

Elliptical Galaxies and Bulges of Disk Galaxies: Summary of Progress and Outstanding Issues

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Abstract Bulge components of disk galaxies are the high-density centers interior to their outer disks. Once thought to be equivalent to elliptical galaxies, their observed properties and formation histories turn out to be richer and more varied than those of ellipticals. This book reviews progress in many areas of bulge studies. Two advances deserve emphasis: (1) Observations divide bulges into “classical bulges” that look indistinguishable from ellipticals and “pseudobulges” that are diskier and (except in S0s) more actively star-forming than are ellipticals. Classical bulges and ellipticals are thought to form by major galaxy mergers. Disky pseudobulges are a product of the slow (“secular”) evolution of galaxy disks. Nonaxisymmetries such as bars and oval distortions transport some disk gas toward the center, where it starbursts and builds a dense central component that is diskier in structure than are classical bulges. Secular evolution explains many regular structures (e. g., rings) seen in galaxy disks. It is a new area of galaxy evolution work that complements hierarchical clustering. (2) Studies of high-redshift galaxies reveal that their disks are so gas-rich that they are violently unstable to the formation of mass clumps that sink to the center and merge. This is an alternative channel for the formation of classical bulges.

This chapter summarizes big-picture successes and unsolved problems in the formation of bulges and ellipticals and their coevolution (or not) with supermassive black holes. I present an observer’s perspective on simulations of cold dark matter galaxy formation including baryonic physics. Our picture of the quenching of star formation is becoming general and secure at redshifts $z < 1$. I conclude with a list of major uncertainties and problems. The biggest challenge is to produce realistic bulges + ellipticals and realistic disks that overlap over a factor of > 1000 in mass but that differ from each other as we observe over that whole range. A related difficulty is how hierarchical clustering makes so many giant, bulgeless galaxies in field but not cluster environments. I present arguments that we rely too much on star-formation feedback and AGN feedback to solve these challenges.

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1 Introduction

This final chapter summarizes areas of major progress in understanding galaxy bulges and tries to distill the important unresolved issues that need further work.

I do not revisit the subjects covered by all chapters – Madore (2015: historical review), Méndez-Abreu (2015: intrinsic shapes), Falcón-Barroso (2015: kinematic observations), Sánchez-Blázquez (2015: stellar populations), Laurikainen & Salo (2015: observations of boxy bulges), Athanassoula (2015: modeling of boxy bulges), Gonzalez & Gadotti (2015: observations of the Milky Way boxy bulge), Shen & Li (2015: modeling of the Milky Way boxy bulge), Cole & Debattista (2015: nuclear star clusters), and Combes (2015: bulge formation within MOND). I comment briefly on Zaritsky’s (2015) chapter on scaling relations.

I concentrate in this summary chapter on three main areas of progress and on two main areas where there are unresolved difficulties:

Two additions to our picture of bulge formation are (1) formation by massive clump instabilities in high- z disks; Bournaud (2015) develops this story, but it deserves emphasis here, too, and (2) our picture of secular evolution of galaxy disks that produces two distinct kinds of dense central components in galaxies, disk pseudobulges (reviewed here by Fisher & Drory 2015) and boxy pseudobulges (discussed in four chapters listed above). Both deserve emphasis here, too.

The main areas with unresolved issues come in two varieties:

Probably the most important chapter in this book is Brooks & Christensen (2015) on the modeling of galaxy – and thus also bulge – formation. These models that add baryonic physics to giant n -body simulations of the hierarchical clustering of cold dark matter (CDM) in a Λ CDM universe define the state of the art in the most general version of galaxy formation theory. Much has been accomplished, and progress is rapid. Brooks & Christensen (2015) is an excellent review of the state of the art as seen by its practitioners. In this chapter, I would like to add the viewpoint of an observer of galaxy archaeology. I suggest a slightly different emphasis on the successes and shortcomings of present models. My main purpose is to promote a dialog between theorists and observers that may help to refine the observational constraints that are most telling and the modeling exercises that may be most profitable. Baryonic galaxy formation is an extraordinarily rich and difficult problem. Many groups struggle honorably and carefully with different aspects of it. In this subject, besides a strong push on remaining limitations such as resolution, the main need seems to me to be a broader use of observational constraints and a consequent refinement of the physics that may succeed in explaining them.

A second issue involves Graham’s (2015) chapter on supermassive black holes. It is inconsistent with all other work that I am aware of on this subject, including McConnell & Ma (2013) and Kormendy & Ho (2013). Section 6 summarizes this subject using results from Kormendy & Ho (2013, hereafter KH13).

Section 7 reviews the quenching of star formation in galaxies. Many different lines of research are converging on a consistent picture of how quenching happens.

Finally, I conclude with a personal view of the most important, big-picture issues that are still unsolved by our developing picture of galaxy evolution.

2 Secular Evolution and the Formation of Pseudobulges

Progress on bulge formation is dominated by two conceptual advances. This section revisits secular evolution in disk galaxies. This is a major addition that complements our picture of galaxy evolution by hierarchical clustering. I begin here because *all further discussion depends on the resulting realization that the dense central components in galaxies come in two varieties with different formation processes, classical and pseudo bulges*. Section 3 discusses the second conceptual advance, the discovery of a new channel for the formation of classical bulges. This is the formation at high z of unstable clumps in gas-rich disks; they sink to the center along with lots of disk gas and starburst and relax violently. In this way, bulge formation proceeds largely as it does during major mergers. This leads to a discussion of the merger formation of both bulges and ellipticals in Section 4.

Our pictures of the merger formation of classical bulges and ellipticals and the secular growth of pseudobulges out of disks both got their start in the late 1970s. The importance of major mergers (Toomre & Toomre 1972; Toomre 1977) in a hierarchically clustering universe (White & Rees 1978) got a major boost from the realization that CDM halos make galaxy collision cross sections much bigger than they look. This subject “took off” and rapidly came to control our formation paradigm. Secular evolution is a more difficult subject – slow processes are hard to study – and it did not get a similar boost from the CDM revolution. However, the earliest papers on the subject come from the same time period: e. g., Kormendy (1979a) emphasized the importance of slow interactions between nonaxisymmetric galaxy components; Kormendy (1979b) first pointed out the existence of surprisingly disk bulges; Combes & Sanders (1981) showed that boxy pseudobulges are edge-on bars. Kormendy (1981, 1982) reviewed and extended the results on disk bulges. This subject did not penetrate the galaxy formation folklore; rather, it remained a series of active but unconnected “cottage industries” for the next two decades. Nevertheless, by the 1990s, the concept – if not yet the name – of disk pseudobulges was well established (see Kormendy 1993 for a review), and the idea that boxy bulges are edge-on bars was well accepted (see Athanassoula 2005 for a more recent and thorough discussion). I hope it is fair to say that the comprehensive review by Kormendy & Kennicutt (2004) has helped to convert this subject into a recognized paradigm – it certainly is so in this book – although it is still not as widely understood or taken into account as is hierarchical clustering.

Kormendy & Kennicutt (2004) remains up-to-date and comprehensive on the basic results and on observations of prototypical pseudobulges. However, new reviews extend and complement it. Kormendy & Fisher (2005, 2008) and Kormendy (2008, 2012) provide the most important physical argument that was missing in Kormendy & Kennicutt (2004): Essentially all self-gravitating systems evolve toward more negative total energies (more strongly bound configurations) by processes that transport kinetic energy or angular momentum outward. In this sense, the secular growth of pseudobulges in galaxy disks is analogous to the growth of stars in protostellar disks, the growth of black holes in black hole accretion disks, the sinking of Jupiters via the production of colder Neptunes in protoplanetary disks,

core collapse in globular clusters, and the evolution of stars into red (super)giants with central proto white dwarfs, neutron stars, or stellar-mass black holes. All of these evolution processes are related. So secular disk evolution and the growth of pseudobulges is very fundamental, provided that some process redistributes angular momentum in the disk. My Canary Islands Winter School lectures (Kormendy 2012) are an up-to-date observational review that includes environmental secular evolution. Sellwood (2014) provides an excellent theoretical review.

Boxy pseudobulges are discussed in four chapters of this book; I concentrate on disky pseudobulges. Fisher & Drory (2015) review the distinction between classical and pseudo bulges from a purely phenomenological point of view. That is, they intercompare observational diagnostics to distinguish between the two bulge types with no reference to physical interpretation. This is useful, because it gives relatively unbiased failure probabilities for each diagnostic. They are not wholly independent, of course, because they are intercompared. But they are independent enough in execution so that we get a sufficient estimate of the failure probability when they are combined by multiplying the individual failure probabilities.

Kormendy & Kennicutt (2004), Kormendy (2012), and KH13 strongly advocate the use of as many bulge classification criteria as possible. The reason is that any one criterion has a non-zero probability of failure. Confusion in the literature (e. g., Graham 2011) results from the fact that some authors use a single classification criterion (e. g., Sérsic index) and so get results that conflict with those derived using multiple criteria. But we have long known that most classical bulges have $n \geq 2$, that most pseudobulges have $n < 2$, and that there are exceptions to both criteria. No-one should be surprised that Sérsic index sometimes fails to correctly classify a bulge. This is the point that Fisher & Drory (2015) make quantitative.

Fisher & Drory (2015) show that the failure probability of each classification criterion that they test is typically 10 – 20 %. A few criteria are completely robust (if $B/T \gtrsim 0.5$, then the bulge is classical) and a few are less reliable (star formation rate cannot be used for S0s). But, by and large, it is reasonable to conclude that the use of M criteria, each with failure probability ϵ_m , results in a classification with a failure probability of order the product of the individual failure probabilities, $\prod_1^M \epsilon_m$. This becomes very small very quickly as M grows even to 2 and especially to $M > 2$. For example, essentially all bulge-pseudobulge classifications in KH13 were made using at least two and sometimes as many as five criteria.

Fisher & Drory (2015) also contribute new criteria that become practical as new technology such as integral-field spectroscopy gets applied to large samples of galaxies. These are incorporated into an enlarged list of classification criteria below.

A shortcoming of Fisher & Drory’s approach is that it is applied without regard to galaxy Hubble types. But we know that both many S0s and many Sbc’s contain pseudobulges, but the latter all tend to be star-forming whereas the former generally are not. This is one reason for their conclusion (e. g.) that high star formation rate near the galaxy center robustly implies a pseudobulge, but no star formation near the center fails to prove that the bulge is classical. Classification criteria that involve gas content and star formation rate cannot be applied to S0 galaxies. Application to Sbc’s is also fragile. Fortunately, most criteria do work for early-type galaxies.

2.1 Enlarged List of Bulge-Pseudobulge Classification Criteria

Kormendy & Kennicutt (2004), Kormendy (2012), and Fisher & Drory (2015) together provide the following improved list of (pseudo)bulge classification criteria. I note again: The failure rate for individual criteria ranges from 0 % to roughly 25 %. Therefore the use of more criteria quickly gives much more reliable results.

- (1) If the galaxy center is dominated by young stars and gas but there is no sign of a merger in progress, then the bulge is mostly pseudo. Ubiquitous star formation must be secular. Fisher & Drory (2015) make this quantitative: if the specific star formation rate $s\text{SFR} \geq 10^{-11} \text{ yr}^{-1}$, then the bulge is likely to be pseudo; whereas if $s\text{SFR} < 10^{-11} \text{ yr}^{-1}$, then the bulge is likely to be classical. Also, if the bulge is very blue, $B - V < 0.5$, then it is pseudo. Criteria (1) cannot be used for S0s.
- (2) Disky pseudobulges (a) generally have apparent flattening similar to that of the outer disk or (b) contain spiral structure all the way to the galaxy center. Classical bulges are much rounder than their disks unless they are seen almost face-on, and they cannot have spiral structure. Criterion 2(a) can be used for S0s; 2(b) can not.
- (3) Pseudobulges are more rotation-dominated than are classical bulges in the $V_{\text{max}}/\sigma - \varepsilon$ diagram; V_{max} is maximum rotation velocity, σ is near-central velocity dispersion, and ε is ellipticity. Integral-field spectroscopy often shows that the central surface brightness excess over the inward extrapolation of the disk profile is a flat central component that rotates rapidly and has small σ .
- (4) Many pseudobulges are low- σ outliers in the Faber-Jackson (1976) correlation between (pseudo)bulge luminosity and velocity dispersion. Integral-field spectra often show that σ decreases from the disk into a pseudobulge. Fisher and Drory make this quantitative: Pseudobulges have rather flat logarithmic derivatives of the dispersion profile $d\log \sigma / d\log r \geq -0.1$ and $V^2/\sigma^2 \geq 0.35$. In contrast, if $d\log \sigma / d\log r < -0.1$ or if central $\sigma_0 > 130 \text{ km s}^{-1}$, then the bulge is classical.
- (5) Small bulge-to-total luminosity ratios do not guarantee that a bulge is pseudo, but almost all pseudobulges have $PB/T \lesssim 0.35$. If $B/T \gtrsim 0.5$, the bulge is classical.
- (6) Most pseudobulges have Sérsic index $n < 2$; most classical bulges have $n \geq 2$.
- (7) Classical bulges fit the fundamental plane correlations for elliptical galaxies. Some pseudobulges do, too, and then the correlations are not useful for classification. More extreme pseudobulges are fluffier than classical bulges; they have larger effective radii r_e and fainter effective surface brightnesses μ_e . These pseudobulges can be identified using fundamental plane correlations.
- (8) In face-on galaxies, the presence of a nuclear bar shows that a pseudobulge dominates the central light. Bars are disk phenomena. Triaxiality in giant Es involves different physics – slow (not rapid) rotation and box (not x_1 tube) orbits.
- (9) In edge-on galaxies, boxy bulges are edge-on bars; seeing one identifies a pseudobulge. The boxy-core-nonrotating side of the “E – E dichotomy” between two kinds of elliptical galaxies (see Section 4.1.1) cannot be confused with boxy, edge-on bars because boxy ellipticals – even if they occur in disk galaxies (we do not know of an example) – are so luminous that we would measure $B/T > 0.5$. Then point (5) would tell us that this bulge is classical.

- (10) Fisher & Drory (2015) conclude that pseudobulges have weak Fe and Mg b lines: equivalent width of $[\text{Fe } \lambda 5150 \text{ \AA}] < 3.95 \text{ \AA}$; equivalent width of $[\text{Mg b}] < 2.35 \text{ \AA}$. In their sample, no classical bulge has such weak lines. Some pseudobulges have stronger lines, so this criterion, like most others, is not 100 % reliable.
- (11) If a bulge deviates from the $[\text{Mg b}] - \sigma$ or $[\text{Mg b}] - [\text{Fe}]$ correlations for elliptical galaxies by $\Delta[\text{Mg b}] < 0.7$ – that is, if the $[\text{Mg}]$ line strength is lower than the scatter for Es – then the bulge is likely to be pseudo (Fisher & Drory 2015).

