

# Coevolution (or not) of supermassive black holes and host galaxies: Black hole scaling relations are not biased by selection effects

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**Abstract.** The oral version of this paper summarized [Kormendy & Ho 2013](#), ARA&A, 51, 511. However, earlier speakers at this Symposium worried that selection effects bias the derivation of black hole scaling relations. I therefore added – and this proceedings paper emphasizes – a discussion of why we can be confident that selection effects do not bias the observed correlations between BH mass  $M_{\bullet}$  and the luminosity, stellar mass, and velocity dispersion of host ellipticals and classical bulges. These are the only galaxy components that show tight BH–host correlations. The scatter plots of  $M_{\bullet}$  with host properties for pseudobulges and disks are upper envelopes of scatter that does extend to lower BH masses. BH correlations are most consistent with a picture in which BHs coevolve only with classical bulges and ellipticals. Four physical regimes of coevolution (or not) are suggested by [Kormendy & Ho 2013](#) and are summarized here.

**Keywords.** black hole physics, galaxies: bulges, galaxies: elliptical and lenticular, cD, galaxies: evolution, galaxies: kinematics and dynamics, galaxies: nuclei, galaxies: structure

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## 1. Introduction

This is two papers in one, as reflected in the title:

My original aim was to summarize the [Kormendy & Ho \(2013\)](#) review of supermassive black hole (BH) mass measurements and their use to investigate whether host galaxies are influenced by radiative or kinetic feedback while BHs grow by accretion as active galactic nuclei (AGNs).

However, other speakers at this conference (e. g., [Bureau 2019](#)) echo published papers that cast doubts on measurements of BH mass  $M_{\bullet}$  scaling relations. They claim that we are biased toward high  $M_{\bullet}$  because BH spheres of gravitational influence are small, so only the highest- $M_{\bullet}$  BHs are preferentially discovered. I therefore added a demonstration that the BHs which satisfy tight  $M_{\bullet}$ –host galaxy correlations – and *only* those BHs – are discovered in classical bulges and ellipticals with no significant bias in favor of special, compact galaxies with respect to fair samples that include more diffuse objects. I was limited in how much detail I could include in real time. Here, Section 3 enlarges on the evidence that derived  $M_{\bullet}$ –host galaxy correlations are not biased by selection effects.

A point of casting doubt can be to introduce a new technique that comes to the rescue. [Bureau \(2019\)](#) emphasizes that molecular gas kinematic measurements with ALMA, the Atacama Large Millimeter Array, can have higher spatial resolution and certainly have

different and better controlled measurement systematics than does optical spectroscopy. Also, measurements of nuclear megamaser disks do not suffer from optical atmospheric blurring. They can find smaller BHs farther away. In Section 4, I add to published BH scaling relations the new BH detections – most of them from molecular gas kinematics – reported at this meeting. I show that the molecular disk mass measurements define the same BH correlations as do stellar and ionized gas dynamic measurements. This is also true for BH masses derived from maser disk dynamics.

## 2. $M_{\bullet}$ Measurements. I. Halo Dark Matter and Broad Emission Lines

Kormendy & Ho (2013) review  $M_{\bullet}$  measurements. Two techniques require “tweaks”:

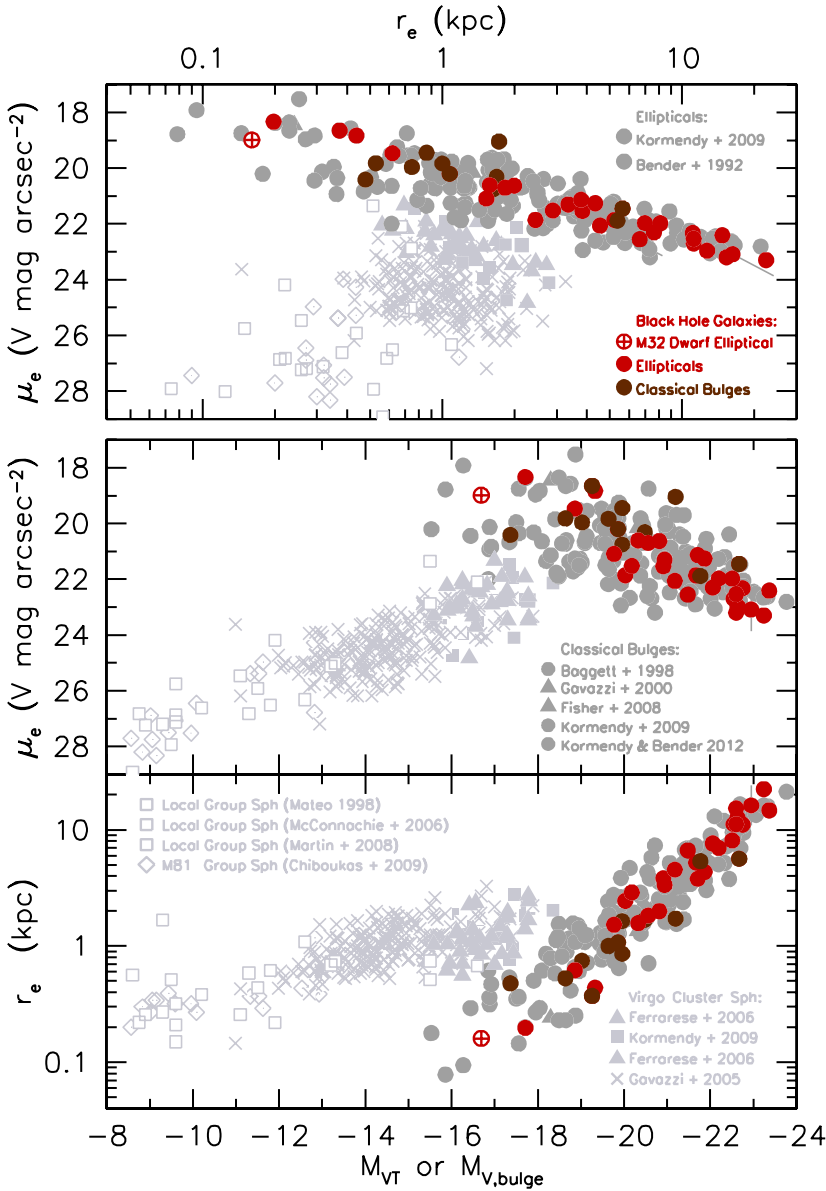
The state of the art for stellar dynamical  $M_{\bullet}$  measurement is Schwarzschild (1979) orbit superposition modeling. This now includes the superposition of tens of thousands of stellar orbital density distributions and the fitting of line-of-sight velocity distributions from two-dimensional spectroscopy. Another improvement is the addition of halo dark matter (DM) to dynamical models (Gebhardt & Thomas 2009; Schulze & Gebhardt 2011; Gebhardt *et al.* 2011; Rusli *et al.* 2013). Adding DM at large radii causes us to decrease the stellar mass-to-light ratio. Because we assume that mass-to-light ratio is independent of radius, we decrease the mass-to-light ratio at small radii, too. Then we have to increase  $M_{\bullet}$  in order to continue to explain high velocities there. This proves to make a bigger difference if the black hole sphere of influence is poorly resolved (Schulze & Gebhardt 2011; Rusli *et al.* 2013). It also tends to be more important for core-nonrotating-boxy ellipticals (see Kormendy *et al.* 2009 for a summary of the division into core and coreless ellipticals). These effects and the improvements in orbit sampling increase our estimates of  $M_{\bullet}$ , in many cases by factors of  $\sim 2$ . In particular, the BH in M 87 is found to have a mass of  $M_{\bullet} = (6.2 \pm 0.4) \times 10^9 M_{\odot}$  (Gebhardt & Thomas 2009; Gebhardt *et al.* 2011).

