

MASTERARBEIT | MASTER'S THESIS

Titel | Title

Assessing the limiting Supermassive black hole mass in IFU
observations of the nucleated Fornax3D galaxy FCC 148

verfasst von | submitted by
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angestrebter akademischer Grad | in partial fulfilment of the requirements for the degree of
Master of Science (MSc)

Wien | Vienna, 2024

Studienkennzahl lt. Studienblatt | Degree
programme code as it appears on the
student record sheet:

UA 066 861

Studienrichtung lt. Studienblatt | Degree
programme as it appears on the student
record sheet:

Masterstudium Astronomie

Betreut von | Supervisor:

Dipl.-Phys. Dr. Sabine Thater

Acknowledgements

I primarily want to thank my great supervisors Dr. Sabine Thater and Dr. Ryan Leaman, along side with Dr. Mariya Lyubenova as an additional advisor for giving me the chance to do research in this fascinating field. I could not have wished for a better, more welcoming supervision. I very much look forward to working with you on future projects. Thank you also to Katja Fahrion for providing the MUSE data set and to Dr. Mariya Lyubenova for preparing the SINFONI data set. Furthermore, I am grateful for the opportunity of working on the Vienna Scientific Cluster (VSC), without which the computational results of this work couldn't have been achieved. Lastly, I want to thank my family and friends who have supported me in every way possible. I wouldn't be where I am without your support. Thank you all!

Abstract

Black holes are one of the most intriguing objects known in astrophysics. While many of their properties are still a mystery, they are found in every corner of the universe. Supermassive black holes (SMBHs) play an even more important role as they are found in multitudes of galaxy centers and are tightly connected to the formation and evolution of galaxies. Their exploration therefore is of utmost significance in the galactic field of research. In this work I want to contribute to the knowledge of SMBHs through the mass measurement of the black hole in the center of the nucleated galaxy FCC 148 by analyzing the dynamics of stars in their vicinity.

The study utilizes high-resolution imaging and spectroscopic data from telescopes such as the Hubble Space Telescope and the Very Large Telescope, specifically using data from the Integral Field Spectrographs MUSE and SINFONI, enabling the observation of stellar motions within the central region.

The core of the thesis involves constructing detailed dynamical models that account for both the gravitational influence of the black hole and the distribution of surrounding stars. By applying Schwarzschild orbit superposition models, I can model the velocities and trajectories of stars, thereby inferring the mass of the central black hole as well as additional physical parameters of the galaxy such as its intrinsic 3D structure, the Mass-to-Light ratio and the dark matter contribution.

Key findings include a first upper mass limit for the supermassive black hole in FCC 148. The research also explores correlations between black hole mass, the Nuclear Star Cluster (NSC) and galactic properties, where the black hole of FCC 148 occupies the lower mass end of most scaling relations. These results contribute to the understanding of the co-evolution of black holes and their host galaxies.

Ultimately, this thesis underscores the critical role of stellar dynamics in unveiling the masses of black holes. Through meticulous analysis and innovative modeling, this research enhances our understanding of these fascinating astronomical objects, advancing the field of astrophysics and our comprehension of the universe.

Kurzfassung

Schwarze Löcher gehören zu den faszinierendsten Objekten der Astrophysik. Obwohl sie in jeder Ecke des Universums zu finden sind, bleiben viele ihrer physikalischen Eigenschaften noch ein Mysterium. Supermassive Schwarze Löcher, also schwarze Löcher mit Massen von Millionen bis Milliarden von Sonnemassen, spielen eine noch wichtigere Rolle, da sie in vielen Galaxienzentren auftreten und eng mit der Entstehung und Entwicklung von Galaxien zusammenhängen. Ihre Erforschung ist daher von größter Bedeutung um den Werdegang von Galaxien zu verstehen. In dieser Arbeit möchte ich zum Wissen dieser Supermassiven Schwarzen Löcher beitragen, indem ich die Masse des Schwarzen Lochs im Zentrum der Galaxie FCC 148 messe. Dabei analysiere ich die Dynamik der Sterne in der zentralen Umgebung des Schwarzen Lochs.

Für die Beobachtungsdaten nutze ich hochauflösende photometrische und spektroskopische Daten von Teleskopen wie dem Hubble-Weltraumteleskop und dem Very Large Telescope, speziell unter Verwendung von Aufnahmen der Integralfeld-Spektrographen MUSE und SINFONI, die die Beobachtung von Sternbewegungen im zentralen Bereich ermöglichen.

Der Kern der Arbeit besteht darin, detaillierte dynamische Modelle zu erstellen, die den gravitativen Einfluss des Schwarzen Lochs auf die umliegenden Sterne berücksichtigen. Durch die Anwendung von Schwarzschild-Orbit-Superpositionsmodellen werden die Geschwindigkeiten und Bahnen der Sterne quantifiziert, wodurch die Masse des zentralen Schwarzen Lochs sowie weitere physikalische Parameter der Galaxie wie die Morphologie, das Masse-zu-Licht-Verhältnis und der Beitrag der Dunklen Materie abgeleitet werden.

Zu den wichtigsten Ergebnissen gehört eine erste obere Massengrenze des supermassiven Schwarzen Lochs in der Galaxie FCC 148. In dieser Arbeit beschäftige ich mich zudem mit den Korrelationen zwischen der Masse des Schwarzen Lochs, dem Nuklearen Sternhaufen (NSC) und den galaktischen Eigenschaften. In diesen Korrelationen zeigt sich, dass das bemessene schwarze Loch vielmehr am niedrigeren Ende der Massenbeziehungen liegt. Diese Resultate tragen vor allem zum Verständnis der Koevolution von Schwarzen Löchern und ihren Wirtsgalaxien bei.

Letztendlich unterstreicht diese Arbeit die entscheidende Rolle der Sternendynamik bei der Berechnung der Massen von Schwarzen Löchern. Durch sorgfältige Analysen und innovative Modellierungen verbessert diese wissenschaftliche Arbeit unser Verständnis von Schwarzen Löchern in Galaxiezentren, fördert das Feld der Astrophysik und unsere Kenntnisse über das Universums.

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¹Image Credit: https://heasarc.gsfc.nasa.gov/docs/objects/agn/agn_model.html, C.M. Urry and P. Padovani

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²eHST archive: <https://hst.esac.esa.int/ehst//pages/search>

³"Image Credit: <https://www.eso.org/public/teles-instr/technology/ifu/>"

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⁴credit: www.scratchapixel.com

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1. Introduction

Black holes are among the most intriguing objects in astrophysics, yet much about them remains a mystery. Understanding their properties is crucial not only for fundamental physics but also for comprehending the broader structure and evolution of galaxies. In this section of the thesis I want to introduce the topic of black holes, in particular Supermassive black holes in the centers of galaxies, their coexistence with their host galaxies and the possible role of Nuclear Star Clusters (NSCs) in the evolution of galaxies and SMBHs. Not fully understood, but certainly interesting is the fact that SMBHs show strong correlations with the host galaxy's large-scale properties, which will also be a point of discussion in this part of the thesis. Furthermore, this chapter shall act as an introduction to the many methods available to measure black hole masses, of which one is the main focus of this research. Overall, this chapter aims to shed light on the role of SMBHs in shaping the dynamics of galaxies and their central regions.

1.1. SMBHs in centers of galaxies

Black holes alone are very sensational objects in our universe. Their existence has been debated on not so long ago, as the physics behind them is highly complicated. The fact that Supermassive black holes, meaning black holes of masses ranging from $10^6 - 10^{10} M_{\odot}$ (Marconi et al. (2004)), are found in many galaxy centers, makes their exploration even more intriguing. Since quasars have been discovered, it is well established that Active Galactic Nuclei (AGNs) are powered by SMBHs in their very centers. Further research in recent years, detecting SMBHs through dynamical models of the movement of gas and stars in many nearby galaxies is evidence for this conclusion (Ferrarese and Merritt (2000)).

In principle, black holes can be considered objects of such small size and simultaneously such large density, that their gravitational pull is so strong that nothing, not even light can escape. What makes them so interesting is the fact, that since not even light is fast enough to escape their attraction, it is impossible to observe anything that goes further than the event horizon marking the edge of a black hole, which is described by the Schwarzschild radius (Schwarzschild (1916)) for stationary aka non-rotating black holes. A radius at which the escape velocity equals the speed of light, as elaborated in Equation 1.1, where G is the gravitational constant, M is the mass of the object and c represents the speed of light. Considering rotating black holes, the event horizon and the Schwarzschild radius have to be differentiated. However, this will not be discussed further in this work.

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$$R_S = 2 \frac{GM}{c^2} \quad (1.1)$$

Nevertheless, there is sufficient evidence for their existence. The most compelling would be the observation of the black hole in the center of our own galaxy. Through the motion of individual stars surrounding Sagittarius A^* , which showed a high velocity only explicable by a Supermassive black hole (Eckart and Genzel (1996)) and the image of our central black hole captured with the Event Horizon Telescope in 2017 (Event Horizon Telescope Collaboration et al. (2022)), really solidified the proof for the existence of SMBHs in the centers of galaxies.

1.1.1. Sphere of influence of SMBHs

Unlike for the Milky Way, outside of our galaxy we barely have the possibility to observe individual stellar orbits to detect a SMBH. As they are simply too far away. On top of that the area of gravitational influence of the SMBH does not extend very far out, even though it has such a strong attraction. This so-called sphere of influence R_H can be calculated as given in Equation 1.2 (Ferrarese and Ford (2005)):

$$R_H \sim \frac{GM_\bullet}{\sigma^2} \quad \text{or} \quad 11.2 \frac{(M_\bullet/10^8 M_\odot)}{(\sigma/200 \text{ km s}^{-1})^2} \text{ pc} \quad (1.2)$$

Where σ is the velocity dispersion of the surrounding stars. The sphere of influence is defined as the radius at which the gravitational influence of the blackhole dominates over the attraction of the nearby stars. It conventionally only extends out a few parsecs, if not less. For our own galaxy, for example this would correspond to a sphere of influence of only 1 pc if we consider the mass of Sgr A^* to be $\sim 4 \cdot 10^6 M_\odot$ and the central velocity dispersion σ to be ca. 125 km/s (Sellgren et al. (1990)).

Detecting or even measuring black holes is therefore exceptionally difficult. To be able to capture the motion of stars so close to the center, one requires very sophisticated high-resolution instruments. Fortunately, in the recent years the quality of observational instruments has been pushed to impressive standards, enabling such measurements in nearby galaxies. With SINFONI an IFS (Integral Field Spectrograph) and HST (Hubble Space Telescope) we are able to observe the most central part of a nearby galaxy (as done in this work) with such high resolution, that a black hole mass measurement is certainly feasible.

1.2. Methods of black hole mass measurement

As discussed in the previous section, it is challenging to observe individual stellar orbits within galaxies that are far away. But this method of deducing the black hole mass through stellar dynamics is not the only technique used in modern astrophysics to measure SMBHs. In this subchapter I want to describe a few different types of dynamical methods to retrieve the mass of a central black hole in a galaxy, other than through stellar dynamics, which is the focus of this work and will later be discussed in greater detail.

1.2. Methods of black hole mass measurement

Stars are not the only matter, which can be influenced by a SMBH. Galaxies also contain gas, dust, eventually water maser clouds etc. All of these entities can be used to obtain information about the central black hole.

1.2.1. Gas Dynamics

For a long time, scientist have been skeptical about using gas or dust dynamics to trace the mass of SMBHs in the nucleus of galaxies. Unlike stars, gas is easily accelerated by even non gravitational forces and therefore can be a complex method for dynamical black hole measurements. Only when, a nuclear dust disk was captured around the nearby galaxy NGC 4261 by the HST in the 90s ([Jaffe et al. \(1993\)](#)), the method evoked interest. The image showed that the dust was not just randomly distributed, but rather was undergoing some form of organized motion. It suggested cold and circular rotation, indicating that the particles were orbiting the center of the galaxy in a "perfectly defined nuclear dust disk" as [Ferrarese and Ford \(2005\)](#) stated, showing that gas/dust indeed is strongly influenced by the gravitational forces within a galaxy, in particular by a SMBH in the center. This discovery quickly lifted the skepticism regarding the method of using gas dynamics to trace gravity in a galaxy. At present, ionized gas is utilized to trace such nuclear gas and dust disks and is commonly observed using radio interferometry.

However, this technique is only applicable occasionally, as not many galaxies contain such a strong dust disk. Simultaneously, it is barely possible to measure black hole masses using both stellar and gas dynamics. If a galaxy inhabits a well-defined dust disk, the obscuration from the dust tremendously complicates the observation of stellar velocities in the central region. On the other hand, ellipticals with higher central surface brightness, which are the favoured targets for stellar dynamical measurements, rarely show gas disks. This makes it very challenging to compare the black hole mass measurements of these two common methods.

1.2.2. Reverberation Mapping

A somewhat different approach to trace a black hole is reverberation mapping. It's concept takes advantage of the processes occurring in an AGN, in particular regarding the different types of radiation. The unified model of AGNs is shown in [Figure 1.1](#) and nicely depicts how an AGN is structured. Reverberation mapping takes a closer look at the areas closely surrounding the Supermassive black hole, specifically the accretion disk and the Broad Line Region, short BLR. In this method, the variations in brightness of the continuum emission from the accretion disk are monitored. These variations cause further changes in the ionizing radiation that illuminates the BLR. The BLR responds to these changes slightly delayed due to the light-travel time from the accretion disk to the BLR. The time delay between changes in the continuum emission and the subsequent feedback in the emission lines from the BLR, helps gather data on the size and structure of the BLR ([Peterson \(1993\)](#)). The reverberation or 'echo' mapping ([Ferrarese and Ford \(2005\)](#)) provides valuable insights into the dynamics and physical properties of the gas

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surrounding the black hole. Once more, the dynamics of the gas can be used to constrain parameters such as the mass of the black hole and the structure of its accretion disk.

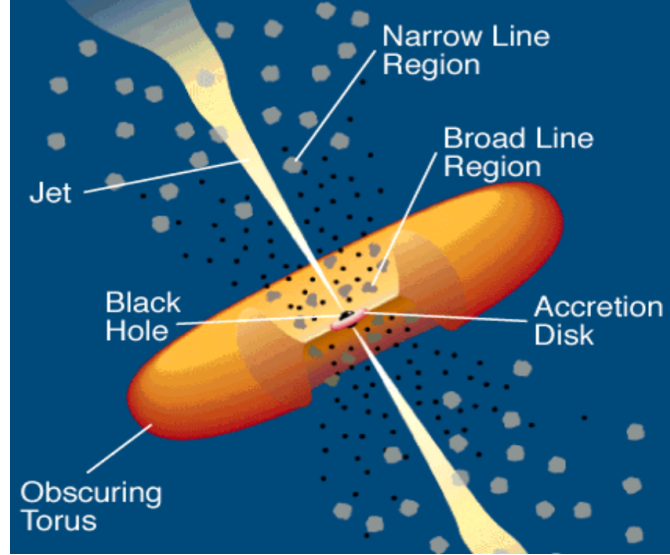


Figure 1.1.: The unified model of an AGN, depicting the central black hole, an accretion disk, the surrounding torus and the Narrow and Broad Line regions¹.

1.2.3. H_2O Megamasers

Similar to the tracing of a central mass through gas disks close to the center, astrophysicists also use H_2O maser clouds as tracers for the mass of a Supermassive black hole. When a galaxy hosts such water maser clouds, their emitted radiation can be observed and tracked to uncover their motion within the gravitational potential of the black hole.

Water mega masers are bright emissions from water molecules in gas clouds that orbit around Supermassive black holes in galaxies, which likely stem from the collisional excitation occurring within the warm interstellar gas (Ferrarese and Ford (2005)). They emit microwave radiation which can be observed with radio telescopes such as the VLBA (Very Large Baseline Array), which makes them great tracers of SMBHs of also smaller mass as a higher spatial resolution is achievable. This no longer limits the detection of a SMBH to it's sphere of influence, which in most cases is just a few parsecs at best. The Doppler shift in the emission can be tracked down to determine the velocities of the gas clouds. Similar to the stellar dynamics one can then trace the velocities back to the gravitational pull of the black hole.

Unfortunately, H_2O masers are rarely found in galaxies, as their detection highly depends on the angle in which the galaxy is observed. Therefore this method is not a as commonly applied technique.

1.2.4. Stellar Proper Motion

The stellar proper motion method is probably the most robust technique to measure black hole masses. It takes advantage of the proper motion data of individual stars orbiting the SMBH and thus predicts the gravitational pull very precisely. The concept is rather simple, the motion of a target is recorded through observing the star over a longer period of time, over and over again. By capturing the apparent motion across the sky of the star(s) in question over time relative to the distant back ground, it is possible to infer their motion in 6D phase space (3D coordinates and another 3D space velocities).

Unfortunately, this accurate measurement method is only applicable to our own galaxy center. As the concept suggests, to observe individual stars a very high spatial resolution is required. With the current instruments it is impossible to resolve individual stars outside of the Milky Way, with just a few exceptions. This means, that we can only utilize the precision of this method for our own galaxy. As mentioned earlier, [Eckart and Genzel \(1996\)](#) predict a mass for the central black hole capturing the proper motion of 39 stars. The Keplerian motion of the stars indicates a central point mass and can only be explained through a SMBH of about $2.45 \times 10^6 M_{\odot}$. This measurement of Sgr A* was later corrected to $\sim 4.5 \times 10^6 M_{\odot}$ by [Ghez et al. \(2008\)](#) using new precision measurements for a larger sample of stars.

1.3. Nuclear Star clusters

In the center of our own galaxy, not only have we been able to detect and characterize the SMBH Sgr A*, but also discover a massive accumulation of stars in the nucleus surrounding said black hole, called a Nuclear Star Cluster. This detection of a NSC in the Milky Way raises the question of what the situation looks like in other galaxies. Furthermore, research is focused on how NSCs end up in the center, how they are connected to the black hole and ultimately the entire galaxy.

Nuclear Star Clusters are very dense and massive accumulations of stars in the nucleus of a galaxy, which very apparently stand out compared to their surroundings in terms of their brightness and compactness. This trend is nicely visualized in [Figure 1.2](#). They are found in various types of galaxies, for which it is still not clear how their presence in the galaxy correlates with their host galaxy's morphology. In [Figure 1.3](#) two galaxies of very different morphology are shown. Both host a NSC in their center. As NSCs are extremely bright and compact stellar clusters with effective radii of about $R_{eff} \approx 3$ pc (comparable to that of Globular Clusters (GC)), they can push the galaxy's surface brightness to very high values in the central few parsecs, leaving a elevated bump in the surface brightness profile ([Neumayer et al. \(2020\)](#)). Their effective surface mass density of $\Sigma_e \sim 10^6 M_{\odot} pc^{-2}$ ([Norris et al. \(2014\)](#)), makes them the densest stellar systems known.

Evidently, NSCs can occur in different types of environments, which raises the question if NSCs are always formed through similar processes and whether they evolve in the same way or if their upbringing does depend on their host galaxy's morphology.

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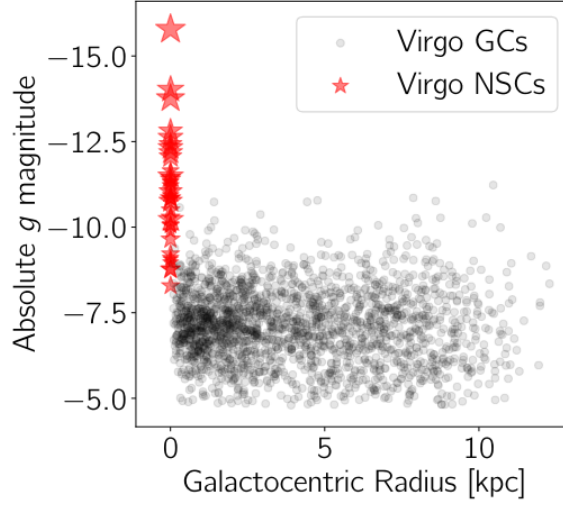


Figure 1.2.: NSCs (red stars) in the Virgo Galaxy Cluster clearly stand out in terms of their brightness (along y-axis) compared to Globular Clusters (GCs, black dots) in the galaxies (Jordán et al. (2009)). It is also distinctly visible from the distribution of the clusters along the x-axis that NSCs are confined to only the innermost region of the galaxies. Neumayer et al. (2020)) designated the size of the NSC data points taken from Côté et al. (2006) to be proportional to their effective radius.

The NSC in our own galaxy, is the best laboratory to study the processes in the central regions of a galaxy and expanding the knowledge to other nearby galaxies. The NSC in the Milky Way consists of a large amount of bright stars, many of them very old and red, as can be expected for an old stellar cluster. However, besides bright old stars, an increasing amount of hot young stars have also been detected in the innermost parsecs of the Milky Way surrounding Sgr A^* . This discovery is highly surprising as it is fairly implausible for early-type stars to occur so close to the central black hole, since its strong gravitational pull provides a highly unstable environment. It is still not understood whether these ~ 200 young stars formed in-situ or whether they somehow migrated to the center but were birthed at larger radii (Genzel et al. (2010)). One of the two most plausible scenarios is, that very dense gas fell into the nucleus a few million years ago and formed a disk around the central black hole. This led the disk to gravitational instability due to the matter being shock-compressed and cooled, further triggering intense in-situ star formation (SF) episodes. Alternatively, a dense and massive cluster formed at larger radii, just outside the central few parsecs of the galaxy and spiraled into the nucleus due to dynamical friction, where it was eventually disrupted tidally. This scenario is also called in-spiral scenario. However, both possibilities still need to be examined further to establish a robust hypothesis. Therefore, having studied the NSC in our own galaxy, it is essential to extend the research to other galaxies as well.

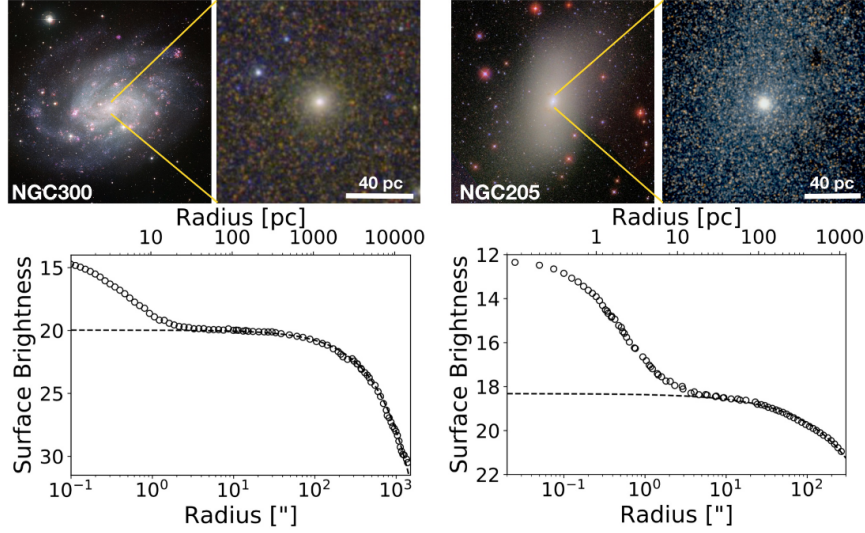


Figure 1.3.: The surface brightness profiles for the late-type galaxy NGC 300(left) and the early-type galaxy NGC 205(right), both hosting a NSC in the center. The plots nicely show how the NSCs influence the surface brightness profile in the center, creating a bump in the central few parsecs (Neumayer et al. (2020)).

