The intriguing life of massive galaxies
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Supermassive black holes: Coevolution (or not) of black holes and host galaxies

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Abstract. Supermassive black holes (BHs) have been found in 75 galaxies by observing spatially resolved dynamics. The *Hubble Space Telescope* (HST) revolutionized BH work by advancing the subject from its 'proof of concept' phase into quantitative studies of BH demographics. Most influential was the discovery of a tight correlation between BH masses $M_\bullet$ and the velocity dispersions σ of stars in the host galaxy bulge components at radii where the stars mostly feel each other and not the BH. Together with correlations between $M_\bullet$ and bulge luminosity, with the 'missing light' that defines galaxy cores, and with numbers of globular clusters, this has led to the conclusion that BHs and bulges coevolve by regulating each other's growth. This simple picture with one set of correlations for all galaxies dominated BH work in the past decade.

New results are now replacing the above, simple story with a richer and more plausible picture in which BHs correlate differently with different kinds of galaxy components. BHs with masses of 10^5—10^6 $M_\odot$ live in some bulgeless galaxies. So classical (merger-built) bulges are not necessary equipment for BH formation. On the other hand, while they live in galaxy disks, BHs do not correlate with galaxy disks or with disk-grown pseudobulges. They also have no special correlation with dark matter halos beyond the fact that halo gravity controls galaxy formation. This leads to the suggestion that there are two modes of BH feeding, (1) local, secular and episodic feeding of small BHs in largely bulgeless galaxies that involves too little energy feedback to drive BH–host-galaxy coevolution and (2) global feeding in major galaxy mergers that rapidly grows giant BHs in short-duration events whose energy feedback does affect galaxy formation. After these quasar-like phases, maintenance-mode BH feedback into hot, X-ray-emitting gas continues to have a primarily negative effect in preventing late-time star formation when cold gas or gas-rich galaxies get accreted. Finally, the highest-mass galaxies inherit coevolution effects from smaller galaxies; the tightness of their BH correlations is caused mainly by averaging during dissipationless major mergers.

Keywords. black hole physics; galaxies: bulges; galaxies: elliptical and lenticular, cD; galaxies: evolution; galaxies: kinematics and dynamics; galaxies: structure; X-rays: galaxies

1. Introduction

This paper summarizes a more detailed *ARAA* review of supermassive black holes (BHs) by Kormendy & Ho (2013). Our understanding of BHs and their coevolution with their host galaxies has begun a period of rapid progress as we have come to realize that BHs correlate differently with different kinds of galaxy components that have different formation histories. This is good news, because it allows us for the first time to distinguish between several different kinds of BH–host-galaxy interactions. But it involves the reader in aspects of the structure and evolution of different kinds of galaxies that deserve full-length reviews of their own. I summarize these subjects as efficiently as I can and provide references for further details. One result that is relevant to this Symposium is evidence that *the main bodies of giant ellipticals form via major mergers.*

2. The history and robustness of black hole mass measurements

Our picture of BHs as engines for nuclear activity in galaxies is well known (Rees 1984). Dynamical searches for central dark objects are reviewed by Kormendy & Richstone (1995); Richstone *et al.* (1998); Ho (1999); Kormendy & Gebhardt (2001), and Ferrarese & Ford (2005). The evidence that the best cases are BHs and not (e. g.) clusters of stellar remnants is strong; these are the maser BH discovery in NGC 4258 (Miyoshi *et al.* 1995) and the case of our Galaxy (see Genzel *et al.* 2010 for a review). The observations of our Galaxy are spectacular: we follow the orbits of individual stars, and each orbit gives an independent measure of $M_\bullet$. X-ray observations of relativistically broadened Fe Kα lines add powerful evidence for BH-depth potential wells and allow us to determine BH spins (Fabian 2013). Thus, growing connections between BH observations and many aspects of galaxy physics are signs of the developing maturity of the field.

The history of $M_\bullet$ measurements based on spatially resolved dynamics is shown in Figure 1. HST BH discoveries began in the mid-1990s and lasted until 2009. It is possible that a few more will be reported, but the HST era appears largely over. Ground-based observations using adaptive optics (AO) or based on H_2O masers are taking over.

The robustness of $M_\bullet$ measurements is measured by how well the PSF radius σ_* of the observations resolves the radius $r_{\rm infl}$ inside which the velocities of the dynamical tracers are influenced by the BH. HST BH discoveries mostly have been made at $r_{\rm infl}/\sigma_* \simeq 1$—10. Pre-HST ground-based BH discoveries were made at the same effective spatial resolution, but successes were restricted to favorable (e. g., nearby) cases. HST revolutionized this subject by allowing us to find BHs in more distant galaxies. Also, confidence is increased because all early ground-based $M_\bullet$ measurements have been confirmed by HST, by better ground-based observations (two-dimensional spectroscopy), and by better analysis (three-integral dynamical models). Meanwhile, $M_\bullet$ estimates have remained remarkably stable. Galaxies do not use their freedom to indulge in perverse orbit structures that would cause simple models to provide wrong masses. Their freedom is limited by formation physics.

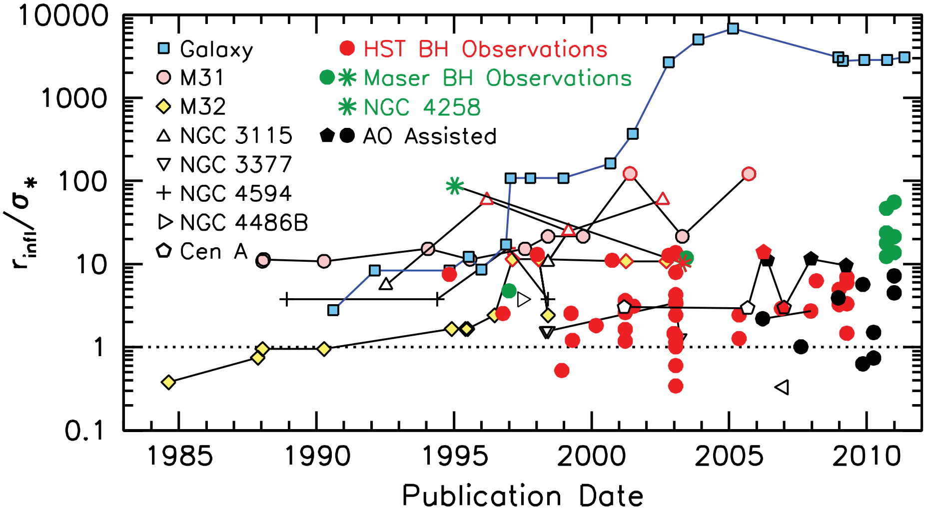


Figure 1. Spatial resolution of $M_\bullet$ spectroscopy vs. publication date (Kormendy & Ho 2013). Multiple measurements for the same galaxy are joined by straight lines to show how resolution has improved. Here $r_{\rm infl} \equiv GM_\bullet/\sigma^2$ is the radius of the BH sphere of influence, σ_* is the Gaussian dispersion radius of the PSF including pixel size and slit width, and G is the gravitational constant. HST BH discoveries are made at similar resolution as ground-based discoveries. But HST has a smaller PSF, so it is used to discover smaller BHs in more distant galaxies.

