The black hole at the Galactic Center: observations and models in a nutshell

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Abstract.
The Galactic Center (Sgr A*) is a peculiar place in our Galaxy (Milky Way). Our Solar system is located at a distance around 8 kpc from the Galactic Center (GC). There were a number of different including exotic ones such as boson stars, fermion balls, neutrino balls, a cluster of neutron stars. Some of these models are significantly constrained with consequent observations and now supermassive black hole with mass around $4 \times 10^6 M_\odot$ is the preferable model for GC. Moreover, one can test alternative theories of gravity with observations of bright stars near the Galactic Center and observations of bright structures near the black hole at the Galactic Center to reconstruct shadow structure around the black hole with current and future observational VLBI facilities such as the Event Horizon Telescope. In particular, we got a graviton mass constraint which is comparable and consistent with constraints obtained recently by the LIGO-Virgo collaboration.

1. Introduction
It is clear that the center of our Galaxy (Milky Way) is a very attractive target and astronomers observe it in different spectral bands from radio up to X-ray excluding optical and UV bands due to a presence of gas and dust along a line of sight [1]. Earlier, for the Galactic Center people proposed many theoretical models such as a dense cluster of stars, fermion balls, neutrino balls, boson stars etc, however, the preferable model is the supermassive black hole [2]. Clearly, that predictions for observations critically depend on choices of theoretical models, however, often it is very hard to distinguish theoretical models in observations as it was shown for shadow formation in the framework of boson stars and conventional black hole models [3]. To test gravitational potential one could analyze motions of test bodies. If astronomers use photons as test particles it would be possible to reconstruct a shadow shape in mm and sub-mm bands with current and future VLBI network such as the Event Horizon Telescope [4]. To interpret observational data one needs general relativity approach in the strong gravitational field limit [5, 6]. Another opportunity is to use bright stars or clouds of hot gas as tracers of gravitational
potential. In this case astronomers objects with large telescopes in IR band. we discuss such an option in the next section.

2. Observations of bright stars at the Galactic Center

There are two groups of astronomers who successfully observe bright stars near the Galactic Center in IR band. One group led by A. Ghez (UCLA, USA) use the twin ten meter Keck telescope in Hawaii. Results of their observations and interpretations may be found in [8, 9, 10, 16]. In [12] the astronomers discussed opportunities to constrain alternative theories of gravity with data on trajectories of bright stars. Another group of astronomers use 4 eight meter telescopes at the Paranal Mountain. R. Genzel (MPE & Berkeley University) is the leader of the group, results of observations of the group may found in [13, 14, 15]. In paper [14] it was claimed that gas cloud G2 may be used as a tracer to test metric near the Galactic Center, however, consequent observations showed probably the G2 object may be a star but not a gas cloud. Several years ago ESO and MPE (Garching) started to built the Very Large Telescope Interferometer (GRAVITY) and astronomers expected to reach angular resolution at a level around 10 micro-arcseconds for bright sources with GRAVITY facilities. First results were published recently [18]. In the future Thirty Meter Telescope (TMT) and European Extremely Large Telescope (E-ELT) will be built and it will give an opportunity to improve current orbit reconstructions for bright stars, therefore, the Galactic Center model will be significantly clarified.

3. Constraints on black hole parameters and gravity theories from trajectories of bright stars at the Galactic Center

3.1. Constraints on black hole parameters and extended mass distribution

As it was mentioned two leading groups of astronomers monitored bright IR stars at the Galactic Center for decades, see [8, 9, 10, 16, 13, 14, 15] and references therein. One of main object for observations of both teams was source 2 (or star S2 or S0-2) with period around 15 years, the pericenter distance around 120 AU, eccentricity $e \approx 0.89$, another star which may be used to improve the black hole parameters is S-38 with eccentricity $e \approx 0.8$ and orbital period around 19 years [16]. In paper [17] it was proposed to use observations for S55/S0-102 star to improve estimates for parameters of the black hole. In 2008 one period of observations for S2 has been finished. A famous relativistic advance (introduced by A. Einstein to explain the Mercury anomaly) for the object is around 1 mas [19, 21, 20] which is greater than a current accuracy for the orbit observations, however at the beginning the orbit reconstruction errors for orbit reconstruction were around 10 mas, therefore one should wait to observe the relativistic effect for S2 star. Sometimes, it is not necessary to monitor one revolution more for the orbit if an accuracy of orbit reconstruction is good enough.

In the case if there is only supermassive black hole and there is no bulk distribution of mass inside stellar orbit there is only relativistic advance (additional terms due to presence black hole spin in around 100 times smaller) [19, 21, 20] (see also recent discussions in [22, 23]). However, if a small fraction of mass distributed inside the orbit it should cause pericenter (and apocenter) shifts in the direction which is opposite to relativistic advance. Therefore, as it was shown in [20] even now one can constrain some theoretical models for dark matter distributions. Astroparticle physicists introduced such models to explain $\gamma$-ray flux from the Galactic Center with neutralino annihilation. In the future probably observations of bright stars will significantly constrain (or even rule out) a wide class of dark matter distributions at the Galactic Center [24].