As mentioned earlier, NSCs are indeed found in all kinds of galaxies. In fact, about 80% of late-type as well as early-type galaxies with masses of up to $10^9 M_{\odot}$ host NSCs in their central region. Such an "occupation fraction" study was carried out by Neumayer et al. (2020) for more than 1100 galaxies nicely summarizing the current detections of NSCs in all kinds of galaxies as seen in Figure 1.4. Most of the observations were done with direct imaging through e.g. the Hubble Space Telescope or ground based spectroscopic instruments like IFS. Sánchez-Janssen et al. (2019) also confirm a comparable occupation fraction to be true for the Virgo Cluster.

Furthermore, Leaman and van de Ven (2022) show that this occupation fraction is not only dependent on the masses of galaxies but also their sizes. Compact galaxies at a fixed stellar mass are more likely to form NSCs and host more massive NSCs than more diffuse systems.

The presence of NSCs in such a big fraction of galaxies makes it especially critical to study their formation and evolution. The best and most direct way to gain understanding of the processes behind the formation of NSCs would be to measure accurate stellar ages and metallicities. Not only in the Milky Way but also in a great number of other galaxies, the NSCs contain a mixture of different stellar populations. Unfortunately, it is barely feasible to resolve individual stars in most galaxies except for a few nearby. For most NSCs in distant galaxies, it is necessary to analyze the integrated light (IFS observations) from the entire cluster. Population fitting techniques are then applied to

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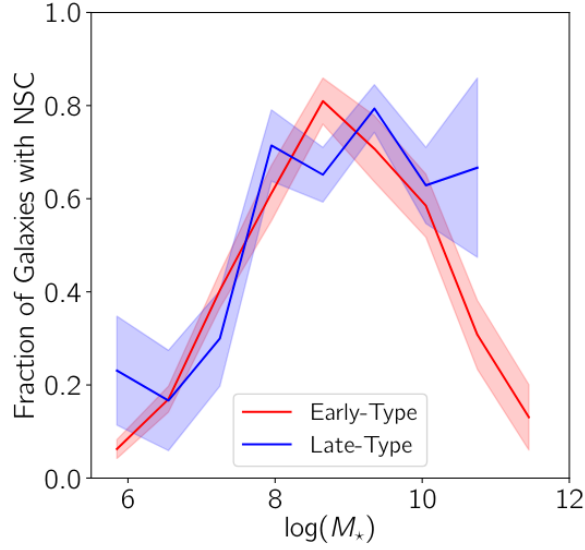


Figure 1.4.: [Neumayer et al. \(2020\)](#) have nicely summarized the detection of NSCs in 1191 galaxies of various studies. The observations are divided into early-type (red) and late-type (blue) galaxies, of which about 80% of each type host a NSC. A somewhat peak of the occupation fraction is clearly visible for preferentially galaxies of masses between $10^8 - 10^{10} M_\odot$.

said integrated light to determine the combination of stellar ages and metallicities that best matches the observed spectral energy distribution. When distinguishing between early- and late-type galaxies, studies have shown that the latter contain a mixture of different stellar populations. Early-type galaxies on the other hand seem to be best described using Single Stellar Population (SSP) models for their observed spectra. This is a very loose description, as ETGs do show more complex stellar populations with a few showing ongoing star formation ([McDermid et al. \(2015\)](#)). Nonetheless, in a very general sense the stellar ages for the majority of early-type galaxies is estimated to be above ~ 1 Gyr. When comparing the NSC metallicities directly with the host galaxy's metallicities as seen in [Figure 1.5](#) one notices a trend of more metal-rich NSCs towards higher galaxy masses. The NSCs in early-type galaxies above roughly $10^9 M_\odot$ are metal-rich than their host galaxies, indicating a very young stellar population compared to rest of the galaxy. This is an indication of different formation scenarios happening in galaxies of different mass ([Fahrion et al. \(2021\)](#)). This will be discussed in more detail in the next section.

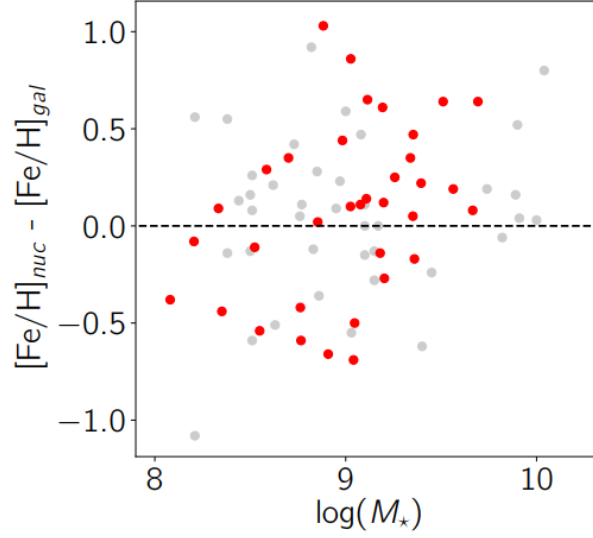


Figure 1.5.: Spectroscopic data (red) of NSC metallicities compared to their host’s metallicities show an upwards trend for early-type galaxies above $10^9 M_\odot$. High mass ellipticals seem to host NSCs with higher metallicities compared to the entire galaxy’s metallicity. The dashed black border indicates the line at which the metallicity of both NSC and host are equal. Grey data points visualize photometric data but is not considered reliable as stated by [Neumayer et al. \(2020\)](#).

1.4. Connection of NSCs to host galaxy and SMBHs

The properties of NSCs and their host galaxies are evidently intertwined and need to be inspected in combination. Other than NSCs and SMBHs, the central region of a galaxy often hosts additional, more complex nuclear structures, that can add to the fueling of the black hole and possible star formation ([Gadotti et al. \(2020\)](#)). Often the SMBH, which is usually embedded in the NSC is the most central component. The NSC in turn can be surrounded by a nuclear stellar disk sometimes accompanied by a ring like structure. All these entities can be found in the central regions of galaxies and may play a role in establishing a efficient pathway for gas to power the central black hole. This is conventionally the case for disk galaxies, which is why I will focus mostly on NSCs and SMBHs, as the target galaxy of this work is a early-type galaxy. However, studying these nuclear structures can give great insights to the formation processes happening in the very center of a galaxy.

NSC mass, size, and stellar population, are closely linked to their host galaxies’ characteristics, which I want to elaborate in this section. As stated earlier, some galaxies seem to host NSCs with very young stellar populations. Understanding how such young stars happen to form in the nucleus as well as inferring the physical properties of NSCs, it is crucial to examine the possible formation scenarios. Additionally, scaling relations

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between the host galaxy and the NSC can help understand the mechanisms that link NSC growth with galaxy growth, aid to distinguish between different formation scenarios and can even improve our ability to use NSCs as tracers of galactic properties in systems where other indicators might be unavailable or less reliable.

1.4.1. Formation/Growth scenarios

As mentioned briefly, there are two probable scenarios on how NSCs might have formed and ended up in the nucleus, which I want to discuss in this section in more detail.

Globular Cluster infall

The GC infall or in-spiral scenario ([Tremaine et al. \(1975\)](#)) suggests that GCs are dragged into the nucleus by dynamical friction as they orbit through the stellar body of their host galaxy. Hereby, their mass plays a crucial role. The strength of this dynamical friction namely depends greatly on the mass of the cluster, making the most massive clusters also the most likely to spiral into the nucleus and contribute to the formation of the NSC. This scenario is fairly promising, as it provides a setting to bring more metal-poor stellar populations to the nucleus of low-mass early-type galaxies. Consequently, the infall of massive stellar clusters into the galaxy nucleus is an expected and perhaps unavoidable process that has likely added a significant amount of stellar mass to present-day NSCs. However, this scenario alone can not truly explain the presence of young stars in many NSCs. Therefore, additional mechanisms are needed to fully describe NSC evolution, such as the in-situ formation scenario ([Neumayer et al. \(2020\)](#)).

In-situ formation

To explain the presence of young stellar populations in many NSCs in galaxies, in situ star formation is typically considered. This process occurs when gas flows into the central few parsecs of the galaxy, triggering intense star formation. This mechanism can be repetitive, driven by feedback from supernovae and strong stellar winds which expel the gas, temporarily interrupting star formation until the energy dissipates and the gas reassembles in the nucleus. These younger populations are often flattened and rotating, which makes sense considering formation from accreted gas ([Seth et al. \(2006\)](#)). Overall, this gas infall into the central regions and the successive nuclear star formation are natural and expected processes that significantly contribute to the growth of NSCs in gas-rich galaxies ([Neumayer et al. \(2020\)](#)).

Transition between both scenarios

While GC infall explains well the more metal-poor NSC populations the in-situ formation scenario is better suited for galaxies with metal-rich population NSCs, indicating a more complex interplay of processes. [Fahrion et al. \(2021\)](#) suggest that for lower mass galaxies, NSCs grow mainly through the infall of globular clusters into the central regions. However, galaxies with high masses form and grow NSCs dominated by in-situ formation. This

1.4. Connection of NSCs to host galaxy and SMBHs

transition happens at roughly $10^9 M_\odot$, while some lower mass galaxies may still experience significant growth through in-situ star formation. In their review [Neumayer et al. \(2020\)](#) show that the evidence for this combined scenario is strongest for early-type galaxies, nonetheless still consistent with the evidence in late-type galaxies as well.

Furthermore, they present strong evidence for central black holes being observed only for galaxies above said threshold of $10^9 M_\odot$, while below this mass there are almost no clear detections. It is possible that the shift in NSC growth mechanisms around $10^9 M_\odot$ is related to the presence of massive black holes ([Antonini et al. \(2015\)](#)). However, it is also plausible that the growth of black holes is driven by the same gas that reaches the center and forms the NSC through in-situ star formation. This connection between NSCs and a present central black hole is discussed in the next section.

Moreover, there have been implications that some sort of hybrid form of both formation scenarios could be possible, a so-called wet migration scenario ([Guillard et al. \(2016\)](#)). In this scenario a massive stellar cluster originates within the gas-rich disk, retaining a supply of gas. As it moves toward the galaxy's center, it grows further by interacting with other structures and through the influence of dynamical friction.

1.4.2. Connection with SMBHs

NSCs are prevalent at the centers of galaxies within the mass range of approximately $10^8 - 10^{10} M_\odot$. Beyond this range however, SMBHs are consistently found in the centers of larger galaxies ([Kormendy and Ho \(2013a\)](#)). Notably, both SMBHs and NSCs exhibit a strong correlation with the masses of their host galaxies. This correlation has led to suggestions that NSCs may assume the role of SMBHs in lower mass galaxies, prompting the term "central massive object" (CMO) ([Ferrarese et al. \(2006\)](#)) to encompass both entities as seemingly similar products of galaxy evolution. However, there are various cases where NSCs and SMBHs are found to co-exist, one especially important case being the Milky way, which makes it again an important laboratory to study such a case of co-existing NSCs and SMBHs. It is however crucial to expand the research to external galaxies as well. It is still not quite understood how NSCs and SMBHs co-evolve but the lack of NSCs in high-mass galaxies might be connected to the presence of a SMBH. Its dynamical interaction might cause the NSC to be destroyed. If SMBHs share similar evolution processes or even co-evolve with NSCs, their mass ratio M_{BH}/M_{NSC} might be a compelling metric to study as realized in Figure 1.6. The ratio of SMBH mass to NSC mass tends to increase with the mass of the host galaxy. An explanation could be that galaxies with lower masses and therefore low dispersion velocities with dynamical timescales shorter than the Salpeter time (the time it takes a SMBH to double its mass, [Fabian \(1999\)](#)) are unable to rapidly increase the mass of their central supermassive black holes. Consequently, gas accumulates at the galaxy's center forming NSCs. However, [Neumayer et al. \(2020\)](#) add that the availability of reliable mass measurements is primarily limited to NSCs in higher mass galaxies and it is still possible that low mass galaxies inhabit black holes but are simply harder to detect.

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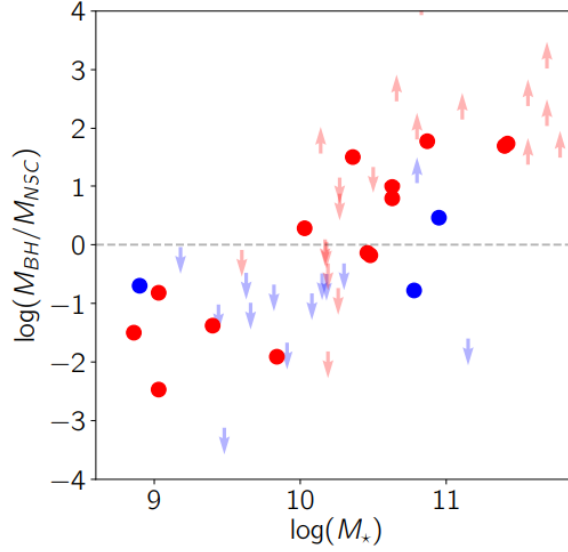


Figure 1.6.: This plot from [Neumayer et al. \(2020\)](#) shows the mass ratio between black hole mass and NSC mass in the center of a galaxy compared to the host galaxy's stellar mass. The red dots represent early-type galaxies and the blue dots represent late-type galaxies. The corresponding arrows are upper and lower limits for the mass measurements. Towards higher galaxy masses ($> 10^{10} M_{\odot}$), a strong trend to higher SMBH masses compared to NSCs is noticeable.

1.5. Black hole scaling relations

Examining scaling relations between NSCs, SMBHs and their host galaxies is a crucial task in astrophysical research. These relations provide key insights into the fundamental processes driving galaxy formation and evolution. By understanding how properties like mass, size, and luminosity of NSCs as well as SMBHs scale with the host galaxy's mass and bulge characteristics, it is possible to infer the mechanisms linking the nucleus growth with the global galaxy development. Additionally, scaling relations reveal the interplay between NSCs and central supermassive black holes, helping to untangle feedback processes that regulate star formation. This understanding aids in distinguishing between the different aforementioned formation scenarios offering a comprehensive picture of NSC, SMBH and galaxy co-evolution. Ultimately, these scaling relations enhance our ability to use NSCs as tracers of galactic properties, improving our knowledge of galaxy structure and dynamics across various environments and epochs.

As stated in the last section, "CMOs" are hosted in the majority of galaxies. While SMBHs occupy the more high-mass end of the galaxy population, NSCs are found in galaxies of masses below roughly $10^{10} M_{\odot}$ ([Turner et al. \(2012\)](#)). Both entities relate to the host galaxy's characteristics in very similar way. In a general sense, the more massive

the host, the more massive CMOs they hold. Although the following scaling relations mostly consider central black holes, NSC are not necessarily excluded to correlate in a similar way. As this work mainly focuses on the black hole mass measurement, I will concentrate on the black hole scaling relations.

1.5.1. $M_{\bullet} - \sigma$ relation

Discovered in the year 2000, [Gebhardt et al. \(2000\)](#) announced that they had found a tight correlation between black hole mass and velocity dispersion. At that time, this was considered a fundamental relation, as its scatter was fairly small. However, this was probably due to observational bias, as further studies added increasingly more samples. TO this day, this relation still holds very strong, and can be considered the universal relation for the connection between SMBHs and their host galaxy. It is highly practical, as it aids to estimate black hole masses from given galaxy velocity dispersions. This relation is shown in Figure 1.7, highlighting the tight connection for all types of galaxies, ranging from dwarf galaxies to the brightest ellipticals ([van den Bosch \(2016\)](#)). The central black hole mass correlates with the galaxy velocity dispersion as follows:

$$M_{\bullet} \propto \sigma^{5.4} \quad (1.3)$$

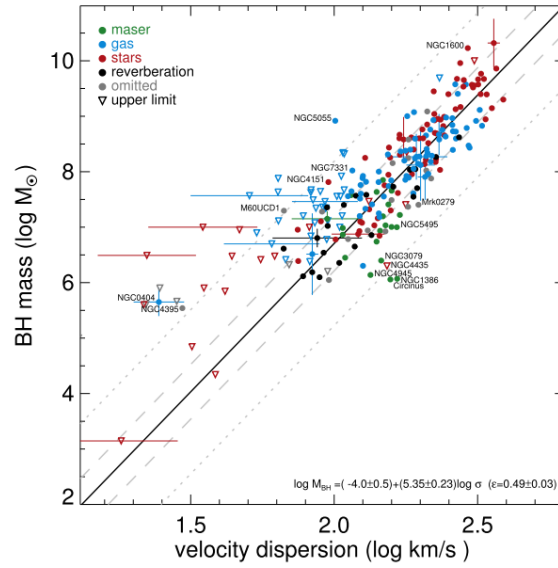


Figure 1.7.: [van den Bosch \(2016\)](#) show in this plot the tight correlation between the black hole mass in the center of a galaxy and its velocity dispersion. This relation holds no matter the galaxy type, from dwarfs to the brightest ellipticals. The data points are colored according to the applied black hole mass measurement method.

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1.5.2. $M_{\bullet} - L_{bulge}$ relation

Another but less universal relation is the correlation between black hole mass and the bulge luminosity. The bulge is the central region where SMBHs reside in and it is thought that the properties of these bodies are closely linked. Formation and growth of these two entities are likely governed by the same processes. Quantitatively, a strong relation is also evident when comparing $M_{\bullet}$ to the entire galaxy's luminosity. Regardless of the fact that more luminous and hence more massive galaxies do indeed host more massive black holes, the bulge luminosity still correlates much stronger to the black hole mass. Figure 1.8 shows the tight $M_{\bullet} - L_{bulge}$ relation from [Kormendy and Ho \(2013b\)](#) revealing a proportionality of:

$$M_{\bullet} \propto L_{bulge}^{1.2} \quad (1.4)$$

Equation 1.4 indicates a nearly linear relationship between the logarithms of black hole mass and bulge luminosity. [Kormendy and Ho \(2013b\)](#) also state that the intrinsic scatter for this relation is almost as small as the intrinsic scatter of the $M_{\bullet} - \sigma$ relation. The bulge luminosity consequently correlates very tightly to the central black hole mass as well. However, it is not considered a universal relation as it is only limited to galaxies with bulges, excluding pseudobulges. As classical bulges and ellipticals are thought to have formed in similar ways and both inhabit old stellar populations, the $M_{\bullet} - L_{bulge}$ relation can also be applied to ellipticals as seen in Figure 1.8.

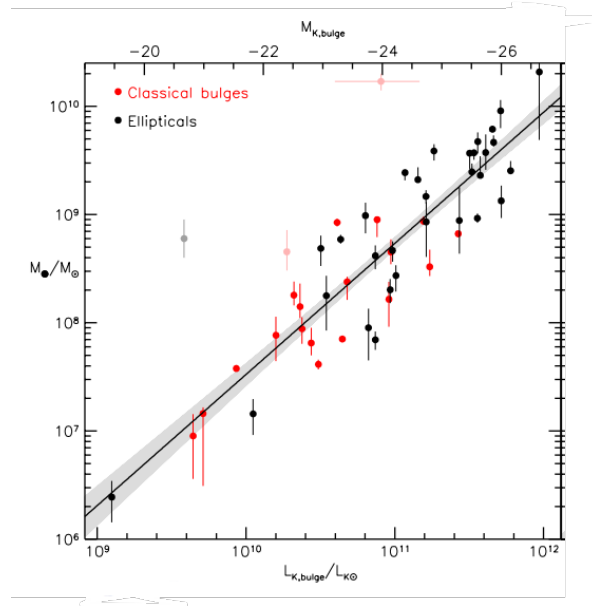


Figure 1.8.: This plot visualizes the tight correlation between black hole mass and bulge luminosity for a sample of classical bulges and ellipticals. [Kormendy and Ho \(2013b\)](#) include ellipticals as they have resembling properties to classical bulges.

1.5.3. $M_{\bullet} - M_{bulge}$ relation

As previously mentioned, more luminous thus more massive galaxies do host more massive black holes, it is only sensible to investigate the correlation between black hole mass and galaxy mass. However, this does not show a pronounced correlation and can not be described using a single power law. It seems as though a direct relation between black hole mass and the entire galaxy's stellar mass shows different slopes for spiral galaxies than for ellipticals. Examining a vast number of galaxies ([van den Bosch \(2016\)](#)), $M_{\bullet}$ seems to have a much tighter correlation with only the bulge mass of the galaxy. Again, favouring the bulge rather than the entire galaxy, also for the aforementioned reasons. It would only make sense that bulge mass similarly relates to black hole mass as the bulge luminosity does, as one would only need the luminosity to be multiplied by the mass-to-light ratio. Unfortunately, this is not as an easy task as it seems ([van den Bosch \(2016\)](#)). Unlike bulge luminosity, bulge mass is inherently less well defined, as the mass-to-light ratios of old stellar populations are fairly uncertain. Nevertheless, IFS observations are rather promising as they produce "well-behaved" mass-to-light ratios for galaxies, in particular in the K-band. Combining various studies, [Kormendy and Ho \(2013b\)](#) conclude with a $M_{\bullet} - M_{bulge}$ relation of:

$$M_{\bullet} \propto M_{bulge}^{1.1} \quad (1.5)$$

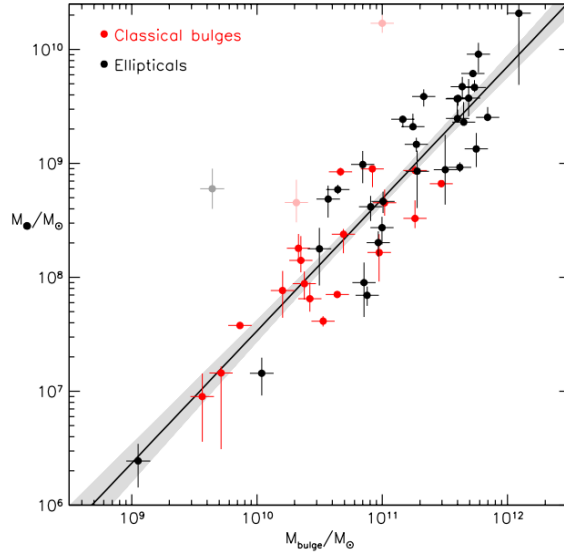


Figure 1.9.: This plot from [Kormendy and Ho \(2013b\)](#) similar to Figure 1.8 shows the tight correlation between black hole mass and bulge/ellipticals luminosity. For the aforementioned reasons ellipticals are included as well.

This relation is visualized in Figure 1.9 by [Kormendy and Ho \(2013b\)](#), showing again a tight near linear correlation between the two properties similar to the $M_{\bullet} - L_{bulge}$ relation. Once more, even though the $M_{\bullet} - M_{bulge}$ relation has a similarly small scatter

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as the $M_{\bullet} - \sigma$ relation, it only applies to a small fraction of galaxies, that in fact have a bulge as well as elliptical galaxies, which most likely are governed by the same formation processes as bulges and also contain old stars.