Tests by Gebhardt *et al.* (2003) show that three-integral dynamical models continue to provide unbiased $M_\bullet$ measurements (albeit with increased random errors) as the spatial resolution is reduced to $r_{\rm infl}/\sigma_* \simeq$ a few tenths (see Kormendy 2004, Figure 1.4). However, systematic errors can result if the physical assumptions used in the models are incorrect. This is a problem mainly for elliptical galaxies with cores (see Section 11), as follows.

Core ellipticals usually have anisotropic velocity dispersions and are somewhat triaxial. Effects of triaxiality have so far been checked only for NGC 3379. It may be a worst-case object, because it is relatively round and face-on. However, including triaxiality increases the $M_\bullet$ estimate by a factor of 2 (van den Bosch & de Zeeuw 2010). Also, core ellipticals have relatively low central stellar densities, so dark matter is relatively important. Inclusion of dark matter generally increases the $M_\bullet$ estimate. The reason is that we assume that the stellar mass-to-light ratio is independent of radius. Attributing velocities at large radii in part to dark matter lowers M/L. In compensation, $M_\bullet$ must be increased to maintain a good fit to the central kinematics. The correction depends on $r_{\rm infl}/\sigma_*$ but can easily be a factor of 2. Gebhardt & Thomas (2009) and Gebhardt *et al.* (2011) correct $M_\bullet$ for M 87 upward by a factor of 2; then $M_\bullet = (6.6 \pm 0.4) \times 10^9\ M_\odot$ (distance = 17.9 Mpc), no longer agrees well with the mass $M_\bullet = (3.8 \pm 1.1) \times 10^9\ M_\odot$ obtained from HST ionized gas kinematic measurements by Macchetto *et al.* (1997). This will be important below. BH mass estimates that include the effects of dark matter are now available for all except one core galaxy discussed in this paper (see the above papers and Shen *et al.* 2010; Schulze & Gebhardt 2011; McConnell *et al.* 2011, 2012; and Rusli *et al.* 2013).

3. BH-host correlations for classical bulges and elliptical galaxies

Belief in BH–host-galaxy coevolution is most directly motivated by the observation that $M_\bullet$ correlates tightly with properties of the host galaxy bulges, including luminosity (Kormendy 1993; Kormendy & Richstone 1995; Magorrian *et al.*ts1998; Ho 1999; Merritt & Ferrarese 2001; Ferrarese & Ford 2005; Greene *et al.* 2010; see also Figure 6), mass (Dressler 1989; McLure & Dunlop 2002; Marconi & Hunt 2003; Häring & Rix 2004), and especially velocity dispersion (Ferrarese & Merritt 2000; Gebhardt *et al.* 2000; Tremaine *et al.* 2002). Recent discussions of these correlations for large samples of galaxies not divided up by bulge type are in Gültekin *et al.* (2009) and in McConnell *et al.* (2011). Figure 2 brings these correlations up-to-date for classical bulges and ellipticals.

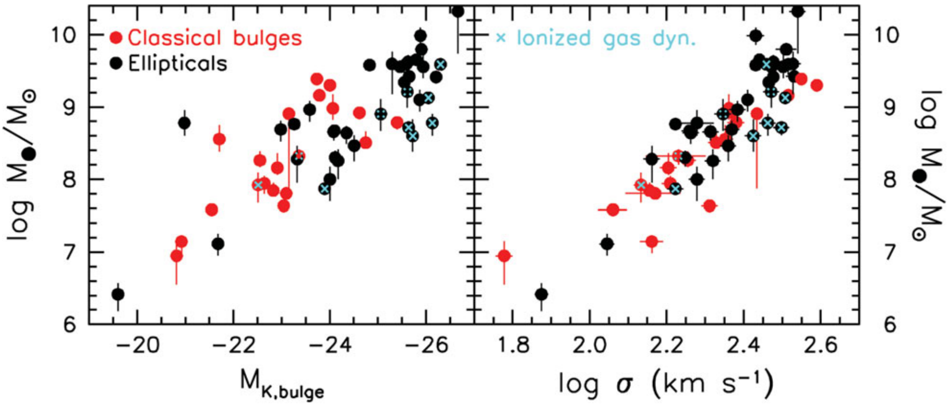


Figure 2. Correlation of dynamically measured BH mass $M_\bullet$ with (left) K-band absolute magnitude $M_{K,\rm bulge}$ of the bulge component and (right) near-central velocity dispersion σ for classical bulges and elliptical galaxies. Points are labeled with crosses if $M_\bullet$ was determined from ionized gas dynamics and if the width of the emission lines was not taken into account.

Classical bulges are observationally indistinguishable from elliptical galaxies living in the middle of a disk (Renzini 1999; see Kormendy & Bender 2012 for a demonstration that they have the same fundamental plane parameter correlations as ellipticals).

Before I discuss interpretation, there is a technical problem with the results in Figure 2. Early measures of $M_\bullet$ based on the kinematics of ionized gas did not take into account the fact that emission line widths are often as large as rotation velocities. Measurements of $M_\bullet$ based on stellar rotation velocities never neglect the dynamical support provided by large velocity dispersions. The disagreement in M 87 of $M_\bullet$ values based on stellar and gas dynamics is a sign that σ can be important for ionized gas, too (Kormendy & Ho 2013). A few galaxies have been analyzed taking emission line widths into account (Barth *et al.* 2001; Walsh *et al.* 2010); results are included in Figure 2 without labels. But mass measurements from optical emission lines that neglect line widths are labeled with crosses in Figure 2. Signs are that they, like the ionized gas result for M 87, underestimate $M_\bullet$. These points are included and labeled in subsequent figures, too, but we use them only when $M_\bullet$ underestimates do not threaten conclusions (e. g., in Section 4 but not here).

