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The center of the Milky Way

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Abstract

This article intends to provide a brief introduction to current Galactic center research. Its approach is observational and it is focused on the massive black hole, Sagittarius A*, and on the Milky Way nuclear star cluster, which surrounds the latter. These two components together are thought to make up $> 90\%$ of the mass in the central few parsecs. The principal topics tackled in this very brief review are mass of and distance to Sagittarius A*, basic properties of the nuclear star cluster, the surprising absence of an observable stellar cusp around the black hole, star formation in the central 0.5 pc, and hypervelocity stars.

1 Introduction

The centers of galaxies are extreme astrophysical environments in many aspects. The stellar density in galactic nuclei can reach values exceeding $10^7\,\mathrm{M_\odot\,pc^{-3}}$ and the nuclei of all galaxies with central bulges are thought to host a supermassive black hole. The correlation between central black hole masses and overall properties of galaxies, like bulge mass, velocity dispersion, or luminosity (e.g.[44, 22, 46]) illustrates the tight relationship between the nuclei and the large-scale properties of galaxies. In spite of their great interest for astrophysics and even fundamental physics, a fundamental difficulty in the study of galactic nuclei is their large distance and the related low spatial resolution of observations.

The center of the Milky Way is located at only $8 - 8.5$ kpc [32, 27, 68] distance from the Solar System. This is roughly 100 times closer than the nucleus of the nearest galaxy comparable to our own, M31, and of the order 1000 times closer than the nearest active galactic nucleus. This closeness of the Galactic center (GC) allows us to resolve angular scales corresponding to about 20 mpc or 4000 AU, with near-infrared observations on 8-10 m class telescopes. The astrometric accuracy is even better by a factor of $\sim$50. Radio/millimeter VLBI observations can currently resolve structures down to about 50 μas, offering prospects to probe the extended emission related to the central black hole on event horizon scales within the next decade. All this means that the Galactic center is a unique target and an irreplaceable template for our understanding of galactic nuclei in general.

Due to the limited scope of this article, I will focus on the objects that make up more than 90% of the mass within the central few parsecs of our Galaxy: the nuclear star cluster and the central black hole. Topics such as the properties of the interstellar medium, magnetic fields, or the emission and accretion processes related to the central black hole cannot be discussed here. The interested reader can find more detailed introductions in various review papers, like [47, 48, 27] or in the book by [19]. Research on the Galactic center is an extremely active field, with high-impact results emerging on timescales of the order half a year and articles appearing weekly. Often new results can modify significantly earlier commonly accepted views.

2 Nuclei of quiescent galaxies: a rough sketch

The Milky Way belongs to the class of so-called quiescent galaxies, i.e. galaxies with no detectable AGN-like nuclear activity. Although there exists some important evidence for a higher activity at the GC in the past (e.g. [57, 65]), the accretion flow/outflow related to black hole at the center of the Milky Way is currently emitting at only $10^{-9...10}$ Eddington luminosities. In Eddington terms, Sagittarius A* at the GC is therefore the weakest black hole observable by current technological means. If it were located in M31, it could not be detected with current technology (with the possible exception of radio observations).

The main constituents of quiescent nuclei are (super-)massive black holes and nuclear star clusters. Although it is widely assumed that all galaxies with a central bulge contain a central, massive black hole (MBH), there exist currently only about 50 reliable mass measurements of MBHs, using stellar or gas dynamics (and maser disks in special cases). There exists a significant correlation between the masses of the central black holes and the bulge velocity dispersion of their host galaxies that appears to hold over 4 orders of magnitude (e.g. [35]).

The paradigm of super massive black holes at the centers of galaxies is already several decades old and mounts back to the discovery of quasars and AGN. There exists, however, a second ingredient of galactic nuclei, which may be of similar importance than the black holes: nuclear star clusters (NSCs). NSCs are compact clusters at the photometric and dynamic centers of galaxies. Only the superior angular resolution of the Hubble Space Telescope in the middle of the 1990s and, since less than a decade ago, adaptive optics assisted near-infrared imaging and spectroscopy from ground-based telescopes, has allowed us to detect NSCs in significant quantities and study their properties. NSCs have typical half-light radii of $2-5$ pc and masses of $10^6 - 10^7\,\mathrm{M}_\odot$ and may thus represent the most massive and densest clusters in the Universe. NSCs appear to be characterized by recurring episodes of star formation. A significant number of NSCs show stellar populations younger than 100 Myr. Intriguingly, there are claims that there exists a similar scaling relationship between NSCs and their host galaxies as for MBHs [21], although this claim is still disputed [39]. A concise review on nuclear star clusters can be found in [8].

