Where do we stand now ?

Concept Design Review: December 2007

Preliminary Design Review: December 2009

Final Design Review: October 2011

First tests at Paranal: 2014

Hopefully first results on Sgr A* in 4 years.

GRAVITY Consortium

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In the last years intensive searches for dark matter (DM), especially its non-baryonic component, both in galactic halos and at galaxy centers have been undertaken (see for example Bertone et al. (2005,2005a) for recent results). It is generally accepted that the most promising candidate for the DM non-baryonic component is neutralino. In this case, the γ-flux from galactic halos (and from our Galactic halo in particular) could be explained by neutralino annihilation (Gurevich et al. 1997,Bergstrom et al. 1998, Tasitsiomi et al. 2002, Stoehr et al. 2003, Prada et al. 2004,Profumo et al. 2005, Mambrini et al. 2005). Since γ-rays are detected not only from high galactic latitude, but also from the Galactic Center, there is a wide spread hypothesis (see, Evans (2004) for a discussion) that a DM concentration might be present at the Galactic Center. In this case the Galactic Center could be a strong source of γ-rays and neutrinos (Bouquet 1989, Stecker 1988, Berezinsky et al. 1994, Bergstrom et al. 1998, Bertone et al. 2004, Gnedin et al. 2004,Bergstrom et al. 2005, Horns 2005, Bertone et al. 2005) due to DM annihilation. Since it is also expected that DM forms spikes at galaxy centers (Gondolo & Silk 1999, Ullio et al. 2001, Merritt et al. 2003) the γ-ray flux from the Galactic Center should increase significantly in that case.

At the same time, progress in monitoring bright stars near the Galactic Center have been reached recently (Genzel et al. 2003,Ghez et al. 2003, Ghez et al. 2005). The astrometric limit for bright stellar sources near the Galactic Center with 10 meter telescopes is today $\delta\theta_{10} \sim 1$ mas and the Next Generation Large Telescope (NGLT) will be able to improve this number at least down to $\delta\theta_{30} \sim 0.5$ mas (Weinberg et al. 2005) or even to $\delta\theta_{30} \sim 0.1$ mas (Weinberg et al. 2005) in the K-band. Therefore, it will be possible to measure the proper motion for about ~ 100 stars with astrometric errors several times smaller than errors in current observations.

The aim of this talk is to constrain the parameters of the DM distribution possible present around the Galactic Center by considering the induced apoastron shift due to the presence of this DM sphere and either available data obtained with the present generation of telescopes (the so called *conservative* limit) and also expectations from future NGLT observations or with other advanced observational facilities.

Celestial mechanics of S2 like stars for BH+cluster (A.A. Nucita, F. De Paolis, G. Ingrosso, A. Qadir, AFZ, PASP, v. 119, p. 349 (2007))

GR predicts that orbits about a massive central body suffer periastron shifts yielding *rosette* shapes. However, the classical perturbing effects of other objects on inner orbits give an opposite shift. Since the periastron advance depends strongly on the compactness of the central body, the detection of such an effect may give information about the nature of the central body itself. This would apply for stars orbiting close to the GC, where there is a "dark object", the black hole hypothesis being the most natural explanation of the observational data. A cluster of stars in the vicinity of the GC (at a distance $< 1 \ \mathrm{arcsec}$) has been monitored by ESO and Keck teams for several years.

For a test particle orbiting a Schwarzschild black hole of mass $M_{\rm BH}$, the periastron shift is given by (see e.g. Weinberg, 1972)

$$\Delta\phi_S \simeq \frac{6\pi G M_{BH}}{d(1-e^2)c^2} + \frac{3(18+e^2)\pi G^2 M_{BH}^2}{2d^2(1-e^2)^2c^4}\ , \tag{9}$$

d and e being the semi-major axis and eccentricity of the test particle orbit, respectively. For a rotating black hole with spin parameter $a = |\mathbf{a}| = J/GM_{\rm BH}$, the space-time is described by the Kerr metric and, in the most favorable case of equatorial plane motion (**(a,v)** $= 0$), the shift is given by (Boyer and Price (1965))

