Homogeneous Distances and Central Profiles for MASSIVE Survey Galaxies with Supermassive Black Holes

Scientific Category: UNRESOLVED STELLAR POPULATIONS AND GALAXY STRUCTURE

Scientific Keywords: Black Holes, Cosmological Parameters And Distance Scale, Galaxy Centers, Galaxy Morphology And Structure

Instruments: WFC3

Proprietary Period: 12

Proposal Size: Small

Orbit Request	Prime	Parallel
Cycle 23	34	0

Abstract

Massive early-type galaxies are the subject of intense interest: they exhibit the most massive black holes (BHs), most extreme stellar IMFs, and most dramatic size evolution over cosmic time. Yet, their complex formation histories remain obscure. Enter MASSIVE: a volume-limited survey of the structure and dynamics of the 100 most massive early-type galaxies within ~100 Mpc. We use integral-field spectroscopy (IFS) on sub-arcsecond (with AO) and large scales for simultaneous dynamical modeling of the supermassive BH, stars, and dark matter. The goals of MASSIVE include precise constraints on BH-galaxy scaling relations, the stellar IMF, and late-time assembly of ellipticals. We have already obtained much of the needed IFS and wide-field imaging for this project; here, we propose to add the one missing ingredient: high-resolution imaging with HST. This will nail down the central profiles, greatly reducing the degeneracy between M/L and BH masses in our dynamical orbit modeling. Further, we will measure efficient, high-quality WFC3/IR SBF distances for all targets, thereby removing potentially large errors from peculiar velocities (especially in the high-density regions occupied by massive early-types) or heterogeneous distance methods. Distance errors are insidious: they affect BH masses and galaxy properties in dissimilar ways, and thus can bias both the scatter and slopes of the scaling relations. The measured distances and central profiles will constrain the stellar, dark matter, and BH masses to high precision, ensuring the success of our ambitious MASSIVE survey.

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Number of investigators: 7
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# US Admin CoI: C Ma
& Phase I contacts: 1

Target Summary:

Target	RA	Dec	Magnitude
NGC-0057	00 15 30.8700	+17 19 42.70	Htot = 8.98
NGC-0315	00 57 48.8800	+30 21 8.80	Htot = 8.20
NGC-0383	01 07 24.9600	+32 24 45.20	Htot = 8.76
NGC-0410	01 10 58.9000	+33 09 6.80	Htot = 8.65
NGC-0507	01 23 39.9100	+33 15 21.80	Htot = 8.68
NGC-0533	01 25 31.3600	+01 45 32.80	Htot = 8.71
NGC-0547	01 26 0.6000	-01 20 43.00	Htot = 8.76
NGC-0665	01 44 56.1000	+10 25 22.90	Htot = 9.05
NGC-0708	01 52 46.4800	+36 09 6.60	Htot = 8.69
NGC-0741	01 56 21.0300	+05 37 44.20	Htot = 8.53
NGC-0777	02 00 14.9000	+31 25 46.50	Htot = 8.66
NGC-0890	02 22 1.0100	+33 15 57.80	Htot = 8.48
NGC-1016	02 38 19.5600	+02 07 9.30	Htot = 8.84
NGC-1060	02 43 15.0500	+32 25 29.90	Htot = 8.48
NGC-1129	02 54 27.3800	+41 34 46.50	Htot = 8.55
NGC-1167	03 01 42.3700	+35 12 20.70	Htot = 8.84
NGC-1272	03 19 21.2900	+41 29 26.30	Htot = 8.99
NGC-1453	03 46 27.2500	-03 58 7.60	Htot = 8.43
NGC-1573	04 35 3.9900	+73 15 44.70	Htot = 8.85
NGC-1600	04 31 39.9400	-05 05 10.50	Htot = 8.34
NGC-1684	04 52 31.1500	-03 06 21.80	Htot = 8.92

Target	RA	Dec	Magnitude
NGC-1700	04 56 56.3100	-04 51 56.80	Htot = 8.32
NGC-2258	06 47 45.8000	+74 28 54.00	Htot = 8.21
NGC-2274	06 47 17.3700	+33 34 1.90	Htot = 8.94
NGC-2513	08 02 24.6700	+09 24 48.80	Htot = 9.01
NGC-2672	08 49 21.8900	+19 04 29.90	Htot = 8.55
NGC-2693	08 56 59.2700	+51 20 50.80	Htot = 8.91
NGC-4914	13 00 42.9500	+37 18 55.00	Htot = 8.90
NGC-5322	13 49 15.2700	+60 11 25.90	Htot = 7.35
NGC-5353	13 53 26.6900	+40 16 58.90	Htot = 7.72
NGC-5557	14 18 25.7200	+36 29 36.80	Htot = 8.34
NGC-6482	17 51 48.8100	+23 04 19.00	Htot = 8.61
NGC-7052	21 18 33.0500	+26 26 49.30	Htot = 8.85
NGC-7619	23 20 14.5300	+08 12 22.50	Htot = 8.35

