Contents

Chapter 1

Introduction

There is a super massive black hole (SMBH) at the center of galaxies. It resides in the bulge of its host galaxy. These SMBHs have a mass $M_\bullet \sim 10^6 - 10^{10} M_\odot$, expressed in solar masses. Similar to galaxy formation, not much is known about the formation of these SMBHs. Additionally the evolution of the bulge and the respective SMBH is not well understood either.

To get new insights into the formation and evolution, one can investigate the correlation between the properties of the SMBH and their host galaxies, especially the bulges. The bulge is large enough not to be under the direct gravitational influence of the SMBH, so any correlations must be caused by either evolution or formation. The most important property of a black hole is its mass, so that will the studied property be.

One can find a close relation between the black hole mass and the stellar velocity dispersion, the luminosity and the mass of the bulge. These will the properties be discussed in this literature review.

There are formation and evolution models trying to reproduce these correlations. One such evolution model will be discussed. Lou and Jiang proposed a modell describing the bulge as a self similar, polytropic quasi-static fluid with self gravity and spherical symmetry.

Chapter 2

bulge relations

2.1 bulge stellar velocity dispersion (Ferrarese, Merritt 2000)

With mounting evidence for SMBHs in the center of galaxies, their relationship to their host galaxies was studied. Earlier works found a linear correlation between absolute blue luminosity B_T^0 of the host bulge and the logarithm of the SMBH mass $M_\bullet$. Later studies had shown, that these measurements suffered from observational biases and display a scatter larger than the uncertainties of the individual measurements.

Ferrarese and Merrit studied therefore a new relation, namely SMBH mass to stellar velocity dispersion σ_c, to find a tighter relation and compared it to the luminosity relation. [FM00]

For their data base they used all secure SMBH mass measurement available at the time. They further divided their set into two samples. Sample A contains 12 galaxies with what was deemed reliable SMBH mass estimates. The masses were obtained from high resolution Hubble Space Telescope observations. Two of these galaxies are especially noteworthy regarding their precision. There is the SMBH masses of the Milky Way by observing the proper motion of the Sagittarius A star cluster and of NGC 4258 by observing the dynamics of the water maser disc. The SMBH masses for the additional galaxies of Sample B were either optained by fitting accretion disc models [NEFH97] or by measurements from the earth.

For their analysis, Ferrarese and Merritt plotted the SMBH mass against either the absolute blue luminosity or the stellar velocity dispersion of the bulge. For the stellar velocity dispersion a double logarithmic plot is used, and for the luminosity, because magnitude is already logarithmic, only the mass is scaled logarithmic. Then they fitted a linear regression against both. See fig. 2.1.

Their findings for the $M_\bullet - B_T^0$ relation are in line with previous findings. While having a similar slope, the correlation is weak, especially for Sample A. The scatter is significantly larger than the errors. The $M_\bullet - \sigma_c$ relation shows negligible scatter compared to the errors for Sample A. As a reason for the weaker correlation for Sample