$$\Delta\phi_K \simeq \Delta\phi_S + \frac{8a\pi M_{BH}^{1/2} G^{3/2}}{d^{3/2}(1-e^2)^{3/2}c^3} + \frac{3a^2\pi G^2}{d^2(1-e^2)^2c^4}\ , \tag{10}$$

which reduces to eq. (9) for $a \rightarrow 0$. In the more general case, **a.v** $\neq 0$, the expected periastron shift has to be evaluated numerically.

The expected periastron shifts (mas/revolution), $\Delta\phi$ (as seen from the center) and $\Delta\phi_E$ (as seen from Earth at the distance $R_0 \simeq\ 8$ kpc from the GC), for the Schwarzschild and the extreme Kerr black holes, for the S2 and S16 stars turn out to be $\Delta\phi^{S2} = 6.3329 \times 10^5$ and 6.4410×10^5 and $\Delta\phi_E^{S2} = 0.661$ and 0.672 respectively, and $\Delta\phi^{S16} = 1.6428 \times 10^6$ and 1.6881×10^6 and $\Delta\phi_E^{S16} = 3.307$ and 3.399 respectively. Recall that

$$\Delta\phi_E = \frac{d(1+e)}{R_0}\Delta\phi_{S,K}\ . \tag{11}$$

Notice that the differences between the periastron shifts for the Schwarzschild and the maximally rotating Kerr black hole is at most 0.01 mas for the S2 star and 0.009 mas for the S16 star. In order to make these measurements with the required accuracy, one needs to know the S2 orbit with a precision of at least $10\ \mu$as.

The star cluster surrounding the central black hole in the GC could be sizable. At least 17 members have been observed within 15 mpc up to now (Ghez et al. (2005)). However, the cluster mass and density distribution, that is to say its mass and core radius, is still unknown. The presence of this cluster affects the periastron shift of stars orbiting the central black hole. The periastron advance depends strongly on the mass density profile and especially on the central density and typical length scale.

We model the stellar cluster by a Plummer model density profile (Binney & Tremaine (1987))

$$\rho_{CL}(r) = \rho_0 f(r) \ , \qquad \text{with} \qquad f(r) = \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-\alpha/2} , \quad (12)$$

where the cluster central density ρ_0 is given by

$$\rho_0 = \frac{M_{CL}}{\int_0^{R_{CL}} 4\pi r^2 f(r)\ dr}\ , \tag{13}$$

R_{CL} and M_{CL} being the cluster radius and mass, respectively. According to dynamical observations towards the GC, we require that the total mass $M(r) = M_{BH} + M_{CL}(r)$ contained within $r \simeq 5 \times 10^{-3}$ pc is $M \simeq 3.67 \times 10^6\ M_\odot$. Useful information is provided by the cluster mass fraction, $\lambda_{CL} = M_{CL}/M$, and its complement, $\lambda_{BH} = 1 - \lambda_{CL}$. As one can see, the requirement given in eq. (13) implies that $M(r) \rightarrow M_{BH}$ for $r \rightarrow 0$. The total mass density profile $\rho(r)$ is given by

$$\rho(r) = \lambda_{BH} M \delta^{(3)}(\overrightarrow{r}) + \rho_0 f(r) \tag{14}$$

and the mass contained within r is

$$M(r) = \lambda_{BH} M + \int_0^r 4\pi r'^2 \rho_0 f(r') \, dr' \ . \tag{15}$$

According to GR, the motion of a test particle can be fully described by solving the geodesic equations. Under the assumption that the matter distribution is static and pressureless, the equation of motion of the test particle becomes (see e.g. Weinberg 1972))

$$\frac{d\mathbf{v}}{dt} \simeq -\nabla(\Phi_N + 2\Phi_N^2) + 4\mathbf{v}(\mathbf{v}\cdot\nabla)\Phi_N - v^2\nabla\Phi_N \ . \tag{16}$$