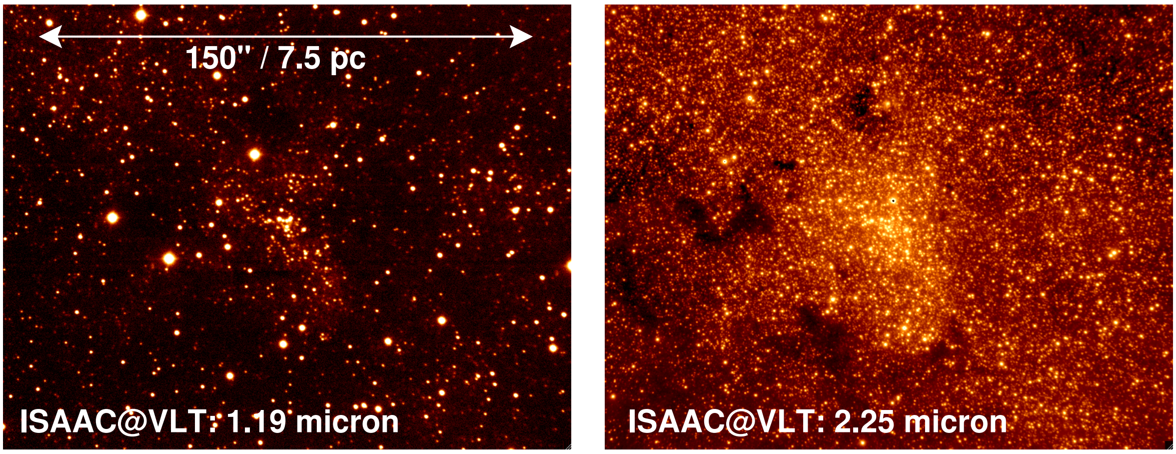


Figure 1: *Left*: Image of the Galactic center obtained with ISAAC at the VLT with a 1.19 μm narrow band filter. *Right*: Image of the Galactic center obtained with ISAAC at the VLT with a 2.25 μm narrow band filter. North is up and east is to the left. The field-of-view of the two images is identical.

3 Infrared observations of the Galactic center

A large amount of interstellar gas and dust lies along the line-of-sight to the Galactic center and makes observations at visible wavelengths all but impossible. Extinction in the visual band is at least $A_V = 25 - 30$ [64], but possibly as high as $A_V = 40 - 50$ [63]. The effect of this strong extinction is demonstrated in Fig. 1, which shows two images of the GC obtained with ISAAC at the VLT. There is obviously an extreme difference between the number of sources visible at 2.25 μm, where extinction amounts to roughly 2.5 magnitudes and at 1.19 μm, where extinction is $\sim$11 mag.

Because of the high extinction, observations of stars at the GC were impossible before the arrival of infrared detectors. The first observations, based on scans with a one pixel detector and resolutions between $1.8'$ and $0.25'$, were presented by [7]. Low-resolution views of the Galactic center with a large field-of-view, observed with contemporary instruments, are shown in Fig. 2.

4 The massive black hole Sagittarius A*

The compact radio source Sagittarius A* (Sgr A*) was discovered in the early 1970s [4], but it took almost three decades until it could be shown to be associated to a massive black hole beyond reasonable doubt. Measurements of stellar kinematics in the 1990s (e.g. [18, 28]) and of individual stellar orbits since 2002 (e.g. [29, 60]) provided firm evidence for the presence of a mass of a few times $10^6\,M_\odot$ enclosed within a radius ≤ 130 AU from Sgr A*. VLBI measurements at ever shorter wavelengths could finally overcome the strong scatter broadening of the radio source Sgr A* due to interstellar material and show that its intrinsic

