Nobel Lecture: A forty-year journey*

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I. PROLOGUE

A **black hole** [e.g., Wheeler (1968)] conceptually is a region of space-time where gravity is so strong that within its event horizon neither particles with mass, nor even electromagnetic radiation (massless photons), can escape from it. Based on Newton's theory of gravity, Rev. John Michell [in 1784 (Michell, 1784)] and Pierre-Simon Laplace [in 1795 (Laplace, 1795)] were the first to note that a sufficiently compact, massive star may have a surface escape velocity exceeding the speed of light. Such an object would thus be "dark" or invisible. A proper mathematical treatment of this remarkable proposition had to await Albert Einstein's theory of general relativity in 1915/1916 (henceforth GR) (Einstein, 1916). Karl Schwarzschild's (1916) solution of the vacuum field equations in spherical symmetry demonstrated the existence of a characteristic **event horizon** of a mass M, the **Schwarzschild radius** $R_s = 2\ \mathrm{GM/c^2}$, within which no communication is possible with external observers (Schwarzschild, 1916). It is a "one-way door." Kerr (1963) generalized this solution to spinning black holes. However, these solutions refer to configurations with sufficiently high symmetry, so that Einstein's equations can be solved analytically, and there was doubt about whether such cases were typical. Roger Penrose, one of the other recipients of this year's Nobel Prize, dropped the assumption of spherical symmetry, and analyzed the problem topologically (Penrose, 1963, 1965). Using the key concept of "trapped surfaces," he showed that any arbitrarily shaped surface with a radius less than the Schwarzschild radius is a trapped surface, and the radial direction becomes timelike as one passes through the horizon. Any observer is then inexorably pulled toward the center where time ends. All the matter that forms the black hole resides at this single moment in time, the singularity.

From considerations of the information content of black holes, there is significant tension between the predictions of GR and general concepts of quantum theory [e.g., Susskind (1995), Maldacena (1998), and Bousso (2002)]. It is likely that a proper quantum theory of gravity will modify the concepts of GR on scales comparable to or smaller than the Planck length, $l_{Pl} \sim 1.6 \times 10^{-33}$ cm, remove the concept of the central singularity, and potentially challenge the interpretation of the GR event horizon (Almheiri *et al.*, 2013).

But are these bizarre objects of GR actually realized in nature?

II. OVERTURE: X-RAY BINARIES AND QUASARS

Astronomical evidence for the existence of black holes started to emerge sixty years ago with the discovery of variable x-ray-emitting binaries in the Milky Way [Giacconi *et al.* (1962) and Giacconi (2003) (Nobel Lecture 2002)] on the one hand, and of distant luminous "quasistellar radio sources/objects" (QSOs, Schmidt, 1963) on the other. For about two dozen x-ray binaries, dynamical mass determinations from Doppler spectroscopy of the visible primary star established that the mass of the x-ray-emitting secondary is significantly larger than the maximum stable neutron star mass, ~2.3 solar masses (McClintock and Remillard, 2004; Remillard and McClintock, 2006; Özel *et al.*, 2010; Rezzolla, Most, and Weih, 2018). The binary x-ray sources thus are excellent candidates for stellar black holes (SBHs). They are probably formed when a massive star explodes as a supernova at the end of its fusion lifetime and the compact remnant collapses to a SBH. The measurements of gravitational waves from inspiraling binaries with LIGO (Abbott *et al.*, 2016a, 2016b, Nobel Prize 2017) have recently provided very strong and arguably conclusive evidence for the existence of SBHs.

The luminosities of QSOs often exceed the entire energy output of the Milky Way Galaxy by three to four orders of magnitude. Furthermore, their strong high energy emission in the UV, x-ray, and γ-ray bands as well as their spectacular relativistic jets can most plausibly be explained by accretion of matter onto massive black holes [henceforth MBHs, e.g., Lynden-Bell (1969), Shakura and Sunyaev (1973), Blandford (1999), Yuan and Narayan (2014), and Blandford, Meier, and Readhead (2019)]. Between 7% (for a nonrotating Schwarzschild hole) and 40% (for a maximally rotating Kerr hole) of the rest energy of an infalling particle can, in principle, be converted to radiation outside the event horizon,

*The 2020 Nobel Prize for Physics was shared by Roger Penrose, Reinhard Genzel, and Andrea Ghez. This paper is the text of the address given in conjunction with the award.

one to two orders of magnitude greater than nuclear fusion in stars. To explain powerful QSOs by this mechanism, black hole masses of 10^8 to 10^9 solar masses and accretion flows between 0.1 to 10 solar masses per year are required. QSOs are located (without exception) in the nuclei of large, massive galaxies [e.g., Osmer (2004)]. QSOs represent the most extreme and spectacular among the general nuclear activity of most galaxies.

A conclusive experimental proof of the existence of a SBH or MBH, as defined by GR, requires the **determination of the gravitational potential on the scale of the event horizon**. This gravitational potential can be inferred from spatially resolved measurements of the motions of test particles (interstellar gas, stars, other black holes, or photons) in close orbit around the black hole (Lynden-Bell and Rees, 1971). Until very recently, this ambitious test was not feasible. A more modest goal then is to show that the gravitational potential of a galaxy nucleus is dominated by a compact nonstellar mass and that this central mass concentration cannot be anything but a black hole because all other conceivable configurations either are more extended, are not stable, or produce more light [e.g., Maoz (1995, 1998)]. Even this test cannot be conducted (yet) in distant QSOs. Lynden-Bell (1969) and Lynden-Bell and Rees (1971) proposed that MBHs might be common in most galaxies (although in a low state of accretion). If so, dynamical tests are feasible in nearby galaxy nuclei, including the center of our Milky Way.

Over the past fifty years, since these seminal papers, increasingly solid **evidence for central "dark" (i.e., nonstellar) mass concentrations** has emerged for about one hundred galaxies [e.g., Kormendy (2004), Gültekin *et al.* (2009), Kormendy and Ho (2013), McConnell and Ma (2013), Greene *et al.* (2016), and Saglia *et al.* (2016)], from optical/infrared imaging and spectroscopy on the Hubble Space Telescope (HST) and large ground-based telescopes, as well as from Very Long Baseline radio Interferometry (VLBI). Further evidence comes from relativistically broadened, red-shifted iron Kα line emission in nearby Seyfert galaxies [e.g., Tanaka *et al.* (1995), Nandra *et al.* (1997), and Fabian *et al.* (2000)]. In external galaxies, the most compelling case that such a dark mass concentration cannot just be a dense nuclear cluster of white dwarfs, neutron stars, and perhaps stellar black holes emerged in the mid-1990s from spectacular VLBI observations of the nucleus of NGC 4258, a mildly active galaxy at a distance of 7 Mpc (Miyoshi *et al.*, 1995; Moran, 2008). The VLBI observations show that the galaxy nucleus contains a thin, slightly warped disk of H_2O masers (viewed almost edge on) in Keplerian rotation around an unresolved mass of 40 million solar masses. The inferred density of this mass exceeds a few 10^9 solar masses pc^{-3} and thus cannot be a long-lived cluster of "dark" astrophysical objects of the type mentioned above (Maoz, 1995). As we will discuss below, the Galactic Center provides a yet more compelling case.

