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.

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.

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 μm, 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 μm 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.

Recent X-ray observations by Jiang et al. have identified an active galactic nucleus (AGN) in the bulgeless spiral galaxy NGC 3319, located just 14.3±1.1Mpc away, and suggest the presence of an intermediate-mass black hole (IMBH; 102≤M∙/M⊙≤105) if the Eddington ratios are as high as 3 to 3×10−3. In an effort to refine the black hole mass for this (currently) rare class of object, we have explored multiple black hole mass scaling relations, such as those involving the (not previously used) velocity dispersion, logarithmic spiral-arm pitch angle, total galaxy stellar mass, nuclear star cluster mass, rotational velocity, and colour of NGC 3319, to obtain ten mass estimates, of differing accuracy. We have calculated a mass of 3.14+7.02−2.20×104M⊙, with a confidence of 84% that it is ≤105M⊙, based on the combined probability density function from seven of these individual estimates. Our conservative approach excluded two black hole mass estimates (via the nuclear star cluster mass, and the fundamental plane of black hole activity — which only applies to black holes with low accretion rates) that were upper limits of ∼105M⊙, and it did not use the M∙–L2−10keV relation's prediction of ∼105M⊙. This target provides an exceptional opportunity to study an IMBH in AGN mode and advance our demographic knowledge of black holes. Furthermore, we introduce our novel method of meta-analysis as a beneficial technique for identifying new IMBH candidates by quantifying the probability that a galaxy possesses an IMBH.

Galaxies can grow through their mutual gravitational attraction and subsequent union. While orbiting a regular high-surface-brightness galaxy, the body of a low-mass galaxy can be stripped away. However, the stellar heart of the infalling galaxy, if represented by a tightly bound nuclear star cluster, is more resilient. From archival Hubble Space Telescope images, we have discovered a red, tidally stretched star cluster positioned ∼5'' (∼400 pc in projection) from, and pointing toward the center of, the post-merger spiral galaxy NGC 4424. The star cluster, which we refer to as "Nikhuli," has a near-infrared luminosity of (6.88 ± 1.85) × 106L⊙,F160W and likely represents the nucleus of a captured/wedded galaxy. Moreover, from our Chandra X-ray Observatory image, Nikhuli is seen to contain a high-energy X-ray point source, with ${L}_{0.5-8\,\mathrm{keV}}={6.31}_{-3.77}^{+7.50}\times {10}^{38}$ erg s−1 (90% confidence). We argue that this is more likely to be an active massive black hole than an X-ray binary. Lacking an outward-pointing comet-like appearance, the stellar structure of Nikhuli favors infall rather than the ejection from a gravitational-wave recoil event. A minor merger with a low-mass early-type galaxy may have sown a massive black hole, aided an X-shaped pseudobulge, and be sewing a small bulge. The stellar mass and the velocity dispersion of NGC 4424 predict a central black hole of (0.6–1.0) × 105 M⊙, similar to the expected intermediate-mass black hole in Nikhuli, and suggestive of a black hole supply mechanism for bulgeless late-type galaxies. We may potentially be witnessing black hole seeding by capture and sinking, with a nuclear star cluster the delivery vehicle.

Building upon three late-type galaxies in the Virgo cluster with both a predicted black hole mass of less than ∼105 M⊙ and a centrally located X-ray point source, we reveal 11 more such galaxies, more than tripling the number of active intermediate-mass black hole candidates among this population. Moreover, this amounts to a ∼36 ± 8% X-ray detection rate (despite the sometimes high, X-ray-absorbing, H i column densities), compared to just 10 ± 5% for (the largely H i-free) dwarf early-type galaxies in the Virgo cluster. The expected contribution of X-ray binaries from the galaxies' inner field stars is negligible. Moreover, given that both the spiral and dwarf galaxies contain nuclear star clusters, the above inequality appears to disfavor X-ray binaries in nuclear star clusters. The higher occupation, or rather detection, fraction among the spiral galaxies may instead reflect an enhanced cool gas/fuel supply and Eddington ratio. Indeed, four of the 11 new X-ray detections are associated with known LINERs or LINER/H ii composites. For all (four) of the new detections for which the X-ray flux was strong enough to establish the spectral energy distribution in the Chandra band, it is consistent with power-law spectra. Furthermore, the X-ray emission from the source with the highest flux (NGC 4197: LX ≈ 1040 erg s−1) suggests a non-stellar-mass black hole if the X-ray spectrum corresponds to the "low/hard state". Follow-up observations to further probe the black hole masses, and prospects for spatially resolving the gravitational spheres of influence around intermediate-mass black holes, are reviewed in some detail.