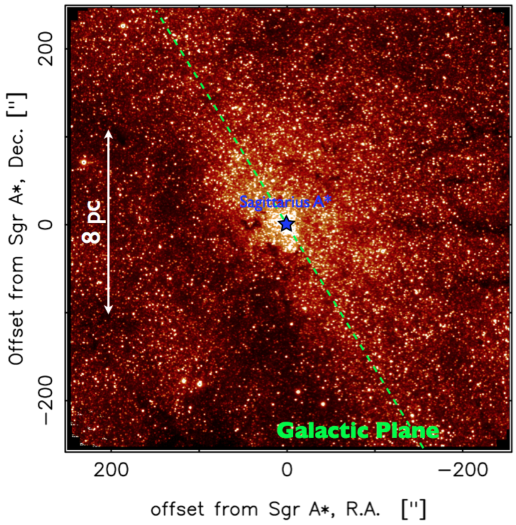


Figure 2: *Left*: Spitzer image of the center of the Milky Way with IRAC, composed of observations at 3.6, 4.5, 5.8, and 8.0 μm (Credit: NASA/JPL-Caltech/S. Stolovy, SSC/Caltech). The horizontal size of the image corresponds to approximately 250 pc at the distance of the GC. *Right*: Ks-band image of the Milky Way nuclear star cluster obtained with SIRIUS at the 1.4 m IRSF; data from [53]. Note that the image on the left is oriented differently than the one on the right. The Galactic plane is oriented horizontally in the left image. In the right image north is up and east is to the left.

size was < 1 AU (e.g. [10, 41]), with the current best value being 37^{+16}_{-10} microarcseconds or ≤ 0.3 AU [16]. Sgr A* is embedded in a dense star cluster and suffers frequent close encounters with stars, some of them as massive as $10 - 20\,\mathrm{M}_{\odot}$. These encounters lead to an expected motion of Sgr A* that is dependent on its mass. VLBI observations of the proper motion of Sgr A* with respect to extragalactic radio sources provided an upper limit to the motion of Sgr A* perpendicular to the Galactic plane of -0.4 ± 0.9 km s^{-1}, which means that about $10^5\,\mathrm{M}_{\odot}$ must be directly associated with the radio source [58]. Rapid variability of the infrared and X-ray counterparts of Sgr A* has been observed on timescales of a few minutes, setting upper limits on the size of the object [2, 25]. Finally, the intrinsic weakness of the emission from Sgr A* at all wavelengths and the properties of its spectral energy distribution require the presence of an event horizon [11].

All these lines of arguments unite to make Sgr A* the currently best case for the existence of massive black holes. Measurements of its mass and distance are being continually improved via constant monitoring of stellar orbits in its vicinity. The parameters of about two dozen orbits have been determined so far [30, 32]. The best current estimates for the mass and distance of Sgr A* are currently $4.1 \pm 0.3 \times 10^6\,\mathrm{M}_{\odot}$ and $R_0 = 8.0 \pm 0.3$ kpc [68], and $4.3 \pm 0.4 \times 10^6\,\mathrm{M}_{\odot}$ and $R_0 = 8.3 \pm 0.35$ kpc [32]. There exists, of course, a degeneracy between the mass and the distance.