Figure 2 shows that classical bulges and ellipticals have the same $M_\bullet - M_{K,\mathrm{bulge}}$ and $M_\bullet$–σ correlations. As in previous work, the $M_{K,\mathrm{bulge}}$ correlation shows more scatter than the σ correlation; the high-$M_\bullet$ outlier elliptical is NGC 4486B (Kormendy *et al.* 1997); the outlier bulge is NGC 4342 (Creton & van den Bosch 1999). From the enlarged sample of high-$M_\bullet$ galaxies provided by McConnell *et al.* (2011, 2012) and by Rusli *et al.* (2013), it now seems clear that bulge luminosity and not σ is the better predictor of the highest BH masses, as suggested, e. g., by Lauer *et al.* (2007) and by the above papers. The Faber-Jackson (1976) $L \propto \sigma^4$ relation saturates at the largest L; that is, $\sigma \sim$ constant independent of L; this is clearly implied by Figure 2.

4. BHs correlate little or not at all with pseudobulges

Complementing our standard paradigm of galaxy formation by hierarchical clustering, a detailed picture of the internal, slow (‘secular’) evolution of essentially isolated galaxy disks has been established by a great deal of research over > 30 years. This subject is too large to be reviewed here; a Canary Islands Winter School review provides an introduction (Kormendy 2013), and a comprehensive review of the literature is in Kormendy & Kennicutt (2004). The part of this story that is relevant here is the conclusion that not all ‘bulges’ – not all central galaxy components whose brightness profiles rise steeply above the inward extrapolation of the disk profile – are like elliptical galaxies. The two kinds of bulges have different origins. How do nonclassical bulges correlate with BHs?

Further explanation is required in order to understand the motivation. Theory tells us that a disk evolves secularly to lower total energy by spreading: it gets more tightly bound gravitationally by expanding its outer parts and shrinking its inner parts. The evolution takes place by the redistribution of angular momentum driven by nonaxisymmetries such as bars. The timescale for a galaxy to change is much longer than the rotation time, and the galaxy is always essentially in dynamical equilibrium. So the evolution is called ‘secular’. The evidence shows that secular evolution rearranges disk gas and builds two kinds of ring structures, ‘inner rings’ at the ends of bars and ‘outer rings’ at 2.2 bar radii. The other main result is relevant here. Much of the inner gas is dumped into the center, where it undergoes a starburst and builds a high-central-concentration inner component that, in the past, was mistaken for a classical bulge but that was grown slowly out of the disk, not built rapidly by major galaxy mergers. Disk-built ‘pseudobulges’ can be recognized because they have more disk-like structure than do classical bulges.

Figure 3 shows $M_\bullet$ correlations for 18 galaxies with classical bulges and 21 galaxies with pseudobulges. We conclude that BHs correlate differently with the two kinds of bulges.

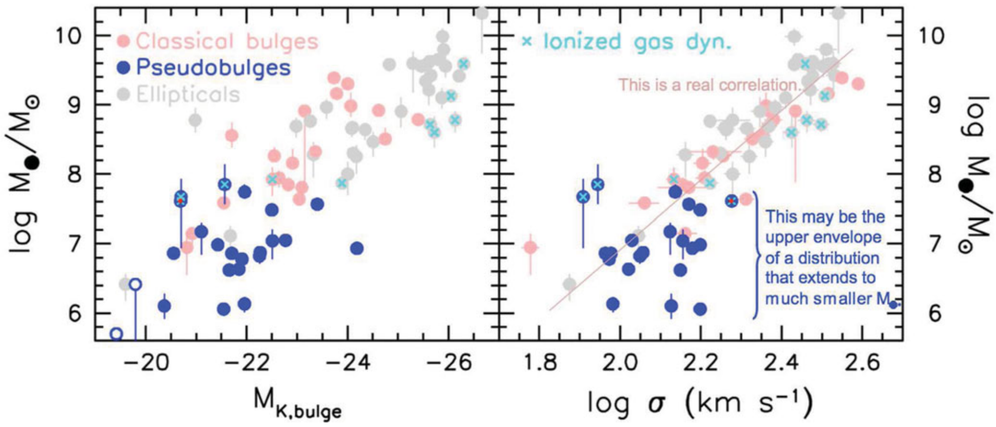


Figure 3. (left) $M_\bullet$ versus $M_{\rm K,bulge}$ and (right) $M_\bullet$ versus σ for pseudobulges with dynamical BH detections (blue filled circles) and for those with $M_\bullet$ upper limits (blue open circles). NGC 2787, which may have a small classical bulge inside a large pseudobulge (Erwin *et al.* 2003) is shown with a blue symbol that has a red center. Classical bulges and ellipticals are shown in ghostly light colors to facilitate comparison. Points are labeled with crosses if $M_\bullet$ was determined from ionized gas dynamics and if the width of the emission lines was not taken into account.

The data are sparse, but BHs in classical bulges appear to correlate tightly with their host bulges even at the lowest $M_\bullet$. In contrast, for galaxies with dynamical BH detections, BHs in pseudobulges show no correlation with their hosts (Kormendy *et al.* 2011, see Hu 2008 for an early version of this result). Samples that include AGN-based $M_\bullet$ measures suggest a weak correlation (Figure 6), but the scatter is too large to imply coevolution.

5. BHs do not correlate with galaxy disks

Figure 4 (Kormendy & Ho 2013) updates results from Kormendy *et al.* (2011) and Kormendy & Gebhardt (2001) that $M_\bullet$ does not correlate with properties of host disks, whether or not these disks include classical or pseudo bulges.

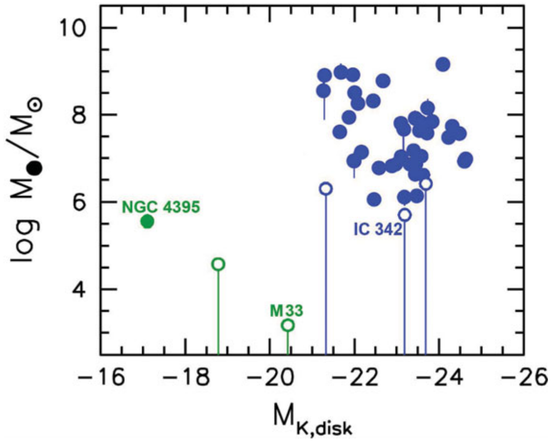


Figure 4. BH mass versus the K-band absolute magnitude of the disk of the host galaxy. Blue points are for galaxies with classical or pseudo bulges; for these galaxies, the BH–(pseudo)bulge correlations are shown in Figures 2 and 3. Green points are for galaxies with neither a classical nor a pseudo bulge but only a nuclear star cluster. The strongest upper limit is $M_\bullet \lesssim 1500\ M_\odot$ for M 33 (Gebhardt *et al.* 2001). For NGC 4395 (Figure 5), $M_\bullet$ is from Peterson *et al.* (2005).

