Effects of inclination on measuring velocity dispersion and implications for black holes

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ABSTRACT
The relation of central black hole mass and stellar spheroid velocity dispersion (the M–σ relation) is one of the best-known and tightest correlations linking black holes and their host galaxies. There has been much scrutiny concerning the difficulty of obtaining accurate black hole measurements, and rightly so; however, it has been taken for granted that measurements of velocity dispersion are essentially straightforward. We examine five disc galaxies from cosmological SPH simulations and find that line-of-sight effects due to galaxy orientation can affect the measured σlos by 30 per cent, and consequently black hole mass predictions by up to 1.0 dex. Face-on orientations correspond to systematically lower velocity dispersion measurements, while more edge-on orientations give higher velocity dispersions, due to contamination by disc stars when measuring line-of-sight quantities. We caution observers that the uncertainty of velocity dispersion measurements is at least 20 km s⁻¹ and can be much larger for moderate inclinations. This effect may account for some of the scatter in the locally measured M–σ relation, particularly at the low-mass end. We provide a method for correcting observed σlos values for inclination effects based on observable quantities.

Key words: methods: numerical – galaxies: bulges – galaxies: kinematics and dynamics – galaxies: spiral.

1 INTRODUCTION
One of the most critical discoveries in recent years is the apparent co-evolution of central supermassive black holes (SMBHs) and their host galaxy spheroids. This phenomenon, often represented in scaling relations such as M–σ, MBH–Mbulge, or MBH–Lbulge, has been observed to hold over several orders of magnitude of SMBH mass and a variety of galaxy properties (e.g. Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002; Marconi & Hunt 2003; Haring & Rix 2004; Gültekin et al. 2009; Graham et al. 2011; McConnell & Ma 2013). Further observational campaigns suggest that these relations may evolve with redshift (Peng et al. 2006; Treu et al. 2007; Woo et al. 2008; Decarli et al. 2010; Bennert et al. 2011), though others refute this claim (Lauer et al. 2007; Volonteri & Stark 2011; Schulze & Wisotzki 2014). The M–σ relation is a key constraint on any theory of the interplay between SMBH growth and galaxy evolution (e.g. Loeb & Rasio 1994; Haehnelt & Kauffmann 2000; Granato et al. 2001; Menou, Haiman & Narayan 2001; Di Matteo, Springel & Hernquist 2005; Wyithe & Loeb 2005; Croton et al. 2006; Micic et al. 2007; Hopkins et al. 2008; Tanaka & Haiman 2009; Volonteri & Natarajan 2009; Micic, Holley-Bockelmann & Sigurdsson 2011; Bellovary et al. 2013; Kormendy & Ho 2013). This relation is so well accepted that both theoretical and observational studies use the M–σ fit to scale the SMBH mass within a galaxy when not directly observable (Volonteri, Haardt & Madau 2003; Somerville et al. 2008; Wild, Heckman & Charlot 2010). To build a theory of...
SMBH assembly in the context of galaxy evolution, it is clear that we need both accurate measurements of SMBH mass and bulge velocity dispersion, and a deep understanding of the biases and limits of these measurements.

Much scrutiny has been given to the difficulty of measuring SMBH masses, and for good reason; accurate mass measurements are very difficult and require a large investment of observational resources and careful analysis. However, measuring the velocity dispersion, $\sigma$, of a galaxy spheroid is also non-trivial. The galaxy orientation is imprinted on any observational measurement of $\sigma$, and unless we understand how this effect biases $\sigma$, we are at the mercy of the structure and viewing angle of every galaxy we observe. Velocity dispersions are commonly measured spectroscopically via the widths of stellar absorption lines, but it is difficult to isolate the light from spheroid stars from those of the disc. Every measurement of $\sigma$ of the spheroid, therefore, will be contaminated by the kinematics of other galaxy components.