III. SCHERZO: SgrA* AND GAS MOTIONS

The central light years of our Galaxy contain a dense and luminous star cluster as well as several components of neutral, ionized and extremely hot gas (Fig. 1) (Genzel and Townes, 1987; Genzel, Hollenbach, and Townes, 1994; Melia and Falcke, 2001; Genzel, Eisenhauer, and Gillessen, 2010; Morris, Meyer, and Ghez, 2012; Reid *et al.*, 2013). Compared to the distant QSOs, the Galactic Center is "just around the corner" [$R_0 = 8.25$ kiloparsecs (kpc), 27 000 light years]. High-resolution observations of the Milky Way nucleus thus offer the unique opportunity of carrying out a stringent test of the MBH paradigm deep within its gravitational "sphere of influence" where gravity is dominated by the central mass ($R < 1$–3 pc). Since the center of the Milky Way is highly obscured by interstellar dust particles in the plane of the Galactic disk, observations in the visible part of the electromagnetic spectrum are not possible. The veil of dust, however, becomes transparent at longer wavelengths (the infrared, microwave, and radio bands) as well as at shorter wavelengths (hard x-ray and γ-ray bands), where observations of the Galactic Center thus become feasible (Oort, 1977).

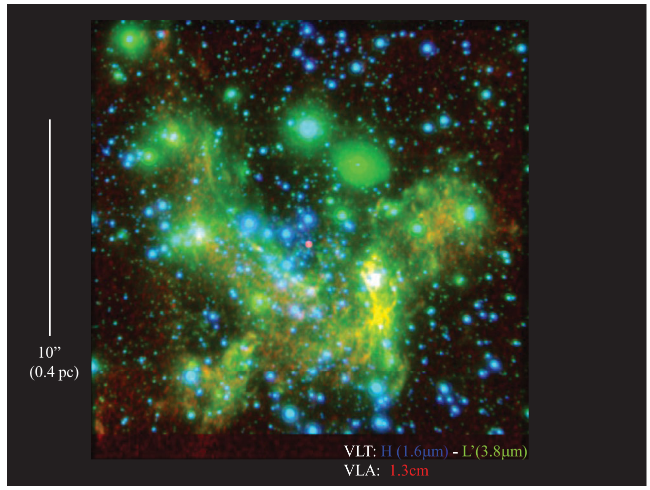

FIG. 1. Near-infrared/radio, color-composite image of the central light years of the Galactic Center. The blue and green colors represent the 1.6 and 3.8 μm broadband near-infrared emission, at the diffraction limit (~0.05") of the 8 m Very Large Telescope (VLT) of the European Southern Observatory (ESO), and taken with the "NACO" AO camera and an infrared wave-front sensor. Adapted from Genzel *et al.*, 2003. Similar work has been carried out at the 10 m Keck telescope (Ghez *et al.*, 2003, 2005). The red color image is the 1.3 cm radio continuum emission taken with the Very Large Array (VLA) of the U.S. National Radio Astronomy Observatory (NRAO). The red dot in the center of the image is the compact, nonthermal radio source SgrA*. Many of the bright blue stars are young, massive O/B and Wolf-Rayet (WR) stars that have formed recently. Other bright stars are giants and asymptotic giant branch stars in the old nuclear star cluster. The extended streamers/wisps of 3.8 μm emission and radio emission are dusty filaments of ionized gas orbiting in the central light years. Adapted from Genzel, Eisenhauer, and Gillessen, 2010.

The stellar density in the nuclear cluster increases inward from a scale of tens of parsecs to within the central 0.04 pc (Becklin and Neugebauer, 1968; Genzel *et al.*, 2003). At its center is a **very compact radio source, SgrA*** (Fig. 1) (Balick and Brown, 1974; Lo *et al.*, 1985; Backer *et al.*, 1993). Millimeter intercontinental VLBI observations have established that its intrinsic radius is a mere 20–50 microarcseconds (μas) (Fig. 2, 2–5 R_S for a 4×10^6 $M_\odot$ MBH)

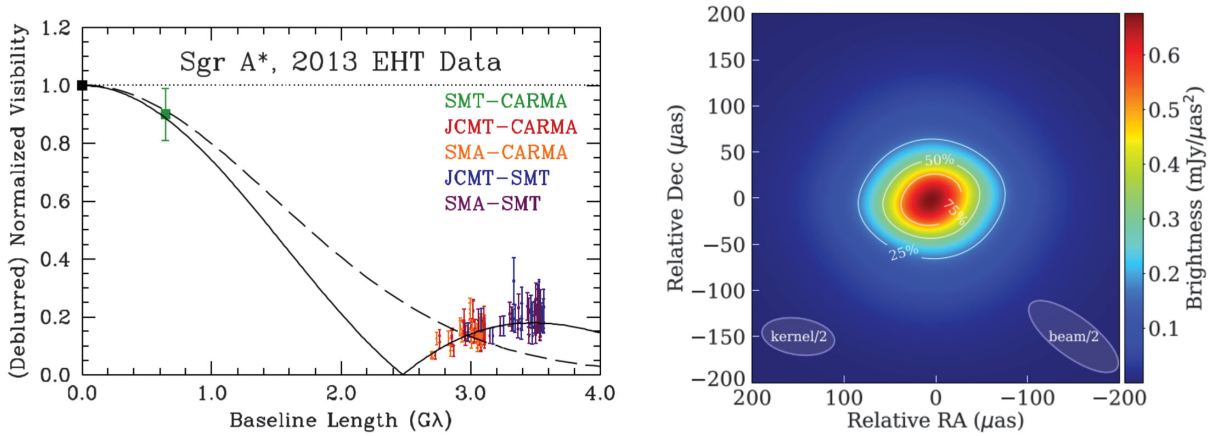

FIG. 2. Total-intensity mm-VLBI of SgrA*. Left: normalized, deblurred visibilities at 1.3 mm taken with the Event Horizon Telescope are shown as a function of baseline length; errors are $\pm 1\sigma$. The dashed line shows the best-fit circular Gaussian (FWHM: 52 μas). An annulus of uniform intensity (inner diameter: 21 μas, outer diameter: 97 μas), shown with a solid line, is perhaps the most plausible model that is consistent with the data. Adapted from Fig. S5 in Johnson *et al.*, 2015, Supplement. Right: 3 mm global mm-VLBI image of SgrA*, after removal of the scattering screen. The reconstructed image has an intrinsic Gaussian source diameter of $\theta_{\mathrm{maj}} = 120 \pm 34$ μas and $\theta_{\mathrm{min}} = 100 \pm 18$ μas. The ellipses at the bottom indicate half the size of the scatter-broadening kernel ($\theta_{\mathrm{maj}} = 159.9$ μas, $\theta_{\mathrm{min}} = 79.5$ μas, PA $= 81.9°$) and of the observing beam. Adapted from Fig. 5 in Issaoun *et al.*, 2019.

