A logarithmic spiral is a prominent feature appearing in a majority of observed galaxies. This feature has long been associated with the traditional Hubble classification scheme, but historical quotes of pitch angle of spiral galaxies have been almost exclusively qualitative. We have developed a methodology, utilizing two-dimensional fast Fourier transformations of images of spiral galaxies, in order to isolate and measure the pitch angles of their spiral arms. Our technique provides a quantitative way to measure this morphological feature. This will allow comparison of spiral galaxy pitch angle to other galactic parameters and test spiral arm genesis theories. In this work, we detail our image processing and analysis of spiral galaxy images and discuss the robustness of our analysis techniques.

We present new and stronger evidence for a previously reported relationship between galactic spiral arm pitch angle P (a measure of the tightness of spiral structure) and the mass M BH of a disk galaxy's nuclear supermassive black hole (SMBH). We use an improved method to accurately measure the spiral arm pitch angle in disk galaxies to generate quantitative data on this morphological feature for 34 galaxies with directly measured black hole masses. We find a relation of log (M/M ⊙) = (8.21 ± 0.16) - (0.062 ± 0.009)P. This method is compared with other means of estimating black hole mass to determine its effectiveness and usefulness relative to other existing relations. We argue that such a relationship is predicted by leading theories of spiral structure in disk galaxies, including the density wave theory. We propose this relationship as a tool for estimating SMBH masses in disk galaxies. This tool is potentially superior when compared to other methods for this class of galaxy and has the advantage of being unambiguously measurable from imaging data alone.

We present our determination of the nuclear supermassive black hole (SMBH) mass function for spiral galaxies in the Local Universe, established from a volume-limited sample consisting of a statistically complete collection of the brightest spiral galaxies in the Southern Hemisphere. Our SMBH mass function agrees well at the high-mass end with previous values given in the literature. At the low-mass end, inconsistencies exist in previous works that still need to be resolved, but our work is more in line with expectations based on modeling of SMBH evolution. This low-mass end of the spectrum is critical to our understanding of the mass function and evolution of SMBHs since the epoch of maximum quasar activity. A luminosity distance ≤ 25.4 Mpc and an absolute B-band magnitude ≤ -19.12 define the sample. These limits define a sample of 140 spiral galaxies, with 128 measurable pitch angles to establish the pitch angle distribution for this sample. This pitch angle distribution function may be useful in the study of the morphology of late-type galaxies. We then use an established relationship between the pitch angle and the mass of the central SMBH in a host galaxy in order to estimate the mass of the 128 respective SMBHs in this sample. This result effectively gives us the distribution of mass for SMBHs residing in spiral galaxies over a lookback time ≤ 82.1 h−167.77 Myr and contained within a comoving volume of 3.37 × 104 h−367.77 Mpc3. We estimate the density of SMBHs residing in spiral galaxies in the Local Universe is 5.54+6.55−2.73 × 104 h367.77 M⊙ Mpc−3. Thus, our derived cosmological SMBH mass density for spiral galaxies is ΩBH=4.35+5.14−2.15 × 10−7 h67.77.

We investigate the use of spiral arm pitch angles as a probe of disk galaxy mass profiles. We confirm our previous result that spiral arm pitch angles (P) are well correlated with the rate of shear (S) in disk galaxy rotation curves. We use this correlation to argue that imaging data alone can provide a powerful probe of galactic mass distributions out to large look-back times. We then use a sample of 13 galaxies, with Spitzer 3.6 μm imaging data and observed Hα rotation curves, to demonstrate how an inferred shear rate coupled with a bulge-disk decomposition model and a Tully-Fisher-derived velocity normalization can be used to place constraints on a galaxy's baryon fraction and dark matter halo profile. Finally, we show that there appears to be a trend (albeit a weak correlation) between spiral arm pitch angle and halo concentration. We discuss implications for the suggested link between supermassive black hole (SMBH) mass and dark halo concentration, using pitch angle as a proxy for SMBH mass.

