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CONSTRAINTS ON GRAVITON MASS FROM S2-LIKE STAR ORBITS AROUND Sgr A*

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Abstract. Here we present our achieved results on the bounding graviton mass by the observed orbits of bright stars around Sgr A*. We used available observations of the S-star orbits in our Galactic center. By comparison of these stellar orbits with their simulated orbits in Yukawa gravitational potential, we estimated the constraints on the parameters of this modified theory of massive gravity. Then, we connected one of these parameters with the Compton wavelength of the graviton and used it for estimation of the graviton mass. In that way we obtained a new method of determining the upper limit of graviton mass, completely independent from other methods published until now. The constraints on the Compton wavelength of the graviton and its mass, obtained using this method, were in a good agreement with the coresponding LIGO results.

1. INTRODUCTION

Our researches connected with graviton mass, which were initiated as one of the topics of the successfully finished national project 176003 ”Gravitation and the large scale structure of the Universe”, are further developing in the scope of new national projects ”Gravitation and cosmology” and ”Gravitation and astroparticle physics”, funded by Ministry of Science, Technological Development and Innovations of the Republic of Serbia. This scientific research has been done at the Astronomical Observatory Belgrade, in cooperation with Vina Institute of Nuclear Sciences.

The results of our researches regarding bounds on graviton mass are presented at more national and international conferences (poster session, short talks, invited talks, seminars), and the papers are published in proceedings and refereed journals, as well. At the end of this paper we give the bibliography of the papers published on this topic.

2. GRAVITON AND ITS MASS

Elementary particles of the Standard Model consist of leptons and quarks (there are 24 of them in total: six leptons and six quarks, as well as the same number of their antiparticles). Elementary particles interact in the way they are exchanging quants of interaction field, i.e. the calibration or gauge bosons. Graviton is a gauge boson of the gravitation interaction which acts on massive particles. Here we give some of its characteristics:

- intrinsic spin (in units of reduced Planck constant $\hbar$): $\sigma = 2$ (tensor boson),
- charge (in units of elementary charge e): $Q = 0$, i.e. it is electrically neutral,
- mass: if it has a mass, then it is very small (we calculate its upper limit).

Graviton, a spin-2 (tensor) and electrically uncharged gauge boson of the gravitational interaction, according to General Relativity travels along null geodesics at the speed of light c (like photon). However, according to some alternative theories, gravity is propagated by a massive field, i.e. by a graviton with some small, nonzero mass m_g. Let us mention here that the existence of massive graviton plays a fundamental role in modern physics, and its non-zero mass leads to modifications of the speed of gravitational waves depending on their frequencies.

3. MASSIVE GRAVITY THEORIES

Theories of massive gravity, which are first proposed by Fierz & Pauli (1939), make the following two important predictions (Will, 1998):

1. the effective Newtonian potential has a Yukawa form: $\Phi(r) \propto r^{-1}\exp(-r/\lambda_g)$, where $\lambda_g = h/(m_g\, c)$ is the Compton wavelength of graviton, and
2. massive graviton propagates at an energy (or frequency) dependent speed v_g: $v_g^2/c^2 = 1 - m_g^2 c^4/E^2 = 1 - h^2c^2/(\lambda_g^2 E^2) = 1 - c^2/(f\lambda_g)^2$.

Gravitational potential with a Yukawa correction can be obtained in the Newtonian limit of any analytic $f(R)$ gravity model given by the following action (Capozziello et al. 2014):

$$\mathcal{S} = \int d^4x\sqrt{-g}\,[f(R) + \mathcal{X}\mathcal{L}_m]\,, \quad \mathcal{X} = \frac{16\pi G}{c^4}. \tag{1}$$

In such a case, the gravitational potential in the weak field limit is given by:

$$\Phi(r) = -\frac{GM}{(1+\delta)r}\left(1 + \delta e^{-\dfrac{r}{\Lambda}}\right), \tag{2}$$

where Λ is the range of Yukawa interaction and δ is a universal constant.

The limits on graviton mass can be obtained through different methods in modified gravity theories. The experimental limits to m_g[1] have been set based on a Yukawa potential, dispersion relation, or other modified gravity theories (Particle Data Group 2024). The massive gravity theories are tested at different astrophysical and cosmological scales. Thus, in addition to the ground and space-based gravitational wave detectors such as LIGO/Virgo or LISA, the graviton mass can be also determined from observations in electromagnetic band of gravitational systems such as: Solar System planetary astrometric data, orbits of S-stars around Sgr A*, binary pulsars, galactic clusters, black holes and their mergers, and weak gravitational lensing. See, for instance, m_g from constrains to the range of Yukawa gravity interaction from S-star orbits around black hole at Galactic Center obtained by Zakharov et al. (2016a); Jovanović et al. (2023). Or, for example, Jovanović et al. (2024a,b) analyzed the Schwarzschild precession of S2 in the framework of Yukawa gravity theory, and set an

[1] Particle Data Group, 2024: `https://pdg.lbl.gov/2024/listings/rpp2024-list-graviton.pdf`

upper limit to the mass of the graviton, which is compatible with limits from aLIGO gravitational-wave data.