This is 1.7 times larger than  $M_{\bullet} = (3.6 \pm 1.0) \times 10^9 M_{\odot}$  given by Hubble Space Telescope (HST) spectroscopy of the emission-line rotation curve  $V(r)$  (Macchetto *et al.* 1997). Similarly, the stellar-dynamic  $M_{\bullet}$  is larger than the gas-dynamic estimate for NGC 3998. In both cases and for several other galaxies with emission-line HST  $M_{\bullet}$  measurements, the authors noted that the emission line widths are comparable to the velocity amplitudes. These widths were ignored in the analysis, based on the assumption that gas clouds may have high internal velocity dispersions but may rotate around the center at lower  $V(r)$ . This is dangerous: Nobody makes stellar dynamical models ignoring velocity dispersions. Now, we have independent confirmation of the M 87 BH mass from the Event Horizon Telescope Collaboration (2019),  $M_{\bullet} = (6.5 \pm 0.2 \pm 0.7) \times 10^9 M_{\odot}$ . Kormendy & Ho (2013) omit from BH correlations nine  $M_{\bullet}$  measurements that they conclude are underestimated because broad emission-line widths were ignored. Caution: these underestimated masses are still included in many published derivations of BH correlations.

## 3. $M_{\bullet}$ Measurements. II. Are Sample Selection Effects Important?

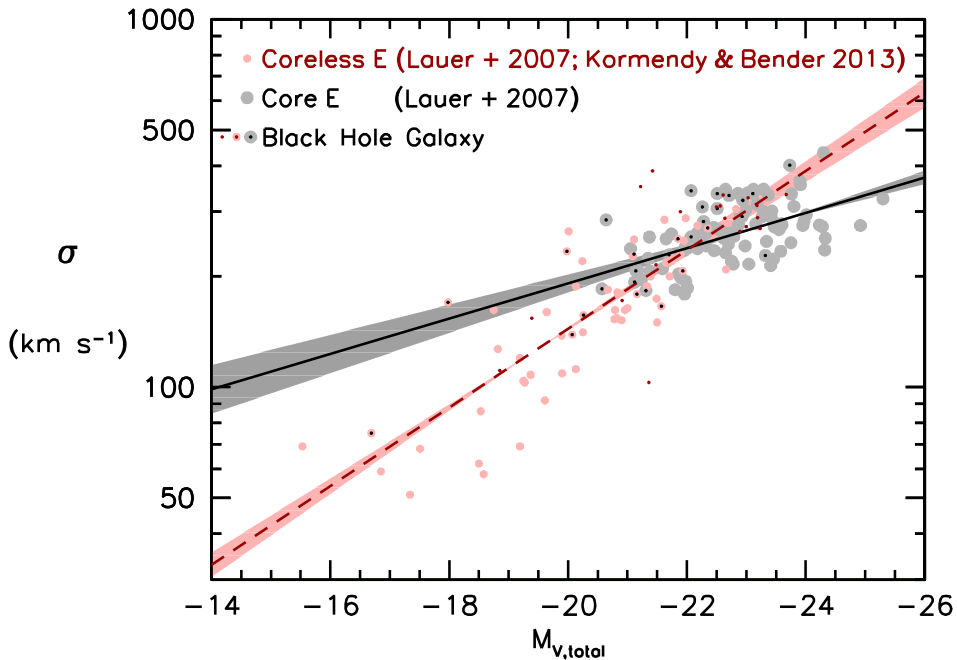
The answer is “no” for the classical bulges and ellipticals that satisfy tight  $M_{\bullet}$ -host correlations but “yes” for pseudobulges and disks that do not satisfy such correlations.

At this meeting, Bureau (2019) and others echo van den Bosch *et al.* (2015) who conclude that BHs are discovered only in “the densest of galaxies, which [are] not representative of the galaxy population at large. This is evident from the distribution of host galaxy properties ... shown in [their] Figure 8. It is striking how the host galaxies trace out a very narrow locus in this parameter space. This is most obvious in the luminosity–size panel, where they lie along a narrow line, sampling preferentially the densest galaxies. Note that the black hole host galaxies are typically denser than the average (early-type) galaxies” (see also van den Bosch 2016).



**Figure 1.** Parameter correlations for elliptical galaxies and classical bulges of disk galaxies (dark gray) and for spheroidal galaxies (lighter gray). The bottom panels show the effective radius  $r_e$  that contains one-half of the  $V$ -band light and the effective surface brightness  $\mu_e$  at  $r_e$  as functions of the total  $V$ -band absolute magnitude of the galaxy component. The top panel shows the [Kormendy \(1977\)](#) relation,  $\mu_e$  versus  $r_e$ ; this projection shows the fundamental plane nearly edge-on and has especially small scatter. Sources are given in the keys [Bender \*et al.\* \(1992\)](#), [Fisher & Drory \(2008\)](#), and [Gavazzi \*et al.\* \(2000\)](#). Galaxies in which supermassive black holes are detected via spatially resolved stellar or gas dynamics are encoded in dark red for ellipticals and dark brown for bulges. This figure is adapted from Figure 16 of [Kormendy & Bender \(2012\)](#), who provide the references in the keys for Sph galaxies.