One way to examine the effect of orientation on measurements of $\sigma$ is through simulations. A simulated galaxy can be rotated and viewed at any orientation, and can be analysed to determine the intrinsic galaxy properties with no observational biases. We employ a sample of disc-dominated galaxies and examine how the viewing angle affects the apparent central velocity dispersion. We choose disc galaxies because the effects of orientation will be the most severe, and we wish to investigate the repercussions for the low-mass end of the $M-\sigma$ relation, which exhibits relatively large scatter. The scatter has been postulated to be due to evolutionary effects, such as merger history and environment (Kormendy, Bender & Cornell 2011; Micic et al. 2011; Mathur et al. 2012), and is dependent on galaxy mass, morphology, and bulge/disc ratio, among other things (Hu 2008; Graham & Li 2009). However, another possibility is that some (or all) of the scatter is actually caused by orientation effects (Gebhardt et al. 2000), which include line-of-sight contamination from disc and halo stars as well as non-symmetric bulge effects and bulge rotation. It is thus critical to quantify the effect of viewing angle when measuring $\sigma$; our understanding of how SMBHs and galaxies grow depends on it.

In this paper, we examine five disc-dominated simulated galaxies with a range of masses and bulge sizes. These galaxies are selected from ‘zoomed-in’ cosmological simulations and have realistic star formation histories, baryon and gas fractions, and bulge and disc scalelengths. In Section 2, we describe these simulations in detail, along with our methodology for measuring $\sigma$. In Section 3, we present our results and provide a correction factor for observed values of $\sigma$. In Sections 4 and 5, we discuss the repercussions for the observed $M-\sigma$ relation and summarize the work.

## 2 SIMULATIONS AND VELOCITY DISPERSION MEASUREMENTS

We use the N-Body smoothed particle hydrodynamics code GASOLINE (Stadel 2001; Wadsley, Stadel & Quinn 2004) to create ‘zoomed-in’ cosmological simulations of disc galaxies with a range of masses. A cosmological context is critical for this study, since it is important that galaxy bulges build naturally without assumptions as to the kinematics of the bulge or disc stars. We select our galaxies from a uniform, dark matter only 50 comoving Mpc box, and resimulate them using the volume renormalization method of Katz & White (1993) to better resolve our regions of interest. In a box of this size, the fundamental mode is non-linear; while this effect changes the number and structure of the most massive haloes, it has negligible effect on the centres of Milky Way galaxies. Our gas, dark, and star particle masses are $m_{\text{gas}} = 2.7 \times 10^4 \, M_\odot$, $m_{\text{dark}} = 1.3 \times 10^5 \, M_\odot$ and $m_{\text{star}} = 8.0 \times 10^4 \, M_\odot$, respectively, and the force resolution is 174 pc. The initial conditions were generated with a WMAP 3 cosmology (Spergel 2007) and were run from $z = 150$ to $z = 0$. At $z = 9$, a uniform ionizing UV background appears, following the model of Haardt & Madau (2001). We identify individual galaxies using the tool AHF (Gill, Knebe & Gibson 2004; Knollmann & Knebe 2009), which finds spherical overdensities with respect to the critical density. Changing the cosmology and reionization technique may affect the total luminosity function and formation time of low-mass haloes, but has little effect on the spheroid velocity dispersion or bulge-to-disc ratios of our selected galaxies.

Gas cooling occurs via metal lines (described in Shen, Wadsley & Stinson 2010) and $H_2$ (Christensen et al. 2012). This low-temperature cooling, in combination with $H_2$ self-shielding and the dust shielding of $H_1$ and $H_2$, allows gas to reach the high densities ($\rho \sim 100$ amu cm$^{-3}$) and low temperatures ($\lesssim 1000$K) needed to appropriately model star formation in cosmological simulations (Governato et al. 2012). Star formation is dependent on the $H_2$ fraction (which itself depends on metallicity and the self-shielding ability of the gas). Star particles are born with a Kroupa IMF (Kroupa 2001), which dictates the occurrence of supernovae. Each supernova deposits $10^{51}$ erg of energy into the ISM within a blast radius described by McKee & Ostriker (1977). The gas particles within the blast radius have their cooling ability quenched until such time as the blastwave equations allow. This process mimics a supernova remnant through the snowplow phase and is described in detail in Stinson et al. (2006). We anticipate minimal effect of the choice of IMF or supernova feedback prescription on the structure and kinematics of the bulge in these galaxies. We do not include SMBH physics in these simulations; we discuss the repercussions in Section 5. In short, while activity from SMBHs is expected to modify the central regions of galaxies, such phenomena are more pronounced among galaxies more massive than L* (Fanidakis et al. 2013), and we do not expect a significant effect here.

