Non-linear (Black Hole Mass)—Spheroid Scaling Laws & The Role of Galaxy Morphology

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The correlations observed between directly (dynamically) measured super massive black hole (SMBH) mass and host galaxy properties holds crucial insights for understanding their (expected) co-evolution and have many direct applications. The most studied correlation is between black hole mass ($M_{\rm BH}$) and the mass of the spheroid ($M_{*,\rm sph}$) of the host galaxy, which was thought to be linear (on a log-log scale) based upon a sample massive early-type galaxies (ETGs) and excluding late-type galaxies (LTGs) with alleged "pseudo-bulges". However, with increasing sample size, subsequent studies have revealed important advancements about the nature of the $M_{\rm BH}$–$M_{*,\rm sph}$ relation. A comprehensive review on scaling relations of $M_{\rm BH}$ with various host galaxy properties (e.g., $M_{*,\rm sph}$, velocity dispersion σ, and central light concentration inferred by Sérsic index n) known until 2016 can be found in [7].

Here we present subsequent crucial advancements in the understanding of BH–Spheroid (*a.k.a.* bulge) correlations based upon a total sample of 127 dynamically measured BH masses and bulge properties measured with unprecedented accuracy, which almost doubles the sample used in [16].

Galaxy Sample and Measurement of Bulge

In order to extract accurate bulge properties (e.g., mass or size), we generated 2D isophotal models of host galaxy images. We performed careful multi-component decomposition of galaxy light profile using in-house software ISOFIT and CMODEL inbuilt in IRAF and PROFILER, respectively, which are publically available [3, 4]. Here, ISOFIT performs a uniform sampling of the quasi-elliptical isophotes of the galaxy image using "eccentric anomaly" (rather than the angular parameter of a circle as used in ELLIPSE). Additionally, it uses higher-order Fourier coefficients which precisely capture the isophotal irregularities in a multi-component galaxy and further provide an excellent galaxy model via CMODEL task. Further, we identified various components present in a galaxy and disassembled total galaxy light into its components (including bulge) with the help of special functions inbuilt in PROFILER. For example, we use a Sérsic or core-Sérsic function to describe the light profile of normal bulges and core-depleted bulges, respectively, which provided us with a measure of luminosity associated with the bulge (converted to stellar mass using an appropriate stellar mass-to-light ratio), and it is the size (e.g., effective half-light radius $R_{e,sph}$).

The image analysis for 127 galaxies was collectively done in [15], [5], and [11]. The dynamical BH mass measurements were taken from other studies, which used stellar and gas dynamical modelling, megamaser kinematics, proper motion (for Sgr A), and the latest direct imaging (for M87) techniques. For a detailed description of the imaging, analysis techniques, multi-component decomposition profiles, bulge/galaxy properties, galaxy morphology, and original sources of BH mass, readers are directed to the above three studies. After excluding mergers (NGC 1316, NGC 5128), stripped galaxies (NGC 4342, NGC 4486B), bulge-less galaxies (NGC 2748, NGC 4395, NGC 6926), more than 2σ outliers (NGC 1277, NGC 1300, NGC 2787), and the only galaxy with intermediate BH mass (NGC 404), our sample comprises of 76 ETGs and 39 LTGs. ETGs include elliptical (E: pure spheroidal), ellicular (ES: galaxies with an intermediate-scale disk within their spheroids) [8], and lenticular galaxies (S0: galaxies with a large-scale disk extending out of their bulges) and LTGs include all kinds of spiral galaxies (S).

Black Hole Mass–Spheroid Correlations

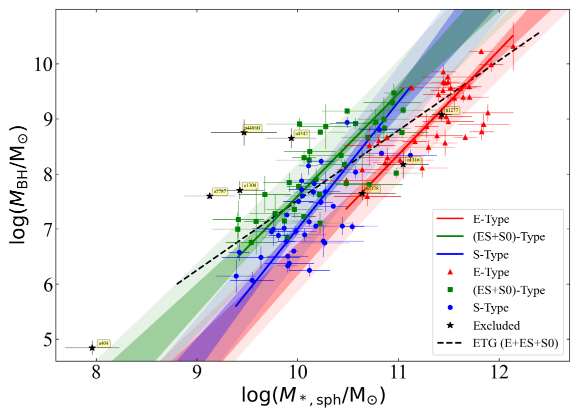

Figure 1: The quadratic $M_{\rm BH}$–$M_{*,\rm sph}$ relations defined by Elliptical (E), Ellicular & Lenticular (ES+S0), and Spiral galaxies (S). The black dash line shows the near-linear relation initially seen for all ETGs (E+ES+S0).

In order to establish the $M_{\rm BH}$–$M_{*,\rm sph}$ relation we used the symmetric application of BCES regression [1] which offers equal treatment and considers substantial uncertainties in both the parameters. Initially, we found that LTGs define a quadratic relation (blue line in Fig 1) that is steeper than the near-linear relation defined by (all) ETGs (dashed black line in Fig 1). However, further investigation showed that ETGs with a disk (ES and S0) and ETGs without a disk (E) define two different almost quadratic relations which are offset from each other by more than an order of magnitude in $M_{\rm BH}$-direction. Thus, ETGs with a disk, ETGs without a disk, and LTGs define three different almost quadratic relations (with power-law slopes ~ 2) in the $M_{\rm BH}$–$M_{*,\rm sph}$ diagram. Figure 1 is adapted from [11], see their Table 5 for the parameters of $M_{\rm BH}$–$M_{*,\rm sph}$ relations.