(Krichbaum *et al.*, 1993; Bower *et al.*, 2004; Shen *et al.*, 2005; Doeleman *et al.*, 2008; Lu *et al.*, 2014, 2018; Johnson *et al.*, 2015; Issaoun *et al.*, 2019). SgrA* thus is the prime candidate for the location and immediate environment of a possible MBH.

VLBI observations also have set an upper limit of about 0.6 km/s and 1 km/s to the motion of SgrA* itself, along and perpendicular to the plane of the Milky Way, respectively (Reid and Brunthaler, 2004, 2020). When compared to the two orders of magnitude greater velocities of the stars in the immediate vicinity of SgrA* (see below), this demonstrates that the radio source must indeed be massive, with simulations giving a lower limit to the mass of SgrA* of $\sim 10^5$ $M_\odot$ (Chatterjee, Hernquist, and Loeb, 2002), but see Tremaine, Kocsis, and Loeb (2021).

The first **dynamical evidence for the presence of a non-stellar mass concentration of 2–4 million times the mass of the Sun** (**$M_\odot$**) and plausibly centered on or near SgrA* came from infrared imaging spectroscopy of interstellar gas clouds, carried out by Charles Townes's group in Berkeley[1] (Wollman *et al.*, 1977; Lacy *et al.*, 1980; Townes, 1983; Crawford *et al.*, 1985; Serabyn and Lacy, 1985). In their 1985 Nature paper, Crawford *et al.* (1985) summarized the then available evidence on the mass distribution obtained from the infrared and submillimeter spectroscopy that traced the ionized and neutral gas components. They concluded that "…the measurements fit a point mass of $\sim 4 \times 10^6$ $M_\odot$ but are also consistent with a cluster where stellar density decreases with radius (R) at least as fast as $R^{-2.7}$, or a combination of a point mass and a stellar cluster…" However, many considered this dynamical evidence not compelling because of the possibility that the ionized gas is affected by nongravitational forces (shocks, winds, magnetic fields).

IV. *ESCURSIONE*: EVER SHARPER, EVER DEEPER

The most critical aspect in testing the MBH paradigm obviously lies in the ability of sensitive, very high-angular-resolution observations. The Schwarzschild radius of a 4 million solar mass black hole at the Galactic Center subtends a mere 10^{-5} arcseconds, or 10 μas.[2]

In the **radio and millimeter** bands such high resolution can be obtained from VLBI. Starting in the 1980s, ever higher-resolution VLBI measurements showed that the radio size of SgrA* decreases with decreasing wavelength, owing to scattering by intervening electrons between SgrA* and Earth (Shen *et al.*, 2005; Bower *et al.*, 2006). Measuring the intrinsic size of the source and imaging its two-dimensional distribution requires short millimeter VLBI observations, which are technically very challenging (Event Horizon Telescope Project in the USA: Doeleman, 2010, Black hole Cam Project in Europe) (Goddi *et al.*, 2017).[3]

For high-resolution **infrared** imaging from the ground, an important technical hurdle is the correction of the distortions of an incoming electromagnetic wave by the turbulent, refractive Earth atmosphere. In the optical/near-infrared waveband the atmosphere distorts the incoming electromagnetic waves on timescales of milliseconds and smears out long-exposure images to a diameter of more than an order of magnitude greater than the diffraction-limited resolution of large ground-based telescopes. The enormous progress in testing the MBH paradigm in the Galactic Center carried out by our group at MPE (at the telescopes of the European Southern Observatory in Chile), and by Andrea Ghez and her

[1]I had joined Townes's group in 1980 as a Miller Postdoctoral Fellow, and then became Associate Professor in the Physics Department in 1981.

[2]10 μas correspond to about 2 cm at the distance of the Moon.

[3]See https://eventhorizontelescope.org/, https://blackholecam.org/.

collaborators (at the Keck telescopes in Hawaii), described in the following sections, largely rests on substantial, continuous improvements in the angular resolution, astrometric precision and sensitivity of near-IR imaging and spectroscopy (by factors between one hundred to one hundred thousand over three decades).

From the early 1990s onward, short-exposure imaging with new infrared imaging detectors was made possible with "speckle imaging," resulting in diffraction-limited resolution (0.05–0.1") near-infrared stellar images (Sibille, Chelli, and Léna, 1979; Christou, 1991; Hofmann and Weigelt, 1993; Matthews and Soifer, 1994). Because of the short exposures and detector noise, speckle imaging is not able to go very deep. In the early 1990s "adaptive optics" techniques (AO: correcting the wave distortions on-line) became available (Rousset *et al.*, 1990; Léna, 1991; Tyson and Wizinowich, 1992), with upgraded imaging cameras (Lenzen and Hofmann, 1995; Lenzen *et al.*, 2003), which have since allowed increasingly precise high-resolution near-infrared observations with the currently largest (10 m diameter) ground-based telescopes. If bright natural guide stars near the science target are not available, laser guide star beacons can be employed for AO corrections (Sellgren *et al.*, 1990; Max *et al.*, 1997; Rabien *et al.*, 2000; Bonaccini-Calia *et al.*, 2006). Increasingly powerful integral field spectrometers (IFUs) coupled with AO have opened up deep imaging spectroscopy near the diffraction limit (Weitzel *et al.*, 1994; Eisenhauer *et al.*, 2003; Weinberg, Milosavljevic, and Ghez, 2005; Larkin *et al.*, 2006). The most recent step forward in the capability of the impressive record of instrumental innovation brought to bear on Galactic Center MBH studies is spatial interferometry, which I discuss separately below (Glindeman *et al.*, 2003; Eisenhauer *et al.*, 2008, 2011; GRAVITY Collaboration, 2017).

V. *MENUETTO*: STELLAR MOTIONS AND ORBITS

A more reliable probe of the gravitational field is stellar motions, which started to become available from Doppler spectroscopy of stellar absorption and emission lines in the late 1980s. They broadly confirmed the results obtained in phase 1 from gas motions (Rieke and Rieke, 1988; McGinn *et al.*, 1989; Sellgren *et al.*, 1990; Krabbe *et al.*, 1991, 1995; Genzel *et al.*, 1996; Haller *et al.*, 1996). As described in the last section, the ultimate breakthrough came from the combination of AO techniques with IFU imaging spectroscopy (Eisenhauer *et al.*, 2003), opening deep near-infrared spectroscopy of thousands of O/B and WR stars and GKM giants [e.g. Trippe *et al.* (2008), Do *et al.* (2013, 2018), Feldmeier *et al.* (2014), Fritz *et al.* (2016), and Habibi *et al.* (2019)].

