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Gravity theory tests with observations of stars near the black hole at the Galactic Center

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Abstract.
One could say that 2018 is very special year since 55 years ago quasars were discovered, the Kerr solution has been found and the First Texas Symposium on Relativistic Astrophysics has been organized. In addition, 50 years ago, in 1968 the pulsar discovery paper has been published and the black hole concept has presented by J. A. Wheeler in his groundbreaking paper which was based on his report in December 1967. In last years remarkable achievements have been done in gravitational physics and related observations, in particular, gravitational waves and binary black holes with high stellar masses have been discovered, VLT, Keck and GRAVITY observe trajectories of bright stars and gas clouds near the Galactic Center (GC) with improving accuracy. It is clear that the Galactic Center (Sgr A^*) is a specific place. Our Sun is located at a distance around 8 kpc from the Galactic Center (GC). Earlier, astronomers suggested 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 ruled out or significantly constrained with consequent observations. A supermassive black hole with mass around 4×10^6 $M_\odot$ is the most realistic model for GC. Precision 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 give opportunities to test alternative theories of gravity. In particular, we got a graviton mass constraint which is comparable and consistent with constraints obtained recently by the LIGO-Virgo collaboration. We consider opportunities to improve current graviton mass mass constraints with future observations of bright stars. Similarly, from an analysis of bright star trajectories one could constrain a tidal charge which was predicted by a gravity theory with an additional dimension.

1. Black hole concept

It is not easy to determine a birthday or birth year of any scientific concept. At the end of XVIII century the Reverend John Michell considered hypothetical stars with solar density and 500 solar radii, so light can not escape from a surface of such an object since its kinetic energy was not high enough in comparison with a potential energy [1] (later, the same problem was considered in [2] and it was considered in details in [3]). One could see historical aspects of the issue in [4, 5]. One of the first solutions of general relativity was spherically symmetric vacuum solution found by Schwarzschild [6], however, there is a question about an opportunity to use such a solution for real astrophysical objects. In 1939 A. Einstein investigated the issue and arrived at a negative answer. At the beginning the paper [7], he formulated a goal of his investigation: “There arises the question whether it is possible to build up a field containing such singularities with the help of actual gravitating masses, or whether such regions with vanishing g_{tt} do not exist in cases which have physical reality”. In other words, Einstein studied a reality of objects with event horizons. His conclusion was rather negative, namely, “The essential result of this investigation is a clear understanding as to why the “Schwarzschild singularities” do not exist in physical reality. Although the theory given here treats only clusters whose particles move along circular paths it does not seem to be subject to reasonable doubt that more general cases will have analogous results. The “Schwarzschild singularity” does not appear for the reason that matter cannot be concentrated arbitrarily”. In thirties of the XX century E. Stoner, S. Chandrasekhar, L.D. Landau found that there exists an upper mass limit for white dwarfs [11, 12, 13, 14]. As it was noted in [15] Landau contributed a lot in a development of the neutron star concept. Soon after the neutron discovery Baade and Zwicky claimed that formation of neutron stars could be observed as supernova explosions [16], a few years later Gamow found an upper mass limit for neutron stars in the framework of Newtonian approximation for a gravitational field of neutron stars [17] (however, the Gamow’s expression had a mistake which was corrected in [18]). Later, the Gamow’s result has been generalized by J. R. Oppenheimer and G. M. Volkoff [19] where the authors described gravity in the framework of GR approach. J. R. Oppenheimer and H. Snyder considered a dust ball which is forming Schwarzschild solution in a result of its collapse [8], but perhaps at this time people thought that their theoretical model is too simple and artificial to be correct. Later, Einstein’s assistant Peter Bergmann wrote in his book [9] ”In nature, mass is never sufficiently concentrated to permit a Schwarzschild singularity to occur in empty space” and as an argument Bergmann quoted the Einstein studies [7].