This paper is the fourth in a series presenting (galaxy morphology, and thus galaxy formation)-dependent black hole (BH) mass, MBH, scaling relations. We have used a sample of 119 galaxies with directly measured MBH and host spheroid parameters obtained from multicomponent decomposition of, primarily, 3.6 μm Spitzer images. Here, we investigate the correlations between MBH and the projected (apparent) luminosity density μ, the projected stellar mass density Σ, and the de-projected (internal) stellar mass density ρ, for various spheroid radii. We discover the predicted MBH–μ0,sph relation and present the first MBH–μe,sph and MBH–ρe,int,sph diagrams displaying slightly different (possibly curved) trends for early- and late-type galaxies (ETGs and LTGs, respectively) and an offset between ETGs with (fast-rotators, ES/S0) and without (slow-rotators, E) a disk. The scatter about various MBH–〈Σ〉R,sph (and 〈ρ〉r,sph) relations is shown to systematically decrease as the enclosing aperture (and volume) increases, dropping from 0.69 dex when using the spheroid "compactness," 〈Σ〉1kpc,sph, to 0.59 dex when using 〈Σ〉5kpc,sph. We also reveal that MBH correlates with the internal density, ρsoi,sph, at the BH's sphere-of-influence radius, such that core-Sérsic (high Sérsic index, n) and (low-n) Sérsic galaxies define different relations with total rms scatters 0.21 dex and 0.77 dex, respectively. The MBH–〈ρ〉soi,sph relations will help with direct estimation of tidal disruption event rates, binary BH lifetimes, and together with other BH scaling relations, improve the characteristic strain estimates for long-wavelength gravitational waves pursued with pulsar timing arrays and space-based interferometers.

Quasi-stationary density wave theory predicts the existence of an age gradient across the spiral arms with a phase crossing at the corotation radius. We have examined evidence for such age gradients using star formation history (SFH) maps derived from LIGHTNING, a spectral energy distribution fitting procedure, and by using spatially resolved stellar clusters. Three galaxies from the LEGUS survey were used to analyse the azimuthal offsets of spatially resolved stellar clusters. Kernel density estimation plots of azimuthal cluster distance offsets reveal prominent central peaks and secondary peaks on the positive side, relative to the density wave for NGC 5194 and NGC 5236. These secondary downstream peaks in the cluster distributions show overall evidence for an age gradient. NGC 628 shows secondary peaks on both sides of the density wave. The cluster distributions also show an increasing spatial spread with age, consistent with the expectation that they were born in the density wave. SFH maps of 12 nearby galaxies were analysed using SPIRALITY, a MATLAB-based code, which plots synthetic spiral arms over FITS images. The SFH maps reveal a gradual decrement (tightening) in pitch angles with increasing age. By analysing the pitch angle differences between adjacent age bins using the error function, the average of the probabilities shows a 69 per cent±25 per cent69 per cent±25 per cent chance that the pitch angle values decrease (tighten) with increasing age. Thus, we see a tightening of the spiral pattern in galaxies, both when segregating stellar populations specifically by age or more generally by colour, as was shown in our previous studies.