With diffraction-limited "speckle" imagery starting in 1991/1992 on the 3.5 m New Technology Telescope (NTT) of the ESO in La Silla/Chile, our group at MPE was able to determine proper motions of stars as close as ~0.1" from SgrA* (Eckart and Genzel, 1996, 1997; Genzel *et al.*, 1997). In 1995, Andrea Ghez's group at the University of California, Los Angeles, started a similar program with the 10 m diameter Keck telescope in Hawaii (Ghez *et al.*, 1998). Both groups independently found that the stellar velocities follow a "Kepler" law ($v \sim R^{-1/2}$) as a function of distance from SgrA* and reach $\geq 10^3$ km/s within the central light month. Assuming that the mass in the center is the sum of a

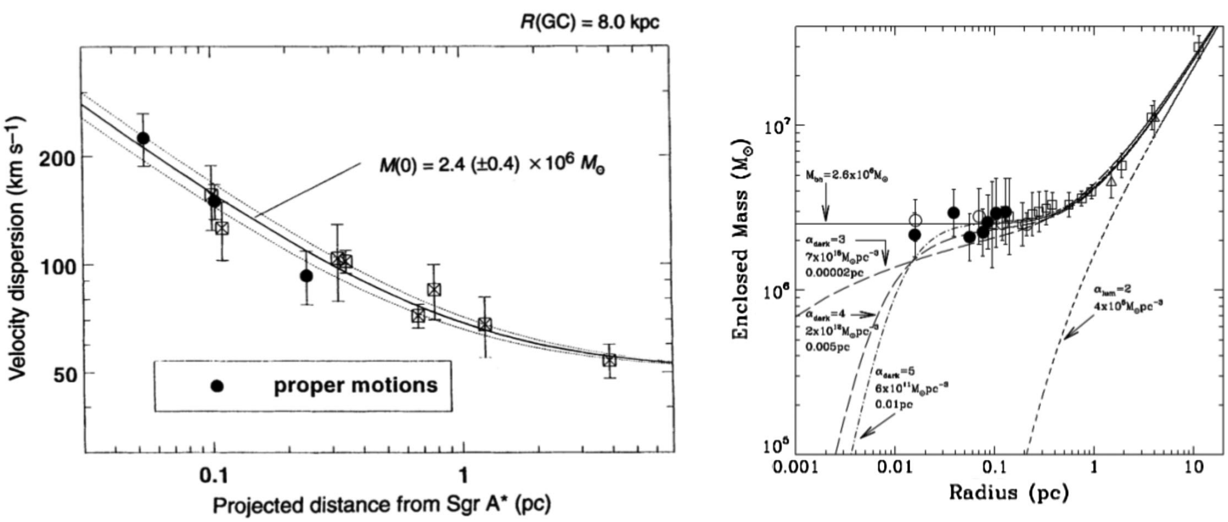

FIG. 3. Mass distribution in the central parsec of the Galactic Center after phase 2 (1996/1998). The left graph shows the projected 1^d stellar velocity dispersion as a function of projected distance from SgrA*, obtained from proper motions (filled circles) and Doppler velocities (crossed squares). Each point is derived from averaging the motions of 9 to 20 stars. The solid curve is a model assuming that the stars move with an isotropic velocity distribution in the potential of a point mass [M(0)] plus an isothermal star cluster of velocity dispersion 50 km/s. The distance of the Galactic Center is assumed to be 8.0 kpc. From Eckart and Genzel, 1996. The right graph shows the mass distribution derived from stellar proper motions published by the Keck group in 1998 (Ghez *et al.*, 1998) (filled black circles), and compared to the Eckart and Genzel (1996, 1997) proper motions (open circles), the Genzel *et al.* (1996) stellar radial velocities (squares), and the Guesten *et al.* (1987) measurement of the rotating gas disk (triangles). From 0.1 to 0.015 pc the enclosed mass appears to be constant with a value of 2.6×10^6 $M_\odot$. For comparison, there are several power law distributions. Adapted from Fig. 7 of Ghez *et al.*, 1998. **The agreement between the results of the MPE and UCLA groups is excellent**.

