.

direct constraint for simulations. Yet, the general notion that MBH at high redshift seem to be able to accrete at or close to their Eddington limit is reassuring that the commonly employed assumption in simulations that accretion is limited to the Eddington rate is not unreasonable (note that due to the lack of radiation in these simulations, the simulated MBHs could have super-Eddington accretion rates at high redshift if not limited by the accretion model).

2.3. *Peak of activity*

Towards lower redshift, at the peak of the MBH accretion rate and star formation rate density at $z = 2{-}3$, the quasar luminosity function can be determined since a significant fraction of active galactic nuclei are observable. This quasar luminosity function is an important constraint on gas accretion onto MBHs. From a modeling perspective, the estimate of the accretion rate for the bulk of the of MBH population is very uncertain. While for very high redshifts and for the most luminous objects the assumption of accretion at the Eddington limit, i.e. a radiation pressure limited accretion, is a reasonable one, this ceases to be the case for the less extreme cases (Weinberger *et al.* 2018). For these less extreme cases it is hard to determine the limiting factor for accretion (possible factors are angular momentum, cooling, interactions with small-scale outflows, ...), let alone to estimate the accretion rate accurately from properties at galactic scales. Many models used in simulations are based on the Bondi accretion, frequently with some modifications. More recently, simulations using other prescriptions such as relations based on a torque, i.e. angular momentum limited accretion, have been performed and have shown to yield orders of magnitude different results for the same large scale conditions (Anglés-Alcázar *et al.* 2013). Considering the large range of unresolved scales (see Figure 2), and the fact that these modes assume different limiting factors for accretion, this discrepancy is not entirely surprising. But considering this uncertainty, it is rather surprising that these models are at all able to produce reasonable agreement with both low redshift MBH scaling relations, as well as high redshift quasar luminosity function constraints.

The main reason for this, in most simulations, is the self-termination of rapid accretion due to AGN feedback towards late times (however, see Anglés-Alcázar *et al.* 2013). Feedback at late times, unlike accretion, acts on resolved, galactic scales, which makes modeling easier.

2.4. *Downsizing and quenching*

Towards low redshift, both the star formation rate density as well as the MBH accretion rate density decrease towards redshift zero. Cosmological simulations reveal that this trend with redshift is not solely caused by feedback, but also visible in the global gas accretion rate density onto halos (van de Voort *et al.* 2011). The drastic decrease in number density of very luminous AGN can consequently, at least in part, be caused by a decrease in luminosity of individual AGNs due to decreased fueling, in combination with a steep negative slope of the quasar luminosity function at high luminosities. Therefore, the existence of these observed global trends cannot be interpreted as evidence for AGN feedback (however the trends might be enhanced due to AGN feedback).

The need for AGN feedback in cosmological simulations is more evident when trying to reproduce a population of massive, central galaxies with sustained low star formation rates, and consequently red intrinsic colors, as well as the X-ray properties of galaxy clusters. Matching observations in this respect has so far only been possible by invoking efficient AGN feedback in galaxies more massive than the Milky Way (e.g. Weinberger *et al.* 2017), a feature all cosmological simulations aiming to reproduce these high mass objects have in common (e.g. Khandai *et al.* 2015; Beckmann *et al.* 2017; Davé *et al.* 2019).

One of the key remaining questions in which simulations differ is how AGN feedback comes to be efficient in massive galaxies, while not being that relevant for the less massive galaxy population that remains star forming to the present day. Different simulations overcome this problem in different ways, some pointing towards the properties of stellar feedback (e.g. Bower *et al.* 2017), others achieve a similar effect by a change in mode of AGN feedback (Weinberger *et al.* 2018), possibly induced by small-scale accretion disk physics or a change in black hole spin (Bustamante & Springel 2019). Future observations, for example of the hot, soft X-ray emitting halo gas might be able to rule out certain models (Oppenheimer *et al.* 2020; Truong *et al.* 2020).

Another major aspect that requires more detailed study is the coupling of the energy released by the AGN with the host galaxy. In cosmological simulations, this is implicitly assumed when constructing a model on kpc scales. Studying this in more detail on smaller scales (e.g. Cielo *et al.* 2018), will be necessary to make a convincing case that whatever, for now, is assumed and required in cosmological simulations, is actually realistic.

3. Summary

Cosmological simulations require AGN feedback to reproduce the properties of massive galaxies. This need for AGN feedback makes it necessary to parameterize the rich and complex physics of MBH formation and evolution in a simplified fashion, but at the same time also allows to investigate the evolution of MBHs over cosmic time in a realistic environment. Some important takeaways are:

- There might be different seeding channels, however they are not modeled in most cosmological simulations, and the high-mass MBHs have likely lost all information about seeding. However, information about seeding can be obtained from low-mass MBHs and gravitational wave events.
- High redshift quasars indicate that early growth in the most extreme environments is close to Eddington-limited. This is very informative for accretion rate estimates at high redshift.
- Accretion rates of less extreme MBHs are significantly more difficult to estimate due to poorly understood physics at unresolved scales.
- Towards low redshift, AGN feedback is required to produce massive, quiescent central galaxies. This trend likely amplifies the general reduction of star formation rate density and downsizing, however is not the sole cause for it.
- The physical cause of the transition from a growth dominated to a feedback dominated regime is still debated, with upcoming observations having the potential to rule out some scenarios.

While cosmological simulations have been remarkably successful over the past years, presenting plausible scenarios of MBH evolution (and rule out a number of alternative ones), future studies that connect modeling of individual processes from first principle with the cosmological evolution are needed to gain further understanding about MBH formation and evolution.

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