The first Texas Symposium on Relativistic Astrophysics has been organized in Dallas in 1963, quasars were discovered a few months before it and Roy Patrick Kerr found his solution which describes rotating black holes. Now the most popular models for quasar energy release are based on consideration of rotating black holes as central engines. Kip Thorne was reminding [10]: “The astronomers and astrophysicists had come to Dallas to discuss quasars; they were not at all interested in Kerr’s esoteric mathematical topic. So, as Kerr got up to speak, many slipped out of the lecture hall and into the foyer to argue with each other about their favorite theories of quasars. Others, less polite, remained seated in the hall and argued in whispers. Many of the rest catnapped in a fruitless effort to remedy their sleep deficits from late-night science. Only a handful of relativists listened, with rapt attention. This was more than Achilles Papapetrou, one of the world’s leading relativists, could stand. As Kerr finished Papapetrou demanded the floor, stood up, and with deep feeling explained the importance of Kerr’s feat. He, Papapetrou, had been trying for thirty years to find such a solution of Einstein’s equation, and had failed, as had many other relativists. The astronomers and astrophysicists nodded politely, and then, as the next speaker began to hold forth on a theory of quasars, they refocused their attention, and the meeting picked up pace”.

Usually, an introduction of black hole concept is associated with J. A. Wheeler, but such a concept has been used earlier at the first Texas Symposium on Relativistic astrophysics in December 1963 as it was explained by A. Rosenfield in a special review for “Life” magazine published on January 24, where he discuss the Hoyle — Fowler model for quasar energy release, namely “as Hoyle theorized, gravitational collapse gravitational collapse would be “catastrophe implosion” on a cosmic scale”, but criticizing the Hoyle’s model, Rosenfield wrote that “... instead of intensely radiating object sending out lavish quantities of light and radio energy, gravitational collapse would result it in invisible “Black hole” in the universe” [20]. A few days before a publication of the “Life” issue, on January 18, 1964 Ann Ewing reported about the the American

Association for the Advancement of Science meeting in Cleveland in January 1964 “Space may be peppered with “black holes” [21], therefore, in December 1963 at the First Texas Symposium and in January 1964 at the AAAS meeting astronomers and relativists discussed black holes in sky, however it is still unknown who were these persons, see, also discussions in book [22] and in article “50 years later, its hard to say who named black holes” by T. Siegfried in “Science News” where the author wrote ”but it didnt catch on until Wheeler began using it a few years later. “Perhaps Wheeler still gets credit”, Bartusiak said. “He never said he originated the term. What was important is that he had the authority to give the scientific community permission to use the term “black hole”. [1] Based on reminding by Hong-Yee Chiu who was a member of the Institute of Advanced Studies on Princeton from 1959 until 1961, it was noted that R. Dicke discussed a collapse of massive stars with a formation of something similar to“”black hole of Calcutta”, see for instance, records by John Zephaniah Holwell [23] where the authors reminded the historical case when after the fall of Fort Williams Siraj ud-Daulah, the Nawab of Bengal, ordered to place many British prisoners of war at a very small room in June 1756 (see also a popular book [24]). Therefore, probably Dicke introduced the term for the scientific community [22]. J.A. Wheeler was reminding circumstances which were stimuli to introduce the black hole concept [25]: “In the fall of 1967, Vittorio Canuto, administrative head of NASAs Goddard Institute for Space Studies, invited me to a conference to consider possible interpretations of the exciting new evidence just arriving from England on pulsars. What were these pulsars? Vibrating white dwarfs? Rotating neutron stars? What? In my talk, I argued that we should consider the possibility that at the center of a pulsar is a gravitationally completely collapsed object. I remarked that one couldn’t keep saying “gravitationally completely collapsed object” over and over. One needed a shorter descriptive phrase. “How about black hole?” asked someone in the audience. I had been searching for just the right term for months, mulling it over in bed, in the bathtub, in my car, wherever I had quiet moments. Suddenly this name seemed exactly right. When I gave a more formal Sigma XiPhi Beta Kappa lecture in the West Ballroom of the New York Hilton a few weeks later, on December 29, 1967, I used the term, and then included it in the written version of the lecture published in the spring of 1968 [26]. (As it turned out, a pulsar is powered by “merely” a neutron star, not a black hole.)...”[2] In his paper [26] Wheeler considered the Crab Nebula which is a supernovae remnant SN 1054 as a brilliant confirmation of Baade–Zwicky scenario for neutron star formation where it was suggested that neutrons stars could be formed in supernova explosions [16]. Really the object has been observed by Chinese astronomers for 21 months since July 4, 1054 (according to the Western chronology). The identification of old Chinese records with Crab Nebula has been done by Dutchman sinologist J. J. L. Duyvendak [28], see also consequent astronomical discussion by N. U. Mayall and J. H. Oort [29]. At the period of a preparation of these two manuscripts Duyvendak and Oort worked in University of Leiden (Oort worked in the Observatory of the University), while Mayall worked in the Lick Observatory (California, USA) and had intensive communications with Baade. Soon after a publication of these two papers [28, 29] W. Baade and R. Minkowski investigated properties of Crab Nebula and concluded that Chinese Nova 1054 A. D. was a supernova of type I [30, 31]. The Crab nebula was identified with a radio source in 1963 and as a X-ray source in 1964 and as a pulsar in 1968. There are the following conclusions from Wheeler’s considerations in [26]. First, sometimes, a time distance between an action and a result could be centuries (or even Millennium) and at this period one could think that the action was useless but it is not. Second, a scientific knowledge is a result of activity of skillfull people working in different areas. In addition, one could note that routine observations almost 1000 years ago and translation and interpretations of old historical record give crucial contribution in studies of nuclear matter