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
NGC-0057	WFC3/IR Imaging F110W		1
NGC-0315	WFC3/IR Imaging F110W		1
NGC-0383	WFC3/IR Imaging F110W		1
NGC-0410	WFC3/IR Imaging F110W		1
NGC-0507	WFC3/IR Imaging F110W		1
NGC-0533	WFC3/IR Imaging F110W		1
NGC-0547	WFC3/IR Imaging F110W		1
NGC-0665	WFC3/IR Imaging F110W		1
NGC-0708	WFC3/IR Imaging F110W		1
NGC-0741	WFC3/IR Imaging F110W		1
NGC-0777	WFC3/IR Imaging F110W		1
NGC-0890	WFC3/IR Imaging F110W		1
NGC-1016	WFC3/IR Imaging F110W		1
NGC-1060	WFC3/IR Imaging F110W		1
NGC-1129	WFC3/IR Imaging F110W		1
NGC-1167	WFC3/IR Imaging F110W		1
NGC-1272	WFC3/IR Imaging F110W		1
NGC-1453	WFC3/IR Imaging F110W		1
NGC-1573	WFC3/IR Imaging F110W		1
NGC-1600	WFC3/IR Imaging F110W		1

Target	Config Mode and Spectral Elements	Flags	Orbits
NGC-1684	WFC3/IR Imaging F110W		1
NGC-1700	WFC3/IR Imaging F110W		1
NGC-2258	WFC3/IR Imaging F110W		1
NGC-2274	WFC3/IR Imaging F110W		1
NGC-2513	WFC3/IR Imaging F110W		1
NGC-2672	WFC3/IR Imaging F110W		1
NGC-2693	WFC3/IR Imaging F110W		1
NGC-4914	WFC3/IR Imaging F110W		1
NGC-5322	WFC3/IR Imaging F110W		1
NGC-5353	WFC3/IR Imaging F110W		1
NGC-5557	WFC3/IR Imaging F110W		1
NGC-6482	WFC3/IR Imaging F110W		1
NGC-7052	WFC3/IR Imaging F110W		1
NGC-7619	WFC3/IR Imaging F110W		1
		Total prime orbits:	34

Scientific Justification

Introduction: The MASSIVE Survey. The most massive early-type galaxies in the Universe today are unique laboratories of galaxy evolution. They formed most of their stars rapidly at redshifts $z > 2$ (e.g., Thomas et al. 2005; Kodama et al. 2007; Blakeslee et al. 2003) but have grown by a factor of two or more since $z \approx 1$ (e.g., van der Wel et al. 2008; van Dokkum et al. 2010), probably in large part through "dry" merging/accretion (e.g., De Lucia et al. 2006; Oser et al. 2010). They contain nuclear black holes (BH) whose mass $M_{\rm BH}$ is strongly correlated with properties of the stellar bulge (e.g., Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; McConnell & Ma 2013; Kormendy & Ho 2013; Rusli et al. 2013). These scaling relations imply an intimate co-evolution between these two components over the lifetime of a galaxy, but the detailed mechanisms remain unclear (e.g., Somerville et al. 2008; Sun et al. 2013).

As demonstrated by the ATLAS$^{\rm 3D}$ project (Cappellari et al. 2011) and other surveys (e.g., VENGA/VIXENS, CALIFA, MaNGA), integral field spectroscopy (IFS) over a wide radial range provides a powerful way to study the structure, star formation histories, and halo masses of local galaxies. However, ATLAS$^{\rm 3D}$ includes only 4 galaxies with stellar mass $M_* \gtrsim 10^{11.5}\ M_\odot$; there have been no systematic surveys of galaxies above this mass. This highest mass range is critical for understanding galaxy and BH assembly. We have therefore undertaken MASSIVE (Ma et al. 2014), an ambitious new survey of the most massive galaxies within ~ 100 Mpc, using a combination of wide-field and adaptive-optics-assisted IFS. Our volume-limited survey targets a distinct stellar mass range ($M* \gtrsim 10^{11.5} M_\odot$; $K < -25.3$) that has not been systematically studied to date (see Fig. 1), and explores a volume more than an order of magnitude greater than ATLAS$^{\rm 3D}$.

MASSIVE is designed to address a wide range of outstanding problems in elliptical galaxy formation, including the variation in dark matter fraction and stellar IMF within and among early-type galaxies, the connection between BH accretion and galaxy growth, and the late-time assembly of galaxy outskirts (e.g., McConnell et al. 2012, Greene et al. 2013). We combine comprehensive ground-based NIR imaging with IFS data ranging from the sphere of influence of the black hole (using AO) out to $\sim 2.5 R_e$ to simultaneously model the supermassive black hole, stellar component, and dark matter halo in each galaxy, as well as to constrain the stellar population parameters at all radii (Greene et al. 2015). Our survey selection and analysis methods promise to more than double the number of massive ($> 10^{11.5}\ M_\odot$) galaxies with reliable $M_{\rm BH}$ values.

We have acquired the necessary wide-field IFS data with the Mitchell Spectrograph for 64 MASSIVE survey galaxies, and this year expect to complete our priority subsample of the 72 most massive (see Sample Selection below). However, the power of this impressive data set, especially for $M_{\rm BH}$ measurement, remains fundamentally limited for two basic reasons: (1) The dynamical models require accurate central luminosity profiles with HST resolution to pin down the potential, which is lacking for the vast majority of our sample. (2) We do not know the distances to high accuracy; thus, all physical information on the galaxies is necessarily limited. We propose to correct both of these outstanding problems using high-resolution WFC3/IR imaging with HST.