4. RECENT RESULTS ON GRAVITON MASS CONSTRAINTS

With aim of obtaining the constraints on the parameters of the Yukawa-like gravitational potentials, as well as on the graviton mass m_g, in our recent investigations we studied the trajectories of bright S-stars around Sgr A* at Galactic Center (GC), representing the central supermassive black hole (SMBH) of our Galaxy, in the frame of Yukawa gravity (see e.g. Borka et al. 2013, 2023; Capozziello et al. 2014; Jovanović et al. 2021, 2023, 2024a,b; Zakharov et al. 2016a,b, 2017a,b,c, 2018a,b,c,d, 2020). For that purpose we used combined astrometric observations of the S-star orbits by both Very Large Telescope (VLT) and Keck telescope available in Gillessen et al. (2017), as well as the recent results by the GRAVITY Collaboration about their detection of the Schwarzschild precession in the orbit of S2 star (GRAVITY Collaboration 2020, 2022).

In these investigations we assumed that the parameter Λ of the Yukawa-like gravitational potential, representing the range of interaction, corresponds to the graviton Compton wavelength λ_g. Besides, we also assumed that the orbital precession in Yukawa gravity should be close to the prediction of General Relativity (GR) for Schwarzschild precession. This enabled us to obtain the constraints on the graviton mass m_g in two different ways:

1. by direct fitting of the simulated orbits in Yukawa gravity into the corresponding observed orbits of S-stars, and
2. from the factor f_{SP} under which the observed orbital precession deviates from the Schwarzschild precession in GR[2], and which was recently measured by the GRAVITY Collaboration.

Regarding the first approach, direct orbital fitting in the frame of Yukawa gravity was performed by minimization of the reduced χ^2 statistics using the differential evolution optimization method, implemented as Python Scipy function `scipy.optimize.differential_evolution` (detailed description of the fitting procedure can be found in Jovanović et al. 2024b). An example of such orbital fitting in the case of S2 star and universal constant of $\delta = 1$ is presented in Fig. 1, while the resulting best-fit values of the parameters, obtained for $\chi^2_{\rm red} = 1.1084$, are given in Table 1. The best-fit value for the graviton Compton wavelength of $\lambda_g = 5.8 \pm 0.98 \times 10^4$ AU corresponds to the graviton mass of $m_g = 142.9 \pm 24.1 \times 10^{-24}$ eV.

In the second approach, we first derived the following relation between the parameter Λ and f_{SP} when universal constant is $\delta = 1$ (Jovanović et al. 2023, 2024a,b):

$$\Lambda(P, e; f_{SP}) \approx \frac{cP}{4\pi}\sqrt{\frac{(\sqrt{1-e^2})^3}{3(f_{SP}-1)}}, \tag{3}$$

for which Yukawa gravity results with practically the same orbital precession as GR in case of a star with orbital period P and eccentricity e. Taking that the graviton Compton wavelength $\lambda_g = \Lambda$, we then obtained the corresponding estimates for the graviton mass m_g in the case of different S-stars. Table 2 presents several such

[2]Factor f_{SP} in GR is equal to 1 and in Newtonian gravity to 0.

estimates in the case of S2 star which are obtained for the best-fit value of f_{SP} given in GRAVITY Collaboration (2020): $f_{SP} = 1.10 \pm 0.19$, as well as for the following three upper bounds which are 1σ compatible with the GR value of $f_{SP} = 1$:

