The assembly history of the milky way nuclear star cluster

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Introduction

On a clear, moonless night one can see a diffuse glowing band across the sky, even without a telescope. This band consists of billions of stars, and is called the Milky Way. In addition to this band there are several smaller diffuse nebulae distributed all over the sky. Many of these nebulae are dense gravitationally bound accumulations of stars, gas, dust, and invisible mass, called dark matter. These structures are called galaxies. Our own solar system is located within the Milky Way, which is one such galaxy.

Galaxy sizes range over four orders of magnitude, from a few tens of parsecs in dwarf galaxies to nearly 100,000 parsecs in giant galaxies. Their masses extend over ten orders of magnitude, from about 10^3 to 10^{13} $M_\odot$. The shape of a galaxy can be elliptical, lenticular, irregular, or disc-like, see Fig. 1.1. High-resolution images show that galaxies can have distinct structures, such as shells, bars, or a cluster of stars in the nucleus. Some galaxies have extraordinary bright nuclei, which can only originate from an accreting supermassive black hole.

These observations lead to several questions: How do galaxies form? Why is there such a huge variety in size and shape? What is at the centre of the galaxy, at the bottom of the gravitational potential well? Do all galaxies contain a supermassive black hole? How did the supermassive black holes and bright star clusters in galactic nuclei form? In order to address the last of these questions, we study the assembly history of the closest galactic nucleus. We investigate the stellar populations and kinematics of the Milky Way's nuclear star cluster in order to find out how it was assembled.

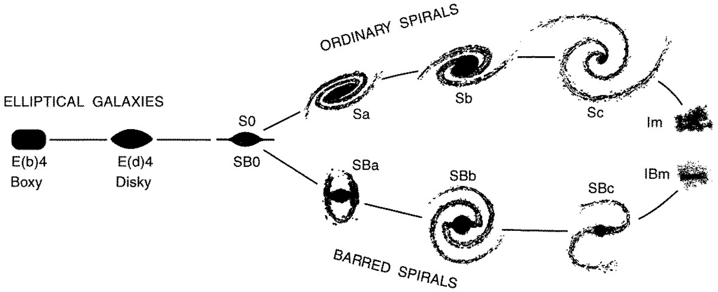

Figure 1.1: Morphological galaxy classification based on Hubble (1926). Galaxies can be divided in ellipticals (E), lenticulars (S0, SB0), spirals (S and SB), and irregulars (Im and IBm, image from Kormendy & Bender 1996).

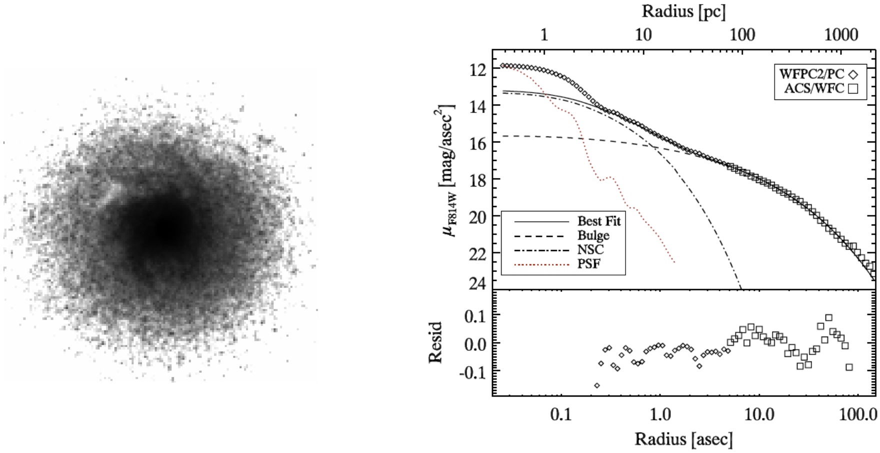

Figure 1.2: Left: *Hubble Space Telescope* WFPC2 image of the central 15″×15″ of NGC 404 (downloaded from the Hubble legacy archive). Right: Surface brightness profile of NGC 404 (upper panel). Diamond and square symbols denote the data, the dashed line is a fit to the outer (bulge) component, the dot-dashed line is a fit to the inner nuclear star cluster component. The combined best fit is shown as solid line. The lower panel shows the fit residuals (image from Seth et al. 2010).