From each simulation, we use the primary galaxy at redshift $z = 0$, whose properties are detailed in Table 1. Our sample spans a range of $3-9 \times 10^{11} \, M_\odot$ in total mass and each galaxy has a prominent bulge and disc (see Fig. 1 for examples). We focus on disc galaxies because elliptical galaxies will have less variation in their velocity dispersion measurements due to orientation effects, and we are specifically interested in the low-mass end of the $M-\sigma$ relation. All of the systems we study are relaxed at $z = 0$ (for an interesting analysis of measuring $\sigma$ in merging galaxies see Stickley & Canalizo 2014). The five simulated galaxies for which we measure bulge velocity dispersion have made previous appearances.

| Table 1. Simulation properties. |
|---------------------------------|
| Run   | $N$ within $R_{\text{vir}}$ (10$^9$) | $M_{\text{vir}}$ ($10^{11} M_\odot$) | $M_{\text{star}}$ ($10^{10} M_\odot$) | $R_{\text{vir}}$ (kpc) | $R_{\text{eff}}$ (kpc) |
|-------|---------------------------------|---------------------------------|---------------------------------|----------------|----------------|
| h239  | 17.2                            | 9.13                            | 4.50                            | 250            | 2.16            |
| h258  | 15.3                            | 7.74                            | 4.46                            | 237            | 2.01            |
| h277  | 13.9                            | 6.79                            | 4.24                            | 227            | 2.41            |
| h285  | 16.6                            | 8.82                            | 4.56                            | 248            | 4.00            |
| h603  | 21.8                            | 3.43                            | 0.78                            | 181            | 3.77            |

Column 1: simulation name. Column 2: number of particles within $R_{\text{vir}}$. Column 3: total mass within $R_{\text{vir}}$. Column 4: stellar mass within $R_{\text{vir}}$. Column 5: the virial radius $R_{\text{vir}}$. Column 6: $R_{\text{eff}}$ in the V band measured for a face-on orientation.
in the literature in Zolotov et al. (2012), Loebman et al. (2012), Christensen et al. (2014a,b) and Munshi et al. (2013). GASOLINE has proven to simulate galaxies with realistic baryon fractions and stellar masses for their halo mass (Munshi et al. 2013), bulge and disc properties (Brooks et al. 2011; Christensen et al. 2014a,b), satellite distributions (Zolotov et al. 2012; Brooks & Zolotov 2014) and which follow the observed Kennicutt–Schmidt relation (Christensen et al. 2012). One of our simulations, h603, was previously shown by (Christensen et al. 2014a) to lie along the bulge scaling relations, demonstrating that the bulge has the appropriate size and surface brightness with respect to its host galaxy. Four of the five galaxies have classical bulges, as defined by having a Sersi่c index $n > 2$; the galaxy h603 is reported to have $n = 1.65$ in Christensen et al. (2014a) and can be classified as a pseudo-bulge. In summary, we are confident that our simulations realistically represent galaxy bulges and discs, and offer an excellent setting to explore orientation effects on bulge properties.

2.1 Theoretical measurements of kinematics and shape

One clear advantage of our galaxy models is that we can kinematically select the bulge stars and measure their dispersion and ellipticities. We follow the method of Abadi et al. (2003) and begin by identifying the stellar disc. We orient the coordinate system so that the angular momentum axis points along the $z$-axis and calculate $J_x$, the angular momentum of each star in the $x$-$y$ plane. We compare $J_x$ to $J_{circ}$, the angular momentum the star would have if it were on a circular orbit with the same energy. We designate disc stars as having $J_x/J_{circ} \geq 0.8$. To identify the spheroid, we iteratively solve for the cutoff in $J_x/J_{circ}$ at which the mean rotational velocity is zero. This value differs for each galaxy but tends to be around 0.5. Using the entire matter distribution (gas, stars and dark matter), we calculate the total energy for each particle in order to differentiate halo stars from the bulge. Bulge stars have higher binding energy than halo stars, and we use the median value of the stars’ total energy to distinguish the bulge from the halo.