Central Light Profiles from High-Resolution Imaging. $M_{\rm BH}$ values measured from stellar kinematics have been published by our group and others for 7 MASSIVE galaxies. We have collected high-resolution IFS data from Gemini and Keck to measure $M_{\rm BH}$ in 15 more galaxies and have several others now in the queue. Robust BH masses, however, hinge on having an accurate inner light profile, particularly in these galaxies that often have central light deficits, or cores, on ∼100 pc scales (e.g., Faber et al. 1997). We propose to obtain the one missing ingredient — high-resolution HST imaging — for high-priority MASSIVE galaxies within 80 Mpc (red circles in Fig. 1). Such massive galaxies likely host BHs with $M_{\rm BH} > 10^9 M_\odot$, and within this distance, we should successfully resolve the BH spheres of influence in all of them (more details in Observations section).

We use the Schwarzchild orbit model (Thomas et al. 2004) and construct stellar orbits in the combined potential of a central BH, a stellar bulge, and a dark matter halo. Because individual stellar orbits can traverse the central region of a galaxy and its outskirts, we require as a model constraint precisely measured light profiles within the BH radius of influence, where our innermost kinematic data trace both $M_{\rm BH}$ and enclosed stellar mass. The potential is multi-component, so $M_{\rm BH}$ and the dark matter mass are partially degenerate with the stellar mass; without an accurate characterization of the core profile, our measurements of individual components suffer significant systematic errors. Massive elliptical galaxies are expected to have typical dark-matter fractions of 20–50% inside their half-light radii (e.g., Cappellari et al. 2013). An uncertainty of 25% in the stellar M/L therefore corresponds to a relative error of $\sim$ 50–100% in the dark-matter fraction, and can also bias $M_{\rm BH}$ by a factor of two (Gebhardt & Thomas 2009; Rusli et al. 2013).

The Role of Galaxy Distances. Accurate distances are essential throughout astrophysics in order to convert observed quantities into physical ones. As a consequence, errors in distance generally translate into equal or larger fractional errors in derived quantities such as masses, luminosities, star formation rates, dynamical timescales, energy budgets, and ages (e.g., from stellar main sequence fitting). In the nearby universe, recessional velocities (redshifts) can never yield precise distances. Peculiar motions range from hundreds of $\mathrm{km\,s^{-1}}$ for galaxy groups in low-density regions (e.g., the Local Group moves at 620 $\mathrm{km\,s^{-1}}$ in the CMB rest frame) to over 1500 $\mathrm{km\,s^{-1}}$ for group motions within dense supercluster environments (e.g., Tonry et al. 2000), not including internal motions within the clusters themselves (e.g., M86 in Virgo is encountering M87 with a relative velocity of over 1500 $\mathrm{km\,s^{-1}}$). As a rule of thumb, for $H_0 = 70$ km s^{-1} Mpc^{-1}, one needs to reach $\gtrsim 70$ Mpc for peculiar motions to amount to less than $\sim 10\%$ of the recessional velocity. For galaxies in dense environments, including the $\sim 60\%$ of MASSIVE galaxies that reside in groups with halo mass $> 10^{13}\ M_\odot$, the limit is necessarily higher. At larger redshifts, peculiar velocities are less important, but we can no longer resolve the scales relevant for BH mass studies.

Kormendy & Ho (2013) point out that for many extragalactic $M_{\rm BH}$ estimates, the distance d is the dominant source of uncertainty, "even though most authors do not include distance errors in $M_{\rm BH}$ uncertainties." For instance, Gebhardt et al. (2011) quote a 6% error on $M_{\rm BH}$ for M87, yet their assumed $d = 17.9$ Mpc is 8.5% larger than the surface brightness fluctuation (SBF) value used by Kormendy & Ho, ATLAS$^{\rm 3D}$, and other BH studies (e.g., McConnell & Ma 2013; Graham & Scott 2013); it is 16% larger than the mean Virgo distance tabulated by Freedman et al. (2001) in the Cepheid Key Project final results paper. If distance can be a significant error source for $M_{\rm BH}$, which scales linearly with d, it is nearly always the dominant error for galaxy luminosity L, which scales as d^2. Many BH scaling relation analyses, including those above, assume a 10–12% error in L, implying d must be known to 5–6%. Such precision is rare: the primary source of distances for BH studies is the ground-based SBF survey of Tonry et al. (2001), for which the median tabulated error is 11%. The exceptions are the HST-based SBF distances in Virgo and Fornax (Mei et al. 2007; Blakeslee et al. 2009), with $\sim$4% errors (see Figs. 2 & 3).

