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Author: Krause-Feldmeier, A.
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Summary

Galaxies

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. Figure S1 shows an image of the Milky Way. In addition, there are many smaller diffuse nebulae distributed all over the sky (see also bottom right of Figure S1). In the 1920s, Edwin Hubble proved that many of these nebulae are galaxies. They are located at great distances, outside of the Milky Way. The Milky Way is only one galaxy among billion others.

Figure S1: The Milky Way galaxy (image by Serge Brunier)

Galaxies consist of stars, planets, gas, dust, and invisible mass, called dark matter. Dark matter does not interact with light, so it cannot be detected directly with a telescope. However, dark matter in the galaxy halo is necessary to explain the motions of stars and gas in galaxies. Systems of globular clusters surround the galaxies. Globular clusters are dense, spherical star clusters in the galaxy halo, which consist of mostly old, metal-poor stars. Many galaxies are so-called spirals, like the Milky Way, but there exist also featureless galaxies, called ellipticals. Figure S2 provides a schematic side view of the Milky Way. The gas and dust are mostly located in the Galactic disc and in the Galactic nucleus. Most stars are also in the disc and in the nucleus, as well as in the bulge.

Nuclear star clusters

In the 1990s, astronomers used the *Hubble Space Telescope* and 8−10 m ground-based telescopes to image the central regions of galaxies. Many galaxies are very bright at the centre,

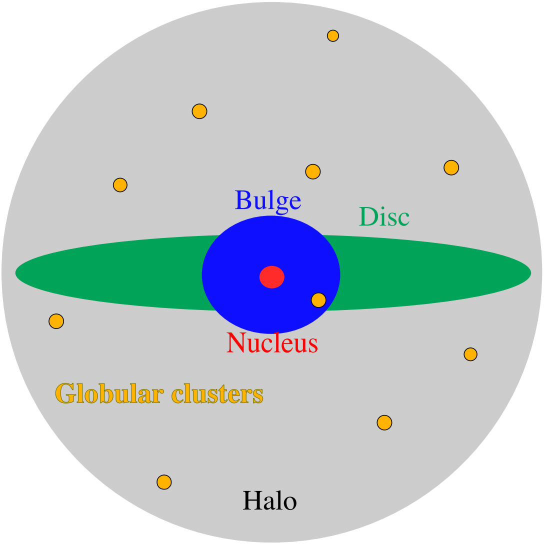

Figure S2: Schematic side view of the Milky Way galaxy. The different components are not to scale.

as there is a dense cluster of stars, called a nuclear star cluster. We show some images of galaxies with nuclear star cluster in Figure S3. Nuclear star clusters contain many millions of stars, and the total masses of the clusters range from about one million to hundred million times the mass of the sun. About 50 to 75 per cent of galaxies, including the Milky Way, contain a nuclear star cluster. The clusters are common in galaxies with low- to intermediate mass. Massive, bright galaxies do not contain nuclear star clusters. Astronomers want to find out how nuclear star clusters formed, and why they are located in some galaxies, but not in all of them.

Nuclear star clusters are more massive when the host galaxy is more massive or more luminous. Such correlations are interesting, since they can possibly tell us something about the common evolution of the galaxy and its nucleus. The clusters have radii of 3 to 30 light-years, whereas their host galaxies have radii ranging from roughly 1 000 to several 100,000 light-years. The correlations can help to understand the physical processes that shape the centres of galaxies. Astronomers suggested different formation mechanisms for nuclear star clusters, which can be divided in two main categories: (a) Gas from the galaxy accumulates in the centre, and stars form directly in the nucleus of the galaxy; and (b) stars form in dense star clusters elsewhere in the galaxy, e.g. in globular clusters. The star clusters migrate towards the centre of the galaxy and become the nuclear star cluster. It is also possible that both processes contribute to the formation of a nuclear star cluster.