After kinematically identifying the bulge, we centre it in position and velocity and determine the half-mass radius. The stars within this radius are those for which we measure $\sigma_{tot}$; however, we exclude stars within a radius of 0.3 kpc (see Section 2.2 and Fig. 2). We calculate velocity in the $x$, $y$ and $z$ directions for each star particle. Summing the variance of these quantities gives us the square of the ‘true’ velocity dispersion, $\sigma_{tot}$, measured directly from the simulation. We expect the three-dimensional dispersion to be a factor of $\sqrt{3}$ smaller than a one-dimensional line-of-sight value for an isotropic spheroid, and so we list the quantities $\sigma_{tot}$ and $\sigma_{tot}/\sqrt{3}$ in Table 2. We also measure the intrinsic shape by calculating the moment of inertia tensor at the half-mass radius. Our bulges are extremely realistic, and are consistent with the measurements made by Christensen et al. (2014a) which show that the bulges obey the observed scaling relations relating surface brightness, magnitude and size.

2.2 Synthetic observations of kinematics and shape

We have developed a process which closely mimics the observational method for determining $\sigma_{los}$ from long-slit spectroscopy. To capture the effect of orientation on the line-of-sight $\sigma_{los}$ measurement, we centre each galaxy in position and velocity space, and then rotate the galaxy along a series of angles, mimicking various
We measure our bulge quantities using all of the stars in the galaxy which fall along the two-dimensional projection within an ellipse with semimajor axis $R_{\text{eff}}$. We present the $R_{\text{eff}}$ for a face-on orientation for each galaxy in Column 6 of Table 1.

For each rotation, we then align a slit along the major axis of the rotated bulge. The slit has a width of 50 pc, which corresponds to 1 arcsec at 10 Mpc, though varying this width has negligible effect on our results. We divide the slit into 50 bins and measure the mean radial velocity ($v_{\text{los}}$) and the dispersion ($\sigma$) for each. Our results are also insensitive to the number of bins, as long as this number is greater than $\sim 5$.

We then integrate along the slit, from $-R_{\text{eff}}$ to $R_{\text{eff}}$, using two methods. Historically, studies have combined the velocity standard deviation $\sigma$ with the line-of-sight velocity $v_{\text{los}}$ in accordance with the virial theorem, e.g. as in Gültekin et al. (2009):

$$\sigma_{\text{los}}^2 = \frac{\int (\sigma(r)^2 + v_{\text{los}}(r)^2) I(r) \, dr}{\int I(r) \, dr},$$

where $I(r)$ is the surface brightness. However, a recent study by Woo et al. (2013) suggests that for systems with substantial rotational support (such as the discy galaxies we focus on here), the contribution of $v_{\text{los}}$ inflates the overall velocity dispersion. In an attempt to mitigate this bias, the authors instead suggest using the more basic equation:

$$\sigma_{\text{los}} = \frac{\int \sigma(r) I(r) \, dr}{\int I(r) \, dr},$$

for systems with a rotational component (see also Kang et al. 2013). It is not clear, however, that ignoring the rotational or anisotropic component of a virialized bulge would be appropriate to track a theoretical link between the SMBH mass and the kinematics of the bulge. For this reason, in this work we primarily focus on the first method, but discuss how using equation (2) affects our results. In Fig. 2, we present our slit measurements of $\sigma_{\text{los}}$ (as calculated in equation 1) and $v_{\text{los}}$ for every galaxy orientation (grey lines) for the simulation h258. We show the median and standard deviation with red and blue curves, respectively. While these profiles are qualitatively similar to those presented in observational papers, the central region of the velocity dispersion profile is not well represented due to the resolution limitations of our simulations. We bracket the region with the central dip (which is about $\sim 15$% of $R_{\text{eff}}$, the red dashed lines in Fig. 2). This distance from peak to peak corresponds to a radius of $\sim 1.8$ softening lengths (or 0.3 kpc). According to Fig. 2, the stars in this region are not reliable for kinematic study; we exclude this area from both our theoretical and synthetic observation velocity dispersion measurements. We have tested our method by excluding ranges of 1, 2 and 3 times the softening, and find that 1.8 is an appropriate factor to maximize meaningful information while excluding that which is unreliable. See Section 5 for a discussion of resolution concerns.