It is important to emphasize that classical and pseudo bulges can occur together. Fisher & Drory (2015) review examples of dominant pseudobulges that have small central classical bulges. And some giant classical bulges contain nuclear disks (e. g., NGC 3115: Kormendy et al. 1996b; NGC 4594: Kormendy et al. 1996a).

Criterion (9) for boxy pseudobulges works only for edge-on and near-edge-on galaxies. In face-on galaxies, it is easy to identify the elongated parts of bars, but they also have rounder, denser central parts, and these are not easily distinguished from classical bulges (Athanasoula 2015; Laurikainen & Salo 2015). So the above criteria almost certainly fail to find some pseudobulges in face-on barred galaxies.

2.2 Secular Evolution in Disk Galaxies: Applications

Progress in many subjects depends on a full integration of the picture of disk secular evolution into our paradigm of galaxy evolution. Examples include the following:

- (1) If the smallest bulges are pseudo and not classical, then the luminosity and mass functions of classical bulges and ellipticals are very bounded: $M_K \lesssim -19$; $M_V \lesssim -16$; $L_V \gtrsim 10^{8.5} L_\odot$; stellar mass $M_{\text{bulge}} \gtrsim 10^9 M_\odot$. In simulations (Brooks & Christensen 2015; Section 4 here), the physics that makes classical bulges and ellipticals does not need to explain objects that are smaller than the above. More accurately: If the same generic physics (e. g., major mergers) is relevant for smaller objects, it does not have to produce remnants that are consistent with low-mass extrapolations of parameter correlations for classical bulges and ellipticals. One possible reason may be that the progenitors of that physics are very gas-rich.
- (2) Our understanding that, below the above limits, lower-mass bulges are essentially all pseudo makes it harder to understand how galaxy formation by hierarchical clustering of CDM makes so many giant, classical-bulge-less (i. e., pure-disk) galaxies. This was the theme of the observational papers Kormendy et al. (2010) and Fisher & Drory (2011). It is addressed in Brooks & Christensen (2015). We return to this issue in Section 4.
- (3) Understanding how supermassive black holes (BHs) affect galaxy evolution requires an understanding that classical and pseudo bulges are different. Classical bulges participate in the correlations between BH mass and bulge luminosity, stellar mass, and velocity dispersion. Pseudobulges essentially do not. This is some of the evidence that BHs coevolve with classical bulges and ellipticals in ways to be determined, whereas BHs exist in but do not influence the evolution of disks or of disk-grown pseudobulges. We return to this subject in Section 6.

3 Giant Clumps in High-z Gas-Rich Disks Make Classical Bulges

The second major advance in our picture of bulge formation involves the observation that many high- z disks are very gas-rich and dominated by $10^8 - 10^9 M_\odot$, kpc-size star-forming clumps (Elmegreen et al. 2005, 2007, 2009a, b; Bournaud et al. 2007; Genzel et al. 2006, 2008, 2011; Förster Schreiber et al. 2009, 2011a, b; Tacconi et al. 2010). These galaxies evidently accrete cold gas so rapidly that they become violently unstable. Bulgeless disks tend to have small epicyclic frequencies κ . If the surface density Σ rapidly grows large and is dominated by gas with low velocity dispersion σ , then the Toomre (1964) instability parameter $Q = 0.30\sigma\kappa/G\Sigma \lesssim 1$ ($G =$ gravitational constant). The observed clumps are interpreted to be the result. Theory and simulations suggest that the clumps sink rapidly toward the center by dynamical friction. They also dump large amounts of additional cold gas toward the center via tidal torques. The result is violent relaxation plus a starburst that produces a classical bulge. Many papers discuss this evolution (e. g., Dekel, Sari, & Ceverino 2009; Ceverino, Dekel, & Bournaud 2010; Cacciato, Dekel, & Genel 2012; Forbes et al. 2014; Ceverino et al. 2015). Bournaud (2015) reviews this subject in the present book. I include it here for two reasons, it is a major advance, so it deserves emphasis in this concluding chapter, and I want to add two science points:

Figure 1 illustrates my first point: *Evolution by clump sinking, inward gas transport, violent relaxation, and starbursts proceeds much as it does in our picture of wet major mergers. That is, in practice (if not in its beginnings), classical bulge formation from clump instabilities is a variant of our standard picture of bulge formation in wet major mergers.* The process starts differently than galaxy mergers –

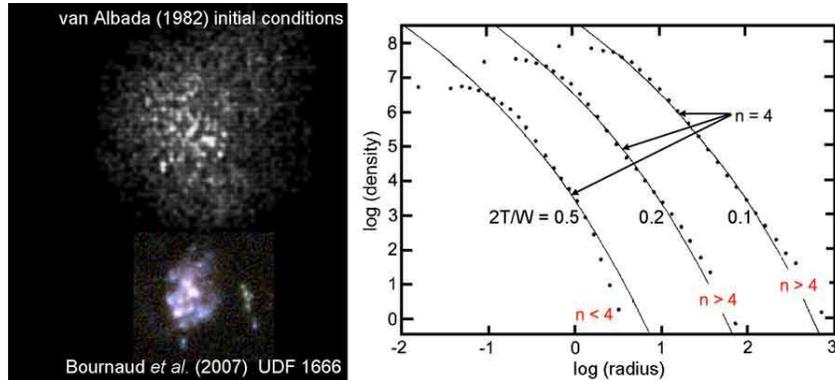


Fig. 1 Mergers of clumpy initial conditions make Sérsic (1968) function remnants with indices $n \sim 2-4$. A remarkably early illustration is the n -body simulation of van Albada (1982), whose initial conditions (grayscale densities) resemble the clumpy high- z galaxy UDF 1666 studied by Bournaud et al. (2007). Van Albada's initial conditions were parameterized by the ratio of twice the total kinetic energy to the negative of the potential energy. In equilibrium, $2T/W = 1$. For smaller values, gentle collapses ($2T/W = 0.5$) make Sérsic profiles with $n < 4$. Violent collapses ($2T/W \lesssim 0.2$) make $n \gtrsim 4$. Clump sinking in high- z disks is inherently gentle. The hint is that the clumps merge to make classical bulges with $n < 4$. This figure is from Kormendy (2012).

what merges here are not finished galaxies but rather are clumps that formed quickly and temporarily in unstable disks. Nevertheless, what follows – although two- and not three-dimensional – is otherwise closely similar to a wet merger with gas inflow and a starburst. That is, it is a slower, gentler version of Arp 220.

Early models by Elmegreen et al. (2008) confirm that gas-rich galaxy disks violently form clumps like those observed. The clumps quickly sink, merge, and make a high-Sérsic-index, vertically thick bulge. It rotates slowly, and rotation velocities decrease with increasing distance above and below the disk plane. These are properties of classical bulges, and Elmegreen and collaborators conclude that this process indeed makes classical (not pseudo) bulges. Many of the later papers summarized above and reviewed by Bournaud (2015) reach similar conclusions.

However, Bournaud (2015) goes on to review more recent simulations that – among other improvements – include strong feedback from young stars. The results complicate the above picture. For example, Genel et al. (2012) find that “galactic winds are critical for [clump] evolution. The giant clumps we obtain are short-lived and are disrupted by wind-driven mass loss. They do not virialize or migrate to the galaxy centers as suggested in recent work neglecting strong winds.” Other simulations produce pseudobulge-like, small Sérsic indices. Some results are inherently robust, such as the conclusion that gas-rich, violently unstable disks at high z gradually evolve into gas-poor, secularly evolving disks at lower redshifts (Cacciato, Dekel, & Genel 2012; cf. Ceverino, Dekel, & Bournaud 2010). However, the conclusions from the models are substantially more uncertain than the inferences from the observations. This is part of a problem that I emphasize in the next section:

Simulations of baryonic galaxy evolution inside CDM halos formed via n -body simulations of cosmological hierarchical clustering are making rapid progress as the baryonic physics gets implemented in better detail. But these simulations still show clearcut signs of missing important physics. In contrast, practitioners of this art who carefully put great effort into improving the physics tend to be overconfident about its results. We are – I will suggest – still in a situation where robust observational conclusions that are theoretically squishy are more trustworthy than conclusions based on state-of-the-art simulations, at least when baryonic physics is involved.

Another caveat is the observation that the clumps in high- z disks are much less obvious in the inferred mass distributions than they are in rest-frame optical or blue light (Wuyts et al. 2012). Frontier observations have opened up a popular new window on the formation of classical bulges, but its importance is not entirely clear.

In the present subject of bulge formation, it seems provisionally plausible that formation via high- z disk instabilities and consequent clump sinking represents a significant new channel in the formation of classical bulges. Meanwhile, a large body of work from the 1980s and 1990s continues to tell us that major galaxy mergers make classical bulges, too. Can we distinguish the results of the two processes? We do not yet know, but my second point is that Figure 1 provides a hint: Although results are still vulnerable to unknown details in (for example) feedback, it seems likely that the classical bulges produced by sinking clumps have Sérsic indices that are systematically smaller than those made by major galaxy mergers. This is one aspect of many that deserves further work. See also point (8) in Section 8.

4 Making Classical Bulges and Ellipticals by Major Mergers

Brooks & Christensen (2015) is perhaps the most important chapter in this book. The mainstream of theoretical work on galaxy formation has come to be the simulation in a cosmological context first of purely collisionless CDM but now with gloriously messy baryonic physics included. Progress is impressively rapid, but we are far from finished. This subject is well reviewed from the perspective of its practitioners by Brooks and Christensen. This includes a discussion of uncertainties and shortcomings in the models, again as seen by theorists. As an observer, I have a complementary perspective on which measurements of galaxies provide the most useful constraints on and “targets” for formation models. It gives me the feeling that modelers are at least partly “barking up the wrong tree.” This section complements Brooks and Christensen (2015) by reviewing these observations.

Pseudobulge formation was covered in Section 2. Here, I focus on the formation of classical bulges and ellipticals. My discussion uses the observations that classical bulges are essentially indistinguishable from coreless-disky-rotating ellipticals (see, e. g., Figure 4). The inference is that they formed in closely related ways.

4.1 Observer’s Perspective on Bulge Formation Via Major Mergers

I begin with giant ellipticals and classical bulges: their structure and formation are understood in the most detail. Classical bulges are identified by the criteria listed in Kormendy & Kennicutt (2004), Kormendy (2012), KH13, Fisher & Drory (2015), and Section 2 here. I know no observational reason to seriously doubt our understanding of bulges with $B/T \gtrsim 0.8$. Then, as B/T drops to $\lesssim 1/2$, the situation gets less clear. Our formation picture may still essentially be correct, but it gets less directly based on observations as B/T or bulge luminosity decreases. Meanwhile, the theoretical problem is that simulations make too many bulges, especially big ones. In this section, I review things that we know and outline things that we do not know. It is critically important to start with a discussion of ellipticals, because our understanding of classical bulges must be within this context.

4.1.1 Observed Properties of Ellipticals: Clues to Their Formation

The observed properties of elliptical galaxies are reproduced by simulations of wet and dry mergers in remarkable detail. These are not embedded in large-scale cosmological simulations, but this is not a fundamental fault if the initial conditions are realistic – galaxies with typical $z \sim 0$ gas fractions and encounter velocities that are roughly parabolic. Kormendy et al. (2009, hereafter KFCB) provide an ARA&A-style review and develop some of the evidence. Hopkins et al. (2009a and 2009b) provide the most detailed models for wet and dry mergers, respectively. These papers are comprehensive; a concise summary of the “E – E dichotomy” in Kormendy (2009) is updated below. The critical observation is that ellipticals come in two varieties and that bulges are similar to one (but not both) of these varieties.

The E–E dichotomy of ellipticals into two kinds is based on these observations:

Giant ellipticals ($M_V \lesssim -21.5 \pm 1$ for $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$) generally

- (1) have Sérsic function outer profiles with $n > 4$;
- (2) have cores; i. e., central missing light with respect to the outer Sérsic profile;
- (3) rotate slowly, so rotation is of little importance dynamically; hence
- (4) are anisotropic and modestly triaxial;
- (5) are less flattened (ellipticity $\varepsilon \sim 0.2$) than smaller ellipticals;
- (6) have boxy-distorted isophotes;
- (7) mostly are made of very old stars that are enhanced in α elements (Figure 2);
- (8) often contain strong radio sources (Figure 3), and
- (9) contain X-ray-emitting gas, more of it in more luminous galaxies (Figure 3).

Normal ellipticals and dwarf ellipticals like M 32 ($M_V \gtrsim -21.5$) generally

- (1) have Sérsic function outer profiles with $n \simeq 2$ to 3;
- (2) are coreless – have central extra light with respect to the outer Sérsic profile;
- (3) rotate rapidly, so rotation is dynamically important to their structure;
- (4) are nearly isotropic and oblate spheroidal, albeit with small axial dispersions;
- (5) are flatter than giant ellipticals (ellipticity $\varepsilon \sim 0.35$);
- (6) have disky-distorted isophotes;
- (7) are made of younger stars with little α -element enhancement (Figure 2);
- (8) rarely contain strong radio sources (Figure 3), and
- (9) generally do not contain X-ray-emitting gas (Figure 3).

These results are established in many papers (e. g., Davies et al. 1983; Bender 1988; Bender et al. 1989; Nieto et al. 1991; Kormendy et al. 1994; Lauer et al. 1995, 2005, 2007a, b; Kormendy & Bender 1996; Tremblay & Merritt 1996; Gebhardt et al. 1996; Faber et al. 1997; Rest et al. 2001; Ravindranath et al. 2001; Thomas et al. 2002a, b, 2005; Emsellem et al. 2007, 2011; Cappellari et al. 2007, 2011, 2013b; KFCB; Kuntschner et al. 2010). A few ellipticals are exceptions to one or more of (1) – (9). The above summary is quoted from Kormendy (2009).

Why is this relevant here? The answer is that classical bulges are closely similar to coreless-disky-rotating ellipticals. No bulge is similar to a core-boxy-nonrotating elliptical as far as I know. This is a clue to formation processes. First, though, we need to understand the difference between the two kinds of ellipticals:

How did the E–E dichotomy arise? The “smoking gun” for an explanation is a new aspect of the dichotomy originally found in Kormendy (1999) and observed in all low-luminosity ellipticals in the Virgo cluster by KFCB. Coreless galaxies do not have featureless power-law profiles. Rather, all coreless galaxies in the KFCB sample show a new structural component, i. e., central extra light above the inward extrapolation of the outer Sérsic profile. Kormendy (1999) suggested that the extra light is produced by starbursts fed by gas dumped inward during dissipative mergers. Starbursts were predicted by merger simulations as soon as these included gas, dissipational gas inflow, and star formation (Mihos & Hernquist 1994). Mihos and Hernquist were concerned that extra components had not been observed. The reason turns out to be that we had not measured ellipticals with enough surface brightness range and spatial resolution. Like Faber et al. (1997, 2007), KFCB suggest that the

origin of the E–E dichotomy is that core ellipticals formed in dry mergers whereas coreless ellipticals formed in wet mergers. Simulations of dry and wet mergers reproduce the structural properties of core and extra light ellipticals in beautiful detail (Hopkins et al. 2009a, b). And, although the formations scenarios differ, Khochfar et al. (2011) similarly conclude that the difference between fast and slow rotators is related to cold gas dissipation and star-formations shutdown, respectively.