The near-absence of compact massive quiescent galaxies in the local Universe implies a size evolution since z ∼ 2.5. It is often theorized that such ‘red nuggets’ have evolved into today’s elliptical (E) galaxies via an E-to-E transformation. We examine an alternative scenario in which a red nugget develops a rotational disc through mergers and accretion, say, at 1 ≲ z ≲ 2, thereby cloaking the nugget as the extant bulge/spheroid component of a larger, now old, galaxy. We have performed detailed, physically motivated, multicomponent decompositions of a volume-limited sample of 103 massive (⁠M∗/M⊙≳1×1011M∗/M⊙≳1×1011⁠) galaxies within 110 Mpc. Many less massive nearby galaxies are known to be ‘fast-rotators’ with discs. Among our 28 galaxies with existing elliptical classifications, we found that 18 have large-scale discs, and two have intermediate-scale discs, and are reclassified here as lenticulars (S0) and elliculars (ES). The local spheroid stellar mass function, size–mass diagram and bulge-to-total (B/T) flux ratio are presented. We report lower limits for the volume number density of compact massive spheroids, nc, Sph ∼ (0.17–1.2)×10−4Mpc−31.2)×10−4Mpc−3⁠, based on different definitions of ‘red nuggets’ in the literature. Similar number densities of local compact massive bulges were reported by de la Rosa et al. using automated two-component decompositions and their existence is now abundantly clear with our multicomponent decompositions. We find disc-cloaking to be a salient alternative for galaxy evolution. In particular, instead of an E-to-E process, disc growth is the dominant evolutionary pathway for at least low-mass (⁠1×1010<M∗/M⊙⪅4×10101×1010<M∗/M⊙⪅4×1010⁠) red nuggets, while our current lower limits are within an alluring factor of a few of the peak abundance of high-mass red nuggets at 1 ≲ z ≲ 2.

We present the MATLAB code Spirality, a novel method for measuring spiral arm pitch angles by fitting galaxy images to spiral templates of known pitch. Computation time is typically on the order of 2 min per galaxy, assuming 8 GB of working memory. We tested the code using 117 synthetic spiral images with known pitches, varying both the spiral properties and the input parameters. The code yielded correct results for all synthetic spirals with galaxy-like properties. We also compared the code’s results to two-dimensional Fast Fourier Transform (2DFFT) measurements for the sample of nearby galaxies defined by DMS PPak. Spirality’s error bars overlapped 2DFFT’s error bars for 26 of the 30 galaxies. The two methods’ agreement correlates strongly with galaxy radius in pixels and also with i-band magnitude, but not with redshift, a result that is consistent with at least some galaxies’ spiral structure being fully formed by z=1.2, beyond which there are few galaxies in our sample. The Spirality code package also includes GenSpiral, which produces FITS images of synthetic spirals, and SpiralArmCount, which uses a one-dimensional Fast Fourier Transform to count the spiral arms of a galaxy after its pitch is determined. All code is freely available.

Laser Interferometer Space Antenna (LISA) will be a transformative experiment for gravitational wave astronomy as it will offer unique opportunities to address many key astrophysical questions in a completely novel way. The synergy with ground-based and other space-based instruments in the electromagnetic domain, by enabling multi-messenger observations, will add further to the discovery potential of LISA. The next decade is crucial to prepare the astrophysical community for LISA's first observations. This review outlines the extensive landscape of astrophysical theory, numerical simulations, and astronomical observations that are instrumental for modeling and interpreting the upcoming LISA datastream. To this aim, the current knowledge in three main source classes for LISA is reviewed: ultra-compact stellar-mass binaries, massive black hole binaries, and extreme or intermediate mass ratio inspirals. The relevant astrophysical processes and the established modeling techniques are summarized. Likewise, open issues and gaps in our understanding of these sources are highlighted, along with an indication of how LISA could help make progress in the different areas. New research avenues that LISA itself, or its joint exploitation with studies in the electromagnetic domain, will enable, are also illustrated. Improvements in modeling and analysis approaches, such as the combination of numerical simulations and modern data science techniques, are discussed. This review is intended to be a starting point for using LISA as a new discovery tool for understanding our Universe.

We present an analysis of the pitch angle distribution function (PADF) for nearby galaxies and its resulting black hole mass function (BHMF) via the well-known relationship between pitch angle and black hole mass. Our sample consists of a subset of 74 spiral galaxies from the Carnegie- Irvine Galaxy Survey with absolute B-band magnitude MB > −19.12 mag and luminosity distance DL ≤ 25.4Mpc, which is an extension of a complementary set of 140 more luminous (MB ≤ −19.12 mag) late-type galaxies. We find the PADFs of the two samples are, somewhat surprisingly, not strongly dissimilar; a result that may hold important implications for spiral formation theories. Our data show a distinct bimodal population manifest in the pitch angles of the Sa–Sc types and separately the Scd–Sm types, with Sa–Sc types having tighter spiral arms on average. Importantly, we uncover a distinct bifurcation of the BHMF, such that the Sa–Sc galaxies typically host so-called “supermassive” black holes (M• ≳ 106 M⊙), whereas Scd–Sm galaxies accordingly harbor black holes that are “less-than-supermassive” (M• ≲ 106 M⊙). It is amongst this latter population of galaxies where we expect fruitful bounties of elusive intermediate-mass black holes (IMBHs), through which a better understanding will help form more precise benchmarks for future generations of gravitational wave detectors.