We note that the bulges identified by our kinematic decomposition and synthetic observations are not identical; each process selects the bulge component based on different criteria. At the moment it is not clear whether either method is ‘correct’ for measuring fundamental scaling relations such as $M-\sigma$. We assert that observations of $\sigma_{\text{los}}$ may exhibit a large scatter due to galaxy orientation, and that simulations can help explain the source of this scatter, in part by determining the $\sigma$ from the kinematically selected bulge.

3 RESULTS

The distribution of $\sigma_{\text{los}}$ measurements (using equation 1) as a function of orientation of each galaxy is shown in Fig. 3. The red vertical
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Figure 3. Distribution of measurements of $\sigma_{\text{los}}$ for every line of sight for all five galaxies. The blue hatched regions are the lower and upper 10 per cent of the distributions, and the red vertical line is the median of each distribution. The vertical green dashed line is the theoretical value of $\sigma_{\text{los}}$ derived directly from the simulations (see Section 2.1).

The lines are the medians of each distribution, and the blue hatched regions are the highest and lowest 10 per cent values. The theoretically calculated line-of-sight velocity dispersion is denoted by the vertical green dashed line for each case. The distribution is non-Gaussian for every galaxy, and is skewed towards high $\sigma_{\text{los}}$. The fact that the distribution is not Gaussian is disturbing; the effects of inclination cause the apparent velocity dispersion to vary by several tens of km s$^{-1}$, with a strong bias towards larger values. The spread of values is around 0.3 dex, consistent with what is observed in $M-\sigma$ intrinsic scatter (Gültekin et al. 2009). Thus, these variations may be a principal source of scatter in the low-mass end of the observed $M-\sigma$ relation. The scatter is larger than the stated observational measurement errors, hinting that the wide spread in the low-mass end of the $M-\sigma$ relation may be caused by evolutionary effects, or by an underestimate of the measurement errors, or both (Harris, Poole & Harris 2014). We recommend that measurement errors
for velocity dispersions of bulges in disc galaxies should never be estimated at less than 20 km s$^{-1}$, simply due to orientation.

The use of equation (2), with the rotational velocity component removed, has a marked difference for galaxies with a noticeable rotational component. In Table 2, we list the median values of $\sigma_{\text{los}}$ for both observational methods, and in Fig. 4, we show the distribution of $\sigma_{\text{los}}$ calculated with both methods for two examples. The distribution without rotation (blue line) is shifted to lower values for galaxy h277 (left-hand panel), indicating that the inclusion of rotational velocities contributes substantially to $\sigma_{\text{los}}$. The distribution is also far narrower, suggesting that the additional rotational motions substantially broaden the range of possible observed values. On the other hand, galaxy h285 (right-hand panel) does not have substantial rotation in its central region, so the distributions are indistinguishable. Of our five galaxies, only h285 lacks significant rotation in the central component; the other four all show a decrease of up to 25 per cent in their median $\sigma_{\text{los}}$ values when equation (2) is used. Overall, the method of equation (2) is successful at isolating purely dispersion-dominated motions, while equation (1) represents the contribution of the full kinematic system. In terms of the $M$–$\sigma$ relation, it remains to be seen which equation is a better metric to decipher how SMBHs and their host bulges are interrelated (see Woo et al. 2013 for more details).

In Table 2, we compare the theoretical velocity dispersion, $\sigma_{\text{rot}}$, to those measured by synthetic observations. Comparing the median observed velocities for both methods (with and without rotation) to the theoretical values, we see that the simulation value is larger than the ‘observed’ value, which is in turn larger than the observed value neglecting rotation. Our estimates of $\sigma_{\text{rot}}/\sqrt{3}$ fall within the extreme low end of most of the line-of-sight measurements. While this result could be because the bulges are not perfectly spherical or isotropic, the major factor is very likely a large population of non-bulge stars contaminating the line of sight for the synthetic observations. Since it is impossible to isolate the bulge light from a two-dimensional photometric projection, this contamination factor will always be present.