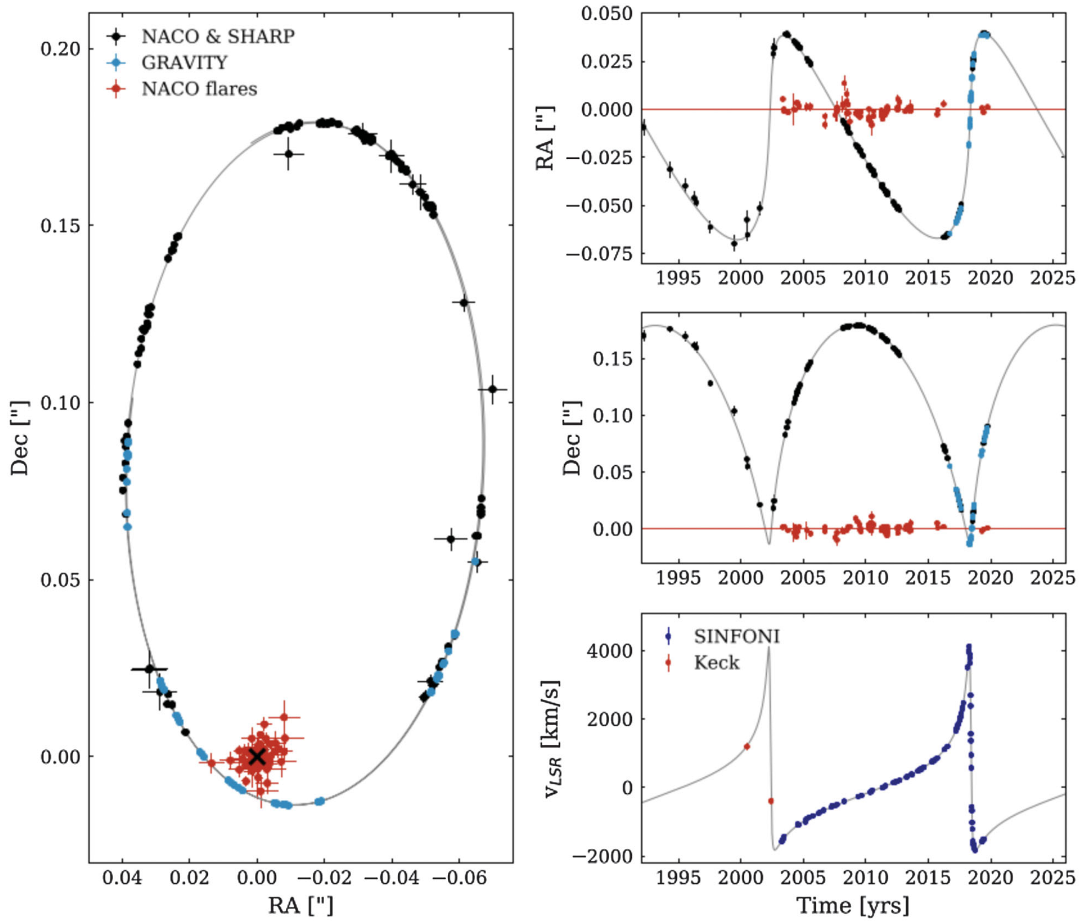

FIG. 4. Summary of the MPE-ESO observational results of monitoring the S2-SgrA* orbit from 1992 to the end of 2019. Left: SHARP (black points with large error bars), NACO (black points), and GRAVITY (blue points) astrometric positions of the star S2, along with the best-fitting GR orbit (gray line). The orbit does not close as a result of the Schwarzschild precession (see text). The mass center is at (0,0), marked by the black cross. All NACO and SHARP points were corrected for a zero-point offset and drift of the reference frame in right ascension (RA) and declination (Dec). The red data points mark the positions of the infrared emission from SgrA* during bright states, where the separation of S2 and SgrA* can be directly inferred from differential imaging. Right: RA (top) and Dec (middle) offset of S2 and of the infrared emission from SgrA* relative to the position of SgrA* (assumed to be identical with the mass center) (same symbols as in the left panel). Gray is the best-fitting GR orbit including the Rømer effect (finite speed of light), special relativity, and GR to "parametrized post-Newtonian" approximation PPN1 (Will, 2008). Bottom right: same for the line-of-sight velocity of the star. Position on the sky as a function of time (left) and Doppler velocity (relative to the local standard of rest) as a function of time (right) of the star S2 orbiting the compact radio source SgrA*. Blue filled circles denote data taken with the SINFONI, red open circles denote data taken with the Keck telescope as part of the UCLA monitoring project (Do *et al.*, 2019). Adapted from Fig. 1 of GRAVITY Collaboration, 2020a.

point mass and an isothermal star cluster, the central mass inferred from projected mass estimators (Bahcall and Tremaine, 1981) is ~2.5 million solar masses, for an isotropic velocity distribution (Fig. 3), in excellent agreement between the two groups. For more elliptical orbits the inferred mass increases (Bahcall and Tremaine, 1981). We now know that the velocity distribution of the innermost stars favors highly elliptical orbits (Schödel *et al.*, 2003; Gillessen *et al.*, 2017), so that the appropriately corrected estimate of M(0) would be $3.5–4.7 \times 10^6$ $M_\odot$, for R(GC) = 8.25 kpc.

In the next phase, the MPE group moved onto ESO's 8.2 m Very Large Telescope (VLT) on Paranal in 2002, and both groups improved their imagery with adaptive optics and upgraded cameras, improving the astrometry to a few hundred μas in the next decade (Schödel *et al.*, 2002, 2003; Ghez *et al.*, 2003, 2008; Eisenhauer *et al.*, 2005; Gillessen, Eisenhauer, Fritz *et al.*, 2009; Gillessen, Eisenhauer, Trippe *et al.*, 2009; Meyer *et al.*, 2012; Boehle *et al.*, 2016; Gillessen *et al.*, 2017; Jia *et al.*, 2019). Ghez *et al.* (2000) detected accelerations for three of the innermost "S" stars [subsequently confirmed by Eckart *et al.* (2002)], opening the prospect of much more precise mass determinations from individual orbits, instead of the statistical evaluation through mass estimators.

In 2001/2002, the star S2 (S02) approached SgrA* to 15 mas and made a sharp turn around the radio source during 2002 (Schödel *et al.*, 2002; Ghez *et al.*, 2003). S2/S02 is on a highly elliptical orbit (e = 0.88), with a peri-distance of 14 mas (17 light hours or 1400 R_S, for M(0) = 4.26×10^6 $M_\odot$) (Fig. 4) and an orbital period of a mere 16 years. Ghez *et al.* (2003, 2005) and Eisenhauer, Schödel *et al.* (2003)

and Eisenhauer *et al.* (2005) also obtained Doppler velocities and accelerations of S2/S02 and several other orbiting stars, allowing precision measurement of the three dimensional structure of the orbits, as well as the distance to the Galactic Center. Figure 4 shows the data and best-fitting GR orbit for S2/S02 in its most recent version [from GRAVITY Collaboration (2020a), see below]. At the time of writing, the two groups have determined individual orbits for more than 40 stars in the central light month. These orbits show that **the gravitational potential indeed is dominated by a point mass, whose position is identical within a mas uncertainty with that of the radio source** SgrA* (Plewa *et al.*, 2015; Sakai *et al.*, 2019).

At the end of phase 3 (~2017), it is clear that >98% of the four million solar mass central mass concentration identified in the first phase is indeed confined to a region <17 light hours around the compact radio source (in a volume a million times smaller than inferred in 1985). The intrinsic size in turn is only a few times the event horizon of that mass. This evidence **eliminates all astrophysically plausible alternatives to a massive black hole.** These include astrophysical clusters of neutron stars, stellar black holes, brown dwarfs and stellar remnants (e.g., Maoz, 1995, 1998; Genzel *et al.*, 1997, 2000; Ghez *et al.*, 1998, 2005), and even fermion balls (Viollier, Trautmann, and Tupper, 1993; Munyaneza, Tsiklauri, and Viollier, 1998; Tsiklauri and Viollier, 1998; Ghez *et al.*, 2005; Genzel, Eisenhauer, and Gillessen, 2010). Clusters of a very large number of mini-black holes and boson balls (Torres, Capoziello, and Lambiase, 2000; Schunck and Mielke, 2003; Liebling and Palenzuela, 2012) are harder to exclude. The former have a large relaxation and collapse time, the latter have no hard surfaces that could exclude them from luminosity arguments (Broderick, Loeb, and Narayan, 2009), and they are consistent with the dynamical mass and size constraints. However, such a boson "star" would be unstable to collapse to a MBH when continuously accreting baryons (as in the Galactic Center), and it is very unclear how it could have formed. **Under the assumption of the validity of general relativity the Galactic Center thus provides the best quantitative evidence that MBHs do indeed exist.**

VI. *RONDO ALLEGRETTO*: TESTING GENERAL RELATIVITY WITH SgrA*

At peri-passage S2 moves at $v \sim 7650$ km/s and $\beta = v/c \sim 0.026$ so that the first order post-Newtonian effects of GR (PPN1: $\sim\beta^2 \sim 6.5 \times 10^{-4}$) (Will, 2008), namely the gravitational redshift and the Schwarzschild in plane orbital precession can be realistically detected in the spectra and the astrometry of the star near pericenter. Knowing that S2 would return in 2018 for its next peri-passage, we proposed to ESO in 2005 to build a novel near-infrared beam combiner instrument (GRAVITY) combining the light of all four 8 m telescopes of the VLT (Eisenhauer *et al.*, 2008; Paumard *et al.*, 2008). GRAVITY would improve the angular resolution and astrometry by more than an order of magnitude and thus reach the required precision to detect the GR effects (Eisenhauer *et al.*, 2011). GRAVITY was designed and built in the next decade by a French-German-Portuguese Consortium of six institutes (plus ESO), under the PI-ship of Frank Eisenhauer at MPE,[4] and installed on Paranal in July 2015. A detailed discussion of this complex and challenging instrument is given in GRAVITY Collaboration (2017).