Cores are thought to be scoured by supermassive black hole binaries that were formed in major mergers. The orbit shrinks as the binary flings stars away. This decreases the surface brightness and excavates a core (Begelman et al. 1980; Ebisuzaki et al. 1991; Makino & Ebisuzaki 1996; Quinlan & Hernquist 1997; Faber et al. 1997; Milosavljević & Merritt 2001; Milosavljević et al. 2002; Merritt 2006). The same process should happen during wet mergers; in fact, gas accelerates the orbital decay (Ivanov, Papaloizou, & Polnarev 1999; Gould & Rix 2000; Armitage & Natarajan 2002, 2005; Escala et al. 2004, 2005; Dotti et al. 2007; Hayasaki 2009; Cuadra et al. 2009; Escala & Del Valle 2011; see Mayer 2013 for a recent review). However, we observe that the fraction of the luminosity that is in extra light in low-luminosity ellipticals is larger than the fraction of the light that is “missing” in the cores of high-luminosity ellipticals. KFCB suggest that core scouring is swamped by the starburst that makes the extra light in coreless-disky-rotating ellipticals.

When did the E–E dichotomy arise? Figure 2 shows observation (7) that core ellipticals mostly are made of old stars that are enhanced in α elements. In contrast, coreless ellipticals are made of younger stars with more nearly solar compositions. This means (Thomas et al. 2002a, b, 2005) that the stars in core Es formed in the first few billion years of the universe and over a period of $\lesssim 1$ Gyr, so quickly that Type I supernovae did not have time to dilute with Fe the α -enriched gas recycled

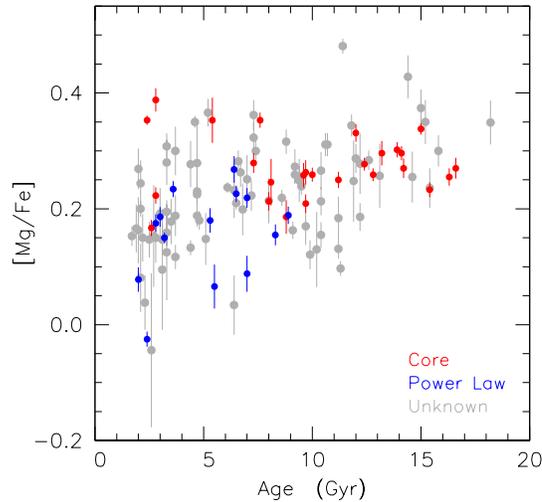


Fig. 2 Alpha element overabundance (log solar units) versus relative age of the stellar population. Red and blue points denote core and “power law” (i. e., coreless) ellipticals. The $[Mg/Fe]$ and age data are from Thomas et al. (2005); this figure is from KFCB.

by Type II supernovae. This does not mean that core ellipticals were made at the same time as their stars. Mass assembly via dry mergers as required to explain their structure could have happened at any time after star formation stopped. Our problem is to explain how star formation was quenched so quickly and not allowed to recur. In contrast, coreless ellipticals have younger, less- α -enhanced stellar populations. They are consistent with a simple picture in which a series of wet mergers with accompanying starbursts formed their stellar populations and assembled the galaxies more-or-less simultaneously over the past 9 billion years. Faber et al. (2007) discuss these issues in detail. A big problem with the present state of the art is that we know so little about mergers and merger progenitors at high z .

Why did the E–E dichotomy arise? The key observations are: (8) core-boxy ellipticals often are radio-loud whereas coreless-disky ellipticals are not, and (9) core-boxy ellipticals contain X-ray gas whereas coreless-disky ellipticals do not (Bender et al. 1989). Figure 3 (from KH13) illustrates these results. KFCB suggest that the hot gas keeps dry mergers dry and protects giant ellipticals from late star formation. This is the operational solution to the above “maintenance problem”. I return to the problem of star-formation quenching in Section 7.

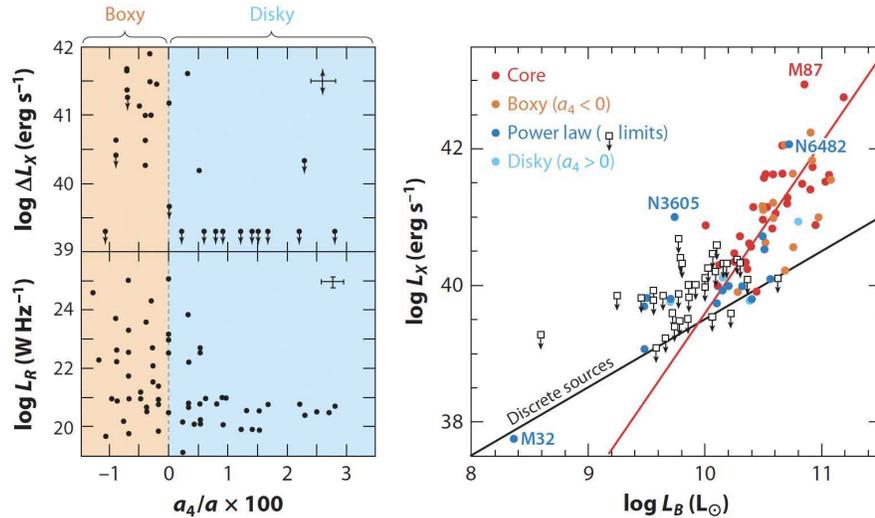


Fig. 3 (Left) Correlation with isophote shape parameter a_4 of (top) X-ray emission from hot gas and (bottom) radio emission (from Bender et al. 1989). Boxy ellipticals ($a_4 < 0$) contain hot gas and strong radio sources; disk ellipticals ($a_4 > 0$) generally do not. (Right) KFCB update of the X-ray correlation. Detections are color-coded according to the E–E dichotomy. The emission from X-ray binary stars is estimated by the black line (O’Sullivan, Forbes, & Ponman 2001); this was subtracted from the total emission in constructing the left panels. The red line is a bisector fit to the core-boxy-nonrotating ellipticals. They statistically reach $L_X = 0$ from hot gas at $\log L_B \simeq 9.4$. This corresponds to $M_V \simeq -20.4$, a factor of 2 fainter than the luminosity that divides the two kinds of ellipticals. Thus, if a typical core E was made in a merger of two equal-mass galaxies, then both were marginally big enough to contain X-ray gas and the remnant immediately was massive enough so that hot gas could quench star formation. KFCB suggest that this is why these mergers were dry. For similar results, see Pellegrini (1999, 2005) and Ellis & O’Sullivan (2006).

In the above story, the challenge is to keep the hot gas hot, given that X-ray gas cooling times are short (Fabian 1994). KFCB review evidence that the main heating mechanism may be energy feedback from accreting BHs (the active galactic nuclei [AGNs] of observation 8); these may also have helped to quench star formation. Many details of this picture require work (Cattaneo et al. 2009). Cosmological gas infall is an additional heating mechanism (Dekel & Birnboim 2006). Still, Figure 3 is a crucial connection between X-ray gas, AGN physics, and the E–E dichotomy.

“**Bottom line:**” In essence, only giant, core ellipticals and their progenitors are massive enough to contain hot gas that helps to engineer the E–E dichotomy.

4.1.2 Classical Bulges Resemble Coreless-Diskv-Rotating Ellipticals

Are both kinds of ellipticals also found as bulges? So far, observations indicate that the answer is “no”. Classical bulges closely resemble only the coreless-disky-rotating ellipticals. There are apparent exceptions in the literature, but all the exceptions that I know about are classification errors brought about (e. g.) by the very large Sérsic indices of some core galaxies (see KFCB Table 1 for examples and KFCB Section 5.2 for discussion). This comment also does not include ellipticals with nuclear disks. All signs are that these involve different physics, so these really are ellipticals, not S0 bulges.

There is physics in this conclusion. The X-ray gas prevents cooling and dissipation during any subsequent mergers or any $z \lesssim 1$ cold accretion. Plausibly, it should also prevent there from being any cold gas left over to make a new disk after a merger is complete. Further checks, both of the observational conclusion and of the theoretical inference, should be made.

4.1.3 The Critically Important Target for Galaxy Formation

The most fundamental distinction between galaxy types is the one between bulges + ellipticals and disks. Bulges and disks overlap over a factor of about ~ 1500 in luminosity and mass (Figure 4), but over that entire overlap range, they are dramatically different from each other. This includes differences in specific angular momentum (Romanowsky & Fall 2012; Fall & Romanowsky 2013), in orbit structure, in flattening, and in radial density profiles (disks are roughly exponential; coreless-disky-rotating ellipticals have $n \gtrsim 2$). At absolute magnitude $M_V \simeq -16.7$ and outer circular-orbit rotation velocity $V_{\text{circ}} \sim 85 \text{ km s}^{-1}$, M 32 is a normal small elliptical galaxy (KFCB). At $M_V \simeq -21.6$ and $V_{\text{circ}} = 210 \pm 15 \text{ km s}^{-1}$, M 101 is almost 100 times more luminous but is thoroughly different from M 32 (Kormendy et al. 2010).

I believe that the goal of galaxy formation modeling should be to produce realistic disks and realistic ellipticals that overlap over the observed factor of ~ 1500 in luminosity but that differ as we observe them to differ over the whole of that range. And over the whole of that range, disks and bulges can be combined with B/T and $D/T \simeq 1 - B/T$ ratios that have the observed distribution (i. e., $B/T \sim 1$ near the upper end of the range, but it can be $\ll 1$ at the bottom of the range). The properties of individual disks and bulges are essentially independent of B/T with structural parameters shown in Figure 4.

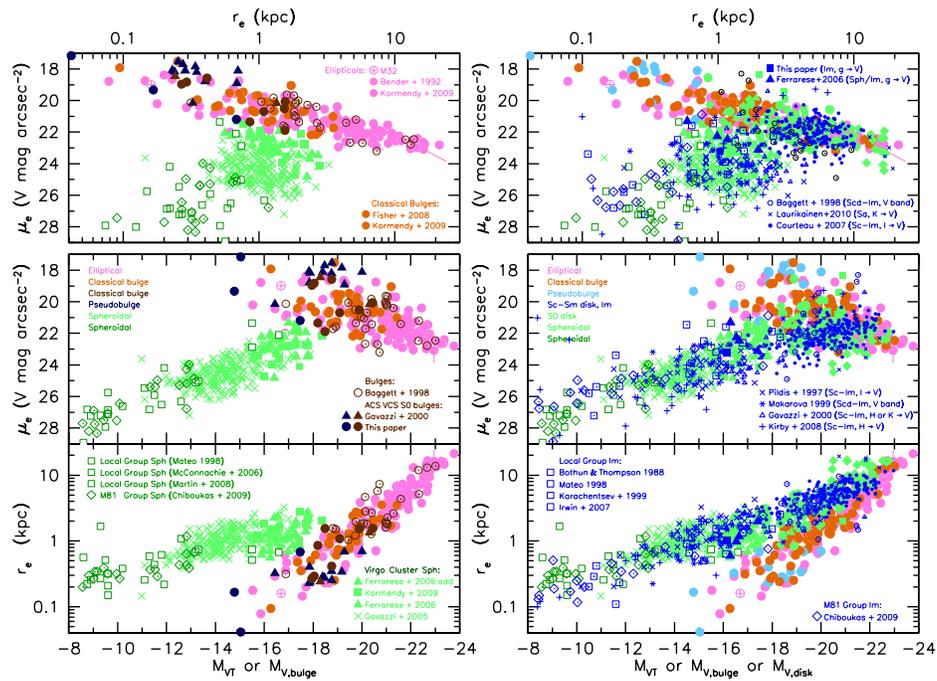


Fig. 4 Correlations between effective radius r_e , effective brightness μ_V , and absolute magnitude M_V for classical bulges and ellipticals (brown and pink points), for spheroidal (Sph) galaxies and S0 disks (green points), and for spiral galaxy disks (blue points). When bulge-disk decomposition is necessary, the two components are plotted separately. Bulges and disks overlap from $M_V \simeq -15$ to $M_V \simeq -23$, i. e., over a factor of about 1500. The left panel shows (1) that Sph galaxies are distinct from bulges + ellipticals and (2) that classical bulges and ellipticals satisfy the same structural parameter correlations. The right panel adds S0 and S galaxy disks. It shows that all disks satisfy the same structural parameter correlations over the whole range of luminosities. Note that disks and ellipticals have similar r_e and μ_e at the highest luminosities, but they have very different Sérsic indices (~ 1 and 2 to > 10 , respectively). As a result, the central surface brightnesses in bulges and ellipticals are more than an order of magnitude higher than the central surface brightnesses of disks (Kormendy 1985, 1987). Bulges + ellipticals and disks also have non-overlapping distributions of intrinsic flattening (e. g., Sandage, Freeman, & Stokes 1970). From Kormendy & Bender (2012),

Of course, bulges and disks are not different in *every* parameter; e. g., the $r_e - \mu_e$ correlations overlap at high luminosities (Figure 4). This makes sense: At the highest masses, it does not require much dissipation to turn a disk into an elliptical, at least in terms of virial parameters. All that is required is to scramble disk orbits into an ellipsoidal remnant. A larger amount of dissipation is required to make the high-density centers, and in *central* parameters and parameter correlations, disks and bulges + ellipticals are very different (Kormendy 1985, 1987).

4.1.4 Critical Observational Clue: The Problem of Giant, Pure-Disk Galaxies Depends on Environment, Not on Galaxy Mass

The most difficult challenge in our picture of galaxy formation – I suggest – is to understand how hierarchical clustering produces so many giant, pure-disk galaxies that have no sign of a classical bulge. CDM halos grow by merging; fragments arrive from all directions, and not all fragments are small. There are two parts to this problem: (1) It is difficult to understand how cold, flat disks survive the violence inherent in the mergers that grow DM halos. And (2) it is difficult to prevent the stars that arrive with the latest accretion victim from adding to a classical bulge that formed in (1) from the scrambled-up disk.