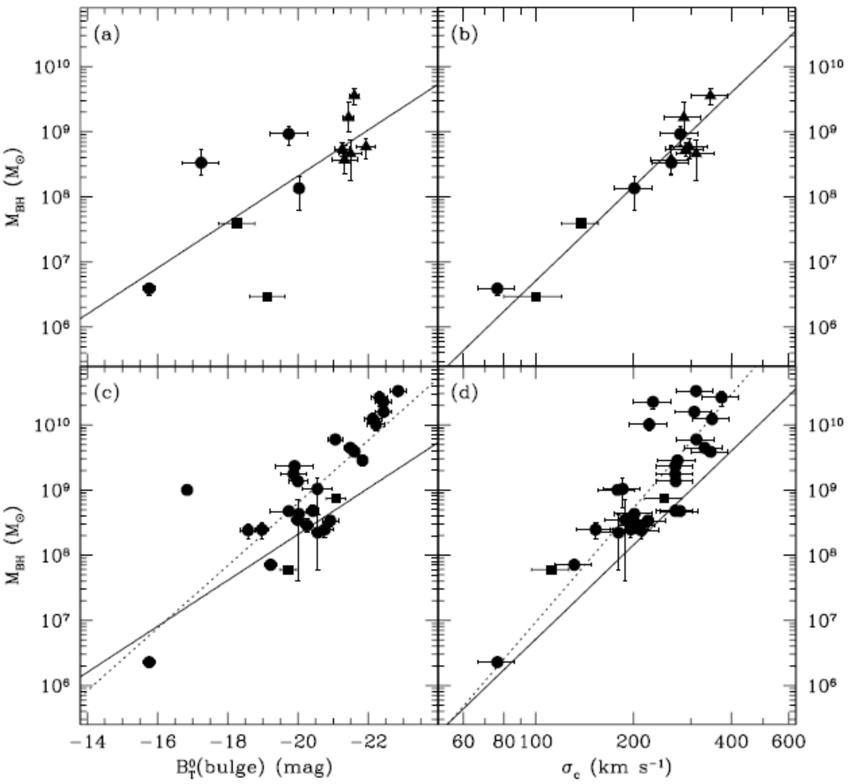

Figure 2.1: top row: Sample A, bottom row: Sample B, solid line: plot for A, dashed line: plot for B

B, Ferrarese and Merritt suggested the larger uncertainties in this sample.

As a linear correlation in a double logarithmic plot represents a power law, Ferrarese and Merritt found the relation $M_\bullet \propto \sigma_c^\alpha$ mit $\alpha = 4.8 \pm 0.5$. As possible reasons for this relation, they name either a SMBH mass to bulge mass relation or a relation between the initial potential well at SMBH formation and velocity dispersion.

2.2 additional relations and the Fundamental Plane (Beifiori et al. 2011)

Following earlier discoveries and the findings of Ferrarese and Merritt, additional relations between the black hole mass and properties of the bulge were studied. These new relations also followed power laws, albeit being less tight than the velocity dispersion relation. This lead to the speculation about the existence of a Fundamental Plane, similar to elliptical galaxies, like some theories about galaxy formation already predicted. This means, that the previously discovered relations are the result of one relation depending on multiple parameters.

To test this, A. Beifiori, S. Courteau, E.M. Corsini and Y. Zhu studied a large sample of galaxies with multiple properties known. They then fitted the relations in question to their data, and tried to improve their fit by fitting multiple properties. [BCCZ12]

For their data, they used two sets of data. For their first set, the gas motion of a thin disc was modeled to the nuclear spectra of 105 nearby galaxies, measured by the HST. This lead to upper limits for the black hole mass [BSC+09]. The black hole mass of the second set is based on resolved kinematics, which lead to 49 secure estimates and 18 upper limits [GRG+09]. 18 galaxies are included in both sets, 15 of which have secure Black Hole mass based on kinematics and 3 have upper limits. The galaxies with only upper limits on black hole mass were grouped with to additional upper limits into Sample A, consisting of 94 galaxies. The black hole mass of the remaining galaxies were rescaled to conform with the upper limits using the 15 galaxies with both upper limits and secure mass, resulting in Sample B.

To study the power laws for the relations, Beifiori et al. fitted a linear regression in a double logarithmic plot, scaling black hole masses to sun masses and the properties to a value near the mean. Because of their use of upper limits the zero points of their relations differ from other publications. Additional to the two fitting parameters of the linear regression, they calculated the total scatter and the intrinsic scatter.

For their study of the $M_\bullet - \sigma_c$ relation, they used all 143 galaxies of Sample A and B combined. The fit can be seen on the left in fig. 2.2. The slope of their relation is, with errors, consistend with previous findings. As noted by Ferrarese, the velocity dispersion relation is the tightest relation Beifiori et al. found, but the scatter is larger than some previous findings. They suspect the higher fraction of late type galaxies in their test population. The earlier publications in question studied mostly early type galaxies. When fitted seperately, the late type galaxies show a larger scatter, whereas

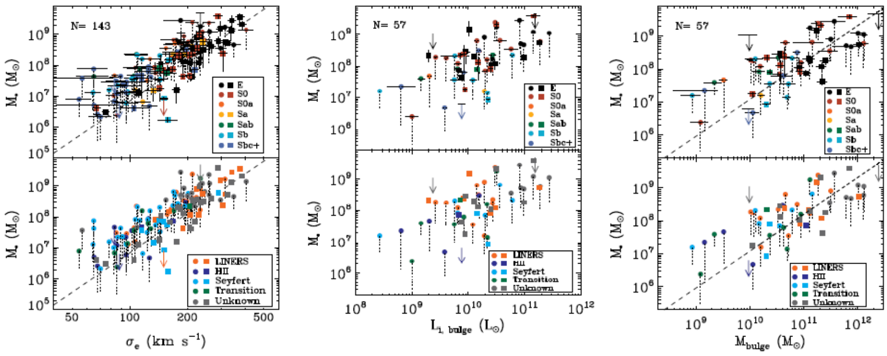

Figure 2.2: circles: Sample A, squares: Sample B, top row: morphological type, bottom row: nuclear activity

the early type galaxies show a scatter similar to previous studies.