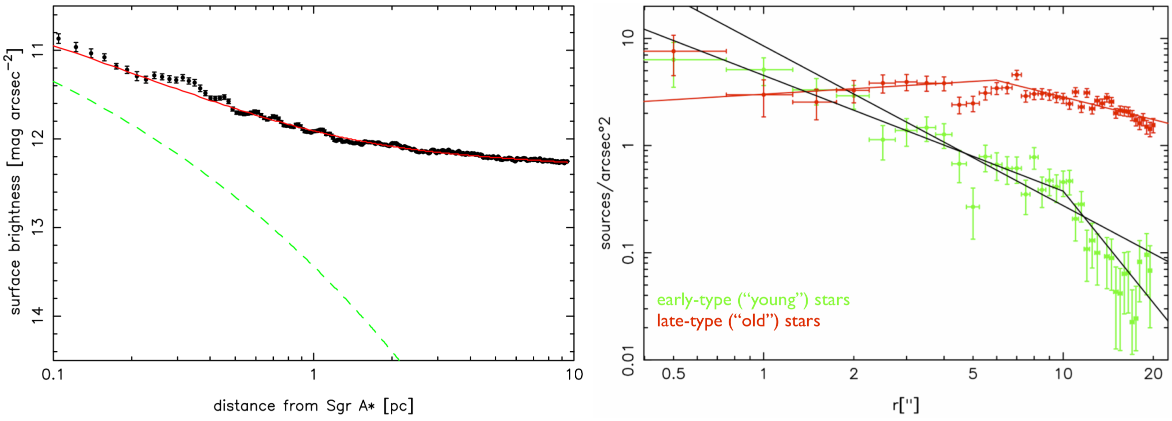


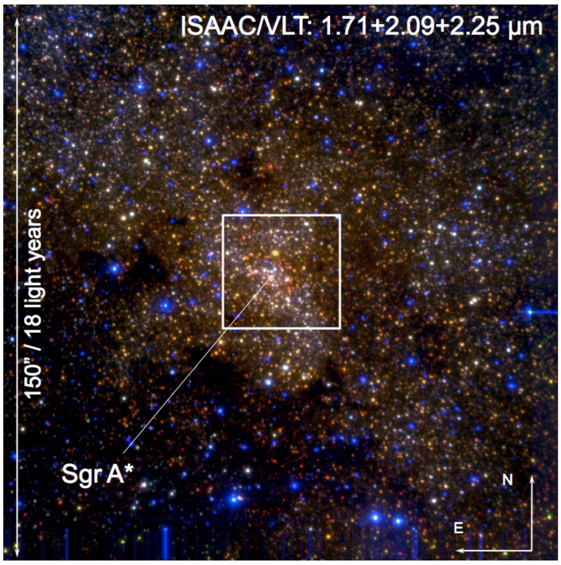
Figure 3: *Left*: Light density profile of the MW NSC derived from SIRIUS/IRSF Ks-band images. The dashed green light is a Sérsic model (with index 3.4). In combination with a constant contribution from bulge/bar stars (straight, red line), it fits the data reasonably well. The corresponding half-light radius of the cluster is $\sim$5 pc. *Right*: Projected surface density of stars in the central parsec [13]. Green crosses show the surface density of young, massive stars (with two different fits indicated by the black lines). Red crosses show the surface density of late-type stars, along with a broken power-law fit. Note that 1 arcsecond corresponds to about 0.04 pc at the distance of the GC.

5 The nuclear star cluster

5.1 Structure of the NSC

The Milky Way NSC is the dense cluster located at the center of the images shown in Fig. 2. From their pioneering infrared observations [7] found an elongation of the NSC along the galactic plane. Also in modern-day images the NSC appears elongated, as can be seen in Fig.2. However, close inspection of the images shows clouds of high extinction throughout the entire GC region. In particular, there is a large high-extinction region to the south-west of the GC, which covers almost half of the NSC(see also Fig. 1 of [56]). The apparent elongation of the NSC is therefore probably an effect of differential extinction. [61] corrected their number density analysis of ISAAC/VLT imaging data of the NSC for differential extinction and found that this correction led to a more circular symmetric appearance of the cluster. [66] find their kinematic data of stars in the central parsec of the NSC consistent with a spherical cluster. There is also some support for spherical symmetry from X-ray observations of point sources in the GC [49]. Hence, the Milky Way NSC may in fact be close to spherically symmetrical, an assumption that is frequently applied because it considerably facilitates modeling.

Strong and variable extinction is also the reason why the overall extent of the star cluster at the GC is difficult to determine. However, an analysis of the azimuthally averaged light profile from SIRIUS/IRSF K-band imaging data (provided by S. Nishiyama), combining a Sérsic profile for the NSC with a constant/exponential light profile for the stars from the Galactic bulge or bar, leads to half-light radius of $\sim$5 pc (see Fig.3). Using a very similar