For the S2 star, d and e given in the literature are 919 AU and 0.87 respectively. They yield the orbits of the S2 star for different values of the black hole mass fraction λ_{BH} shown in Figure 20. The Plummer model parameters are $\alpha = 5$, core radius $r_c \simeq 5.8$ mpc. Note that in the case of $\lambda_{BH} = 1$, the expected (prograde) periastron shift is that given by eq. (9), while the presence of the stellar cluster leads to a retrograde periastron shift. For comparison, the expected periastron shift for the S16 star is given in Figure 31. In the latter case, the binary system orbital parameters were taken from Schödel et al. (2003)) assuming also for the S16 mass a conservative value of $\simeq 10$ M$_{\odot}$.

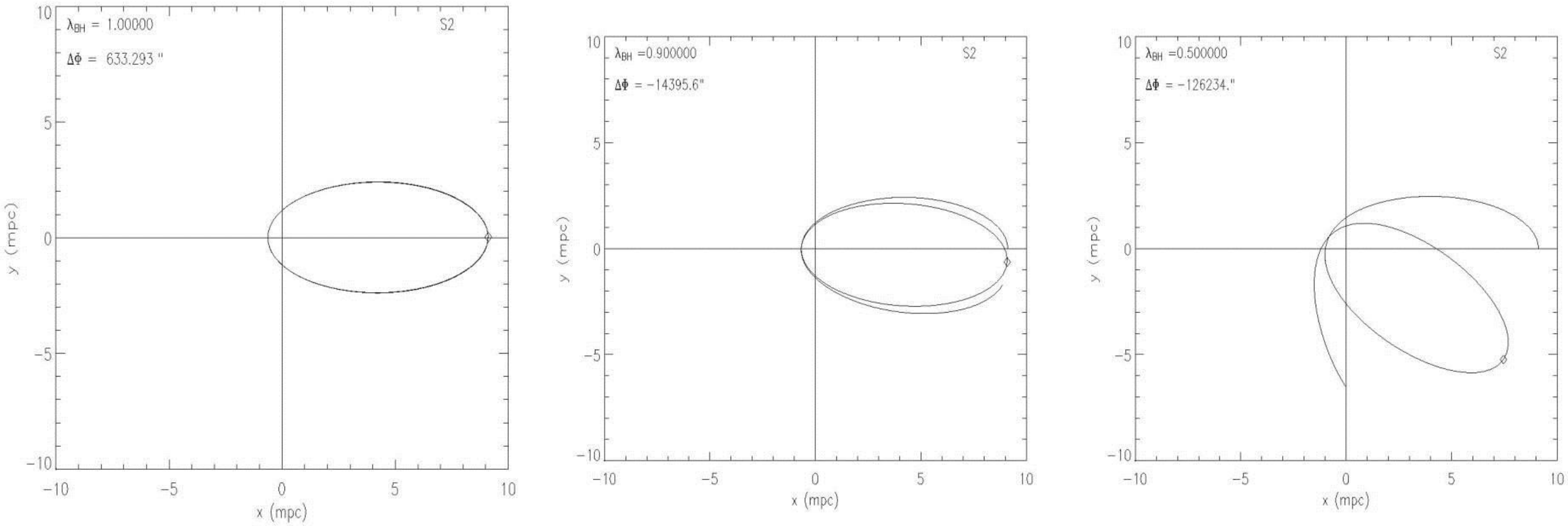


Figure 20: Post Newtonian orbits for different values of the black hole mass fraction λ_{BH} are shown for the S2 star (upper panels). Here, we have assumed that the Galactic central black hole is surrounded by a stellar cluster whose density profile follows a Plummer model with $\alpha = 5$ and a core radius $r_c \simeq 5.8$ mpc. The periastron shift values in each panel is given in arcseconds.