In this chapter we summarise the main properties and formation scenarios of nuclear star clusters in Section 1.1, and give an overview on the Milky Way nuclear star cluster in Section 1.2. The Milky Way harbours a supermassive black hole in the centre, and we introduce these objects in Section 1.3. In this thesis we study stellar populations, and construct dynamical models for the nuclear star cluster. The applied concepts and methods are briefly summarised in Section 1.4 and Section 1.5. We give an overview on the content of this thesis in Section 1.6. We conclude and close with an outlook in Section 1.7.

1.1 Nuclear star clusters

In the 1990s, nuclear star clusters were discovered in large numbers (e.g. Phillips et al. 1996; Carollo et al. 1998; Matthews et al. 1999). Only the *Hubble Space Telescope* and large 8−10 m telescopes with adaptive optics reach the required angular resolution to resolve the centres of galaxies and the compact sources therein. Galaxies with a nuclear star cluster have a surface brightness profile that exhibits a sharp rise at the centre. Fig. 1.2 shows the image and surface brightness profile of a galaxy with a nuclear star cluster. The surface brightness profile can only be fitted by including a separate component for the nuclear star cluster (dot-dashed line).

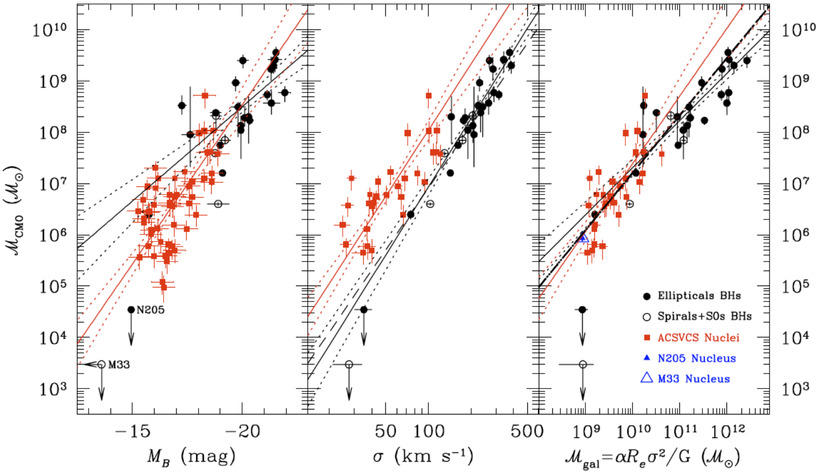

Figure 1.3: Scaling relations of the nuclear star cluster mass (red symbols) and supermassive black hole mass (black symbols) with different galaxy properties, such as $B-$band magnitude M_B (left panel), velocity dispersion σ (middle panel), and galaxy mass $\mathcal{M}_{gal}$ (right panel, image from Ferrarese et al. 2006).

1.1.1 Properties

The effective radii[1] of nuclear star clusters are in the range of 1−10 pc. This means their size is similar to the size of Galactic globular clusters. However, nuclear star clusters are more luminous (by ∼4 mag) and more massive than globular clusters (by ∼2 orders of magnitude). Typical masses of nuclear star clusters range over 10^6 – 10^8 $M_\odot$. The surface mass density of nuclear star clusters is $\sim 10^3 – 10^5$ $M_\odot \cdot \mathrm{pc}^{-2}$, which makes them the densest stellar systems in the Universe (Böker et al. 2004; Walcher et al. 2005; Côté et al. 2006; Misgeld & Hilker 2011; Georgiev & Böker 2014).