Figure 5. The Sdm galaxy NGC 4395 (SDSS *gri* image). The low surface brightness, the lack of a bulge, and the presence of a nuclear star cluster are characteristic of dwarf, late-type galaxies. M 33 and M 101 are more luminous, higher-surface-brightness analogs (Kormendy *et al.* 2010).

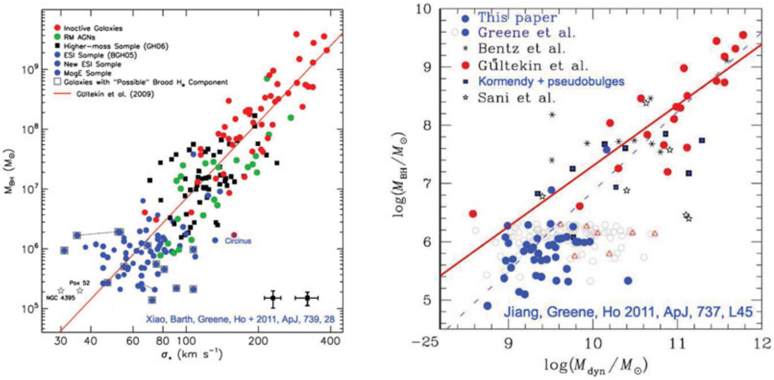


Figure 6. BH – host-galaxy correlations for AGNs with BH masses derived from reverberation mapping (green points) and from broad emission-line widths (blue and black points). Most of these galaxies contain pseudobulges or no bulges. It is important to note that the green, black, and blue points have been zeropointed to the red points for galaxies whose BH masses were measured using observations of spatially resolved kinematics. Shifts in $M_\bullet$ with respect to these points (similar to the offsets of pseudobulge points in Fig. 3) may have been removed.

6. Bulges are not necessary equipment for BH growth

Figure 4 shows the striking difference between M 33 and NGC 4395. M 33 is a bulgeless galaxy with an outer rotation velocity $V_{\rm circ} \simeq 120 \pm 10$ km s^{-1} (Corbelli 2003) and no BH. In contrast, NGC 4395 is a smaller bulgeless galaxy ($V_{\rm circ} \simeq 75 \pm 10$ km s^{-1}; Swaters *et al.* 2009) that contains a BH with $M_\bullet = (3.6 \pm 1.1) \times 10^5\ M_\odot$. The pure-disk nature of NGC 4395 is illustrated in Figure 5. The galaxy does not even contain a pseudobulge, yet it contains a BH and one of the faintest Seyfert 1 active galactic nuclei (AGNs) known (Filippenko *et al.* 1993; Filippenko & Ho 2003). Much work shows that NGC 4395 is no fluke: *Bulges are not necessary equipment for BH formation and growth* (Barth *et al.* 2004; Greene & Ho 2004, 2007b; Thornton *et al.* 2008; Greene *et al.* 2008, 2010; Reines *et al.* 2011; Jiang *et al.* 2011; Xiao *et al.* 2011; Dong *et al.* 2012; see Ho 2008; Kormendy & Ho 2013 for reviews). Most of this evidence comes from Seyfert 1 activity. The large scatter of $M_\bullet$ with host galaxy properties is further illustrated in Figure 6.

7. Feeding the monster with and without BH-galaxy coevolution

The results reviewed in Sections 3 – 6 led Kormendy *et al.* (2011) to suggest that there are two modes of BH feeding, (1) local, secular and episodic feeding of small BHs in largely bulgeless galaxies that involves too little energy feedback to result in BH-host coevolution and (2) global feeding in galaxy mergers that rapidly grows giant BHs in short-duration events whose energy feedback does affect galaxy formation. Plausibly, the former, smaller BHs are the seeds of the latter, giant BHs.

8. BHs do not correlate directly with dark matter halos

Several authors suggest that $M_\bullet$ correlates at least as well with dark matter (DM) halos as it does with bulges (Ferrarese 2002; Baes *et al.* 2003; Pizzella *et al.* 2005). This is based on proxy parameters: σ for $M_\bullet$ and the asymptotic outer rotation velocity $V_{\rm circ}$ of galaxy disks for DM. The claimed observation is a tight correlation between σ and $V_{\rm circ}$. The implications would be profound, because the unknown physics of nonbaryonic DM might be necessary to engineer BH-galaxy coevolution. The result would also be attractive for modelers of galaxy formation, because the simplest galaxy property that is provided by hierarchical clustering n-body simulations could then be used to control AGN feedback.

However, Kormendy & Bender (2011) show that BHs do not correlate tightly with DM. Is a BH – DM relation more fundamental than the BH–bulge relation that we know about? A simple test is to ask whether $M_\bullet$ correlates tightly with $V_{\rm circ}$ in the absence of a bulge. Kormendy *et al.* (2010) measure σ in the biggest bulgeless galaxies that are close enough so we can observe their globular-cluster-like nuclear star clusters. Kormendy & Bender (2011) then update the $V_{\rm circ} - \sigma$ correlation from Ferrarese (2002) as shown in Figure 7. Absent a bulge (color data), the correlation has too much scatter to imply coevolution, even if σ is a valid proxy for $M_\bullet$ (which we do not know). This is true even for giant galaxies ($V_{\rm circ} \sim 200$ km s^{-1}). Overlapping these in $V_{\rm circ}$, the black points show galaxies

