The central light-year of the Milky Way: How stars and gas live in a relativistic environment of a super-massive black hole

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Abstract. The central region of our Milky Way is extremely active. It harbors the closest galactic nucleus that is accessible to us allowing us to study it in fine detail. Here we present a concise summary of some of the most recent results obtained with state of the art instruments providing sensitive measurements at their highest angular resolution. The central star cluster harbors a small cusp of high velocity mostly young and dusty stars that are in orbit around the 4 million solar mass super massive black hole (SMBH) Sagittarius A* (SgrA*). Molecular and atomic gas is streaming towards this region in the form of a spiral connecting it to the Circum Nuclear Ring. Using the Large Atacama Millimeter Array (ALMA) we investigated the kinematics and composition of this material in detail highlighting signatures of star formation and the interaction with a wind emerging form the direction of SgrA*. Using results from the Very Large Telescope (VLT) we will highlight the dynamics of the ultra-fast stars and present theories on their origin. We demonstrate that one of the innermost stars shows clear signs of relativistic motion in the deep potential well of the SMBH. The interaction of plasma with SgrA* reveals that matter is orbiting and is being accreted onto the SMBH to produce powerful flares. These are detectable all across the electromagnetic spectrum and help us to understand the region close to the event horizon of SgrA* which is currently under investigation using the Event Horizon Telescope (EHT).

1. Introduction

The Galactic Center is the closest center of a Milky Way. It is a very active region. In addition to stars, dust, gas at different temperatures and different states of ionization, we find an accreting super massive black hole (SMBH) that is located at the center of a small cluster of high velocity stars. The SMBH is Sagittarius A* (SgrA*, for an overview see, e.g., Eckart et al. 2017) with a mass of about 4 million solar masses. Its immediate surroundings can be observed across the electromagnetic spectrum - from the radio to the X-ray domain. The motion and radiation in that region is also subjected to relativistic effects. Using the motion of stars and ionized plasma we can map out space time in the vicinity of SgrA*. An overview of the region is given in Fig. 1.

In this brief overview, we present a brief description of the accretion processes onto SgrA*. Using results from a statistical analysis of the emission at different wavelengths and in infrared
polarimetry we explore the geometrical properties of SgrA* accretion flow.

At a scale of several parsecs we can investigate the X-ray Bremsstrahlung radiation of the plasma that surrounds SgrA* and the central stellar cluster. We also have a close look at the relativistic motion of stars, in particular the fast moving bright star S2. Very close to the last stable orbit around SgrA* we provide indications for hot plasma that moves at relativistic speeds. Finally we summarize the achieved and expected results from interferometric observations in the radio mm-domain and the infrared. A spectrum is shown in Fig. 2.

2. SgrA* Emission across the electromagnetic spectrum

Sketches of the broad band SgrA* spectrum during the quiescent and flaring phase allow us to discuss the important radiation mechanisms from gyro-synchrotron, Bremsstrahlung, and synchrotron to synchrotron self-Compton (SSC) radiation (Fig. 2). Frequently used data sets to base the broad band spectrum on are in the radio the compilation by Falcke et al. (1998) in the radio and Zhao et al. (2003), in the IR the data is often taken from publications using the VLT and Keck telescope (see e.g. Eckart et al. 2017 and references in there). The X-ray data are provided by, e.g., Baganoff et al. (2001, 2003), Porquet et al. (2003, 2008) and Neilsen et al. (2013). The theoretical coverage of the broad band spectrum is based on ADAF models by e.g. Yuan et al. (2003), Narayan et al. (1998, 2008). The non-thermal variable source associated with SgrA* can only be permanently observed in the radio to longer mid-infrared domain (see e.g. Schödel et al. 2011). For current angular resolutions and sensitivities it is below the detection/confusion limit during the quiescent phases in the X-ray domain. In the NIR domain a quiescent (though still variable) state may be reached (see, e.g., Witzel et al. 2018, GRAVITY Collaboration 2018b, Schödel et al. 2011). During its flare phase the variable source SgrA* is very well observable in all spectral domains also including harder X-rays (see e.g. Zhang et al. 2017).