Nuclear star clusters are very common in low- to intermediate-mass galaxies, regardless of the host galaxies' morphological type. However, nuclear star clusters are absent in massive, bright galaxies ($B-$band magnitude $M_B \lesssim -20$ mag). The fraction of galaxies with an unambiguous nuclear star cluster detection is ≈70 per cent in spheroidal galaxies (Hubble types E and S0), ≈50 per cent in early-type spirals (Hubble types Sa-Sc), and ≈75 per cent in late-type spirals (Hubble types Scd-Sm). However, these numbers are only lower limits, as bright bulges or dust lanes can prevent the detection of a nuclear star cluster (Carollo et al. 1998; Böker et al. 2002; Côté et al. 2006; Turner et al. 2012; den Brok et al. 2014; Georgiev & Böker 2014).

Some properties of nuclear star clusters correlate with large-scale properties of their host galaxies. These correlations are physically interesting since nuclear star clusters are several orders of magnitude smaller than their host galaxy. The correlations indicate a strong

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[1] The effective radius indicates the region within half of the total light of a stellar system is emitted.

connection in the evolution of the central component and the galaxy. Finding these correlations makes it worthwhile to study the central regions of galaxies, in order to understand how galaxies themselves formed and evolved. Several studies found different types of correlations, for example between the mass of the nuclear star cluster and the host galaxy's luminosity, velocity dispersion, or mass (Carollo et al. 1998; Böker et al. 2004; Ferrarese et al. 2006; den Brok et al. 2014; Georgiev et al. 2016). We show such correlations in Fig. 1.3. Similar scaling relations are found for the mass of a supermassive black hole and the luminosity, mass, or velocity dispersion of the host galaxy (Kormendy & Richstone 1995; Häring & Rix 2004; Gültekin et al. 2009). This suggests that nuclear star clusters are the low-mass counterparts of supermassive black holes, which are mainly detected in more massive, brighter galaxies (Wehner & Harris 2006; Côté et al. 2006; Ferrarese et al. 2006). However, more recent studies have shown that nuclear star cluster scaling relations differ from supermassive black hole scaling relations (Balcells et al. 2007; Leigh et al. 2012; Scott & Graham 2013). There are also some galaxies, including the Milky Way, which host both a nuclear star cluster and a central supermassive black hole within it (Filippenko & Ho 2003; Seth et al. 2008a; Graham & Spitler 2009).

The star formation history of nuclear star clusters is complex, as they consist of multiple stellar populations. The dominating stellar populations in nuclear star clusters are rather old (10^8 – 10^{10} yr), however, the youngest population can be $\lesssim 10^6$ yr old (Walcher et al. 2006; Rossa et al. 2006; Seth et al. 2006; Carson et al. 2015). Koleva et al. (2011) and Lyubenova et al. (2013) found that some galactic nuclei are more metal-enriched and younger than their host galaxies.

1.1.2 Formation

The process that leads to the formation of nuclear star clusters remains an open question. The formation scenario can be divided in two main categories:

- Gas falls to the centre, and stars are formed in-situ, i.e., in the central parsecs of the galaxy (e.g. Loose et al. 1982; Milosavljević 2004; Schinnerer et al. 2008; Pflamm-Altenburg & Kroupa 2009; Aharon & Perets 2015).

- Dense star clusters, which formed elsewhere in the galaxy, migrate towards the centre of the galaxy (e.g. Tremaine et al. 1975; Capuzzo-Dolcetta & Miocchi 2008; Gnedin et al. 2014; Antonini et al. 2012; Antonini 2013; Perets & Mastrobuono-Battisti 2014).

The first scenario, dissipational gas infall and in-situ star formation, is supported by a number of observations. For example, some nuclear star clusters co-rotate with their host galaxies (Seth et al. 2008b), which indicates accretion from the galactic disc. Moreover, some nuclear star clusters contain molecular gas, or show signs of recent star formation (Schinnerer et al. 2003; Walcher et al. 2006). Stellar winds from recently formed stars and supernovae may reduce the gas supply, leading to episodic star formation (Schinnerer et al. 2008).