Figure 1 shows projections of the fundamental plane correlations for ellipticals and classical bulges;  $r_e$  vs.  $M_V$  is the bottom panel. BH detections sample the complete range of parameters for bulges and ellipticals. We do not preferentially find BHs in the most compact galaxies. Contrast unrelated spheroidal galaxies: they are more diffuse.

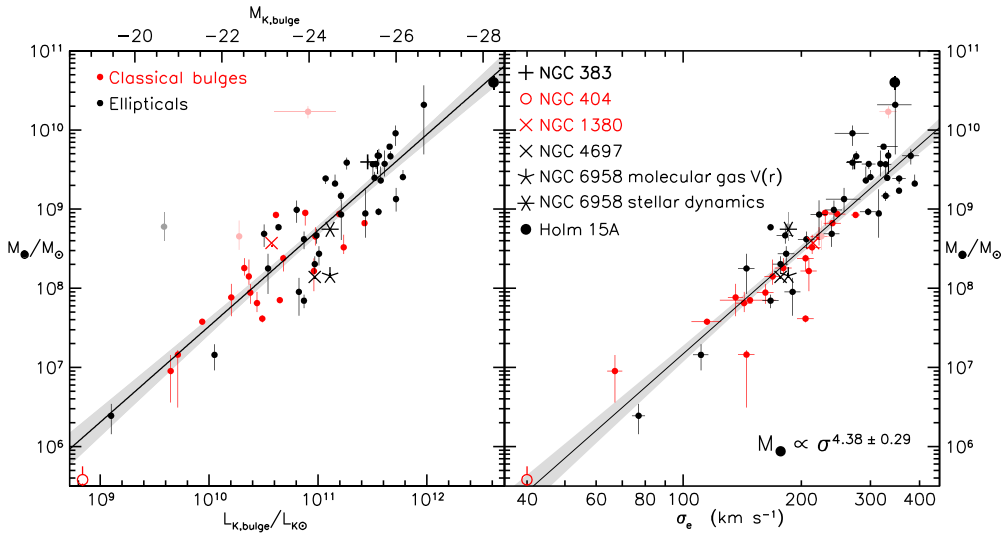


**Figure 2.** Faber & Jackson (1976) correlations for ellipticals with and without a “core”, i. e., a break in the density profile near the center from a steep outer profile to a shallow inner cusp. Total  $V$ -band absolute magnitudes and velocity dispersions are from Lauer *et al.* (2007) with corrections from Kormendy *et al.* (2009) and Kormendy & Bender (2013). This figure is from the latter paper, here labeling galaxies that have BH detections from spatially resolved near-central dynamics. The lines are symmetric least-squares fits (Tremaine *et al.* 2002) to the core galaxies (solid line with gray shading) and the coreless galaxies (dashed line with lighter shading of  $1\text{-}\sigma$  fit uncertainties). The kink at  $\sigma \simeq 250 \text{ km s}^{-1}$  was also emphasized by Lauer *et al.* (2007).

In Figure 1, the scatter for the BH host galaxies is actually smaller than the scatter for the galaxies that define the fundamental plane, both toward compactness (small  $r_e$  and bright  $\mu_e$  at a given  $M_{VT}$ ) and toward diffuseness (large  $r_e$  and faint  $\mu_e$ ). The reason is that the BH hosts tend to be relatively nearby and are studied more accurately (e. g., in Kormendy *et al.* 2009, where many sources of photometry are combined) than the more heterogeneous data on more distant ellipticals and bulges. The fundamental plane is well known to have small intrinsic scatter perpendicular to the plane (e. g., Jørgensen *et al.* 1996). That’s why BH hosts “trace out a very narrow locus in  $[r_e - M_V]$  space” (van den Bosch’s words).

Shankar *et al.* (2016) also worry about  $M_\bullet$  bias: “We confirm that the majority of black hole hosts have significantly higher velocity dispersions  $\sigma$  than local galaxies of similar stellar mass. We use Monte Carlo simulations to illustrate the effect on black hole scaling relations if this bias arises from the requirement that the black hole sphere of influence must be resolved to measure black hole masses with spatially resolved kinematics. We find that this selection effect artificially increases the normalization of the  $M_\bullet$ – $\sigma$  relation by a factor of at least  $\sim 3$ ; the bias for the  $M_\bullet$ – $M_{\text{bulge}}$  relation is even larger.”

Figure 2 shows the Faber & Jackson (1976) correlation between  $\sigma$  and absolute magnitude from Kormendy & Bender (2013). I use this because the galaxies are relatively nearby and well studied; e. g., HST was used to look for cores. BH hosts tend to be high in luminosity; we do not search for BHs in distant, tiny ellipticals for which we know



**Figure 3.** Correlations of BH mass with (*left*)  $K$ -band luminosity and absolute magnitude and (*right*) velocity dispersion of the host elliptical galaxy or classical bulge. This is Figure 17 of Kormendy & Ho (2013) with six galaxies added (see the key). Lines and shaded  $1\text{-}\sigma$  uncertainties are symmetric least-squares fits to the Kormendy & Ho sample. The fits omit BH monsters that have BH mass fractions of  $>10\%$  (two lightly shaded points). Important: this figure omits pseudobulges and major mergers in progress. Pseudobulges show no tight  $M_{\bullet}$ –host correlations. Mergers in progress also do not participate in these correlations: they have undermassive BHs. Only classical bulges and ellipticals as shown here participate in tight  $M_{\bullet}$  correlations that are suggestive of BH–host coevolution. Figures 1 and 2 show that these objects fairly sample the fundamental plane correlations. We see no signs that the detected BH masses are biased by sample selection. And the new BH detections mostly added at this meeting extend and are consistent with the  $M_{\bullet}$ –host correlations.

we don’t have sufficient spatial resolution. But the  $\sigma$  scatter is fairly sampled at least at  $M_V > -22$ . The BH host at  $M_V \simeq -18$  and  $\sigma \simeq 170 \text{ km s}^{-1}$  is NGC 4486B; this is one of the “BH monsters” that lie far above the BH correlations in Figure 3. At  $M_V < -22$ , the core ellipticals that are known to be BH hosts do have slightly higher  $\sigma$  than the galaxies that are not known to be BH hosts. However, *the reason is not that we looked for BHs and failed. If that were the case, then Shankar’s criticism would be valid.* Rather, these are (e. g., more distant) galaxies that have not been searched for BHs. The BH correlations in Figure 3 do not show a kink at  $M_K \simeq -25$  corresponding to  $M_V \simeq -22$  as would be the case if  $M_{\bullet}$  values were fairly sampled at  $M_V > -22$  but, at  $M_V < -22$ , were overestimated by an “even larger” factor than “at least  $\sim 3$ ” as Shankar suggests.