Our goal and hope were that the combination of SINFONI, NACO and GRAVITY data would allow us to turn the problem around and use SgrA* as a **laboratory** to test general relativity and the MBH paradigm in a hitherto unexplored regime [e.g., Johannsen (2016)]. As already mentioned the peri-passage of S2 in May 2018 is a unique opportunity to test GR to PPN1 [e.g., Zucker *et al.* (2006)]. Waisberg *et al.* (2018) showed that a star with a peri-passage 3–5 times smaller than that of S2 may be used to measure the MBH spin through the Lense-Thirring precession of its orbit. Finally, SgrA* itself exhibits continuous variability (Baganoff *et al.*, 2001; Genzel, Schödel *et al.*, 2003; Dodds-Eden *et al.*, 2011; Witzel *et al.*, 2018), and in some cases the fluxes of these "flares" approach the flux of S2 ($K \sim 14$), such that 20 μas astrometry on timescales of a few minutes becomes feasible. Several authors had previously speculated that such flares might come from strongly magnetized "hot spots" of accelerated electrons whose orbital motions might be detectable and used for exploring the innermost accretion zone on the scale of the innermost stable circular orbit, ISCO ($R_{ISCO} < 6\ R_S$) (Broderick and Loeb, 2006; Genzel, Eisenhauer, and Gillessen, 2010; GRAVITY Collaboration, 2018b, 2020c).

It is remarkable to look back in late 2020, two and half years after the peri of S2 on May 19, 2018, and realize that most of these hopes actually turned into reality (Fig. 6). The gravitational redshift of S2 has been well determined (5–50σ) by both groups (GRAVITY Collaboration, 2018a, 2019a, 2020a; Do *et al.*, 2019). The Schwarzschild precession has been detected at ~5σ (GRAVITY Collaboration, 2020a). Flare motions in three flares of 2018 were consistent with the orbital motions near ISCO around a four million solar mass MBH (GRAVITY Collaboration, 2018b, 2020b). Using the HeI and HI lines as independent "clocks" GRAVITY Collaboration (2019b) has confirmed the local positional invariance of Einstein's equivalence principle to about 5%. Significant upper limits can be placed on the presence of a hypothetical "fifth force" (Hees *et al.*, 2017). Faint stars close to SgrA* have also been recently detected (GRAVITY Collaboration, 2021, 2022b) but are likely not inside the S2 orbit. Overall, these discoveries have strengthened the MBH paradigm and GR significantly further (Fig. 7).

VII. *CODA*

Besides its role at the center stage of testing the black hole paradigm, the Galactic Center has also provided many important **discoveries and surprises on the astrophysics side,** which I have not described in this paper so far. One is the fact that the central parsec contains ~200 massive, early-type stars (O/B and Wolf-Rayet stars), which must have formed in the last few million years [cf. Genzel *et al.*, 1996, 2000;

[4] See https://www.mpe.mpg.de/938240/Overview, https://www.eso.org/public/teles-instr/paranal-observatory/vlt/vlt-instr/gravity/, https://www.eso.org/sci/facilities/paranal/instruments/gravity.html.