For the second scenario, the dissipationless infall of star clusters, Tremaine et al. (1975) suggested that massive globular clusters migrate to the galactic centre due to dynamical friction. Simulations show that about ten consecutive infalls of globular clusters can recover several properties of nuclear star clusters, for example their size, velocity dispersion, density distribution, and the scaling relations (Capuzzo-Dolcetta & Miocchi 2008; Antonini et al. 2012; Antonini 2013). The accretion of young massive star clusters, which formed near the galactic centres, could also explain the presence of young stars and the rotation of nuclear star clusters (Agarwal & Milosavljević 2011; Hartmann et al. 2011). A combination of the two different formation scenarios is also possible (Neumayer et al. 2011; Hartmann et al. 2011; Leigh et al. 2012), and the relative importance of the two processes may depend on the galaxy mass or morphology. Turner et al. (2012) suggested that star cluster infall is most important for low-mass galaxies, whereas gas accretion is dominant in high-mass galaxies.

1.2 The Milky Way nuclear star cluster

The Milky Way nuclear star cluster offers a unique opportunity to study the structure and dynamics of a nuclear star cluster in much more detail than possible in other galaxies. The Milky Way nuclear star cluster was discovered by Becklin & Neugebauer (1968) in the near-infrared. They detected a $5'$ large source, elongated along the Galactic plane, in the Galactic centre, and suggested that the radiation originates from a cluster of cool (~4 000 K) stars. Later observations resolved several discrete sources, which could be identified as stars (Becklin et al. 1978).

There are two important obstacles when observing the Milky Way nuclear star cluster. One of them is the high stellar density. Since the cluster is extremely crowded, it is difficult to resolve single stars. This problem can be addressed by using adaptive optics. However, the correction works only for rather small fields (Clénet et al. 2001; Genzel et al. 2003; Eisenhauer et al. 2005). The other problem is high interstellar extinction. Since the cluster is located in the centre of the Galaxy and the Solar system lies within the Galactic disc, the line-of-sight goes through the Milky Way's spiral arms and the central molecular zone, which are rich in molecular gas. This causes high extinction and reddening, making it effectively impossible to observe the Galactic centre in the optical and ultraviolet. The extinction decreases with wavelength (e.g. Schödel et al. 2010), and the Galactic centre becomes accessible in the near-infrared, at wavelengths $\lambda \gtrsim 1.2\,\mu$m.

Our distance to the Milky Way nuclear star cluster is approximately 8 kpc (Malkin 2012). The cluster's size is rather typical for nuclear star clusters, with an effective radius of $r_{\mathrm{eff}} = (4.2 \pm 0.4)$ pc and a total mass of approximately $(2.5 \pm 0.4) \times 10^7\, M_\odot$ (Schödel et al. 2014a). The Milky Way nuclear star cluster is not spherically symmetric but point-symmetric in projection, and flattened along the Galactic plane, with a ratio $q = 0.71 \pm 0.02$ between minor and major axis (Schödel et al. 2014a). The flattening is consistent with observations of other nuclear star clusters in edge-on galaxies (Seth et al. 2006). Figure 1.4 illustrates the Galactic centre. The nuclear star cluster is embedded in the nuclear stellar disc, which has a radius of 230 ± 20 pc, and a scale height of 45 ± 5 pc (Launhardt et al. 2002). These components form the nuclear bulge (panel a). The nuclear star cluster is shown in panel b). In the very centre