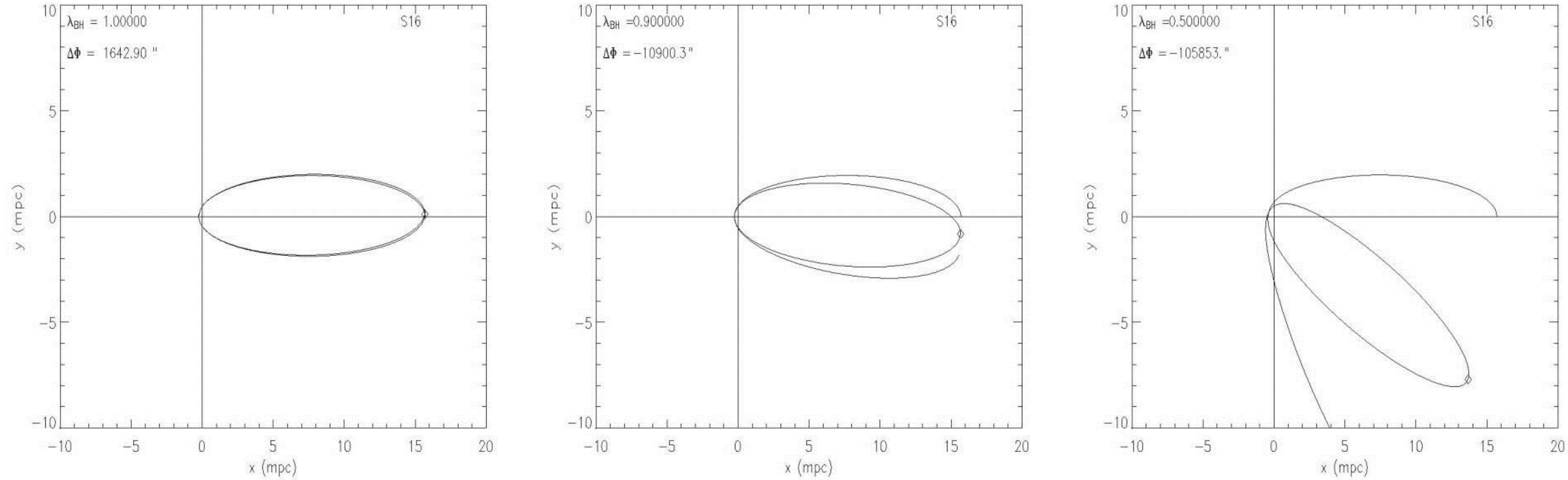
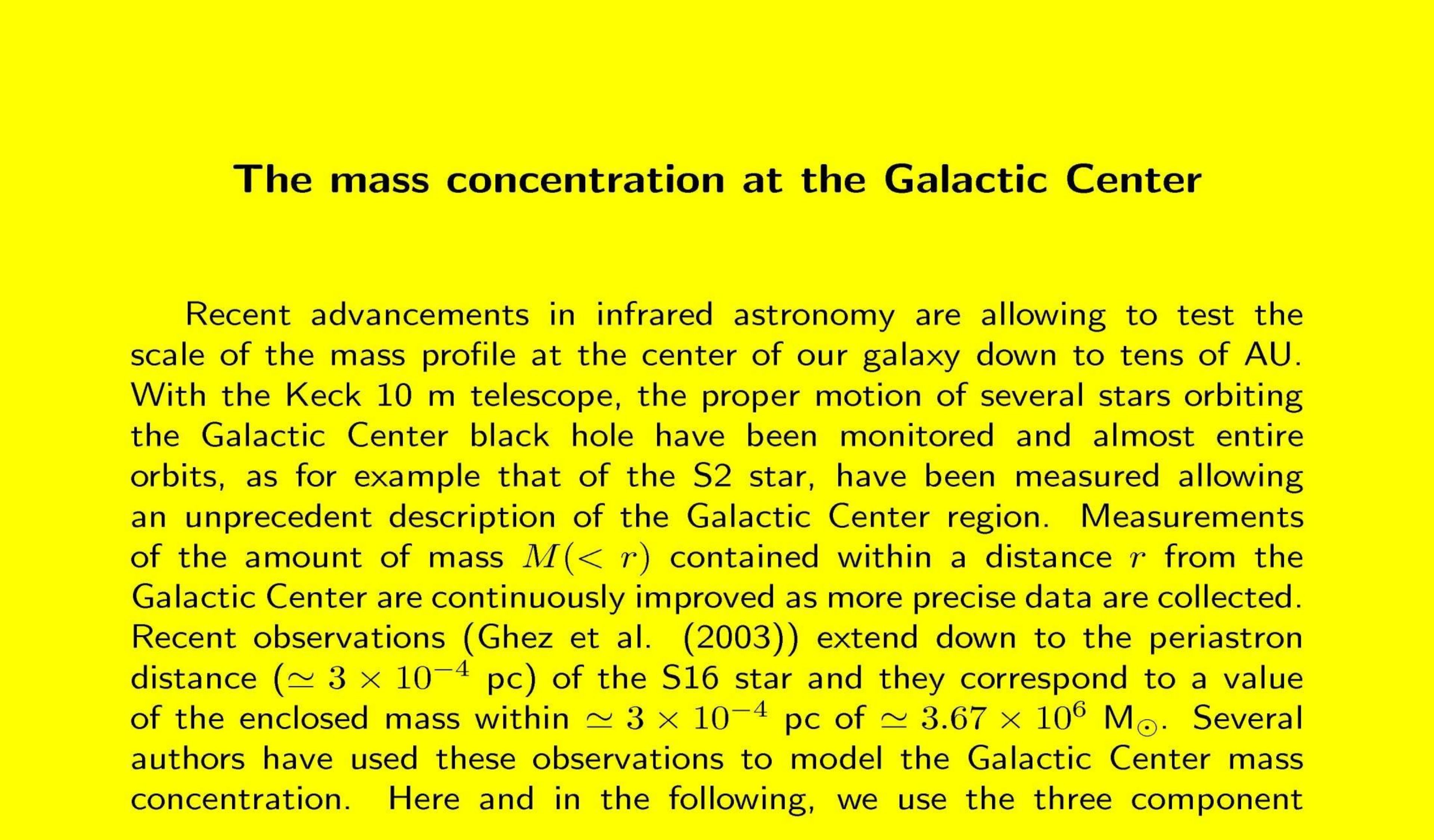