Note in Figure 2 that coreless ellipticals have the well known  $L_V \propto \sigma^4$  correlation, whereas core ellipticals have an  $L_V \propto \sigma^8$  correlation. These are understood to result, respectively, from “wet” major mergers with cold gas dissipation and central starbursts and dissipationless, “dry” mergers in which  $\sigma$  grows only slowly with luminosity  $L_V$ .

Shankar and van den Bosch believe that typical galaxies are more diffuse than BH hosts because they compare to large samples of galaxies measured by the Sloan Digital Sky Survey. These must mainly be far away, so spectroscopic apertures sample large radii that include outward  $\sigma$  decreases and – more importantly – galaxy disks. Also, they do not make bulge-disk decompositions but rather include galaxy disks and pseudobulges in single measurements of  $r_e$ ,  $\mu_e$ , and  $\sigma$ . Pseudobulges and disks are fluffier than classical bulges and ellipticals. They do not participate in BH – host correlations (Section 5).

#### 4. $M_{\bullet}$ –Host Galaxy Correlations for Classical Bulges and Ellipticals

Figure 3 shows the correlations of  $M_{\bullet}$  with the  $K$ -band luminosity and the velocity dispersion of the host bulge measured outside the BH sphere of influence. The intrinsic scatter is essentially the same for both correlations, respectively, 0.30 and 0.28 dex. Using mass-to-light ratios to convert  $L_K$  to bulge stellar mass  $M_{\text{bulge}}$  (Figure 4, bottom left),

$$\frac{M_{\bullet}}{10^9 M_{\odot}} = (0.49^{+0.06}_{-0.05}) \left( \frac{M_{\text{bulge}}}{10^{11} M_{\odot}} \right)^{1.17 \pm 0.08}; \text{ intrinsic scatter} = 0.28 \text{ dex.} \quad (1)$$

The canonical BH-to-bulge mass ratio,  $M_{\bullet}/M_{\text{bulge}} = 0.49^{+0.06}_{-0.05} \%$  at  $M_{\text{bulge}} = 10^{11} M_{\odot}$ , is 2–4 times larger than previous values, because (1) we omit pseudobulges; they do not satisfy  $M_{\bullet}$  correlations; (2) we omit galaxies with  $M_{\bullet}$  measurements based on ionized gas dynamics that do not account for broad emission-line widths; (3) we omit mergers in progress: Kormendy & Ho show that these have undermassive black holes, in part because progenitor disks have undermassive BHs. And (4) many BH masses were revised upward when halo DM and more complete orbit sampling were added to dynamical models.

To further address possible bias in deriving BH – host correlations, I add six new BH mass measurements to Figure 3, five of them reported at this meeting. They are identified in the key; NGC 1380 (Tsukui 2019); NGC 383, NGC 404, and NGC 4697 (Bureau 2019), NGC 6958 (Thater 2019), and Holm 15A (Mehrgan *et al.* 2019).

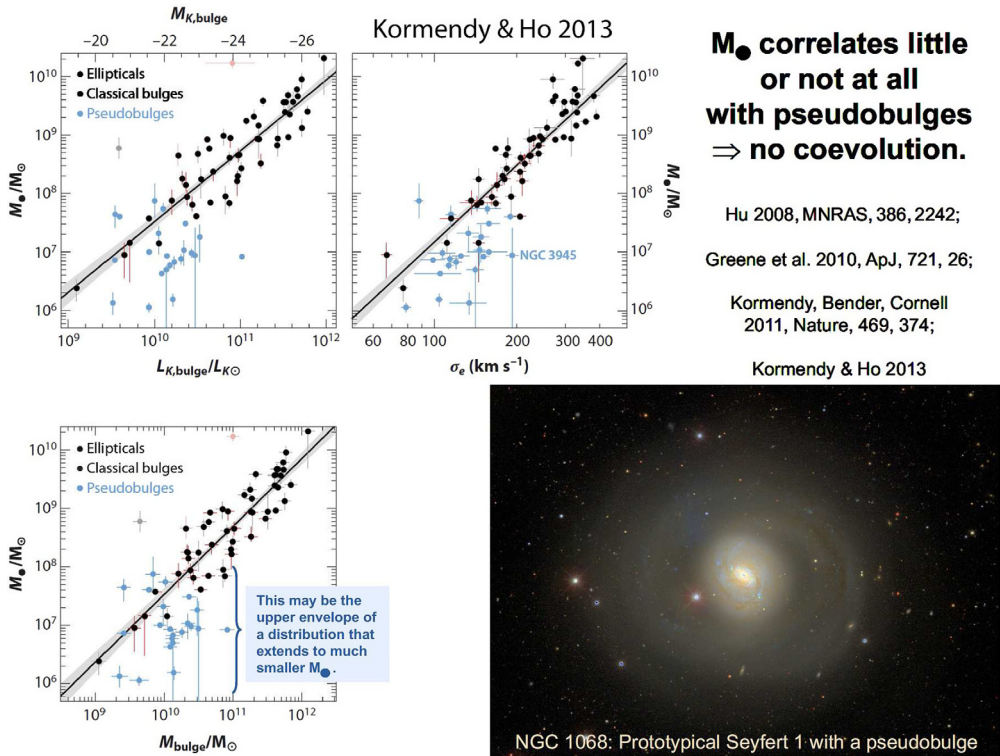
Bureau’s measurement in NGC 4697 of  $M_{\bullet} = 1.39^{+0.07}_{-0.03} \times 10^8 M_{\odot}$  via an ALMA molecular gas rotation curve (scaled to distance 12.54 Mpc as in Kormendy & Ho 2013) is slightly smaller than but consistent with  $M_{\bullet} = 2.02^{+0.51}_{-0.50} \times 10^8 M_{\odot}$  from stellar dynamics. The same appears true of NGC 6958 (all new  $M_{\bullet}$  measurements reported at this meeting are preliminary). If differences persist between ALMA-derived and stellar dynamical  $M_{\bullet}$  measurements, this may point to a systematic error in one or both techniques. If the problem is stellar dynamics, then a likely culprit is the assumption that  $M/L$  is independent of radius. Allowing stellar  $M/L$  to increase toward galaxy centers may decrease BH mass estimates by a few tens of percents (McConnell *et al.* 2013).