2.1. The radio to sub-mm wavelength domain

SgrA* is highly variable in the millimeter and sub-millimeter radio domain. The region that dominates the variable flux density is most likely the nuclear accretion region close to the supermassive black hole SgrA* (e.g. Moscibrodzka et al. 2009, 2013). Given the positional coincidence and the short flare time scales it has been suggested from the beginning on (Baganoff et al. 2001) that the flares arise in the immediate vicinity of a supermassive black hole. Very likely flare mechanisms involve accretion of matter, heating of matter or magnetic acceleration. All of these processes will result in enhanced emission. In addition the flares will carry the signature of relativistic effects given the large mass close to which they originate. In particular relativistic lensing and boosting effects influence the shape of the flare light curves as they originate close to the black hole (e.g. Broderick & Loeb, 2005, 2006, Eckart et al. 2006ab). Essential for the understanding of the nature of radiating plasma close to SgrA* are effects that are described by General Relativistic Magneto Hydrodynamics (GRMHD; e.g., Moscibrodzka et al. 2017, 2014, 2013, Broderick et al., 2011, Shcherbakov, Penna, & McKinney 2012). This includes mid-planes or disks, jets, outflows and more diffuse and extended zones of emission. Emission on very short terms is also often explained by hotspots originating in the mid-plane. Due to the conservation of angular moment these mid-plane often forms in GRMHD simulations (e.g. Meyer et al. 2006ab, Eckart et al. 2006ab, Broderick & Loeb, 2005, 2006, Bao & Ostgaard 1995).

A detailed statistical analysis of the emission in the sub-millimeter and radio bands allows for an investigation of the radiation mechanism and the origin of the radiation. The frequency bands around 345 GHz and 100 GHz are well suited for such a program. In Subroweit et al. (2016) and Borkar et al. (2016) report on the results of the investigation. The authors used the Australia Telescope Compact Array (ATCA) in 2010 to 2014 and the Large Apex Bolometer
Figure 1. a) The central parsec of the Milky Way seen with the near infrared camera and adaptive optics system NACO at the ESO VLT. Two narrow band images (at 2.18\(\mu\)m and 2.36\(\mu\)m) were combined with a broad band image at 3.8\(\mu\)m to obtain a pseudo-color image. The red extended emission is due to gas and dust in the mini-spiral or due to circumstellar material of individual stars (see section 3 and references therein). b) The orbits of three of the innermost stars orbiting SgrA*. Star S2 can be used to determine the relativistic nature of the supermassive black hole environment (see section 4.1; GRAVITY Collaboration 2018a, Parsa et al. 2017, Eckart et al. 2018b). c) Sketch of a possible scenario in the immediate vicinity of SgrA* (black circle at the center) with material in orbit around it (grey band with yellowish source component as a hotspot; see section 4.2; GRAVITY Collaboration 2018a, also, e.g., Meyer et al. 2006ab, Eckart et al. 2006ab).
Camera (LABOCA) at the APEX telescope in Chile between 2008 and 2014. The effort was supported by 345 GHz literature data for the years 2004 to 2009. The ATCA measurements revealed six 1.5 to 3 hour flux density excursions between 0.5 and 1.0 Jy.

![SgrA* spectrum](image)

**Figure 2.** Spectrum of SgrA* in quiescent and flaring state (see e.g. Yuan et al. 2003, Narayan et al. 1998, 2008).

The Galactic Center is also a target for the Atacama Large Millimeter/submillimeter Array (ALMA). Here Moser et al. (2017) present 0.5” resolution maps of continuum emission and line emission from a variety of atomic and molecular species. These data could be used to derive estimates of the density and temperature of the gas close to the Galactic Center. The continuum emission could be used to derive the spectral indices ($S\propto \nu^\alpha$) of the emission. Towards different source components Moser et al. (2017) find indices for SgrA* of $\alpha=0.5$ at 100 - 250 GHz indicating a steep spectrum and around $\alpha=0.0$ at 230 - 340 GHz interval pointing at a rather flat spectrum. From other observations we know the overall spectrum of SgrA* then drops strongly if one goes towards the far-infrared domain at frequencies of 350 GHz and above (Marrone 2006, Marrone et al. 2006a,b, Eckart 2012). Investigating Galactic Center sources other than SgrA*, one find regions that indicate contributions from Bremsstrahlung (around $\alpha=-0.1$). One also find spectral contributions origination from cold dust that may result in flat or inverted spectral indices (Garcia-Marin et al. 2011).

The radiation between the sub-millimeter and radio domain is linked via the process of adiabatic expansion. Subroweit et al. (2016) and Borkar et al. (2016) show for the Galactic Center SgrA* measurements how as a result from adiabatic expansion, the peak flux decreases and the spectral width of the component increases. The corresponding plasmon blobs may be generated in the temporary disk or corona component of SgrA*.