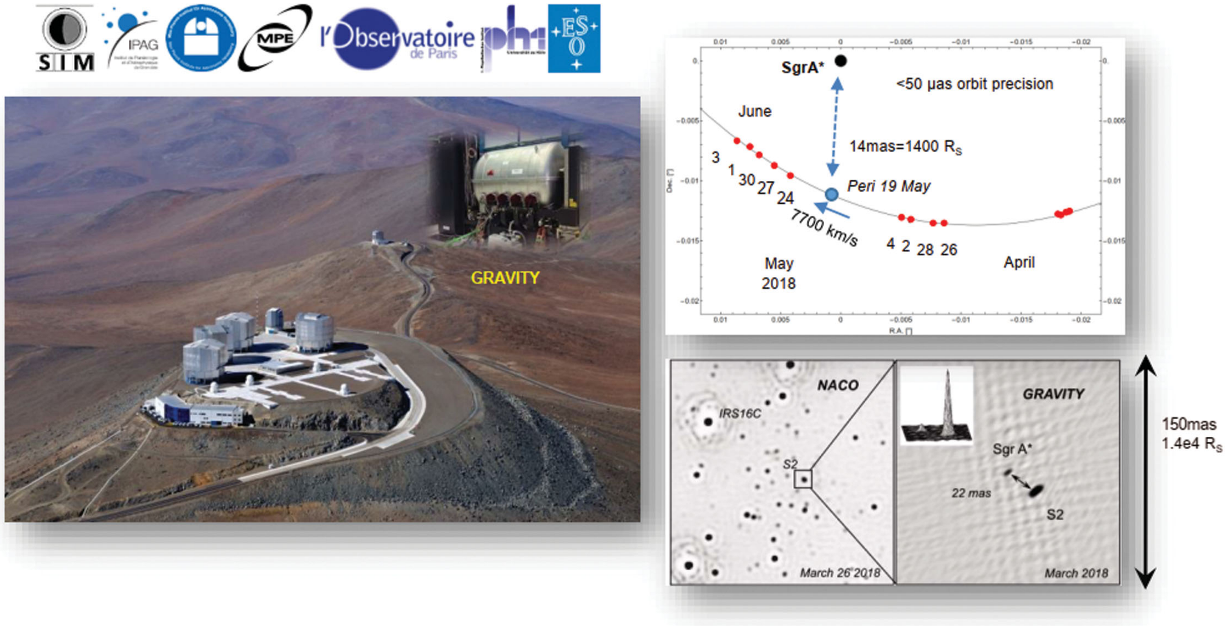

FIG. 5. Left: the ESO-Very Large Telescope (VLT) on Cerro Paranal (Chile), where most of the observations by our group were obtained. The Observatory in the Atacama desert is at 2,635 m altitude and -24.7^0 latitude. It hosts 4×8.2 m telescopes (large silvered structures) as well as 4×1.8 m Auxiliary Telescopes (white round domes). Both arrays can be combined optically as a spatial interferometer (VLTI) through mirror trains, where the relative geometric path lengths to a given celestial source can be compensated by movable delay line mirrors in the linear white structure underneath the platform (Glindeman *et al.*, 2003). The final combined set of four beams finally arrives at the beam combiner facility structure underneath the rectangular building in the center of the array. Here, the light beams are brought together in the cryogenic beam combiner instrument GRAVITY [built by a French-German-Portuguese consortium of six institutions (logos above the VLT image), plus ESO itself]. In GRAVITY, we calibrate and optimize the data and extract the visibilities and relative phases of the science object as well as that of a nearby, fringe-tracking reference object, as a function of wavelength, guiding and manipulating the infrared light in single-mode fibers and combining the six two-telescope combinations in a microchip (GRAVITY Collaboration, 2017). Bottom right: after calibration of the phases using laser metrology, images with 2×4 mas FWHM resolution are reconstructed by Fourier transformation. In the case shown, the VLTI science fibers were placed on the star S2/SgrA* in the left image, while the interferometer phases were tracked on the bright star IRS16C 1” NE of SgrA*, in the top left of the AO image. All four telescopes are equipped with infrared adaptive optics, which uses the $K = 7$ bright star IRS7 5” north of S2/SgrA* as a natural guide star to flatten the wave fronts. The image at the bottom right was taken in March 2018, about two months before the peri-passage of S2, and both S2 and SgrA* can be clearly detected and its ~22 mas separation measured to ~40–100 μas precision. Top right: during the peri-passage in 2018, the motion of S2 can be easily detected night for night, then moving at ~7,700 km/s at ~1,400 Schwarzschild radii from SgrA*. Adapted from Fig. 2 of GRAVITY Collaboration, 2018a.

Sanders, 1998; Paumard *et al.*, 2006; Bartko *et al.*, 2009; Lu *et al.*, 2009; Genzel, Eisenhauer, and Gillessen, 2010)]. This “paradox of youth” (Ghez *et al.*, 2003) is completely unexpected, as the MBH should disrupt moderately dense gas clouds tidally, and prevent star formation through local gravitational instabilities and cloud collapse. Perhaps the most likely solution of this riddle is that a large gas cloud fell in a few million years ago, was initially tidally disrupted and shocked, but then cooled and became denser over time, so that gravitational collapse did become possible [cf. Morris and Serabyn (1996), Bonnell and Rice (2008), Hobbs and Nayakshin (2009), Genzel, Eisenhauer, and Gillessen (2010), and Alexander (2017)].

Possibly connected is the question how the “S stars” were captured so close to the MBH, on solar system scales. These B, A, G, and K stars could never ever have migrated to their current position through normal two-body relaxation processes, which take several Gyrs. Instead, rapid stochastic injection of binaries into “loss-cone” radial orbits from large distances (Hills, 1988), and perhaps assisted by massive perturbers (Perets, Hopman, and Alexander, 2007), could have led to a capture of one member of the binary near pericenter, and rapid ejection of the second as a hypervelocity star [cf. Alexander (2005, 2017) and Genzel, Eisenhauer, and Gillessen (2010)].

A tidal disruption of a star by the MBH is expected to occur only once every 30,000 years (Alexander, 2005, 2017). In 2012 [Gillessen *et al.* (2012, 2019), and references therein] reported the near-radial infall, tidal disruption and eventual slowing down by drag forces near ~2,000 R_S of an ionized gas cloud (“G2”). The discussion is ongoing whether this gas cloud is isolated, or whether the gas is the envelope of a central single or binary star.

A third riddle is the lack of a strong cusp of old late-type stars around the MBH (Do *et al.*, 2009; Buchholz, Schödel, and Eckart, 2009; Schödel *et al.*, 2018) (Fig. 7), which is expected in equilibrium ($\rho \sim R^{-1.5...-1.75}$) (Bahcall and Wolf, 1977; Alexander, 2005, 2017). Finally, the lack of any substantial mass close to SgrA*-MBH greater than a few hundred to one thousand solar masses (Fig. 7) (GRAVITY Collaboration,