All new galaxies except Holm 15A were measured using molecular gas rotation curves. Bureau (2019) emphasizes that they have different systematics from other  $M_{\bullet}$  machinery. Despite his concerns about biases, they are consistent with the Figure 3 correlations.

Agreement between stellar dynamics, ionized gas dynamics, megamaser dynamics, and ALMA-based molecular gas dynamics supports our conclusion (Kormendy & Ho 2013) that the BH – host bulge correlations are robust. The discussion of Section 3 further reassures us that biased BH samples do not significantly affect the derived correlations.

Important: This conclusion applies only to  $M_{\bullet}$  correlations for classical bulges and ellipticals. Section 5 reviews the evidence that  $M_{\bullet}$  shows no such strong correlations with pseudobulges, disks, or dark matter halos. BH searches in such objects have frequently yielded only  $M_{\bullet}$  upper limits. The BH masses observed in these components almost certainly are upper envelopes of BH mass distributions that extend to lower masses.

Returning to astrophysical conclusions: Figure 3 adds the biggest BH discovered so far in the nearby Universe,  $M_{\bullet} = (4.0 \pm 0.8) \times 10^{10} M_{\odot}$  in Holm 15A, the giant elliptical with the largest known core (Mehrgan *et al.* 2019). It extends the  $M_{\bullet}$ – $L_{K,\text{bulge}}$  correlation toward larger luminosities and strengthens an important conclusion that has become evident as we find more giant BHs. As concluded by Kormendy & Ho (2013) and as seen also by McConnell *et al.* (2011), the  $M_{\bullet}$ – $\sigma$  correlation “saturates” at  $\sigma \sim 250 \text{ km s}^{-1}$ . For velocity dispersions higher than this value,  $\sigma$  grows slowly or not at all as  $M_{\bullet}$  increases. Figure 2 indicates why: Core galaxies are remnants of dry mergers in which  $\sigma$  grows only slowly while  $M_{\text{bulge}}$  and  $M_{\bullet}$  grow rapidly in successive mergers. If the Faber–Jackson



**Figure 4.** Powerpoint slide showing the correlations (or lack of correlations) of BH mass  $M_{\bullet}$  with (left)  $K$ -band luminosity and stellar mass and (right) velocity dispersion of the host elliptical, classical bulge, or pseudobulge. Classical bulges and ellipticals participate in tight correlations with intrinsic scatter  $\sim 0.28$  dex. *Pseudobulge BHs (lightly shaded) show no significant correlation with their hosts.* This is Figure 21 of Kormendy & Ho (2013) adding references and a Sloan Digital Sky Survey *gri* color image of the Seyfert galaxy NGC 1068, a prototypical unbarred but oval (R)SAB galaxy with a pseudobulge. Another such galaxy is the Seyfert NGC 4151.

relation has a kink at  $M_V \sim -22$  and  $\sigma \sim 250$  km s $^{-1}$ , then  $M_{\bullet}$ - $L$  and  $M_{\bullet}$ - $\sigma$  cannot both be straight lines in Figure 3, without a kink. Holm 15A and other giant ellipticals define a single, straight correlation between  $\log M_{\bullet}$  and  $\log L$  or  $\log M_{\text{bulge}}$  (Equation 1). The more famous  $M_{\bullet}$ - $\sigma$  correlation has a kink at large  $M_{\bullet}$  and  $\sigma$ . This possibility was foreseen by Lauer *et al.* (2007).

## 5. $M_{\bullet}$ Does Not Correlate with Pseudobulges, Disks, or Dark Matter

Figure 4 repeats the  $M_{\bullet}$  correlations with  $K$ -band luminosity and velocity dispersion of the host classical bulge and elliptical and adds the correlation with bulge stellar mass derived using mass-to-light ratios zeropointed to SAURON dynamical models (Cappellari *et al.* 2006; Williams *et al.* 2009). Pseudobulges are added in light blue shading. They demonstrate the result (Hu 2008; Greene *et al.* 2010; Kormendy *et al.* 2011; Kormendy & Ho 2013) that BH masses do not correlate tightly enough with pseudobulges to be suggestive of BH-host coevolution. Since coevolution generally involves feedback that controls star formation, it is worth emphasizing that pseudobulges are *not* quenched in their star formation. Rather, they form stars very vigorously, at least as vigorously as their associated disks (Kormendy & Kennicutt 2004; Fisher 2006; Fisher *et al.* 2009).

Recognition of pseudobulges as distinct from elliptical-galaxy-like classical bulges is part of a picture of the slow, “secular” evolution of disk galaxies that complements our picture of hierarchical clustering (Kormendy 1993; Kormendy & Kennicutt 2004; Kormendy 2013 provide reviews). Prototypical examples occur in the globally oval disk galaxies NGC 1068 (Figure 4), NGC 4151, and especially NGC 4736. Bars and oval disks transport disk angular momentum outward and rearrange disk gas into outer rings (NGC 1068 shows an example), inner rings that encircle the ends of bars, and gas that falls toward the center. There, high gas densities drive strong star formation as described by the Schmidt (1959)–Kennicutt (1998a,b) law. The result is to make both ring types visible in starlight and to build, near the center, a compact stellar component that was grown slowly out of the disk, not assembled rapidly via galaxy mergers. These high-density centers were misidentified as classical bulges by early morphologists (e. g., Hubble 1936; de Vaucouleurs 1959; Sandage 1961) and so are called “fake bulges” or “pseudobulges”. They recognizably remember their disky origin – they are flatter than classical bulges, often as flat as their outer disks; they are more rotationally supported, i. e.,  $V/\sigma$  is larger than in classical bulges; they often show spiral structure and nuclear bars that can only be sustained in flat, cold disks, and (except in S0s) they show vigorous star formation. Central components in BH disk galaxies were classified as classical or pseudo before the BH correlations were derived. It is a success of the secular evolution picture that classical and pseudo bulges then prove to correlate differently with their BHs. Many of these BHs are actively accreting AGNs (e. g., NGC 1068 and NGC 4151). This is part of the evidence that feedback from AGNs does not quench the star formation or otherwise influence the evolution of galaxy disks.