Brooks & Christensen (2015) review how the modeling community tries to solve this problem. In spite of several decades of evidence that mergers make bulges, they do not use mergers to turn disks into bulges. Instead, they use feedback from young stars and active galactic nuclei to “whittle away” the low-angular-momentum part of the distribution of gas angular momenta and argue that this prevents bulge formation. And they use feedback to delay disk formation until the halo is assembled. Feedback is likely to be important in the formation of dwarf galaxies (Governato et al. 2010), and indeed, they essentially never have bulges (e. g., Kormendy & Freeman 2015, Figure 10).

However, it is difficult for me to believe that feedback, either from star formation or from AGNs, is responsible for the difference between bulges and disks. Feedback is fundamentally an internal process that is controlled by the galaxy’s potential well depth. It is not clear how *only* tweaking the feedback can make a small elliptical like M 32 (different from small disks) and a giant disk like M 101 (different from similarly giant ellipticals) with no intermediate cases. Bulge-to-total ratios vary widely, but classical bulges are always like ellipticals no matter what the B/T ratio, and disks are always different from ellipticals no matter what the D/T ratio. Observations do not suggest that it is primarily feedback that results in this difference. Rather:

There is a fundamental observational clue that modelers are not using:

Whether evolution makes disks or whether it makes bulges does not depend mainly on galaxy mass. Rather, it is a strong function of environment. Kormendy et al. (2010) show that, in the extreme field (i. e., in environments like the Local Group), most giant galaxies ($V_{\text{circ}} \geq 150 \text{ km s}^{-1}$) are pure disks. Only 2 of 19 giant galaxies closer to us than 8 Mpc have B/T as big as 1/3.

Only 2 more are ellipticals. A few have smaller classical bulges, but 11 of the 19 galaxies have essentially no classical bulge. In contrast, $> 2/3$ of all stars in the Virgo cluster live in bulges or elliptical galaxies. *There is no problem of understanding giant pure-disk galaxies in the Virgo cluster.* It is a mature, dense environment that contains large amounts of X-ray-emitting, hot gas. Rich clusters are places where most of the baryons live suspended in hot gas (e. g., Kravtsov & Borgani 2012). I argue in Section 4.1.1 that various heating processes maintain this situation for very long times. In contrast, poor groups are environments in which accretion of cold gas from the cosmic web can dominate, as long as the galaxies involved – i. e., the aforementioned pure disks – are low enough in mass so that they cannot hold onto X-ray gas.

As long as this environmental dependence is not a primary, essential part of the explanation, I believe that attempts to solve the problem of overproduction of bulges in Λ CDM cosmology are “barking up the wrong tree”.

Why can't we use feedback to delay star formation until the halo is assembled? As reviewed by Brooks & Christensen (2015), this is commonly suggested. The counterexample is our Galaxy: The oldest stars in the thin disk are $\sim 10^{10}$ yr old, so much of the growth of our Galaxy happened when the thin disk was already in place (Kormendy et al. 2010, p. 73).

4.1.5 It is not a problem that major mergers are rare

The prevailing theoretical paradigm is more and more converging on the view that major mergers are rare – are, in fact, almost irrelevant – and that, instead, minor mergers make both bulges and ellipticals (see Naab 2013 for a review), even some core-boxy-nonrotating ellipticals (Naab et al. 2014). It will be clear from this writeup that, based on observational evidence, I agree that major mergers are rare. But I disagree that they are unimportant in the formation of bulges and ellipticals.

The above papers make important points that are robust. They argue convincingly that major mergers are rare – that only a small fraction of galaxies undergo several of them in their recent history (say, since $z \sim 2$). And many authors argue that most star formation does not occur during mergers; rather, it occurs in a “main sequence” of disks of various masses, with higher star formation rates at higher masses (e. g., Schiminovich et al. 2007; Noeske et al. 2007; Elbaz et al. 2007; Daddi et al. 2007; Finlator & Davé 2008; Karim et al. 2011; Peng et al. 2010; Rodighiero et al. 2011; Wuyts et al. 2011; Salmi et al. 2012; Whitaker et al. 2012; Tacconi et al. 2013; Speagle et al. 2014). These authors conclude that the duty cycle of star formation is large. Therefore most star formation does not occur in rare events. I made the same argument in Section 2: If almost all galaxies of a particular type are energetically forming stars, then star formation must be secular; it cannot be episodic with short duty cycles. Caveat: the star formation that is associated with mergers is not instantaneous. Puech et al. (2014) argue that merger-induced star formation

is significant. Are these results consistent with a picture in which essentially all formation of classical bulges and ellipticals happens via major mergers?

I believe that the answer is yes, although the details need further work. Elliptical galaxies are observed to be rare; the morphology-density relation (Dressler 1980; Cappellari et al. 2011) shows that they are a small fraction of all galaxies except in rich clusters. Classical bulges are rarer than we thought, too; this is a clear conclusion of the work on disk secular evolution. *Therefore the events that make bulges must be rare.* It is also not a problem if most star formation happens in disks. For example, only a small fraction of the galaxy mass is contained in the extra light components that are identified by KFCB and by Hopkins (2009a) as the parts of coreless/disky/rotating ellipticals that formed in the most recent ULIRG-like starburst (e.g., Genzel et al. 2001). Most of the mass was already in stars before these late, wet mergers. And in dry mergers, essentially all the mass was already in stars (or in X-ray gas that stays X-ray gas) and essentially no new stars are formed.

How many mergers do we need to explain elliptical galaxies? Toomre (1977) already pointed out that a reasonable increase in merger rate with increasing z would suffice. He based this on ten mergers-in-progress that he discussed in his paper. He assumed that such objects are identifiable for \sim half a billion years. Then, if the number of mergers in progress increased as (lookback time)^{5/3} consistent with a flat distribution of binding energies for galaxy pairs, the result is that the number of remnants is consistent with the number of elliptical and early-type disk galaxies. This estimate was made for the level of completeness of the Second Reference Catalogue of Bright Galaxies (de Vaucouleurs, de Vaucouleurs, & Corwin 1976).

Conselice (2014) reviews observational estimates of how merger rates depend on z . As Toomre predicted, the major merger rate is inferred – e.g., from counting close pairs of galaxies – to increase rapidly with z . Observations of high- z galaxies show that close binary fractions increase roughly as $(1+z)^m$ with $m \sim 2$ to 3 (e.g., Bluck et al. 2009, 2012; Conselice et al. 2009; López-Sanjuan et al. 2013; Tasca et al. 2014). ULIRGs increase in comoving energy density even faster toward higher redshift, at least out to $z = 1$ (Le Floch et al. 2005). The necessary connections between these results to establish or disprove whether bulges + ellipticals are made via major mergers have not been established. Important uncertainties include (1) the low-mass end of the mass functions for ellipticals and especially for classical bulges, and (2) the degree to which mass-clump sinking in disks contributes. However, the above results on merger frequencies appear at least qualitatively consistent with the conclusion that bulges and ellipticals are made in major mergers, as the pre-2000 history of observational work established (see Schweizer 1998 for a review).

A shortcoming of many current investigations is that they concentrate on a few parameter distributions for large galaxy samples and not specifically on the histories of bulges and disks. E.g., they look at the statistics of what fraction of galaxies experience mergers. Outcomes are difficult to estimate, because with samples of 10^4 to 10^5 $z \sim 0$ galaxies or 10^2 high- z galaxies, the typical galaxy is only a few pixels in radius. Then it is difficult to identify and classify galaxy components.

4.1.6 Uncertainties With Our Picture of Bulge Formation in Major Mergers

Two major uncertainties are a concern (see also Brooks & Christensen 2015). Virtually all observational evidence on mergers-in-progress (e. g., Toomre 1977; Joseph & Wright 1985; Sanders et al. 1988a, b; Hibbard et al. 1994, 1995, 1996, 2001a, b; see Schweizer 1987, 1990, 1998 for reviews) involves giant galaxies. And the detailed evidence is for $z \sim 0$ galaxies with gas fractions of a few to $\sim 10\%$. (1) We do not have comparable evidence for dwarfs. That is, we have not studied a sample of dwarfs that fill out a merger sequence from close pairs to mergers engaged in violent relaxation to train wrecks that are still settling down to mature objects. And (2) we do not have comparably detailed studies of galaxies at high z that have gas fractions $\gtrsim 50\%$. It is possible that mergers behave differently for such objects.

4.1.7 The Problem of Giant, Pure-Disk Galaxies: Conclusion

My most important suggestion in this section is that the modeling community relies too strongly on feedback as the only way to prune excessive bulge formation. On the contrary, I suggest that environmental differences in the amount of dynamical violence in galaxy formation histories are the central factor. I suggest that the solution is not a to whittle away the low-angular-momentum tail of the distribution of angular momenta in forming galaxies. Nearby galaxies dramatically show us the importance of violent relaxation. To me, the issue is: How much does violent relaxation dominate? How much is the evolution controlled by gentle accretion? And how do the answers depend on environment?

5 Universal Scaling Relations For All Galaxies?

How we best construct parameter correlations depends on what we want to learn. Projections of the fundamental plane correlations *separate* galaxy classes; e. g., bulges+ellipticals from disks+Sphs (Figure 4). So they teach us about differences in formation processes. In contrast, it is possible to construct parameter correlations that make most or all galaxy types look continuous. *These encode less information about galaxy formation*. E. g., in a projection of the structural parameter correlations that encodes mass-to-light ratio, the difference between ellipticals, spheroidals, and even irregulars largely disappears (Bender, Burstein, & Faber 1992). Zaritsky (2015) regards this as progress – as replacing correlations that are flawed with ones that capture some inherent simplicity. That simplicity is real. But it is insensitive to the power that other correlations clearly have to tell us things about galaxy formation.

I therefore disagree, not with Zaritsky’s operational results but with his motives. If you look at the fundamental plane face-on, it contains lots of information. If you look at it edge-on, then it looks simple. This may feel like a discovery. But it just means that you are looking at a projection that hides the information content in the parameter plane. Other combinations of parameters make still more types of objects look continuous and indistinguishable. But this means that we learn still less, not more, about their nature and origin. The simple correlations are not uninteresting, but the ones that teach us the most are the ones that correctly identify differences that turn out to have causes within formation physics.

6 Coevolution of Supermassive Black Holes and Host Galaxies

The observed demographics of supermassive black holes (BHs) and their implications for the coevolution (or not) of BHs and host galaxies are discussed in Kormendy & Ho (2013). This is a 143-page ARA&A review that revisits methods used to measure BH masses M_{\bullet} using spatially resolved stellar and gas dynamics. It also provides a detailed analysis of host galaxy morphologies and properties. Careful treatment of the M_{\bullet} and galaxy measurements allows Kormendy and Ho to reach a number of new science conclusions. They are summarized in this section.

Graham (2015) reviews the same subject in the present book. Some of his review is historical, especially up to the beginning of his Section 4.1 but also sporadically thereafter. I do not comment here on the historical review. However, on the science, I cannot “duck” my responsibility as author of this concluding chapter:

I disagree with most of the scientific conclusions in Graham (2015). Starting in his Section 4.1, his discussion uses data and repeats conclusions from Graham & Scott (2013, 2015). Problems with the 2013 data are listed in KH13 (p.555); a point made there that is not repeated further here is that many of Graham’s galaxy classifications are incorrect. Here, rather than write a point-by-point rebuttal to Graham (2015), I first concentrate on a summary of the unique strengths of the KH13 analysis and data. However, a few comments are added to further explain the origin of the disagreements with Graham (2015). I then summarize the KH13 results and conclusions about M_{\bullet} – host-galaxy correlations (Sections 6.1 and 6.2).

Before I begin, a comment is in order about how readers react to disagreements in the literature. The most common reaction is that the subject needs more work. Specialists may know enough to decide who is correct. But the clientele community of non-specialists who mainly want to use the results often do not delve into the details deeply enough to decide who is correct. Rather, their reaction is that this subject needs further work until everybody agrees that the disagreement is resolved. Sometimes, this is an appropriate reaction, when the issues are more complicated than our understanding of the physics, or when measurements are still too difficult, or when results under debate have low significance compared to statistical errors or systematic effects. My reading of the community is that reactions to disagreements on BH demographics take this form.

However, I suggest that we already know enough to decide who is correct in the disagreement between KH13 and Graham (2015). Our ARA&A review and the Graham & Scott papers both provide enough detail to judge the data and the analysis. It is particularly important to note how these separate discussions do or do not connect up with a wide body of results in other published work, including other chapters in this book. A strength of the Kormendy & Ho analysis is that it connects up with – i. e., it uses and it has implications for – a wide variety of aspects of galaxy formation.

Strengths of the data and supporting science that are used by KH13 include the following. Some of these points are discussed more fully in the Supplemental Material of KH13.

- (1) BH masses based on absorption-line spectroscopy are now derived by including halo dark matter in the stellar dynamical models. This generally leads to an upward revision in M_{\bullet} by a factor that can be $\gtrsim 2$ for core galaxies. Kormendy and Ho use these masses. For some galaxies (e. g., M 87), Graham uses them; for other galaxies (e. g., NGC 821, NGC 3377, NGC 3608, NGC 4291, NGC 5845), he does not, even though such masses are published (Schulze & Gebhardt 2011).
- (2) Kormendy and Ho include new M_{\bullet} determinations for mostly high-mass galaxies from Rusli et al. (2013). Graham & Scott (2013) did not include these galaxies. It is not clear whether they are included in Graham (2015), but observation that the highest M_{\bullet} values plotted in his Figure 4 are $\sim 6 \times 10^9 M_{\odot}$ and not $> 10^{10} M_{\odot}$ suggests that they are not included, at least in this figure.
- (3) BH masses derived from emission-line gas rotation curves are used without correction when the emission lines are narrow. However, when the emission lines are wide – often as wide in km s^{-1} as the rotation curve amplitude – some authors have ignored the line widths in the M_{\bullet} determinations. KH13 argue that these BH masses are underestimated and do not use them. Graham (2015) uses them.
- (4) All disk-galaxy hosts have B/T values based on at least one and sometimes as many as six bulge-disk decompositions. Graham & Scott (2013) use a mean statistical correction to derive some bulge magnitudes from total magnitudes.
- (5a) All disk-galaxy hosts have (pseudo)bulge classifications that are based on at least two and as many as five criteria such as those listed here in Section 2.1. Graham (2015) rejects this approach and instead compares BH–host correlations for barred and unbarred galaxies. However, Kormendy and Ho emphasize that some barred galaxies contain classical bulges, whereas many unbarred galaxies contain pseudobulges. If classical and pseudo bulges correlate differently with their BHs (Figure 7), then a division into barred and unbarred galaxies does not cleanly see this. It should be noted that other derivations of BH–host correlations (e. g., the otherwise very good paper by McConnell & Ma 2013), also do not differentiate between classical and pseudo bulges. They compare early and late galaxy types. But many S0s contain pseudobulges, and a few SbcS contain classical bulges (e. g., NGC 4258: Kormendy et al. 2010).
- (5b) The picture of disk secular evolution and the conclusion that pseudobulges are distinguishable from classical bulges is fully integrated into the analysis. Graham (2011, 2015) does not use this picture and argues that classical and pseudo bulges cannot reliably be distinguished. Kormendy & Kennicutt (2004), Kormendy (2012), Kormendy & Ho (2013), Fisher & Drory (2015) in this book, and Section 2 in this summary chapter disagree. The subject is growing rapidly, and whole meetings are devoted to it (e. g., 2012 IAU General Assembly Special Session 3, “Galaxy Evolution Through Secular Processes,” <http://bama.ua.edu/~rbuta/iau-2012-sps3/proceedings.html> and Kormendy 2015; XXIII Canary Islands Winter School, “Secular Evolution of Galaxies”, Falc3n-Barroso & Knapen 2012). Kormendy & Ho make a point of

distinguishing classical and pseudo bulges by purely morphological criteria such as those given in Section 2.1. The fact that we then discover that BHs correlate differently with classical and pseudo bulges is a substantial success of the secular evolution picture.