The stars in a nuclear star cluster have different ages. Some of the stars are young, only a few million years old, other stars are up to 10 billion years old. This means that the clusters contain multiple "stellar populations". Stellar populations may be distinct in age, but they can also have a different chemical composition, as the stars did not form at the same time and

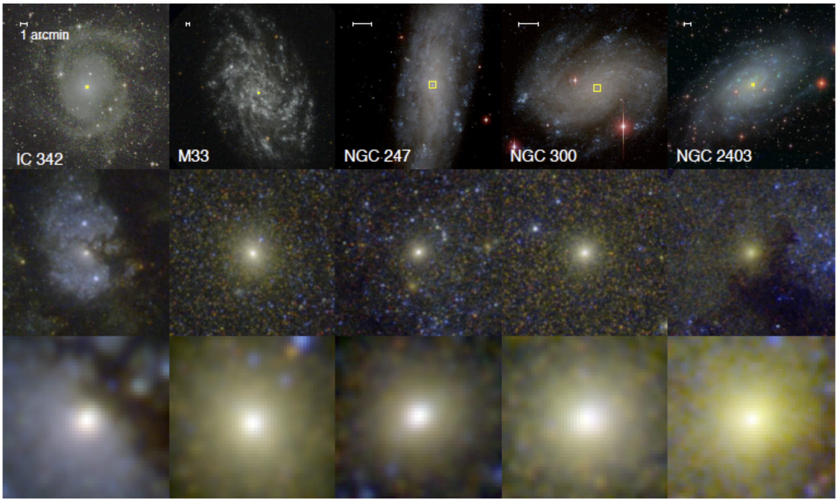

Figure S3: Images of different spiral galaxies with nuclear star cluster. The top panel shows the entire host galaxy, the middle panel is a zoom to the inner region of the galaxy (approximately 500 light-years × 500 light-years), and the bottom panel shows the central nuclear star cluster (approximately 80 light-years × 80 light-years). The scale bars on the top row denote 1 arcmin (approximately 2 400 light-years, image from Carson et al. 2015).

from the same material. The stellar populations may have a characteristic spatial distribution, or move in a characteristic way. Investigating the properties of different stellar populations is useful to understand the formation and evolution of the nuclear star cluster.

Supermassive black holes

It is hard to imagine a black hole: An object that is so massive that nothing can escape from it. Black holes are not visible; particles or light that fall on a black hole can never leave it again. Due to gravity, a black hole influences the surrounding stars and gas. It is possible to infer the existence and mass of the black hole from the motions of stars in orbits around it.

Supermassive black holes are between ten thousand to ten billion times as massive as the sun. They are located in the centres of most galaxies, especially in massive galaxies. 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. The black hole seeds must then have grown rapidly to explain the presence of supermassive black holes in the young universe, only about one billion years after the Universe formed.

Also the Milky Way contains a supermassive black hole at its centre, within the nuclear star cluster. The stars around the Milky Way black hole have been monitored over more than a decade, they move in ellipses around an invisible object. From the stellar motions, the mass

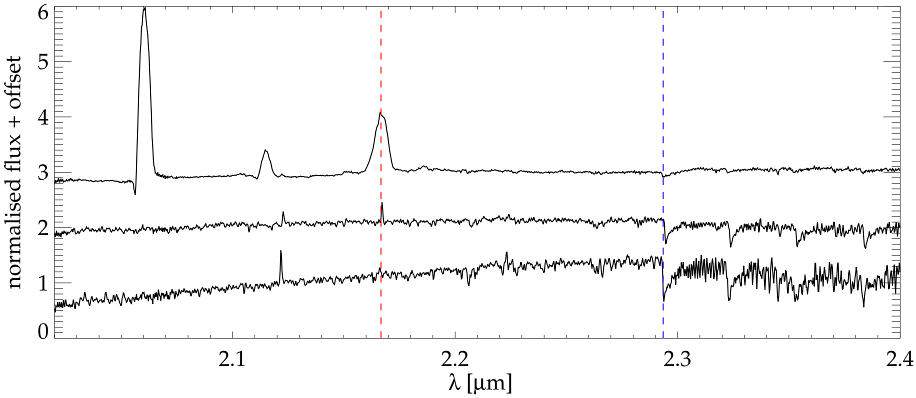

Figure S4: Spectra of three different stars, measured with the instrument KMOS at the *Very Large Telescope* in Chile. The light flux is shown as a function of wavelength (λ) in the near-infrared. The red dashed line marks one of the emission lines, the blue dashed line marks one of the absorption lines. The top spectrum is from a hotter star than the two lower spectra.

of the supermassive black hole was measured to four million solar masses. At the moment, this method to detect a supermassive black hole is only possible in the nearby Milky Way centre.