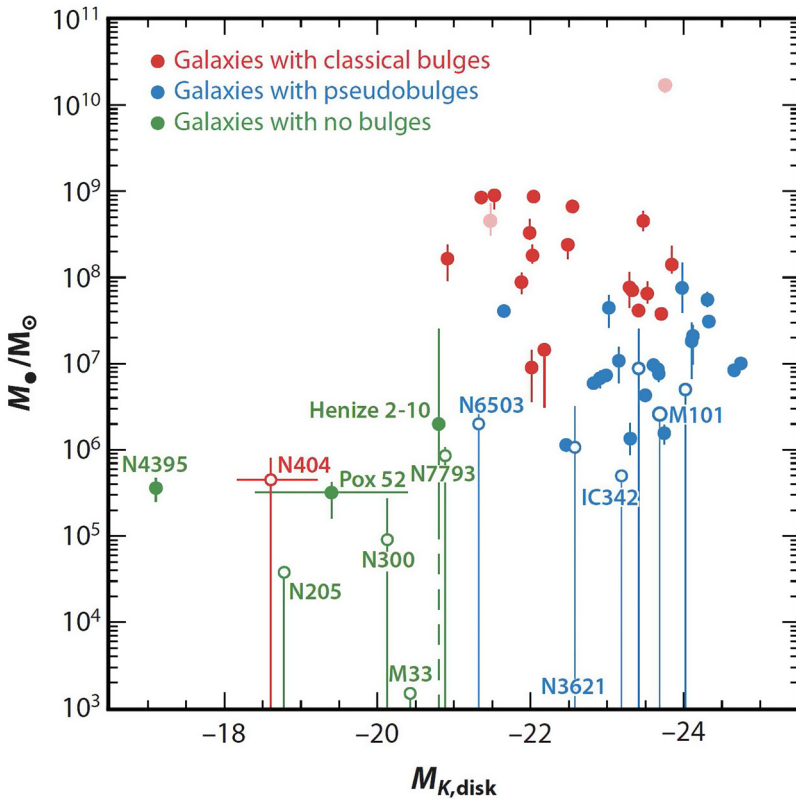
A further indication that BHs do not affect disk evolution is the observation that BH masses do not correlate with the  $K$ -band luminosities and hence the stellar masses of disks. This is shown in Figure 5. Not surprisingly, for disk galaxies with BH discoveries,  $M_{\bullet}$  correlates less well with total galaxy luminosity and stellar mass than it does with classical bulge properties.

Finally,  $M_{\bullet}$  does not correlate with DM halos beyond the correlation implied by Figure 3. This result is unpopular with galaxy formation theorists, especially numerical modelers who add baryon physics to simulations of DM hierarchical clustering. DM mass  $M_{\text{DM}}$  is arguably the most fundamental parameter associated with a galaxy, and it would have been convenient if it controlled galaxy evolution partly via AGN feedback. Unfortunately, this is not the case, as suggested already by the fact that dwarf ellipticals such as M 32 participate in tight  $M_{\bullet}$  correlations whereas giant disks such as M 101 do not.

Ferrarese (2002) and Baes *et al.* (2003) suggested that  $M_{\bullet}$  *does* correlate with  $M_{\text{DM}}$ . Their conclusions seem to reflect the conspiracy that baryons and DM are arranged so  $V(r)$  is featureless even though baryons dominate at small  $r$  and DM dominates at large  $r$ .

Kormendy & Bender (2011) and Kormendy & Ho (2013) present seven arguments against the hypothesis that  $M_{\bullet}$  correlates fundamentally with  $M_{\text{DM}}$ . One is illustrated in Figure 6. The correlation of galaxy stellar mass  $M_{\star}$  with DM mass  $M_{\text{DM}}$  is complicated. The ratio  $M_{\star}/M_{\text{DM}}$  is largest at  $M_{\text{DM}} \equiv M_{\text{crit}} = 10^{12} M_{\odot}$ , the critical mass above which galaxies can gravitationally hold onto large amounts of hot, X-ray-emitting gas. This keeps baryons increasingly suspended in hot gas – not stars – in bigger galaxies, accounting for the decrease in  $M_{\star}/M_{\text{DM}}$  at larger  $M_{\text{DM}}$ . The decrease in  $M_{\star}/M_{\text{DM}}$  at  $M_{\text{DM}} \ll 10^{12} M_{\odot}$  is believed to result from more supernova-driven baryon ejection in smaller galaxies. As a result, the correlation of  $M_{\bullet}$  with  $M_{\text{DM}}$  must be very different at  $M_{\text{DM}} \ll 10^{12} M_{\odot}$  and at  $M_{\text{DM}} \gg 10^{12} M_{\odot}$ . But the correlation of  $M_{\bullet}$  with  $M_{\star} \equiv M_{\text{bulge}}$  is continuous across  $M_{\text{DM}} = 10^{12} M_{\odot}$ . Thus Equation 1 appears to be the fundamental correlation.





**Figure 5.** BH mass vs.  $K$ -band absolute magnitude of the host disk (Figure 22 of Kormendy & Ho 2013). Solid symbols represent BH detections; open symbols are for BH mass upper limits. BH masses do not correlate with properties of their host disks. At  $M_{K,disk} \simeq -21 \pm 1$ , BH masses range from detections with  $M_{\bullet} \simeq 10^9 M_{\odot}$  to the upper limit of  $1500 M_{\odot}$  in M 33 (Gebhardt *et al.* 2001; Merritt *et al.* 2001).

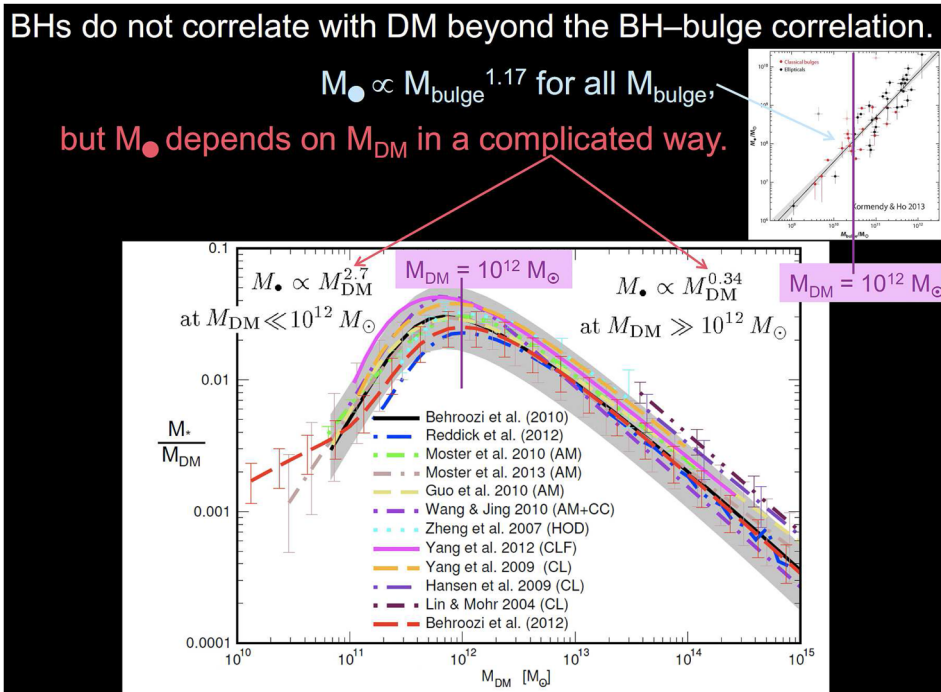
## 6. Four Regimes of BH – Host Galaxy Coevolution