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[1] https://www.sciencenews.org/blog/context/50-years-later-it%E2%80%99s-hard-say-who-named-black-holes.

[2] The standard model in particle physics has been proposed in 1967, see an overview of foundations of the model and its development in [27], therefore, 1967–1968 were amazingly fruitful for physics.

which are still very important and interesting for a scientific community. Third, a scientific process is very fragile and it may be terminated due to many different reasons, for instance old historical records may be destroyed, forgotten or ignored and in this case a confirmation of the Baade– Zwicky scenario for NS formation will be incomplete. A rapid development of Mega Science facilities for studies of nuclear matter such FAIR (Facility for Antiproton and Ion Research) (Darmstadt, Germany) and Nuclotron Based Facility (NICA, Dubna, Russia) is an illustration of an importance of further investigations of nuclear matter and its evolution for a fundamental science. Therefore, these observations have an important value for fundamental physics and nuclear physics in particular, but a justification astronomical observations for a fundamental science could come many years later.

No doubt that the proper terminology is extremely important, however, according to my view, Wheeler's suggestion to use the black hole term consists of two important statements, first, in spite of infinite time of gravitating object for complete gravitational collapse, a distant observer could use a limiting metric which is result of the collapse, since after a finite time interval differences between a dynamical metric of collapsing matter and a static or stationary metric which describes a result of gravitational collapse are very small, therefore, one could use a simpler static (stationary) model. Second, Wheeler believed that black holes do exist as results of stellar collapses and as engines in AGNs and quasars. When the section was finished an interesting paper [32] was published where historical aspects of a black hole concept development were also discussed. A discussion of a relativistic astrophysics development before 1940 is presented in [33] in a more wider context.

2. Astrophysical black holes

Classical black holes do not emit particles and photons, but in 1974 S. Hawking discovered radiation of particle due to quantum tunneling [34] (long before the Hawking's paper publication Soviet physicist V. N. Gribov in his conversations with Ya. B. Zeldovich insisted that black holes have to radiate [35]). The Hawking radiation could be important for primordial black holes with masses significantly smaller than stellar ones. A subsequent analysis showed that the radiation for black holes with stellar masses and heavier is negligible in comparison with other astrophysical processes. An opportunity to discover black holes with observations of electromagnetic radiation from accreting matter has been discussed by E. Salpeter [36] and Ya. B. Zeldovich [37]. Evaluating the energy for inner most stable circular orbit in the Schwarzschild metric one could conclude that an energy release could be a few percent of accreting matter mass (or which is close to nuclear fusion), while for extreme Kerr metric such an energy release could be almost 50% of mass or comparable with annihilation.