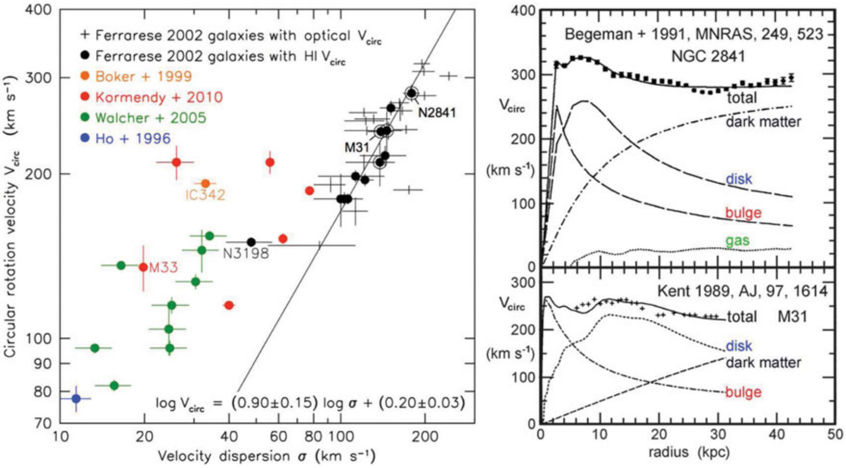
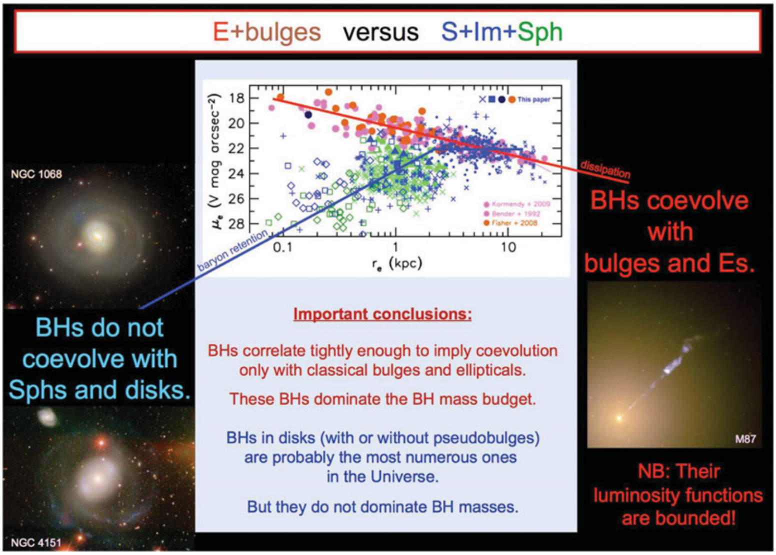


Figure 7. (left) Outer rotation velocities $V_{\rm circ}$ of spiral galaxy disks versus near-central velocity dispersions σ. Black points show the correlation from Ferrarese (2002, circled if the galaxy has a classical bulge) unless the σ measurement was compromised by low wavelength resolution. Added in color are points for galaxies that have no classical bulge and essentially no pseudobulge but that are measured with wavelength resolution (dispersion $\sigma_{\rm instr} < 10$ km s^{-1}) high enough to resolve the smallest σ in galactic nuclei. The line (equation; velocities are in units of 200 km s^{-1}) is a symmetric least-squares fit. (right) Decomposition of observed rotation curves (data points) into contributions from the bulge, disk, gas, and dark matter for two classical-bulge galaxies labeled in the left panel. From Kormendy & Bender (2011), which lists references in the key.

from Ferrarese (2002) that do show a tight correlation between $V_{\rm circ}$ and σ. But only four of these contain classical bulges (circled points). The rest have pseudobulges, and we already know that σ is not a proxy for $M_\bullet$ for pseudobulges. If pseudo and classical bulges nevertheless show the same, tight $V_{\rm circ}$–σ correlation, then that correlation has nothing to do with BHs. Instead, Kormendy & Bender (2011) conclude that the correlation of the black points in Figure 7 (left) is a manifestation of the conspiracy between visible and dark matter to have approximately the same maximum $V_{\rm circ}$ (van Albada & Sancisi 1986). This is shown in Figure 7 (right) for two classical bulges in Figure 7 (left). Kormendy & Bender (2011) and Kormendy & Ho (2013) review other arguments against the idea that DM correlates with BHs beyond the bulge correlation.

9. BHs and the fundamental plane correlations of their host galaxies

BHs correlate tightly with classical bulges and ellipticals but not with pseudobulges, disks or dark matter halos. In deciphering coevolution, this focuses our attention on major galaxy mergers (Sections 10, 11). Figure 8 summarizes some additional implications. BHs coevolve only with the galaxy components that define the fundamental plane correlations. Therefore the mass function of the BHs that coevolve with ellipticals is bounded: we know of no ellipticals that are much smaller than M 32. In contrast, the mass function of spiral, irregular, and spheroidal galaxies is not known to be bounded at low masses (green and blue points in Figure 8). However, there are signs that even the BHs that live in these galaxies have mass functions that become bounded at $M_\bullet < 10^6\ M_\odot$ (Greene & Ho 2007a).



E+bulges versus S+Im+Sph

BHs coevolve with bulges and Es.

BHs do not coevolve with Sphs and disks.

Important conclusions:

BHs correlate tightly enough to imply coevolution only with classical bulges and ellipticals.

These BHs dominate the BH mass budget.

BHs in disks (with or without pseudobulges) are probably the most numerous ones in the Universe.

But they do not dominate BH masses.

NB: Their luminosity functions are bounded!

Figure 8. Powerpoint slide showing the relationships of BHs that coevolve with classical bulges and ellipticals (red line and text; pink and brown points; e. g., M 87) and those that do not evolve with disks and Sph galaxies (blue lines and text; blue and green points; Seyfert galaxy examples). Here r_e is the effective radius that contains half of the light of the bulge or disk and μ_e is the surface brightness at r_e. For classical bulges and ellipticals, this correlation (Kormendy 1977: red line) is an almost–edge-on projection of the fundamental plane; it is a sequence of increasing dissipation during galaxy formation at decreasing luminosity (lower-right toward upper-left). For disks (blue), surface brightness is independent of r_e or luminosity L at high L (Freeman 1970). Fainter than absolute magnitude $M_V \simeq -18$ or at $r_e < 2$ kpc, surface brightness decreases with decreasing r_e and L (upper-right toward lower-left); this is a sequence of decreasing baryon retention in shallower gravitational potential wells. Adapted from Kormendy & Bender (2012).

10. A brief introduction to AGN feedback

The idea that BHs and bulges coevolve by regulating each other's growth is popular for many reasons: (1) The tightness of the $M_\bullet - M_{K,\mathrm{bulge}}$, $M_\bullet - \sigma$, $M_\bullet -$globular-cluster (Burkert & Tremaine 2010; Harris & Harris 2011) and other (Section 11.2) correlations suggests that BH growth and galaxy formation are connected. Particularly compelling is the conclusion by Ferrarese & Merritt (2000) and by Gebhardt *et al.* (2000) that the scatter in the $M_\bullet - \sigma$ correlation is consistent with measurement errors. (2) The binding energy of a BH is much larger than the binding energy of its host bulge; if only a few percent of AGN energy couples to gas in the forming galaxy, then all of the gas can be blown away (e. g., Silk & Rees 1998; Ostriker & Ciotti 2005). Thus BH growth may be self-limiting and AGNs may quench star formation and evolve their hosts from the blue cloud to the red sequence in the color-magnitude correlations. (3) Figure 9 (left) shows that the histories of BH growth and star formation in the universe are closely similar.