- (6) KH13 find that the $\log M_{\bullet} - M_{K,\text{bulge}}$, $\log M_{\bullet} - \log \sigma$ and $\log M_{\bullet} - \log M_{\text{bulge}}$ correlations for classical bulges and ellipticals have intrinsic scatter of 0.30, 0.29, and 0.28 dex, respectively. This small scatter is a consequence of the care taken in (1)–(5), above, in implementing a uniform, accurate distance scale based as much as possible on standard candles, in correcting galaxy classifications when detailed photometry reveals errors, and in correcting K -band magnitudes for systematic errors. Given this small scatter, it was possible to discover a new result; i. e., that five sample galaxies that are major mergers in progress deviate from the above correlations in having undermassive BHs for their host size (see Figure 14 in KH13). Having noted this result, the five mergers are omitted from our correlation fits shown below. However, mergers in progress are included in Graham (2015) and in McConnell & Ma (2013).

These procedural differences plus others summarized in KH13 or omitted here for the sake of brevity account for most of the differences in the correlation plots shown in Graham (2015) and those in KH13. Generically, they have the following effects (ones in italics also apply to McConnell & Ma 2013). (1) *At the high- M_{\bullet} end, Graham's BH masses are biased low, because he uses underestimated values from emission-line rotation curves*, because he uses M_{\bullet} values that are not corrected for effects of halo dark matter, and because he does not consistently use the Rusli et al. (2013) high- M_{\bullet} galaxies. (2) At the low- M_{\bullet} end, Graham's BH masses are biased low, because he includes pseudobulges. Differentiating barred and unbarred galaxies is not sufficient to solve this problem. *McConnell and Ma also include pseudobulges, differentiating early- and late-type galaxies helps, although many S0s contain pseudobulges.* (3) Graham regards M 32 as pathological and omits it. KFCB show that it is a normal, tiny elliptical. Including it in KH13 helps to anchor the BH correlations at low BH masses. (4) *The result is that the BH–host correlations have much larger scatter in Graham (2015) and in McConnell & Ma (2013) than they do in KH13 (see Figures 5 and 7 below).* Also, Graham sees a kink in the $\log M_{\bullet} - M_{K,\text{bulge}}$ correlation whereas we do not, and he sees no kink in the $\log M_{\bullet} - \log \sigma$ whereas we see signs of a kink at high σ where M_{\bullet} becomes largely independent of σ . McConnell & Ma (2013) and KH13 agree on the kinks (and lack of kinks) in the M_{\bullet} –host-galaxy correlations.

6.1 Correlations Between BH Mass and Host Galaxy Properties from Kormendy & Ho (2013)

This section summarizes the BH–host-galaxy correlations from KH13.

The procedures summarized above lead in KH13 to Table 2 for 44 elliptical galaxies and Table 3 for 20 classical bulges and 21 pseudobulges. Figure 5 shows the resulting $\log M_\bullet - M_{K,\text{bulge}}$ and $\log M_\bullet - \log \sigma$ correlations for classical bulges and ellipticals. Mergers in progress are omitted as explained above, and three “monster” BHs that deviate above the correlations are illustrated in faint symbols but are omitted from the fits. Also shown are symmetric, least-squares fits (Tremaine et al. 2002) symmetrized around $L_{K,\text{bulge}} = 10^{11} L_{K\odot}$ and $\sigma_e = 200 \text{ km s}^{-1}$:

$$\log\left(\frac{M_\bullet}{10^9 M_\odot}\right) = -(0.265 \pm 0.050) - (0.488 \pm 0.033)(M_{K,\text{bulge}} + 24.21); \quad (1)$$

$$\log\left(\frac{M_\bullet}{10^9 M_\odot}\right) = -(0.509 \pm 0.049) + (4.384 \pm 0.287) \log\left(\frac{\sigma}{200 \text{ km s}^{-1}}\right). \quad (2)$$

Here, we adopt equal errors of $\Delta M_{K,\text{bulge}} = 0.2$ and $\Delta \log M_\bullet = 0.117$, i. e., the mean for all fitted galaxies. Then the intrinsic scatters in Equations (1) and (2) are 0.30 dex and 0.29 dex, respectively. In physically more transparent terms,

$$\frac{M_\bullet}{10^9 M_\odot} = \left(0.544^{+0.067}_{-0.059}\right) \left(\frac{L_{K,\text{bulge}}}{10^{11} L_{K\odot}}\right)^{1.22 \pm 0.08} \quad (3)$$

$$\frac{M_\bullet}{10^9 M_\odot} = \left(0.310^{+0.037}_{-0.033}\right) \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{4.38 \pm 0.29} \quad (4)$$

Both relations have shifted to higher BH masses because of corrections to M_\bullet , because mergers in progress are omitted, and because pseudobulges are postponed.

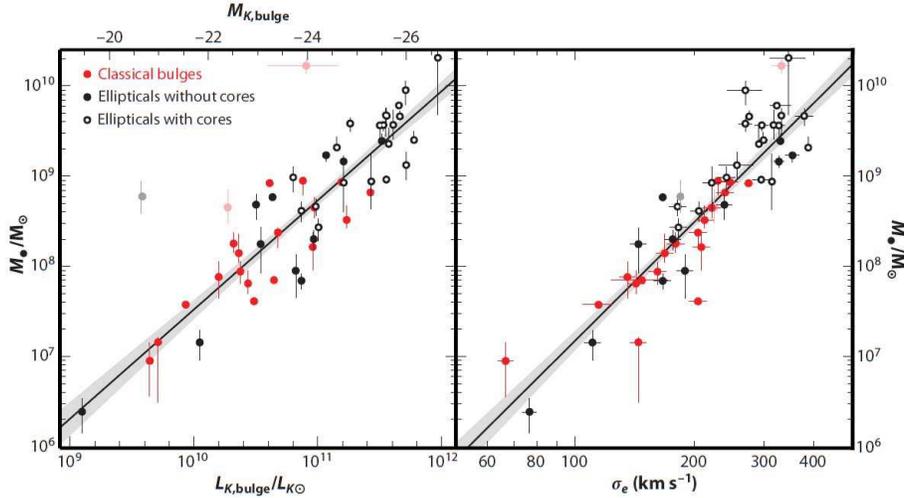


Fig. 5 Correlations of BH mass M_\bullet with the K -band absolute magnitude and luminosity of the host bulge (*left panel*) and with its velocity dispersion at radii where σ_e is unaffected by the BH (*right panel*). Black points are for ellipticals; a white center indicates that this galaxy has a core. Red points are for classical bulges. The lines are Equations (1) and (2). Note: the $M_\bullet - M_{K,\text{bulge}}$ correlation remains log-linear with no kink at high luminosities. In contrast, the biggest BH masses look essentially independent of σ_e in ellipticals that have cores. From KH13.

The $\log M_\bullet - L_{K,\text{bulge}}$ correlation in Figure 5 is converted to a correlation with bulge stellar mass M_{bulge} by applying mass-to-light ratios that were engineered by KH13 to be independent of the papers that determine M_\bullet , to have zeropoints based on the Williams et al. (2009) dynamical models, but also to take variations in stellar population age into account. The resulting mass correlation is:

$$100 \left(\frac{M_\bullet}{M_{\text{bulge}}} \right) = \left(0.49_{-0.05}^{+0.06} \right) \left(\frac{M_{\text{bulge}}}{10^{11} M_\odot} \right)^{0.15 \pm 0.07}, \quad (5)$$

with an intrinsic scatter of 0.28 dex. The BH mass fraction, $M_\bullet/M_{\text{bulge}} = 0.49_{-0.05}^{+0.06} \%$ at $M_{\text{bulge}} = 10^{11} M_\odot$, is approximately a factor of 4 larger than we thought before the M_\bullet values were corrected (Merritt & Ferrarese 2001; Kormendy & Gebhardt 2001; McClure & Dunlop 2002; Marconi & Hunt 2003; Sani et al. 2011).

Note again that $M_\bullet - L_{\text{bulge}}$ is a single power law with no kink, whereas $M_\bullet - \sigma$ is a power law that “saturates” at high M_\bullet (see also McConnell & Ma 2013). That is, M_\bullet becomes nearly independent of σ in the highest- σ galaxies that also have cores (Figure 5). We understand why: The Faber-Jackson $L - \sigma$ correlation saturates at high L , because σ does not grow very much once galaxies are massive enough so that all mergers are dry (Figure 6). This is seen in simulations of dry, major mergers by (e. g.) Boylan-Kolchin, Ma, & Quataert (2006) and by Hilz et al. (2012). Section 4.1.1 reviewed arguments why core ellipticals are remnants of dry mergers.

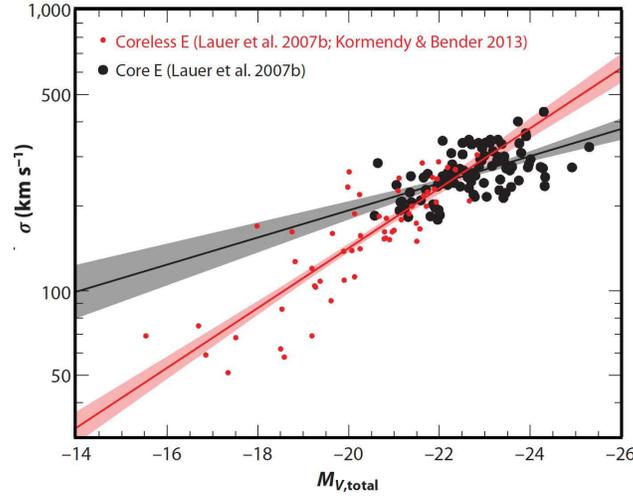


Fig. 6 Faber-Jackson (1976) correlations for core ellipticals (*black*) and coreless ellipticals (*red*). Total V-band absolute magnitudes $M_{V,\text{total}}$, velocity dispersions σ , and profile types are mostly from Lauer et al. (2007b) or otherwise from KFCB. The lines are symmetric least-squares fits to core Es (*black line*) and coreless Es (*red line*) with 1- σ uncertainties shaded. The coreless galaxies show the familiar relation, $\sigma \propto L_V^{0.27 \pm 0.02}$. But velocity dispersions in core ellipticals increase only very slowly with luminosity, $\sigma \propto L_V^{0.12 \pm 0.02}$. As a result, M_\bullet becomes almost independent of σ for the highest- σ galaxies in Figure 5. This figure from KH13 is based on Kormendy & Bender (2013). Lauer et al. (2007a) and Cappellari et al. (2013a, b) show closely similar diagrams.

The pseudobulges that were postponed from Figure 5 are added to the BH–host correlations in Figure 7. Hu (2008) was the first person to show that pseudobulges deviate from the $M_\bullet - \sigma_e$ correlation in having small BH masses. This was confirmed with larger samples and extended to the $M_\bullet - M_{K,\text{bulge}}$ and $M_\bullet - M_{\text{bulge}}$ correlations by Greene et al. (2010) and by Kormendy, Bender, & Cornell (2011). Figure 7 now shows this result for the largest available sample, that of KH13.

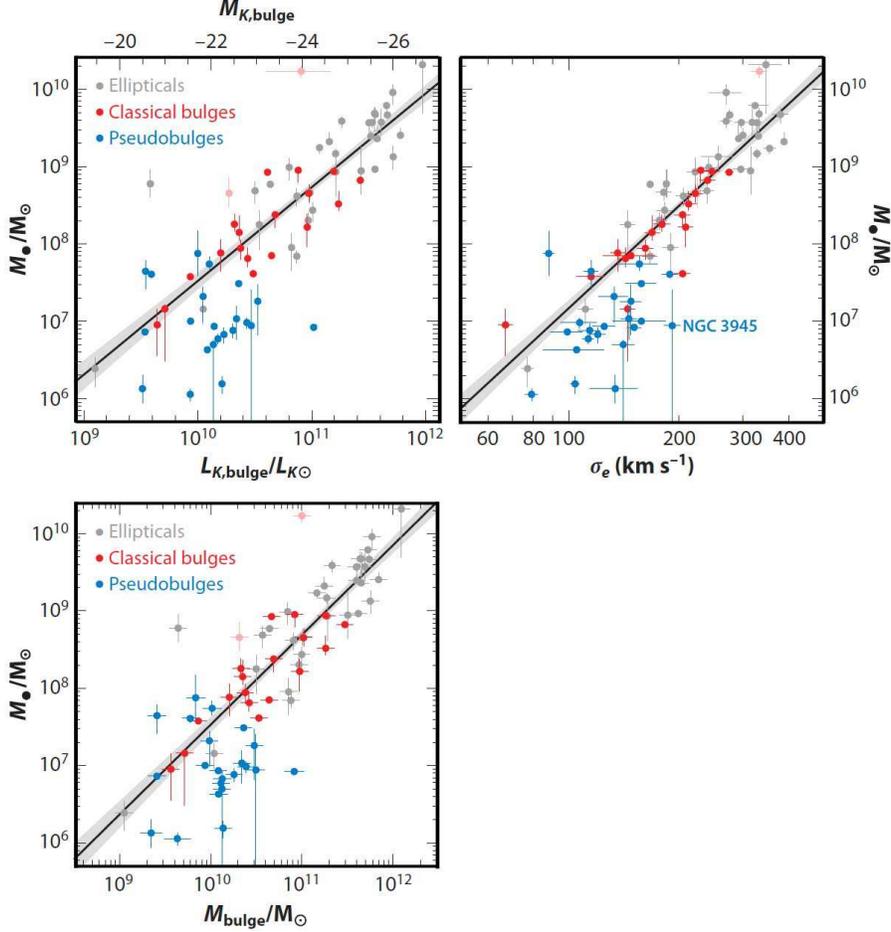


Fig. 7 Correlations of BH mass with the K -band absolute magnitude and luminosity of the host bulge (*top-left panel*), with its stellar mass (*bottom panel*), and with the mean velocity dispersion of the host bulge at radii that are large enough so that σ_e is unaffected by the BH (*right panel*). Gray points are for ellipticals, red points are for classical bulges, and blue points are for pseudobulges. The lines with shaded 1- σ uncertainties are symmetric least-squares fits to the classical bulges and ellipticals. In all panels, pseudobulge BHs are offset toward smaller M_\bullet from the correlations for classical bulges and ellipticals. Absent any guidance from the red and gray points, we conclude the pseudobulge BHs do not correlate with their hosts in any way that is strong enough to imply BH–host coevolution. From KH13, who tabulate the data and give sources.