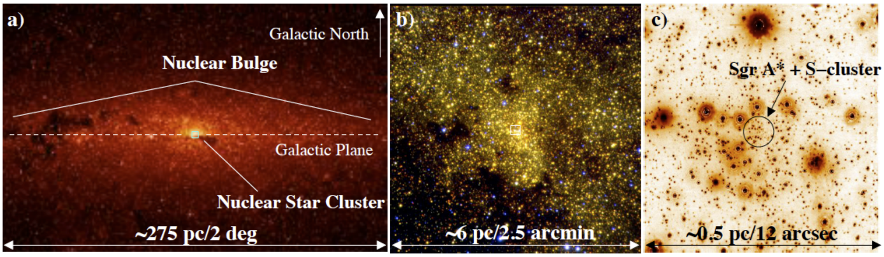

Figure 1.4: a) *Spitzer* 4.5 μm image of the central 275 pc of the Milky Way. (b) ISAAC near-infrared image of the central 6 pc × 6 pc of the nuclear star cluster. (c) The central 0.5 pc × 0.5 pc of the Milky Way observed with NACO in the near-infrared. All images are centred on the supermassive black hole Sgr A* (image from Schödel et al. 2014b).

of the Milky Way nuclear star cluster lies the radio source Sgr A*, which is surrounded by the so-called S-stars, a star cluster with a size of $1''$.

1.3 Supermassive black holes

Supermassive black holes are located in the centres of most galaxies, especially in massive galaxies. Also the Milky Way contains a supermassive black hole at its centre. It is associated with the radio source Sgr A*. The S-stars in the central arcsec of the Galaxy around Sgr A* have been monitored over more than a decade. From the measurements of the stellar orbits of the S-stars, the mass of the supermassive black hole was derived to $(4.1 \pm 0.6) \times 10^6\, M_\odot$ (Ghez et al. 2008), $(4.3 \pm 0.39) \times 10^6\, M_\odot$ (Gillessen et al. 2009b), and $(4.02 \pm 0.20) \times 10^6\, M_\odot$ (Boehle et al. 2016).

Supermassive black holes can be detected and weighted through their gravitational influence on the surrounding stars and gas, also in other galaxies. The masses of supermassive black holes range from $\mathrm{M}_\bullet \gtrsim 10^4\, M_\odot$ (e.g. in RGG 188, Baldassare et al. 2015) to several $10^9\, M_\odot$ (e.g. in M87, Gebhardt et al. 2011). There is no consensus on the processes that formed supermassive black holes and let them grow. It was suggested that black holes either formed as the end-product of stellar evolution, or directly from a collapsing gas cloud in the early Universe (e.g. Volonteri 2010; Greene 2012, and references therein). The black hole seeds must then have grown rapidly to explain the detection of supermassive black holes at high redshift, only about 10^9 yr after the Big Bang (Barth et al. 2003).

1.4 Stellar populations

The concept of stellar populations is used to describe subgroups of stars with distinct properties in a stellar system. Each subgroup or stellar population has a characteristic age, metallicity, spatial distribution, and distinct kinematic properties, bearing witness to their different formation history and evolution. Understanding the stellar populations in a stellar system helps to derive the assembly history of the stellar system itself.

A key tool to study stellar populations is spectroscopy. The absorption lines in stellar spectra carry information on the physical structure and chemical composition of the stellar atmosphere. We measure the absorption line strength and equivalent width of stellar spectra in the near-infrared to discern hot and cool stars, and use full spectral fitting to measure the effective temperature T_{eff}, metallicity $[M/H]$, and radial velocity v_z of stars. We use synthetic spectra and stellar libraries of stars for which these properties are known in order to calibrate our measurements.

1.5 Dynamical models

Dynamical models are a useful tool to infer the mass distribution of a stellar system. In a dynamical model, the observed light distribution and kinematics of the visible stars can be reconstructed. Since the stellar kinematics is influenced by the entire gravity of the system, the dynamical model reveals the total mass distribution of the stellar system, including the mass of invisible components such as black holes and dark matter. We use dynamical models to measure the mass distribution of the Milky Way nuclear star cluster and the mass of the central supermassive black hole. We apply axisymmetric Jeans models and triaxial orbit-based Schwarzschild models. Both types of model assume that the stellar system is in dynamical equilibrium. This means that the modelled stellar system has neither formed recently, nor has it been perturbed recently (Schwarzschild 1979).