Supermassive black holes (SMBHs) are tiny in comparison to the galaxies they inhabit, yet they manage to influence and coevolve along with their hosts. Evidence of this mutual development is observed in the structure and dynamics of galaxies and their correlations with black hole mass (MBH). For our study, we focus on relative parameters that are unique to only disk galaxies. As such, we quantify the structure of spiral galaxies via their logarithmic spiral-arm pitch angles (ϕ) and their dynamics through the maximum rotational velocities of their galactic disks (vmax). In the past, we have studied black hole mass scaling relations between MBH and ϕ or vmax, separately. Now, we combine the three parameters into a trivariate MBH-ϕ-vmax relationship that yields best-in-class accuracy in prediction of black hole masses in spiral galaxies. Because most black hole mass scaling relations have been created from samples of the largest SMBHs within the most massive galaxies, they lack certainty when extrapolated to low-mass spiral galaxies. Thus, it is difficult to confidently use existing scaling relations when trying to identify galaxies that might harbor the elusive class of intermediate-mass black holes (IMBHs). Therefore, we offer our novel relationship as an ideal predictor to search for IMBHs and probe the low-mass end of the black hole mass function by utilizing spiral galaxies. Already with rotational velocities widely available for a large population of galaxies and pitch angles readily measurable from uncalibrated images, we expect that the MBH-ϕ-vmax fundamental plane will be a useful tool for estimating black hole masses, even at high redshifts.

We analyzed images of every northern hemisphere Sd galaxy listed in the Third Reference Catalogue of Bright Galaxies with a relatively face-on inclination (θ ≤ 30°). Specifically, we measured the spiral arms' winding angle, ϕ, in 85 galaxies. We applied a novel black hole mass planar scaling relation involving the rotational velocities (from the literature) and pitch angles of each galaxy to predict central black hole masses. This yielded 23 galaxies, each having at least a 50% chance of hosting a central intermediate-mass black hole (IMBH), 102 < M• ≤ 105M☉. These 23 nearby (≲50 Mpc) targets may be suitable for an array of follow-up observations to check for active nuclei. Based on our full sample of 85 Sd galaxies, we estimate that the typical Sd galaxy (which tends to be bulgeless) harbors a black hole with log(M∙/M⊙)=6.00±0.14, but with a 27.7% chance of hosting an IMBH, making this morphological type of galaxy fertile ground for hunting elusive IMBHs. Thus, we find that a ∼106M☉ black hole corresponds roughly to the onset of bulge development and serves as a conspicuous waypoint along the galaxy–supermassive black hole coevolution journey. Our survey suggests that >1.22% of bright galaxies (BT ≲ 15.5 mag) in the local Universe host an IMBH (i.e., the "occupation fraction"), which implies a number density >4.96 × 10−6 Mpc−3 for central IMBHs. Finally, we observe that Sd galaxies exhibit an unexpected diversity of properties that resemble the general population of spiral galaxies, albeit with an enhanced signature of the eponymous prototypical traits (i.e., low masses, loosely wound spiral arms, and smaller rotational velocities).

We present the High-z Evolution of Large and Luminous Objects (HELLO) project, a set of ∼30 high-resolution cosmological simulations aimed to study Milky Way analogues (⁠M⋆∼1010−11 M⊙⁠) at high redshift (⁠z∼[2−4]⁠). Based on the numerical investigation of a hundred astrophysical objects, HELLO features an updated scheme for chemical enrichment and the addition of local photoionization feedback. Independently of redshift and mass, our galaxies exhibit a smooth progression along the star formation main sequence until M⋆∼1010.5⁠, around which our sample at z∼4 remains mostly unperturbed while the most massive galaxies at z∼2 reach their peak star formation rate (SFR) and its subsequent decline, due to a mix of gas consumption and stellar feedback. While active galactic nucleus feedback remains subdominant with respect to stellar feedback for energy deposition, its localized nature likely adds to the physical processes leading to declining SFRs. The phase in which a galaxy in our mass range can be found at a given redshift is set by its gas reservoir and assembly history. Finally, our galaxies are in excellent agreement with various scaling relations observed with the Hubble Space Telescope and the JWST, and hence can be used to provide the theoretical framework to interpret current and future observations from these facilities and shed light on the transition from star-forming to quiescent galaxies.