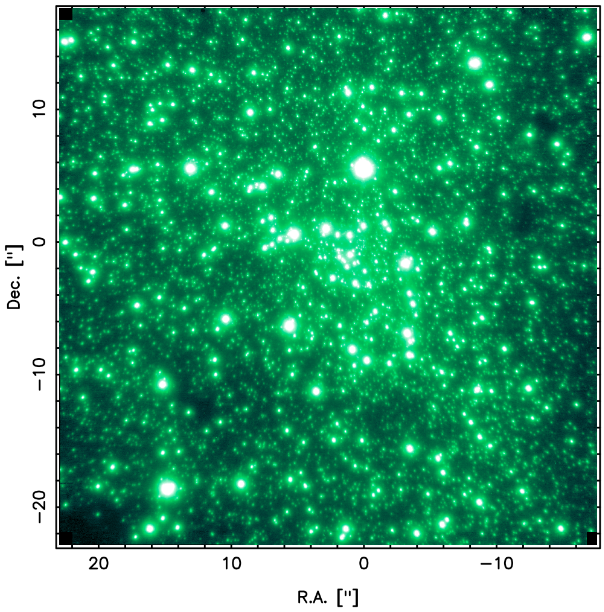


Figure 4: *Left*: Image of the nuclear star cluster with ISAAC at the ESO VLT. Blue corresponds to 1.71 μm, green to 2.09 μm, and red to 2.25 μm. The image is seeing limited and has a PSF FWHM of approximately $0.5''$. *Right*: Adaptive optics assisted Ks-band image of the central parsec (marked by a white square in the left panel) with NaCo at the VLT. The PSF FWHM is approximately $0.06''$.

analysis and 2MASS data, [34] obtained a half-light radius of $\sim$3 pc, which gives us an idea of the uncertainty of this value.

The presence of a few dozen bright stars (massive, young stars and supergiants) combined with the extreme stellar surface density within $\sim$0.5 pc of Sgr A* require an angular resolution $< 0.1''$ and the use of stellar number counts to infer the cluster structure in this innermost region. Otherwise, the light from the bright stars dominates and leads to erroneous results [61].

Theoretical stellar dynamics predicts that a dynamically relaxed stellar cluster around a massive black hole, should display a so-called *cusp* in its stellar number density profile. The cusp would be visible as a density excess (relative to a flat core) centered on the black hole. The stellar density within such a cusp is predicted to follow a power-law, $\rho \propto r^{-\gamma}$, where r is the distance from the black hole and $3/2 < \gamma < 7/4$ (e.g. [3, 42, 50]). [26] analyzed the first adaptive optics assisted images from the NaCo instrument at the ESO VLT and reported $\gamma = 1.4 \pm 0.1$ within $\sim$0.5 pc of Sgr A*. [61] continued this analysis with improved data and analysis methods, combining both seeing limited data on a large field-of-view and adaptive optics assisted data (see Fig.4). After correction for completeness and extinction, they found $\gamma = 1.2 \pm 0.05$ in the inner half-parsec, i.e. a significantly flatter density than expected from classic cusp theory.

In a next step, [13] repeated this analysis with narrow-band imaging data, which allowed them to distinguish between hot and therefore massive, young stars and late-type stars, which are significantly older and therefore more probable to be dynamically relaxed. The old stellar population shows a flat projected density law close to Sgr A*, as can be seen in the right panel of Fig.3. This was confirmed by spectroscopic observations [15, 6]. [15] find $\gamma < 1.0$ for the late-type stars in the innermost few arcseconds at a 99.7% confidence level. It appears therefore clear that there is no classical stellar cusp around the black hole Sgr A*. Possible explanations for the absence of the cusp are, for example, that the nuclear star cluster is younger than its (two-body) relaxation time [45] or that stellar collisions in the dense cusp environment destroy the envelopes of giant stars and thus render them effectively invisible (e.g. [14]). In any case, one has to keep in mind that because of the extreme stellar crowding, we can only observe of the order 10% of the stellar sources close to Sgr A* [61].

5.2 Kinematics of the NSC

The kinematics of stars within a projected radius of $R \approx 1\,\mathrm{pc}$ of Sgr A* was examined by [66] and [62]. They focused on the late-type stellar population, i.e. the old and therefore possibly dynamically relaxed component. [66] found that the NSC rotates, with its rotation axis consistent with the direction of overall Galactic rotation. [62] confirmed this result, but pointed out that there are still important quantitative uncertainties in our knowledge of the cluster rotation. In the central parsec $v_{\mathrm{rot}}^2/\sigma^2 < 0.1$, i.e. rotation can normally be neglected in Jeans modeling.