Spiral structure is the most distinctive feature of disk galaxies and yet debate persists about which theory of spiral structure is correct. Many versions of the density wave theory demand that the pitch angle be uniquely determined by the distribution of mass in the bulge and disk of the galaxy. We present evidence that the tangent of the pitch angle of logarithmic spiral arms in disk galaxies correlates strongly with the density of neutral atomic hydrogen in the disk and with the central stellar bulge mass of the galaxy. These three quantities, when plotted against each other, form a planar relationship that we argue should be fundamental to our understanding of spiral structure in disk galaxies. We further argue that any successful theory of spiral structure must be able to explain this relationship.

The density-wave theory of galactic spiral-arm structure makes a striking prediction that the pitch angle of spiral arms should vary with the wavelength of the galaxy’s image. The reason is that stars are born in the density wave but move out of it as they age. They move ahead of the density wave inside the co-rotation radius, and fall behind outside of it, resulting in a tighter pitch angle at wavelengths that image stars (optical and near-infrared) than those that are associated with star formation (far-infrared and ultraviolet). In this study we combined large sample size with wide range of wavelengths, from the ultraviolet to the infrared to investigate this issue. For each galaxy we used an optical wavelength image (B-band: 445 nm) and images from the Spitzer Space Telescope at two infrared wavelengths (infrared: 3.6 and 8.0 μm) and we measured the pitch angle with the 2DFFT and Spirality codes. We find that the B-band and 3.6 μm images have smaller pitch angles than the infrared 8.0 μm image in all cases, in agreement with the prediction of density-wave theory. We also used images in the ultraviolet from Galaxy Evolution Explorer, whose pitch angles agreed with the measurements made at 8 μm.

We present a determination of the supermassive black hole (SMBH) mass function for early- and late-type galaxies in the nearby universe (z < 0.0057), established from a volume-limited sample consisting of a statistically complete collection of the brightest spiral galaxies in the southern hemisphere. The sample is defined by limiting luminosity (redshift-independent) distance, D L= 25.4 Mpc, and a limiting absolute B-band magnitude, {{M}}B=-19.12. These limits define a sample of 140 spiral, 30 elliptical (E), and 38 lenticular (S0) galaxies. We established the Sérsic index distribution for early-type (E/S0) galaxies in our sample. Davis et al. established the pitch angle distribution for their sample, which is identical to our late-type (spiral) galaxy sample. We then used the pitch angle and the Sérsic index distributions in order to estimate the SMBH mass function for our volume-limited sample. The observational simplicity of our approach relies on the empirical relation between the mass of the central SMBH and the Sérsic index for an early-type galaxy or the logarithmic spiral-arm pitch angle for a spiral galaxy. Our SMBH mass function agrees well at the high-mass end with previous values in the literature. At the low-mass end, although inconsistencies exist in previous works that still need to be resolved, our work is more in line with expectations based on modeling of black hole evolution.

Aims: This work is the first stage of a campaign to search for intermediate-mass black holes (IMBHs) in low-luminosity active galactic nuclei (LLAGN) and dwarf galaxies. An additional and equally important aim of this pilot study is to investigate the consistency between the predictions of several popular black hole scaling relations and the fundamental plane (FP) of black-hole activity (FP-BH).   
Methods: We used well established X-ray and radio luminosity relations in accreting black holes, along with the latest scaling relations between the mass of the central black hole (MBH) and the properties of its host spheroid, to predict MBH in seven LLAGN, that were previously reported to be in the IMBH regime. Namely, we used the recently re-evaluated MBH-Msph(Msph: spheroid absolute magnitude at 3.6 μm) scaling relation for spiral galaxies, the MBH-nsph (nsph: major axis Sérsic index of the spheroid component) relation, the MBH-PA (PA: spiral pitch angle) relation, and a recently re-calibrated version of the FP-BH for weakly accreting BHs, to independently estimate MBH in all seven galaxies.   
Results: We find that all LLAGN in our list have low-mass central black holes with log MBH/M⊙ ≈ 6.5 on average, but that they are, most likely, not IMBHs. All four methods used predicted consistent BH masses in the 1σ range. Furthermore, we report that, in contrast to previous classification, galaxy NGC 4470 is bulge-less, and we also cast doubts on the AGN classification of NGC 3507.   
Conclusions: We find that our latest, state-of-the-art techniques for bulge magnitude & Sérsic index computations and the most recent updates of the MBH-Lsph, MBH-nsph, and MBH-PA relations and the FP-BH produce consistent results in the low-mass regime. We thus establish a multiple-method approach for predicting BH masses in the regime where their spheres of gravitational influence cannot be spatially resolved. Our approach mitigates against outliers from any one relation and provides a more robust average prediction. We will use our new method to revisit more IMBH candidates in LLAGN.