To find supermassive black holes in other galaxies, astronomers apply different methods. One of them is to construct dynamical models. Dynamical models are a useful tool to infer the entire mass distribution of a stellar system. In a dynamical model, the observed light distribution and the movements of visible stars are reconstructed. Since the stellar motions are 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.

Spectroscopy

A spectrograph splits light into a spectrum, this means the flux becomes a function of the wavelength. Spectra contain a wealth of information on the source of the light. There can be lines in the spectra, either bright lines on a dark background, called emission lines, or dark lines on a bright background, called absorption lines. The lines are generated by interactions of electromagnetic radiation with matter. The intensity, wavelength, and width of the lines are useful to infer properties of the spectrum's source. We show the spectra of three stars in Figure S4. The red dashed line marks one of the emission lines, the blue dashed line marks one of the absorption lines.

Each line in a spectrum is generated by a certain type of matter, e.g. an atom or a molecule. The line intensity depends on the number of atoms or molecules of the specific matter in the star. For example, an iron line becomes stronger when there are more iron atoms in the star. But the line intensity is also influenced by the surface temperature of the star. Certain lines are only visible above or below a certain temperature. Also, the lines are weaker or stronger at different temperatures. Thus, by measuring the intensity of the lines in a stellar spectrum, we can determine the so-called metallicity and effective temperature of the star. In Figure S4, the strength of the absorption line (marked with a blue dashed line) changes for the different stars. Further, there are some emission lines in the top spectrum that are not seen in the two lower spectra, since the two bottom stars are much cooler.

When the source is moving at a certain velocity with respect to the observer, the spectral lines are shifted to a different wavelength. This is the so-called Doppler effect. By measuring the wavelength of the observed line, we can determine the velocity of a star along the line-of-sight. Also the spectra shown in Figure S4 are slightly shifted with respect to each other, as the stars are moving with different velocities.

Sometimes it is not possible to observe the spectrum of a single star, as the star is too far away and hence too faint. But we can observe the unresolved integrated spectrum of an ensemble of stars. Such a spectrum contains the light of many stars, weighted by their respective brightness. This means the measured velocity, effective temperature and metallicity will be a luminosity-weighted average of the stars that contribute to the spectrum. But as not all stars move with the same velocity, each spectral line will be broadened with respect to the line of only one star. The amount of broadening contains information about the relative motion of the stars with respect to each other. If the stars move all with roughly the same speed and in the same direction, the line broadening will be small, but if the random motion (i.e. the velocity dispersion) of the stars is large, the line broadening will increase. This velocity dispersion is important for dynamical modelling, as it depends on the underlying total (luminous and dark) mass.

This thesis

In this thesis we study the assembly history of the nuclear star cluster in the Milky Way. The cluster's size is rather typical for a nuclear star cluster, with a radius of approximately 14 light-years. The Earth's distance to the Milky Way nuclear star cluster is approximately 26,000 light-years. It is the closest nuclear star cluster, and for that reason it can be studied in much more detail than possible in other galaxies. We show an image of the Milky Way nuclear star cluster in Figure S5.

In **Chapter 2** 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 a large area of 640 light-years squared of the Milky Way nuclear star cluster. In addition we observe six smaller fields out to a radius of 62 light-years along the Galactic plane. The data extend out to the radius of influence of the central supermassive black hole of approximately 9 light-years. We measure line-of-sight velocities and CO absorption line strengths from 1 375 spectra of individual stars. We derive velocity and velocity dispersion

Figure S5: Image of the central 45 light-years × 30 light-years of the Milky Way, where the nuclear star cluster is located (image from VVV survey, Saito et al. 2012).

maps using the unresolved integrated light spectra of red giant stars. The velocity map reveals the rotation of the nuclear star cluster, and additional complex structures. In particular, we discover a misalignment of the rotation axis by 9° with respect to the photometric minor symmetry axis, and indications for a rotating substructure perpendicular to the Galactic plane at a radius of about 2.6 light-years. These structures may be the signatures of distinct accretion events. In addition to the kinematic maps, we use photometry from the *Spitzer Space Telescope* and NACO on the VLT and construct anisotropic axisymmetric Jeans dynamical models. We derive the mass distribution of the nuclear star cluster and measure the black hole mass. The resulting black hole mass is half the amount measured directly via the resolved orbits of individual stars.