The observed measurement of $\sigma_{\text{los}}$ excluding rotation is characteristically lower (by $\sim$20 per cent) than the traditional method, which is understandable since there is no contamination by stars with rotational motions. The bulges of late-type galaxies have negligible rotation, with the exception of h285; in this case the line-of-sight methods match each other. Notably, the measurement without rotation is very close to the one-dimensional theoretical measurement. Since both methods purposely exclude rotational motions, it is reasonable that they should roughly agree. Using equations (1) and (2) together gives us an idea of how rotation- versus dispersion-dominated a sphere is; further studies with such considerations may give us more clues to how SMBHs grow and evolve with respect to the evolution of their hosts.

If $\sigma_{\text{los}}$ measurements are larger for more inclined systems, we expect to see a dependence of $\sigma_{\text{los}}$ with the inclination angle $\theta$. Edge-on systems exhibit a large quantity of disc stars along the line of sight, which inflate the observed dispersion. This geometrical argument has been made by Brown et al. (2013), who studied the velocity structure of collisionless simulations of disc galaxies using an integral field method. Contamination by line-of-sight disc stars has been quantified by Hartmann et al. (2014) and Debattista, Kazantzidis & van den Bosch (2013), who suggest that a highly inclined system artificially boosts $\sigma_{\text{los}}$ values by 25 per cent; our results agree with this assessment. However, Graham & Li (2009) used ellipticity as a proxy for inclination and found no trend among the $M$–$\sigma$ residuals. Our simulations actually do not show clear trends of $\sigma_{\text{los}}$ with ellipticity either; since ellipticity changes with radius and may be affected by non-axisymmetric shapes as well as inclination, we recommend that the use of a kinematic estimate of inclination rather than one purely due to shape.

We find that the relationship between velocity dispersion and orientation is somewhat straightforward – in Fig. 5, we plot velocity dispersion versus $\theta$ for all 1024 lines of sight for each galaxy (black points). The points fall in a fairly smooth curve, with some exceptions at edge-on orientations where the scatter increases and the overall value of $\sigma_{\text{los}}$ dips. The increased scatter is due to the existence of substructure and other anisotropies present in the galaxy. The global decrease in $\sigma_{\text{los}}$ at high inclination is due to the fact that

1 This galaxy is actually about to experience a merger, and is not in equilibrium, which may explain its lack of bulge rotation.
the disc stars along the line of sight are moving both coherently and with only a slight radial component, which decreases the overall dispersion measurement. Overall, face-on values of $\sigma_{\text{los}}$ have the lowest scatter.

One of our goals with this work is to provide observers with an inclination correction to more easily compare samples of galaxies and to ascertain more realistic values for the intrinsic velocity dispersion. We employ Eureqa (Schmidt & Lipson 2009), a machine learning tool, to solve for a relation between $\theta$ and $\sigma_{\text{los}}$. We include two additional parameters, which are observationally measurable: the circular velocity $v_{\text{rot}}$ of the galaxy$^2$ in km s$^{-1}$, and the quantity ($v/\sigma_{\text{spec}}$), measured from our simulated spectra at the radius of influence (as in Fig. 2). The galaxies in our sample have varied

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$^2$ We measure $v_{\text{rot}}$ by creating a synthetic H I emission line profile for an edge-on orientation and measuring $W_{20}$, the width of the line at 20 per cent of the peak. See Governato et al. (2009) for details.
reflecting the different kinematics of each bulge, while \(v_{\text{los}}\) is similar for all but h603. Adding these parameters allows us to include some broader differentiating properties and create a universal model for the relation between \(\sigma_{\text{los}}\) and inclination. For this fit, we neglect inclination angles \(70 < \theta < 110\), due to the increased scatter and drop in \(\sigma_{\text{los}}\) at very edge-on orientations. These orientations are not reliable for observationally determined bulge measurements because the bulge is obscured by the disc; in fact, such galaxies are commonly discarded from samples for this reason. We also add weight to the \(\theta = 0\) values, because these have the lowest scatter and will be the most useful for the purposes of correcting to a universal orientation; it is vital that our fit be excellent in this region.