AGN feedback has the potential to solve many problems in galaxy formation. E. g., (1) The mass function of visible galaxies drops more steeply at high masses than that of DM halos that is predicted by our standard cosmology. The proposed solution is that AGN feedback is more efficient at higher $M_\bullet$ at keeping galaxies from growing more massive. (2) Episodic AGN feedback is believed to solve the 'cooling flow' problem, i. e. that, in the absence of energy input, X-ray halos in giant galaxies and in clusters of galaxies would cool quickly, but this produces no visible star formation (e. g., Ostriker & Ciotti 2005).

Figure 9 (right) shows the danger of overdoing feedback. The scatter in the $M_\bullet$–host correlations decreases strongly from the smallest to the largest BHs (Fig. 3, 6). Several authors emphasize that such a decrease results naturally from the averaging that is inherent in galaxy mergers. ' "Fine-tuning" through feedback is unnecessary and produces too low a dispersion in [the final] $M_\bullet/L$' (Gaskell 2010). As shown in Figure 9 (right), merging can convert no correlation at all into correlations that are essentially as tight as the ones observed (Jahnke & Macciò 2011; see also Peng 2007; Hirschmann *et al.* 2010).

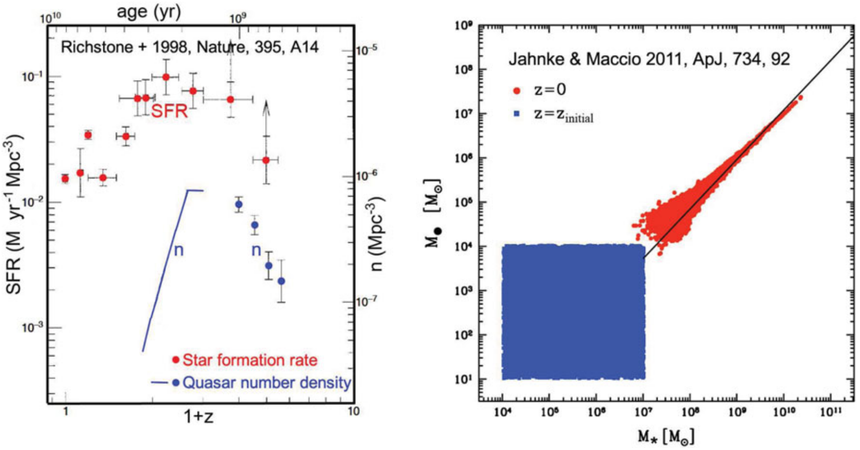


Figure 9. Arguments (left) for and (right) against AGN feedback as a factor in creating tight correlations between $M_\bullet$ and bulge L or σ. The left panel shows that the evolution with redshift (bottom) or age of the Universe (top) of the volume density of bright quasars (blue points and right axis labels) is very similar to the evolution of the star formation rate (red points and left axis labels). The right panel shows how an increasingly tight correlation between $M_\bullet$ and the stellar mass M_* of the host bulge (red points compared with the correlation observed by Häring & Rix 2004) can be manufactured from no correlation (blue square) by averaging in dry mergers.

11. Two kinds of elliptical galaxies have different AGN feedback

The rest of this paper discusses evidence for the two different kinds of AGN feedback that are introduced in the second paragraph of Section 10. They happen in two different kinds of elliptical galaxies summarized here and in Kormendy & Bender (2013) and reviewed in Kormendy *et al.* (2009, hereafter KFCB). These are illustrated in Figure 10.

Giant ellipticals ($M_V \lesssim -21.6$ for $H_0 = 70$ km s^{-1} Mpc^{-1}) *generally* (1) *have cores, i. e., central missing light with respect to an inward extrapolation of the outer Sérsic profile* (Figure 10, left); (2) rotate slowly, so rotation is of little importance dynamically; (3) hence are anisotropic and modestly triaxial; (4) have boxy-distorted isophotes; (5) are made of very old stars that are enhanced in α elements; (6) often contain strong radio sources, and (7) contain X-ray-emitting gas, more of it in more luminous galaxies.

Smaller ellipticals with $M_V \gtrsim -21.5$ *generally* (1) *are coreless – they have central extra light with respect to an inward extrapolation of the outer Sérsic profile* (Figure 10, left); (2) rotate rapidly; (3) are nearly isotropic and oblate spheroidal; (4) have disky-distorted isophotes; (5) are made of (still old but) younger stars with little α-element enhancement; (6) rarely contain strong radio sources, and (7) rarely contain X-ray-emitting gas.

The SAURON/ATLAS^{3D} division of ellipticals into fast and slow rotators (Emsellem *et al.* 2007, 2011; Cappellari *et al.* 2007, 2011) is closely similar.

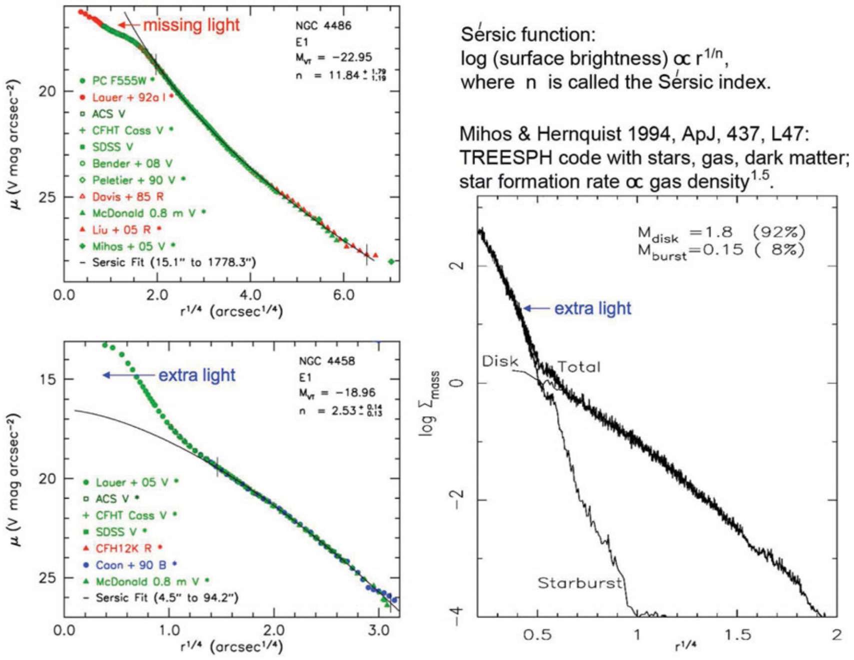


Figure 10. (left) From KFCB, brightness profiles of prototypical elliptical galaxies (top) with and (bottom) without cores. The core is defined to be the region of missing light with respect to the inward extrapolation of the outer Sérsic (1968) function brightness profile. KFCB showed that all Virgo cluster ellipticals with $M_V \leqslant -21.6$ have cores, whereas all Virgo ellipticals with $M_V \geqslant -21.5$ have central extra light above the inward extrapolation of the outer Sérsic profile. This core–no-core difference correlates with many other physical parameters that distinguish the two kinds of ellipticals. (right) Stellar mass density profile of the remnant of a merger of progenitor galaxies that each consisted of a stellar disk containing 92 % of the mass plus cold gas containing 8 % of the mass plus a dark matter halo. During the merger, the gas falls to the center and produces the 'Starburst' profile. Note that the outer profile is well described by a Sérsic function with $n < 4$, exactly as in the extra light elliptical. From Mihos & Hernquist (1994).