Distance is the main source of controllable error in the L-$M_{\rm BH}$ relation and all other galaxy scaling relations that depend on stellar mass (such as the Fundamental Plane and a mass-dependent bottom-heavy IMF; e.g., Conroy & van Dokkum 2012). Because they feed into both quantities, systematic errors in d may significantly bias the slope of these scaling relations, especially if sample selection results in a correlation of d with galaxy mass. Indeed, in Fig. 1 (right panel) we see that the rare high-mass galaxies targeted by MASSIVE have a significantly larger mean distance than the low-mass ATLAS$^{\rm 3D}$ sample. Notably, ATLAS$^{\rm 3D}$ used the HST SBF distances in Virgo and ground-based SBF distances for the others; the ground and HST SBF data have been tied together to high accuracy. For MASSIVE we must rely on either inhomogeneous distance compilations or redshift-based distances, sometimes with uncertain group associations (see Fig. 4). As quantified above, peculiar velocities contribute significant uncertainties to redshift-based distances within this volume. Distance errors only impact the relation between $M_{\rm BH}$ and velocity dispersion σ_* linearly, but recent studies (e.g., Kormendy & Ho 2013) suggest that the scaling relation between $M_{\rm BH}$ and bulge stellar mass M_* may be even more fundamental, and M_* again scales as d^2.

We propose to measure high-precision SBF distances with WFC3/IR for the highest priority MASSIVE galaxies within 80 Mpc. The SBF method with HST is the most precise and complete distance indicator for early-type galaxies in the MASSIVE distance range (resolved stellar methods are only useful for nearer galaxies, while Type Ia supernovae are rare events). The method has become extremely efficient with the launch of WFC3/IR, allowing 5% distance measurement out to 80 Mpc in a single orbit (Blakeslee 2013; Jensen et al. 2015). These data will vastly improve our distance estimates for MASSIVE galaxies, minimize observational errors in galaxy properties, and eliminate potential systematic differences with lower-mass samples (ATLAS$^{\rm 3D}$) that could result in mass-dependent biases in fundamental scaling relations. Thus, the proposed observations are essential to the success of the ongoing MASSIVE project. *See the* ***Description of the Observations*** *section for full details on the sample selection and the SBF distance method.*

Additional Science and Legacy Value. The immediate outcome of this proposal will be accurate measurements of galaxy central profiles and redshift-independent distances, which together will yield far more precise and reliable galaxy and BH masses. These HST WFC3/IR images will also resolve central cores, disks, multiple nuclei, and nuclear dust structures (e.g., Lauer et al. 2005; Ferrarese et al. 2006), useful for understanding the statistics and origin of such features. The data can also be used to constrain the size (but not color) of the globular cluster populations, which correlate well with dark halo mass (Alamo-Martinez et al. 2013; Hudson et al. 2014) and possibly with $M_{\rm BH}$ (Kormendy & Ho 2013; Harris et al. 2014). The measured distances and peculiar velocities for our target galaxies will also significantly add to the detailed understanding of the local velocity field (e.g., Tonry et al. 2000; Tully et al. 2013) and provide another important constraint on the Hubble constant. The lingering $2.5\,\sigma$ discrepancy between local and CMB values of H_0 (Riess et al. 2011; Freedman et al. 2012; Bennett et al. 2013; Planck 2015 results) would have major implications for fundamental physics; independent confirmation of the local distance scale is essential. Thus, our observations will have both immediate applications for our MASSIVE survey and great legacy value for diverse other applications.