Figure 21: The same as in Figure 20 but for the S16–Sgr A* binary system. In this case, the binary system orbital parameters were taken from Ghez et al. (2005) assuming for the S16 mass a conservative value of $\simeq 10$ M$_\odot$.

AFZ, A.A. Nucita, F. De Paolis, G. Ingrosso, PRD 76, 062001 (2007)



The mass concentration at the Galactic Center

Recent advancements in infrared astronomy are allowing to test the scale of the mass profile at the center of our galaxy down to tens of AU. With the Keck 10 m telescope, the proper motion of several stars orbiting the Galactic Center black hole have been monitored and almost entire orbits, as for example that of the S2 star, have been measured allowing an unprecedent description of the Galactic Center region. Measurements of the amount of mass $M(<r)$ contained within a distance r from the Galactic Center are continuously improved as more precise data are collected. Recent observations (Ghez et al. (2003)) extend down to the periastron distance ($\simeq 3 \times 10^{-4}$ pc) of the S16 star and they correspond to a value of the enclosed mass within $\simeq 3 \times 10^{-4}$ pc of $\simeq 3.67 \times 10^{6}$ $M_{\odot}$. Several authors have used these observations to model the Galactic Center mass concentration. Here and in the following, we use the three component

model for the central region of our galaxy based on estimates of enclosed mass given by Ghez et al (2003, 2005) recently proposed by Hall and Gondolo (2006). This model is constituted by the central black hole, the central stellar cluster and the DM sphere (made of WIMPs), i.e.