Our equation is plotted as a red dashed line in Fig. 5 and is as follows:

\[
\sigma_{\text{los}} = 3.963v_{\text{los}} + 0.00376v_{\text{los}}\theta \left( \frac{V}{\sigma} \right)_{\text{spec}} + 0.0019750^2 - 278 - 0.010v_{\text{los}}^2 - 0.3187 \theta \left( \frac{V}{\sigma} \right)_{\text{spec}}^2 \text{ km s}^{-1}.
\]

This relation between \(\sigma_{\text{los}}\) and \(\theta\) allows us to propose a correction for inclination effects. The maximum error of this fit for any line-of-sight measurement of \(\sigma_{\text{los}}\) is 10 per cent, and is generally less than 6 per cent. We recommend observers correct \(\sigma_{\text{los}}\) to a face-on value in order to compare samples of galaxies with different orientations more carefully. We caution the use of measurements with inclinations larger than \(70^\circ\), as they are contaminated with a large number of non-bulge stars and plagued by large scatter.

### 4 REPERCUSSIONS FOR THE M–σ RELATION

Thus far we have demonstrated that observational measurements of \(\sigma_{\text{los}}\) may not be as reliable as previously thought. This revelation has many repercussions on galaxy dynamics and evolution. In this section, we focus on the effects on the observed \(M–\sigma\) relation.

The low-mass end of the observed \(M–\sigma\) relation has larger scatter than the high-mass end (Hu 2008; Gadotti & Kaufmann 2009; Gültekin et al. 2009; Greene et al. 2010; Graham et al. 2011). A common explanation for the scatter is simply hierarchical evolution; as galaxies and black holes grow over time, they increase in mass together and more tightly adhere to their scaling relations (Peng 2007; Jahnke & Macciò 2011). Lower mass galaxies in particular have likely undergone fewer major mergers, and the above argument may not even apply (Kormendy et al. 2011). SMBHs in low-mass galaxies may have different growth mechanisms than their larger counterparts as well. SMBH fuelling in isolated disc galaxies may more likely be triggered by secular, stochastic processes such as disc or bar instabilities (Cisternas 2011; Schawinski et al. 2011; Kocevski 2012; Athanassoula 2013; Simmons et al. 2013) or by minor mergers (Miccia et al. 2011; Van Wassenhove et al. 2012).

Additionally, mergers with other massive black holes may contribute substantially to SMBH mass in low-mass galaxies (Miccia et al. 2011). These processes may not cause the tight trends between SMBHs and larger mass galaxy spheroids. Evolutionarily speaking, the larger scatter for both \(\sigma\) and black hole mass for late-type galaxies is expected.

However, the orientation effects presented in this paper may be able to account for a substantial fraction of the scatter. The distributions of \(\sigma_{\text{los}}\) have a width of several tens of km s\(^{-1}\), and correspond to about 0.3 dex, which is approximately the width of scatter seen in the low-mass \(M–\sigma\) relation. We show how this scatter translates to a scatter in estimated black hole mass in Fig. 6; using the relation from McConnell & Ma (2013), we input the values of \(\sigma_{\text{los}}\) for each line of sight to obtain \(M_{\text{BH}}\). The values of \(M_{\text{BH}}\) span about an order of magnitude. This wide scatter serves as a warning that estimates of black hole masses from \(\sigma_{\text{los}}\) measurements may have much larger errors than previously assumed (e.g. 0.33 dex in Shankar et al. 2004) for late-type galaxies. Conversely, theoretical studies wishing to compare to the observed \(M–\sigma\) relation must take care to measure \(\sigma_{\text{los}}\) in a way that is consistent with observational methods.