Subroweit et al. (2016) pointed out that a shifted power law can describe the radio sub-
millimeter light curves, just like the near-infrared (NIR) light curves as shown by Witzel et al. (2012). The spectral index of the radio power laws (about 4.0 for APEX data and about 4.7 for the ATCA data) is very similar to the value of 4.0 found in the optically thin NIR wavelength regime (Witzel et al. 2012, 2018). This is a very strong indication that the optically thick radio flares and the optically thin NIR flares belong to the same population of flares. Hence, the fluxes in both wavebands (radio/sub-mm and NIR) originate from the same source components and statistically reflect the same single state red noise process. The overall analysis of the radio/sub-mm flare emission indicates that the expansion rate of the plasmons is of the order of a tenth of the speed of light and the turnover frequencies of the synchrotron components are located just above the 300-400 GHz region. This also means that for the brighter radio/sub-mm flares that Subroweit et al. (2016) investigated the contribution of flares from faster expanding components or components with turnover frequencies well below 300 GHz is small.

2.2. SgrA* in the near-infrared wavelength domain

In the NIR the spectral index of the flare emission is consistent with optically thin synchrotron radiation. In general the spectral index reflects the index of the relativistic electron energy distribution. For the brighter flares we obtain $\alpha_{\text{NIR/MIR}} = -0.7$ ($S \sim \nu^{1+\alpha}$). Several observational facts indicate that the spectral index might be steeper for fainter flares (see summary by Bremer et al. 2011 and references there in; see also Witzel et al. 2018). A picture emerges in which the distribution of spectral indices depends on the brightness at 2$\mu$m wavelength. It can successfully be expressed by an exponential cutoff proportional to $\exp[-(\nu/\nu_0)^{0.5}]$. This cut off is due to synchrotron losses and $\nu_0$ is a characteristic cutoff frequency. If $\nu_0$ varies between the NIR and sub-mm domain and if the sub-mm flux density varies around one Jansky then the spectral properties of SgrA* can very well be described by the above expression. On the one hand it appears that infrared 'flares' are flux density excursions of the variable emission of SgrA* in the NIR and that they reflect a stationary red-noise flux density distribution of the form $p(x) \propto x^{-\beta}$ with a power-law index $\beta_{\text{NIR}} \sim 4$ (Witzel et al. 2012). On the other hand it seems that some of the variation is modulate by relativistic effects of emitting plasma that orbits the super massive black hole.

2.3. Infrared Polarimetry probes the structure of SgrA*

The geometry of emitting source components reflects itself in the polarization properties provided by the emission process. For SgrA* we find a strongly linear polarized NIR continuum emission. The source was regularly observed at a wavelength of 2.2$\mu$m, using the NACO instrument at ESO VLT. The observations cover the interval form 2004 to 2012. During this time many flares could be measured in the NACO polarization mode in the NIR K-band. The observations revealed that there is a preferred polarization angle ($13^\circ \pm 15^\circ$) and that the polarization degrees are usually about 20% for bright flares. For flares stronger than 5mJy (Shahzamanian et al. 2015) could show that the exponent of the number density histogram for polarized flare fluxes is very close to the value found for the NIR flare distribution ($dN/dS \sim 4$; Witzel et al. 2012). This implies that the accreting SgrA* system consists of the black hole, a wind or jet, and a potential temporary disk as it is indicated by simulations in the form of a mid-plane and represents a rather stable geometrical configuration.

2.4. Properties of SgrA* in the X-ray and $\gamma$-ray domain

Radiatively inefficient accretion flows (e.g. advection dominated accretion flows - ADAF; Narayan et al. 1998) or a strong involvement of a jet-disk system can be identified by a difference between the bolometric luminosity and the Eddington luminosity of the source. This is the case for SgrA*. Here, the bolometric luminosity amounts to $L_{\text{bol}} \sim 10^{36}$ erg/s whereas the Eddington luminosity gives a value of $L_{\text{Edd}} = 3 \times 10^{44}$ erg/s (Yuan et al. 2003).
SgrA* also exhibits strong variability in the X-ray domain. A variable unresolved source component is embedded in a 1" diameter quiescent Bremsstrahlung component. The first X-ray flares of SgrA* were discovered by Baganoff et al. (2001). A statistical investigation shows that one finds typically one bright X-ray flare per day (Neilsen et al. 2013), which is about 10 times the quiescent (2-8 keV) Bremsstrahlung luminosity of SgrA* of about $3.6 \times 10^{33}$ erg/s (Baganoff et al. 2003; Nowak et al. 2012). However, flares can have a substantial brightness. Flux density excursions of more than 160 times the quiescent flux value have been reported (Ponti et al., 2017, Porquet et al. 2003, 2008; Nowak et al. 2012).