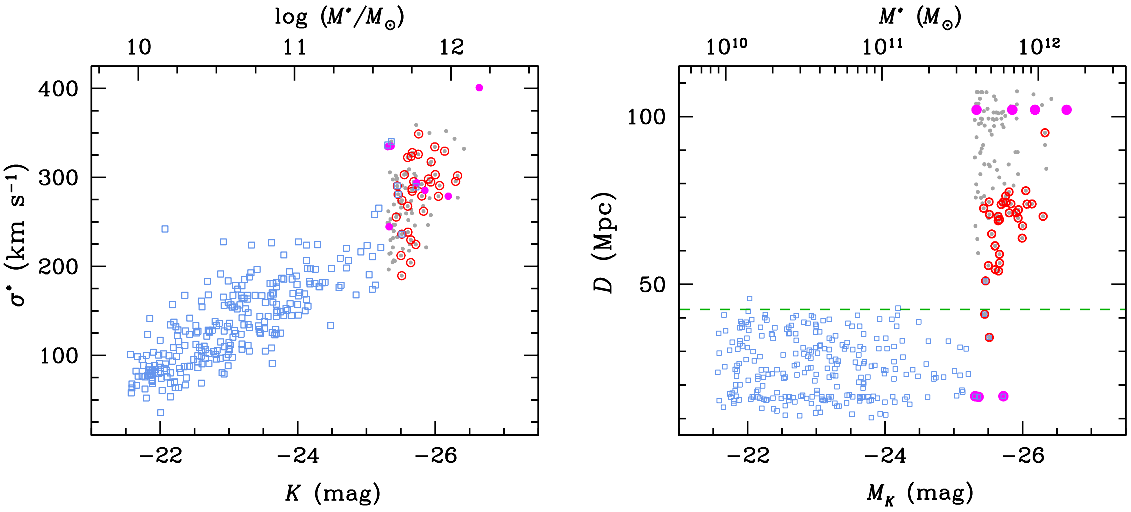

Figure 1. Comparison of ATLAS-3D/Sauron surveys (blue squares; Cappellari et al. 2011) with our MASSIVE survey (red circles for galaxies targeted in the present proposal; gray circles for the remainder of the sample). MASSIVE galaxies in Virgo and Coma (magenta circles) already have HST SBF distances. *Left:* Faber-Jackson relation for the surveys, showing a change in slope at high masses. K-band magnitudes are from 2MASS and velocity dispersions are from HyperLeda. Stellar mass is derived from K mag following Cappellari et al. (2013); we are carrying out our own wide-field K imaging to improve the photometry. *Right:* Estimated distance versus stellar mass: ATLAS-3D distances are primarily from ground-based SBF, while distances for MASSIVE galaxies here are mainly based on redshift. ATLAS-3D is dominated by low-mass galaxies because of its volume limit (green dashed line), which derives from the ground-based SBF limit. MASSIVE targets ellipticals above $10^{11.5} M_\odot$, and thus necessarily probes a larger volume.

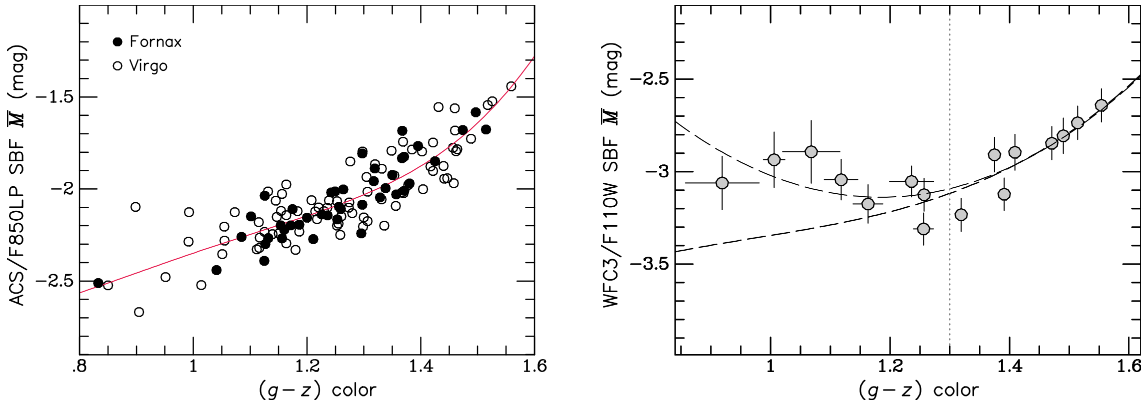

Figure 2. Absolute SBF magnitude $\overline{M}$ in the ACS z_{850} (*left*; Blakeslee et al. 2009) and WFC3/IR J_{110} (*right*; Jensen et al. 2015) bandpasses, calibrated as a function of galaxy $(g-z)$ color. The z_{850} SBF data have a median error of 0.075 mag (3.5% in distance) for $(g-z) > 1$, including 0.06 mag of intrinsic scatter, and give the relative distance of the Virgo and Fornax clusters to 1.7% uncertainty (including systematics). The red curve is a simple polynomial fit to the combined Virgo+Fornax SBF data. The plot at right confirms that J_{110}-band SBF is likewise an excellent distance indicator with $< 5\%$ distance scatter for giant ellipticals, which exclusively have $(g-z) > 1.3$ (vertical dotted line). (For bluer dEs and S0s with $g-z \lesssim 1.15$, models predict increased scatter due to stellar population effects, illustrated by the diverging curves). The SBF is much stronger in J_{110} than in z_{850}, and the bandpass has much higher throughput, making WFC3/IR far more efficient for SBF. Our proposed observations will vastly improve the distance estimates (errors $\lesssim 5\%$), and therefore luminosities and masses, for the MASSIVE survey galaxies.