2.1. Black holes with stellar masses

A model of disk accretion has been developed in [38, 39, 40, 41][3] and it was predicted that black holes with stellar masses could be found in X-ray stellar binary systems. A few dozen BH systems have been found in X-ray binaries with masses ($M_{BH} = 4 - 16 M_\odot$) and around one hundred neutron stars (NSs) as X-ray binaries [44, 45, 46]. We would like to note that there is a clear mass gap between NSs and BHs with stellar masses and sometimes even alternative theories of gravity have been used to explain such a phenomenon [47], however fine tuning for parameters of population synthesis gives an opportunity to explain such a puzzle [48, 49].

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[3] An interesting historical description of this period of theoretical studies of black holes in binaries is given firsthand by one of the authors of the disk accretion model in [42, 43].

2.2. Supermassive black holes in galactic centers
Usually supermassive black holes are associated with centers of galaxies and could evolve in interaction with their galaxies [50]. Their masses significantly exceed typical stellar masses and intermediate-mass black holes which could exist in centers of globular clusters. In active galactic nuclei black hole masses are evaluated with reverberation method or a spectroscopy of absorption and emission lines. Namely, variations in the strengths of the central source in a quasar will generate variations in the strengths and profiles of the emission lines. These "reverberations" (or "echos") in the emission lines will delay in respect to continuum variations. The reverberation method was suggested in [51] but similar ideas were proposed earlier in [52], see also [53, 45, 46] for subsequent development and more recent reviews.

2.3. Primordial black holes
As it was suggested many years ago, at the early stage of the Universe evolution black holes could be formed [54, 55] and their masses could rather small and Hawking radiation should be significant for such objects [56]. These black holes are called primordial or PBHs. At the moment PBHs are not discovered yet, however, they are very attractive as a response for many astrophysical puzzles such as a formation of supermassive black holes with high redshifts and discoveries of relatively heavy binary black holes with LIGO – Virgo gravitational interferometers [57].[4] If such binary black holes are results of stellar evolution then their progenitors should have very strong stellar wind and binary black holes are placed not in vacuum but in matter and at the moment of a final merger of black holes an gravitational wave energy around $3M_\odot c^2$ (as for the first GW event GW150914) was released as strong gravitational wave it is naturally to expect to detect electromagnetic counterpart. It was proposed PBHs with intermediate masses as objects forming dark matter [58]. Astrophysical applications of PBHs with different masses are considered in a number of review [59, 60, 61] (see also references therein).

3. Observations of bright stars near the Galactic Center
Since the closest supermassive black hole is located in our Galactic Center, this object is very attractive and astronomers observe the Galactic Center in different spectral band including γ, X-ray, IR, optical, radio and mm-band [62, 63, 64]. Moreover, such an object is a natural laboratory to test general relativity and its alternatives in a strong gravitational field limit. After observations of S2 star pericenter passage in May 2018 the GRAVITY collaboration reported about the discovery of general relativity effects for S2 star [65]. Similarly to observations of planets which give an opportunity for Newton to discover the universal gravity law or the Rutherford's analysis of α-particle trajectories to investigate atomic structure one could use bright stars as test bodies to evaluate a gravitational potential at the Galactic Center. Now there are two groups observing bright IR stars near the Galactic Center with largest telescopes equipped with adaptive optics facilities. One (US) group uses the twin Keck telescopes with 10 m diameters at Hawaii, another ESO-MPE group uses four VLT telescopes with 8 m diameters. Generally speaking, results of these two groups are consistent and complimentary. Observations showed that stars are moving almost precisely along elliptical orbits and therefore, one could conclude that as a first approximation motions of these stars are fitting rather well with point like mass around $M_{SBH} = 4 \times 10^6\ M_\odot$ in the framework of Newtonian gravity law. One of the most interesting probe of a gravitational potential at the Galactic Center is S2 star. It has eccentricity $e = 0.88$, period $T = 16$ yr and an expected visible relativistic precession of its orbit is around $\Delta s \approx 0.83$ mas [66, 67] in assumption that extended mass distributions