The projected radial and tangential velocity dispersions vs. projected distance from Sgr A* are shown in the right panel of Fig.5. In the central parsec, they agree within their uncertainties. If the potential of the cluster were dominated completely by a point mass and if the stellar motions were isotropic, the velocity dispersion would be a projected, stellar density weighted Kepler law. Such a Kepler law is indicated by the red line in the right panel of Fig. 5. The fit is only approximate because of important unknowns as concerns the intrinsic structure of the cluster (see [62]). Nevertheless, two points become immediately clear. First, the projected velocity dispersion follows a Kepler law only at projected distances of $R < 0.5\,\mathrm{pc}$ (about $13''$). This means that it would be very hard, if not impossible, to detect Sgr A* unambiguously by kinematic measurements if it were located in another galaxy. Second, the velocity dispersion deviates from a Kepler law at $R > 0.5\,\mathrm{pc}$ because of the extended mass of the star cluster.

It is not trivial to model the mass distribution in the central parsec because of reasons such as: Sgr A* dominates the mass and thus the potential in the central parsec; we do not know the exact model for the shape of the NSC; we do not know the exact distribution of old stars in the central few 0.1 pc near Sgr A*; we do not know whether the mass-to-luminosity ratio is constant in the central parsec. [62] find that even a *decreasing* density of the extended mass toward Sgr A* could be consistent with the data, although this is considered unlikely given that the projected stellar surface density, i.e. the visible extended mass, increases toward Sgr A*. According to [62], the extended mass within 1 pc of Sgr A* is at least $0.5 \times 10^6\,\mathrm{M}_\odot$ under the assumption that its density increases toward Sgr A*. If the density of the extended mass is proportional to the stellar mass density and the mass of

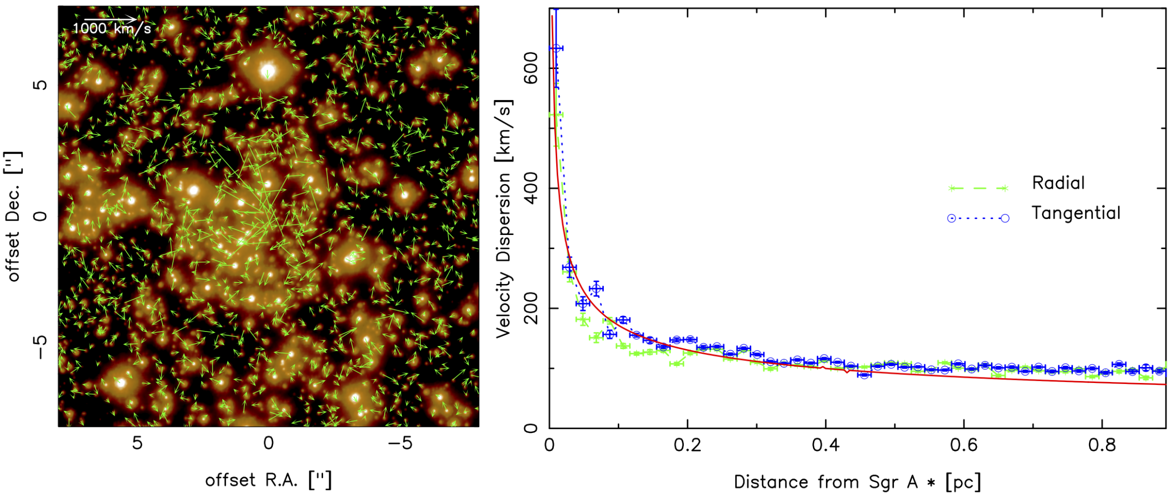


Figure 5: *Left*: NaCo adaptive optics assisted Ks-band image of the central $14'' \times 14''$. The arrows indicate the magnitude and direction of the stellar proper motions [62]. *Right*: Radial and tangential projected velocity dispersion for late-type stars vs. projected distance from Sgr A* [62]. The red line indicates an approximate fit with a projected Kepler law.

Sgr A* is fixed to $4.0 \times 10^6\,M_\odot$, then there are about $1.5 \times 10^6\,M_\odot$ of extended mass present in the central parsec.