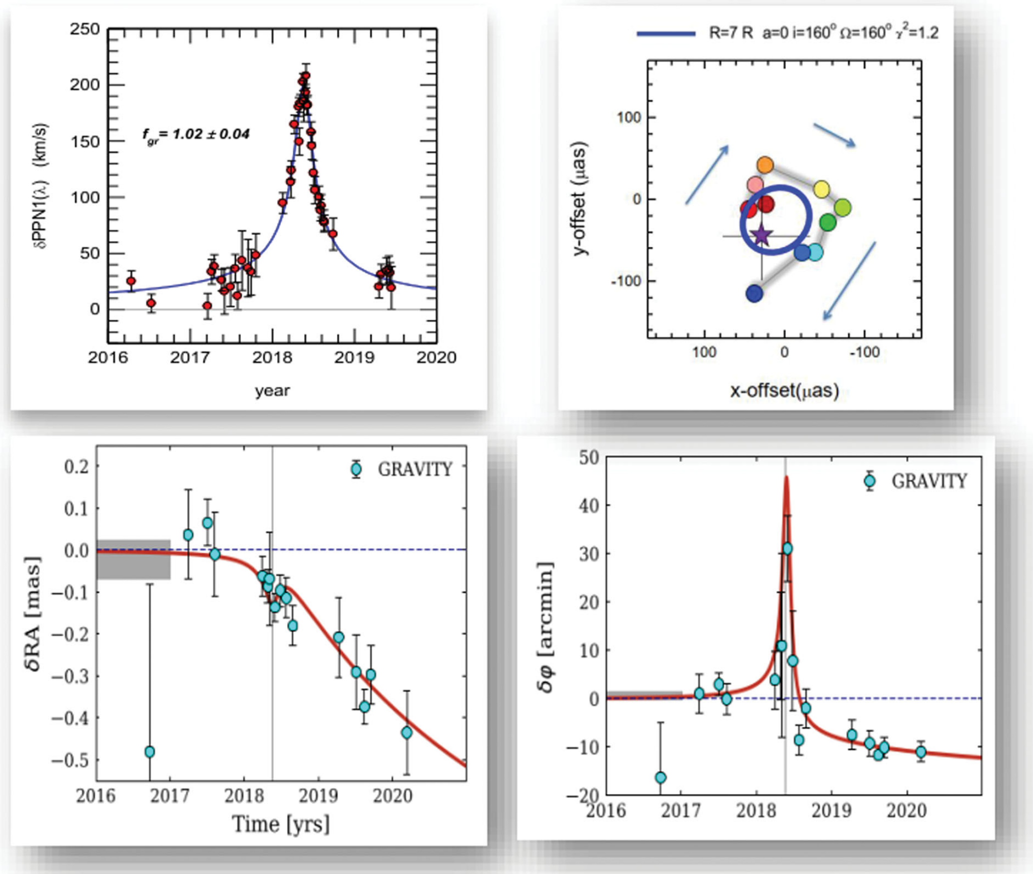

FIG. 6. Testing GR and the MBH paradigm with relativistic effects near SgrA*. Top left: residuals between the SINFONI HeI/HI Brγ line centroid velocities in the local standard of rest (filled red circles with 1σ uncertainties) and the best-fitting Newton/Kepler orbit of all spectroscopic and astrometric data over the past three decades (gray horizontal line at 0). The blue line is the best-fitting relativistic orbit including all PPN1 terms (as well as the Rømer effect), and fitting a free parameter f_{gr} to the PPN1 wavelength term including gravitational redshift and transverse Doppler effect. GR has $f_{gr} = 1$ and our best fit yields $f_{gr} = 1.02 \pm 0.04$ (GRAVITY Collaboration, 2018a, 2019a, 2020a). Bottom plots: residuals in RA (left) and angle on the sky φ (right) between the GRAVITY (filled cyan circles and 1σ uncertainties) and average NACO astrometry before 2017 (gray bar) and the best-fitting relativistic orbit without precession ($f_{SP} = 0$, blue dotted horizontal line at 0). The best-fitting relativistic orbit including precession has $f_{SP} = 1.1 \pm 0.19$. Adapted from Figs. 3 and B2 in GRAVITY Collaboration, 2020a. Top right: residual motion of the 2 μm light centroid of SgrA* originating from polarized synchrotron emission from $\gamma > 1{,}000$ accelerated electrons in the inner accretion zone in a bright “flare” on July 22, 2018, cf. Genzel, Eisenhauer, and Gillessen (2010) as a function of time over about 30 minutes, and relative to the location of the mass as estimated from the S2 orbit (dark gray asterisk and 1σ errors). The blue curve denotes a circular particle orbit at 3.5 R_S around a nonspinning MBH of 4.3 million solar masses, inclined at 160°. From Fig. 1 in GRAVITY Collaboration, 2018b, 2020b, 2020c.

2020a) is highly exciting and important for other MBH systems and needs to be confirmed by further measurements.

Another aspect I did not cover is the important role MBHs apparently had in the cosmological **coevolution with their galactic hosts** [e.g., Fabian (2012), Kormendy and Ho (2013), and Madau and Dickinson (2014)].

In this paper, I have tried to describe the stepwise progress in proving that massive black holes do exist in the Universe. As compared to the first phase forty years ago, these measurements have pushed the “size” of the 4 million solar mass concentration downward by almost 10^6, and its density up by 10^{18}! Looking ahead toward the future, the question is probably no longer whether SgrA* must be an MBH, but rather whether GR is correct on the scales of the event horizon, whether space-time is described by the Kerr metric and whether the “no hair theorem” holds. Further improvements of GRAVITY (to GRAVITY$^+$) and the next-generation 25 to 40 m telescopes (the ESO-ELT, the TMT and the GMT) promise further progress. A test of the no-hair theorem in the Galactic Center might come from combining the stellar dynamics with EHT measurements of the photon ring of SgrA* (Falcke, Melia, and Algol, 2000; Psaltis and Johanssen, 2011; Johannsen, 2016; Psaltis, Wex, and Kramer, 2016). The gravitational waves emanating from the extreme mass ratio inspiral of a stellar black hole into a massive black hole with the LISA space mission[5] might provide the ultimate culmination of this exciting journey, which Albert Einstein started more than a century ago.

[5]See https://www.elisascience.org/.

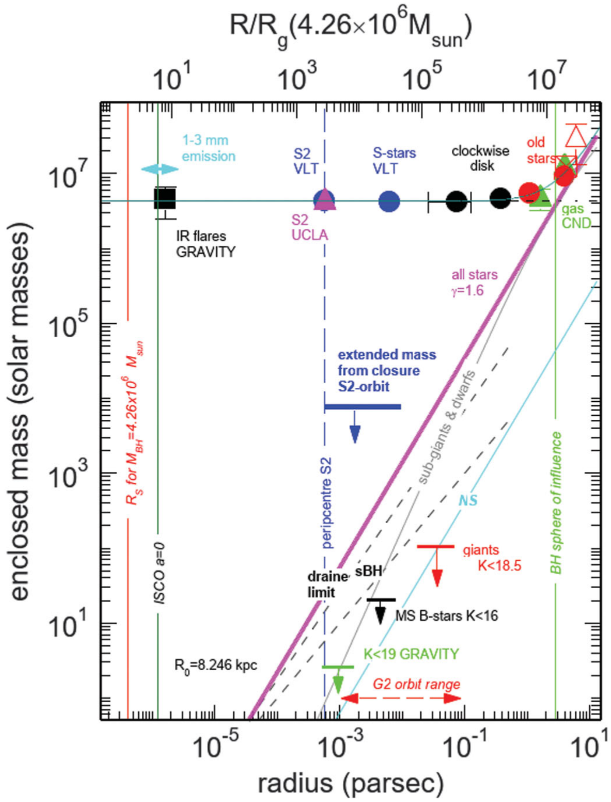

FIG. 7. Status of the Galactic Center mass distribution after phase 4. Constraints on the enclosed mass in the central 10 pc of the Galaxy. The blue, black and red circles, the pink, green and red triangles are estimates of the enclosed mass at different radii obtained from stellar and gas motions [see Genzel, Eisenhauer, and Gillessen (2010) and GRAVITY Collaboration (2022a) for details]. The filled black rectangle comes from the clockwise loop motions of synchrotron near-infrared flares (GRAVITY Collaboration, 2018b). The cyan double arrow denotes current VLBI estimates of the 3 mm size of SgrA* (Issaoun *et al.*, 2019). The continuous magenta line shows the total mass model from all stars and stellar remnants (Alexander, 2017). The gray line marks the distribution of $K < 18.5$ subgiants and dwarfs from Schödel *et al.* (2018). The gray dashed lines indicate the distribution of stellar black holes and neutron stars from theoretical simulations of Alexander (2017) and Baumgardt, Amaro-Seoane, and Schödel (2018), which span a range of roughly factor 5. Red, black and green upper limits denote upper limits on giants, main-sequence B stars and $K < 19$ GRAVITY sources. The Schwarzschild radius of a $4.26 \times 10^6\ M_\odot$ black hole and the innermost stable circular orbit radius for a nonspinning black hole are given by orange and dark green vertical lines. The pericenter radius of S2 is the dashed vertical blue line and the sphere of influence of the black hole is given by the vertical light green line. The blue horizontal line denotes the 2σ upper limit of any extended mass around SgrA* obtained from the lack of retrograde precession in the S2 orbit. Adapted from Fig. D1 in GRAVITY Collaboration, 2020a.

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