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[4] After data analysis of two observational runs the LIGO–Virgo collaboration reported about discoveries of ten gravitational wave signals from binary black hole mergers and one signal from binary neutron star merger, see "GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs" compiled on November 30, 2018.

such as a stellar cluster or dark matter near the Galactic Center do not have a significant impact on relativistic precession of its orbit. Currently the Keck uncertainty in the S2 star orbit reconstruction is around $\sigma_{Keck} \approx 0.16$ mas [68], while for Thirty Meter Telescope(TMT) which will be constructed within a several years $\sigma_{TMT} \approx 0.015$ mas.

4. GRAVITY in action

4.1. Gravitational redshift of S2 star near its pericenter passage

There is a permanent improvement of accuracy of S2 star orbit reconstruction for both teams, for instance for MPE–ESO team, since in 1990s a precision of SHARP facilities were around 4 mas, in 2000s NACO had a precision around 0.5 mas, but in 2018 GRAVITY reached a precision around 30 μas [65]. In 2018 with these new GRAVITY data it was shown that GR approach in post-Newtonian (PN) approximation provide much better fit in comparison with the Newtonian approach. The GRAVITY collaboration estimated gravitational redshift in the orbit of S2 star near its pericenter passage and relativistic precession of its orbit and showed that observational data are much better fitted with GR model in the first PN approach than in comparison with Newtonian one. Therefore, general relativity successfully passed its test for the Galactic Center. It means that almost after 100 years after the confirmation of the GR prediction about a deflection of light during Solar eclipse in 1919 [69], astronomers checked GR prediction in much stronger gravitational field at high distances from our Solar system and Einstein's theory of relativity successfully passed one important test more. A theoretical approach for gravitational redshift evaluation if sources are moving in binary system was presented in [70, 71, 72]. In May 2018 S2 star passed pericenter and it is clear that relativistic corrections have to be taken at the period near this passage. At the pericenter S2 moves with a total space velocity $V_{\rm peri} \approx 7650$ km/s or $\beta_{\rm peri} = V_{\rm peri}/c = 2.55 \times 10^{-2}$ [65].[5] Taking into the PPN(1) correction a total gravitational redshift could expressed in the following form [70, 71, 72, 65]

$$z_{\rm GR} = \frac{\Delta\lambda}{\lambda} = B_0 + B_{0.5}\beta + B_1\beta^2 + \mathcal{O}(\beta^3), \tag{1}$$

where $B_1 = B_{1,tD} + B_{1,grav}$, $B_{1,tD} = B_{1,grav} = 0.5$, $B_{1,tD}$ is the special relativistic transverse Doppler effect, $B_{1,grav}$ is the general relativistic gravitational redshift , $B_{0.5} = \cos\theta$, where θ is the angle between the velocity vector and line of sight [71], the total redshift B_0 which is independent on a star velocity β

$$B_0 = z_\odot + z_{\rm gal} + z_{\rm star} + \frac{1}{2}\Upsilon_0, \tag{2}$$

therefore the redshift B_0 consists of four parts, $z_\odot$ is due a total motion of the Sun and the Earth in respect to Galactic Center and blue shift due to potential of the Sun and the Earth, $z$gal is redshift due to Galaxy potential, $z_{\rm star}$ is redshift due to the star's potential, the redshift $\frac{1}{2}\Upsilon_0 = \frac{GM}{2a}$ due to the location of star in the SMBH potential [71]. The GRAVITY collaboration estimated the total redshift from spectroscopical observations and concluded that it corresponds to $z \approx \frac{200\ km/s}{c}$ [65]. One could represent the total redshift obtained from spectroscopical observations in the form [65] $z_{\rm tot} = z_K + f(z_{GR} - z_K)$, where $z_K = B_0 + B_{0.5}\beta$ is the Keplerian redshift, $f = 0$ corresponds to Keplerian (Newtonian) fit, while $f = 1$ corresponds to PPN(1) fit. The GRAVITY collaboration found that $f = 0.90 \pm 0.09|_{\rm stat} \pm 0.15|_{\rm sys}$ and the authors also concluded that S2 data are inconsistent with a pure Newtonian dynamics. Since f-value is slightly less than its expected value estimated with pure PPN(1) fit, perhaps an extended mass