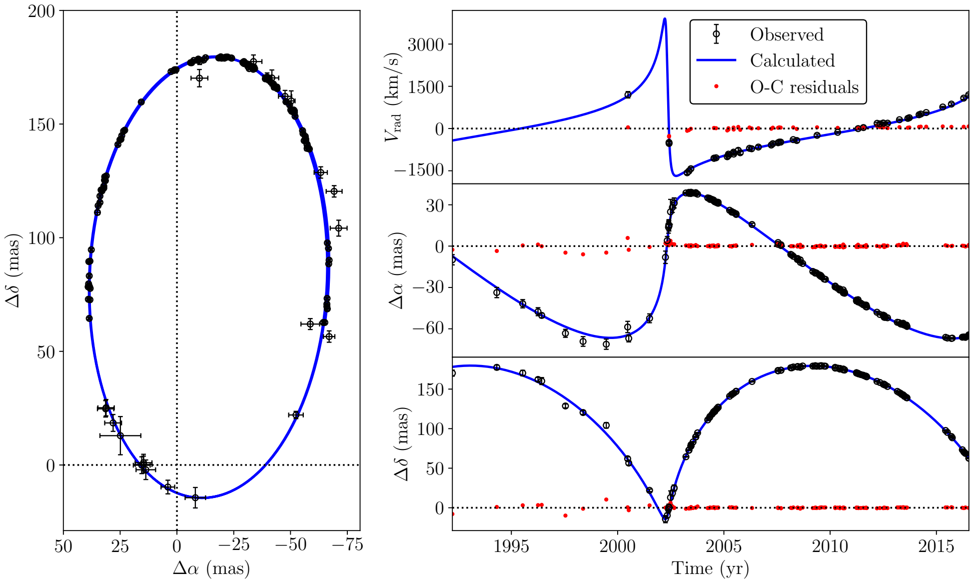

Figure 1: *Left:* Comparison between the best-fit simulated orbit of the S2 star in Yukawa gravity (blue solid line), and the corresponding astrometric observations from Gillessen et al. (2017) (black circles with error bars). *Right:* The same for the radial velocity of the S2 star (top), as well as for its α (middle) and δ (bottom) offset relative to the position of Sgr A* at the coordinate origin. Red dots in the right panels denote the corresponding O-C residuals.

Table 1: Best-fit values of the graviton Compton wavelength λ_g, SMBH mass M, distance R to the GC and the osculating orbital elements $a, e, i, \Omega, \omega, P, T$ of the S2 star orbit.

Parameter	Value	Fit error	Unit
λ_g	5.8	0.98	10^4 AU
M	4.10	0.579	$10^6\ M_\odot$
R	8.30	0.246	kpc
a	0.1229	0.00527	arcsec
e	0.8787	0.01213	
i	134.90	2.049	°
Ω	224.51	6.840	°
ω	62.70	5.781	°
P	16.05	0.541	yr
T	2018.29626	1.629346	yr

$f_{SP} = 1.19 \pm 0.19$, $f_{SP} = 1.16 \pm 0.16$ and $f_{SP} = 1.144 \pm 0.144$. These 1σ measurement errors are taken from GRAVITY Collaboration (2020, 2022).

Table 2: The Compton wavelength of the graviton λ_g, its mass m_g, as well as their relative and absolute errors, calculated for four different values of f_{SP} in the case of S2 star.

f_{SP}	Δf_{SP}	$\lambda_g \pm \Delta\lambda_g$ (AU)	$m_g \pm \Delta m_g$ (10^{-24} eV)	R.E. (%)
1.100	0.190	4.7e+04 ± 4.5e+04	176.6 ± 170.0	96.3
1.190	0.190	3.4e+04 ± 1.7e+04	243.5 ± 124.8	51.3
1.160	0.160	3.7e+04 ± 1.9e+04	223.4 ± 114.6	51.3
1.144	0.144	3.9e+04 ± 2.0e+04	211.9 ± 108.7	51.3

As it can be seen from the presented results, our constraints on the graviton mass obtained using the above two methods are independent, but consistent with the corresponding LIGO's result of $m_g \leq 1.2 \times 10^{-22}$ eV estimated from the first gravitational wave signal GW150914 (LIGO/Virgo Collaboration, 2016).

In addition to the mentioned references, our graviton mass constraints are also presented and cited in the below Seminars and White Paper: **Seminar 1:** Vesna Borka Jovanović and Duško Borka, *Nobel prize for Physics for 2020 and our researches at this topic*, Seminar for geometry and applications, 22^{nd} October 2020, Mathematical Faculty, University of Belgrade; **Seminar 2:** Predrag Jovanović, *Observational cosmology and cosmological tests*, Seminar for geometry and applications, 8^{th} April 2021, Mathematical Faculty, University of Belgrade; **White Paper:** CosmoVerse White Paper - Addressing observational tensions in cosmology with systematics and fundamental physics (CA21136), Chapter "Modified gravity" (in preparation, 2024).

5. CONCLUSIONS

Here we presented a short overview of our recent results on the bounding graviton mass by analysis of the stellar orbits around Sgr A* in the frame of Yukawa gravity. For that purpose we used two different approaches based on: (i) direct orbital fitting and (ii) recovering the recently detected Schwarzschild precession in the orbit of S2 star using the Yukawa-like gravitational potential. The both approaches resulted with the constraints on the graviton mass which are independent, but consistent with the corresponding LIGO's estimate. The obtained results also demonstrate that the existence of massive graviton plays a fundamental role in modern physics, and that it is important to further develop this topic.

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