1.6. Global formation scenarios

In a grander scale, it is not only sensible to consider formation scenarios of CMOs within a galaxy, but also investigate the formation and evolution of galaxies from high redshifts on, expanding the research to more global scales. Since black holes and NSCs much likely already shaped the galaxy's evolutionary path early on, it is necessary to examine how SMBHs or even IMBHs (Intermediate-mass black holes) are formed and how the galaxies we observe nearby might have formed from some type of seed black hole or protogalaxy.

Mezcua (2017) gives an interesting overview of the possible formation scenarios happening at high redshifts ($z=12$) including potential scenarios for IMBH formation. They are thought to be the seed black holes at high redshift, that grew to become the SMBHs in the centers of galaxies. IMBHs are black holes of mass ranging from 100 to a million solar masses and create the link between stellar black holes and supermassive black holes. These seed black holes that did not grow to become SMBHs are now found in the present universe and are called leftover IMBHs. In her review, Mezcua (2017) introduces 4 scenarios.

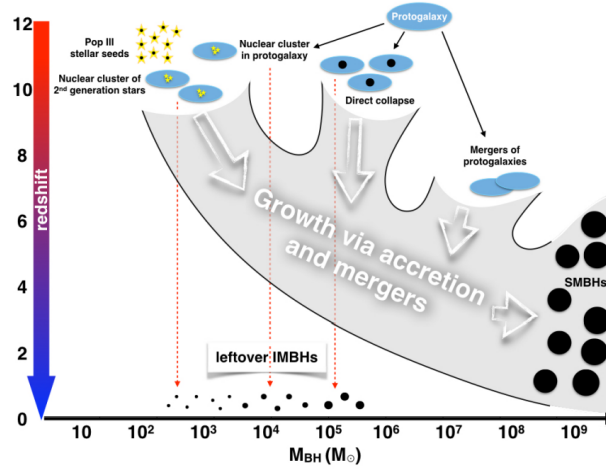


Figure 1.10.: In this illustration Mezcua (2017) visualizes the possible formation scenarios of IMBHs in the early universe, further forming SMBHs found in the center of galaxies at present. The IMBHs that do not grow into SMBHs are called leftover IMBHs and have been detected in some nearby galaxies.

- The first being initial stellar seeds at high redshift, called Population III stars. These stars form early on in the universe from primordial gas that cools down and collapses. Only the most massive stars then collapse further to form IMBHs. These IMBHs can

then grow into SMBHs if they are bound in a primordial NSC fed by constant flows of cold gas. This scenario is shown on the top left corner of Figure 1.10, indicating that NSCs fuel the growth of SMBHs in the centers of galaxies.

- The second possibility is a formation of IMBHs caused by direct collapse of inflowing gas in protogalaxies also depicted in Figure 1.10. For this gas to reach the halo center and collapse, it must avoid fragmentation as well as possess low angular momentum to undergo gravitational instabilities. If the gas is cooled down enough in the halo it can even collapse into a supermassive star, which can further end up to become a SMBH.

- IMBHs can also form through runaway collisions of stars in dense stellar clusters also seen in the top left part of Figure 1.10. Compact NSCs, emerging from second-generation low-mass stars formed from gas polluted by first-generation Population III stars. These often see frequent stellar mergers leading to supermassive stars that collapse into black holes of intermediate mass. Additionally, dense clusters formed at the centers of protogalaxies, where central densities are increased by metal-poor gas inflow, can produce supermassive stars that collapse into black holes as well. Again, linking the growth and formation of NSCs and SMBHs.

- Lastly, instead of requiring seed black holes at redshifts greater than 10 to grow through accretion and mergers to masses of $10^9 M_\odot$ by $z \sim 7$, the presence of SMBHs in such a young universe can also be explained by the direct formation through mergers of massive protogalaxies around redshift 5 - 6, seen on the right of Figure 1.10. When these protogalaxies merge, the resulting merger-driven inflows of metal-enriched gas create a massive, compact nuclear gas disk with high angular momentum. This leads to the formation of an ultra-dense, massive disk core in the inner parsecs, which can evolve into a supermassive star and collapse directly into a SMBH.

1.7. Target galaxy: FCC 148

FCC 148, the target galaxy of this work, too contains a massive NSC in its center. The early-type galaxy also known as NGC 1375, belongs to one of the many galaxies in the Fornax Cluster and lies at a distance of about 20 Mpc. It is also believed to host a SMBH, which I will be attempting to uncover in this thesis. Its morphological type is S0. This means that it is considered a lenticular shaped galaxy as apparent from Figure 1.11. Iodice et al. (2019b) derive a stellar mass of $0.53 \cdot 10^{10} M_\odot$ in the i-band as well as an effective radius of 2.42 kpc for this galaxy.

Generally, NGC 1375 is a fairly inconspicuous galaxy. Nevertheless, its near location makes it a great target to study the most central regions, where Turner et al. (2012) have verified the existence of a NSC through surface brightness analysis. Furthermore, Lyubenova and Tsatsi (2019) have recently studied the nuclear angular momentum in FCC 148 along side with a number of other Fornax Cluster galaxies, connecting the nuclear angular momentum to possible formation scenarios of NSCs. Fahrion et al. (2021) have also studied possible formation scenarios for FCC 148 investigating the star formation history. As FCC 148 is believed to also host a SMBH in the center, additional research concerning the black hole is an obvious next step. This would aim to expand

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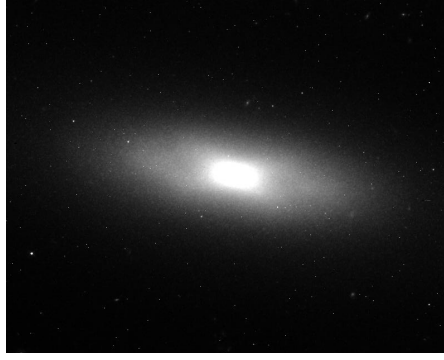


Figure 1.11.: This works target galaxy FCC 148 as captured by the HST Wide Field Camera 3²

the knowledge about the co-existence of NSCs and SMBHs in an early-type galaxy and reveal more about their potential formation processes.

1.8. Key goals of the thesis

The primary goal of this thesis is to accurately measure the mass of the possible SMBH located at the center of FCC 148 through the advanced dynamical modeling technique DYNAMITE developed by [van den Bosch et al. \(2008\)](#). This study aims to contribute to the broader understanding of the role and evolution of SMBHs in galactic nuclei. The specific goals of this research are as follows:

Prepare the input data required for dynamical modeling:

Objective: Produce correct input files of the photometric and kinematic data.

Methods: Utilizing observational data from high-resolution telescopes, particularly from the Hubble Space Telescope as well as ground-based IFS instruments like MUSE and SINFONI. Executing a MGE fit for the surface brightness of the galaxy and examining the compatibility of the two IFU data sets.

Accurate Measurement of Black Hole Mass:

Objective: Derive a robust measurement of the SMBH mass using stellar dynamical models.

Methods: Implementing the Schwarzschild orbit-superposition modeling technique of DYNAMITE to the prepared data sets and determine the SMBH mass as well as other galaxy properties.

Discussion of Results:

Objective: Analyze the calculated best-fit values for the SMBH and the galaxy.

Methods: Discussing how the results fit into current theoretical frameworks and if or how future improvements need to be made.

1.8.1. Significance of the Research

Understanding the precise mass of SMBHs in galaxy centers is crucial for several reasons:

A precise mass measurement gives validation to theoretical models as it provides empirical data to validate or refine theoretical models of galaxy evolution and black hole growth. It gives insights into galaxy dynamics, enhancing the understanding of the dynamic processes at the heart of galaxies, including the interaction between the SMBH and surrounding stars. Lastly, it improves the accuracy of scaling relations, which are fundamental tools for estimating SMBH masses in distant galaxies.

1.8.2. Scope and Limitations

This study focuses on a detailed analysis of a single galaxy, leveraging high-resolution observational data and advanced dynamical modeling. The findings, while specific, aim to contribute to the broader understanding of SMBH dynamics and scaling relations applicable to a wide range of galaxies.

2. Method

In observational astrophysics, determining the mass of central black holes is critical for understanding the structure of galaxies and how they evolve over time. This chapter explains the method used to measure the mass of a central black hole within FCC 148. The technique presented here is aimed at extracting precise measurements of the black hole's mass through analyzing the combined movements of stars around it, revealing the black hole's gravitational influence.

This chapter provides a detailed explanation of the method used to measure the mass of a central black hole apart from constraining additional mass components, in particular for the target galaxy FCC 148.

2.1. Stellar Dynamics

Modelling the stellar kinematics is a very common approach to assess mass measurements for a galaxy. For one, stars are always present in a galaxy and moreover their movement is always gravitational, facilitating the calculation of the gravitational potential.

With this approach, galaxies can in principle be viewed as collisionless stellar systems. In this scenario, we can consider each star as moving within the combined gravitational potential, generated by all other stars together with any gas or dark matter in the galaxy. This means that the system can be described analytically in a rather simple way. Consider the gravitational potential given as $\Phi(\vec{x}, t)$, and the distribution function, describing the number of stars contained in a given 6D phase space volume as $f(\vec{x}, \vec{v}, t)$. These are related through the following Equation 2.1, called the Collisionless Boltzmann Equation (CBE):

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla} f - \vec{\nabla} \Phi(\vec{x}, t) \cdot \frac{\partial f}{\partial \vec{v}} = 0 \quad (2.1)$$

Simultaneously, $\Phi(\vec{x}, t)$ is connected to the total mass density ρ through the Poisson Equation 2.2:

$$\nabla^2 \Phi(\vec{x}, t) = 4\pi G \rho(\vec{x}, t) \quad (2.2)$$

In which ρ includes all mass components, such as the stellar mass, the mass of the SMBH and dark matter, which is the main quantity I want to compute through the gravitational potential. In general, one could then reconstruct the DF if the stellar mass density and the velocity tensor is known, as they involve integrals of the DF $f(\vec{x}, \vec{v}, t)$. Furthermore, if the DF is known, the gravitational potential is retrievable through the

CBE. Unfortunately, with the typical extragalactic observational data, it is only feasible to measure the surface brightness and the line-of-sight velocity and velocity distribution, rather than all three velocity components. Therefore, more simplifications need to be made in order to recover the mass distribution of interest. One approach would be to assume for the system to be in a steady-state, requiring it to be a spherically symmetric and isotropic system. However, in reality such an assumption is not sensible and can cause large systematic changes to the mass distribution recovered by the dynamical model. The best approach is therefore to analyze the Line-of-sight velocity distribution, which is defined as the distribution function integrated over all positions and velocities along the line-of-sight given in Equation 2.3:

$$LOSVD(v_z, x, y) = \frac{1}{\mu} \iiint f(\vec{x}, \vec{v}, t) dv_x dv_y dz \quad (2.3)$$

μ is the projected surface brightness at a given position. Observationally, the LOSVD, reflects the shape of the absorption line profiles in the superimposed spectra of all the stars in a given region of a galaxy. The method of using the LOSVD to parametrize the DF is in principle the best approach with the given observational constraints. However in practice, a comprehensive evaluation of the LOSVD requires extraordinary quality in said data and therefore very high S/N, which is not easy to obtain for most galaxies (Ferrarese and Ford (2005)). Furthermore, the intricacy of dynamically modelling systems, highly depends on the complexity of the distribution function itself. If we again consider a system to be spherical and isotropic the DF can be described using only one integral of motion, the total energy of the system. This simplification though is very problematic as hardly any galaxies obey to this assumption. In case of the velocity dispersion being anisotropic, the systems DF depends on two integrals (2I) of motion, namely $f(E, L_z)$, where L_z is the vertical component of the angular momentum and E the total energy as described for the first scenario. Such a 2I ansatz can be solved using Jeans Equations, however even this assumption is an overly simplified description of the conditions of stellar systems, e.g. galaxies in reality. Therefore to retain the most flexibility, models with three integrals of motion have been introduced. A solution for the 3 integral representation of the DF was presented by Schwarzschild in 1979, now called the Schwarzschild super position method (Schwarzschild (1979)). It is a dynamical modelling technique to numerically solve the 3 integral model, which does not require prior knowledge of the 3 integrals of motion for the galaxy, making it a useful instrument to study the internal dynamics of galaxies. This method is the basis for the DYNAMITE procedure and will be discussed in more detail in the following sections.

2.1.1. DYNAMITE

The DYNAMITE code serves as a valuable tool for recovering a galaxy's mass distributions and orbit structure. In this chapter I will describe what DYNAMITE can do and how it determines the mass of black holes. By simulating the movements of stars, DYNAMITE provides crucial insights into the gravitational influence of SMBHs in the centers of galaxies. In this chapter, I want to delve into the specifics on how the DYNAMITE code

2. Method

works, exploring the fundamental method it is based on, the Schwarzschild method and its versatility when it comes to the stellar systems one can model with it.

DYNAMITE, short for **DY**Namics, **A**ge and **M**etallicity **I**ndicators **T**racing **E**volution (Thater et al. (2022)), is the open-source successor of the Schwarzschild python code developed by van den Bosch et al. (2008) and is a procedure, to model the dynamics of galaxies, specifically triaxial galaxies using the Schwarzschild orbital super-position method. It can model diverse types of galaxies, from barred spiral galaxies, to massive triaxial elliptical galaxies. Successful models not only provide the mass distribution of the various components (stars, DM and BHs), but also the orbital structure.

Most dynamical modelling methods, assume axisymmetry for the modelled galaxies, which in principle can not always be assumed since there is evidence for galaxies to be triaxial in shape as the stars in ellipticals may also show slow rotation as argued by Binney (1976). A triaxial approach is therefore, the best most general and flexible method to describe the intrinsic shape of a galaxy. Triaxiality in principle means that all axes(a, b, c) of a galaxy are of different length where $a \neq b \neq c$, giving the shape no strong constraints. With DYNAMITE as an umbrella procedure, one is not required to know the intrinsic shape of the galaxy a priori and therefore has the freedom of modelling all galaxies no matter the axis ratio, making it a powerful tool in the field of stellar dynamics.

Modelling procedure

First, a potential is chosen based on the luminosity distribution of the galaxy. To be able to retrieve the intrinsic luminosity density from the surface brightness of the galaxy using photometric data, a deprojection is needed. This is often a very complicated and time consuming process, in particular for triaxial galaxies. Therefore, the Multi-Gaussian Expansion (discussed in Chapter 4.1) is applied to obtain such a deprojection and parameterize the luminosity/mass distribution of the target galaxy. The gravitational potential is thus chosen depending on the MGE for the galaxy's surface brightness. In principle, for the potential, one needs to differentiate between the different mass components in the galaxy. In the DYNAMITE code it is possible to additionally retrieve the black hole mass and dark matter contribution. As van den Bosch et al. (2008) describe, the potential is calculated as such that it corresponds to the mass distribution derived from the MGE using the classical Chandrasekhar formula. The central concentration of the black hole is characterized through a Plummer potential, while the dark matter contribution can additionally be added, parametrized with a Navarro, Frank and White (NFW) (Navarro et al. (1996)) density profile.

Based on this initial guess for a gravitational potential, including both luminous and dark matter, an initial set of orbits is calculated. For each orbit the essential characteristics or observables are then stored, taking into account the integrals of motion, which restrict the orbit to its possible positions in phase-space. Further combining all the stars from the given orbit library results in a vast and as general as possible collection of stellar orbits representing the chosen potential as nicely visualized in Figure 2.1. The Schwarzschild

superposition approach is a method to then find a numerical solution for the distribution function through weighting different kinds of orbits accordingly to reproduce the observed kinematics and mass density (Thater et al. (2022)).

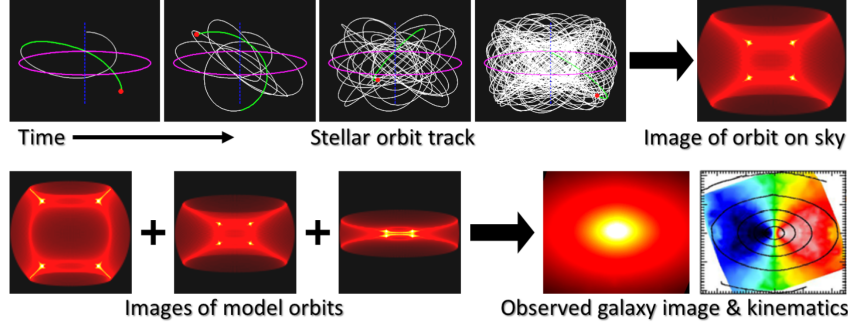


Figure 2.1.: Visual representation of the Schwarzschild super position method by Cappellari (2015). The first row depicts the numerical integration of an orbit over time until it converges to a fixed distribution. The second row shows how the dynamical modelling method ultimately finds the combination of a vast number of orbits to best fit the galaxy data.

These orbital weights are a direct representation of the importance an individual orbit (van den Bosch et al. (2008)) in reconstructing the observed velocity field has. The kinds of orbits or orbit types are classifications for regular orbits bound to the gravitational potential of the galaxy. They can be subdivided into box or boxy orbits and axis tube orbits. Box orbits are centrophilic and can cross the center while tube orbits are centrophobic and steer clear of the center. Whether more boxy orbits or tube orbits are used for the observed data highly depends on what type of galaxy is modelled. The weighting is greatly influenced by the triaxiality of the galaxy, if it's more disk-like in shape or maybe bulge-dominated etc. An individual orbit furthermore can be characterized by its angular momentum and energy.

The weights are optimized so that the superposition of the orbits in the chosen potential, best represent the observed surface brightness and kinematic maps. This process is then repeated for different choices of the gravitational potential parameters (e.g., BH mass, M/L) until best fit model parameters are found. This procedure thus acts as a sophisticated modelling application to better comprehend the internal structure of galaxies and uncover their evolutionary history, which for this work is applied to FCC 148.

3. Observations

In this chapter, we explore the crucial role of observations specifically used for the dynamical mass measurement of FCC 148. The focus will be on spectroscopic Integral Field Unit (IFU) data from MUSE and SINFONI and photometric data from the Hubble Space Telescope (HST). IFU data provides precious insights by capturing spatially resolved spectra, essential for unraveling the complex dynamics within stellar systems, such as galaxies. HST observations are particularly valuable for determining the surface brightness profile of galaxies through techniques like Multi-Gaussian Expansion (MGE). They enable the precise characterization of galaxy structures, shedding light on the distribution of mass within galaxies.

3.1. Instruments

3.1.1. HST - Hubble Space Telescope

The large space-based observatory, named after the great astronomer Edwin Hubble, the Hubble Space Telescope has uncovered a vast extent of the universe since 1990, when it first launched into space. It's domain extends from the UV through the visible and into the near-infrared through the six instruments contained in the spacecraft. The main imager or camera on the telescope is the Wide Field Camera 3, short WFC3, which is also the instrument utilized in my study. It covers a wide wavelength range of 200 to 1700 nm, producing high-quality images in the visible, but also completing the ultraviolet and near-infrared coverage of the telescope, hence the name Wide Field Camera ([Marinelli and Dressel \(2024\)](#)).

It is a two detector instrument, directing the incoming light into the near-infrared channel (IR) and UV/Visible channel (UVIS). While the Field of View (FoV) of the UVIS detector spans over $160'' \times 160''$, the IR detector covers a smaller field of $123'' \times 137''$ with an average pixel size of $0.13''/\text{pixel}$ ([Marinelli and Dressel \(2024\)](#)).

Each channel has an extensive set of filters. 63 in the UVIS channel and 17 in the IR channel, covering the whole wavelength range regulated by the detectors. The HST image I in particular use is captured with the wide filter F110W in the IR channel, which transmits wavelengths from around 900 nm to 1400 nm, with a peak transmission at 1100 nm as seen in Figure 3.1. The optical performance or spatial resolution of an instrument is usually described through the FWHM of the point-spread function (PSF). A function that describes the spatial distribution of the flux of a point-source in an image ([Marinelli and Dressel \(2024\)](#)). It is an important measure of the images quality as it quantifies the 'blurriness' of said point-source caused by the imaging system. The FWHM of the PSF

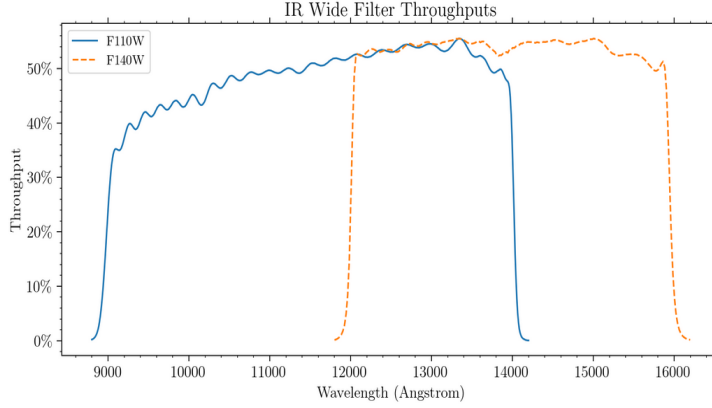


Figure 3.1.: HST WFC3 IR wide filter transmission throughputs in % for the utilized filter F110W and a similar filter F140W from the Instrument Handbook ([Marinelli and Dressel \(2024\)](#)). The wavelength is given in Å.

at a wavelength of 1100 nm, corresponding to the used filter, is also 0.13'' or 1.019 pixels.

I extracted the HST image of FCC 148 from the eHST archive ¹, observed within the program number 11712. The chosen image is a composite of four images and has a combined exposure time of 1196.93 seconds. More information is further mentioned in Chapter 4.1 ².

3.1.2. Integral Field Spectroscopy

IFUs are spectroscopic instruments in modern astronomy, which are specifically constructed to observe extended objects like nebulae, galaxies, or dense star and galaxy clusters in one exposure. The according technique is called integral field spectroscopy and it channels the signal from each individual pixel within the field into a dispersive element, generating a spectrum for each cell, the so-called spaxel. These individual spectra are then assembled into a three-dimensional datacube, which contains the complete 2D field of view along with a third spectral dimension, where the light is split into its wavelengths as visualized in Figure 3.2. This 3D dataset not only enables detailed spectral analysis but also permits spatial mapping at the same time. Thanks to this technique, IFUs provide a vast set of information about the dynamics, composition, and physical properties of galaxies. This in turn facilitates a deeper understanding of the underlying structures and evolutionary processes of such extended objects.

¹eHST archive: <https://hst.esac.esa.int/ehst//pages/search>

²As this image did not deliver satisfactory results for the MGE, my supervisor Sabine provided a more extended MGE for me, using an image captured by the Wide Field and Planetary Camera 2 (WFPC2) with the filter F814W in combination with an OmegaCAM i-band image from the VLT Survey Telescope (VST). Further implementation will be discussed in Chapter 4.1 and the revised MGE output provided by my supervisor can be found in the Appendix A.