The steeper than linear relation between BH mass and bulge mass has been suspected by previous simulation and semi-analytic studies as well [2, 6]; however, the offset between ETGs with a disk and purely spheroidal elliptical galaxies has been realized in [11] for the first time. Subsequently, the same substructures were observed in the BH mass and spheroid effective half-light radius diagram due to ETGs with a disk, ETGs without a disk, and LTGs. The relation between $M_{\rm BH}$ and spheroid half-light radius, $R_{\rm e,sph,eq}$, along spheroid's geometric-mean axis are shown in Figure 2 (adapted from [13]). The three $M_{\rm BH}$–$R_{\rm e,sph,eq}$ relations are almost quadratic power-laws, and their full expressions can found in [13, their Table 2].

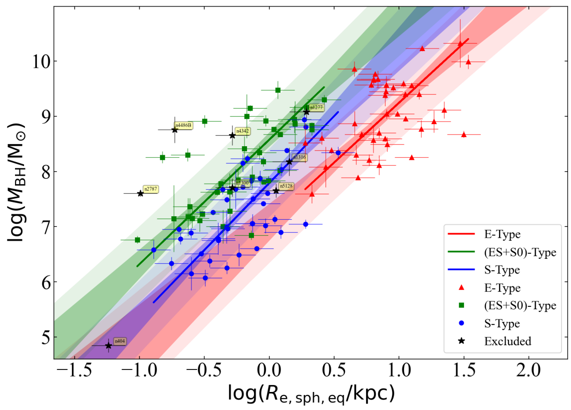

Figure 2: The quadratic $M_{\rm BH}$–$R_{\rm e,sph,eq}$ relations defined by Elliptical (E), Ellicular & Lenticular (ES+S0), and Spiral galaxies (S).

This offset appears to be due to smaller/less massive bulges of ETGs with a disk relative to the spheroids of elliptical galaxies, hosting similar BH mass and has been subsequently observed in the $M_{\rm BH}$–$M_{*,\rm sph}$ diagram via a simulation studying high-redshift evolution of black holes and their host galaxies [10]. Interestingly, the same substructures are observed in the $M_{\rm BH}$–(μ_e or Σ_e: projected bulge density at $R_{\rm e,sph}$) and the $M_{\rm BH}$–(ρ_e: internal bulge density at $R_{\rm e,sph}$) diagrams [14].

On investigating the $M_{\rm BH}$–(total galaxy stellar mass: $M_{*,\rm gal}$), we found that the offset between ETGs with and without disk reduces, suggesting a single $M_{\rm BH}$–$M_{*,\rm gal}$ relation for all ETGs; whereas, the LTGs define a relation with a slope twice as that of ETGs (see [11]). The $M_{\rm BH}$–$M_{*,\rm gal}$ diagram has a slightly higher scatter in $M_{\rm BH}$-direction than the $M_{\rm BH}$–$M_{*,\rm sph}$ relations, but provides an easier way to predict BH mass in other galaxies, without going through the multi-component decomposition of galaxy light.

Conclusion and Future Scope

The revelation of consistent morphology-dependent substructures significantly improve the previous linear relation and advance our understanding of BH mass–bulge connection, which is now known to depend on host galaxy morphology shaped by evolutionary processes (accretion) quenching, mergers) the galaxy goes through. This discovery was possible with accurate bulge properties and detailed galaxy morphology achieved via state-of-the-art modelling and multi-component decomposition of a galaxy image. In addition to the above-discussed BH scaling relations, the we also found morphology-dependent divisions in the $M_{\rm BH}$–σ [12], $M_{\rm BH}$–(bulge central light concentration or $n_{\rm sph}$) [13], and $M_{\rm BH}$–($\rho_{\rm soi}$: bulge density at the gravitational sphere-of-influence of it's SMBH) [14], and additionally, established $M_{\rm BH}$–$\mu_{0,sph}$ and $M_{\rm BH}$–(bulge compactness: Σ_{1kpc} and ρ_{1kpc}) relations [14]. These relations form alternatives to estimates $M_{\rm BH}$ in other galaxies, to be used depending on their known property and morphology.

The newly discovered morphology-dependent BH scaling relations have important ramifications for calibration of virial-factor required for reverberation mapping of AGNs, estimation of morphology-aware BH mass function, modelling of SMBH merger rate, and the expected long-wavelength gravitational-wave signals (see [14] for description). Importantly, these relations hold tests and insights for simulations, semi-analytic, and theoretical studies trying to understand BH–Galaxy co-evolution. In an upcoming paper [9] we explore more-realistic color-dependent stellar mass-to-light ratios for our bulge/galaxy masses, update $M_{\rm BH}$–$M_{*,\rm sph}$ relations, and discuss the role of mergers and/or AGN feedback in interpreting these morphology-dependent BH scaling relations.

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