We have conducted an image analysis of the (current) full sample of 44 spiral galaxies with directly measured supermassive black hole (SMBH) masses, MBH, to determine each galaxy's logarithmic spiral arm pitch angle, ϕ. For predicting black hole masses, we have derived the relation: log (MBH/M⊙) = (7.01 ± 0.07) - (0.171 ± 0.017)[|ϕ| - 15°]. The total root mean square scatter associated with this relation is 0.43 dex in the log MBH direction, with an intrinsic scatter of 0.30 ± 0.08 dex. The MBH-ϕ relation is therefore at least as accurate at predicting SMBH masses in spiral galaxies as the other known relations. By definition, the existence of an MBH-ϕ relation demands that the SMBH mass must correlate with the galaxy discs in some manner. Moreover, with the majority of our sample (37 of 44) classified in the literature as having a pseudobulge morphology, we additionally reveal that the SMBH mass correlates with the large-scale spiral pattern and thus the discs of galaxies hosting pseudobulges. Furthermore, given that the MBH-ϕ relation is capable of estimating black hole masses in bulge-less spiral galaxies, it therefore has great promise for predicting which galaxies may harbour intermediate-mass black holes (IMBHs, MBH < 105 M⊙). Extrapolating from the current relation, we predict that galaxies with |ϕ| ≥ 26.7° should possess IMBHs.

The (supermassive black hole mass, MBH)-(bulge stellar mass, M∗,sph) relation is, obviously, derived using two quantities. We endeavor to provide accurate values for the latter via detailed multicomponent galaxy decompositions for the current full sample of 43 spiral galaxies having directly measured MBH values; 35 of these galaxies have been alleged to contain pseudobulges, 21 have water maser measurements, and three appear bulgeless. This more than doubles the previous sample size of spiral galaxies with a finessed image analysis. We have analyzed near-infrared images, accounting for not only the bulge, disk (exponential, truncated, or inclined), and bar but also for spiral arms and rings and additional central components (active galactic nuclei (AGNs), etc.). A symmetric Bayesian analysis finds log(MBH/M⊙)=(2.44+0.35−0.31)log{M∗,sph/[υ(1.15×1010M⊙)]}+(7.24±0.12), with υ a stellar mass-to-light ratio term. The level of scatter equals that about the MBH-σ∗ relation. The nonlinear slope rules out the idea that many mergers, coupled with the central limit theorem, produced this scaling relation, and it corroborates previous observational studies and simulations, which have reported a near-quadratic slope at the low-mass end of the MBH-M∗,sph diagram. Furthermore, bulges with AGNs follow this relation; they are not offset by an order of magnitude, and models that have invoked AGN feedback to establish a linear MBH-M∗,sph relation need revisiting. We additionally present an updated MBH-(Sérsic index, nsph) relation for spiral galaxy bulges with a comparable level of scatter and a new M∗,sph-(spiral-arm pitch angle, ϕ) relation.

Black hole mass (MBH) scaling relations are typically derived using the properties of a galaxy's bulge and samples dominated by (high-mass) early-type galaxies. Studying late-type galaxies should provide greater insight into the mutual growth of black holes and galaxies in more gas-rich environments. We have used 40 spiral galaxies to establish how MBH scales with both the total stellar mass (M∗,tot) and the disk's stellar mass, having measured the spheroid (bulge) stellar mass (M∗,sph) and presented the MBH-M∗,sph relation in Paper I. The relation involving M∗,totmay be beneficial for estimating MBH either from pipeline data or at higher redshift, conditions that are not ideal for the accurate isolation of the bulge. A symmetric Bayesian analysis finds log(MBH/M⊙)=(3.05+0.57−0.49)log{M∗,tot/[υ(6.37×1010M⊙)]}+(7.25+0.13−0.14). The scatter from the regression of MBHon M∗,tot is 0.66 dex; compare 0.56 dex for MBH on M∗,sph and 0.57 dex for MBH on σ∗. The slope is >2 times that obtained using core-Sérsic early-type galaxies, echoing a similar result involving M∗,sph, and supporting a varied growth mechanism among different morphological types. This steeper relation has consequences for galaxy/black hole formation theories, simulations, and predicting black hole masses. We caution that (i) an MBH-M∗,tot relation built from a mixture of early- and late-type galaxies will find an arbitrary slope of approximately 1-3, with no physical meaning beyond one's sample selection, and (ii) evolutionary studies of the MBH-M∗,tot relation need to be mindful of the galaxy types included at each epoch. We additionally update the M∗,tot-(face-on spiral arm pitch angle) relation.