3. Observations

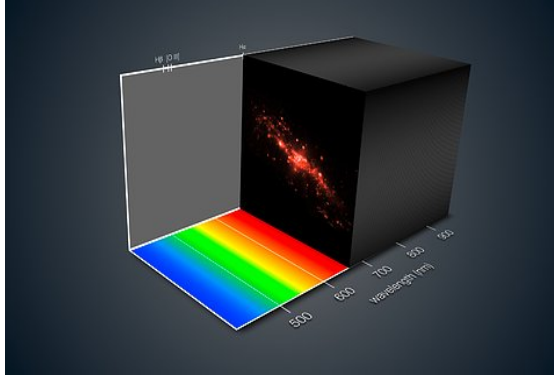


Figure 3.2.: A visual representation of 3D datacube of the integral field spectrograph MUSE ³. It nicely shows the 2D spatial field along side the 3rd spectral dimension in wavelengths

Adaptive optics

Unlike the HST, MUSE and SINFONI are ground-based instruments causing their resolution to suffer tremendously due to the seeing effects of the atmosphere. Nevertheless, SINFONI is still able to observe with an impressive spatial resolution. This is the case because of the adaptive optics system of its telescope. A technique to improve the resolution of a ground-based instrument to the point where it can reach its diffraction limit. In principle one continuously measures the variations of the incoming light due to atmospheric turbulence and tries to feed back this information so that the mirror is able to adapt to the deviations. Within such a system, the so-called wavefront sensor measures the said variations of the incoming light waves (wavefront), further an appropriate correction is calculated and then applied to a deformable mirror. This correction process is iterated hundreds of times per second, resulting in a superior spatial resolution for the instrument (Davies and Kasper (2012)).

MUSE

MUSE, short for 'Multi Unit Spectroscopic Explorer', is an integral field spectrograph part of the ESO's ground-based Very Large Telescope (VLT) at the Paranal Observatory. It operates in the visible wavelength range of 465 – 930 nm. In the Wide Field Mode (WFM) it is able to cover a Field of View of $1' \times 1'$ and a FoV of $7.5'' \times 7.5''$ in the Narrow Field Mode (NFM). The data of FCC 148 is captured with the Wide Field Mode, the primary modus for MUSE. Beside its fine spatial resolution aka FWHM PSF of $0.8''$ for the image of FCC 148 and a pixelsize of $0.2''$ it is further able to observe with a spectral resolving power of 2989, which corresponds to a velocity resolution of about 100.3 km/s. The spectral resolution is a measure describing the ability of a spectrograph to resolve individual features in the electromagnetic spectrum (Bacon et al. (2010)). An example spectrum of FCC 148 obtained by MUSE is given in Figure 3.3. The spectra for FCC 148

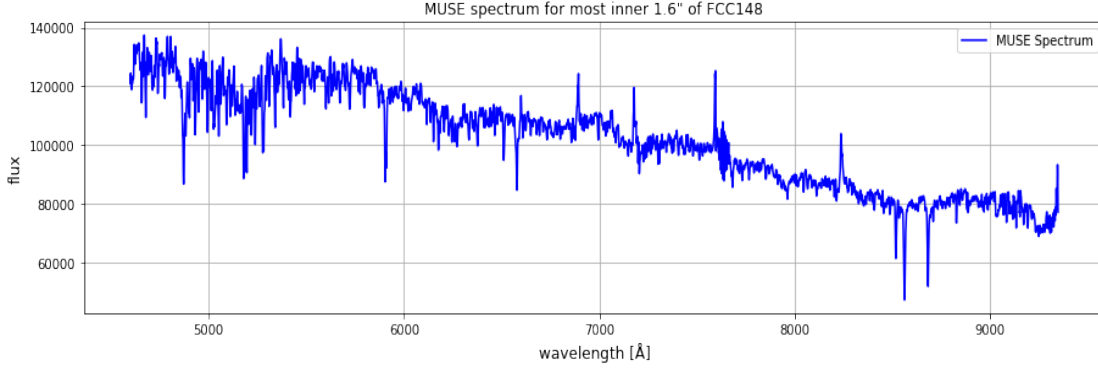


Figure 3.3.: MUSE spectrum averaged over the central 1.6'' of the FCC 148 image, nicely depicting the corresponding absorption lines from the innermost part of the galaxy. Early-type galaxies, as FCC 148 show mostly absorption lines such as the Calcium triplet between 8500 Å and 9000 Å with a very few exceptional emission lines in their spectra.

was taken with an exposure time of 4500 seconds.

SINFONI

Similar to MUSE, SINFONI is an integral field spectrograph installed at the VLT. In particular called the 'Spectrograph for INtegral Field Observation in the Near-Infrared'. The instrument is used together with ESO's Adaptive Optics module SPIFFI (SPectrometer for Infrared Faint Field Imaging), the world's first infrared integral field spectrometer. It offers 3 spatial magnifications. The high resolution mode, the intermediate mode and the coarse mode (Bonnet et al. (2004)). As I am using the data from the intermediate mode, the focus will only be lying on this system. Furthermore, it also offers 4 spectral modes using the J-, H- and K-gratings including a fourth combination of the H- and K-grating, covering a full wavelength range of 1.05 - 2.45 μm (Eisenhauer et al. (2003)). The intermediate spatial mode in combination with the spectral K-band grating, FCC 148 is captured with, results in a FoV of $3'' \times 3''$ and a wavelength range of 1.95–2.45 μm . The instrument's spectral resolving power is around 3500 in the K-band and the pixelscale has a value of 0.05'' per pixel (Lyubenova and Tsatsi (2019)). Due to its spatial resolution of a FWHM PSF of 1.2'' for FCC 148 we are able to capture the very center of the galaxy. Such a SINFONI spectrum for the center of FCC 148 is shown in Figure 3.4. Lyubenova and Tsatsi (2019), who provided the data set for me used a library of seven template spectra of K and M giant stars, fitting the wavelength range of 2.1 – 2.36 μm or 21000 - 23600 Å.

Conclusively, all the most important characteristics of the used instruments are listed in Table 3.1.

3. Observations

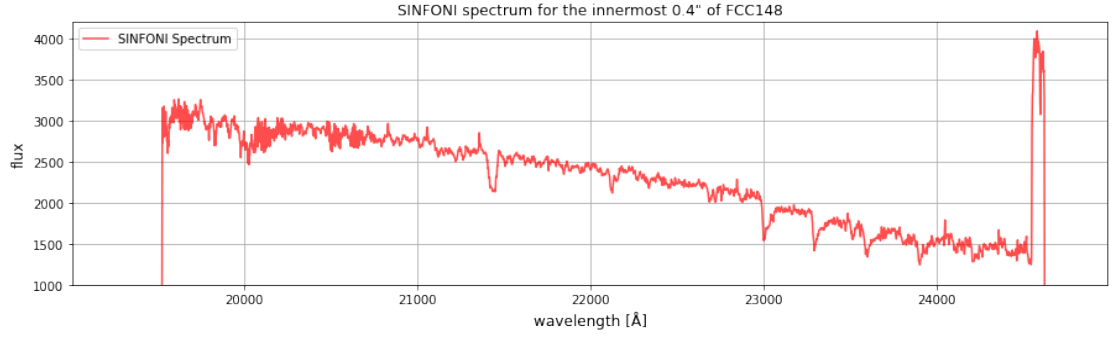


Figure 3.4.: SINFONI spectrum averaged over the central pixels of the FCC 148 image, nicely depicting the corresponding absorption lines from the most inner 0.4'' of the galaxy.

	HST WFC3 F110W	MUSE	SINFONI
wavelength range	900-1400 nm	4650–9300 Å	19500–24500 Å(K-band)
FoV	123'' × 137''	1' × 1'	3'' × 3''
spatial resolution (FWHM PSF)	0.13''	0.8''	0.12''
spectral resolution R	-	2989	3500 (K-band)
pixelsize	0.13''/px	0.2''/px	0.05''/px

Table 3.1.: Listing of all the important observational characteristic for the HST WFC3 instrument, MUSE and SINFONI in the given filters/bands capturing FCC 148.

4. Data Preparation and Analysis

In this chapter, we delve into the critical phase of data preparation, which lays the foundation for the entire data analysis process. This phase is the most extensive and includes modelling of the galaxy surface brightness and analysis of the provided stellar kinematics to ensure its quality and suitability for the modelling in DYNAMITE. This chapter provides insights into the significance of data preparation and its role in producing reliable and meaningful results.

4.1. Multi-Gaussian Expansion

One of the key preparation steps is to determine the galaxy’s stellar surface brightness distribution. It is of high importance to know the light distribution of the target galaxy to be able to constrain its mass and further the mass of the central black hole. The so called Multi-Gaussian Expansion (MGE), specifically the algorithm established by [Cappellari \(2002\)](#), is a technique to determine the distribution of a galaxy’s light profile in a highly efficient way. The basic idea behind it is to model the complex and often irregular light profiles of galaxies with the sum of multiple simple Gaussian functions. Each Gaussian function represents a small component of the galaxy’s light distribution, and by combining these Gaussians, one can model the overall surface brightness profile more accurately than only using a single Gaussian. Not only is the MGE much more robust when it comes to the applicability on ‘imperfect’ or irregular galaxies than the Sersic fitting, but it also expands surface brightness measurements to galaxies (e.g. with higher z) for which one might not have prior knowledge of its photometric structure ([Breda et al. \(2019\)](#)). Sersic fitting is mostly limited to regular and therefore Early-Type Galaxies (ETGs) and often can not accurately model additional luminosity components for instance bulges or nucleated galaxies like FCC 148.

4.1.1. MGE-fitting

I used the HST image introduced in Chapter 3 to obtain a mass model of the target galaxy FCC 148. The chosen image is then used for further preparation and analysis. Since the selected image was composed of a number of NaNs (Not a Number), therefore empty pixels at the edges, I cropped it to a size in which the galaxy was isolated in a way that adjacent objects are excluded from the frame but also no empty pixels could disrupt the calculations. This guaranteed that the algorithm eventually was able to find the center of the galaxy using the function `find_galaxy()` as seen in Figure 4.1 ensuring an appropriate starting point for the brightness measurements.

4. Data Preparation and Analysis

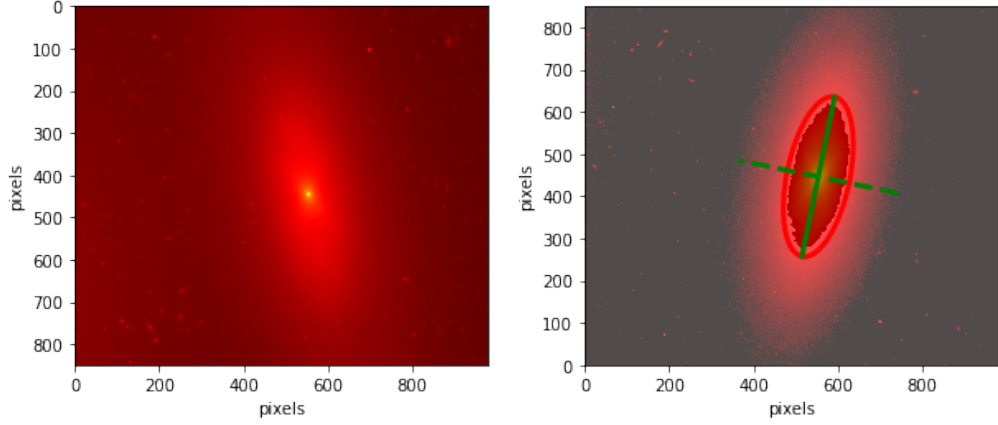


Figure 4.1.: Left: Selected cropped HST image of FCC 148 in the z-band of the WFC3. Right: `find_galaxy()` applied to the image showing the ellipticity of the galaxy (red ellipse), as well as a computation of the position angle indicated by the green lines: the major axis (solid) and the dashed line perpendicular to it intersecting in the center of the galaxy equal to the coordinates of the brightest pixel.

<code>skylev</code>	<code>scale</code> [arcsec pixel^{-1}]	<code>minlevel</code>	<code>ngauss</code>	<code>exp_time</code> [s]
1.10	0.128	-0.43	12	1196.93

Table 4.1.: Listing of all the initial parameters I set before running the fitting procedure. Both `skylev` and `minlevel` are given in the flux units of the image.

To ensure that the fitting can be executed accurately more information about the image of the galaxy is needed. For one, deriving the background flux is essential and it is first subtracted from the image flux. This parameter is defined as `skylev`. I obtained this parameter using the average value of a small area of pixels that lie at the very edge of the images frame listed in Table 4.1 with all the other parameters needed to be defined beforehand. Furthermore, the pixelscale of the image needs to be provided. Its units are defined as arcsec per pixel. This parameter is most of the time given in the header of the fits file. For the target galaxy FCC 148 the near-infrared image file states a pixelscale of 0.128 arcseconds per pixel in the header. Likewise, the header lists the exposure time for the image, which is another necessary parameter that the algorithm needs to know before compiling the best fit. Lastly, the lowest count per pixel for the total image is required, defined as `minlevel` and the amount of Gaussians that one expects to be applied on the galaxy's profile calculations. As a default value, the `ngauss` is set to 12. This can vary as one needs to get a feel for the value of this number after executing the script a few times until the best possible fit is reached. In my case 12 Gaussians proved to be a fitting value and I therefore did not change this any further.

However, this is adapted at the very end, when all further input has been evaluated.

Before the correct fit can be compiled an additional very crucial input parameter needs to be defined. The PSF is an essential attribute of the camera and filter, with which the galaxy image was captured. If this characteristic is unknown the results can become falsified as the program might overfit the images details. Of course one can start the fitting with just a simple Gaussian PSF first but for a significant output an appropriate PSF for the image is essential at last.

The MGE's algorithm requires an array of a sigma-PSF and a normalized PSF. This is calculated by applying the MGE on a PSF image for the galaxy beforehand. My supervisor provided this PSF image using the PSF-modeling tool Tiny Tim ([Krist et al. \(2011\)](#)), for which the camera, the filter and the galaxy's center are needed as an input. This image as seen in figure 4.2 is the representation of how a point-source is spread out using the WFC3 and the near-infrared filter F110W as conducted for the target galaxy FCC 148. Applying the MGE algorithm on this image results in a final table containing the '*Total counts*', '*sigma_{pixels}*' and a value for the deprojection '*q_{obs}*', where the latter is not needed for the PSF calculations but is limited beforehand setting the `qbounds` parameter close to 1, thus between 0.999 and 1. in the `mge_fit_sectors()`-function. This ensures that the ellipticity for the PSF is circular. Of course, the spikes at the edges of the PSF can therefore hardly be fitted effectively. The values for *sigma_{pixels}* can be directly utilized as the required sigma-PSF array and therefore do not need further modification. Unlike, the *Total counts*, which need to be converted to normalized PSF values. In the simplest way, one divides 1 by the sum of all the *Total counts* elements, which in this case are 3 values. The resulting factor is then multiplied with the 3 counts, which gives us a normalized array of total counts that sum up to be unity. The final PSF values are listed in Table 4.2.

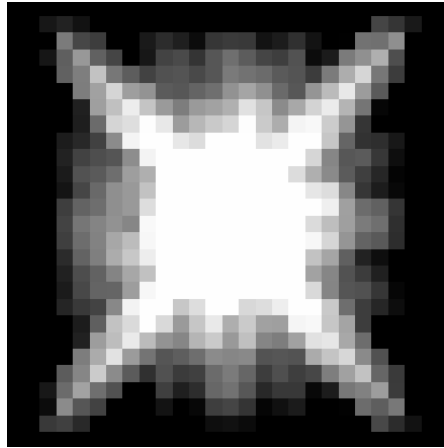


Figure 4.2.: PSF for the galaxy image captured with the Wide-Field camera 3 using the near-infrared filter F110W, which was modelled with TinyTim.

The preliminary steps have been taken and the initial parameters are set, the MGE fit can therefore finally be executed. As mentioned earlier, I first and foremost determined the

4. Data Preparation and Analysis

sigma PSF	0.380000	0.822819	3.07495
normalized PSF	0.50959947	0.37508279	0.11531774

Table 4.2.: calculated PSF values required for the MGE

galaxy center using the function `find_galaxy()`. It additionally computes the orientation and ellipticity of the galaxy in the image. This ensures the accurate measurement of surface brightness profiles over the whole extend of the galaxy. Subsequently, the function `sectors_photometry()` evaluates the galaxy's photometry along a number of sectors, that uniformly spaced in angle cover the entire galaxy image (Cappellari (2002)). This number of sectors is a variable input within the python function. It is the number of triangular sectors within a quadrant of the galaxy's surface area and was left to be the default value of `n_sectors = 19` as it delivered satisfactory results for the fit with an angle width of 5 degrees each. The distribution of such sectors can be seen in Figure 4.3.

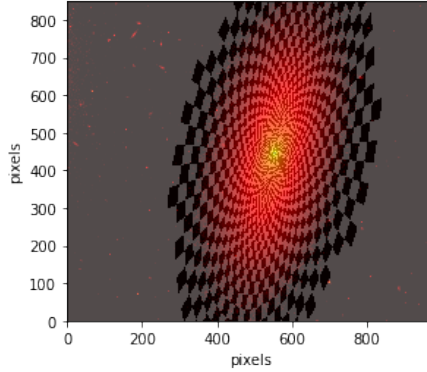


Figure 4.3.: Surface brightness map of the galaxy, with the geometric divisions into sectors used as part of the MGE creation during the `sectors_photometry()` step.

These photometric measurements along the sectors directly serve as the basis of the following fitting. Using the function `mge_fit_sectors()` the main fitting procedure of the surface brightness is performed. Each sector consists of various chessboard-like rectangles as seen in Figure 4.3. Within every rectangle, the average coordinates for each photometric point from the contained pixels is used, which is conducted in the `sectors_photometry()`-function. Notably, the luminosity-weighted coordinates of the pixels are averaged and not the pixel values themselves to ensure that the calculations are conducted representatively and as precise as possible (Cappellari (2002)). The brightness measurement of the averaged pixel coordinate is hence used as one data point in the fitting procedure.

This is implemented for the entire extent of a sector resulting in a sufficient amount of data points to be fitted. As seen in Figure 4.4 the best fit for each sectors surface brightness is completed using the number of Gaussians defined earlier on or less. Depending on the distribution of the light within the galaxy, the Gaussians are weighted differently.

4.1. Multi-Gaussian Expansion

Based on the shape of the galaxy and if there might be a isophotal twist the light profiles along the various angles can flatten and/or drop towards the outer radii to different extents. This function additionally to the surface brightness fitting also outputs various information on the fitting process such as number of iteration and their individual χ^2 -values, as well the used Gaussians and the computation time. From the 12 Gaussians defined earlier on, only 7 were implemented in the fit. This means that the surface brightness profile of the galaxy can be well described using only 7 Gaussians. These Gaussians are usually averaged taking into account the sectors at different angles. This leads to the most important output, the final results of the *Total Counts* of the Gaussian components, given in units of electrons per second, the σ_{pixels} , the standard deviation or dispersion of the best fitting Gaussians, given in pixels and q_{Obs} , the axial ratio of said Gaussian components. Leaving us with a set of 7 values for each parameter.

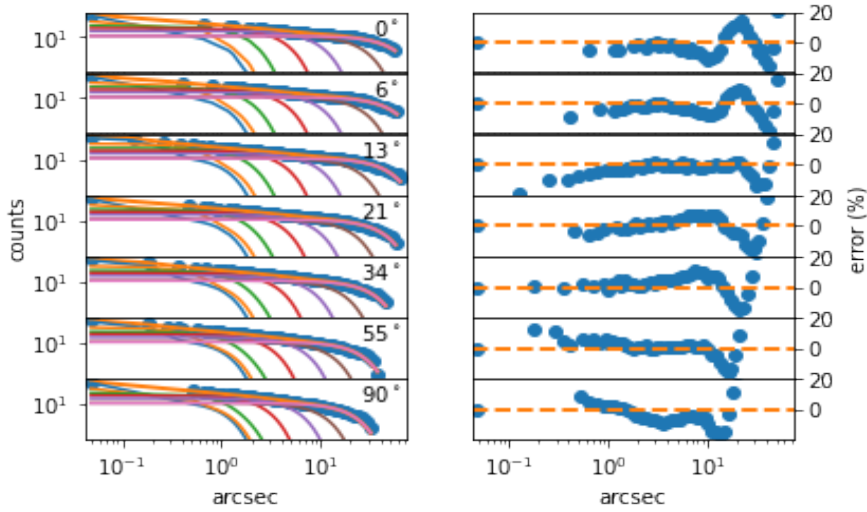


Figure 4.4.: Left: Surface brightness fit using multiple Gaussians (coloured lines) within the sectors at angle 0, 6, 13, 21, 34, 55 and 90 degrees. Right: The corresponding residuals for the fits at the different angles.

To simplify the dynamical modeling process, the function `mge_fit_sectors()` is extended to the regularized version `mge_fit_sectors_regularized()`. Essentially, this expansion restricts the allowed range of q_{obs} to higher values, thus rounder isophotes to guarantee that the inclination values are not artificially limited.

Thus, leaving the inclination as free as possible of the galaxy helps to better constrain the three-dimensional shape of the galaxy, which is crucial to the dynamical modeling later on. The regularization function of the MGE fit is applied as the most final step, when the parameters are all set and the fitting results hence the following contour plots are satisfactory. It serves as a cleanup of the final output. The concluding contour plots best visualize the best fit results. These are produced using the `mge_print_contours()` module. This simply plots a contour map of the galaxy using the central coordinates of

4. Data Preparation and Analysis

the galaxy from the `find_galaxy()` function before, which essentially also benefits to produce a zoomed-in cropout image as seen in Figure 4.5. The contours connect points of equal surface brightness to the so-called isophotes (Schneider (2015)). In astronomy, this type of visualization helps to display three dimensional data of a galaxy into a two dimensional plot. The displayed contour map in Figure 4.5 is one of the quality indicators of the MGE best fit. As one can clearly see the fitted contours align very well with the surface brightness data and can therefore be adopted for further calculations. The final MGE output values are listed in Table 4.3 below.

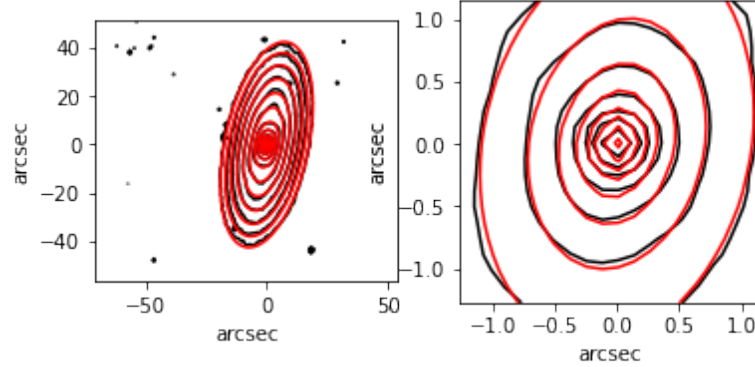


Figure 4.5.: Left: Surface brightness contour map of the whole target galaxy FCC 148. Right: Zoom-in into the central $1'' \times 1''$. The black contour represents the data and the red contour is the overplotted fit.