3.2. Constraints on $R^n$ theory

If us the conventional general relativity we unavoidably face with dark matter (DM) and dark energy (DE) problems. As it was noted in [25] famous French astronomer U. J. Le Verrier
proposed a way to resolve any anomaly, namely, the first option is to add additional component into model, the second option is to change a fundamental law (the Newtonian gravity law in the Le Verrier’s case). To avoid DM and DE problems people suggested to introduce generalizations of Einstein – Hilbert Lagrangian and change scalar curvature $R$ with another function, generally speaking with arbitrary function $f(R)$ [26, 27, 28]. Using such a generalizations of gravity one can explain a number of cosmological and astrophysical phenomena such as an accelerating expansion of the Universe, flat rotation curves for spiral galaxies etc. But, in the framework of these theories sometimes gravity law has no Newtonian limit in a weak gravitational field approximation and one should check the validity of gravity law for all scales. For instance, alternative theory proposed in [27] does not fit observational data in Solar system. Another class of theories with $f(R) = R^n$ (the case $n = 1$ corresponds to GR) can describe accelerating expansion of the Universe and flat rotation curves and in these cases parameter $n$ has to be significantly differ from 1 ($n \in [1.5, 3]$), however as it was shown in [29] to fit observational data in Solar system $n \approx 1$ (it means that gravity theory should be very similar to the classical GR), therefore we have a contradiction with cosmological fits.

One can use observations of bright stars near the Galactic Center to test the alternative gravity law, and as it was shown in paper [30] analyzing observational data from Keck and VLT telescopes for S2 star orbit we should conclude that $n \approx 1$ and as it was pointed out earlier, it contradicts to suitable $n$ values obtained from cosmological SNeIa data and rotation curves of spiral galaxies. In paper [31] we considered a central object and a stellar cluster in the framework of alternative theory of gravity and concluded that a presence of cluster does not change our previous conclusions that $n \approx 1$ and a gravity theory should be very close to GR.

3.3. Constraints on Yukawa gravity theory

As it was discussed in [33] $f(R)$ theories of gravity may have Yukawa limit in a weak gravitational field approximation and different authors successfully used the Yukawa like gravity to fit observational data for spiral galaxies and galactic clusters.

In paper [33], we used the Yukawa like gravity to constrain parameters of the potential with S2 star orbit data collected in observations of VLT and Keck telescopes. So, we considered the following potential

$$\Phi(r) = -\frac{GM}{(1 + \delta)r} \left[ 1 + \delta e^{- \frac{r}{\Lambda}} \right], \quad (1)$$

where $\Lambda$ and $\delta$ are parameters of the Yukawa potential.

In the paper [33] we showed that the preferable range of $\Lambda$ parameter in the case of S2 star and it has to be $\Lambda \in [5000, 7000]$ AU and we found that it is very difficult hard to constrain on $\delta$ parameter due behavior of $\chi^2$ function. We also found that the same the same $\delta = 1/3$ may be used to observational data for S2 star orbit and for galactic clusters and rotation curves of spiral galaxies.

3.4. Constraints on massive graviton theory

Many years ago Fierz and Pauli introduced a theory of massive gravity [34] (see a simple introduction in [35]). After that later a lot of defects have been found in massive theories of gravity such as a presence of ghosts, discontinuities for vanishing graviton mass. In last years, theorists overcome many technical problems [36, 37].

Yukawa modification of a Newtonian potential may be written in the following form [7, 35, 38]

$$V(r) = \frac{GM}{r} \exp(-r/\lambda_g). \quad (2)$$
C. Will discussed an opportunity to evaluate a graviton mass with an analysis of delays of gravitational waves in respect to electromagnetic radiation from supernovae or GRB. One can obtain also constrain graviton mass analyzing a structure of gravitational wave signal because if graviton has a mass then gravitons with higher masses propagate faster. This idea has been used by the LIGO-Virgo collaboration to evaluate a graviton mass [7, 38].

Using S2 orbit data obtained with VLT and Keck telescopes we found that with 90% confidence level we have $\lambda_g > 2900$ AU $= 4.3 \times 10^{14}$ km or $m_g < 2.9 \times 10^{-21}$ eV [39, 40, 41, 42].

In February 2016 the LIGO-Virgo collaboration reported about the discovery of gravitational waves from merger of binary black holes with masses about 30 $M_\odot$ [43], moreover, it was claimed that there is the graviton mass constraint $1.2 \times 10^{-22}$ eV. So, the LIGO-Virgo collaboration not only discovered gravitational waves and an existence of binary black holes with high stellar masses but they obtained also the result of constraints on possible generalizations of GR considering massive gravity theories. In June 2017 the LIGO-Virgo collaboration reported about the discovery of the third GW event from mergers of the BHs with 31 and 19 solar masses at redshift $z=0.19$ and improved the graviton mass constraint $m_g < 7.7 \times 10^{-23}$ eV [44]. The LIGO graviton mass constraint is in around 40 times better than our bound obtained from an analysis of S2 star trajectory, but our estimate is independent and it may be improved with current and future observational data as it was noted in [12, 45].

4. Shadows for the black hole at the Galactic Center
In papers [46, 47] the authors considered a toy model for a shadow formation around a black hole. For the case of the Galactic Center the size of the shadow is around 50 $\mu$as. The shadow may be detectable at mm and sub-mm bands while in cm band scattering is spoiling black hole images [46, 47]. Consequent simulations and observations have basically confirmed these claims. It was significant progress to reach better angular resolution in mm-band for the Sgr A* [48], and Doeleman et al. claimed that found the smallest spot with a size $37^{+16}_{-10}$ $\mu$as [48] and the size is comparable with shadow size evaluated in the framework of the simple model. The observations have been done with VLBI technique. In the future radioastronomers plan to create world wide VLBI network [4] and they call it as The Event Horizon Telescope because the angular resolution of the network will be better than the angular size of the event horizon for the Galactic Center or for the center of galaxy M87. One can find theoretical investigations sizes and structures of shadows in papers [49, 50, 51, 52, 53].

5. Conclusions
One can use precise observations of bright stars near the Galactic Center to check alternative theories of gravity and to investigate a presence of an extended mass distribution near the Galactic Center. One can the graviton mass constraint from an analysis of S2 star trajectory and the bound is consistent and comparable with the constraint presented recently by the LIGO collaboration.

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