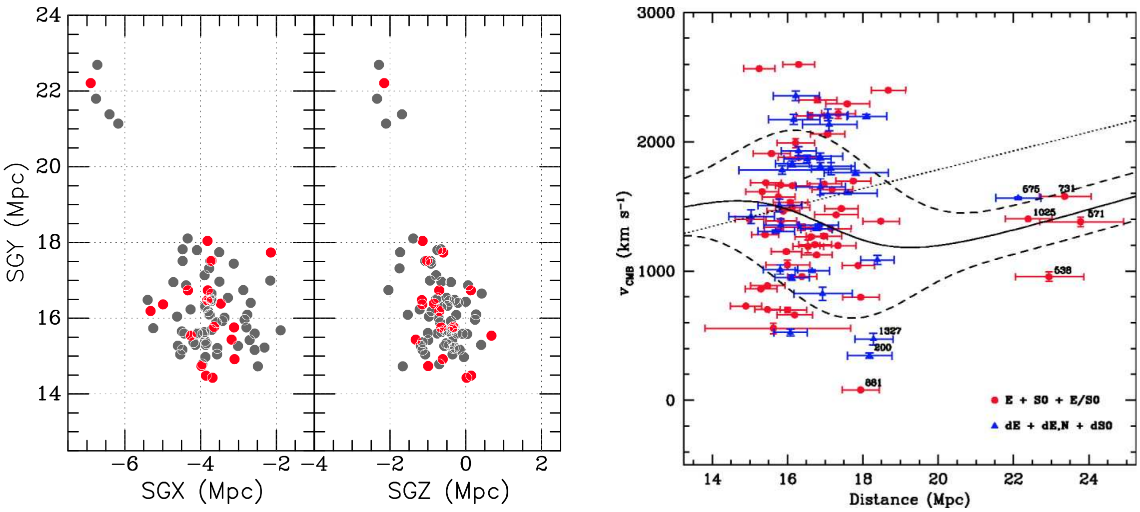

Figure 3. Illustration of the power of the HST SBF method for 91 Virgo galaxies, 63% of which are in ATLAS-3D. Random distance error per galaxy is $\lesssim 4\%$. *Left:* Projections of the cluster galaxies in supergalactic coordinates, using our HST SBF distance measurements (Mei et al. 2007; Blakeslee et al. 2009); SGY is approximately along the line of sight. The structure of Virgo is resolved: the galaxies have a tight spatial distribution with a dispersion of about 0.6 Mpc, and flattened in the SGZ direction. Five of the galaxies were found to belong to a compact group about 6 Mpc behind the Virgo core. *Right:* Hubble diagram through the Virgo cluster based on the HST SBF distances. The dotted line shows the unperturbed Hubble flow; curves show the expected infall. The 5 background galaxies are infalling at ~ 500 km s^{-1}.

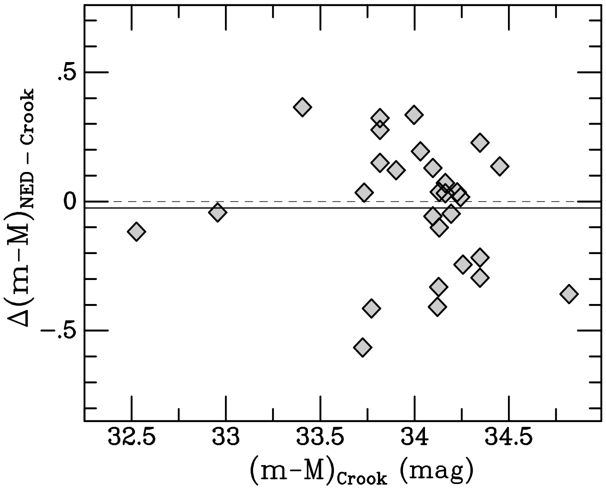

Figure 4. Current distance situation for MASSIVE galaxies targeted in this proposal: 29 have redshift-independent distances in NED. Differences between the (median) NED distance moduli and group-averaged moduli from Crook et al. (2007) are shown, after rescaling the NED distances for H_0. The mean offset is small (solid line) but the rms scatter is 0.24 mag, with a total range of ~ 1 mag. Notably, 20% of the galaxies have distances that differ by > 10 Mpc (cf. the rms of 0.08 mag in Fig. 2 and distance precision in Fig. 3). This scatter estimate is optimistic because most of the NED distances are from Tully-Fisher, group-averaged in a similar way as in Crook et al.; membership for any given early-type target is uncertain. Only one galaxy has a supernova distance; the nearest two galaxies have ground-based SBF distances, but we include them for the sake of homogeneity and improved precision. The proposed single-orbit WFC3/IR imaging will yield a threefold improvement in distance precision and, even more critically, remove the danger of large systematic scaling errors between our MASSIVE survey and previous, lower mass, IFS and BH studies.

References:
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Description of the Observations

Sample Selection. As described by Ma et al. (2014), the MASSIVE survey sample is defined using the 2MASS redshift survey (Huchra et al. 2012) and the group catalog of Crook et al. (2007) by selecting all early-type galaxies within a velocity-distance $d < 108$ Mpc, declination $\delta > -6°$, $M_K < -25.3$ mag (corresponding to $M_* \gtrsim 10^{11.5} M_\odot$), and extinction $A_V < 0.6$ mag. Rejecting mergers and a few galaxies near extremely bright stars leaves 116 galaxies, only six of which were in ATLAS-3D due to their smaller volume limit of $d < 42$ Mpc (see Fig. 1 above).

Ma et al. (2014) further defined a "Priority sample" of the 72 most luminous ($M_K < -25.5$ mag) galaxies in MASSIVE, and we have been concentrating our observational efforts on these. We have acquired wide-field IFS data from the Mitchell Spectrograph (formerly VIRUS-P) at McDonald Observatory for 64 MASSIVE galaxies, about 90% of which are in the Priority sample. We have already been awarded three more nights this spring to make further progress.

Because peculiar velocities become fractionally smaller with increasing distance, redshifts (at least with group averaging) provide adequate distances ($\lesssim 8\%$ error) beyond ~ 80 Mpc; moreover, it becomes increasingly difficult to measure BH masses because of the decreased angular size of the sphere of influence. A total of 37 MASSIVE Priority sample galaxies lie within 80 Mpc, based provisionally on redshift: three are in Virgo and have excellent HST SBF distances (Blakeslee et al. 2009); NGC 7626 also has an ACS SBF distance (Cantiello et al. 2007), leaving 33. To these we add NGC 1016, a galaxy for which we have excellent wide-field IFS data and a $M_{\rm BH}$ measurement; its group redshift gives $d > 90$ Mpc, but the NED distance is 73 ± 13 Mpc, corresponding to a difference of $\sim 40\%$ in luminosity and stellar mass. Thus, we target a total of 34 galaxies in this proposal for SBF measurement; with NGC 7626, the three Virgo galaxies, and four galaxies in Coma (which has both ACS and WFC3/IR SBF distances from our GO-11711 program), a total of 42 MASSIVE galaxies will then have high-precision HST SBF distances.