<i>Total Counts</i>	<i>sigmaPixels</i>	<i>qObs</i>
11532.8	0.683375	0.65
13219.3	2.21906	0.65
20791.8	5.20764	0.65
54303.7	12.012	0.65
126350	27.3869	0.61
198426	76.8317	0.4
782001	158.953	0.4

Table 4.3.: final MGE output table

4.1.2. Conversion of the MGE output into physical magnitudes

The final Multi-Gaussian expansion output table in the next step needs to be converted into Surface Density values. The conversion process is explained in the `readme_mge_fit_sectors.pdf` file, saved within the site packages of the MGE module of Cappellari (2002). The first necessary formula computes the peak surface brightness C_0 using the *Total Counts*, *sigmaPixels* and *qObs* as in Equation 4.1:

4.1. Multi-Gaussian Expansion

$$C_0 = \frac{\text{Total Counts}}{2\pi (\text{sigma}_{\text{Pixels}})^2 q_{\text{Obs}}} \quad (4.1)$$

Having determined C_0 with units counts pixel^{-1} , it can be further converted into a Johnson-Cousins z-band surface brightness μ_z in $[\text{mag arcsec}^{-2}]$. This equation 4.2 is highly dependent on the camera and filter settings with which the image was captured.

$$\mu_z = P_0 + 0.1 + 5 \log_{10}(S) + 2.5 \log_{10}(t_{\text{exp}}) - 2.5 \log_{10}(C_0) - A_{F110W} \quad (4.2)$$

As mentioned earlier the used camera is the Wide-Field Camera 3, short WFC3 with the filter F110W. P_0 , the photometric AB zeropoint was obtained from the HST User Documentation website for said instrument (Dressel and Marinelli (2023)). S represents the pixel scale stated in the header of the HST image and t_{exp} is the exposure time in seconds also given in the header. Finally A_{F110W} is the galactic extinction in the corresponding wavelength band in mag. This information was gained from the NED - NASA/IPAC Extragalactic Database Helou et al. (1991). The term +0.1 corrects for infinite aperture in the surface brightness measurements. Equation 4.2 therefore in this case transforms to Equation 4.3.

$$\mu_z = 26.819 + 0.1 + 5 \log_{10}(0.128) + 2.5 \log_{10}(1196.9292) - 2.5 \log_{10}(C_0) - 0.012 \quad (4.3)$$

Finally, the surface density I' can be calculated from the z-band surface brightness μ_z using the following formula:

$$I' = \left(\frac{68400}{\pi} \right)^2 10^{0.4(M_{\odot, F105W} - \mu_z)} \quad (4.4)$$

$M_{\odot, F105W}$ in Equation 4.4 is the absolute magnitude of the sun in the NIR wavelength range. As the filter F110W was used, this value needs to be established. In Willmer (2018) the target filter is not listed and only the WFC3-filter F105W is included, thus the $M_{\odot, F105W}$ of said filter was implemented, which states an absolute magnitude of the sun of 4.51 mag in the AB magnitude system.

This leads to the final surface density values I' in $L_{\odot} pc^{-2}$ listed in Table 4.4. The $\text{sigma}_{\text{Pixels}}$ were simply converted to σ'_j given in arcsec by multiplying the values with the scale $S = 0.128$ and the flattening parameter q_{Obs} was not modified but its nomenclature altered to q'_j for a uniform record.

This final conversion table acts as the input data for the dynamical modelling. Before the MGE input can ultimately be applied, one should check for the sum of the total luminosity of the Gaussians to be in the right order. As the total luminosity's unit is $L_{\odot}$ the σ'_j needs to be converted to parsecs first. Due to the distance dependency of the conversion to parsecs, the following equation is used with a distance D of 18 Mpc (Helou et al. (1991)) for the galaxy.

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$I'_j [L_\odot pc^{-2}]$	$\sigma'_j ["]$	q'_j
69057.95	0.088	0.65
7507.02	0.284	0.65
2143.91	0.667	0.65
1052.44	1.538	0.65
505.20	3.506	0.61
152.75	9.834	0.4
140.64	20.346	0.4

Table 4.4.: Final conversion of the MGE output

$\sigma'_j [pc]$
7.633
24.787
58.170
134.175
305.915
858.218
1775.522

Table 4.5.: Sigma conversion to parsec

$$\sigma_{pc} = \frac{\pi D \sigma_{arcsec}}{180 \cdot 3600} \quad (4.5)$$

The $\frac{\pi}{180 \cdot 3600}$ serves as the conversion factor from arcseconds to radians. The basis of this equation is the simple trigonometrical approach of $d = D \cdot \tan(\alpha)$, which is simplified to $d = D \cdot \alpha$ for small angles. Using Equation 4.5 I yield a new σ_{parsec} listed in Table 4.5, which is further applied for the final total luminosity calculation.

In this case the surface density of all 7 Gaussian components can be converted to a total luminosity L_j using the following equation 4.6.

$$L_j = 2\pi I'_j \sigma'^2_j q'_j \quad (4.6)$$

Applying this to all 7 Gaussian components, the total luminosities are found to be as follows, listed in Table 4.6.

Summing the luminosities up for the whole galaxy one finds that the total luminosity for the galaxy L_{tot} equals $1.72 \cdot 10^9 L_\odot$. Multiplying the result with the expected M/L-ratio for FCC 148 of 0.83 (Iodice et al. (2019b)) one ends up with a stellar mass M_* of $1.43 \cdot 10^9 M_\odot$. Compared to the stellar mass in the literature of $5.8 \cdot 10^9 M_\odot$ (Iodice et al. (2019b)) the calculated value passes in an appropriate ratio of a factor of 4.06. The MGE output was therefore ready to be implemented into the dynamical modeling with DYNAMITE.

4.1. Multi-Gaussian Expansion

$L_j[L_\odot]$
$1.64 \cdot 10^7$
$1.88 \cdot 10^7$
$2.96 \cdot 10^7$
$7.74 \cdot 10^7$
$1.80 \cdot 10^8$
$2.83 \cdot 10^8$
$1.11 \cdot 10^9$

Table 4.6.: Total luminosity for each Gaussian component

Unfortunately, after a few runs in DYNAMITE, I realised that the MGE's σ -extent was not sufficient enough to properly model the galaxy's gravitational potential. I noticed high errors for the models in the outer parts of the galaxy, consequently discarding my current MGE computation. As my supervisor Sabine is more experienced with this method, she offered to prepare a MGE herself using a combination of 2 images, a VST WFPC2 image and an OmegaCAM image. Using her calculations, I was able to reach σ -values up to 126", which much better suit the coverage of the MUSE data¹.

¹The corresponding MGE output is listed in the Appendix A including details about the images used and the final total stellar mass.

4.2. Kinematics

This chapter serves as a crucial juncture in the data preparation process, as it not only shows the information the kinematic data sets provide but it can also be regarded as a preliminary data analysis. The kinematic data for the galaxy includes a data set from MUSE which captures the greater extended radii of FCC 148 and a data set from SINFONI which particularly focuses on the galaxy's most central parts. In this section, the most important parameters of the kinematical data are narrated, as well as what initial indication they give on the large scale characteristics one might expect for the elliptical target galaxy.

4.2.1. Voronoi binning

Before starting off with an introduction to the kinematic maps, a technique to homogenize the signal-to-noise in IFU observations, needs to be discussed. The so-called voronoi-binning is used for IFS data, as the SNR in spatially resolved data can often vary from the bright central regions of a galaxy to its faint outskirts and aids to reach a common SNR over the entire Field-of-View. Using the voronoi tessellation or tiling method, one can locally group datapoints together and average their SNR, which results in a coarser sampling and lower number of datapoints. Furthermore, 'adaptive binning' can facilitate to compensate for the large variation of the S/N from the central parts to the outskirts of the galaxy image, adjusting the sizes of the bins to the local SNR ([Cappellari and Copin \(2003\)](#)). Voronoi binning is also the technique used to bin the aforementioned MUSE and SINFONI datasets.

4.2.2. pPXF - Penalized Pixel Fitting

To understand how the kinematic maps are retrieved from the observational IFU data, the essential technique for recovering the LOSVD, the so-called pPXF needs to be discussed. If we view galaxies as a large assembly of stars, the spectrum we observe at a point in the sky can be considered the sum of spectra of all individual stars. With this assumption, one can use template spectra convolved with an estimated LOSVD to fit to the observed spectrum and retrieve the true LOSVD. For IFU data specifically one can fit the convolution of template spectra and the initial LOSVD to the observed spectrum of the individual pixels or bins. By adjusting the LOSVD parameters (Gauss-Hermite parametrization) pPXF is able to optimize the fit and provide estimates of the LOSVD parameters for each spatial pixel or bin ([Cappellari and Emsellem \(2004\)](#)).

The LOSVD is parameterised by 4 Gauss-Hermite moments. The first moment of the LOSVD is the stellar mean velocity, $\langle V \rangle$, the second moment, the velocity distribution σ , the third moment h_3 , which is also known as skewness and describes the symmetry or asymmetry of the distribution. Lastly, the fourth moment h_4 , the kurtosis, is a parameter that quantifies the 'tailedness'. This simply expresses whether the LOSVD is peaked or broadened compared to a Gaussian distribution. These Gauss-Hermite moments are visualized in Figure 4.6.

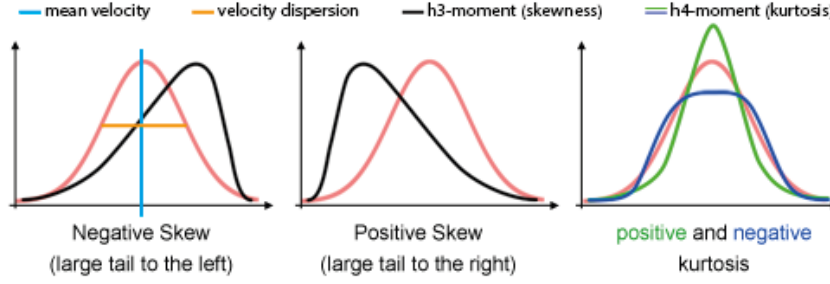


Figure 4.6.: A visualization of the 4 LOSVD parameters. The mean velocity in blue, the velocity dispersion in orange, the h3-moment visualized as the skewness in black and lastly the h4-moment depicted in green and dark blue showing a broadened and peaked distribution plotted over a usual Gaussian distribution in pink.²

The best-fitting Gauss-Hermite parameters are found by minimizing the χ^2 , which is the quantity evaluating the agreement between the model and the observed galaxy spectrum. The final best-fit parameters for each, in my case, bin can then be used to construct kinematic maps of the LOSVD across the entire field of view.

To be able to apply both kinematic data sets to the dynamical modelling, the data sets need to be inspected and properly aligned to produce a coherent input.

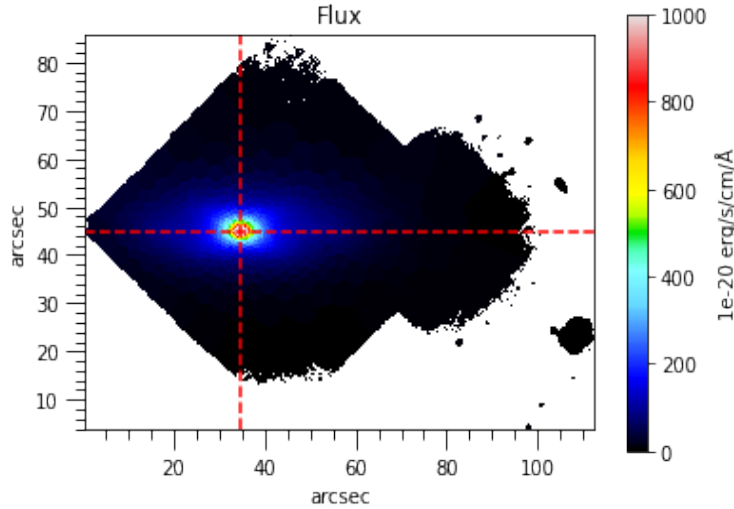


Figure 4.7.: MUSE flux map including the vertical and horizontal red dashed lines to highlight the position of the central coordinates.

Before any analysis of the data sets can be executed, I had to ensure that I understood the structure of how the fits data was organized to further be able to extract the necessary

4. Data Preparation and Analysis

data points. I quickly realized that the MUSE coordinates were not centered to the central point of the galaxy. Therefore, I again used the `find_galaxy()` function from the MGE package to track the galaxies center. This generated peak pixel coordinates for the flux map of [174, 223] in Figure 4.7, which means that the center also lies at these coordinates. I then shifted the x- and y-axis to said values and furthermore converted the pixel values to arcseconds using the pixelscale of 0.2 arcseconds per pixel stated in [Bacon et al. \(2010\)](#) for the MUSE Wide Field Mode. The shifted axis are already implemented in the kinematic maps shown in Figure 4.8.

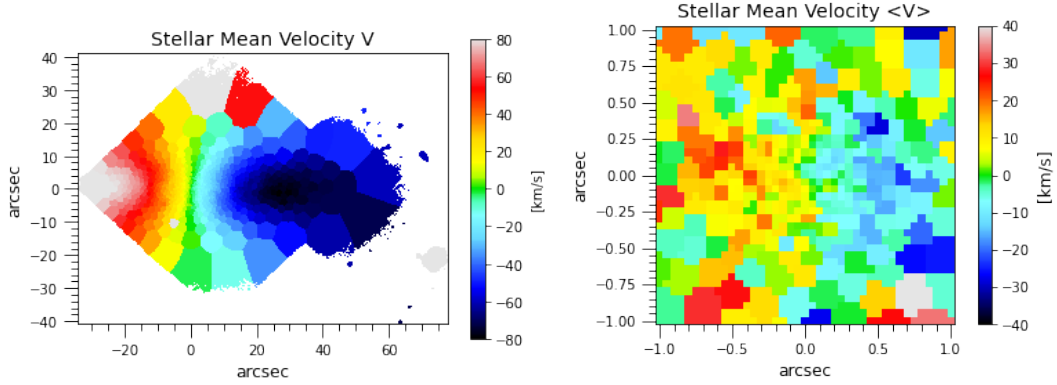


Figure 4.8.: Left: Full Field-of-View Image of the Stellar Mean Velocity of FCC 148 with MUSE after subtraction of the systematic velocity of 760 km/s. Right: SINFONI Stellar Mean Velocity Map of FCC 148 cropped to a size of $1'' \times 1''$ excluding the empty bins at the edge of the image.

As mentioned earlier in Chapter 3 the LOSVD is parameterised by 4 Gauss-Hermite moments. Each of these four parameters describe the kinematics of FCC 148. While with the stellar mean velocity the overall rotation of the galaxy is extracted, the velocity dispersion depicts how strong the velocities of the assembly of stars differ from one another. What we expect for the analyzed galaxy is to have a regular rotation with one side of the galaxy clearly moving towards us (colored in blue) and the other moving away (colored in red). Fortunately, for both the MUSE data set as well as for the SINFONI data set, I perceived such a rotation as seen in Figure 4.8.

However, for my black hole mass measurement the expected peak of the velocity dispersion at the center of the galaxy is much more important. As the relation between the velocity dispersion of a galaxy and its central Supermassive Black Hole ([Kormendy and Ho \(2013a\)](#)) is well established, it is expected that for each galaxy containing a SMBH an extremum of the velocity dispersion is observed, as the gravitational pull of the black hole causes the stars to orbit at a much faster rate. A traceable maximum at the central regions is therefore a key indicator that a SMBH is found in the target galaxy and is crucial to determining the mass of the central black hole. As seen in Figure 4.9, the MUSE data for the galaxy clearly shows a peak velocity dispersion of around 60 km/s at the center compared to the outskirts of the galaxy. Therefore, I can very likely expect

a SMBH in FCC 148. This peak is also observed in the SINFONI data set, for which it is even more important to detect a visible peak as the SINFONI data serves as the basis kinematic input for the central black hole mass measurement.

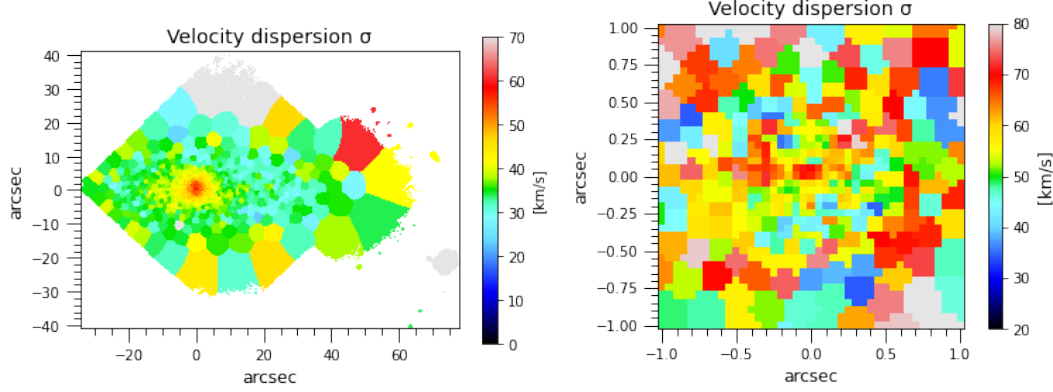


Figure 4.9.: Left: Velocity dispersion map of MUSE showing a clear peak at the center of the galaxy. The velocity range for the colormap was limited from 0 to 70 km/s. Right: The SINFONI data reveals a higher σ -value in the center as well. This velocity colormap ranges from 20 km/s to 80 km/s.

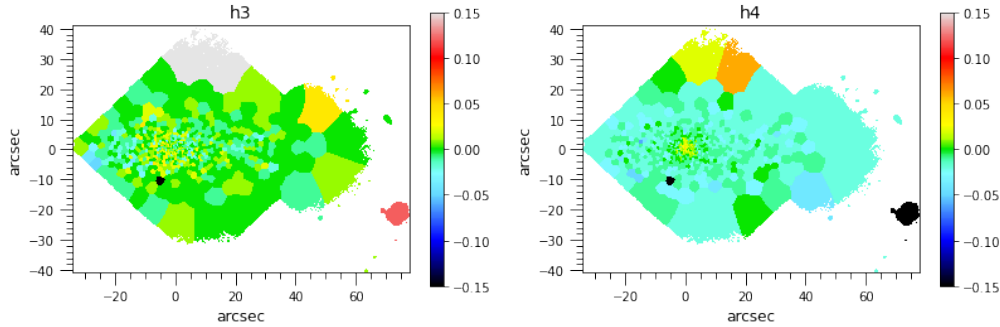


Figure 4.10.: Left: The h3-map of the MUSE data set limited to a value range of -0.15 to +0.15. Right: The h4-map of the MUSE limited to the same range.

Furthermore, the h3-map shows a somewhat subtle opposing pattern of features compared to the stellar mean velocity while the h4-map is a counter map to the velocity dispersion as seen in Figure 4.10. The same applies to the SINFONI data which is found in Figure 4.11.

Once I was satisfied by the configuration of the kinematic maps for both MUSE and SINFONI, I proceeded with the next step. As I want to use both MUSE and SINFONI data in combination for the dynamical modeling of FCC 148, I have to make sure that the data sets align with each other in terms of their kinematic position angle, which means that both data sets need to have the same orientation concerning their rotation to be

4. Data Preparation and Analysis

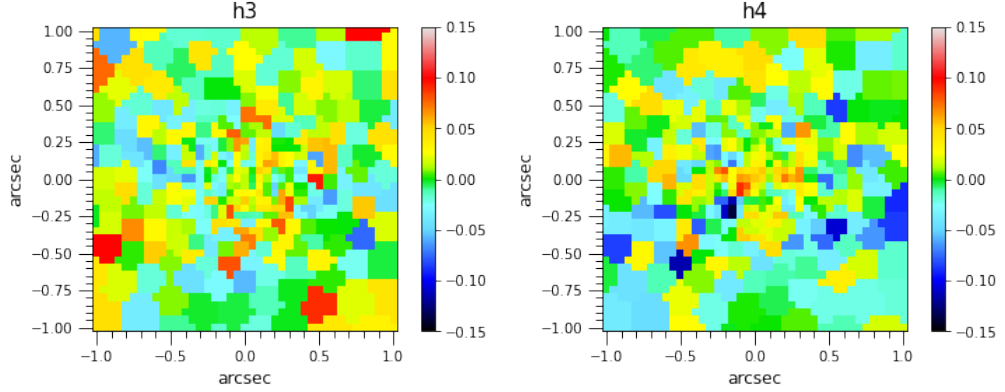


Figure 4.11.: Left: The h3-map of the SINFONI data set in $1'' \times 1''$ cut-out constrained to the same range of -0.15 to 0.15 as MUSE. Right: The h4-map of the SINFONI data set with the same dimensions and constraints.

able to compare them. One must bear in mind that the kinematic position angle is not identical to the photometric position angle, since the PA is related to the major axis and the photometric major axis does not necessarily have to be equivalent to the kinematic major axis (Ene et al. (2018)).

The function `fit_kinematic_pa()`, which I imported from the module `pafit` (Capellari (2016)) computes this said kinematic position angle. Using the centered x and y coordinates of the galaxy as well as the velocity measurements as input parameters the function is able to determine the global kinematic position angle and a correction for the systematic velocity. As this algorithm can be time intensive to compute, I also adapted the keyword `nsteps` to a lower value than the default number. This simply is the number of steps along which the position angle is sampled (Krajnović et al. (2006)). I set it to `nsteps=30` instead of 361. The systematic velocity as mentioned earlier is only corrected for. Therefore, a rough assumption of this parameter should also be determined beforehand as it needs to be subtracted from the velocity input. The systematic velocity often refers to the average velocity of the galaxy as a whole object. This includes the velocity of movement of the galaxy's centre of mass taking into account the Hubble expansion and therefore it's redshift velocity as well as the galaxy cluster interactions. I obtained an estimate of the systematic velocity by extracting the median velocity from the velocity map of MUSE, which was a value of approximately 760 km/s. This can be computed numerically or just read off by eye from the velocity map. With this information the `fit_kinematic_pa()`-function computed the best fit for the kinematic position angle, described as the angle along which the absolute velocity is at a maximum (Krajnović et al. (2006)) as well as it's error and a correction for the systematic velocity called `velocity offset`:

$$\text{Kin PA} = 86.9 \pm 3.1 \text{ degrees}$$

$$\text{Velocity Offset} = 2.46 \text{ km/s}$$

After one run, I adjusted the systematic velocity to 762 km/s, giving the algorithm an even better initial input. Doing this might ascend the accuracy of the position angle calculation. But in my case the kinematic PA still resulted in a value of **86.9 degrees**, only lowering the velocity offset to 0.8 km/s. Additionally, the function returns two plots. For one a plot with a symmetrized velocity map. This symmetrization along the major axis aids to simplify the deduction of the line of zero velocity, thus the axis of rotation. It is tremendously helpful with data of low Signal-to-noise, which is not the case for my target galaxy but also with data that does not show a clear rotation as for FCC 148. However, galaxies with irregular rotation patterns, such as a counter-rotating core can be problematic for this procedure. The second plot returns the rotational axis on the velocity map as a dashed black line and the corresponding major axis as a green solid line.

In Figure 4.12 the Kin PA would then be the angle between the black line and the horizontal zero point-line turning clockwise.