6 Star formation at the Galactic center

Already at the end of the 1980s/beginning of the 1990s evidence was found for the presence of hot, massive stars in the central parsec of the GC (e.g. [1]). Later spectroscopic observations revealed ever more young stars and showed that they are concentrated toward Sgr A* and display a distinct rotation pattern (e.g. [40, 23, 36, 51]). A burst of star formation must have occurred $3 - 7 \times 10^6$ yr ago. Additionally, there is evidence for another star formation event about a 100 Myr ago. Note that repeated episodes of star formation are typical for NSCs (see Section 2).

Adaptive optics assisted integral-field and long-slit spectroscopy combined with ever more accurate measurements of stellar kinematics has brought significant progress to our understanding of the recent star formation event at the center of the Milky Way. At the moment, about 180 massive, early type stars (O/B giants and main sequence stars as well as Wolf Rayet stars) have been reliably classified. The total stellar mass formed during the star burst is about $1.5 \times 10^4\,M_\odot$ and its age $\sim 6 \times 10^6$ yr [54, 6]. There is some evidence for a significantly top-heavy (or bottom light) initial mass function for this star burst event (e.g. [52, 6]). About 50% of the young stars rotate clockwise (in projection on the sky) in a disk-like structure around Sgr A* and are strongly concentrated toward the black hole (e.g. [54, 43]). There exists some evidence for a second disk-like structure of young stars that rotates counter-clockwise (e.g. [5, 6]). The best model to explain the formation of the young, massive stars is currently that they formed *in situ* in a dense gas disk around Sgr A* (e.g. [54, 9, 38, 43, 6]).

The disk(s) of massive, young stars appear to be truncated inside a projected radius $R \leq 0.8''$ from Sgr A*. In this immediate vicinity of the black hole there exists a dense agglomeration of stars that is termed the *S-star cluster*[1]. Spectroscopic observations have shown that at least 75% of the stars brighter than $K = 16$ in this region are probably main sequence B-dwarfs [29, 20, 32]. The orbital parameters of a large fraction of these stars have been derived from their proper motions and, for the brighter ones, from their line-of-sight velocities. The eccentricities and orientation of the S-star orbits are consistent with an isotropic distribution, which means that these B-dwarfs are not directly related to the disks of massive, young stars [32].

It is highly improbable that the B-dwarfs in the S-cluster formed at their current location. It is also improbable that they formed at larger distances and migrated inward via dynamical friction because the involved timescales are too long compared to the main sequence lifetime of B dwarfs (see, e.g., discussions in [29, 20, 6]). One of the currently favored scenarios to explain the presence of the B main sequence stars near Sgr A* is that they formed at larger distances, were scattered into orbits that brought them close to Sgr A*, and subsequently captured (e.g. [37, 55]). Massive stars frequently form in binary or multiple systems. If a binary B-dwarf passes close to Sgr A*, one component can get captured on a tight, eccentric orbit, while the other one is ejected at high velocity. This is the so-called *Hills mechanism* [37]. The recent discovery of hypervelocity stars in the Galactic halo provides considerable support to this model. Several such unbound (to the Galaxy) hypervelocity stars have been discovered so far. They are A/B type main sequence stars and, if proper motions or line-of-sight velocities are available, can be traced back to the Galactic center [12].

7 Outlook

The unique role of the Galactic center as a template to understand black hole physics and the phenomena occurring at galactic nuclei in general is a strong motivator for continued research. Galactic center research has been extremely fruitful in the past decades and has been providing a large number of high impact scientific results. Continued monitoring of the GC from X-rays to the radio bands will maintain this stream of important new insights. A particularly important role is given to the monitoring of stellar orbits around the black hole, with the mid-term goal to detect and test effects of general relativity. While it may be possible to reach some of the proposed goals with current 8-10 m-class telescopes, given sufficiently long observational time series, the breakthrough is expected with new instruments and telescopes, such as the VLTI, the TMT, or the E-ELT (e.g. [59, 67, 69, 31, 33]). There exists also the tantalizing prospect of obtaining images of the accretion flow onto Sgr A* at resolutions corresponding to the scale of the event-horizon with sub-millimeter interferometry [17]. Exciting times lie behind us, exciting times lie ahead!

[1] note that the "*S*" stands simply for "*source*" and goes back to the designation of point sources in early speckle images, see, e.g.[24, 28].

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