In Fig. 7, we depict the expected scatter in the context of the \(M–\sigma\) relation. We randomly draw \(10^6\) values of \(\sigma_{\text{los}}\) for each galaxy from the measured distributions, and assign a black hole mass
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5 DISCUSSION AND CONCLUSIONS

While this work has focused on repercussions for the $M$-$\sigma$ relation, our simulations do not include black hole physics such as accretion and feedback. We do not expect this exclusion to have a significant effect; our galaxy sample is at a low enough mass that black hole feedback effects do not dominate over other processes. SMBH feedback does affect star formation in the bulge region, and it is possible that our velocity dispersion measurements are characteristically large due to neglecting SMBH feedback quenching. In fact, the bulge/disc ratios in these simulated galaxies may already be larger than expected compared to observations (Christensen et al. 2014a); if SMBH feedback reduces the size of the bulge relative to the disc, our results concerning contamination from disc stars are likely strengthened. Regardless, we do not expect our result of asymmetric $\sigma_{\text{los}}$ distributions due to orientation to be changed in any way, since the asymmetry is primarily caused by contamination from disc stars and not by intrinsic bulge properties.

We also do not include the effects of internal dust extinction and reddening when calculating surface brightness. Stickley & Canalizo (2012) employ a simple model for dust extinction and find that significant dust presence can lead to a modest decrease ($\sim 13$ per cent) in the measured value of $\sigma_{\text{los}}$. Since dust preferentially affects edge-on orientations, it is possible that for these lines of sight the observed $\sigma_{\text{los}}$ would be lower. We do not expect any of our galaxies to be heavily obscured, however, and so our results will not be affected strongly.

In Section 2, we discuss eliminating the central region of each simulated galaxy from our analysis for resolution reasons. That this step is necessary is unfortunate, because in observations the highest signal-to-noise region is the centre, and there is no way to compensate for its loss in a simulation with finite resolution. Indeed, if we could include the central region, we expect that our measurements of $\sigma_{\text{los}}$ using equations (1) and (2) may be brought closer into agreement, since this region exhibits lower rotational velocities and higher dispersions. However, the main points of our results are not affected by this issue. We treat the theoretical measurements and synthetic observations in the same manner, excluding the region from both, which assures we are making valid comparisons.

In addition, the behaviour of $\sigma_{\text{los}}$ out to $R_{\text{eff}}$ is well behaved outside of the excluded region (Fig. 2), suggesting that the majority of the data is of high quality. We have also verified that increasing the slit width (by up to a factor of 10) and adjusting the length of the slit (by factors of a few in either direction) bring no quantitative changes to our findings. While the magnitude of our $\sigma_{\text{los}}$ measurements may be slightly underestimated because we are missing the very peak of the central distribution, the remainder of our results are still solid.

We caution the use of measurements of $\sigma_{\text{los}}$ in late-type galaxies to derive bulk galaxy properties. In fact, any global correlation that relies on $\sigma$, such as the Fundamental Plane, will be biased. The variation due to orientation alone is $\sim 20$ km s$^{-1}$, and the inability to eliminate disc stars from an observational measurement introduces a contamination which artificially increases $\sigma_{\text{los}}$. The method of Woo et al. (2013) may mitigate this effect somewhat; however, if a bulge has a rotational component, the full kinematics will not be properly accounted for. We encourage the use of the relation of equation (3) to correct for orientation effects for inclinations $\theta < 70^\circ$.

In summary, using state-of-the-art high resolution cosmological simulations of disc galaxies, we quantify the effect of galaxy orientation on the measurement of bulge velocity dispersion. We carefully designed our measurements to closely mimic observational methods, and found that the value of $\sigma_{\text{los}}$ is highly dependent on viewing angle. The distribution of $\sigma_{\text{los}}$ is asymmetric and skewed towards higher values, which correspond to more inclined orientations. The scatter in $\sigma_{\text{los}}$ of $\sim 0.3$ dex is approximately equal to that of the low-mass end of the $M$-$\sigma$ relation, suggesting that orientation may substantially contribute to the scatter. Estimates of black hole masses using scaling relations such as $M$-$\sigma$ must be taken with extreme caution in this range, as the spread in $\sigma_{\text{los}}$ corresponds to a 1.0 dex variation in black hole mass.

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