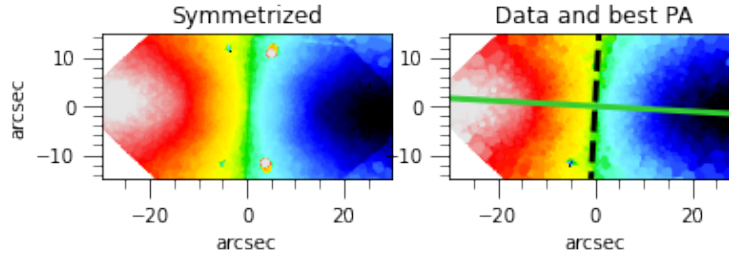


Figure 4.12.: Output plots of the `fit_kinematic_pa()` function for the MUSE velocity map. Left: The symmetrized velocity map along the major axis. Right: The true velocity map including the best fit position angle overplotted with the major axis (green solid line) and the rotational axis (black dashed line).

I executed the same procedure with the SINFONI velocity map, which produced the output maps seen in Figure 4.13. However, for this data set the initial assumption for the systematic velocity was ca. 790 km/s applying the same process as for the MUSE data. The results of the SINFONI kinematic PA are the following:

$$\text{Kin PA} = 74.5 \pm 24.8 \text{ degrees}$$

$$\text{Velocity Offset} = 2.14 \text{ km/s}$$

Again, I corrected the initial systematic velocity after the first run. This time to a value of 792 km/s, which also did not change the kinematic position angle as the assumption was close to the true value. Only the velocity offset decreased to a value of 0.14 km/s.

4. Data Preparation and Analysis

When comparing the 2 data sets, one quickly notices, that the SINFONI kinematic PA contains a much larger error by a factor of ca. 8. This is due to the very small radial extent of SINFONI. As MUSE covers large radii, it is much more straightforward to retrieve an accurate position angle than for SINFONI, which only stretches over an area of 1" squared.

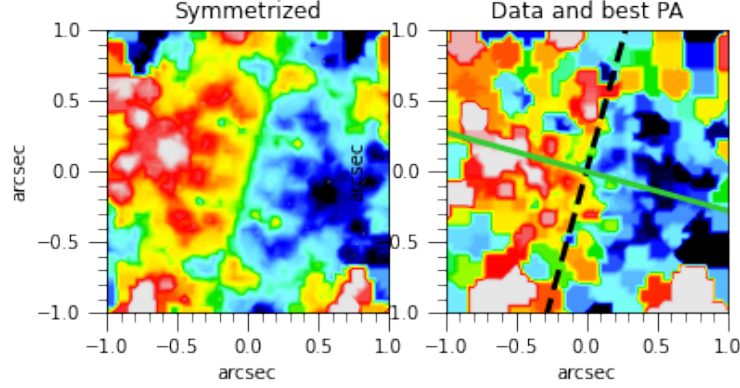


Figure 4.13.: Output plots of the `fit_kinematic_pa()` function for the SINFONI velocity map. Left: The symmetrized velocity map along the major axis. Right: The true velocity map including the best fit position angle overplotted with the major axis (green solid line) and the rotational axis (black solid line).

After obtaining the results for the kinematic PA, I proceeded to rotate both data sets such that they align at an angle of 90 degrees. Since the MUSE data was almost at a right angle, I only had to rotate it by 3.1 degrees. The SINFONI data set on the other hand was shifted further. I rotated the SINFONI maps by 15.5 degrees. The easiest way. I found, to do this was to use the `JamPy` (Jeans Anisotropic Modelling for Galactic Dynamics) package from [Cappellari \(2020\)](#). Within this package one can find the `rotate_points()`-function in the `jam_axi_proj` procedure. The function is a simple code to rotate the coordinates `x` and `y` by an input angle counter-clockwise. I therefore only had to specify the `x` and `y` coordinates as well as the preferred rotation angle of e.g. 3.1 degrees for MUSE. The output is a new set of coordinates for `x` and `y`, which I can implement for all MUSE maps. The same applies for SINFONI, only rotating by 15.5 degrees. Once, I completed this task for all kinematic maps (the velocity map, velocity dispersion map, the `h3`-map and the `h4`-map of both MUSE and SINFONI), I attempted to extract rotation curves, velocity dispersion profiles, and Gauss-Hermite profiles, to visualize how well the data sets match.

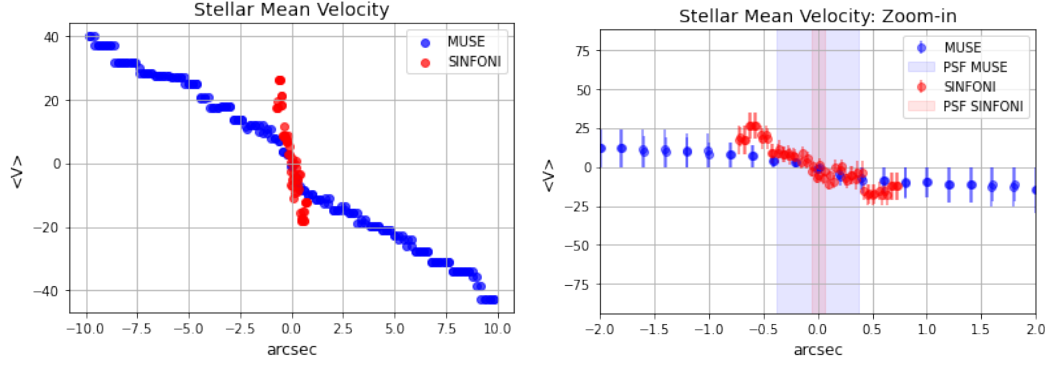


Figure 4.14.: Left: Scatterplot of the MUSE (blue) and SINFONI (red) data sets for the stellar mean velocity for the complete range of the slit. Right: Zoom-in of the scatterplot including the errorbars for SINFONI with a limited x-range of -2 to +2 arcseconds including the errors for both data sets. The transparent red area visualizes the FWHM PSF range of SINFONI (0.12") and the blue transparent area indicates the range of the FWHM PSF of MUSE (0.8").

I cut out a slit along the major axis along the vertical zero line for both of the data sets. Hereby, limiting the MUSE x-range from -10 arcsec to +10 arcsec and the SINFONI x-range to -0.75 arcsec to +0.75 arcsec. For the y-range, I wanted to constrain the data to a very small unit, which would correspond to a limit equal the pixelscale of the data sets. Therefore, the y-range of MUSE was set to -0.2 to +0.2 arcsec and for SINFONI to -0.05 to +0.05 arcsec. The stellar mean velocity profiles are shown in Figure 4.14. Clearly, the two data sets mostly match very well with a few data points in the SINFONI data set with increased velocities around 1". Simultaneously, in the zoomed-in plot, I added errorbars for the SINFONI data to highlight that within the error the data points seem to align well nevertheless. However, these higher velocities in SINFONI might not be that much of an inaccuracy. Since, SINFONI observes with a much better spatial resolution, it is able to capture an increased mean velocity for example due to a nuclear star cluster. Additionally the MUSE data set is somewhat compressed in the central parts of the galaxy due to resolution effects. Correcting for this spread therefore is unfavourable. The spatial resolution of both instruments is depicted through their PSFs in the plot. The FWHM (Full Width Half Maximum) PSF of MUSE is 0.756" ($\approx 0.8''$) (Sarzi et al. (2018)) which is the span from one blue dashed line to the other blue dashed line. SINFONI has a much finer FWHM PSF of 0.12" (Lyubenova and Tsatsi (2019)) spanning from one red dashed line to the other.

The same applies to the Velocity Dispersion profile in Figure 4.15. Here, the SINFONI velocity dispersion also shows higher velocities in the center compared to MUSE. Again, given by the higher spatial resolution which is evident.

In the h3-profile a slight mismatch is visible. When comparing the average values for the two maps, I found that the MUSE map in the central part of the galaxy has a median of 0.0 and the SINFONI map an median value of 0.003. To correct for this, I shifted the

4. Data Preparation and Analysis

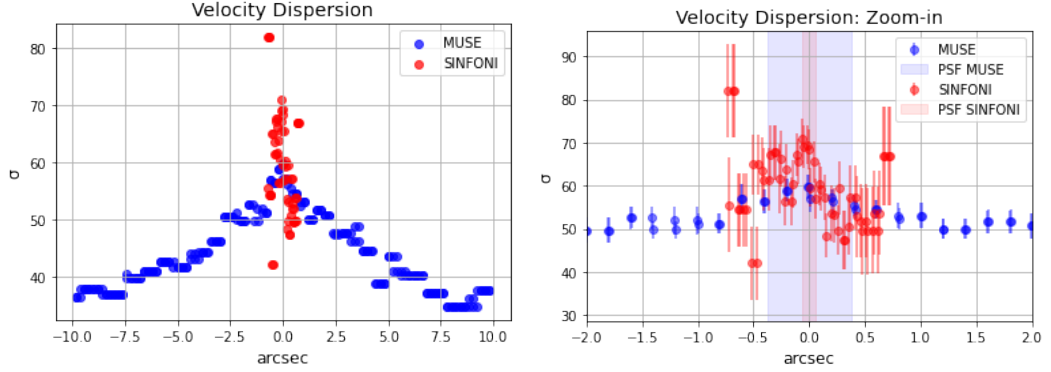


Figure 4.15.: Left: Scatterplot of the MUSE (blue) and SINFONI (red) data sets for the velocity dispersion for the complete range of the slit. Right: Zoom-in of the scatterplot with a x-range of -2 to +2 arcseconds including the errors for both data sets. Again the transparent red area visualizes the FWHM PSF range of SINFONI (0.12'') and the blue transparent area indicates the range of the FWHM PSF of MUSE (0.8'').

SINFONI data points by -0.003, aligning both data sets at the zero-line as seen in the Zoom-In of Figure 4.16. We want the median of the h_3 data to be at 0 as we expect a map with clear distinction between a red and blue side similar to the mean velocity map. Aligning the data sets at 0 facilitates DYNAMITE to model the data well.

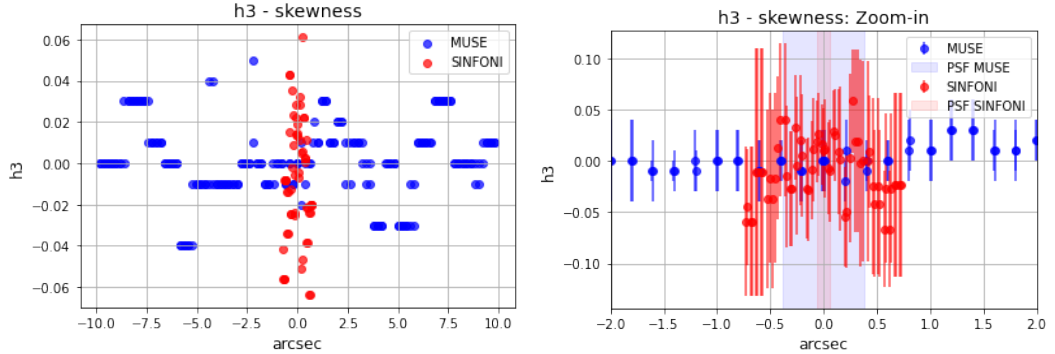


Figure 4.16.: Left: Scatterplot of the MUSE (blue) and SINFONI (red) data sets of the h_3 moment for the complete range. Right: Zoom-in of the scatterplot with a x-range of -2 to +2 arcseconds including the errors for both data sets and the corresponding PSFs in the shaded areas. The SINFONI data points were shifted down by 0.003 to compensate for the misalignment of the two data sets.

Lastly, the h_4 -profiles are shown in Figure 4.17. These appear to have a subtle misalignment as well, causing me to also check the h_4 values for the maps. For this profile,

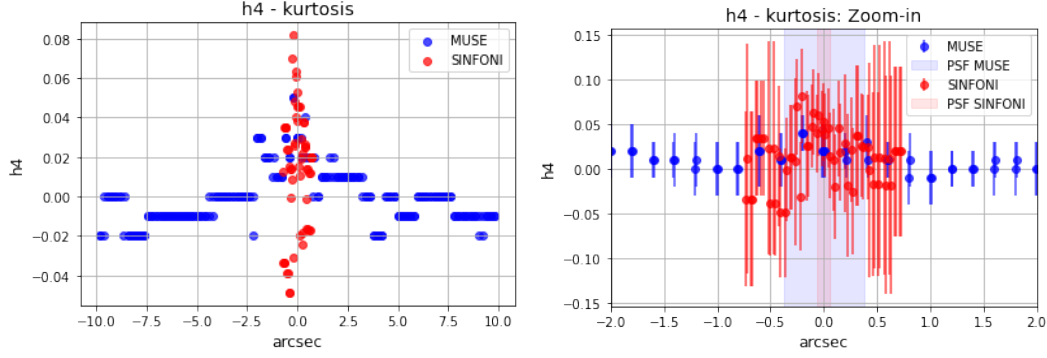


Figure 4.17.: Left: Scatterplot of the MUSE (blue) and SINFONI (red) data sets of the H4 moment for the complete range. Right: Zoom-in of the scatterplot with a x-range of -2 to +2 arcseconds including the errors for both data sets and the corresponding PSFs in the shaded areas. The MUSE data points were shifted down by 0.01 to compensate for the misalignment of the two data sets.

I only inspect the maps by eye. Comparing the FoV maps with the same colorbar limits, I noticed that a by -0.01 shifted MUSE data set aligns best with the SINFONI colormap. Therefore the final h_4 of MUSE is lowered by -0.01 before running the dynamical models.

Ultimately, the data preparation and analysis is concluded. The data sets are centered, checked for their kinematic PA to further inspect if they match and aligned if any mismatch is detected. I can therefore apply the dynamical modelling to the data.

5. The Vienna Scientific Cluster (VSC) and DYNAMITE configuration

In this chapter I want to shortly introduce the supercomputer, I execute my calculations on and expand on the configurations I did before running the DYNAMITE models. The dynamical modelling code requires the MGE and kinematics input as mentioned in Chapter 4 in specific files, but also an essential configuration file. In this file, one sets all the parameters being fitted and defines the orbit library as well as some other settings, such as the weight solver. Additionally, a python script is needed to in fact run the models and specify the plotting routine. Lastly, I prepared a small jobscript for the VSC, which simply demands the models to be executed next in line, ensuring the best computational performance for the supercomputer.

5.1. The VSC

The VSC, short for Vienna Scientific Cluster¹ is a supercomputer, set up in collaboration with various Austrian Universities, like the University of Vienna, the Technical University of Vienna, The University of Innsbruck and many more. It is a high performing computer established to run calculations that demand high computational power for chosen academic projects only. I specifically have been permitted access to the latest system of the VSC, the VSC-5, installed in 2022 at the Arsenal in Vienna. It consists of more than 1500 processors and over 98500 cores, which is more than double of its predecessor, the VSC-4. VSC-5's collective peak computational performance lies at 4.30 PFlops, Peta-Floating-point operations per second. For comparison the performance for a fairly powerful conventional processor lies at just a dozen Giga-Flops. My supervisor Sabine, took care of the access request and set up an account for me to run my models. Despite the fact that the VSC is a high performing supercomputer, my calculations typically ran for approximately two to four days, highlighting how computationally expensive dynamical galaxy models can be.

5.2. DYNAMITE configuration

Other than preparing the MGE and kinematic data for the DYNAMITE runs, I also had to create input data sets for it to be used correctly by DYNAMITE. Within the package, a data preparation script is provided. Through the `generate_kin_input.py` code, I was able to save the kinematic data into a file format that DYNAMITE can use. The necessary

¹Information on VSC-5: <https://vsc.ac.at//systems/vsc-5/>

data format is an csv file. How this needs to be done is well described on the DYNAMITE webpage². For the MGE data the final values for Intensity, sigma, q and PA twist can simply be copied and saved into a csv file. While generating the needed kinematic input files, I had to make sure that the necessary data is read in correctly into the script and that the uncertainties for the MUSE data in the most inner region (within a radius of 1") of the galaxy is increased, so that the SINFONI data can be accounted for properly in this region. Later, when the input csv files are produced, it is very crucial to check the file and add or correct for the sigma PSF and its weight as it can notably alter the quality of the model outputs. Additionally, I had to add another line to the header of the kinematic files, namely "# meta: !!omap". This rectifies an error, with which DYNAMITE is not able to continue its calculations. Moreover, the `generate_kin_input.py` script also generates 2 additional files: `bins.dat` and `aperture.dat`, which as the names suggests contain details regarding the bins and the spatial apertures for kinematic extraction. As soon as the input files are produced, I can continue with the true configuration file, which tells DYNAMITE which parameters to model, which values these should have and more on how large of an orbit library to use as well as some other specifications.

The configuration file, usually a .yaml file, firstly contains a section, where the physical system needs to be defined. This includes general system attributes like the name, distance and position angle of the object and thereafter, the system components. Thus the black hole mass, the dark matter fraction and the shape parameters. Here, the script requires various settings for each of those parameters, such as a lower limit, an higher limit, an expected value, a step size and an minimum step size, if the parameters value should be fixed or not and a few more. These component settings are highly depend on the system of course and need to be re-evaluated after the first couple runs. Furthermore, the input files for the MGE and the kinematics need to be defined, while 2 sets are used for the kinematics, one for MUSE and the other for SINFONI. And lastly, some specifics on the M/L are asked for. In the second section, I am requested to specify settings for the orbit library, the weight solver and the parameter space as well as some details on the directory paths for the input and output files. Such a example configuration file is listed in the Appendix A.

Ultimately, I can run the final script, in which the modelling is executed. Within this python code, I need to specify the name of the correct configuration file and run the models as well as set up the plotting routine and print the best fit results. When all the files are ready to be executed, I only need to generate a simple jobscript for DYNAMITE to run the mentioned python script and create a text file to save all the outputs in. The jobscript³ is mainly relevant for the requested job to be run next in line and not executed immediately while too many other calculations might be ongoing on the supercomputer. This system of submitting jobs to queues increases the run time quality and ensures a smooth execution.

²https://dynamics.univie.ac.at/dynamite_docs/tutorial_notebooks/1_data_prep_for_gauss_hermite.html

³<https://wiki.vsc.ac.at/doku.php?id=doku:slurm>

6. Results

In this chapter, I want to present the findings from my comprehensive analysis of black hole measurements, highlighting key observations and interpretations. By applying advanced dynamical modeling techniques and leveraging data from state-of-the-art instruments, I have derived significant insights into the mass and characteristics of the supermassive black hole at the center of FCC 148.

6.1. Kinematic maps

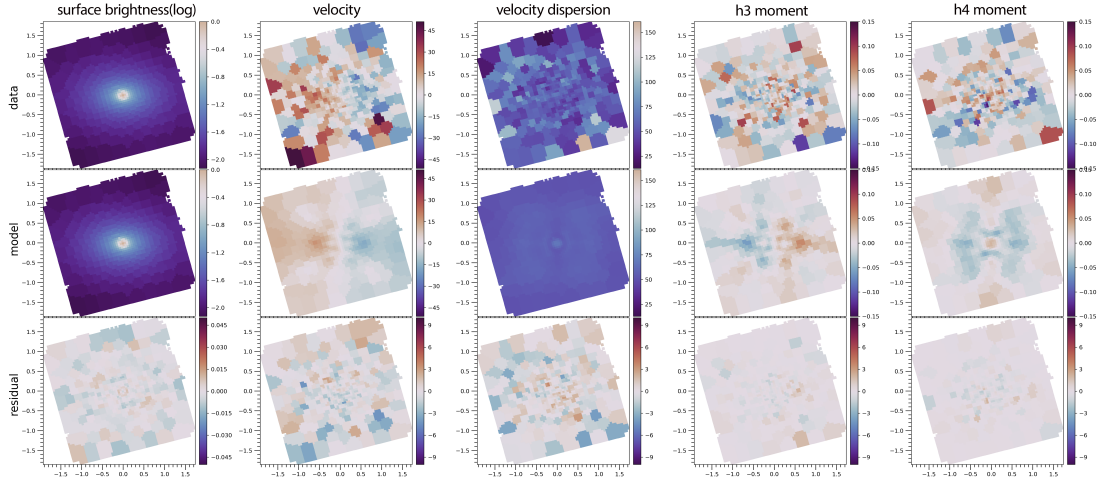


Figure 6.1.: Kinematic map of SINFONI data: The first row shows the kinematic maps of the data of surface brightness in $[mag/arcsec^2]$, stellar mean velocity, velocity dispersion both in $[km/s]$ and the higher moments h3 and h4. The second row correspondingly consists of the maps of the fitted model and the last row shows the residuals for each of the moments.

After a few difficulties with the MGE input and the numerous attempts of running and re-running models, I obtained satisfactory results for the black hole mass measurement and additional characteristics of FCC 148. Firstly, I want to highlight the precision of the dynamical models, reproducing the input data of both photometric and kinematic nature. In Figure 6.1 I present the fitted kinematic maps of the SINFONI data incorporating the surface brightness fit in the first column. The first row consists of all maps from the input data, the second is the corresponding fitted model and the third row shows the

residuals of each map. At first glance, one clearly notices that for all of the maps, the residuals are very small. These are calculated as follows:

$$\text{residual} = \frac{\text{model} - \text{data}}{\text{uncertainties}} \quad (6.1)$$

For most of the bins evidently the residuals are very close to zero, meaning that the model is able to reproduce the data very accurately. This is a significant accomplishment, considering the fact that the most inner part of the galaxy, thus the most relevant for black hole measurement can be fitted so precisely.

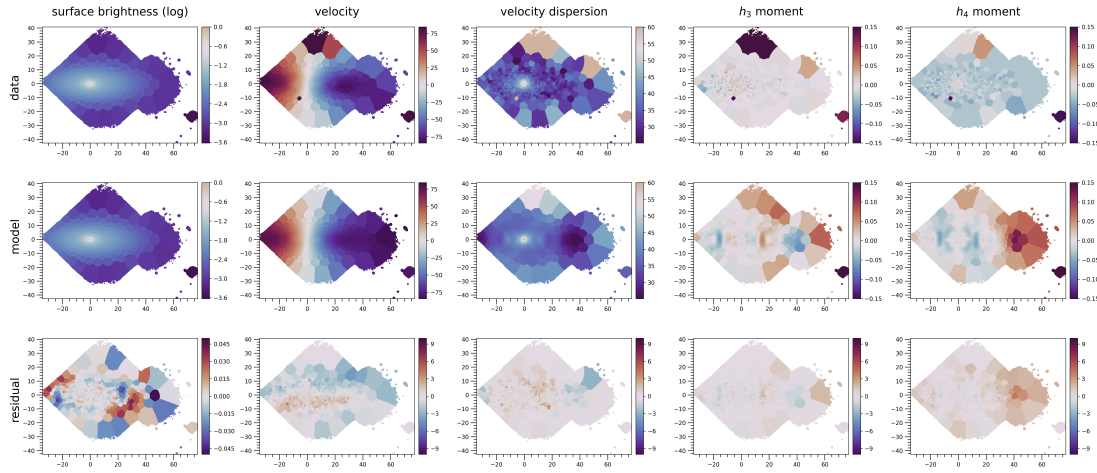


Figure 6.2.: Kinematic map of MUSE data: The first row shows the kinematic maps of the data of surface brightness in $[mag/arcsec^2]$, stellar mean velocity, velocity dispersion both in $[km/s]$ and the higher moments h_3 and h_4 . The second row correspondingly consists of the maps of the fitted model and the last row shows the residuals for each of the moments.