This review concentrates on the demographics of BHs discovered via spatially resolved stellar or gas dynamics in and near the sphere-of-influence radius of the BH. BHs in classical bulges and ellipticals are typically discovered using spatial resolution  $\gtrsim 4$  times the radius of the BH sphere of influence (Kormendy & Ho 2013, Figure 1). This was true even for the BHs discovered using ground-based spectroscopy before HST became available. Most of these BHs could still have been discovered if they were several times less massive. But they weren't. The conclusion that  $M_{\bullet}$  correlates tightly with the luminosity, stellar mass, and velocity dispersion of host classical bulges and ellipticals is robust.

On the other hand,  $M_{\bullet}$  is found not to correlate with any other structural component in galaxies – not pseudobulges, not disks, and not dark matter halos. This, together with other evidence reviewed in Kormendy & Ho (2013), allows us to refine our picture of when BHs do and when they do not coevolve with their hosts. We suggest that there are four distinct regimes of coevolution. Quoting from our review:

“(1) Local, secular, episodic, and stochastic feeding of small BHs in largely bulgeless galaxies involves too little energy to result in coevolution.”

“(2) Global feeding in major, wet galaxy mergers rapidly grows giant BHs in short-duration, quasar-like events whose energy feedback does affect galaxy evolution. The resulting hosts are classical bulges and coreless-rotating-disky ellipticals.”



**Figure 6.** Powerpoint slide illustrating one argument why we conclude (Kormendy & Bender 2011; Kormendy & Ho 2013) that  $M_{\bullet}$  does not correlate with dark matter (DM) halos beyond the known correlation with the masses of classical bulges and ellipticals. The correlation (inset) of  $M_{\bullet}$  with stellar masses  $M_*$  of bulges and ellipticals is continuous across the dark matter transition mass  $M_{DM} \simeq 10^{12} M_{\odot}$ , but the correlation of stellar mass  $M_*$  (or  $M_*/M_{DM}$  as illustrated here from Behroozi *et al.* 2013) changes slope sharply at  $M_{DM} \simeq 10^{12} M_{\odot}$ . Therefore the correlation of  $M_{\bullet}$  with  $M_{DM}$  must be different at  $M_{DM} \gg 10^{12} M_{\odot}$  and at  $M_{DM} \ll 10^{12} M_{\odot}$ . Arrows point to these different correlations. The references in the key are not included here.

“(3) After these AGN phases and at the highest galaxy masses, maintenance-mode BH feedback into X-ray-emitting gas has the primarily negative effect of helping to keep baryons locked up in hot gas and thereby keeping galaxy formation from going to completion. This happens in giant, core-nonrotating-boxy ellipticals. Their properties, including tight correlations between  $M_{\bullet}$  and core parameters [Kormendy & Bender 2009], support the conclusion that core ellipticals form by dissipationless major mergers. They inherit coevolution effects from smaller progenitor galaxies.”

“(4) Independent of any feedback physics, in BH growth modes 2 and 3, the averaging that results from successive mergers plays a major role in decreasing the scatter in  $M_{\bullet}$  correlations from the large values observed in bulgeless and pseudobulge galaxies to the small values observed in giant elliptical galaxies” (Peng 2007; Gaskell 2010; Hirschmann *et al.* 2010; Jahnke & Macciò 2011). It is no accident that pseudobulge BH masses range from the largest  $M_{\bullet}$  observed in ellipticals of similar mass down to much smaller masses. Mergers convert pseudobulges into classical bulges and ellipticals, adding new stars in starbursts, merging the progenitor BHs, and in general growing the remnant BHs further by gas accretion.

## 7. Conclusions

Figure 7 lists astrophysical conclusions of this paper, echoing Kormendy & Ho (2013). I also emphasize the practical conclusion of this paper:

**TAKE-AWAY POINTS**

I know of no convincing evidence that BHs “coevolve” with disk galaxies, i. e., that feedback from BH accretion affects disk evolution. Feedback from star formation looks much more important.

The era of BH – galaxy coevolution was  $z \sim 1 - 3$  and maybe before. The era of BH – galaxy coevolution is now mostly over.  
E. g., major mergers of Es with disks now damage the correlation. But E – E major mergers still tighten the correlation (central limit theorem).

The “arena” in which to look for BH – galaxy coevolution is quasar mode AGN feedback in wet mergers with dust-shrouded starbursts (ULIRGs) at  $z \sim 0$  and submm galaxies at  $z > 1$ ) that make disky-rotating Es.

The fundamental feature that makes coevolution work may be quasar feedback (radiative or kinetic or both) into the working surface of  
(1) 3-dimensional surrounding gas  
(2) that is opaque (e. g., Hopkins et al. 2006, ApJS, 163, 1).

**Figure 7.** Powerpoint slide of astrophysical conclusions of this paper of this paper (see also [Hopkins et al. 2006](#)).

Selection effects do not invalidate the  $M_{\bullet}$  correlations shown here and in [Kormendy & Ho \(2013\)](#). Only classical bulges and elliptical galaxies participate in tight correlations of  $M_{\bullet}$  with the stellar mass and velocity dispersion of the host (intrinsic scatter  $\simeq 0.28$  dex). Classical bulges and ellipticals are well sampled over the complete range of their masses; objects with BH detections sample essentially completely the tight fundamental plane correlations of their hosts. In contrast, BH searches frequently fail for pseudobulges and disks: the BHs that we detect in these objects are very likely to be the high- $M_{\bullet}$  part of a scatter that extends to lower  $M_{\bullet}$  masses. Thus our picture of disk secular evolution ([Kormendy 1993](#); [Kormendy & Kennicutt 2004](#); [Kormendy 2013](#)) is an indispensable part of our understanding of how BHs do and do not coevolve with their host galaxies.