In **Chapter 3** we further study the mass distribution and orbital structure of the Milky Way nuclear star cluster. We construct triaxial orbit-based Schwarzschild dynamical 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 $M_\bullet$. We now obtain a black hole mass that is in agreement with the black hole mass measurement via resolved stellar orbits. Our best-fitting model recovers the complex kinematic substructures in the velocity map.

Chapter 4 presents a study of the young stellar population in the central 43 light-years squared 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 in different subgroups. The young stars are very centrally concentrated, in contrast to the cool stellar population, which is distributed over the entire radial range of the data. The strong concentration of hot, young stars indicates that they formed in-situ in the centre of the cluster, as we would expect more young stars at larger radii in the case of inward radial migration.

In **Chapter 5** we analyse the metallicity distribution of the late-type stellar population in the Milky Way nuclear star cluster. We use the late-type stellar spectra of the KMOS (VLT) data from Chapter 4. The late-type stars have stronger Na I lines 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, metallicities, surface gravities, and radial velocities. Most of the stars in our data set are cool red giants with temperatures in the range of $3\,000 - 5\,000\,\mathrm{K}$. We find a smooth metallicity distribution, ranging from $[M/H] < -1$ dex (i.e. 1/10 of solar metallicity) to $\gtrsim +0.3$ dex (i.e. 2 times solar metallicity). Only approximately five per cent of the stars are metal-poor ($[M/H] \leq -0.5$ dex, i.e. 1/3 of solar metallicity). Stars with $[M/H] \leq 0.0$ dex (solar metallicity) might originate from infalling globular clusters. Most stars (about 75 per cent) have super-solar metallicities, and for those stars the globular cluster infall scenario can be ruled out.

Conclusions and outlook

We found indications for two different formation mechanisms of the Milky Way nuclear star cluster. Velocity maps of the old red giant star population 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 star cluster infall scenario, as globular clusters consist of such stars. However, metal-poor stars are also observed in the Galactic disc and bulge, and may also have formed there. 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 3 light-years of the Milky Way. They are very centrally concentrated, which is inconsistent with a migration scenario.

Although we studied the stellar populations in a significantly larger area than previous studies, our data cover only a small region of the nuclear star cluster. Studying the stellar populations over a larger area, and searching for possible gradients of age and metallicity would be useful to increase our understanding of the nuclear star cluster formation. As we showed, there are only few metal-poor stars in the centre of the Milky Way nuclear star cluster. It could be that there are more metal-poor stars further out, in particular if these stars were stripped off a globular cluster during its infall. There might also be isolated young stars at larger radii, which have not been detected yet. These young 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 verify our metallicity measurements and to measure element abundances of cool stars, observations at higher spectral resolution are needed. High-resolution spectra are also required to determine the spectral type and age of the newly discovered young stars. 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. Our kinematic map does not cover the entire nuclear star cluster. The rotation curve of the inner Galaxy and the central Galactic potential are still largely unconstrained. We obtained more data with KMOS (VLT) and FLAMINGOS-2 (*Gemini South Telescope*) to address some of these issues. These two data sets can be combined and used for dynamical modelling. One can extend the models by including a gas disc component, and implementing stellar proper motions. Another improvement is using models that do not require binning of the kinematic data.

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. Due to its high sensitivity and spatial resolution it will be possible to study stellar population gradients in extragalactic nuclear star clusters. 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), the *Thirty Meter Telescope* (TMT, d = 30 m), and the *European Extremely Large Telescope* (E-ELT, d = 39.3 m). The high spectral and spatial resolution instruments of these telescopes are useful to search for supermassive black holes in extragalactic nuclear star clusters. These sensitive telescopes are capable to observe fainter stars in the Milky Way nuclear star cluster than currently possible, including A- and F-type dwarfs. 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.