Correlation does not imply causation, but patterns of statistical association between variables can be exploited to infer a causal structure (even with purely observational data) with the burgeoning field of causal discovery. As a purely observational science, astrophysics has much to gain by exploiting these new methods. The supermassive black hole (SMBH)–galaxy interaction has long been constrained by observed scaling relations, which is low-scatter correlations between variables such as SMBH mass and the central velocity dispersion of stars in a host galaxy's bulge. This study, using advanced causal discovery techniques and an up-to-date data set, reveals a causal link between galaxy properties and dynamically measured SMBH masses. We apply a score-based Bayesian framework to compute the exact conditional probabilities of every causal structure that could possibly describe our galaxy sample. With the exact posterior distribution, we determine the most likely causal structures and notice a probable causal reversal when separating galaxies by morphology. In elliptical galaxies, bulge properties (built from major mergers) tend to influence SMBH growth, while, in spiral galaxies, SMBHs are seen to affect host galaxy properties, potentially through feedback in gas-rich environments. For spiral galaxies, SMBHs progressively quench star formation, whereas, in elliptical galaxies, quenching is complete, and the causal connection has reversed. Our findings support theoretical models of hierarchical assembly of galaxies and active galactic nuclei feedback regulating galaxy evolution. Our study suggests the potentiality for further exploration of causal links in astrophysical and cosmological scaling relations, as well as any other observational science.

Recent James Webb Space Telescope observations have revealed a peculiar class of galaxies at redshifts z ≳ 6, characterized by extremely high central stellar densities and overmassive central supermassive black holes (SMBHs), "little red dots" (LRDs). A critical question remains: if LRDs were common at high redshifts, how would they evolve into local elliptical galaxies with significantly lower central densities? To address this, we performed direct N-body simulations of LRD mergers, focusing on the coevolution of host galaxies and central SMBHs. We track the complete evolution of SMBH binaries into the three-body hardening and gravitational-wave (GW) emission phase. Our results demonstrate that during galaxy mergers, the central SMBHs can eject a substantial amount of mass from the galactic core via the three-body slingshot effect, leading to a decrease in central stellar surface density by an order of magnitude. Additionally, GW recoil can further contribute in making the galaxy centers less dense and more in alignment with low-redshift quiescent galaxies. This transformation occurs on a relatively short timescale of a few ∼100 Myr, implying that LRDs can evolve into lower-redshift elliptical galaxies by z < 4. The timescales for our SMBH mergers vary between 100 and 800 Myr, depending on the initial orbital parameters of the merging galaxies and the mass ratio of the SMBHs. Our findings provide a plausible mechanism for the transformation of LRDs into elliptical galaxies while highlighting the efficiency of SMBH mergers in such high-density environments, which plays a crucial role in SMBH growth.

The origins of the colours of trans-Neptunian objects (TNOs) represent a crucial unresolved question, central to understanding the history of our Solar system. Recent observational surveys revealed correlations between the eccentricity and inclination of TNOs, and their colours. This rekindled the long-standing debate on whether these colours reflect the conditions of TNO formation or their subsequent evolution. We address this question using a model-agnostic, data-driven approach that unanimously converges to a common causal graph from the analysis of two different data sets, each from two different conditional independence test methods. For evaluation, we demonstrate how our model is consistent with the currently-accepted paradigms of TNOs’ dynamical histories, without involving any orbital modelling or physics-based assumptions. Our causal model (with no knowledge of the existence of Neptune) predicts the need for an unknown confounding variable, consistent with Neptune’s effects. The model predicts that the colour of TNOs is the root cause of their inclination distribution, rather than the other way around. This strongly suggests that the colours of TNOs reflect an underlying dynamical property, most likely their formation location. Our model excludes formation scenarios that invoke substantial colour modification by subsequent evolution. We conclude that the colours of TNOs are predominantly primordial.