11.1. *Quasar-mode AGN feedback in extra light ellipticals*

The extra light seen in coreless/rotating/disky ellipticals closely resembles the compact components that form via central starbursts in wet mergers (Fig. 10, right, from Mihos & Hernquist 1994). This led Kormendy (1999) to suggest that extra light and core ellipticals formed in wet and dry mergers, respectively. Further support is provided by more extensive observations (e. g., Côté *et al.* 2007; KFCB), including mergers in progress (Rothberg & Joseph 2004), and by structural details in some extra light components that point to dissipative formation (disky structure, rapid rotation; KFCB). Extra light components are widely seen in detailed simulations of major mergers with gas (e. g., Springel & Hernquist 2005 [see Fig. 43 in KFCB]; Cox *et al.* 2006; Hopkins *et al.* 2008, 2009). However, if AGN feedback is too strong too early in the merger, the starburst is quenched and the extra light component does not form (e. g., Cox *et al.* 2006). This provides an engineering constraint for AGN feedback in extra light ellipticals.

In this context, an attractive picture that looks consistent with all observations is one in which most BH growth happens in 'quasar' events in the late stages of dissipative major mergers that grow host bulges (e. g., Hopkins *et al.* 2006). This 'quasar-mode feedback' from a bright BH accretion disk is where we need to engineer the magic that produces tight BH–galaxy correlations. Quenching of star formation, evolution of the galaxy from the blue cloud to the red sequence in the color-magnitude diagram, and expulsion of remaining cold gas plausibly happen in this context. AGN feedback may cooperate with starburst-driven outflows (Weiner *et al.* 2009; Newman *et al.* 2012). For both kinds of outflow, the fundamental feature to be exploited is radiation (and possibly jets) fed into a *three-dimensional* surrounding distribution of *very opaque gas.* The devil is in the details.

11.2. *Maintenance-mode AGN feedback in core ellipticals. I. Cores as evidence for dry major mergers*

In contrast, I will suggest that AGN feedback takes a different form and has different results in core ellipticals. To see why, I need first to provide further evidence for their formation in both *major* and *dry* mergers. I begin with further evidence for dry mergers.

Figure 11 shows that the Faber-Jackson $L-\sigma$ relation is shallower for core ellipticals than it is for coreless ellipticals. This accounts for the steepening of the relation at low L (Tonry 1981; Davies *et al.* 1983). A shallow dependence on stellar mass, $\sigma \propto M_*^{0.091\pm0.022}$, is consistent with n-body simulations of *dry major* mergers (Hilz *et al.* 2012). The reason

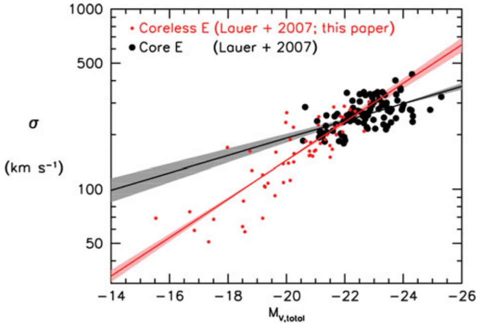


Figure 11. Faber-Jackson (1976) relation between σ and $M_{V,\mathrm{total}}$ for ellipticals without (red) and with (black) cores. The lines are symmetric least-squares fits. Converting $M_{V,\mathrm{total}}$ to stellar mass M_* via $M/L \propto L^{0.32\pm0.06}$ (Cappellari *et al.* 2006), $\sigma \propto M_*^{0.20\pm0.04}$ for coreless ellipticals and $\sigma \propto M_*^{0.091\pm0.022}$ for elliptical galaxies with cores. From Kormendy & Bender (2013).

why σ does not stay constant as in simple virial theorem arguments (Lake & Dressler 1986) is that some exchange in energy between stars and dark matter results in merger remnants that are slightly more compact (smaller size, higher density, higher velocity dispersion) than predicted if no orbital energy is added to the merger remnant.

Note that σ *does not decrease with increasing luminosity as predicted for minor mergers or for scenarios in which cores form by the expansion of the center after ejection of large amounts of gas* (Naab 2013). This does not mean that minor mergers are unimportant; they may build the large-Sérsic-index *halos* of giant ellipticals (Naab *et al.* 2009; Hopkins *et al.* 2010; van Dokkum *et al.* 2010; Oser *et al.* 2011; Hilz *et al.* 2012; Naab 2013). But the evidence does suggest that the main bodies of ellipticals are made by major mergers.

Another argument for *major* and *dry* mergers follows from Figure 12. The bottom-left panel shows that the mass that is missing in cores with respect to the outer Sérsic profile correlates tightly with $M_\bullet$. The correlation is well known (e. g., Milosavljević *et al.* 2001, 2002) but more accurately measured in KFCB. The RMS scatter (~ 0.20 dex in $\log M_\bullet$) is formally smaller than the scatter (~ 0.30 dex in $\log M_\bullet$) in the $M_\bullet - \sigma$ relation (Tremaine *et al.* 2002). And (Fig. 12, right), although the dispersion in BH mass fractions $M_\bullet / M_*$ around the mean of 0.13 % (Merritt & Ferrarese 2001; Kormendy & Gebhardt 2001) is large, it is not random: it correlates tightly with core light deficit. Kormendy & Bender (2009) argue that these results are a 'smoking gun' that connects cores with BHs. In fact, we believe that BHs are responsible for cores. Here's why:

Mergers tend to preserve the highest densities in their progenitors. Smaller ellipticals have higher central densities (Fig. 10). So mergers do not naturally make low-density cores (Faber *et al.* 1997). The proposed solution is that cores are scoured by the orbital decay of binary BHs that form in major mergers (e. g., Ebisuzaki *et al.* 1991; Faber *et al.* 1997; Milosavljević *et al.* 2001, 2002). The orbit shrinks as the binary flings stars away. This decreases the brightness and excavates a core. The effect of a series of mergers is cumulative. *Only if core ellipticals are made in several mergers with mass ratios* ~ 1 *do the resulting BH binaries fling away enough stars to account for the observed cores.*

Why did BH scouring fail in extra light ellipticals? Kormendy & Bender (2009) suggest that starbursts – which are massive (Fig. 12, left) – swamp BH scouring in wet mergers.