Witzel et al. (2012) have investigated the statistics of the variable NIR emission, that is dominated by optically thin synchrotron radiation emission with a spectral index of $\alpha \sim -0.7$ (here, $\alpha$ is defined via $S_\nu \propto \nu^{\alpha}$). Comptonization requires the least demanding conditions to produce the observed X-ray flux densities. Low energy relativistic electrons with $\gamma \sim 10^3$ and only a moderate volume densities of $10^6$ cm$^{-3}$ are required (e.g. Eckart et al. 2004, 2008, Yusef-Zadeh et al. 2006, Mossoux et al. 2016). A recent detailed statistical analysis of the X-ray flare flux distribution was performed by Neilsen et al. (2015). The authors could show that the flux density counts of the flares follow a distribution with a power-law index $\beta_{\rm X-ray} \sim 2$. Neilsen et al. (2015) highlight that in case the X-ray flux density is produced by the Synchrotron Self Compton (SSC) effect this index is in agreement with the index of $\beta_{\rm NIR} \sim 4$ found for the NIR flare flux distribution (Witzel et al. 2012). Therefore, one can assume that the X-ray flare emission is dominated by SSC radiation and that pure synchrotron flares are rare or absent. This agrees with the modeling result presented by Eckart et al. (2012) who investigated 8 flares for which simultaneous NIR- and X-ray measurements were available. The calculations show that for NIR synchrotron flares the corresponding SSC X-ray flare are in agreement with a volume density of relativistic electrons larger than $10^6$cm$^{-3}$ with a typical expectation value around $10^9$cm$^{-3}$. This is high but not excessive (Eckart et al. 2012 and Mossoux et al. 2016). The advantage is that the electron energies only need to be of the order of $10^3$ eV rather than above $10^6$ eV if only synchrotron radiation is involved in the X-ray domain (see discussion by Eckart et al. 2006a, 2008, 2012). In the pure synchrotron case also the magnetic fields will be very large, in the range of 10-100 G (Baganoff et al. 2001, Markoff et al. 2001, Yuan et al. 2004).

No unique $\gamma$-ray counterpart for SgrA* has been reported yet, although the overall SgrA complex has indeed been detected by ground-based Cherenkov Telescopes (e.g. Aharonian et al. 2004, Kosack et al. 2004, Albert et al. 2006). Photons in that energy range are most likely be comptonized NIR or X-ray photons. The MAGIC Imaging Atmospheric Cherenkov Telescopes have monitored SgrA* over the time interval from 2012 to 2015 (Ahnen et al. 2017). The observations had the goal to detect elevated high-energy flare emission above an energy of 100 GeV as they had been predicted for the pericenter passage of the Dusty S-cluster Object mid-2014 (e.g. Valencia-S. et al. 2015). No significant excess variability or emission was detected and previous results on the SgrA* $\gamma$-ray spectrum were confirmed.

3. Conditions for Forming Young Stars

3.1. The environment of the central stellar cluster: Shadow of the Circum Nuclear Disk

The Circum Nuclear Disk (CND) is part of the central nuclear arrangement of the Milky Way. In Fig.3 we show the location of the CND as traced through its shadow in X-ray light. The figure also shows where the mini-spiral connects to the CND leading towards the central stellar cluster. It is very prominent in the radio/sub-millimeter/ Far-infrared domain. Recently Mossoux & Eckart (2018) report on the first detection of the CND as an X-ray "shadow" against the diffuse X-ray background of the entire region. Thanks to the 4.6 Ms of Chandra observations of the Galactic Center region, as described by Mossoux & Eckart (2018) aimed at The 4.6 Ms of ACIS-I and ACIS-S/HETG Chandra observations covering the time between 1999 to 2012 are the basis for this investigation. The detection of the CND shadow allowed the authors to obtain
Figure 3. Sub-millimeter, NIR, and inverted X-ray composite image of the inner 5.6 pc×5.6 pc of the Galactic Center. **Yellow:** Stellar background from a combination of ISAAC 1.19µm, 1.71µm, and 2.25µm narrow filters (from Nishiyama & Schödel 2013); **red:** NACO L’-band dust emission. Sub-millimeter ALMA measurements: **blue:** GC mini-spiral is traced by 250 GHz continuum and H39α ionized emission; **green:** Inner regions of the CND (in projection) shine in CS(5-4) molecular line; **cyan:** N2H+ (1-0) molecular-gas major structures coincide with foreground dark clouds (Moser et al. 2017). **Extended white shadow:** This shadow shows the footprint of the circumnuclear disk as seen by the depression of the X-ray diffuse emission observed with CHANDRA (Mossoux & Eckart 2018). **Enclosed with white lines:** Prominent dust extinction patches, possibly star-forming regions, visible as dark silhouettes over the bright stellar background are enclosed with white lines. Some emission regions are also identified e.g. the South East Extension (SEE), that towards the west of it (SEW), the V-cloud, the Central Association (CA) and the Triop (see Moser et al. 2017 for more information).