The Chandra X-ray Observatory's Cycle 18 Large Program titled "Spiral galaxies of the Virgo Cluster" will image 52 galaxies with the ACIS-S detector. Combined with archival data for an additional 22 galaxies, this will represent the complete sample of 74 spiral galaxies in the Virgo cluster with star-formation rates ≳ 0.3 M⊙/yr. Many of these galaxies are expected to have an active nucleus, signalling the presence of a central black hole. In preparation for this survey, we predict the central black hole masses using the latest black hole scaling relations based on spiral arm pitch angle φ, velocity dispersion σ, and total stellar mass M∗,galaxy. With a focus on intermediate mass black holes (102<Mbh/M⊙<105), we highlight NGC 4713 and NGC 4178, both with Mbh≈103-104 (an estimate which is further supported in NGC 4718 by its nuclear star cluster mass). From Chandra archival data, we find that both galaxies have a point-like nuclear X-ray source, with unabsorbed 0.3-10 keV luminosities of a few times 1038 erg/s. In NGC 4178, the nuclear source has a soft, probably thermal, spectrum consistent with a stellar-mass black hole in the high/soft state, while no strong constraints can be derived for the nuclear emission of NGC 4713. In total, 33 of the 74 galaxies are predicted to have Mbh<(105-106) M⊙, and several are consistently predicted, via three methods, to have masses of 104-105M⊙, such as IC 3392, NGC 4294 and NGC 4413. We speculate that a sizeable population of IMBHs may reside in late-type spiral galaxies with low stellar mass (M∗,galaxy≲1010M⊙).

Using the latest sample of 48 spiral galaxies having a directly-measured supermassive black hole mass, MBH, we determine how the maximum disk rotational velocity, vmax (and the implied dark matter halo mass, MDM), correlates with MBH, central velocity dispersion (σ0), and spiral arm pitch angle (ϕ). We find that MBH∝v10.58±1.35max∝M4.34±0.65DM, significantly steeper than previously reported, and with a total root mean square scatter (0.63dex) equal to that about the MBH-σ0relation for spiral galaxies - in stark antithesis with claims that MBH does not correlate with disks. Moreover, this MBH-vmax relation is consistent with the unification of the Tully-Fisher relation (involving the total stellar mass, M∗,tot) and the steep MBH∝M3.05±0.53∗,tot relation observed in spiral galaxies. We also find that σ0∝v1.54±0.25max∝M0.63±0.11DM, consistent with past studies connecting stellar bulges (with σ0≳100kms−1), dark matter halos, and a non-constant vmax/σ0 ratio. Finally, we report that tan|ϕ|∝(−1.17±0.19)logvmax∝(−0.48±0.09)logMDM, providing a novel formulation between the geometry (i.e., the logarithmic spiral arm pitch angle) and kinematics of spiral galaxy disks. While the vmax-ϕ relation may facilitate distance estimations to face-on spiral galaxies, via the Tully-Fisher relation and using ϕ as a proxy for vmax, the MDM-ϕ relation provides a path for determining dark matter halo masses from imaging data alone. Furthermore, based on a spiral galaxy sample size which is double that used previously, the self-consistent relations presented here provide dramatically revised constraints for theory and simulations.