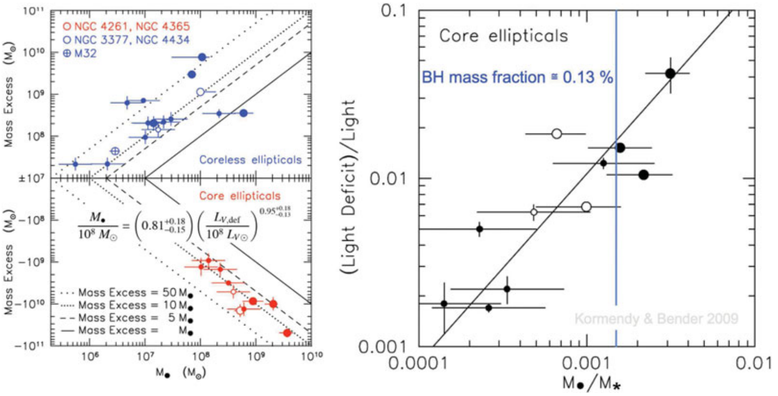


Figure 12. (left) Stellar mass that is 'missing' (in cores, lower panel) or 'extra' (in coreless galaxies, upper panel) as a function of BH mass $M_\bullet$ measured directly using spatially resolved dynamics observations (large symbols) or inferred from σ (small symbols). (right) Fraction of the total V-band luminosity 'missing' in cores versus the ratio of BH mass to the total stellar mass of the galaxy. Filled circles are for ellipticals in the Virgo cluster. From Kormendy & Bender (2009).

11.3. *Maintenance-mode AGN feedback in core ellipticals. II. Importance of X-ray gas*

This brings us to our conclusions about AGN feedback in core ellipticals. If the last (one or several) mergers that make core ellipticals are dry, then quasar-mode feedback presumably cannot operate. A different kind of AGN feedback takes over, as follows.

KFCB suggest that core ellipticals are protected from further gas dissipation and star formation by X-ray-emitting gas that is kept hot by 'maintenance-mode AGN feedback'. Figure 13 (from Bender *et al.* 1989) shows that only core/nonrotating/boxy ellipticals contain large amounts of hot gas. Also, radio ellipticals tend to be core/nonrotating/boxy; coreless/rotating/disky ellipticals are almost always radio-quiet. None of these galaxies have quasar-like BH accretion disks. But radio sources – especially jets – inject substantial energy and momentum into the surrounding hot gas. Evidence reviewed by Cattaneo *et al.* (2009) and by Fabian (2012) supports the idea that this helps to keep the gas hot. Other heating processes exist, too; e. g., continued gas infall from the cosmological hierarchy (Dekel & Birnboim 2006) and recycling of gas lost by dying stars. Further work is required to determine the relative importance of these processes. But this is engineering. The existence of a working surface against which feedback can operate is not in doubt; the Bender *et al.* (2009) results are confirmed by Pellegrini (1999, 2005) and by KFCB.

X-ray gas protection from late star formation is proposed to account for the rapidly quenched star formation implied by α-element enrichment (point 5 in Section 11). This is the '$M_{\rm crit}$ quenching picture' of Cattaneo *et al.* (2006, 2008) and Dekel & Birnboim (2006). A small amount of mass must trickle in to the BH in order to feed AGN activity, but no substantial $M_\bullet$ or M_* growth needs to occur by any means other than dry mergers. So the suggestion is that the role of maintenance-mode AGN feedback is mainly negative, to hold up the completion of galaxy formation by keeping baryons suspended in hot gas.

Meanwhile, the core galaxies at the high-mass end of the BH–galaxy correlations inherit the tightness of the scatter from coreless galaxies that formed by wet mergers (Figure 14). No further magic from AGN feedback is required.

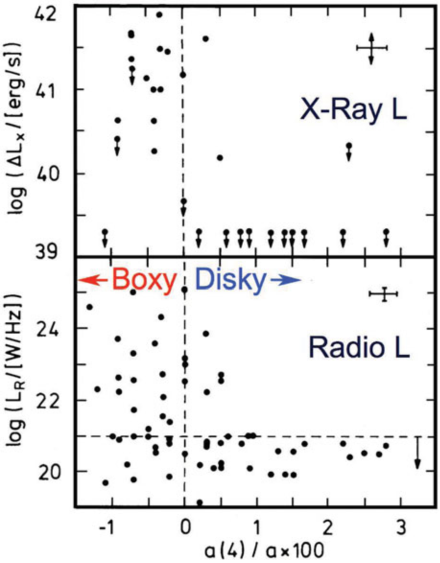


Figure 13. Correlation of (top) X-ray emission from hot gas and (bottom) radio emission with isophote shape parameter a_4 of E galaxies. Boxy isophotes have $a_4 < 0$; disky isophotes have $a_4 > 0$. These correspond to core and coreless galaxies, respectively. From Bender *et al.* (1989).

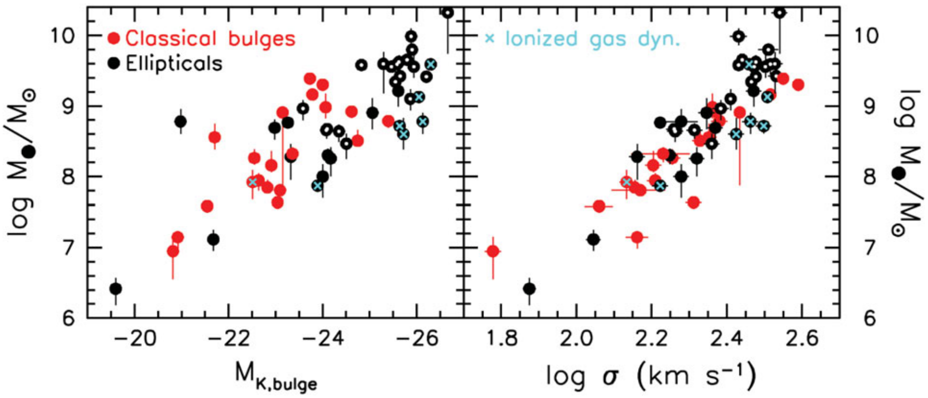


Figure 14. From Figure 2, the $M_\bullet - M_{\rm K,bulge}$ and $M_\bullet - \sigma$ correlations with core galaxies identified using white dots. Core galaxies inherit the tightness of their correlation scatter from coreless galaxies. From Kormendy & Ho (2013).

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