The same kinematic maps for MUSE data are visualized in Figure 6.2. Again showing the data in the first row, the model in the second row and the residuals in the last. Likewise, the model reproduce the data very well, resulting in very small, near zero residuals. Only the surface brightness residuals show slightly higher values compared to the other maps, especially at larger radii. This is however very likely due to the fact that the MGE of the surface brightness is not well-fitted in the outer regions of the galaxy.

Nonetheless, the kinematic maps in general show satisfactory results with residuals very close to zero. I therefore expect qualitative results for my black hole mass measurement.

6.2. Best fit solutions

In this section I want to discuss the values the best fit model produced for all parameters in question. These parameters are generated using the "LegacyGridSearch" parameter

6. Results

space subclass. This parameter generator is designed to only search for models that are reasonable, which lie within a specified threshold with $|\chi^2 - \chi_{min}^2|$. A corresponding χ^2 -plot is found in Figure 6.3. This shows the values of the model parameters for the grid of models I ran. The points are coloured by this relative goodness of fit metric. The fit values are marked with a cross and are colored in yellow. The poorer the fit gets, the darker/bluer the color of the data point.

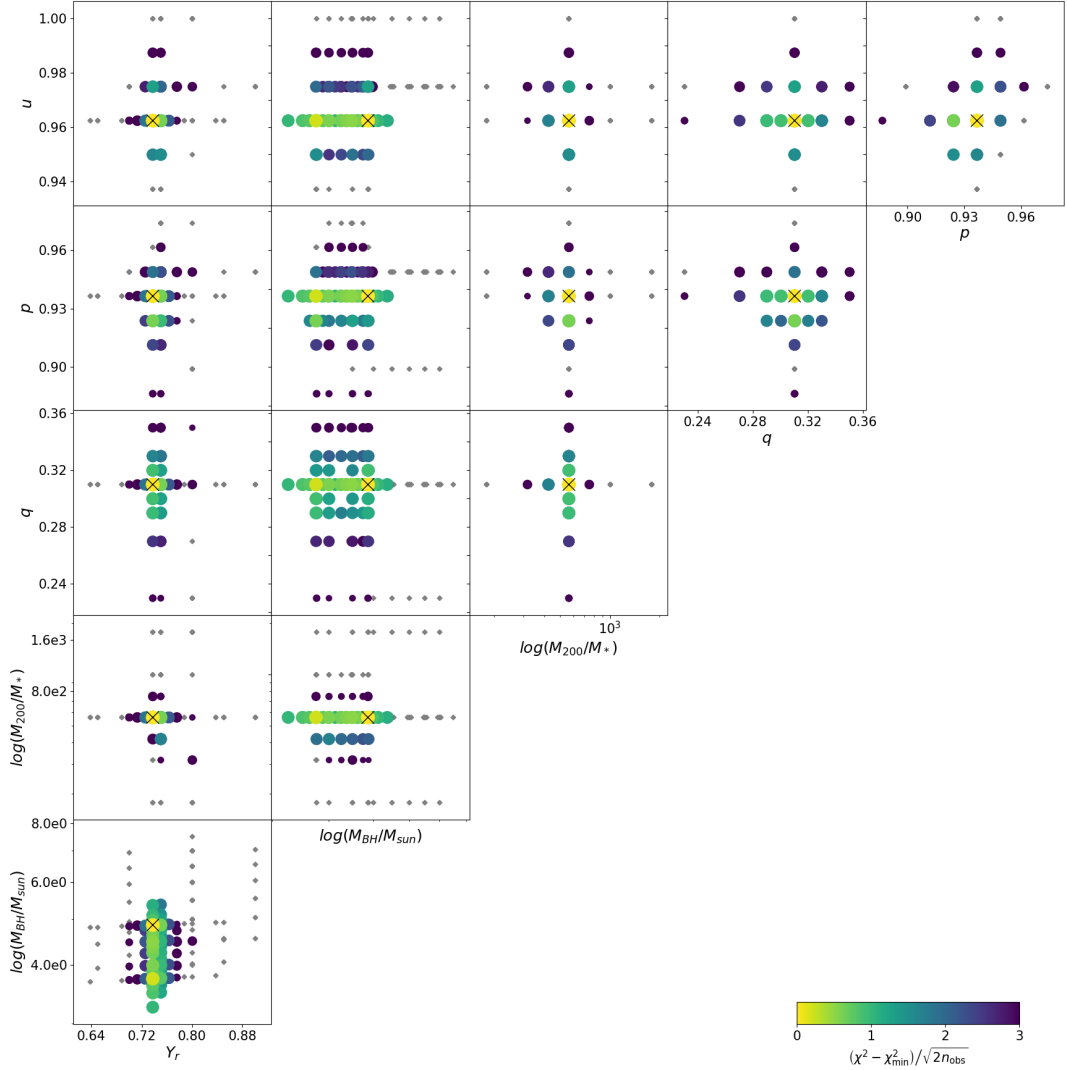


Figure 6.3.: χ^2 -plot of the parameter space generated through the LegacyGridSearch. The yellow points represent the best quality model fits, continuously evolving into poorer fits the bluer the color gets. The cross marks the best fit values in every grid.

6.2.1. Shape parameters

The parameters, p , q and u , the intrinsic shape parameters, describe the three dimensional shape of the galaxy. p is the ratio between the semi-axes B/A . q describes the ratio between the semi-axes C/A , also called intrinsic flattening. The following applies for the semi-axes: $A > B > C$. Lastly, u is a parameter used to describe the ratio between the observed sigma and the intrinsic sigma of the MGE Gaussians, known as scalelength projection compression factor as stated by [van den Bosch et al. \(2008\)](#).

The best fit model obtains the following results for the intrinsic shape parameters with 3σ confidence intervals listed in Table 6.1.

$$\begin{aligned} q &= 0.31^{+0.04}_{-0.08} \\ p &= 0.937^{+0.025}_{-0.05} \\ u &= 0.9624^{+0.025}_{-0.0125} \end{aligned}$$

Table 6.1.: Best fit results for the shape parameters p , q and u including their uncertainties.

Since p is nearly unity and stays constant at all radii as seen in Figure 6.4, FCC 148 can be considered a fairly axisymmetric galaxy. This is also evident from the kinematic maps. The stellar mean velocity map shows a clear red shifted and blue shifted side in the galaxy. The intrinsic flattening q is rather small, which means that the galaxy is fairly flat based on the respective axis ratio. The parameter u is not necessarily connected to the shape of the galaxy itself but is more dependent on the inclination of the galaxy. Since u for my case is very close to unity, the observed standard deviation of the MGE-Gaussians is fairly similar to the deprojected Gaussian standard deviation, indicating a small difference between the observed and deprojected structure. In Figure 6.4 the axis ratios are plotted against the radius of the galaxy. In blue, p is very consistent at all radii and remains very close to 1 as mentioned before. The black line on the other hand, which represents q along different radii, is larger in the central region of the galaxy and slowly declines in the outskirts. The triaxiality parameter T in black is, as the name suggests, a measure for the triaxiality of the galaxy calculated as follows:

$$T = (1 - p^2)/(1 - q^2) \quad (6.2)$$

For FCC 148, as mentioned earlier, the shape is not triaxial. The low value of T suggests a axisymmetric galaxy shape, which is furthermore valid for all radii shown in Figure 6.4.

6.2.2. Mass-to-Light ratio

A very important parameter, obtained through the dynamical model is the M/L ratio. It is certainly one of the most if not most critical parameter to measure an accurate black hole mass. A proper stellar mass distribution of the galaxy can only be inferred through a reliable M/L , which is relevant for understanding the influence a black hole has on the observed stellar population. If the M/L ratio is for example underestimated, the inferred

6. Results

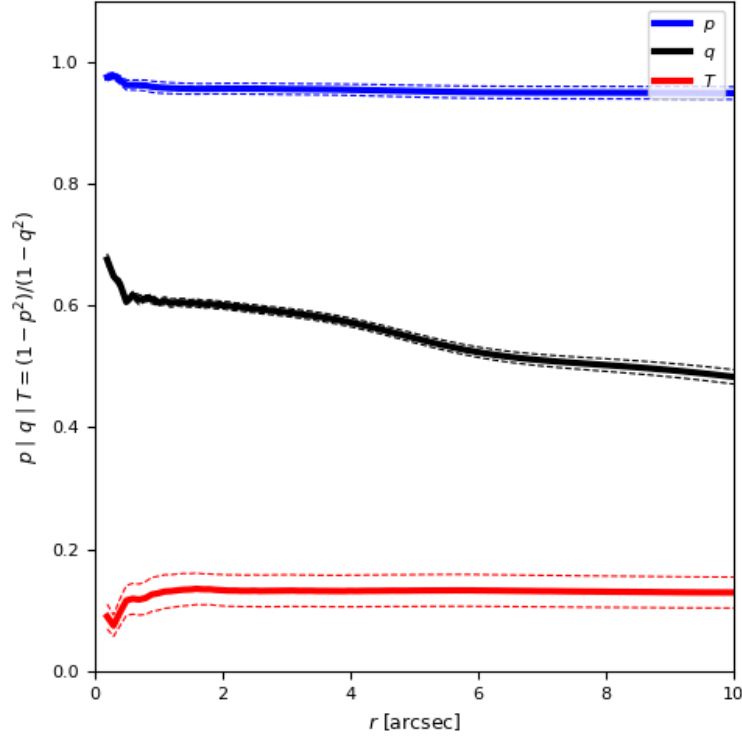


Figure 6.4.: This plot shows the axis ratios p (blue) and q (black) as functions of the radius of the galaxy including their errors in dashed lines. Additionally, the triaxiality parameter defined on the y-axis, is plotted in red.

BH mass and DM halo may become biased. In the prior configuration the M/L ratio can be adapted and even fixed if a valid value is known beforehand. In my case [Iodice et al. \(2019b\)](#) state a M/L ratio of 0.83 for FCC 148. This was used as an initial estimate in my calculations, repeatedly corrected to a value that best fit the data after each run. Ultimately, the Schwarzschild models were able to constrain the M/L ratio of FCC 148 to:

$$M/L = 0.7375^{+0.0625}_{-0.0375}$$

The result is also found in the lowest panel of Figure 6.3, where the M/L or γ_r is very tightly constrained to said value.

6.2.3. Dark Matter Contribution

In Figure 6.5 I show the enclosed mass profile for FCC 148 along different radii up until 10 arcseconds. The total mass in black contains about $10^9 M_\odot$, including the mass inferred from the M/L ratio and the dark matter contribution, which increases at larger radii. As mentioned in the last section, the total mass of the galaxy is composed of the

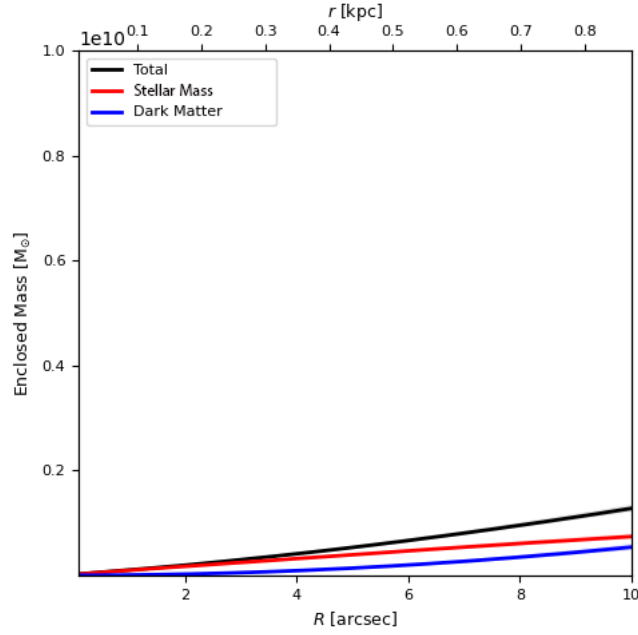


Figure 6.5.: In black the total enclosed mass of FCC 148 at a radius up until 10 arcsec or 0.9 kpc is plotted. The red line represents the stellar mass in the galaxy and the blue line the dark matter contribution.

baryonic mass and the dark matter. While an accurate dark matter measurement is fairly uncertain, as the models are not able to fit the outskirts of the galaxy very well, an estimation for the dark matter contribution in FCC 148 was still calculated. The best fit model assesses a dark matter contribution of:

$$M_{200}/M_* = 562.34^{+187.55}_{-246.11}$$

6.2.4. Black Hole Mass

Most importantly, my models were able to constrain a black hole mass, or at least provide an upper limit. As seen in Figure 6.3 the second column of the plot depicts the model results for the black hole mass. It is very evident that even though a best fit result is found for the central black hole mass, marked with a cross, a lot of models with a lower mass constraint seem to be a good estimate as well, as seen in the spread of the data points. The best fit model constrains the upper mass limit for the central black hole in FCC 148 to:

$$M_{BH} = 74989.42^{+162147.95}_{-73211.14} M_{\odot}$$

The models therefore suggest the possible black hole to be a fairly low-mass black hole with only $\sim 0.7 \cdot 10^5 M_{\odot}$. While formally we find 3-sigma confidence intervals on both

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sides of the best fit BH mass, the limited number of models at low BH masses, makes this something to be investigated further.

7. Discussion

In this chapter, I want to discuss what implications the results of the stellar dynamical model could have on the connection of the central black hole with the NSC in FCC 148, as well as some insights they might give in terms of the formation scenario. I will further compare my results to recent literature and conclude with some improvements that need to be implemented in the future. These conclusions not only validate existing theories but also contribute to a deeper understanding of black hole dynamics within galaxies. Additionally, this work paves the way for future research in astrophysics, offering new perspectives on the fundamental nature of black holes and their role in galactic evolution.

7.1. Comparison to literature

Even though my target galaxy FCC 148, has been included in various papers from the Fornax3D Cluster survey, a black hole mass measurement has not been carried out yet. Indeed, it is not even known if this galaxy hosts a black hole at all. Therefore, it is very exciting to present the first estimate of a possible black hole mass in this galaxy. As, I have no results in the literature I can compare my calculations with, the focus will be on comparing the parameters from my dynamical models of the galaxy that have been constrained in the past.

One such set of parameters, the true intrinsic shape of FCC 148 has not been studied so far except by [Ding et al. \(2023\)](#), who do not further mention their results in their publication. Older surface photometry surveys suggest a value for an axis ratio q of about 0.4 ([Lauberts and Valentijn \(1989\)](#)). While this is a projected axis ratio, not a true axis ratio such as returned by my dynamical model, its value is slightly larger than the value I have constrained, which sets q to around 0.31. Given the deprojection angles (e.g. inclination) the slightly larger value for the projected axis ratio reported in the literature would be expected for an intrinsic axis ratio of 0.3.

As mentioned earlier, [Iodice et al. \(2019b\)](#) constrain the M/L ratio for FCC 148 to a value of 0.83, however derived not via dynamical models but based on the $g - i$ colour of the galaxy and therefore is different to the Schwarzschild models of this work, which suggest a lower M/L of about 0.74. Regarding the dark matter fraction [Ding et al. \(2023\)](#) obtained a value of 0.47 ± 0.03 . My calculations suggest a dark matter fraction (see Figure 6.5) of M_{DM}/M_{tot} to be at roughly 0.45. My findings therefore are very close to the results of [Ding et al. \(2023\)](#).

Other than the direct comparisons in literature for FCC 148 specifically, it is also sensible to investigate similarities with other galaxies hosting low mass black holes. One

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very obvious target galaxy is our own. The Milky Way as mentioned earlier hosts a SMBH of around $4 \cdot 10^6 M_\odot$, making it a comparable object. The NSC however in the Milky Way is less massive with an approximate mass of only $10^6 M_\odot$ (Genzel et al. (2010)), a possible indication that the NSC might have transferred its mass to fuel the central black hole. Furthermore, NGC 7469 another spiral galaxy like the Milky Way, also hosts a relatively less massive black hole with around $12.2 \cdot 10^6 M_\odot$ (Peterson et al. (2004)) or as the recent measurements of Nguyen et al. (2021) suggest, a mass of about $1.8 \cdot 10^7 M_\odot$. However both those galaxies have stellar masses larger than FCC 148 of around $\log(M_*/M_\odot) \sim 10.8$ (Licquia and Newman (2015); Samantaray et al. (2024)). A more comparable stellar mass galaxy is the Fornax Cluster galaxy FCC 47, with a M_* of about $9 \cdot 10^9 M_\odot$ (Liu et al. (2019)). FCC 47 also hosts a SMBH of comparable mass, namely of approximately $4 \cdot 10^7 M_\odot$ (Ding et al. (2023)). Furthermore, the galaxy hosts a very massive NSC of about $10^{8.74} M_\odot$ similar to FCC 148 with $10^{8.37} M_\odot$ (Fahrion et al. (2021)) and is unlike the other aforementioned galaxies also a early-type galaxy of type S0 like FCC 148. With its slightly larger stellar mass of ca. $10^{10} M_\odot$ it falls into the more massive range in the scaling relations, but is a perfect object for comparison, as it also is a part of the same cluster and might have evolved in a very similar way as FCC 148, considering the fact that it shows numerous similarities.

7.2. Black hole scaling relations

7.2.1. $M_\bullet - \sigma$ relation

The upper limit I obtain for the central black hole in FCC 148, indicates a fairly low mass SMBH. With a central velocity dispersion of about 60 km/s as mentioned in Chapter 4 inferred from the MUSE kinematic maps, which is also consistent with the SINFONI peak velocity dispersion. I can include my findings to the $M_\bullet - \sigma$ scaling relation. In Figure 7.1 I use the sample from van den Bosch (2016), where they include measurements of various nearby galaxies discussed in Chapter 1 and included my black hole mass measurement in red. As my mass estimate may be an upper limit I show it on the plot as an arrow. If I were to run more models and find that the lower confidence interval is robust and unchanged, I can include it in the literature sample to see if the slope of the scaling relation changes significantly given its extreme values. Fitting including FCC 148 with the preliminary 3-sigma confidence intervals, I find the slope only changes from 5.45 to 5.55.

7.2.2. $M_\bullet - M_{bulge}$ relation

Similarly, I have investigated the position of the resulting black hole mass upper limit for the $M_\bullet - M_{bulge}$ scaling relation. In Figure 7.2 I once more use the sample from van den Bosch (2016) of only galaxies with a bulge mass measurement. As I do not further study the bulge mass of FCC 148 in this work, I have used a minimum estimate of $10^{8.4} M_\odot$ for the bulge mass as the bulge must incorporate the NSC and Fahrion et al. (2021) state a NSC mass of $10^{8.37}$. In this sparsely populated sample FCC 148 falls into the very low

7.3. Interpretation of the resulting black hole mass measurement

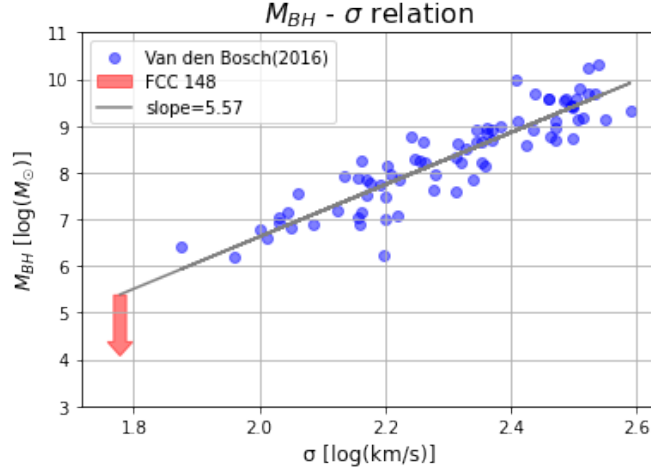


Figure 7.1.: The $M_{\bullet} - \sigma$ relation using the sample from [van den Bosch \(2016\)](#) (blue). In red I have added my measurement of the black hole mass in FCC 148. The grey line represents the accommodated slope for the scaling relation when including FCC 148.

mass end of both bulge mass and black hole mass. While the upper limit is offset by about 0.6 dex from the calculated relation, the measurement is still in agreement when comparing the scatter of the other galaxy data points. Additionally, the slope is perfectly consistent with the value of 1.1 mentioned in the introduction. FCC 148 does not seem to scatter too far from the relation but with a relatively low black hole mass and a low mass bulge it is fairly isolated from the expected relation. A comparatively low position in the relation does make sense as the NSC embedded in the bulge is extremely massive compared to the black hole.

7.3. Interpretation of the resulting black hole mass measurement

7.3.1. Connection to the NSC mass and formation scenarios

As there are no results in the literature I can compare the BH mass measurement to I will rather focus on how the calculated black hole mass might correlate to the recently obtained mass measurement for the NSC in FCC 148 and the resulting formation scenario the mass measurements suggests. [Fahrion et al. \(2021\)](#) constrain a NSC mass of about $10^{8.37} M_{\odot}$. FCC 148 therefore hosts a very high mass NSC. Comparing this to my black hole mass of $\sim 10^5 M_{\odot}$ the NSC is a factor of 10^3 times more massive than its embedded black hole. Having obtained the ratio of black hole mass to NSC mass for FCC 148, I can add to the study of [Neumayer et al. \(2020\)](#) and include FCC 148 on the scaling relation of M_{BH}/M_{NSC} vs. M_{*} mentioned in Chapter 1. For the stellar mass of the galaxy I use

7. Discussion

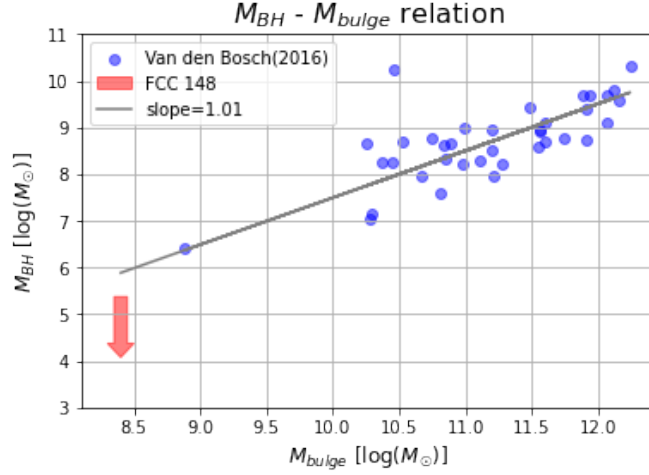


Figure 7.2.: The $M_{\bullet} - M_{bulge}$ relation using the sample from [van den Bosch \(2016\)](#) (blue). In red I have added my measurement of the black hole mass in FCC 148 using the approximate bulge mass of around $10^{8.4}$. The grey line represents the accommodated slope for the scaling relation when including FCC 148.

an estimate of $10^9 M_{\odot}$ as constrained from the models in this work. The additional data point is included in Figure 7.3. FCC 148 seems to be on the extreme end of the sample considering the calculated black hole mass upper limit. With a relatively low stellar mass and a massive NSC, the galaxy occupies the bottom left corner of the plot and is one of the more extreme galaxies in this parameter space, however still consistent with the observed scatter.