Analyzing a sample of 84 early-type galaxies with directly-measured super-massive black hole masses---nearly doubling the sample size of such galaxies with multi-component decompositions---a symmetric linear regression on the reduced (merger-free) sample of 76 galaxies reveals MBH∝M1.27±0.07∗,sph with a total scatter of Δrms= 0.52 dex in the log(MBH) direction. However, and importantly, we discover that the ES/S0-type galaxies with disks are offset from the E-type galaxies by more than a factor of ten in their MBH/M∗,sph ratio, with ramifications for formation theories, simulations, and some virial factor measurements used to convert AGN virial masses into MBH. Separately, each population follows a steeper relation with slopes of 1.86±0.20 and 1.90±0.20, respectively. The offset mass ratio is mainly due to the exclusion of the disk mass, with the two populations offset by only a factor of two in their MBH/M∗,gal ratio in the MBH-M∗,gal diagram where MBH∝M1.8±0.2∗,gal and Δrms=0.6±0.1 dex depending on the sample. For MBH≳107M⊙, we detect no significant bend nor offset in either the MBH-M∗,sph or MBH-M∗,galrelations due to barred versus non-barred, or core-Sérsic versus Sérsic, early-type galaxies. For reference, the ensemble of late-type galaxies (which invariably are Sérsic galaxies) follow MBH-M∗,sph and MBH-M∗,gal relations with slopes equal to 2.16±0.32 and 3.05±0.70, respectively. Finally, we provide some useful conversion coefficients, υ, accounting for the different stellar mass-to-light ratios used in the literature, and we report the discovery of a local, compact massive spheroid in NGC 5252.

The density-wave theory of spiral structure proposes that star formation occurs in or near a spiral-shaped region of higher density that rotates rigidly within the galactic disk at a fixed pattern speed. In most interpretations of this theory, newborn stars move downstream of this position as they come into view, forming a downstream spiral which is tighter, with a smaller pitch angle than that of the density wave itself. Rival theories, including theories which see spiral arms as essentially transient structures, may demand that pitch angle should not depend on wavelength. We measure the pitch angle of a large sample of galaxies at several wavelengths associated with star formation or very young stars (8.0 *μ*m, H-*α* line and 151 nm in the far-UV) and show that they all have the same pitch angle, which is larger than the pitch angle measured for the same galaxies at optical and near-infrared wavelengths. Our measurements in the *B* band and at 3.6 *μ*m have unambiguously tighter spirals than the star-forming wavelengths. In addition we have measured in the *u* band, which seems to fall midway between these two extremes. Thus, our results are consistent with a region of enhanced stellar light situated downstream of a star-forming region.

Using 143 early- and late-type galaxies (ETGs and LTGs) with directly-measured super-massive black hole masses (MBH), we build upon our previous discoveries that: (i) LTGs, most of which have been alleged to contain a pseudobulge, follow the relation MBH∝M2.16±0.32∗,sph; and (ii) the ETG relation MBH∝M1.27±0.07∗,sph is an artifact of ETGs with/without disks following parallel MBH∝M1.9±0.2∗,sph relations which are offset by an order of magnitude in the MBH-direction. Here we searched for substructure in the MBH-(central velocity dispersion, σ) diagram using our recently published, multi-component, galaxy decompositions; investigating divisions based on the presence of a depleted stellar core (major dry-merger), a disk (minor wet/dry-merger, gas accretion), or a bar (evolved unstable disk). The Sérsic and core-Sérsic galaxies define two distinct relations: MBH∝σ5.86±0.33 and MBH∝σ8.54±1.07, with Δrms|BH=0.51 and 0.47 dex, respectively. We also report on the consistency with the slopes and bends in the galaxy luminosity (L)-σrelation due to Sérsic and core-Sérsic ETGs, and LTGs which all have Sérsic light-profiles. The bend in the MBH-σ diagram (superficially) reappears upon separating galaxies with/without a disk, while we find no significant offset between barred and non-barred galaxies, nor between galaxies with/without active galactic nuclei. We also address selection biases purported to affect the scaling relations for dynamically-measured MBH samples. These new, type-dependent, *MBH* –*σ* relations more precisely estimate *MBH* in other galaxies, and hold implications for galaxy/black hole co-evolution theories, simulations, feedback, the pursuit of a black hole fundamental plane, and calibration of virial *f* -factors for reverberation-mapping.