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### References

- Baes, M., Buyle, P., Hau, G. K. T., & Dejonghe, H. 2003, *MNRAS*, 341, L44  
 Baggett, W. E., Baggett, S. M., & Anderson, K. S. J. 1998, *AJ*, 116, 1626  
 Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, *ApJ*, 770, 57  
 Bender, R., Burstein, D., & Faber, S. M. 1992, *ApJ*, 399, 462  
 Bureau, M. 2019, in IAU Symposium 353, Galactic Dynamics in the Era of Large Surveys, ed. M. Valluri & J. A. Sellwood (Cambridge: Cambridge University Press), in press

- Cappellari, M., Bacon, R., Bureau, M., *et al.* 2006, *MNRAS*, 366, 1126
- de Vaucouleurs, G. 1959, *Handbuch der Physik*, 53, 275
- Event Horizon Telescope Collaboration 2019, *ApJ*, 875, L6
- Faber, S. M. & Jackson, R. E. 1976, *ApJ*, 204, 668
- Ferrarese, L. 2002, *ApJ*, 578, 90
- Fisher, D. B. 2006, *ApJ*, 642, L17
- Fisher, D. B. & Drory, N. 2008, *AJ*, 136, 773
- Fisher, D. B., Drory, N., & Fabricius, M. H. 2009, *ApJ*, 697, 630
- Gaskell, C. M. 2010, in *The First Stars and Galaxies: Challenges for the Next Decade*, ed. D. J. Whalen *et al.* (Melville, NY: AIP), 261
- Gavazzi, G., Franzetti, P., Scodreggio, M., Boselli, A., & Pierini, D. 2000, *A&A*, 361, 863
- Gebhardt, K., Adams, J., Richstone, D., *et al.* 2011, *ApJ*, 729, 119
- Gebhardt, K., Lauer, T. R., Kormendy, J., *et al.* 2001, *AJ*, 122, 2469
- Gebhardt, K. & Thomas, J. 2009, *ApJ*, 700, 1690
- Greene, J. E., Peng, C. Y., Kim, M., *et al.* 2010, *ApJ*, 721, 26
- Hirschmann, M., Khochfar, S., Burkert, A., *et al.* 2010, *MNRAS*, 407, 1016
- Hopkins, P. F., Hernquist, L., Cox, T. J., *et al.* 2006, *ApJS*, 163, 1
- Hu, J. 2008, *MNRAS*, 386, 2242
- Hubble, E. P. 1936, *The Realm of the Nebulae* (New Haven: Yale University Press)
- Jahnke, K. & Macciò, A. V. 2011, *ApJ*, 734, 92
- Jørgensen, I., Franx, M., & Kjaergaard, P. 1996, *MNRAS*, 280, 167
- Kennicutt, R. C. 1998a, *ApJ*, 498, 541
- Kennicutt, R. C. 1998b, *ARA&A*, 36, 189
- Kormendy, J. 1977, *ApJ*, 218, 333
- Kormendy, J. 1993, in *IAU Symposium 153, Galactic Bulges*, ed. H. Dejonghe & H. J. Habing (Dordrecht: Kluwer), 209
- Kormendy, J. 2013, in *XXIII Canary Islands Winter School of Astrophysics, Secular Evolution of Galaxies*, ed. J. Falcón-Barroso & J. H. Knapen (Cambridge: Cambridge University Press), 1 ([arXiv:1311.2609](https://arxiv.org/abs/1311.2609))
- Kormendy, J. & Bender, R. 2009, *ApJ*, 691, L142
- Kormendy, J. & Bender, R. 2011, *Nature*, 469, 377
- Kormendy, J. & Bender, R. 2012, *ApJS*, 198, 2
- Kormendy, J. & Bender, R. 2013, *ApJ*, 769, L5
- Kormendy, J., Bender, R., & Cornell, M. E. 2011, *Nature*, 469, 374
- Kormendy, J., Fisher, D. B., Cornell, M. E., & Bender, R. 2009, *ApJS*, 182, 216
- Kormendy, J. & Ho, L. C. 2013, *ARA&A*, 51, 511
- Kormendy, J. & Kennicutt, R. C. 2004, *ARA&A*, 42, 603
- Lauer, T. R., Faber, S. M., Richstone, D., *et al.* 2007, *ApJ*, 662, 808
- Macchetto, F., Marconi, A., Axon, D. J., *et al.* 1997, *ApJ*, 489, 579
- McConnell, N. J., Chen, S.-F. S., Ma, C.-P., *et al.* 2013, *ApJ*, 768, L21
- McConnell, N. J., Ma, C.-P., Gebhardt, K., *et al.* 2011, *Nature*, 480, 215
- Mehrgan, K., Thomas, J., Saglia, R., *et al.* 2019, *ApJ*, 887, 195
- Merritt, D., Ferrarese, L., & Joseph, C. L. 2001, *Science*, 293, 1116
- Peng, C. Y. 2007, *ApJ*, 671, 1098
- Rusli, S. P., Thomas, J., Saglia, R. P., *et al.* 2013, *AJ*, 146, 45
- Sandage, A. 1961, *The Hubble Atlas of Galaxies* (Washington: Carnegie Institution of Washington)
- Schmidt, M. 1959, *ApJ*, 129, 243
- Schulze, A. & Gebhardt, K. 2011, *ApJ*, 729, 21
- Schwarzschild, M. 1979, *ApJ*, 232, 236
- Shankar, F., Bernardi, M., Sheth, R. K. *et al.* 2016, *MNRAS*, 460, 3119
- Thater, S. 2019, in *IAU Symposium 353, Galactic Dynamics in the Era of Large Surveys*, ed. M. Valluri & J. A. Sellwood (Cambridge: Cambridge University Press), in press
- Tremaine, S., Gebhardt, K., Bender, R., *et al.* 2002, *ApJ*, 574, 740

- Tsukui, T. 2019, in IAU Symposium 353, Galactic Dynamics in the Era of Large Surveys, ed. M. Valluri & J. A. Sellwood (Cambridge: Cambridge University Press), in press
- van den Bosch, R. C. E. 2016, *ApJ*, 831, 134
- van den Bosch, R. C. E., Gebhardt, K., Gültekin, K., Yıldırım, A., & Walsh, J. E. 2015, *ApJS*, 218, 10
- Williams, M. J., Bureau, M., & Cappellari, M. 2009, *MNRAS*, 400, 1665