Hints of this result are seen in McConnell & Ma (2013); they compare early- and late-type galaxies and note that many late-type galaxies have undermassive BHs. This captures some of the result in Figure 7 but not all of it, because many S0 galaxies contain pseudobulges. Similarly, Graham (2015) compares barred and unbarred galaxies and concludes that many barred galaxies have undermassive BHs. Again, this result is related to Figure 7 – many (but not all) barred galaxies contain pseudobulges, and many (but not all) unbarred galaxies contain classical bulges.

In Figure 7, the highest- M_{\bullet} pseudobulge BHs largely agree with the correlations for classical bulges and ellipticals; the lowest- M_{\bullet} BHs deviate, but not by much more than an order of magnitude. Note that the BHs that we find in pseudobulges may be only the high- M_{\bullet} envelope of a distribution that extends to much lower BH masses. Still, why are pseudobulge BHs even close to the correlations? KH13 argue that this is natural: even one major merger converts a pseudobulge to a classical bulge, and then merger averaging manufactures an essentially linear correlation with a zeropoint near the upper end of the mass distribution of progenitors (see Figure 37 in KH13 and Peng 2007; Gaskell 2010, 2011; Hirschmann et al. 2010; Jahnke & Macciò 2011, who developed this idea).

Turning next to disks: Figure 8 confirms the conclusion reached in Kormendy & Gebhardt (2001) and in Kormendy, Bender, & Cornell (2011) that BH masses are completely uncorrelated with properties of their host disks.

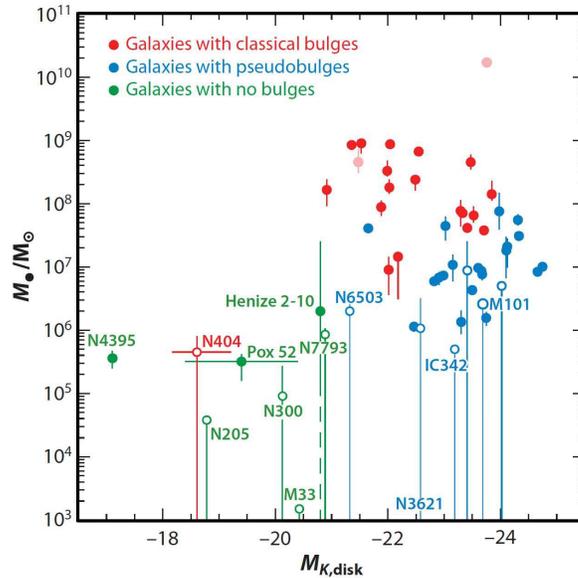


Fig. 8 Black hole mass M_{\bullet} vs K -band absolute magnitude of the disk of the host galaxy. Filled circles are for galaxies with BH detections based on spatially resolved stellar or gas dynamics; open circles are for galaxies with upper limits on M_{\bullet} . The strongest upper limit is $M_{\bullet} \lesssim 1500 M_{\odot}$ in M 33 (Gebhardt et al. 2001). Red and blue circles are for galaxies with classical and pseudo bulges, respectively. Green points are for galaxies with no classical bulge and (almost) no pseudobulge but only a nuclear star cluster. From KH13, who tabulate the data and give sources.

M 33, with its strong upper limit on M_{\bullet} , briefly gave us the feeling that pure disks might not contain BHs. But it was clear all along that they can have AGNs. Figure 8 includes bulgeless galaxies in which we find $10^{6\pm 1} M_{\odot}$ BHs. The prototypical example is NGC 4395, a dwarf Sd galaxy with $M_V = -18.2$, with no classical or pseudo bulge, but with only a nuclear star cluster that has an absolute magnitude of $M_B \simeq -11.0$ and a velocity dispersion of $\sigma \lesssim 30 \pm 5 \text{ km s}^{-1}$ (Filippenko & Ho 2003; Ho et al. 2009). And yet, NGC 4395 is the nearest Seyfert 1 galaxy known (Filippenko & Ho 2003). It shows the signatures of BH accretion – broad optical and UV emission lines (Filippenko, Ho & Sargent 1993), variable X-ray emission (Shih, Iwasawa, & Fabian 2003), and a compact, flat-spectrum radio core (Wrobel & Ho 2006). Peterson et al. (2005) get $M_{\bullet} = (3.6 \pm 1.1) \times 10^5 M_{\odot}$ by reverberation mapping. This is the smallest BH mass measured by reverberation mapping. But the BH in NGC 4395 is much more massive than $M_{\bullet} \lesssim 1500 M_{\odot}$ in the brighter pure-disk galaxy M 33 ($M_V = -19.0$).

This is the best example of many that are revealed in the observing programs of Ho, Barth, Greene, and collaborators and reviewed by Ho (2008) and by KH13. Other important galaxies include Pox 52 (Barth et al. 2004; Thornton et al. 2008) and Henize 2-10 (Reines et al. 2011). Broader AGN surveys to find low-mass BHs, many of them in late-type, pure-disk galaxies, include Greene & Ho (2004, 2007), Barth, Greene, & Ho (2008), and Dong et al. (2012). The general conclusion is that classical and even pseudo bulges are not necessary equipment for the formation and nurture of supermassive BHs.

We need one more result before we discuss implications for galaxy evolution:

Very popular for more than a decade has been the suggestion that the fundamental correlation between BHs and their host galaxies is not one with bulge properties but rather is a correlation with halo DM. This was suggested by Ferrarese (2002) and supported by papers such as Baes et al. (2003). The idea is attractive for galaxy formation theory, because then halo mass is the natural parameter to control AGN feedback (e. g., Booth & Schaye 2010). The most robust part of our effort to model galaxy formation is the calculation of DM hierarchical clustering. Conveniently, DM mass is then provided by halo-finder algorithms.

However, we can now be confident that *halo DM does not correlate directly with M_{\bullet} , independent of whether or not the galaxy contains a bulge* (Kormendy & Bender 2011). This result is reviewed in detail and with the largest galaxy sample in KH13. They list eight arguments against Ferrarese’s conclusion. Some are based on examining the proxy parameters that she used to make her arguments (σ for M_{\bullet} and V_{circ} for the DM; e. g. we now know that σ is not a proxy for BH mass for pseudobulge galaxies: Figure 7 here). Some arguments are based on the direct correlation of measured M_{\bullet} with V_{circ} : there is essentially no correlation unless the galaxy has a classical bulge. Perhaps the most telling argument is based on the well determined relationship between the stellar mass M_* and the DM mass M_{DM} of galaxies. Behroozi, Wechsler, & Conroy (2013) show that M_*/M_{DM} reaches a maximum at $M_{\text{DM}} \simeq 10^{12} M_{\odot}$ and is smaller at both higher and lower M_{DM} (see also Fig. 9 here). Together with the correlation (Equation 5) between M_{\bullet} and $M_{\text{bulge}} \simeq M_*$

(exact for ellipticals and approximate for bulge-dominated galaxies), Behroozi's result implies that the relationship between M_{\bullet} and M_{DM} is complicated,

$$M_{\bullet} \propto M_{\text{DM}}^{2.7} \quad \text{at } M_{\text{DM}} \ll 10^{12} M_{\odot}, \quad (6)$$

but

$$M_{\bullet} \propto M_{\text{DM}}^{0.34} \quad \text{at } M_{\text{DM}} \gg 10^{12} M_{\odot}, \quad (7)$$

with a kink in the correlation at $M_{\text{DM}} \simeq 10^{12} M_{\odot}$. Meanwhile, the $M_{\bullet} - M_{\text{bulge}}$ correlation is log linear with small scatter from the lowest to the highest bulge masses in Figure 5. This correlation shows no kink at $M_{\text{DM}} \sim 10^{12} M_{\odot}$ corresponding to $M_{\text{bulge}} \sim 3 \times 10^{10} M_{\odot}$ (see Figure 7). The simplicity of $M_{\bullet} - M_{\text{bulge}}$ versus the complexity of $M_{\bullet} - M_{\text{DM}}$ is another argument in favor of the conclusion that BHs coevolve with bulges and ellipticals but not directly with DM halos.

6.2 AGN Feedback and the Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies

Implications for the coevolution (or not) of BHs and host galaxies are reviewed by Kormendy & Ho (2013). They distinguish four modes of AGN feedback:

- (1) Galaxies that are not dominated by classical bulges – even ones like NGC 4736 that contain big pseudobulges – can contain BHs, but these grow by low-level AGN activity that involves too little energy to affect the host galaxy. Whether or not AGNs are turned on when we observe them, these galaxies actively form stars and engage in secular evolution by the redistribution of gas. Most AGNs at $z \sim 0$ and probably out to $z \sim 2$ are of this kind. They include giant galaxies such as our Milky Way, with outer circular-orbit rotation velocities $V_{\text{circ}} > 220 \text{ km s}^{-1}$. These galaxies are not correctly described by simple prescriptions in which gravitational potential well depth controls AGN feedback.
- (2) Most consistent with the prevailing emphasis on AGN feedback are classical bulges and coreless-disky-rotating ellipticals. They satisfy the tight correlations between M_{\bullet} and bulge properties in Figure 5. It is likely (although the engineering is not fully understood) that AGN feedback helps to establish these M_{\bullet} -host relations during dissipative (“wet”) major mergers. This must happen mostly at high z , because gas fractions in major mergers at $z \sim 0$ are small, and indeed, mergers in progress at $z \simeq 0$ do not satisfy the M_{\bullet} correlations. It is important to note that even small Es with $V_{\text{circ}} \lesssim 100 \text{ km s}^{-1}$ (e. g., M 32) satisfy the M_{\bullet} -host correlations, whereas even giant pure disks (e. g., M 101) do not. Coevolution is not about potential well depth. Coevolution (or not) is determined by whether (or not) the galaxy contains a classical bulge of elliptical – i. e., the remnant of at least one major merger.
- (3) The highest-mass ellipticals are coreless-boxy-nonrotating galaxies whose most recent mergers were dissipationless (“dry”). These giant ellipticals inherit any feedback magic – including the M_{\bullet} -host relations – from (2). In them, AGN feedback plays a different, essentially negative role. It keeps galaxy formation from “going to completion” by keeping baryons suspended in hot gas. With

masses $M > M_{\text{crit}}$ in Section 7, these galaxies hold onto hot, X-ray-emitting gas that is believed to prevent cold-gas dissipation and to quench star formation. However, X-ray gas cooling times are short, and so – given that we observe only weak temperature gradients – something must keep the hot gas hot. One such process is gas infall from the cosmological web (Dekel & Birnboim 2006). Another is “maintenance-mode AGN feedback” (see Fabian 2012 for a review). All proposed heating processes may be important. See Section 7.

- (4) The averaging that is inherent in galaxy mergers may significantly decrease the scatter in the M_{\bullet} –host correlations. That is, during a merger, the progenitors’ stellar masses add and so do their BH masses. In the absence of new star formation, the effect is to decrease the correlation scatter. Recall a conclusion in Section 4 that only a modest amount of star formation happens during mergers. So the central limit theorem ensures that the scatter in BH correlations with their hosts decreases as M_{\bullet} increases via either wet or dry mergers.

In summary, KH13 provides the largest available database on BH detections via spatially resolved dynamics, putting the many heterogeneous discovery papers on a homogeneous system of (for example) distances and magnitudes, and incorporating many M_{\bullet} corrections from the recent literature. Homogeneous data are also provided for all BH host galaxies, including all disk-galaxy hosts, many of which had not previously been studied. Bulge-pseudobulge classifications are provided based on multiple classification criteria (cf. Section 2.1 here), and (pseudo)bulge-disk photometric decompositions are derived for all galaxies that did not previously have photometry. The results (their Tables 2 and 3) are an accurate enough database to allow Kormendy & Ho (2013) to derive a number of new conclusions about BH–host correlations and their implications. Some of these are reviewed above. Others, such as correlations (or not) with nuclear star clusters and globular cluster systems, are omitted here, in part to keep the length of this paper manageable, and in part because the connection with galaxy bulges is less direct than it is for subjects that we cover.

Many of our conclusions disagree with Graham (2015). Within the subjects that I have reviewed in this paper, I have tried to explain why. Readers are encouraged to compare the accuracy of our data sets (particularly M_{\bullet} measurements), our results, and the physical picture in which they are embedded. We believe that the observational conclusions reached in KH13 are robust, and the essential implications for galaxy evolution – the big picture of what happens, if not the engineering details – are well established. Section 7 is an important example.

7 Quenching of Star Formation

Many papers on star formation histories begin by setting up a “straw-man target” that the quenching of star formation is mysterious. In contrast, it strikes me that the literature shows encouraging convergence on a picture at least at $z < 1$ in which well defined processes convert “blue cloud” star-forming galaxies to “red sequence” red and dead galaxies. This section rephrases Section 6.2 to describe this picture.

The essential observation that has driven progress on this subject is summarized in Figure 9. The left panel shows the Allen et al. (2011) version of the Behroozi et al. (2013) result that led to Equations (6) and (7) in Section 6.1. I use it because the abscissa is in the same units as in the right panel. It shows that the ratio of stellar mass to total mass reaches a maximum at $V_{\text{circ}} \sim 300 \text{ km s}^{-1}$ or, in Behroozi et al. (2013), at $M_{\text{DM}} \sim 10^{12} M_{\odot}$. This maximum is $\sim 1/5$ of the cosmological baryon fraction, so most baryons in the universe have not yet made stars. Lower-mass halos have smaller stellar fractions (*left panel*) and smaller baryon fractions (*right panel*) because – we believe – the baryons have increasingly been ejected from DM halos by star-formation and supernova feedback or never accreted after cosmological reionization. But the focus here is on higher DM masses. They, too, have smaller stellar mass fractions than at the “sweet spot” halo mass of $10^{12} M_{\odot}$. But Figure 9 (*right*) shows that these baryons are not “missing” at $M_{\text{DM}} \gg 10^{12} M_{\odot}$. On the contrary, the total baryon fraction converges to essentially the cosmological value in the highest-mass halos, which are halos of rich clusters of galaxies. This is the by-now well known result that, as M_{DM} grows above $10^{12} M_{\odot}$ and V_{circ} grows above 300 km s^{-1} , an increasingly large fraction of the baryons are indeed present but have not made stars. Rather, they are suspended in hot, X-ray-emitting gas, until in rich clusters of galaxies, that hot gas outmasses the stellar galaxies in the cluster by 1.0 ± 0.3 dex (Kravtsov & Borgani 2012). This has led to the essential idea of “ M_{crit} quenching” of star formation by X-ray-emitting gas, which can happen provided that the DM mass is larger than the critical mass, $M_{\text{DM}} \gtrsim M_{\text{crit}} \simeq 10^{12} M_{\odot}$, that is required to support the formation and retention of hot gas halos (e. g., Birnboim & Dekel 2003; Kereš et al. 2005; Cattaneo et al. 2006, 2008, 2009; Dekel & Birnboim 2006, 2008; Faber et al. 2007; KFCB; Peng et al. 2010, 2012; KH13, Knobel et al. 2015, and Gabor & Davé 2015).