temperatures and column densities for specific regions that could now sensibly be defined. The general model that emerges from this investigation is that the plasma at the location of the CND is cooler in general and may, in fact, act as a barrier between the hot plasma insight and outside of the CND.
3.2. The central light year contains young stars

Several observational findings suggest that star formation is both permanently and episodically an ongoing process in the central stellar cluster very close to the supermassive black hole SgrA*. This is supported by the presence of luminous He-stars (Krabbe et al. 1991 Ghez et al. 2003), the presence of young stars based on a 2µm NIR color excess (Buchholz, Schödel, Eckart 2009), as well as the presence of several dusty objects like the DSO (Meyer et al. 2014, Eckart et al. 2013). The CND harbors dense gas and dust clouds that may be (or are) the place of star formation if only a suitable trigger mechanism is applied. This could be additional compression of the gas elevating the density above the Jeans density so that clouds can collapse to form stars. However, this appears to be difficult for the central few arcseconds since the strong gravitational forces close to SgrA* may tend to disrupt dense clouds and may prevent classical forms of star formation.

For the massive young He-stars, one assumes that they have been generated in a massive gaseous disk (Nayakshin, Cuadra & Springel 2007, Nayakshin & Cuadra 2005), since they are found to be located in a stellar disk within the central cluster (Nayakshin & Cuadra 2005, Levin & Beloborodov, A.M., 2003; Alexander et al. 2008; Bonnell & Rice 2008). While this process is rather episodical the bulk of the younger lower mass stars may have been formed by a different, more steady process. Jalali et al. (2014) could show that molecular clumps of a mass of about 100 M⊙ at a radius of less than 0.2 parsec may start forming stars due to the orbital compression of the gas during pericenter passage close to the black hole at the center. These massive clumps may may lose angular momentum via dissipative cloud-cloud collisions in the CND. Consequently, they fall towards the center and can form stars. Hence, if their temperature is similar to that found in CND clumps they are subject to black-hole supported star formation while they go through periape. The higher gas temperature in the Nayakshin case leads to the formation of more massive stars. The Jalali-mechanism works with substantially lower gas temperatures (e.g. 50K-100K as found in the CND) and can result in the formation of low and intermediate mass stars. This mechanism may be the reason for the presence of the red dusty DSO-like sources in the central cluster. This population of stars may also include the high velocity S-stars with masses between 8 and 14 M⊙ (Habibi et al. 2017) or even lower mass stars (around 2 M⊙), just like the Dusty S-cluster Object (DSO; e.g. Zajacek et al. 2014, 2016, 2017, Valencia-S. et al. 2015, Peissker et al. 2019 in prep.).

The presence of young stars close to the supermassive black hole implies that they must have been formed there. The comparatively young ages of only about a few times 10⁶ years in combination with their orbital eccentricities which are not very large suggest that the formation of the massive luminous central emission line stars must have taken place in-situ. Most likely they formed in a dense dusty accretion disk.

3.3. The DSO: The Dusty S-cluster Object

A dusty source had been approaching the black hole SgrA* and passed by in 2016. The faint DSO was discovered in 2011 (Gillessen et al. 2012) on its way towards the supermassive black hole SgrA*. The object is very faint in the NIR K-band, however, well detectable in its Brγ-line emission and considerable brighter continuum emission of the longer wavelength infrared L-band. After its discovery large monitoring programs were started by several groups. We covered the investigation of the source properties between the years 2006 to 2016 using the SINFONI camera at the ESO VLT.

The NIR 2.2 µm continuum emission of the DSO was first found Eckart et al. (2013) making use of the NACO camera at the ESO VLT. A confirmation of its detection could also be achieved using public data of the NIRC system at the Keck telescope (Eckart et al. 2014). Furthermore, the continuum source clearly showed itself in SINFONI data obtained at the VLT (Eckart et al. 2015). As the source passed by SgrA* it showed a very obvious transit from a red- to a
blue-shifted Brγ-line emission (Valencia et al. 2015). Given that the source was not disrupted during and after the flyby around SgrA* - and given the fact that it stayed very compact in its continuum and line emission (Valencia et al. 2015, Witzel et al. 2014), it became obvious that it is not an extended and coreless cloud as previously claimed (e.g. Gillessen et al. 2012, Pfuhl et al. 2015, Schartmann et al. 2015). 