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[5] On December 4, 2018 it was reported precise measurements of gravitational redshifts with Galileo satellites [73].

distribution of stellar cluster should be taken into account in this model and in this case future observations of relativistic redshifts (and astrometric monitoring the bright stars) will help to evaluate parameters of an extended mass distribution. Similar the GRAVITY collaboration evaluated f-value from observational data comparing Schwarzschild precession and Newtonian fit for a point like mass (without any precession) and they concluded that the f-value is much closer to GR quantity ($f = 0.94 \pm 0.09$).

4.2. Observations of motions of hot spots near ISCO

The GRAVITY collaboration observed two bright flares on July 22 and July 28, 2018, as well as a fainter flare on May 27, 2018 [74]. The authors claimed that the position centroids exhibited clockwise looped motion on the sky, on scales of typically 150 μas over a few tens of minutes, corresponding to about 30% the speed of light. Meanwhile, the flares exhibited continuous rotation of the polarization angle, with about the same 45(±15) min period as that of the centroid motions. Typical radius of spot orbits are around 7 M_{SBH} (in mass units), while the ISCO radius is 6 M_{SBH} for a Schwarzschild black hole.

4.3. Spacially resolved rotation of broad line region for 3C273

Recently GRAVITY collaboration reported that the team found a spatial offset (with a spatial resolution of 10^{-5} arcseconds, or about 0.03 parsecs for a distance of 550 million parsecs) between the red and blue photo-centres of the broad Paschen-α line of the quasar 3C 273[6] perpendicular to the direction of its radio jet [78]. The data are fitted by a broad-line-region model of a thick disk of gravitationally bound material orbiting a black hole of 3×10^8 solar masses. The authors concluded that disk radius is around 150 light days and earlier a radius of 100400 light days was found previously using reverberation mapping, therefore, new estimates are consistent with previous ones.

5. Constraints on alternative theories of gravity with observations of bright stars near the Galactic Center

5.1. Graviton mass constraints

If graviton is massive a number of different ways to constrain a graviton mass from astronomical observations could be used [80, 79]. The LIGO-Virgo collaboration reported about the first detection of gravitational waves from a merger of two black holes (it was detected on September 14, 2015 and it is called GW150914) [81]. Moreover, the team constrained the graviton Compton wavelength $\lambda_g > 10^{13}$ km which could be interpreted as a constraint for a graviton mass $m_g < 1.2 \times 10^{-22}$ eV [81]. Constraints on speed of gravitational waves from binary neutron star merger (GW170817) have been found $-3 \times 10^{-15} < (v_g - c)/c < 7 \times 10^{-16}$ [82]. Graviton energy is $E = hf$, therefore, assuming a typical LIGO frequency range $f \in (10, 100)$, from the dispersion relation one could obtain a graviton mass estimate $m_g < 3 \times (10^{-21} - 10^{-20})$ eV which a slightly weaker estimate than previous ones obtained from binary black hole signals detected by the LIGO team [83]. Assuming Yukawa gravitational potential of a form $\propto r^{-1} \exp(-r/\lambda_g)$ this result indicates that it can be used to constrain the lower bound for Compton wavelength λ_g of the graviton, i.e. the upper bound for its mass $m_{g(upper)} = h\,c/\lambda_g$. In paper [84] we obtained constraints on Yukawa gravity from observational data on S2 star orbit. Later, we found constraints on graviton mass $m_g < 2.9 \times 10^{-21}$ eV from avaliable observational data [85] (see also [86, 87, 88] for more details). In these considerations we used available data