The spiral arms spanning disc galaxies are believed to be created by density waves that propagate through galactic discs. We present a novel method of finding the co-rotation radius where the spiral arm pattern speed matches the velocities of the stars within the disc. Our method uses an image-overlay technique, which involves tracing the arms of spiral galaxies on images observed in different wavelengths. Density wave theory predicts that spiral arms observed from different wavelengths show a phase crossing at the co-rotation radius. For the purpose of this study, 20 nearby galaxies were analysed in four different wavelengths with pitch angle measurements performed by two independent methods. We used optical wavelength images (B band 440 nm), two infrared wavelength images provided by Spitzer (3.6 and 8 μm) and ultraviolet images from GALEX (1350, 1750 Å). The results were compared and verified with other records found in the literature. We then found rotation curve data for six of our galaxies and used our co-rotation radii estimates to measure the time that would elapse between star formation and moving to their observed positions in the B-band spirals. The average time lapse for this motion was found to be ∼50 Myr. The success of this new method of finding the co-rotation radius confirms density wave theory in a very direct way.

For 123 local galaxies with directly measured black hole masses (*M* BH), we provide the host spheroid's Sérsic index (*n* sph), effective half-light radius (*R* e,sph), and effective surface brightness (${\mu }_{{\rm{e}}}$), obtained from careful multicomponent decompositions, and we use these to derive the morphology-dependent *M* BH–*n* sph and *M* BH–*R* e,sph relations. We additionally present the morphology-dependent *M* \*,sph–*n* sph and *M* \*,sph–*R* e,sph relations. We explored differences due to early-type galaxies (ETGs) versus late-type galaxies (LTGs), Sérsic versus core-Sérsic galaxies, barred versus non-barred galaxies, and galaxies with and without a stellar disk. We detect two different *M* BH–*n* sph relations due to ETGs and LTGs with power-law slopes 3.95 ± 0.34 and 2.85 ± 0.31. We additionally quantified the correlation between *M* BH and the spheroid's central concentration index, which varies monotonically with the Sérsic index. Furthermore, we observe a single, near-linear *M* \*,sph–${R}_{{\rm{e}},\mathrm{sph}}^{1.08\pm 0.04}$ relation for ETGs and LTGs, which encompasses both classical and alleged pseudobulges. In contrast, ETGs and LTGs define two distinct *M* BH–*R* e,sph relations with ${{\rm{\Delta }}}_{\mathrm{rms}| \mathrm{BH}}\sim 0.60\,\mathrm{dex}$ (cf. ~0.51 dex for the *M* BH–*σ* relation and ~0.58 dex for the *M* BH–*M* \*,sph relation), and the ETGs alone define two steeper *M* BH–*R* e,sph relations, offset by ~1 dex in the $\mathrm{log}{M}_{\mathrm{BH}}$ direction, depending on whether they have a disk or not and explaining their similar offset in the *M* BH–*M* \*,sph diagram. This trend holds using 10%, 50%, or 90% radii. These relations offer pivotal checks for simulations trying to reproduce realistic galaxies, and for theoretical studies investigating the dependence of black hole mass on basic spheroid properties.

In this dissertation, I explore the geometric structure of spiral galaxies and how the visible structure can provide information about the central mass of a galaxy, the density of its galactic disk, and the hidden mass of the supermassive black hole in its nucleus. In order to quantitatively measure the logarithmic spiral pitch angle (a measurement of tightness of the winding) of galactic spiral arms, I led an effort in our research group (the Arkansas Galaxy Evolution Survey) to modify existing two-dimensional fast Fourier transform software to increase its efficacy and accuracy. Using this software, I was able to lead an effort to calculate a black hole mass function (BHMF) for spiral galaxies in our local Universe. This work effectively provides us with a census of local black holes and establishes an endpoint on the evolutionary history of the BHMF for spiral galaxies. Furthermore, my work has indicated a novel fundamental relationship between the pitch angle of a galaxy's spiral arms, the maximum density of neutral atomic hydrogen in its disk, and the stellar mass of its bulge. This result provides strong support for the density wave theory of spiral structure in disk galaxies and poses a critical question of the validity of rival theories for the genesis of spiral structure in disk galaxies.