As also mentioned in Chapter 1, there is believed to be a transition between the two possible NSC formation scenarios at an approximate galaxy mass of 10^9 solar masses, where FCC 148 falls right into. In that sense GC in-spiral and in-situ star formation can both be expected to have built up the NSC in FCC 148. [Fahrion et al. \(2021\)](#) do not only study the NSC masses of various galaxies in the Fornax and Virgo Cluster but also uncover the metallicities and thus the age of the nuclear stellar populations. For FCC 148 specifically, they suggest that in-situ star formation in the nuclear star cluster is the dominant scenario, as the nucleus essentially hosts a very young stellar population compared to the entire host galaxy. Additional evidence for in-situ formation of the NSC in FCC 148 was found in [Fahrion et al. \(2022\)](#), where they analyze the link between NSC masses and the present GC system in the galaxy to infer whether a GC infall formation scenario is more plausible or if the NSC masses are better explained by in-situ formation. Those authors' model suggest this NSC should have had significant growth through in-situ star formation, as the number of GCs needed to in-spiral and merge to make up the mass would be extremely large. This conclusion is also in agreement with the independent estimates of strong in-situ contributions based on the SFH of the NSC relative to the host galaxy ([Fahrion et al. \(2021\)](#)). Despite the evidence for significant in-situ star formation

7.3. Interpretation of the resulting black hole mass measurement

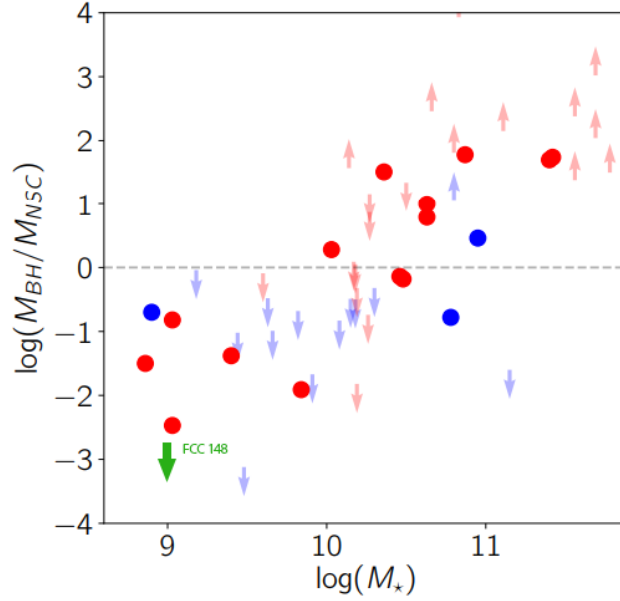


Figure 7.3.: Data point of my FCC 148 black hole upper limit compared to the NSC mass and the galaxies stellar mass added to the study performed by [Neumayer et al. \(2020\)](#).

in the massive NSC of FCC 148, it appears that the BH mass growth was not exceptional, as the BH mass limit is rather modest ($\sim 10^5 M_\odot$). Other processes therefore might have stopped the BH to grow further.

7.3.2. Environmental Processes

As mentioned before, FCC 148 is part of the Fornax galaxy cluster with a total virial mass of $7 \cdot 10^{13} M_\odot$ ([Iodice et al. \(2019a\)](#)). Therefore, the question arises if and how the cluster environment might have influenced the evolution of FCC 148, especially in terms of it being an extreme object in the scaling relations. As a galaxy falls into a cluster it is exposed to a lot of interactions with other galaxies and is subjected to gravitational interactions from the total cluster potential. Such a low SMBH mass and comparatively massive NSC as observed for FCC 148 might therefore be the result of the infall process into the Fornax Cluster ([Iodice et al. \(2019a\)](#)). Tidal interactions between galaxies can tremendously alter the galaxies' morphology and SFRs ([Park and Hwang \(2009\)](#)). Ram pressure and tidal stripping for example can remove the gas of a galaxy, remove stars in the outskirts and alter the morphology to the point that it can even turn a late type galaxy into an early-type. When comparing similar central black hole masses of other galaxies that host low mass SMBHs, a striking amount seem to be spiral galaxies. For these LTGs the central black hole likely is still able to be fueled and further grow. It is therefore possible that FCC 148 initially entered the cluster as a late-type galaxy and

7. Discussion

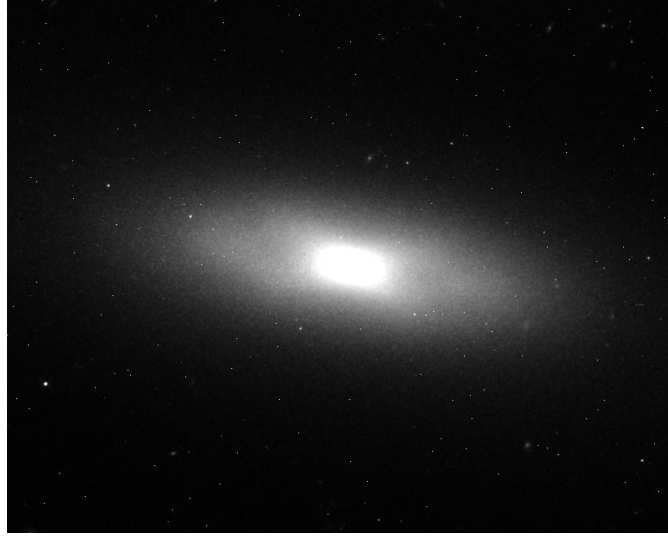


Figure 7.4.: This image of FCC 148 shows a slight X-shaped structure in the inner parts of the galaxy.

through tidal interactions with other more massive galaxies was stripped of its gaseous resources, making it a lenticular galaxy. Such a scenario might also result in the total stellar mass of the galaxy being reduced over time as tidal stripping slowly removes stars from the outskirts leaving the nucleus and BH unaltered. This might explain an overly large NSC mass, but doesn't immediately suggest why the NSC is so much more massive than the implied BH mass in this study. Arguments against strong environmental processing of FCC 148 are that it still shows a blue nucleus and is therefore thought to have fallen into the cluster rather recently, thus less than 4 Gyrs ago ([Ding et al. \(2023\)](#)). Furthermore, while it is currently in close proximity to its neighbour galaxy FCC 147 those two galaxies do not seem to show signs of interactions, which is consistent with the fact that FCC 147 shows signs of being an ancient infaller ([Iodice et al. \(2019a\)](#)) and hence have not likely had a significant amount of time being close to each other in the cluster. Nevertheless, there are still some possible signatures of interactions affecting the morphology of FCC 148, which for example shows a somewhat X-shaped structure in the inner regions as seen in Figure 7.4. Even though, this strange shape has not been studied well yet, it is an interesting artifact of possible changes in the structure of the galaxy, stemming from environmental interactions and is a compelling subject to be investigated further.

Considering that FCC 148 could have undergone mass loss in its outskirts from tidal stripping, it is furthermore interesting how its position in the black hole scaling relations has changed compared to it not being tidally stripped. A possible scenario had the gas and stars not been removed from the galaxy is that through continuous fueling of the SMBH in the center and possible transition of mass from the NSC to the SMBH it could have grown more massive. This would push the data point for FCC 148 upwards towards

the slope making it more consistent with both scaling relations. This is because the host stellar mass would have remained larger in absence of tidal stripping and the M_{BH} growth could have continued with the gas reservoir of the galaxy remaining intact. The cluster environment, though limited in time, may therefore play a role in why it is an extreme object on several scaling relations.

Overall, I have obtained an upper mass limit for the possible black hole in FCC 148, which falls on to the very low mass end of SMBHs. My measurements are in agreement with the proposed formation scenarios of the NSC and the black hole in FCC 148. Despite it being a very extreme case in the scaling relations, it still follows the correlations appropriately but further investigations concerning additional environmental processes, which might have lead FCC 148 to host such an extraordinary nucleus need to be done. Such extreme objects provide the strongest constraints in interpreting the cause behind the scaling relations. This works results can therefore be considered profitable to the knowledge of black holes in the centers of galaxies and support the ongoing research of the formation and evolution of the galaxy nuclei.

7.4. Future Improvements

In general, the Schwarzschild models were able to provide satisfactory results as aforementioned and are enriching to the research field of galactic nuclei. Nevertheless, there is still some room for improvements to obtain a more accurate and reliable measurement, which I want to discuss in this last section.

7.4.1. Data Resolution

To enhance the data quality and therefore increase the accuracy of the dynamical models, it would be beneficial to use an improved MGE. The MGE utilized in this work does fit the surface brightness of FCC 148 very well in the central parts of the galaxy but the outskirts in the kinematic maps show high residuals, indicating that the MGE is not sufficient enough to model the galaxy's surface brightness at larger radii. New observations therefore with for example the James Webb Space Telescope using the imaging device NIRCcam with an impressive FoV of $9.7' \times 9.7'$ and a spatial resolution of about 0.1 arcseconds ([JWST User Documentation \(JDox\) \(2016\)](#)) would provide great improvements to the data set. Furthermore, together with an improved MGE more pointings in the outer regions of the galaxy with MUSE could not only enhance the flux map accuracy but also aid to model the kinematics better. Additionally, it might also be sensible to potentially use Globular Cluster kinematics observed with MUSE to further refine the kinematic maps at larger radii.

7.4.2. Symmetrization

Symmetrization has proved itself beneficial for galaxies with regular rotations. As mentioned in Chapter 4 FCC 148 shows signs of a regular and symmetric rotation pattern

7. Discussion

and no counter-rotating cores or additional anomalies and is therefore suited for such adaptations. Symmetrization is a process used to symmetrize the velocity maps along the major axis to simplify the determination of the zero velocity line, as done for the PA fitting discussed earlier. For future improvement, I want to perform a symmetrization of the kinematic stellar mean velocity map before the modeling procedure as it is extremely useful for low S/N data, which would be valuable for bins at larger radii in my case. This could help improve the residuals in some of the MUSE bins seen in Figure 6.2.

7.4.3. FullGrid parameter space

In Chapter 6 I mention the parameter space subclass with which the resulting parameters were generated in a grid. Besides the "LegacyGridSearch" I also want to additionally implement the "FullGrid" parameter search. This executes a full cartesian grid for all free parameters resulting in a much larger number of models ranging from 10 to up to 100 times more models than with the "LegacyGridSearch" depending on how many parameters are set to be free. Performing this parameter search generator, I hope to obtain model results for lower black hole masses as well and be able to not only constrain an upper limit for a possible black hole mass but also acquire a more robust black hole detection.

7.4.4. Varying M/L ratio along radii

Lastly, it would be beneficial to utilize a varying M/L ratio for the stellar dynamical modeling. Bear in mind that the M/L is assumed to be constant at all radii in this work, which is a rough assumption as stellar populations can change at different radii, also altering the M/L. Therefore, a radial M/L profile could improve an accurate calculation of the gravitational potential and the underlying mass distribution of the different components. This could be especially important to take into account in the case of FCC 148, given that its NSC has such a large mass ($>10\%$ of the total galaxy) and therefore has very different M/L to the entire host galaxy. Hence we might expect significant changes with radius (especially as the SFH variations show strong differences; [Fahrion et al. \(2021\)](#)). As [Thater et al. \(2023\)](#) find for the galaxy FCC 47, a constant mass to light ratio overestimates the black hole mass, which might be the case in this work as well. Furthermore, as the nucleus shows signs of a young stellar population while at larger radii the stellar population is observed to be old, it is important to revise the dynamical modelling using a varying M/L.

7.5. Conclusion

In this thesis, I have successfully measured an upper mass limit for the Supermassive black hole in the Fornax Cluster galaxy FCC 148, contributing valuable data to the field of extragalactic astronomy. By leveraging advanced observational techniques and robust data analysis, I not only estimated the black hole mass but also retrieved critical

properties of the host galaxy, including the dark matter contribution, mass-to-light ratio, and 3D structure of the galaxy.

The measurement of the black hole's upper mass limit is particularly significant as FCC 148 presents an extreme example of black hole masses as it occupies the very low mass range of the aforementioned scaling relations. Such extreme cases are crucial for testing the boundaries of current theoretical models of black hole as well as nuclear formation and growth. By identifying and studying galaxies with unusually massive or light black holes, we can refine our understanding of the underlying physical processes that govern their evolution, especially in connection with NSCs. FCC 148 provides a valuable case for exploring this relationship, as understanding the co-evolution of NSCs and SMBHs can offer significant insights into the hierarchical formation processes of galaxies. Notably, the mass-to-light ratio is another critical parameter I have derived, providing information on the distribution of luminous and non-luminous matter in the galaxy. Additionally, the quantification of the dark matter contribution within FCC 148 offers insights into the dark matter halo's structure and its influence on the overall mass distribution. Understanding the dark matter profile helps to shed light on the nature of dark matter itself and its role in galaxy formation and evolution. Furthermore, the shape parameters of FCC 148 have been meticulously analyzed, revealing the galaxy's morphological characteristics.

This work's findings represent a valuable addition to current research, particularly in the context of extreme black hole masses. This work not only enriches the existing database of black hole mass measurements but also provides a comprehensive set of galactic properties that can be used for comparative studies and can trace the interactions a galaxy might go through as falling into a cluster environment. Future research can build upon these results to explore the implications for galaxy evolution theories and the role of supermassive black holes in shaping their host galaxies.

In summary, this thesis highlights the importance of detailed observations and careful analysis in uncovering the complexities of galactic structures and their components. The extreme nature of the black hole in FCC 148 makes this research a notable contribution to the field, offering new perspectives and challenging existing paradigms in black hole and galaxy studies. Including the massive NSC within FCC 148 in this analysis further enhances our understanding of the mutual relationship between SMBHs and their surrounding in the nucleus, providing a more universal view of galactic evolution.

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A. Appendix

A.1. improved MGE

As mentioned earlier, my MGE's radial extent was not sufficient enough to obtain good models. Therefore, my supervisor offered to execute a MGE on a combination of 2 images, a HST WFPC2 image and an OmegaCAM image, which together cover a wider extent of the galaxy. The WFPC2, short for Wide Field and Planetary Camera 2, is an instrument on board of the HST and was constructed to have a field of view($36'' \times 36''$) to obtain full disk images of our planets as well as observe with a larger FoV($80'' \times 80''$) in one device (McMaster and et al. (2008)). The applied image was captured with the F814W Filter, which has its peak transmission at around $8000 \text{ \AA}$, thus the near infrared range. This image covers the essential parts of the galaxy and is the main input image. The second, more extended image is captured by OmegaCAM, the imaging device within the VLT Survey Telescope (Mieske et al. (2013)). It covers a FOV of a full $1^\circ \times 1^\circ$. Similar to the first image the VST image was also recorded using a infrared filter.

In the following Table A.1, I list the MGE output of my supervisor Sabine, which I eventually use as the input for the dynamical models:

$I'_j [L_\odot pc^{-2}]$	$\sigma'_j ["]$	q'_j
1040493.37	0.028	0.65
39473.72	0.113	0.65
12099.01	0.296	0.65
4115.79	0.679	0.65
1778.46	1.579	0.65
513.54	3.315	0.56
446.51	4.577	0.60
389.62	14.596	0.40
48.98	28.219	0.40
20.37	38.135	0.47
2.94	73.508	0.55
1.10	126.769	0.45

Table A.1.: Final conversion of the MGE output provided by my supervisor

I can further convert the σ values from arcseconds to parsec as listed in Table A.2, as explained in Chapter 4.

Finally, I can calculate the total luminosity of each Gaussian component as seen in

$\sigma'_j [pc]$
2.47
9.84
25.85
59.27
137.79
289.27
399.44
1273.72
2462.58
3327.89
6414.79
11062.69

Table A.2.: Sigma conversion to parsec

Table A.3 using the converted σ in parsec and sum up all Gaussian luminosities to obtain the total luminosity of the galaxy.

$L_j [L_\odot]$
$2.59 \cdot 10^7$
$1.56 \cdot 10^7$
$3.30 \cdot 10^7$
$5.91 \cdot 10^7$
$1.38 \cdot 10^8$
$1.52 \cdot 10^8$
$2.66 \cdot 10^8$
$1.59 \cdot 10^9$
$7.47 \cdot 10^8$
$6.72 \cdot 10^8$
$4.20 \cdot 10^8$
$3.82 \cdot 10^8$

Table A.3.: Total luminosity for each Gaussian component

The total luminosity for the galaxy L_{tot} essentially equals $4.50 \cdot 10^9 L_\odot$. Multiplying the result with the expected M/L-ratio for FCC148 of 0.83 (Iodice et al. (2019b)), as discussed in Chapter 4 one ends up with a stellar mass M_* of $3.74 \cdot 10^9 M_\odot$. Compared to the stellar mass of $5.8 \cdot 10^9 M_\odot$ from Iodice et al. (2019b) the calculated value is very similar and is only by a factor 1.55 smaller than in the literature. This MGE output is therefore much more appropriate to be used with DYNAMITE than my previous MGE.

A. Appendix

A.2. Modelling configuration

```
1 # Example yaml configuration file for the legacy implementation
2 # All relevant input is in one file with two sections: SYSTEM and
  SETTINGS
3
4 # Start of yaml document
5 ---
6 #
  #####
7 # SECTION 1 : SYSTEM
8 # Define the physical system (e.g. the galaxy, globular cluster etc being
  modelled)
9 #
  #####
10
11 system_attributes:
12   distMPc: 18
13   name: "FCC148"
14   position_angle: 86.9
15
16 system_components:
17
18   bh:
19     parameters:
20       m:
21         par_generator_settings:
22           lo: 0.0 #6.0
23           hi: 10.0
24           step: 0.5
25           minstep: 0.1 #
26           fixed: False #True #
27           value: 7.0 #expected value of bh_mass
28           logarithmic: True
29           LaTeX: "$\log(M_{\text{BH}}/M_{\text{sun}})$"
30         a:
31           fixed: True
32           value: 0.001
33           LaTeX: "$a_{\text{BH}}$"
34         type: "Plummer"
35         include: True
36         contributes_to_potential: True
37
38   dh:
39     parameters: #
40       f: # NFW dark-matter fraction M200/M*
41       par_generator_settings:
42         lo: -1.5
43         hi: 5 #3.5
44         step: 0.5
45         minstep: 0.1
```

```

46         logarithmic: True
47         fixed: False
48         value: 2.75 #3 # 2.45
49         LaTeX: "$\log(M_{200}/M_*)$"
50     type: NFW_m200_c
51     include: True
52     contributes_to_potential: True
53
54     stars:
55         parameters: # suggested by dynamite algorithm
56             q: # intrinsic flattening (C/A)
57                 par_generator_settings:
58                     lo: 0.01
59                     hi: 0.99 #0.40
60                     step: 0.08
61                     minstep: 0.01
62                     fixed: True #False
63                     value: 0.31 #0.18
64                     LaTeX: "$q$"
65             p: # intrinsic flattening (B/A)
66                 par_generator_settings:
67                     lo: 0.5 #0.01
68                     hi: 0.999
69                     step: 0.05 #0.20
70                     minstep: 0.01
71                     fixed: True #False
72                     value: 0.9365 #0.949 #0.63
73                     LaTeX: "$p$"
74             u: # sigma_obs / sigma_intrinsic
75                 par_generator_settings:
76                     lo: 0.8 #0.02
77                     hi: 1.0
78                     step: 0.05 #0.20
79                     minstep: 0.01
80                     fixed: True #False
81                     value: 0.9624 #0.9749
82                     LaTeX: "$u$"
83         type: "TriaxialVisibleComponent"
84     mge_pot: "fcc148_new_mge_Sabine.ecsv"
85     mge_lum: "fcc148_new_mge_Sabine.ecsv" #corrected_MGE_MD.ecsv"
86     include: True
87     contributes_to_potential: True
88     kinematics:
89         set1:
90             weight: 1.0
91             type: GaussHermite
92             datafile: "gauss_hermite_kins_MUSE_final_cut.ecsv"
93             aperturefile: "aperture_MUSE_final.dat"
94             binfile: "bins_MUSE_final.dat"
95         set2:
96             weight: 1.0
97             type: GaussHermite
98             datafile: "gauss_hermite_kins_SINFONI_final.ecsv"

```

A. Appendix

```

99         aperturefile: "aperture_SINFONI_final.dat"
100         binfile: "bins_SINFONI_final.dat"
101
102 system_parameters:
103     ml:
104         par_generator_settings:
105             lo: 0.5
106             hi: 5.0 #3.0
107             step: 0.1
108             minstep: 0.01 # better 0.1
109             fixed: False
110             value: 0.8 #1.1
111             LaTeX: "$Y_{r}$"
112
113 #
114 #####
115 # SECTION 2: SETTINGS
116 # Define other settings e.g. for the orbit library and weight solver
117 #
118 #####
119
120 orblib_settings:
121     nE: 21 #35 #21 # 7 # pick small orbit library for fast
122         tutorial exaecution
123     logrmin: -2.0 #0.1 #lowest orbit extent in arcsec
124     logrmax: 2.4 #
125     nI2: 11 #11 # 5 # must be >= 4
126     nI3: 7 #11 #7 # 3
127     dithering: 5 #5 # 1 # pick dithering=1 for for fast tutorial
128         exaecution
129     # the following values should usually not be changed
130     orbital_periods: 200
131     sampling: 50000
132     starting_orbit: 1
133     number_orbits: -1 # i.e. integrate all orbits
134     accuracy: '1.0d-5'
135     random_seed: -1 # fixed rnd. seed for reproducible tutorial (set
136         to 0 for stochastic seed) #
137
138 weight_solver_settings:
139     type: "LegacyWeightSolver"
140     nnls_solver: 1
141     regularisation: 0
142     number_GH: 4
143     GH_sys_err: '0.0 0.0 0.0 0.0' #0.0 0.0 0.6 0.6'
144     lum_intr_rel_err: 0.01
145     sb_proj_rel_err: 0.02
146     CRcut: True
147
148 parameter_space_settings:
149     generator_type: "LegacyGridSearch" # "FullGrid"
```

A.2. Modelling configuration

```
145   which_chi2: "kinmapchi2" # only use kinematic part of chi2 for
146   parameter search (recommended)
147   generator_settings:
148     # For LegacyGridSearch, specify ONE of the following two settings
149     # threshold_del_chi2_abs: 0.5 # absolute change in chi2
150     threshold
151     threshold_del_chi2_as_frac_of_sqrt2nobs: 0.15
152     stopping_criteria:
153       min_delta_chi2_abs : 0.5 # absolute "optimality tolerance"
154       #min_delta_chi2_rel : 0.05 # relative "optimality tolerance"
155       n_max_mods : 5000 #1500
156       n_max_iter : 15 #2 #5 #30 #5 #15 #2
157
158   io_settings: # paths can be given with or without trailing slash
159     input_directory: "data_prep/"
160     output_directory: "FCC148_combined_7th_run/"
161     all_models_file: "all_models.ecsv"
162
163   multiprocessing_settings:
164     ncpus: 16 #96 # integer or 'all_available'
165     #ncpus_weights: 16
166     #modeliterator: 'SplitModelIterator'
167
168   legacy_settings:
169     use_legacy_mode: True
170     directory: "/gpfs/data/fs71474/duffekm18/dynamite/legacy_fortran" #"
171     default"
```