Shahzamanian et al. (2016) could detect and measure the polarization of the DSO as it was descending towards its periapse close to SgrA*. These observations showed that it is very likely a compact dust-enshrouded - probably young - star. The high degree of polarization implies that the scattering material is not distributed highly symmetrically around the source (see e.g. Zajacek, Karas & Eckart 2014, Zajacek et al. 2016). The data point at a combination of a bow shock and a bipolar wind propagating and surrounding a central star (Shahzamanian et al. 2016, Zajacek et al. 2014, 2016, 2017, Valencia-S. et al. 2015).

4. Tracing relativistic effects close to SgrA*

4.1. Relativistic motion of the star S2

Infrared spectroscopy measurements using the integral field spectrometer SINFONI at the ESO VLT in combination with recent interferometric observations with the GRAVITY system at the ESO Very Large Telescope Interferometer (VLTI) have lead to the detection of the gravitational redshift on the orbit of the star S2 near the Galactic center massive black hole (GRAVITY Collaboration 2018a). Orbiting stars are sensitive probes of the gravitational field of SMBHs. In particular this is true for the star S2 in the Galactic center. Here, the orbit takes about 16 years and the pericenter is reached at about 120 AU corresponding to 1400 Schwarzschild radii. During pericenter the star had an orbital velocity of about 7650 km/s (GRAVITY Collaboration 2018a). Therefore, relativistic effects start to become important. In particular the observational capabilities now allow us to detect the first-order effects of Special and General Relativity. The orbit of S2 has been measured over the past 26 years, leading to a detailed knowledge of its proper motion and radial velocity as a function of time (i.e. orbital phase). These data have been obtained using the SINFONI and NACO adaptive optics instruments on the ESO Very Large Telescope. The passage through pericenter in May 2018 could be observed with GRAVITY which is a four-telescope interfemeteric instrument. The combined gravitational redshift and relativistic transverse Doppler effect for the star S2 amounts to a maximum velocity offset from the Newtonian motion of about 200 km/s. The GRAVITY measurements indicate that the S2 motion is inconsistent with motion on a purely Newtonian orbit. The new interferometric measurements also allow the Gravity collaboration to give a very precise determination of the black hole mass of $M_{BH} = (4.100 \pm 0.034) \times 10^6 M_\odot$ and a distance to the object of $R_0 = 8.122 \pm 0.031$ kpc. Here we quote the values obtained with Schwarzschild precession of the orbit.

In order to investigate the physical conditions close to the supermassive black hole SgrA* one needs suitable test particles. This could be gas to study the plasma in the black hole vicinity or stars to study the gravitational physics in detail. Here the S-star cluster surrounding SgrA* is ideally placed an provides stars very close to the central region. Hence, the stars S2, S38, and S55/S0-102 are ideally suited to perform dynamical tests of general relativity. Here, proper motions and radial velocities covering a large time span are available. The possibility of detecting even fainter stars inside the S2 orbit has been discussed by Zajacek & Tursunov (2018). Using these stars, recently, Parsa et al. (2017) derived a black hole mass of $M_{BH} = (4.15 \pm 0.13 \pm 0.57) \times 10^6 M_\odot$ and a distance to the object of $R_0 = 8.19 \pm 0.11 \pm 0.34$ kpc. Despite the fact that no interferometric data were used here, and within the therefore larger uncertainties, these values are in excellent agreement with the exact values obtained by the more elaborate fit using GRAVITY data. The authors involved a first-order post-Newtonian approximation to determine stellar orbits close to the black hole covering a wide range of periapse
Figure 4. a) Sky projected orbit of the flare emitting source component. The cross indicates the position of the SgrA* mass center based on the S2 orbit. The positions can be subject to lensing, effects of relativistic beaming as well as azimuthal shearing of the emitting hotspot (see GRAVITY Collaboration (2018b) for more detailed explanations). b) The dependence of the orbital period $P$ on the orbital radial distance $R$ in comparison to the three flare events in which orbital motion was detected (see GRAVITY Collaboration 2018b). The lines indicate the dependency for a black hole spin of $a = -1, 0, +1$ (Schwarzschild 1916; Bardeen et al. 1972). All three flares can be accounted for by the same Schwarzschild $R_g \sim 6 - 10 R_g$ circular orbit with a period of about 45 minutes.