Jeans models are based on the Jeans (1922) equations, which are derived from the collisionless Boltzmann equation. We solve the Jeans equations using the surface brightness and stellar root-mean-square velocity $V_{\mathrm{rms}} = \sqrt{V^2 + \sigma^2}$ as constraints, where V is the velocity and σ is the velocity dispersion of stars in the system. The solutions provide constraints on the black hole mass $\mathrm{M}_\bullet$, dynamical mass-to-light ratio Υ, and velocity anisotropy $\beta = 1 - \sigma_z^2/\sigma_R^2$. We use the Jeans Anisotropic Models by Cappellari (2008).

Schwarzschild (1979) models require a representative library of orbits in the modelled stellar system. The orbits are integrated in the gravitational potential. Then, a combination of orbit weights is fitted that reproduces the observed density distribution and kinematics of the stellar system. One can include all higher order kinematic moments of the line-of-sight velocity distribution to the fit, i.e. the velocity V, velocity dispersion σ, and the Gauss-Hermite moments h_3, h_4, etc. (Rix et al. 1997). Schwarzschild models have the advantages that they make no assumptions on the velocity anisotropy, and they allow to study the orbital structure of the stellar system (van de Ven et al. 2008). We use the triaxial orbit-based modelling code by van den Bosch et al. (2008).

1.6 This thesis

In this Ph.D. thesis we study the assembly history of the Milky Way nuclear star cluster. We combine spatially extended spectroscopic and photometric data with state-of-the-art dynamical modelling codes and spectral fitting methods.

In **Chapter 2** (based on Feldmeier et al. 2014) we study the kinematics and mass distribution of the Milky Way nuclear star cluster. We use the near-infrared long-slit spectrograph ISAAC at the *Very Large Telescope* (VLT) to map the central ~60 pc^2 of the Milky Way nuclear star cluster. In addition we observe six smaller fields out to 19 pc along the Galactic plane. The data extend out to the radius of influence of the central supermassive black hole. We measure radial velocities and CO absorption line strengths on 1375 spectra from individual stars. We derive line-of-sight velocity and velocity dispersion maps of the unresolved integrated light spectra. The velocity map reveals rotation of the nuclear star cluster, and additional complex structures. In particular, we discover a misalignment of the kinematic position angle by 9° with respect to the Galactic plane, and indications for a rotating substructure perpendicular to the Galactic plane at a radius ~0.8 pc. These structures may be the signatures of distinct accretion events. In addition to the kinematic maps we use *Spitzer* and NACO photometry and run anisotropic axisymmetric Jeans models. We derive the mass distribution of the nuclear star cluster and measure the black hole mass. The resulting black hole mass is 50 per cent lower than measured via resolved orbits of individual stars.

In **Chapter 3** (based on Feldmeier-Krause et al. submitted b) we study the mass distribution and orbital structure of the Milky Way nuclear star cluster. We construct triaxial orbit-based Schwarzschild models of the Milky Way nuclear star cluster, and apply them to the spectroscopic maps and photometric *Spitzer* data from Chapter 2. We use these models to constrain the triaxial shape of the nuclear star cluster, the dynamical mass-to-light ratio Υ, and supermassive black hole mass $\mathrm{M}_\bullet$. We obtain a black hole mass of $\mathrm{M}_\bullet = (3.0^{+1.1}_{-1.3}) \times 10^6\, M_\odot$, in agreement with the black hole mass measurement via resolved stellar orbits. Our best-fitting model recovers complex kinematic substructures in the velocity map. We find tangential anisotropy in the central $r = 2$ pc, but isotropy at larger radii.