The SBF Distance Method. The SBF signal arises from the stochastic fluctuations in the numbers and luminosities of individual stars per pixel with respect to the smooth galaxy profile. The ratio $\overline{f}$ of this variance to the local mean galaxy surface brightness scales inversely with the square of the galaxy distance, i.e., more distant galaxies are quantitatively smoother. The measured $\overline{f}$ has units of flux and is converted to a magnitude $\overline{m}$; the distance modulus ($\overline{m} - \overline{M}$) immediately follows once the SBF absolute magnitude $\overline{M}$ is known. The value of $\overline{M}$ depends on the photometric bandpass in which the SBF is measured and the stellar population of the galaxy. The SBF method has been tied directly to the Cepheid distance scale to an accuracy of 0.08 mag, or 4% in distance (Tonry et al. 2001; Blakeslee et al. 2010).

To first order, the maximum distance to which the method can be applied scales inversely with the size of the point spread function (PSF). The accuracy also increases with the number of resolution elements within the galaxy, and thus benefits from well sampled, high resolution data. The installation of ACS on HST engendered a renaissance in the optical SBF method, including the first clear resolution of the 3-D structure of the Virgo cluster (Mei et al. 2007), determination of the relative Virgo–Fornax distance to better than 2% (Blakeslee et al. 2009), and the first optical SBF distances beyond 100 Mpc (Cantiello et al. 2007; Biscardi et al. 2008). Compared to ground-based facilities, HST/ACS can measure SBF distances to galaxies at least six times as distant with a threefold improvement in precision (Blakeslee et al. 2009, 2010).

The SBF signal is much stronger in the near-IR because the main contributors are red giant branch stars (e.g., Jensen et al. 2003), but early studies were hampered by the bright near-IR sky from the ground and/or the small format and poor cosmetics of early near-IR cameras such as NICMOS. The large format and vastly improved characteristics of WFC3/IR has opened a new era in the measurement of IR SBF distances, similar to the improvement seen in the optical from ACS. Moreover, thanks to a dedicated calibration proposal (GO-11712) targeting sixteen galaxies from the Blakeslee et al. (2009) ACS study of Virgo and Fornax, we have now reliably characterized the stellar population dependence of the SBF method in the F110W and F160W bandpasses of WFC3/IR (Jensen et al. 2015; Fig. 2 above), which makes it possible to measure the distance to any luminous, evolved galaxy out to perhaps 100 Mpc (limited by contamination to the image power spectrum by undetected point sources; see below) with a single orbit in one of these WFC3/IR bandpasses. Our adopted distance limit of 80 Mpc is thus conservative for one orbit.

At these distances, no other method can compare to space-based SBF's combination of superb accuracy and completeness for early-type galaxies, exactly the targets most suitable for BH studies. In particular, we note that the large angular sizes and smooth profiles of the MASSIVE galaxies make them ideal SBF targets. The one additional requirement is a broad-band optical color to characterize the stellar population. As shown in Fig. 2 above, $g-z$ is ideal because of the wide baseline, but many other indices have been used in the past for SBF calibrations (e.g., $V-I$,

$B-R$, $g-i$, $J-H$, and even Mg_2). Rather than spending additional orbits with HST on the stellar population calibration, we have confirmed that we can obtain the necessary color information for all galaxies from Pan-STARRS; most galaxies also have SDSS imaging as an additional check.

Observing Strategy and Total Orbit Request. We will image each galaxy with WFC3/IR for one orbit in F110W, using a four-point dither to improve PSF sampling and a pre-defined accumulation and non-destructive readout sequence, as described in the WFC3 Handbook, to avoid detector saturation. The typical visibility for our targets is about 50 min per orbit. Allowing for guide star acquisition, two sets of four small dithers, and multiple readouts, we are left with ~2200 sec of integration per orbit. From our WFC3/IR calibration program (GO-11712; Fig. 2), we know the expected SBF magnitude $\overline{m}_{\mathrm{F110}}$ as a function of distance; at 80 Mpc, the SBF S/N per resolution element will be over 10 in 2200 sec. Given the many resolution elements per galaxy, the SBF signal can be measured to very high precision.