4.2. Relativistic motion of plasma blobs close to the supermassive black hole
Recent interferometric measurements with GRAVITY at the VLTI have lead to the detection of orbital motions of synchrotron radiation source components near the last stable circular orbit of the supermassive black hole SgrA* (GRAVITY Collaboration 2018b). The GRAVITY
Collaboration reports the detection of continuous changes in position and polarization of SgrA* during positive flux excursions (flares) in the near-infrared K-band. Over a few ten minutes the flux density centroid of the SgrA* emission performed a motion around a central position with typically 150 micro-arcsecond diameter (Fig. 4a). At the distance of SgrA* this motion corresponds to about 0.3 times the speed of light. The rotation of the polarization angle took also about 45 minutes and indicates the presence of a strong poloidal magnetic field. The Gravity collaboration finds that this motion corresponds to a close to face-on circular motion of a hotspot at about 6-10 times the gravitational radius around an approximately 4 million solar mass black hole. The emission must originate from synchrotron emission in the infrared. This emission region lies just beyond the innermost stable pororgrade orbit (ISCO) of a high spin Kerr black hole. Alternatively, it could originate from a region close to the ISCO of a retrograde high spin Kerr black hole (Fig. 4b).

A close investigation of the brightest X-ray flare lightcurves from SgrA* (including the latest one reported by Ponti et al. 2017) shows that they have the shape one expects from plasma blobs that are in orbit around the SMBH close to the last stable orbit (Karssen et al. 2017 and Eckart et al. 2018ab). It is likely that this finding is also true for the brightest NIR flares since they are usually correlated with synchronous NIR flares (see e.g. Eckart et al. 2012). The brightest flares in the X-ray domain are less likely contaminated by fainter flare emission which may be the case in the NIR and particular the radio/sub-mm domain. As a characteristic feature these bright flares all have a shoulder on the ascending part of the flare lighcurve. We interpret this as being due to the lensing amplification of the otherwise boosting dominated light curve. Here, it is important to note that the broad boosting signature sets in before the lensing occurs.

It shows that by fitting the flare shapes in a scale free way (e.g. in gravitational time scales $GM/c^3$) by making use of the predicted theoretical light curves one can, by introducing the scaling via the measured flare length, determine the mass of the black hole the plasma blob is orbiting. This is possible since the orbital period in seconds is proportional to the orbital period in geometrical units and the black hole mass in solar masses (Karssen et al. 2017, Dovciak 2004). This procedure underlines the high degree of relativity present in the immediate vicinity of SgrA*.

### 4.3. Shadow of the supermassive black hole

Upcoming sub-millimeter very-long-baseline-interferometry (VLBI) maps of Sgr A* obtained by the Event-Horizon-Telescope (EHT) will help to provide essential evidence for the existence and nature of the SgrA* SMBH (Mizuno et al. 2018). It may be possible to determine from the expected maps if a Kerr BH - as it is predicted by Einstein’s theory of general relativity (GR) - or an alternative compact object is present. A key element for the interpretation of the results will be general-relativistic magnetohydrodynamical (GRMHD) simulations that include radiative transfer to describe the expected shadow within the accretion flow towards the Black Hole. However, the differences between Kerr Black Holes and alternative very compact scenarii are very likely so small that it may prove to be difficult to distinguish between these options.

The Event Horizon Telescope project (EHT) is a high angular resolution very long baseline (VLBI) interferometer at mm-wavelengths of SgrA*. One of its goals is to measure the shadow of the SMBH. This is a region with highly suppressed emission seen against the putative emission of orbiting luminous plasma all around the supermassive black hole. The region is largely free of emission due to the light bending properties of the large, highly concentrated mass (see Falcke, Melia & Agol 2000). The size one predicts in the case of SgrA*, if the conditions are favorable to see the shadow, i.e. a clean accretion process and a suitable inclination of the accretion disk, lies around 30–50μas. It needs to be pointed out, however, that the detection of a shadow will not strictly be the prove for the existence of a supermassive black hole at the center of the Milky Way. Putative alternative solutions for a massive object still need to be rejected (for a
Figure 5. The gravitational potential that is measured by a number of tests of gravity presented in comparison to the mass responsible for the potential (based on Psaltis 2004). We have selected terrestrial labs, the precession of Mercury orbit, light deflection and the Shapiro delay in the solar system, the Hulse-Taylor pulsar, QSO QPOs, and the gravitational wave detection GW150914 (Abbott et al. 2016). In addition we show the results for the Galactic Center S2 orbit presented by the GRAVITY Collaboration (2018a), Parsa et al. (2017) and the X-ray lightcurve fitting presented by Karssen et al. (2017) and the GRAVITY Collaboration (2018b).

summary see, e.g., Eckart et al. 2017). In addition the observing wavelength must be of the order of 1 mm or less in order to overcome the effects of the interstellar scattering screen along the line of sight toward Sgr A*. Another unknown difficulty for imaging may originate from a phenomenon similar to the speckle effect known from optical/infrared wavelength. This effect may set in when the scattering screen becomes transparent but potentially results in multiple images of the source under observation. Recently, Ru-Sen Lu et al. (2018) published first 1.3 mm results obtained with an interferometer similar to the EHT. The authors detected an intrinsic structure of Sgr A* at approximately the size scale expected for the black hole shadow. While their data is in general consistent with the amplitudes and phases expected resulting from a shadow, a detailed image that clearly shows the disk structure has not been published yet.