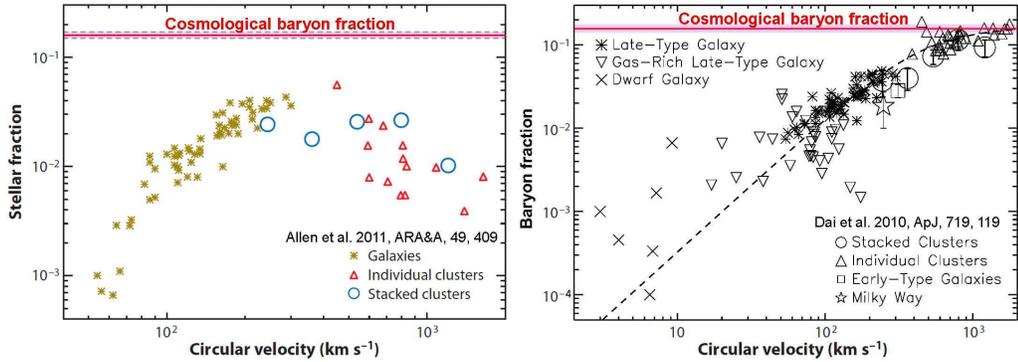


Fig. 9 Stellar mass fraction $M_*/(M_{\text{baryon}} + M_{\text{DM}})$ (*left*) and total baryon mass fraction $M_{\text{baryon}}/(M_{\text{baryon}} + M_{\text{DM}})$ (*right*) versus a circular-orbit rotation velocity $V_{\text{circ}} \sim \sqrt{GM_{\text{DM}}/r}$ (Dai et al. 2010) that approximately characterizes the total mass distribution. Here M_* is the stellar mass, M_{DM} is the DM halo mass, r is the radius of the halo, and G is the gravitational constant. The cosmological baryon fraction has been adjusted very slightly to 0.16 ± 0.01 , i. e., the mean of the WMAP and Planck measurements (Hinshaw et al. 2013 and Planck Collaboration 2014, respectively). Both figures originally come from Dai et al. (2010).

The transition mass between galaxies that should contain X-ray gas and those that should not is consistently derived by a variety of theoretical arguments and is consistently checked via a variety of observational tests. It should occur at the DM mass at which the hot gas cooling time is comparable to the infall time (Rees & Ostriker 1977). Birnboim & Dekel (2003) and Dekel & Birnboim (2006, 2008) argue from theory and Kereš et al. (2005) find from SPH simulations that gas that is accreted during hierarchical clustering falls gently into shallow potential wells and makes star-forming disks, whereas gas crashes violently onto giant galaxies and is shock-heated to the virial temperature. It is this hot gas that quenches star formation. Calculated hot-gas cooling times are short; this led to the well known “cooling flow problem” (Fabian 1994). But X-ray measurements of temperature profiles now show that they are much shallower than cooling-time calculations predict in the absence of heating (McNamara & Nulsen 2007; Kravtsov & Borgani 2012; Fabian 2012). Debate continues about how the gas is kept hot; Dekel & Birnboim (2006, 2008) suggest that the required heating is caused by continued accretion; AGN feedback is another candidate (e. g., Best et al. 2006; Best 2006, 2007a, b; Fabian 2012; Heckman & Best 2014), and dying stars return gas to the intergalactic medium at just the right kinetic temperature (Ostriker 2006). The engineering details need to be sorted out. It is likely that all processes are important. But from the point of view of this paper, the engineering is secondary. The important point is that the galaxies and clusters tell us that they know how to keep the gas hot.

Many observed properties of galaxies can be understood in the context of M_{crit} quenching. E. g., it allows semianalytic models of galaxy formation to reproduce the color bimodality of galaxies (“red sequence” versus “blue cloud”; Blanton & Moustakas 2009) as a function of redshift (Cattaneo et al. 2006, 2008, 2009).

Faber et al. (2007) and KFCB emphasize the connection of the above results to this paper: *M_{crit} star-formation quenching is believed to explain the difference between the two kinds of ellipticals discussed in Section 4.1.1.* I noted there that classical bulges and coreless-disky-rotating ellipticals generally do not contain X-ray-emitting gas, whereas core-boxy-nonrotating ellipticals contain more X-ray gas as their luminosities increase more above $L_{\text{crit}} = 10^{10.2} L_{B\odot}$ (Figure 3). Now, L_{crit} corresponds to $M_V \simeq -20.9$; i. e., 0.6 mag fainter than the divide between coreless-disky-rotating and core-boxy-nonrotating ellipticals. This is a factor of almost 2. If the most recent event that made an elliptical was an equal-mass merger, then *the divide between coreless-disky-rotating and core-boxy-nonrotating ellipticals happens at a luminosity below which neither of the merger progenitor galaxies should have contained X-ray gas and above which one or both progenitor galaxies should have contained X-ray gas. Thus KFCB point out that the E–E dichotomy occurs at the correct luminosity so that coreless-disky-rotating ellipticals formed in wet mergers whereas core-boxy-nonrotating ellipticals formed in dry mergers.*

Specifically, $M_V \simeq -20.7$ for merger progenitors corresponds (using $M/L_V \sim 6$) to a stellar mass of $M_* \simeq 1 \times 10^{11} M_\odot$ or, using a baryon-to-total mass ratio of 1/6 (Komatsu et al. 2009), to $M_{\text{DM}} \simeq 6 \times 10^{11} M_\odot$. And the divide between coreless-disky-rotating Es and core-boxy-nonrotating Es happens at $M_{\text{DM}} \simeq 10^{12} M_\odot$. So the agreement with the above picture of M_{crit} star-formation quenching is good.

Thus our picture of the formation of classical bulges and elliptical galaxies by wet and (at $M_{DM} > 10^{12} M_{\odot}$) dry major mergers (Section 4 of this paper) is a tidy addition to our developing paradigm of star-formation quenching. Many details of the structure of classical bulges and ellipticals (e. g., the list in Section 4.1.1) fit into and support this paradigm. But the paradigm is more general than just an explanation of the E – E dichotomy. I turn to these more general aspects next:

In a seminal paper, Peng et al. (2010) use a few robust observations to derive very general conclusions about how quenching must work. They do this completely operationally, without any need to identify the physical mechanism(s) of quenching. At redshift $z \sim 0$ (Sloan Digital Sky Survey) and out to $z \sim 1$ (zCOSMOS survey; Lilly et al. 2007) the most essential observations used are (1) that the specific star formation rate is almost independent of galaxy mass (there is a “main sequence” of star formation) but with rapidly decaying specific star formation rate as $z \rightarrow 0$, and (2) that star-forming galaxies satisfy a Schechter (1976) mass function whose characteristic mass is almost independent of z . From a discussion of how star formation operates to reproduce the above and other observations, they deduce that quenching is driven by galaxy mass and by galaxy environment and that these two modes (not identified physically) are separable and independent. Plus there must be an additional quenching mode that is associated with bulge formation via mergers. Figure 10 connects their picture with the quenching paradigm that we review here.

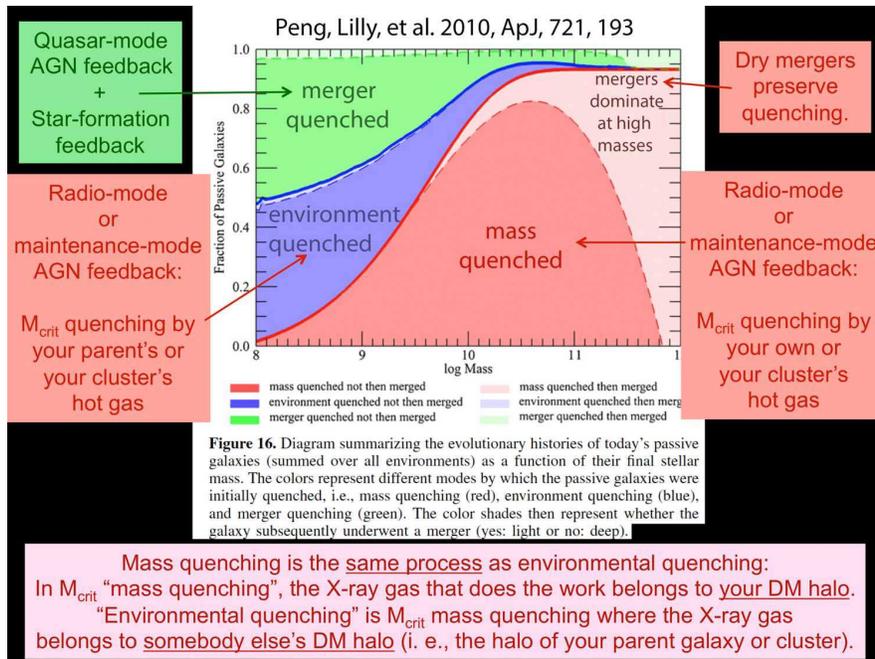


Fig. 10 Powerpoint slide connecting the star-formation quenching picture of Peng et al. (2010: central figure and its caption) with the picture that is summarized in this paper (surrounding text).

Peng et al. (2010) emphasize that their analysis is operational: it identifies the conditions in which quenching must operate, but it does not identify quenching mechanisms. However, with this section’s background on M_{crit} quenching and with results from KH13 on BH – host-galaxy coevolution (or not), we can identify aspects of our developing physical picture of star-formation quenching with the conclusions of Peng et al. (2010). This is illustrated in Figure 10.

The masses used in Peng et al. (2010) are estimated by integrating star formation rates and by fitting spectral energy distributions; in essence, they are stellar masses. Figure 10 suggests that mass quenching tends to happen at masses $\sim 10^{10.5} M_{\odot}$. In Figure 7 of Peng et al. (2010), the fraction of quenched galaxies (independent of environment) reaches 50 % at $\sim 10^{10.6} M_{\odot}$ and 80 % at $\sim 10^{11.25} M_{\odot}$. These correspond to $M_{\text{DM}} \sim 10^{11.4}$ to $10^{12} M_{\odot}$. The good agreement with M_{crit} suggests that Peng’s “mass quenching” is precisely our “ M_{crit} quenching” by hot gas.

Peng et al. (2010) conclude further that some low-mass galaxies are quenched by their environments. That is, these galaxies are quenched because they are satellites of higher-mass objects – ones (either individual galaxies or clusters of galaxies) that *can have masses $M_{\text{DM}} \gtrsim M_{\text{crit}}$. I suggest that Peng’s “environmental quenching” is the same physical process as mass quenching, but in Peng’s mass quenching, the X-ray gas that does the work belongs to the galaxy that is being quenched, whereas in environmental quenching, the X-ray gas that does the work belongs to somebody else; i. e., to the quenched galaxy’s parent giant galaxy or galaxy cluster.* This idea is verified by Peng et al. (2012), Knobel et al. (2015), and Gabor & Davé (2015).

The suggested connection with KH13 then is this: Both mass and environment quenching are aspects of point 3 in Section 6.2 – they are effects of hot gas that is kept hot by a combination of maintenance-mode AGN feedback and other processes such as continued infall of gas from the cosmological hierarchy and the injection of the kinetic energy of gas that is shed by dying stars.

But the above quenching processes are not sufficient. It is easy to explain why – to give an example that mass quenching and environment quenching cannot explain. *What quenches field S0 galaxies with masses $M \ll M_{\text{crit}}$? Kormendy & Ho (2013) suggest that they are quenched in the context of wet galaxy mergers that include starbursts, with energy feedback from the starburst beginning the job of quenching and AGN feedback (Section 6.2, point 2) finishing the job. It seems natural to suggest that this is the Peng’s “merger quenching”. Observations of gas outflows in high- z , star-forming galaxies such as submillimeter galaxies – at least some of which are mergers – are reviewed in KH13. Of course, bulge-formation and M_{crit} quenching can be mutually supportive (e. g., Woo et al. 2015).*

Once star formation is quenched at $M > M_{\text{crit}}$, then dry mergers preserve both the quenched state and the M_{\bullet} – host correlations (Section 6.2, point 4 and modes “mass quenched then merged”, “environment quenched then merged”, and “merger quenched then merged” in Figure 10).

The biggest remaining question in our $z < 1$ picture is this: *In merger-quenched galaxies that have $M \ll M_{\text{crit}}$, i. e., in objects in which X-ray gas is not available even after the merger is finished, what preserves the quenched, red and dead state? We do not know, but episodic, low-level AGN feedback may be the answer.*

The biggest overall uncertainty is that quenching may operate differently at $z \gtrsim 2$. Dekel and Birnboim argue (1) that M_{crit} is higher at high z , when gas fractions in galaxies and gas accretion rates onto galaxies are both higher and (2) that cold streams can penetrate hot gas at high z and contribute to the growth of disks at masses that are unattainable at $z \sim 0$ (Dekel et al. 2009). Another difference involves the observation that most star-forming galaxies define a main sequence of star formation with few outliers, implying that duty cycles are long and hence that star formation is not driven primarily by short-duration events such as mergers (Section 4.1.5). When strong gas outflows are seen in star-forming galaxies at $z \sim 2$, the inference is that some combination of star formation and AGN feedback is responsible but that these are not primarily driven by major mergers (e.g., Förster Schreiber et al. 2014; Genzel et al. 2014). Because these processes are also associated with bulge growth in disk galaxies (Lang et al. 2014), the most consistent interpretation that also includes the M_{\bullet} correlation results is that the bulge growth in these objects is by clump cluster sinking (Section 3 here). Genzel (private communication) suggests that Peng’s mass quenching may be this outflow process associated with more-or-less steady-state star formation, AGN feedback, and classical bulge growth. On the “plus side”, there is clearly a danger that our tidy $z < 1$ picture is basically correct but not a description of what happens at $z \gg 1$. On the other hand, we already know that many details of galaxy structure are well explained by the $z \sim 0$ picture. Particularly important is the natural explanation of cores in dry-merger remnants and central extra light in wet-merger remnants (see KFCB). Alternative suggestions for quenching mechanisms at high z have not addressed and solved the problem of also explaining these aspects of $z \sim 0$ galaxy structure. This is not a proof that the suggested high- z processes are wrong.