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[6] 3C 273 is the first quasar ever been identified. It was observed with Parkes Radio Telescope by Lunar occultation method [75]. M. Schmidt found its redshift $z \approx 0.158$ with Palomar 200-in telescope [76], while J. B. Oke evaluated its flux in optical band. 3C273 is the closest and brightest quasar. According to the standard paradigm supermassive black holes in quasar centers are important components of quasar engines.

constrain graviton mass. Later, Keck group followed our ideas to improve our estimates with new observational data $m_g < 1.6 \times 10^{-21}$ eV [68]. In paper [89] we evaluated perspectives to improve a graviton mass estimate with future observational data for S2 and other bright stars observed with VLT and Keck telescopes, in particular, we evaluated orbital precession for Yukawa potential and obtained an upper limit for a graviton mass assuming that GR prediction about orbital precession will be confirmed with future observations.

As it was shown in [89] the longest Compton wavelength could be expressed as

$$\Lambda \approx \frac{c}{2}\sqrt{\frac{(a\sqrt{1-e^2})^3}{3GM}} \approx \sqrt{\frac{(a\sqrt{1-e^2})^3}{6R_S}}, \tag{3}$$

or after observations of bright stars for several decades an upper bound for a graviton mass could reach around 5×10^{23} eV.

5.2. *Tidal charge constraints*

The line element of the spherically symmetric Reissner–Nordström–de-Sitter metric is

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2, \tag{4}$$

where $f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2} - \frac{1}{3}\Lambda r^2,$ M is a black hole mass, Q is its charge and Λ is cosmological constant. In the case of a tidal charge [90], Q^2 could be negative. In paper [91] it was shown that a total relativistic advance for metric (4) in PPN(1) approximation is

$$\Delta\theta(total) := \frac{6\pi M}{L} - \frac{\pi Q^2}{ML} + \frac{\pi\Lambda a^3\sqrt{1-e^2}}{M}. \tag{5}$$

and apocenter shift dependences on eccentricity and semi-major axis are the same for Schwarzschild and Reissner–Nordström cases while corresponding factors ($6\pi M$ and $-\frac{\pi Q^2}{M}$) are different, therefore, it is very hard to distinguish a presence of a tidal charge and black hole mass evaluation uncertainties. For $Q^2 > 0$, there is an apocenter shift in the opposite direction in respect to GR advance. In paper [91] bounds in Q^2 and Λ are presented for current and future accuracies for Keck and Thirty Meter telescopes which were discussed [68]. Similarly to [91, 92] if we adopt uncertainty $\sigma_{\rm GRAVITY} = 0.030$ mas for the GRAVITY facilities as it was used in [65] ($\delta_{\rm GRAVITY} = 2\sigma_{\rm GRAVITY}$) or in this case $\Delta\theta(GR)_{S2} = 13.84\delta_{\rm GRAVITY}$ for S2 star and assuming again that GR predictions about orbital precession of S2 star will be confirmed with $\delta_{\rm GRAVITY}$ accuracy (or $\left|\frac{\pi Q^2}{ML}\right| \lesssim \delta_{\rm GRAVITY}$), one could conclude that $|Q^2| \lesssim 0.432M^2,$ or based on results of future observations one could expect to reduce significantly a possible range of Q^2 parameter in comparison with a possible hypothetical range of Q^2 parameter in comparison with current and future Keck data.

6. Conclusions

Precise observations of bright stars near the Galactic Center is very efficient tool to check alternative theories of gravity and to investigate a presence of an extended mass distribution near the Galactic Center. One could obtain 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. In our current studies we discuss an opportunities to evaluate parameters of supermassive black hole, stellar cluster and dark matter cloud near the Galactic Center or evaluate parameters of alternative gravity model analyzing apocenter (pericenter) advance after at least one star revolution, however, in the future we will have a possibility to evaluate a static gravitational potential at the Galactic Center analyzing only small part of stellar orbit similarly to [93], where it was shown even around 40% of stellar phase coverage is enough for an orbit reconstruction. However, if a contribution of time-dependent component of gravitational potential caused by stellar encounters is significant an orbit reconstruction problem may be more complicated.

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