The main source of error arises from contamination by unresolved globular clusters within the target galaxy. Fortunately, from our GO-11711 program, we have multi-orbit WFC3/IR F110W and F160W imaging (as well as deep ACS data as an external check) in the Coma cluster at 100 Mpc, and we have done extensive testing to optimize our observing strategy, including globular cluster detection and removal. These tests indicate that while the SBF is brighter in F160W, the contamination correction is more robust in F110W because we reach further along the globular cluster luminosity function, and even a single orbit in F110W yields a robust measurement at the distance limit of our sample. **With 34 targets, we therefore request a total of 34 orbits.**

The above considerations led to our selection of F110W as the optimal band for this project. We are aware of the time-variable excess background in this filter, reported in the recent WFC3 ISR 2014-03 by Brammer et al.; we have observed it in some of our own data. As long as we are careful to note its presence, and manually rerun the calwfc3 pipeline in extreme cases where the cosmic ray rejection has been compromised, the strong SBF signal means that the variable background is not a significant problem. Our team has proven expertise in all aspects of this program, including WFC3/IR reductions, galaxy photometry, central profile measurement, and SBF analysis. Members of our team are leaders in the fields of galaxy distance measurement, galaxy stellar populations, and black hole studies. The timely completion of this program to obtain reliable distances for our MASSIVE survey galaxies will be a high priority for our team.

■ Special Requirements

■ Coordinated Observations

■ Justify Duplications

About 1/3 of our targets have WFPC2 or ACS in assorted bands, and varying depths (mostly an orbit or less per filter). These can provide useful additional constraints on the stellar population M/L from the central color profiles. None of our targets have been observed with WFC3/IR, as we are proposing here for high-quality, homogeneous distance measurements.

Past HST Usage

(DOES NOT count against the page limits of the proposal.)

The PI has had the following HST programs:

GO-10429: *Streaming Towards Shapley: The Mass of the Richest Galaxy Concentration in the Local Universe*. Data reduced and analyzed, yielding 2 refereed journal articles (see list below) and a completed PhD thesis by R. Barber-DeGraaff (now a lecturer at Western Washington University).

AR-10642: *Measurements of Surface Brightness Fluctuations Gradients in Normal and Peculiar Early-type Galaxies*. Data fully reduced and published in refereed journal.

GO-10911: *Calibration of ACS F814W Surface Brightness Fluctuations*. Data fully reduced and published in refereed journal.

GO-11710: *The Extreme Globular Cluster System of Abell 1689: The Ultimate Test of Universal Formation Efficiency*. Data fully reduced and published in refereed journal and a completed PhD thesis by K. Alamo-Martinez. Results of this program were featured in NASA press release 13-282 and STScI-2013-36, "Hubble Uncovers Largest Known Group of Star Clusters, Clues to Dark Matter" (9/2013), and is highlighted in the 2014 issue of *Hubble Science Year in Review*.

GO-11711: *A Definitive Distance to the Coma Core Ellipticals*. Data fully reduced and presented at several conferences, most recently the April 2014 Cosmic Distance Scale workshop at STScI; two manuscripts in preparation, and the data also form part of H. Cho's PhD thesis.

GO-11712: *Calibration of Surface Brightness Fluctuations for WFC3/IR*. Data fully reduced (shown in Fig. 2 above); one paper on globular clusters already published; the main data paper presenting the SBF calibration has been submitted to ApJ and posted on arXiv.

Referred publications: The PI has been a co-I on 10 other GO programs (acting as administrative PI for three) and has led several publications based on the resulting data; the six PI-led programs listed above have so far produced the following refereed articles (with 3 others in preparation):

"Measuring Infrared Surface Brightness Fluctuation Distances with HST/WFC3: Calibration and Advice," Jensen, J.B., Blakeslee, J.P., Gibson, Z., et al. 2015, ApJ, submitted (see arXiv)

"The Rich Globular Cluster System of Abell 1689 and the Radial Dependence of the Globular Cluster Formation Efficiency," Alamo-Martínez, K.A., Blakeslee, J.P., Jee, M.J., et al. 2013, ApJ, 775, 20.

"The Distance to NGC 1316 (Fornax A): Yet Another Curious Case," Cantiello, M., Grado, A., Blakeslee, J.P., et al. 2013, A&A, 552, A106.

"Surface Brightness Fluctuations as Primary and Secondary Distance Indicators," Blakeslee, J.P. 2012, Ap&SS, 341, 179.

"Optical and Infrared Photometry of Globular Clusters in NGC 1399: Evidence for Color–Metallicity Nonlinearity," Blakeslee, J.P., Cho, H., Peng, E.W., et al. 2012, ApJ, 746, 88.

"Surface Brightness Fluctuations in the Hubble Space Telescope ACS/WFC F814W Bandpass and an Update on Galaxy Distances," Blakeslee, J.P., Cantiello, M., Mei, S., et al. 2010, ApJ, 724, 657.

"Ultra-Compact Dwarf Candidates Near the Lensing Galaxy in Abell S0740," Blakeslee, J.P. & Barber DeGraaff, R. 2008, AJ, 136, 2295.

"Surface Brightness Fluctuations from Archival ACS Images: A Stellar Population and Distance Study," Cantiello, M., Blakeslee, J.P., Raimondo, et al. 2007, ApJ, 668, 130.

"Detection of Surface Brightness Fluctuations in Elliptical Galaxies Imaged with the Advanced Camera for Surveys: B- and I-Band Measurements," Cantiello, M., Raimondo, G., Blakeslee, J.P., et al. 2007, ApJ, 662, 940.

"Discovery of Strong Lensing by an Elliptical Galaxy at z = 0.0345," Smith, R.J., Blakeslee, J.P., Lucey, J.R., & Tonry, J.L. 2006, ApJ, 625, L103.