Chapter 4 (based on Feldmeier-Krause et al. 2015) presents a study of the young stellar population in the central 4 pc^2 of the Milky Way nuclear star cluster. Our near-infrared KMOS (VLT) data contain spectra of 114 hot, young stars that formed only 3−8 Myr ago. We classify the young stars as O/B-type stars, Wolf-Rayet stars, and bow-shock sources. The young stars are very centrally concentrated, in contrast to the cool red giant population, which is distributed over the entire radial range of the data. The strong concentration of hot, young stars indicates that their formation happened in situ, as we would expect more young stars at larger radii for the migration scenario.

In **Chapter 5** (based on Feldmeier-Krause et al. submitted a) we analyse the metallicity distribution of late-type stars in the Milky Way nuclear star cluster. The data were obtained with KMOS (VLT) and cover the central 4 pc^2 of the cluster. The stars have a higher average Na I equivalent width than comparable stars in spectral libraries. We apply full spectral fitting on the spectra of more than 700 stars. Using a library of synthetic spectra, we fit the stellar effective temperatures T_{eff}, metallicities $[M/H]$, surface gravities $\log(g)$, and radial velocities v_z. Most of the stars in our data set are cool red giants with $T_{\mathrm{eff}} = 3\,000 - 5\,000$ K. We find a smooth metallicity distribution, ranging from $[M/H] < -1$ dex to $\gtrsim +0.3$ dex. Only approximately five per cent of the stars are metal-poor ($[M/H] \leq -0.5$ dex), most stars have super-solar metallicities. The metal-poor stars might originate from infalling globular clusters. However, the cluster is dominated by metal-rich stars, for which the globular cluster infall scenario can be ruled out.

1.7 Conclusions and outlook

Detailed studies of nuclear star clusters can provide insight into the physical processes that formed and shaped the centres of galaxies. We study the stellar kinematics and stellar populations of the nearest nuclear star cluster at the heart of the Milky Way, and use it as a benchmark to understand the formation and evolution of nuclei in other galaxies.

We found indications for two different formation mechanisms of nuclear star clusters. Velocity maps of old red giant stars reveal complex structures. This indicates that star clusters were accreted by the nuclear star cluster. The detection of metal-poor stars is another indication for the cluster infall scenario, in particular the migration and merger of a globular cluster. Metal-poor stars are also observed in the Galactic disc and bulge, and may have formed within the Galaxy. Based on the low fraction of metal-poor stars, globular cluster infall cannot be the major formation process for the Milky Way nuclear star cluster. Most stars have solar or super-solar metallicities, which are inconsistent with a globular cluster origin. These stars must have formed from enriched material. They either formed directly in the Galactic nucleus, or somewhere inside the Milky Way with later migration to the nucleus. The young stars, though, formed directly within the central parsec of the Milky Way. They are very centrally concentrated, which is inconsistent with a migration scenario.

Our stellar population study was limited to only 4 pc^2. Although this is already a significantly larger area compared to previous studies, it is only a small region of the nuclear star cluster. The cluster's effective radius is 4.2 pc, and the nuclear stellar disc becomes only dominant at 30 pc. It is interesting to study the stellar populations over a larger area of the nuclear star cluster, and search for possible gradients of age or metallicity. As we showed, there are only few metal-poor stars in the centre of the Milky Way nuclear star cluster, but it could be that there are more metal-poor stars further out. If globular clusters migrated to the centre of the Milky Way, they would have lost stars on their way to the centre. These stars could be located at the outer regions of the nuclear star cluster. There might also be isolated young stars at larger radii, which have not been detected yet. These stars would trace recent accretion events. A gradient of the stellar populations also implies that the mass-to-light ratio, which we assumed to be constant, is spatially varying. This would change our results of the cluster's stellar mass distribution.