It seems reasonable to conclude that our $z < 1$ picture of star formation quenching is robust. Mostly, it needs clarification of engineering details. In marked contrast, star formation quenching at $z \gtrsim 2$ is less well understood, although progress is rapid.

8 A Partial Summary of Outstanding Problems

I conclude with a summary of the most important outstanding problems. I restrict myself to big-picture issues and do not address the myriad engineering details that are unsolved by our present state of the art. They are, of course, vitally important. But a comprehensive list would require a paper of its own. I therefore refer readers to earlier chapters of this book, which discuss many of these problems in detail.

- (1) I emphasized in Section 4.1.3 that, to me, the most important goal is to produce realistic classical bulges + ellipticals and realistic disks that overlap over a factor of > 1000 in mass but that differ from each other in ways that we observe over the whole of this range. They can combine with any B/T from 0 to 1, but the differences between bulges and disks depend very little on B/T .
- (2) Four decades of work on $z \simeq 0$ galaxies showed convincingly that major mergers convert disks into classical bulges and ellipticals with the observed properties,

including Sérsic index, fundamental plane parameter correlations, intrinsic shape and velocity distributions, both as functions of mass, the presence of cores or central extra light, and isophote shape. This work also suggested that merger rates were higher in the past, and modern observations confirm this prediction. By the mid-1990s, we had converged on a picture in which classical bulges and ellipticals were made in major mergers. Enthusiasm for mergers was probably overdone, but now, the community is overreacting in the opposite direction. The successes of the 1970s–1990s are being forgotten, and – I believe – we have come to believe too strongly that minor mergers control galaxy evolution. Reality probably lies between these extremes. For today’s audience, the important comment is this: The observations that led to our picture of E formation via major mergers have not been invalidated. I suggest that the profitable way forward is to use what we learn from $z \simeq 0$ mergers-in-progress to explore how mergers make bulges and ellipticals at higher z , including (of course) differences caused (for example) by large gas fractions and including new ideas, such as violent disk instabilities that make clumps that make bulges. For this still-elusive true picture, it is OK that mergers are rare, because ellipticals are rare, too, and classical bulges are rarer than we thought. And it is OK that most star formation does not happen in mergers, because ellipticals are rare anyway, and because their main bodies are made up of the scrambled-up remnants of already-stellar progenitor disks.

- (3) The most important unsolved problem is this: How did hierarchical clustering produce so many giant galaxies (say, those with $V_{\text{circ}} \gtrsim 150 \text{ km s}^{-1}$) with no sign of a classical bulge? This problem is a very strong function of environment – in field environments such as the Local Group, most giant galaxies are bulgeless, whereas in the Virgo cluster, most stars live in classical bulges and elliptical galaxies. The clue therefore is that the solution involves differences in accretion (gentle versus violent) and not largely internal physics such as star-formation or AGN feedback.
- (4) Calculating galaxy evolution *ab initio*, starting with Λ CDM density fluctuations, constructing giant n -body simulations of halo hierarchical clustering, and then adding baryonic physics is the industry standard today and the way of the future. It is immensely difficult and immensely rewarding. It is not my specialty, and I have only one point to add to the excellent review by Brooks & Christensen: *Observations hint very strongly that we put too much reliance on feedback to solve our engineering problems in producing realistic galaxies. Observations of supermassive BH demographics tell us that AGN feedback does not much affect galaxy structure or star formation until mergers start to make classical bulges. And point (3) emphasizes that environment and not gravitational potential well depth is the key to solving the problem of giant, pure-disk galaxies.*
- (5) We need to fully integrate our picture of disk secular evolution into our paradigm of galaxy evolution. As observed at $z \simeq 0$, this picture is now quite detailed and successful. Essentially all of the commonly occurring morphological features of galaxies – bars, (nuclear, inner, and outer) rings, nuclear bars, and pseudobulges – are at least qualitatively explained within this picture. Some of these details are beyond the “targets” of present galaxy-formation simulations. But pseudobulges

are immediately relevant, because our recognition of them has transformed our opinions about classical bulges. They are much rarer than we thought. In particular, small classical bulges are *very* rare. And although some galaxies have structure that is completely determined by the physics of hierarchical clustering, others – and they dominate in the field – appear to have been structured almost exclusively by secular processes. Incorporating these processes is a challenge, because slow processes are much more difficult to calculate than rapid processes. But secular evolution is an idea whose time has come (Sellwood 2014), and we need to include it in our paradigm.

- (6) At the same time, our *quantitative* understanding of secular evolution needs more work. For example, we need a study similar to Dressler’s (1980) work on the morphology-density relation: We need to measure the luminosity and mass functions of disks, pseudobulges, and classical bulges+ellipticals, all as functions of environmental density. At present, we have essentially only two “data points” – the extreme field (Kormendy et al. 2010; Fisher & Drory 2011) and the Virgo cluster (see Kormendy et al. 2010). This is already enough to lead to point (3) in this list. We need corresponding studies in more environments that span the density range from the field to the richest clusters. This will not be easy, first because we need high spatial resolution whereas observing more environments drives us to larger distances, and second because of point (7).
- (7) Our picture of disk secular evolution predicts that many galaxies should contain both a classical and a pseudo bulge. Work on the subject has concentrated on extremes – on galaxies that are dominated by one kind of bulge or the other. Samples of large numbers of galaxies will inevitably have to face the challenge of separating at least three components (bulge, pseudobulge, and disk) and in many cases more (bar, lens, . . .). We also need to be able to find pseudobulges in face-on barred galaxies (see Section 2.1). But it is easy to overinterpret details in the photometry. The best way to approach this problem is probably to begin with infrared observations of nearly-edge-on galaxies (e. g., Salo et al. 2015).
- (8) Are classical bulges really indistinguishable from ellipticals? The structural parameter scaling relations shown in Figure 4 (based on many authors’ work) show that they are closely similar. I use this result throughout the present paper. It is central to Renzini’s (1999) paraphrase of the classical morphological definition: “A bulge is nothing more nor less than an elliptical galaxy that happens to live in the middle of a disk.” But not everybody agrees. Based on multi-component decompositions, different fundamental plane correlations for classical bulges and ellipticals have been found by Gadotti (2008, 2009, 2012) and by Laurikainen et al. (2010). We need to resolve these differences. At stake is an understanding of whether classical bulges and ellipticals form – as I suggest – by essentially the same major merger process or whether important variations in that process produce recognizably different results. In particular, it is not impossible that we can learn to distinguish ellipticals and perhaps *some* bulges that form via mergers of distinct galaxies from other bulges that form via the mergers of mass clumps that form in unstable disks. Both processes drive additional gas toward the center, but it is possible that bulge formation via disk

instabilities is intrinsically more drawn out in time with the result (for example) that “extra light components” such as those studied in Kormendy (1999), KFCB, and Hopkins et al. (2009a) are smoothed away and unrecognizable in the resulting classical bulges but not in disk-coreless-rotating ellipticals.

- (9) Returning to elliptical galaxies: KFCB present a detailed observational picture and ARA&A-style review of the two kinds of ellipticals in large part as seen in the Virgo cluster. Hopkins et al. (2009a, b) present modeling analyses of wet and dry mergers, respectively. *We need to know how this very clean picture as seen in the nearest rich cluster translates into other environments.* Much of the work published by Lauer et al. (1995, 2005, 2007a, b), by Faber et al. (1997), by Kormendy & Bender (1996, 2013), and by Bender et al. (1989) applies to broader ranges of environments. It suggests that the picture summarized here in Section 4.1.1 is basically valid but that the distinction between coreless-disk-rotating and core-boxy-nonrotating galaxies is somewhat “blurred” in a broader range of environments. For example, $M_V = -21.6$ cleanly separates the two kinds in Virgo, with only one partial exception (NGC 4621 at $M_V = -21.54$ has $n = 5.36^{+0.30}_{-0.28}$ characteristic of core galaxies, but it has a small amount of extra light near the center). However, the above papers and others show that the two galaxy types overlap over a range of absolute magnitudes from about $M_V = -20.5$ to about $M_V = -23$. In the overlap range and occasionally outside it, some classification criteria in Section 4.1.1 conflict with the majority. We should not be surprised that heterogeneous formation histories can have variable outcomes; on the contrary, it is encouraging to see as much uniformity as we see. Still, a study of how the systematics depend on environment should be profitable.
- (10) Still on ellipticals and classical bulges: The SAURON and ATLAS^{3D} teams have carried out an enormous amount of truly excellent work on nearly all aspects of bulge+E structure and evolution. A review is in preparation by Cappellari (2015). *It is natural to ask how the picture of bulges and ellipticals developed by the SAURON and ATLAS^{3D} papers compares with the one outlined in Section 4 here. The answer is that they agree exceedingly well.* There are differences in emphasis, and the large SAURON + ATLAS^{3D} teams address many subjects that are beyond the scope of studies by our team or by the Nuker team. There is also one difference in analysis that makes me uncomfortable – in their work, they generally do not decompose galaxies into bulge and disk parts. *It is therefore all the more remarkable that careful work without using component decomposition and our work that always is based on component decomposition converge on pictures that are so similar.* E. g., the separate parameter correlations for bulges and disks that are shown here in Figure 4 are visible as pure-bulge and pure-disk boundaries of parameter correlation *regions* shown in Cappellari et al. (2013b). In their diagrams, the parameter space between our bulge and disk correlations is filled in with intermediate-Hubble-type galaxies that have $0 < B/T < 1$. Similarly, Cappellari et al. (2011) and Kormendy & Bender (2012) both revive the “parallel sequence” galaxy classification of van den Bergh (1976), as do Laurikainen et al. (2011). Kormendy and Bender (2012) also add Sph galaxies (as distinct from ellipticals) to the classification.

What may appear as a difference between Section 4 and the SAURON + ATLAS^{3D} work is our emphasis on many E–E dichotomy classification criteria versus their distinction based only on fast versus slow rotation. However, Lauer (2012) shows that the SAURON + ATLAS^{3D} division into fast and slow rotators is essentially equivalent to the division between coreless and core galaxies. The equivalence is not exact based in the rotation amplitude parameter $\lambda_{r_e/2}$ (within 1/2 of the effective radius r_e) chosen by the SAURON and ATLAS^{3D} teams. But it becomes much more nearly exact if slow and fast rotators are divided at a slightly higher rotation rate, $\lambda_{r_e/2} = 0.25$. In unpublished work, I found an essentially equivalent result for the original SAURON kinematic classification, in which slow rotators have $\lambda_R < 0.1$ and fast rotators have $\lambda_R > 0.1$ as defined in Emsellem et al. (2007). If the division is instead made at $\lambda_R = 0.175$, then core and coreless ellipticals are separated essentially perfectly. (The only exception in KFCB is NGC 4458, which is slowly rotating but coreless. But it is almost exactly round, and rotating galaxies that are seen face-on will naturally look like slow rotators.) The more nuanced ATLAS^{3D} look at elliptical galaxy dynamics leads to a revised suggestion that fast and slow rotators should be separated at $\lambda_{r_e/2} = (0.265 \pm 0.01) \times \sqrt{\epsilon_{e/2}}$ (Emsellem et al. 2011, Equation 4). A typical $\epsilon = 0.2$ for core-boxy galaxies and $\epsilon = 0.35$ for coreless-disky galaxies (from Tremblay & Merritt 1996) then implies a division at $\lambda_{r_e/2} = 0.16$ and 0.12, respectively. The typical intrinsic ellipticity of 0.4 found by Sandage, Freeman, & Stokes (1970) for all ellipticals implies $\lambda_{r_e/2} = 0.17$. These values are closer to the rotation parameters 0.25 and 0.175 that divide core and coreless galaxies as found by Lauer (2012) and by my work, respectively.

I suggest that the best way to divide slow rotators from fast rotators is not to pick some arbitrary value of the rotation parameter but rather to ask the galaxies what value of the rotation parameter produces the cleanest distinction into two kinds of galaxies as summarized in Section 4.1.1. When this is done, the E–E dichotomy as discussed in this paper and the large body of work done by the SAURON and ATLAS^{3D} teams are remarkably consistent.

(2+3 redux) A partial exception to the above conclusion is some of the n -body simulation work, e. g., by Naab et al. (2014). They acknowledge the importance of major mergers in some ways that are consistent with the story advocated in this paper. But their conclusion that “The galaxies most consistent with the class of non-rotating round early-type galaxies grow by gas-poor *minor* mergers alone” (emphasis added) is at best uncomfortable within the picture presented here. The core-boxy-nonrotating galaxies have a large range of mostly homogeneous properties with respect to which the round ones do not stand out as different (e. g., KFCB). In particular, our understanding of cores – especially the tight correlations between core properties and BH masses – depends on our picture that cores are scoured by black hole binaries that are formed in major mergers (see KFCB and Kormendy & Bender 2009 for both the data and a review). At best, *it remains to be demonstrated that minor mergers – which necessarily involve many small galaxies with (from Figure 7) undermassive BHs – can produce the very large BH masses and cores that are seen in giant core*

ellipticals. Dry minor mergers cannot do better than to preserve the $M_{\bullet}/M_{\text{host}}$ mass ratio. Also, if many minor mergers are necessary – and these galaxies are so massive that very many minor mergers are necessary to grow them – then there is a danger of producing a central cluster of low-mass BHs that is never observed as a cluster of compact radio sources and that is inherently unstable to the ejection of objects in small- n n -body systems (see KH13, p. 634).

- (11) I conclude with two sociological points: It is worth emphasizing that galaxy evolution work did not start in the 2000s. Many results that were derived in the 1960s – 1990s remain valid today. We should not forget them. We should integrate them into our current picture of galaxy evolution.
- (12) And finally: Galaxy evolution work has changed profoundly in the SDSS and HST eras. Before the early 1990s, *our goal was to understand the evolution of galaxy structure*. Now, most emphasis on galaxy structure has disappeared. *Now, our goal is to understand the history of star formation in the universe*. The main reason for this change is the common ground found between SDSS studies of many thousands of galaxies and HST studies of very distant galaxies. Necessarily, both kinds of studies concentrate on galaxies whose images are a few arcsec across. We do not resolve structural details. Mainly, we measure colors and magnitudes. So galaxy evolution has evolved into the study of the red sequence and blue cloud in the color-magnitude relation. Star formation and its quenching are, of course, important. But it would be enormously healthy if we could improve the dialog between SDSS+HST people and those – such as this author – who work on nearby galaxies whose star formation histories and structures can be studied in great detail. Conselice (2014) is an example of a paper that tries to bridge the gap. We would benefit greatly if we could completely connect the two approaches to galaxy evolution.

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