5. Charge of supermassive black hole
According to the famous no-hair theorem, any black hole in general relativity can be fully characterized by only three externally measurable parameters: mass, spin and electric charge. However, the later is often set to be zero due to neutralization occurring by the presence of a plasma. It appears, however, that both classical and relativistic processes can lead to the formation of non-zero electric charge of black holes, which is potentially measurable (Zajacek et al. 2018). Based on the classical arguments the net black hole charge can arise from the
difference in thermal velocities of electrons and protons in the fully ionized plasma surrounding SgrA*. This charge has an upper limit of about $10^9$ C and is of a transient nature on the viscous time-scale. More strictly, the black hole can induce a net electric charge due to the frame dragging effect of the twisting of magnetic field lines close to the event horizon. In other words, rotation of a black hole immersed into magnetic field induces an electrical field and associated charge. There are known pieces of evidence that strong and highly oriented magnetic field is present in the vicinity of a supermassive black hole SgrA* (Eatough et al. 2013, Morris 2015, GRAVITY Collaboration 2018b) with a strength around $\sim 10G$. This implies that the gravitationally induced electric charge of SgrA* is $\leq 10^{15}$ C. This charge is too weak to be able to perturb the spacetime metric, hence, Kerr metric approximation can be still used. On the other hand, for the motion of charged particles such as electrons and protons this charge can significantly shift the location of the ISCO around SgrA*. Even such a small charge of the order of $10^6 - 10^{10}$ C can mimic the spin of SgrA* of $a \approx 0.6$. The charge of SgrA* is plausibly positive due to expected alignment of the accretion flow with the black hole rotation close to the horizon. Moreover, according to Komissarov theorem (Komissarov 2004), a plasma surrounding the black hole cannot screen the central charge of the black hole at least within the ergo-sphere. Thus, it is likely that SgrA* possess a small positive electric charge with an upper limit $10^{15}$ C. A novel observational test of the presence of a charge of SgrA* has been proposed (Zajacek et al. 2018), based on the observations of a flattening and decrease in the thermal bremsstrahlung surface brightness profile inside the region coinciding with the location of S-cluster. With this, using the recent X-ray observations of Chandra X-ray observatory, we put observational upper limit on the charge of the supermassive black hole SgrA* as $\leq 3 \times 10^8$ C.

6. Summary and Conclusions

We have shown that the center of the Milky Way presents itself as a region in which stars and gas are exposed to the relativistic environment of the super massive black hole Sagittarius A* (SgrA*). In addition to adaptive optic measurements of the stellar spectra and positions over the years, the new GRAVITY interferometric instrument allows state of the art sensitive measurements at the highest angular resolution currently possible in the near-infrared. The combination of these instruments allows us detailed determinations of the proper motion and radial velocities of the stars in the central arcsecond. The presence of dusty objects, young stars and plenty of molecular gas in the Circum Nuclear Ring, as well as the mini-spiral, indicates that periodic and ongoing star formation may be prevalent in that region.

The interaction of hot gas with the central supermassive black hole SgrA* reveals that matter can be detected as it is orbiting the center close to being accreted onto SgrA*. This process is most likely responsible for the flare emission we observe all across the electromagnetic spectrum from SgrA*.

Instruments like GRAVITY at the VLT in the near-infrared and the Event Horizon Telescope (EHT) in the sub-mm domain now allow us to study and understand the physics close to the event horizon of SgrA*. In Fig.5 we compare the gravitational potential that is measured by a number of tests of gravity to the mass responsible for the potential (based on Psaltis 2004). This figure uses results from terrestrial labs, the precession of Mercury, light deflection and the Shapiro delay in the solar system, the Hulse-Taylor pulsar, QSO QPOs, and the gravitational wave detection GW150914 (Abbott et al. 2016). In addition we show the results for the Galactic Center S2 orbit presented by the GRAVITY Collaboration (2018a), Parsa et al. (2017) and the X-ray lightcurve fitting presented by Karssen et al. (2017) and the GRAVITY Collaboration (2018b). Due to interferometric measuring techniques we can now study the effects of relativity in the high mass regime.
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