In order to analyse if there is a gradient in the stellar populations, we observed a larger area of the Milky Way nuclear star cluster. In particular, we observed eight further fields with KMOS, out to and beyond the effective radius. From these data we will extract spectra of about 7 000 stars. To analyse the spectra, we will benefit from spectral libraries in the $K-$band that will be available in the near future. They will allow us to compare the spectra with different abundances and metallicities. We will implement different abundance ratios and stellar age in the spectral fitting. The spectroscopic data will be complemented with the HAWK-I photometric data of a large observing programme (P. I. Schödel). In order to verify our metallicity measurements and to measure element abundances of cool stars, we will propose observations at higher spectral resolution, e.g. with the instruments X-SHOOTER or CRIRES at the VLT. It is also interesting to obtain higher resolution spectra of the newly discovered young stars, in order to determine their spectral type and age. In this thesis we assumed that their age is consistent with the already known young stars, but this assumption should be tested.

There is also room for improvement in the kinematic studies of the nuclear star cluster. The rotation curve of the inner Galaxy and the central Galactic potential are still largely unconstrained. Our kinematic map extends only to the effective radius. We observed a larger region of 140 pc^2 along the Galactic plane with the spectrograph FLAMINGOS-2 (Gemini South Telescope). This is more than twice the area we observed with ISAAC. We will extract spectra from a further ~3 000 stars and measure their radial velocities and stellar parameters. We will also measure the kinematics of the integrated light from underlying faint stars, towards the outer edge of the nuclear star cluster. Our measurement of the central Galactic potential will be useful to compute the deceleration of hypervelocity stars (Kenyon et al. 2008), and the dynamical friction timescale of infalling star clusters (Antonini et al. 2012).

These two data sets can be combined and used for dynamical modelling. The kinematics of individual stars can be studied in discrete dynamical models, which do not require binning (Chanamé et al. 2008; Watkins et al. 2013). It is also possible to include proper motion measurements. In the future, it will be interesting to include the knowledge of the stellar ages and metallicities to dynamical models, and model the different populations separately. Such models are under development. Further, we neglected the neutral gas disc in the orbit-based models. By adding an additional gas disc component, the dynamical mass-to-light ratio would decrease. We also ignored figure rotation, which causes chaotic orbits and influences the orbital structure. Modelling figure rotation is computationally expensive, but will be possible in the future with more powerful computers.

The future will open new horizons for observations of galactic nuclei. New observing facilities are presently planned and built. For example, the *James Webb Space Telescope* (*JWST*) will be launched in 2018. At wavelengths from 0.6 to 28 μm it will reach high spatial resolution ($0\farcs023$ to $1\farcs01$). The small field of view of the *JWST* spectrographs is unpractical to observe the Milky Way nuclear star cluster, but *JWST* will be very useful to study nuclei of other galaxies. Its high sensitivity and spatial resolution are needed to detect and image distant nuclear star clusters. Further, the low- to medium- resolution integral field spectrographs MIRI and NIRSpec will allow us to observe stellar populations in galactic nuclei, and due to the high spatial resolution, also stellar population gradients.

In addition, a new generation of ground-based telescopes is currently being constructed: Extremely large telescopes with mirror diameters d >20 m. The *Giant Magellan Telescope* (GMT, d = 24.5 m) and the *European Extremely Large Telescope* (E-ELT, d = 39.3 m) are built in Chile, the *Thirty Meter Telescope* (TMT, d = 30 m) possibly in Hawai‘i. All three facilities allow observations of the Galactic centre, and together cover the northern and southern hemisphere. Due to their high sensitivity, it will be possible to observe fainter stars in the Galactic centre, including A- and F-type dwarfs. The spatial resolution reached by extremely large telescopes with adaptive optics will be better than what can be achieved with the *Hubble Space Telescope* and *JWST*. In combination with high-spectral resolution instruments, it will be possible to search for supermassive black holes in other nuclear star clusters. Such measurements are useful to study the aforementioned scaling relations.

New telescopes and models will help to achieve a better understanding of the formation and evolution of galactic nuclei, and their host galaxies. We are looking into a bright future for the research of galactic nuclei.