When comparing barred to unbarred galaxies, no significant difference in the relation could be found. The relation for bulges and pseudo-bulges differs in slope, but the relation for pseudo-bulges has a low significance. While there is some correlation between nuclear activity and the stellar velocity, the same $M_\bullet - \sigma_c$ relation holds true for all activities.

The relation between SMBH-mass and the bulge luminosity was also studied. For this analysis they used 38 Sample A and 19 Sample B galaxies. While still a tight relation, the scatter of the bulge luminosity relation is larger than the stellar velocity dispersion relation. There was no dependency on morphological type and nuclear activity. These findings were in line, within errors, with previous findings.

Similarly, the relation between bulge mass and SMBH mass was studied. The same 38 Sample A and 19 Sample B galaxies were used. The scatter of this relation, while tighter than the bulge luminosity relation, is still worse than the velocity dispersion relation. While correlating with the mass, the Hubble type does not influence the SMBH mass relation. When compared to previous findings, the slope of Beifiori et als relation is slightly shallower, while still within errors.

They also studied additional relations, namely Sersic index, galaxy luminosity, galaxy masses and stellar velocity. The galactic mass and luminosity relations where somewhat tight, but had a much larger scatter than the corresponding bulge relations. These were line with previous findings. The other relations had a far smaller significance and where in conflict to some previous studies.

With this collection of data, Beifiori et al tried to improve these relations by fitting the SMBH mass to two bulge or galaxy parameters. These improvements would suggest the existence of a Fundamental Plane. Only the addition of the bulge radius as an parameter lead to an small improvement. For the other multi-parameter relations, their quality was governed by the tightest parameter involved.

This lead Beifiori et al to the conclusion, that there are no independent relations between SMBH mass and galaxy parameters, but these are all expressions of the same relations linked by interdependencies. The best representative is still the bulge stellar velocity dispersion relations.

Chapter 3

Self similar, polytropic quasi-static fluid (Lou, Jiang 2008)

After earlier studies of the dynamics of self similar polytropic fluids [LW06], Lou and Jiang found a quasi-static solution which approaches singular polytropic spheres at infinity. These models have been used to study proto star formation, formation of compact stellar objects, galaxy clusters as well as other stellar and galactic phenomena. Lou and Jiang used this solution to describe the bulge and its central SMBH. [LJ08]

For their model, they adopted a few simplifications. First they assumed that the bulge age is large, so the fluid is continously relaxed. Secondly the stars are described as a stellar fluid and the interstellar medium is merged into said fluid, because of negligible mass. Thirdly small scale structures like the AGNs and the disc around the SMBH are ignored.

With these assumptions they described the bulge as a general polytropic fluid, where the stellar velocity dispersion leads to pressure counteracting the self gravitation. To solve the hydrodynamic equations a self-similar transformation was used. The solution is dependent on to scaling indices K and n and the polytropic index γ.

To see the desired correlation, one has to compute the two properties. Because the mean stellar dispersion results in a pressure, one can derive it from the found solution for the pressure. To find the mass of the SMBH one computes the enclosed mass in a sphere with a given radius by integrating the density, which is also found as a solution of the hydrodynamic equations. This mass is then compared to the mass needed to produce a Schwarzschild radius. The intersection of these two is the mass of the black hole.

Ultimately Lou and Jiang found the relation $M_\bullet \propto \sigma^{1/(1-n)}$ with $2/3 < n < 1$ for positive mass. Different galaxies are described by a different K value. This model can reproduce the empirical relation between black hole mass and stellar velocity dispersion for bulges, which leads to a fixed n. With a given n one can derive other relations, for example between black hole mass and bulge mass, again reproducing empirical data.

One can try to describe pseudo bulges with this model and get the correct velocity dispersion relation. This leads to a different n and therefore a different bulge mass relation. This contradicts empirical data, because this relation is independent on morphology. The is not a flaw in the model, because one assumes spherical symmetry and pseudo bulges are no spheres and might have significant substructures.

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