$$M(<r) = M_{BH} + M_*(<r) + M_{DM}(<r) \ , \tag{17}$$

where M_{BH} is the mass of the central black hole Sagittarius A*. For the central stellar cluster, the empirical mass profile is

$$M_*(<r) = \begin{cases} M_* \left(\frac{r}{R_*}\right)^{1.6} \ , & r \leq R_* \\ \\ M_* \left(\frac{r}{R_*}\right)^{1.0} \ , & r > R_* \end{cases} \tag{18}$$

with a total stellar mass $M_* = 0.88 \times 10^6$ M$_\odot$ and a size $R_* = 0.3878$ pc.

As far as the mass profile of the DM concentration is concerned, Hall & Gondolo (2006) have assumed a mass distribution of the form

$$M_{DM}(<r) = \begin{cases} M_{DM}\left(\frac{r}{R_{DM}}\right)^{3-\alpha}, & r \le R_{DM} \\ M_{DM}, & r > R_{DM} \end{cases} \qquad (19)$$

M_{DM} and R_{DM} being the total amount of DM in the form of WIMPs and the radius of the spherical mass distribution, respectively.

Hall and Gondolo (2006) discussed limits on DM mass around the black hole at the Galactic Center. It is clear that present observations of stars around the Galactic Center do not exclude the existence of a DM sphere with mass $\simeq 4 \times 10^6 M_\odot$, well contained within the orbits of the known stars, if its radius R_{DM} is $\lesssim 2 \times 10^{-4}$ pc (the periastron distance of the S16 star in the more recent analysis (Ghez et al. 2005)). However, if one considers a DM sphere with larger radius, the corresponding upper value for M_{DM} decreases (although it tends again to increase for extremely extended DM configurations with $R_{DM} \gg 10$ pc). In the following, we will assume for definiteness a DM mass $M_{DM} \sim 2 \times 10^5 M_{\odot}$, that is the upper value for the DM sphere (Hall & Gondolo (2006)) within an acceptable confidence level in the range $10^{-3} - 10^{-2}$ pc for R_{DM}. As it will be clear in the following, we emphasize that even a such small value for the DM mass (that is about only 5% of the standard estimate $3.67 \pm 0.19 \times 10^6\ M_{\odot}$ for the dark mass at the Galactic Center (Ghez et al. 2005)) may give some observational signatures.

Evaluating the S2 apoastron shift [1] as a function of R_{DM}, one can further constrain the DM sphere radius since even now we can say that there is no evidence for negative apoastron shift for the S2 star orbit at the

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[1] We want to note that the periastron and apoastron shifts $\Delta\Phi$ as seen from the orbit center have the same value whereas they have different values as seen from Earth (see Eq. (23)). When we are comparing our results with orbit reconstruction from observations we refer to the apoastron shift as seen from Earth.

level of about 10 mas (Genzel et al. 2003). In addition, since at present the precision of the S2 orbit reconstruction is about 1 mas, we can say that even without future upgrades of the observational facilities and simply monitoring the S2 orbit, it will be possible within about 15 years to get much more severe constraints on R_{DM}.

Moreover, observational facilities will allow in the next future to monitor faint infrared objects at the astrometric precision of about 10 μas (Eisenhauer et al. 2005) and, in this case, previous estimates will be sensibly improved since it is naturally expected to monitor eccentric orbits for faint infrared stars closer to the Galactic Center with respect to the S2 star.

In Fig. 30, the mass profile $M(< r)$ (Ghez et al. 2003) obtained by using observations of stars nearby the Galactic Center is shown (solid line). The dotted line represents the stellar mass profile as given in Eq. (18), while the dashed lines are for DM spheres with mass $M_{DM} \simeq 2 \times 10^5$ M$_\odot$ and radii $R_{DM} = 10^{-3}$ and 10^{-2} pc, respectively.